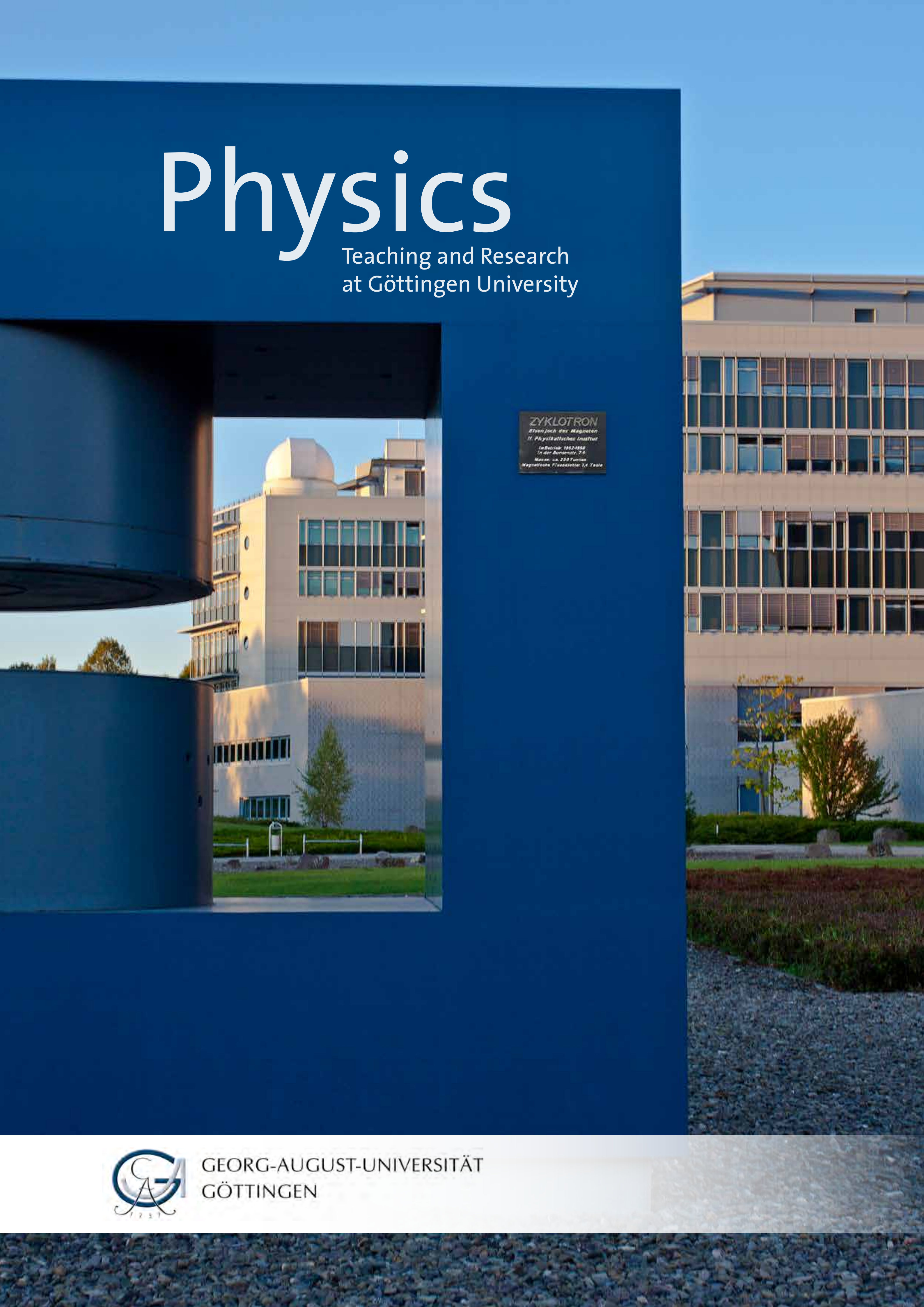

Physics

Teaching and Research
at Göttingen University

GEORG-AUGUST-UNIVERSITÄT
GÖTTINGEN

Greeting from the President

Physics has always been of particular importance for the Georg-August-Universität Göttingen. As early as 1770, Georg Christoph Lichtenberg became the first professor of Physics, Mathematics and Astronomy. Since then, Göttingen has hosted numerous well-known scientists working and teaching in the fields of physics and astronomy. Some of them have greatly influenced the world view of physics. As an example, I would like to mention the foundation of quantum mechanics by Max Born and Werner Heisenberg in the 1920s. And Georg Christoph Lichtenberg and in particular Robert Pohl have set the course in teaching as well.

It is also worth mentioning that Göttingen physicists have accepted social and political responsibility, for example Wilhelm Weber, who was one of the Göttingen Seven who protested against the abrogation of the constitutional law by King Ernst August in 1837. More recently, by signing the Göttingen declaration of 1957, eighteen nuclear scientists fought against the nuclear armament of the Federal Republic of Germany.

Physics in Göttingen experienced its heyday from about 1900 onwards, when famous scientists such as Werner Heisenberg, Max Born, Emil Wiechert and Karl Schwarzschild taught and did research here. When the National Socialists came into power in 1933, this golden age came to an abrupt end. Not until the end of the Second World War could physics in Göttingen start to successfully develop again.

Affiliated with the Faculty of Physics is the Institute of Astrophysics, which originated from the University Observatory. This observatory was founded in 1751 and has always been in close contact with physics since the time when Carl Friedrich Gauß was its first director. Furthermore, the Institute of Geophysics, which was founded in 1898, and the Institutes for Experimental Physics, dating back to Weber and later at the beginning of the 20th century to Pohl (1st Institute), Franck (2nd Institute) and Simon (3rd Institute), were part of the Faculty. James Franck came to Göttingen in 1921, at the same time as Max Born, when the Institute for Theoretical Physics was founded. In the second half of the 20th century, the 4th Institute, the Institute for Materials Physics, and, with the availability of synchrotrons as intensive X-ray sources, the Institute of X-ray physics were added. Today the Faculty of Physics comprises ten institutes, providing a broad spectrum of research disciplines and offering a large variety of lectures and seminars (teaching).

Current research focuses on solid state and materials physics, astrophysics and particle physics, biophysics and complex systems, as well as multi-faceted theoretical physics. Since 2003, the Physics institutes have been housed in a new physics building on the north campus in close proximity to chemistry, geosciences and biology as well as to the nearby Max Planck Institute (MPI) for Biophysical Chemistry, the MPI for Dynamics and Self Organization and the MPI for Solar System Research. The Faculty of Physics with its successful research activities and intense interdisciplinary scientific cooperations plays a central role within the Göttingen Campus. With this booklet, the Faculty of Physics presents itself as a highly productive and modern faculty embedded in an attractive and powerful scientific environment and thus perfectly prepared for future scientific challenges.

Prof. Dr. Ulrike Beisiegel
President of Georg-August-Universität Göttingen

Greeting from the Dean

The great history of the Faculty of Physics has been pointed out in her greetings by the President Prof. Beisiegel. Due to my absolute admiration for Carl Friedrich Gauß I reserved for myself a mention to him and his illuminating acting in Göttingen over half a century in astronomy, physics and towards the end of his life even in philology. After having studied mathematics from 1795 to 1798 at the University of Göttingen he returned at the Georgia Augusta 1807 when he was appointed Director of the Göttingen Observatory by the duke of Hanover and where he stayed until his death in 1855. At the time the government committed him with the huge task of the calibration and measurement revision of the whole kingdom, revealing a certain underestimation of Gauß genius. In the Theoria motus (1809) he describes the method of determining precisely unknown planet orbits from close observations without any assumption. At the same time Gauß engaged in Theoretical Dioptric Studies showing how to improve performances of telescopes. 1831 he started to think about Crystallography pioneering the notation later made known by Miller. In the same year, soon after the appointment of the physicist Wilhelm Weber at the Georgia Augusta he focused on basic physical questions in the field of Electromagnetism. With his 27 year younger Göttingen colleague he had a very fruitful and close collaboration leading e.g. to the practical realization of the first electric telegraph (1833-34).

Inspired by the spirit of Gauß the Faculty of Physics is characterized by a broad spectrum of disciplines in research and teaching such as astrophysics and cosmology, particle physics, solid state- and material physics, biophysics and complex systems. The wide offer attracts a lot of physics students to Göttingen, more than 200 beginners each year (bachelor of science and double-major bachelor). Since 2003 the whole Faculty of Physics is housed in the "new" Physics building located in the north Campus area where most research and teaching activities take place thus promoting scientific exchange and giving both the Faculty and its students a visible corporate identity.

The Faculty is structured in 10 Institutes that currently host 33 professorships. Collaborative laboratories join innovative competences in nanoscale photonic imaging and spectroscopy, in ultra-fast and high spatial resolution in-situ Electron Microscopy. Groups from the particle and astrophysics are involved in large-scale collaborations contributing e.g. with the development of detectors for the LHC at CERN and with the construction of instrumentation for the European Southern Observatory. The theoretical research activities are focused on Quantum Field Theory and Cosmology, Statistical Physics, Condensed Matter as well as Soft Matter and Biophysics. Therefore a fruitful basis for exchange and collaboration has been established within the Faculty.

Beyond that and due to the embedding in the stimulating Göttingen Campus many Faculty Principal Investigators successfully cooperate with colleagues from other science faculties and local non-university research institutions, such as the Max Planck Institutes. This is reflected in three current collaborative research programs funded by the DFG and the research centers Bernstein Center for Computational Neuroscience (BCCN) and Center for Molecular Physiology of the Brain (CMBP). We are very proud to count among our adjunct Professors the 2014 Nobel Prize Laureate in Chemistry Stefan Hell from the Max-Planck-Institut for Biophysical Chemistry. 2004 he was appointed as Honorarprofessor at the University of Göttingen after nomination by the Faculty of Physics.

Furthermore, the Faculty of Physics participates in national research networks in particle physics and condensed matter physics as well as international collaborations in the field of particle physics and astrophysics.

With the introduction of bachelor and master study programs also including the double-major Bachelor and Master of Education, and the structured graduate programs leading to the degrees of Dr. rer.nat. or Ph.D the process of comparability in the standards and quality of higher education qualification within Europe has been accomplished. For the Faculty of Physics, it was of utmost importance to transfer the recognized high quality of the previous diploma study program to the bachelor and master programs. Moreover, novel teaching concepts were implemented in the new study programs and a variety of choices for specialization are currently offered. With the new study programs, the faculty is also striving to open up internationally, e.g. with the Master of Science in English starting in 2016.

With this booklet, the Faculty of Physics presents itself as a modern and forward looking academic institution – yet conscious of its responsibility towards the achievements of our great predecessors – and gives an overview of its broad research spectrum, comprehensive teaching and modern infrastructure. I am convinced that the Faculty of Physics will be an inspiring place for scientific exchange more than ever. Scientists and students from all over the world are cordially welcome to visit and join the Faculty of Physics in Göttingen.

Angela

Prof. Angela Rizzi
Dean of the Faculty of Physics

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	Service Centre (for financial accounting)	
	Central mechanical workshop	
	Collection of lecture hall experiments	
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Institutes	I. Institute of Physics	Prof. Samwer
		Prof. Mathias
	II. Institute of Physics	Prof. Quadt
		Prof. Frey
		Prof. Hofsäss
		Prof. Lai
		Jun.-Prof. Schumann
	III. Institute of Physics	Prof. Enderlein
		Prof. Schmidt
		Prof. Wörgötter
	IV. Institute of Physics	Prof. Ropers
		Prof. Rizzi
	Institute for Nonlinear Dynamics	Prof. Geisel
		Prof. Bodenschatz
		Prof. Klumpp
	Institute for Theoretical Physics	Prof. Covi
		Prof. Kehrein
		Prof. Müller
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		Prof. N.N.
	Institute for Materials Physics	Prof. Volkert
		Prof. Jooß
		Prof. Kirchheim
	Institute for Geophysics	Prof. Bahr
		Prof. Tilgner
	Institute for X-ray Physics	Prof. Salditt
		Prof. Köster
		Prof. Techert
	Institute for Astrophysics	Prof. Dreizler
		Prof. Niemeyer
		Prof. Reiners
		Prof. Gizon

Dean's office, Dean of Studies Office and Service Centre (for financial accounting)

Faculty of Physics: research and structure

The Göttingen Faculty of Physics is organized into several central facilities and ten institutes, most of them comprising several groups working in three main fields of research: (i) *Solid State Physics and Materials Physics*, (ii) *Biophysics and Physics of Complex Systems*, and (iii) *Astrophysics and Elementary Particle Physics*.

Via shared professorships, the faculty is linked to interdisciplinary research centres of the university: **DFG – Research Centre** *Molecular Physiology of the Brain*, and **BMBF** – *Bernstein Centre for Computational Neuroscience*.

There are further shared professorships at renowned external research facilities in Göttingen, supporting the excellent multidisciplinary research of the faculty: **Max-Planck-Institute for Solar System Research, Max-Planck-Institute for Dynamics and Self-organization, and Institute for Aerodynamics and Flow Technology (German Aerospace Centre).**

In collaborative research projects, the faculty cooperates closely with the **Faculties of Chemistry, of Mathematics, of Medicine**, and with the **Max-Planck-Institute for Biophysical Chemistry**, and the **Laser-Laboratorium Göttingen**. Therefore the faculty is involved in numerous interdisciplinary and cross-departmental collaborative research projects, like **DFG-Collaborative Research Centres**:

- **No. 755** *Nanoscale Photonic Imaging*
- **No. 803** *Functionality Controlled by Organisation in and between Membranes*
- **No. 860** *Integrative Structural Biology of Dynamic Macromolecular Assemblies*
- **No. 937** *Collective Behavior of Soft and Biological Matter*
- **No. 1073** *Atomic scale control of energy conversion*

There are further important national and international collaborations, for example two **BMBF-Research Foci:**

- Research Focus **No. 103 (ATLAS)**: closely connected to CERN
- Promotional Focus *Astrophysics with Earthbound Telescopes*, involved in the international very large telescope projects of ESO.

The Study Paths in Physics

Located at the North Campus, the modern physics building in Göttingen offers an excellent infrastructure for study and research: five lecture halls with an extensive collection of demonstration experiments and excellent technical equipment, numerous seminar rooms, state-of-the-art laboratories which meets the high technical demands of top physics research, computer rooms with more than 100 computers for student access and computer-aided lectures, free w-lan, a spacious study area with group and individual workstations and an in-house library.

The Faculty of Physics offers three consecutive Bachelor – Master programmes as well as several PhD programmes. From the beginning of their studies over the entire progress of the program (incl. the changeover to Master or PhD programme) to the career entry there is a very competent and proactive advisory service. The study office serves as a central contact point for students for any information.

The three-year **Bachelor programme in Physics (B.Sc.)** imparts basic knowledge of experimental and theoretical physics as well as mathematics and other natural sciences. From the fifth semester onwards, Bachelor students will deepen their knowledge in nuclear, particle and solid state physics. But even at this early stage of their studies, students have the possibility to choose courses regarding further current research areas such as Astrophysics, Geophysics, Biophysics, Physics of Complex Systems or Materials Physics.

Fig. 1: The physics of rockets: the mass changes during the flight

The subsequent two-year international **Master programme in Physics (M.Sc.)** consists of a graduate coursework phase (first year) and a research phase (second year). In the first two semesters students take courses of their preferred study focus, such as astrophysics and geophysics, biophysics and the physics of complex systems, solid state and material physics or nuclear physics and particle physics. The second year is dedicated to the compilation of the master thesis, including preceding methodical courses. This includes a main research lab/theory course or a module of research networking, meaning to participate and present their own results at a conference. At this stage students already work intensively on a specific experiment / theory and research question. The Thesis's research project is carried out in one of our ten institutes or other institution of the Göttingen Campus (e.g. Max Planck Institutes). Students will be fully integrated in the research activity at our faculty. Graduates are highly qualified for demanding tasks in industry and economy and excellent prepared for a PhD programme in Physics.

Fig. 2: A lecture hall

The **PhD programmes** in physics and related fields are embedded within the Georg-August University School of Science (GAUSS) graduate programme, offering the grades Dr. rerum naturalium (Dr. rer. Nat.) and philosophiae doctor (Ph.D). Aside from some several specialized programmes the structured PhD programme in physics is the core of the physics' branch ensuring a high quality graduate programme and defining mandatory requirements regarding research, curriculum, supervision and participation in teaching. The duration of the research-oriented thesis work is typically three years and can be carried out at one of the ten institutes of the faculty of physics, the related Max-Planck Institutes, the Laser laboratory and the DLR. Together, they provide a large variety of possible thesis projects in fundamental and applied research.

Students who are planning to become a teacher initially complete the three-year **Bachelor programme for two subjects** (B.A.; teaching profile) in which Physics is chosen in combination with another subject like Mathematics, Chemistry, Biology, English, French, Latin or Spanish. This programme imparts fundamental and methodical knowledge in two disciplines as well as technical didactics and related-to-practice education relevant for teaching at the German Gymnasium. Starting with basic courses together with the above B.Sc. programme, the Physics' curriculum contains specific courses in optics, quantum physics, theoretical physics and technical didactics adjusted to the needs of future teachers.

Fig. 3: A demonstration experiment

A successful completion of the degree qualifies participants for the subsequent two-year **Master of Education** (M.Ed.) programme, which, apart from the subject-specific aspects, focuses on theories, methods and projects in empirical teaching and school research. The programme is closely linked to the Central Organisation for Teacher Training (ZELB). Its objective is to foster the young scientists in the field of empirical teaching and school research as well as to foster specialised didactics. A special aspect of this programme is the close connection between teaching and empirically oriented research. The degree enables graduates to enter into the practical teaching period necessary for a teaching profession at the Gymnasium.

Beside the basic Bachelor/Master programme in Physics, we offer a consecutive interdisciplinary **Bachelor/Master programme in Materials Sciences**. Students will experience the promising combination of the chemical and physical fundamentals concerning materials. This Bachelor degree programme spans various subjects and, as well as Chemistry and Physics, it also has geoscientific and wood science-based parts. The subsequent Master programme imparts extensive knowledge of the scientific and technical principles of the production, characterization, development and application of functional materials. The interdisciplinary programme prepares students for professional fields related to research and development which includes the possiblility to continue with a PhD in physics, chemistry and other related areas.

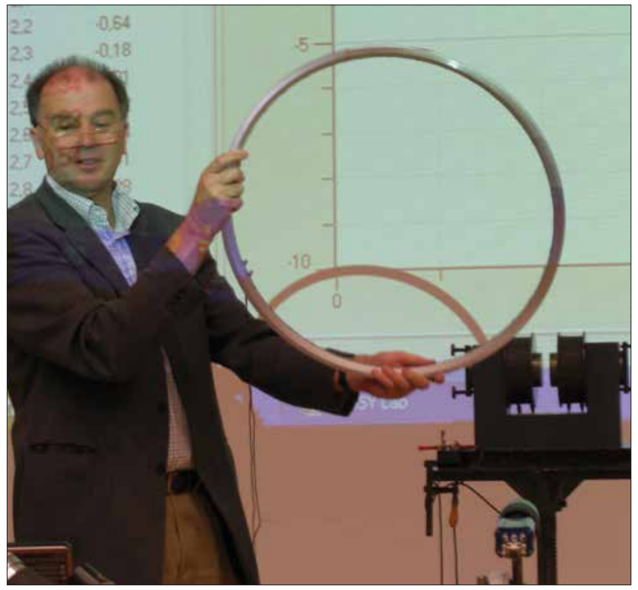
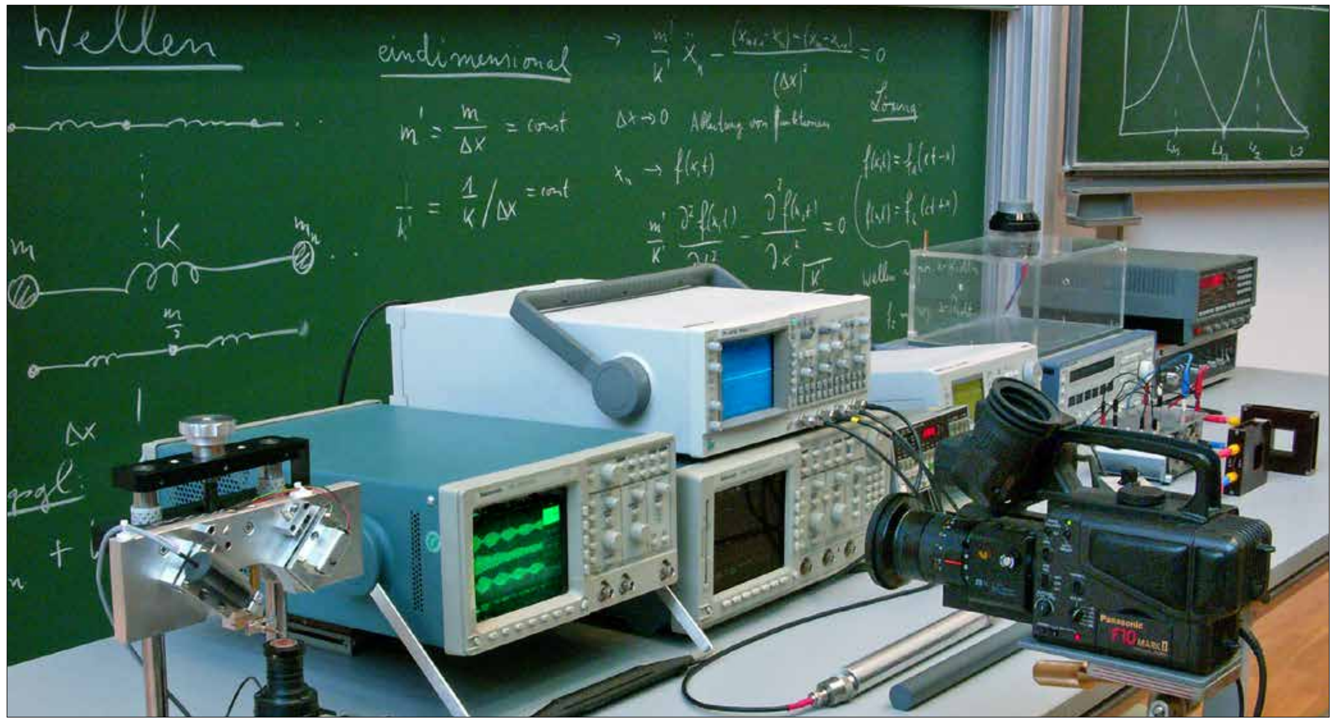


Fig.4: A better demonstration experiment



Overview of the Physics Programmes

(as of May 2016)

Bachelor's programme Physics

Standard period of study: 6 semesters
ECTS Credits: 180
Language: German
Open admission
Current number of students: 551

Two-subjects Bachelor's programme including Physics

Standard period of study: 6 semesters
ECTS Credits: 180
Language: German
Open admission
Current number of students: 97

Bachelor's programme Materials Sciences

Standard period of study: 6 semesters
ECTS Credits: 180
Language: German
Open admission
Current number of students: 64

Master's programme Physics

Standard period of study: 4 semesters
ECTS Credits: 120
Language: English, German
Limited admission
Current number of students: 293

Number of students in total: 1.238 (summer semester 2016)

Master of Education including Physics

Standard period of study: 4 semesters
ECTS Credits: 120
Language: German
Limited admission
Current number of students: 78

Master's programme Materials Sciences

Standard period of study: 4 semesters
ECTS Credits: 120
Language: German
Limited admission
Current number of students: 36

Doctoral programmes

- structured PhD programme in Physics
- PTCN, *Theoretical and Computational Neuroscience;*
- GGNB, *the Graduate School of Neurosciences and Molecular Biosciences;*
- IMPRS, *the international Max-Planck-Research School for Solar System Science;*
- GrK, *Graduate Training Programmes "Graduiertenkollegs", currently the Host Stars of Extrasolar Planets (GrK 1351) together with the University of Hamburg.*

Current number of students: 237

Activities of the Student Body

The faculty of physics also has a very committed student body, which is represented by the student council. Students are involved in various activities such as the committee work of the student council, which can be contacted by the students for any questions or problems. They also take part in the pupil information days, where pupils get the opportunity to gain insight into the faculty of physics and are informed about studying physics in Göttingen. Another program called "Physikspion" offers pupils the opportunity to spend one day with a student, who will be dedicated to answering all questions and showing the daily life at the university.

The student body also takes care of the freshman students. Their first week starts with an "orientation week" during which they get information about the most important things, like the course of studies, as well as a guided tour through the faculty and the opportunity to meet their future professors.

There also is a lecture series called "Bier und Brezeln", which is hosted in cooperation with the jDPG (jDPG means "young German Physical Association"). These series consists of lectures about recent scientific topics given by a professor of the university or an invited extern. Afterwards there is space for a casual discussion while beer and pretzels are served.

In order to honor good teaching, the student body is awarding the Pohl-Medal, named after the famous physicist Robert Wichard Pohl from Göttingen, given annually to the best lecturer during the last term. Last but not least, there are of course some social events organized by students as well, like the table football tournament, the annual dance called "Maiball" and the annual summer festival, which make studying physics in Göttingen even more enjoyable.

On the Shoulders of Giants: a Brief History of Physics in Göttingen

18th and 19th centuries

Georg Ch. Lichtenberg (1742-1799) may be considered the forefather of experimental physics in Göttingen. His lectures were accompanied by many experiments with equipment which he had bought privately. To the general public, he is better known for his thoughtful and witty aphorisms. Following Lichtenberg, the next physicist of world renown would be Wilhelm Weber (1804-1891), a student, coworker and colleague of the „prince of mathematics“ C. F. Gauss, who not only excelled in electrodynamics but fought for his constitutional rights against the king of Hannover (1830). After his re-installment as a professor in 1839, the two Göttingen physics chairs, W. Weber and B. Listing, approximately corresponded to chairs of experimental and mathematical physics. After Listing, Woldemar Voigt (1850-1919), working in optics, took over the theoretical physics department. He discovered what Poincaré named „Lorentz transformations“. Due to Voigt's lectures, his student Max von Laue decided to become a theoretical physicist. During this time Eduard Riecke (1845-1915) held the experimental chair and Johannes Stark (1874-1957) did his experiments on the Doppler effect of canal rays (1905) in Göttingen. This brought him a Nobel prize (Stark Effect). In experimental physics, a division for applied electricity under H. Th. Simon was created in 1907.

Since C. F. Gauss, the astronomical observatory has been in contact with physics. Its director from 1901-1909 was Karl Schwarzschild (1873-1916), who derived a famous solution of Einstein's gravitational theory which led to the concept of the black hole.

Also, a geophysical institute was founded in 1898 under Emil Wiechert (1861-1928), where seismic methods for the study of the Earth's interior were developed. An institute for applied mathematics and mechanics under the joint directorship of the mathematician Carl Runge (1856-1927) (Runge-Kutta method) and the pioneer of aerodynamics, or boundary layers, Ludwig Prandtl (1875-1953) complemented the range of institutions related to physics proper. In 1925, Prandtl became the director of a newly established Kaiser-Wilhelm-Institute for Fluid Dynamics.

A new and well-equipped physics building opened at the end of 1905. After the turn to the 20th century, Walter Kaufmann (1871-1947) did precision measurements on the velocity dependence of electron mass; they played an important role for the discussion of Einstein's special relativity and a rival theory of the Göttingen lecturer Max Abraham. In 1914, a professorship for the Dutch theoretician and later Nobel prize winner Peter Debye (1884-1966) was established (Debye-Scherrer method). Debye left Göttingen in 1920. When the three chairs in physics had to be refilled around 1920, a fortunate choice brought the theoretician Max Born (1882-1970) as well as the experimental physicists James Franck (1982-1964) and Robert Pohl (1884-1976) to the university. Early in the 1920's, physics was reorganized into four institutes: two experimental, a theoretical, and an upgraded „Institute for Applied Electricity“ under Max Reich (1874-1941). The „faculty for mathematics and natural sciences“ separated from the philosophical faculty only in 1922.

Fig. 1: Wolfgang Pauli and Paul Ehrenfest (1929)

Fig. 2: Viktor Weisskopf, Maria Goeppert, Max Born

Fig. 3: I. Institute of Physics and II. Institute of Physics

Weimar Republic

With the coming to Göttingen of the three friends Born, Franck and Pohl, an exceptional decade for physics began. Franck received a Nobel Prize in 1925 (Franck-Hertz experiment). Among his students, the names Patrick M. S. Blackett (Nobel prize 1948) and Edward Condon (Franck-Condon effect) appear as well as those of numerous subsequent physics professors (e.g., W. Hanle, H. Kopfermann, H. Maier-Leibnitz, Herta Sponer). Born and his coworkers Werner Heisenberg (1901-1976, in Göttingen 1923/26 and 1948/57) and Pascual Jordan (1902-1980) were responsible for the completion of quantum theory (1925-1927). The concept „quantum mechanics“ was coined by Born in 1924. From the observed atomic spectra Heisenberg distilled a mathematical formalism permitting the calculation of observables like transition frequencies, intensity and polarization of atomic radiation (Nobel Prize 1932). Born recognized the hidden mathematical structure (matrices, linear operators) and showed that Schrödinger's wave function must be connected with a probability interpretation (Nobel Prize 1954). P. Jordan, at the same time as P. A. M. Dirac, published a formalism combining both Schrödinger's wave- and Heisenberg's matrix theory. He also found what now is called Fermi-Dirac statistics. Born's probability interpretation and Heisenberg's uncertainty relations have immensely furthered our understanding of nature. Among Born's PhD students, assistants and scientific guests were five later Nobel prize winners: Max Delbrück, Maria Goeppert-Mayer, Wolfgang Pauli, Enrico Fermi and Gerhard Herzberg. Many other outstanding physicists also worked under Born, among them George Gamov, Walter Heitler, Erich Hückel, Friedrich Hund, Lothar Nordheim, Robert Oppenheimer, G. Uhlenbeck and Viktor Weisskopf. The long-time tradition of a strong interaction with mathematics continued, as is exemplified by the 1926 lecture on quantum mechanics by David Hilbert, and the subsequent mathematical foundation of quantum theory by John v. Neumann in Göttingen.

1933-1945 and thereafter

With the seizure of power by the National Socialists and the expulsion of both Jewish and democratically minded physicists from the university and from Germany, this golden era of physics came to an abrupt end. During the Nazi period and the 2nd world war, Robert Pohl pursued his research in the foundations of solid state physics (inner photo effect in crystals, thin layers) and transformed the lecture hall into a show room. He and the nuclear physicist Hans Kopfermann (1895-1963) (hyperfine structure, nuclear moments, betatron for medical use) and the theoretical physicist Richard Becker (1887-1953) working on magnetic properties of materials, succeeded to keep a high standard both in teaching and research. All four institutes continued uninterrupted through 1945. One of the people who took over courses from M. Born was Gustav Heckmann from the observatory. In the early 30's, he had made an important contribution to cosmology. During the war, the observatory's director Paul ten Bruggencate (1901-1961) even built a special station for studies of the sun's activity.

The end of the second world war had some advantageous consequences for the university. The town had remained in good order such that many well-known physicists, among them the three Nobel prize recipients (Max Planck, Max v. Laue, and the chemist Otto Hahn) moved here from a ruined Berlin. Others coming from the areas lost to Poland and the USSR followed suit. In 1946, the Kaiser-Wilhelm- (later Max-Planck-) Institute for Physics in Berlin with its director, Heisenberg, re-opened in Göttingen and stayed here until 1958. This included a department headed by C. F. v. Weizsäcker and a new department of astrophysics. In Kopfermann's Institute, Wolfgang Paul (1913-1993) worked as a professor on nuclear quadrupole moments while Hans Georg Dehmelt (1922-) wrote his PhD thesis. Together, they received the Nobel Prize in 1989 (atom traps). In 1952, at the Institute for Theoretical Physics, Herbert Kroemer received his doctoral degree

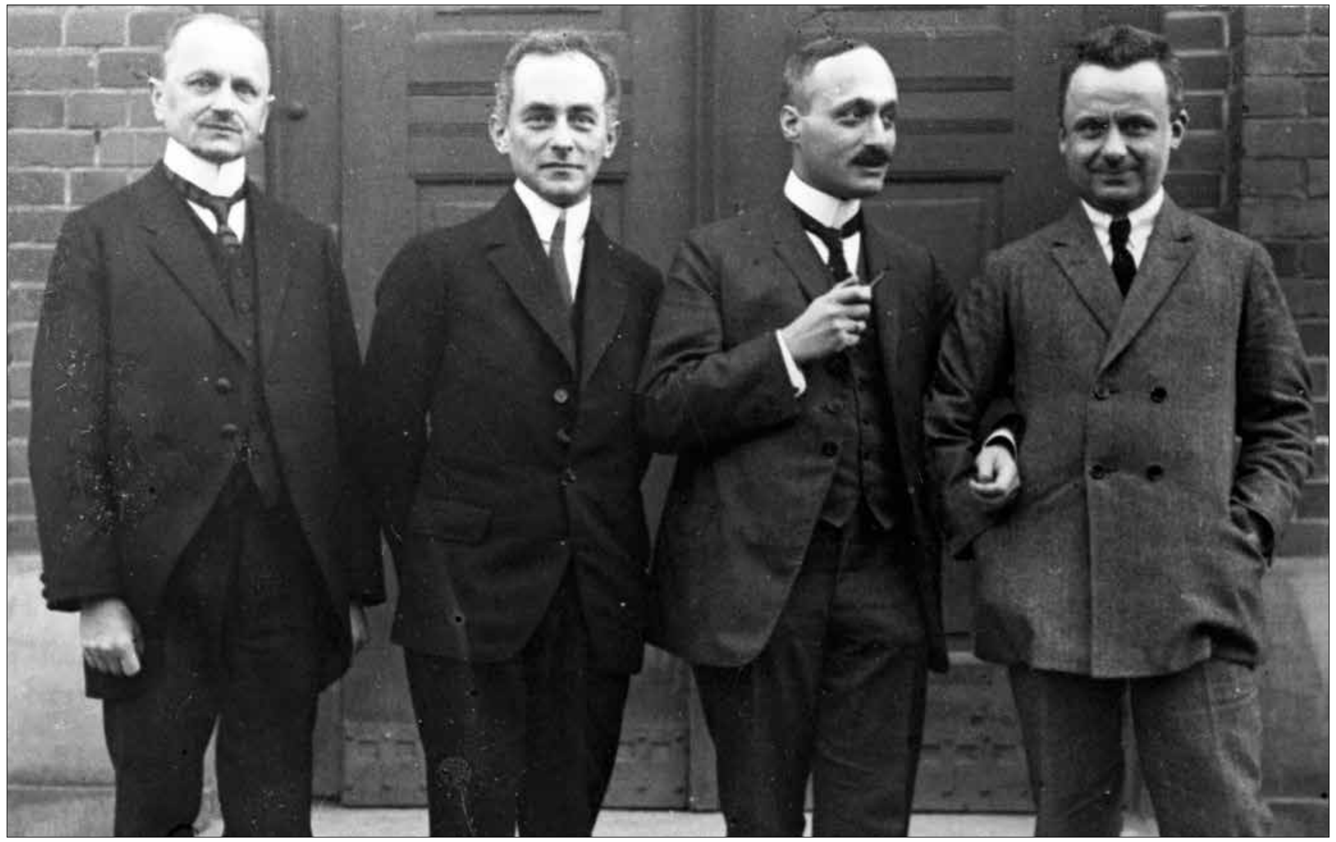


Fig. 4: Max Reich, Max Born, James Franck, Robert Pohl

under Fritz Sauter (1906-1983), who would later be full professor in Cologne. Kroemer became a Nobel prize winner in the year 2000 (opto-electronics). In place of the discontinued institutes for applied mechanics and applied electricity, a third experimental institute for the physics of vibrations and acoustics was opened in 1947. Its longtime director Manfred Schroeder (1926-2009) was known to a larger public by his work on the acoustics of concert halls and his computer graphics. The Institute for Metal Physics was transfered from the chemistry department to physics and directed by Peter Haasen (1927-1993). It would then be expanded into the present large institute for material science. Prandtl' successors as directors at the Max-Planck-Institute for Fluid Dynamic were also given the position of full professor of physics at the university. Likewise, a link of director's positions between geophysics and the Max-Planck-Institute for Aeronomy in Katlenburg/Lindau, now MPI for Solar Systems Research on the Göttingen science campus came about. In 1957, prominent physicists like M. v. Laue, M. Born (who had returned to Bad Pyrmont near Göttingen), W. Heisenberg, W. Paul, H. Kopfermann, and C. F. v. Weizsäcker formulated a protest against the nuclear arming of the German Armed Forces and worldwide nuclear arms build-up.

The late 1960's and early 1970's brought a big influx of students and a sizable increase in both positions and institutions in physics. A fourth experimental Institute for semiconductor physics had opened in 1965, and an institute for X-ray physics in the 70s (X-ray microscopy). A third Max-Planck-Institute, for Biophysical Chemistry, had been established in 1949. Under its subsequent directors, Manfred Eigen (Nobel prize in 1967), Erwin Neher (Nobel prize in 1991) and Stefan Hell (Nobelprize in 2014) a closer relationship with physics ensued. The cooperation with the Max-Planck-Institutes complemented the research opportunities for physics students and post-docs. An outgrowth of this cooperation is the Institute for Nonlinear Dynamics (since 1996). Since the 1990s, a larger importance was given to overlapping fields of physics and biology. By now, the mere two professors of physics with a dozen helpers of the 19th century have been replaced by 110 positions for research and teaching salaried by the university. About the same number of technical and administrating personnel were added. By external funds roughly 250 additional research positions are available. The present size of physics in Göttingen reflects the changes in research: the increasing topical and instrumental differentiation of the field, and the trend away from the single researcher toward research groups and interdisciplinary interactions. At present, the faculty of physics, since 2005 in its new building, is involved in three Collaborative Research Centers (SFBs) funded by German Research Foundation: "Nanoscale Photonic imaging", "Collective behaviour of soft and biological matter" and "Atomic scale control of energy conversion". In addition there exist a joint Graduate School with the mathematics faculty "Mathematical Structures of Modern Quantum Physics", a Research Focus "Physics on the TeV Scale with ATLAS at the LHC", a "Bernstein Center for Computational Neuroscience" and a Courant Research Centre "Nano-Spectroscopy and X-Ray Imaging". Nevertheless, as this summary focusing on the personalities behind some highlights of physics in Göttingen shows, creative ideas spring from individual minds.

Hubert Goenner

Museum „Physicalisches Cabinet“

One of three collections of historic instruments in the faculty of physics is located in the foyer in front of the lecture halls. It showcases the history of physics in Göttingen, from the beginnings of systematic research in the 18th century to its most famous period as the world-leading center for physics and mathematics in the first half of the 20th century.

Physics in the early years of the university

The witnesses of more than 275 years of physics tradition in Göttingen give us unique insight in the university teaching and research in the 18th and 19th century. The first physics lectures were given by the philosopher Samuel Christian Hollmann (1696-1787) in 1734, preceding the official founding of the university in 1737. He came as a well-known critical mind from the University of Wittenberg to teach ethics, psychology, logic and metaphysics and established the tradition of well-visited lectures on natural sciences. Due to the approach of the newly funded university to appoint researchers with fresh thoughts, Göttingen became a well-known German university for advanced education of students. Researchers in the spirit of the period of enlightenment were gathered in Göttingen. One of them was Tobias Mayer (1723-1762) who joined in 1751. His field was applied mathematics and astronomy and he developed an outstanding reputation for the precise moon observations, fixed star map using and lunar tables, later earning him the title "Mayer Immortalis", from Gauß. His quadrant holding the telescope made by Bird (London 1756) was at the first observatory in the city, which can still be seen in the new physics building.

18th century: Lichtenberg

When Georg Christoph Lichtenberg (1742-1799) came from Darmstadt as a student in 1763 for three years, the lectures he listened to were mainly devoted to mathematics, but he was also introduced into astronomy. In 1778 Lichtenberg assumed the lectures on physics from his colleague, the natural scientist Johann Polycarp Erxleben (1744–1777), and gave his famous experimental physics lectures from 1778 to 1799. A novelty at that time, he put the experiments in focus, giving the first experimental physics lectures. He had more than hundred students listening in his private rooms at that time, out of the university's a few hundred in total. This stands as a testament to his popularity and for the popularity of over 600 demonstration experiments, investments, at that time purchased from private funds. They ranged from small experiments in mechanics and energy conservation, density of liquids and thermal expansion, spectrum of light and optics to the demonstration of magnetic forces (a selection is given in Fig. 1; the full Lichtenberg collection can be found online at http://snail.ph4.physik.uni-goettingen.de/MathNatFak/phycab.php).

Fig. 1: Historic instruments from Lichtenberg's collection "Physicalische Apparate", built up in between 1771-1779.

His most expensive instrument was a vacuum pump crafted by Naire and Blunt (London 1782) which was an investment corresponding to one year of his salary (Fig. 2).

It allowed the demonstration of the effect of evacuation, which inhibits the propagation of sound from a metal bell in the evacuated glass jar. This experiment prompted a maidservant to repeat the experiment with a captured nightingale, a situation depicted on a contemporary copperplate print. In 1777 he started to work in the field of electricity. He bought his first apparatus, an electrostatic generator, and experimented with large isolating dielectrics (electrophorus) to produce electrostatic charge via electrostatic induction. The flat 'cake' of resinous material like tar pitch on a metal plate (Fig. 3) is rubbed with a cat’s fur which builds charge in the dielectric. He could study electric discharges 70 cm in length. By accident, he recognized that the plates decorated by the resin dust showed two well defined shapes: one fine-structured and symmetric looked positive and the other rather unstructured viewed as negative. With this important discovery he could show that there are two types of electric charges, which are not connected to the material but reveal a general character of electricity. In 1789, Lichtenberg sold his impressive collection of instruments to the university, which formed the basis for demonstration experiments in the following years and the foundation of our current collection.

Fig. 2: Vacuum pump (manufactured by Naire and Blunt, London 1782). It was the most expensive piece of equipment in Lichtenberg’s collection, reaching a vacuum of 0.5 mbar (Quelle: Sauer Marketing).

19th century: Gauss and Weber

It was Carl Friedrich Gauß (1777-1855) who set new standards in astronomy, mathematics and physics. Born in Brunswick, his school tuition was financed by his duke, who recognized his mathematical talent. At the age of twenty, he was in the first league of mathematicians already. His mathematical knowledge allowed him to calculate the orbit of the small planet Ceres with data of only 41 days of observation. He predicted the position for its rediscovery, which founded his worldwide fame as an astronomer. Since the electorate of Hannover wanted to fund a novel observatory, his appointment as a professor in 1807 was accelerated and he moved into the newly built observatory outside of Göttingen a few years later. Besides mathematics and astronomy the third field he strongly contributed to was physics. Inspired by the observation that sunlight reflected by the St. Michaelis church in Hamburg could be observed as a bright spot while he visited Lüneburg about 50 km away, he developed a new method to measure distances for a land survey campaign in the kingdom of Hanover. The instrument he developed, the so called Vizeheliotrop, is exhibited in our collection (Fig. 4). With this sensitive instrument, he could measure the spherical excess of the curved surface on 100 km distance. In fact, this inspired his work on conformal maps in the field of mathematics, later addressed by Riemann in detail. Following a discussion with Alexander von Humboldt, exploration of the earth’s magnetic field became another topic of interest. Through the coordination of the exploration of the earth’s field components at hundred places around the world, it was possible for Gauß by using his mathematical knowledge to calculate a map of the full magnetic field of the earth in its components (Fig. 5, from a publication of the magnetic society “atlas of the earth magnetism” 1840).

This was at a time when Wilhelm Eduard Weber (1804-1891) had been appointed as a professor of physics in Göttingen, the former chair of Lichtenberg. As a candidate strongly supported by Gauß, they developed a fruitful collaboration. Weber’s novel research field at Göttingen “electromagnetism” was stimulated by Oersted’s finding of a force in between live wires. With Weber’s experiments (Fig. 6) precise measurements of the strength of the magnetic field in absolute units became possible and his definition of the current is still valid. This allowed Weber and Gauß to realize a unit system connecting electric and magnetic quantities to the basic units of length, time and mass. Webers theory, which he completed in experiments together with Rudolf Hermann Kohlrausch (1809-1858) contained only one parameter connecting the force between static and dynamic charges. The determination of this parameter was the first electric determination of the propagation speed of light, later verified by Maxwell’s theory. To satisfy Gauß’ and Weber’s need for highest quality optical and electric apparatuses, local fine mechanics workshops florished. One most famous instrument maker was Moritz Meyerstein (1808–1882), who made the transportable magnetometer developed by Gauß to ensure the highest possible sensitivity (Fig. 5). This laid the foundation for many companies of Göttingen’s measurement valley like Lambrecht, Sartorius and other companies founded later in the periphery of the university. Ernst Abbe, founder of the world renowned Zeiss, was a student of Weber and Riemann. Another example of the excellent engineering skills of Weber and Gauß is the first telegraph, built in 1833. They put up a one kilometer long wire in-between the observatory outside the town walls and Weber’s institute, transmitting messages by using an induction transducer and detection of the binary coded current pulses by a mirror galvanometer. This setup was shown at the world exhibition in Vienna 1873, during a dispute on patent rights, and can be visited in the museum (Fig. 7).

Fig. 3: Electrophorus and cat fur on the left at around 1780. With the tin foil coated wooden plate the charge could be separated and impressive electric sparks up could be generated. Lichtenberg figure for a positive charge on the right (Quelle: Sauer Marketing).

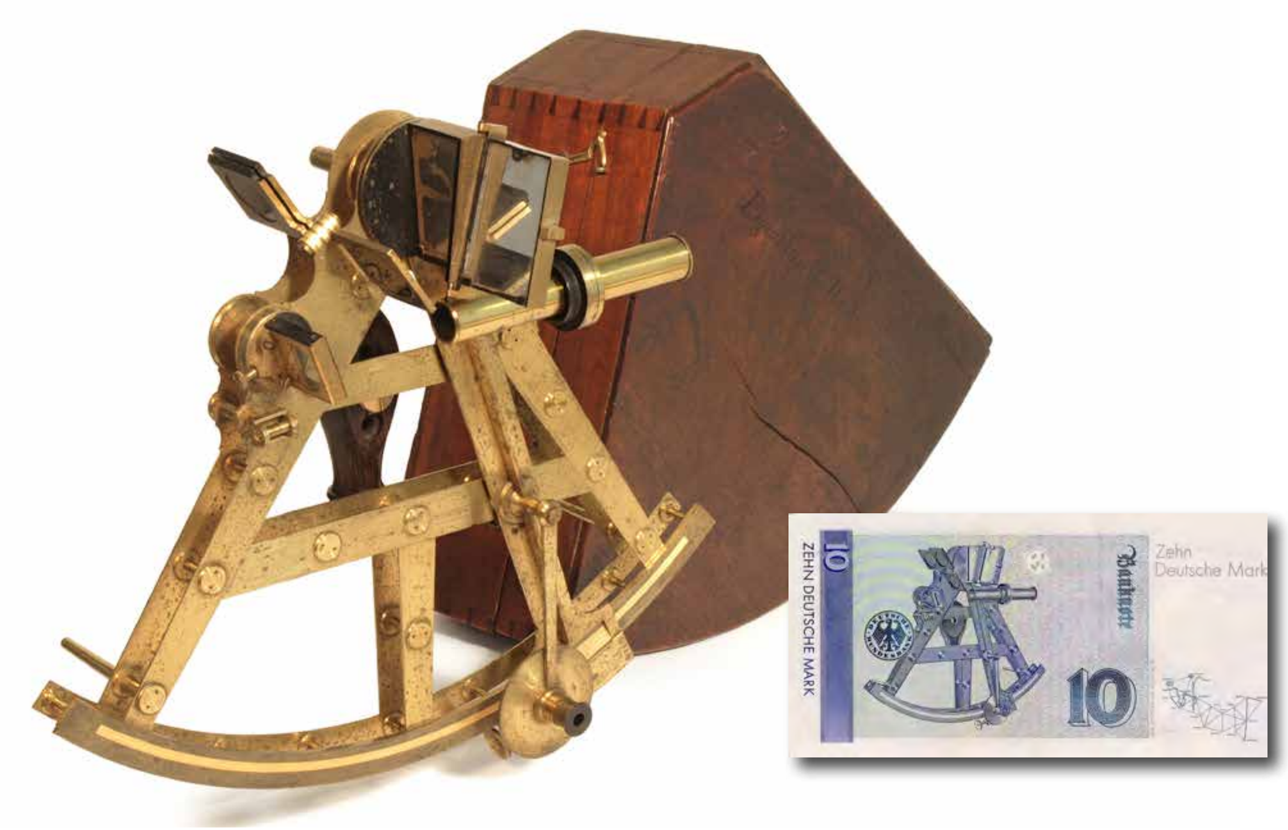


Fig. 4: Gauß’s Vizeheliotrop (manufactured by Troughton, London, 1810). It was on the back of the 10 DM note. It was developed for a measurement campaign in the kingdom of Hanover, and its sensitivity allowed the study of the spherical excess of the curved earth’s surface (Quelle: Sauer Marketing).

20th century: birth of quantum mechanics

At the turn of the century, major aims of experimental research were to understand the nature of electric conductivity (“electron gas” in metals), the study of cathode rays to determine the nature of the electron (e/m) and spectroscopy to access the nature of the atom. A collection of various first generation spectrometers and X-ray tubes remain from that time and are exhibited in the museum.

Fig. 5: Transportable magnetometer from Weber (manufactured by Meyerstein Göttingen, 1839). It was motivated by Alexander von Humboldt to map the earth’s magnetic field component, which was deduced from 100 experimental stations all over the world and printed in Gauß’ and Weber’s atlas of the earth’s magnetism.

Fig. 7: Gauß-Weber telegraph as shown at the world exhibition in Vienna 1873 (Quelle: Sauer Marketing).

The mathematics institute with Felix Klein (1849-1925), David Hilbert (1862-1943) and Hermann Minkowski (1864-1909) was a well-known international centre of mathematics. Belonging now to Prussia, the ministry at Berlin wanted to further develop Göttingen as a centre for mathematics and physics. These sciences were on the verge to become an important motor for industrial developments. Klein and Hilbert wanted to get Max Born (1882-1970) for the chair of theoretical physics as a successor to Peter Debye (1884-1966). With Born, James Franck (1882-1964) came to Göttingen. Together with Robert Pohl (1884-1976), they led the three physics institutes (I., II. and theory). In the 1920's. Göttingen was one of the birthplaces of quantum mechanics and attracted important people from outside. The interaction between Hilbert, Born, Franck and Pohl created a unique atmosphere. Their seminar on the "structure of matter" brought all physicists and mathematicians together. These famous years of quantum mechanics ended abruptly by the devastating rise of National Socialism in Germany in the 1930's. The beginnings of atomic physics and solid state physics are the latest exhibits found in the museum. Some of the most important work on quantum mechanics of that time is displayed permanently in the foyer of the museum.

Fig. 6: Weber's instruments to measure the magnetic field generated by the circular current loop from 1837. With the Tangenten-bussole (Bussole = compass), sensitive deviations of the needle could be determined thus it was the first practical instrument to measure the magnetic field generated by the current through the wire loop. The wiring can be seen at the bottom.

The Museum

The history of the museum begins when the exhibits were moved from the Michaelishaus to the new physics building on Bunsenstrasse. Being in an naturally acclimatized cellar they luckily survived mostly undisturbed. In the last century, when the university had its 250th jubilee the "Sammlung Physicalischer Apparate" of the I. Physics Institute was described and newly catalogued by Prof. von Minnigerode and Prof. G. Beuermann. The collection of historic instruments of the early days of physics in Göttingen was built up and found a new home in the museum „Physicalisches Cabinet and Lichtenberg collection“ in the new physics building. In addition, the museum hosts exhibits of the collection of historical instruments of the astrophysics observatory "Historische Instumente der Sternwarte", from geophysics, "Geophysicalische Historische Sammlung", and on the birth of quantum mechanics. It is opened to the public on a regular basis. The unique contemporary witnesses of more than 275 years physics tradition of the University of Göttingen can be found there and were newly arranged by Prof. M. Münzenberg, now at the University of Greifswald. One can imagine Lichtenberg sitting at his desk taking notes, an electrophorus nearby, surrounded by dull leather, misty glass and fragile brass. It is the hands on experience that makes a tour through 275 years of physics in Göttingen an impressive experience. Most recently the digitization of the collections of Lichtenberg and Gauss were completed. These are now available online as high resolution images, with some even as 3d-animated objects. Weber's instruments are undergoing digitization.

Guided tours with the current curator, Prof. K. Samwer, I. Physics Institute, can be arranged. (Tel: 0551 39-7602, http://www.uni-goettingen.de/de/47114.html).

[1] Friedrich Hund, Die Geschichte der Göttinger Physik, Göttingen 1987, in Göttinger Universitätsreden, Vandenhoeck Ruprecht.

[2] Ausstellungskatalog: Die Göttinger Sieben. Eine Ausstellung der Georg-August-Universität Göttingen, Hrsg. von H. Wellenreuther, Göttingen 1987.

Faculty Building

Lichtenberg lecture hall with 350 seats

Since spring 2005 the Faculty of Physics has had a building on Goettingen North Campus where various science faculties and non-university research centres are located. Chemistry, informatics, geoscience, forestry, microbiology and genetics, molecular bioscience, the Laser Laboratory Goettingen, the German Primate Centre, the European Neuroscience Institute, and the Experimental Laboratory for Young People are within spitting distance of physics. Also nearby are the medical school as well as the Max-Planck-Institutes for Biophysical Chemistry, Dynamics and Self-Organization, Experimental Medicine, and Solar System Research.

Providing an overall ground-plan area of 45.600 m² the faculty building contains all facilities for teaching and research under one roof. Five lecture halls with extra space for the preparation of experiments, eighteen seminar rooms, laboratories for the practical training of students, space for computer pools as well as for doing assignments and tutorials form the core area for teaching. The in 2015 newly established Learning and Study Area features about 50 freely accessible individual and group workstations for students. It is complemented by the physics division of the Goettingen State and University Library, which offers freely accessible and systematically categorised monographs, textbooks, periodicals, manuals and encyclopedias.

Practical training laboratory

Cafeteria

Ultra-high vacuum installation

A light cafeteria gives a pleasant atmosphere to work on assignments. The cafeteria is also a place of communication and of lively scientific debate among the staff.

The varied research groups occupy more than 170 laboratories and measuring rooms as well as 340 workrooms. The conceptual design of the building guarantees extremely little vibration from structure-born noise. Special measuring rooms are provided with separate base-plates keeping vibration amplitudes to below 150 nm. Constant temperature is maintained by the treatment of 200.000 m³ air per hour in centralised air-conditioning plants. For some laboratories temperature variations are smaller than 0.1K per 10 minutes. Care is taken to avoid interfering electromagnetic fields in general. For particular applications laboratories are shielded to keep amplitudes of disturbing magnetic fields to less than 100 nT. Special facilities such as a hall for a particle accelerator, cleanrooms, chemistry, and cell culture laboratories are also available.

The research groups benefit greatly from the expertise of the technical staff in precision mechanics, electronics, and information technology. The faculty building houses almost 40 workshops with a total area of 2500 m² for the development and construction of complex devices which are not commercially available.

Precision-mechanics workshop

Air-conditioning plant

The Mechanical Workshop

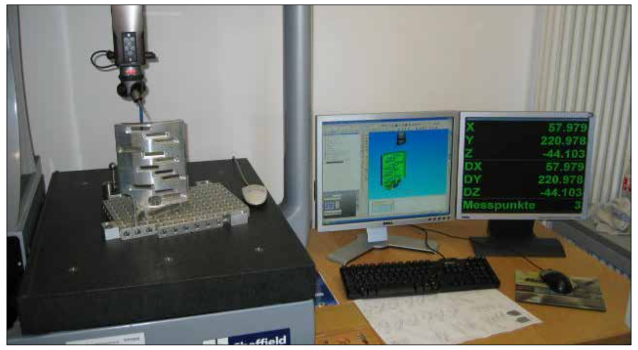
The central mechanical workshop of the Faculty of Physics is a state-of-the-art workshop equipped with various 5-axis CNC-controlled (computerized numerical control) machines. There are milling machines, lathes, wire EDM and a center for machining hard and brittle materials. The machines are programmed by a modern CAM program directly with the CAD data. Anodizing techniques as well as various welding and painting techniques are available. Currently 8 members of staff and 4 trainees are constructing and manufacturing complex workpieces, complete instruments, ultra-high vacuum systems and mechanical components as one-of-a-kind or small batch series. These complex components can be measured after manufacturing with a high precision coordinate measuring machine. The mechanical workshop manufactures custom-built research equipment for the different institutes as well as equipment for lab courses and lecture demonstration experiments. The mechanical work shop is able to process a variety of different materials and manufactures high-precision workpieces that meet industry standards.

This stainless steel plate was manufactured on behalf of the Institute of Astrophysics. It is used for detecting the so-called *Dark Energy* in the context of the "Dark Energy Experiment HETDEX" at the *Hobby Eberly Telescope* (HET) in Texas. It is the central component of the system, in which are up to one hundred recording heads for bundles with four hundred optical fibers each to illuminate the spectrograph with starlight. Affixed on a spherically curved surface high-precision bores are positioned with a precision of microns and arc minutes in the focal plane of this 11-meter telescope.

This picture shows a precision measurement of an opto-mechanical component using a 3D coordinate measuring Machine. This is a lens holder for the optical beam path of the "Multi Unit Spectroscopic Explorer" *MUSE*. The required precision to be measured was 1/100 of a mm and 1/10 degree.

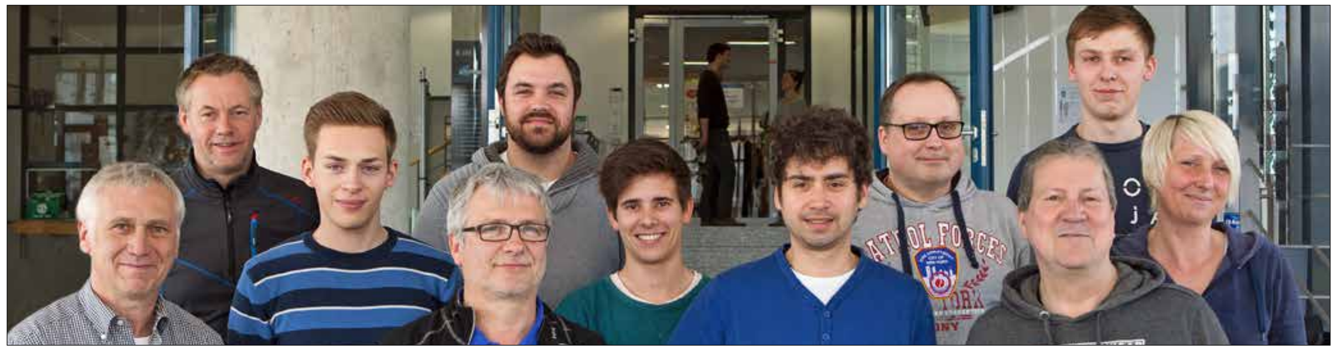
Machining of a Transmission-Electron-Microscope (TEM) sample holder on a CNC turning machine with driven tools. Axial and radial features may be cut in one clamping.

Precision manufacturing



Precision measurement

CNC lathe with driven tools



Collection of Lecture Hall Experiments

The faculty of physics houses an extensive collection of lecture hall experiments for the introductory lectures in experimental physics but also more specialized lectures on quantum and atomic physics, nuclear physics, biophysics, solid state physics and low temperature physics. Supported by three technicians, the lecturers regularly present selected physics experiments in the 5 lecture halls of the faculty. The tradition of presenting lecture hall experiments was initiated by Robert Wichard Pohl in the 1920s, who invented numerous outstandingly designed and in the meantime widespread demonstration experiments until his retirement in 1952. In honor of his achievements the German Physical Society annually awards the "Robert-Wichard-Pohl-Award" for outstanding achievements in Physics, in particular for the proliferation of scientific knowledge in education and didactics of physics. The Göttingen collection of lecture hall experiments is continuously supplemented and modernized to meet the requirements of modern experimental physics lectures.

Fig. 1: Measurement of the isotherm of Carbon-Dioxide.

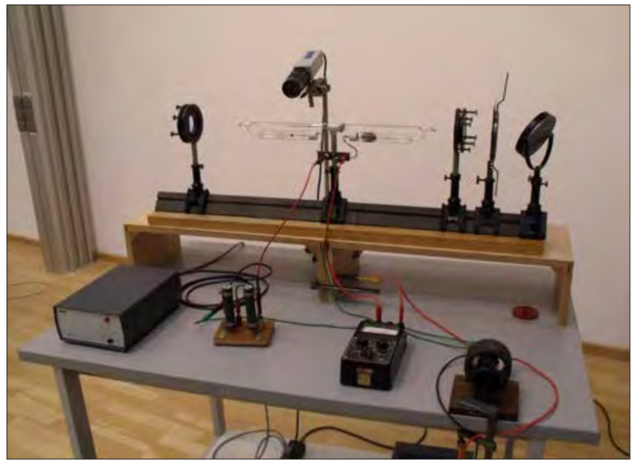
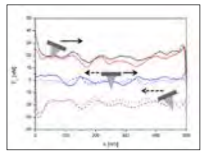


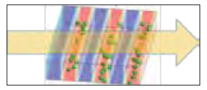
Fig. 2: Model of He-Ne-LASER.

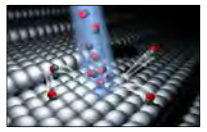
Fig. 3: Zeeman-effect and Stern-Gerlach experiment.

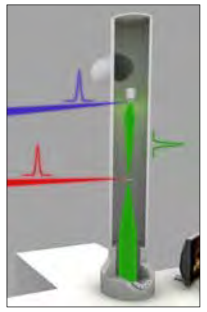
Solid State Physics and **Materials Physics**

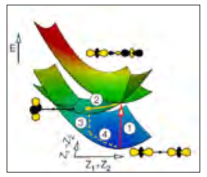
SFB 1073: Atomic Scale Control of Energy Conversion

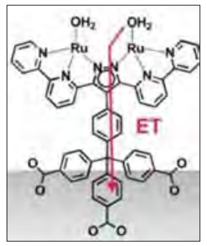


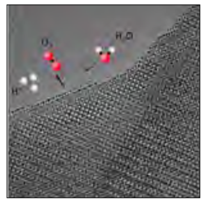


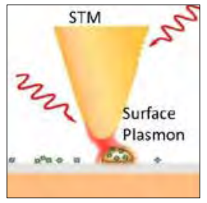


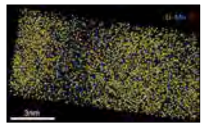












The SFB 1073 focuses on the fundamental understanding of the microscopic mechanisms involved in energy conversion steps

- to avoid unfavorable conversion paths like dissipation
- to direct energy conversion to favorable paths

by materials' design and active control.

The SFB 1073 is organized into three project groups with 17 projects involving 28 project leaders and 33 doctoral students from the Faculty of Physics, the Faculty of Chemistry, the Max Planck Institute for Biophysical-Chemistry and the Technical University of Clausthal.

Project group A: Control of dissipation

Can dissipation be controlled by tuning phononic and electronic states? Can dissipation channels be switched by active control?

- *Friction in strongly correlated systems under active control* - Samwer, Volkert
- *Understanding and manipulating relaxation channels to tailor energy transport* - Ulrichs, Krebs
- *Energy dissipation and transport in switchable polymeric nanostructures* - Müller, Vana
- *Controlling surface energy dissipation via tailored interface properties* - Bünermann, Schneider, Wodtke
- *Nanoscopic probing of spatio-temporal relaxation in heterogeneous structures using ultrafast transmission electron microscopy* - Ropers, Schäfer

Project group B: Conversion of optical excitations

What is the nature of optical excitations in correlated systems? Can phonon energy conversion be controlled by tunable correlations like electron-phonon interactions?

- *Photon-induced structural phase transition controlled by electronic correlations* - Ulrichs, Samwer
- *Photon driven energy transfer across correlated interfaces* - Jooss, Seibt
- *Relaxation, thermalization, transport and condensation in highly excited solids* - Blöchl, Kehrein, Manmana
- *External field control of photon energy conversion in manganites* - Moshnyaga, Damaschke
- *Energy conversion processes underlying the light-powered reversible guest exchange of photochromic coordination cages* - Clever, Schwarzer
- *Real time investigation of light harvesting processes in redox switching oligonuclear charge transfer metal complexes* - Meyer, Techert
- *Elementary steps of energy conversion after a strong non-equilibrium excitation in correlated materials* - Mathias, Kehrein

Project group C: Photon and electron driven reactions at interfaces

What is the nature of active states, involved intermediates and barriers? Can multi-step reactions be controlled via different types of correlations and active intervention?

- *Hybrid assemblies for fundamental studies of photo-induced multi-step charge transfer catalysis* - Meyer, Siewert, Jooss
- *In-situ atomic scale study of active states during photo-electrochemical water splitting* - Jooss, Techert
- *From electron transfer to chemical energy storage: first-principles studies of correlated processes* - Mata, Blöchl
- *Study and control of surface photochemistry using a local excitation microscope* - Ropers, Wenderoth, Wodtke
- *Spatially resolved in-situ investigation of electro-chemical processes at internal interfaces* - Nowak, Volkert
- *Redox reactions of adsorbates at supported catalyst: influence of a buried Schottky contact* - Pundt

Physics of Amorphous Materials, Dynamical Heterogeneities in undercooled Melts and Relaxation Phenomena

A material is referred to a „glass", if it has an amorphous structure in the solid state and undergoes a glass transition when heating into an undercooled melt. Bulk metallic glasses are often composed of many components. Appearance and some properties of such glasses are similar to that of crystalline metals, but their mechanical (rheological) behaviour is completely different. Using dynamical mechanically spectroscopy we analyse the excitation processes and compare with simulation data on the microscopic (nanometer) scale.

Sample preparation

The samples can be prepared by rapid quenching from the melt using various techniques:

- Splat-Quenching: The liquid sample is quenched between two copper pistons.
- Melt-spinning: This method, which is commonly used commercially, produces narrow ribbons by quenching the melt on a rotating copper wheel.
- Mold-Casting: Solidification in a cooled copper mold yields bulk samples.
- Vapor deposition of glass forming alloys onto a cold substrate under UHV-conditions yields amorphous thin films.

Mechanical Spectroscopy

Mechanical spectroscopy on different time scales offers a way to measure elastic constants, viscosity of liquids, polymers, biological systems and glasses as well as to investigate loss mechanisms in those complex fluids.

For low frequencies (0.1-50 Hz) and a temperature range of -100°C to 1000°C, we use a dynamic mechanical analyzer (DMA) to apply static and dynamic forces on the sample.

For the kHz range (about 5.4 kHz), the double paddle oscillator (DPO) is a very sensitive tool. Operated at its resonance frequency, it allows for the analysis of mechanical properties of thin films.

For low temperatures (Room temperature down to 2 K) a pulse echo ultrasound measurement unit (USO) is used, which can detect very small changes in the elastic moduli for a given frequency in the MHz range.

Most recently an Acoustic Atomic Force Microscope (AFAM) was built with the help of W. Arnold, which allows also local spectroscopy at surfaces.

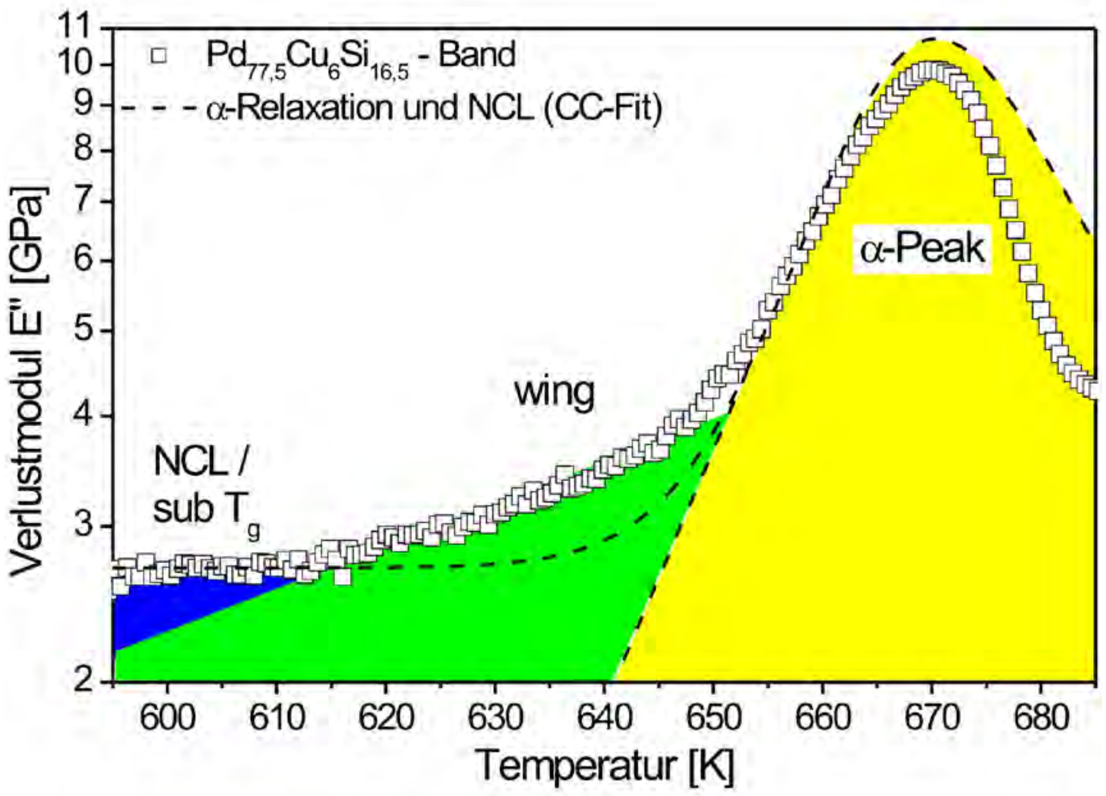


Fig. 1: Loss spectroscopy as a function of temperature: Identification of the β-process (wing) in the loss spectra of PdCuSi

For a deeper understanding of the connection of microscopic and macroscopic behaviour of glasses, the correlation between α- und β-relaxation as seen in loss spectra needs further explanation. At the moment, we discuss the α-process in the context of shear transformation zones (STZ) and the β-process with chain like excitations (strings). The former dominates the liquid above T_g, the latter below T_g. At high temperatures ($T > T_g$) both merge. Using higher mechanical forces we recently demonstrate the interaction of (vectorial) mechanical forces with the (scalar) temperature and identify local avalanches as the main relaxation process in creep and stress-strain curves.

To examine microscopic processes which are not accessible experimentally, molecular dynamics simulations are employed for comparisons, which are done in collaboration with several colleagues. The great progress achieved recently in the description of the primary (α-) and secondary (β-) relaxation as well as in the avalanche dynamics is supported by the results of computer simulations.

The thermophysical properties of semiconductor melts are investigated in an international project with experiments in microgravity environment (parabola flights, International Space Station). The samples are processed in an electromagnetic levitator in UHV and can be analysed with contactless techniques to measure thermal expansion, surface tension and viscosity. The connection of fragility and thermal expansion is now also mathematically established.

References

[1] Local elastic properties of a metallic glass, H. Wagner, D. Bedorf, S. Küchemann, M. Schwabe, B. Zhang, W. Arnold and K. Samwer, Nature Materials 2011, 10, 439.

[2] Dynamic Singularity in Multicomponent Glass-Forming Metallic Liquids, S.M. Chathoth, B. Damaschke, M.M. Koza, and K. Samwer, Phys. Rev. Lett. 2008, 101, 037801

[3] Anelastic to Plastic Transition in Metallic Glass-Forming Liquids, J.S. Harmon, M.D. Demetriou, W.L. Johnson, K. Samwer, Phys. Rev. Lett. 2007, 99, 135502

[4] A universal criterion for plastic yielding of metallic glasses with a (T/Tg)2/3 temperature dependence, W.L. Johnson, K. Samwer, Phys. Rev. Lett. 2005, 95, 195501

[5] Interatomic repulsion softness directly controls the fragility of supercooled metallic melts, J. Krausser, K. Samwer and A. Zaccone, PNAS 2015, 10.1073/1503741112

[6] Unified Criterion for temperature-Induced and Strain-Driven Glass Transitions in Metallic Glasses, H.B. Yu, R. Richert, R. Maass, K. Samwer, Phys. Rev. Lett. 2015, 115, 135701

[7] Strain induced fragility transition in metallic glass, H.B. Yu, R. Richert, R. Maass, K. Samwer, Nature Communications 2015, 6, 7179

[8] Crossover from random three-dimensional avalanches to correlated nano shear bands in metallic glasses, J.-O. Krisponeit, S. Pitikaris, K.E. Avila, S. Kuechemann, A. Krueger, K. Samwer, Nature Communications 2014, 5, 3616

Konrad Samwer

Konrad Samwer was born 1952 in Goettingen. He studied physics at the universities of Goettingen and Bonn and got his doctoral degree 1981 in the group of G. von Minnigerode, Goettingen. After Postdoc positions in Goettingen and at the California Institute of Technology, he obtained his habilitation in Goettingen. In 1989, he became a C4 professor at the University of Augsburg and accepted an offer to come back to Goettingen also as full professor for experimental physics (1999).

Konrad Samwer has received a number of respected awards, including having been awarded the DFG's prestigious Leibniz Prize in 2004. He is a member of the Academy of Sciences at Goettingen and the National Academy (Leopoldina). He has held a lot of official positions in the science community including a service as vice president of the DFG from 2007 to 2013.

Strongly Correlated Electronic Oxides

Research focus lies on electronic correlations in oxide thin films. Due to Coulomb electron-electron interaction and strong electron-phonon and spin-phonon coupling the 3d-transition-metal oxides demonstrate a number of coupled phase transitions, i.e. Metal-Insulator, Ferro(Antiferro)-Paramagne-tic, Charge/Orbital Ordering and Structural Phase Transition. The strongly correlated electronic oxides (SCEO) include materials with perovskite structure, ABO_3, containing 3d-(V, Mn, Co, Fe) and 4d-(Mo, Ru) transition metal ions at the B-site and rare earth (La, Pr) and alkali (Ca, Sr, Ba) ions occupying A-sites. Electronic correlations and phase transitions in bulk SCEO can be controlled by chemical doping and/or isovalent substitutions. In thin films an additional nanoscale control by tuning the film architecture, dimensionality and interfaces is possible.

Growth challenges

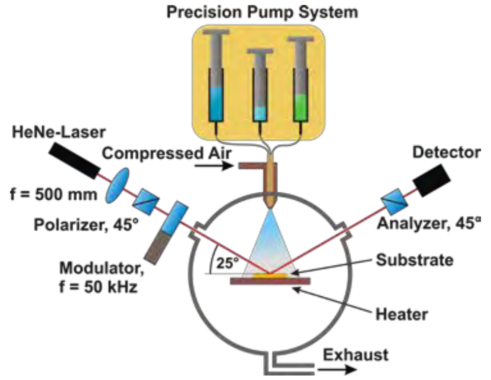
We are developing novel approaches and technologies to grow thin films and hetero-structures of SCEO using in-situ atomic layer growth control by optical ellipsometry. Our technique (see Fig), Metalorganic Aerosol Deposition (MAD), is a chemical deposition route, which uses aerosols of metalorganic precursors to control the stoichiometry of the grown film. MAD is a vacuum-free technique and provides growth conditions close to the equilibrium (temperature, deposition rate and oxygen partial pressure), which could be advantageous for growth of SCEO. Our current interests are: a) fine controlling of the growth atmosphere (Ar/O2 ratio); b) an adaptive MAD growth by getting feedback between the ellipsometry signal and precursor dosing units and c) in-situ growth of microstructured films with extremely high deposition rates ~1 μ/s.

Structure

The crystal structure and architecture of SCEO hetero-structures is studied by global (X-ray diffraction and reflectometry) and local (STM/AFM, SEM) techniques. In addition, Raman & Tip-Enhanced Raman Spectroscopy (TERS) allow us to correlate the phonon spectra and crystal symmetry, which could be especially advantageous by monitoring phase transitions, driven by temperature, electric and magnetic field as well as by light.

Electronic properties and magnetism

Transport and magnetism is studied by dc/ac electric (PPMS) and magnetic (SQUID, MOKE) techniques in a wide range of temperatures and applied magnetic fields. The main aim is to study emergent exchange coupling (AFM/FM) phenomena mediated by correlated Jahn-Teller polarons at the 1 order transition in electronically and/or structurally phase separated manganites. A possibility to tune the exchange coupling and crystal structure in manganite/titanite superlattices by means of interface engineering and strain was demonstrated. Electronic reconstructions at atomically sharp interfaces in A-AFM/G-AFM superlattices were shown to result in a new interfacial high-Tc ferromagnetic phase.



Vasily Moshnyaga

Vasily Moshnyaga, born 1956 in Chisinau (Republic of Moldova), studied physics at the Moscow Engineering Physical University (honor Diploma, 1979). He received PhD in physics in 1984 (A.M. Prokhorov General Physics Institute of Russian Academy of Sciences) and worked in different institutes of Academy of Sciences. In 1999 he moved to the University of Augsburg (Prof. Dr. K. Samwer) and in 2005 finished habilitation in physics at the University of Göttingen. Since 2010, apl Professor and group leader at the I. Physical Institute at the University of Göttingen. Member of German Physical Society (1999).

Ultrafast Dynamics in Solids, at Surfaces and Interfaces

Charge transfer, chemical reactions, photovoltaic processes or phase transitions are often triggered by an initial primary excitation that induces subsequent dynamics starting on an ultrafast timescale, i.e., attoseconds (10^{-18}) to femtoseconds (10^{-15}). In our research we apply such controlled primary excitations to study the impact of these excitations on dynamical mechanisms in materials, which are driven by non-equilibrium electron, spin, and lattice dynamics. A microscopic understanding of these ultrafast physics allows us to gain insight into the fundamental mechanisms that determine electronic, magnetic, and structural changes in materials. Our tools comprise time-resolved photoemission spectroscopy and magneto-optical techniques with pulsed laser sources, and in particular the application of photons in the extreme ultraviolet from high-harmonic generation table-top light sources.

Energy conversion in correlated electron materials

In materials with strong correlations, the interactions of spin, charge, and lattice determine the path of energy conversion after optical excitation. Depending on the dominant interaction, the deposited energy is directed into different forms of work inducing electronic, magnetic, and structural changes. Often, however, the main interaction that would be responsible for the pathway of energy flow after an excitation is hard to determine in thermal equilibrium. Here, ultrafast time-resolved spectroscopies are a powerful way to overcome this problem and to investigate non-equilibrium energy flow in correlated materials. In particular, time-resolved photoemission techniques are well suited, since they can follow in a direct manner the optically induced redistribution of charge carriers. Hence, ultrafast time-resolved mapping of the electrons' energies, spins, and momenta after a strong optical excitation sheds light on band-structure formation, its relaxation to equilibrium, and the pathways of energy flow that are determined by the material's spin-charge-lattice interactions.

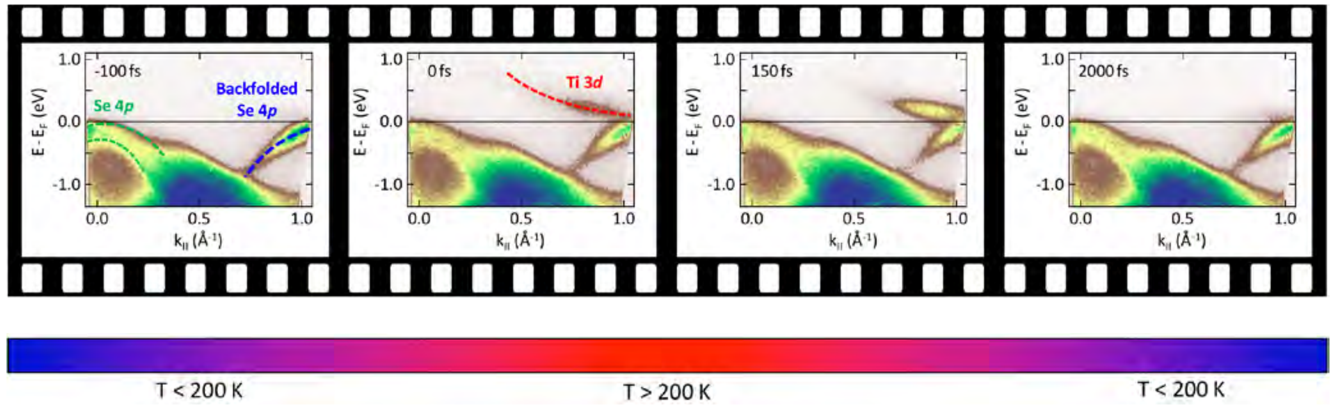
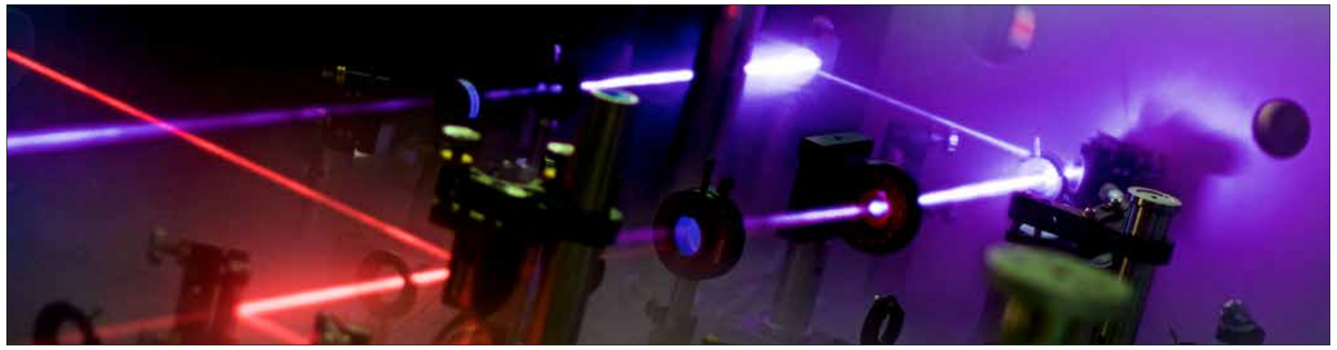


Fig. 1: Time-resolved snapshots of a photo-induced charge-density-wave to semi-metal phase transition, measured with time- and angle-resolved photoelectron spectroscopy, [1].



Ultrafast magnetization dynamics in nanostructures

The speed at which a magnetic state can be manipulated and, hence, data can be magnetically stored depends ultimately on the elementary spin-photon interaction, spin-scattering, and spin-transport processes. Until the mid-1990s, dynamics in magnetic systems were believed to occur on time scales of ~100 picoseconds or longer, determined by the interaction of the spins with the lattice. However, studies using femtosecond laser pulses starting from 1996 revealed the presence of other processes beyond this simple spin-lattice relaxation picture.

In this research field, we use novel methods based on the combination of coherent ultrafast X-ray pulses from laser-based high-harmonic generation with a variety of magneto-optical techniques. These combinations allow us to probe ultrafast spin dynamics with element-specificity and highest time-resolution. Highlights of our research are, e.g., elucidating the role of superdiffusive spin-currents in a femtosecond demagnetization process, and probing the timescale of the exchange interaction in a ferromagnetic alloy. Currently, we study cooperative effects of interacting magnetic subsystems in magnetic multilayers, alloys, and nanostructures.

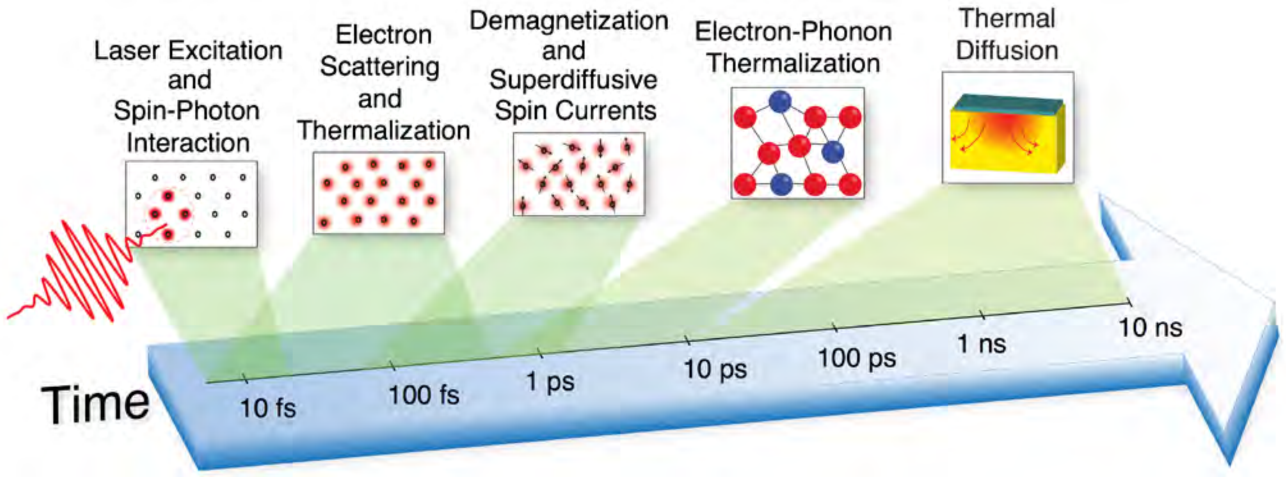
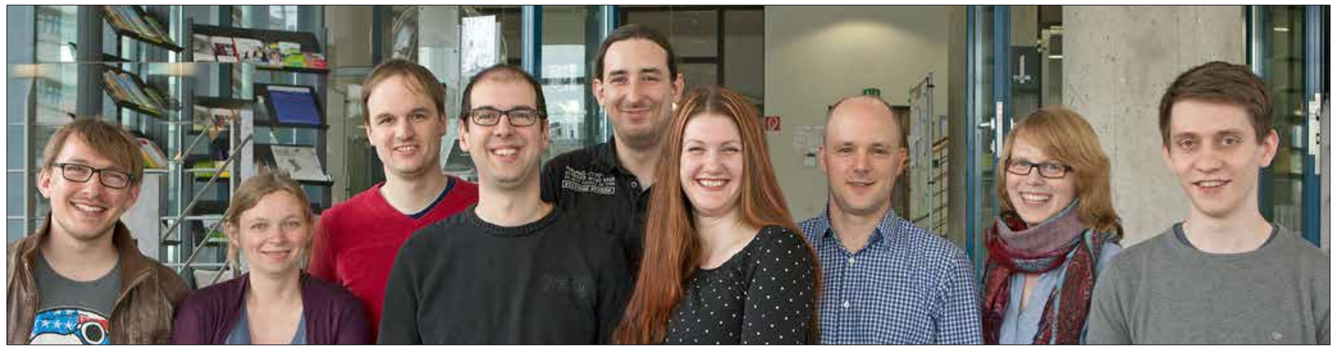


Fig. 2: Schematic timeline of ultrafast photon–electron–spin–lattice interactions after an ultrafast laser excitation. During the ultrafast excitation of the electron system by a femtosecond laser pulse, ultrafast spin-photon interaction can be a source of coherent magnetization dynamics. On a longer femtosecond timescale, various scattering processes between electrons, phonons, and magnons, as well as superdiffusive spin-currents determine the dynamic response of the material. The different contributions of the above-mentioned processes to the ultrafast magnetic dynamics are widely debated and a field of active research, [6].

The short life of electrons at interfaces

The idea in this research area is to study photo-stimulated electron dynamics after an optical excitation in real time. In particular, we are interested in the fate of excited electrons, i.e., their decay processes and their according ultrashort lifetimes. In general, the investigation of the dissipation of such "hot electrons" is of relevance, for instance, in femtochemistry, spin-dynamics, for spin-injection processes, and for energy conversion mechanisms. Since the lifetime of excited electrons plays a central role in all photo-stimulated processes, and also depends on a diverse range of physical parameters, our works extend from dynamics in quantum-well nanostructures to molecule/surface hybrid systems and topological materials with high spin-orbit coupling. As an experimental method to access the relevant ultrafast dynamical processes, we employ time-resolved two-photon photoemission spectroscopy. This real-time pump-probe technique is then combined with different photoemission methods which include angular- ("ARPES"), spin-, and/or real-space resolution.



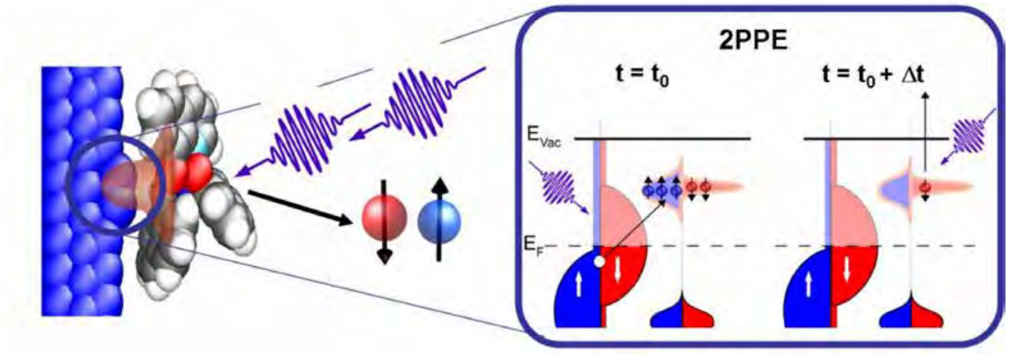


Fig. 3: Schematic of a time- and spin-resolved two-photon photoemission experiment from an organic molecule/metal hybrid system [5].

New tools to study ultrafast materials dynamics

Rapid progress in ultrafast X-ray science worldwide, both in high-harmonic generation (HHG) and X-ray free electron laser (FEL) sources, has paved the way for a new generation of light-matter experiments investigating ultrafast electronic, magnetic, and structural dynamics in materials. Here, we developed in recent years several ultrafast material science experiments that are based on the use of table-top HHG lightsources. By the virtue of the short wavelength pulses produced by high-harmonic generation lightsources, we could show that HHG is an ideal probe for even the fastest dynamics in matter. Using elemental absorption edges, site-specific magnetic, electronic, structural, and chemical dynamics can be captured, providing unique capabilities for the study of complex emerging materials.

In our activities, the development of such novel tools for the study of ultrafast dynamics in materials is an integral part of our research.

[1] S. Mathias et al., Self-amplified photo-induced gap quenching in a correlated electron material, Nature Comm. 7, 12902 (2016)

[2] S. Jakobs et al., Controlling the spin-texture of topological insulators with organic molecules, Nano Letters 15, 6022 (2015)

[3] E. Turgut et al., Controlling the Competition between Optically Induced Ultrafast Spin-Flip Scattering and Spin Transport in Magnetic Multilayers, Phys. Rev. Lett. 110, 197201 (2013).

[4] D. Rudolf et al., Ultrafast magnetization enhancement in metallic multilayers driven by superdiffusive spin current, Nature Comm. 3, 1037–6 (2012)

[5] S. Steil et al., Spin-dependent trapping of electrons at spinterfaces, Nature Phys. 9, 242 (2013)

[6] S. Mathias et al., Probing the timescale of the exchange interaction in a ferromagnetic alloy, PNAS 109, 4792–4797 (2012)

[7] T. Rohwer et al., Collapse of long-range charge order tracked by time-resolved photoemission at high momentum, Nature 471, 490 (2011)

[8] S. Mathias et al., Quantum-well induced giant spin-orbit splitting, Phys. Rev. Lett. 104, 066802 (2010)

Stefan Mathias

Stefan Mathias, born in 1977 in St. Wendel, studied Physics at the University of Kaiserslautern and the University of Uppsala. From 2004 until 2008 he conducted his PhD in the group of Martin Aeschlimann on ultrafast dynamics on surfaces. In 2009, he was a visiting lecturer at the Kigali Institute of Science and Technology, Rwanda, and moved afterwards to JILA, University of Colorado and NIST, Boulder, USA as part of an EU Marie-Curie International Outgoing Fellowship. In 2012, he was appointed Junior-Professor for Laser Physics and Ultrafast Phenomena in Solids at the University of Kaiserslautern. He joined the University of Göttingen as a full professor in 2015, where he continues his research on ultrafast dynamics in materials.

Ion Beams and Materials

Ion beams are essential for fabricating electronic devices, thin film coatings, for surface processing and for elemental thin film analysis. Our group operates several ion beam facilities providing ion beams from eV to GeV energies for materials modification, synthesis of thin films, ion implantation of impurities, dopant atoms and probe atoms as well as ion beam analysis of materials. Material modifications include ion implantation, surface pattern formation by keV ion irradiation, ion track formation by irradiation with GeV heavy ions, and 3D-microstructuring using MeV proton beams. Low energy ion beam deposition is ideal to synthesize diamond-like materials and cubic boron nitride. We also use ultra-low energy mass selected ions for controlled doping of graphene and related 2D materials. Semiconductors and metallic compounds are implanted with radioactive probe atoms for nuclear spectroscopy. Our ion beam analysis techniques are RBS, high resolution RBS (nm resolution), PIXE and nuclear reaction analysis.

Ion beam facilities

Our group operates several low energy ion beam systems for thin film growth and surface modification. A dedicated mass selected UHV ion beam system provides low energy mass selected ions in the energy range 10 eV to 60 keV for graphene doping and the synthesis of high quality diamond-like materials, like tetrahedral amorphous carbon (ta-C) and cubic boron nitride (c-BN), and for shallow surface modification of materials.

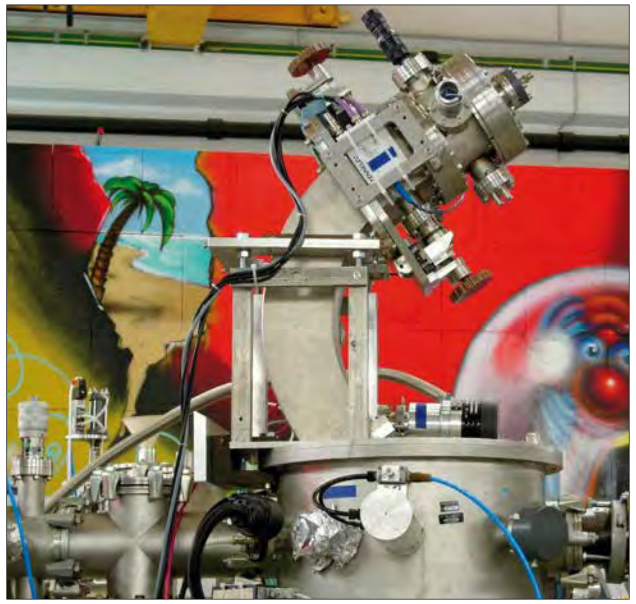


Fig. 1: High resolution RBS setup showing the scattering chamber and the cylindrical electrostatic analyzer providing a depth resolution of < 2 nm.

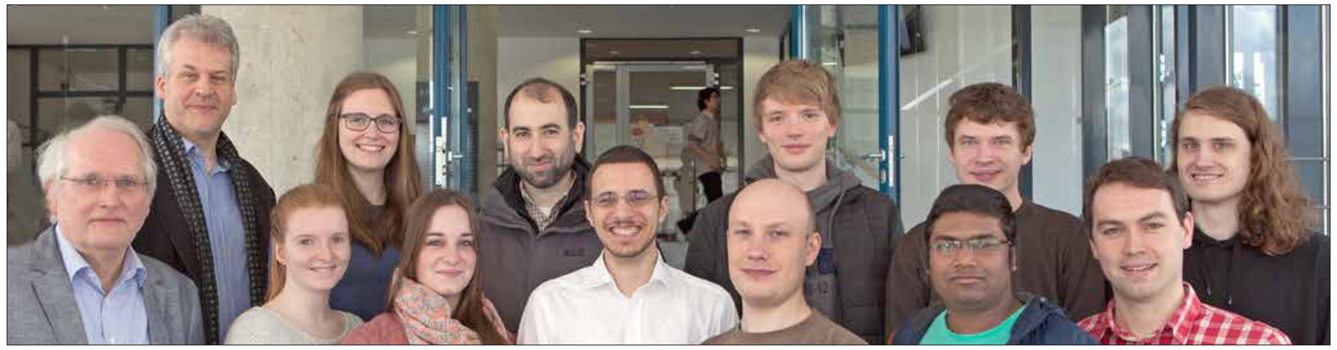
Three low energy ion beam systems are optimized for ion beam erosion of surfaces to investigate pattern formation processes at surfaces in particular under the influence of metallic surfactant atoms.

A 500 keV multi purpose heavy ion implanter is available for ion implantation of nearly all elements, including some radioactive isotopes (^{111}In). The implanter also provides up to 1 MeV He^{2+} for RBS analyses as well as protons for nuclear reaction analysis. A high resolution RBS setup provides a depth resolution of 1-2 nm for thin film analyses (Fig.1).

A 3 MeV Pelletron tandem accelerator is equipped with beam lines for RBS, external beam PIXE, micro beam PIXE, proton beam writing of 3D microstructures and nuclear reaction analysis. A dedicated setup for hydrogen profiling using the resonant $^{1}H(^{15}N,\alpha\gamma)^{12}C$ reaction is available.

Materials modification

Formation of nanoscale periodic ripple and dot patterns at surfaces by ion beam erosion with keV ions is a well known phenomenon. We have extended this process by introducing surfactant atoms by co-deposition during sputter erosion. These surfactant atoms strongly modify the erosion process and lead to a variety of novel surface patterns, to surface smoothing and to the formation of nanostructured ultrathin films. Nanopatterns on Si with a designed pattern symmetry can be created by ion irradiation and simultaneous co-deposition of Fe (Fig. 2).



Swift heavy ions (SHI) with energies up to GeV cause a tremendous local electronic energy loss up to 40 keV/nm in materials leading to the formation of ion tracks. We are also able to perform irradiations with charge selected swift heavy ions and charge states higher than 60+, corresponding to electronic energy loss up to about 55 keV/nm. SHI irradiation of high resistivity diamond-like ta-C creates highly conducting filaments with few nm diameter. These filaments are identified using atomic force microscopy by measuring the topography and the corresponding current mapping of an irradiated ta-C film. Both conducting ion tracks and self-aligned ion track lithography are investigated regarding the electronic transport in reduced dimensions.

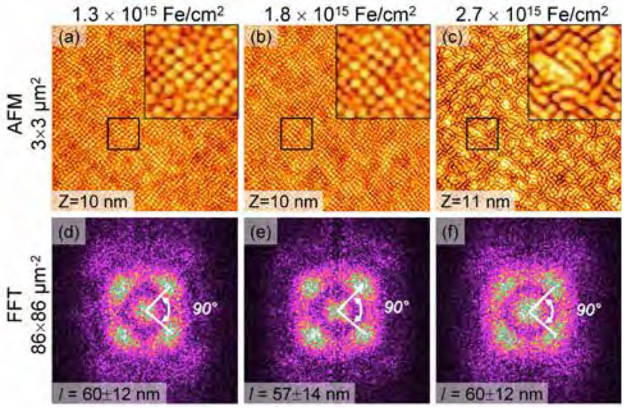


Fig. 2: (a)-(c): AFM topography of a Si-Fe surface for increasing steady-state Fe coverage obtained by Ar irradiation and co-deposition of Fe using the four-fold symmetric sputter target geometry. Z is the range of the color height scale. The inserts show the magnified 500fk500 nm2 regions marked by the squares. (d)-(f): Fast Fourier transformation (FFT) images of the AFM images (a)-(c) above. The value l is the dot spacing related to the maxima in the FFT.

Ion implantation doping of graphene and related 2D materials

With our dedicated low energy mass selected ion beam system, we have recently demonstrated the successful implementation of ion implantation doping of graphene with 20 eV B and N. The dopant atoms are incorporated on substitutional sites without generating a significant amount of defects. Besides B and N we are able to perform ultra-low energy ion implantation under UHV conditions for C, F, P, Se and other species with energies down to 10 eV at beam intensities of several µA. Graphene doped in this ways shows the characteristics of p-type and n-type dopant impurities, which was analysed with scanning tunnelling spectroscopy, angle resolved photo emission spectroscopy, near K-edge electron energy loss spectroscopy or magneto transport measurements.

3D microstructuring of semiconductors by proton beam writing

The manufacturing of smallest three-dimensional structures in the micro- and sub-micrometer range in semiconductors represents a rapid growing high-technology area. In order to produce such MEMS systems typically conventional lithography is applied. In contrast, the proton beam writing (PBW) process is a maskless direct writing process, utilizing a high energetic focused proton beam for a local modification of the physical properties of the substrate in the micrometer range, and in case of advanced setups even on the nanometer range. We apply PBW to directly write 3-dimensional microstructures into semiconductors. The underlying process consists of the creation of 3D defect distribution, which influences the subsequent electrochemical etching process. An example of a freestanding 3D microstructure in GaAs, made by just one irradiation and one etching step is shown in Fig.3.

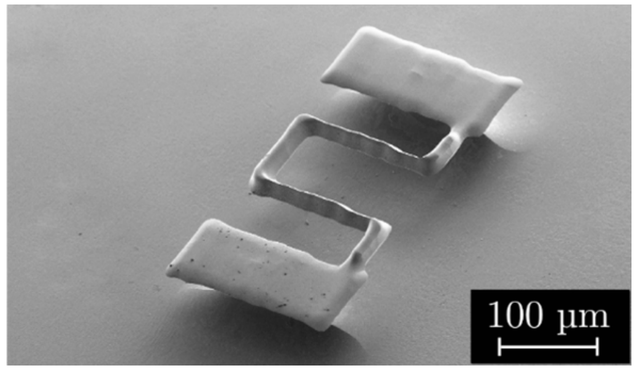


Fig. 3: Free-standing microstructure on GaAs prepared by proton beam writing using a 2 focused MeV proton beam and a subsequent electrochemical etching process.

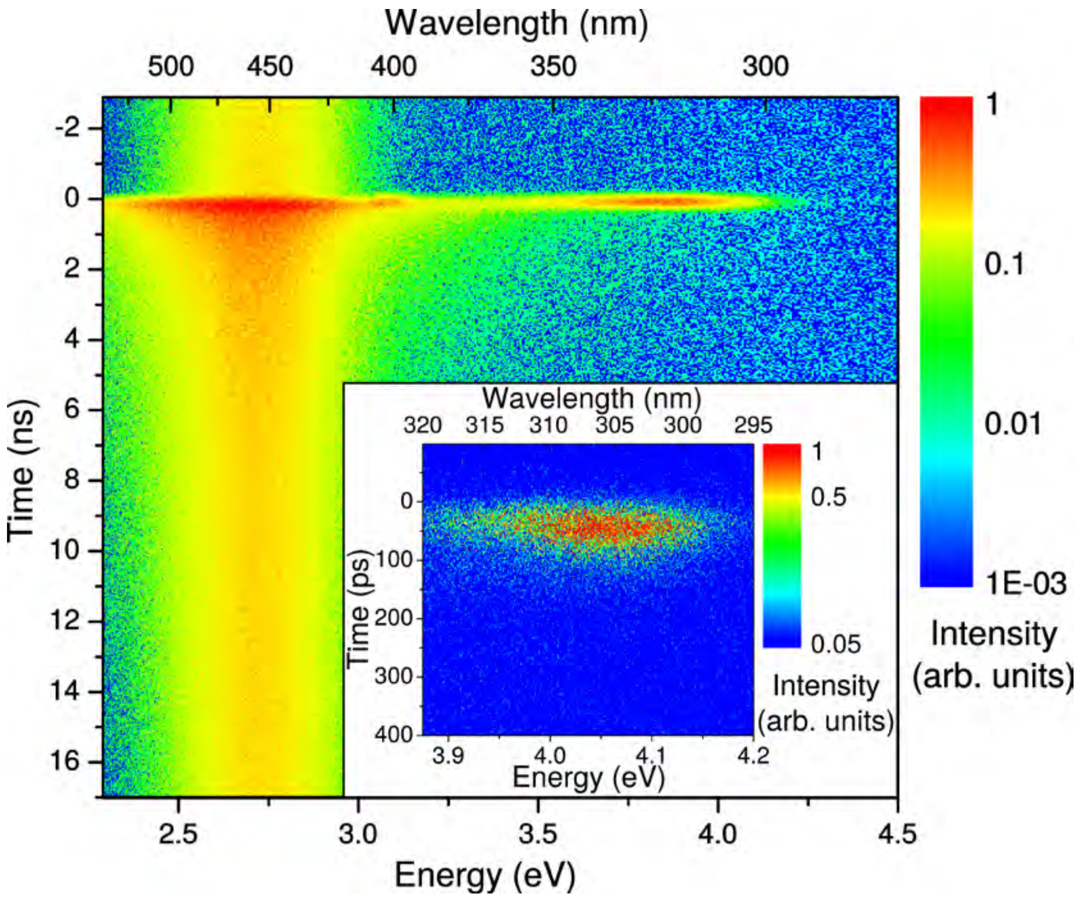


Fig. 4: Room temperature defect luminescence in aluminum nitride after excitation with femtosecond Laser pulses of 267 nm. The luminescence at 460 nm decay with a long time constant of several ns. The insert shows the short-lived luminescence around 305 nm with high time resolution. The defect luminese is most likely due to oxygen complexes and carbon impurities.

Time resolved Photoluminescence

Rare earth doped semiconductors and phosphors have attracted much interest because of their high chemical durability and wide range of attractive applications. We investigate the luminescence properties of those materials using time-resolve photoluminescence spectroscopy. The spectrometer is based on a tunable femtosecond Laser system for wavelengths between 193 nm and 1 µm. Luminescence spectra are recorded with a streak camera with a time resolution down to 20 ps or with high spectral resolution using a 1m spectrograph. The example of defect luminescence in Aluminium nitride is shown in Fig.4.

[1] K Zhang, O Bobes and H Hofsäss, Nanotechnology 25 (2014) 085301.

[2] U. Bangert, W. Pierce, D. M. Kepaptsoglou, Q. Ramasse, R. Zan, M. H. Gass, J. A. Van den Berg, C. B. Boothroyd, J. Amani, and H. Hofsäss, Nano Letters 13 (2013) 4902.

[3] M. K. Mahata, T. Koppe, T. Mondal, C. Brüsewitz, K. Kumar, V. Kumar Rai, H. Hofsäss, U. Vetter, Phys. Chem. Chem. Phys. 17 (2015) 20741.

[4] M. Schulte-Borchers, U. Vetter, T. Koppe, H. Hofsass, J. Micromechanics and Microengineering 22 (2012) 025011

[5] J Krauser, H-G Gehrke, H Hofsäss, J Amani, C Trautmann, and A Weidinger, New J. Phys. 17 (2015) 123009.

Hans Hofsäss

Hans Hofsäss was born in 1956. After studying physics at Konstanz University he received his Dr. rer. nat. in 1986. For his doctoral thesis on electron emission channelling he received the Dornier research award in 1988. Following a post doc stay in the group of Wei-Kan Chu at the University of North Carolina, Chapel Hill, he was a research assistant in Ekkehard Recknagel's group at Konstanz University working on nuclear solid state physics, semiconductor physics and synthesis of diamond-like films. He directed a research group at the ISOLDE facility at CERN. In 1994 he obtained his habilitation from Konstanz University. Since 1998 he is a professor at the 2nd Institute of Physics of Georg-August University. From 2009-2013 he was Dean of the Faculty of Physics. His research interests are ion beam synthesis and modification of materials, nuclear solid state physics, semiconductor physics and physics of nanostructures.

Ultrafast Dynamics and Nano-Optics

In the tiny world of atoms, molecules and nanostructures, many of the important electronic and structural processes occur on extremely short timescales of picoseconds, femtoseconds (10^{-15} s) or even attoseconds (10^{-18} s). We are interested in such ultrafast dynamical phenomena and are developing new experimental techniques to explore them. Employing modern laser technology, we investigate the classical and quantum mechanical behavior of electrons driven by very intense optical fields at nanoscale metal structures. Moreover, we use sharp metallic needles to generate ultrashort pulses of electrons and create time-resolved versions of electron microscopy and electron diffraction.

Highly nonlinear optics in metallic nanostructures

Functioning as optical antennas, metallic nanostructures have the ability to collect, confine and locally enhance light fields in nanoscopic, sub-wavelength volumes. We utilize different types of nanostructures (see Fig. 1) to amplify nonlinear optical processes that require high light intensities. This includes the emission of photoelectrons or the ionization of atomic gases, which can lead to nanometer-scale sources of extreme ultraviolet light.[2]

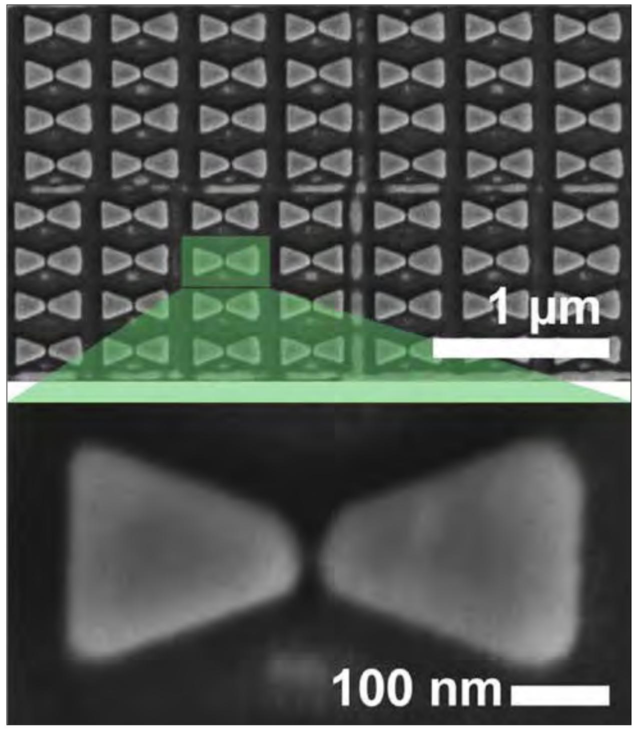


Fig. 1: Optical "bow-tie" antennas. Illumination of the structures creates strongly enhanced fields in the nanoscale gap between opposing triangles (see. Ref. [1])

Electron pulses from nanotips

Sharp metallic needles (Fig. 2) are particular types of nanostructures, which can enhance optical fields similar to a lightning rod. Illuminating such nanotips with femtosecond laser pulses can cause the emission of electrons from the apex. We use this effect to create a very localized, pulsed source of free electron beams. In order to actively tune the properties of these ultrashort electron bursts, we follow various approaches, including the use of electrical field pulses at Terahertz frequencies (1 Terahertz = 10^{12} Hz). Overlapping a visible laser pulse with a THz pulse on a metallic nanotip allows us to control both the number and the velocities of the electrons emitted from the end of the tip (Refs. [2,3]). In this way, we can precisely shape the energy spectrum and duration of the electron pulses generated.

Ultrafast Transmission Electron Microscopy (UTEM) and Ultrafast Low-Energy Electron Diffraction (ULEED)

We harness the laser-triggered electron emission from nanotips to develop new experimental methods, which provide us with unprecedented views into ultrafast dynamics on the nanoscale. Specifically, our group recently developed two unique instruments, an Ultrafast Transmission Electron Microscope (UTEM) and an Ultrafast Low-Energy Electron Diffraction (ULEED) setup. With these two instruments, we observe rapid structural and electronic dynamics with atomic-scale resolution in solids, nanostructures, and at surfaces. The measurement principle in both cases is similar: In stroboscopic, so-called "pump-probe" experiments, the investigated sample is excited by an intense optical pump beam, and the resulting change in the atomic arrangements of the sample is "probed" by the pulsed electron beam. The UTEM operates with femtosecond electron pulses at an energy of 200 kilo-electronvolt, which can be focused down to a diameter of only one nanometer, yielding extremely high spatial and temporal resolution for samples about 10-100 nm thick. In a different mode, the UTEM can also operate as an ultrafast "Lorentz microscope", which senses the local magnetization in nanostructures and thin films that are relevant for magnetic data storage and switching.

Fig. 2: Laser-illuminated metallic nanotips (left) can emit electrons from their apex. Right: Such tips are placed in an electron gun for generating ultrashort electron pulses, see Ref. [4] for details.

The ULEED setup, on the other hand, uses much lower electron kinetic energies of only 50-200 electronvolt. These slow electrons are very surface-sensitive and can give us information about fast structural processes within the first few atomic layers of a material, such as the formation of a surface reconstruction or the dynamics of a molecular monolayer on a substrate.

We are constantly working on improvements of the capabilities of UTEM and ULEED to track the ultrafast changes in atomic configurations associated with complex ordering phenomena and phase transitions in novel materials, heterostructures and at surfaces.

Quantum optics with free-electron beams

Besides applications in solid state physics, the UTEM approach also provides for very interesting possibilities to study the interaction of swift electrons with local optical modes. In particular, the spectroscopic study of electrons interacting with optical near-fields facilitates quantum-coherent manipulations of the momentum distribution in ultrashort electron pulses (Fig. 3). This opens up a completely new area in quantum optics, namely the investigation of coherent couplings and control mechanisms for free electrons.

Coherent Imaging with High Harmonics

In a complementary approach to our work with electron beams, we also use short pulses of extreme-ultraviolet (EUV) light or soft x-rays for high-resolution imaging. This radiation is produced as a very high multiple of the frequency of a laser field in a nonlinear optical process called "high harmonic generation". We use the short wavelengths of these high harmonics – in the range of few tens of nanometers and less – to image field distributions and the polarization properties of waveguides and other EUV optical components, and currently work towards establishing magnetic contrast imaging with this radiation.

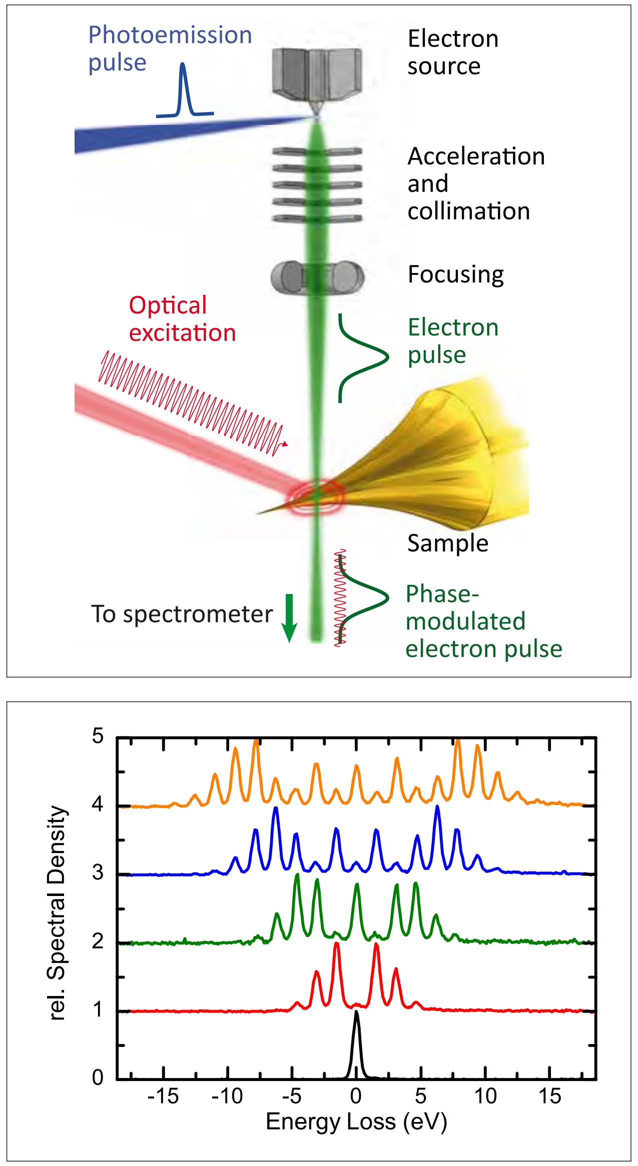


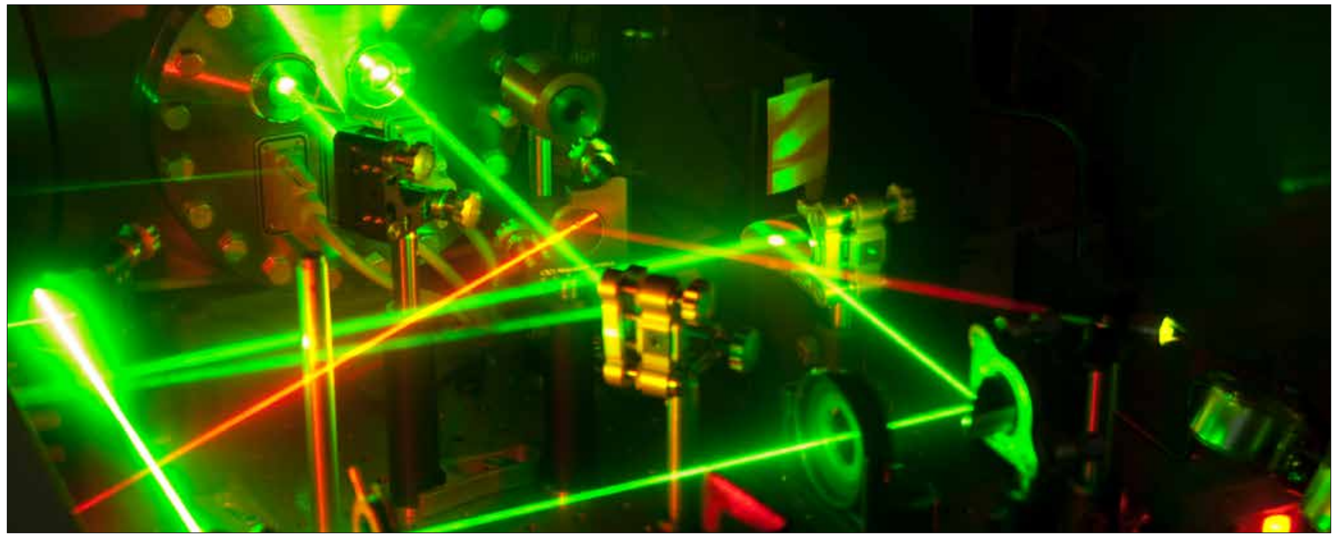
Fig. 2: Top: Principle of a UTEM experiment. A photoemission laser pulse (blue) generates a femtosecond electron pulse (green), which then interacts with an optically excited sample. Various contrast mechanisms for imaging, diffraction and spectroscopy are possible. Bottom: One of the possible interaction processes generates a quantum mechanical superposition of free-electron momentum states, evident as equidistant spikes in the electron energy distribution. (increasing excitation field from black to orange). This coupling represents a striking instance of quantum optics with free-electron beams; see Ref. [5] for details.

Real-time Spectroscopy and Laser Physics

Finally, as a further line of research, we apply recently established optical spectroscopy tools to study complex processes in nonlinear optics and laser physics. In collaboration with our colleagues at the University of California at Los Angeles (UCLA), we combine high-speed electronics with optical fiber technology to build an optical spectrometer capable of recording 100 million frames per second. With this device, we investigate transient phenomena in nonlinear optics and the dynamics of multiple pulses (solitons) in laser cavities.

Collaborations and Joint Research Projects

In order to make best use of our expertise and that of others, we actively collaborate with a number of groups on the Göttingen Campus, across Germany and elsewhere in the world. Our work is part of two collaborative research centers (SFB 755 "Nanoscale Photonic Imaging" and SFB 1073 "Atomic Scale Control of Energy Conversion"), and we participate in the DFG-funded Priority Programs "Ultrafast Nano-Optics" (SPP 1391) and "Quantum Dynamics in Tailored Intense Fields" (SPP 1841).



[1] M. Sivis, M. Duwe, B. Abel and C. Ropers, "Extreme-ultraviolet light generation in plasmonic nanostructures", Nature Physics 9, 304–309 (2013)

[2] G. Herink, D. R. Solli, M. Gulde, and C. Ropers, "Field-driven photoemission from nanostructures quenches the quiver motion, Nature 483, 190 (2012)

[3] L. Wimmer, G. Herink, D. R. Solli, S. V. Yalunin, K. E. Echternkamp, and C. Ropers, "Terahertz control of nanotip photoemission", Nature Physics 10, 432 (2014).

[4] M. Gulde, S. Schweda, G. Storeck, M. Maiti, H. K. Yu, A. M. Wodtke, S. Schäfer, and C. Ropers, "Ultrafast low-energy electron diffraction in transmission resolves polymer/graphene superstructure dynamics", Science 345, 200 (2014).

[5] A. Feist, K. E. Echternkamp, J. Schauss, S. V. Yalunin, S. Schäfer, and C. Ropers, "Quantum coherent optical phase modulation in an ultrafast transmission electron microscope", Nature 521, 200 (2015).

Claus Ropers

Claus Ropers studied physics at the University of Göttingen and the University of California at Berkeley. Conducting his doctoral studies at the Max Born Institute (Berlin), he received a Dr. rer. nat. degree from the Humboldt University in Berlin in 2007. At the University of Göttingen, he was appointed Assistant Professor at the Courant Research Centre "Nano-Spectroscopy and X-Ray Imaging" (2008), Associate Professor at the Institute of Materials Physics (2011), and Full Professor for Experimental Solid State Physics at the 4th Physical Institute (2013). For his scientific achievements, he was awarded the Carl-Ramsauer Prize (2008), Nanoscience Prize (AGeNT-D, 2008), and Walter-Schottky Prize (German Physical Society, 2013). In 2014, he received an ERC Starting Grant for the development of ultrafast low-energy electron diffraction.

Spectroscopy on the Atomic Scale

The miniaturization of future electronic devices is intimately connected with the ability to analyze the system on the atomic scale. This requires more than just knowing the local defect structure and the electronic properties, but it has to include the characterization of transport fields and dynamic processes of single defects. Scanning Probe Microscopy (SPM) has opened up a way to access surface as well as bulk properties. Our group is applying and developing SPM tools for challenging questions of fundamental research in this field investigating e.g. metal-semiconductor interfaces, transport in graphene, charge dynamics of single dopants in GaAs, Kondo effect and material classes like pnictides, hexaborides and iridates [1-5].

Dynamic processes studied atom by atom

Pump-probe experiments combined with SPM allow to resolve dynamic processes on the nanometer scale. We have utilized this to study the charging process of single donors in GaAs. Our experiments show that the combined dynamics of bound and free charges become important to better understand the physics of nano-scaled systems.

Scanning Tunneling Potentiometry: Access to local transport properties

Electronic transport on a macroscopic scale is often described by spatially averaged electric fields and scattering processes. To capture electronic transport on the atomic scale, local and non-local scattering processes need to be considered separately. An experimental study based on low-temperature scanning tunneling potentiometry (see Fig. 2) has allowed us to separate different scattering mechanisms in graphene. Most importantly, we are able to show that the voltage drop at a monolayer/bilayer boundary is not located strictly at the structural defect [3].

Correlated electron systems

Scanning tunneling spectroscopy allows to study single magnetic impurities in bulk crystals (see Fig.3) [4,5]. This surprising finding has opened up a new way to investigate the interplay between the Ruderman-Kittel-Kasuya-Yosida interaction and the Kondo effect, which is expected to provide the driving force for the emergence of many phenomena in strongly correlated electron materials. We have investigated iron dimers buried below a Cu(100) surface by means of low-temperature scanning tunneling spectroscopy. Two magnetic impurities in a metal are the smallest possible system containing all these ingredients and define a bottom-up approach towards a long-term under-standing of dense systems.

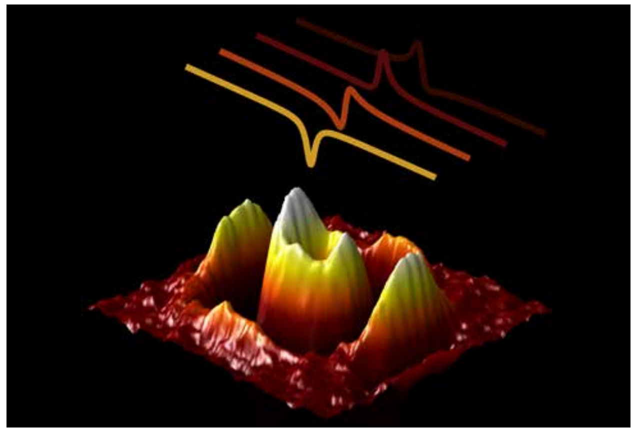


Fig. 3: (bottom) Constant current topography of a single Fe atom in Cu, (top) spatially varying differential conductivity giving access to the Kondo effect of a single magnetic impurity in a bulk crystal.

[1] P. Kloth, K.Kaiser, and M. Wenderoth,: Controlling the screening process of a nanoscaled space charge region by minority carriers, Nat. Comm. 7,10108 (2016)

[2] T. Iffländer, S. Rolf-Pissarczyk, L. Winking, R.G. Ulbrich, A. Al-Zubi, S. Blügel, and M. Wenderoth: Local Density of States at Metal-Semiconductor Interfaces: An Atomic Scale Study, Phys. Rev. Lett 114,146804 (2015)

[3] P. Willke, T. Druga, R. G. Ulbrich, M. A. Schneider, and M. Wenderoth, Spatial Extent of a Landauer Residual-Resistivity Dipole in Graphene quantified by Scanning Tunneling Potentiometry, Nat. Comm. 6,6399 (2015)

[4] H. Prüser, M. Wenderoth, P.W. Dargel, A. Weismann, R. Peters, T. Pruschke, R.G. Ulbrich: Long-range Kondo signature of a single magnetic impurity, Nature Physics 7,203-206 (2011)

[5] A. Weismann, M. Wenderoth, S. Lounis, P. Zahn, N. Quaas, R. G. Ulbrich, P. H. Dederichs, S. Blügel: Seeing the Fermi Surface in Real Space by Nanoscale Electron Focusing, Science 323,1190 (2009)

Martin Wenderoth

Martin Wenderoth was born in 1961 in Hohenlimburg/Hagen and studied Physics at the University of Dortmund and at the Georg-August-University of Göttingen, where he received his PhD in 1992. He accepted a permanent position (Akademischer Direktor) in the group of Rainer Ulbrich, becoming the group leader for scanning probe microscopy in the 4. Physical Institute at the Georg-August-University of Göttingen. His work focusses on the development of state of the art scanning probe techniques and nano scale characterization of transport and correlation effects in electronic and magnetic properties of semiconductors and metals.

Group III-N Based Functional Hetero- and Nanostructures

In the last three decades GaN, InN, AlN and related alloys have played a major role among the compound semiconductor materials. GaN is impressive in its successful application for solid-state lighting and lasers, with excellent performances in emitted luminous intensity and short wavelength read/write processing, respectively. Indeed the Nobel Prize in Physics 2014 was awarded jointly to Isamu Akasaki, Hiroshi Amano and Shuji Nakamura "for the invention of efficient blue light-emitting diodes which has enabled bright and energy-saving white light sources". Our aim is to explore new functionalities of the group III-N material class through interfacial phenomena and low dimensional nanostructures, as well as to obtain a fundamental understanding of the microscopic processes. The know-how in our group and the facilities at our disposal allow for the preparation and characterization of state-of-the-art GaN-based material, heterostructures and nanostructures by molecular beam epitaxy (MBE) through both top-down and bottom-up approaches.

Molecular Beam Epitaxy and III-N Compound Semiconductors

The technique of molecular beam epitaxy (MBE, from the greek *epi* : above and taxis : in ordered manner) allows the reproducible preparation of multilayer structures with atomically abrupt material changes at the interfaces as well as with controlled profiles of composition and doping on a nanometer scale, $d \sim 10^{-9}$ m. MBE takes place under ultra high vacuum conditions, $p \sim 10^{-11}$ mbar (Fig. 1). Band gap engineering and novel functionalities are achieved by combination of different semiconductors in hetero- and nanostructures. In Fig. 2 the heteroepitaxy road map – semiconductor band gap value over crystal lattice constant – is shown for the compound semiconductors most relevant for optoelectronic applications. AlN, GaN, InN and related alloys cover a wide wavelength range of the electromagnetic spectrum, from the infrared to the ultraviolet.

Heterostructures and Interfaces

Combination of different semiconductors to achieve new functionalities as compared with a bulk material can be realized through stacking of different layers in quasi-two-dimensional structures. Quantum confinement is observed once the thickness of the layers is comparable to the de Broglie wavelength of the electrons or holes ($\lambda \sim 17$ nm for GaN with electron effective mass $m_e^* = 0.2$ and electron energy $E = 25$ meV).

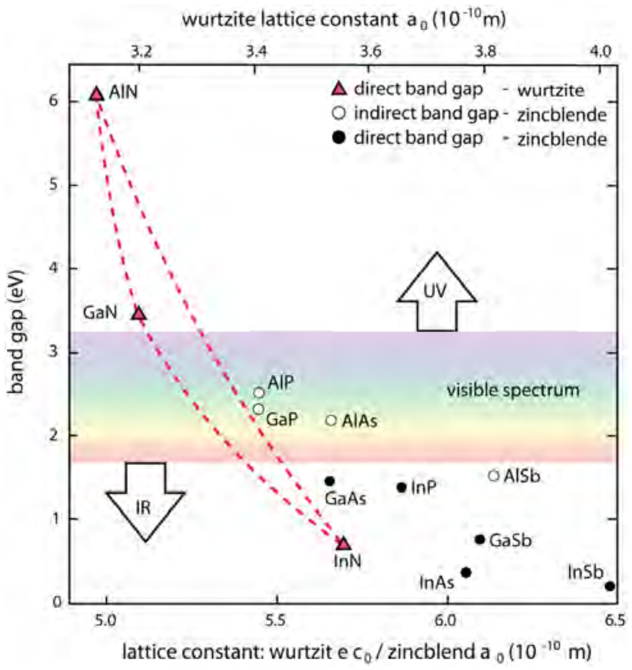


Fig. 2: Band gap values of III-V compound semiconductors over crystal lattice constants. The dashed red lines emphasize the III-N materials and their alloys.

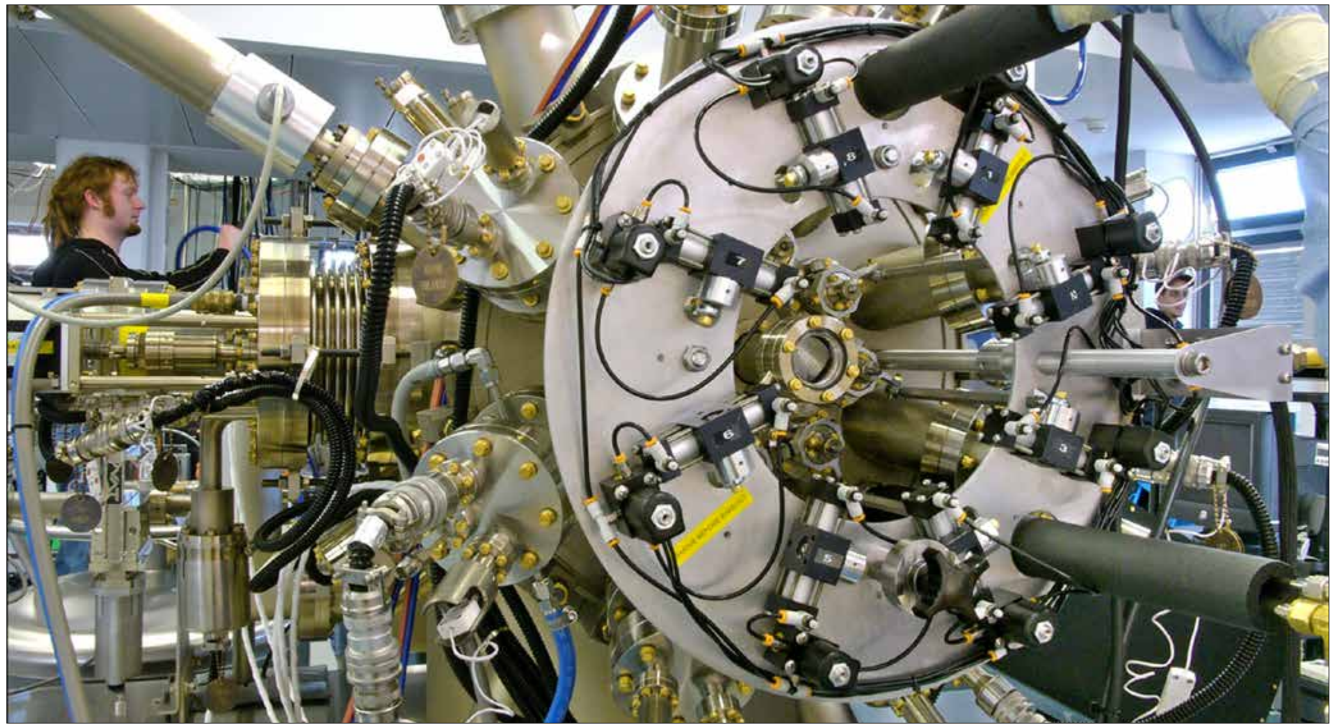


Fig. 1: MBE growth chamber. Close-up view of the material source flange.

GaN/AlGaN quantum well (QW) structures grown along the polar axis induce an accumulation of electronic charge at the interface, forming a quasi two-dimensional electron gas (2DEG) whose motion along the growth direction is confined by the QW potential (Fig. 3).

Optimum crystal and interface quality are prerequisite for achieving a high electron mobility μ in 2DEG heterostructures. Furthermore, μ depends on the electron sheet carrier density n_s. The magnetoresistance at low temperatures of optimized heterostructures in our group is shown in Fig. 4 with $\mu = 20.500\ \mathrm{cm^2/Vs}$ at $ns = 2.13 \times 10^{12}\ \mathrm{cm^{-2}}$. Clear Shubnikov-de Haas (SdH) oscillations were observed above 2 T.

The modulation of the 2DEG conductance by an external potential is a key process, which finds applications in high-frequency, high-power transistors as well as in biosensors. For pH-sensors applications e.g. when ions are deposited on a GaN or AlGaN surface, the surface charge is modified. This leads to a change in the band profile and thus to a change of the carrier concentration in the 2DEG. As a result, a change in the conductivity is measured.

A 2DEG heterostructure is a versatile and powerful system for interdisciplinary studies and applications.

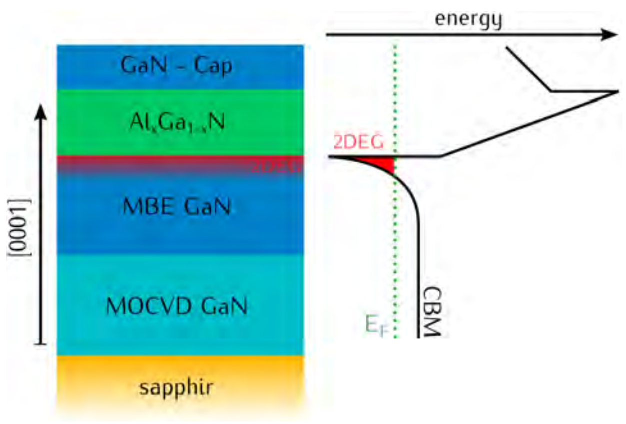


Fig. 3: Typical GaN/AlGaN stacking forming a quasi-two-dimensional electron gas with a sketch of the conduction band minimum (CBM) indicating the 2DEG at the interface.

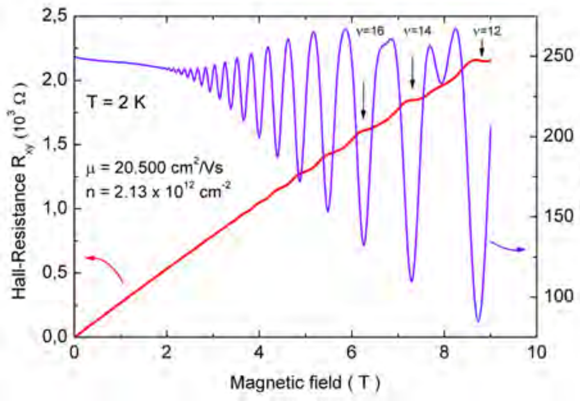


Fig. 4: Magnetic field dependence of the transverse (red) and longitudinal (violet) resistance of a high mobility AlGaN/GaN(0001) 2DEG heterostructure at low temperature. The plateaus in the Hall resistance (red) arise from the Quantum-Hall Effect.

Nanowires

Further reduction in dimensionality, namely reduction in the degree of freedom in the electron (or hole) momentum, is achieved by going from quantum wells down to quasi-one-dimensional quantum wires and eventually to a quasi-zero-dimensional quantum dot. Besides quantum confinement effects the morphology of semiconducor nanowires has the potential for the development of a new generation of devices benefiting from high aspect ratios, large surface to volume ratios, small active volumes and integration in complex architectures on the nanoscale. Most nanowire applications rely on the ability to grow, characterize (structurally, optically and electronically) and manipulate both individual and collections of nanowires. As an example Fig. 5 shows highly spatially resolved cathodoluminescence (CL) spectroscopy performed on a single GaN nanocolumn (NC) in a scanning transmission electron microscope (STEM) at liquid helium temperatures. The GaN NCs were grown by MBE on a masked GaN surface. Selective area growth in the mask holes occurs providing an ordered array of NCs. A small NC ensemble was prepared in cross-section for transmission electron microscopy and STEM-CL using focused ion beam (FIB).

[1] A. Urban, M. Müller, C. Karbaum, G. Schmidt, P. Veit, J. Malindretos, F. Bertram, J. Christen, and A. Rizzi, "Optical emission of individual GaN nanocolumns analysed with high spatial resolution", Nano Letters 15(8),5105-5109 (2015)

[2] Jaime Segura-Ruiz, G. Martinez-Criado, C. Denker, J. Malindretos and A. Rizzi, "Phase Separation in Single In$_x$Ga$_{1–x}$N Nanowires Revealed through a Hard X-ray Synchrotron Nanoprobe", Nano Letters 14,1300 (2014)

[3] A Urban, J Malindretos, J-H Klein-Wiele, P Simon and A Rizzi, "Ga-polar GaN nanocolumn arrays with semipolar faceted tips" New Journal of Physics 15,053045 (2013)

[4] F. Werner, F. Limbach, M. Carsten, C. Denker, J. Malindretos, A. Rizzi, "Electrical Conductivity of InN Nanowires and the Influence of the Native Indium Oxide Formed at Their Surface", Nano Letters 9 (2009) 1567

[5] J. Segura-Ruiz, N. Garro, A. Cantarero, C. Denker, J. Malindretos, A. Rizzi, "Optical studies of MBE-grown InN nanocolumns: Evidence of surface electron accumulation", Phys. Rev. B. 79, (2009) 115305

Principal investigators

Dr. Jörg Malindretos, Prof. Angela Rizzi

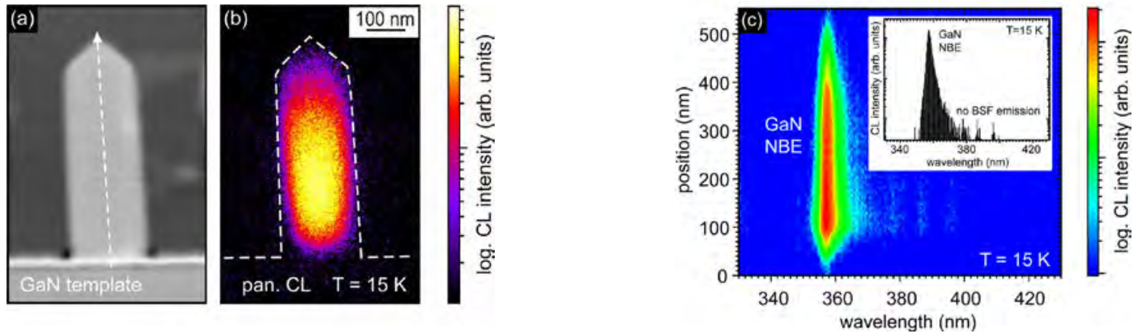


Fig. 5: STEM image (a) of a single defect-free GaN nanocolumn and the simultaneously recorded panchromatic CL mapping at 15 K (b). The CL intensity image shows a homogeneous luminescence distribution exclusively from the GaN nanocolumn. The spectrally and spatially resolved CL linescan (c) reveals a dominant near-band-edge emission. [1]

Angela Rizzi

After studying Physics at the University of Modena, Italy, Angela Rizzi received 1987 her PhD from the Technical University in Milano. After a post-doc stay at the Forschungszentrum Jülich as a Humboldt-fellow she held a Researcher position with teaching duties at the University of Modena, Italy still maintaining her main research activity at the Forschungszentrum Jülich. In 2002 she was appointed a professorship in Experimental Physics at the Georg-August University of Göttingen. She was Guest Professor at Université d'Aix-Marseille II, France, at the Hokkaido University, RCIQE, Sapporo, Japan and at the University of Cagliari, Italy.

Electronic and Atomistic Structure of Defects and Interfaces

Electronic and optical properties of semiconducting materials, devices and nanostructures are governed by defects and interfaces that introduce electronic states into the bandgap. In order to address the relation of their atomistic and electronic structure, atomically resolved transmission electron microscopy (HRTEM) is combined with spectroscopic techniques. Currently, our research focuses on materials for photonic and photovoltaic applications aiming at understanding and quantitatively modeling relevant processes at the atomistic level as a basis for successful defect engineering in such materials.

Quantitative high-resolution and analytical electron microscopy

At interfaces between crystalline and amorphous solids, atomic arrangements qualitatively change from long-range to short-range ordering. In collaboration with Prof. Borgardt (MIET, Moscow), a fully quantitative procedure has been developed to extract the atomic distribution function at such interfaces [1] (see Figure), from HRTEM image series showing that long-range atomic correlations decay from the crystalline to the amorphous material on a length scale of a few atomic layers. Furthermore, strain-induced lateral variations on a mesoscopic scale are observed.

Materials for photonics and photovoltaics

Defects and impurities in various forms reduce the efficiency of crystalline silicon solar cells. A plethora of reactions with intrinsic and extrinsic point defects as well as with dislocations and grain boundaries, make their control a formidable task which needs fundamental understanding of the underlying physics. Within a longstanding collaboration with Prof. Kveder (ISSP, RAS) spectroscopic and structural investigations combined with physics-based simulations are used to study the atomistic and electronic structure as well as thermodynamic properties in order to successfully adjust processing conditions minimizing deteriorating effects [2]. Photovoltaic energy conversion concepts beyond the Shockley-Queisser limit involve intermediate band solar cells [3] and long-living intraband transitions in polaronic materials [4] which are studied by structural and electrical microscopy techniques with Prof. Jooß within the CRC 1073. Control and understanding of spatially well controlled laser-induced formation of Si nanoparticles for efficient light emission is a topic pursued in collaboration with the Laser Laboratory Göttingen [5].

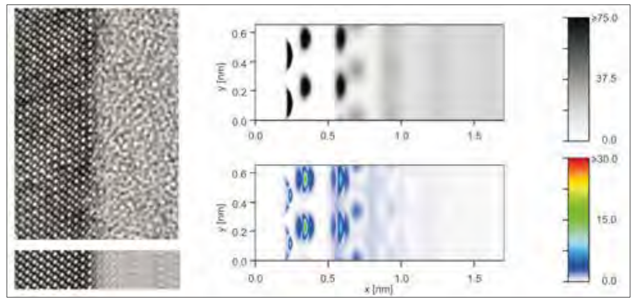


Fig. 1: The interface between crystalline Si and amorphous Ge: HRTEM image and its periodic average (left column), atom density distribution and its standard deviation (right column).

[1] K. Thiel, N. Borgardt, B. Plikat, M.Seibt, Ultramicroscopy 126, 1-9 (2013), Mesoscopic properties of interfacial ordering in amorphous germanium on Si(111) determined by quantitative digital image series matching

[2] M. Seibt, V. Kveder, in: Advanced Silicon Materials for Photovoltaic Applications, p.127 (2012), Gettering processes and the role of extended defects (invited review)

[3] P. Saring, A. L. Baumann, B. Schlieper-Ludewig, S. Kontermann, W. Schade, M.Seibt , Appl. Phys. Lett. 103, 061904 (2013), Electronic and structural properties of femtosecond laser sulfur hyperdoped silicon pn-junctions

[4] B. Ifland, Patrick Peretzki, Birte Kressdorf, Philipp Saring, Andreas Kelling, Michael Seibt and Christian Jooss, Beilstein Journal of Nanotechnology 6, 1467-1484 (2015), Current-voltage characteristics of manganite-titanite perovskite junctions

[5] T. Fricke-Begemann, N. Wang, P.Peretzki, M.Seibt, and J. Ihlemann, J. Appl. Phys. 118, 124308 (2015), Generation of silicon nanocrystals by damage free CW laser annealing of substrate-bound SiO films

Michael Seibt

Michael Seibt was born in Bremen in 1958. After studying physics at the Georg-August- University in Göttingen he received his diploma in 1982 and his PhD in 1986. During his time as a post-doc in Göttingen he worked on solid-state reactions and the atomistic and electronic structure of defects and interfaces in semiconductors. In the early 90's he joined Bell Laboratories in Holmdel, New Jersey, as a Humboldt scholar (Feodor-Lynen scholarship) and worked on quantitative high-resolution electron microscopy which has since become a branch of his research. His work in semiconductor defect physics is now mainly focused on materials for photonic and photovoltaic applications aiming at understanding and quantitatively modeling relevant processes at the atomic level. Michael Seibt is currently appointed as an apl. Professor at the Institute for Solid State and Nanostructure Physics and is liaison lecturer of the sdw group Göttingen-Kassel.

Quantum Many-Body Systems

The theory of quantum many-body systems provides the theoretical framework for understanding condensed matter including all electronic properties of solid state physics. Our group is particularly interested in the non-equilibrium properties of quantum many-body systems, that is the dynamics far away from the linear response regime. Recent experimental advances in ultracold gases, nanostructures and pump-probe spectroscopy have opened up this exciting new field with many fundamental questions that still need to be understood. Our group pursues these questions with mainly analytical tools supplemented with numerical methods for both understanding fundamental theoretical problems and experimental measurements. We are also interested in developing new theoretical methods inspired by AdS/CFT correspondence, that is the duality between certain strong-coupling quantum field theories and geometrodynamics like Einstein's theory of general relativity.

Thermalization and Irreversibility

Reconciling the 2nd law of thermodynamics, i.e. the observed arrow of time in nature, with microscopic time-reversal invariance is a fundamental question in many-particle physics. While this question is by now well understood for classical many-particle systems, much less is known for quantum many-particle systems. Cold atomic gases can nowadays be so well isolated from their environment that some experiments do not show thermalization during the experimentally accessible time scales. This observation challenges fundamental assumptions of quantum statistical mechanics underlying all calculations in quantum many-particle systems. Likewise, the emergence of irreversibility in the dynamics of a closed quantum many-particle system is essential for for example understanding the limitations of spin echo experiments.

Our group addresses these questions using mainly analytical tools supplemented with numerical methods. Apart from many-body diagrammatics, field theoretic methods, renormalization theory and bosonization techniques, we also specialize in the flow equation method. The flow equation approach is an renormalization group like method based on a sequence of infinitesimal unitary transformations, which has turned out to be particularly useful for addressing non-equilibrium problems. Our group has contributed a lot to the development of this new theoretical method.

One universal feature of thermalizing dynamics in condensed matter systems first discovered by us is prethermalization. Fig. 1 shows the non-equilibrium dynamics after a quantum quench in the Hubbard model with three typical time regimes: quasiparticle and correlation buildup, prethermalization and eventual thermalization. Some open questions which we are pursuing in this context are the relation between integrability/non-integrability and thermalization or irreversibility, the microscopic understanding of the foundations of quantum statistical mechanics and the relaxation dynamics of correlated materials in pump-probe spectroscopy.

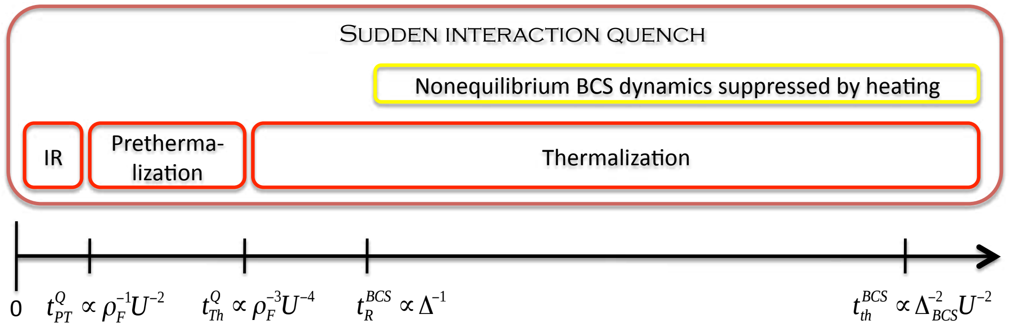


Fig. 1: Generic time regimes in the thermalization dynamics of an interacting many-particle system: Quasiparticle and correlation buildup (IR), prethermalization and thermalization. [From: M. Moeckel, S. Kehrein, New J. Phys. 12, 055016 (2010)]

$$\begin{tikzcd}
H,\, O,\, |\psi_i\rangle \arrow[r, "U"] \arrow[d, dashed, "\boxed{\text{Non-perturbative solution of H{\scriptsize EISENBERG} e.o.m. for operator } O}"'] & \tilde{H},\, \tilde{O},\, |\tilde{\psi}_i\rangle \arrow[d, "\boxed{\text{time evolution}}"] \\
O(t),\, |\psi_i\rangle & \tilde{O}(t) = e^{i\tilde{H}t}\tilde{O}e^{-i\tilde{H}t},\, |\tilde{\psi}_i\rangle \arrow[l, "U^{\dagger}"']
\end{tikzcd}$$

Fig. 2: Unitary perturbation theory is a combination of the flow equation method with canonical perturbation theory.

Far-From-Equilibrium Dynamics

Understanding correlations and order in equilibrium has been a central topic of quantum many-body theory for many decades. Ordered phases and their properties play an important role in solid state physics, important examples being magnetism and superconductivity. However, the buildup of correlations and order, that is the far-from-equilibrium dynamics leading to order is much less understood. One key problem is that many theoretical methods that work well in equilibrium situations have severe limitations in non-equilibrium. Therefore the development of new methods for far-from-equilibrium dynamics is an important goal in our group. We combine the flow equation method with well-known canonical perturbation theory (Fig. 2) and use this approach to study a variety of problems in condensed matter physics and cold atomic gases.

Our approach avoids secular terms in time evolution and leads to a much more stable long time expansion than conventional perturbation theory.

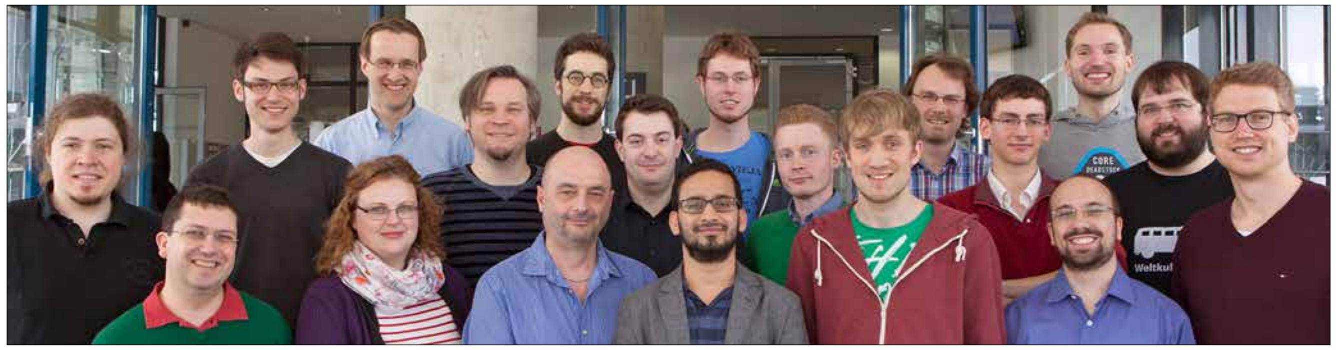
One important novel feature in non-equilibrium is the violation of the fluctuation-dissipation theorem, which can lead to significant differences between susceptibilities and correlations before the system has thermalized. We have studied this in correlated impurity models and observed how pre-existing entanglement can make a major contribution to the correlation buildup (Fig. 3). Our group continues to investigate related questions in correlated materials, both from a fundamental point of view and with respect to experiments.

Entanglement and AdS/CFT Correspondence

The most important difference between quantum systems and classical systems is quantum entanglement, which has no correspondence in the classical world. Entanglement is responsible for the enormous complexity of quantum many-particle systems as compared to classical many-particle systems, thereby rendering computer simulation methods much less efficient for quantum systems. Especially for strongly coupled quantum field theories comparatively little is known. A major breakthrough in this field was the discovery of AdS/CFT correspondence that allows the mapping of a strongly coupled quantum field theory to a weakly coupled classical geometric theory. The latter is still highly nontrivial, but does not suffer from an exponentially growing Hilbert space and can therefore be solved in a much more efficient manner.

To date one limitation of this approach is that it can only be applied to very specific theories that bear little resemblance to the models relevant for condensed matter physics. Research in our group aims at making use of such dualities between quantum models and geometric theories also for the Hamiltonians of generic interest in condensed matter physics. Our ultimate goal is a better understanding of strongly interacting quantum many-particle systems in and out of equilibrium.

The AdS/CFT correspondence is especially well suited for studying thermalization (via formation of a "black hole"), irreversibility and quantum chaos in such models.



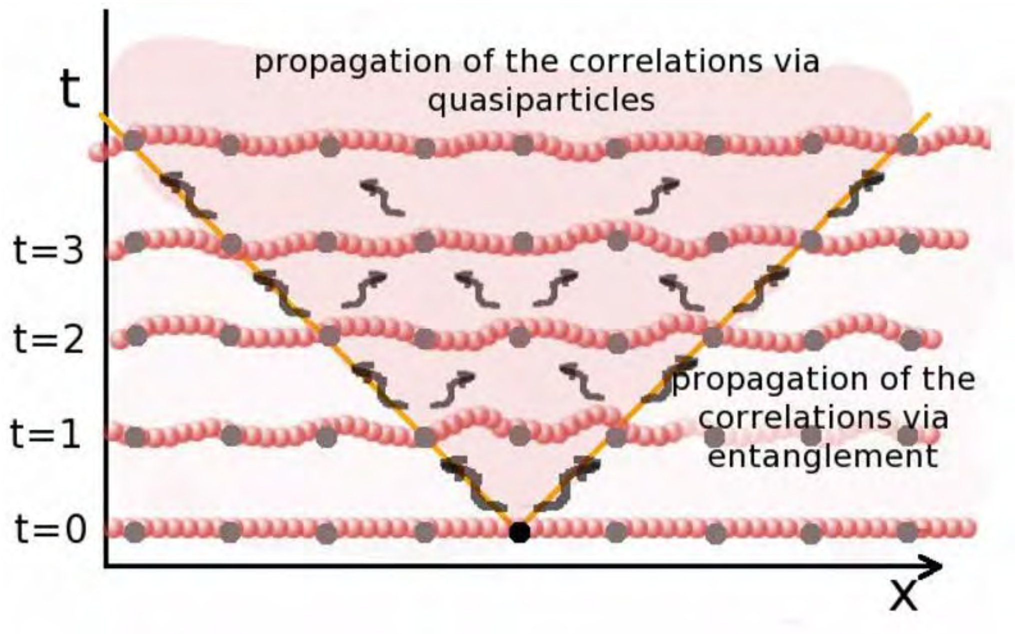


Fig. 3: Mechanisms contributing to correlation buildup: quasiparticle propagation and pre-existing entanglement. [From Ref. [7].]

[1] S. Kehrein: Flow equation solution for the weak to strong-coupling crossover in the sine-Gordon model, Phys. Rev. Lett. 83, 4914 (1999)

[2] S. Kehrein: Scaling and Decoherence in the Nonequilibrium Kondo Model, Phys. Rev. Lett. 95, 056602 (2005)

[3] S. Kehrein: The Flow Equation Approach to Many-Particle Systems, Springer Tracts in Modern Physics (Springer Verlag, 2006)

[4] M. Moeckel and S. Kehrein: Interaction Quench in the Hubbard Model, Phys. Rev. Lett. 100, 175702 (2008)

[5] M. Heyl and S. Kehrein: The Crooks relation in optical spectra - universality in work distributions for weak local quenches, Phys. Rev. Lett. 108, 190601 (2012)

[6] M. Heyl, A. Polkovnikov and S. Kehrein: Dynamical Quantum Phase Transitions in the Transverse Field Ising Model, Phys. Rev. Lett. 110, 135704 (2013)

[7] M. Medvedyeva, A. Hoffmann and S. Kehrein: Spatiotemporal buildup of the Kondo screening cloud, Phys. Rev. B 88, 094306 (2013)

[8] F.H.L. Essler, S. Kehrein, S.R. Manmana and N.J. Robinson: Quench dynamics in a model with tuneable integrability breaking, Phys. Rev. B 89, 165104 (2014)

Stefan Kehrein

Stefan Kehrein studied physics at the University of Kaiserslautern, the University of Heidelberg and Imperial College, London. For his doctoral thesis on conformal symmetry he received his Dr. rer. nat. in 1994. Afterwards he worked as a postdoc at the University of Augsburg and Harvard University. In 2001 he did his Habilitation on the flow equation approach to many-particle systems and shifted his research focus to the new field of non-equilibrium quantum many-particle systems. He was awarded a Heisenberg scholarship in 2003 and had numerous research stays in Rutgers University, Boston University and Harvard University. From 2005 to 2011 he was associate professor at the Ludwig-Maximilians-Universität München and since 2011 he is full professor in the Institute of Theoretical Physics at the Georg-August-Universität Göttingen. His research interests are non-equilibrium quantum many-particle systems, correlated matter entanglement and applications of the holographic principle to condensed matter systems.

First-Principles Calculations of Molecules and Solids

Our research prepares the ground for future intelligent materials design using first-principles calculations. On the one hand, we broaden the understanding of dynamic and reactive processes in materials, and, on the other hand, we develop new simulation algorithms for their quantitative description. The solid-state research goes hand in hand with the study of catalytic processes, where we venture into chemistry and biochemistry. The theoretical basis for our first-principles quantum mechanical description is density-functional theory, for which Walter Kohn was awarded the Nobel Prize in 1998.

Projector-augmented wave method

Our first-principles calculations are performed with the CP-PAW code package, which is the original implementation of the projector augmented wave method. This method, invented by P. Blöchl in the early 90s, is one of the most widespread algorithms for first-principles electronic-structure calculations. The code is used for numerical first-principles calculations and it serves as testbed for our development of new algorithms.

New methods for materials with strong correlations

Materials with strong electron correlations pose a particular challenge to first-principles calculations. A number of interesting properties such as superconductivity, giant magnetoresistance, multi-ferroicity, emerge from the synchronized behavior of electrons. We explore, how different theoretical descriptions of interacting many-electron systems can be translated into a unified framework that is transparent and numerically efficient. Recently, we found a fundamental relation between many-body Green's functions and density-matrix functional theory. This opens up new directions for describing correlated materials, which are currently explored.

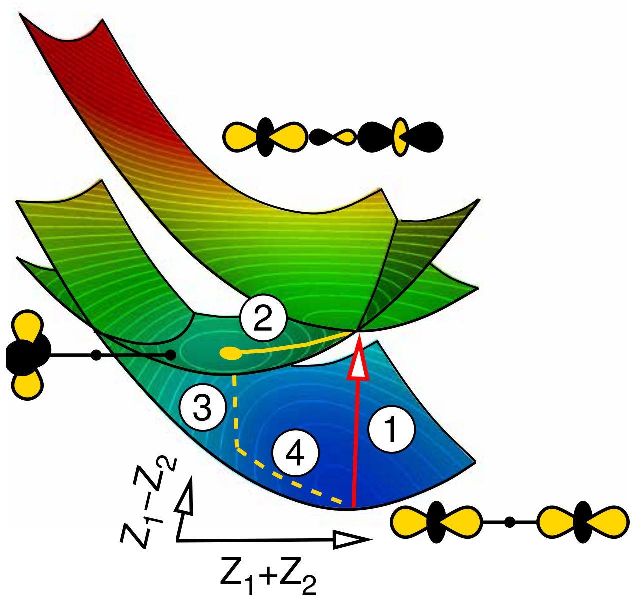


Fig. 1: Electronic energy surfaces in a two dimensional model of the relaxation process of in half-doped manganites PrCaMnO3. The model explains the strong optical excitation (1) in a so-called Zener polaron. After passing through a conical intersection, the system can be trapped in a long-lived metastable hot-polaron state. Relaxation into the ground state via (3) are symmetry forbidden.

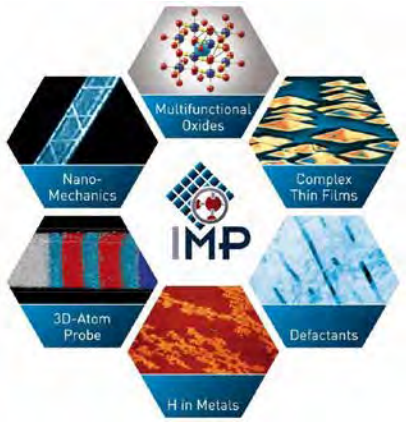
Energy-conversion processes in complex oxides

One of the major problems for the quest to exploit solar energy is to control the energy-relaxation towards thermal equilibrium. The ultimate goal is to steer the energy conversion process efficiently towards long-lived intermediates and finally to convert it into chemical fuels. We explore the fate of an optical excitation beginning with the first atto-second-processes of the initial excitation, via the relaxation processes, towards the formation of compound quasi-particles and self-organization in the form of metastable phases. Finally we explore the competing mechanism of hydrogen storage on the one side and the decomposition of the catalyst on the other. We use a combination of first-principles calculations and simpler model simulations to access large length and time scales.

Peter Blöchl

Peter Blöchl studied physics at Karlsruhe University. In 1984 he joined the Max-Planck Institute for Solid-State Research to develop new first-principles simulation methods and to study interfaces at the atomic scale. After receiving his doctorate in 1989, he stayed for two years at the renowned IBM T. J. Watson Research Center in New York. In 1990, he assumed a permanent research staff position at the IBM Zurich Research Laboratory, where he stayed for the following 10 years. During this period he held a visiting professorship at Vienna University of Technology in 1995, from where he also received the habilitation for Theoretical Physics in 1997. In 2000 he assumed a professorship at Clausthal University of Technology, where he directs the Institute for Theoretical Physics. Peter Blöchl is inventor of 8 patents and received five international prices.

Institute for Materials Physics



Understanding atomic level mechanisms in nano-scale materials

The goal of research at the Institute of Materials Physics (IMP) is to understand how collective behavior emerges from the interactions of individual atoms or entities and to apply this understanding to develop new and better materials for applications such as renewable energy and information technologies. Over the years, IMP has moved from studying bulk metals, in the time of Peter Haasen, to investigating properties of nano-scale materials. Some of the current fundamental topics involve designing properties by changing length scale, composition, and correlations, studying phase and mechanical stability at the nanoscale and controlling energy conversion and dissipation. This work is performed in five different research groups (Nano-Mechanics, Nanoscale multifunctional oxides, Thermodynamics and kinetics of nanoscale systems, Complex pulsed laser deposited thin films, and Defactant/Defect-Interactions) and is supported by four cross-cutting atomic scale method groups (Thin film deposition, Atom probe tomography, In-situ electron microscopy, and Atomic scale modeling).

Teaching fundamental concepts of materials physics

IMP contributes to teaching of the general physics curricula, of specialized courses in the area of Condensed Matter and Materials Physics, and in the inter-Faculty Bachelors and Masters programs in Materials Science. We supervise ca. 50 Bachelor, Master, and Doctoral students in cutting-edge research projects. IMP also has active trainee programs with 4 lab and electronics technician apprentices. Public outreach contributes to informing the general community of important materials science issues, including developing materials and processes for a sustainable future, and is performed together with the collaborative research center CRC 1073 "Atomic scale control of energy conversion".

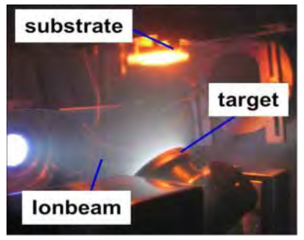
Equipment and Resources

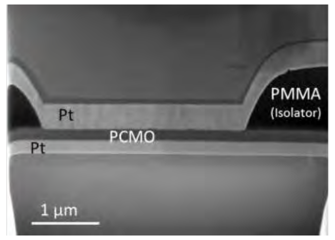
The research and teaching at IMP is made possible by advanced equipment and high quality technical support. Using in-situ transmission and scanning electron microscopy, scientists at IMP are able to observe real-time processes in materials during mechanical, electrical, and optical stimulation. Atomic level chemical structure is determined using field ion microscopy and atom probe tomography. Nanoscale mechanical characterization is performed using atomic force microscopy and nanoindentation. Synthesis and nanostructuring are available through a variety of controlled thin film preparation techniques, a focused ion beam microscope and lithography. In addition, IMP houses a joint electronics and a precision machine shop.

Ultimately, the goal of materials physics is to understand the underlying atomic scale mechanisms that determine the properties and performance of materials. To this end, high quality model material systems are needed and are synthesized in the research group on Complex Thin Films as well as in the central IMP facility for Thin Film Deposition. Atomic scale characterization is essential and performed in the central IMP facilities using Atom Probe Tomography and In-Situ Electron Microscopy, where dynamic processes can also be investigated. Finally, to bridge the gap between atomic scale observations and actual mechanisms which often proceed at faster time scale than the measurements, we use methods such as molecular dynamics simulations performed in the group Atomic Scale Modeling.

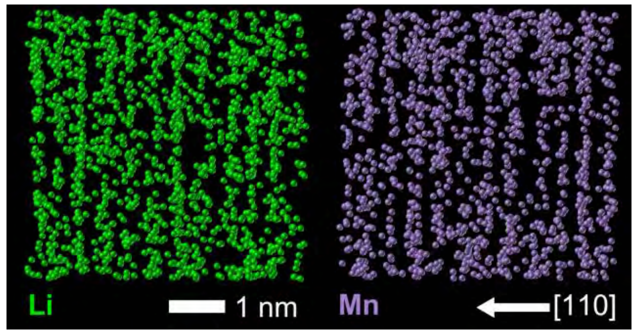
Thin Film Deposition: For gaining understanding of the fundamental relations between physical properties, crystallographic structure, and micro-structure, high quality fabrication of the materials is essential. The preparation of thin film samples by means of a number of different physical vapor deposition methods allows for a controlled variation of the micro-structure based on the application of thermodynamics and kinetics of thin film growth [left figure on next page which shows an ion-beam sputtering setup]. The defect formation is affected by the momentum and kinetic energy of the atoms sputtered from the target, scattering in the gas phase, deposition rate and deposition temperature. Depending on the selected substrate, the detailed deposition parameters and the method of preparation, a variety of different defect structures and lattice strain states can be realized. The selected model systems involve complex oxides such as titanites, manganites and cobaltites, where the physical properties sensitively depend on the interplay of preparation induced defects and lattice strain. This offers new opportunities to tailor the physical properties of such materials systems.

The investigation of physical properties often requires the fabrication of a stack of different layers and device-like structure, and therefore the combination of different deposition and lithographic steps [right figure, which shows a cross-sectional TEM image of a Pt/$Pr_{0.7}Ca_{0.3}MnO_3$/Pt stack lithographically patterned and etched to an electron-transparent lamella]. We are therefore using different deposition methods (ion-beam sputtering, magnetron ac and dc sputtering, pulsed-laser-deposition) as well as lithographic and ion beam nano-structuring techniques in order to prepare the required systems for our scientific work (contact: Dr. Jörg Hoffmann, see also "AG Krebs: Complex pulsed laser deposited thin films").



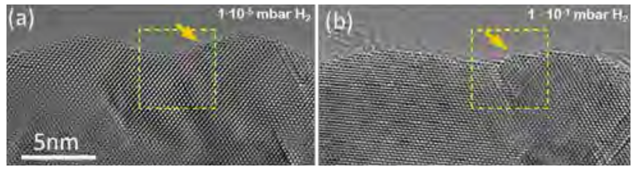


Atom Probe Tomography: Atom Probe Tomography is an experimental method for the spatially resolved chemical characterization of solids. Combining high-resolution microscopy and single atom mass spectrometry, the chemical composition of materials can be determined in three dimensions with sub-nanometer resolution.

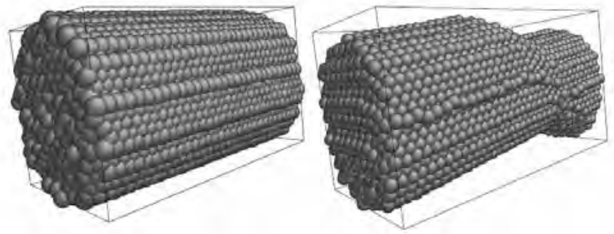


At IMP, atom probe tomography is used for the nanoscale characterization of metals, semiconductors and oxides. Of particular interest is the characterization of complex microstructures of nanomaterials at different stages of a surface or interface reaction to gain insight into reaction mechanisms. Current research activities include nanoporous materials and materials relevant for studies of electrochemical energy conversion. The figure shows an atom probe tomography reconstruction detail of a crystalline lithium-manganese-oxide where Li and Mn atoms are displayed as spheres. Local compositional information on the atomic scale is easily obtained by counting the atoms and results can be related to structural information from transmission electron microscopy. Insights into local reaction mechanisms are obtained by characterizing different reaction stages. Besides materials characterization, the potential of atom probe tomography for in-situ and dynamic studies is explored (contact: Dr. Carsten Nowak).

In-Situ Electron Microscopy: In situ observation of structural changes occurring during the interaction of gases with solid materials is a rapidly growing and very challenging topic. Thanks to the use of spherical aberration corrector and the monochromated high brightness electron gun it becomes possible to study the structure of materials in a gaseous medium with a spatial resolution of about 0.1 nm and energy resolution better than 0.2 eV. This opens opportunities to understand better the properties of materials under conditions which are similar to real operation conditions. Various specimen holders provide the additional capabilities to use different stimuli such as heating, cooling, electrical field and light illumination to understand and control the structure of materials under different conditions. Even simple systems demonstrate a rich variety of phenomena when exposed to a gaseous environment.



For example, thin metal films (Pd) are used as a working element of gas sensors to detect trace amounts of explosive gases, such as hydrogen. Transmission electron microscopy reveals remarkable changes of the surface, for example, formation of terraces (marked with arrows) during the increase of H2 pressure, and moving of defects (compare selected areas). Students at IMP can use advanced electron microscopy techniques such as aberration corrected imaging, high resolution STEM, EELS and EDX within Bachelor, Master, or PhD projects (contact: Dr. Vladimir Roddatis).



Atomic Scale Modeling: At IMP computer simulations are routinely applied to complement experiments. These simulations provide detailed information, such as particle positions as a function of time, which is not always available in experiments. In this way, a more complete picture of the phenomena occurring in the real material emerges. The graphic shows the breaking of a nano-wire obtained in a Molecular Dynamics simulation which mimics in-situ tensile test experiments performed in the Nano-Mechanics group. The left frame shows the starting configuration. Upon increasing the tensile stress, dislocations are formed, shown right. Ultimately, necking will occur, and complete breakage shortly thereafter (not shown).

Further processes that are being simulated are the "loading" of selected materials with ionic species, the prototype application in mind being battery materials, or friction-related phenomenon occurring at the nano-scale. Again, both these phenomena are also investigated experimentally at IMP, providing a rich synergy. For our computer simulations, we rely on standard computer codes, as well as on in-house programmed tailored codes for more specialized problems. Students at IMP are closely involved in these efforts, for example within the context of Bachelor, Master, or PhD projects (contact: Dr. Richard Vink).

Nano-Mechanics

Mechanical stress can impose huge free energy changes in materials, thereby altering both the equilibrium states and the dynamic behavior. Particularly in nanoscale materials where the defects are constrained by interfaces and surfaces, very large stresses are reached and dynamic processes such as deformation and phase transformations may follow entirely different paths than in bulk materials. We investigate a variety of different nanoscale model systems using in-situ electron microscopy and micro-mechanical testing, with the goal of revealing the underlying principles controlling material stability, defect dynamics, and energy dissipation.

Understanding Nucleation

Nucleation remains one of the central puzzles of materials science and is often the rate-limiting and microstructure-determining step in transformations. Unfortunately, we rarely have the temporal and spatial resolution necessary to experimentally interrogate the actual nucleation process and must rely on comparing resultant microstructures with models and simulations to test our understanding. We have recently investigated [Fig. 1] nucleation controlled deformation in Au nanowires which provide indirect yet clearly interpretable information about nucleation [1,2]. We find that the qualitative features of our results can be understood in terms of classical nucleation theory, but that the values for the nucleation rates disagree by many orders of magnitude. We believe that a new view on local stress concentrations or on dislocation loop energies may provide the resolution for this discrepancy.

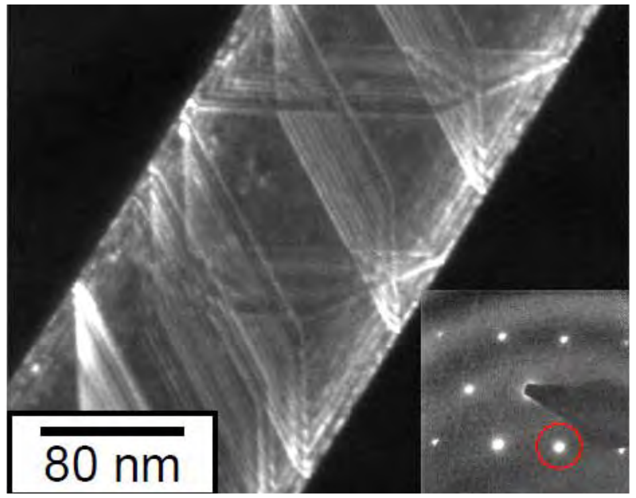


Fig. 1: Transmission electron microscope image of stacking faults and twins that are created in a single crystal Au nanowire as a result of dislocation nucleation during in-situ tensile testing [1].

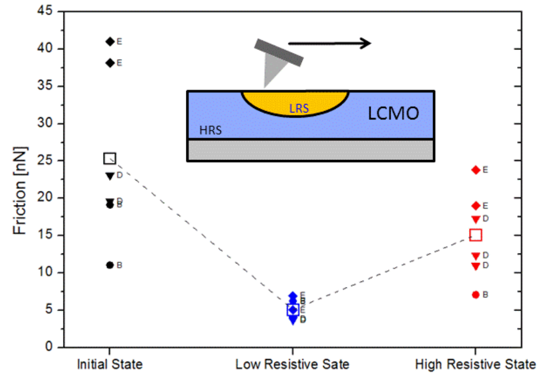


Fig. 2: Reversible change in friction in $La_{0.55}Ca_{0.45}MnO_3$ as measured using lateral force measurements in the atomic force microscope (AFM). The friction is high in the insulating state and can be reversibly reduced almost to zero by switching the manganite to the conducting state [H. Schmidt, K. Samwer, C.A. Volkert, unpublished].

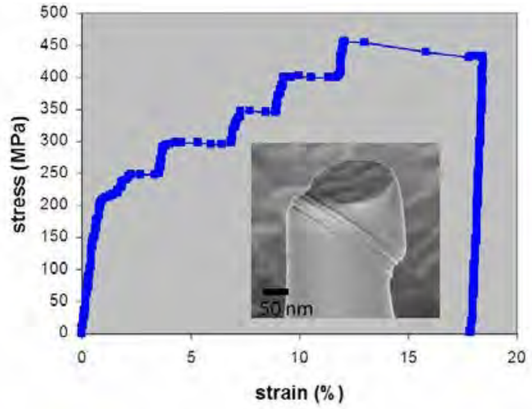


Fig. 3: Stress-strain curve for compression of a sub-micrometer Au pillar showing elastic behavior interrupted by intermittent strain bursts. The inset shows the slip plane morphology of the deformed pillar [3].

Controlling Friction

The conversion of mechanical and kinetic energy into heat is the major path by which useful energy in today's society is lost. We aim to understand and control these frictional losses by varying the electronic and acoustic degrees of freedom in the underlying materials. In one recent example, we have used atomic force microscopy methods to show that we can reversibly control frictional losses at the surface of a manganite by resistively switching the material [Fig. 2]. We attribute the increased friction in the insulating state of the manganite to electrostatic forces due to trapped charges. This work is performed within the CRC 1073 (Project A01).

Detecting Defect Avalanches

It is widely observed that the onset of driven processes such as deformation and phase growth do not occur continuously but rather by intermittent instabilities. We investigate these instabilities during the onset of deformation in amorphous and crystalline metals under mechanical load. These so-called strain bursts provide insights into the initiation and evolution of the deforming state [Fig. 3]. We use experimental methods such as micro-compression [3,4], nanoindentation [5], fracture [6], and time-resolved electron microscopy [1,6]. We also investigate the motion of interfaces during phase transformations, such as during electrochemical lithiation of a manganese oxide [Fig. 4]. The statistical behavior of these intermittent events is compared with other avalanche processes, which are widely observed in both physical and social dynamics.

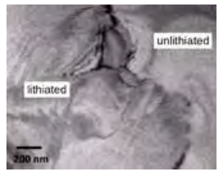


Fig. 4: Transmission electron microscopy image of the moving interface between the electrochemically lithiated phase (left) and the unlithiated phase (right) during in-situ lithiation of $LiMn_2O_4$ [T. Erichsen, C.A. Volkert, unpublished]. This work is performed within the CRC 1073 (Project C05).

[1] Surface dislocation nucleation controlled deformation of Au nanowires, B. Roos, B. Kapelle, G. Richter, C. A. Volkert, Appl. Phys. Lett. 105, 201908 (2014)

[2] Approaching the theoretical strength in nanoporous Au, C.A. Volkert, E.T. Lilleodden, D. Kramer, J. Weissmüller, Appl. Phys. Lett. 89, 061920 (2006)

[3] Size effects in the deformation of sub-micron Au columns, C.A. Volkert, E.T. Lilleodden, Phil. Mag. 86, 5567 (2006)

[4] Room Temperature Homogeneous Ductility of Micrometer-sized Metallic Glass, D. Tönnies, R. Maaß, C.A. Volkert, Adv. Mat. 26, 5715 (2014)

[5] Rate-dependent shear-band initiation in a metallic glass, D. Tönnies, K. Samwer, P. M. Derlet, C. A. Volkert, R. Maaß, Appl. Phys. Lett. 106, 171907 (2015)

[6] Investigating fracture of nanoscale metallic-ceramic multilayers in the transmission electron microscope, A. Kelling, K.R. Mangipudi, I. Knorr, T. Liese, H.-U. Krebs, C.A. Volkert, Scripta Mat. 115, 42 (2016)

Cynthia A. Volkert

Cynthia A. Volkert studied physics at McGill University in Montreal, Canada and at Harvard University in Cambridge, Massachusetts. She then spent 10 years working at Bell Labs in New Jersey before moving to Germany. Cynthia went first to the Max-Planck-Institute for Metal Research in Stuttgart and then to the Karlsruhe Institute of Technology where she studied ion-solid interactions, grain growth, mechanical behavior, and atomic transport in metal films and small structures, primarily using in-situ methods. She joined the University of Göttingen as a professor in 2007, where she continues her research in nanoscale materials and in-situ electron microscopy.

Nanoscale Multifunctional Oxides

Multifunctional metal oxide compounds reveal a broad richness of physical phenomena spanning from superconductivity, resistance changes in external fields to new mechanisms for energy conversion in thermoelectric, photovoltaic or photocatalytic processes. The strong correlation of electronic, magnetic and atomic degrees of freedom gives rise to a novel complexity, where small changes in microstructure or small external stimulations have huge effects on physical properties. An improved fundamental understanding of structure-property relations of these fascinating materials offers new strategies for the development of highly-efficient devices for electronic or energy applications.

Oxide interfaces

The controlled materials design of interfaces in complex oxides and the understanding of their structure-property relation on atomic scales is the basis for our work on understanding and controlling mechanisms of energy conversion. Such interfaces often exhibit new emergent properties which are absent in the bulk. Interfaces enable selective charge-transfer and thus provide the essential functionality for photo-voltaic, thermoelectric and electrochemical energy conversion. Nanoscale oxides are often dominated by their interface properties.

Polaron photovoltaics

Charge carriers in complex oxides often strongly interact with the atomic structure dynamics, forming polarons. Understanding their role in photovoltaic energy conversion and their interactions with interfaces is studied in the CRC 1073 (Project B02).

Electro-catalytic water splitting

The design of highly active and stable oxide materials for electro-catalytic water splitting and the in operando study of the oxide-water interface the active state of oxide is a very active research field, where materials physics meets physical chemistry. The role of dynamic point defects and the functionalization of oxide surfaces by molecular catalysts are studied within the projects C02 and C01 of the CRC 1073, respectively. Activity and corrosion stability of photo-electrochemical devises are studied within a priority program in solar hydrogen SPP 1316.

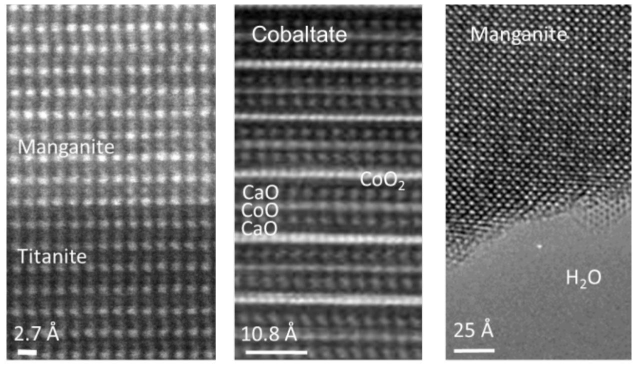


Fig. 1: Transmission electron microscopy images of the atomic structure of interfaces involved in photovoltaics, thermoelectrics and electrocatalysis. Thin film material and interface design is based on a variety of sputtering techniques provided by Dr. Jörg Hoffmann.

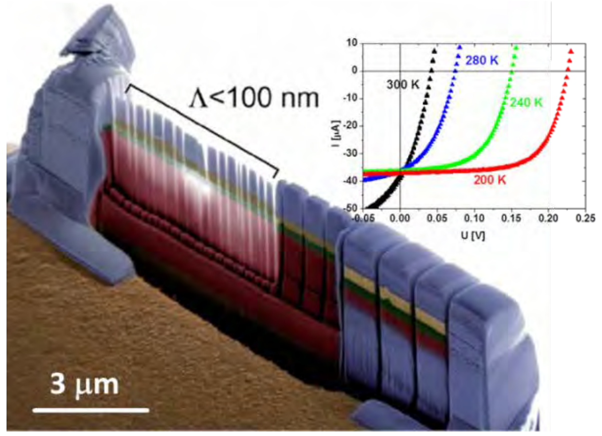


Fig. 2: Nanostructured lamella of a $SrTi_{1-x}Nb_xO_3$ / $Pr_{0.7}Ca_{0.3}MnO_3$ pn-junction for in situ electrical characterization and polaron photovoltaics.

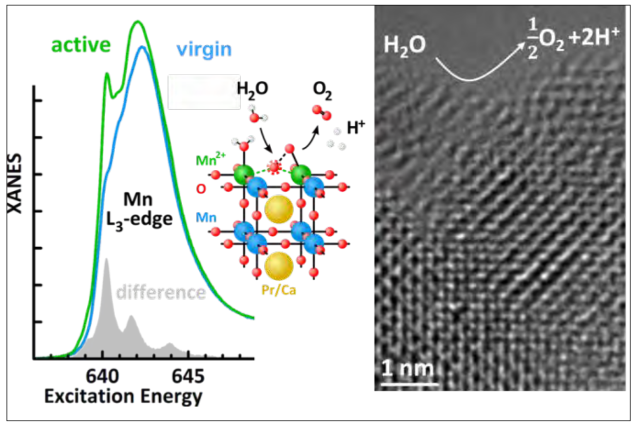


Fig. 3: Active states during electro-catalytic water splitting at manganite surfaces observed by Environmental-TEM and x-ray absorption spectroscopy.

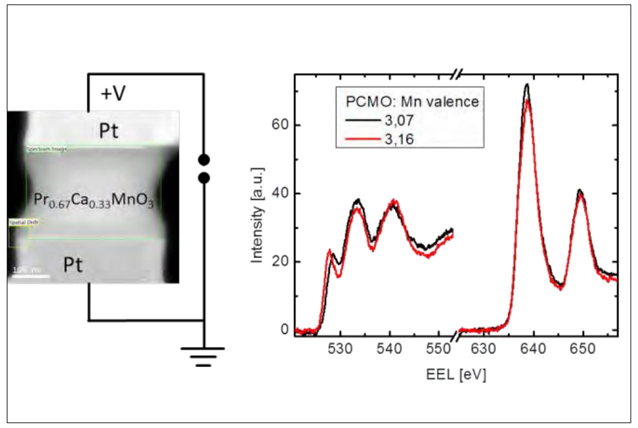


Fig. 4: Cross-sectional TEM image of a Pt/manganite/Pt sandwich structure for in situ resistive switching combined to analysis of anionic and cathodic redox processes by Electron Energy Loss Spectroscopy.

Thermal transport across interfaces

Thermal transport in complex oxides is dominated by phonons and sensitively depends on lattice disorder. We apply thermal conductivity measurements of thin films and heterostructures in order to shed light on the effect of point defects, polaronic order and interfaces on phonon transport. This gives access to subtle types of disorder in oxides and semiconductors which is not accessible by other methods.

Resistive switching

Electric pulses can induce non-volatile resistance changes in oxides sandwiched by metal electrodes. This effect is which are of high interest for new type of synaptic memories. The underlying mechanisms such as change in redox state and vacancy distributions are studied by in-situ TEM methods within a DFG funded project [Fig. 4].

Electro-chemistry in Transmission Electron Microscopy

Studying how single atoms are transformed in electrochemical reactions on atomic scale is a big scientific challenge. Based on a FEI Titan 300 keV with its Environmental TEM (ETEM) capabilities, we systematically develop methods for controlled electrochemical experiments with atomic resolution and approaches for knowledge transfer to "real world" catalysis in collaboration with Dr. V. Roddatis.

[1] M. Scherff, B.U. Meyer, J. Hoffmann, C. Jooss, M. Feuchter, M. Kamlah, Pulse length and Pt-Pro.67Cao.33MnO3-Pt amplitude dependent resistive switching mechanisms in sandwich structures, New J. Phys. 17, 033011 (2015)

[2] S. Mildner, J. Hoffmann, P.E. Blöchl, S. Techert, and C. Jooss, Temperature- and doping-dependent optical absorption in the small-polaron system Pr1-xCaxMnO3, Phys. Rev. B 92, 035145 (2015)

[3] S. Mildner, M. Beleggia, D. Mierwaldt, T.W. Hansen, J.B. Wagner, S. Yazdi, T. Kasama, J. Ciston, Y. Zhu and C. Jooss, Environmental TEM Study of Electron Beam Induced Electro-chemistry of Pro.64Cao.36MnO3 Catalysts for Oxygen Evolution, J. Phys. Chem. C 119, 5301 (2015)

[4] J. Norpoth, S. Mildner, M. Scherff, J. Hoffmann, C. Jooss, In-situ TEM analysis of resistive switching in manganite based thin-film heterostructures, Nanoscale 6, 9852 (2014)

[5] S. Raabe, D. Mierwaldt, J. Ciston, M. Uijttewaal, H. Stein, J. Hoffmann, Y. Zhu, P. Blöchl, and C. Jooss, In-situ electrochemical electron microscopy study of oxygen evolution activity of doped manganite perovskites, Adv. Func. Mat. 22, 3378 (2012)

Christian Jooss

Christian Jooss was born 1967 in Stuttgart. He performed his PhD at the Max-Planck-Institute of Metal Research, Stuttgart in the field of High-Temperature Superconductors. In 1998, he started a research group on oxide thin films at the Institute of Materials Physics, University of Göttingen, where he received his habilitation 2002. In 2006, he moved to Brookhaven National Laboratory, where he turned his attention to in-situ Transmission Electron Microscopy. He obtained a professor position at University of Göttingen in 2008.

Thermodynamics and Kinetics of Nanoscale Systems

Thermodynamic and kinetic properties of alloy thin films, multi layers and clusters differ from that of the related bulk systems. We often choose metal-hydrogen (M-H) systems acting as model systems to study general material properties changes like phase stabilities or defect generation on the nanoscale. By changing length scale, geometry and chemistry, the system’s properties can be tuned and optimized, for example, for energy storage applications.

Strong impact of the stabilizer or the substrate on thin films or clusters properties results from mechanical stress [1]. Recently, we have tuned a nano-system in such an extent that it reaches the maximum theoretical possible value of - 10 GPa just by hydrogen absorption, which is the highest reported stress so far [2]. Such high mechanical stress affects solubility limits of the nano-system as well as its chemical potentials. Monitoring the systems surface with scanning probe microscopy provides insights into the lateral distribution of phases and their development during hydrogen absorption [Fig.1]. Therewith we recently proved that mechanical stress can be used to even suppress alloy phase transformations [3]. Small-size systems further show finite size effects, such as new lattice structures with 5-fold symmetry [1].

Lattice defects such as interfaces, grain- and phase-boundaries also influence the system kinetics, its thermodynamics and its surface catalytic behavior. As one of the first groups worldwide we successfully determined the interface-affected hydrogen distribution and concentration on the atomic scale, by atom probe tomography. Vice versa, hydrogen influences the vacancy formation, as well as the dislocation generation and mobility in the nano-system [1]. This affects the so-called hydrogen embrittlement of materials.

The knowledge of property changes with size reduction is essential for the design of nano-materials, suitable for sensor or catalysis applications, for energy conversion, storage and transport.

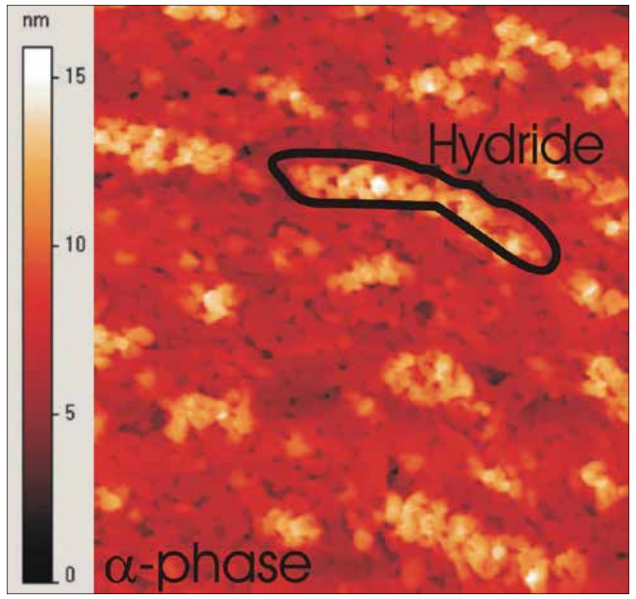


Fig. 1: Topographical STM image of an 80 nm Nb-H film. Bright areas relate to hydride parts (one marked), dark regions to the α-phase [Nörthemann & Pundt, Phys. Rev. B 78, 014105 (2008)].

[1] Hydrogen in metals: Microstructural aspects, A. Pundt and R. Kirchheim, Ann. Rev. Mater. Res. 36, 555 (2006)

[2] Achieving ultrahigh stress in Nb-H thin films, M. Hamm et al., Appl. Phys. Lett. 106, 243108 (2015)

[3] Quasi-thermodynamic model on hydride formation in palladium-hydrogen thin films, S. Wager and A. Pundt, Int. J. Hydrogen En. 41, 2727 (2016)

Astrid Pundt

Astrid Pundt (1966) studied physics at the Technical University of Braunschweig and graduated 1991 in the group of Prof. J. Hesse at the institute of metal physics and nuclear solid state physics. She continued her doctoral studies at the institute of metal physics in Göttingen with Prof. P. Haasen, especially by performing field ion microscopical studies and thermodynamical calculations on thin magnetic films. In collaboration with Prof. R. Kirchheim she turned to hydrogen in metals in 1996. She founded a research group on nano-sized M-H systems and habilitated in 2001 at the University of Göttingen. In 2013 she visited Uppsala University as lecturer and researcher. Astrid Pundt is currently Apl.-Professorin financed by the Heisenberg program of the Deutsche Forschungsgemeinschaft. She is married and has two young children.

Complex Pulsed Laser Deposited Thin Films

Complex thin films and multilayers consisting of different materials are of high interest for todays technical applications and offer new properties. For the preparation we use the versatile pulsed laser deposition (PLD) technique allowing us to deposit almost all kinds of materials. Actually, a variety of complex systems are of interest as metallic alloys, polymers, polymer-metal composites, and metal-polymer as well as metal-ceramics multilayers. Our research is supported by the German Research Foundation in the collaborative research centers SFB-755 and SFB-1073.

Our actual studies are concerned for instance with the fabrication of multilayer zone plate (MZP) optics for X-ray microscopy, which is of large interest in biological science. Recently, we developed metal/ceramics MZPs (Fig. 1) by the combination of PLD and FIB (focused ion beam) and reached a focal size for hard x-rays of below 5 nm and suitable imaging properties [1,2].

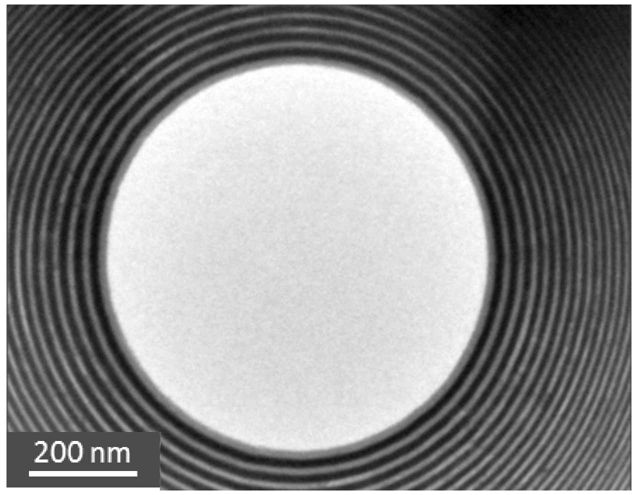


Fig. 1: Multilayer zone plate with a glass wire (in the middle).

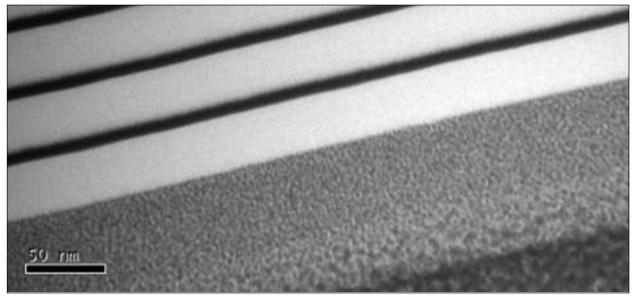


Fig. 2: Cross-section electron microscopy (TEM) of a metal/polymer multilayer.

Another aim is to develop multilayer systems (metal-ceramics, metal-polymers) with ultrathin layers for phonon blocking and low thermal conductivity [3]. Recently, we obtained very low conductivity values in the range of 1 W/mK by using W/oxide multilayers [Fig. 2].

[1] F. Döring et al., Sub-5 nm hard x-ray point focusing by a combined Kirkpatrick-Baez mirror and multilayer zone plate, Optics Express 21, 19311 (2013)

[2] C. Eberl et al., Fabrication of laser deposited high-quality multilayer zone plates for hard x-ray nanofocusing, Appl. Surf. Sci. 307, 638 (2014)

[3] F. Döring et al., Phonon localization in ultrathin layered structures, Appl. Phys. A. 119, 11 (2015)

Hans-Ulrich Krebs

Hans-Ulrich Krebs was born 1955 in Wertheim. After studying physics at the Universities of Würzburg and Göttingen, he performed his PhD thesis at the Institute of Metal Physics, Göttingen, in the field of amorphous metallic glasses in 1984. During 1986 he was post-doc at the Stanford University in California, USA. In 1993 he got his habilitation in metal physics at Göttingen University on ``Characteristic properties of laser deposited metallic systems''. In 1998, he became Apl.-Professor at the University of Göttingen. His research topics are now the design of the microstructures and properties of complex films by controlling and tuning the growth processes.

Defactant/Defect-Interaction

Besides their composition and structure (crystalline vs. amorphous), properties of materials are also controlled by the interaction of solute atoms and crystalline defects on the micro- and nanometer scale. The mechanical properties are affected by the solute/defect-interaction in both a positive and negative way [1]. Understanding these interactions is indispensable for the development of novel materials.

In liquids so-called surfactant molecules (surface acting agent) are enriched on the surface and reduce surface tension. Therefore, surface or interface areas can be enlarged with ease in the presence of surfactants. Then expanding lungs, forming foams and emulsions as well as removing dirt by washing can be achieved with less energy. The relation between surface tension, excess surfactants and their thermodynamic activity were derived by Willard Gibbs a long time ago. But only recently [1,2,3] was this relation generalized to include all kinds of discontinuities of crystals or crystalline defects of solid, respectively. Solutes enriching at defects and reducing defect formation energies are called defactants (defect acting agent). By this general approach surfactants at surfaces are comprised. Many phenomena of solute/defect-interaction will be understood in a novel way by the defactant concept [1,2,3].

Example 1: Hydrogen induced cracking - Fig. 1 shows scanning electron micrographs of blisters (Fig. 1a) and cracks (Fig. 1b) formed on or in high purity iron after hydrogen loading [4]. By the formation of blisters and cracks internal surfaces are created and their formation energy is reduced by the defactant hydrogen. In addition, high gas pressures build up by recombination of hydrogen atoms to H2 within cracks and blisters leading to further growth of these defects. Besides damage caused in iron alloys (i.e. steel) by hydrogen, the effect is relevant for tungsten used as a first wall material in fusion reactors.

Example 2: Hydrogen induced hardening - Fig. 2a) shows that the addition of hydrogen to Pd obviously increases the strength of the material [5]. Figs. 2b) and c) reveal the background of this finding: The addition of hydrogen to Pd shortly before it is cold rolled leads to a drastic increase of the dislocation density by a factor up to 5 [6] due to a reduction of the formation energy of dislocations by the defactant hydrogen. The increase of dislocation density by hydrogen causes the increased slope in the stress strain curve in Fig. 2 (work hardening).

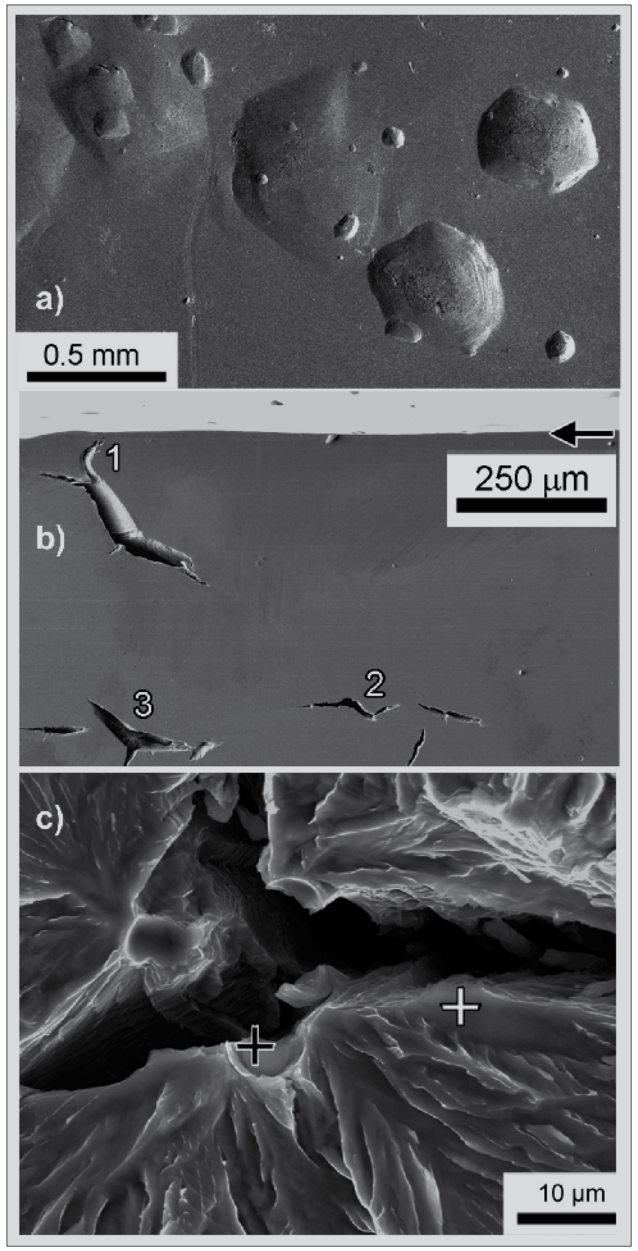


Fig. 1: Hydrogen induced cracking (Example 1).

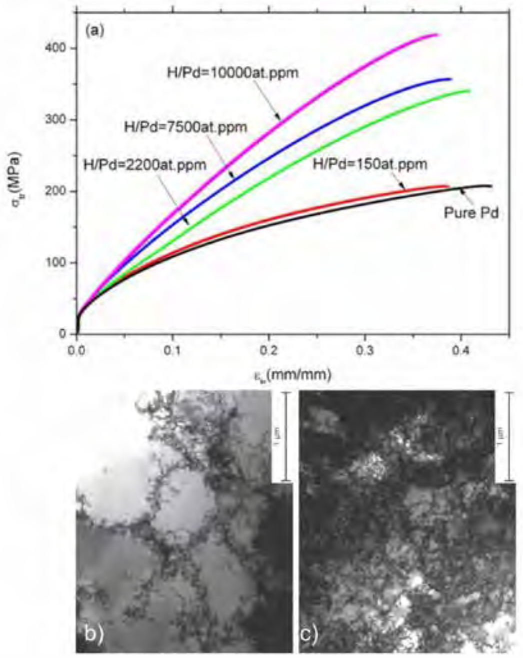


Fig. 2: Hydrogen induced hardening (Example 2).

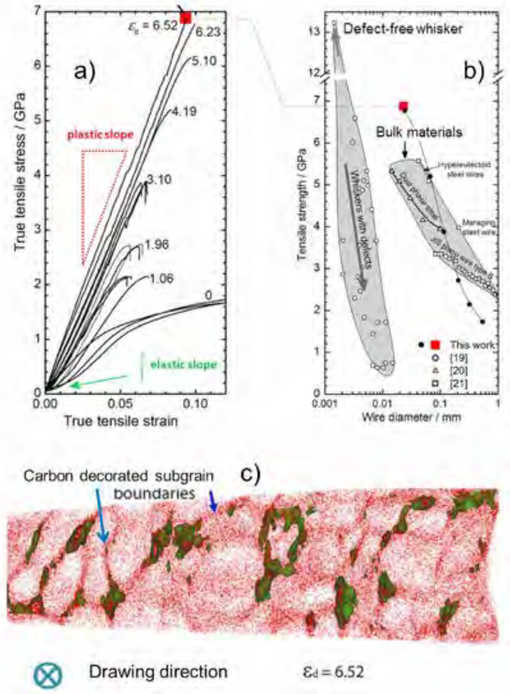


Fig. 3: Carbon induced super-strength steel (Example 3).

Example 3: Carbon induced super-strength steel - Fig. 3a) shows stress strain curves of steel wires produced by wire drawing to degrees labeled ε_d [7]. For the highest ε_d a maximum stress of close to 7 GPa (world record for steel) was measured which is more than five times higher than the highest values for spider silk. The strength is compared to that of iron whiskers and bulk materials in Fig. 3b). The extraordinary strength is due to the defactant carbon segregating to grain boundaries of the nanocrystalline steel, see Fig. 3c) [7], reducing the boundary energy and, therefore, stabilizing the favorable nanostructure.

[1] R. Kirchheim, Int. J. Mater. Res. 100, 483 (2009)

[2] R. Kirchheim, Acta Mater. 55, 5129 (2007); ibid., p. 5139

[3] R. Kirchheim, Solid solutions of hydrogen in complex materials, In: Solid State Physics, eds. H. Ehrenreich and F. Spaepen, Elsevier, Amsterdam, Vol. 59, 203-305 (2004)

[4] M. Tiegel, A. Lehmberg, M. Martin, M. Deutges, C. Borchers, R. Kirchheim, Verhandl. DPG 2015, MM 15.5; M. Tiegel, M. Martin, A. Lehmberg, M. Deutges, C. Borchers, R. Kirchheim, submitted to Acta Mater. (2016)

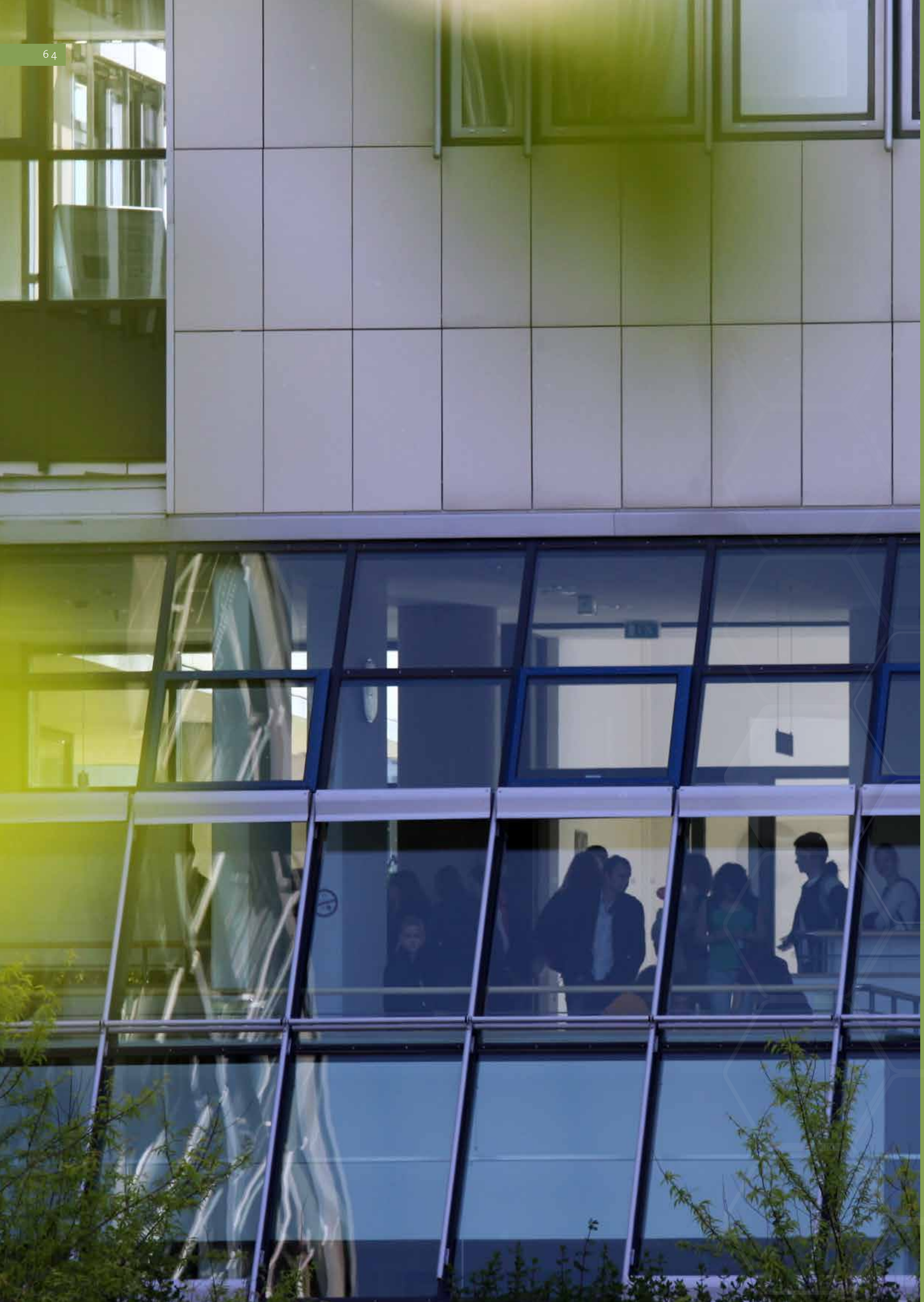
[5] Y. Chen, X. Ma, X. Shi, T. Suo, C. Borchers, K. Zhang, F. Liu, R. Kirchheim, Scripta Mater. 98, 48 (2015)

[6] M. Deutges, H.-P. Barth, Y. Chen, C. Borchers, R. Kirchheim, Acta Mater. 82, 266 (2015)

[7] Y. Li, D. Raabe, M. Herbig, P. Choi, S. Goto, A. Kostka, H. Yarita, C. Borchers, R. Kirchheim, Phys. Rev. Lett. 113, 106104 (2014)

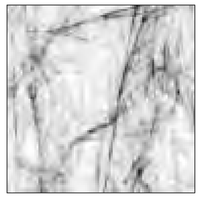
Reiner Kirchheim

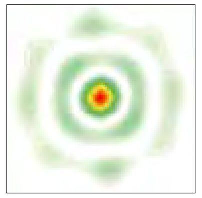
Reiner Kirchheim was born in 1943 in Halle/Saale. He studied physics at the University of Stuttgart and conducted his diploma, thesis and habilitation work devoted to the physico-chemical behavior of solutes in metals, transport phenomena and passivity of metals at the MPI for Metals Research in Stuttgart. This period was interrupted by extended stays at Rice-University, University of Illinois and Ohio State University. In 1993 Reiner Kirchheim accepted an offer from the Georg-August-University becoming the director of the Institute for Metal Physics. He extended his studies including the behavior of hydrogen in metals with reduced dimensions and the interaction of solute atoms with defects. He also set-up an Atom Probe Tomography Lab studying solute segregation, precipitation and interdiffusion on the atomic scale. Since 2009 he is continuing his work as a Professor of Lower Saxony focusing on the defactant concept.

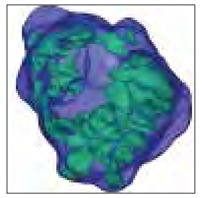


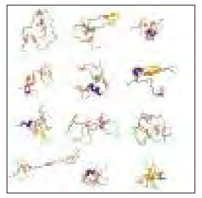
Biophysics and **Physics of Complex Systems**

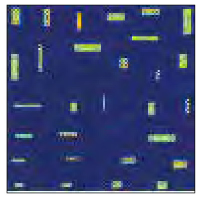
SFB 755: Nanoscale Photonic Imaging (3rd Funding Period)

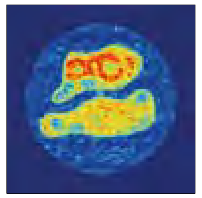












SFB 755 "Nanoscale Photonic Imaging" develops and applies high resolution optical methods to visualize structures and dynamics in space and time on the nanometer scale and on timescales extending over many orders of magnitude down to the femtosecond range. Participating university institutes are the 3rd and 4th Institute of Physics, the Institute for Material Physics, Institute for X-ray Physics, the Institute for Numerical and Applied Mathematics, the Institute for Mathematical Stochastics, and the University Hospital of Göttingen (Neurology). Non-university institutions which participate include the Max Planck Institute for Biophysical Chemistry, DESY, the GWDG and the Laser-Laboratorium GmbH Göttingen. The SFB 755 is divided into three project areas:

Area A: Visible light beyond limits

Area A is devoted to the development of high-resolution methods using visible light and their application to complex fluids and cells:

A01 isoSTED microscopy within tissue (Alexander Egner)

A03 High-resolution stress-field mapping in fiber networks and cells (Christoph F. Schmidt, Florian Rehfeldt, Max Wardetzky)

A04 Statistical multi-scale analysis for photonic imaging: from modeling to algorithms (Axel Munk, D. Russell Luke)

A05 Nanoscale dynamics of proteins and their interaction (Jörg Enderlein, Helmut Grubmüller)

A06 Statistical reconstruction methods for time varying nanoscale imaging problems (Axel Munk, Alexander Egner)

A07 Statistical inference for molecules: How many, when and where? (Axel Munk, Stefan W. Hell)

Area B: Spectromicroscopy of complex fluids

Area B, intercalated between A and C, is devoted to spectro-microscopic and time-resolved studies of complex fluids and biological systems in both the optical and the x-ray spectral domains.

B03 Ultrafast dynamics of chemical reactions investigated by femtosecond x-ray pulses (Simone A. Techert)

B04 Biomolecular structures from few photons single molecule x-ray diffraction data (Helmut Grubmüller)

B07 Dynamics of intermediate filament self-assembly (Sarah Köster)

B08 Formation of stress fibers in adult stem cells (Florian Rehfeldt, Tatyana Krivobokova, Stefan Huckemann)

B10 Structure-dynamics-function in photo-switchable proteins (Simone A. Techert, Stefan Jakobs)

Area C: X-ray optics and imaging

Area C is devoted to x-ray optics and imaging and the corresponding proof-of-principle experiments.

C01 X-ray holo-tomography: less constraints and higher dimensions! (Tim Salditt)

C02 Inverse scattering problems without phase (Thorsten Hohage, D. Russell Luke)

C04 Soft x-ray spectro-microscopy with a lab-scale source (Klaus Mann)

C08 Coherent FEL and high-harmonic pulses and their wavefronts (Claus Ropers, Klaus Mann)

C09 Inverse problems with Poisson data (Thorsten Hohage)

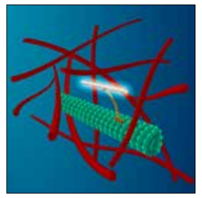
C10 Coherent x-ray imaging of cells with femtosecond x-ray pulses (Tim Salditt, Sarah Köster)

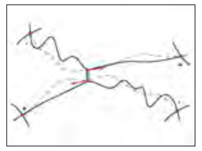
C11 Fresnel wavelets for coherent diffractive imaging (Gerlind Plonka-Hoch)

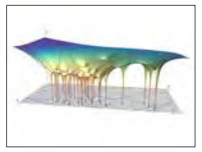
C12 Hard x-ray imaging by multilayer zone plates (Markus Osterhoff, Hans-Ulrich Krebs)

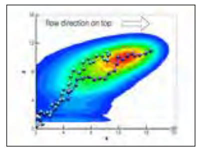
INF Data Infrastructure (Markus Osterhoff, Ramin Yahyapour)

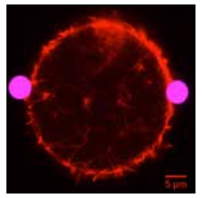
SFB 937: Collective Behavior of Soft and Biological Matter (2nd funding period, 2015-2018)

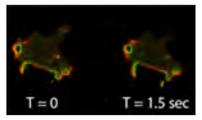


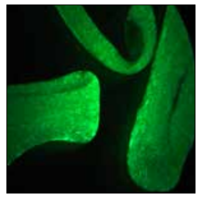












SFB 937 aims at a quantitative understanding of the physical mechanisms at work when soft and biological matter self-organize into complex structures to perform dynamic functions such as cell division, cell locomotion or tissue development. We analyze the ways in which biological and non-biological macromolecules as well as biological cells interact physically, exert forces, respond viscoelastically, move each other, and self-organize into complex functional patterns on mesoscopic length scales. A special emphasis lies on the study of "active matter" and non-equilibrium phenomena and their description in terms of statistical physics. We combine physics, chemistry, biology and medicine, as well as theory, modeling and experiment and employ a two-pronged approach, studying simplified model systems, on the one hand, and whole organisms and tissues on the other hand. Participating university institutes are the 3rd Institute of Physics, the Institute for Theoretical Physics, the Institute for X-ray Physics, the Institute for Non-Linear Dynamics, the Institute for Physical Chemistry, the Institute for Organic and Biomolecular Chemistry, the Institute for Mathematical Stochastics, and from the University Medical School the Institute of Developmental Biochemistry and the Institute of Pharmacology. The Max Planck Institute for Dynamics and Self-Organization participates as a non-university institution. The Institute for Physics and Astronomy at the University of Potsdam is integrated as an external collaborator.

Projects:

A01 Elasticity of anisotropic macromolecular networks (Annette Zippelius, Claus Heussinger)

A02 Active model biopolymer networks in vitro and in vivo (Christoph Schmidt)

A04 Dynamics and non-equilibrium states of randomly cross-linked block copolymer melts (Annette Zippelius, Philipp Vana, Marcus Müller)

A05 Polymer brushes in motion (Marcus Müller, Jörg Enderlein, Philipp Vana)

A07 Membrane organization under strong curvature (Jörg Enderlein, Marcus Müller, Tim Salditt)

A08 Mechanics and dynamics of biological adhesion (Andreas Janshoff, Marco Tarantola)

A09 Oscillatory instabilities of intracellular fiber networks (Carsten Beta, Eberhard Bodenschatz)

A10 Self-organization of the nuclear array in early Drosophila embryos (Jörg Großhans, Christoph Schmidt, Timo Aspelmeier)

A11 Pattern formation in the actin cortex of motile cells (Eberhard Bodenschatz, Jörg Enderlein, Tim Salditt)

A12 Spreading dynamics and force generation in blood platelets (Sarah Köster)

A13 Morphogenesis of the force-generating machinery in cells (Christoph Schmidt, Florian Rehfeldt)

A14 Dynamics and mechanics of epithelial-to-mesenchymal transition (Andreas Janshoff, Alexey Chizhik)

A16 Reversible crosslink binding in cytoskeletal filament bundles and networks (Claus Heussinger)

A17 Self-organization and mechanics of actomyosin networks attached to artificial and cellular plasma membranes (Claudia Steinem, Andreas Janshoff)

A18 Soft matter guided self-assembly of oscillating heart cells into functional macro-myocardium (Wolfram-Hubertus Zimmermann, Stefan Luther, Ulrich Parlitz)

A19 Morphogenesis control by mechanical stresses (Karen Alim)

A20 Biofilm growth of exoelectrogens (Marco Mazza, Stephan Herminghaus)

Cluster of Excellence

“Center for Nanoscale Microscopy and Molecular Physiology of the Brain” (CNMPB)

The human brain is probably the most complex structure that nature has ever produced. One hundred billion neurons and ten times as many glia cells make up a complex network that accomplishes extraordinary tasks, such as sensation, learning and memory. These functions are ultimately performed by interacting biomolecules. The CNMPB pursues a broad interdisciplinary research program striving to link molecular mechanisms to system function, with the ultimate goal of applying the findings to the diagnosis and therapy of neuronal diseases. In parallel, the Cluster of Excellence pursues innovative technological developments, such as super-resolution STED microscopy, atomic-force microscopy, X-ray microscopy and new methods of nuclear magnetic resonance spectroscopy, and applies those techniques to neurophysiological problems.

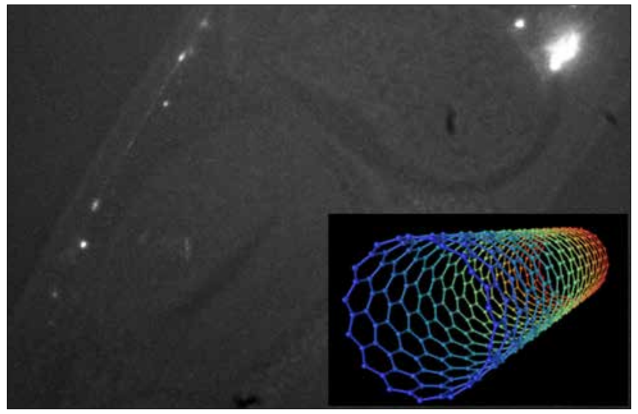


Fig. 1: Tracking single kinesin motors in C. Elegans neurons by specific labeling with infrared-fluorescent single-walled carbon nanotubes (SWNTs) (Schmidt group). SWNTs are only ~1 nm in diameter (insert) and fluoresce at around 1 µm wavelength, where there is almost no autofluorescence in cells and tissues. With specific targeting methods, single motors can be followed with high temporal and spatial resolution in living worms (bright dots).

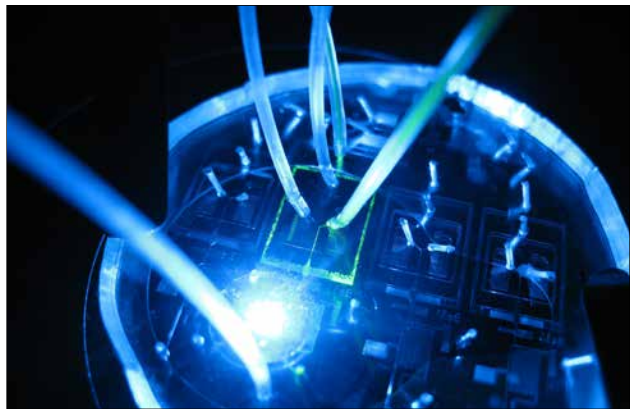


Fig. 2: Microfluidic device that can be combined with fluorescence microscopy, small angle-x-ray scattering (SAXS) or fluorescence correlation spectroscopy (FCS) (Köster group). The photograph shows a device which is used for the production of water-in-oil emulsions (green fluorescent drops in the channels) for encapsulation of proteins.

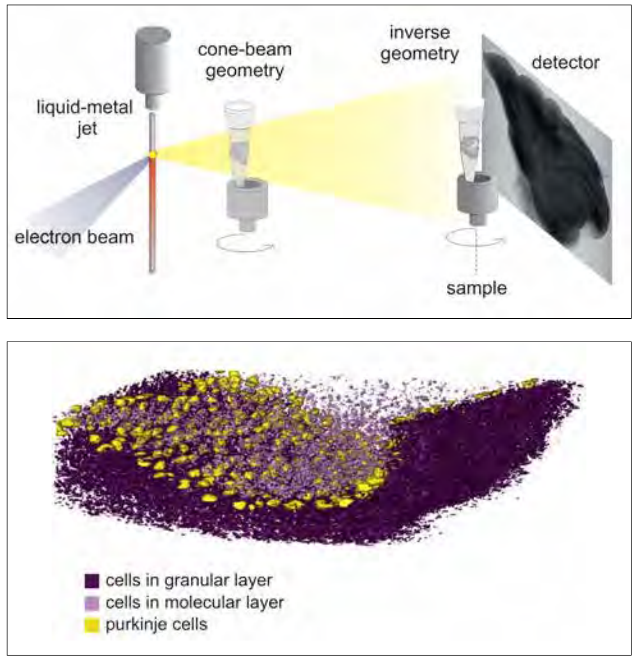


Fig. 3: X-ray phase contrast computed tomography (CT) of neuronal tissue (Salditt group). (Top) Micro-CT setup with liquid-jet anode, geometrical magnification, and phase contrast formation by free propagation of a partially coherent beam. (Bottom) In contrast to classical histology, the structural information extends over the entire sample volume at a resolution that allows one to identify individual cells.

Participating Institutions are the Medical School and the Faculties of Physics and Biology of the Georg August University, the German Primate Center, and the Max Planck Institutes for Biophysical Chemistry and for Experimental Medicine.

Participating groups in the Faculty of Physics are: J. Enderlein, D. Klopfenstein, S. Köster, T. Salditt, C. Schmidt.

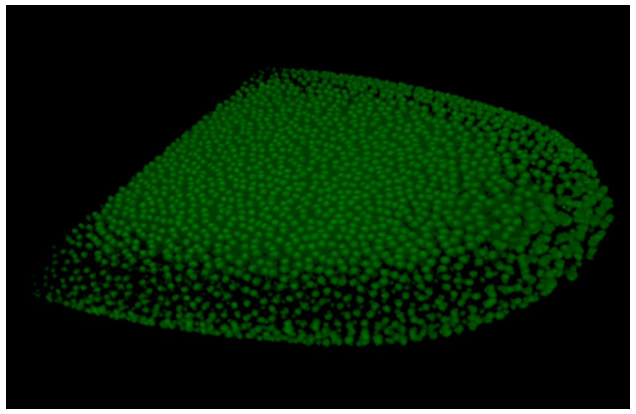


Fig. 4: Two-Photon Image Scanning Microsopy (Enderlein group). Chemically fixed Drosophila embryo, nuclear membrane labeled by gfp localized in the nuclear pore complexes. Imaged section 250 µm x 250 µm x 30 µm.

Bernstein Center for Computational Neuroscience (BCCN) Göttingen

Coordinator

Prof. Dr. Fred Wolf
Max Planck Institute for Dynamics and Self-Organization,
Göttingen

The Bernstein Center for Computational Neuroscience (BCCN) Göttingen founded to advance Theoretical Neurophysics unites research groups across disciplines to better discern the workings of the brain. BCCN-research examines the dynamics and adaptability of nervous systems using mathematical theories, models and computer simulations in conjunction with cutting edge experiments.

The brain is extremely flexible. With every new experience, it changes and thus responds to the next situation a little different. Every perception and every action plan is encrypted in the brain in complex spatial and temporal patterns of neuronal activity. How do networks in the nervous system, such as brain regions, neurons or molecules, cooperate to generate its cognitive capabilities? How does the adaptivity of the brain result from the interactions among its parts? These are the questions that the Bernstein Center Göttingen is addressing.

In the BCCN research groups from three faculties of the University of Göttingen (Physics, Biology, and Medicine), three Max Planck Institutes, MPI for Dynamics and Self-Organization, MPI for Biophysical Chemistry, and MPI for Experimental Medicine, the German Primate Center, European Neuroscience Institute Göttingen and the research lab of Otto Bock HealthCare GmbH collaborate in joint projects applying a wide range of modern experimental and theoretical methods. BCCN-research also contributes to emerging medical and computer science applications e.g. in neuroprosthetics and in robotics.

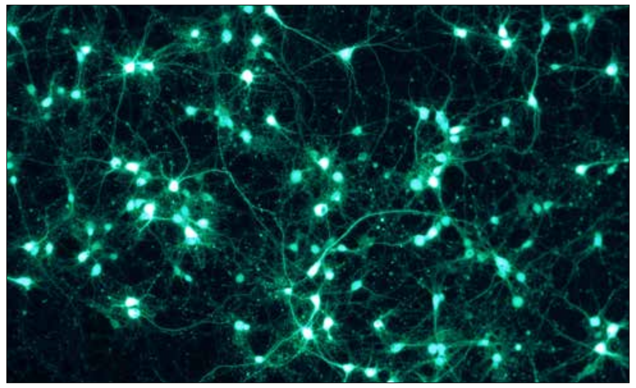


Fig. 1: Living nerve cells in a culture dish marked by fluorescent proteins engineered to report electrical activity. Interdisciplinary research projects in the BCCN investigate the dynamics and self-organization of biological neuronal networks from the biophysical level of single molecules and cells to the functioning of large-scale networks with millions of components.

Participating Institutions and Members

J. Enderlein, T. Geisel, R. Kree, U. Parlitz, C. Schmidt, F. Wörgötter, A. Zippelius, Faculty of Physics, University of Göttingen

A. Fiala, J. Fischer, M. Göpfert, S. Löwel, S. Treue, Faculty of Biology, University of Göttingen

A. Fischer, T. Gollisch, T. Moser, W. Paulus, D. Schild, M. Wilke, Medical School, University of Göttingen

E. Bodenschatz, T. Geisel, S. Luther, A. Neef, U. Parlitz, V. Priesemann, M. Timme, F. Wolf, Max Planck Institute for Dynamics and Self-Organization, Göttingen

J. Frahm, E. Neher, K. Willich, Max Planck Institute for Biophysical Chemistry, Göttingen

W. Stühmer, R. Gütig, Max Planck Institute for Experimental Medicine, Göttingen

J. Fischer, A. Gail, H. Scherberger, S. Treue, German Primate Center

M. Silies, O. Schlüter, European Neuroscience Institute Göttingen

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Bernstein Focus Neurotechnology (BFNT) Göttingen

Coordinator

Prof. Dr. Florentin Wörgötter
Georg-August-Universität Göttingen

The Bernstein Focus Neurotechnology (BFNT) in Göttingen is tightly linked to the Bernstein Centre for Computational Neuroscience (BCCN) and it focuses on the investigation and design of Neuro-Bionic Closed-Loop Systems. In a Neuro-Bionic Closed-Loop System biological and technical components are functionally tightly linked to form a control loop where a neuronal system influences a technical device, which in turn provides feedback to the neuronal system. Such systems require the extraction and analysis of neuronal activity, by which the device is adaptively controlled, and the generation of appropriate stimulation signals for neural control.

In the Bernstein Focus Neurotechnology (BFNT) Göttingen, engineers and theoreticians with a long-standing involvement in neuroscience collaborate with advanced experimental groups. The research focus includes theoretical research groups based in the faculty of Physics of the Georg-August-University Göttingen, and the Max Planck Institute for Dynamics and Self-Organization, as well as experimental groups from the faculties of Medicine and Biology of the Georg-August-University Göttingen, the Max Planck Institute for Biophysical Chemistry, the Max Planck Institute for Experimental Medicine, the German Primate Center, the Hannover Medical School, and the Max Planck Institute for Biophysics in Frankfurt. Moreover, active collaboration with industrial partners further defines the scientific and technological core of the BFNT Göttingen: Otto Bock HealthCare GmbH, MED-EL GmbH, and Thomas Recording GmbH.

Fig. 1: Neuronal methods allows efficient robot control. Parts of the BFNT work is concerned with transferring such methods to the control of human prostheses.

Research highlights are, for example, the design of adaptive prostheses (Faculty of Physics, Univ. Göttingen; German Primate Centre; and Otto Bock Healthcare) or the development of an optical cochlea implant (Medical School, Univ. Göttingen and MED-EL).

Participating Institutions and Members

T. Geisel, F. Wörgötter, Faculty of Physics, University of Göttingen

S. Treue, Faculty of Biology, University of Göttingen

T. Moser, W. Paulus, D. Schild, Medical School, University of Göttingen

T. Geisel, M. Herrmann, A. Neef, F. Wolf, MPI for Dynamics and Self-Organization, Göttingen

J. Frahm, MPI for biophysical Chemistry, Göttingen

W. Stühmer, MPI for Experimental Medicine, Göttingen

A. Gail, S. Treue, German Primate Center

E. Bamberg, MPI for Biophysics, Frankfurt

T. Lenarz, Hannover Medical School

B. Graimann, Otto Bock HealthCare Company

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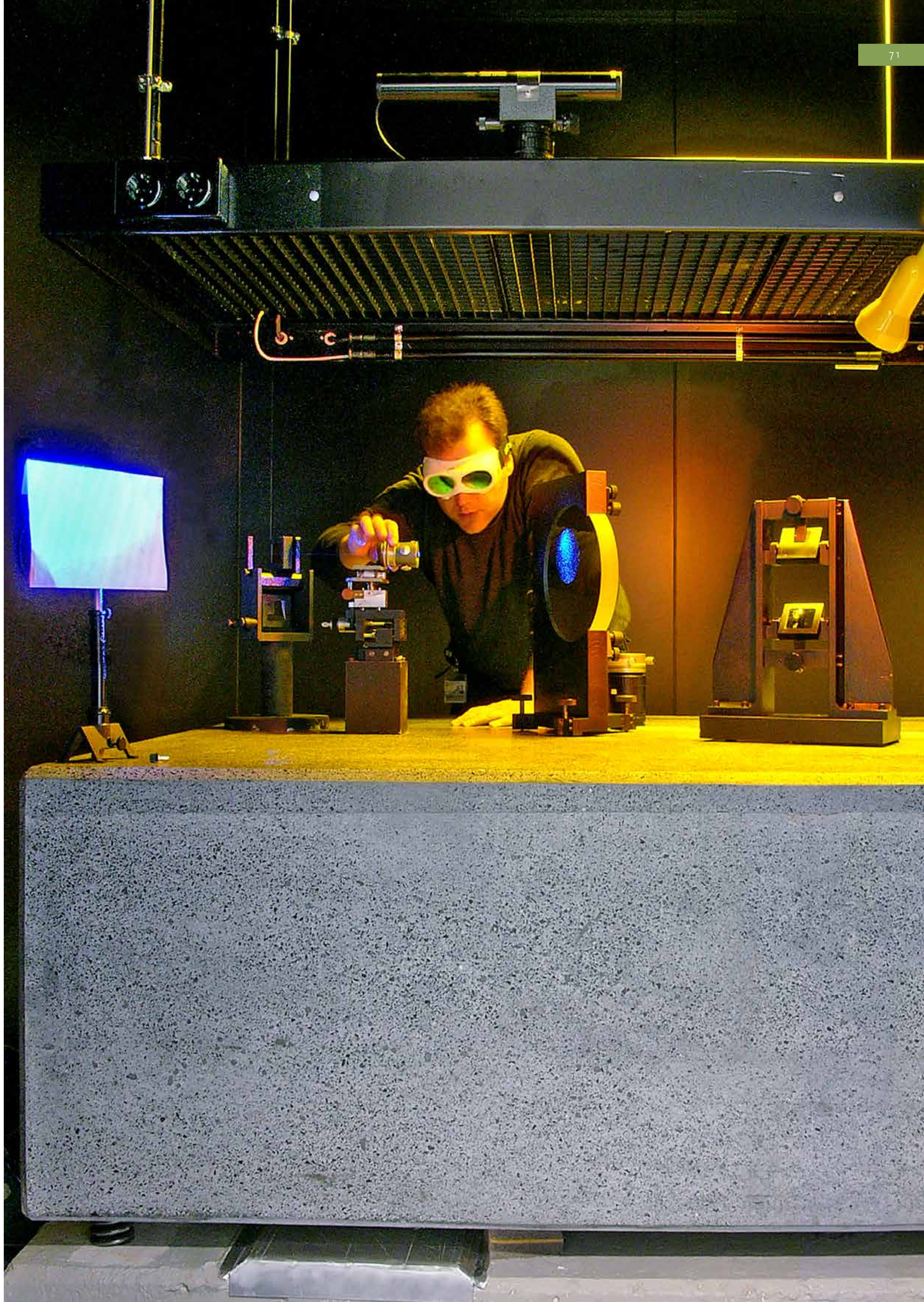


Single-Molecule Fluorescence Spectroscopy and Microscopy

Fluorescence spectroscopy and microscopy is one of the most advanced and important group of techniques in biophysical research. The sensitivity fluorescence detection can be as good as to allow the direct detection, spectroscopy and imaging of individual molecules. During the last 25 years, this has led to completely new insights into the functioning, dynamics and interaction of individual bio-molecules such as proteins, DNA and RNA. Single molecule methods offer a unique way to directly observe the stochastic nature of molecular processes and thus connect advanced biophysics with fundamental statistical physics. Moreover, due to the non-invasive character of fluorescence detection, it is possible to track and watch individual molecules inside living cells. Last but not least, fluorescence microscopy has seen a dramatic development over the last decade, improving its resolving power by more than one order of magnitude, allowing for resolving cellular structures of only a few dozen nanometers wide.

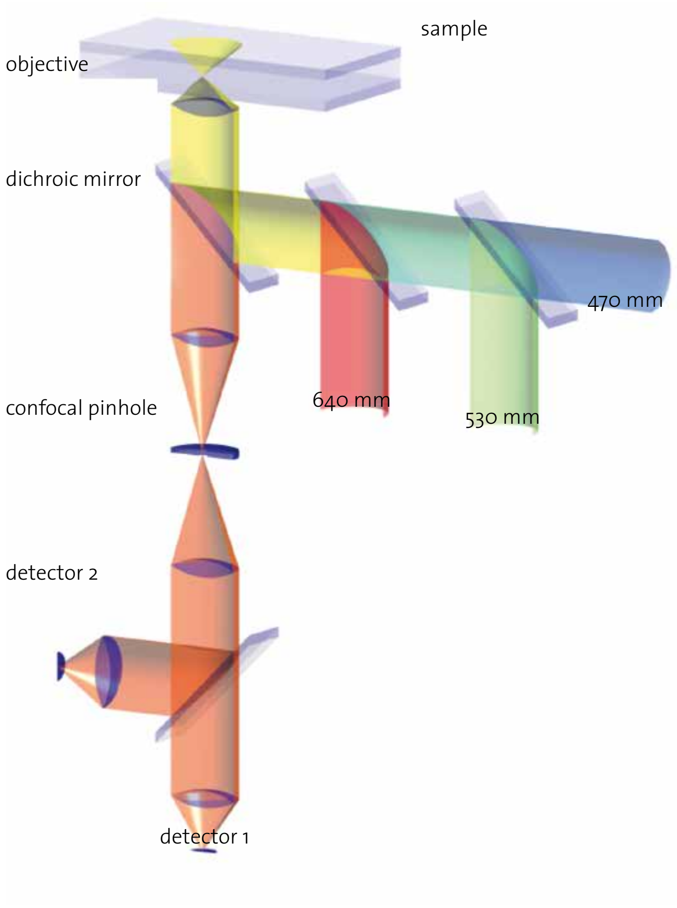


Fig. 1: Schematic of a single-molecule fluorescence spectrometer

Single-molecule fluorescence spectroscopy

The research group of Prof. Dr. Jörg Enderlein has developed advanced spectroscopic techniques to monitor the conformational and interaction dynamics of molecules from nanoseconds up to seconds. One group of these techniques belongs to so-called fluorescence correlation spectroscopy type. In fluorescence correlation spectroscopy, the fast fluctuations of the fluorescence generated by single molecules within a very small volume of only one picoliter are recorded and analyzed by correlation techniques. Any change in a molecule's conformation or its environment that affects its fluorescence properties will lead to temporal fluctuations in the recorded signal and leave a characteristic trace in the fluorescence signal correlation. Because fluorescence correlation spectroscopy can be performed on all time-scales from picoseconds to hours, this technique has the unique capability to reveal molecular dynamics on these time scales. One of the most important application of this technique is to study protein folding. Proteins are the most important molecular building blocks of life, consisting of highly ordered structure made of long chains of amino acids. The mechanisms of how a disordered long chain of amino acids (unfolded protein) finds the highly ordered final structure of the folded protein within a short time has remained one of the big questions of biophysics since the envisioning of this problem some 50 years ago. The ability to watch the folding (and unfolding) of individual proteins offers an unprecedented view on this process and yields invaluable information for a better theoretical understanding of the protein folding mechanism.

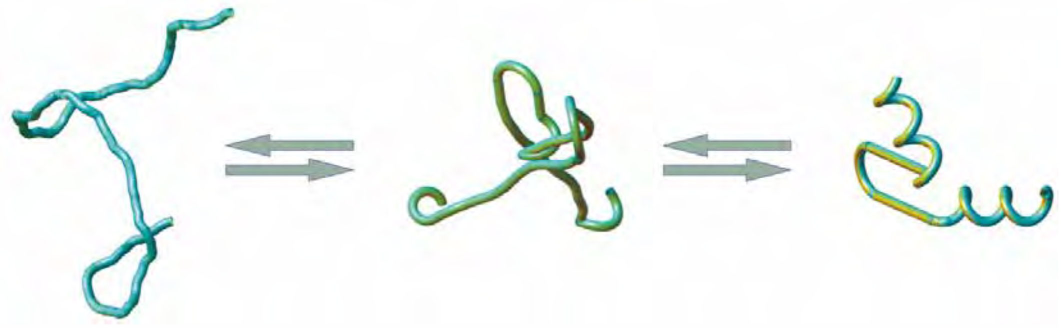


Fig. 2: Transition between unfolded and folded state of a mini-protein

Single-molecule fluorescence imaging

Besides watching the fluorescence fluctuations of a single molecule, one can nowadays directly image single molecules using specialized high-sensitive CCD cameras. This is the core technique when using single molecule fluorescence for following molecular processes in living cells. The ability to 'see' a single molecule allows for localizing its position in space with nanometer accuracy, far finer than the conventional resolution-limit of a light microscopy. This has been used in the past to resolve cellular structures with nanometer accuracy, or to watch the motion of individual proteins with similar resolution. A fascinating application was, for example, the observation of the discrete steps of so-called motor proteins along linear protein filaments, which is the molecular basis of force generation and active transport in all living beings. Moreover, we have developed a particular version of single-molecule imaging which enables us not only to see its position in space but also its three-dimensional orientation. In combination with the positional information, we are thus able to watch the complete motion and rotation of individual molecules and to elucidate how a protein turns and moves when functioning and interacting with other molecules. The same method is also used to study the local structure and dynamics of polymers and complex liquids.

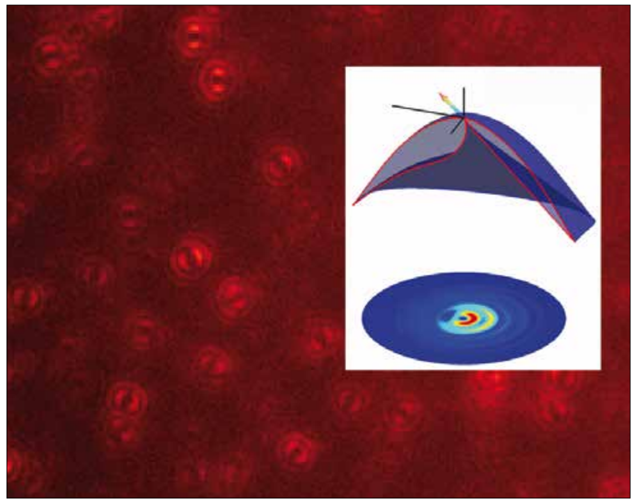


Fig. 3: Angular distribution of emission of a single molecule together with observed defocused images of single molecules

Super-resolution fluorescence microscopy

Fluorescence microscopy is one of the most important tools when studying the architecture and structure of cells and tissues. The main reasons for this are its exceptional sensitivity (even individual molecules can be 'seen'), its non-invasiveness (using moderate light intensities does not harm a cell, in contrast to electron microscopy, which can only be performed on dead samples), and its specificity (the possibility to label

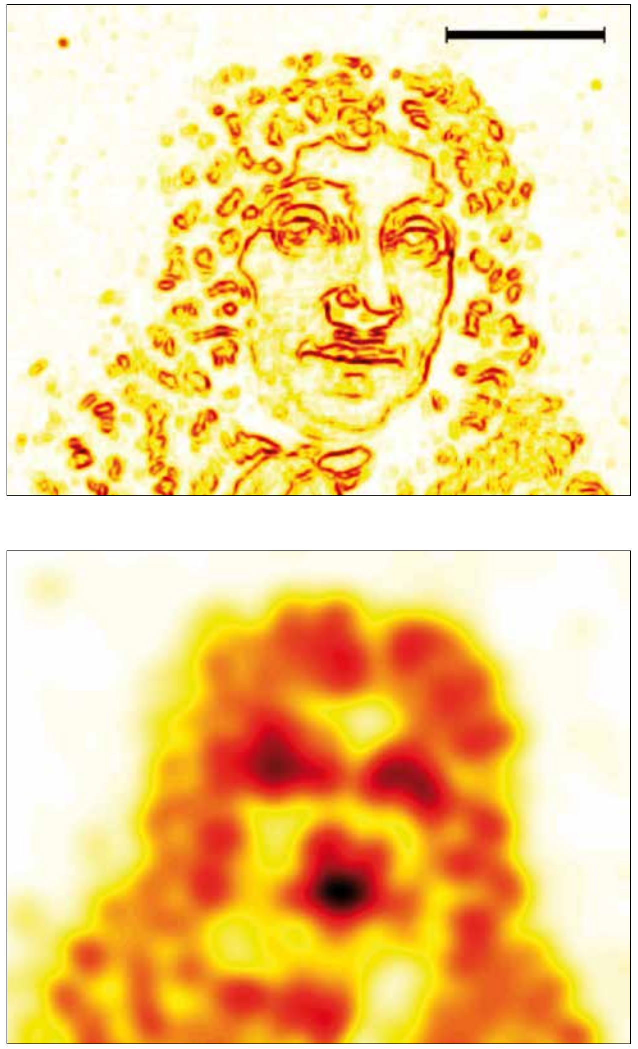
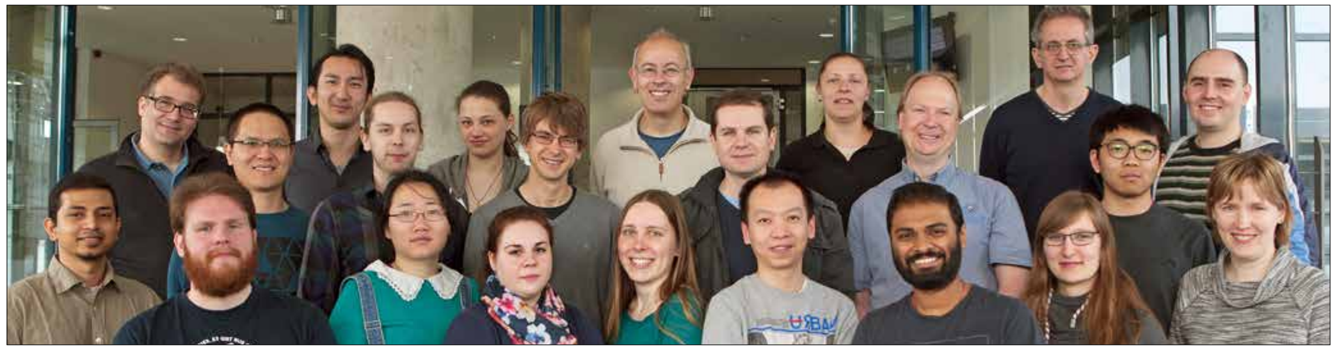


Fig. 4: Fluorescent microstructure as seen in super-resolution (left, bar = 1 m) and with a conventional fluorescence microscope (right)



different molecules of interest with different and well distinguishable fluorescent dyes). Unfortunately, for many years the spatial resolution of fluorescence microscopy was limited to ca. 250 nm, due to the wave nature of light. Electron microscopy achieves a spatial resolution of up to three orders of magnitude better, using the short quantum wavelength of energetic electrons, but can be used only treated dead samples. However, in recent years, the classical resolution limit of fluorescence microscopy has been overcome by exploiting various non-linear properties of fluorescence excitation and detection. Our group is involved in the further development and extension of these so called super-resolution microscopy techniques, which improve the spatial resolution of fluorescence microscopy by one order of magnitude. This opens a fascinating new window into living cells, visualizing cellular structure and dynamics with nanometer resolution.

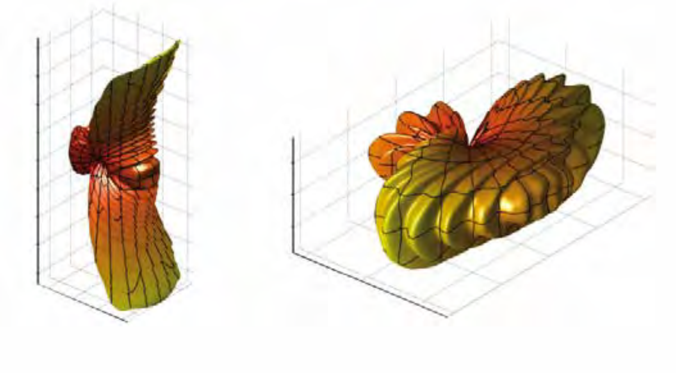


Fig. 5: Angular emission patterns of single molecules in a metallic nano-cylinder

Fluorescence nano-optics

From an electrodynamic point of view, fluorescent molecules can be understood as nanoscopic antennas that absorb and emit electromagnetic radiation. These nano-antennas probe the local density of states of the electromagnetic field. By placing them in nanometric metallic and/or dielectric structures, one can study how these structures alter the local density of states by measuring the changes in absorption and emission of the molecular fluorescence. This is of enormous importance for our fundamental understanding of the interaction between light and matter, but offers also the fascinating way to tune and tailor the fluorescence properties of molecules. Our group studies fluorescence nano-optics with sophisticated numerical modeling, and by performing advanced single-molecule spectroscopy measurements.

[1] Karedla, N.; Stein, S.; Hähnel, D.; Gregor, I.; Enderlein, J. "Simultaneous Measurement of the Three-Dimensional Orientation of Excitation and Emission Dipoles" Phys. Rev. Lett. 115, 173002 (2015).

[2] Chizhik, A.I., Rother, J., Gregor, I., Janshoff, A.; Enderlein, J."Metal-induced energy transfer for live cell nanoscopy" Nature Photonics 8, 124-127 (2014).

[3] Schulz, O.; Pieper, C.; Clever, M.; Pfaff, J.; Ruhlandt, A.; Kehlenbach, R.H.; Wouters, F.S.; Großhans, J.; Bunt, G.; Enderlein, J. "Resolution doubling in fluorescence microscopy with Confocal Spinning-Disk Image Scanning Microscopy" PNAS 110, 21000-21005 (2013).

[4] Müller, C.B.; Enderlein J. "Image scanning microscopy" Phys. Rev. Lett. 104, 198101 (2010).

[5] Toprak E.; Enderlein J.; Syed S.; McKinney S.A.; Petschek R.G.; Ha T.; Goldman Y.E.; Selvin P.R. "Defocused orientation and position imaging (DOPI) of myosin V", PNAS 103, 6495-6499 (2006).

Jörg Enderlein

Jörg Enderlein was born in 1963 in Berlin. After studying physics at the Ilya-Mechnikov-University in Odessa, he received his PhD from Humboldt-University in Berlin in 1991. During his PhD he was mainly concerned with the physics and chemistry of non-linear reaction-diffusion systems, but later turned his attention towards to the then developing field of single molecule fluorescence spectroscopy and imaging. After a post-doc stay in Dick Keller's group at the Los Alamos National Laboratory in New Mexico, he obtained his habilitation from Regensburg University in 2000. Becoming a Heisenberg-Fellow of the DFG, he established his own research group at the Forschungszentrum Jülich, and with a short detour as a Professor for Biophysical Chemistry at Eberhard-Karls University in Tübingen, he switched to his current position at the 3rd Institute of Physics of the Georg-August University in late 2008.

Molecular and Cellular Biophysics

Research in the group is focused on molecular and cellular biophysics, studying the mechanics and dynamics of living systems on all levels, from single molecules, via biomacromolecular assemblies such as cytoskeletal filaments, virus particles or primary cilia, to cells and tissues. A particular interest lies on the non-equilibrium statistical physics of "active matter" in biology and on mechanosensory phenomena in cells. Experimental approaches include light and fluorescence microscopy, optical trapping, atomic force microscopy, micro- and macrorheology. Pioneering projects at the interface between physics and medicine are currently developed.

Active Matter

Life can only exist out of thermodynamic equilibrium. Living organisms constantly dissipate energy derived from photosynthesis or metabolism to build and maintain structures and dynamic functions. Many of the materials cells and tissues are built of are "active materials", i.e. materials with integrated microscopic force generators. These materials can perform amazing feats, make a cell crawl towards a source of food, drive cell division, self-organize into muscle fibers that make the heart beat and much more. Expanding statistical physics to describe this new form of matter is a major challenge [5]. In this area we study patterns and flows in the cell cytoskeleton that show steady states, critical phenomena and non-equilibrium phase transitions, we analyze stochastic cell "self-stirring" that facilitates intracellular transport [4] (Fig. 1). We measure the fluctuating forces exerted by cells on their environment [3,6] and how these change in cells that develop specialized internal structures (Fig. 2), such as stem cells developing into heart muscle cells. We also study the collective fluctuations and movements in tissues on larger scales, such as the 2-dimensional layer of duplicating nuclei in early Drosophila embryos. In this area we also apply and extend fundamental concepts of theoretical statistical physics, such as the fluctuation-dissipation theorem [7] or the principle of detailed balance [1] (Fig. 3).

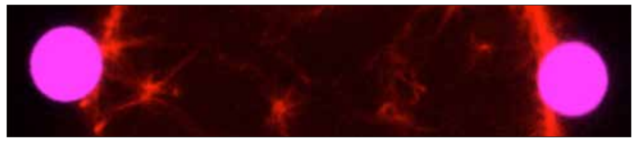


Fig. 2: Cellular forces measured by optical traps. Suspended cells typically round up due to osmotic pressure. In that geometry the actin cortex (red) forms a < 1 µm thick layer right under the cell membrane. Bundles, such as stress fibers or filopodia can also occur. Although cell shape does much not change the cortex is very dynamic, due to fluctuations of myosin activity. We measured force fluctuations by optically trapping two 4 beads (purple) that are also used to suspend the cell [3].

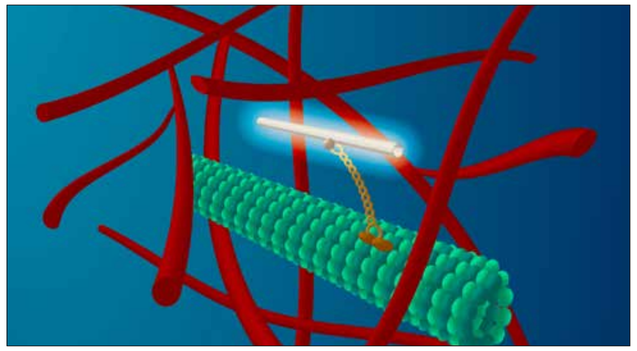


Fig. 1: Cell stirring (schematic). The strongest motors in cells are myosins. Myosins are inserted in the actin cytoskeleton (red) and cause contractions. Microtubules (green) are in many parts of the cell embedded in the actin cytoskeleton and cargos pulled by motors along microtubules will experience both, the direct stress generated by the motors plus the forces transmitted through the fluctuating tracks. We measured these fluctuations by tracking Single-walled carbon nanotubes (white) attached to kinesin motors (gold) [4].

Mechanosensing

Cells can not only produce forces, but can also extremely accurately sense forces. This plays important roles in hearing, touch-reception, or proprioception, but also in steering the development of stem cells or the collective self-organization of organs and active tissues such as muscle. We study mechanosensing in a number of systems at different scales. We mechanically probe single bacteria with an atomic force microscope to measure the opening and closing of the mechanosensitive MsC membrane channels that serve the bacteria as emergency pressure release valves. In eukaryotic cells, we investigate the mechanism by which primary cilia detect extracellular fluid flow, for example in kidneys [1,2] (Fig. 4). In Drosophila larvae we study the physical function of chordotonal organs that are specialized mechanosensors providing feedback to the central nervous system about body motion.

Motor proteins

We study biological motor proteins of the kinesin family in single-molecule experiments with the goal of understanding the basics of biological force generation in active transport processes [10,12]. Kinesin motors are mostly involved in intracellular vesicle transport and in cell division (Fig. 5). In in vitro experiments, we measure forces exerted by single motor molecules with optical traps, observe single molecules on the move directly with fluorescence microscopy, and explore the dynamics of the motors' building blocks with atomic force microscopy (AFM). In cells and in whole organisms such as Drosophila or C. elegans, we use fluorescent single-walled carbon nanotubes to track motor motion in the complex and collective functional context of the cell.

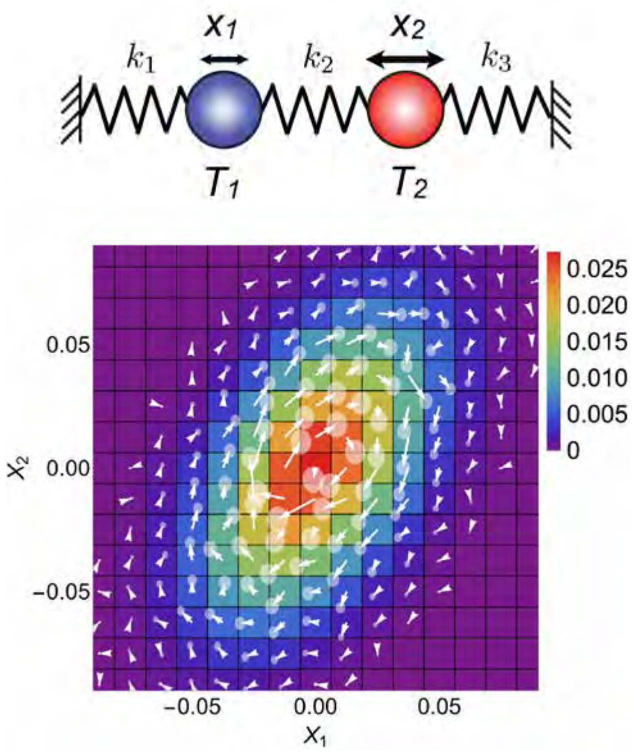


Fig. 3: Non-equilibrium leads to broken detailed balance. The principle of detailed balance is a fundamental statement of equilibrium thermodynamics. It postulates that transition rates between pairs of states of a system need to be strictly balanced, or that there cannot be net flux in phase space. Conversely, if one can detect flux in phase space (rotational flux if the system is in a steady state) then one can be sure that the system is out of equilibrium. Thus is illustrated by a simulation of two over-damped beads connected by a Hookean spring at different temperatures (top). Rotational probability flux ensues in a phase space spanned by the two locations of the beads (bottom) [1].

New tools:

Carbon nanotubes as novel probes for cellular mechanics

We use infrared-fluorescent single-walled carbon nanotubes (SWNTs) to study mechanical properties and processes in living cells. SWNTs are tubular carbon structures, related to Buckminster fullerenes and graphene, with unique physical properties. Due to their extreme aspect ratio (10 µm : 1 nm) they can be used as multi-scale stealth probes to measure viscoelasticity and fluctuations inside cells. The ultra-stable fluorescence emission of these novel probes is in the near infra-red. We target SWNTs to specific cellular components and can thereby follow local dynamics with very good resolution in time and space without physically perturbing the dynamics of the cell.

DNA nanostructures

We use the unique programmability of DNA to assemble nanometer-sized constructs, for example loop constructs or tetrahedra, from oligomeric DNA [9]. We use such constructs, for example, as molecular force sensors that make it possible to perform high-resolution stress-field mapping in living cells.

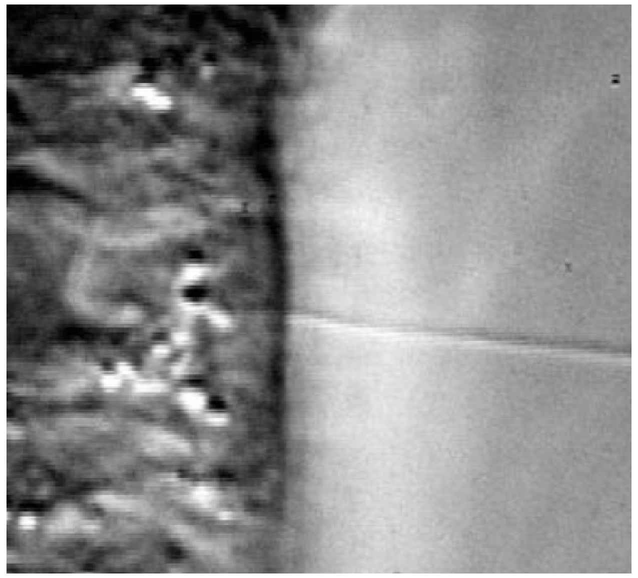


Fig. 4: Mechanosensory primary cilium. Primary cilia serve as mechano- and chemosensors for many cells. Shown here is a DIC microscopy image of a cilium (~10 µm length) attached to a kidney epithelial cell (MDCK). Although primary cilia possess no motors, we found that they are actively driven by the myosin motors in the cell cortex [1,2].

Atomic force microscopy (AFM) and laser-optical microrheology

We develop tools to probe the mechanical properties and non-equilibrium dynamics of systems ranging from synthetic colloids and polymers, single protein polymers, via protein tubes and shells, to whole cells and cells in culture or in tissue. We probe these systems with atomic force microscopy [8] or with microrheology techniques [11]. An approach that our group has pioneered is nano-shell mechanics with AFM, i.e. the study of elastic properties of virus shells and protein tubes such as microtubules by AFM indentation. Microrheology based on optical trapping of micron-sized colloids and laser interferometry is another technique we have developed (Fig. 6). We use it mainly to study equilibrium and non-equilibrium polymer networks in vitro, but also the cytoskeleton of living cells. We combined a high-bandwidth dual optical trap system with a confocal microscope that has super-resolution capabilities (cw-STED). This allows us to monitor in situ mechanical properties and active cellular force transmission while imaging the cellular force-generating machinery.

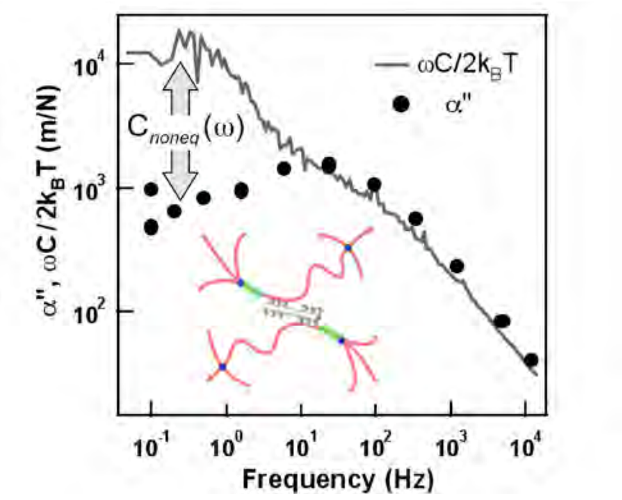


Fig. 6: Active and passive microrheology. Mechanical response of a model network of cross-linked actin network (red lines) driven out of equilibrium by myosin motors (grey bundles). Black dots show the frequency dependence of the elastic response function measured by active microrheology using an optically trapped bead. The fluctuation spectrum, (grey line) measured by passive microrheology in the same experiment, deviates at low frequencies from the response function, demonstrating the violation of the fluctuation-dissipation theorem in this non-equilibrium material [6,7].

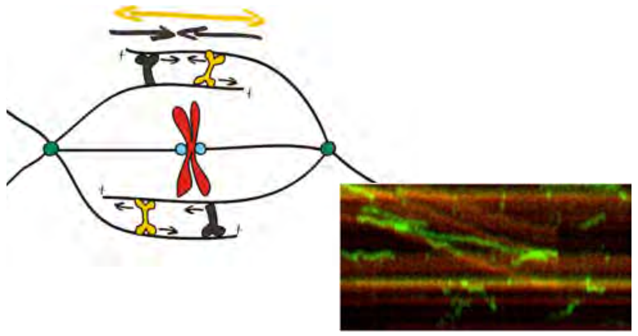


Fig. 5: Motor proteins drive cell division. The mitotic spindle is the machine built of microtubules that separates chromosomes during cell division. This is done by motor proteins of the kinesin family, producing a delicate balance of forces. The sketch shows a four-headed Kinesin 5 (yellow) balancing a two-headed Kinesin 14 (black), between two microtubules (black lines). Insert: the single-molecule fluorescence microscopy kymograph shows how a Kinesin 5 (green line) slides one microtubule (slanted red lines) over a stationary microtubule (horizontal lines) [10].

[1] Battle, C., C. P. Broedersz, N. Fakhri, V. F. Geyer, J. Howard, C. F. Schmidt and F. C. MacKintosh (2016). "Broken detailed balance at mesoscopic scales in active biological systems", Science 352(6285): 604-607.

[2] Battle, C., Ott, C.M., Burnette, D.T., Lippincott-Schwartz, J., Schmidt, C.F. (2015). "Intracellular and extracellular forces drive primary cilia movement", Proc. Natl. Acad. Sci. (USA), 112: 1410-1415.

[3] Schlosser, F., F. Rehfeldt and C. F. Schmidt (2015). "Force fluctuations in three-dimensional suspended fibroblasts", Phil. Trans. Royal Soc. London B: Biol. Sci. 370: 20140028.

[4] Fakhri, N., A.D. Wessel, C. Willms, M. Pasquali, D.R. Klopfenstein, F.C. MacKintosh and C.F. Schmidt (2014). "High-resolution mapping of intracellular fluctuations using carbon nanotubes", Science 344: 1031-1035.

[5] MacKintosh, F.C. and C.F. Schmidt (2010). "Active cellular materials", Curr. Opin. Cell Biol. 22: 29-35.

[6] Mizuno D.; R. Bacabac ; C. Tardin; D. Head, C.F. Schmidt (2009). "High-resolution probing of cellular force transmission", Phys. Rev. Lett. 102: 168102.

[7] Mizuno D.; C. Tardin; C.F. Schmidt; F.C. MacKintosh (2007). "Nonequilibrium mechanics of active cytoskeletal networks", Science, 315: 370-373.

[8] Michel J.P.; I.L. Ivanovska; M.M. Gibbons; W.S. Klug; C.M. Knobler; G.J.L. Wuite; C.F. Schmidt (2006). "Nanoindentation studies of full and empty viral capsids and the effects of capsid protein mutations on elasticity and strength", Proc. Natl. Acad. Sci. (USA), 103: 6184-6189.

[9] Goodman R.P.; I.A.T. Schaap; C.F. Tardin; C.M. Erben; R.M. Berry; C.F. Schmidt; A.J. Turberfield (2005). "Rapid chiral assembly of rigid DNA building blocks for molecular nanofabrication", Science 310: 1661-1665.

[10] Kapitein, L.C., E.J.G. Peterman; B.H. Kwok; J.H. Kim; T.M. Kapoor; C.F. Schmidt (2005). "The bipolar mitotic kinesin Eg5 moves on both microtubules that it crosslinks", Nature 435: 114-118.

[11] Gittes F.; B. Schnurr; P.D. Olmstedt; F.C. Mackintosh; C.F. Schmidt (1997). "Microscopic viscoelasticity: Shear moduli of soft materials determined from thermal fluctuations", Phys. Rev. Lett. 79: 3286-3289.

[12] Svoboda, K., C.F. Schmidt, B.J. Schnapp, S.M. Block (1993). "Direct observation of kinesin stepping by optical trapping interferometry", Nature 365: 721-727

Christoph Schmidt

Christoph Schmidt was born 1956 in Frankfurt/M. He received a PhD in physics in 1988 from the Technical University Munich, developing light scattering and advanced fluorescent methods for the analysis of biomolecular dynamics. For his postdoctoral work at Harvard and the Rowland Institute for Science in Cambridge, Massachusetts he worked with Dan Branton, David Nelson and Steven Block, studying 2D polymers in physics and motor proteins in biology. Here he pioneered single-molecule experiments with optical traps. After rising to the rank of tenured professor of physics at the University of Michigan in Ann Arbor, MI, he established a biophysics group at the Vrije Universiteit of Amsterdam before eventually moving to Göttingen to head the 3rd Institute of Physics in 2006, which was at that point fundamentally reoriented towards biophysics. Since 2013 he is speaker of the SFB 937 and in 2014 he was awarded an ERC Advanced Grant. Since 2016 he is a member of the Göttingen Academy of Sciences and Humanities.

Computational Neuroscience and Neuro-Robotics

We are mainly interested in understanding the dynamics and the self-organization (learning) in neuronal systems embedded in their environment. Over decades, neurons and brains have mainly been investigated as stimulus-response systems, where the output of the system does not affect its own inputs. Animals (and humans), however, operate differently in quite a fundamental way: Whatever action we perform, it will almost always immediately affect our sensory inputs. In writing these lines I see my fingers moving over the keyboard, feel their touch, hear the clicking of the keys, notice letters appearing bksp bksp bksp bksp del appearing, where every typo (feedback error-signal) will enact a correction closing the perception-action loop. Hence, such perception-action loops are the normal mode of operation of all animals. It is our goal to understand the dynamics and the adaptivity of such systems in term of modern physics.

It is known that within such a loop some signals that come back to the animal's sensors are of direct relevance (like the seeing of a typo in writing), while others do not immediately drive the loop (like the clicking of the keys). Fundamentally, it is only the animal/human/agent who can decide which of the arriving sensor signals are relevant for the momentarily existing task and which are not. The behavior of any creature is therefore controlled by measuring its own inputs (input-control) and normally not by reinforcement from an external observer. Improved fitness will arise if an animal can do this in a predictive way, hence if it can use predictive mechanisms to anticipate the outcome of its own actions and, to some degree, also the "behavior of the world".

The goal of our studies is to understand how autonomous behavior arises in animals and agents through the development of complex perception-action loops and the learning of adaptive, anticipatory behavior through input-control with minimal external interference.

To this end we investigate (using neuro-physiological data as well as robots):

Input: Information processing in the visual system and its use in machine vision.

Dynamics and Adaptation: The biophysics of synaptic plasticity and correlation based learning mechanisms in animals and robots.

Reasoning: Decision making, planning and the discovery of the structure of the agent's environment.

Output: The sequencing of actions towards goal-directed behavior and the dynamics of such systems.

Naturally, this creates a rather wide research spectrum as we have to address all these aspects together without which we could neither design artificial closed loop systems (robots) nor could we try to understand real ones (animals/humans).

Vision and Machine Vision

Vision is the most important sensory modality for many vertebrates and especially for us humans. We can perform remarkable recognition tasks using our eyes and brain. For most robots, vision is equally important. In recent years, scientists working in this field have developed real-time vision algorithms with which moving scenes can be analyzed, objects found, and actions interpreted. For example the figure above shows how one can extract depth information from two stereoscopic images in scenes with little structure and large perspective shift ("disparity"). Our brain can easily perform such a task, which is difficult due to occlusions and perspective distortions. Recent research by our group has now made it possible to implement a brain-inspired and very efficient vision algorithms for depth and object perception also in machines.

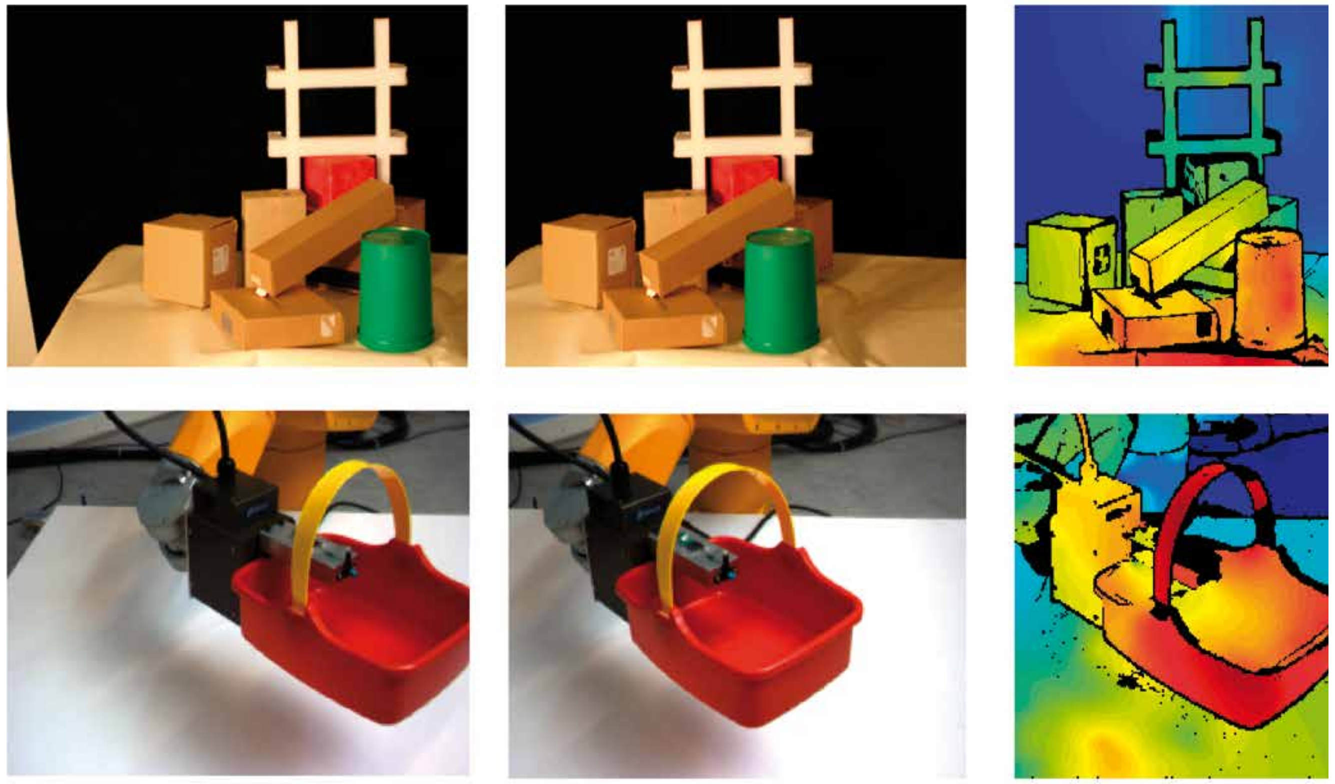


Fig. 1: Stereo image pair (left) and visual distance analysis (right, red encodes close objects and blue distant ones).

Adaptation and Learning

In a robot, any pre-processed input (e.g. from vision) is used to trigger actions and this is usually done not in a stereotypical but rather in an adaptive way. Adaptation and learning are vital for the survival of any autonomous agent as these processes allow dealing with non-stationary environments, hence with situations that change albeit within a restricted range. Animals and some robots can do the same and we use neural network mechanisms to emulate (fast) adaptation and (slow) learning processes. During the last years we have developed a mathematical theory of a certain type of neural learning (differential hebbian synaptic plasticity) and implemented it in several robots to optimize their behavior. The walking robot RunBot, which for some time has been the fasted dynamic biped walking machine existing (given its size) can this way learn to walk up a slope, like a little child would do. It uses the experience from falling backwards to learn changing its gait and to lean its upper body component forward as soon as it needs to climb.

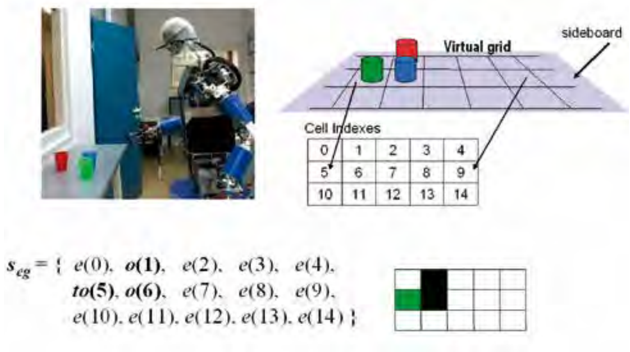


Fig. 3: A humanoid robot (ARMAR III, Univ. Karlsruhe) learns the action sequence required to sort cups on a sideboard.

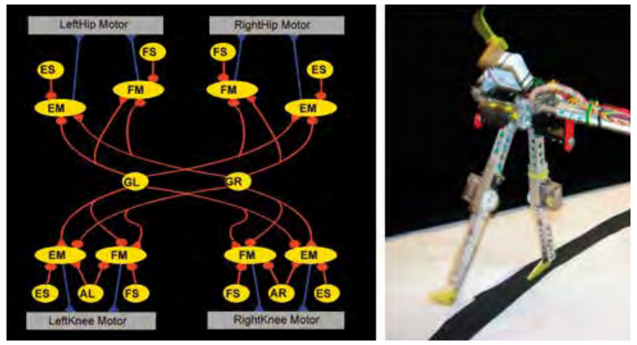
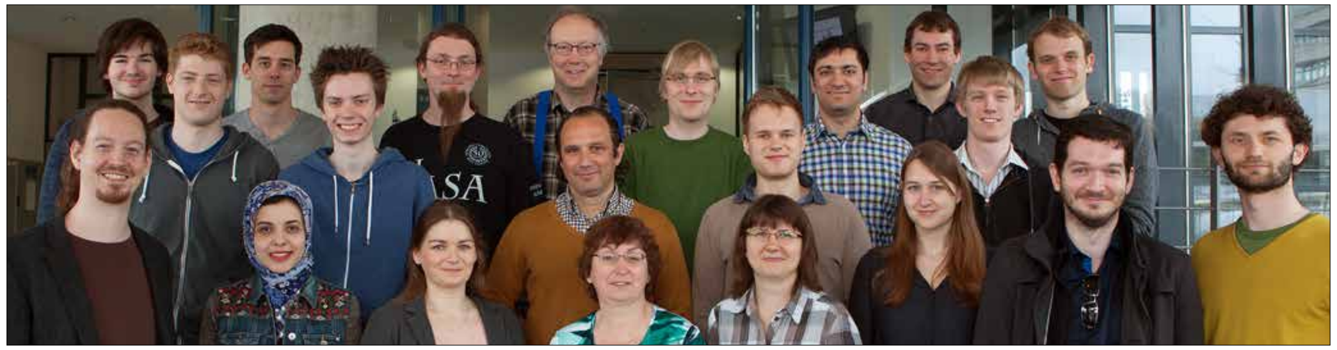


Fig. 2: The control network (left) of the biped RunBot, which allows it to learn walking up a slope (right).

Decision Making, Reasoning and Planning

Adaptation and learning will still only deal with resolving situations from moment to moment. However, more advanced agents -- those with cognitive properties -- are able to learn from time-delayed events. For example, each of us can learn the correlation between opening the fridge, getting a drink, drinking it and its outcome, which is the quenching of your thirst. Cause and effect are in these cases temporally far removed from each other and the execution of such an action sequence requires decision making and planning. In a cooperation with the University of Karlsruhe (Prof. Dr. R. Dillmann, Dr. T. Asfour) and the Consejo Superior de Investigaciones Científicas (Barcelona, Prof. C. Torras), we have developed a set of algorithms which allow a robot to learn the rules of an action plan by interacting with a human. The machine can, for example, be taught to sort cups on a sideboard starting with no initial planning knowledge. Here, too, our methods are inspired by the neurosciences and by psychology asking how children would learn such a task.



Actions and Dynamics

Sensing, learning, and planning do not suffice to close the perception-action loop. For this the agent must finally execute its plan. It must move and act. Given the high number of sensors and the multitude of muscles which we have, it is quite amazing that animals and humans have reached such a high degree of proficiency in sensor-motor coupling. Skillful dancing, difficult manipulation using complex tools, and advanced skiing are examples how terrific our sensor-motor coordination indeed is. We address this problem, for example, by a small adaptive 2-neuron network which initially operates in a chaotic way. By ways of sensor driven input the network can be controlled into expressing period oscillations and these can then – in turn – lead to periodic walking patterns (gaits) similar to those observed in real insects. Together with some neuronal post-processing one can this way achieve a very versatile and realistic behavioral repertoire: An autonomous, artificial insect that can sense, learn and act.

This shows how we address the problem of perception-action loops by ways of studying neural systems and building artificial agents which emulate certain neuronal operations. The long-term future challenge behind all this is the attempt to understand brain function to the degree that it will ultimately be possible to build advanced artificial cognitive systems that can interact and communicate with humans. There is still a long way to go, but the examples shown above demonstrate how autonomous systems can be built which express certain animal-like sub-functions with increasing degrees of complexity and realism and how we can understand those in terms of mathematical modeling.

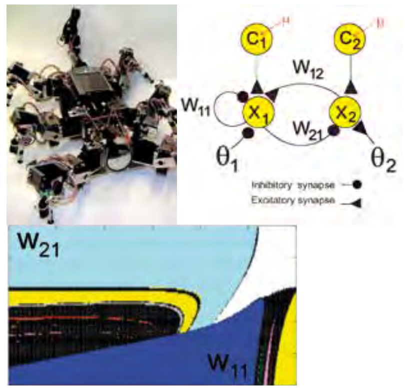


Fig. 4: The walking gait of the six-legged robot AMOS-WD6 (left) is determined by two neurons x (top right), which can be controlled by inputs c to operate in periodic or chaotic domains (bottom right, black denotes chaos, colors stand for different oscillations periods) depending on their mutual connection strengths w.

[1] Schoeler, M., Papon, J. and Wörgötter, F. (2015) Constrained Planar Cuts - Object Partitioning for Point Clouds, Computer Vision and Pattern Recognition (CVPR), 2015 IEEE Conference on, pp: 5207 - 5215, DOI: 10.1109/CVPR.2015.7299157.

[2] Schoeler, M. and Wörgötter, F. (2015) Bootstrapping the Semantics of Tools: Affordance analysis of real world objects on a per-part basis. IEEE TAMD, Volume: PP, Issue: 99, Pages: 1 - 1, DOI: 10.1109/TAMD.2015.2488284, IEEE Early Access Articles.

[3] Steingrube, S.; Timme, M.; Wörgötter, F. and Manoonpong, P. (2010) Self-Organized Adaptation of Simple Neural Circuits Enables Complex Robot Behavior. Nature Physics 6, 224-230. doi:10.1038/nphys1508.Tetzlaff C., Dasgupta S., Kulvicius T., and Wörgötter F. (2015). The use of hebbian cell assemblies for nonlinear computation. Sci. Rep. 2015 Aug 7;5:12866. doi: 10.1038/srep12866.

[4] Tetzlaff C., Dasgupta S., Kulvicius T., and Wörgötter F. (2015). The use of hebbian cell assemblies for nonlinear computation. Sci. Rep. 2015 Aug 7;5:12866. doi: 10.1038/srep12866.

[5] Wörgötter, F., Geib, C., Tamosiunaite, M., Aksoy, E.E., Piater, J., Xiong, H., Ude, A., Nemec, B., Kraft, D., Krüger, N., Wächter, M. and Asfour, T. (2015) Structural bootstrapping - a novel concept for the fast acquisition of action-knowledge. IEEE TAMD, 140-154, DOI:10.1109/TAMD.2015.2427233

[6] Wörgötter, F. (2013), Roboter auf dem Weg zur Kognition. Jubiläumsband der Universität Göttingen, Springer.

[7] Xiong, X., Wörgötter, F. and Manoonpong, P. (2015) Adaptive and Energy Efficient Walking in a Hexapod Robot under Neuromechanical Control and Sensorimotor Learning, IEEE Cyb. 10.1109/TCYB.2015.2479237.

Florentin Wörgötter

Florentin Wörgötter studied Biology and Mathematics in Düsseldorf, finishing these studies with the electronic design of a neural-pattern recognizer. He obtained his PhD in experimental visual neuroscience in Essen in 1988. As a postdoc he worked for 2 years at CALTECH in the field of modeling the visual system. Between 1990 and 2000 he was leader of the group of computational neuroscience and during the last 5 years of this period Heisenberg Fellow at the Ruhr-University Bochum. During this time he continued his neuroscience research but also started to develop "neuronal" computer vision algorithms. This has led to several scientific and commercial applications in the field of image segmentation, data-fusion and stereo-depth analysis. Between March 2000 and June 2005 he held a Chair in the psychology department of the University of Stirling in Scotland. Since June 2005 he is professor for Computational Neuroscience at the Bernstein Center for Computational Neuroscience at the University of Göttingen, Germany, where he joined the Inst. of Physics III in August 2009.

Christian Doppler Laboratory for Cavitation and Micro-Erosion (CDLCME)

The CDLCME was established in 2009 in the Faculty of Physics. It is located in the 3rd Institute of Physics (Biophysics). The CDLCME is jointly funded by the Austrian Christian Doppler Research Association (CDG) and an industrial partner, Lam Research AG. According to the CDG goals, the work is dedicated to applied fundamental research and thus explores basic physical phenomena needed for advanced industrial applications.

The CDLCME investigates the effect of acoustic streaming, cavitation and bubble collapse in liquids on solid surfaces on a microscopic scale. The envisaged major application of the results of this research is in wet processing and cleaning of nanostructured silicon wafers (computer chips), which is the expertise of the industrial partner. Settled in a multidisciplinary environment of acoustics, fluid dynamics and optics, the project builds on the traditional strengths of the 3rd Institute.

Participating researchers are: C. F. Schmidt, R. Mettin (Laboratory Head), T. Kurz.

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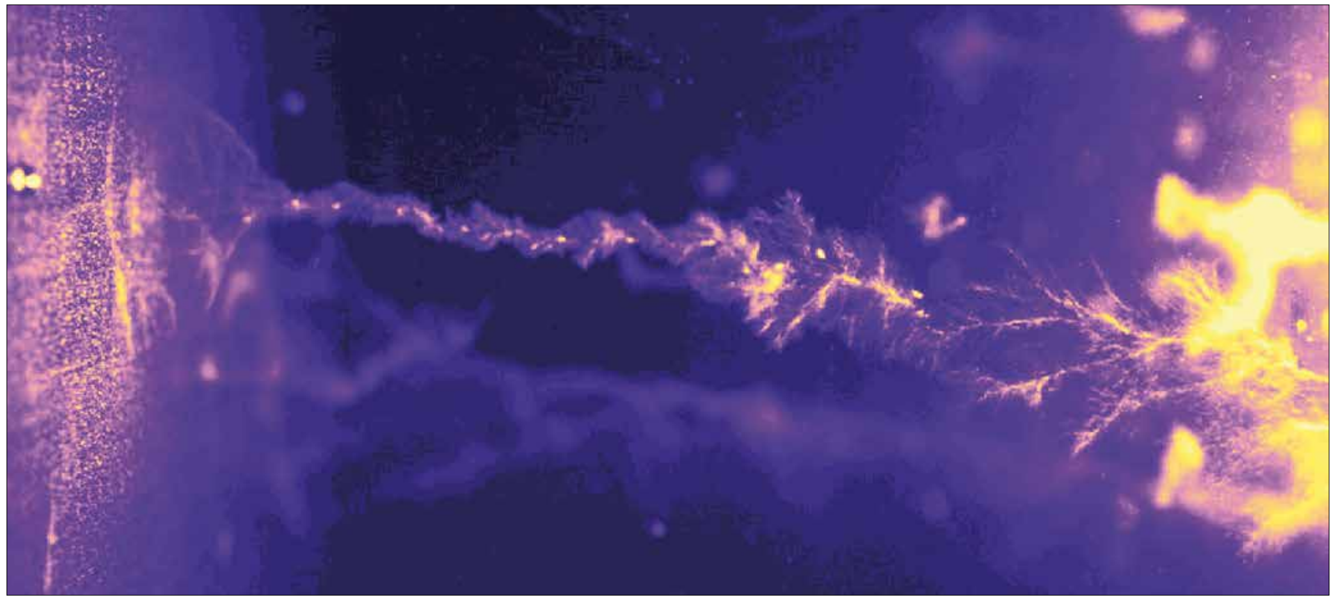


Structure of Biomolecular Assemblies and X-ray Optics

Our group "Structure of biomolecular assemblies and x-ray physics" studies soft matter and biomolecular assemblies, from the molecular level to biological cells and tissues. We seek to describe the non-crystalline self-assembly of biomolecular systems in quantitative physical terms, and we want to understand how functional properties of biomolecular assemblies depend on their nanoscale structure and dynamics.

To access the required length and time scales, we adapt and develop x-ray based methods for structure analysis in non-crystalline, hydrated states, and in the native functional environments. Since diffraction methods are mostly restricted to large ensembles and relatively well-ordered and homogeneous structures, we currently extend x-ray diffraction to x-ray (diffractive) imaging in many of our studies. For example, we use nano-focused x-ray beams to study biomolecular assemblies in cells and holographic phase contrast x-ray tomography to study cells in biological tissues. In our experiments, we want to get a maximum of information from a minimum of photons. This entails significant efforts in optics, including optimized focusing, wave-front control, coherence, phase retrieval, reconstruction algorithms, information theory and image processing. Some of this work is useful for biomedical imaging in a broader sense.

By modern x-ray diffraction and x-ray imaging we can access the structure, the collective dynamics, the self-assembly and the interactions of biological macromolecules, from model systems, to cells and tissues. In the past, we have for example studied the self-assembly of lipid and DNA, the thermal unfolding of membrane proteins, the structural mechanisms of antibiotic peptides in lipid membranes, the structure of spider silk and its changes during mechanical load, the collective dynamics of membranes, the ion distribution at charged membranes, the interactions between membranes, and more recently the non-equilibrium dynamics of membranes after optical excitation [1]. At present, our research in membrane biophysics concentrates on the problem of membrane fusion. We have shown that fusion intermediate structures in model membranes can be analyzed in 3D by high resolution x-ray diffraction [2] and have probed the interaction of model membranes with native synaptic vesicles [3], see Fig.1. We have also devised a way to image lipid membranes by x-ray phase contrast based on Fresnel diffraction and free space propagation. Beyond model systems, we extend x-ray diffraction methods to entire biological cells, which we scan by nano-focused x-ray beams, recording and analyzing the local diffraction pattern. In this way, we investigate protein networks in biological cells, myelin structure in nerve fibers, and the packing of DNA in bacterial nucleoids [4]. For such experiments, we use different optics to focus or confine x-ray radiation.

A particular new x-ray microscopy approach which we have developed is based on x-ray waveguide optics, providing a highly coherent a quasi-point source for holographic imaging [5]. X-rays can be guided through small channels of low electron density material embedded in a cladding material with higher electron density, similar to the way that visible light is guided through an optical fibre. X-ray waveguides can deliver nano-meter sized x-ray beams of defined shape and coherence properties. We achieve spot sizes down to 10nm, and can now use such x-ray nano-beams for spatially resolved diffraction, and as quasi point sources for holographic imaging and tomography. Recently, we have shown that one can even guide nano-sized x-ray beams "around the corner" [6], see Fig.2, enabling new functionalities (beam splitters, time delays, reference beam).

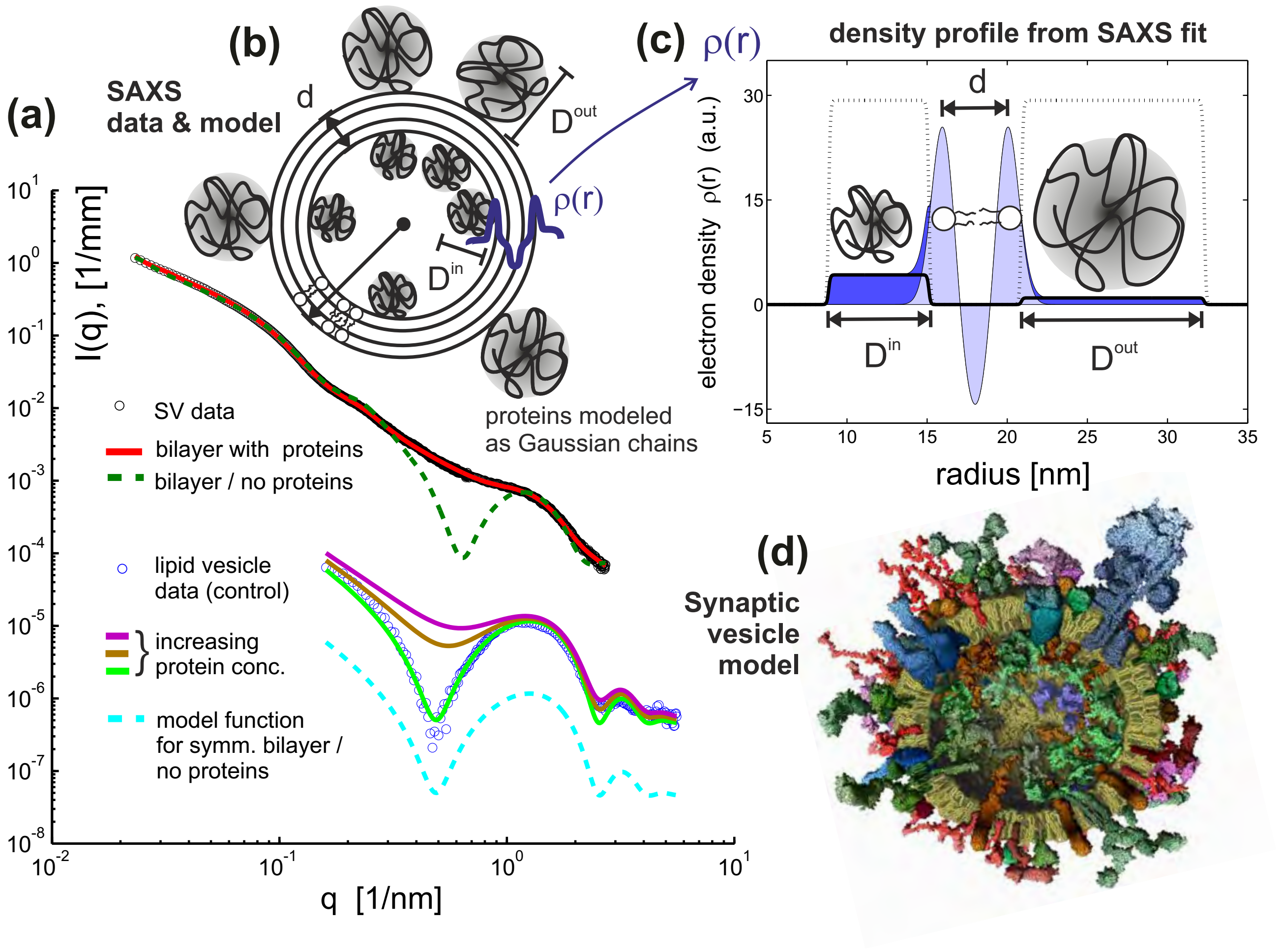


Fig. 1: Structure of synaptic vesicles by small-angle x-ray scattering: (a) SAXS curve of a SV suspension (black open circles, shifted for clarity) with the least-square fit (solid red line) to a model of protein covered vesicle sketched in (b). The structural model parameterizes the protein layers with protein radii of gyration, effective number of protein patches, and densities as free fitting parameters. Models without patchy proteins cannot reproduce the data (dahed green curve). The lower curves correspond to a control sample and to simulations. (c) The density profile of the SV membrane with the adjacent protein layers as obtained from the least square fit of the SAXS curve shown in (a). The structural results confirm and further quantify the biochemical model with the densely packed layer of proteins reported earlier (Takamori, Jahn et al.), as visualized in (d). Adapted from [3].

In short, we perform substantial development in coherent x-ray imaging, x-ray waveguide optics, holography, and tomography [7] to reach our goals. Experiments are carried out both at in-house x-ray sources (cw and pulsed), as well as synchrotron, and free electron lasers (FEL). We also closely interact with mathematicians, mainly on phase retrieval and tomographic reconstruction methods. In the end, all the enjoyment we take from advancing x-ray optics has to serve challenging applications, such as the example shown in Fig.3, where the interior structure of peripheral nerves with thousands of axons and connected neurons is reconstructed by phase contrast tomography [8], yielding 3D data without cutting of the tissue, going far beyond the standard histological cross sections.

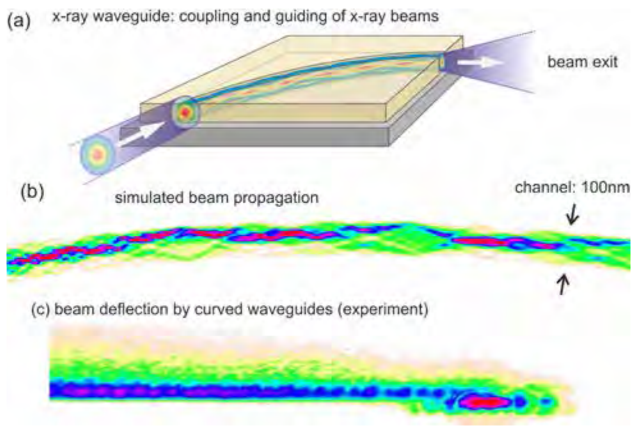
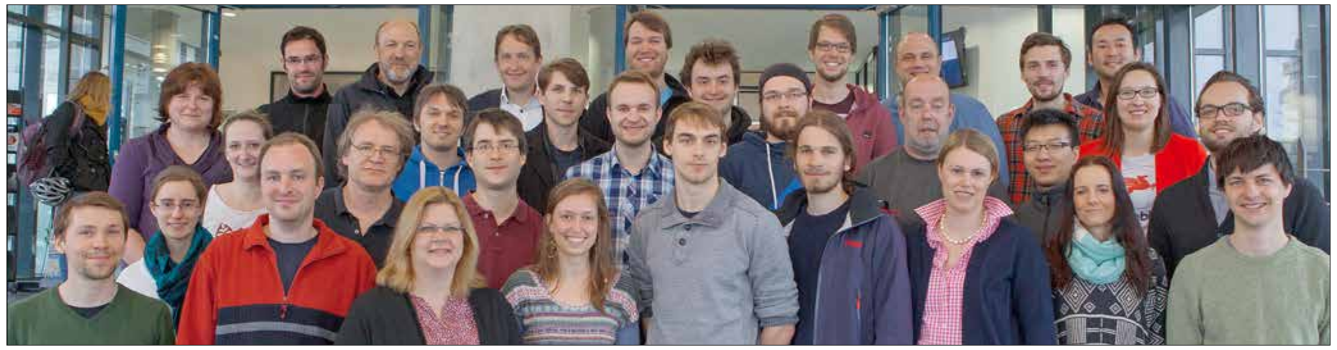


Fig. 2: Wave-guiding of x-rays: We develop advanced x-ray waveguide optics to filter, confine, concentrate and guide x-rays in controlled ways at the nanoscale. The exit radiation of x-ray waveguides provides an excellent illumination for x-ray holography. Recently, we have shown how x-ray waveguides can accommodate high curvature, which is an important step to realize "x-ray optics on a chip" [6].



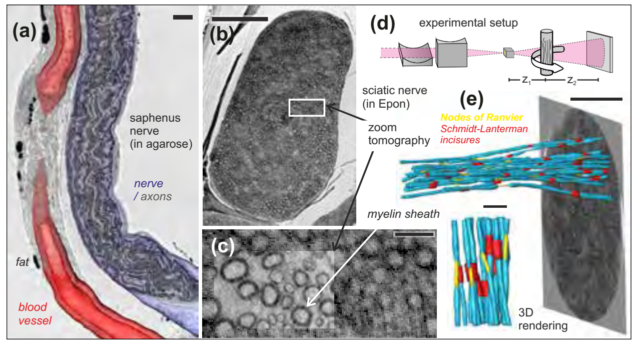


Fig. 3: X-ray phase contrast tomography of nerve tissue: (a) Three dimensional reconstruction of a mouse saphenus nerve (blue) with adhering blood vessel (red). The rendering shows a longitudinal virtual slice, and (b) virtual slice through an stained sciatic nerve (430nm voxel size). (c) Magnified view of the region marked in (b) along with data obtained from a zoom-tomogram (50nm voxel size). (d) Experimental setup: The undulator beam is focused by two elliptically shaped mirrors (KB) and (optionally) filtered by an x-ray waveguide system. The nerve is placed at various distances from the focus within the divergent (partially) coherent beam and magnified Fresnel diffraction patterns (holograms) are recorded. Subsequent phase retrieval and tomographic reconstruction allows quantitative 3D electron density determination. (e) 3D rendering of a sciatic nerve with rendered axon structures (Nodes of Ranvier, Schmidt-Lanterman incisures).Scale bars: (a) 50µm. (b) 100µm, (c) 10µm, (e, top) 100 µm, (e, bottom) 10µm. Adapted from [8].

Our research is funded by SFB 755 Nanoscale Photonic Imaging, SFB 937 Collective Behavior of Soft and Biological Matter and SFB 803 Functionality Controlled by Organization in and Between Membranes, as well as the neuroscience cluster of excellence Microscopy at the Nanometer Range within the Center for Molecular Physiology of the Brain. Together with collaborating groups at HASYLAB / DESY and other partner groups, we also form a virtual institute on In-Situ Nano-Imaging of Biological and Chemical Processes funded by the Helmholtz Association. Finally, our group operates an endstation of nano-imaging at the coherence beamline P10 at the storage ring PETRAIII at DESY.

[1] T. Reusch, D. D. Mai, M. Osterhoff, D. Khakhulin, M. Wulff, T. Salditt Nonequilibrium Collective Dynamics in Photoexcited Lipid Multilayers by Time Resolved Diffuse X-Ray Scattering, Physical Review Letters 111, 268101 (2013).

[2] S. Aeffner, T. Reusch, B. Weinhausen and T. Salditt, Energetics of stalk intermediates in membrane fusion are controlled by lipid composition , Proc. Natl.Ac.Sci. 109, 1609-1618, (2012).

[3] S. Castorph, D. Riedel, L. Arleth, M. Sztucki, R. Jahn, M. Holt, T. Salditt Structure Parameters of Synaptic Vesicles Quantified by Small-Angle X-Ray Scattering Biophysical Journal 98, 1200 (2010)

[4] K. Giewekemeyer, P. Thibault, S. Kalbfleisch, A. Beerlink, C. M. Kewish, M. Dierolf, F. Pfeiffer and T. Salditt , Quantitative biological imaging by ptychographic x-ray diffraction microscopy , Proc.Natl.Ac.Sci. 107, 529-534 (2010).

[5] M. Bartels, M. Krenkel, J. Haber, R. N. Wilke, and T. Salditt , X-Ray Holographic Imaging of Hydrated Biological Cells in Solution , Phyical. Review Letters, 114, 048103 (2015).

[6] T. Salditt, S. Hoffmann, M. Vassholz, J. Haber, M. Osterhoff, J. Hilhorst , X-Ray Optics on a Chip: Guiding X Rays in Curved Channels , Physical Review Letters 115, 203902 (2015).

[7] M. Vassholz, B. Koberstein-Schwarz, A. Ruhlandt, M. Krenkel, T. Salditt New X-Ray Tomography Method Based on the 3D Radon Transform Compatible with Anisotropic Sources , Physical Review Letters 116, 088101 (2016).

[8] M. Bartels, M. Krenkel, P. Cloetens, W. Möbius, T. Salditt Myelinated mouse nerves studied by X-ray phase contrast zoom tomography J. Structural Biology 3, 561-568 (2015).

Tim Salditt

Tim Salditt (born 1965) studied physics in Munich and in Grenoble, France. He received his Ph.D. under the supervision of J. Peisl, University of Munich, and was awarded the Ernst-Eckhard-Koch prize for an outstanding research work in his thesis using synchrotron radiation. He started to study the structure of biomolecular assemblies at the University of California at Santa Barbara (1996) with C. R. Safinya, funded by a NATO/DAAD postdoctoral fellowship (1997). Returning to Munich he joined the Center for Nanoscience, where he finished his habilitation. In 2000 he was appointed Associate Professor at Universität des Saarlandes. In 2002 he became Full Professor for Experimental physics at Universität Göttingen.. Tim Salditt is an active user of several national and international synchrotron radiation facilities, spokesperson of the collaborative research center Nanoscale Photonic Imaging in Göttingen, and member of the Akademie der Wissenschaften zu Göttingen.

Nanoscale Imaging of Cellular Dynamics

The human body contains over 200 cell types and each of them is perfectly well adapted to its physical function: (heart) muscle cell are exposed to repeated extension; epithelial cells, which line the outside of the major organs, are exposed to high stresses; and brain cells bear hydrostatic pressures, to name a few examples. These highly variable mechanical properties are encoded by the so-called cytoskeleton, which consists of three major protein filament systems, namely actin filaments, intermediate filaments and microtubules, along with a large variety of cross-linking proteins and molecular motors. By varying the fraction of the components and by specific structure formation, such as bundling and network creation, this intriguing composite material equips each cell type with exactly the mechanical properties it needs for its specific function. Deciphering the link between molecular interactions of the cytoskeletal components and cell mechanics is therefore an important step in understanding cellular function.

Biological cells are highly complex objects and besides biology and biochemistry, biomechanics plays a great role in cell function. Currently, we are still far from a complete understanding of the physical processes taking place in cells on the relevant length and time scales. However, by combing cell experiments with investigations of reconstituted in vitro systems, which contain one or very few components of a cell, it is possible to assemble a picture of cellular function to ever-greater detail. Cell mechanics are to a great part determined by the cytoskeleton and two of the three cytoskeletal filament systems, actin filaments and microtubules, have been well characterized from a physics point of view. In particular, a plethora of binding proteins associated with these filaments is known, giving rise to pronounced structural variability inside cells. Furthermore both filament types are polar with distinguished ends enabling the directed motion of molecular motors.

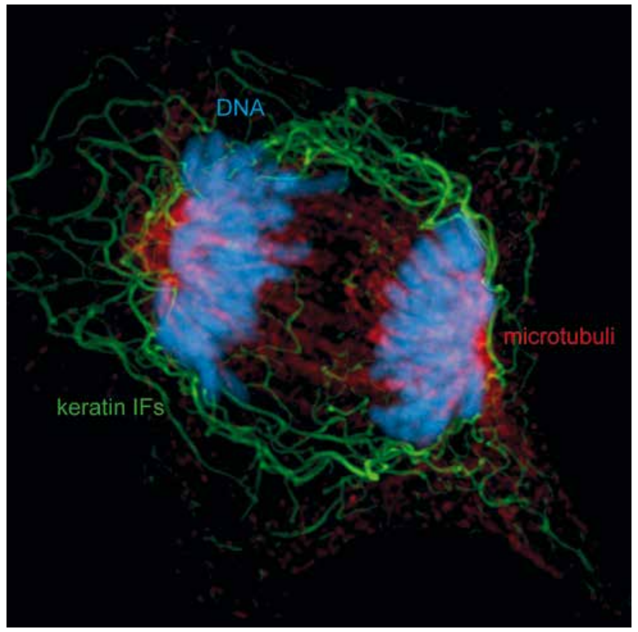


Fig. 1: Fluorescence micrograph of a biological cell. The DNA in the chromosomes is labeled in blue, the microtubules in red and keratin intermediate filaments in green. Actin filaments are not shown in this image. The cell is in the process of dividing and the microtubules drag the chromosomes into the two daughter cells. Image taken by Hubert Bauch.

The third system, intermediate filaments (IFs), has moved into the focus of physicists only during the past few years and recent studies have shown astonishing mechanical properties [1,2]. For example, IFs are much more flexible than the other cytoskeletal filament and they can be elongated to at least three times their original length, much more than actin filaments or DNA strands, which tend to break already at lower strains. Both these special mechanical properties may be linked to the molecular architecture of IFs, which follows a strictly hierarchical building plan. Like many other biological filaments, IFs show strain stiffening, which could serve as a “rescue option” for cells when they are exposed to pronounced strains, yet keeping them flexible at small strains.

Another important particularity of IFs with respect to actin filaments and microtubules, which are highly conserved among cell types and organisms, is their tissue specificity. IFs form a large family of proteins, which share a common secondary structure but differ in their exact amino acid sequence. These differences might play a role for the ability of the protein filaments to form adapted networks, bundles or networks of bundles. Thus, for example, epithelial cells express keratins, connective tissue cells vimentin, neurons neu-

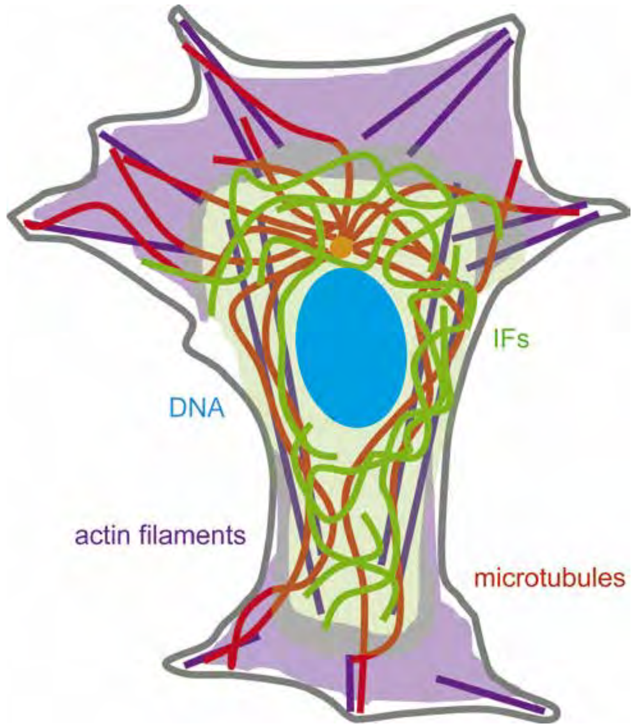


Fig. 2: Sketch of the major cytoskeletal component of a mammalian cell. Actin filaments, microtubules and intermediate filaments form distinct polymer networks which equip the cell with the required mechanical characteristics.

rofilaments and muscle cells desmin. A prominent example for the adaptability of cells to specific mechanical requirements is the so-called epithelial-to-mesenchymal-transition (EMT). During important biological processes such as wound healing, embryogenesis and cancer metastasis, stationary cells, which contain mostly keratin, transition into migratory mesenchymal cells containing mostly vimentin.

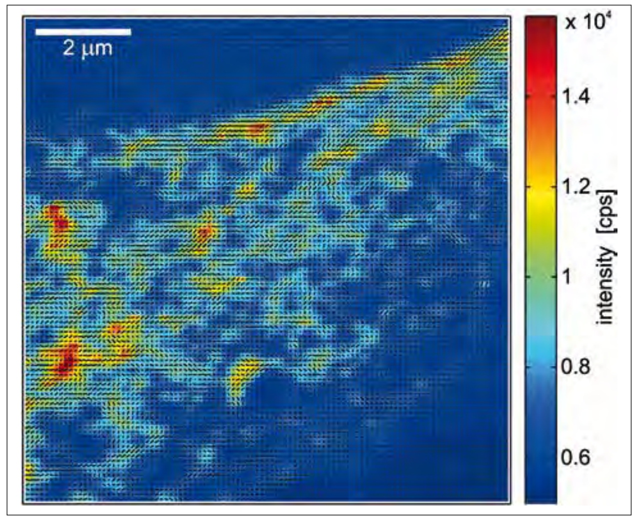


Fig. 3: X-ray dark field image of a keratin IF network in a cell. The color scale shows the total scattered intensity in each measurement position. The black lines indicate the local direction and degree of orientation of the keratin bundles [6, 7].

A key factor for these discoveries is the emerging availability of state-of-the-art biophysical tools, both in the field of high-resolution imaging in space and time, and in terms of manipulating methods. Piconewton to nanonewton forces can now be applied and measured by optical traps, atomic-force-microscopy, microfluidics, and traction force microscopy [3]. Microfluidic methods provide particularly well-suited tools for investigation of micrometer-sized systems, such as controlled biochemical micro-gradients, defined flow fields and shear forces, geometric confinement and micro-compartments. Many of these techniques are very suitable for combination with fluorescence microscopy and spectroscopy or x-ray imaging and scattering. Thus, the response of the biological system to external forces can be characterized in situ. In our experiments we match the relevant time-, length-, and force scales by the employed experimental methods. For example, microfluidics adds superior control and high time resolution to otherwise inherently "slow" techniques such as single molecules fluorescence spectroscopy and x-ray scattering. By combining different imaging modalities and thus collecting complementary information, we are able to characterize biological systems on multiple length scales.

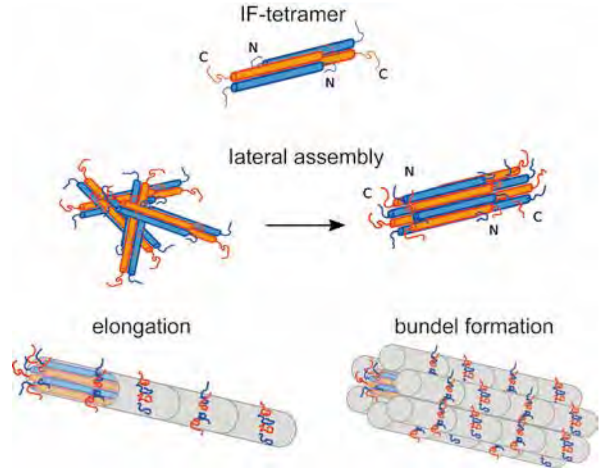
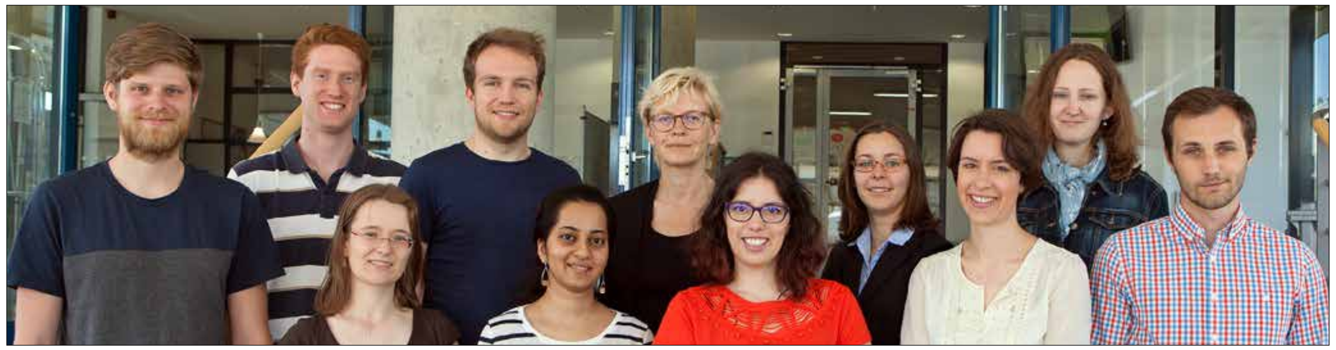


Fig. 4: Hierarchical self-assembly of IF proteins into extended filaments and bundles. Tetramers are stable in buffer solution and first laterally, then longitudinally associate upon the addition of ions at physiological concentrations. In a further structure formation step, the filaments may form bundles [4].

The most well established methods for imaging biological cells are certainly electron microscopy (EM) and fluorescence microscopy, both of which experience recent advances and improvements. EM offers nanometer resolution at the expense of extensive sample preparation. Fluorescence microscopy may be applied to living cells and fluorophores are bound to cellular components in a molecule-specific manner. Currently, X-ray imaging, is being developed by us and others as a third, complementary technique [4,5,6,7]. Here, the high spatial resolution, owing to the small wavelength of x-rays, is combined with a high penetration power. Thus, local structural information about intracellular assemblies can be derived from whole, unsliced and unlabeled cells, even in living state. A serious challenge in X-ray imaging, however, remains radiation damage. Different approaches to reduce harm on the sample exist, like cryoprotection by cold nitrogen streams or continuous flow of buffer solution in microfluidic flow devices [7]. Alternatively, combination of different imaging modalities enables us to obtain overview images at comparatively low dose. In these overview images regions of interest (ROIs) may be identified which are then imaged at higher resolution [4]. A great advantage of X-ray imaging over other methods is the combined real space and reciprocal space information. Thus, we obtain direct images of the cells and additionally in each position of the sample structural information such as local orientation, filament distances, thicknesses and spatial arrangements.



Understanding the physical principles determining cell function is a necessary prerequisite for understanding malfunction in pathological situations. Apart from the obvious impact on biomedical research, however, cellular biophysics also opens up new possibilities in materials science. As mentioned above, biological materials display extraordinary mechanical properties and a deep understanding of the molecular interactions, which encode these properties, may help to develop biomimetic materials with similar characteristics. Last but not least, biological systems provide a wealth of interesting and important soft condensed matter physics questions, ranging from hierarchical self-assembly, polymer and colloid physics, structure formation, non-equilibrium dynamics and collective effects. Thus, as much physics helps biology, biology provides great model systems for studying physical phenomena.

[1] S. Köster, D. Weitz, R. Goldman, U. Aebi, H. Herrmann, *Intermediate filament mechanics in vitro and in the cell: From coiled coils to filaments, fibers and networks*, Curr. Opin. Cell Biol. 32 (2015), 82

[2] B. Nöding, S. Köster, *Intermediate filaments in small configuration spaces*, Phys. Rev. Lett. 108 (2012), 088101

[3] S. Schwarz Henriques, R. Sandmann, A. Strate, S. Köster, *Force field evolution during human blood platelet activation*, J. Cell Sci. 125 (2012), 3914

[4] C.Y.J. Hémonnot, J. Reinhardt, O. Saldanha, J. Patommel, R. Graceffa, B. Weinhausen, M. Burghammer, C.G. Schroer, S. Köster, *X-Rays Reveal the Internal Structure of Keratin Bundles in Whole Cells*, ACSNano 10 (2016), 3553

[5] V. Piazza, B. Weinhausen, A. Diaz, C. Dammann, C. Maurer, M. Reynolds, M. Burghammer, S. Köster, *Revealing the Structure of Stereociliary Actin by X-Ray Nano-Imaging*, ACSNano 8 (2014), 12228

[6] B. Weinhausen, O. Saldanha, R.N. Wilke, C. Dammann, M. Priebe, M. Burghammer, M. Sprung, and S. Köster, *Scanning X-ray Nano-Diffraction on Living Eukaryotic Cells in Microfluidic Environments*, Phys. Rev. Lett. 112 (2014) 088102

[7] B. Weinhausen and S. Köster, *Microfluidic devices for X-ray studies on hydrated cells*, Lab Chip 13 (2013) 212

Sarah Köster

Sarah Köster, born in 1979 in Reutlingen, Germany, studied physics at the University of Ulm and performed her PhD work at the University of Ulm, Boston University and the Max Planck Institute for Dynamics and Self-Organization, Göttingen. She received her PhD from the University of Göttingen in 2006. Her thesis was awarded the Berliner-Ungewitter-Preis of the Göttingen physics faculty as well as the Otto-Hahn-Medaille of the Max-Planck-Society. In 2008, after two years of postdoctoral work at Harvard University with David Weitz, she returned to Göttingen as a junior professor. In 2010 she was awarded the Helene-Lange-Preis of the EWE-Foundation. In 2011 she was promoted to a tenured W2 professor in the faculty of physics of the University of Göttingen, where she leads the research group Nanoscale Imaging of Cellular Dynamics.

Structural Dynamics and Ultrafast Spectroscopy

The typical time scales for atomic and molecular motions in transforming matter (in solids or in chemical reactions) are femtoseconds. The transformation of bigger complex macroscopic entities in biophysical processes, however, can be as slow as seconds. In the workgroup we design and build apparatus which utilize the properties of radiation, generated in high flux large scale X-ray facilities, such as synchrotrons and free electron lasers, to "watch" and to study complex chemical and biophysical processes in real time – from femtoseconds up to seconds. With the developed methods we try to find structural and electronic links propagating into each other on the journey of a system through the various scales of time. We would also like to understand to what extend structural motifs "freeze in" in time and dynamics information during dynamic and kinetic transformations.

Ultrafast multidimensional X-ray spectroscopy and ultrafast high resolution X-ray diffraction

Characteristic for the X-ray photons generated in synchrotrons and free electron lasers are their (i) energy tunability (allowing for excitation energy sensitive method development like X-ray spectroscopy or advanced x-ray diffraction methods), (ii) pulsed structure (allowing for the development of in-situ and time-resolved X-ray methods), (iii) polarizability (allowing for advances in X-ray spectroscopy), (iv) coherence (allowing for x-ray imaging or correlation spectroscopy methods) and (v) high flux (allowing for high resolution x-ray experiments in all experimental domains). Combining i.e. the properties of (i)+(ii)+(iii)+(v) lead to the "from local to global" concept of time-resolved and ultrafast X-ray photon-in / photon-out techniques as have been developed in the workgroup. The single technique alone is already experimentally demanding: ultraprecise structure determination through X-ray diffraction techniques requires the use of very hard X-ray radiation (starting from 18 keV X-ray energy) and the collection up to very high angular momentum space, on one hand; on the other hand, X-ray spectroscopy with ultra-high energy resolution requires highest spectrometer grating resolution (down to 10-5 - 10-6 keV resolution at 5 keV X-ray energy) or the implementation of 2-dimensional X-ray laser spectroscopy techniques, and all of that on the ultrafast time scale (and combined). The listed resolutions are necessary in order to be element and chemical site specific and specific to the type of bonds which are broken and / or formed during a reaction. Figure 1 shows a photo of one of our experimental laboratories which is a photon endstation at the free electron laser FLASH/DESY. The next generation of such an endstation is currently under construction at the European X-ray Free Electron Laser facility.

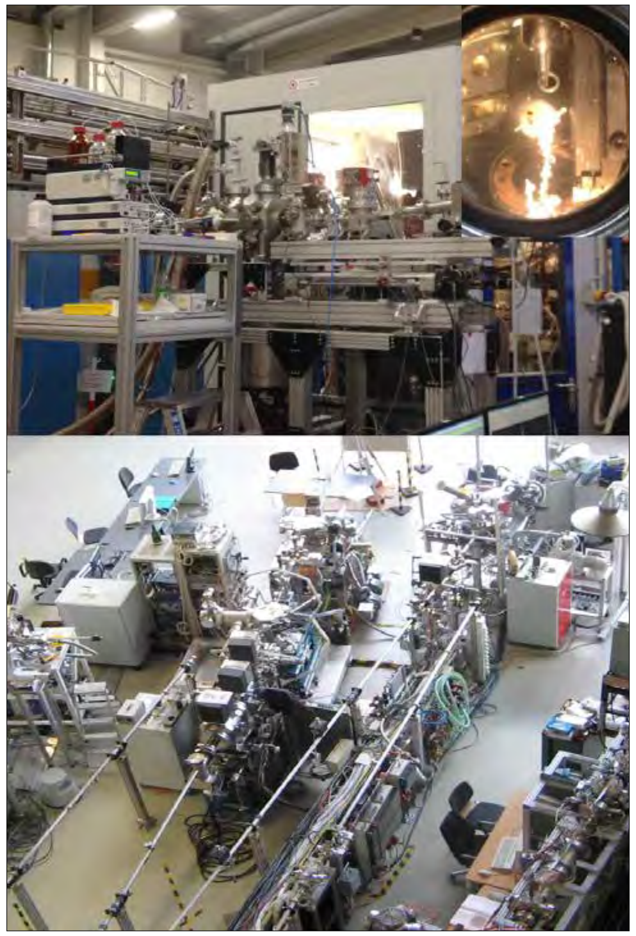


Fig. 1: One of our experimental laboratories is a photon endstation at the free electron laser FLASH / DESY. The endstation is used for developing methods for the study of complex chemical reactions important for energy research or the "molecular view" into the dynamics of bio physicochemical and biophysical processes.

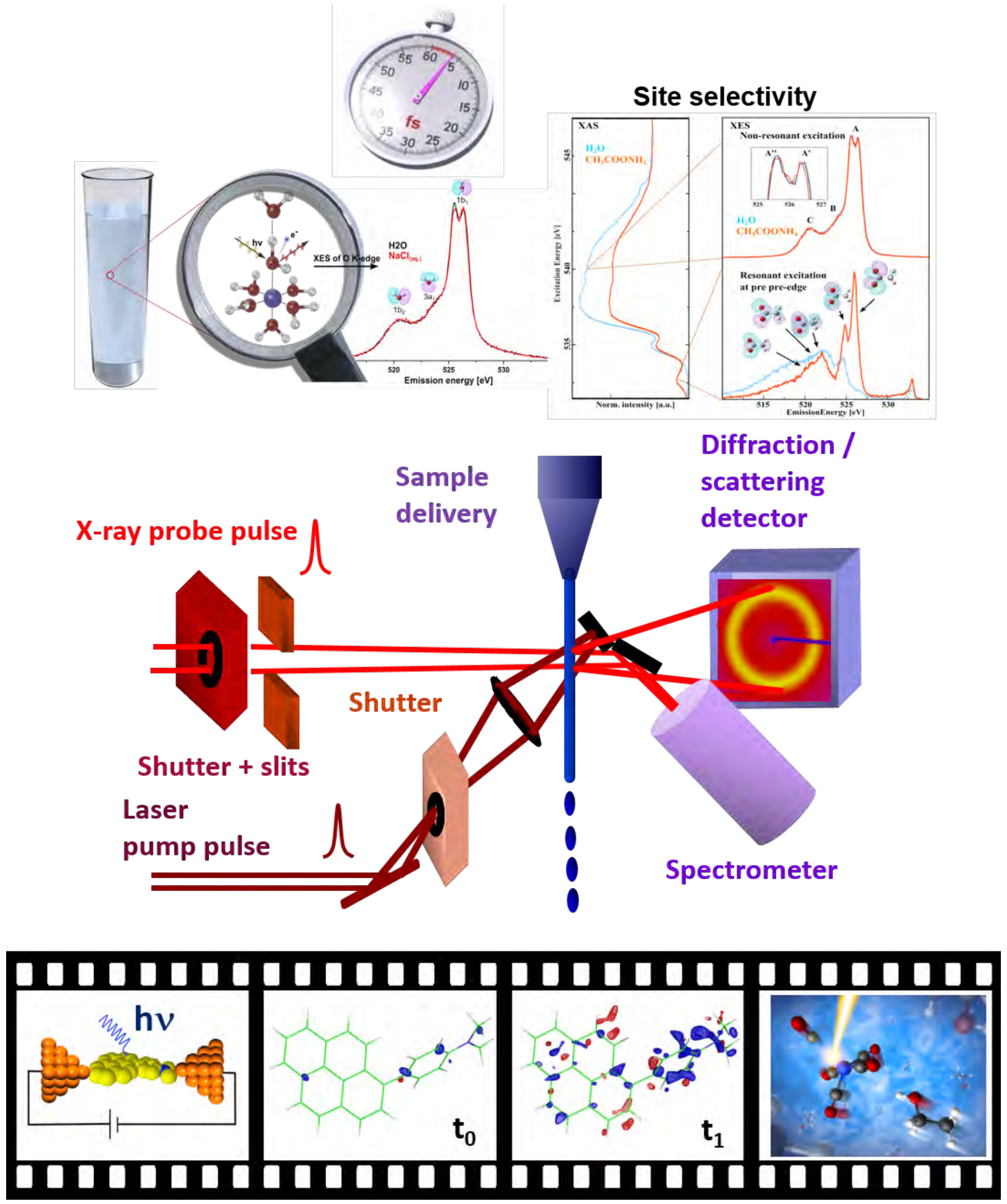


Fig. 2: The local to global approach. Middle as starting point: Time-resolved X-ray science, based on ultrafast multidimensional X-ray spectroscopy and high-resolution ultrafast X-ray diffraction: the optical laser pump initiates the reaction and the X-ray laser pulse probes the ultrafast proceeding chemical reaction by collecting the X-ray spectroscopic signal and / or the X-ray diffraction signal in common photon in / photon out type of approach. Top: In ultrafast X-ray spectroscopy, site-specific and element specific electron properties are probed (such as bonding or oxidation state changes) – it is called the local approach. Bottom: in ultrafast X-ray diffraction or scattering the structural changes of the whole bulk are probed – therefore the *global approach*.

The methods can be utilized for studying reactions and structural transformations in all thermodynamic phases (gaseous, liquid and solid). Proof of principle experiments include free electron laser radiation induced photo electron diffraction or Coulomb explosion schemes, free electron laser based ultrafast two dimensional X-ray spectroscopy, ultrafast X-ray emission spectroscopy, ultrafast X-ray scattering schemes and ultrafast X-ray diffraction (high resolution). The methods allow studying various types of transformations in matter, such as photo-induced phase transition, but also simple unimolecular dissociation reactions of small molecules or complex bimolecular or association reactions in proteins.

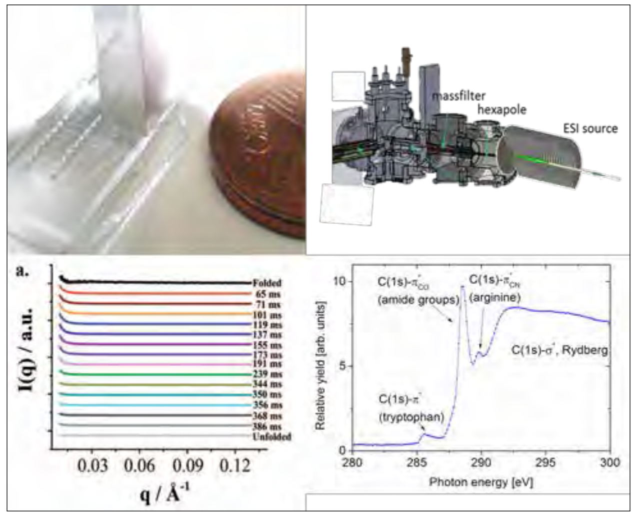


Fig. 3: Time-resolved X-ray experiments on macromolecules: developing methods for investigating "transient time stamps" and the structures and structure distributions of ultrashort living intermediates of proteins during their structural transformations. Besides optical stimuli, complementary tools such as rapid mixing devices utilizing the x-ray diffraction properties of synchrotron and free electron laser sources (left side) or coupled free electron laser, mass spectrometry and core hole clock spectroscopy (right side) have been developed to study the dynamics of proteins.

Application examples

One of the first evident applications of X-ray free electron laser based ultrafast photon-in / photon-out approaches points towards characterizing complex photophysical and photochemical energy redistribution processes in complex matter. The new procedures in structural dynamics have been applied for optimizing functional dynamics design of fully organic material based solar cells or organic light emitting diodes leading to optimized built-up strategies and high efficiencies of the energy storing and energy releasing devices.

In biophysics, the ultrafast photon-in/photon-out developments utilizing high flux pulsed X-ray radiation allow us to investigate and determine "transient time stamps" and the structures and structure distributions of ultrashort living intermediates of proteins during their structural transformations. These transformations are either a result of optical photo excitation or energy transforming steps after driving the system far out of the equilibrium. In order to study the dynamics of proteins without optical photon stimuli, complementary tools such as rapid mixing devices coupled to free electron lasers or mass spectrometry / coupled free electron lasers have been developed. With the latter experimentally high precision binding energies and ionization processes during ion and radical formation or hydrogen bonding processes can be determined and characterized.

[1] Techert, S.; Schotte, F.; Wulff, M.: Picosecond X-ray Diffraction Probed Transient Structural Changes in Organic Solids, Phys. Rev. Lett. 86 (2001) 2030

[2] Bari, S.; Boll, R.; Canton, S.E.; Glaser, L.; Idzik, K.; Kubicek, K.; Raiser, D.; Thekku Veedu, S.; Yin, Z.; Techert, S.: High flux X-ray sources and Free Electron Lasers for Studying Ultrafast Time Structure Imprints in Complex Chemical and Biochemical Reactions, in: X-ray Free Electron Lasers, eds. U. Bergmann, P. Pellegrini, Oxford University Press (2016)

[3] Boll, R; et al.: Imaging Molecular Structure through Femtosecond Photoelectron Diffraction on Spatially Aligned and Oriented Gas Phase Molecules, Faraday Discuss. 171 (2014) 1

[4] Wernet, P.; et al.: Orbital-specific Mapping of the Ligand Exchange Dynamics of Fe(CO)5 in Solution, Nature 520 (2015) 78

[5] Rajkovic, I.; et al.: Diffraction properties of periodic lattices under free electron laser radiation, Phys. Rev. Lett. 104 (2010) 125503

Simone Techert

Simone Techert performed her PhD in ultrafast optical spectroscopy at the Max Planck Institute for Biophysical Chemistry (Prof. Troe) and received her PhD at the Georg August University Göttingen in 1997. After her postdoc in ultrafast X-ray diffraction at the European Synchrotron Radiation Facility, Grenoble (Prof. Wulff), in 2000 she turned back to the MPIbpC with an Emmy Noether fellowship. In 2005 (habilitation Chemistry Department, Göttingen University), she was awarded with a Minerva professorship of the Max Planck Society. Since 2012 she holds, as the first female leading scientist, a Helmholtz research professor position between the German Synchrotron DESY, Hamburg and the Institute for X-ray Physics, Göttingen University. For covering the various development aspects of ultrafast x-ray science she still accesses the MPIbpC through a research group. For her pioneering contributions to the field of ultrafast x-ray science she received various prizes, among them the Roentgen Prize of the Justus Liebig University Gießen, or the Winnacker prize of the Aventis foundation.

Computational Soft Matter and Biophysics

Soft and biological matter involves a fascinating interplay between properties on vastly different time, length and energy scales. Understanding how the characteristics of individual molecules cooperatively dictate macroscopic structure and dynamics is a great challenge. It is important for applications, e.g., block copolymer lithography, and simultaneously involves fundamental problems, e.g., defect motion in soft nanostructures. Statistical physics provides a unifying framework to understand soft matter because properties often rely on universal physical principles, e.g., thermal fluctuations of interfaces, entropy, self-assembly, and the kinetics of collective structure formation is important. We aim at identifying the relevant characteristics and devise models that are both, simple and predictive, and study them by large-scale simulation and theory. We investigate fusion and fission of lipid membranes, study surface properties and transport across interfaces, and design processes to direct structure formation in copolymers.

Collective phenomena in lipid membranes and copolymers

Amphiphiles (e.g., lipids, alkyl-based surfactants, or copolymers) spontaneously form similar structures, like lamellar sheets or wormlike micelles, despite great differences in their chemical nature. The large degree of universality motivates top-down, coarse-grained models that only retain the relevant interactions but sacrifice atomistic details in order to allow for an analytic description or access large length and time scales in simulations. The self-assembly results from a competition between the free-energy cost of interfaces and the entropy loss of arranging molecules in space. The delicate balance gives rise to minuscule free-energy differences between multiple competing metastable states, e.g., localized structures like dislocations in stripe patterns or hydrophobic bridges (stalks) between lipid membranes. This feature is corroborated by the protracted annealing times needed to obtain well-ordered copolymer structures or the requirement of specialized proteins that provide the free energy to overcome barriers in fusion and fission of membranes. The complex, rugged free-energy landscape of amphiphiles has even been likened to that of glass-forming materials. The structure often does not reach the thermodynamically stable state of lowest free energy but, instead, becomes trapped in a metastable state. By exploring these metastable states and the minimum free-energy paths connecting them [1-4], one can reproducibly trap the system in desired non-equilibrium morphologies [2] (Fig. 1), accelerate equilibration in copolymers [3], or control changes of membrane topology involved in cellular transport processes [5].

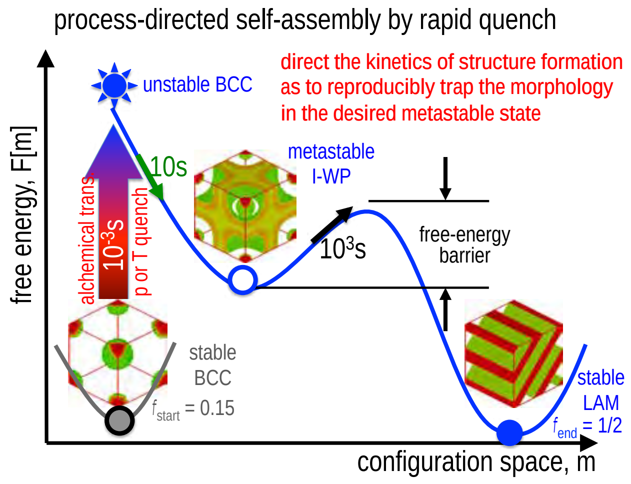


Fig 1: Process-directed self-assembly from a stable BCC-sphere morphology of an AB copolymer at an effective volume fraction f_{start} = 0.15 of A segments to f_{end} = 0.5. The spontaneous structure formation after this rapid quench becomes quickly trapped in a metastable I-WP network morphology instead of reaching the new equilibrium lamellar structure.

Process-directed self-assembly of copolymers on guiding patterns

Block copolymer lithography directs the self-assembly of copolymers by sparse, lithographically fabricated guiding patterns into dense nanostructures. Microelectronic applications require an extraordinarily low defect density of less than 1 defect per 100 cm². Our simulations and SCF calculations demonstrate that the free energy of defects exceeds 100 kT, making the probability that thermal fluctuations generate defects in equilibrium vanishingly small. Since defects are observed in experiments, they must arise during the self-assembly process. Our study explores the mechanisms of defect annihilation and identifies a process window for defect-free assembly because defect annihilation occurs spontaneously at weak segregation [3] (Fig. 2).

Dynamin-mediated membrane fission

The structuring of organisms into (sub)cellular compartments is maintained by lipid bilayers undergoing frequent but carefully regulated topological changes. During fission a membrane tube is divided into two separate bilayers. The intermediate stages involve highly bent membranes, and dynamin proteins provide the concomitant free energy. Dynamins form helical assemblies around the membrane tube, inducing curvature and causing constriction, elongation, and twisting. Our simulations show that constriction initially gives rise to flickering states (Fig. 3) and, eventually, formation of a worm-like micelle. Subsequent constriction of the dynamin scaffold alone, however, is insufficient to complete fission by rupturing this metastable hemifission intermediate, instead, disassembly of the dynamin scaffold and axial tension may facilitate the final severance of the hourglass-shaped bridge [5].

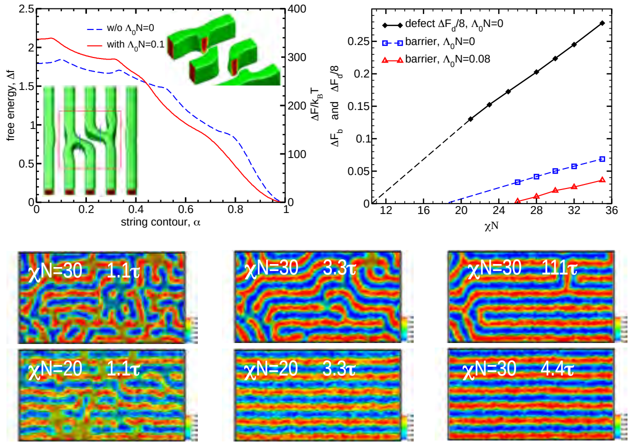


Fig. 2: *top left:* Minimum free-energy path from a metastable defect (lower left inset) in a symmetric copolymer to its equilibrium structure with and without guiding pattern, $\Lambda_o N$. The upper right inset presents the first saddle point. *top right:* Defect free energy (diamonds) and barrier of defect annihilation as a function of segregation, χN. *bottom:* Kinetics of self-assembly from the disordered state to large segregation, χN=30, does not result in defect-free assembly, whereas a shallow quench to χN=20 does because the defect-annihilation barrier vanishes around χN^*=26 (see top-right panel).

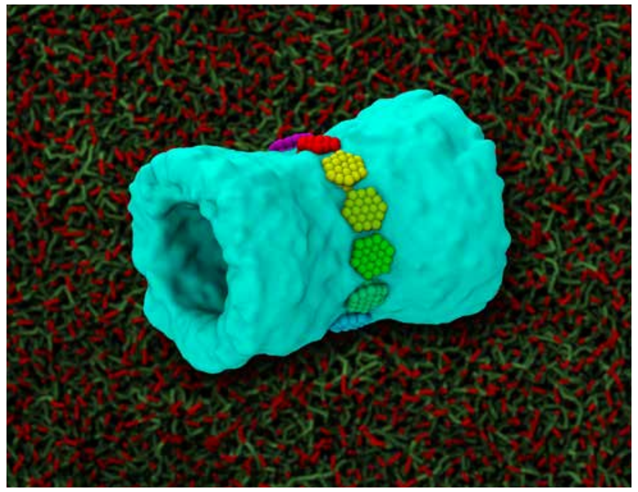
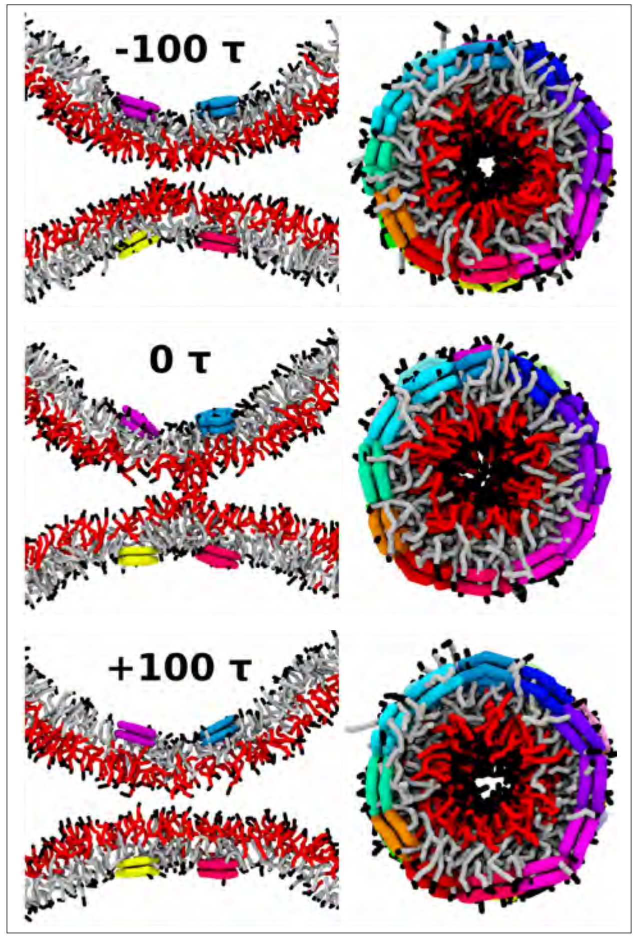


Fig. 3: *top:* Illustration of constriction of a membrane tube by a ring of amphiphlic disks representing the PH domains of dynamin. *right:* Flickering (temporary closing) of a membrane tube induced by the constriction of two dynamin rings.

Modeling and algorithmic developments

We employ MC and MD simulations, SCF theory and polymer-DFT to study highly, coarse-grained models of soft and biological matter. A major thrust of our research is to combine particle models with field-theoretic or continuum descriptions. What are the appropriate collective order parameters that describe structure transformation? How to encode the molecular dynamics of individual molecules into a collective description? Our research benefits from the development of efficient models (e.g., slip-spring model to mimic polymer entanglements) and computational techniques (e.g., field-theoretic umbrella sampling [1]) on high-performance supercomputers (GWDG, HLRN, NIC) and GPUs. This allows us to explore the free-energy landscape of collective phenomena and design processes – time protocols of thermodynamic control parameters (e.g., pressure) or localized stimuli imparted by functional molecules (proteins) – that reproducibly direct their kinetics. Such process-directed self-assembly enables access to a plethora of non-equilibrium, metastable structures [2-4].



[1] Müller, M.; Smirnova, Y.G.; Marelli, G.; Fuhrmans, M.; Shi, A.C. “Transition path from two apposed membranes to a stalk obtained by a combination of particle simulations and string method”, Phys. Rev. Lett. 108, 2012, 228103

[2] Müller, M.; Sun, D.W. “Directing the self-assembly of block copolymers into a metastable complex network phase via a deep and rapid quench”, Phys. Rev. Lett. 111, 2013, 267801

[3] Li, W.H.; Nealey, P.F.; de Pablo, J.J.; Müller, M. “Defect removal in the course of directed self-assembly is facilitated in the vicinity of the order- disorder transition”, Phys. Rev. Lett. 113, 2014, 168301

[4] Müller M.; Tang, J. “Alignment of copolymer morphology by uniaxial step elongation during spinodal self-assembly”, Phys. Rev. Lett. 115, 2015, 228301

[5] Mattila, J.P.; Shnyrova, A.V.; Sundborger, A.C.; Rodriguez Hortelano, E.; Fuhrmans, M.; Neumann, S.; Müller, M.; Hinshaw, J.E.; Schmid, S.L.; Frolov, V.A. “A hemi-fission intermediate links two mechanistically distinct stages of membrane fission” Nature 524, 2015, 109

Marcus Müller

Marcus Müller received his Ph.D. in 1995 from the University Mainz, working with K. Binder. After studying ring polymers with M. Cates at the EPCC Edinburgh, he went as Feodor Lynen fellow to the University of Washington, investigating amphiphilic self-assembly and, later, membrane fusion with M. Schick. He returned to Mainz and obtained his Habilitation in 1999. Before joining the ITP, 2005, he was an associate professor at the University of Wisconsin-Madison, and a DFG Heisenberg fellow. He worked at the IFF Jülich, and INIFTA and CNEA, Argentina. In 2004 the APS awarded him the Dillon Medal and he received a Lichtenberg professorship from the VW foundation. Since 2008, he is full professor at ITP. In 2015 he was elected APS fellow, and currently is vice-chairman of the scientific council of the von-Neumann Institute for Computing and associate editor of ACS Macro Letters.

Complex Fluids

Complex fluids and soft matter are materials intermediate between conventional liquids and solids, displaying fluid-like as well as solid-like behavior. Examples are polymeric melts or solutions, glasses, gels, foams and granular matter. Many of these systems are inherently disordered and strongly heterogeneous with large fluctuations on a wide range of length- and time-scales. Furthermore many complex fluids, such as glasses or gels, never relax to equilibrium, which makes a theoretical analysis difficult. In our group we aim to understand the cooperative behavior of complex fluids and soft matter on the basis of the underlying constituents and their mutual interactions. For example we want to know: What structures can be formed in and out of equilibrium? What are the underlying principles of self-organization and what are other emergent phenomena as observed in complex fluids?

Biopolymer networks

Many important biopolymers, such as DNA, the cytoskeletal filaments as well as collagen in the extra cellular matrix are fluctuating macromolecules with a bending stiffness intermediate between that of a flexible random coil and a rigid rod. A variety of linker proteins is known, which bind two filaments together, thereby generating complex structures, such as bundles, fibrils and networks. One of the most important characteristics of these binding proteins is their lifetime, which sets the timescale for the crossover from elastic to viscous behavior of the cross-linked network. Two limiting cases are of particular interest: so called reversible cross-links which open and close a bond on the timescales of the polymers motion and irreversible crosslinks, which persist indefinitely once they have formed. Whereas the irreversible cross-links are responsible for the stability and persistence of shape of the structures, the reversible ones allow for a reconstruction of the network, which is e.g. required for a cell to move.

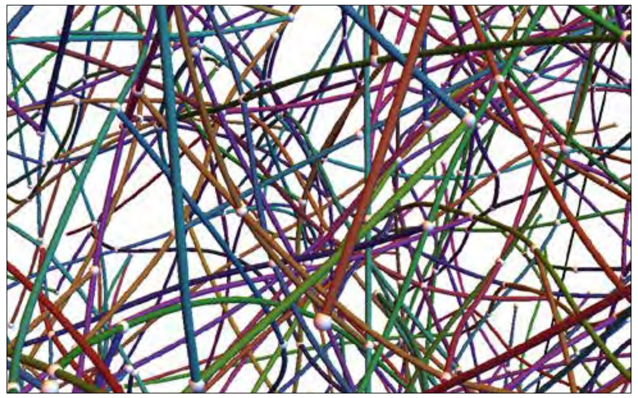


Fig. 1: Snapshot of a network of cross-linked semiflexible filaments.

We are studying the elasticity of biopolymer networks with help of simulations [1] and analytical theory [2]. The biopolymers are modeled as semi-flexible chains which are characterized by a highly nonlinear force-extension relation and are cross-linked irreversibly. We perform simulations of large networks (an example is shown in Fig. 1) under different loading conditions and determine the linear and nonlinear response of the network. The elastic modulus, G, displays an intermediate super-stiffening regime as can be observed in Fig. 2. Here the modulus increases much stronger with applied stress σ than predicted by the force-extension

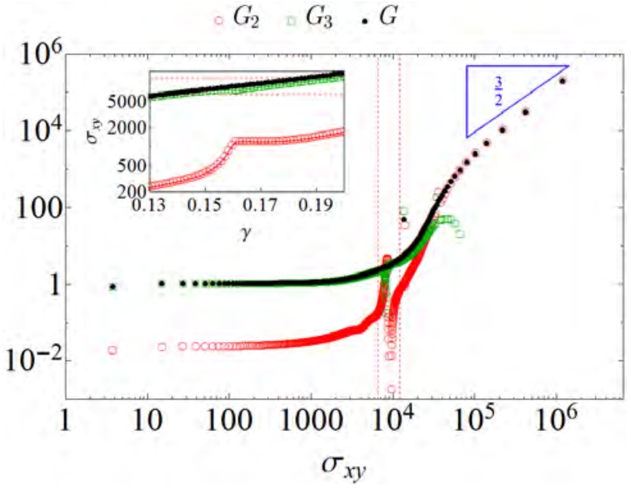


Fig. 1: Elastic modulus G as a function of applied shear tress; G is constant in the linear regime (small σ) and increases like $\sigma^{3/2}$ for large stresses; in between super-stiffening is observed; also shown are the contributions from particle (G_2) and 3 particle interactions (G_3) with G_3 dominating for small σ and (G_2) dominating for large σ.

relation of a single wormlike chain ($G_{wlc} \sim \sigma^{3/2}$). We interpret this super-stiffening regime in terms of the reorientation of filaments with the maximum tensile direction of the deformation field. A simple model for the reorientation response gives an exponential stiffening, $G \sim e^{\sigma}$, in qualitative agreement with our data. We are currently generalizing the model to include active elements, i.e. motors, and study their effects on the elastic properties of the network.

Other projects tackled with analytical theory are the bundling transition of reversibly crosslinked, grafted polymers [3], i.e. brushes, the phase diagram of cross-linked block-copolymers [4] and the tension induced binding of reversibly cross-linked filaments [5].

Granular fluids

Granular media are an important and popular subject of current research which is owed partly to the striking phenomena which they reveal and partly to their ubiquity in nature and industry which makes a good understanding of their properties indispensable. Examples are sand, snow, gravel, and seeds to mention but a few. In fact the majority of industrial products are processed and handled in the form of granular media, such as powders. The materials are composed of macroscopic particles, which are big enough to render thermal agitation negligible. The interactions are in general dissipative, so that granular systems continuously loose energy unless they are externally driven to a stationary state.

Non-equilibrium glass transition

The glass transition has been studied extensively in thermal fluids and colloids – systems which are in equilibrium at high temperature or low density and fall out of equilibrium when the viscosity increases dramatically at the glass transition. We are interested in fluids which are inherently out of equilibrium, but nevertheless undergo a glass transition [6]. The prototype example is a granular fluid which is driven into a stationary state. As the dynamical arrest is approached, not only does the dynamics become dramatically slower, but it becomes increasingly heterogeneous. Large scale simulations of 2d driven granular fluids allow to determine spatial correlations via the four-point structure factor $S_4(q,t)$. The latter is shown to obey scaling, which is remarkably universal with respect to the strength of dissipation. Both the dynamic susceptibility, X_4, and the correlation length, ξ, increase dramatically as a function of density and can be fitted to power law divergencies, see Fig. 3.

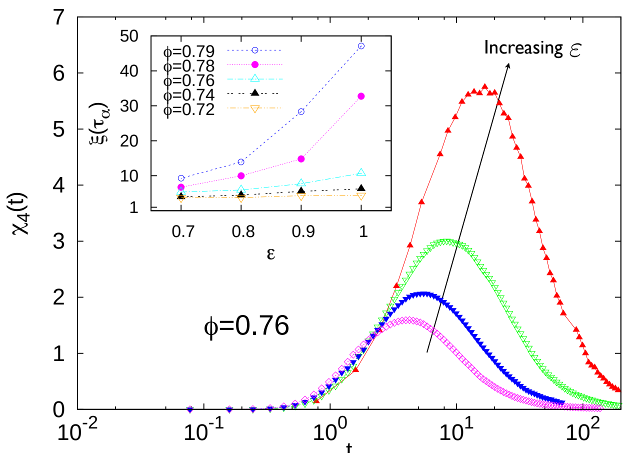


Fig. 3: Four point susceptibility X_4 *(t)* for various packing fractions φ, revealing a strong increase as the glass transition is approached; inset: correlation length ξ as a function of the coefficient of restitution for several values of φ.

Mode-coupling theory is an analytical approach to the glass transition which can be generalized to non-equilibrium systems [7]. A phase diagram, shown in Fig. 4, can be derived in the plane of packing fraction, φ, and driving strength, ξ_0^2. The glass transition in granular fluids is qualitatively similar to thermal fluids with, however, non-universal exponents.

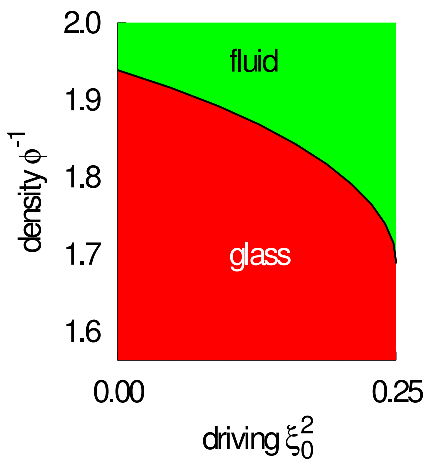


Fig. 4: Phase diagram of a driven granular fluid displaying a glassy phase; the origin of the graph lies at random-close packing.

Rheology

Whereas jamming of frictionless particles has attracted a lot of interest and is reasonably well understood, the effects of friction are less clear, even though almost all experimental realizations of granular fluids involve frictional forces between the grains. The phase diagram of frictional grains, see Fig. 5, is substantially different from the frictionless case. It resembles an equilibrium first order phase transition [8] with a nonzero yield stress at jamming and reentrance as a function of applied stress σ. Small systems (N ≤ 20.000 in 2d) show discontinuous shear thickening and hysteresis as a function of the applied strain rate, see Fig 6. For large systems on the other hand, there is a region in phase space where neither stationary flow nor a jammed state is observed. Instead the system displays rheological chaos with time-dependent heterogeneous flow. We are currently trying to understand microscopic mechanisms of shear thickening and frictional granular matter. These projects are done in collaboration with Dr. Claus Heussinger, who is leading a junior research group funded by the Emmy-Noether program of the DFG.

[1] H. E. Amuasi, C. Heussinger, R. Vink, and A. Zippelius: Nonlinear and heterogeneous elasticity of multiply cross-linked networks, New J. Phys. 17, 083035 (2015).

[2] P. Benetatos and A. Zippelius: Anisotropic random networks of semiflexible polymers, Phys. Rev. Lett 99, 198301 (2007).

[3] P. Benetatos, E. M. Terentjev, and A. Zippelius: Bundling in brushes of directed and semiflexible polymers, Phys. Rev. E 88, 042601 (2013).

[4] A. von der Heydt and A. Zippelius: Phase diagram of selectively cross-linked block copolymers show chemically microstructured gel, J. Chem. Phys. 142, 054901 (2015).

[5] P. Benetatos, A. von der Heydt, and A. Zippelius: Tension-induced binding of semiflexible biopolymers, New. J. Phys. 16, 113037 (2014).

[6] K. E. Avila, H. E. Castillo, K. Vollmayr-Lee, and A. Zippelius: Strong dynamical heterogeneity and universal scaling in driven granular fluids, Phys. Rev. Lett. 113, 025701 (2014).

[7] T. Kranz, M. Sperl, and A. Zippelius: Glass transition for driven granular fluids, Phys. Rev. Lett. 104, 225701 (2010).

[8] M. Grob, C. Heussinger, and A. Zippelius: Jamming of frictional particles: A nonequilibrium first order phase transition, Phys. Rev. E 89, 050201 (2014).

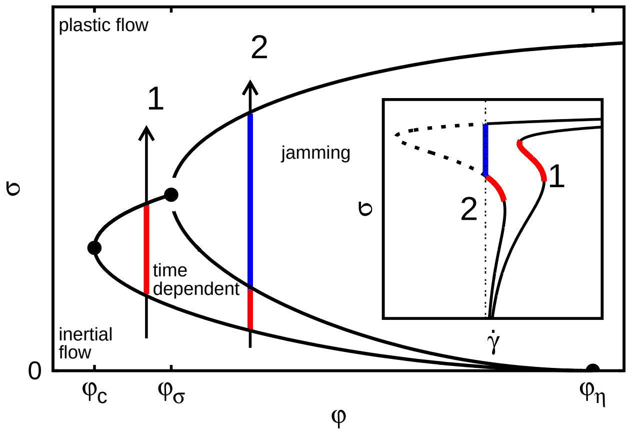


Fig. 5: Phase diagram of frictional granular matter as a function of packing fraction ***φ*** and shear stress ***σ***.

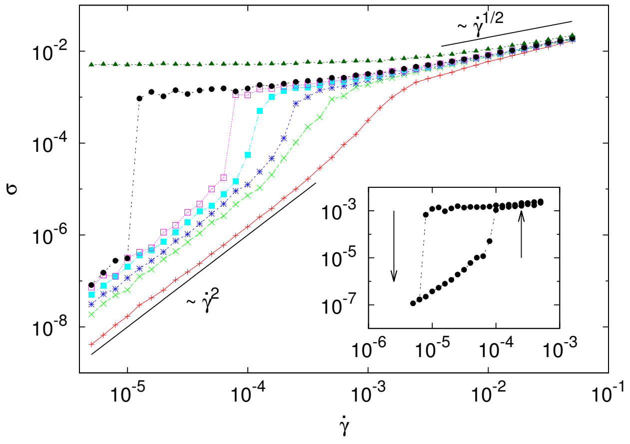


Fig. 6: Flow curves ***σ***$(\dot{\gamma})$ for different packing fractions ***φ***=0.78, 0.7925, 0.795, 0.7975, 0.79875, 0.80, 0.82 (from bottom to top). Main part: Flow curves obtained by decreasing $\dot{\gamma}$. Inset: Example of a hysteresis loop for ***φ***=0.80.

Annette Zippelius

Annette Zippelius studied physics at the Technical University of Munich and the University of Colorado in Boulder, USA, where she received a Masters degree. After finishing her PhD in Munich in 1977, she spent two years as a postdoc in Harvard and a third year in Cornell. Back in Munich she got her habilitation in 1982, joined the staff at the Forschungszentrum in Jülich in 1983 and became a full professor in Göttingen in 1988. Since 1993 she is a member of the Akademie der Wissenschaften in Göttingen. She was awarded the Gottfried-Wilhelm-Leibniz prize in 1998 and was a member of the Wissenschaftsrat from 2005 to 2011. She was elected fellow of the American Physical Society in 2008 and she was a Max Planck fellow at the MPI for Dynamics and Self-Organization from 2007 to 2014.

Pattern Formation in Complex Systems

Complex systems are composed of a large number of much simpler parts, which interact via simple, mechanical forces. They are called complex if they display properties which cannot be derived from studies of their isolated simple parts. Understanding the general mechanisms, which lead to such cooperative properties, is one of the deep and fundamental questions of contemporary physics. Two outstanding challenges in this field are the characteristic properties of living biological cells and the higher cognitive properties of the human brain. Can we understand these properties from interacting molecules, and electrophysiologically interacting neurons, respectively? We approach these questions by studying much simpler model systems, like non-equilibrium transitions to ordered phases, the glass transition and pattern formation in active systems, all of them inspired from biology, technology and other fields inside and outside of physics. These problems need several levels of description from microscopic dynamics to non-linear, stochastic continuum theories and use both analytical and simulation techniques.

Patterns in network models

Networks form a universal paradigm for modeling complex real world systems. This is illustrated by two examples, from completely different contexts: models of networks of neurons, interconnected via axons, which transport electrophysiological signals from one neuron to the synaptic contacts of other neurons are schematically shown in Fig. 1. Glasses are physical systems with an extremely complicated energy landscape, and the glassy dynamics is largely determined by the network of minima and saddle-points of this landscape in the high dimensional configuration space. This network can be explored by molecular dynamics computer simulations. Although the networks are very different, they share common features and it is interesting to study the relevance of these features in the vastly differing contexts. In this way, properties of natural neural networks – like efficient learning by examples – can be shown to be less mysterious than it appears at first sight.

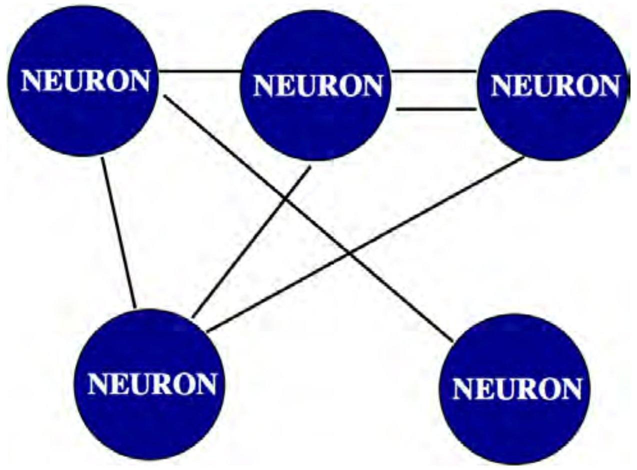


Fig. 1: A schematic network of interconnected neurons. The state of each neuron is updated, depending upon the input of electro-physiological signals it receives from other neurons or from sensory cells.

Nano-patterns at driven surfaces

Nearly everybody has admired ripples in the sand at the beach or underwater. How do these regular structures appear – seemingly out of nothing – on the surface of sand driven by wind or water? They are good examples of pattern formation at driven surfaces, but we are more interested in the analogous patterns on a completely different scale, the nanometer scale. Reproducible, self-organized nano-patterns at solid surfaces would render more expensive and complicated fabrication processes for nanotechnologies unnecessary. Besides, it is an amusing intellectual challenge to find out, whether gigantic desert sand dunes, little ripples on the beach and 1 000 000 000 times smaller ripples on solid surfaces driven, for example, by ion beams or by added material from vapor are created by the same laws of physical pattern formation. Understanding the physical laws helps to diversify the patterns, which may form via self-organization and at the same time improve their quality. If the surfaces are driven by ions impinging with energies around 1000 eV (electron Volt), theoretical analysis has to bridge all physical processes from 1000 eV down to fractions of an eV, the typical room temperature scale governing diffusional motion of atoms at a surface. This is achieved by two approaches: either using coarse-grained continuum descriptions or setting up Monte Carlo models and running computer simulations.

Active matter

Modern molecular biology has provided a gigantic list of molecular parts of a biological cell and complicated circuit diagrams of chemical reactions between these parts. But still, this approach misses essential aspects of life, which unfolds in time and space, creating most beautiful and useful structures for its purposes on the basis of physical mechanisms. Such unusual forms of ordered matter provide new challenges for the statistical physics of condensed matter, which traditionally dealt with atoms and molecules in perpetual thermal motion. An important new paradigm is active matter, which consists of elementary parts with intrinsic energy sources, which can perform work on the external environment. We want to understand the basic physics, which underlies the internal machinery of such systems, which appear as biological cells, as whole organisms, but also as non-living model systems. Self-propulsion is one of the astonishing capabilities of even the smallest living organisms. We are interested in understanding this capability from a physicist's point of view, using hydrodynamics at small scales (i.e. small Reynolds number) and statistical physics (see Fig.4). An important and universal piece of the molecular machinery inside biological cells is polymerization. The processes of building polymers and degrading polymers are very dynamic in biological systems. During the time of polymerization, the structure of the polymer in space may change considerably. This leads to new phenomena as depicted in Fig.5, which shows that under conditions of ongoing polymerization, the properties of a flexible polymer may change qualitatively at sharp transitions.

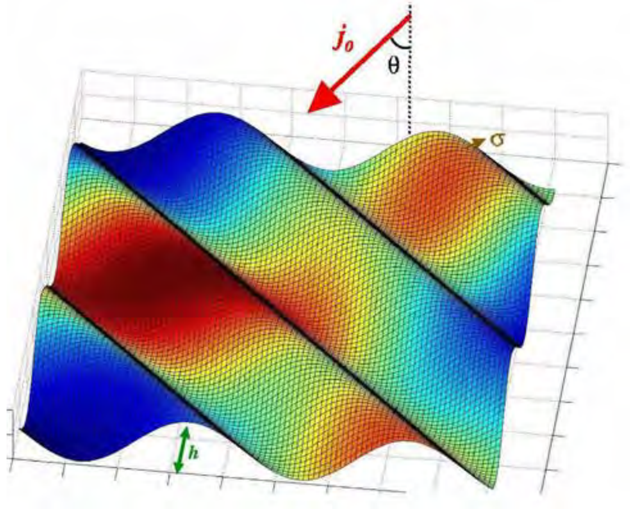


Fig 2: Continuum picture of a driven surface. The arrow indicates the direction of the driving force, the colors indicate the state of the atoms (or grains) at the surface: red: high mobility, blue: low mobility. Differences in mobility arise from extra energy, transported to the surface by the driving force.

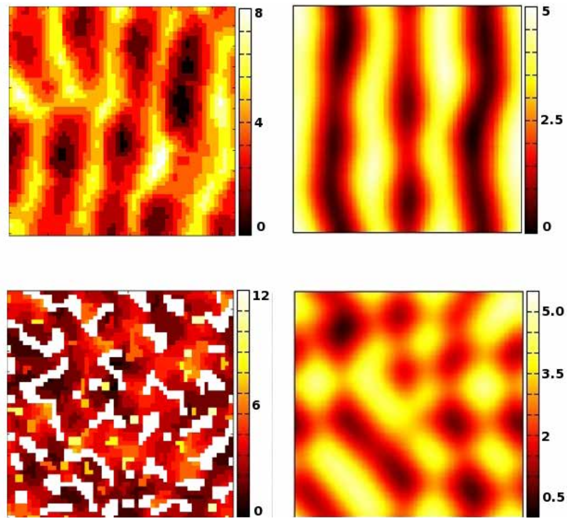


Fig 3: Results of Monte Carlo simulations (left column) and continuum theory (right column) for pattern formation on a surface irradiated by ions, while at the same time, atoms of a different material are added by co-sputtering a nearby target. Nano-ripples and ordered nano-dots may appear.

Fig 4: From left to right: directions of active polar molecules within a droplet filled with a viscous liquid are shown in a cross section (left); they create a force field (middle), which sets the liquid into motion. The active surface velocity (right) leads to self-propelled motion of the droplet, if it immersed in water.

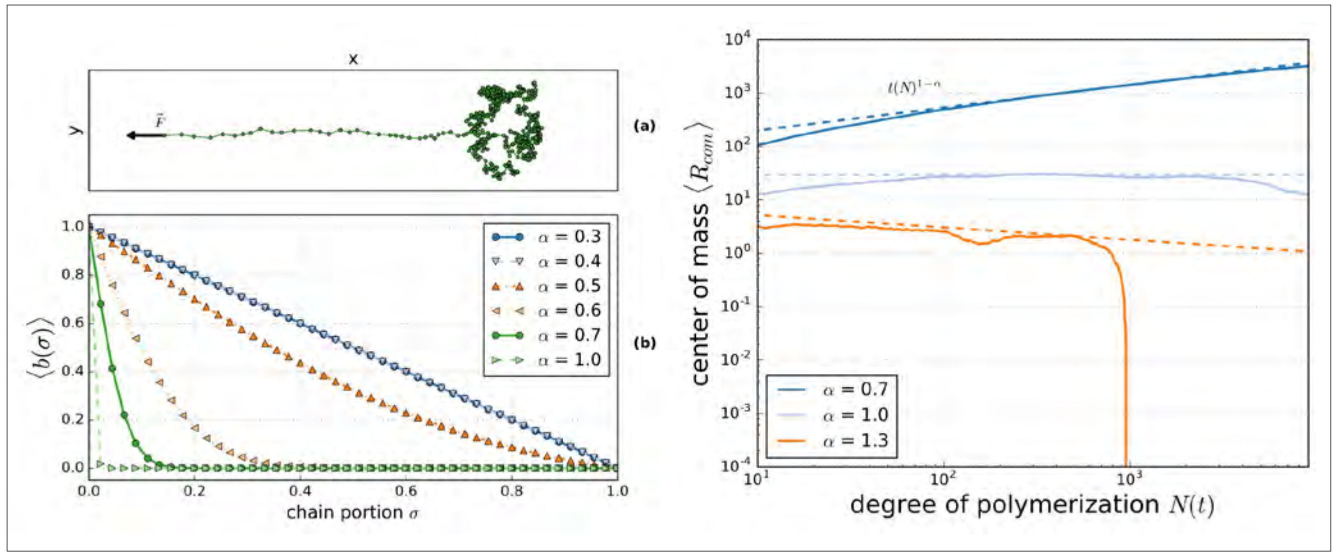


Fig 5: The shape of a flexible polymer chain growing at one end and being dragged at the other end develops into a „stem flower" (upper left) even if the growth rate is steadily decreasing. The line tension may pile up at the dragged end, if the decay of growth rate is slow enough (lower left). If the growth rate does not decay but is increasing, the motion of the chain as a whole quite suddenly stops (right panel).

[1] Ban, D., Funk.M, ..., Kree, R et.al.: „Kinetics of conformational sampling in Ubiquitin", Angew. Chemie Int. Ed., 50, 11437 (2012)

[2] Lenius, M., Kree, R. Volkert, C.: „Influence of crystal orientation on pattern formation of focused-ion-beam milled Cu surfaces", Phys. Re. B84, 035451 (2011) [1] Hartmann, A.K., Kree, R., Yasseri, T., : „Simulating discrete models of pattern formation by ion beam sputtering", J.Phys. Mond.Mat. 224015, (2009)

[2] Yewande E. O., Hartmann A. K., Kree R.: „Morphological regions and oblique-incidence dot formation in a model of surface sputtering ", Physical Review B 73, 115434 (2006)

[3] S.C. Kramer, R. Kree, „Pattern formation of on channels with state-dependent charges and diffusion constants", Phys. Rev. E 65, 051920 (2002)

[4] K. Bhattacharya, K. Broderix, R. Kree, A. Zippelius, „Energy Landscape and overlap distribution of binary Lennard-Jones glasses", Europhys. Lett. 47, 449 (1999)

[5] D. Drasdo, R. Kree and J.S. McCaskill: „A Monte-Carlo Approach to Tissue Cell Populations", Phys. Rev E 52, 6635 (1995)

[6] R. Kree: „Neural Networks: Architectures, Learning and Performance" in Information Systems and Data Analysis, Springer-Verlag (1993)

Reiner Kree

was born 1954 in Hamm in Westphalia. He studied physics at the universities of Dortmund, Cambridge (UK) and Karlsruhe, where he received his PhD in 1984 for work on disordered electronic systems. After a stay at Cornell University, he joined the theoretical physics group of Prof. Richard Bausch at the University of Düsseldorf, where he worked on a variety of topics in disordered systems, using methods from field theory applied to statistical physics. In 1990, he became a professor at the Institute for theoretical physics at the Georgia-Augusta. His main research interest has been and still is the understanding of complex physical systems, like neural networks, glasses and spin-glasses, biological and biologically inspired matter. From 1999 to 2002 he was dean of the faculty of physics and from 2002-2006 he was vice-president of the Georgia-Augusta.

Fluid Dynamics and Biocomplexity

Dynamics and self-organization occurs in many-body systems that are out of energetic equilibrium. If we want to understand the world around us, we must rely on simplifying descriptions that capture the fundamental physical principles. Thus we need to identify complex systems that include all necessary parameters, boundary conditions and initial conditions. These together with a rigorous mathematical description, must allow for a quantitative understanding. The understanding and controlling of complex systems poses a major challenge both to physics and mathematics, since the equations are usually coupled, nonlinear, and nonlocal. Nonetheless, though very different in detail, the fundamentals of complex systems can be described by unifying concepts. Our aim is the search for and the understanding of those concepts in the physics of fluid- and biomechanics. In our approach we rely on methods from non-equilibrium statistical mechanics and nonlinear systems theory.

Synthetic and Quantiative Biology

We are interested in how self-organization in biological systems leads to function. In particular we investigate topics in "physics and medicine", "synthetic biology", "collective biological dynamics", and "cellular mechanics".

Physics and Medicine

We study fluid flow, its self-organization, and its function inside living mammals. We are investigating in experiments and numerical simulation cilia driven flow of cerebrospinal fluid in the 3rd ventricle of the mammalian brain. Our work in collabration with the MPIbpC reveals the generation of a complex spatio-temporally regulated transport systems (see Figure 1). In another project we are investigating with numerical experiments the flow in the human heart for a patient specific contraction profile. The ultimate goal is to give the surgeon suggestions of where to implant in vitro grown muscle on the heart.

Synthetic Biology

Fluid flow based transport of cargo is a ubiquitous and essential process in life. The most common transport motif in nature involves flows driven by local pressure gradients. This flow is in stark contrast to the technological flows that rely on large-scale pressure gradients. In spite of its fundamental importance in nature and ultimately in technology, synthetic biology approaches using self-organizing principles to create locally driven fluid transport have received little attention. We investigate this very important problem with a two-pronged approach. Frist, we generate synthetic cilia from basic building blocks derived from biomolecules. Second, in parallel and in complement, we are isolating individual cilia/flagella from living organisms, which we use to build man-made transport systems.

Collective Biological Dynamics

One of the prime examples of pattern formation in living systems is a starved population of Dictyostelium discoideum (D. d). In this reaction-diffusion systems spirals and targets can be observed. While it is easy to observe patterns in these systems, inferring their dynamics is more complex. In D. d, not only is it unclear whether the dynamics is oscillatory or excitable, but it also changes with time due to the varying expression levels of enzymes. A systematic approach to recover the model parameters from the experimental data is needed. In collaboration with the Mathematics Department we produce quantitative data that we assimilate into models for pattern formation in D. d. In a further project we show that reaction diffusion-advection has important consequences for biological systems that use solutes as signaling agents.

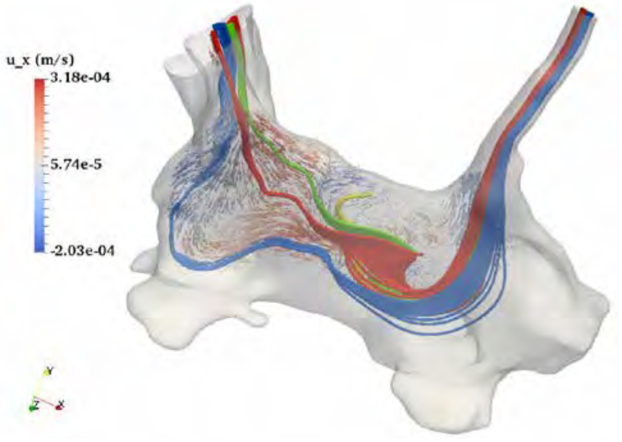


Fig. 1: Cilia driven velocity fields in the ventral third brain ventricle of a mouse.

Fig. 2: Göttingen Turbulence Facility. The red tunnel is 18m long and 6m high. The blue "submarine" has a 2.5 m diameter and is 5 m long, the turret is 4m high. The vessels can be filled up to 20 bar with SF6 gas.

Cellular Mechanics

To understand biomechanical processes we focus on the model organism D.d. and cardiomyocyte-fibroblast co-cultures. With microfluidics, advanced light microscopy, electrical impedance spectroscopy, AFM and theoretical modeling, we investigate the dynamics and mechanics including adhesion. For D.d. we investigate actin-driven membrane protrusions that are a key component underlying the locomotion of eukaryotic cells.

Fundamental Properties of Turbulent Flows and Particle Transport

In turbulent flows, mixing and transport are dominated by the huge fluctuations ranging from the scale where energy is injected to the scale where energy is dissipated by viscosity. Turbulence plays a central role, for example, in the reduction of emissions in aeronautics, in the efficient energy production, for the understanding of climate change, and in astrophysical galaxy formation. Considering its importance, our understanding of the physics of turbulence remains rudimentary. We focus our investiagtions on "thermal convection", "homogenous turbulence" and "multiphase flows".

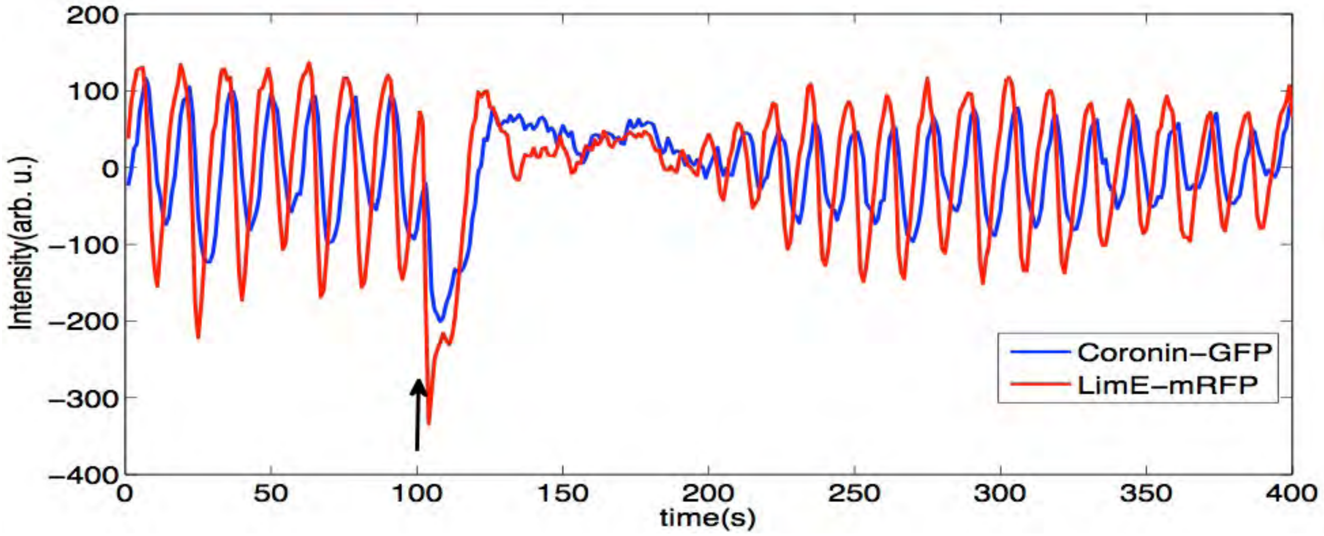
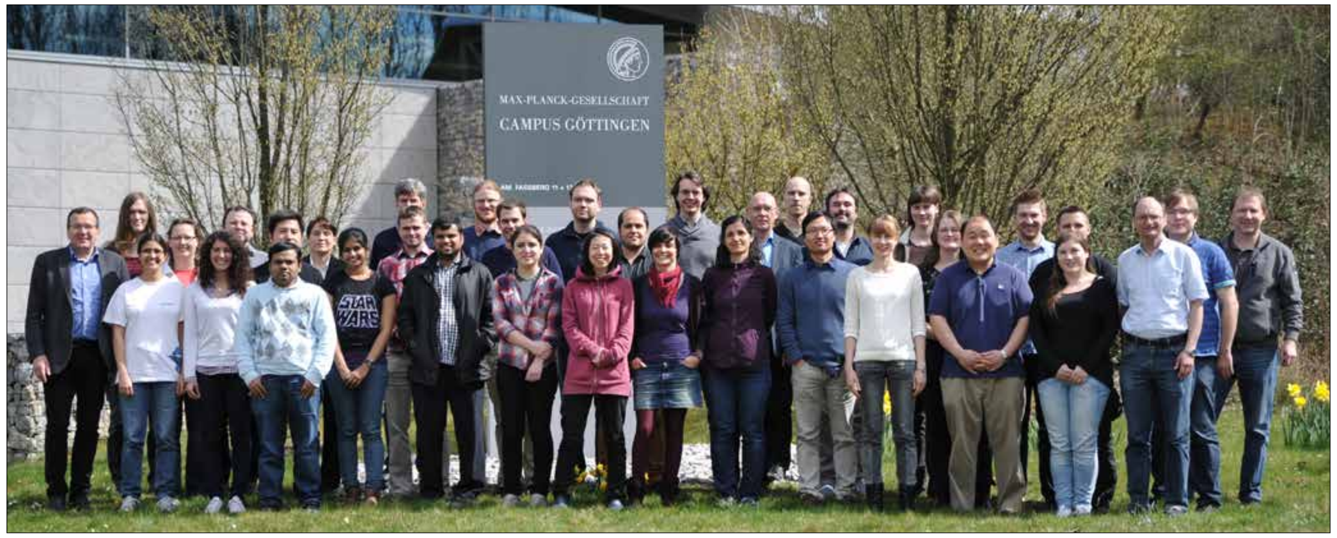


Fig. 3: Oscillatory D.d. cell responding to a chemicalk stimululs.



Turbulent Thermal Convection

Rayleigh-Bénard convection (RBC), where a fluid is confined by a warm plate from below and a cold one from above, serves as a paradim for buoyancy-driven convection which occurs for instance in astrophysical and geophysical systems as well as in industrial processes. Within the unique high-pressure facility (Figure 3) we reach very large turbulence levels and make detailed measurements of heat transport and other flow properties. Recently we added a rotating table capable of carrying a load of 3000 kg and rotating at up to 3 rad/s. We are especially interested in the turbulent geostrophic regime where local Coriolis forces are balanced by local pressure gradients. This regime is very important for the understanding of planetary and astrophysical flows.

Homogeneus Turbulence

High Reynolds-numbers at manageable temporal and spatial scales can be realized with compressed and heavy gases. Thus, we have installed unique facilities that use pressurized SF6 gas at up to 20 bar. We have built a wind tunnel with an extra long measurements section, allowing particle tracking of decaying turbulence. We are developing and applying advanced measurement technology for our studies. This inlcudes ultra-high-speed particle tracking systems that follow thousands of micron size particles in 3D and nano-machined sensors.

Multiphase Flows

Convection and turbulence play an essential role in cloud-micro-physical processes. They drive entrainment and mixing of temperature, moisture, aerosols, and droplets. They also impact droplet coalescence and collisions. Rain initiation in clouds and the associated dynamics of cloud droplets remains one of the open questions of meteorology. The lack in understanding of cloud-micro-physics leads to the largest uncertainty in climate predictions. We are investiagting on the Schneeferner Haus on mount Zugspitze this topic (see movie "Poetry of the Clouds" on youtube).

[1] Pumir, A., Xu, H., Bodenschatz, E. and Grauer, R., "Single-Particle Motion and Vortex Stretching in Three-Dimensional Turbulent Flows", Phys. Rev. Lett., 2016, 116, 124502

[2] Bodenschatz, E., "Clouds resolved", Science, 2015, 350, 40

[3] Risius, S., Xu, H., Di Lorenzo, F., Xi, H., Siebert, H., Shaw, R. A. and Bodenschatz, E., "Schneefernerhaus as a mountain research station for clouds and turbulence", Atmos. Meas. Tech., 2015, 3209

[4] Gholami, A., Steinbock, O., Zykov, V. S. and Bodenschatz, E., "Flow-Driven Waves and Phase-Locked Self-Organization in Quasi-One-Dimensional Colonies of Dictyostelium discoideum", Phys. Rev. Lett., 2015, 114, 018103

[5] Sinhuber, M., Bodenschatz, E. and Bewley, G. P., "Decay of Turbulence at High Reynolds Numbers", Phys. Rev. Lett., 2015, 114, 034501

[6] He, X., van Gils, D., Bodenschatz, E. and Ahlers, G., "Logarithmic Spatial Variations and Universal f^{-1} Power Spectra of Temperature Fluctuations in Turbulent Rayleigh-Bénard Convection", Phys. Rev. Lett., 2014, 112, 174501

Eberhard Bodenschatz

After graduating in theoretical physics from University of Bayreuth in 1989, he went to UCSB with a DFG research fellowship. From 1992 to 2005 he was Professor of experimental Physics at Cornell University. In 2003, he became Director of the MPIDS, in 2005 Adjunct Professor of Physics and of Mechanical and Aerospace Engineering at Cornell University, and in 2007 Full Professor of Physics at the University of Göttingen. He is an Alfred P. Sloan Research Fellow (1993), a Cottrell Scholar (1995), and a Fellow of the APS (2003). He is the recipient of the Corrsin Award of the APS and is a member of the Göttingen Akademie der Wissenschaften. He holds a honaray doctorate from the ENS Lyon. For 11 years he served as Editor in Chief of *New Journal of Physics*. He is on the Editorial Board of *Annual Review of Condensed Matter Physics* and associate editor of *Physical Review Fluids*. He is on the advisory board of arXiv and is the Chair of Chemistry, Physics and Technology Section of the Max Planck Society.

Nonlinear Dynamics, Chaos, and Theoretical Brain Research

Complex systems typically exhibit nonlinearities in their equations of motion; the field of nonlinear dynamics offers the mathematical basis for their investigation, e.g., for one of the most complex systems we know, the network of interacting nerve cells in our brains. Here, one of our goals is to understand their collective dynamics, which forms the essence of brain function. As ground-breaking experimental progress, e.g. based on multiphoton imaging, now promises the observation of large brain networks at work in cognitive tasks, it is a challenging and promising endeavor for theoreticians to model this nonlinear many-body system in order to unravel brain function. More generally, our research led by Theo Geisel, Ragnar Fleischmann, and Viola Priesemann focuses on modelling a broad range of nonlinear dynamical systems in physics and biology, from theoretical brain research to chaotic transport in nanostructures and wave propagation in complex media.

Quantum dynamics and wave propagation in complex media

The interplay of nonlinear dynamics and wave propagation is a rich area of complex phenomena. Reaching back to the very beginnings of nonlinear science and computational physics in the celebrated Fermi-Pasta-Ulam computer experiment on the statistical physics of heat transport, this area of physics became prominent in the field of quantum chaos. Its implications are now subject of research in many fundamental and applied sciences, from atom-optics to oceanography.

The phenomena we address in our own research reach from the chaotic motion of ballistic electrons in graphene, to the dynamics of Bose-Einstein condensates in optical lattices and to the occurrence of extreme events in wave propagation through complex media.

Complex media due to their internal structure can often be described as random fields with spatial correlations. When waves are weakly scattered by such a medium, the weak but correlated random forces conspire with nonlinear dynamics and diffraction to cause waves of extreme height or intensity in characteristic branch-like spatial structures [2]. This phenomenon can cause unexpected conductance features in semiconductors as well as giant “rogue waves” at sea. And even tiny fluctuations in the height-profile of the ocean floor can scatter tsunami waves and focus their energy by an order of magnitude (see Fig.1), with severe consequences for tsunami predictability. This line of our research is complemented by our studies on the intrinsic localization of nonlinear waves, e.g. of Bose-Einstein condensates in leaky optical lattices, which also leads to extreme events albeit by very different mechanisms.

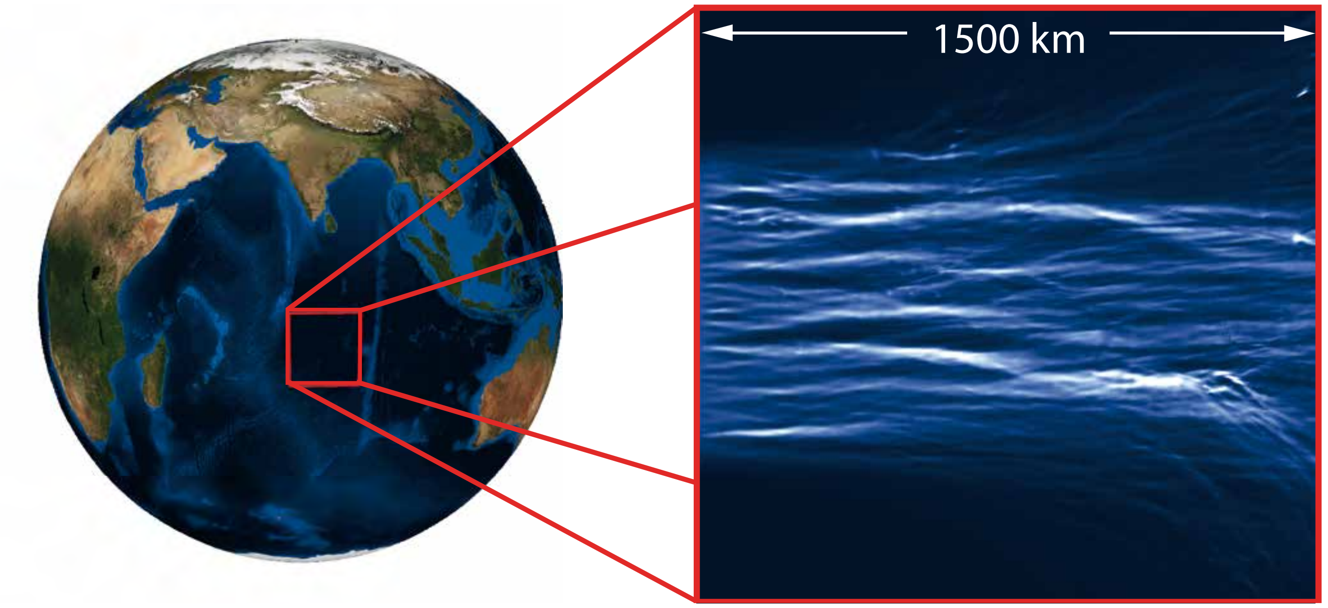


Fig. 1: The simulation of a tsunami wave in a region of the Indian Ocean where the ocean depth variations have a standard deviation of only less than 7% reveals the strong impact of branching on tsunami propagation [1].

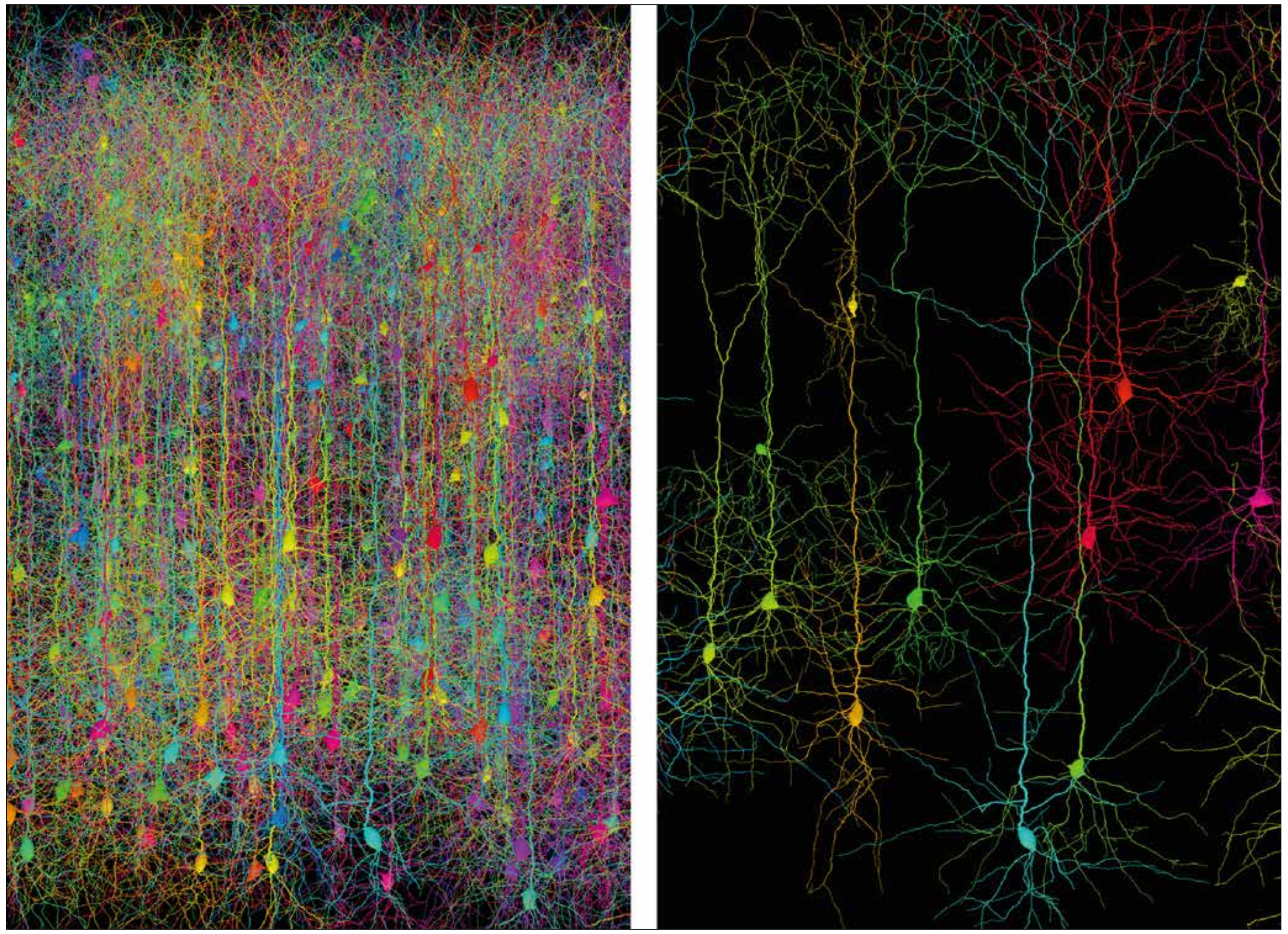


Fig 2: The collective dynamics of the network of interacting nerve cells in our brains forms the basis of brain function and provides formidable challenges for innovative theoretical research. When recording activity from a brain area (left), we are constrained to sampling only a fraction of the neurons (right). We are developing approaches for inferring the collective dynamics despite this subsampling constraint (figure generated using TREES toolbox by H. Cuntz).

Neural Dynamics and Information Processing

Studying the human brain, one is faced with a complex network of 80 billion neurons, each of them interacting with thousands of other neurons by means of action potentials, short electrical pulses. In our research at the Institute for Nonlinear Dynamics and the Max Planck Institute for Dynamics and Self-Organization we address three major questions: What is the collective dynamics of the interacting neural network? How does this network give rise to information processing and thus to our cognitive abilities? And how can we infer these properties from neural recordings, if we can assess the activity of only a fraction of all neurons? We investigate these questions building on approaches from statistical physics and information theory. In collaboration with experimentalists from the Hôpital Salpetrière in Paris we recently showed that the human brain can exhibit collective dynamics close to a “critical state”, as in a 2nd order phase transtition [3,5]. This state appears functionally particularly versatile for brain function, because in models it has been found to maximize information processing capacity. To precisely infer the properties of collective dynamics from neural recordings, we are deriving mathematical approaches that allow to infer the collective dynamics from only a small subset of all neurons (subsampling). This approach for the first time formalizes the inference of system dynamics from observations that are limited to a small fraction of units, and is thus relevant not only for brain research, but also for infering system properties from sparsely sampled networks in general.

Human Dynamics and Neural Mechanisms of Timing

Human dynamics is a new branch of statistical physics, which aims to understand statistical properties of human behavior as expressed e.g. in inter-event times and waiting time distributions. This is particularly important for the modeling and forecast of the spreading of epidemics, where reliable statistics of human traveling behavior is required. In a seminal study [6], we have used banknotes (dollar bills) as a proxy for human travel and determined e.g. an inverse power law for the traveling distances. More recently we have investigated the nature of temporal fluctuations in performed musical rhythms (Fig. 3). We found that these fluctuations exhibit long-range correlations, i.e., a small rhythmic fluctuation at some point in time still influences rhythmic fluctuations after tens of seconds [4]. Our findings have led to patents for the so-called humanizing of computer-generated musical sequences.

[1] H. Degueldre, J. J. Metzger, T. Geisel, and R. Fleischmann, "Random focusing of tsunami waves," Nature Phys. 12, 259–262 (2016).

[2] J. J. Metzger, R. Fleischmann, and T. Geisel, "Statistics of Extreme Waves in Random Media," Phys. Rev. Lett. 112(20), 203903 (2014).

[3] V Priesemann, M Valderrama, M Wibral, M Quyen, "Neuronal Avalanches Differ from Wakefulness to Deep Sleep–Evidence from Intracranial Depth Recordings in Humans", PLOS Comp Biol 9, e1002985 (2013)

[4] H. Hennig, R. Fleischmann, and T. Geisel, "Musical rhythms: The science of being slightly off," Physics Today 65(7), 64–65 (2012).

[5] A. Levina, J.M. Herrmann, and T. Geisel, "Dynamical synapses causing self-organized criticality in neural networks", Nature Phys. 3:857-860 (2007).

[6] D. Brockmann, L. Hufnagel, and T. Geisel, „The scaling laws of human travel", Nature 439:462-465 (2006)

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Fig. 3: We aim to characterize the nature of temporal fluctuations in musical performances and the neuronal mechanisms underlying musical timing.

Fig. 4: Some of the problems we address require extensive computing power. For that purpose our group operates dedicated high-performance computing platforms with approximately 10,000 CPU cores.

Theo Geisel

Theo Geisel studied physics and mathematics at the Universities of Frankfurt and Regensburg. Following postdoctoral research at the Max Planck Institute for Solid State Research and the Xerox Palo Alto Research Center he was Heisenberg Fellow of the DFG. In 1988 he was appointed Professor of Theoretical Physics at the University of Würzburg, in 1989 at the University of Frankfurt. Since 1996 he is Professor of Theoretical Physics at the University of Göttingen and Director at the Max Planck Institute for Dynamics and Self-Organization, where he founded the Bernstein Center for Computational Neuroscience in 2005. Theo Geisel is editorial board member of Physical Review X, Fellow of the American Physical Society, and recipient of the Gottfried Wilhelm Leibniz Prize (1994) and the Gentner-Kastler Prize (2009) of the Deutsche Physikalische Gesellschaft and the Société Française de Physique.

Theoretical Biophysics

Living beings are subject to the laws of physics, but also shaped by the forces of evolution and subject to functional requirements. Our group is interested in the interplay of physical and biological forces, mostly at the molecular and cellular level, where dynamic processes are inherently stochastic and far from thermodynamic equilibrium. Specifically, we are interested in how functional requirements are implemented within given physical constraints. To that end, we make use of methods from stochastic dynamics and statistical physics as well as computer simulations. We address these questions in three interrelated areas, molecular machines, gene circuits and cell growth, and bacterial motility.

Molecular machines

A long-standing interest of the group is the dynamics of molecular machines, in particular the molecular motors that transport cargo along the cytoskeleton and the machines that read out the genetic information. We study the chemo-mechanical cycles underlying the stochastic stepping of individual machines, the coupling of teams of motors by mechanical forces and the economic strategies of their use in cells [1]. One focus of our work is the mechanical coordination of molecular machinery: Molecular motors exert forces by pulling on each other, which affect the dynamics of the motor that is pulled upon. Specifically, force-dependent unbinding rates lead to an instability, which enables rapid bi-directional motion in a tug-of-war of two motor teams. The tug-of-war model has been extended to two dimensions to describe bacterial twitching motility [2], in which molecular machines called type IV pili pull the cell along a surface. Unexpectedly, the dimensionality has a strong effect; mechanical coordination by a tug-of-war is more efficient in one dimension than in two.

Beyond these mechanistic aspects, we study molecular machines under the viewpoint of cellular resource allocation, in particular the cost of protein synthesis. The allocation of limited numbers of RNA polymerases and ribosomes provides a constraint on global protein synthesis and results in indirect regulation, as increased synthesis of one class of proteins is necessarily coupled to a reduction of synthesis of other proteins.

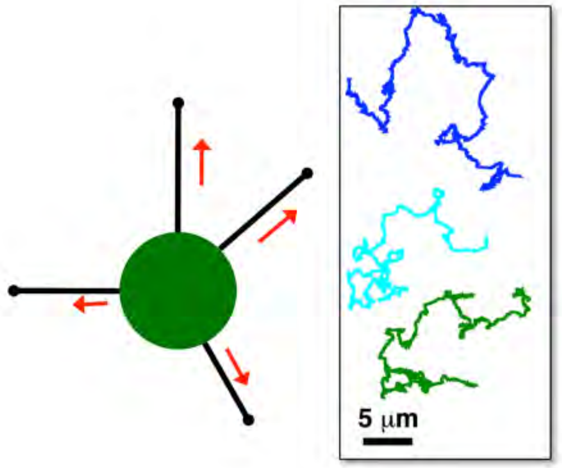
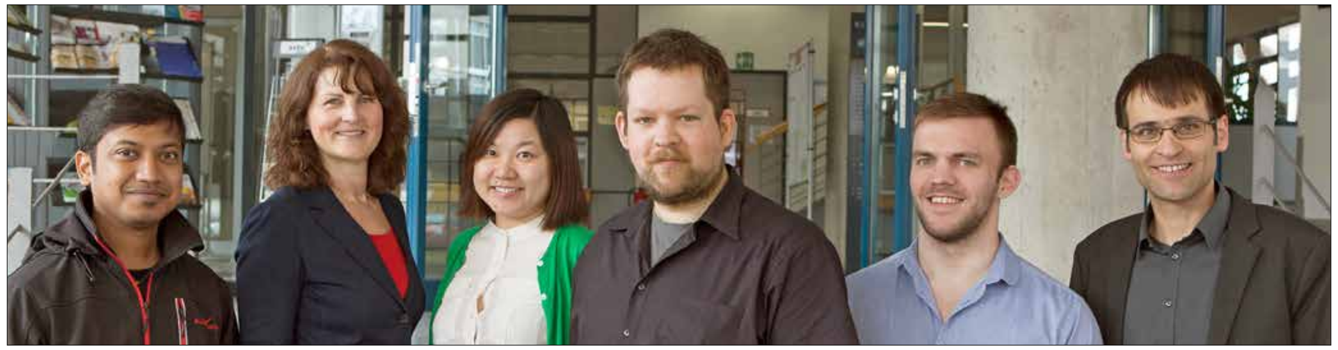


Fig. 1: Tug-of-war between pili pulling a cell into four different directions and example trajectories of the resulting persistent random walks.

Gene circuits, cell growth, and population dynamics

A second field of interest is genetic circuits, networks of genes that are coupled through regulatory interactions and that control the genetic program of a cell. We develop a theoretical framework for describing such circuits that includes their coupling to cellular "background" processes such as cell growth and the cell division cycle. These background processes modulate the availability of the machinery needed to read out the genes in the circuit and can thus affect its performance. They can be included in circuit models through empirical growth dependencies [3,4].

Cell growth can also provide a feedback mechanism, when growth affects gene expression and gene expression affects growth. We study specific examples of such systems as well as their general properties such as the resulting coupling of gene circuit dynamics and population dynamics. For much of our work in this area, bacterial persistence, the tolerance of bacteria to antibiotics, serves us as a model system.



Bacterial motility

Physical forces also have an important role in cell motility. We study the molecular mechanisms powering movements and the corresponding navigation strategies. Specifically, magnetotactic bacteria [5] provide a beautiful model system to address the interplay of generic physical (magnetic) forces and active biological processes such as intracellular transport and propulsion by the rotation of flagella. These bacteria align along field lines of a magnetic field with the help of an intracellular compass needle, the magnetosome chain. Alignment is passive, but with non-thermal fluctuations arising from active processes in the cell. Their swimming is powered by the rotation of their flagella.

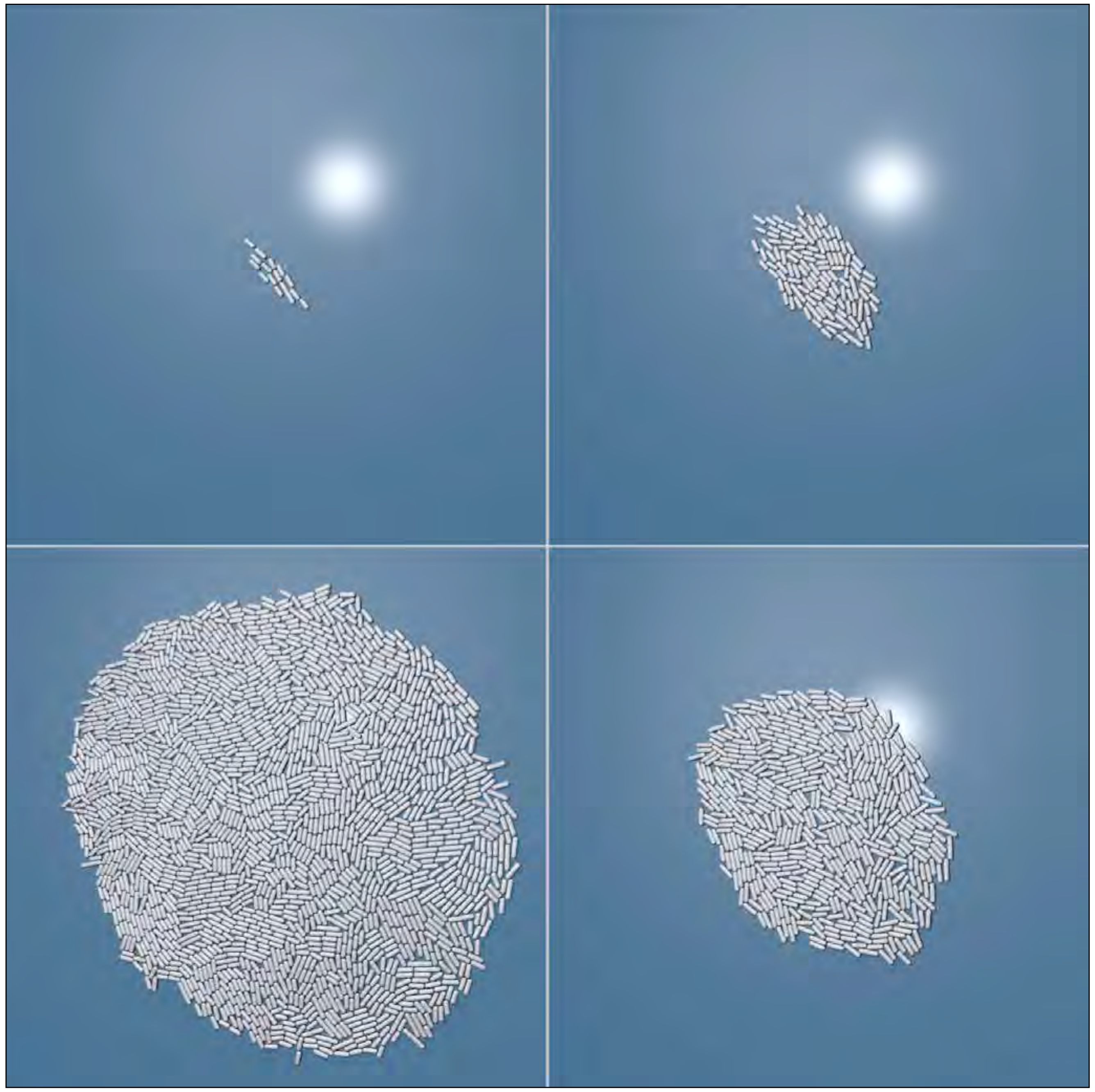


Fig. 2: Simulation of the growth of a bacterial colony.

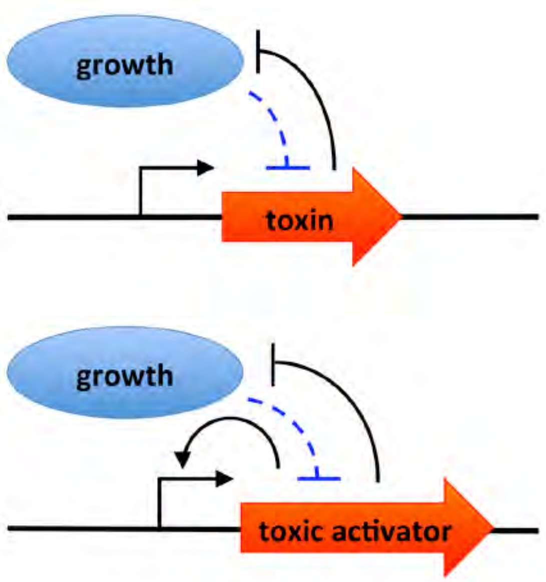


Fig. 3: Two gene circuits with growth-mediated positive feedback.

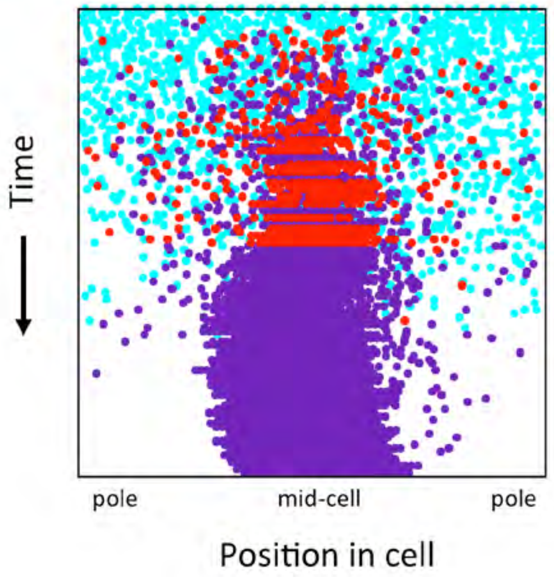


Fig. 5: Assembly of a magnetosome chain.

Depending on the question under study, we use a variety of approaches including random walk models for search strategies, active particle models to incorporate the effect of external forces (e.g., magnetic fields), and detailed simulations of the molecular machinery, i.e. the flagellum and the magnetic moment of the cells. In addition to their swimming, we also study the process of assembly of the magnetosome chain and its mechanical properties [6].

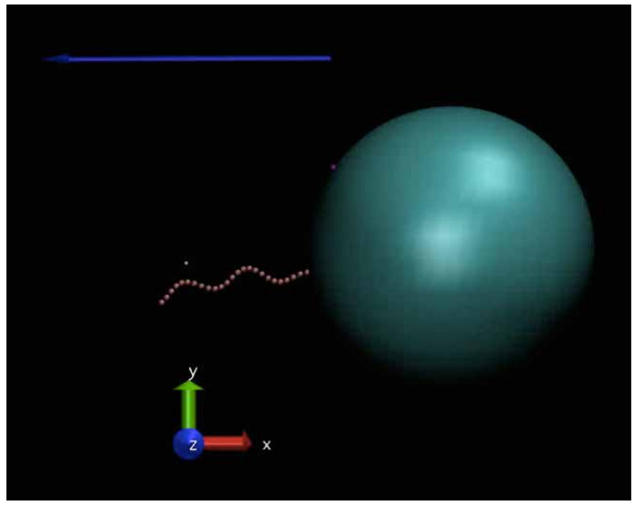


Fig. 4: Snapshot from a simulation of the bacterial flagellum.

[1] Klumpp, S.; Keller, C.; Berger, F.; Lipowsky, R.: Cooperative phenomena of multiple molecular motors, in: Multiscale Modeling in Biomechanics and Mechanobiology. edited by De, S.; Hwang, W.; Kuhl, K. (Springer, London, 2015), pp. 27-61

[2] R. Marathe, R.; Meel, C.; Schmidt, N.C.; Dewenter, L.; Kurre, R.; Greune, L.; Schmidt, M. A.; Müller, M.J.I.; Lipowsky, R.; Maier, B.; Klumpp, S.: Bacterial twitching motility is coordinated by a two-dimensional tug-of-war with directional memory, Nature Commun. 5 (2014) 3759

[3] Bierbaum, V.; Klumpp, S.: Impact of the cell division cycle on gene circuits. Phys. Biol. 12 (2015) 066003

[4] Klumpp, S.; Hwa, T.: Bacterial growth: global effects on gene expression, growth feedback and proteome partition, Curr. Opin. Biotech. 28 (2014) 96-102

[5] C.T. Lefèvre, C.T.; Bennet, M.; Landau, L.; Vach, P.; Pignol, D.; Bazylinski, D.A.; Frankel, R.B.; Klumpp, S.; Faivre, D.: Diversity of magneto-aerotactic behaviors and oxygen sensing mechanisms in cultured magnetotactic bacteria, Biophys. J. 107 (2014) 527-538

[6] Kiani, B.; Faivre, D.; Klumpp, S.: Elastic properties of magnetosome chains, New J. Phys. 17 (2015) 043007

Stefan Klumpp

Stefan Klumpp was born in 1973. He studied physics at the University of Heidelberg and received his Dr. rer. nat. in 2003 from the University of Potsdam with a thesis on molecular motors, done at the Max Planck Institute of Colloids and Interfaces (with R. Lipowsky). From 2006-2009 he was a postdoc at the University of California at San Diego (in the group of T. Hwa), where he started to work on gene regulation and growth physiology. In 2009, he returned to the Max Planck Institute of Colloids and Interfaces to head an independent research group on "Regulation of Bio-Processes". Since 2015 he is a professor for Theoretical Biophysics at the Institute for Nonlinear Dynamics of Georg-August University. His research interests are biophysics at the molecular and cellular level, specifically molecular machines, gene regulation, cell growth, and cell motility.

Mechanics of Small Systems

The behavior of small systems (<100 nm) attracts great interest in biology, chemistry and physics since nanoscopic entities such as molecular motors and machines manifest striking properties as a direct result of their small size. The physics of small systems is strongly governed by thermal fluctuations that produce significant deviations from the behavior of large ensembles. The ultimate small device is a single molecule, where fluctuations can be considered to be large and stochasticity dominates its thermal behavior. We are interested in the mechanics of small systems ranging from single molecules over supramolecular assemblies such as biological membranes to living cells. We pursue top-down and bottom-up approaches to mimic native biological systems.

Nanotechnology is not a novel conception as it has been used by nature for a long time giving rise to complex and highly efficient machines on the nanometer scale, e.g. ATPase or flagella. Hence, artificial replications of biological concepts are envisioned in many scientific branches. For example, in materials science, the development of self-cleaning surfaces was inspired by the lotus plant that is in Buddhism a symbol for purity. Although the structure behind the "lotus effect" is a famous example of nature's nanotech toolbox, it is merely one out of many principles used for biomimetic engineering.

Mimicking detailed features of complex natural systems, like living cells, remains a challenge in actual research. Quantitative, systematic and reliable studies of individual biological phenomena are often only feasible by usage of simplified systems that focus exclusively on the subject of investigation, but with limited degree of complexity that still permits an authentic representation of biological activity. Hence, in actual research there is an ongoing demand for new and innovative biomimetic model systems enabling the investigation and understanding of fundamental processes in biology, in a bottom-up approach.

Mechanics of single molecules

Chemical reactions and structural transitions of supramolecular systems require a comprehensive understanding of the stochasticity of transformations on small length scales. Particularly, mechanically driven transformations as carried out by single molecule stretching experiments offer a unique way to study fundamental theorems of statistical mechanics. In our research group, we design single-molecule experiments either based on rational design or by using macromolecules provided by nature itself. Stochastic modeling of bond breakage under external load allows reconstruction of the energy landscape.

Mechanics of biological membranes

Biological membranes are mechanically challenged in various ways, during adhesion of cells, migration, growth and cell division. Membrane mechanics essentially include its resistance to bending, stretching and compression. Atomic force microscopy allows not only visualizing the topography of submicrometer structures, it also permits to study mechanical properties using various imaging modes based on material contrast or force distance measurements. In this context we create membrane models that allow investigating the elastic response of membranes to external stimuli. Membrane models range from solid supported lipid bilayers over giant liposomes to hybrids such as pore spanning bilayers and cortex models of epithelial cells. Figure 1 shows mechanical probing of an adherent giant liposome.

Cellular mechanics

Cellular mechanics plays a crucial role in many biological processes such as cell migration, cell growth, embryogenesis, and oncogenesis. Epithelia respond to environmental cues comprising biochemical and physical stimuli through defined changes in cell elasticity. For instance, cells can differentiate between certain properties such as viscoelasticity or topography of substrates by adapting their own elasticity and shape. Resolving cell mechanics on various length scales is therefore pivotal to understand how cells respond to mechanical stress and how the entity of plasma membrane and cytoskeleton framework interact with each other on a supramolecular level (figure 2).

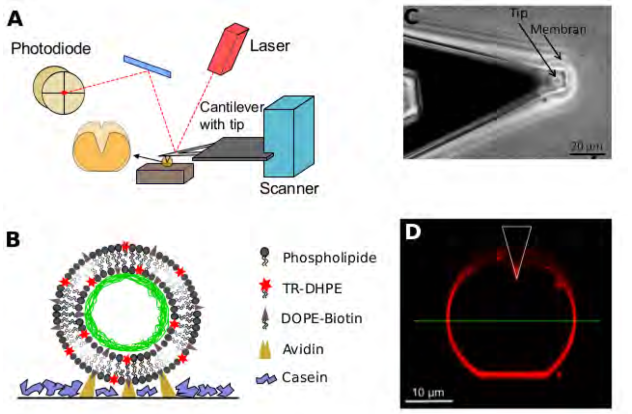


Figure 1. A/B Experimental setup used to measure elastic properties of GUVs with an AFM. GUVs adhere to the surface via biotin/avidin and might optionally be lined with an actin cortex. Vesicles are labeled with a red fluorophor tagged to a phospholipid. **C** Bright field image of a GUV in contact with an AFM tip. **D** Confocal laser scanning image of a sessile GUV subject to a normal force of 2 nN overlaid with the same vesicle prior to indentation.

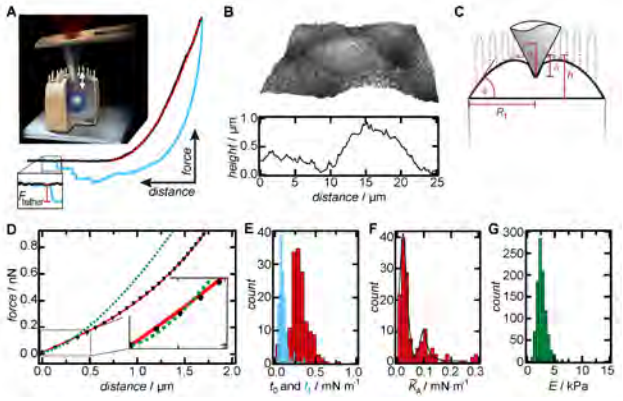


Figure 2. Principle of AFM indentation experiments for computing mechanical parameters of epithelial cells. **A** Force indentation curve (black curve) taken on the center of an epithelial cell and regression of a tension model (red dotted curve). Retraction curve (blue) shows formation of membrane tethers. **B** AFM height image of confluent MDCK II cells. **C** Parameterization of the apical cap of an epithelial cell. **D** Force indentation curve recorded in the center of a confluent MDCK II cell using a pyramidal indenter (triangles). The curve was subject to fitting of a contact model (green dotted line) and the tension model (red solid line). The tension model describes the experimental data over the full indentation range. **E** Histograms showing the typical distribution of cortical tension values (red) and membrane tension (blue). **F** Histogram of the apparent area compressibility modulus. **G** Histogram of the Young's modulus.

[1] Brückner, B.R.; Pietuch, A.; Nehls, S.; Rother, J.; Janshoff, A. (2015) Ezrin is a Major Regulator of Membrane Tension in Epithelial Cells. Sci. Rep. 5, 14700.

[2] Janshoff, A., Steinem, C. (2015) Mechanics of lipid bilayers: What do we learn from pore-spanning membranes? BBA-MCR 1853, 2977-2983.

[3] Brückner, B.R.; Janshoff, A. (2015) Elastic properties of epithelial cells probed by atomic force microscopy. BBA-MCR 1853, 3075-3082.

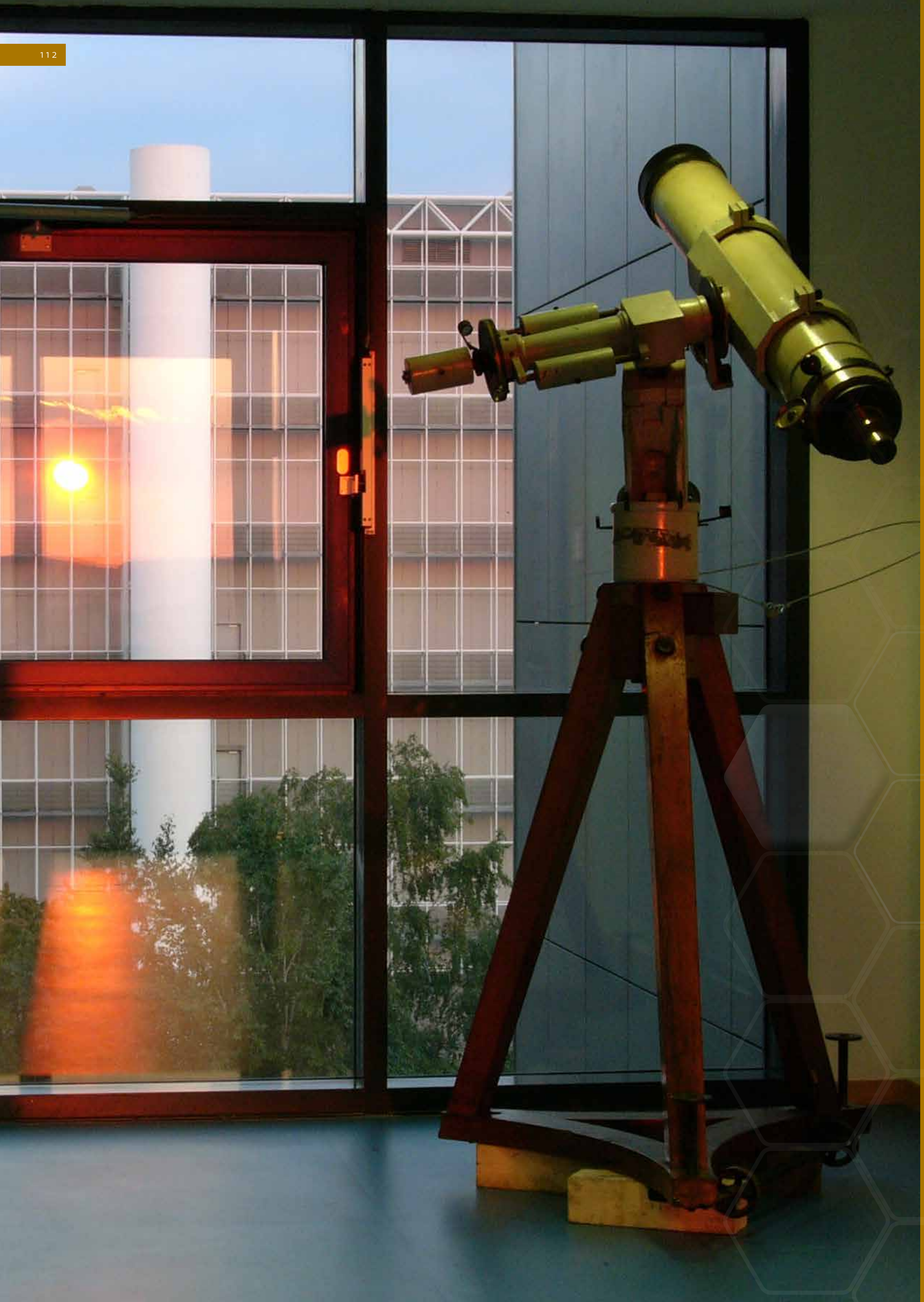
[4] Berger, R.; Binder, K.; Diezemann, G.; Gauss, J.; Helm, M.; Hsu, H.-P.; Janshoff, A.; Metzroth, T.; Mey, I.; Milchev, A.; Paul, W.; Rostiashvili, V. G.; Vilgis, T. A. (2014) Mechanical Properties of Single Molecules and Polymer Aggregates. Adv. Polym. Sci. 260, 1-60.

[5] Rother, J.; Nöding, H.; Mey, I.; Janshoff, A. (2014) AFM-based microrheology reveals significant differences in the viscoelastic response between malign and benign cell lines. Open Biol. 4, 140046.

[6] Janke, M.; Rudzevich, Y.; Molokanova, O.; Metzroth, T.; Mey, I.; Diezemann, G.; Marszalek, P.E.; Gauss, J.; Böhmer, V.; Janshoff, A. (2009) Mechanically locked nanocapsules under force allow reversible hydrogen bond breakage. Nat. Nanotechnol. 4, 225-229.

Andreas Janshoff

Andreas Janshoff, born in 1966, obtained a B.Sc. in Biology and a M.Sc. in Chemistry from the Westfälische Wilhelms-University Münster. Under the guidance of Hans-Joachim Galla, he received his PhD in 1997. After a postdoctoral stay at the Scripps Research Institute in La Jolla, CA (USA) in the group of Prof. M. Reza Ghadiri, he returned to the Institute of Physics at the University of Münster in 1999 as a DFG-fellow. Andreas Janshoff became associate professor for scanning probe techniques at the Institute of Physical Chemistry at the Johannes Gutenberg University in Mainz in 2001. In 2006, he was appointed a full professorship for Biophysical Chemistry. He received an offer from the University of Göttingen for a full professorship in 2008. Since August 2008, he is full professor at the Institute of Physical Chemistry at the Georg August University of Göttingen with his main research focus on soft matter physics and biophysical chemistry.



Astrophysics and Elementary Particle Physics

Collaborative Research Centre by the Federal Ministry of Science and Education (BMBF-Forschungsschwerpunkt) FSP 103-ATLAS "Physics at the TeV-Scale at the Large Hadron Collider"

The BMBF-FSP 103-ATLAS consists of 13 university institutes together with one Max-Planck-Institute and DESY as associated partners at the international ATLAS experiment at the Large Hadron Collider LHC of the European laboratory for particle physics, CERN, in Geneva, Switzerland. Its predecessor research centre, FSP 101, was established by the BMBF in 2006 in order to enable the best German research groups to participate and compete in demanding scientific challenges on an international level. This was recently renewed as FSP 103-ATLAS until 2018.

The Large Hadron Collider, the world's highest energy collider, has started shedding light on the microcosm with unprecedented detail. With data taking starting in the fall 2009, initially at 7 and 8 TeV, and now reaching 13 TeV centre-of-mass energy currently, the LHC has provided new insights into elementary particles, the question of how particles acquire their mass and will allow for searches for heavy new particles. One of the highlights was the discovery of the Higgs-Boson in the year 2012 by the ATLAS- and the CMS-experiments. Other findings might explain long-standing mysteries such as cold dark matter and perhaps cause a paradigm shift in our understanding of fundamental phenomena.

The main physics activities of the German groups are the search for the Higgs boson, the search for supersymmetric particles, studies of exotics scenarios of physics beyond the standard model, physics of the standard model, physics of the top quark, B-meson physics as well as luminosity measurements and forward physics. Furthermore, the German groups are involved in the development, operation and maintenance of several detector components of ATLAS as well as development of a World-Wide LHC Computing Grid. The FSP-103 also includes theoretical particle physicists who pursue studies of direct relevance for the LHC physics program, for example in the area of Monte Carlo simulations of physics processes.

Research Infrastructure by the Federal Ministry of Science and Education (BMBF-Forschungsinfrastruktur – FIS) "The ATLAS-Experiment at the HL-LHC"

Fundamental physics research to support the long-term LHC research programme at CERN is supported by the BMBF research infrastructure programme (BMBF-FIS). The discovery of the Higgs boson in 2012 was a groundbreaking milestone for the LHC, confirming the existence of a scalar field responsible for the electroweak symmetry breaking. Nevertheless, further progress in exploring phenomena beyond the Standard Model at TeV energy scales and high-precision measurements of the Higgs sector are dependent on the further operation of the LHC with an increased centre-of-mass energy of 13-14 TeV. This higher centre-of-mass energy, critical for the sensitivity for these searches and measurements, was reached in 2015.

In order to fully exploit the full potential of the LHC accelerator, it will be upgraded to operate at a luminosity of 5×10^{34} cm^{-2} s^{-1} in 2025 (High-Luminosity LHC or HL-LHC), an increase of a factor of five above the original design luminosity. With a data-taking period of ten years, the total integrated luminosity is projected to reach 3000 fb^{-1}, a sample size of 100 times more data than collected until now. This data will allow the full understanding of electroweak symmetry breaking, the investigation of vector boson scattering at high energies, and highly sensitive searches for new particles in the TeV energy range, enabling research at the energy and intensity frontiers.

For the next two decades, the HL-LHC will be the quintessential machine for precision Standard Model measurements and the preeminent instrument for the discovery of new, undiscovered phenomena beyond the Standard Model. Therefore, the upgrade of the LHC is considered with the utmost priority at the international level, particularly in the European future strategy for particle physics. The ATLAS Collaboration is fully engaged in long-term studies to ensure that the detector will fully exploit and capitalize on this future dataset. Detailed plans for the upgrade of the ATLAS detector have been researched extensively, with a Letter of Intent for this upgrade presented to the Resource Review Board at CERN.

Hadron Collider Physics with the ATLAS Experiment at the LHC

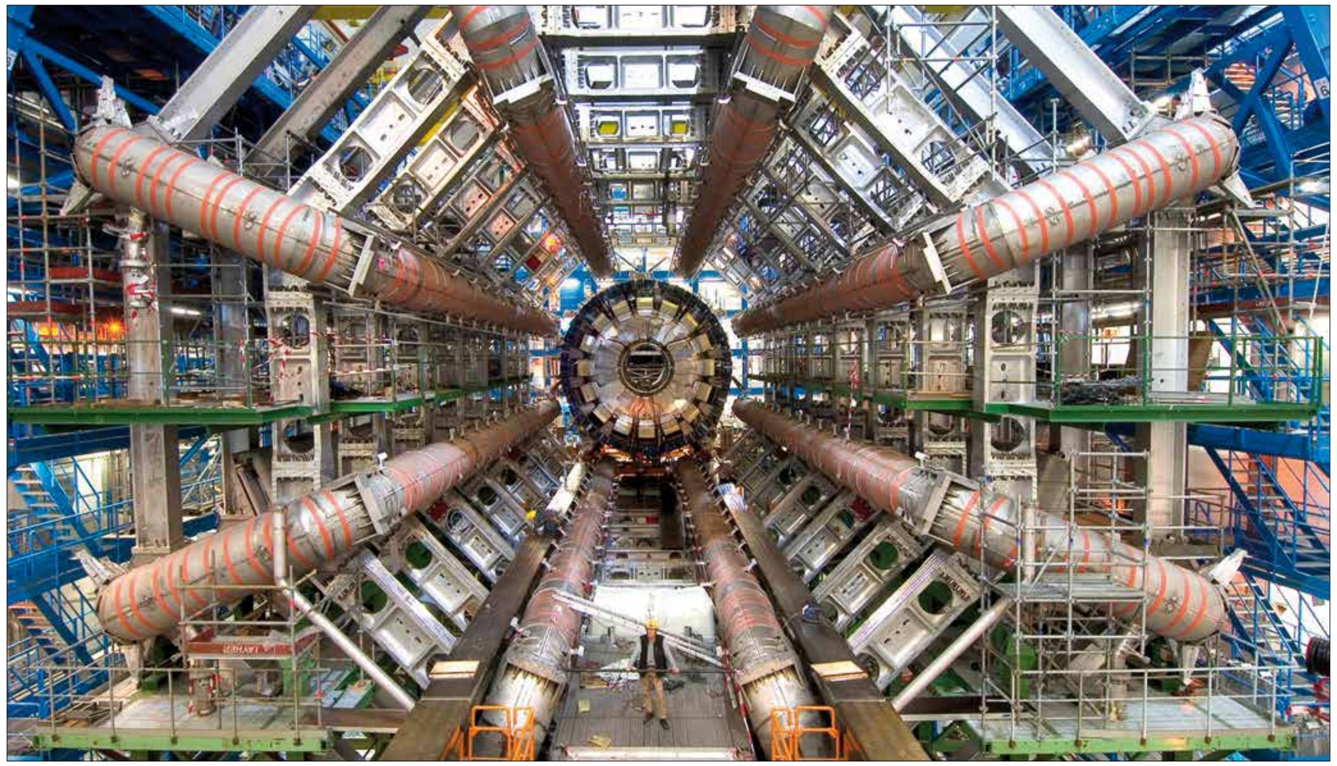
The hadron collider physics experiments ATLAS at the LHC and D0 at the Tevatron provide today's deepest insight into the microcosm and the physics at the Terascale. The hadron collider physics working group was established in the fall of 2006. It is involved in the ATLAS experiment at the proton-proton collider LHC at CERN and in the D0 experiment at the proton-antiproton collider Tevatron at Fermilab. The group is a member of the collaborative research centre BMBF-FSP 103-ATLAS, the BMBF-FIS research infrastructure and of the Helmholtz-Alliance "Physics at the Terascale", HA-101. The main research focus is the investigation of the physics of the top quark, studies of the Higgs boson, the search for supersymmetric particles as candidates for dark matter as well as contributions to the development of the ATLAS pixel detector, and the operation of a regional (Tier-2) and local (Tier-3) Grid computing centre as part of the World-Wide LHC Computing Grid. After initial data taking at 7 and 8 TeV centre-of-mass energies, the present data taking is pursued at 13 TeV and will soon move to 14 TeV energy.

Physics of the top quark:

The top quark is by far the heaviest known elementary particle, allowing studies of this quark without chromomagnetic effects of bound states. It was discovered recently, in 1995, at the CDF and D0 experiments at the Tevatron. Relatively little is still known about the top quark. Due to its large mass - comparable to that of a single gold atom - the top quark is speculated to play a special role in the mechanism of electroweak symmetry breaking. The properties of the top quark such as its mass, electric charge, its spin and its gauge couplings are being measured. Top quarks produced via strong interactions are used to calibrate the detector and to study instrumental and physics background process. Furthermore, precision measurements allow the search for physics beyond the standard model in the top sector and to test the validity and consistency of the standard model. For that purpose, a statistical analysis software toolkit, KLfitter, has been developed, and distributed to the international community with widespread use in LHC data analyses.

Studies of the Higgs boson:

The standard model successfully describes the interactions of fermions and bosons. The concept of particle masses is introduced via electroweak symmetry breaking, in particular via the Higgs mechanism. Thanks to the unprecedented LHC discovery potential, the ATLAS- and CMS-experiments managed to discover the Higgs boson with a mass of approximately 125 GeV/c^2 in the year 2012. Our group has been involved in this discovery. At present, experiment at data indicates that the Higgs boson is consistent with the Standard Model Higgs boson. Nevertheless, further studies are pursued and necessary to prove this. For that purpose, the couplings of the Higgs-boson to fermions also need to be established. One of the most promising channels is the Higgs boson production via weak boson fusion with subsequent decay to tau leptons. This channel would allow the independent establishment of the Higgs signal, the measurement of its mass and the determination of its couplings to fermions and bosons. Another channel is the associate production of the Higgs-boson with a top-quark pair, tth with subsequent h → bb decay. The first tests of the Higgs-boson quantum numbers, its couplings and hence the underlying mechanism are being performed. In the minimal supersymmetric extension of the standard model, the existence of five Higgs bosons is predicted with the lightest one having a mass below 135 GeV/c^2. Searches for these Higgs bosons are also carried out, in particular with b-quarks or with tau-leptons in the final state, providing high sensitivity in a large kinematic range.



Search for supersymmetric particles as candidates for dark matter:

In supersymmetry, new partner particles to the known fermions and bosons are introduced. Despite the increased particle content, this new symmetry has appealing consequences that could help answer fundamental questions about the stability of the Higgs boson mass, the hierarchy problem, the possible unification of the gauge couplings as predicted by Grand Unified Theories (GUTs), and the prediction of new particles which could serve as candidates for cold dark matter, observed in astrophysics. Searches for associate chargino-neutralino production, resulting in signatures of high-P_T leptons, missing transverse energy and jets in the detector are pursued at the LHC. Furthermore, studies towards the extraction of the underlying parameters of the new theory in case of the observation of a signal for new physics are in preparation.

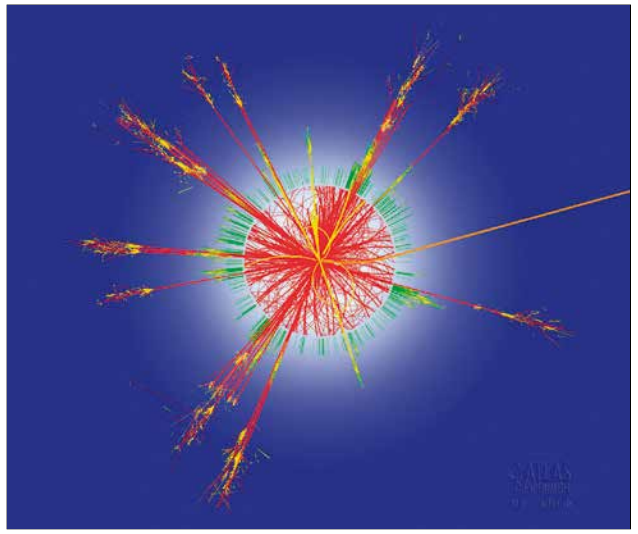
Workgroups of Ariane Frey, Stan Lai and Arnulf Quadt

Development of a Pixel Detector for ATLAS:

The ATLAS pixel detector allows the measurement of the trajectory and the momentum of charged particles resulting from the high-energy proton-proton collisions at a rate of 40 MHz. It is a hybrid silicon detector and is comprised of about 80 million readout channels of 50 by 400 μm^2 pixels. The group is involved in the operation of the existing pixel detector, in recent upgrades of the pixel detector with an additional fourth layer as well as in the development of the readout electronics and new sensor and module designs for the upcoming upgrade of ATLAS in the future for a high-luminosity LHC.

Grid Computing:

The data volume recorded at the CMS and ATLAS experiment per year corresponds to stacks of DVDs 22 km tall. Conventional data storage and processing methods can no longer be used to analyse the data. Rather distributed computing and data distribution management need to be developed, called the Grid. The group has setup and operates a regional and a local Grid computer center (Tier-2/3) for the World-Wide LHC Computing Grid (WLCG) in cooperation with DESY. The cluster is part of the grid resource centre GoeGrid, setup and operated jointly with groups in MediGrid, TextGrid, theoretical physics and the GWDG Göttingen.



[1] Measurement of the F2 structure function in deep inelastic e+p scattering using 1994 data from the ZEUS detector at HERA, Z.Phys.C72:399-424,1996.

[2] Measurement of the top quark mass in the lepton+jets final state with the matrix element method. By Do Collaboration (V.M. Abazov et al.), Phys.Rev. D74:092005,2006.

[3] Top quark physics at hadron colliders, A. Quadt, Eur.Phys.J.C48:835-1000, 2006.

[4] Review of Particle Physics. By Particle Data Group (K.A. Olive et al.), Chin. Phys. C, 38, 090001 (2014) and 2015 update.

[5] The ATLAS Collaboration, Evidence for the Higgs-boson Yukawa coupling to tau leptons with the ATLAS detector, J. High Energy Phys. 04 (2015) 117.

[6] The ATLAS Collaboration, Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC, Phys. Lett. B 716:1-29 (2012).

Arnulf Quadt

Arnulf Quadt (*1969 in Troisdorf) studied physics and mathematics at the University of Bonn and the University of Oxford, where he received his DPhil in 1996. His research focus was the structure of the proton, studies of the strong interaction and the development of the track trigger of the ZEUS experiment. For this work, he received the EPS prize 2001. In 1999, he moved on to the search for the Higgs boson at the OPAL experiment and the LEP-Higgs-Working Group at CERN. In 2001, at the University of Bonn, he worked on the search for Higgs bosons at the OPAL and ATLAS experiments. In Bonn and later as Feodor-Lynen fellow at the University of Rochester and Fermilab, he focused on the physics of the top quark at the Do experiment. After an interim professorship at the University of Göttingen in 2005 and a DFG Heisenberg fellowship to work on the ATLAS experiment at the MPI für Physik in Munich in 2006, he established particle physics the University of Göttingen in the fall 2006.

The Higgs Sector and Beyond at the LHC

Electroweak symmetry breaking and the Higgs boson lie at the heart of the Standard Model (SM) of particle physics. Without them, the phenomena of particle masses cannot be explained. With the discovery of a Higgs boson in 2012 by the ATLAS and CMS experiments at the Large Hadron Collider (LHC), the physics of electroweak symmetry breaking has now become experimentally accessible. Continued data-taking at the LHC allows for detailed investigations into the Higgs sector of the Standard Model, possibly pointing to physical phenomena beyond the current SM paradigm. Analysis of this data requires high performance parallel computing, provided for by the World-Wide LHC Computing Grid (WLCG), of which the grid resource centre GoeGrid is a part. Upgrades to the ATLAS detector and preparation for the High-Luminosity LHC will be paramount in ensuring sensitivity to measuring the Higgs boson self-coupling, the pinnacle of the experimental Higgs boson physics programme.

Precision Higgs Measurements

In the years since the discovery of a Higgs boson, spectacular progress has been made in characterizing this new fundamental particle. Nevertheless, open questions still exist: is the Higgs boson a CP-even state as predicted by the Standard Model? Or is it perhaps an admixture state of CP-even and CP-odd components? If it is the latter, then the Higgs sector violates CP-symmetry, and could have played a role in causing the matter-antimatter asymmetry in the universe.

Our group carries out precision measurements of Higgs boson properties with the ATLAS detector, in order to answer some of these questions. Kinematic distributions of Higgs boson decays in di-photon or di-tau final states are compared with SM predictions, as well as predictions from Beyond-the-Standard-Model (BSM) theories, such as models with CP-admixture states of the Higgs boson. Effective field theories can also be used to describe Higgs boson interactions with other SM particles, and measurements of the Higgs boson differential cross-sections can restrict the range of coefficients of the operators in the effective Higgs-Lagrangian.

Searches for Physics beyond the Standard Model

Given the central role that electroweak symmetry breaking plays in the SM, new phenomena beyond the Standard Model could potentially be manifested in the Higgs sector. The Higgs boson mass is particularly sensitive to new physics at higher energy scales, while many theoretical extensions, such as supersymmetry, predict an extended Higgs sector of at least 5 different Higgs bosons.

Our group also uses data collected from the ATLAS experiment to search for signs of extended Higgs sectors, particularly searching directly for additional Higgs bosons. Currently, the decay $H \rightarrow hh$ is being investigated, where a heavier Higgs boson (H) decays into two lighter Higgs bosons (h) which correspond to the recently discovered particle. Such searches also help prepare for studies of SM di-Higgs production, allowing future measurements of the Higgs-boson self-coupling with the High-Luminosity LHC.

Reconstruction Algorithms with the ATLAS Detector

The performance of reconstruction algorithms for final state particles such as photons and hadronically decaying tau leptons is of vital importance in ensuring the suppression of background processes that can mimic the physical process of interest. Our group's involvement in optimizing these algorithms, and measuring quantities such as the identification efficiency and energy scale for tau and photon candidates directly benefits the sensitivity of physics processes containing $h \rightarrow \gamma\gamma$ and $h \rightarrow \tau\tau$ decays. Performance studies require a good understanding of detector physics as well as data analysis.

Tracking Performance Studies for HL-LHC

The LHC will undergo an upgrade where the instantaneous luminosity will be increased by a factor of five, enabling experimental measurements of extremely rare processes, such as di-Higgs production. In order to cope with the increased luminosity, an entirely new inner tracker (ITk) will be installed in approximately 2024 for the ATLAS detector, constructed using silicon pixel and strip sensors. Simulation and performance studies for the upgraded ITk are of paramount importance for making optimal design choices and forecasting the sensitivity of the ATLAS experiment for measurements of rare physics processes and searches for new phenomena. In addition, the tracking reconstruction algorithms are investigated and optimized for high luminosity pile-up conditions.

[1] The ATLAS Collaboration, "Identification and energy calibration of hadronically decaying tau leptons with the ATLAS experiment in pp collisions at $\sqrt{s}=8$ TeV", Eur. Phys. J.C (2015) 75:303.

[2] The ATLAS Collaboration, "Evidence for the Higgs-boson Yukawa coupling to tau leptons with the ATLAS detector", J. High Energy Phys. 04 (2015) 117.

[3] The ATLAS Collaboration, "Search for charged Higgs bosons decaying via $H^+ \rightarrow \tau^+\nu$ in fully hadronic final states using pp collision data at $\sqrt{s}=8$ TeV with the ATLAS detector", J. High Energy Phys. 03 (2015) 088.

[4] The ATLAS Collaboration, "Search for the neutral Higgs bosons of the Minimal Supersymmetric Standard Model in pp collisions at $\sqrt{s}=7$ TeV with the ATLAS detector", J. High Energy Phys. 02 (2013) 095.

[5] The ATLAS Collaboration, "Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC", Phys. Lett. B 716:1-29 (2012).

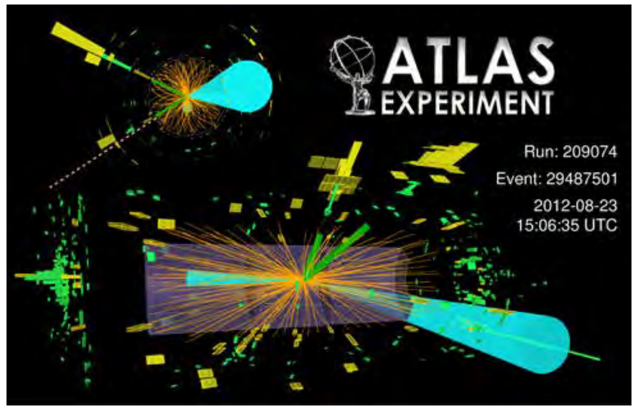


Fig. 1: Candidate $h \rightarrow \tau\tau$ event recorded with the ATLAS experiment in 2012. It features two high energetic forward jets as well as two tau candidates with an invariant mass consistent with the discovered Higgs boson, consistent with production of a Higgs boson with vector boson fusion.

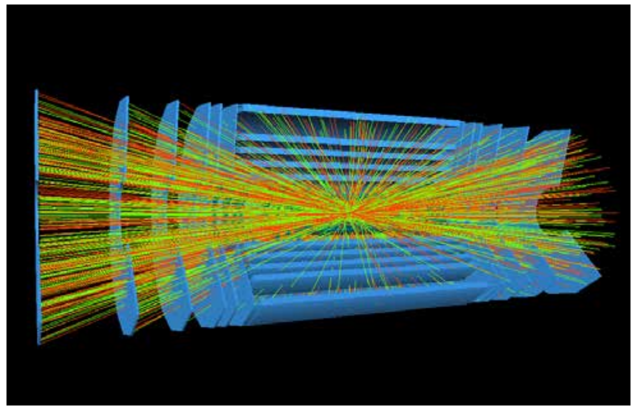
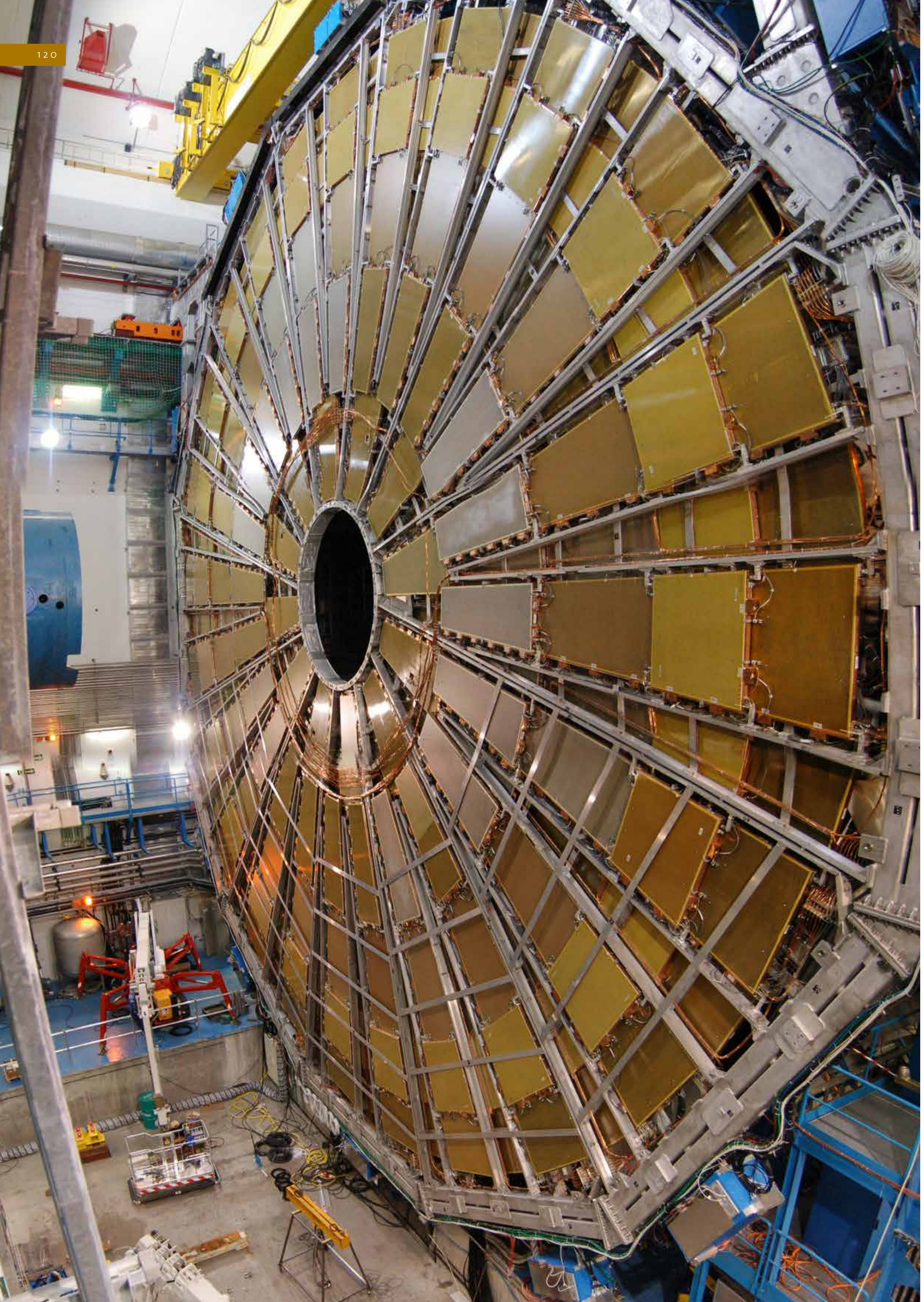


Fig. 2: Simulated event at the high-luminosity LHC. The large event activity shows the environment of high luminosity proton collisions. High performance precision tracking will be imperative to reconstruct events in this environment.

Stan Lai

Stan Lai studied physics and received his PhD in 2006 at the University of Toronto. His thesis topic was a search for the Higgs boson at the CDF experiment using proton-antiproton collisions generated by the Tevatron at Fermilab. In 2006, he moved to the University of Freiburg and began his involvement with the ATLAS experiment at CERN. He focused his efforts on the reconstruction and identification of tau leptons, and played a leading role in establishing evidence for Higgs boson decays to tau leptons in data recorded with the ATLAS detector. Since 2015, he is a professor at the 2nd Institute of Physics at the University of Göttingen. His research interests include tracking simulation studies for High-Luminosity LHC, precision measurements of Higgs boson properties, searches for extended Higgs sectors, and physics beyond the Standard Model.



Precision Particle Physics at (future) Electron-Positron-Colliders

Experiments at particle colliders have been pivotal in advancing our knowledge about the fundamental building blocks of matter and the interactions between them. While the LHC will operate during the next years at the highest energy frontier, a complementary approach is taken in collisions of electrons with their anti-particles, positrons. The advantage of colliding these fundamental particles is the far superior achievable precision. To match this precision, the requirements on the detectors that record the interactions are very stringent. The area closest to the particle interactions is equipped with pixel detectors to measure the trajectory of charged particles. Novel silicon pixel detectors based on DEPFET technology are under development, which combine several favorable aspects: an integrated first amplification stage and thus low noise, large signal allowing for very thin sensors and sufficient radiation hardness. DEPFET pixel sensors are developed for two different projects, the upgrade of the B-Meson factory in Japan and the International Linear Collider.

Belle II – Upgrade of the B-Meson factory at KEK

The study of neutral B mesons, particles containing a beauty quark, holds very special interest: the Standard Model of particle physics predicts the occurrence of CP violation, the symmetry breaking that is responsible for the observed matter-antimatter asymmetry in our universe. Two experiments (BaBar at SLAC, USA and Belle at KEK, Japan) at accelerators optimized to produce copious amounts of B mesons have indeed confirmed CP violation in the B system, results which led to the award of the Nobel prize 2008 to Kobayashi and Maskawa for their theory of quark mixing and CP violation. At KEK, the Japanese particle physics center, an upgrade of the accelerator is underway in order to increase the beam intensity by more than an order of magnitude. This will allow even more precise determinations of the Kobayashi-Maskawa quark mixing parameters as well as studies of rare decays and possibly hints of new physics phenomena. In order to deal with the increased rate, the inner subdetector parts of Belle have to be completely replaced, notably a novel DEPFET pixel detector will be installed by 2017. The group is also involved in the analysis of the data collected so far.

Fig. 1: Areal view of the KEK site located about 70 km from Tokyo with Mount Tsukuba in the background. The 400 m long electron/positron linear accelerator and the buildings above the collider ring whose circumference is about 3 km can be seen.

DEPFET Pixel Sensors

The DEPleted Field Effect Transistor (DEPFET) is a device with built-in amplification: The electrostatic field in a fully sideways oriented depleted silicon structure is shaped such that all electrons generated by ionizing particles, Xrays or photons are collected in a small volume which is located under the channel of an integrated p-channel field effect transistor. The negative charge in this internal gate leads to a modulation of the channel current.

Thanks to the large signal, very thin sensors can be operated with still comfortably large signal-to-noise ratio. A special procedure has been developed allowing the production of pixel matrices thinned down to 50 µm in the active area and with a support frame entirely made from silicon for stability. Small DEPFET devices have undergone several successful beam tests and the Göttingen group is heavily involved in the analysis of the collected data.

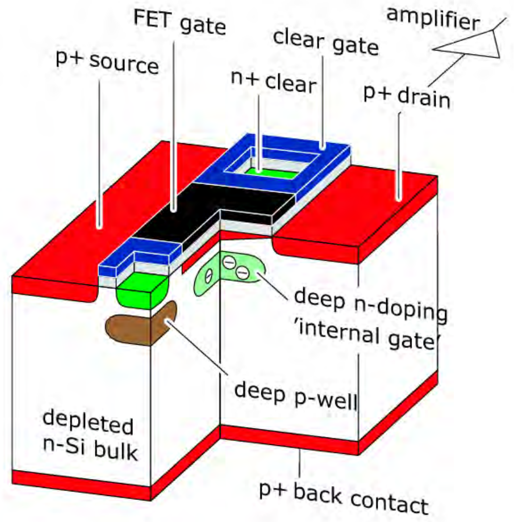


Fig. 2: Schematic of a DEPFET pixel cell, corresponding to a field effect transistor on top of a fully depleted Silicon bulk.

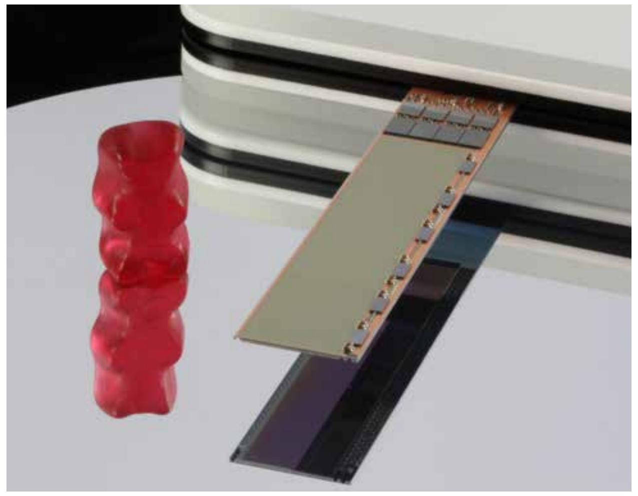


Fig. 4: The first fully equipped module for the new Belle II vertex detector.

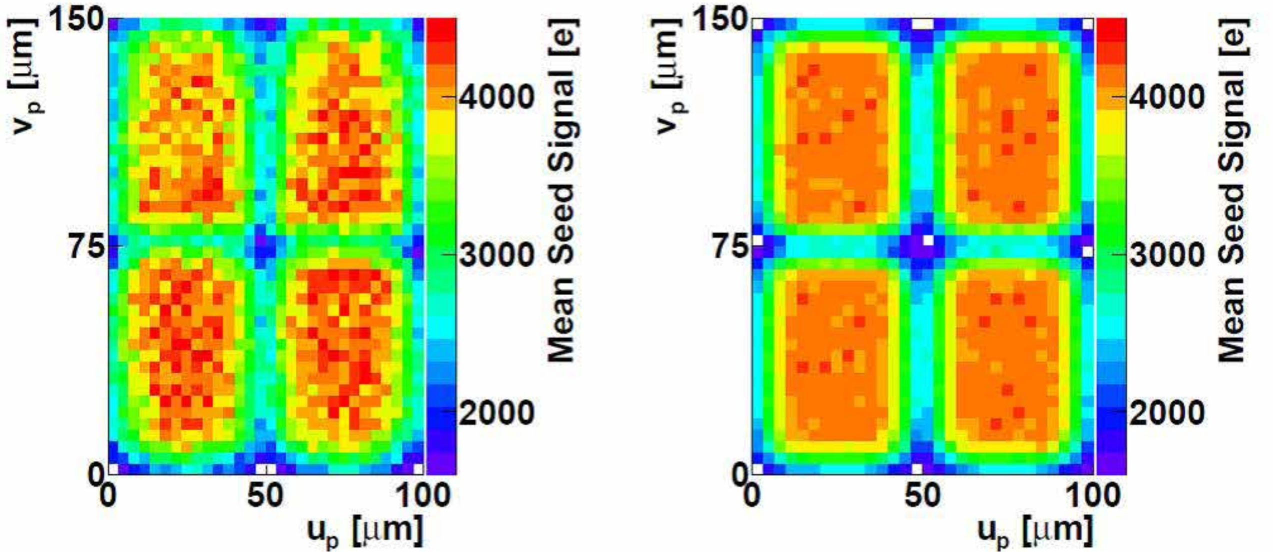


Fig. 3: Signal left by a traversing particle in a quadruple DEPFET pixel cell from beam test data (left) compared to simulations (right).

The International Linear Collider

The ILC is planned to be the next large particle physics accelerator. It will provide e^+e^- collisions at center-of-mass energies between 500 and 1000 GeV, accelerated by superconducting cavities. The linear structure is chosen in order to minimize the energy loss due to synchrotron radiation. A possible site has been identified in Northern Japan. The results from the ILC together with LHC will certainly elucidate our understanding of the microcosm. Precise determination of all properties of the recently discovered Higgs Boson will be possible, and possibly measurements of the hypothetical supersymmetric particles that include a good candidate to explain the dark matter in the universe. For accurate measurement of Higgs properties as well as precise studies of physics processes beyond the Standard Model, efficient distinction of heavy quark flavors, most notably, of bottom and charm quarks, is a must. This requires precise secondary vertex detection and results in a targeted single hit resolution better than 5 micrometers. DEPFET pixel detectors are one of the advanced semiconductor devices considered for the ILC vertex detector.

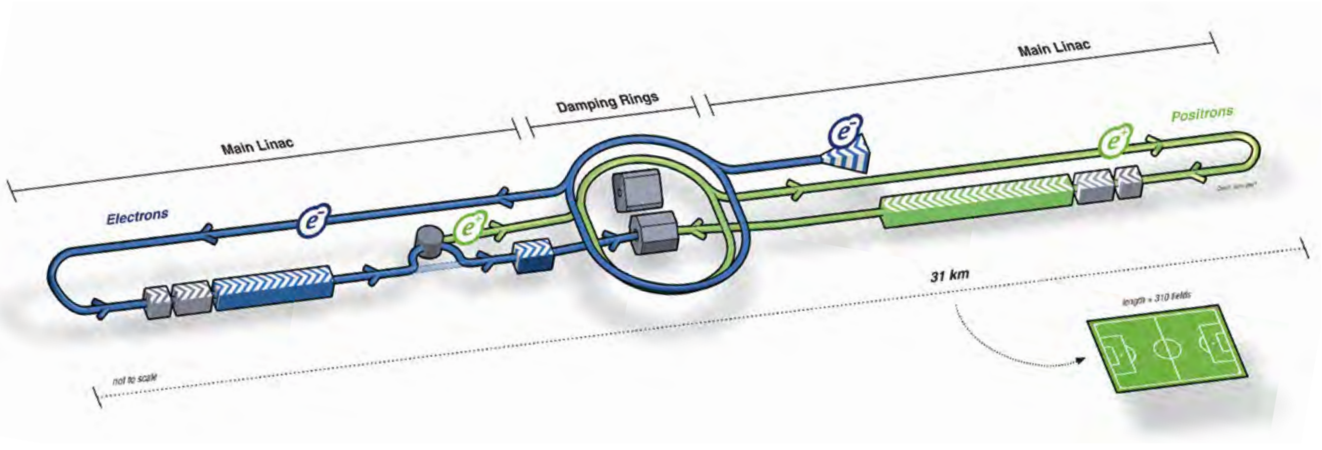


Fig. 1: The layout of the projected International Linear Collider with a length of 31 km. Particle collisions happen in the central region, where two detectors will record the data alternately. The positron beam is derived from the electron beam by directing the latter onto a suitable target.

[1] DEPFET, a monolithic active pixel sensor for the ILC; J.J. Velthuis et al ; Nucl. Instr. Meth. A 579:685-689, 2007

[2] A DEPFET based beam telescope with submicron precision capability; J.J. Velthuis et al ; IEEE Trans. Nucl. Sci. 55:662-666, 2008

[3] Intrinsic resolutions of DEPFET detector prototypes measured at beam tests; L. Andricek et al., Nucl. Instr. Meth. A 638:24-32, 2011

[4] Physical limitations to the spatial resolution of solid-state detectors; M.Boronat et al ; IEEE Trans. Nucl. Sci. 62:381-386, 2015

[5] Search for $B^0 \rightarrow \pi^- \tau^+ \nu_\tau$ with hadronic tagging at Belle; P. Hamer, A. Frey et al ; Phys. Rev. D93:032007, 2016

[6] Inclusive and exclusive measurements of B decays to χ_{c1} and χ_{c2} at Belle ; V. Bhardwaj et al ; Phys. Rev. D93:052016, 2016

Ariane Frey

Ariane Frey studied physics at the University of Heidelberg and received her PhD in 1996 from the University of Bonn for a measurement of the internal structure of the proton performed with the ZEUS experiment at DESY/Hamburg. As a Feodor-Lynen fellow at the University of California Santa Cruz she developed the read out electronics for the innermost tracking detector of the BaBar experiment at the Stanford Linear Accelerator Center. From 1998 until 2005 she was research staff at the European particle physics center CERN in Geneva. Her work focused on R&D for the Silicon tracking device of the CMS experiment at the LHC. Moving to the Max Planck Institute for Physics in Munich in the framework of the MPG excellence initiative, she became project leader of the International Linear Collider group. In 2008 she joined the physics faculty in Göttingen as a Lichtenberg professor.

Theoretical Particle Physics

High-energy scattering experiments provide the means to study some of the most fundamental laws of physics – the electroweak and the strong force – and to search for yet unknown physics at smallest length scales and highest energies. Understanding the final state of high-energy particle collisions such as those at the Large Hadron Collider (LHC) is an extremely challenging theoretical problem. Typically hundreds of particles are produced with momenta that range over many orders of magnitude. Our group is developing both analytical and numerical methods to make predictions for the outcome of such collider experiments. Furthermore we perform dedicated phenomenological studies of Standard Model and New Physics processes for the LHC and devise novel strategies and analysis techniques to search for hints of New Physics at presently available and planned future high-energy colliders.

Monte Carlo simulations for collider experiments

A successful description of hadron-hadron collider data demands a profound understanding of Quantum Chromodynamics (QCD), the quantum field theory of the strong interaction. Inevitably, the complexity of strong-interaction phenomena requires the use of a large variety of theoretical techniques – from perturbative cross-section calculations up to the modelling of exclusive hadronic final states. Our research group is devising numerical methods to stochastically simulate individual scattering events in a fully exclusive manner, i.e. at a level that can directly be compared to experimental measurements, cf. Fig. 1. We are involved in the development of the Sherpa Monte-Carlo event generator, that comprises models for all aspects of collider scattering events. Our focus thereby lies on the efficient evaluation of multi-particle transition amplitudes, and accurate parton-shower simulations. Due to the confinement property of the strong interaction the partons produced in shower simulations have to form hadrons, e.g. protons, pions or kaons, that constitute the experimentally observed final states. However, these inherently non-perturbative hadronization and fragmentation processes cannot yet be calculated from first principles but need to be described by phenomenological models.

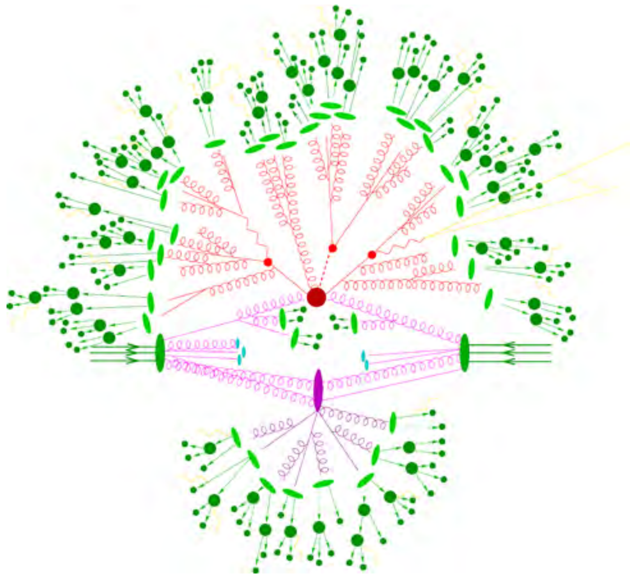


Fig. 1: Sketch of an LHC proton-proton collision event. Illustrated are the various intermediated stages of the event evolution (purple, red, light green) and the resulting, detectable, final-state particles (dark green, yellow).

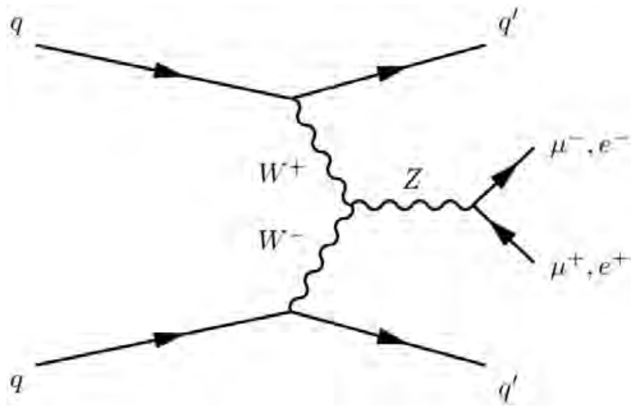


Fig. 2: Example for a lowest order Feynman diagram contributing to the electroweak production of a Z boson associated by two jets.

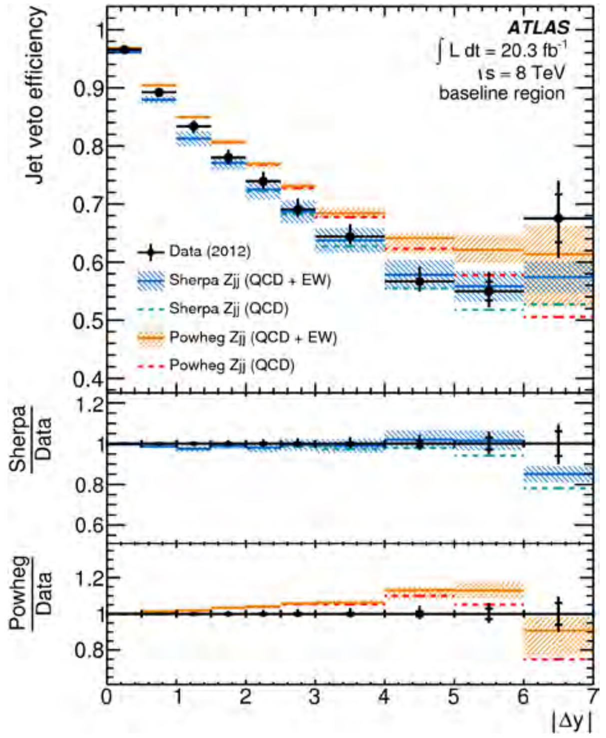


Fig. 3: The veto efficiency of additional jets in the electroweak production of a Z boson associated by two jets, differential in the rapidity separation of the two jets, as measured by the ATLAS collaboration. The experimental data are compared to theoretical predictions from the Sherpa and Powheg Monte Carlo event generators. (Figure taken from Aad et al. JHEP 1404 (2014) 031)

Together with the unprecedented precision of the LHC experimental data, such theoretical Monte-Carlo simulations enable us to establish a solid understanding of hadron-hadron collision physics at the TeV scale. This allowed the discovery of the Higgs boson announced in July 2012 and is vital for estimating the Standard Model backgrounds in searches for New Physics phenomena.

The Sherpa Monte-Carlo generator is being developed in an international collaboration with colleagues in the United States, Schwitzerland and the United Kingdom. We are participating in the EU funded FP7 network MCnetITN, through which not only part of our research is funded, but that allows us to offer training opportunities such as summer schools and shortterm internships for postgraduate students from all over the globe.

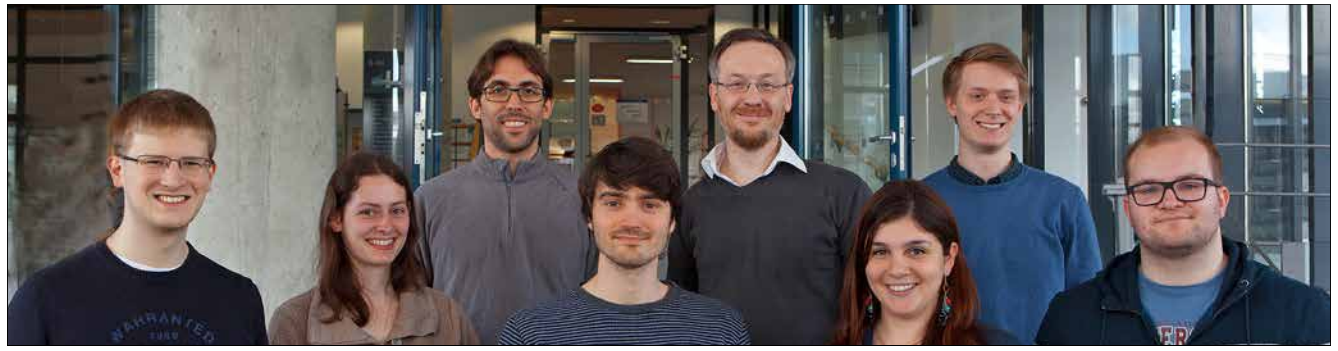
Precision calculations of scattering cross sections

Our current understanding of the dynamics and interactions of the fundamental constituents of matter, i.e. the elementary quark and lepton particles, is encapsulated in the Standard Model of particle physics. It provides a unified description of the electro-magnetic, the weak and the strong interactions by means of quantized gauge-field theories. The apparent breaking of the electro-weak symmetry is therein accomplished by means of the Brout-Higgs-Englert-Guralnik-Hagen-Kibble mechanism, or Higgs mechanism for short, that provides a consistent explanation for the observed non-vanishing masses of the electro-weak gauge boson, the W and Z particles, as well as the quarks and leptons. Furthermore, this theory predicted the existence of a new fundamental scalar particle, the long searched for Higgs boson.

For quantitative predictions based on the Standard Model Lagrangian one typically has to rely on perturbation theory, i.e. an expansion in the relevant coupling parameters. In order to match the accuracy achieved by the LHC experiments, the evaluation of the leading and sub-leading QCD and electroweak corrections even for very complex multi-particle processes is necessary. This requires to consider additional real emissions as well as virtual loop corrections. Both, the quick rise in the number of contributing Feynman diagrams and the growing dimensionality of the corresponding phase-space integrals render this a highly non-trivial theoretical challenge.

Within our group we are developing theoretical methods and numerical algorithms to evaluate one-loop QCD and electroweak corrections in a largely automated manner for in principle arbitrary scattering processes. A further emphasis of ours is the consistent matching of higher-order transition matrix element calculations with subsequent parton shower evolutions, which is vital for a successful description of experimental data. Furthermore we are specialising in the fast and efficient estimation of the inherent uncertainties of theoretical predictions. This comprises the dependence on the QCD input parameters like the parton density functions or the coupling parameter as well as the residual impact of the choice for the renormalization and factorization scales appearing in truncated perturbative series.

Figure 3 illustrates a use case of our Sherpa generator to predict the signal of electroweak production of a Z boson associated by two QCD jets, cf. Fig. 2 for an example of a contributing Feynman diagram, as it has been measured by the ATLAS experiment at the LHC.



Physics Beyond the Standard Model

Contemporary experimental and theoretical high-energy collider physics aims for an understanding of the physics of electroweak symmetry breaking and the TeV scale in general. Culminating in the discovery of the Higgs boson by the LHC experiments in the year 2012 the Standard Model of particle physics provides an extremely succesful description of basically all known collider signatures. However, further high-precision measurements at the LHC and future collider experiments will put further stringent tests on the theory and might reveal deviations from the Standard Model expectations to be interpreted as New Physics, i.e. physics beyond the Standard Model. A huge variety of candidate theories exist and are being developed, trying to address the questions and challenges the Standard Model leaves open. Examples thereof are the quest of the nature of Dark Matter, an explanation for the matter—antimatter asymmetry observed in the universe, or, the persistent hierarchy problem related with the apparent void between the electroweak scale and the scale of gravity, the Planck scale. The collider signatures of models addressing these issues need to be tested against existing data for discovery, in order to constrain their parameter values, or, ultimatly, rule them out as valid extensions of the Standard Model.

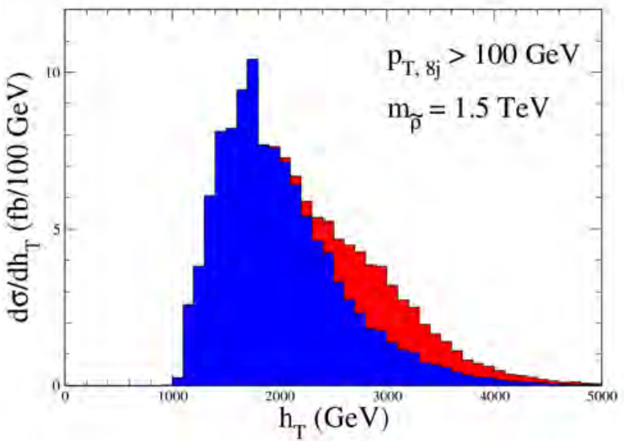


Fig. 4: Hypothetical LHC signal for the pair production of new colour-octet vector particles of mass 1.5 TeV, subsequently decaying into eight-jet final states (red) superimposed on the Standard Model background expectation (blue). (Figure taken from Kilic, Schumann, Son JHEP 0904 (2009) 128)

Our group is engaged in the development of new models for TeV-scale physics, specialing in new strong interactions, i.e. theories featuring new composite states, cf. Fig. 4. We are furthermore developing technologies to largely automate the calculation of scattering processes in New Physics models and contribute to the construction of novel data-analysis strategies that will help to establish a detailed understanding of the underlying principles of physics at the TeV scale.

[1] Höche, S.; Kuttimalai, S.; Schumann, S.; Siegert, F.: Beyond Standard Model calculations with Sherpa, Eur. Phys. J. C 75 (2015) 3

[2] Gerwick, E.; Höche, S.; Marzani, S.; Schumann, S.: Soft evolution of multi-jet final states, JHEP 1502 (2015) 106

[3] Kröninger, K.; Schumann, S.; Willenberg, B.: (MC)**3 – a Multi-Channel Markov Chain Monte Carlo algorithm for phase-space sampling, Comput. Phys. Commun. 186 (2015) 1

[4] Gerwick, E.; Schumann, S.; Gripaios, B.; Webber, B.: QCD jet rates with the inclusive generalized kt algorithms, JHEP 1304 (2013) 089

[5] Gerwick, E.; Plehn, T.; Schumann, S.: Understanding jet scaling and jet vetoes in Higgs searches, Phys. Rev. Lett. 108 (2012) 032003

[6] A. Buckley et al.: General-purpose event generators for LHC physics, Phys. Rept. 504 (2011) 145

Steffen Schumann

Steffen Schumann was born in Dresden in 1978. He studied physics at the TU Dresden where he also received his Ph.D. degree in theoretical physics in 2008. He has worked as a post-doctoral researcher at The University of Edinburgh and the Institute for Theoretical Physics at Heidelberg University before moving to Göttingen where, in 2011, he became a tenure-track junior professor for theoretical particle physics and collider phenomenology.

His main field of interest is the development of numerical and analytical methods for the description of high-energy particle collisions. Steffen Schumann is prinicipal investigator of BMBF funded projects focusing on the development of theoretical tools for the LHC experiments and is node leader of the EU funded FP7 training network MCnetITN.

Geophysical Fluid Dynamics

Navigation has relied on compass needles for centuries. Nowadays, we mostly use more sophisticated tools for navigation, but the magnetic field of the Earth is still considered essential for human life because it protects the Earth from particles arriving from space. The origin of the geomagnetic field remains mysterious in many ways. The only plausible mechanism for its creation is a dynamo effect which converts the kinetic energy of motion in the electrically conducting outer core into magnetic energy. The Earth's outer core being liquid, its dynamics share many characteristics with the dynamics of the atmosphere and the oceans. Geophysical fluid dynamics is a field of research exploring those common features, in particular the turbulence at small length scales and the organization into persistent large scale structures.

Planetary Magnetic Fields

All planets except Venus and Mars presently have their magnetic fields. Of course, we know Earth best, and thanks to observations made since Gauss, we can deduce the magnetic field at the core mantle boundary at a depth of 2900 km. The field is rather more complex than a simple dipole and it has been observed to have a time-dependence. The motion inside the core is likely to consist of numerous small eddies. It is impossible to numerically compute this complex flow, in the same way as it is impossible to predict the weather and atmospheric flow because of its small scale features. We therefore do not attempt to simulate any planet directly and study simplified geometries instead.

Precession and Tides

There needs to be an energy source to maintain the motion in the liquid core. The precession of the Earth's rotation axis about the normal to the ecliptic with a period of 26,000 years is too slow to have any noticeable effect on everyday life, but it possibly contributes significantly to the energy budget of the core. Columnar vortices appeared in computer simulations of precessing fluid bodies performed in this group. These simulations also showed that a magnetic field can be generated by precession, but it is not known whether this actually happens in the Earth because of the uncertainty on the precise value of the viscosity of the core material. The mathematical descriptions of precession and tides are very similar. Even though tides are of little relevance for the Earth's core, they are more important for exoplanets which are close to their host star.

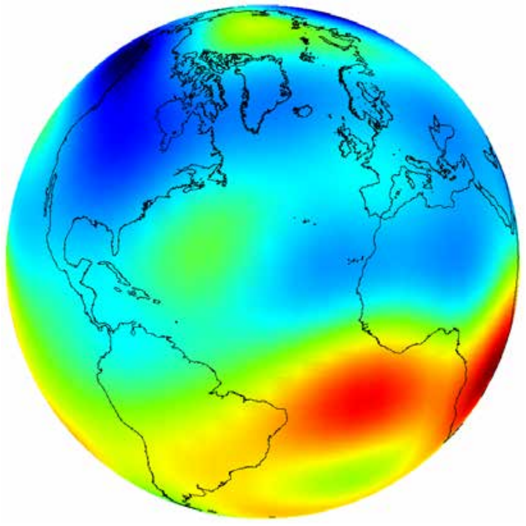


Fig.1 : The radial component of the magnetic field at the core mantle boundary at a depth of 2900 km in the year 1995.

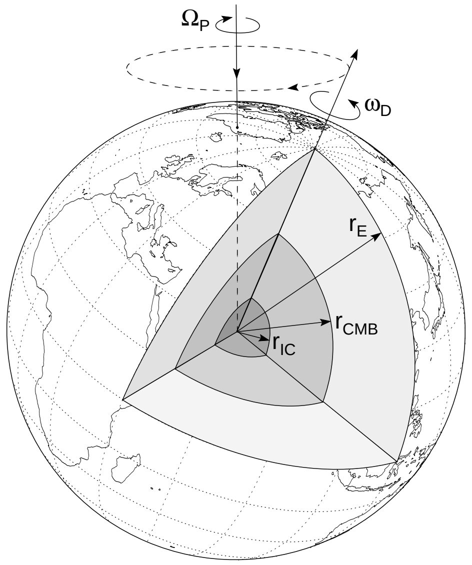


Fig. 2: Sketch of the preceseing Earth. Shown are the axis of rotation, the geographic axis, and the radii of the Earth, the core mantle boundary, and the inner core.

Convection

Thermal convection has many applications. It appears in the climate problem because the heat transported through the atmosphere needs to be calculated accurately in climate models. The whole planet Earth is cooling down as it ages, setting up a thermal gradient between the hot center and the cold surface, which allows convection. Buoyancy in the Earth's core is probably the strongest driving force for the geodynamo. Thermal convection is also a common problem in engineering. Fundamental properties of thermal convection have fascinated physicists since Rayleigh. In more recent times, the organization of convection at large scales has received much attention. It is remarkable that convection cells, rolls and plumes survive in a turbulent environment. However, these rolls can be destroyed in double diffusive convection which is frequently oserved in the oceans, where both temperature and salinity determine water density. Global rotation of the convecting system also modifies the circulation pattern. Current research focuses on mechanisms responsible for the existence of these structures in turbulent flows and on the heat transported by them.

Dynamo experiments

Neither numerical simulations nor laboratory experiments are able to exactly reproduce the dynamics of the Earth's interior. A combination of both approaches is necessary in order to obtain a complete picture of the geodynamo. Dynamo experiments require considerable technical effort and volumes of several cubic meters of liquid sodium moving at velocities of several meters per second. There is no experiment of this type in Göttingen, but the group has been involved in both the design and the interpretation of such experiments. One result from this line of research is an estimate of the power dissipated by the geodynamo in the Earth's core. All previous experiments used non-rotating containers filled with liquid sodium. Future experiments will include rotation and even precession, so that the Coriolis force will influence the dynamics, and possibly show polarity reversals as observed in the Earth's magnetic field.

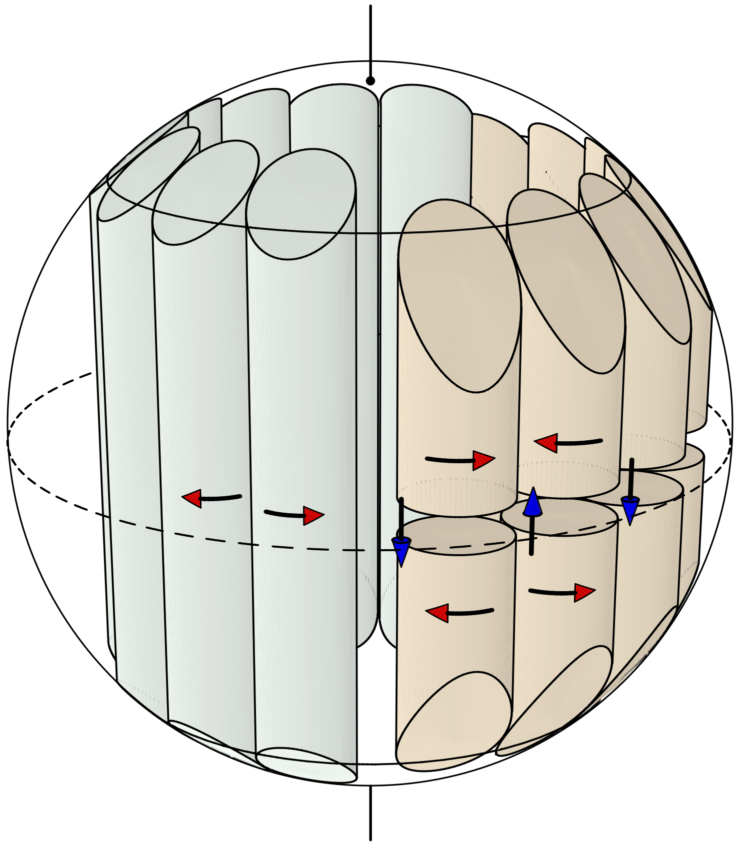
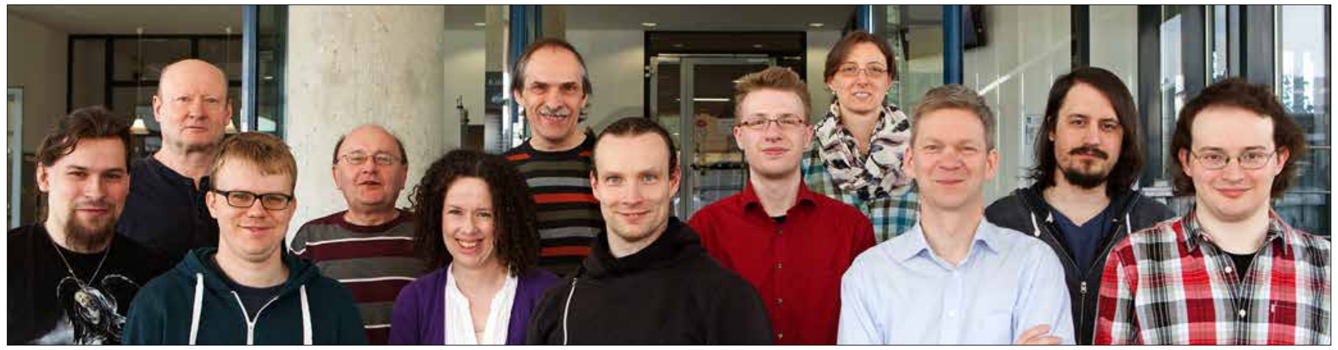


Fig. 3: Sketch of a flow driven by precession. Two belts of columnar vortices with opposite parity with respect to the equator appear. Only half of the vortices are drawn for clarity.



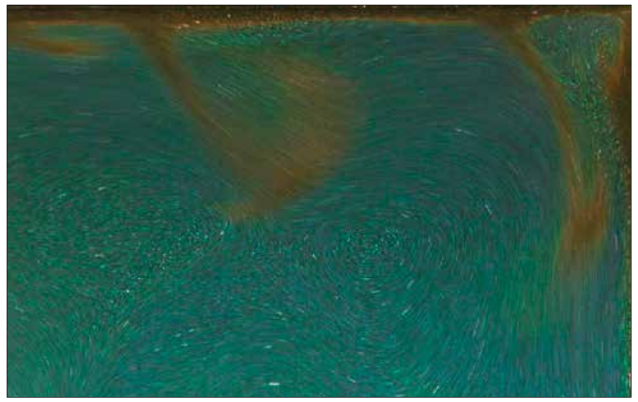


Fig. 4: Picture of eddies and plumes detaching from a cold plate at the top of the picture in convecting water. Particles filled with thermochromic liquid crystals have been suspended in the water. The liquid crystals change color with temperature, and the velocity field is visible as streaklines in this photograph with a 1 s exposure time.

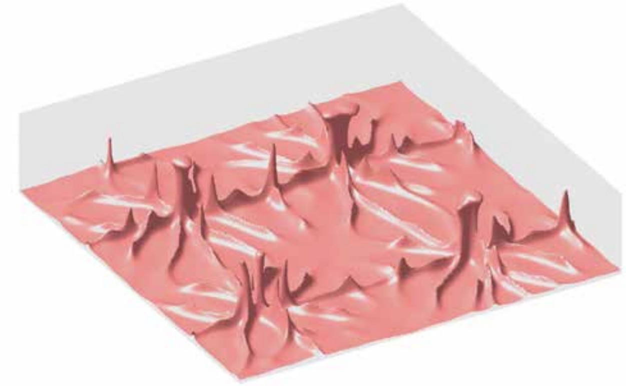


Fig. 5: Isosurface of temperature in a numerical simulation of thermal convection showing plumes emanating from the bottom boundary layer.

References

[1] Tilgner A.: "Precession driven dynamos" Phys. Fluids 17, 2005, 034104.

[2] Schmitz S., Tilgner A.: "Heat transport in rotating convection without Ekman layers" Phys. Rev. E 80, 2009, 015305(R).

[3] Morize C., Le Bars M., Le Gal P., Tilgner A.: "Experimental determination of zonal winds driven by tides" Phys. Rev. Lett. 104, 2010, 214501.

[4] Tilgner A.: "Transitions in rapidly rotating convection dynamos" Phys. Rev. Lett. 109, 2012, 248501.

[5] Kellner M., Tilgner A.: "Transition to finger convection in double-diffusive convection" Phys. Fluids 26, 2014, 094103.

[6] Tilgner A.: "Rotational Dynamics of the Core" Treatise on Geophysics Vol. 8, Schubert G. editor, Elsevier 2015.

Andreas Tilgner

Andreas Tilgner was born in 1965 in Braunschweig. He studied physics at the Technische Hochschule Darmstadt until the Vordiplom and continued his studies at the Université Joseph Fourier in Grenoble until his PhD. The topic of his PhD thesis was laser spectroscopy on polymers at low temperatures, an example of a disordered system. During his Postdoc with Albert Libchaber at Princeton University, his attention shifted towards an even more disordered system: turbulent convection. In the period leading to his habilitation at the University of Bayreuth in the group of F. Busse in 2000, he worked mostly on the dynamo effect and in particular on the design of the Karlsruhe experiment, which was one of the two experiments demonstrating the dynamo effect in 1999. Work on precession and inertial modes also started during that time. He arrived in Göttingen in 2001.

Stellar and Planetary Astrophysics

All the chemical elements except hydrogen, helium, and lithium are the most tangible results of stellar evolution. Nuclear reactions in the interiors of the first stars started a cosmic recycling process that turned the primitive primordial gas created by the Big Bang into the mixture of heavier elements needed for the formation of terrestrial planets and life. Mixing and mass loss as well as supernova explosions continue to release ever more enriched material into the interstellar medium, from which new stars can be formed out of interstellar gas clouds. As a by-product of star formation, planets may form out of the dusty gas disks left over from the contraction of interstellar clouds during star formation. While the general scenario of star and planet formation and evolution is clear, many important details remain to be investigated. The continuous improvement of astronomical instrumentation, observing programs at large international observatories, as well as sophisticated numerical simulations for the analysis and interpretation of the data are all required.

Instrumentation Projects

Progress in astronomy and astrophysics is tied intimately to the capability of the astronomical instruments. While larger and larger telescopes permit observations of fainter objects and space based observatories open new observing capabilities, the instrumentation for these telescopes has to keep up with the new possibilities and adapt to scientific requirements defined by the astronomical community. An active participation in this process has a long tradition in our group, namely with instruments for the Very Large Telescope of the European Southern Observatory at Paranal in Chile and for the future European Extremely Large Telescope (E-ELT, Fig. 1). A recently finished and successfully commissioned instrumentation project (MUSE, Fig. 2, http://muse-vlt.eu/science/) has been developed and built as part of an international collaboration partly funded by the BMBF: a spectrograph that provides optical spectra not only for single point sources but rather for a complete field of view of one square arcminute with a spatial resolution of 0.2 arcseconds. While this instrument opens up new perspectives for projects ranging from cosmology to planetary science, our group in Göttingen is especially interested in using this instrument for stellar objects in the Milky Way and in nearby galaxies. MUSE will be updated with an Adaptive Optics Module in 2017, further increasing the spatial resolution of the instrument.

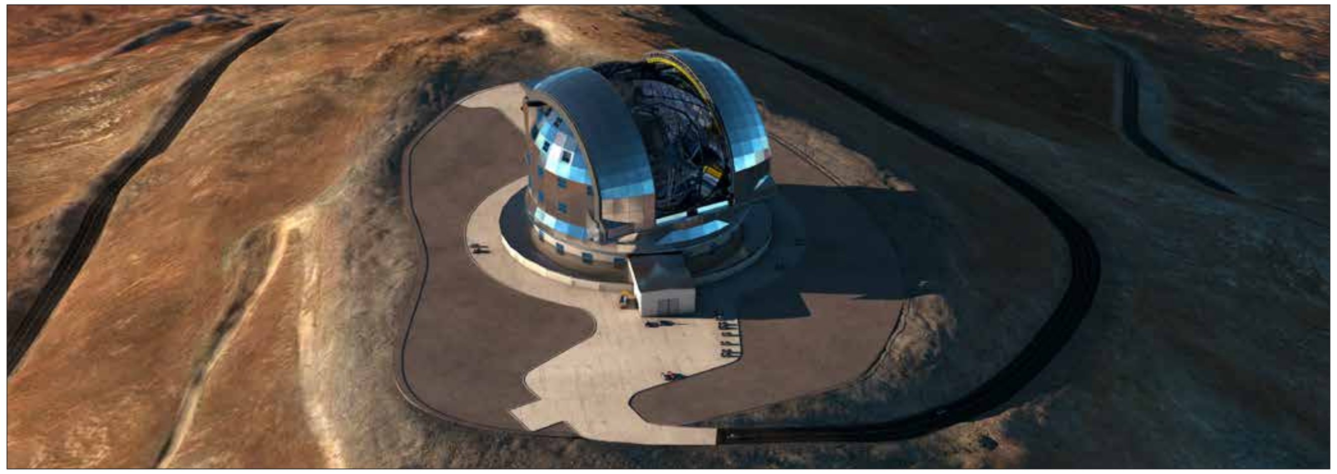


Fig.1: Artists impression of the European Extermeley Large Telescope in the Atacama desert in Chile. (credit ESO)

Fig. 2: The Multi Unit Spectroscopic Explorer at the Very Large Telescope. (credit ESO)

We will also contribute to three of the instruments foreseen for the E-ELT. Our main contribution is to MICADO, the first-light instrument of E-ELT (http://www.mpe.mpg.de/ir/micado). It is an infrared imager and spectrograph with a spatial resolution at the diffraction limit of the 39m telescope. For example, this will enable us to measure the 3-D velocities of stars in star clusters with an unprecedented precision. Our group has also contributed to the CARMENES spectrograph at the Calar Alto Observatory in Spain. The goal of that high-resolution spectrograph is the detection of habitable planets around low-mass stars (https://carmenes.caha.es/). The science preparation and exploitation of these instruments will be a significant part of the scientific activities for the next decade.

While observing time at large international observatories is very limited, long term projects are ideally conducted at dedicated telescopes. With funds from the Alfried Krupp von Bohlen und Halbach Foundation, two robotic telescopes (MONET, Fig. 3) have been built, one at McDonald Observatory in Texas, one at the South African Astronomical Observatory. These telescopes allow long term monitoring projects, e.g. the search for extrasolar planets. The remote observations make the MONET telescopes also ideal for educational purpose; half of the observing time is devoted for school use, providing access to professional astronomical equipment for school classes all over the world.

Research topics

Fig. 3: MONET South, a 1.2m robotic telescope operated by the Stellar Astrophysics group in Göttingen along with the South African Astronomical Observatory with the Milky Way in the background. (Photo: S. Potter/SAAO)

The Stellar and Planetary Astrophysics group concentrates on extrasolar planets, low mass and solar-type stars as well as on late stages of stellar evolution. With the discovery of the first planet orbiting a star other than the sun in 1995 and the subsequent detection of thousands of extrasolar planets, the aspects of planet formation having to do with the evolution, and interaction with the host star have become key scientific topics. Our group participates in the direct search of extrasolar planets with various techniques. These techniques include detection of radial velocity variations where we concentrate on very low mass planet host stars (CARMENES), detection and characterization of planets with transit and eclipse time variations (KOINet), and gravitational lensing (MONET), the latter providing an unbiased extrasolar planet search over a large distance range in our Milky Way.

In stellar astrophysics, we currently concentrate on a large stellar census of galactic globular clusters using part of our guaranteed observing time for MUSE (Fig. 4). In these old star clusters, composed of about hundred thousand to one million stars, MUSE enables us to obtain tens of thousands of stellar spectra per cluster. With a technique developed in our group it is possible to disentangle the overlapping spectra in theses dense stellar fields (Fig. 5). The spectral information allows us to study the stellar populations and we will be able to test the hypothesis that these star clusters host black holes of masses of the order of thousand solar masses in their centers, i.e. scaled down versions of the super-massive black holes in galaxies.

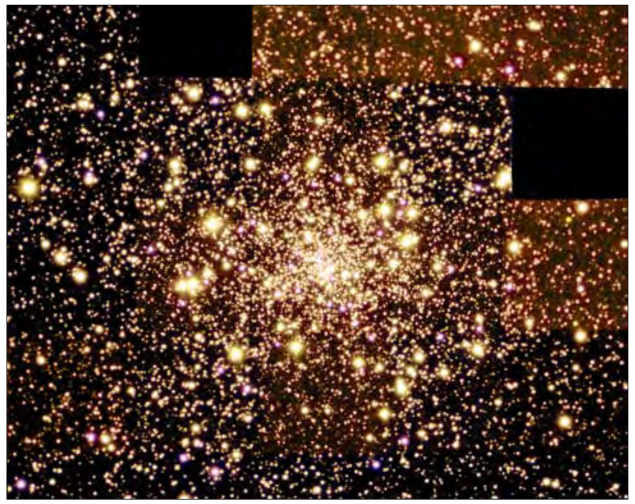
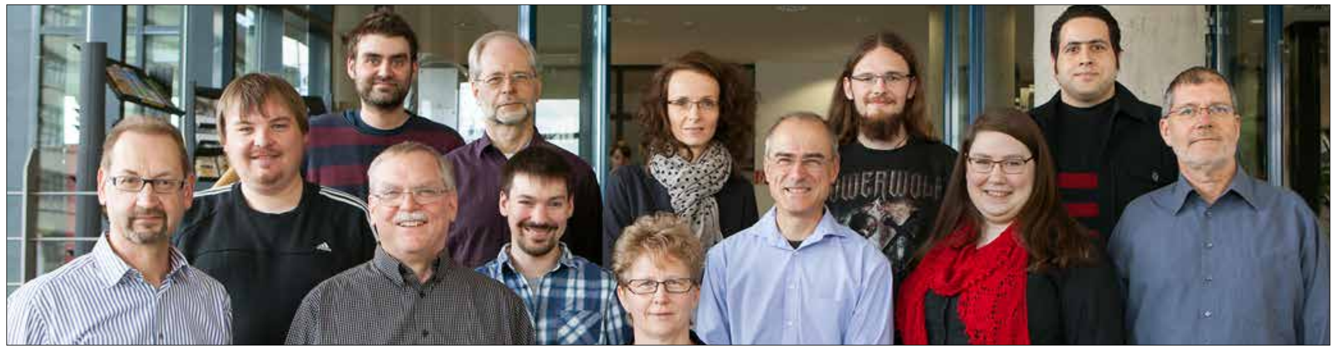


Fig. 4: The globular cluster NGC6397 obtaind with MUSE. The color of the stars is reconstructed from the spectral information. Credit T.O. Husser und S. Kamann



Numerical Simulations

Most of the information of the physical condition of astronomical objects is obtained from the analysis of the emitted light. The derivation of temperature and density stratifications, chemical composition, velocity or magnetic fields require a comparison of simulated and observed spectra.

These numerical simulations have to keep up with the advances in observing techniques. The steady development of sophisticated radiative transfer simulations is therefore an important tool in stellar astrophysics. A recent contribution of our group to that topic is a new, very extensive spectral library for a large number of applications

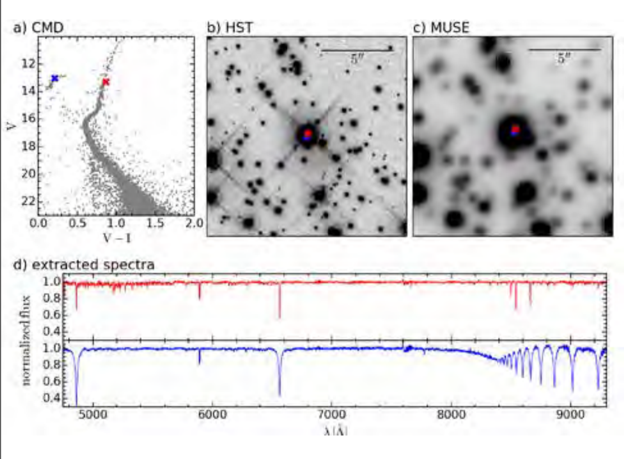


Fig. 5: An example for the disentangling of stellar spectra in a dense stellar field. The position of the two stras (red and blue crosses) is known from an image taken by the Hubble Space telescope (b). With the known positions the individual spectra of the stars can be extracted (d) from the MUSE observation (c). Their derived color and brighnes is indicated in the colr-magnitude diagram (a). Credit T.O. Husser und S. Kamann

[1] T.-O. Husser, S. Kamann, S. Dreizler, et al. MUSE crowded field 3D spectroscopy of over 12,000 stars in the globular cluster NGC 6397 - I. The first comprehensive spectroscopic HRD of a globular cluster. Astron. Astrophys. accepted, arXiv:1602.01649

[2] D. R. G. Schleicher, S. Dreizler. Planet formation from the ejecta of common envelopes. Astron. Astrophys., 563:A61, March 2014.

[3] K. Beuermann, S. Dreizler, and F. V. Hessman. The quest for companions to post-common envelope binaries. IV. The 2:1 mean-motion resonance of the planets orbiting NN Serpentis. Astron. Astrophys., 555:A133, July 2013.

[4] A. Ofir and S. Dreizler. An independent planet search in the Kepler dataset. I. One hundred new candidates and revised Kepler objects of interest. Astron. Astrophys., 555:A58, July 2013.

[5] T.-O. Husser, S. Wende-von Berg, S. Dreizler, et al., A new extensive library of PHOENIX stellar atmospheres and synthetic spectra. Astron. Astrophys., 553:A6, May 2013

[6] K. Werner and S. Dreizler. The classical stellar atmosphere problem. Journal of Computational and Applied Mathematics, 109:65–93, September 1999.

Stefan Dreizler

Stefan Dreizler, born 1963 in Freiburg, studied physics at the Christian Albrechts University Kiel, where he received his PhD in 1992 under the supervision of Prof. Dr. K. Hunger. After postdoctoral studies at Erlangen University with Prof. Dr. U. Heber (1992) and at University Kiel with Prof. Dr. D. Koester (1996), he obtained a position as a research assistant at Tübingen University where he finished his habilitation in 2000. In 2003 he was appointed as full professor at the Georg August University Göttingen. From 2007 to 2009 he served as Dean of the physics faculty.

Stars and Extrasolar Planets

Our Galaxy is made of stars, one of them is the Sun that comfortably warms planet Earth on which we live. We know of billions of stars, each of them is a laboratory demonstrating the laws of nature under conditions that cannot be realized in any experiment on Earth. Many of the stars host planets that may or may not be suitable for life. To understand the stars, to answer the question about life elsewhere in the universe, and to access the laws of nature ruling the formation of stars, planets, and life, we observe the stars with large telescopes and compare our observations to computer simulations. Our main interest is the physics of the most numerous types of stars, low-mass stars, and on the search for extrasolar planets. We are developing methods and instrumentation for detailed astronomical observations at the world's leading observatories.

Fig. 1: Artist's impression of a planetary system around a low-mass star. Our team is participating in the search for Earth-like planets around low-mass stars. The image was created on the occasion of the discovery of two planets around Kapteyn's star, a very old and nearby member of the galactic halo. One of the two planets receives the right amount of energy to support liquid water (© G. Anglada-Escudé).

Low-Mass Stars

The majority of stars in our Galaxy are less than half as massive and half as large as the Sun. More than 2/3 of the stars in our universe are of this type; they are the closest stellar neighbors to the solar system, they show complex and little understood molecular chemistry, they are fascinating laboratories for stellar electrodynamics, and they are in the focus of exoplanet search programs with the goal to find planets similar to Earth. We use the world's largest telescopes as well as dedicated observatories to obtain high-quality spectroscopy from these stars. The spectra contain information about stellar composition and the formation of stars, stellar activity, and the presence of planetary companions. We are using orbital simulations and detailed atmosphere models to decipher the information encrypted in starlight, and we develop software and build instrumentation to improve our understanding of stars and their planets.

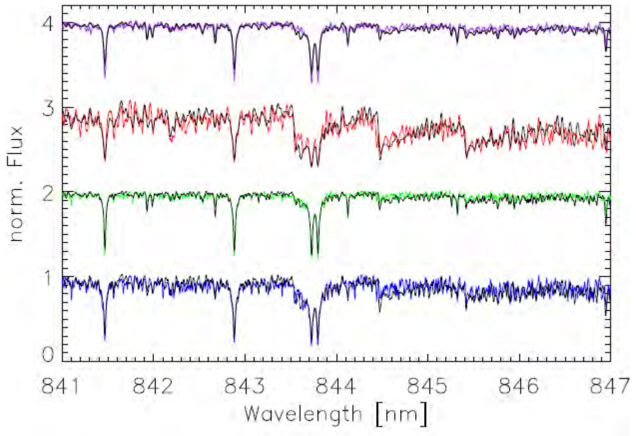


Fig. 2: Spectra of four different low-mass stars around a spectral band-head of molecular TiO. Stellar data are shown in color. Synthetic model spectra are shown for comparison. From such a comparison, we can learn about stellar parameters like temperature and element abundances.

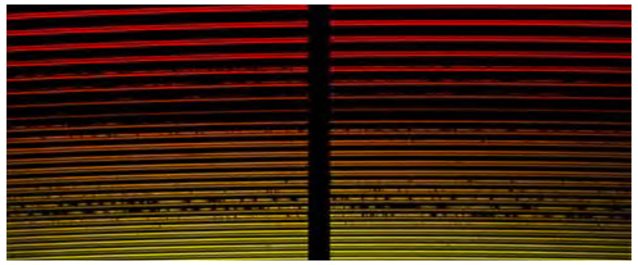


Fig. 3: Unprocessed observation of the low-mass star Gliese 273, named "Luyten's star", observed with the infrared arm of the CARMENES spectrograph. From bottom to top, the imageshows several spectral orders. Wavelength increases from bottom to top and within the orders from left to right. Colors are artificial. Each spectral order shows light from two sources: the spectrum of the star and the spectrum from a Fabry-Pérot Interferometer. Light from this calibration source is obtained simultaneously for accurate frequency calibration as required for the search for extrasolar planets.

Stellar Magnetism

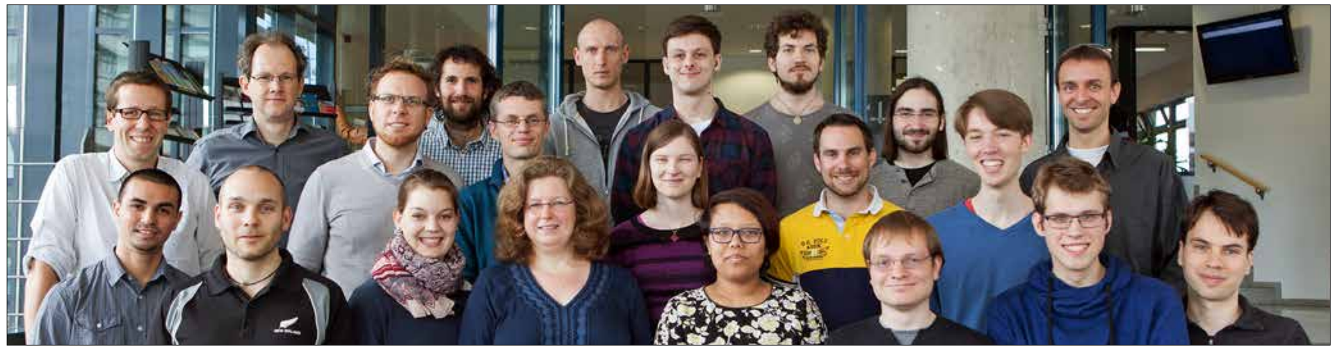
The Sun is known for its 11-year activity cycle during which dark spots, flares, faculae, and other transient events occur. These events are of magnetic nature, the magnetic field is induced by the vast amounts of moving plasma that act as a gigantic dynamo. Magnetic activity also occurs on other stars, often much stronger, manifested in huge spots, massive energy releases, and very strong magnetic fields. Low-mass stars are particularly active showing mean surface magnetic fields that are orders of magnitude larger than the solar one. Measuring these fields is one of our main research areas. We have no good idea how such a strong field affects the star's atmosphere, its evolution, and its environment where life could potentially develop on a terrestrial planet. A key question is the influence of activity on the development of life, and for this, whether the planet itself has a relevant magnetic field. The latter is probably ruled by laws similar to the generation of stellar magnetism and therefore matter of research addressed using similar methods.

Exoplanets

Planets orbit around a star, and planets with a solid surface can potentially host life that can develop into intelligence – this is what we know from Earth. Is this the rule or an exception, and if, it is a natural consequence of physical laws, and how often does it occur? To answer these questions, we need a detailed understanding of the frequency of planets around other stars, about their properties like mass, density, composition, and atmospheres. We need to know the requirements under which they can form and remain in orbit around their host stars. The quest for other planets has always fascinated men and therefore is among the oldest questions of mankind. The science of exoplanets, however, is among the youngest fields; the first successful discovery of a planet in orbit around another sun-like star did not happen before the year 1995 – truly a topic of our generation. Since then, exoplanets developed into one of the most active and prominent research fields. Today, we know thousands of exoplanets and we are starting to look deeper and deeper into the secrets of their existence, their atmospheres, and distribution.

Fig. 5: At the Institut für Astrophysik, we are operating two telescopes: 50cm Cassegrain nighttime telescope (left), and a 50cm Siderostat (right) for daytime observations of the Sun

Fig. 4: The Very Large Telescope of the European Southern Observatory in the Atacama desert on Paranal, Chile. We use the world's largest telescopes to observe stars, brown dwarfs, and planets (© Ulf Seemann).



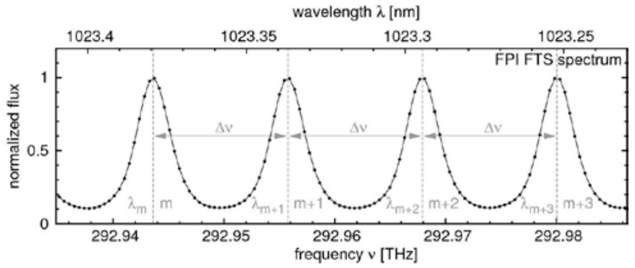


Fig. 6: High-resolution spectrum from a Fabry-Pérot Interferometer taken with our Fourier Transform Spectrograph.

Publications

[1] Reiners, A.; Mrotzek, N.; Lemke, U.; Hinrichs, J.; Reinsch, K. "The IAG solar flux atlas: Accurate wavelengths and absolute convective blueshift in standard solar spectra", Astronomy & Astrophysics 587, 2016, 65

[2] Reiners, A.; Schüssler, M.; Passegger, V.M. "Generalized investigation of the rotation-activity relation: Favoring rotation period instead of Rossby number", The Astrophysical Journal 794, 2014, 144

[3] Anglada-Escudé, G. et al. "Two planets around Kapteyn's star : a cold and a temperate super-Earth orbiting the nearest halo red-dwarf", Monthly Notices of the Royal Astronomical Society 443, 2014, 89

[4] Reiners, A. "Observations of Cool-Star Magnetic Fields", Living Reviews in Solar Physics, 9, 2012, 1

[5] Reiners, A.; Mohanty, S. "Radius Dependent Angular Momentum Evolution in Low-Mass Stars. I.", The Astrophysical Journal 746, 2012, 43

[6] Reiners, A.; Basri, G. "A Volume-limited Sample of 63 M7-M9.5 Dwarfs II. Activity, magnetism, and the fade of the rotation-dominated dynamo", The Astrophysical Journal 710, 2010, 924

[7] Christensen, U.R.; Holzwarth, V.; Reiners, A. "Energy flux determines magnetic field strength of planets and stars", Nature 457, 2009, 167-169

[8] Reiners, A.; Basri, G. "Chromospheric Activity, Rotation, and Rotational Braking in M and L Dwarfs", The Astrophysical Journal 684, 2008, 1390

[9] Reiners, A.; Basri, G. "The First Direct Measurements of Surface Magnetic Fields on Very Low Mass Stars", The Astrophysical Journal 656, 2007, 1121-1135

[10] Reiners, A.; Schmitt, J.H.M.M "Rotation and differential rotation in field F- and G-type stars", Astronomy and Astrophysics 398, 2003, 647-661

Precision Spectroscopy and Astronomical Instrumentation

As member of the European Southern Observatory (ESO), institutes in Germany have access to ESO's facilities in South America, including the Very Large Telescope (VLT). We secure a large fraction of our telescope time through participation in consortia that develop and build instruments for astronomical observatories. A major project of our group is CARMENES, a visual and near-infrared spectrograph for the search for exoplanets. CARMENES is a German-Spanish consortium that receives several hundred observing nights for the development and construction of two high-precision spectrographs. Other examples are the infrared spectrograph CRIRES+ for the VLT, and the planned high-resolution spectrograph for ESO's extremely large telescope E-ELT. Our focus is on wavelength (or frequency) calibration. Many of our developments are built in the institute or physics faculty workshops. Tests and characterization are carried out in our laboratories where we have access to high-precision instrumentation like a Fourier Transform Spectrometer and a Laser Frequency Comb. We are in the unique position that our laboratory facilities allow tests with light from the Sun and other stars; the institute operates two telescopes: a siderostat for observations of the Sun and a 50cm telescope for nighttime observations. Light from both instruments can be fed into our laboratory. We are observing the Sun as a star to improve our understanding of stellar observations, from which for example we produced a standard atlas of the solar flux.

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[1] http://carmenes.caha.es/

[2] https://www.eso.org/sci/facilities/develop/instruments/crires_up.html

[3] https://www.eso.org/sci/facilities/eelt/

Ansgar Reiners

Born in 1973, Ansgar Reiners studied physics in Heidelberg and Uppsala, Sweden. In 2000, he finished his Diploma on magnetic hot star stars before he went to Hamburg for his PhD. In 2003, he finished his PhD thesis on differential rotation in sun-like. As a Marie Curie International Outgoing Fellow he spent two years, from 2004 to 2006, at the University of California at Berkeley, where he started working on magnetic fields of low mass stars and brown dwarfs. In 2006, he returned to Germany and came to Göttingen in 2007, where he established a research group as an Emmy Noether Fellow followed by a Heisenberg Professorship. Since 2011, he is a full professor at IAG.

Solar and Stellar Interiors

The magnetic field in stars like the Sun is commonly explained by dynamo action, whereby subsurface flows amplify and maintain the magnetic field. It is not clear, however, how and where the dynamos operate, and what sets the periods of activity cycles. Naturally excited oscillations of the Sun and stars inform us about their internal structure, dynamics, and evolution. Our group activities focus on the observation, analysis and interpretation of solar and stellar oscillations, i.e. helioseismology and asteroseismology. Research is driven by space-based observations from the SDO and Kepler missions and by modeling wave propagation through stellar interiors. Our group is also involved in preparations for the ESA Solar Orbiter and PLATO missions, which are to be launched in 2018 and 2024 respectively. Solar Orbiter will study the polar regions of the Sun, while PLATO will enable asteroseismology to be carried out on many tens of thousands of cool dwarf stars, including planet-host stars.

Solar interior in 3D

Millions of modes of vibration, excited by solar convection, enable astrophysicists to see inside the Sun, just as geophysicists can probe the internal structure of the Earth using earthquakes. Over the past twenty years, helioseismology has produced a considerable number of discoveries in solar, stellar, and fundamental physics. Helioseismology has provided by far the most precise tests for the theory of stellar structure and evolution, indicating, in particular, that the standard model of particle physics should be revised in order to solve the solar neutrino problem. Today, the most exciting aspect of helioseismology is the search for clues regarding the origin and variability of the Sun's magnetic field, possibly the most important unsolved problem in solar physics. The magnetic field lines are wound up, amplified and twisted by internal shearing motions and convective motions, in such a way as to cause surface activity in the form of sunspots and active regions. Helioseismology is the only tool we can use to confirm this paradigm: by mapping internal mass motions, structural asphericities, and their temporal variations. Thanks to over 20 years of observations from the SOHO and SDO spacecraft (Fig. 1), helioseismology has already provided some important results, revealing regions of rotational shear in the Sun's interior and solar-cycle variations in the rotation rate.

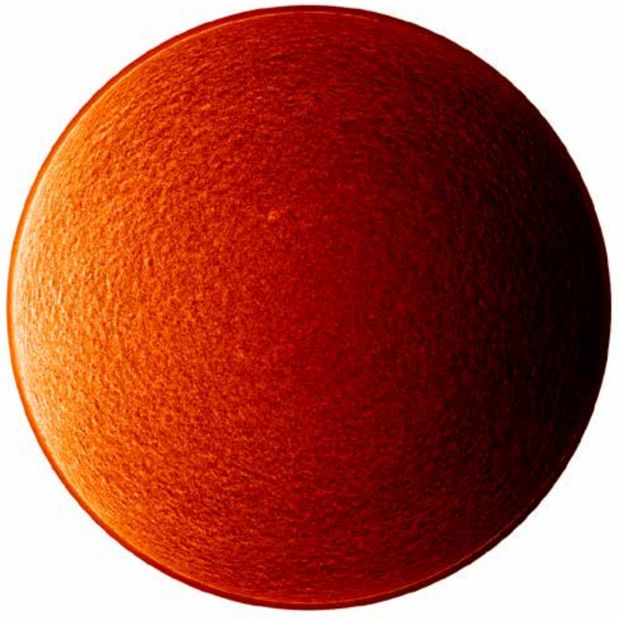


Fig. 1: Line-of-sight velocity measured by SDO at the surface of the Sun. The signal consists of rotation, convection (granulation and supergranulation), as well as solar oscillations.

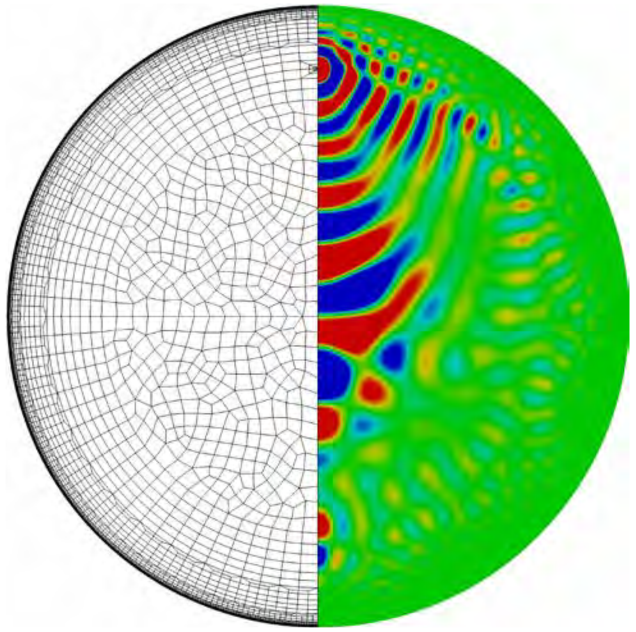


Fig. 2: Numerical simulations of wave propagation in heterogeneous backgrounds are key tools for interpreting helioseismic observations. The figure shows an example mesh for a finite element code (left) and an example Green's function calculation at fixed frequency (right).

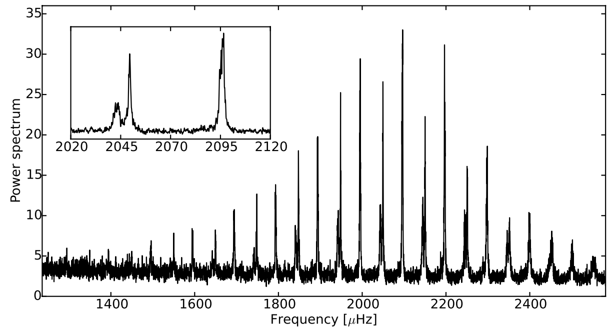


Fig. 3: Power spectrum of oscillation of the Sun-like star KIC 006116048 as observed by Kepler. Each peak corresponds to a resonant mode frequency. When interpreted all at once, mode frequencies constrain the fundamental parameters of stars.

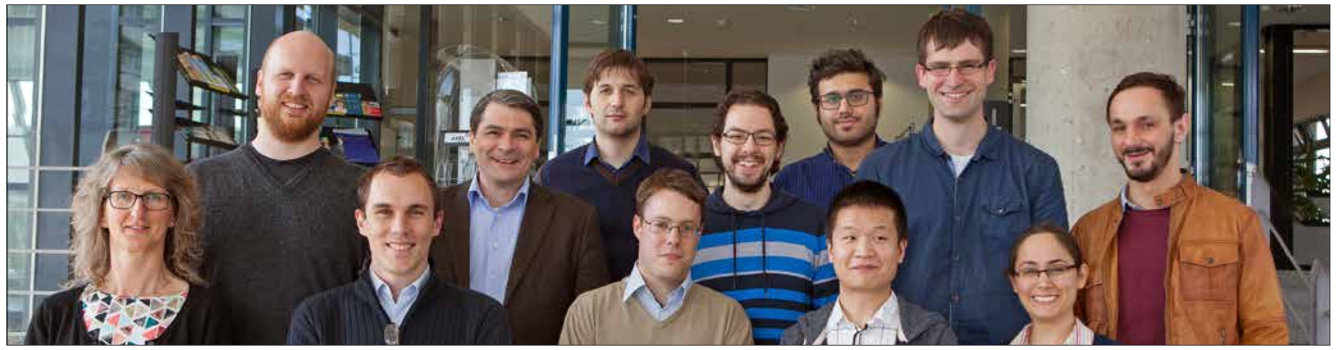
The next advances are expected to come from local helioseismology, which provides 3D views of the solar interior. Although still a developing science, it has already pinpointed a mechanism for the latitudinal transport of the magnetic flux that could determine the eleven-year period of the solar cycle. Detailed 3D maps of subsurface flows will be key to understanding the complex phenomena that control solar activity. In another application, local helioseismology can be used to detect active regions on the far side of the Sun, thus providing advance warning for extreme space weather events.

The launch of SDO in 2010 was an important technological step for helioseismology. With a high spatial resolution over the entire visible solar hemisphere, SDO gives continuous access to high solar latitudes and enables us to follow the evolution of solar active regions as they move across the solar disk. Before the end of this decade, ESA's Solar Orbiter should, for the first time, give access to the subsurface dynamics of the Sun's polar regions. Further advances will rely on new techniques of computational helioseismology (Fig. 2), inspired from terrestrial seismology.

Precision stellar parameters

Asteroseismology, the study of global oscillations of distant stars, has entered a very exciting period of discovery. Many stars, covering a wide range of masses and evolutionary states, are known to oscillate. Much progress has been made with the operation of the CNES/ESA CoRoT satellite and the NASA Kepler mission, which have delivered excellent oscillation power spectra for dozens of Sun-like stars (Fig. 3).

Stellar oscillations have considerable diagnostic potential and allow stellar mass and age to be determined with unprecedented precision. Such knowledge for a sufficient sample of stars will revolutionize stellar evolution and galactic evolution studies. Asteroseismology also has the potential to constrain internal stellar rotation and locate the borders of convection and ionization zones. This information would help to understand dynamo-generated stellar activity cycles and the solar-stellar connection. These exciting possibilities for the study of stellar structure, evolution, and activity will be fully realized once future missions deliver high-precision observations for a large and diverse sample of bright stars.



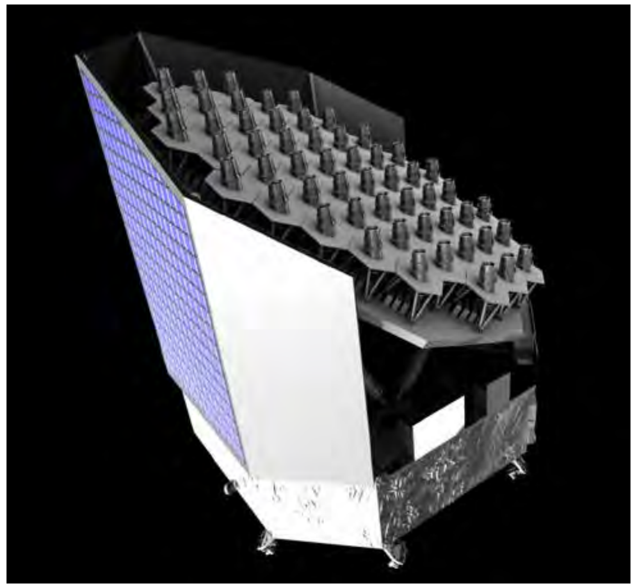


Fig. 4: Artist's impression of PLATO. The payload consists of 34 telescopes, which will measure the brightness variations of about one million stars over a large fraction of the sky.

The asteroseismology of planet-host stars will be particularly useful to characterize the properties of detected exoplanets. Precise seismic estimates of the masses and radii of host stars will make it possible to infer the masses and radii of transiting planets. With asteroseismology, the ages of planet-host stars will be measured, which will be crucial information for studies on the evolution of exoplanetary systems.

PLATO is an ESA M-class mission, scheduled for launch in 2024 (Fig.4). PLATO will measure the oscillation frequencies of over 80,000 Sun-like stars, bright enough to be studied further with high-precision spectroscopy from the ground. Confirmed planetary systems will be fully characterized through the asteroseismology of their host stars and the follow-up observations. Our group is an important partner in the PLATO mission consortium, as it will contribute to the calibration and processing of the PLATO observations from the ground.

[1] Ball, W.H.; Gizon, L. 2014: A new correction of stellar oscillation frequencies for near-surface effects, Astron. & Astrophy., 568, A123

[2] Gizon, L.; Birch, A.C.; Spruit, H.C. 2010: Local Helioseismology: Three-Dimensional Imaging of the Solar Interior, Annual Review of Astron. & Astrophys., 48, 289-338

[3] Langfellner, J.; Gizon, L.; Birch, A.C. 2015: Spatially resolved vertical vorticity in solar supergranulation using helioseismology and local correlation tracking, Astron. & Astrophys., 581, A67

[4] Löptien, B.; Birch, A.C.; Gizon, L.; Schou, J.; Appourchaux, T.; Blanco Rodríguez, J.; Cally, P.S.; Dominguez-Tagle, C.; Gandorfer, A.; Hill, F.; Hirzberger, J.; Scherrer, P.H.; Solanki, S.K. 2015: Helioseismology with Solar Orbiter, Space Science Reviews 196, 251-283

[5] Nielsen, M.B.; Schunker, H.; Gizon, L.; Ball, W.H. 2015: Constraining differential rotation of Sun-like stars from asteroseismic and starspot rotation periods, Astron. & Astrophys., 582, A10

[6] Reinhold, T.; Gizon, L. 2015: Rotation, differential rotation, and gyrochronology of active Kepler stars, Astron. & Astrophys., 583, A65

Laurent Gizon

Laurent Gizon obtained his PhD in physics from Stanford University in 2003 and worked there as a Research Associate until 2005. In 2005 he started a Max Planck Research Group at the Max Planck Institute for Solar System Research in Katlenburg-Lindau. In 2011 he was jointly appointed Professor of Astrophysics at the University of Göttingen and Director at the Max Planck Institute for Solar System Research. Prof. Gizon has been the recipient of several awards including the JOSO Prize for Solar Physics (2005), a Starting Grant of the European Research Council (2007), the Karen Harvey Prize of the American Astronomical Society (2009), and two NASA Group Achievement Awards (2012 and 2016). His current research focuses on analyzing oscillations of the Sun and stars measured by SDO and Kepler.

Astrophysical Cosmology

Cosmology seeks to understand the structure and evolution of our universe as a whole in physical terms. In the past decades, it has advanced into a quantitative science driven by a wealth of data from satellites and ground based telescopes. Numerical simulations carried out on the world's most powerful computers are necessary to extract the underlying physics from observations of complex, nonlinear phenomena involving gravity, gas dynamics, radiation transport, and magnetic fields. Presently, the main parameters describing the contents and geometry of our universe are known at the level of a few percent. Two of the major challenges that remain are to understand the nature of the dark matter and dark energy that make up roughly 95 percent of the matter content, and to confirm or falsify the occurrence of a phase of inflation prior to the hot big bang.

Physics of the Very Early Universe

A number of serious problems due to combination of the causal structure and the nearly flat spatial geometry of our universe can be solved by postulating a phase of accelerated expansion called "inflation" in the very early universe. In addition to creating the homogeneous spatial geometry that we observe, inflation predicts the generation of small curvature perturbations from quantum fluctuations which later gave rise to the formation of cosmological structures. Hence, an accurate reconstruction of the statistical distribution of primordial density fluctuations allows a rare glimpse at physics at otherwise inaccessibly high energy scales, perhaps as high as the Planck scale where quantum gravity becomes relevant.

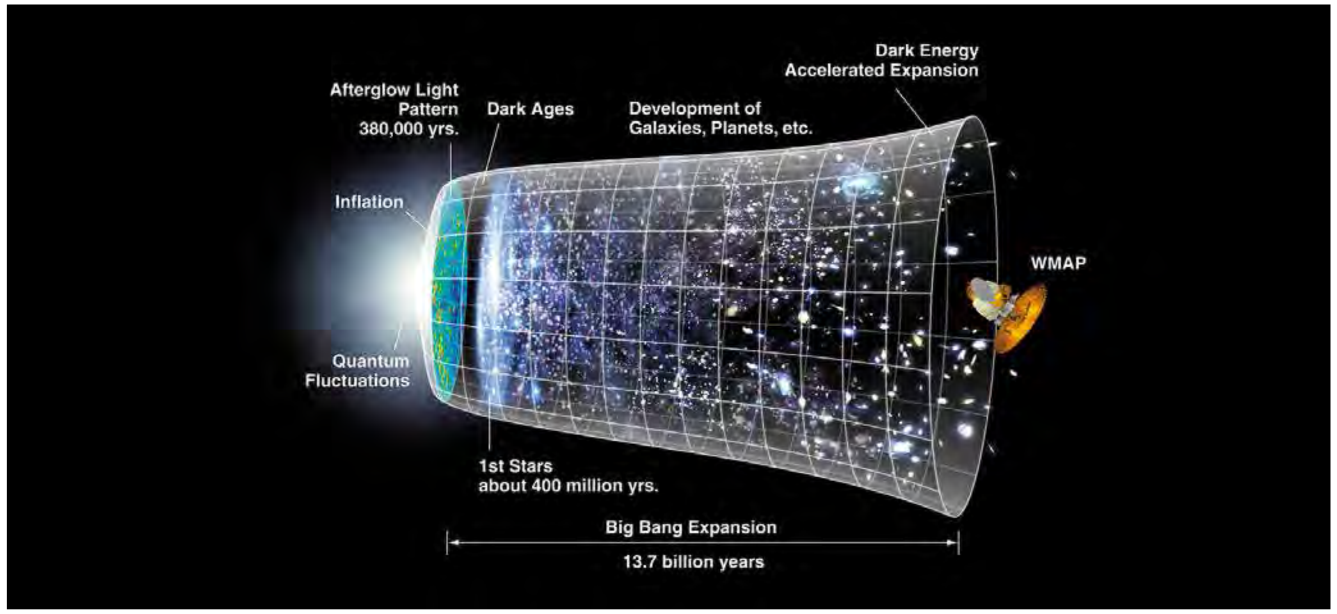


Fig. 1: Timeline of the universe. The far left depicts the earliest moment we can now probe, when a period of "inflation" produced a burst of exponential growth in the universe. For the next several billion years, the expansion of the universe gradually slowed down as the matter in the universe pulled on itself gravitationally. More recently, the expansion has begun to speed up again as the repulsive effects of dark energy have come to dominate the expansion of the universe. (NASA / WMAP Science Team)

Fig. 2: Simulations of the formation of cosmological structures numerically solve the coupled equations of gas dynamics and pressureless dark matter under the influence of their own gravity on an expanding background. The figure shows a volume rendering of the baryon density of a collapsed halo with approximately the same mass as our Galaxy.

This goal presents two very distinct challenges. First, we must look for unique signatures in the predictions of candidate theories for inflation – constructed, for instance, in the framework of superstring cosmology – in order to identify the underlying physics. Above all, this part of the work involves expertise in high energy and gravitational physics. Second, the primordial fluctuation spectrum must be extracted from observations of the cosmic microwave background (CMB) and the distribution of astrophysical objects – stars, galaxies, and intergalactic gas – governed by a variety of complex, nonlinear phenomena which must be well understood in order to be modeled accurately. Here, numerical simulations and statistical analysis of huge data sets require the use of supercomputers.

From Intergalactic Gas to Stars and Galaxies

To our current knowledge, cosmological structures have evolved from the gravitational collapse of dark matter, followed by infalling baryonic gas from which, in turn, stars and galaxies were formed. Observations of quasar absorption lines and, using radio telescopes currently under development, the 21cm emission of neutral hydrogen, allow us to measure the density and temperature distribution of the gas at different epochs. By accurately modeling the dominant physical processes, we can indirectly learn more about the properties of the dark matter – for instance, whether it consists of heavy elementary particles or light scalar fields – and a possible time dependence of the dark energy proposed to explain the accelerated expansion of the universe.

This combination of nonlinear, non-equilibrium phenomena can only be treated numerically with the help of large-scale simulations. Further difficulties arise from the strongly resonant scattering behavior of Lyman alpha radiation which serves as the primary diagnostic for distant galaxies. In order to predict the fraction of Lyman alpha radiation that is scattered in the intergalactic medium (as opposed to reaching our telescopes directly from each emitting galaxy), we run large radiation transport simulations that follow the trajectories of millions of photons.

Apart from exploring the physics of distant galaxies and the diffuse gas in between them, these simulations contribute to the analysis of the HETDEX survey which uses Lyman alpha emitters to map out the expansion history of the universe. The Hobby-Eberly-Telescope Dark Energy Experiment (HETDEX) is a high-redshift galaxy survey that will detect roughly 0.8 million Lyman alpha emitters at redshifts $z = 1.9 - 3.5$ starting in 2016. Its key science goal is to improve current bounds on time variability of the cosmological constant using baryonic acoustic oscillations in the galaxy power spectrum.

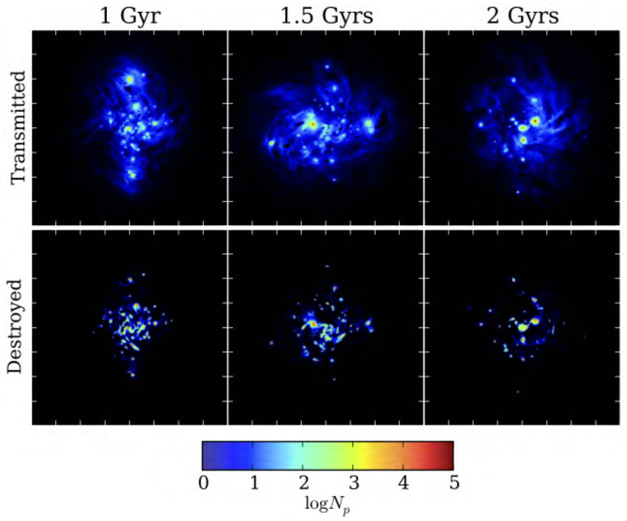
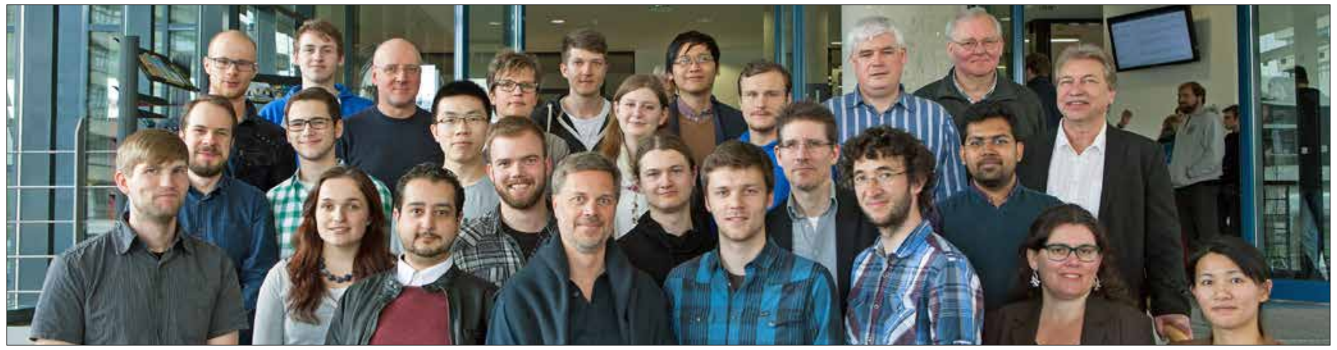


Fig. 3: Spatial distribution of escaping (top) and absorbed Lyman alpha photons (bottom) for various snapshots of a high-resolution simulation of an isolated disk galaxy at different ages. Each plot shows the central 130 thousand lightyears of the disk.



Exploring the nature of dark matter

The existence of a dark, cold (i.e., nonrelativistic), and nearly collisionless matter component called „dark matter" is a meanwhile well established part of the standard model of cosmology, confirmed by independent probes ranging in scale from the Hubble length to galactic radii and in time from the first seconds to the last million years of cosmic evolution. Yet all attempts to identify the nature of dark matter, for instance in direct or indirect detection experiments or by direct production at the LHC, have so far been unsuccessful. Most candidates for elementary particle dark matter can be classified into one the following two categories. Weakly Interacting Massive Particles (WIMPs), such as the lightest supersymmetric partner (LSP), are thought to be thermally produced and have typical masses of more than 100 GeV. Being nonrelativistic and dissipationless in the standard cold dark matter (CDM) scenario, their dynamics can be numerically represented by large N-body simulations.

On the other hand, Weakly Interacting Sub-eV Particles (WISPs) have to be produced non-thermally in order to be viable dark matter candidates. Their most popular representative is the QCD axion which is a predicted by-product of the Peccei-Quinn solution to the strong CP problem. Still, as long as the axion mass is significantly above roughly 10^{-22} eV, axions are dynamically indistinguishable from CDM on galactic and cosmological scales and hence can also be treated numerically with N-body methods.

This is not true, however, for the class of ultra-light axions predicted by string theory whose masses can be of the order of 10^{-22} eV or less. In this case, the de Broglie wavelength of virialized particles in dark matter halos is of the order of the halo core radius. In the linear treatment of cosmological perturbation growth, it gives rise to an effective Jeans length below which the growth of structure is suppressed. These effects have been used to derive constraints on the mass of ultra-light axions from the observations of the CMB, cosmic reionization, and dwarf galaxy rotation curves. The nonlinear behavior of dark matter clustering can no longer be computed by means of N-body simulations which fail to account for the quantum effects. Our group has been developing two distinct methods for cosmological simulations with ultra-light axion dark matter, one based on the Schrödinger equation and one using the Madelung fluid formalism. These methods will allow us to explore the physics of galaxy formation with ultra-light axion dark matter in the fully nonlinear regime.

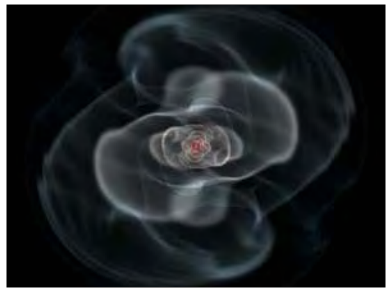


Fig. 4: Volume rendering of the density of two ultra-light axion dark matter halos immediately after they merged into one gravitationally bound object. The dynamics is described by the Schrödinger equation coupled to the Poisson equation for the self-gravity of the axion field.

[1] *Large-eddy simulations of isolated disc galaxies with thermal and turbulent feedback,* H. Braun, W. Schmidt, J.C. Niemeyer and A.S. Almgren, MNRAS, 442, 3407 (2014)

[2] *Beamed Lyman Alpha Emission through Outflow-Driven Cavities,* C. Behrens, M. Dijkstra and J.C. Niemeyer, Astron. Astrophys., 563, A77 (2014)

[3] *Impact of baryonic streaming velocities on the formation of supermassive black holes via direct collapse,* M. A. Latif, J. C. Niemeyer, D. R. G. Schleicher, MNRAS, 440, 2969 (2014)

[4] *The formation of massive Pop III stars in the presence of turbulence,* M.A. Latif, D.R.G. Schleicher, W. Schmidt and J.C. Niemeyer, Astrophys. J. Lett., 772, L3 (2013)

[5] *Effects of Lyman alpha scattering in the IGM on clustering statistics of Lyman alpha emitters,* C. Behrens and J.C. Niemeyer, Astron. Astrophys., 556, A5 (2013)

Jens Niemeyer

Born near Munich in 1968, Jens Niemeyer received his Diploma and PhD from the Technical University of Munich. For his PhD thesis, he developed models for thermonuclear explosions of White Dwarf stars under the supervision of Wolfgang Hillebrandt at the Max-Planck-Institut for Astrophysics in Garching. As part of this research, he spent one year at the University of California in Santa Cruz working in Stan Woosley's group. His interest in the physics of the very early universe started as a postdoc when he began to work on primordial black holes with Karsten Jedamzik. He went to the University of Chicago as an Enrico-Fermi Fellow in 1997 before returning to Garching, where he obtained his habilitation in 2001. Following a faculty position at the University of Würzburg, he started his position at the University of Göttingen in April 2009 where he is leading a group in theoretical and observational cosmology.

Computational Radiation Hydrodynamics

Flows in the presence of strong radiation fields are typical for astrophysical situations. Their theoretical description and numerical treatment is the subject of "Computational Radiation Hydrodynamics". An example for research in this field is described here.

Radiation hydrodynamics of stellar envelopes

The envelopes of many luminous stars are characterized by a large contribution of the radiation pressure to the total pressure. Massive primordial stars, massive stars in the Galaxy like the spectacular object η Carinae, and some central stars of planetary nebulae and their progenitors are examples which exhibit this situation. The large fraction of radiation pressure gives rise to violent instabilities, whose mechanism and final result is investigated using a theoretical approach.

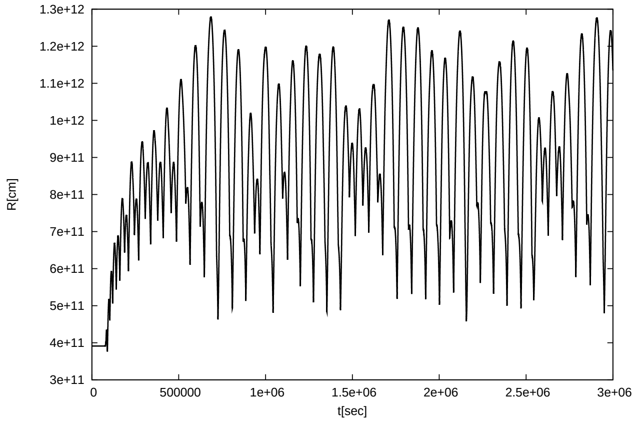


Fig. 1: Stellar radius as a function of time for a massive Wolf-Rayet star (from [2]). A radiation driven instability in the stellar envelope leads to finite amplitude pulsations.

Stellar evolution calculations and the linear stability analysis of the generated stellar models form the basis of these studies. For unstable stellar models the time evolution of the instability is then followed numerically into the nonlinear regime using a radiation hydro code [1] to determine the fate of the corresponding star. Depending on the particular stellar parameters, the instabilties can lead to finite amplitude periodic pulsations (Fig. 1) or may show indications of chaotic behaviour. The mechanical energy flux associated with the pulsations turns out to be high enough to drive a stellar wind with significant mass loss rates [2].

Stellar mass loss is fundamental not only for stellar evolution but also for the environment of galaxies, yet it is still a poorly understood phenomenon. Accordingly, the aim of the current studies consists of proving strictly a connection between stellar pulsations and mass loss for the luminous stars considered. Numerically determined mass loss rates will considerably improve not only the understanding of their evolution but will also provide more reliable input for galactic matter circulation.

[1] Grott, M.; Chernigovski, S.; Glatzel, W.: *The simulation of non-linear stellar pulsations,* Mon. Not. R. Astron. Soc. 360, 2005, 1532 - 1544.

[2] Glatzel, W.: *Nonlinear strange-mode pulsations,* Comm. in Asteroseismology 158, 2009, 252 - 258.

Wolfgang Glatzel

Wolfgang Glatzel received his PhD in physics from the University of Göttingen in 1983. After postdoc positions at the Institute of Astronomy in Cambridge, England, and the Max Planck Institute for Astrophysics, Garching, he returned to Göttingen and completed his habilitation in 1992. He holds a position as Akademischer Rat at the Institute for Astrophysics Göttingen and was appointed außerplanmäßiger professor in 1998. His research interests are theoretical and numerical astrophysics, in particular astrophysical fluid mechanics, stellar structure, stability and evolution, and the physics of accretion discs.

Active and Normal Galaxies

Normal galaxies consist of around 100 billion stars, in addition to significant amounts of gas and dust. Galaxies evolve on cosmological timescales (14 billion years) with respect to their morphology, stellar composition, gaseous content and chemical composition. Massive black holes, a billion times more massive than our sun, reside in the center of nearly every galaxy in the Universe. The central activity around these black holes enables us to measure their mass and to study the physics of their close environment in Active Galactic Nuclei (AGN). The activity is connected with the feeding of fresh gas from the outskirts of the galaxy into the central black hole. Tidal interactions of moving galaxies might be responsible for the feeding processes. Active Galactic Nuclei are the most luminous objects in the Universe.

By using two- and three-dimensional spectroscopy, multifrequency observations (at optical, UV, radio, and X-ray frequencies), as well as by comparison with model calculations we are working on the following topics:

- Physical processes in the central region of AGN: their central accretion disks, structure and kinematics in the innermost regions that immediately surround the central black hole.
- Galaxy studies: morphology, internal kinematics, starburst activity, stellar population/evolutionay synthesis.
- Environment of active and normal galaxies: merging of galaxies, interacting galaxies, and clusters of galaxies, study of deep fields.

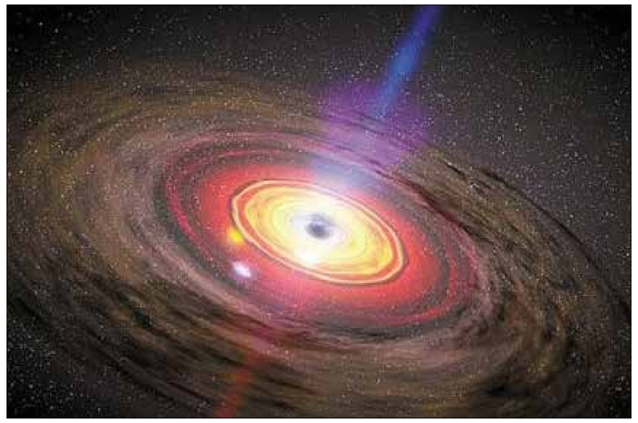


Fig.1: Artist's impression of the innermost region in AGN. A disk of hot gas is surrounding the central black hole. Two jets of high energy particles are propelled away from the vicinity of the black hole.

Fig. 2: The interacting galaxies NGC5426-5427 (Gemini observatory).

[1] Kollatschny, W., Schartel, N., et al.: "Proving strong magnetic fields near to the central black hole in the quasar PG0043+039 via cyclotron lines", 2015, A&A 577, L1

[2] Kollatschny, W., Zetzl, M.: "Accretion disk wind as explanation for the broad-line region structure in NGC5548", 2013, A&A 551, L6

[3] Kollatschny, W., Zetzl, M.: "Broad-line active galactic nuclei rotate faster than narrow-line ones ", 2011, Nature 470, 366

[4] Kessler, R., ... Kollatschny, W., ... : "First Year SDSS-II Supernova Results: Hubble Diagram and Cosmological Parameters ", 2009, ApJS 185, 32

[5] Kollatschny, W.: "Spin orientation of supermassive black holes in active galaxies", 2003, A&A 412, L61

Wolfram Kollatschny

Wolfram Kollatschny obtained his PhD in 1983 and his habilitation in 1991 at the University of Göttingen. He worked as a visiting professor at the University of Erlangen (1991), at the University of Texas in Austin (1999-2000), and at the University of Padua (2008, 2010). He carried out observations worldwide, at nearly every major optical observatory (ESO/Chile, LaPalma/Spain, MacDonald Observatory/USA, CalarAlto/Spain, Sutherland/SouthAfrica), with radio telescopes (VLA/NewMexico), and with satellite telescopes (IUE, ROSAT, HST). He was the German representative to the ESO Users Committee, a member of the program committee of Calar Alto Observatory and a Board Member of many international large scale telescope projects (Hobby-Eberly Telescope in Texas, Southern African Large Telescope, European Network of Ultraviolet Astronomy).

Quantum Field Theory

Quantum field theory is the „language" describing the fundamental physics in the relativistic microcosmos, notably elementary particles. In the search for candidates for Dark Matter and Inflation and in the realization of baryogenesis, it is also relevant for Cosmology, the physics at the largest scales. Our groups work on complementary questions on QFT, by studying new models and applications in particle physics and cosmology, and by analyzing the inner mathematical structures of QFT.

New models for Cosmology (Laura Covi)

Even if the Standard Model of particle physics, based on QFT and gauge symmetry, is one of the most successful physical models we have, tested to unprecedented precision in collider and low energy experiments, we know without doubts that it is not complete. On one side it does not include the gravitational force, which is still treated classically in General Relativity, on the other side it does not provide explanations for our cosmological observations of Dark Matter and Dark Energy, nor can give a realization of an inflationary phase.

In our group we develop and study extensions of the Standard Model that can address these cosmological puzzles and provide a more complete cosmological history. We study old and new mechanisms for generating Dark Matter and the Baryon Asymmetry of the Universe as well as the conditions on the theories imposed by the present de Sitter phase and a past inflationary epoch. We compare the new models with present data and give predictions for future observables, which may help disentangle the different models.

The long-term goal is to realize a merger between the particle physics Standard Model and the Standard Cosmological model into a new and possibly all-compassing „Model Beyond the Standard Models".

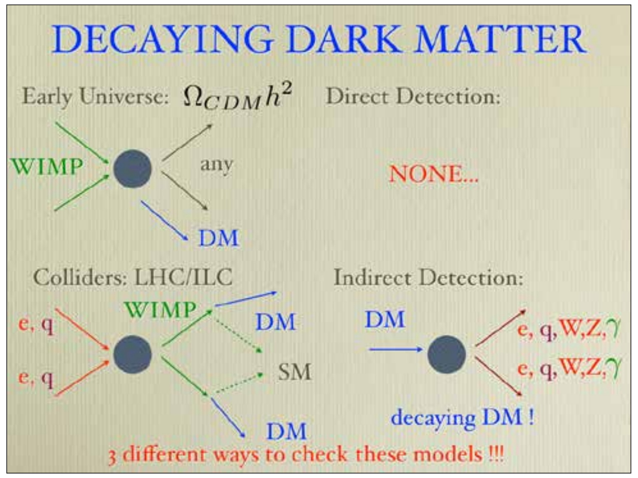


Fig. 1: Connection between production and possible detection for decaying Dark Matter models.

Dark Matter and Baryogenesis

In the last decades a wealth of evidence for the presence of Dark Matter in the Universe has been accumulated and we have a relatively clear idea what it cannot be, e.g. no particle in the Standard Model of particle physics can play its role. But we are still missing a convincing evidence for a particular type of candidate. Since cosmology is not very sensitive to the details of the interactions of the Dark Matter particle at short distances, many different Dark Matter candidates have been proposed, with couplings from the electroweak strength to the purely gravitationally interacting case.

In our group we are particularly interested in candidates which interact much more weakly than the weak interaction and are embedded in the extensions of the Standard Model of particle physics for symmetry reasons, like the gravitino, superpartner of the graviton, or the axino, superpartner of the Peccei-Quinn axion. Even if these candidates are very difficult to detect in direct detection of DM, they can leave significant signatures in the cosmic rays and the photon and neutrino background via their decay and give rise to special signals at the LHC, especially connected to exotic long-lived particles [Fig. 1].

Another interesting puzzle in cosmology is the question of why Dark Matter and Baryonic Matter have very similar energy densities, differing just by a factor of five. In many models these two components arise in completely different cosmological epochs and through unrelated production processes, giving rise to an amazing coincidence of numbers. We proposed and are studying a particular class of models, such that one can achieve at the same time Dark Matter production and baryogenesis, so that the similarity in the energy densities can be traced to particular couplings in the theory. One possible embedding of such models is in supersymmetry with R-parity violation.

Inflation

After many years since its proposal, inflation is still a paradigm in search of a model. From the observational point of view, the simplest slow-roll models seem to fit the data perfectly and there seem to be no special feature during the inflationary dynamics. In our group we study models of inflation in connection with the present vacuum of the theory, trying to realize in supersymmetric models the present de Sitter phase of acceleration. The requirement of a past and present de Sitter phase, gives very strong constraints on the scalar field sector of the theory. Another important issue is the renormalization in curved space-times and its application to inflationary models.

Algebraic methods in quantum field theory (Karl-Henning Rehren)

One of the great challenges of quantum field theory, complementary to the computation of perturbative or lattice approximations, is to rigorously establish that particle interactions are compatible with the fundamental requirements: relativistic invariance, causality, and quantum probabilistic interpretation. This is a hard task even at the level of simplified models.

In our group, we pursue an operator algebraic approach based on a far-reaching insight due to R. Haag: For the physical interpretation of (say) a collider experiment, in terms of particle species and their interactions, it is more important to record where something has happened („particle tracks"), than what exactly has been measured. Translated into mathematical language, a model of quantum field theory is determined by the knowledge of the subalgebras of Hilbert space operators that correspond to localized observables, rather than the precise field content and its equations of motion. Because of the essential role of Einstein's principle of causality: localized observables commute at spacelike distance, the approach is known under the brand mark „Local Quantum Physics".

The framework opens conceptionally new approaches to the concept of charge, to the IR problem [5], and to QFT on curved spacetime. Much progress has been made towards the construction of new nontrivial models, e.g., by variants of a deformation method originally developed in our group (G. Lechner, PhD thesis 2006). Model-independent structure analysis of two-dimensional models with conformal symmetry has led to classification results (universality classes), showing that in low dimensions there is much more room beyond the Fermi-Bose alternative.

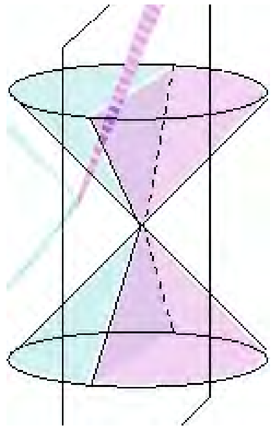


Fig. 2: Schematic view of a phase boundary in relativistic quantum field theory.

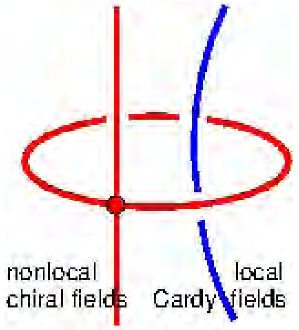


Fig. 3: Diagrammatic formula (involving the „braiding") for the projection operator onto a local quantum field theory contained in an auxiliary theory of nonlocal fields.

The QFT group (also including D. Bahns in the Mathematical Institute) initiated and hosts an international Workshop series „Foundational and constructive aspects of quantum field theory" in which these and related issues, like quantum field theory on curved spacetime, are addressed. It is held twice a year, alternating between Göttingen and other places.

Boundaries

Quantum field theories with boundaries find increasing attention. The boundary (Fig. 2) may be a conducting plate, causing the Casimir effect; it may be an interface between thermodynamic phases; or it may be a gravitational horizon with a holographic relationship between observables in the bulk and on the boundary. Two-dimensional models with conformal symmetry allow for rigorous treatments. We have studied the holographic behaviour of quantum observables in the presence of a hard boundary, and we have classified algebraic boundary conditions at phase boundaries that are transparent for energy and momentum [6]. Ongoing research aims at a more general understanding of possible physical phenomena between these two extremes.

Quantum Statistics

The fundamental Spin-Statistics Theorem does not hold in low-dimensional spacetime. Here, far more possibilities than the Fermi-Bose alternative arise for the quantum statistics. These are described by the braid group which admits complex phases or matrices to control the permutation of particles. In recent years it became clear that the braiding encodes far more information than the statistics; e.g., it also constrains the possibilities of embedding one theory into another (see Fig. 3), and it controls admissible boundary conditions. We are investigating methods how to extract more, even dynamical information.

Infinite spin

Particles transforming in the so-called „infinite spin representation" of the Poincaré group have never been observed in a detector. Various No-Go theorems (beginning with J. Yngvason's Göttingen diploma thesis in 1969) support the explanation that this is due to the bad localization properties of the associated quantum fields. The recent discovery that multi-particle states can be much better localized, raised hopes of finding local composite observables. We could exclude this possibility for non-interacting infinite spin particles [7]; the case with self-interaction (Dark Matter?) is still open.

[1] R. Catena, L. Covi: SUSY dark matter(s), Eur. Phys. J. C 74 (2014) 2703, [arXiv:1310.4776 [hep-ph]]

[2] G. Arcadi, L. Covi: Minimal Decaying Dark Matter and the LHC, JCAP 1308 (2013) 005, [arXiv:1305.6587 [hep-ph]]

[3] G. Arcadi, L. Covi, M. Nardecchia: Out-of-equilibrium Baryogenesis and SuperWIMP Dark Matter, Phys. Rev. D 89 (2014) 095020, [arXiv:1312.5703 [hep-ph]]

[4] G. Arcadi, L. Covi, M. Nardecchia: Gravitino Dark Matter and Low Scale Baryogenesis, Phys. Rev. D 92 (2015) 115006, [arXiv:1507.05584 [hep-ph]]

[5] D. Buchholz, J.E. Roberts: New light on infrared problems: Sectors, statistics, symmetries and spectrum, Commun. Math. Phys. 330 (2014) 935-972.

[6] M. Bischoff, R. Longo, K.-H. Rehren, Y. Kawahigashi: Phase boundaries in algebraic conformal QFT, Commun. Math. Phys. 342 (2016) 1-45.

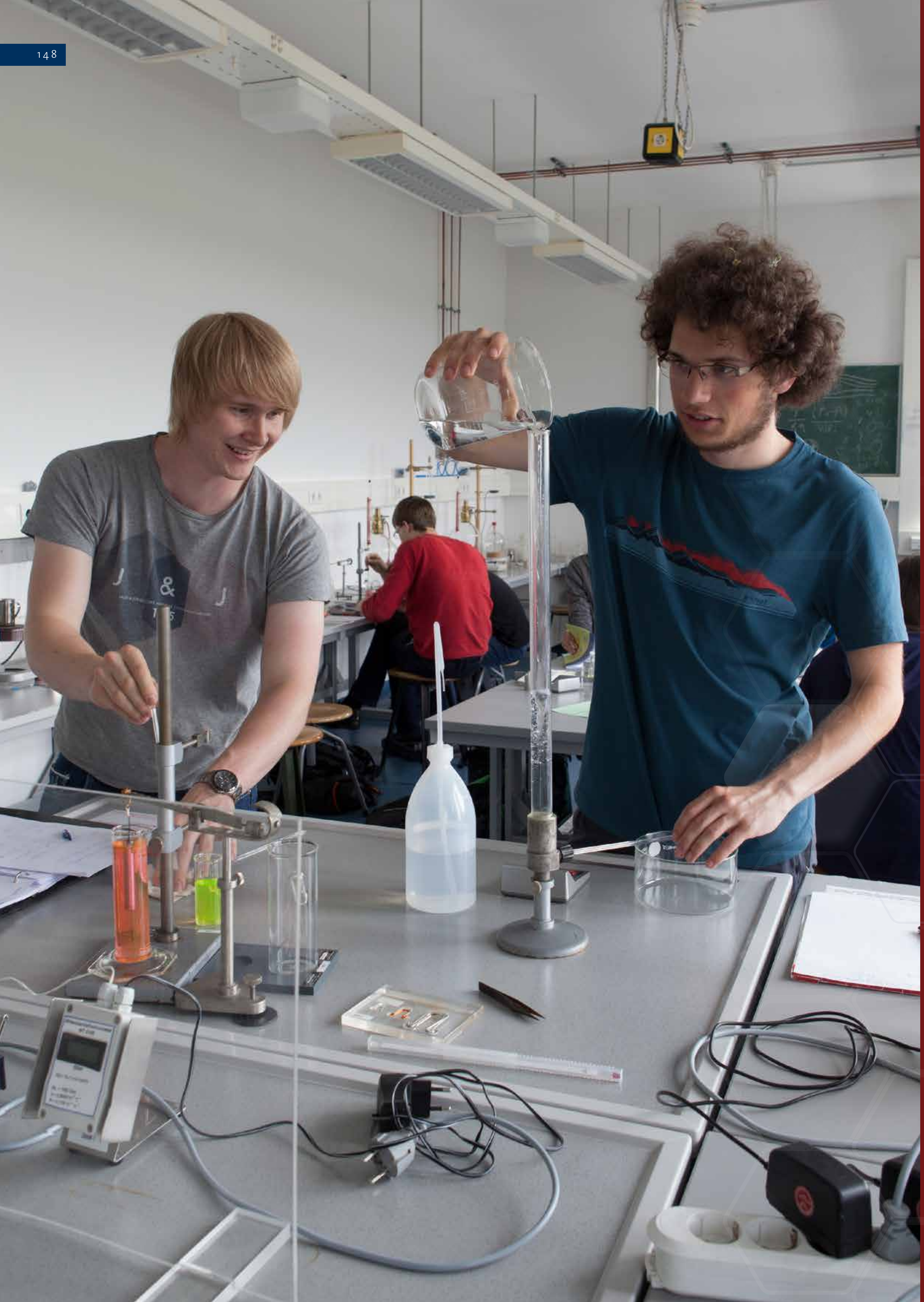
[7] R. Longo, V. Morinelli, K.-H. Rehren: Where infinite spin particles are localizable, Commun. Math. Phys. 345 (2016) 587-614

Laura Covi

Laura Covi, born in 1969, studied physics in Trento and at SISSA in Trieste, Italy, where she graduated in 1997. She worked as a Post-Doc at Lancaster University, U.K., in the Theory Group of DESY Hamburg and CERN, and then became permanent staff researcher in the DESY Theory Group in Hamburg in 2005. Since 2010 she is Professor at the Institute for Theoretical Physics, Göttingen University. She is Principal Investigator in the Graduiertenkolleg 1493 „Mathematical Methods in Modern Quantum Physics" and local coordinator of the EU ITN „Elusives" and the RISE Project „Invisibles-Plus".

Karl-Henning Rehren

Karl-Henning Rehren, born in 1956, studied physics in Göttingen, Heidelberg and Freiburg im Breisgau, where he received his PhD in 1984. He had PostDoc positions at the Freie Universität Berlin, where he got his habilitation in 1991, and in Utrecht (Netherlands). He was assistant at Hamburg University, and is Hochschuldozent (since 1997) und Professor (since 2002) at the Institute for Theoretical Physics, Göttingen University. He is Principal Investigator in the Graduiertenkolleg 1493 „Mathematical Methods in Modern Quantum Physics", member of the Counsel of the Deutsche Physikalische Gesellschaft, and section editor for the Annales Henri Poincaré.



Studies of Physics Education

Physics Education

Our research focuses on questions regarding the influence of pre-university factors on the academic success of physics education students, the relation between physics education and the development of decision-making competencies of upper secondary students, and the design of cross-curricular instruction in science education. In all cases, we apply empirical and statistical methods for the quantitative assessment of our research.

Higher education:

Academic success and the university dropout phenomena

What are individual determinants of a student's academic success and the university dropout phenomena? In longitudinal studies, we follow student cohorts from the beginning to the end of their studies and investigate the long-term influence of pre-university factors like competencies in physics and mathematics, motivation, personality traits, socio-demographic background and university factors like satisfaction, workload and learning strategies. We compare Physics with several other subjects of study like Biology, Economics and Mathematics. For the long-term analysis, we combine the data of surveys and university databases.

Decision-making competencies related to physics education

We develop a test instrument to assess students' decision-making competencies related to physics education at upper secondary schools. This paper-and-pencil test deals with physical aspects of renewable energy sources as a basis of decision-making. Of special interest is the relation between students' ability measures and subject grades in German, mathematics, and politics.

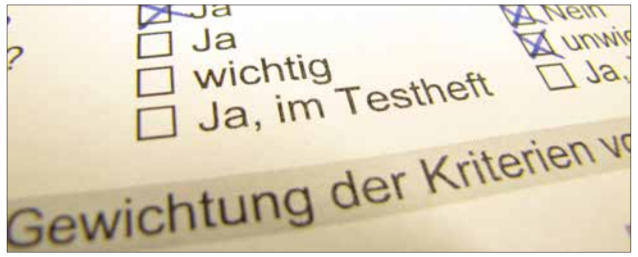


Fig. 1: Scoring Guide for analysis of questionnaire in empirical studies.

Integrated science instruction

Integrated science instruction teaches science in an interdisciplinary manner; it goes beyond the individual boundaries of separated subjects such as biology, chemistry and physics to form an interdisciplinary, a broader oriented approach to the teaching and understanding of science concepts. Such an instruction is believed to stimulate students' learning through the constructivist linking of existing knowledge and embedding educational subjects in realistic contexts. Interdisciplinary instruction acknowledges the fact that real world challenges are seldom treated with the means of a single scientific discipline. Rather than developing only single subject competencies, students are encouraged to exhibit interdisciplinary problem solving skills to face diverse problems. Moreover, integrated science instruction is believed to foster students interest in science – a claim which needs further empirical research. In our research program, we design and evaluate training for future teachers to adequately prepare them for the interdisciplinary aspects of integrated concepts.

Susanne Schneider

After completing her undergraduate diploma in physics, physics education, and German language education in 1988, Susanne Schneider went on to receive her PhD in physics in 1992 from the University of Göttingen. In 1993 she became a Dorothea von Erxleben fellow of the state of Lower Saxony and spent two years as research fellow with Prof. W.L. Johnson at the California Institute of Technology in Pasadena (USA). She earned her Habilitation in 2001. In 2005 she was awarded an extraordinary professorship at the University of Göttingen. She is head of the section Physics Education, which was established at the University of Göttingen in 2008.

Adjunct Professors

Theoretical and Computational Biophysics

The aim of the group is to reveal the physics, the function, and the underlying mechanisms of biomolecules – particularly proteins – at the atomic level. These true 'molecular nano-machines' are essential for all life forms; their structure and their atomic motions determine their function. The figure shows one of our favorites, the F-ATP synthase, which produces up to 60 kg of ATP per day in our bodies. In contrast to conventional chemical synthesis, which rests on random thermal motion, the F-ATP synthase literally 'puts together' the product molecule in a highly concerted fashion. Nearly all biomolecular functions are carried out by proteins, and their malfunction is the origin of most diseases.

Can we reveal the tricks which nature has developed during the past billion years?

We address this question using large-scale molecular dynamics simulations, which implies highly interdisciplinary research at the interface between statistical mechanics, quantum mechanics, biochemistry, structural biology, mathematics and computer science. We further seek for new physical concepts that properly describe biomolecular dynamics. In this endeavor, close collaboration with experimental groups is essential.

Our field is a young one, rapidly developing and expanding. Up to now there is no unifying 'protein theory'; rather, there is an evolving 'patch-work' of new methods and concepts, each capable of describing a different facet of these quite complex many-particle systems. Accordingly, success depends on the ability to develop, to apply, to combine, and to implement many of these 'patches'. Our group thus offers projects with many different 'flavors' to students, ranging from new method developments to projects that put the focus on a particular 'molecular nano-machine'.

Atomistic simulations of large biomolecular systems often involve several million atoms and are computationally quite demanding; currently accessible time scales range up to microseconds. An increasing number of biomolecular processes occur in this range and can thus be studied directly today. Many others occur at slower time scales, however. We therefore strive for methodological, algorithmic, or computational advancements, each of which opens up access to new systems. One particularly challenging example is protein folding, which typically requires milliseconds to seconds to be completed and is one of the 'holy grails' of molecular biophysics.

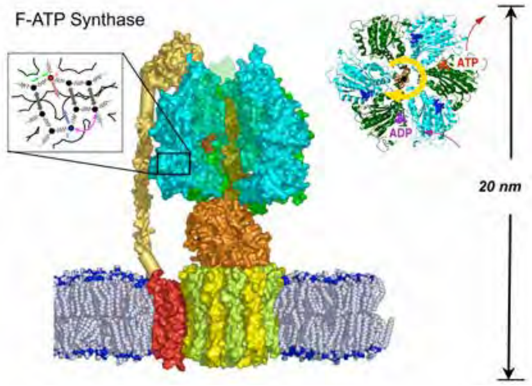


Fig. 1: F-ATP synthase embedded in a lipid membrane. Remarkably, the membrane part drives rotation of the orange axis which in turn transmits the energy for ATP synthesis to the ATP binding sites via fine-tuned atomic motions. This electroosmotic-mechano-chemical energy conversion proceeds at close to 100% thermodynamically possible efficiency.

New ways to separate relevant from irrelevant degrees of freedom, novel non-equilibrium statistical mechanics and sampling techniques, advanced quantum chemistry, as well as algorithms for massively parallel computer clusters are our methodological focus.

Most of the molecular territory is still uncharted. Exploring an increasing number of biomolecular systems, we seek to push the limits by sharpening our computational tools, to check newly developed concepts and methods against experiment, to suggest new experiments, and thus to expand our knowledge on how life works at the atomic level.

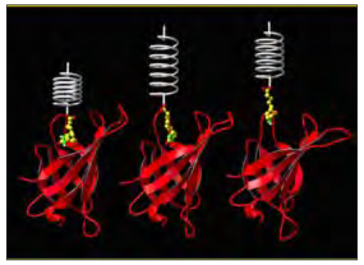


Fig. 2: Atomistic simulation of a single molecule atomic force microscopy experiment in which the binding force between the vitamin biotin and its receptor streptavidin is measured. This complex forms one of the strongest non-covalent biological interactions known.

[1] Bock LV, Blau C, Schröder GF, Davydov II, Fischer N, Stark H, Rodnina MV, Vaiana AC, Grubmüller H. Energy barriers and driving forces in tRNA translocation through the ribosome. Nature Struct. Molec. Biol. 20 (12), 1390–1396 (2013)

[2] Kappel C, Dölker N, Kumar R, Grubmüller H. Universal relaxation governs the nonequilibrium elasticity of biomolecules. Phys. Rev. Lett. 109, 118304 (2012)

[3] Sieber JJ, Willig KI, Kutzner C, Gerding-Reimers C, Harke B, Donnert G, Rammner B, Eggeling C, Hell SW, Grubmüller H, Lang T. Anatomy and Dynamics of a Supramolecular Membrane Protein Cluster. Science 317, 1072–1076 (2007)

Helmut Grubmüller

Professor Dr. Helmut Grubmüller received his PhD in theoretical physics at the Technical University of Munich in 1994. From 1994 to 1998, he worked as a research assistant at the Ludwig Maximilians University in Munich. In 1998, he moved to the Max Planck Institute for Biophysical Chemistry as research group head. Research visits brought him to the University of Illinois, U.S.A., Grenoble, and the ETH Zurich, Switzerland. He has led the Department of Theoretical and Computational Biophysics at the Max Planck Institute for Biophysical Chemistry as a director since 2003. Helmut Grubmüller is also honorary professor of physics at the University of Göttingen and is contributing numerous lectures and classes within the physics curriculum of the University of Göttingen.

Optical Nanoscopy / NanoBiophotonics

Since the discovery of the diffraction barrier by Ernst Abbe in 1873, it was commonly accepted that the resolution of a light microscope is limited to about half the wavelength of light (>200 nm). The diffraction barrier also affects fluorescence microscopy, which is the most popular microscopy modality in the life sciences, because it allows the specific observation of labeled proteins, lipids and nucleic acids. In recent years, we have demonstrated that in fluorescence microscopy, the resolution-limiting role of diffraction can be fundamentally overcome by exploiting specific transitions between fluorophore molecular states. Concretely, switching the ability of markers to fluoresce enables imaging without a limit set by diffraction, if the switching is implemented in such a way that neighboring molecules emit successively in time. Switching is realized by toggling the fluorophores between an emitting and a dark molecular state.

Stimulated Emission Depletion (STED) Microscopy is the first focused light microscopy method that is no longer fundamentally limited by diffraction. Here, the focal spot of an excitation beam is accompanied by a (usually) doughnut-shaped 'STED' beam of longer wavelength which transiently switches off the fluorophores at the spot periphery using stimulated emission. Whereas the molecules subject to the STED beam are essentially confined to the ground ('off') state, those at the doughnut center remain in the fluorescence 'on' state and fluoresce freely. Typically, the resolution is improved by 10-fold compared to conventional microscopes, thus allowing to discern labeled protein assemblies that are only 20 - 30 nm apart. However, increasing the brightness of the STED beam reduces the region where fluorescence remains allowed further in size, in principle down to the size of a molecule. In other words, the diffraction barrier is truly broken. Undergoing development at a fast pace, STED microscopy has been applied to areas as diverse as biology and the material sciences. Examples include the imaging of the diffusion of synaptic vesicles inside a neuron, lipid molecules in the plasma membrane of a cell, novel cytoskeletal structures in neurons, nanoscale self-assembled structures in polymer films, or crystal defects in diamond, to name but a few.

A fascinating alternative to switching off with stimulated emission is to switch markers between metastable (long-lived) states; this allows to break the diffraction barrier at low light levels. In a method called **RESOLFT**, fluorophores are switched between such metastable conformational states or binding states of organic molecules or fluorescent proteins with a light intensity distribution featuring one or many zero(s), similarly to STED. Switching individual fluorophores randomly in space is also very effective for producing images with resolution on the nanometer scale, as pursued in the methods **STORM, PALM,** and **GSDIM**.

Our interdisciplinary group, which has initiated this research area of 'far-field optical nanoscopy', comprises physicists, chemists, and biologists working together to conceive, develop, and apply radically new optical microscopes with resolution at the nanometer scale. In physics, our daily research topics encompass 1) theoretical and computational aspects of physics such as imaging theory, molecular statistics, 2) experimental (bio)physics such as the study of biomolecules in the cell, and 3) applied aspects such as single-molecule spectroscopy, ultrafast lasers, and modern optical instrument development.

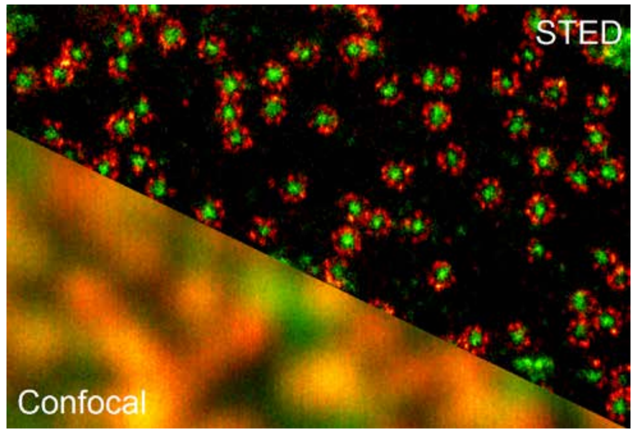


Fig. 1: Comparison of high-end diffraction-limited conventional microscopy ("Confocal", bottom) to STED nanoscopy (up). Protein superstructures called nuclear pore complexes in the membrane of an intact cell nucleus are shown. The eight-fold symmetry can be seen in the red channel of the STED recording, where resolution is improved about ten-fold compared to confocal.

Stefan W. Hell

Prof. Dr. Dr. h.c. mult. Stefan W. Hell, Nobel Laureate in Chemistry 2014, received his PhD in physics at the University of Heidelberg in 1990 and, from 1991 to 1993, worked at the European Laboratory for Molecular Biology in Heidelberg. From 1993 to 1996, he worked at the Universities of Turku (Finland) and Oxford (UK). Subsequently, he obtained his habilitation in physics from Heidelberg. In 1997, he moved to the Max Planck Insti-tute for Biophysical Chemistry in Göttingen, where he was appointed director and head of the Department of NanoBiophotonics in 2002. Stefan Hell has received numerous awards for his research, among them the Kavli Prize in Nanoscience and 2014 the Nobel Prize in Chemistry "for the development of superresolved fluorescence microscopy.

Computational Biomolecular Dynamics

Proteins are biological nanomachines. They enable, control or support nearly all the processes occurring in our bodies. Accordingly, the consequences are frequently severe when proteins do not function properly. Many diseases are caused by such dysfunctions.

Which interactions give rise to aggregation of proteins and thus cause disorders such as Alzheimer's or Parkinson's disease? How do cells regulate the influx and efflux of molecules such as water, ions and nutrients? How does molecular recognition function? These are some of the questions we investigate in the computational biomolecular dynamics group.

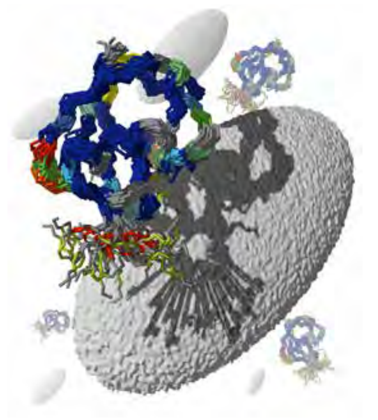


Fig. 1: Molecular recognition by ubiquitin. Since ubiquitin can rapidly assume other shapes, it recognizes many different binding partners. One can imagine it to be like a key ring with which different locks can be opened.

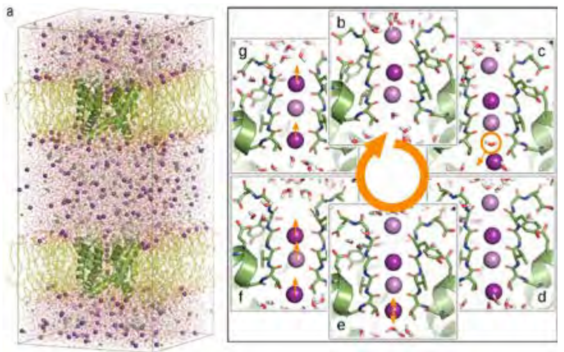


Fig. 2: Permeation mechanism of potassium ions through the selectivity filter of a potassium channel. A double membrane simulation system is used for computational electrophysiology (a). An incoming ion displaces a water molecule, resulting in unfavourable ion-ion interactions, allowing the transmembrane voltage to drive an upward permeation event (b-g).

In order to understand the function and dysfunction of proteins, it is usually insufficient to know their structure. Many proteins fulfill their respective task only by means of well-orchestrated movements. Our objective is to understand protein dynamics at the molecular level and to unravel the mechanisms underlying such dynamics.

One class of proteins investigated in the group are ion channels. They form pores in the cell membrane, which function as perfect, highly selective ion filters. Only specific ions can pass through, which is the basis of e.g. signal transduction in nerve cells. What is the physical basis of such a remarkable selectivity, enabling at the same time a high efficiency, close to the diffusion limit? Molecular dynamics simulations allow to resolve these questions at the atomistic level.

In addition, we have a true multi-talent among the proteins under investigation: ubiquitin. It is part of a sophisticated recycling system in the cell, which marks certain proteins as cellular "trash". But how does ubiquitin manage to recognize and bind so many different partner molecules? With the aid of molecular dynamics calculations and NMR experiments we were able to demonstrate that ubiquitin is surprisingly mobile. Like a swiss army knife it continuously changes its shape, extremely rapidly – within a millionth of a second – until it accidentally fits its partner.

[1] *O.F. Lange, N.A Lakomek, C. Fares, G.F. Schröder, K.F.A. Walter, S. Becker, J. Meiler, H. Grubmüller, C. Griesinger, B. L. de Groot:* Recognition dynamics up to microseconds revealed from RDC derived ubiquitin ensemble in solution. *Science* 320, 1471-1475 (2008).

[2] *Servaas Michielssens, Jan Henning Peters, David Ban, Supriya Pratihar, Daniel Seeliger, Monika Sharma, Karin Giller, Thomas Michael Sabo, Stefan Becker, Donghan Lee, Christian Griesinger and Bert L. de Groot*. A Designed Conformational Shift To Control Protein Binding Specificity. *Angewandte Chemie Int. Ed.* 53: 10367-10371 (2014).

[3] *David A. Köpfer, Chen Song, Tim Gruene, George M. Sheldrick, Ulrich Zachariae and Bert L. de Groot*. Ion permeation in K+ channels occurs by direct Coulomb knock-on. *Science* 346: 352-355 (2014).

Bert de Groot

Bert de Groot received his PhD in biophysical chemistry at the University of Groningen (The Netherlands) in 1999. From 1999 to 2003 he worked as a postdoctoral fellow in Helmut Grubmüller's research group at the Max Planck Institute for Biophysical Chemistry in Göttingen. He heads the "Computer-Aided Biomolecular Dynamics" Research Group there since 2004. Bert de Groot is an adjunct professor of physics at the University of Göttingen since 2009.

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Dynamics of Complex Fluids

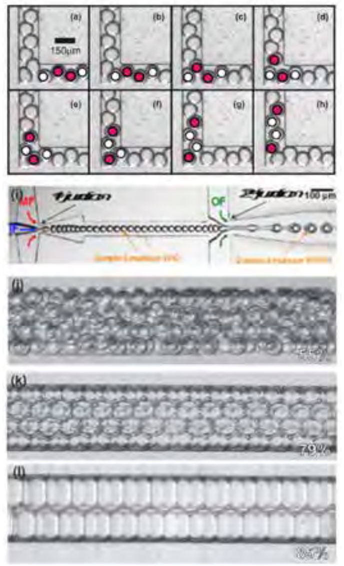
A fluid is called 'complex' if its constituents are complex systems on their own: the macro-molecules in the polymer melt, the lamellae within the foam, the (dissipative) grains in the granulate, or the bio-molecules in the cytoplasm. Can one predict, on the basis of the properties of these constituents, the dynamic behavior of the complex fluid, i.e. the polymer, the foam, the granulate, or the biomaterial? It has become clear that these materials are governed by self-organization and self-assembly processes. Macroscopic properties emerge from these processes on larger scales. Are there general principles of such 'emergence'? We tackle these questions by means of experimental as well as theoretical methods. We are led not only by fundamental interest, but also by the wealth of potential applications. Once one has achieved a detailed understanding of these systems, the design of self-organized 'soft' micro- or nano-machines may come within reach, pointing to fascinating novel technologies for the future.

Granular matter, dry and wet

Processes of self-organization and emergence require the system under study to be far from thermal equilibrium. Since most textbook physics is limited to equilibrium systems, there is still a need for model systems which allow to study the principles of dynamics far from thermal equilibrium. One such system, which belongs to the class of complex fluids, is granular matter. Fluid interfaces, which span between the grains by virtue of surface forces and rearrange in response to displacements of the latter, determine the 'free energy landscape' of the whole system, and thereby its macroscopic static and dynamic properties. There are two main avenues of study. One concerns the collective properties of granular gases, such as dense granular flows, or the formation of planetesimals from dusty accretion discs. The other focuses on the interaction of fluid interfaces with granular packings. Here we investigate the possible geometries of packing, the effects of grain shape upon this geometry, and the dynamics of liquid interfaces forming within such packings when these are wetted. Aside from a wide range of other applications, these studies are of great importance for geophysical problems, such as oil recovery or the storage of carbon dioxide in depleted oil reservoirs.

Collective phenomena in life-mimicking systems

One of the great open questions of science is what fundamentally distinguishes 'dead' materials from living matter. Within a large endeavor including several Max-Planck institutes, we try to create systems which exhibit self-reproduction and motility. While self-reproduction poses severe conceptual challenges which we try to meet by means of non-biological pathways, motility can be achieved by harnessing dynamic instabilities and spontaneous symmetry breaking. The swarming behavior of self-propelling emulsion droplets and their buoyant coupling to fluid flow is essential for understanding pattern formation in the plankton population of the oceans. There are furthermore indications that swarming is an indispensable ingredient in the formation of some biofilms. We use micro-fluidic techniques to generate and study these and similar soft-matter systems which we hope will provide us with a deeper insight into the functional principles of early life forms.



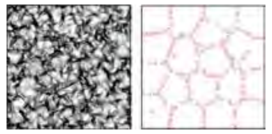


Fig. 2: FarFromEquilibrium: "Patterns emerging in systems far from thermal equilibrium. Left: clustering in a granular gas, similar to the formation of primordial cluster structures preceeding the formation of planetesimals in accretion discs. Right: spontaneous order emerging in a population of actors exhibiting a minimal model of intelligence, provided by a simplified scalar representation of their 'environment'. The order optimizes the actor's options to move among their peers."

Fig. 1: Microfluidics: "Emulsions can be generated and precisely controlled in microfluidic devices. (a) to (h): the relative position of densely packed droplets can be changed when the emulsion flows along a bent microchannel. (i) Two consecutive constrictions can be used to create double-emulsions, a precursor to unilamellar vesicles. (j) to (l): As the density of droplets is increased, a spontaneous order emerges resulting in an arrangement of lipid bilayers which is reminiscent of a foam.

Stephan Herminghaus

Stephan Herminghaus was born in 1959 in Wiesbaden. He studied physics at the University of Mainz, where he received his PhD in 1989 with a thesis on laser ablation. After a postdoctoral stay at the IBM research labs in San Jose (CA), where he studied optically non-linear polymer films, he moved to the University of Konstanz, where he obtained his Habilitation in 1994 with investigations on wetting and thin film optics. In 1996, he started an independent research group at the MPI for Colloid and Interface Science (Berlin), where he initiated and coordinated the DFG Priority Program 'Wetting and Structure Formation at Interfaces'. In 1999, he became full professor and head of the applied physics department at the University of Ulm. Since 2003, he is a director at the MPI for Dynamics and Self-Organization in Göttingen.

Biomedical Physics

How do life-threatening cardiac arrhythmias occur? Why are they so difficult to control? The Biomedical Physics Group seeks to unravel the mechanisms and genetics of cardiac arrhythmias and develops novel approaches for their control.

Mechanisms and Genetics of Cardiac Arrhythmias

Self-organized complex spatial-temporal dynamics underlie health and disease states in excitable biological systems such as the heart. During cardiac fibrillation, synchronous contraction is disrupted by vortex-like rotating waves of electrical activity, resulting in complex – and often chaotic – spatial-temporal excitation patterns 1. This electro-mechanical malfunction of the heart can rapidly evolve into Sudden Cardiac Death (SCD). SCD is a leading cause of mortality worldwide, with an estimated 738.000 deaths per year in the European Community alone. Yet the physical mechanisms underlying the dynamics and control of electrical turbulence pose a scientific riddle that still remains unanswered today: how do arrhythmias arise, and how can they be terminated efficiently? Our interdisciplinary team develops and applies numerical models, advanced data analysis algorithms, high-resolution fluorescence imaging techniques, and optogenetic tools2,3 to answer these questions.

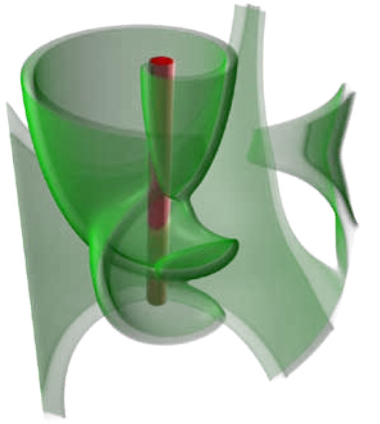


Fig. 1: Scroll waves in a three-dimensional medium with negative filament tension may break up and display spatio-temporal chaos.[6]

From Physics to Medicine: Controlling Spatial-temporal Complexity in the Heart

Today, the only effective method of terminating fibrillation is a high-energy electric shock (1 kV, 30 A, 12 ms). This empirical approach has intolerable side effects, including traumatic pain, tissue damage, and worsening of the prognosis. Our research suggests an entirely new approach to the control of spiral-defect chaos in the heart. While the prevailing high-energy control paradigm aims at indiscriminately eliminating all waves, we are developing methods that selectively target the system where it is most susceptible to perturbations, i.e. at the vortex or spiral cores. This approach permits low-energy control of cardiac fibrillation4-6, removing the drawbacks of conventional techniques.

By combining theoretical and experimental methods from physics, biology and computer science, the Biomedical Physics Group aims at elucidating physical mechanisms that may – over the long-term – open new paths for translating fundamental research into practical applications aimed at improving human health.

[1] Gray, R., Pertsov, A. M. & Jalife, J. Spatial and temporal organization during cardiac fibrillation. Nature 392, 75–78 (1998).

[2] Zaglia, T. et al. Optogenetic determination of the myocardial requirements for extrasystoles by cell type-specific targeting of ChannelRhodopsin-2. Proc. Natl. Acad. Sci. 112, E4495–E4504 (2015).

[3] Chang Liao, M.-L. et al. Sensing Cardiac Electrical Activity With a Cardiac Myocyte–Targeted Optogenetic Voltage Indicator. Circ. Res. 117, 401–412 (2015).

[4] Luther, S. et al. Low-energy control of electrical turbulence in the heart. Nature 475, 235–239 (2011).

[5] Bittihn, P., Hoerning, M. & Luther, S. Negative curvature boundaries as wave emitting sites for the control of biological excitable media. Phys. Rev. Lett. 109, (2012).

[6] Spreckelsen, F., Hornung, D., Steinbock, O., Parlitz, U. & Luther, S. Stabilization of three-dimensional scroll waves and suppression of spatiotemporal chaos by heterogeneities. Phys. Rev. E 92, 42920 (2015).

Stefan Luther

Stefan Luther studied Physics at the University of Hannover and at the Georg August University, where he received his PhD in 2000. He was then a post-doc at the University of Enschede (NL) with D. Lohse and at the Laboratory of Atomic and Solid State Physics (LASSP), Cornell University, Ithaca NY, with E. Bodenschatz. Since 2006 he is the head of the independent Max Planck Research Group Biomedical Physics at the MPI for Dynamics and Self-Organization. In 2008 he was appointed Honorary Professor at the Georg August University and in 2015 Professor at the University Medical Center Goettingen. In 2015 he was appointed adjunct Associate Professor in the Departments of Physics and Bioengineering at Northeastern University, Boston. In 2008, his group received the Medical Innovation Award from the BMBF. His research interests include nonlinear dynamics, data analysis, and complex systems.

Mathematical Physics of Integrable Systems

The modelling of physical systems typically involves *nonlinear* partial differential/difference equations (PDEs), which often exhibit quite unexpected features. For most equations there is hardly a chance to find sufficiently generic *exact* solutions, but examples of relevance for physics exist that are, in some sense, solvable. Such integrable PDEs appear as special cases or approximations, e.g., in fluid dynamics, optics, general relativity and string theory. Some exhibit *soliton* solutions, which are nonlinear superpositions of localized waves. Integrable PDEs and related structures also play an important role in various branches of mathematics.

Combinatorics of Soliton Interactions

A prominent soliton equation is the *Kadomtsev-Petviashvili*, or short *KP equation*. Soliton solutions of one of its versions (KP-II) describe, in a wave crest limit, network-like patterns on a shallow water surface. For a subclass of solutions, the evolution corresponds to a sequence of binary trees, forming a maximal chain of a *Tamari lattice* [1], a combinatorial structure that originally emerged from associativity relations [2]. See Fig. 1.

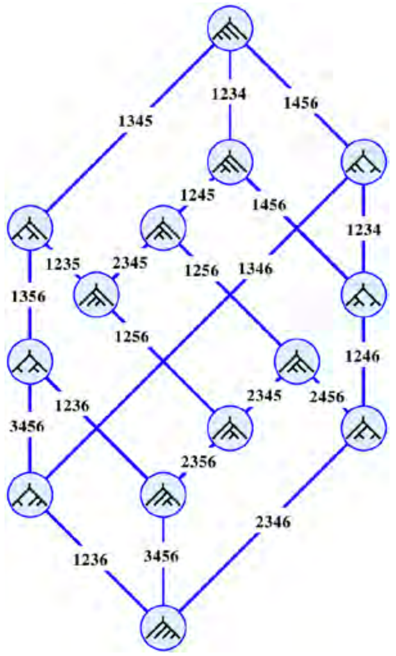


Fig. 1: A Tamari lattice. The tree at the top represents the initial KP-soliton configuration (t«0). There are different possibilities for an evolution toward the final configuration (t»0), the tree at the bottom. Numbers attached to edges indicate transition times t_{ijkl}.

Simplex and Polygon Equations

Simplex equations generalize the famous *Yang-Baxter* equation, which is at the heart of two-dimensional quantum integrable systems and exactly solvable models of statistical mechanics. The underlying combinatorics is governed by *higher Bruhat orders* (Y. Manin and V. Schechtman 1986). A certain decomposition leads to *higher Tamari orders*, and associated with them is the new family of "polygon equations" [3], to be explored. It includes the ubiquitious *pentagon equation*.

Bidifferential Calculus

Most integrable PDEs share certain properties and, in particular, solution-generating methods. A framework to prove or elaborate them in a *universal* way is *bidifferential calculus*. See, e.g., [4,5].

[1] Dimakis, A.; Müller-Hoissen, F.: *KP line solitons and Tamari lattices*, J. Phys. A: Math. Theor. 44, 2011, 025203.

[2] Müller-Hoissen, F.; Pallo, J.; Stasheff, J.: Associahedra, Tamari Lattices and Related Structures, Progress in Mathematics 299, Birkhäuser, Basel, 2012.

[3] Dimakis, A.; Müller-Hoissen, F.: *Simplex and polygon equations*, SIGMA 11, 2015, 042.

[4] Dimakis, A.; Müller-Hoissen, F.: *Binary Darboux transformations in bidifferential calculus and integrable reductions of vacuum Einstein equations*, SIGMA 9, 2013, 009.

[5] Chvartatskyi, O.; Dimakis, A.; Müller-Hoissen, F.: *Self-consistent sources for integrable equations via deformations of binary Darboux transformations*, Lett. Math. Phys., 2016.

List of Publications:

http://mueller-hoissen.math-phys.org/index.php?navi=publ

Folkert Müller-Hoissen

Folkert Müller-Hoissen studied physics at the Georg-August Universität Göttingen, where he also received his doctoral degree in 1983. After postdoctoral positions at the MPI for Physics in Munich and at Yale University, USA, he returned to Göttingen as an assistant professor (Hochschulassistent) for theoretical physics, obtained his habilitation (Privatdozent) in 1993 and was promoted to apl. Professor in 2000. In 1995-96 he spent half a year as a research scholar at the MPI for History of Science in Berlin, before he became a scientific staff member of the MPI for Flow Research, now MPI for Dynamics and Self-Organization, in Göttingen. His research experience includes general relativity, noncommutative geometry, integrable systems and solitons, and related mathematical structures.

Dynamical Systems

How do complex patterns and strange oscillations arise? Why is it so difficult to forecast the temporal evolution of many systems? What are the conditions for cooperative behavior, synchronization, or other phenomena of self-organization? These are major topics in Nonlinear Dynamics and Complex Systems research providing a unifying framework for emergent structure formation processes in natural and human made systems.

Nonlinear Dynamics and Complex Systems

Nonlinearity is a prerequisite for interesting and often surprising behavior of natural systems. In a nonlinear system, cause and action are not proportional to each other. Nonlinear systems are in general difficult to solve mathematically but exhibit many interesting features like chaotic dynamics or structure formation. Chaotic systems are characterized by oscillations that appear irregular but are purely deterministic and very sensitively depend on changes of start values or external perturbations. This sensitive dependence on initial conditions makes it so difficult to forecast chaotic systems. Chaos may occur in all kinds of systems including lasers, neurons, physiological rhythms, etc., and special methods have been devised for signal analysis and control of chaotic dynamics. If many systems or elements are combined, larger networks of components arise which may exhibit collective and adaptive behavior (incl. synchronization). Such emergent self-organization phenomena are relevant for information processing, learning or evolution, in general without being governed by some central control units.

Excitable Media and Cardiac Dynamics

An important class of dynamical systems are excitable media. If an excitable system at rest is stimulated by a perturbation that exceeds some specific threshold, the system responds with a large pulse before it converges to the equilibrium state again. Immediately after the pulse the system is in its refractory period, during which it cannot be excited again. Extended excitable media exhibiting different types of (spiral) wave patterns and chaotic dynamics (Fig.1). Many biological systems are excitable in this sense. For example, electrical excitation waves in cardiac tissue govern the contraction pattern of the pumping heart and there, turbulent wave patterns may lead to arrhythmias and other malfunctions. Understanding dynamical features of arrhythmias is crucial for developing novel therapies for avoiding or terminating them.

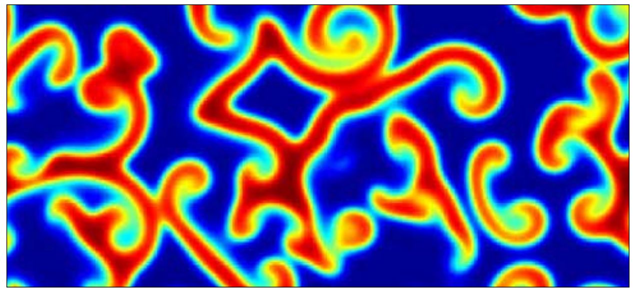


Fig. 1: Snapshot of a complex wave pattern occurring in a computer simulation of an excitable medium.

Signal Analysis and Data Assimilation

Important links between mathematical modeling of physical (or physiological) processes and experiments are time series analysis and data assimilation methods, that can be used for state and parameter estimation, and for evaluating a given model's efficiency and predictive power with respect to the process it describes.

[1] Kocarev L.; Parlitz U., "Generalized synchronization, predictability and equivalence of unidirectionally coupled systems", Phys. Rev. Lett. 76, 1996, 1816.

[2] Parlitz U., "Estimating model parameters from time series by auto-synchronization", Phys. Rev. Lett. 76, 1996, 1232.

[3] Ahlborn A.; Parlitz U., ”Stabilizing Unstable Steady States using Multiple Delay Feedback Control", Phys. Rev. Lett. 93, 2004, 264101.

[4] Parlitz U.; et al., "Classifying Cardiac Biosignals using Ordinal Pattern Statistics and Symbolic Dynamics", Computers in Biology and Medicine 42, 2012, 319–327.

[5] Parlitz U.; Schumann-Bischoff J.; Luther S., "Quantifying uncertainty in state and parameter estimation", Phys. Rev. E 89, 2014, 050902(R).

Ulrich Parlitz

Ulrich Parlitz was born in 1959 in Hameln and studied physics at the Georg-August-Universität Göttingen, where he also received his PhD in 1987. After five years at the Institute for Applied Physics of the TU Darmstadt he returned to Göttingen in 1994 where he obtained his habilitation in 1997 and was appointed apl. Prof. in 2001. Since 2010 he is with the Research Group Biomedical Physics at the Max Planck Institute for Dynamics and Self-Organization. Ulrich Parlitz's research interests include nonlinear phenomena, data analysis, modeling, and cardiac dynamics.

Network Dynamics

Networks are everywhere. And most of them are dynamic. From the neuronal circuits in our brains that make us behave to the power grids that provide huge amounts of electric energy; a range of complex systems form networks of units that interact to yield collective emergent forms of functions – and all are crucial to our everyday life.

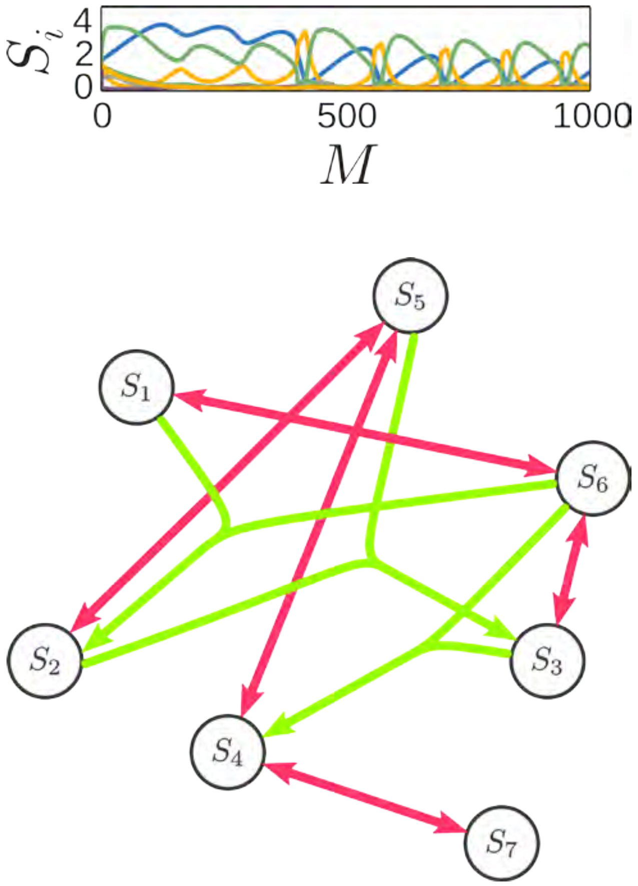


Fig. 1: Who with whom? Can we tell from a network's dynamics how the units interact? © Jose Casadiego, 2016

Cross-disciplinary Concepts for Network Dynamics

Fundamental research on the dynamics of networks thus is an intrinsically transdisciplinary endeavor. A researcher starting to work on what is on its way to become "Network Science" in the future thus needs to read text books and articles on graph theory and stochastics, nonlinear dynamics, statistical physics, computation, and algorithms, as well as the specific subject she is aiming to investigate, e.g. in biology, physics or engineering.

From Biological Computation to Future Energy and Mobility

In the Network Dynamics team, we are working towards a unifying understanding of the fundamentals underlying the dynamics of large, nonlinear interconnected systems. We study topical questions arising from a broad range of phenomena in physics, in neurobiology, in evolution, in computation and in the engineering of self-organizing "intelligent" systems. A substantial part of our work is investigating emergent mathematical objects and developing tools necessary to understand the novel phenomena. Current applications range from power grids and future mobility to neural circuits and non-standard computation [1-7].

[1] Dynamic Information Routing in Complex Networks, C. Kirst, M. Timme and D. Battaglia, Nature Comm., 7:11061 (2016)

[2] Critical Links and Nonlocal Rerouting in Complex Supply Networks D. Witthaut, M. Rohden, X. Zhou, S. Hallerberg, M. Timme, Phys. Rev. Lett., 116:138701 (2016)

[3] Revealing Networks from Dynamics – An Introduction, M. Timme and J. L. Casadiego, J. Phys. A: Theor. Math. (Invited Topical Review) 47:343001 (2014).

[4] Computation by Switching in Complex Networks of States, F. Schittler Neves and M. Timme, Phys. Rev. Lett. 109:018701 (2012b).

[5] Impact of Single Links in Competitive Percolation, J. Nagler, A. Levina, and M. Timme, Nature Phys. (Article) 7:265 (2011).

[6] Self-Organized Adaptation of a Simple Neural Circuit Enables Complex Robot Behaviour, S. Steingrube, M. Timme, F. Wörgötter, and P. Manoonpong, Nature Phys. (Article) 6:224 (2010).

[7] Revealing Network Connectivity From Response Dynamics, M. Timme, Phys. Rev. Lett. 98:224101 (2007).

Marc Timme

studied physics and mathematics in Würzburg, Stony Brook (New York, USA) and Göttingen. He received a Masters' degree in physics in 1998 (Stony Brook) and a doctorate in theoretical physics in 2002 (Göttingen). After a Postdoc at the MPI for Flow Research from 2003, he was a Research Scholar at the Center of Applied Mathematics, Cornell University (USA), in 2005 and 2006. In December 2006 he became the head of the research group Network Dynamics of the Max Planck Society and in 2009, Adjunct Professor at the University of Göttingen. He is part of the steering committees of the International Max Planck Research School (IMPRS) Physics of Biological and Complex Systems as well as the Program for Theoretical and Computational Neuroscience and faculty member at the Georg August University School of Science (GAUSS).

Dynamics of Planetary Interiors

The planetary theory group at the Max Planck Institute for Solar System Research studies the internal structure and dynamics of planetary bodies. We simulate the generation of magnetic field in planetary cores in numerical models. Flow of electrically conducting fluids is driven by convection and is strongly influenced by the Coriolis force of planetary rotation. Electro-magnetic induction generates electric currents and magnetic field in a self-sustained dynamo process. We aim at (1) understanding the dynamo process in general, (2) explaining the properties of the magnetic fields of various planets, and (3) understanding what is common and what is different in dynamos of planets and stars. The illustration shows results from a dynamo model for a rapidly rotating low-mass star. The radial magnetic field at the surface (lower panel) has a fine structure, but is dipolar at large scales, like the field of the Earth. A strong magnetic flux concentration near the North pole suppresses convective flow (upper panel), which leads to the formation of a dark starspot. While dark spots at the surface of the Sun are found at low latitudes, at more rapidly rotating stars much larger spots have been observed in polar regions. Such spots appear selfconsistently in the simulation. We also model the internal circulation in gas planets such as Jupiter, which gives rise to jet streams that cause the banded appearance of their surfaces. We prepare for analyzing forthcoming data from space missions that will provide information on structures and processes in the interior of several planets. The Juno mission will reveal the details of Jupiter's magnetic field. The tidal deformation of Mercury will be measured by laser altimetry and provides information on the size of the planets liquid metal core. The INSIGHT mission will deploy a seismometer at the surface of Mars that records signals from marsquakes, meteoroid impacts and tidal deformation of Mars. Its recordings will be analysed in order to constrain the structure and composition of the planet.

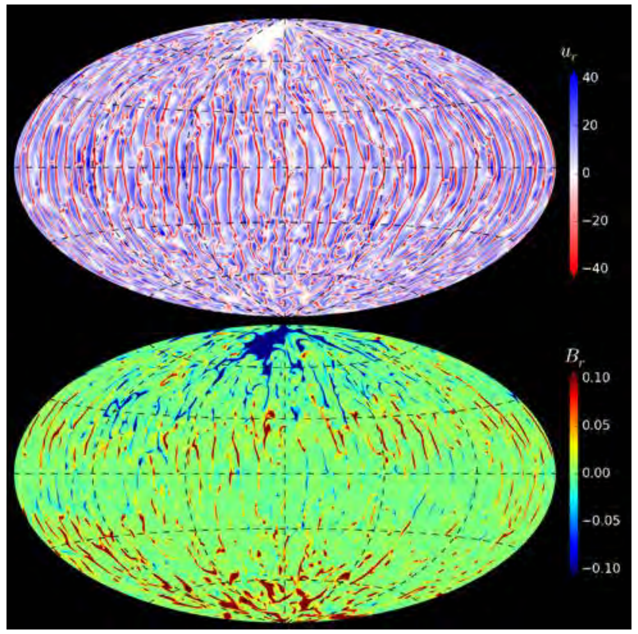


Fig. 1: Snapshot from a numerical simulation of convection and magnetic field generation in a rapidly rotating star. The upper panel shows a map view of upwelling (blue) and downwelling (red) motion close to the stellar surface, with little radial flow in white regions. The lower panel shows the radial magnetic field at the surface of the star, with field lines pointing outward in red regions and inward in blue regions. Note the small flow velocity in the strong magnetic field patch near the North pole, where magnetic forces inhibit convection..

Ulrich Christensen

Ulrich Christensen obtained his doctoral degree in geophysics from the Technical University Braunschweig in 1980. He worked as a staff scientist at the Max Planck Institute for Chemistry in Mainz and at the Arizona State University in Tempe on problems of convection in the Earth's mantle. From 1992 to 2003 he was full professor at the Institute of Geophysics at the University in Göttingen. Since 2003 he is director of the Department for Planets and Comets at the Max Planck Institute for Solar System Research. He received various awards such as the Gottfried Wilhelm Leibniz prize (1994) or the Augustus Love Medal of the European Geoscience Union (2009).

Theory and Simulation of Solar System Plasmas (TSSSP)

Our work focusses on the physics and mathematical description of hot, collisionless astrophysical plasmas, their turbulence and self-organization in particular on the accumulation of magnetic energy and its consequent, often explosive, release. Our theoretical investigations are based on in situ spacecraft measurements and remote observations in the solar system and beyond as well as on labo-ratory experiments. We utilize numerical simulations on super-computers to better understand the complex dynamics of the hot and turbulent plasmas of the Universe by addressing both the microphysical fundaments and their macroscopic consequences for the plasma dynamics.

Motivation

Including the solar system the whole Universe is filled with electrically charged particles, electrons, ions, dust. This plasma is quasi-neutral on average but electrically conducting, called the forth state of matter. Electric currents in plasmas generate magnetic fields and cause Lorentz forces which form structures, let magnetic energy accumulate to be, often explosively, released later. Most prominent examples are solar eruptions, magnetic storms, phenomena of the space weather. Since the human life on Earth increasingly depends on the actual space weather conditions an ever growing amount of spacecraft data is collected to watch and predict them. But a prediction of the space weather is impossible without the development of appropriate plasma theories and their verification by quantitative, i.e. mathematical models and numerical simulations of the usually highly non-linear plasma dynamics and their validation on space observations.

From micro-turbulence to structure formation

The hot and dilute plasmas of the Universe are full of free energy whose fluctuations permanently cause instabilities turbulence, but also forming structures. The nonlinear interaction between the plasma particles and their self-induced or external electromagnetic field, current and density fluctuations lets plasma waves grow and propagate over long distances, piling up at obstacles to shocks and accumulating energy in magnetic confinements such as shown in Figure 1.

We investigate the strongly non-linear and non-local plasma processes behind by means of numerical simulations appropriate to bridge a huge range of scles from the smallest-kinetic scales of the micro-turbulence to large macroscopic, fluid-like processes. This way we try to understand, e.g., the conditions for a magnetic confinement of hot plasmas structures in space as shown in Figure 1, verifying our finding by laboratory experiments carried out by our collaborators in Greifswald, Princeton and Tokyo.

Explosive release of accumulated magnetic energy

The energy accumulated in plasmas, magnetically confined like in the solar corona, occasionally becomes explosively released by a process called magnetic reconnection. We investigate the interaction between the confined and ambient plasma, particles and electromagnetic fields, which often become turbulent, by means of numerical simulations, test theories and conjectures about their nature. Figure 2 shows the observed situation in the solar corona prior to an eruption, which we could simulate numerically. For its animation see http://www.mps.mpg.de/1763214/Plasma-Simulations.

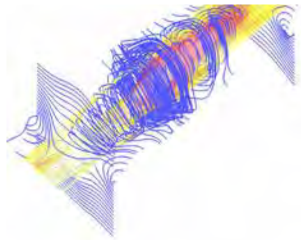


Fig. 1: Magnetically confined hot plasma: yellow and red colored are plasma and current density, the bounding magnetic field is depicted by blue lines. Result of a numerical simulation by the TSSSP group.

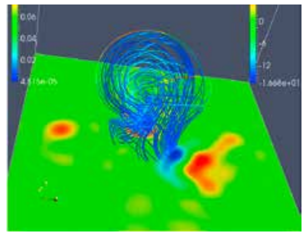


Fig. 2: Magnetic field observed at the solar surface (red/ yellow) prior to an eruption observed by the Göttingen University solar physics group. The coronal magnetic field (blue) was obtained by our simulations as the whole evolution till the eruption.

Jörg Büchner

Jörg Büchner obtained his PHD on the quantum-non-demolition detection of gravitational waves (1980). Worked at the Potsdam Astrophysical Institute on nonlinear plasma phenomena in the iono- and magnetosphere of the Earth, later also in the solar wind, the Sun and other astrophysical objects. Guest-professor at the UCLA (Los Angeles, 1990-91). Run from 1992 till now the Max-Planck- group "Theory and Simulation of Solar System Plasmas", first (till 1996) in the Berlin branch of the Max-Planck institute for Extraterrestrial Physics, from 1997 on at the MPAE ("for Aeronomy") at Katlenburg-Lindau, since 2004 renamed MPI for Solar System Research, moved in 2014 to the North-Campus of the Georg August University. Professorships at the Universities of Nagoya (Japan) and Nanchang (China). Steering Committees, e.g., of the Max-Planck-Princeton Center for Plasma Physics (MPPC) and the International School for Space Plasma Simulation (ISSS).

The Dynamic Corona of the Sun

Cool stars like our Sun are surrounded by a million Kelvin hot outer atmosphere. During a total solar eclipse this corona is visible to the naked eye, remotely resembling a crown. In the 1940ies spectroscopy revealed the high temperature of the corona, launching the interest in the physical processes that could heat a hot gas surrounding a comparably cool body. Still today this is one of the most interesting questions in stellar astrophysics and relates to the more general questions of stellar activity and the generation of hot plasma in other parts of the universe.

Motivation

The structure, dynamics, and heating of the outer solar atmosphere is the result of the interaction of the plasma with the magnetic field. The latter is rooted on the surface of the Sun, where the convective motions drive the changes in the magnetic field, which is the first step of a cascade of processes that lead to the actual heating. Essentially, the braiding of magnetic field lines induces currents in the upper atmosphere that are dissipated, similarly to an electric resistor getting hot.

Models

We capture this process (in its more elaborate complexity) through three-dimensional magneto-hydrodynamic (3D MHD) models. In such numerical experiments we have full access to the state of the plasma and the magnetic field in each grid cell. Most importantly, from the models we can derive synthetic observations. For example, based on density, temperature, and velocity we can synthesize the profiles of emission lines forming in the corona and construct a data set that is directly comparable to a real observation on the Sun (see Fig. 1). Through this we can investigate to what extent the model captures reality, and decide if the model is built on the correct assumptions for the mechanisms governing the structure and heating of the corona.

Observations

New observations, in particular of unexpected features, constantly challenge the existing models, underlining that astronomy is a science driven by measurements. We use spectroscopic and imaging data in the extreme ultraviolet acquired by space-based observatories not only to drive and test our models, but in particular also to build new scenarios based on the observations alone. This is a key to set up new numerical experiments and constantly pushes the limits of our understanding of the solar corona.

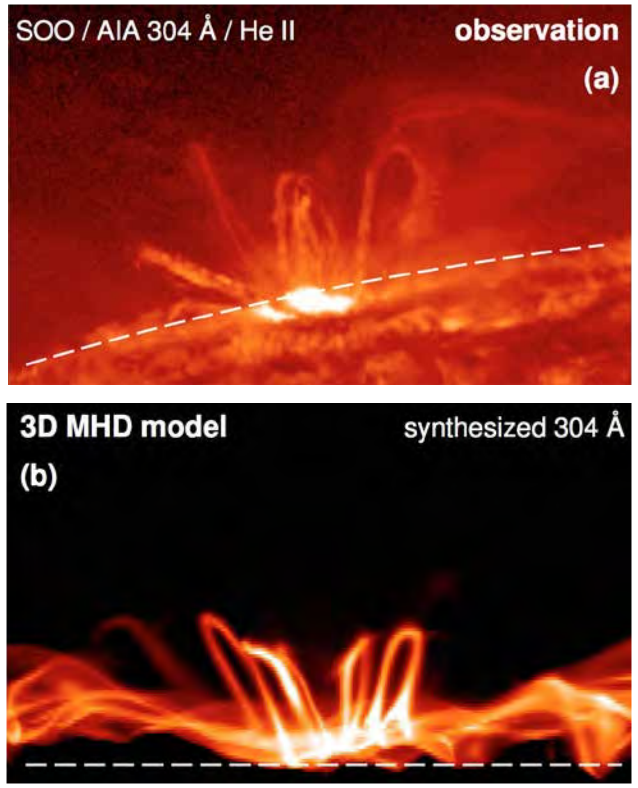


Fig. 1: Plasma loops as observed on the Sun (a) and in a 3D MHD simulation (b). Both observation and simulation show a band around 30.4 nm dominated by emission from singly ionized He forming at around 100.000 K (from Chen F., Peter H., Bingert S., Cheung M.C.M., 2015; Nature Phys. 11, 492).

Hardi Peter

Hardi Peter studied physics in Darmstadt and Göttingen and conducted his doctorate research at the Max Planck Institute for Aeronomy in Katlenburg-Lindau. Following a two-year postdoctoral research stay at the High Altitude Observatory of the National Center for Atmospheric Research in Boulder, USA, in 1999 he moved to the Kiepenheuer Institute for Solar Physics in Freiburg, where he built up a group on the physics of the solar corona and became a permanent staff member. Since 2009 he is a scientist at the Max Planck Institute for Solar System Research and leads a research team working on the outer solar atmosphere. Hardi Peter is a faculty member at the Max-Planck Research School on "The Solar System and beyond" and since 2012 an associate Professor at the University Göttingen. Since 2007 he serves as Editor of the peer-reviewed journal Astronomy & Astrophysics.

Fluid Mechanics

DLR (German Aerospace Center) is Germany's national research centre for aeronautics and space. DLR's research portfolio ranges from fundamental research to innovative development of the applications and products of tomorrow in aeronautics, space, transportation and energy. Approximately 8,000 people work for DLR; the center has 32 institutes and facilities at 16 locations in Germany.

The Institute of Aerodynamics and Flow Technology at DLR's site Göttingen is engaged in numerical and experimental investigations on air, space and ground vehicles. Experiments are performed in wind tunnels and in real flight.

The Department of **Experimental Methods** develops optical and acoustical field measurement techniques for the acquisition of fluid mechanical (velocity, pressure, density, deformation) and aero-acoustical quantities (sound pressure). Application is mainly performed with mobile measurement systems in large industrial wind tunnels and at in-flight testing in the scope of national and European projects, providing high quality data sets which constitute a reliable basis for the validation of numerical codes.

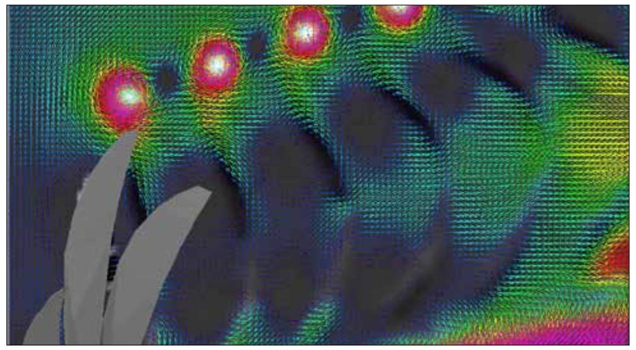


Fig. 1: Propeller slipstream development with wing interaction (Particle Image Velocimetry method - PIV).

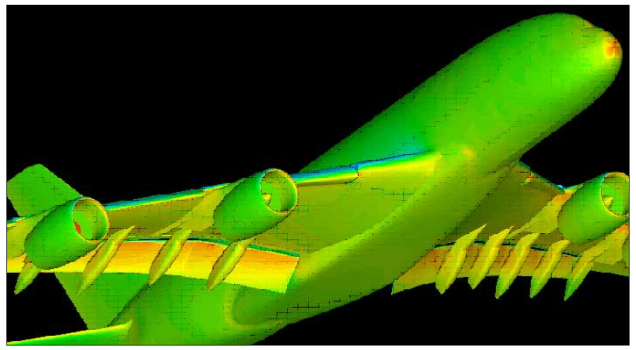


Fig. 2: Flow simulation about Airbus-like model in landing configuration with pressure distribution on the surface and vorticity in different cuts of the aircraft wake (grid adapted to the wake).

The department **C²A²S²E** (Center for Computer Applications in AeroSpace Science and Engineering) develops methods for the numerical simulation of flows about complex configurations based on hybrid, unstructured grids, which it provides to users in research and industry. These methods are the DLR-TAU Code, which e.g. is employed Europe-wide by Airbus as their tool for flow simulation of complete aircraft, as well as the THETA Code, which is mainly directed to the simulation for incompressible flows with varying density, e.g. in combustions or cabin simulations. The department works furthermore on improvement and development of physical models for turbulence and transition.

The major objective of the **Spacecraft** Department is the virtual design of hypersonic vehicles and spacecrafts and their qualification in ground based facilities and flight. The core research topic is aerothermodynamics - a field with an extremely wide spectrum of applications in aerospace engineering. The major focus of the department is on space transportation, rocket propulsion, hypersonic technology and orbital technology. Numerical prediction methods and major ground based test capabilities are developed applied and validated. The department was involved in all major German and European Space Technology programs during the last two decades.

In the Department **Fluid Systems** the aim of the research is to combine modelling with methods used for experimental and analytic-numerical studies of turbulent and multiphase flows. Problems of technical applications are thus solved through measurements, computation and the improvement of fluid dynamical systems. The latter are fluid systems in airplanes and the aircraft cabin as well as the flows which are of interest for the transportation, aerospace and energy industry.

The department **Technical Flows** develops solutions for the fluid mechanical optimization of helicopters, cars, trucks and trains. For this purpose conventional force, pressure and

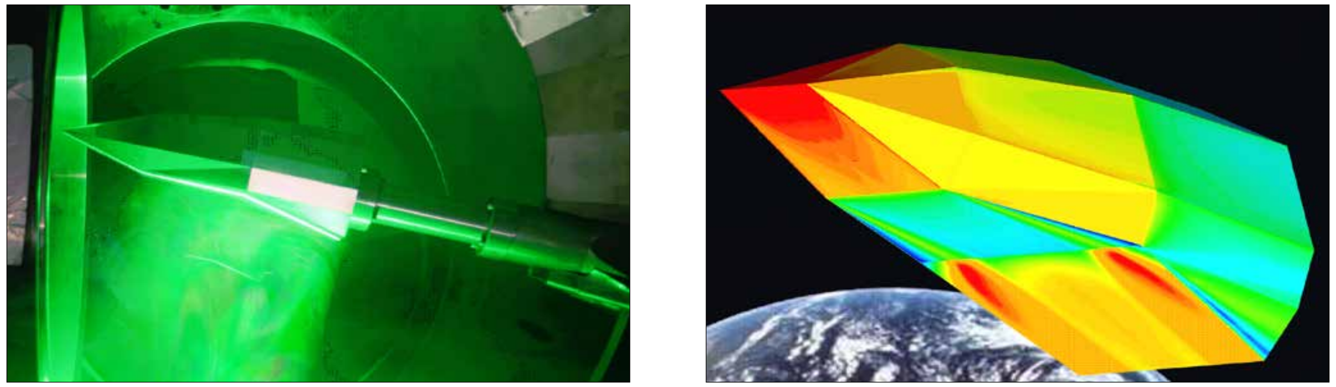


Fig. 3: Aerothermodynamical investigation of the DLR SHEFEX (SHarp Edge Flight EXperiment) configuration in the High Enthalpy Shock Tunnel Göttingen, HEG (left) and with the DLR TAU code (right).

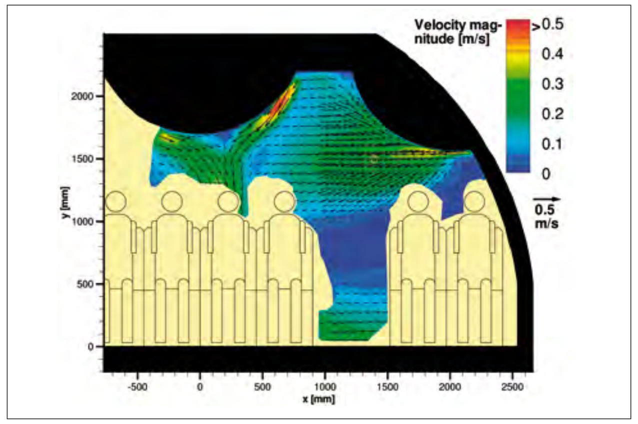


Fig. 4: Air flow in a generic 1:1 aircraft cabin model measured with large scale Particle Image Velocimetry.

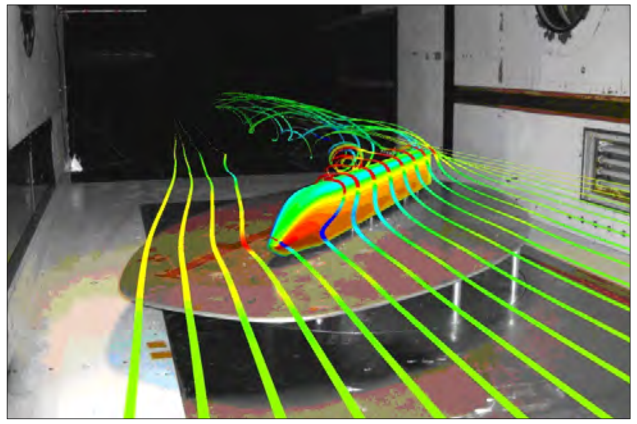


Fig. 5: Numerical simulation: streamlines and surface pressures on a high speed train model in the DNW-KKK wind tunnel under cross-wind conditions.

velocity measurements are applied as well as modern laser-optical tools (e. g. Particle Image Velocimetry). They are used in modern simulation rigs, wind and water tunnels. Furthermore, noise prediction methods are developed in order to reduce traffic noise.

Special phenomena on flight vehicles at transonic and hypersonic speeds are the research topics of the **High Speed Configurations** department. Flow control methods for the enhancement of aerodynamic performance and unsteady effects on maneuvering flight vehicles and in separating flows are investigated. Advanced numerical tools as well as complex test and measurement techniques for wind tunnel experiments are being used to enhance aerodynamic performance such as lift, drag, maneuverability and heat loads.

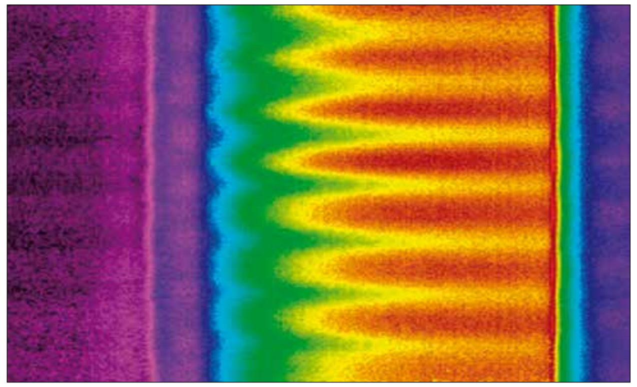


Fig. 6: Heat flux pattern underneath boundary layer structures at Mach 3.8.

Andreas Dillmann

Born in 1961 in Karlsruhe, Andreas Dillmann got his diploma in mechanical engineering from the University of Karlsruhe in 1986. He completed his dissertation on homogeneous nucleation of supersaturated vapors at the Max Planck Institute for Fluid Dynamics and received his PhD from Georg-August-University Göttingen in 1989. After changing to DLR, Institute of Fluid Mechanics in Göttingen he got his habilitation in fluid mechanics from the University of Hannover in 1995. From 1996 to 1998 he hold a Heisenberg-Scholarship from the German Research Foundation (DFG). In 1998 he was appointed full professor of Theoretical Fluid Mechanics at the Technical University (TU) of Berlin. Since 2003 he is a full professor of fluid mechanics at Georg-August-University Göttingen and Director of the Institute of Aerodynamics and Flow Technology, German Aerospace Center (DLR), Göttingen. His main scientific interests are in the fields of analytical fluid mechanics and aerodynamics.

Fluid Mechanics

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Current research relates to compressible and multiphase flows as well as to aerodynamics. Related studies are partly fundamental in nature with an emphasis on obtaining insight into the physical mechanisms that govern various flow phenomena, and partly happen against the background of applications, especially relating to the performance of aircraft. The approach is mostly experimental but analytical and numerical methods are also applied.

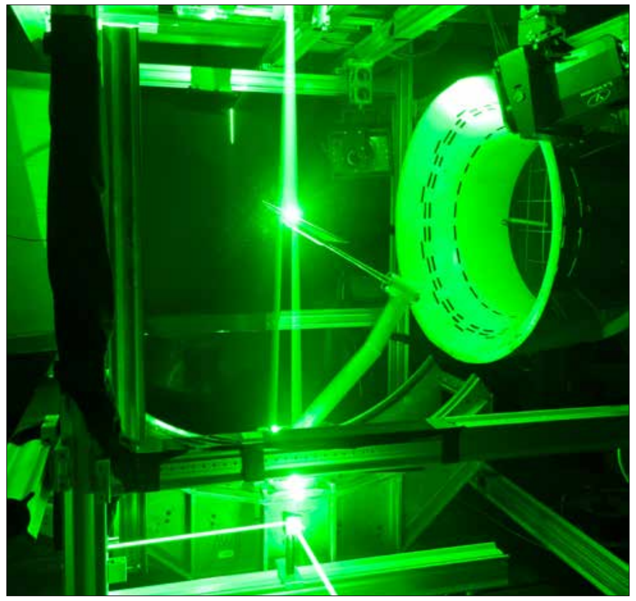

Fig. 1: Investigation of the flow field around a delta wing by particle image velocimetry in a low-speed wind tunnel.

The aerodynamic studies concern novel concepts for the control and stability of aircraft, the reduction of wave drag, and diffuser and nozzle flows. For example, the flow field around delta wings at positive angles of attack is dominated by large-scale vortices on the upper surface due to flow separation at the leading edge. The separated flow rolls in forming vortices that provide additional lift, the so-called vortex lift. The goal is to change strength and position of the vortex cores by slight modifications of the wings' leading edges. This strategy aims at producing an unsymmetrical distribution of lift on the wings and thus, for example, rolling moments to be used in controlling the model. The effectiveness of different approaches is tested both by measuring forces and moments acting on the model and by investigating the flow field around the model by particle image velocimetry (Fig. 1). Wave drag that limits the maximum economic cruise speed of airplanes is caused by nearly normal shock waves terminating supersonic regions formed locally above wings at transonic speeds. Wave losses can be reduced by changing a normal shock into a system of oblique shocks. This can be achieved in different ways that are tested in a wind tunnel. Another topic is boundary layer ingestion into highly integrated intakes of embedded propulsion systems on blended wing bodies (BWB). Here, engines are typically embedded into the upper side at the rear end of the BWB. Therefore, boundary layers formed ahead of the intake need either to be diverted or ingested. The effect of ingested boundary layers is twofold. On the one hand it can provide energetic benefits. On the other hand, the resulting distortion of the flow and a reduction in stagnation pressure may reduce the efficiency of engines. Studies are performed in the cryogenic wind tunnel of the German-Dutch Wind Tunnels (Fig. 2). A turbulent boundary layer is formed on a flat plat ahead of the intake. Within the diffuser means of flow control as, for example, vortex generators are applied to mitigate distortions that are determined by a distortion rake located at the end of the diffuser.

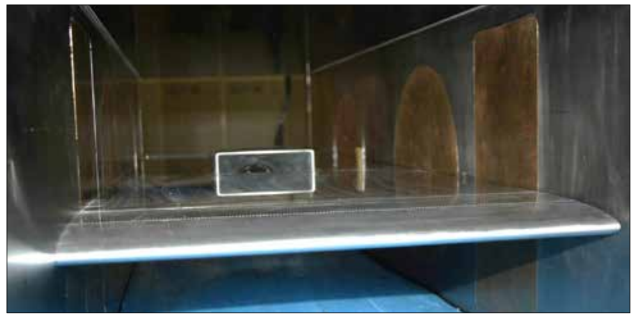

Fig. 2: Generic intake on a flat plate in the cryogenic wind tunnel KRG of the German-Dutch Wind Tunnels DNW.

Martin Rein

Martin Rein received his diploma (1984) and doctoral (1987) degrees in Physics from the University of Göttingen while working at the Max-Planck-Institut für Strömungsforschung. After a postdoctoral stay (1988-1989) at GALCIT, Caltech, he returned to Göttingen where he held positions at the Max-Planck-Institut für Strömungsforschung (1990-1993) and the Universities of Göttingen (1994) and Hannover (1997-1998). During a habilitation stipend (1994-1997) he also stayed at the Institute of Fluid Mechanics and Heat Transfer, Technical University of Vienna (1995), where he received a venia docendi in fluid mechanics in 1998. In 1999 he joined the Institute of Aerodynamics and Flow Technology of the German Aerospace Center (DLR). He obtained a venia legendi at the University of Göttingen in 2004, spent a sabbatical leave at UCSB in 2007, and was appointed senior scientist of DLR in 2006 and apl. Professor at the University of Göttingen in 2008.

Applied Optical Technologies

The research activities at the Laser-Laboratorium Göttingen range from the development of non-contacting laser measurement engineering, the manufacturing of new products and product processing by using lasers, the development of new laser systems to applications in medical technology and the live sciences.

Optical Nanoscopy

The department focuses on basic research and the resulting practical implementations for use in the field of superresolution fluorescence microscopy. Switchable optical transitions are used to circumvent limitations due to the laws of diffraction which are inherent for all optical methods. The emphasis is on the development of physiologically compatible systems which allow the studying of the interaction of molecules and finest structures within (living) cells on the 20-200 nm scale.

Short Pulses / Nanostructures

The department concentrates on the generation of high power subpicosecond DUV laser pulses and the development of equipment for the compression of multimillijoule pulses to few-cycle duration. Further, material processing by laser ablation and surface modification which enables the flexible fabrication of microstructures and nanostructures, e.g. for fluidic, medical or optical applications is investigated.

Optics / Short Wavelengths

The department is concerned with the characterisation of laser sources, as well as high-quality optics for beam steering and shaping. Additionally, laser-induced damage thresholds, thermal lensing as well as absorption and degradation behaviors of optical components are investigated and the coherence properties of laser radiation are precisely characterized. Furthermore, compact EUV / XUV sources for metrological applications with soft X-rays are being developed.

Photonic Sensor Technologies

The department devotes its research to the development of novel optical measurement procedures-mainly based on Raman scattering, IR absorption and fluorescence emission, often combined with chemometric analysis. The strengths of these methods are that they lead to a non-destructive, contact-free and fast measurement of substances, structures, complex matrices and biological systems.

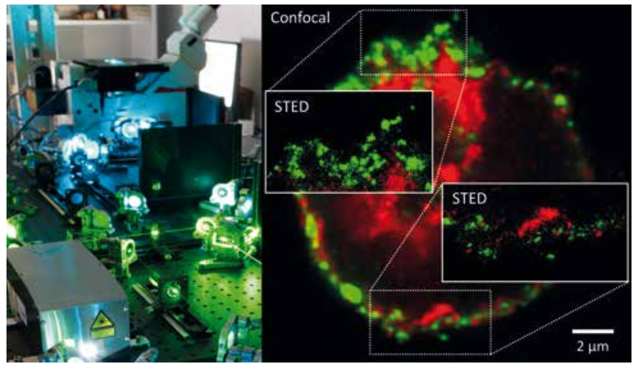

Fig. 1: Left: Optical setup for nanoscopy. Right: Two-colour confocal image with high resolution STED insets of the distribution of the protein mortalin (red) and the complement protein C9 (green) in a suspended K562 cell. The STED images allow to analyse not only the clustering of C9 (top) but also the colocalization of both proteins (bottom).

Alexander Egner

Alexander Egner, born 1970 in Mannheim, studied physics at the University in Heidelberg, where he received his doctorate in physics in 2002. He was subsequently postdoctoral researcher and later senior scientist in the department of NanoBiophotonics at the Max-Planck-Institute for Biophysical Chemistry. In 2010 he became director of the Laser-Laboratorium Göttingen where he also heads the department of Optical Nanoscopy. He is a faculty member of the graduate school for "Neurosciences, Biophysics, and Molecular Biosciences" and serves on the boards of the cooperated research center "Nanoscale Photonic Imaging" and the cluster of excellence "Nanoscale Microscopy and Molecular Physiology of the Brain".

Neurophysiology and Cellular Biophysics

The research in our group focuses on the biophysics and the physiology of how molecules or mixtures of molecules are detected by biological and artificial sensors and how the resulting signals are processed to allow the identification or perception of odorants and odors.

The experimental and computational projects carried out in our lab are concerned with single molecule inter-actions using fluorescence correlation spectroscopy, optical as well as metal oxid semiconductor sensors as the hardware input stage for electronic nose algorithms, high-resolution microscopy, electrophysiology and imaging of olfactory receptor neurons in the nose of tadpoles, single molecule processes and modulation (e.g., by endocannabinoids) electrophysiology (patch clamp) and imaging of the olfactory bulb as the secondary computational neuronal network of the olfactory system.

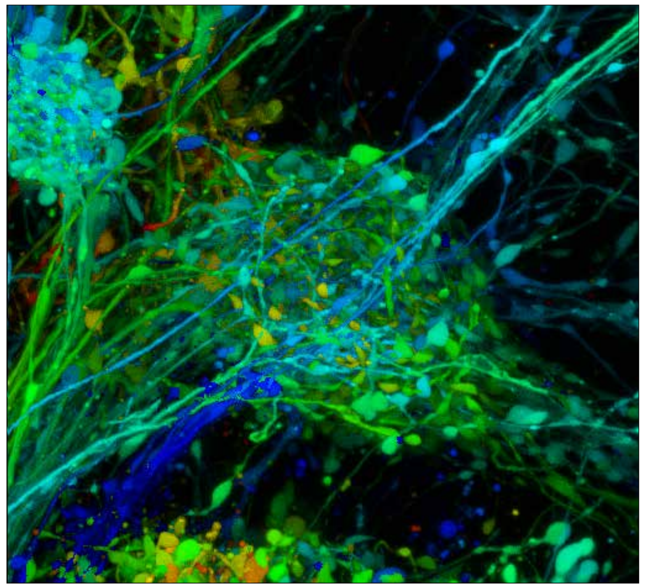

Fig. 1: Synaptical network of sensory fibers. The image was taken by Eugen Kludt using a two-photon absorption laser scanning microscope. The individual nerve fibers that can clearly be seen have a diameter of less than 1µm.

Motivation

The five classical senses are vision, hearing, touch, taste and smell. For the former three we have reasonably good instruments for recording the underlying physical parameters, e.g., frequencies of sound or light, etc. For the sense of smell everyday instrumentation is still in its infancy. There are virtually no simple devices for the online, real-time detection of pollutants in water, hazardous substances in food, or for differentiating various species of coffee, olive oil, or wine. This motivates both our research on the olfactory system and the development of artificial chemosensory systems.

Olfactory System

This sensory modality mainly consists of three stages: (i) the olfactory receptor neurons, (ii) the olfactory bulb, and (iii) higher olfactory brain centers. We analyse (i) single molecule processes in signal cascades in sensory cells using the patch clamp technique as well as confocal imaging metods and FCS, (ii) the functional map from the sensor cells onto the olfactory bulb in order to understand the selforganization of this map, and (iii) the synaptic interactions within the olfactory bulb in order to understand the filtering and transfer function of this neuronal network.

Electronic nose

Currently we are interested in measuring chemical components of grain in order to differentiate polluted from wild-type grain. We are setting up artificial sensor array systems that yield chemotypical signals from which the relevant features are extracted.

Detlev Schild

Detlev Schild, born 1951 in Detmold, studied Physics and Medicine in Göttingen, where he obtained his PhD in 1985 and his Dr.med. in 1987. After an initial interest in biorhythmicity, frequency entrainment and nonlinear oscillations he turned to the study of membrane biophysics, in particular in excitable cells in the brain. After stays in Siena and Brighton he started to study the properties of olfactory sensory neuron as well as the neuronal network involved in the combinatorial coding of odors. Since 1997 he is the chair of the department of neurophysiology and cellular biophysics. Cozzarelli Prize of the National Academy of Sciences USA (2008). Amongst his various administrative activities, he is a member of the academic senate (2007-09) and of the foundation council of the university.

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