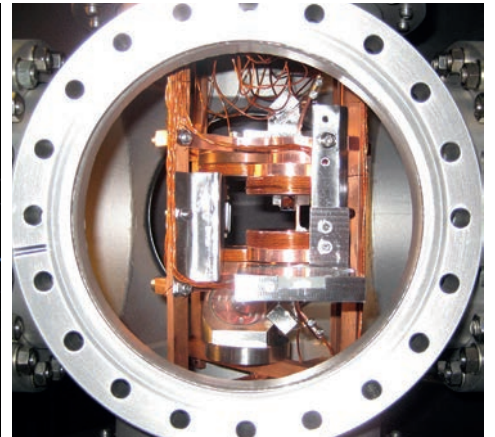
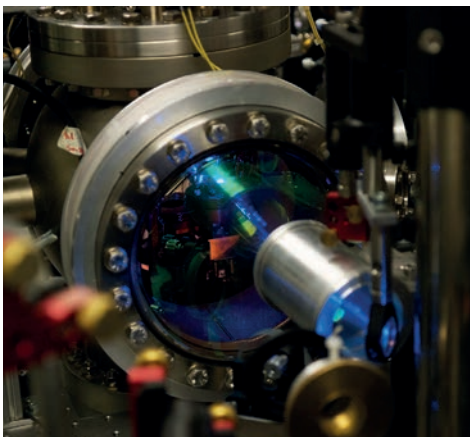
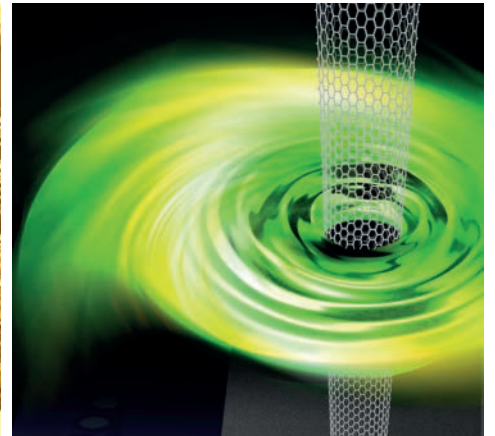
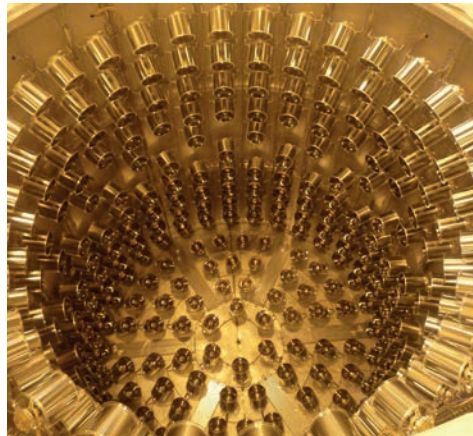
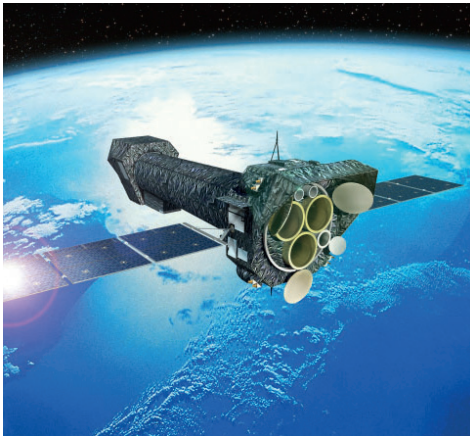


EBERHARD KARLS  
UNIVERSITÄT  
TÜBINGEN



# DEPARTMENT OF PHYSICS

Astro & Particle Physics - Quantum Science - BioNanoPhysics - Neuroscience

FACULTY OF SCIENCE  
Department of Physics



# IMPRINT

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## Photography

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Boris Hofmann/University of Tübingen: p 26 portrait Hofmann

CERN: p 11

CQ/University of Tübingen: cover 1<sup>st</sup> row middle and right

Daniel Braun/University of Tübingen: p 17 bottom

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ESA, Ducros: cover 1<sup>st</sup> row left

ESA/Herschel/PACS/SPIRE/J. Fritz/University of Gent: p 9 Infrared

ESA/XMM-Newton: p 28

ESA/XMM-Newton/EPIC/W. Pietsch/MPE: p 9 X-rays

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Kepler Center/University of Tübingen: cover 2<sup>nd</sup> row right

Klaus Scheffler/MPI for Biological Cybernetics: p 31 bottom

Kostas Kokkotas/University of Tübingen: p 10 bottom

Matthias Bethge/University of Tübingen: pp 24, 25

NASA: p 8

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Sebastian Slama/University of Tübingen: p 17 top

Tilman Schäffer/University of Tübingen: p 19

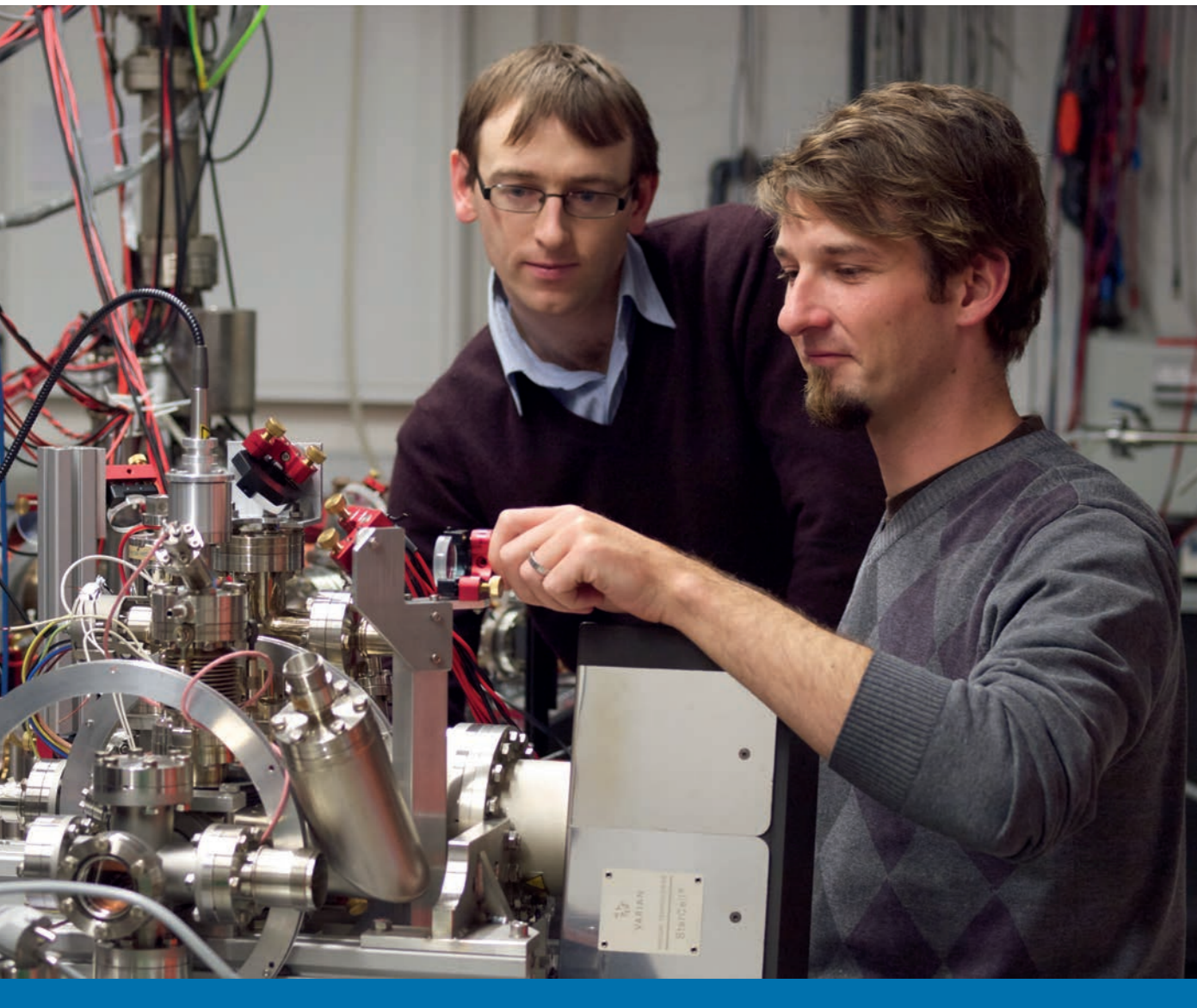
Verlag des Forschungszentrums Jülich: p 18 bottom

For centuries, researchers at the [University of Tübingen](#) have been pushing back the boundaries of fundamental science and technology. Today, some 33 research groups in the [Department of Physics](#) at our university continue to explore the frontiers. The focus of their work ranges from the tiniest subatomic particles to the largest structures in the universe, from the hottest stars to the coldest quantum objects, via the most intricate nanoscale physics and biotechnology.

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## Studying at the Department of Physics

Tübingen is a historic city of research and teaching, and with 28,500 students among 86,000 inhabitants, it remains forever young. The University of Tübingen, founded in 1477, is one of Germany's most renowned. Rich in tradition and culture, with a picturesque old town, punts on the Neckar River and a geographical location close to the mountains of the Black Forest and the Swabian Jura, Tübingen offers a unique and inspiring environment for study and creativity. The Department of Physics offers Bachelor & Master courses in physics, nanoscience, and physics for teachers, as well as a wide variety of PhD opportunities. The University of Tübingen has been selected for funding in the German government's Excellence Initiative, making Tübingen one of Germany's eleven universities distinguished with that title of excellence.



### Bachelor Course

The Bachelor course (8 semesters) includes modules in higher mathematics, experimental and theoretical physics, laboratory courses, and specialized modules in

- Astronomy and Astrophysics
- Nuclear and Particle Physics
- Astroparticle Physics
- Condensed Matter Physics
- Quantum Optics
- Nanostructures and Interfaces
- Biological and Medical Physics
- Scientific Computing

An overseas semester can be arranged, typically during the third year. The department has a large number of contacts with other leading universities worldwide and supports applicants. Bachelor studies require the completion of a major project and thesis.

[For PhD opportunities please visit the websites of the Research Centers!](#)

### Master's Program

The Master's Degree program (2 semesters) in the department's groups is research-oriented. The aim is to develop skills for independent scientific work. The program requires the completion of a Master's thesis. We offer a double degree program in which students of the universities of Tübingen and Trento (Italy) spend 2 semesters at the partner institution to broaden their education and experience.

### Physics for Teachers

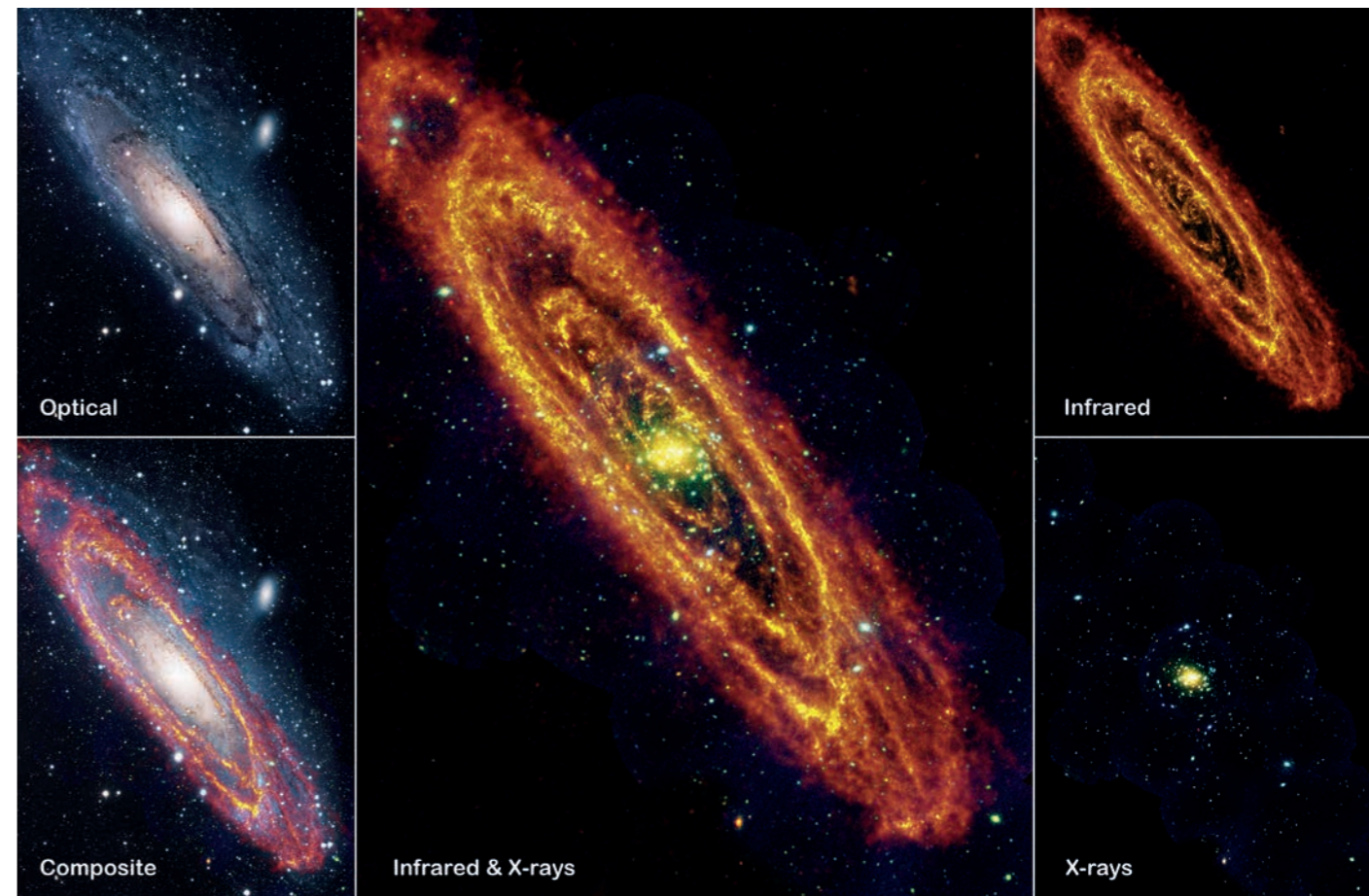
The Physics Department is strongly committed to the high-quality education of teachers, who have the vital mission of passing on modern physics ideas, and a basic understanding of our world, to the next generation of pupils and students. The study plan for the first three semesters, concentrating on basic classical physics, is the same as that for the Bachelor in Physics. After a practical semester at a school, the prospective teachers attend lectures and seminars in which subjects of modern physics are taught, with special attention paid to didactic aspects. Additional seminars and laboratory courses are dedicated to the presentation and demonstration of experiments. The degree is completed within a 10-semester period by studies of a second subject, e.g. mathematics, and by studies of didactics and education.





## Kepler Center for Astro and Particle Physics

Research at the Kepler Center is at the cutting edge of particle physics, astrophysics, and cosmology. The Kepler Center comprises the groups of astrophysics, computational astrophysics, general relativity, and particle physics, and combines a rich experimental program with intense theoretical studies. The physics goals are multi-messenger observations of the universe, using the universe as a laboratory for elementary particles and extreme physical conditions, studying the properties of elementary particles and their influence on the evolution and the structure of the universe, while constructing theoretical models to understand the processes at work within our universe.



Andromeda-Galaxy M31

### Astronomy

One research topic of the Astronomy group is focusing on the late stages of stellar evolution, i.e., white dwarfs and neutron stars. Quantitative spectral analyses across the entire electromagnetic range from the X-ray to the infrared regimes, performing radiation transfer calculations and stellar atmosphere modeling allow us to derive stellar parameters and to draw conclusions on the structure and evolution of these objects. Element abundance determinations in white dwarfs based on high-resolution optical and ultraviolet spectra obtained at ground- and space-based observatories provide insight into stellar nucleosynthesis networks and interior convection processes. Mass and radius determinations of neutron stars constrain the equation-of-state of matter at supernuclear densities. Based on the simulation of neutron star atmospheres and X-ray spectroscopy, we can derive stellar parameters.

The group is also investigating accretion disks around compact stars, which are supplied with matter either by a stellar companion in close binary systems or by circumstellar material around solitary stars, such as disks formed from supernova-fallback material or planetary debris.

Another experimental topic is the development of detectors for ultraviolet radiation for application on space-based observatories.

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### High Energy Astrophysics

The main scientific goal of the High Energy Astrophysics group is the exploration of the extremes of the Universe from space and from the ground. We are active in experimental developments for future space missions that will observe our galaxy, the Milky Way and the far universe using X-rays. We are members of the teams working on the eRosita telescope on board the Spectrum X-Gamma satellite and on the future challenging missions of the European Space Agency: the Large Observatory For X-ray Timing (LOFT) and ATHENA, the Advanced Telescope for High Energy Astrophysics. For all these missions we develop digital electronic systems - while testing prototypes of the detectors in our laboratories. We also develop simulations to help us understand the background that these missions will experience and the response of the instruments. Today high energy astrophysics also means very high energy gamma rays. This is why we are active in the operation of the HESS Cherenkov Array Telescope in Namibia, and are taking part in the future Cherenkov Array Telescope-CTA. The control and alignment systems of the mirrors, the testing of the mirrors, and the development of fast electronics are our main challenges. We also investigate the extreme properties of compact stars like neutron stars, black holes and the mysteries of the remains of supernovae.

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Warm interstellar medium in the 30 Doradus region, obtained with data of the Magellanic Cloud Emission Line Survey.

### General Relativity and Relativistic Astrophysics

The Theoretical Astrophysics Group, led by Kostas Kokkotas, works primarily on problems related to sources of gravitational waves, with secondary work on the processes generating gamma rays and X-rays from neutron stars and black holes. Gravitational waves are expected to open a window for observing the universe and to provide unique information from astronomical objects and events which may not emit electromagnetic radiation. The group focuses on neutron stars, which are among the primary sources of gravitational waves. It is expected that by analyzing their gravitational wave spectrum we may understand the details of their structure. The group investigates the formation and subsequent evolution of neutron stars as well as the instabilities that may be induced via fast rotation. The effects of superfluidity, superconductivity, and the presence of extreme

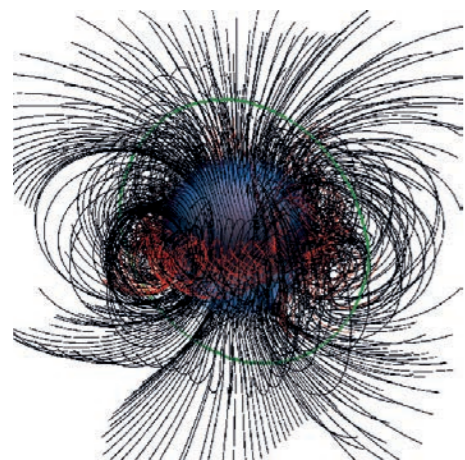
magnetic fields on their dynamics are also under thorough investigation. Moreover, the group is working on problems related to black-hole dynamics: their relation to gravitational waves and both thermodynamics and quantum processes near black holes. Finally, in recent years we have developed expertise in alternative theories of gravity, especially in the use of observational astrophysics to reveal possible deviations from the classical Einstein's theory.

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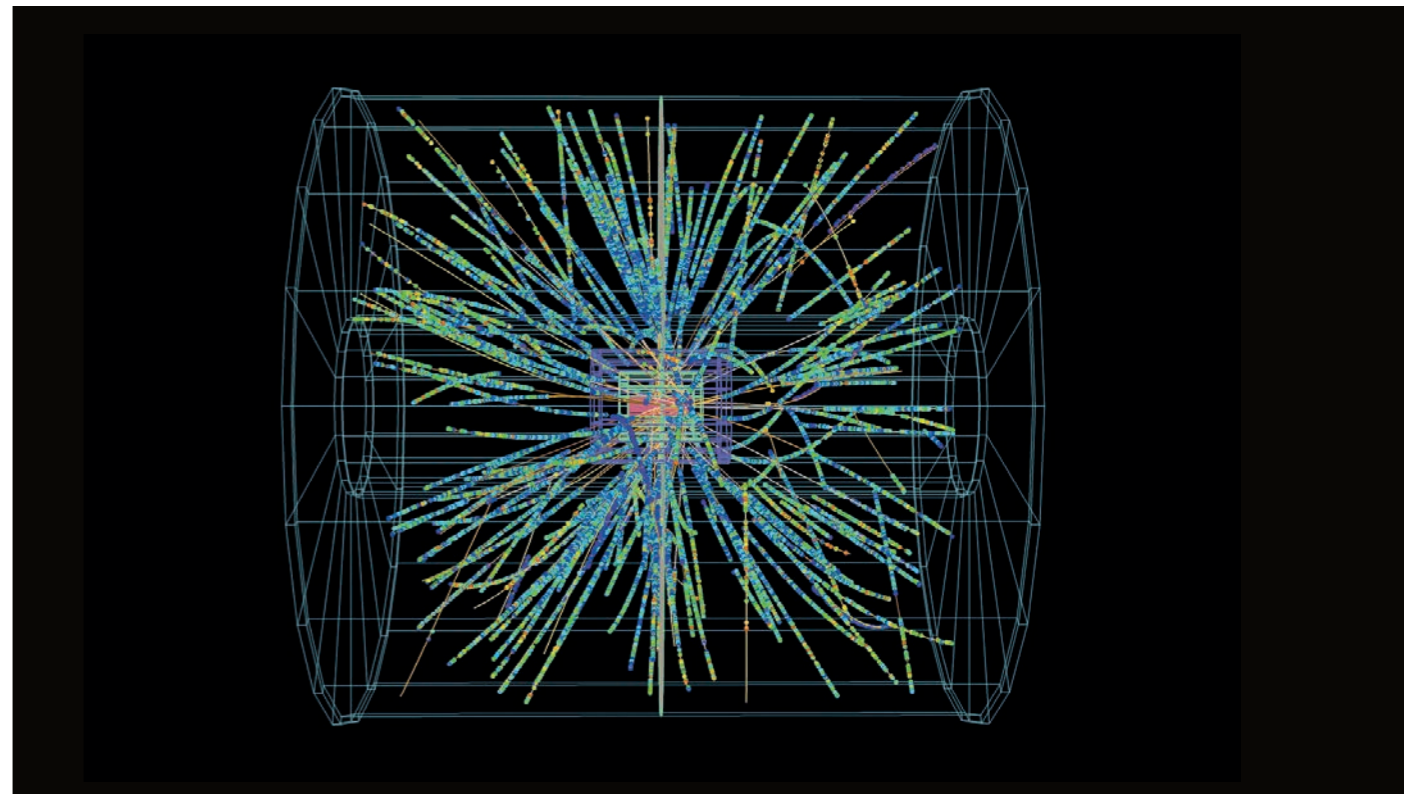
### Computational Astrophysics

The Computational Astrophysics Group deals with the numerical modelling of complex astrophysical phenomena. For that purpose we develop and apply complex numerical algorithms to solve the time-dependent equations of magneto-hydrodynamics including radiative transport and solid state physics. The group performs intense simulations using highly parallelized state-of-the-art particle and mesh-based codes. Major research topics include understanding the growth of planets in the solar system and exoplanetary systems. We model the process of planet formation from  $\mu\text{m}$ -sized particles to the giant planets and study the evolution of whole planetary systems. We study the structure and evolution of accretion discs, for example, in close binary stars and around young protostars.

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General Relativity and Relativistic Astrophysics; the structure of the ultra strong magnetic field of a neutron star.



Tracks of a high energy proton-lead collision seen with the ALICE detector at CERN-LHC.

### Theoretical Nuclear and Particle Physics, Quantum Field Theory

The activities in Theoretical Particle Physics are devoted to the low energy regime of quantum chromodynamics, QCD. We focus on the explanation of such non-perturbative effects of the strong interaction such as confinement of quarks and gluons and the spontaneous breaking of chiral symmetry.

We also investigate the deconfinement phase transition and the restoration of chiral symmetry at finite temperature and baryon density.

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### Theoretical Nuclear and Particle Physics

Our research activities focus on Quantum Chromodynamics (QCD), the established theory of the strong interactions. We perform phenomenological studies of lepton-proton and proton-proton scattering, with the goal of using the available experimental data to learn about the distributions of quarks and gluons inside a proton. We are especially interested in finding out how quarks and gluons provide the spin of the proton. Our work also includes precision QCD calculations for observables at hadron colliders, among them the Large Hadron Collider (LHC) at CERN and machines in the US.

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### Nuclear Matter under Extreme Conditions

Heavy-ion collisions at ultra-relativistic energies provide the unique possibility to compress matter in the laboratory to baryonic densities as they occur in the interior of neutron stars, or to heat up matter to temperatures as high as  $10^{12}$  K. At these extreme temperatures, which prevailed a few microseconds after the Big Bang, the universe underwent a phase transition from a quark-gluon plasma to a hadron gas. These conditions are presently recreated in ultra-relativistic nuclear collisions, which are conducted in the ALICE experiment at the CERN-LHC in Geneva.

Similarly, the enormous pressure in a neutron star leading to high baryonic densities will be simulated in the CBM experiment, which is presently under construction at the future accelerator center FAIR in Darmstadt. In this experiment, heavy nuclei will be smashed into each other at energies allowing the nuclei to interpenetrate and compress each other. This creates regions with several times the saturation density of nuclear matter.

In both experiments complex detectors register the very high number of fragments produced in these collisions. Subsequent intricate analyses have to be performed to reveal the properties of the primordial matter existing only for a few  $10^{-23}$  seconds during the early stages of the collision.

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Fisheye (GERDA Collaboration)

## Theoretical High Energy Physics

The Theoretical High Energy Physics Group investigates the phenomenology of elementary particles via precision calculations for collider experiments at high energies, such as the CERN Large Hadron Collider. Our aim is an improved understanding of the strong and electroweak interactions that govern the dynamics of elementary particles.

A particular focus of our research is on the physics of the recently discovered Higgs boson. By means of advanced numerical simulations we provide predictions that help to pin down the nature of this particle. Moreover, we try to identify possible signatures of new physics that cannot be accounted for within the Standard Model of elementary particles.

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## Low-energy QCD and the Physics of Hadrons

We pursue research in the theoretical understanding of strongly interacting composite particles called hadrons. Hadrons range from the nucleon, an elementary building block of atoms, to the so-called Z mesons, recently discovered unusual particles produced and observed in lab experiments such as at the LHC. Our aim is the theoretical description of the structure and interactions of these hadrons as based on the non-perturbative features of the fundamental strong force described by Quantum Chromodynamics (QCD). Our work includes the following research topics: exotic hadrons and their properties, hadrons as a laboratory for physics beyond the standard model of particle physics, structure details of the nucleon, and novel tools in higher-dimensional space-time. The research projects are closely connected to experimental activities at the LHC and at other laboratories worldwide.

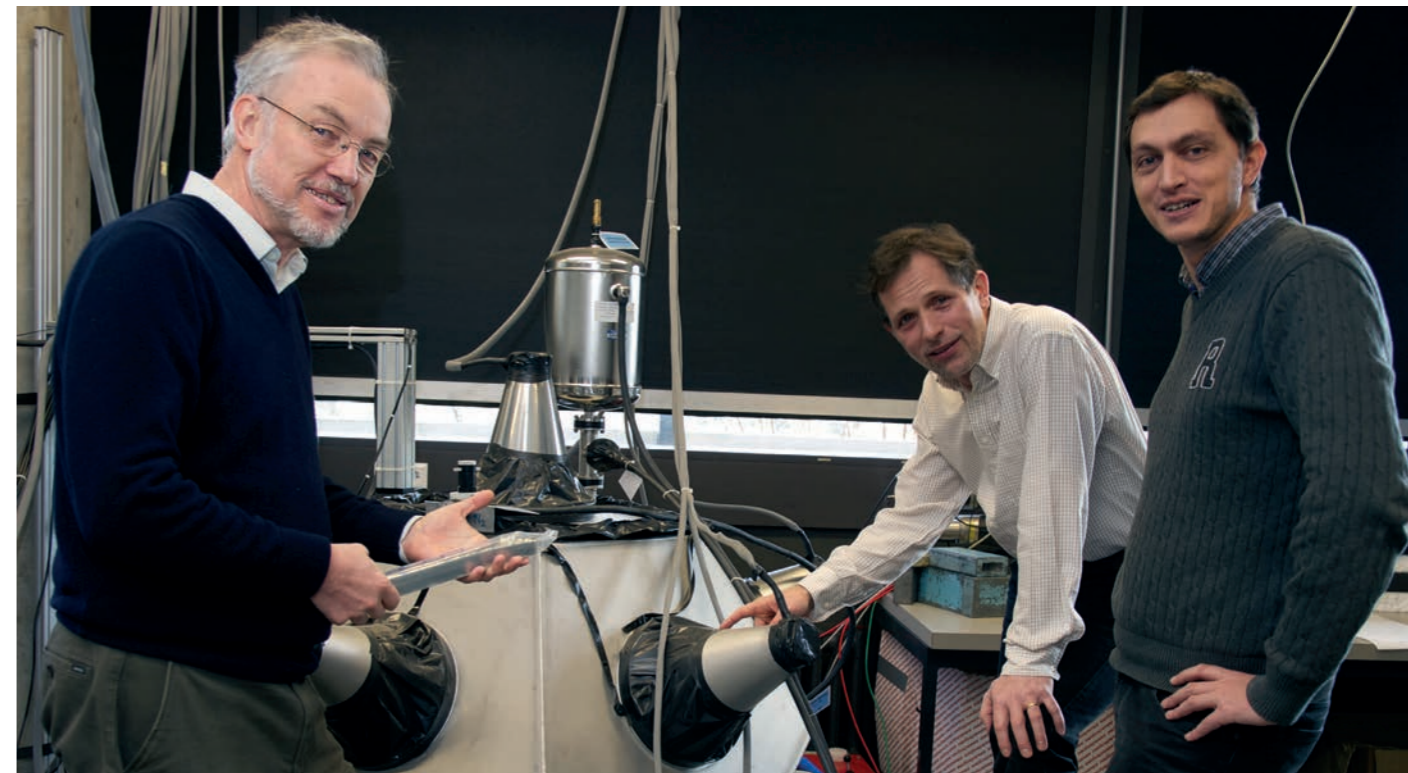
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[www.tphys.physik.uni-tuebingen.de/faessler/sec/gutsche.html](http://www.tphys.physik.uni-tuebingen.de/faessler/sec/gutsche.html)

## Astroparticle Physics

Our field is the investigation of physics beyond the standard model of particle physics by experiments in astroparticle physics. Our projects aim to direct dark matter detection and investigate aspects of neutrino physics. About 85% of the matter in the universe is of an unknown nature and cannot be explained by the particles of the standard model, which is why the search for dark matter particles is of great interest both for particle physics and cosmology. Our group contributes to the CRESST/EURECA direct dark matter search project. In direct searches, we look for scatters of Dark Matter particles on nuclei in a target material. CRESST is using a combination of cryogenic calorimetry and scintillation for the detection of the nuclear recoils. By this combination of signals radioactive background and nuclear recoils can be distinguished. CRESST is set up in the Gran Sasso underground laboratory in Italy. The group contributes with sophisticated data analysis, the investigation of low temperature scintillation, the manufacture of superconducting phase transition thermometers, Monte Carlo simulations for background studies and by investigating new types of SQUID read out systems. The group operates the shallow underground lab at the Morgenstelle close to building D, where SQUID read out systems for CRESST are developed.

Our projects in neutrino physics are GERDA the search for neutrino-less double beta decay and ECHO, an experiment to determine the neutrino mass by beta endpoint spectroscopy with new types of cryogenic detectors. We operate veto systems for the detection of cosmogenic muons and investigate other background sources.

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## Neutrino Physics

The group on experimental particle physics focuses on the measurement of fundamental properties of neutrinos. The observation of neutrino mass and mixing is a phenomenon that required an extension of the standard model of particle physics and opens up the possibility of explaining the matter-anti-matter asymmetry in the Universe by CP violation in the leptonic sector. The present and future precision measurements of the neutrino parameters are important input for finding a possible extended theoretical description leading to physics beyond the standard model. Currently, three neutrino oscillation experiments with man-made neutrino sources are pursued with international partners: The Double Chooz experiment measures the smallest neutrino mixing angle with a nuclear power plant in France as an intense neutrino source. The SOX experiment at the Gran Sasso National Laboratory in Italy searches for sterile neutrinos using a very strong radioactive neutrino emitter placed near to large liquid scintillator detector. The Jiangmen Underground Neutrino Observatory planned to start in 2019 in China is the largest reactor neutrino project and aims at the clarification the structure of neutrino masses and at the most precise measurement of the neutrino mixing matrix. In all projects, scientists from our group working in collaboration with institutes around the world. The group develops hardware for the experiments and is directly involved in the data analysis of all the current experiments.

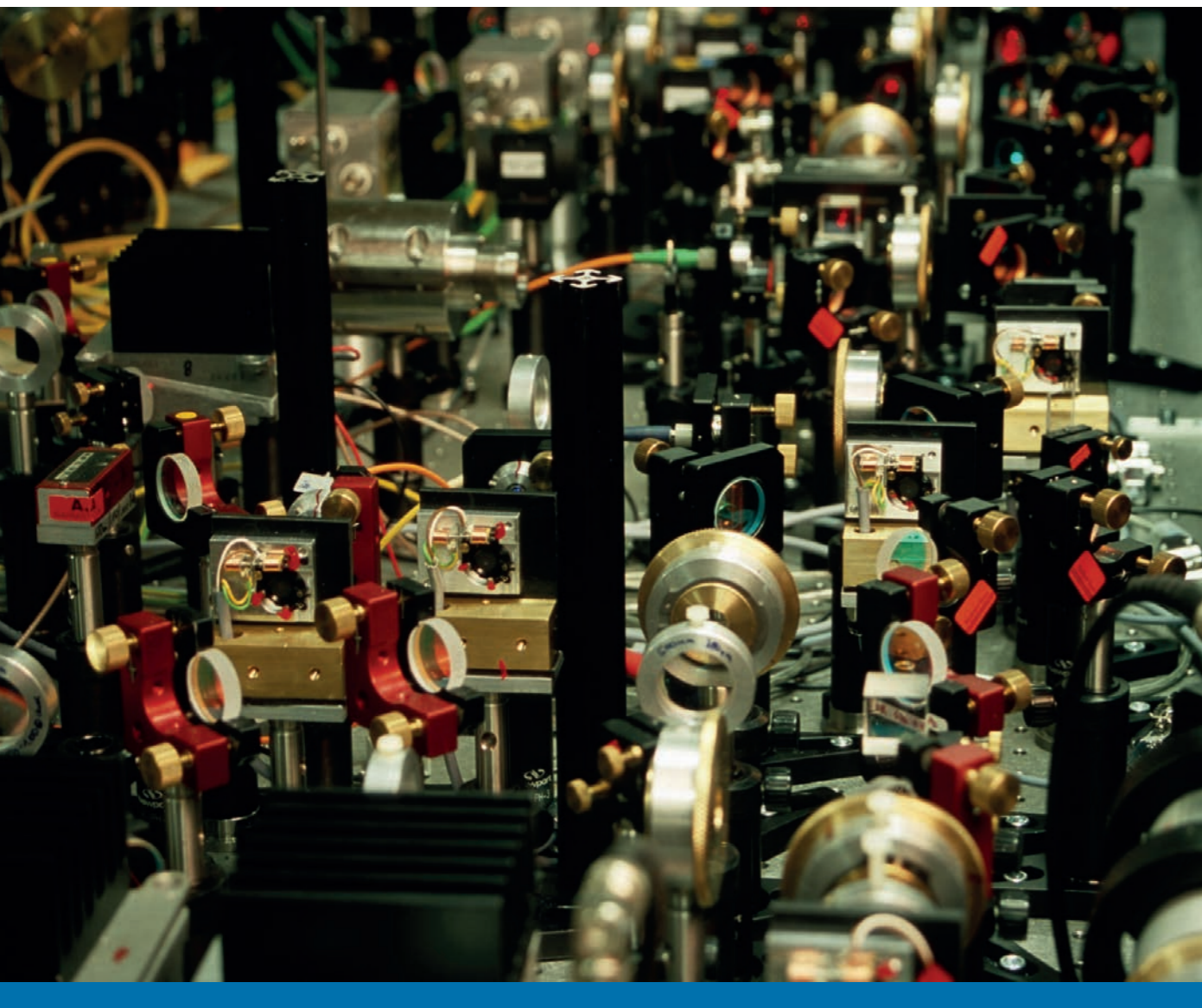
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## Beyond the Standard Model

The GERDA group searches for a special property of the neutrino which no other known particle could have; it can be phrased as the question: *{Is the neutrino its own anti-particle?}* The answer can be given by a very rare decay of a few atomic nuclei, the so-called neutrino-less double beta decay. If this lepton number violating process is observed, clearly the standard model of particle physics must be extended. Consequences for our understanding of the development of the universe after the Big Bang are unavoidable. The international GERDA collaboration aims at the search for this decay in the nucleus Ge-76 via a novel method: several tens of kilograms of Ge-76 are produced to build high-purity detectors of highest resolution which then are operated in liquefied noble gases for cooling and optimal shielding against environmental backgrounds. A further background reduction is attained since the GERDA experiment is placed in the underground laboratory LNGS below the Gran Sasso massive in Italy. In its first phase with unprecedented low background no signal was observed after 18 month of measurements which set a most stringent limit of the half life at  $2,1 \cdot 10^{25}$  years. A second phase with more detectors and further improved background rejection due to instrumentation of the cooling liquid is presently in preparation. The Tübingen group contributes to technical developments as well as to the analysis. Auxiliary measurements are being performed in Osaka (Japan), Munich (Germany) and Beijing (Tsinghua University China).

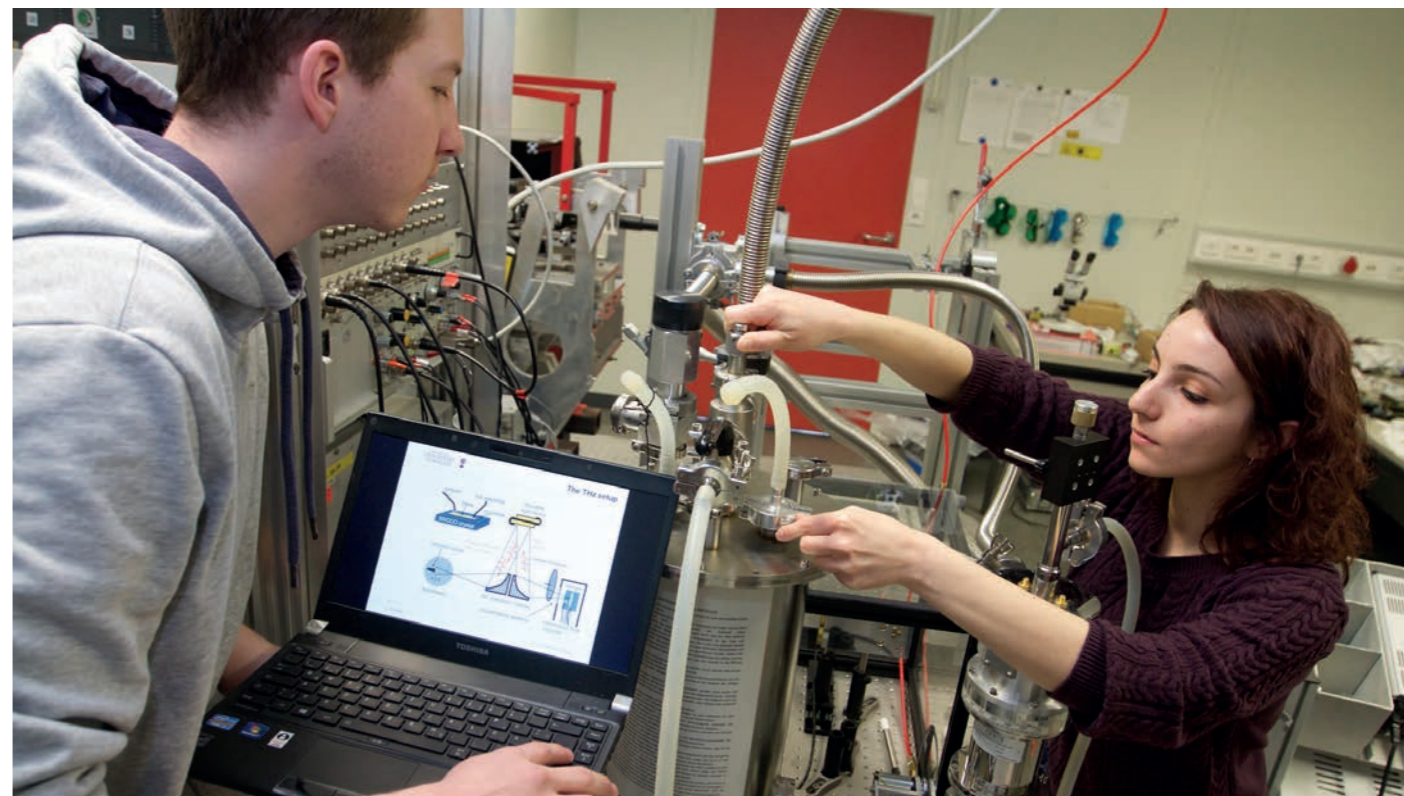
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## CQ Center for Quantum Science

Superconductivity, cold atom physics and nanotechnology are the research areas of the Center, involving seven experimental groups and three theory groups. Merging of these fields establishes novel quantum technology with immense perspectives for fundamental research and applications.



Superconductor as an emitter of terahertz radiation.

### Experimental Solid State Physics

The experimental group of Reinhold Kleiner and Dieter Kölle works on superconducting and magnetic structures, with a focus on tunneling, Josephson effects and superconducting quantum interference devices (SQUIDs). Coherent terahertz generation with so-called intrinsic Josephson junctions, formed naturally in high-temperature superconductors, is studied in close collaboration with research groups in Nanjing, Moscow and Tsukuba. Nano-sized SQUIDs for the detection of ultra-small magnetic particles are developed in close collaboration with research groups in Basel, Berlin, Braunschweig, Dresden, Lausanne and Munich. The group has created novel types of Josephson junctions based on superconductor/ferromagnet hybrids and special current injection methods. In collaboration with the experimental group of Jozsef Fortágh, we are investigating hybrid quantum systems combining cold atoms and superconducting structures like resonators and SQUIDs. In terms of methods, the group has expertise in the preparation and characterization of thin film nanostructures, low temperature scanning electron/laser microscopy, high frequency measurements and numerical simulations of Josephson junction based superconducting devices.

Prof. Dr. Reinhold Kleiner und Prof. Dr. Dieter Kölle  
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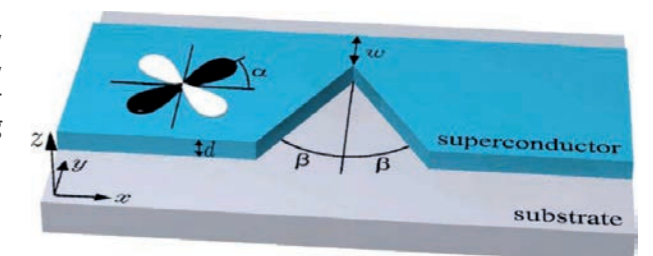
### Theoretical Solid State Physics

The theory group of Nils Schopohl works on superconductivity and superfluidity based on the microscopic Dyson-Schwinger-Gorkov many body physics approach.

Recent activities of the group govern applications of the microscopic theory to Josephson effects with nodal surfaces in high-temperature superconductors, the non linear Meissner effect, collective modes of dipolar BEC condensates, matter waves in waveguides, highly excited alkali atoms, and a first principles theory of optical activity in crystals.

There is a strong link between the experimental and theory groups with common seminars and research projects devoted to miscellaneous topics in superconductivity, cold atom research and quantum optics.

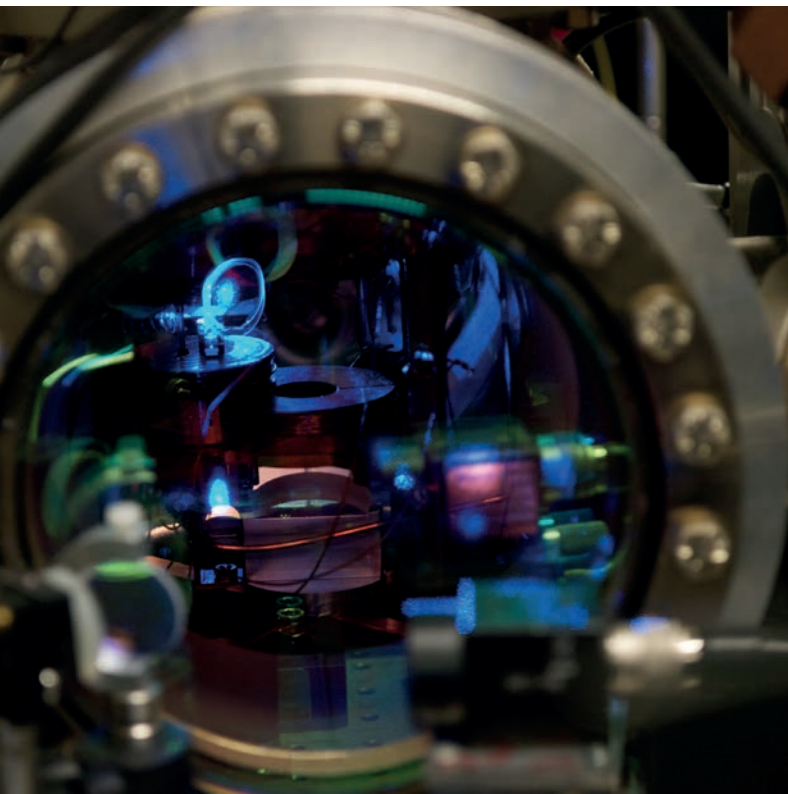
Prof. Dr. Nils Schopohl  
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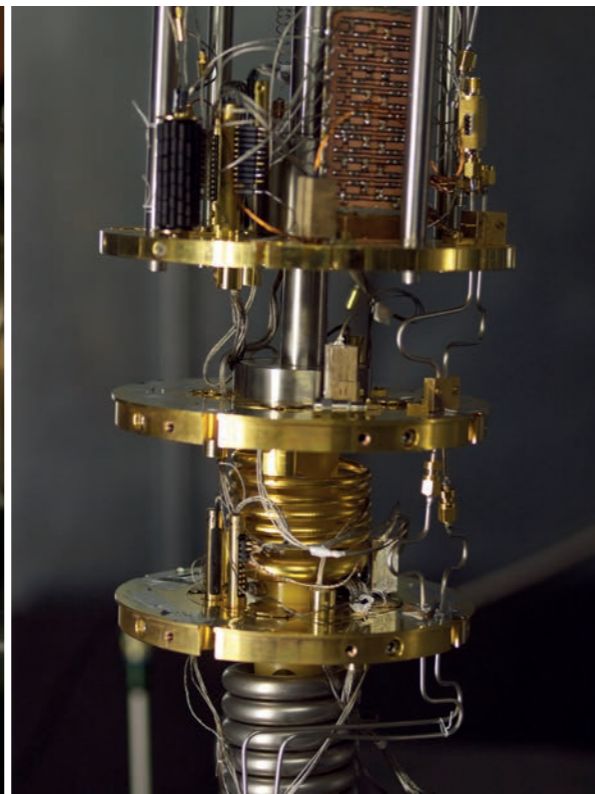
Formation of a  $\pi$ -Josephson junction with a geometrical constriction at a nodal surface of a thin film d-wave superconductor.

Scanning electron microscopy image of a Niobium thin film nanoSQUID gradiometer.





Setups for realizing cold atom/superconductor hybrid structures.



### Nano Atomoptics

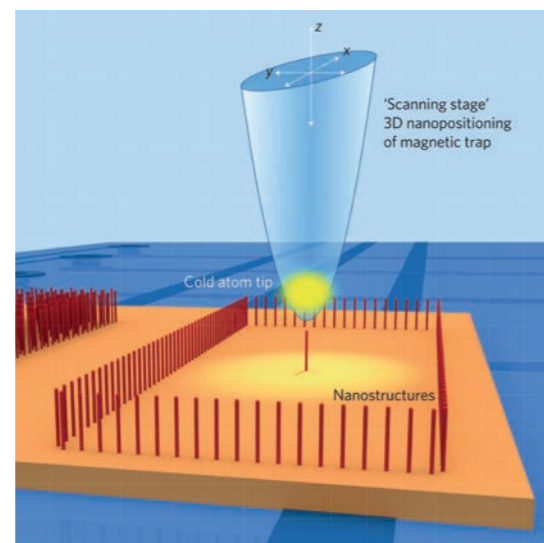
Quantum science deals with various aspects of physics taking place on the level of single atoms up to large systems with emerging quantum phenomena. It also looks at the development of quantum measurement and quantum information technologies. Several research fields contribute to the breathtaking development in this area, in fields such as cold atomic physics, photonics, condensed matter physics, material- and nano-sciences.

Built on the exchange between researchers in these subfields, the group of József Fortágh follows interdisciplinary approaches to deepening insights in quantum science and for the development of innovative quantum technologies.

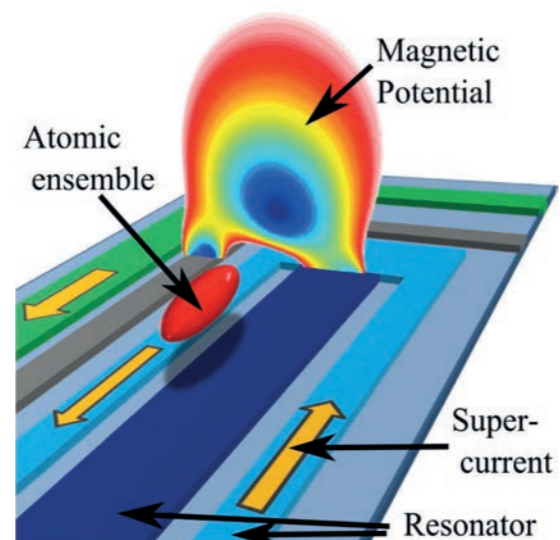
Atoms, photons, quantum gases, superconducting circuits and nano-mechanical systems make up the quantum toolbox of the group. Combining them offers unprecedented opportunities to develop chip-based atomic clocks, quantum sensors, secure communication networks and to process information faster and more efficiently than any conceivable conventional machine. The grand challenge is here to establish coherent quantum interfaces between printed electronic circuits, nano-machines, atoms and photons. The development of protocols for quantum measurements, quantum simulations and information processing complement this research.

Advances in quantum science drive technologies. The group is involved in application inspired international research collaborations and cooperates with industrial partners in the area of optical technologies.

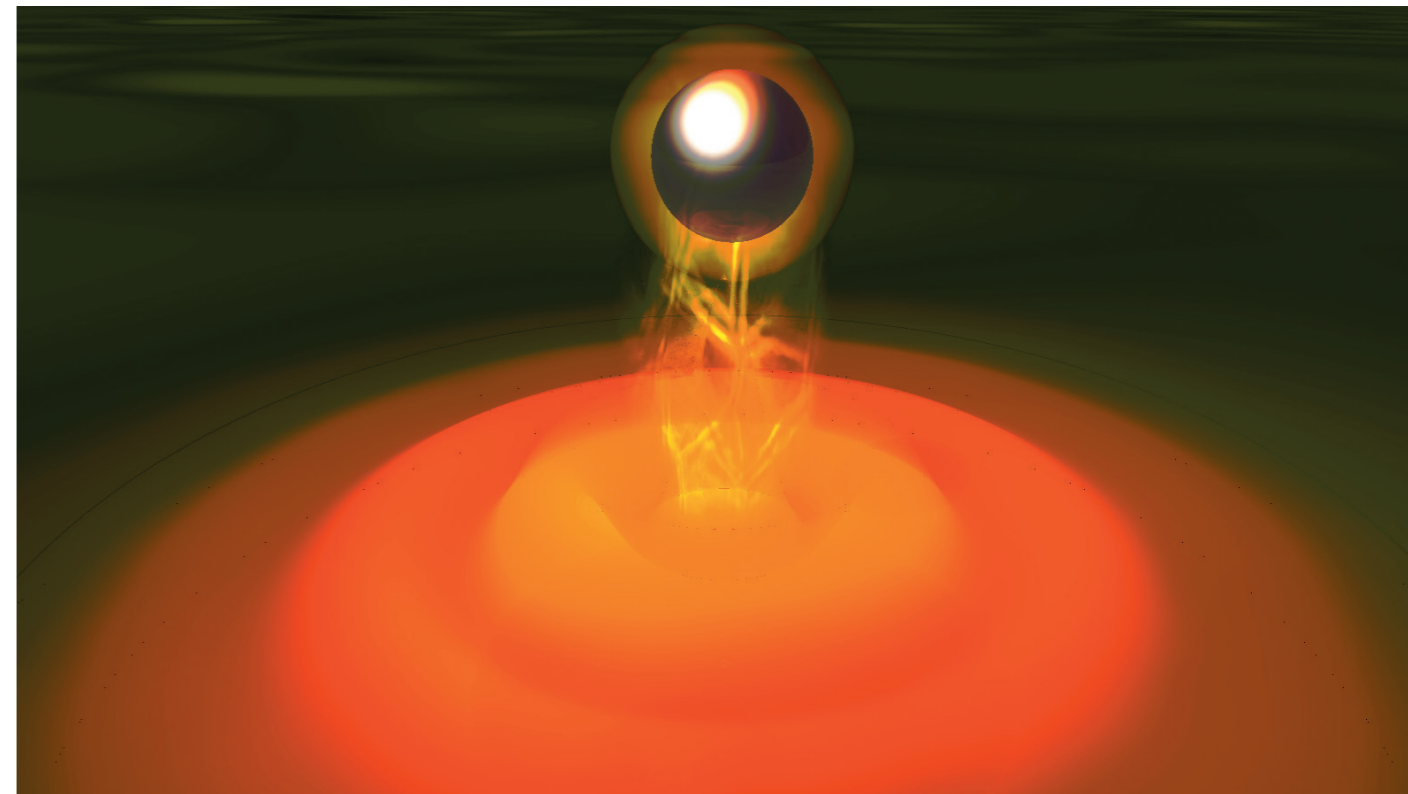
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Scanning-probe-microscopy with ultra-sensitive atomic quantum sensors.



Quantum electronics with superconductors, atoms and photons.



An atom exits a surface plasmon by fluorescence (Artist's impression).

### Quantum Optics

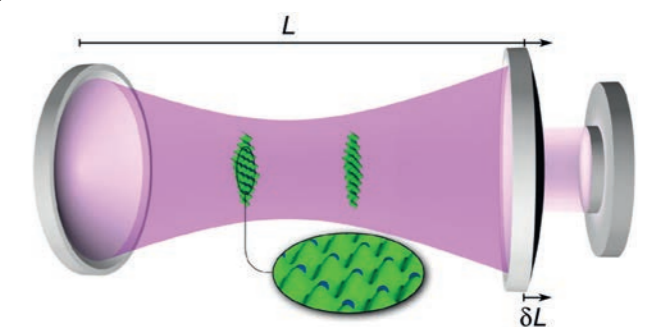
In the Quantum Optics group of Claus Zimmermann, the research focus is on light matter interaction and degenerate Quantum gases. Atoms in optical cavities provide clean model systems for understanding the fundamental interaction between a Bose-Einstein condensate and single optical light modes. Phenomena such as self-organization and quantum phase transitions are investigated. In collaboration with Junior Dozent Sebastian Slama (see p. 27), Bose Einstein condensates and ultra-cold gases are brought in contact with nano-optical structures. A current topic is the coupling between cold atoms and surface plasmon polaritons. A third project combines quantum gases of different atomic species. In such mixtures, Efimov-type quantum many body states are explored. A number of smaller projects cover the fields of optical cooling of nano-membrans, selective reflection spectroscopy, the development of narrow band single mode lasers, and frequency conversion in nonlinear crystals.

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### Theoretical Quantum Optics

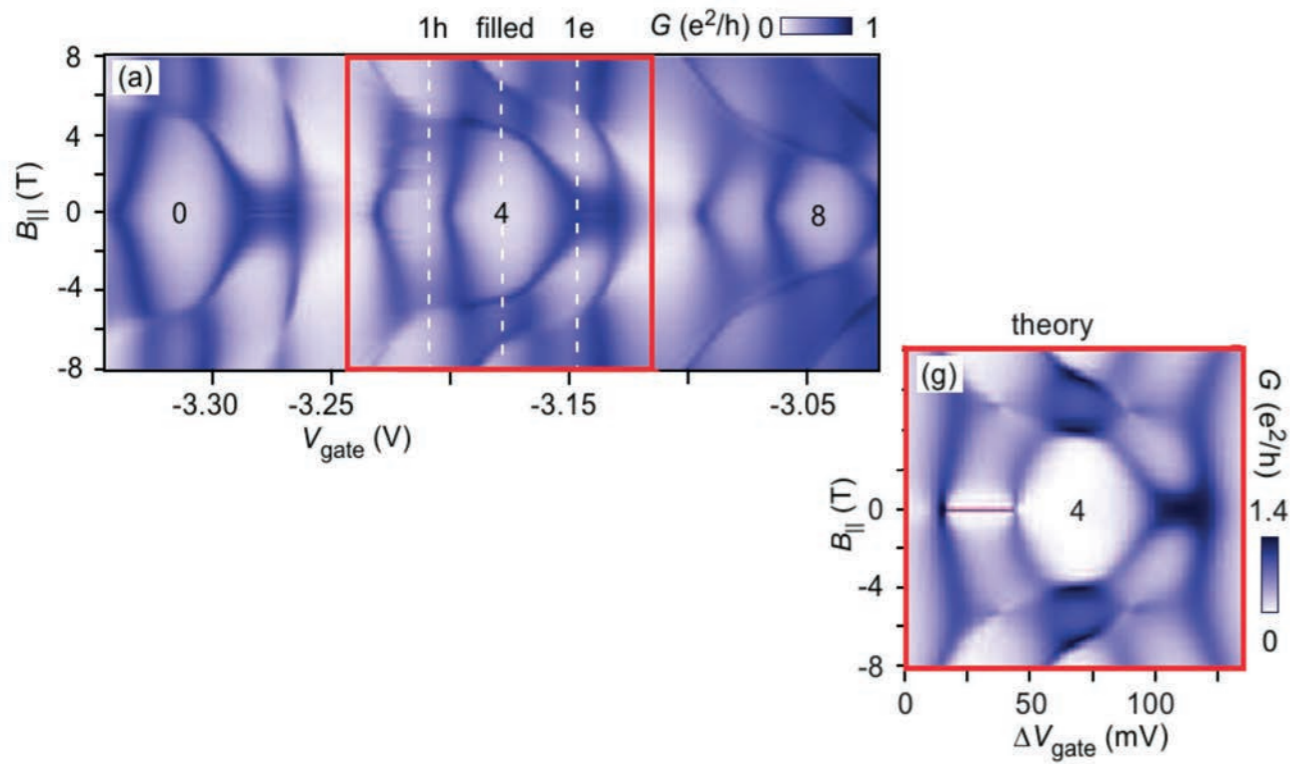
This group led by Daniel Braun conducts research in the theory of quantum measurements, quantum information theory, and quantum thermodynamics. We strive to determine the ultimate limits of sensitivity for the measurement of a given physical quantity imposed by the laws of quantum mechanics and develop new measurement principles that can achieve this sensitivity. A more formal part of our research is the identification and quantification of quantum resources that play a fundamental role in quantum information processing, such as quantum interference and entanglement, and the development of new quantum algorithms and protocols.

Prof. Dr. Daniel Braun  
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$N$  atoms (or ions) are trapped at fixed positions in two two-dimensional optical lattices perpendicular to the cavity axis. A dipole transition of the atoms is in resonance with a single, leaky cavity mode.





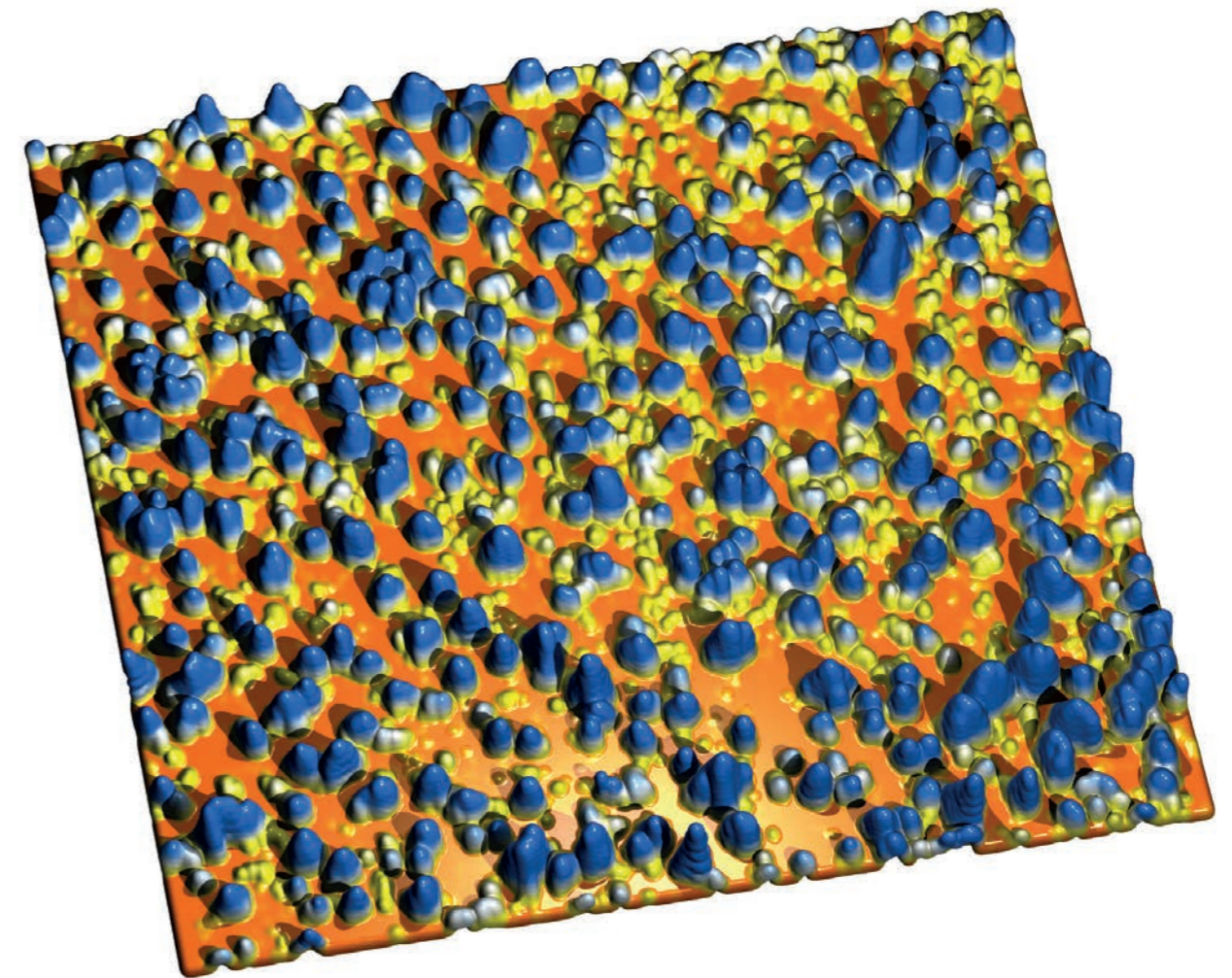
Linear conductance through a carbon nanotube quantum dot and theoretical description. (Grove-Rasmussen et al., Physical Review Letters 108, 2012).

### Quantum Many-Body Theory

The research activities of our group focus on the emergent physical behavior of strongly correlated electron systems. Prominent examples of fascinating phenomena arising from electronic correlations are high-temperature superconductivity or quantum criticality. The impressive technological advancements in the device fabrication strongly stimulated the exploration of new phases of matter. At the same time, the development of new many-body techniques for their theoretical description became a central aspect of the forefront research. In recent

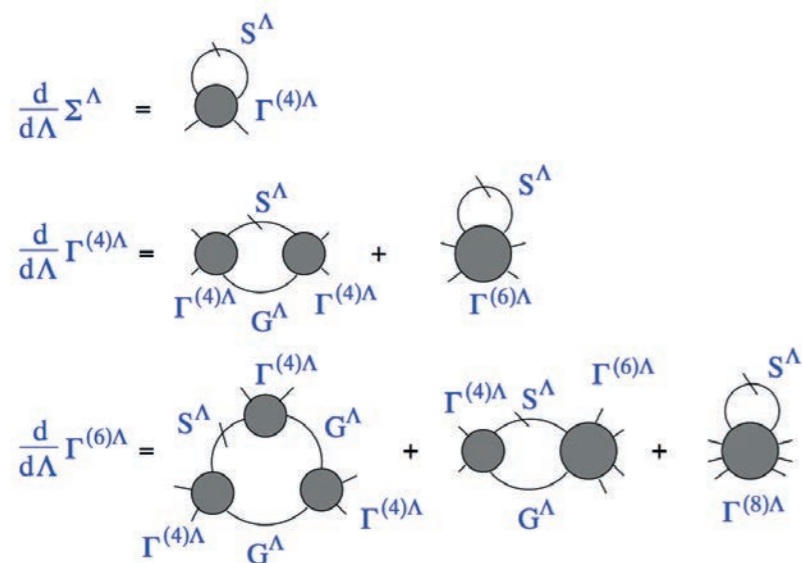
years, various renormalization-group approaches lead to significant progress in the understanding of correlated electron systems in and out of equilibrium. In particular, by means of these approaches and of their most recent developments, we investigate the fundamental mechanisms underlying the physical behavior of model systems for materials, cold atomic gases and nanostructures.

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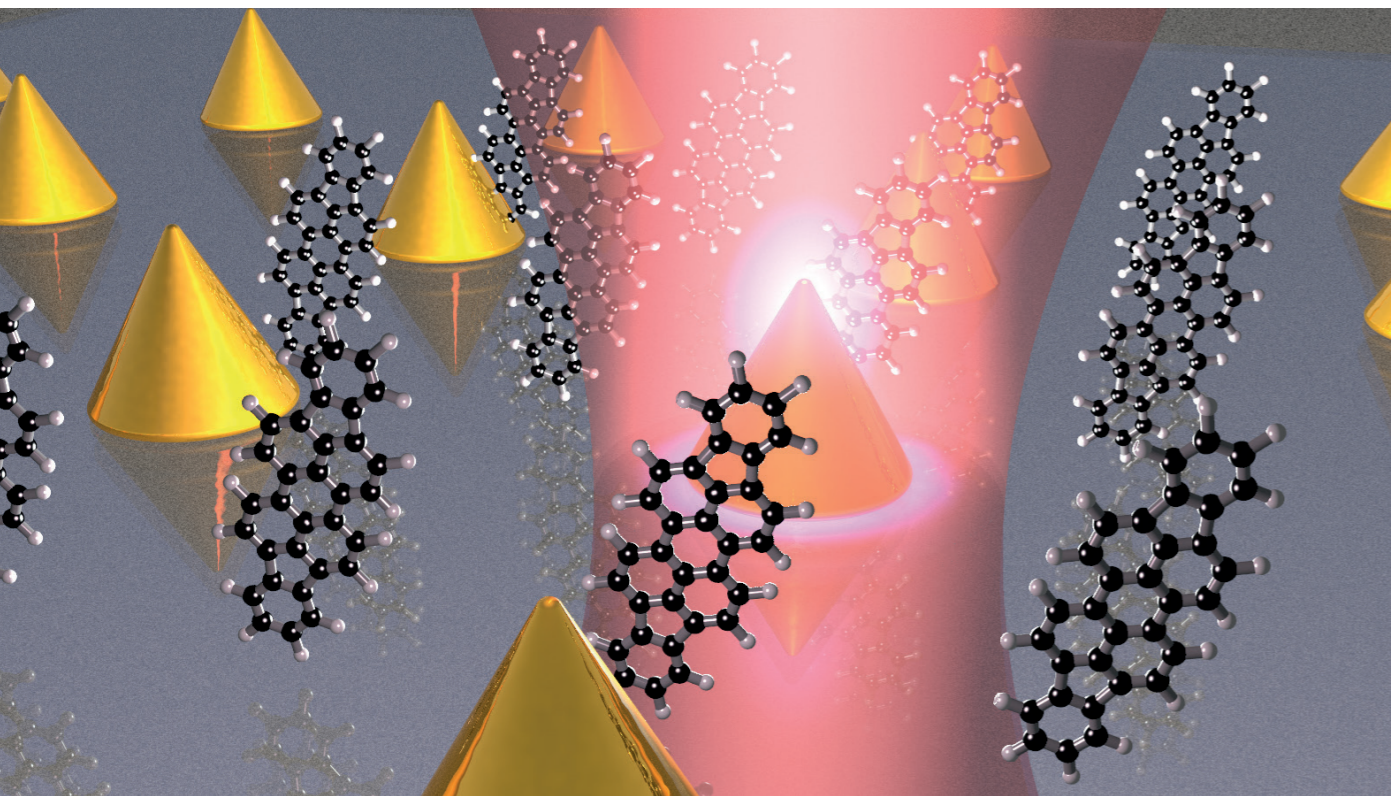
## Center for BioNanoPhysics

Bionanotechnology, soft-hard interfaces, along with scattering and spectroscopy, are the research areas of the Center for BioNanoPhysics. Applying state-of-the-art experimental techniques from physics to biological and other complex or hybrid matter offers fascinating new perspectives in this interdisciplinary research area. The experimental work is complemented by theoretical modeling.



Diagrammatic representation of the functional renormalization group flow equations. (Pavarini et al., DMFT at 25: Infinite Dimensions - Modeling and Simulation, Vol. 4, Verlag des Forschungszentrum Jülich, 2014).





Representation of gold nanocone antennas interacting with individual molecules under excitation with a focused laser beam (not to scale).

### Scattering, Microscopy, and Spectroscopy

A prerequisite for understanding the physical properties of complex nanomaterials is to investigate their nanostructure and chemical composition. Scattering, microscopy and spectroscopy methods are applied for this purpose and include electron microscopy and spectroscopy of electrons and x-rays.

Oliver Eibl's group applies quantitative electron microscopy and spectroscopy to device-relevant materials for energy technology, such as high-efficiency solar cells (Si), thermoelectric materials ( $\text{Bi}_2\text{Te}_3$  and  $\text{CoSb}_3$ ) and high-temperature superconductors ( $\text{MgB}_2$  and cuprates) to study structure-physical property correlations. Understanding and reducing electrical losses due to front side metallization in solar cells, optimizing the figure of merit of thermoelectric materials by nanostructuring and improving critical current densities in superconducting wires are research matters we have addressed. Research is focused on materials with reduced dimensions (nanowires, thin films) and artificially designed nanostructures for optimizing their functional properties. Quantitative spectroscopic methods with x-rays and electrons are used as analytical tools and yield the local chemical composition, plasmon energies and dispersions, and insight into the electronic structure of materials on the sub-nm scale.

The group has established and applied quantitative electron microscopy to tissue and cells for understanding age- and disease-induced changes of pigments in eye and brain tissue. This research allows for the simultaneous investigation of the chemical composition and ultrastructure.

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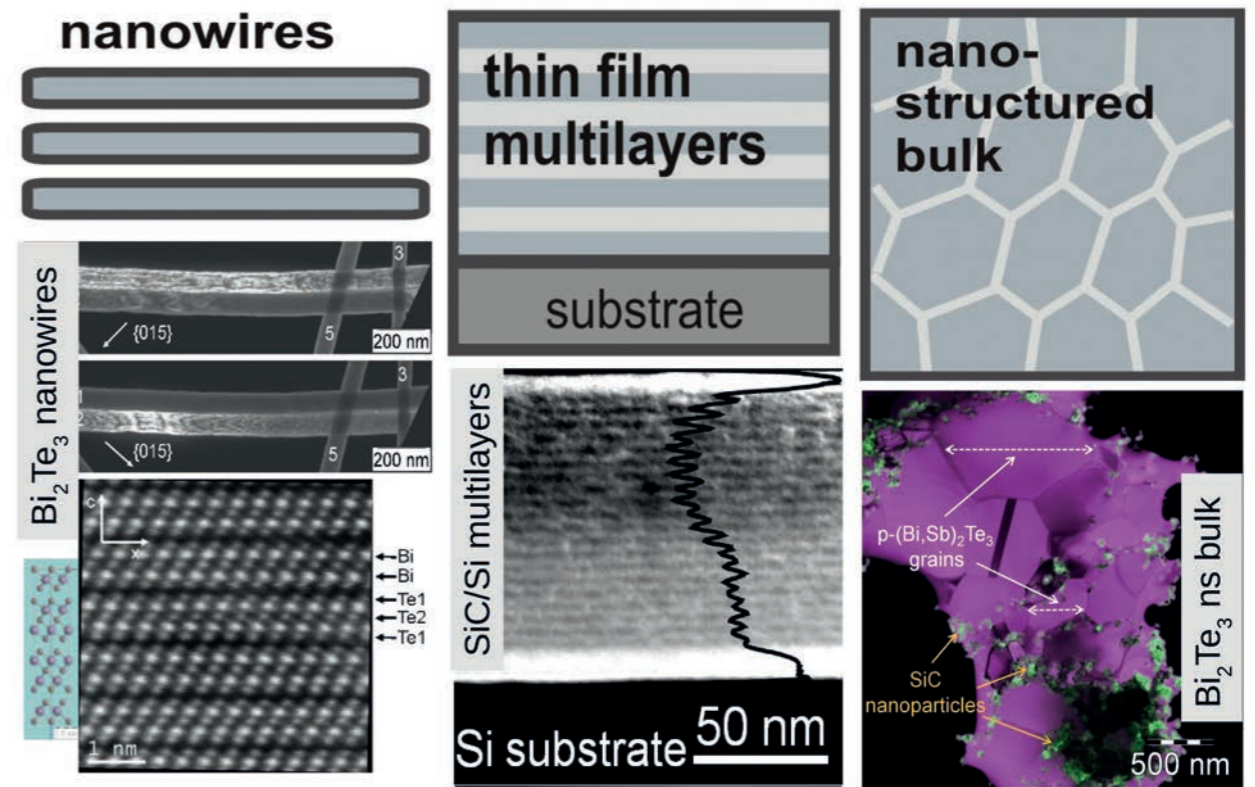
### Plasmonic and Hybrid Nanostructures

The group of Monika Fleischer has a strong background in micro- and nanofabrication. Using nanolithographic techniques, the group particularly creates nanostructures for nano-optics and plasmonics. Additional areas of expertise include structures for opto- and nano-electronics, carbon-nanotube or mesoscopic devices, and microfluidics. Optical, electron beam, colloidal and nanoimprint lithography are employed as well as thin film deposition, etching, or self-assembly to create novel plasmonic and hybrid structures.

Plasmonic nanostructures can act as nano-antennas for visible light. Their plasmon resonances depend on the details of the structural configuration. Numerical simulations are applied to model and predict the optical properties. Based on the calculations, specifically tailored structures are experimentally engineered. With such nano-antennas, fundamental processes in light-matter-interaction are investigated.

The plasmonic nano-antennas are extended into hybrid configurations by combination with organic or inorganic components such as molecular layers, quantum dots, or ultra-cold atoms. The nano-antenna parts are used to perform nano-spectroscopy on the added components, to modify their properties in the hybrid configuration, or to act as high-sensitivity sensors. The work includes close collaborations with groups from physics and chemistry.

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Nanostructured materials with improved physical properties – structural analysis by electron microscopy techniques.

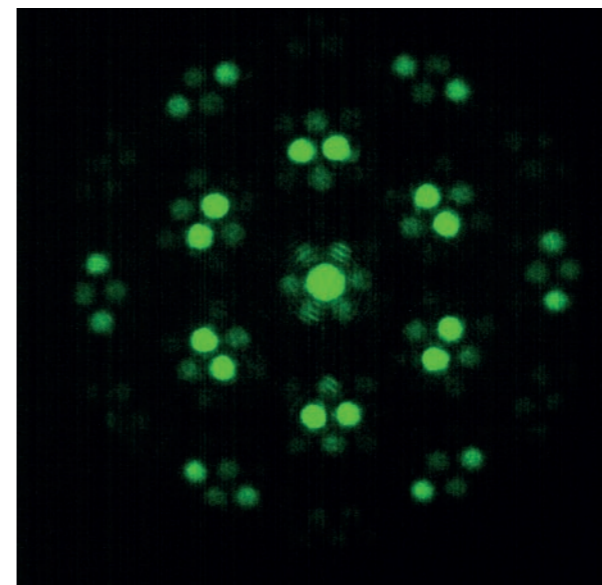
### Theoretical and Computational Nanoscience

The research focus in Martin Oettel's group lies on statistical theory and simulations of nanoparticle systems.

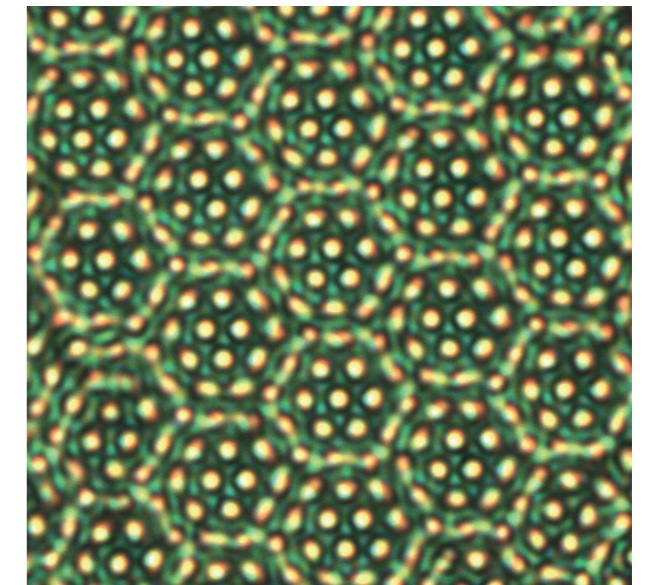
The systems currently under study are colloidal particles forming artificial crystals, small particles trapped at fluid interfaces, forming a model of a self-gravitating system, and models for the growth of organic thin film structures as studied in Frank Schreiber's group. For nanoparticle systems, thermal fluctuations are important and relevant for their properties and functionality, therefore we focus

on developing and applying methods of Classical Statistical Mechanics to such systems. One of these methods is Density Functional Theory, where we collaborate closely with Roland Roth from Theoretical Physics. Via the Nanoscience degree program we also maintain close research ties with Erik Schäffer's group in the Biology Department.

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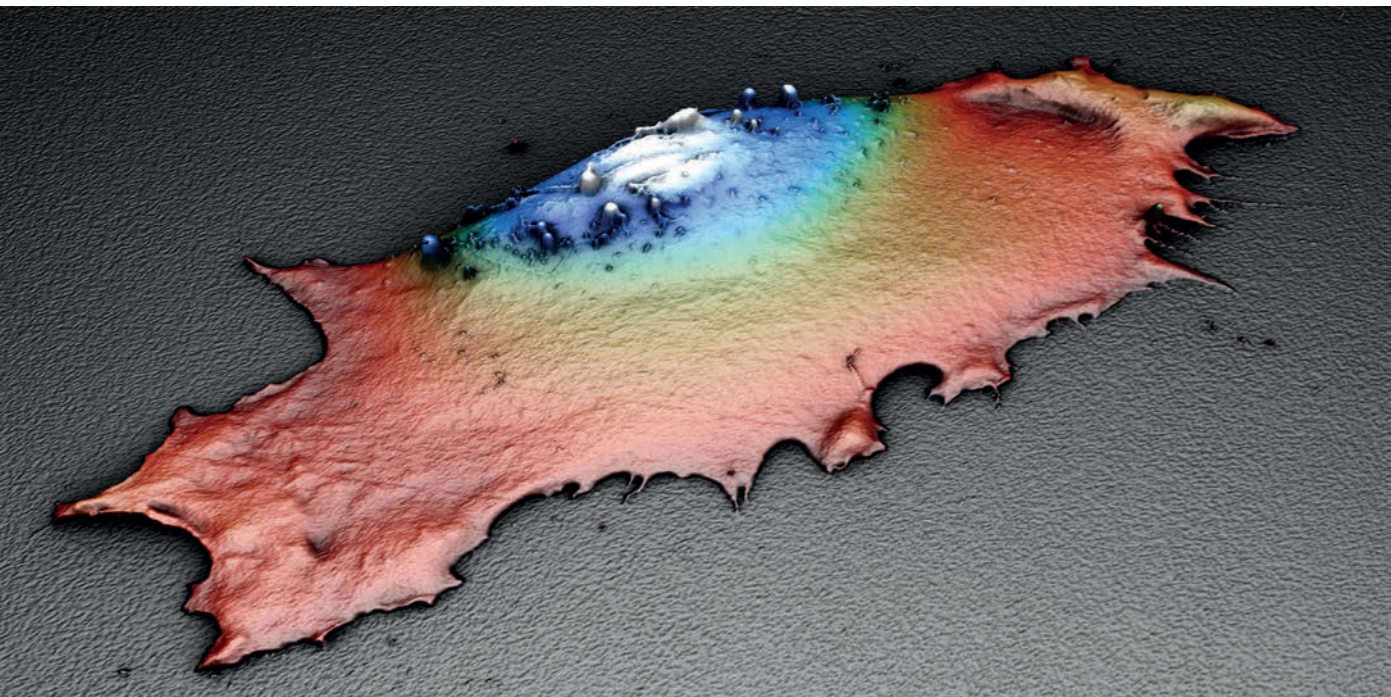


Optical micrograph of a colloidal crystal consisting of two crystalline layers of particles. These are slightly rotated and shifted with respect to each other, giving rise to beautiful Moiré patterns.



Light scattering picture of the same crystal (see left picture) in reciprocal space.



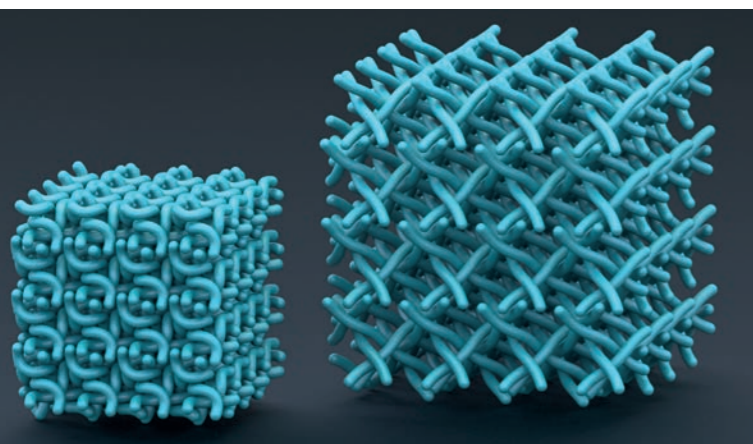


3D scanning ion conductance micrograph of a human pancreatic cell.

### Statistical Physics of Soft Matter

The group of Roland Roth studies the equilibrium behavior and dynamics of systems in soft matter or biological physics using modern techniques of statistical physics such as density functional theory for classical systems. Many of these systems, such as liquids in porous materials, colloidal suspensions, and proteins in solution, give rise to strong geometrical confinement of fluids. These confinements, which occur on various length scales ranging from about a nanometer in the case of simple atomic or molecular liquids up to micrometers in colloidal systems, have a defining impact on the structure, the phase behavior, and the dynamics of the fluid. We are interested both in fundamental research and in applications.

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Two different states of the highly ordered keratin fiber network of the outer skin cells. On the left the keratin network is in a compact state with little water. When water is adsorbed the network can swell and the skin cell expands. The transition between these states is reversible.

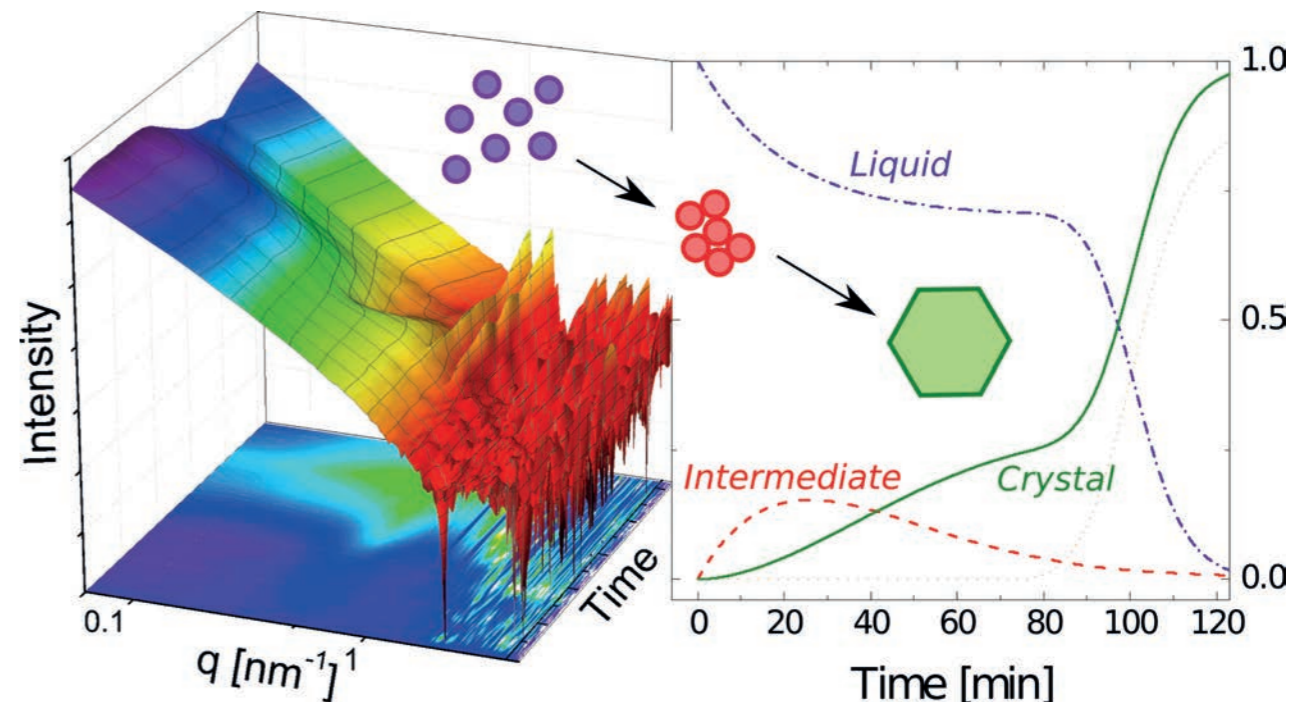
### NanoBioPhysics and Medical Physics

The group of Tilman Schäffer addresses questions of biological and medical relevance using physical methods. Seeking to descend deeper and deeper into the Nanoworld, the design and development of new instruments and methods with high-speed and low-noise characteristics is placed at the foundation of the research. The main tools are various species of scanning probe microscopes. For example, scanning ion conductance microscopy (SICM), which allows non-invasive imaging of living cells, is extended toward the measurement of local mechanical properties of living cells. Atomic force microscopy (AFM) is combined with small cantilevers, which have mechanical resonant frequencies in the Megahertz range, to allow for high-speed and low-noise imaging.

Applications include elucidating the dynamic interactions of single biomolecules, revealing mechanical properties of living cells and tissues, exposing biomaterials and biomineralization on the molecular scale, and illuminating transport processes in artificial and natural membranes.

One of the goals is to deduce viscoelastic properties of cellular, sub-cellular, and molecular structures from the measurement of their stress-strain behavior. The measurement and modeling of mechanical sample properties has recently been extended to biological tissues. Another goal is to image dynamic interactions of single biomolecules in real-time, to visualize individual binding processes and to test interaction models.

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Schematic of a possible route for protein crystallization followed in situ and in real time (modified from Sauter et al., JACS (2015)).

### Physics of Molecular and Biological Matter

Our group is working on different projects related to the physics of molecular and biological soft matter. To fully understand these complex systems, we work in close collaboration with theoretical groups (in particular Martin Oettel and Roland Roth) and employ a number of complementary experimental techniques. A particular strength is the use of advanced X-ray and neutron scattering and optical methods for the structure, dynamics, and excitations, in many cases in situ and in real time. In this context our strong connections to large scale facilities (synchrotron and neutron sources) play a key role.

Current projects include the tailoring of protein interactions by the use of multivalent ions to control their phase behavior with a number of exciting effects including charge inversion, reentrant condensation, liquid-liquid phase separation, and also crystallization. This route of charge manipulation has enormous potential for a deeper understanding of the physics of macromolecules as well as a wide range of applications in biotechnology.

A related line of research concerns the control of the adsorption of proteins at the solid-liquid interface. Here the functionalization of these interfaces by self-assembled monolayers (SAMs) is an additional way to control the behavior, which is crucial for a number of applications such as bio-compatible implants.

Interfaces are also an important factor for organic semiconductor thin films, which we are studying in projects related to organic and hybrid electronics and optoelectronics. We have developed high-precision techniques for the investigation of organic pi-systems at interfaces.

Moreover, we are working on strategies to control the structure evolution of donor-acceptor mixtures to tailor and exploit the level of charge transfer in these systems, which is a fundamental issue as well as a key point of their device performance.

All these research activities are strongly connected to the teaching program in physics and in nano-science, involving students at various levels of their training.

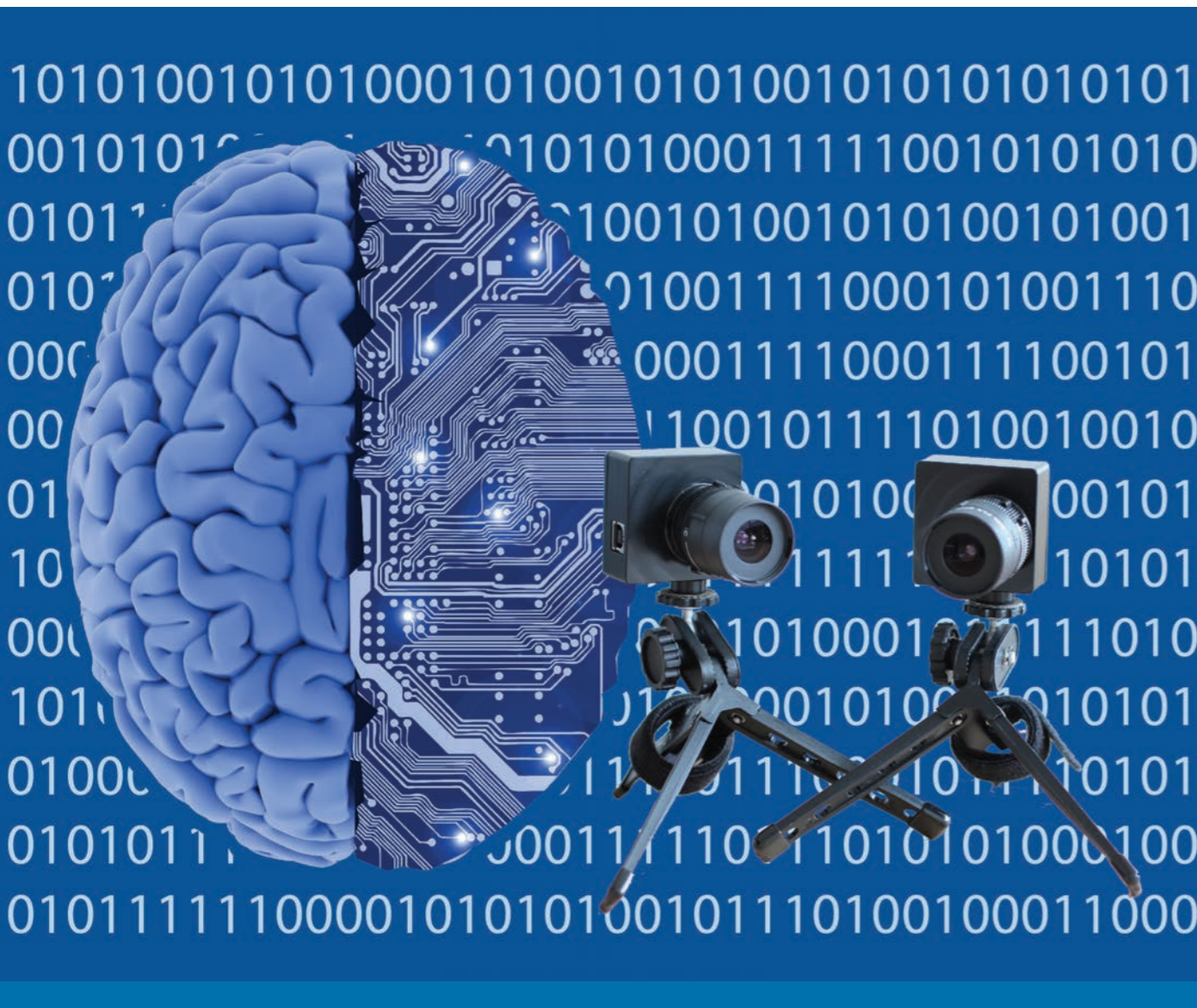
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### Mesoscopic Physics

This experimental group led by David Wharam is involved in the research of semiconductor nanostructures and related mesoscopic devices. We investigate the low-temperature electronic properties of both quantum point contacts as well as quantum dot devices with an emphasis on the understanding of the fundamental physics. Conductance and charge quantization lead to the observation of novel phenomena – e.g. Coulomb blockade and single electronics. The thermal properties of nanostructures are also investigated – e.g. the 3 $\Omega$ -method in thin film samples and thermal transpiration in nanostructures.

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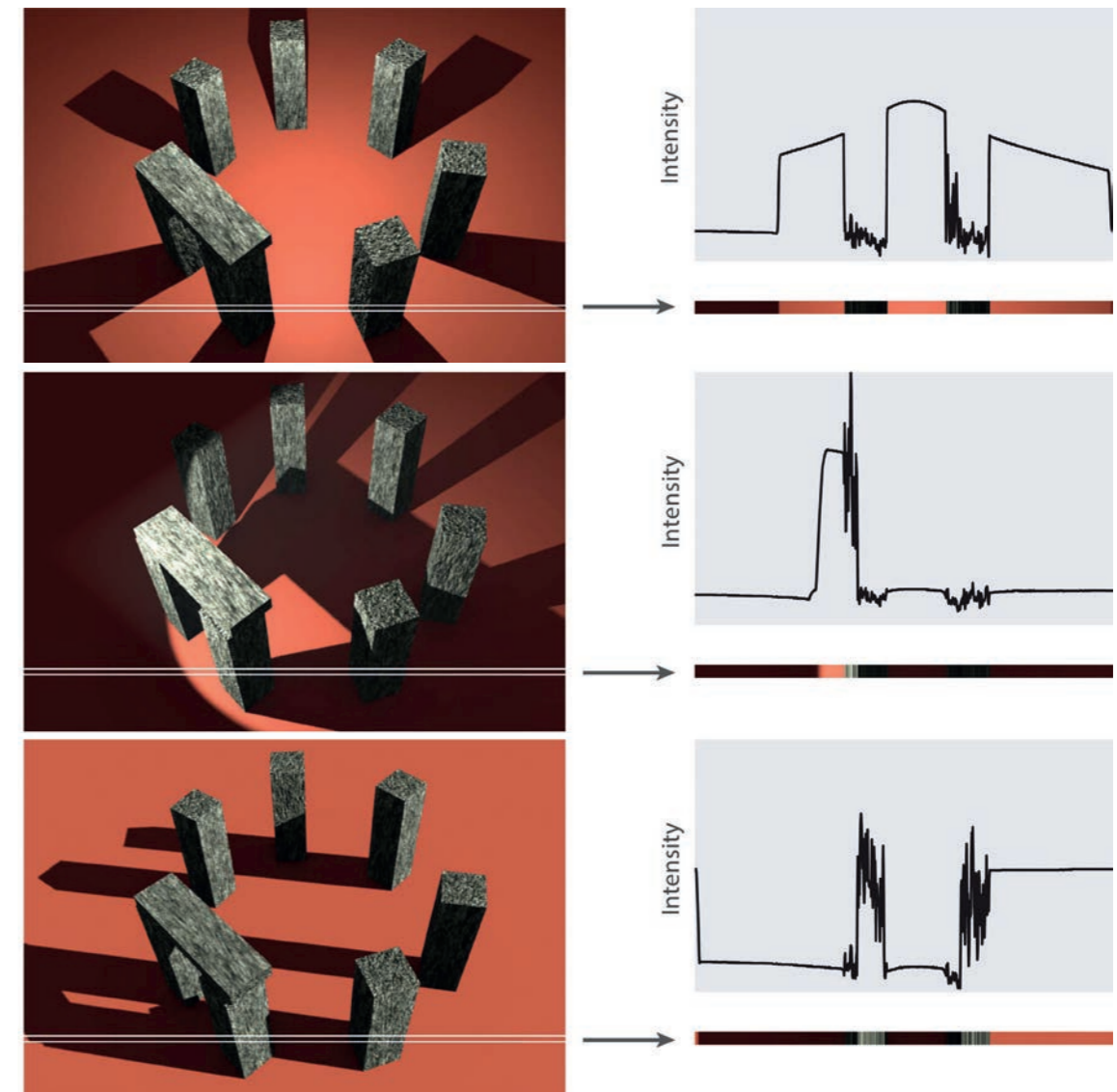




## Physics in Neuroscience

Physics plays an important role in neuroscience both for the development of new measurement techniques and for the theoretical understanding of the function of the brain. The physics department maintains the professorship for Computational Neuroscience in the excellence cluster [Center for Integrative Neuroscience \(CIN\)](#) and established the [Bernstein Center for Computational Neuroscience \(BCCN\)](#) Tübingen.

The CIN and the BCCN are interdisciplinary institutions at the Eberhard Karls Universität Tübingen that aim at understanding the neural mechanisms and algorithms in the brain underlying perception, cognition, and behaviour. Several faculties of the university, two Max Planck Institutes (MPI for Biological Cybernetics and MPI for Intelligent Systems), the Hertie Institute for Clinical Brain Research and the Fraunhofer Institute for Manufacturing, Engineering and Automation are involved in these centers. The interdisciplinary concept is further supported by the [international graduate training center for neuroscience](#) which hosts three Master and PhD programs that are shared between the Faculty of Sciences and and the Faculty of Medicine.



Images of the same scene under different illumination conditions (left panel) give rise to completely different visual input. To make this most obvious, the intensities taken from the same row of pixels in the three different images are shown in the right panel. Despite the huge variation in the visual input our visual system has no difficulty in recognizing the same scene in all three images. About hundred-fifty years ago, Hermann von Helmholtz was among the first to point out the computational challenge underlying this problem and posed the question of how these unconscious computations are carried out so efficiently in the brain.

### Neural Information Processing Systems

Besides the Turing machine and its well-known technological implementation as personal computers, there are other intriguing possibilities to build information processing systems. One example are quantum computers which may be able to solve computational problems such as prime number factorizations that are difficult to solve with classical computers. Another example are neural systems like the human brain which are particularly powerful for solving perceptual inference problems such as visual object recognition.

Based on recent breakthroughs in machine learning more and more complex artificial neural networks are developed that become increasingly powerful in mimicking our perceptual inference abilities. At the same time, it remains a challenge to understand these systems and describe them in a concise manner. Similar to thermodynamic systems, a principal difficulty in the analysis of neural networks originates from the large number of degrees of freedom in both the sensory input and the neuronal responses. Different from thermodynamic systems, the interactions between neurons are much more

complex and have evolved for the purpose of computation.

The research agenda of Matthias Bethge's group aims at understanding the information processing principles underlying high-performing neural networks (both artificial and biological ones) and seeks to develop better tools for analyzing them. More specifically, using methods of statistical inference and learning theory, as well as signal processing, nonlinear dynamics and optimization theory, Bethge's research group studies the problem of perceptual inference and its neural basis at different levels: neural network theory (e.g. Macke et al, *Physical Review Letters*, 106 (20), 2011), neural data analysis (e.g. Froudarakis et al., *Nature Neuroscience*, 17, 851-857, 2014), and psychophysics (e.g. Gerhard et al., *PLoS Computational Biology*, 9(1), 2013). The group is part of the excellence cluster "Center for Integrative Neuroscience" (CIN) and Bethge is the chair of the Bernstein Center for Computational Neuroscience Tuebingen. The group also maintains close links to the MPI for Intelligent Systems and the MPI for Biological Cybernetics.

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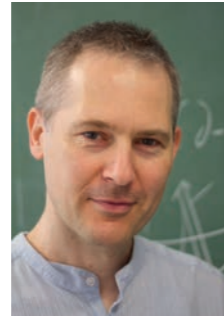
# Professors and Research Group Leaders



Prof. Dr. Sabine Andergassen  
Quantum Many-Body Theory



Prof. Dr. Matthias Bethge  
Neural Information Processing Systems



Prof. Dr. Daniel Braun  
Theoretical Quantum Optics



Prof. Dr. Oliver Eibl  
Scattering Microscopy, and Spectroscopy



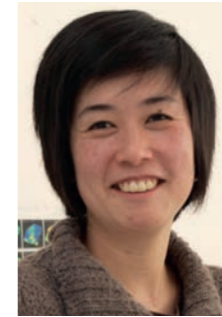
Prof. Dr. Monika Fleischer  
Plasmonic and Hybrid Nanostructures



Prof. Dr. Roland Roth  
Statistical Physics of Soft Matter



Prof. Dr. Andrea Santangelo  
High Energy Astrophysics



Dr. Manami Sasaki  
Evolution of Galaxies



Prof. Dr. Erik Schäffer  
Cellular Nanoscience



Prof. Dr. Tilman Schäffer  
BioNanoPhysics and Medical Physics



Prof. Dr. József Fortágh  
Nano-Atomoptics



Apl. Prof. Dr. Peter Grabmayr  
Neutrino Physics



Apl. Prof. Dr. Thomas Gutsche  
Low-Energy QCD and the Physics of Hadrons



Hon. Prof. Dr. Boris Hofmann  
Neuromodulation



Prof. Dr. Barbara Jäger  
Theoretical High Energy Physics



Prof. Dr. Klaus Scheffler  
Biomedical Magnetic Resonance



Prof. Dr. Hans Rudolf Schmidt  
Nuclear Matter under Extreme Conditions



Prof. Dr. Dr. Fritz Schick  
Experimental Radiology



Prof. Dr. Bernhard Schölkopf  
Empirical Inference, Decoding Complexity



Prof. Dr. Nils Schopohl  
Theoretical Solid State Physics



Prof. Dr. Josef Jochum  
Astroparticle Physics



Prof. Dr. Reinhold Kleiner  
Experimental Solid State Physics



Prof. Dr. Wilhelm Kley  
Computational Astrophysics



Prof. Dr. Konstantinos Kokkotas  
General Relativity and Relativistic Astrophysics



Prof. Dr. Dieter Kölle  
Experimental Solid State Physics



Prof. Dr. Frank Schreiber  
Physics of Molecular and Biological Matter



Jun. Doz. PD Dr. Sebastian Slama  
Surface Quantum Science



Dr. Alexander Stibor  
Quantum Electron- & Ion-Interferometry



Prof. Dr. Daniela Thorwarth  
Biomedical Physics



Prof. Dr. Werner Vogelsang  
Theoretical Nuclear and Particle Physics



Dr. Rolf Kuiper  
Massive Star Formation



Prof. Dr. Tobias Lachenmaier  
Neutrino Physics



Prof. Dr. Martin Oettel  
Theoretical and Computational Nanoscience



Prof. Dr. Bernd Pichler  
Preclinical Imaging and Imaging Technology



Prof. Dr. Hugo Reinhardt  
Theoretical Nuclear and Particle Physics, Quantum Field Theory



Prof. Dr. Klaus Werner  
Astronomy

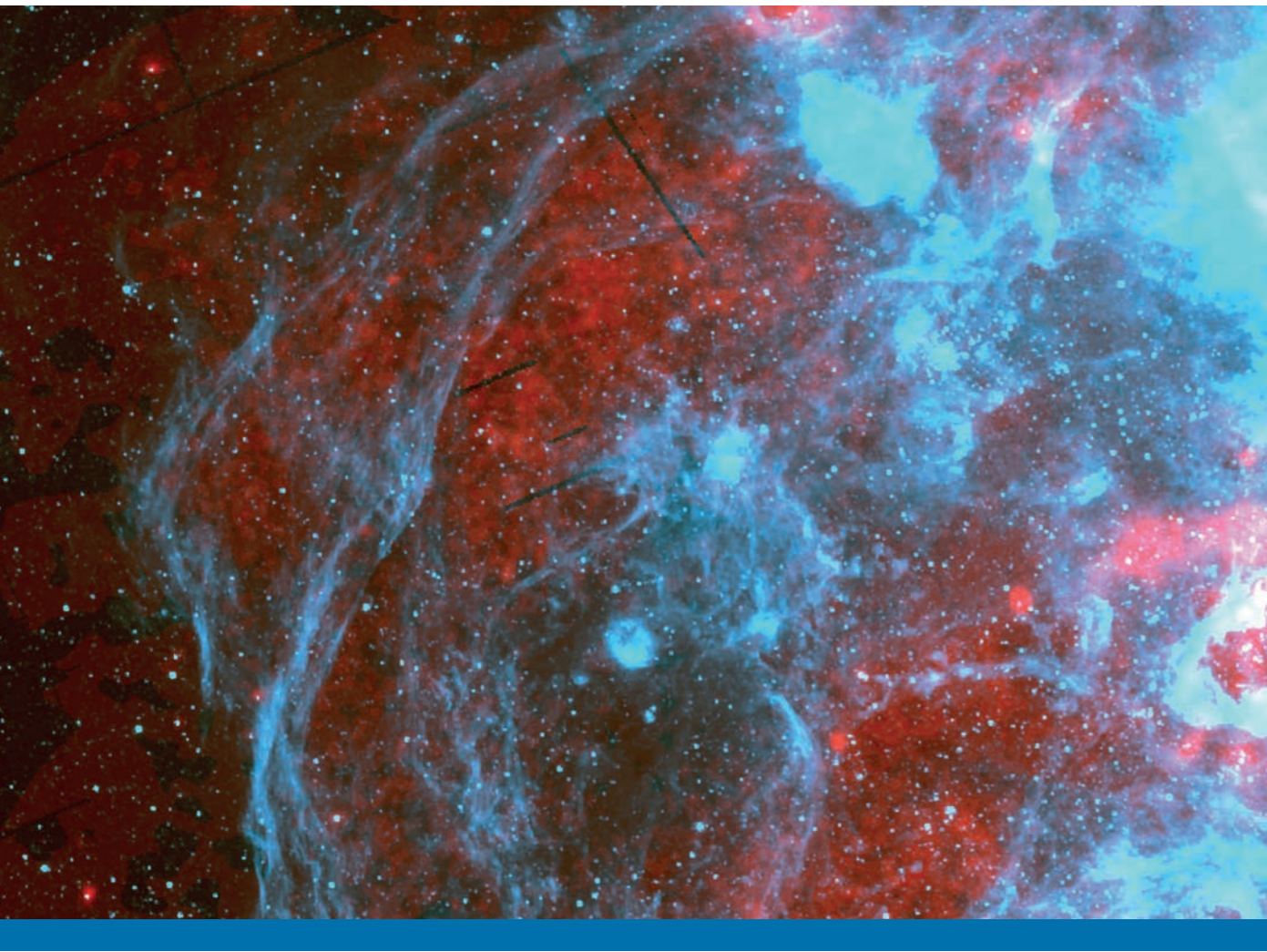


Prof. Dr. David Wharam  
Mesoscopic Physics



Prof. Dr. Claus Zimmermann  
Quantum Optics





## Junior Research Groups

### Astrophysics: Evolution of Galaxies (Emmy Noether)

The evolution of galaxies is studied by using the x-ray sources as observational probes: e.g. x-ray binaries, which contain a neutron star or a black hole, or supernova remnants, which are responsible for the chemical enrichment, the energy budget, and the dynamics in the interstellar medium. Physical phenomena in these systems like gravitation, nuclear fusion, radiation, or shock waves also played a major role in the formation of the first cosmological structures.

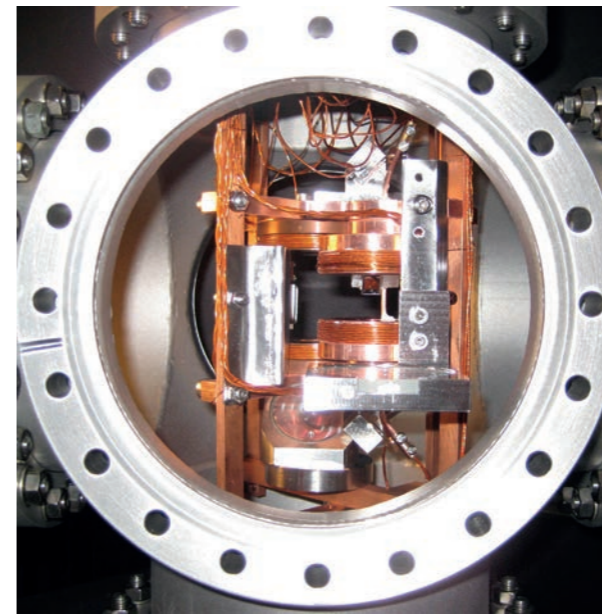
Dr. Manami Sasaki  
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### Astrophysics: Massive Star Formation (Emmy Noether)

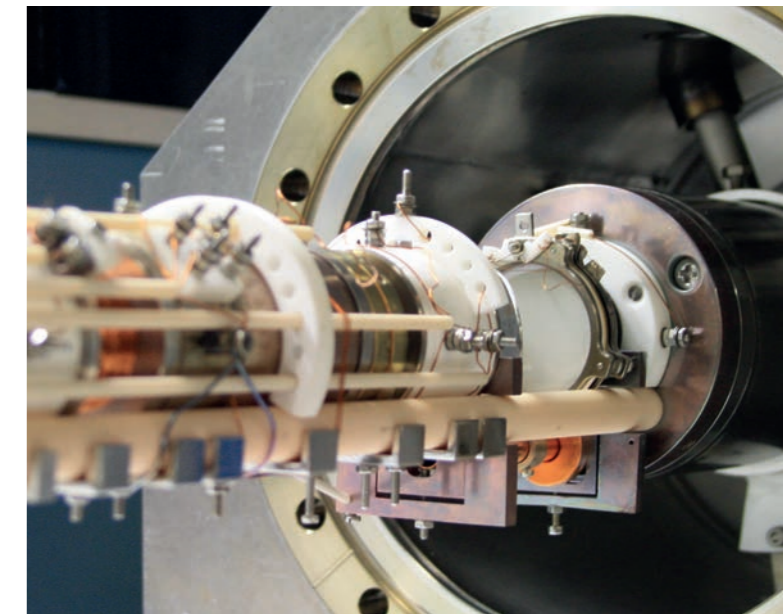
Qualitatively similar to their lower-mass siblings, massive protostars on the one side accrete material from their host cloud of gas and dust through a circumstellar accretion disk and on the other side inject material into their environment via protostellar outflows. Due to their extreme luminosities, massive stars impact the evolution of their natal cloud, whole star forming regions, and even their host galaxies.

The newly established research group investigates various of these feedback effects onto the disk – outflow system of forming massive protostars in multi-physics numerical models. The epochs of successive feedback can be chronologically classified in 1) magneto-centrifugal acceleration 2) radiation pressure, and 3) ionization. Special focus is given on, first, ordering the feedback effects by their strength and epochs to derive their corresponding impact on the star formation efficiency, and secondly, testing a number of hypotheses for explaining the upper mass limit of stars in general.

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Bose-Einstein condensates



A matter wave interferometer for electrons and ions (G. Schütz et al., Ultramicroscopy 141, 9 (2014), F. Hasselbach, Rep. Prog. Phys. 73, 016101 (2010))

### Quantum Science: Surface Quantum Optics

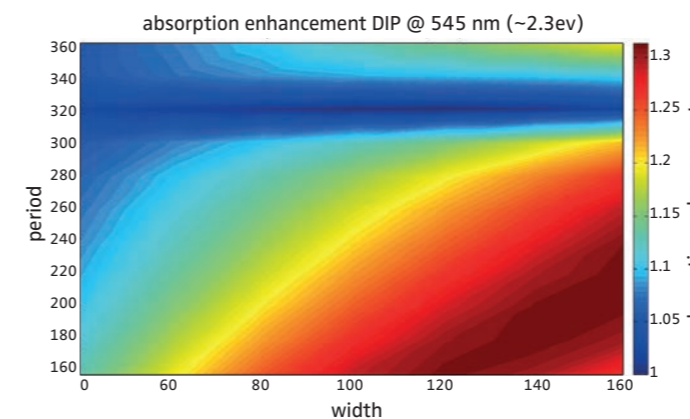
The junior research group Surface Quantum Optics investigates hybrid systems which are composed of ultracold atoms (Bose-Einstein condensates) and solid state surfaces. Particular interest is devoted to the interaction of atoms with optical near-fields above plasmonic nanostructures. This combination enables strong coupling between single atoms and plasmonic excitations which may be used in the future for applications in quantum information and optical computing. Moreover, fundamental physical problems of quantum electrodynamics (QED) are addressed by measuring Casimir-Polder forces above structured metallic surfaces. The group is also working on the generation of plasmonically tailored surface traps in order to investigate the many-particle physics of cold atoms in potentials with local symmetry.

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### Quantum Science: Quantum Electron- & Ion-Interferometry (Emmy Noether)

The objective of our research group is the coherent manipulation of charged particle waves of ions and electrons. Compared to neutral atomic or molecular matter waves, the additional parameter charge opens the door to fundamental quantum mechanical experiments, such as the direct proof of the electric Aharonov-Bohm effect. Another focus of our group is to study decoherence effects of electron matter waves in the vicinity of metallic or superconducting surfaces. This loss of quantum mechanical behavior is relevant for various novel quantum devices that apply free or trapped coherent electrons.

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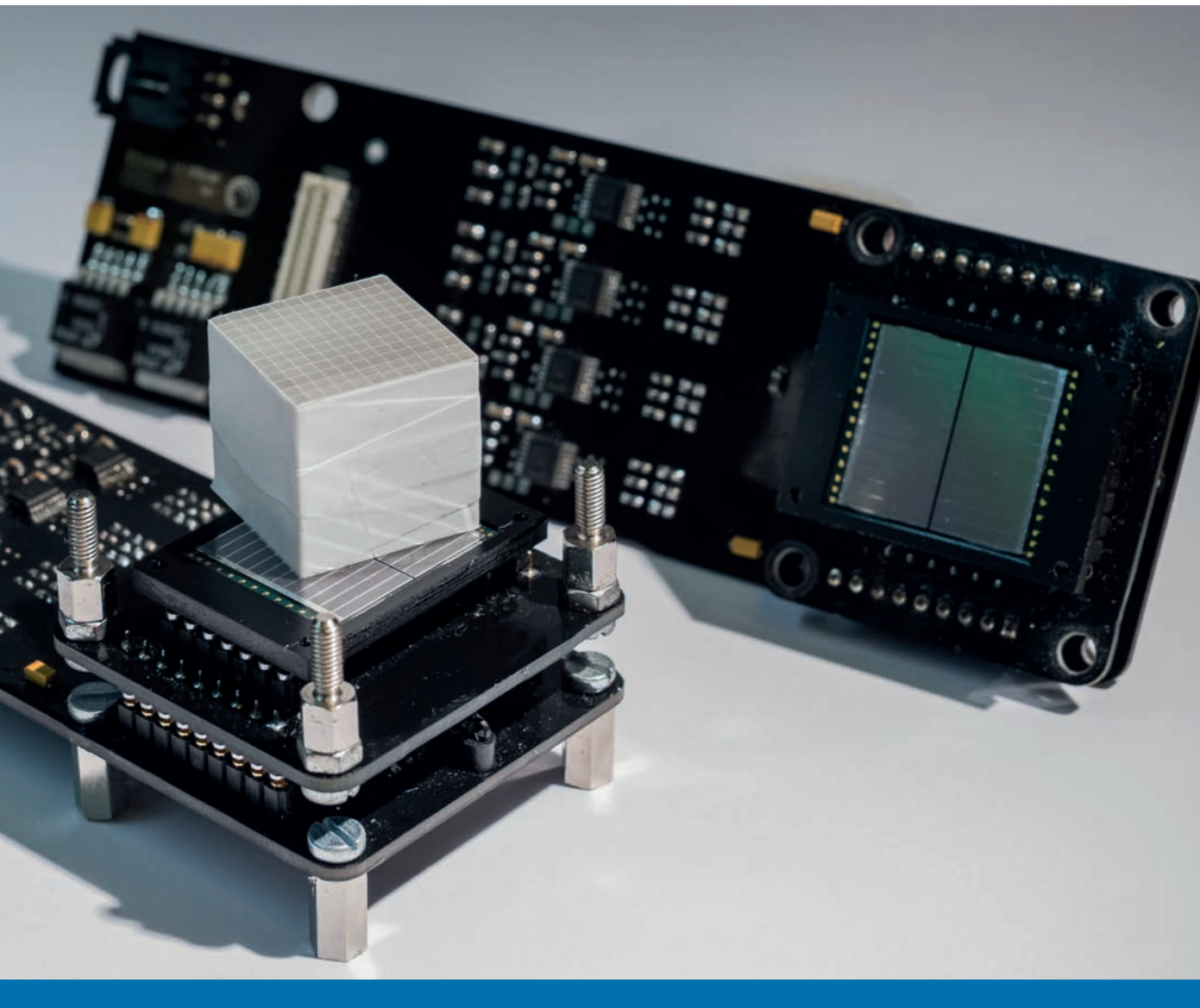
Simulation of the geometry-dependent absorption enhancement in an organic thin film (DIP) on a plasmonic gold line nanotemplate.

### BioNanoPhysics: Plasmonic Nanostructures

The junior group Plasmonic Nanostructures addresses the design, fabrication, characterization and integration of metallic nanostructures acting as optical antennas. Processes for rings, corrals, sharp-tipped cones and more are developed based on electron beam lithography, etch mask transfer and self-assembly. The optical properties are determined by 3D extinction spectroscopy, single particle dark field scattering and fluorescence imaging. The plasmon resonance is tailored via the geometry, metal and substrate. The structures are utilized to focus light beyond the diffraction limit and create strong electric near-fields for researching light-matter interactions, and implemented for applications in near-field micro-spectroscopy, sensing and photovoltaics.

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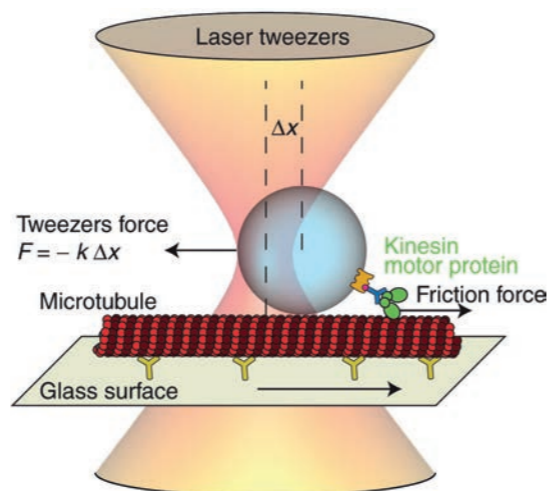


## Adjunct and Coopted Professors

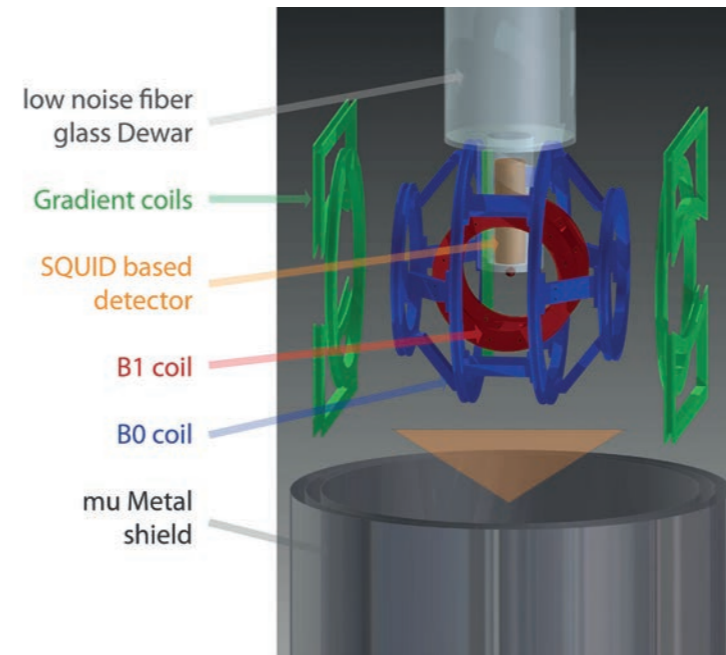
### BioNanoPhysics: Cellular Nanoscience

Molecular machines are fascinating devices that drive self-organization in cells. While the protein components of many biological machines have been identified, the mechanical principles that govern the operation of biological machines are poorly understood. For example, how much force can they generate; and what limits their speed and efficiency? Currently, our research in biophysics focuses on developing and applying single-molecule fluorescence and force microscopy techniques - high-resolution optical tweezers and novel trapping probes - to understand how molecular machines, such as kinesin motors and DNA repair proteins, work mechanically to fulfil their cellular function.

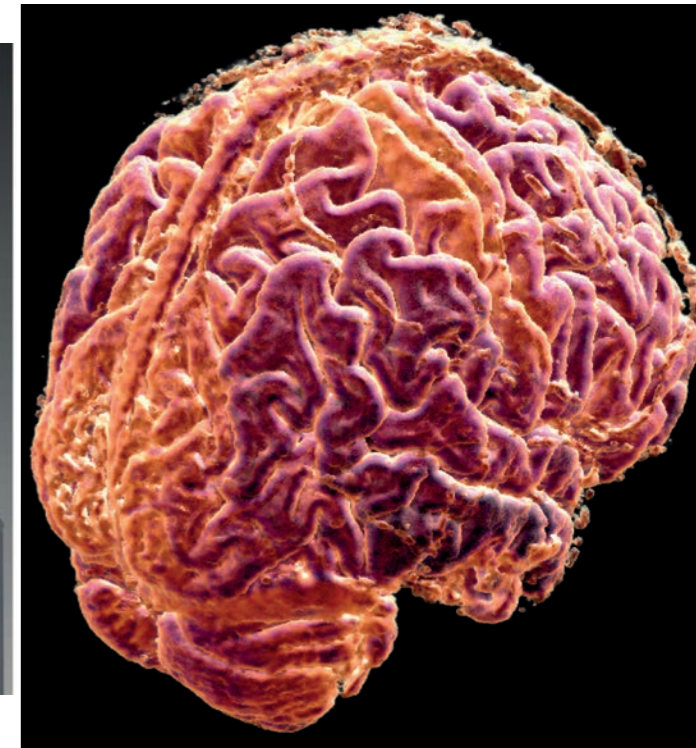
Prof. Dr. Erik Schäffer  
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<http://www.zmbp.uni-tuebingen.de/nano>



Schematic: By dragging diffusing kinesin molecules with laser tweezers over a microtubule, the friction force between the motor and its microtubule track can be measured very precisely. (adapted from Bormuth et al., Science 2009)



Myelination of human cortex measured with ultra-high field MR



### Physics in Neuroscience: Empirical Interference and Decoding Complexity

The term empirical inference refers to inference performed on the basis of observational data. The type of inference can vary, and includes for instance inductive learning, i.e. the estimation of models such as functional dependencies that generalize to novel data sampled from the same underlying distribution. Of particular interest to us is the inference of causal structures from data, leading to models that provide insight into the underlying mechanisms, and make predictions about the effect of interventions. We are studying algorithms and theory of inference processes, and apply them to a range of empirical data in fields ranging from astronomy to neuroscience.

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### Physics in Neuroscience: The Aesculap Industry on Campus Group

As a research group that bridges the gap between industry and basic research, the focus of our research is on tools for neuromodulation. Our research especially concentrates on the development of sensors capable of measuring neurotransmitter concentrations in vivo. One day they might serve as a tool to evaluate physiological parameters that can then be used to optimize stimulation and adapt it to the current physiological state of the patient. Furthermore, the encapsulation of the implantable devices is crucial, as they have to operate in the human body. The harsh environmental conditions require a special encapsulation, which is another focus of Research.

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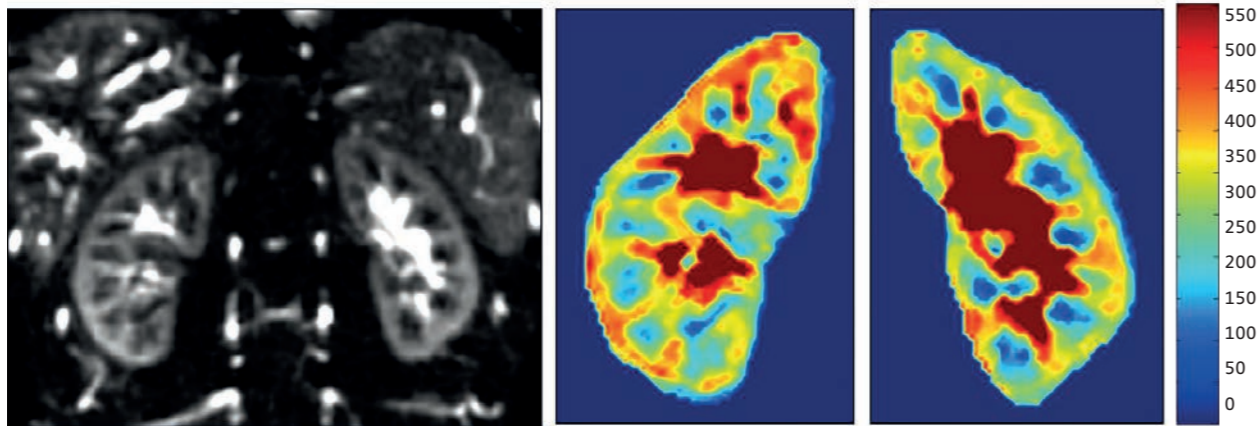
### Biomedical Physics: Biomedical Magnetic Resonance

Although magnetic resonance is one of the least sensitive methods to detect, for example, water in living tissue, it offers an unparalleled diversity and flexibility to read biologically relevant information beyond the simple information of local water distribution. Our primary goal is to develop new magnetic resonance techniques that are able to specifically probe the structural, biochemical composition and function of living tissue. This is closely linked with our interest to understand the details of magnetic resonance signal formation within a living environment, as nuclear magnetization is continuously influenced by different processes during its live time between excitation and relaxation. Simultaneous combination of optical methods with magnetic resonance provides the missing microstructural and functional information. Highly miniaturized MR coils combined with integrated transmit and receive electronics as well as optical and electrophysiological recordings are used to correlate changes in the magnetization with electrical and optical signals with very high temporal and spatial resolution.

The MR Center at the Max Planck Institute for Biological Cybernetics is equipped with a 3T and 9.4 T human scanner and a 14.1 T animal scanner. In addition, and in close collaboration with the Departments of Physics (Profs Kleiner and Kölle) and Chemistry (Prof. Mayer), we recently started to develop an ultra-low field MR system (1-20 mT) in combination with SQUID-detection and hyperpolarization via electron resonance.

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Assessment of blood perfusion in the kidneys (in ml/100g/min)

### Biomedical Physics: Preclinical Imaging and Imaging Technology

The Department of Preclinical Imaging and Radiopharmacy at the Medical Faculty focuses on the technology and application of novel imaging modalities, specifically on positron emission tomography (PET) and magnetic resonance imaging (MRI). The research group developed a combined PET/MRI for preclinical research in small laboratory animals. For this approach, novel gamma detectors based on lutetium oxyorthosilicate (LSO) scintillation crystals and avalanche photo diodes (APDs) as well as a fast and low noise non-magnetic readout-electronics were developed. The next generation of PET detectors enable depth of interaction detection to calculate the absorption depth within the scintillation crystal. This new detector is also based on Geiger-mode APDs yielding excellent spatial and timing resolution. The close connection with the Physics Department allows cross-disciplinary collaborations (Prof. Jochum, Prof. Grabmayr) on next generation gamma detector technology and fast readout electronics. It further opens opportunities for students to get exposed to the interdisciplinary field of medical physics (Prof. Eibl) and biomedical imaging.

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### Biomedical Physics: Experimental Radiology

Research in the Section on Experimental Radiology aims at development of new magnetic resonance (MR) imaging and spectroscopy techniques for improved non-invasive tissue characterization of the human body. Besides data acquisition, also post-processing tools for automatic image and spectra analysis are developed. Those techniques are used either for diagnostic examinations of diseased tissues (eg, in patients with tumors or inflammatory disease) or in preclinical studies dedicated to elucidate variability of anatomical, metabolic and functional properties in cohorts of healthy subjects. We are also working together with industrial partners for developing and testing MR-compatible implants and instruments for surgery.

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### Biomedical Physics: Medical Physics in Radiation Oncology

Modern cancer therapy concepts aim for treatment individualization according to patient-specific factors. Our research section develops technical and methodological concepts for improving state-of-the-art high-precision radiotherapy (RT). A main research focus is the integration of molecular imaging (MI) using positron emission tomography or functional magnetic resonance imaging into individualized RT treatment. We investigate technical aspects of MI-based RT planning, including the design of theoretical models on image formation and biomarker distribution in tumors, treatment response models and MI-based-dose prescription functions.

Prof. Dr. Daniela Thorwarth  
Daniela.Thorwarth@med.uni-tuebingen.de



Radiation Therapy Planning based on PET/CT Imaging



## Key Facilities of the Physics Department

Research and teaching at the Department of Physics greatly benefit from high-tech laboratories and an extensive array of unique research facilities. The infrastructure continues to grow at an accelerating rate with national and international funding of the individual groups and investments from the University.

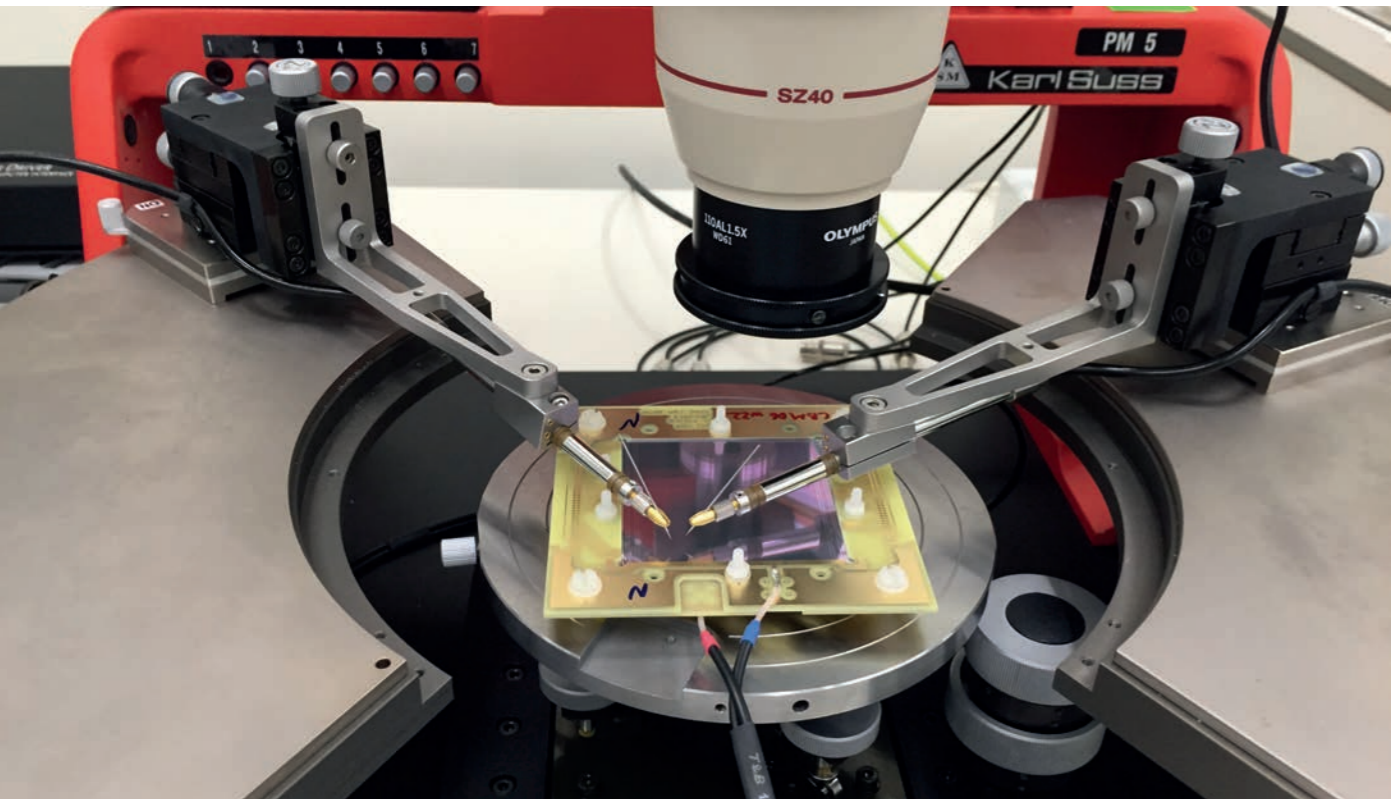
### Astrophysics

Clean room and dark room facilities; thin-film deposition; 1-m vacuum chamber with UV monochromator; climatic chamber; UHV system; 100-m optical bench; 80-cm telescope; 2.30-m radio telescope.

### BioNano Laboratories

Clean room; optical & e-beam lithography; thin-film deposition; microscopy (optical, SEM, TEM, AFM, SICM, dark field, fluorescence, Raman); spectroscopy (Raman, Auger, photo electron, mass, UV/vis, FTIR); surface analysis; wet and dry etching; ovens; cryostats (variable, 4 K, 100 mK, 8 T); UHV station for field-emitter characterization; cell culture equipment; X-ray Scattering (reflectometry, grazing-incidence scattering, small-angle scattering).





Four-point probe for current-voltage measurements.

### Cold Atom and Quantum Optics Laboratories

Ultracold rubidium, lithium and strontium experiments, atom-cavity systems, Rydberg setups, cold atom/solid state interface, 4K and 25mK cryostats, Bose-Einstein condensates at superconductors, cold atom scanning probe microscopes. Frequency comb technology, laser, optical, interferometric, spectroscopic measurement technologies.

### Core Facility LISA<sup>+</sup> - Center for Light-Matter Interaction, Sensors and Analytics

The Department of Physics participates in the University's core facility LISA<sup>+</sup>, a joint research and service facility created around the Nano-structure Laboratory. Clean room and dark room facilities; thin-film deposition (pulsed laser deposition, sputtering, thermal & e-beam evaporation, organic layers, LPCVD, PECVD carbon nanotube growth); micro- and nano-structuring (e-beam&photo/nanoimprintlithography, dual beam focused ion beam, argon ion milling, plasma & reactive ion etching, ashing); thin film/surface analysis (Microscopy: UHV-scanning tunneling, Auger, atomic force and scanning electron. Spectroscopy: photo-electron, transmission and Fourier transform infrared. X-ray diffractometry; Rutherford backscattering; UV/vis fluorescence; ellipsometry, mass spectrometry, gas chromatography, profilometry, 4-point measurements); laser scanning microscopy/spectroscopy (confocal/near-field, parabolic mirror based, UHV low temperature, single molecule); <sup>3</sup>He/<sup>4</sup>He dilution fridges.

### Particle Physics

Rosenau Accelerator: 3MV Van de Graaf, ion beams from H to C; neutron beams; RBS analysis.

Underground Laboratory: shielding 16 mwe, ultra pure Ge spectrometer, dilution refrigerator (5 mK base temperature), SQUID read out array.

Dark Room Facility: PMT single-photon testing; scintillator testing; cryostat for optical characterization (scintillation, reflectivity, etc.) at low temperatures (down to 1.7 K); large volume (1 qm) liquid scintillator or water Cherenkov detector, 11 PMTs 8 inch. UNV deposition system for tungsten superconducting thin films.

Custom fully-automated wafer prober, semi-automatic bonding station.

### Supercomputer

HPC Resources located at all bwHPC-Sites in Baden Württemberg can be used easily. Clustersystems of the physics department (LISA<sup>+</sup>, Astrophysics, Quantum Optics) are additionally accessible. Access to all these systems is granted by the ZDV which is managing some of these clusters and which is member of the bwHPC consortium. The existing bwGRID Systems will be replaced by new powerful clusters for Astrophysics, Material Science, Nanophysics and Particle Physics in Tübingen and Freiburg.

## INSTITUTES OF THE DEPARTMENT OF PHYSICS

### Institute for Astronomy and Astrophysics

Astronomy & High Energy Astrophysics, Sand 1  
Theoretical Astrophysics, Auf der Morgenstelle 10  
Computational Physics, Auf der Morgenstelle 10

### Institute for Applied Physics

Auf der Morgenstelle 10

### Physical Institute

Auf der Morgenstelle 14

### Institute for Theoretical Physics

Auf der Morgenstelle 14

### Center for Plant Molecular Biology

Auf der Morgenstelle 32

### Department for Medical Physics

Hoppe-Seyler-Str. 3

### Department for Experimental Radiology

Hoppe-Seyler-Str. 3

### Radiologic University Clinic

Otfried-Müller-Str. 51

### Department of Radiology

Röntgenweg 13

### Max Planck Institute for Intelligent Systems,

### Max Planck Institute for Biological

### Cybernetics

Spemannstrasse 38

1 Auf der Morgenstelle 10

2 Auf der Morgenstelle 14

3 Auf der Morgenstelle 32

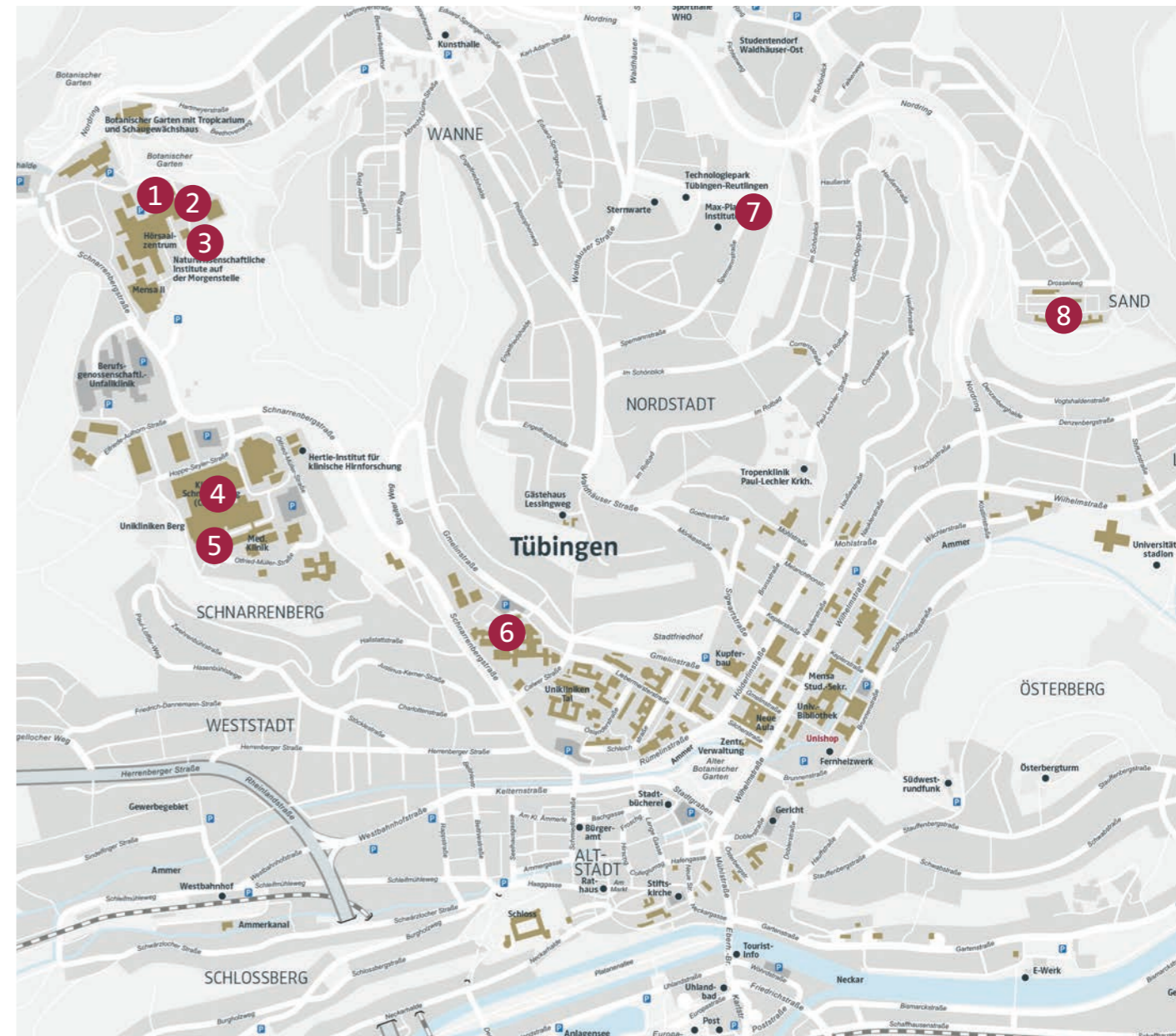
4 Hoppe-Seyler-Str. 3

5 Otfried-Müller-Str. 51

6 Röntgenweg 13

7 Spemannstr. 38

8 Sand 1



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