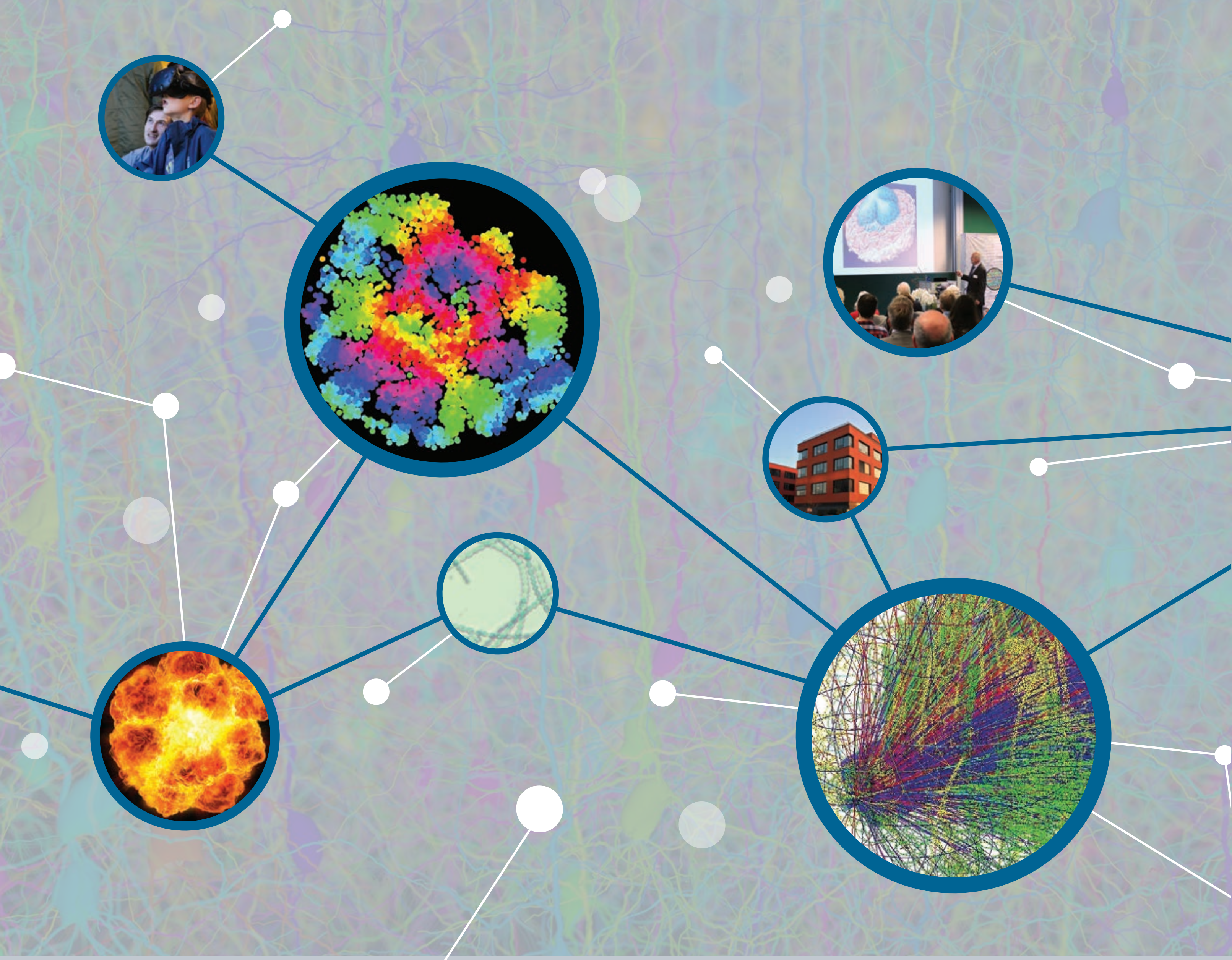
FIAS Frankfurt Institute for Advanced Studies

2017



FIAS

connecting science

– the year 2017 was marked by the advancement of interdisciplinary projects at FIAS.

The second Giersch Symposium took place and bridged the gap between fundamental physics and medical applications. A new group working on deep learning started its work at FIAS and is aiming to use neural networks in physics and other fields of science.

The 5th International FAIR School was organised by FIAS and brought together junior scientists from all over the world from a variety of disciplines. The third Karl Schwarzschild Meeting brought together specialists from the fields of gravitational and quantum physics to discuss the advancement of quantum gravity.

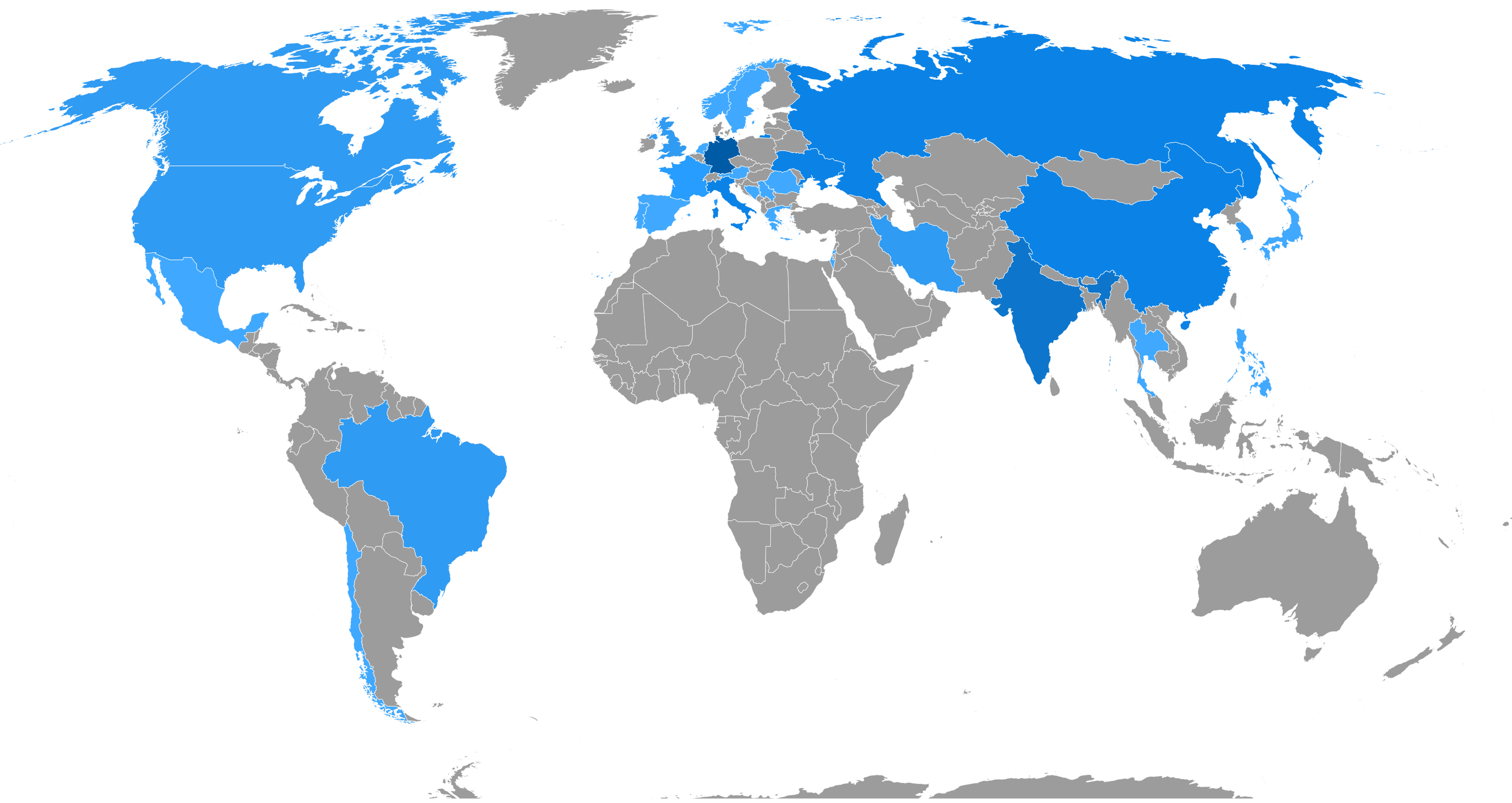
The newly founded project "Computational Connectomics" is aiming to further understand the interconnections of the brain.

Thus it was no coincidence that FIAS hosted the workshop on "Interdisciplinary Science Communication 2017" which highlighted the various efforts to promote interdisciplinary science communication projects in Germany.

These topics can only show a small part of the various interdisciplinary projects at FIAS in 2017. On the following pages you will get a closer look what scientists at FIAS achieved in the previous year.

Content

People at FIAS



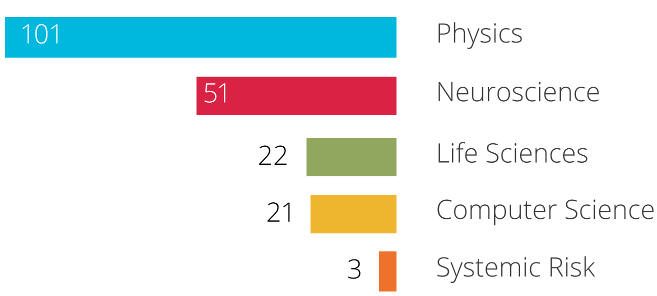
The performance of any scientific institute depends crucially on the people involved with it. This is not different at FIAS – with their enthusiasm and engagement our researchers are the foundation of our success.

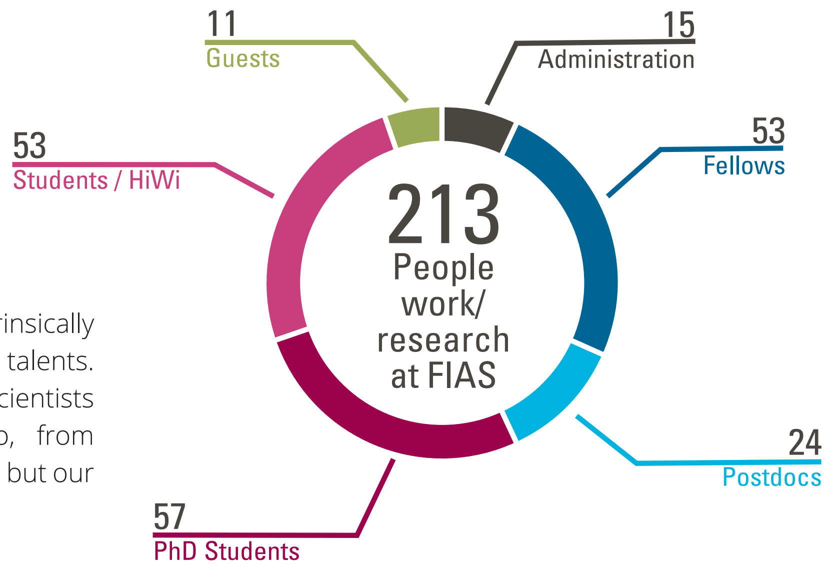
With 35% of our researchers being not from Germany, FIAS is very international. In 2017, we had scientist from 30 different nations working at our institute.

Many scientists are in Frankfurt only for a short time: PhD students stay for 3-4 years, and post-doctoral researchers mostly stay for 1-2 years. In addition we have about 10 guest researchers monthly, they visit FIAS for just a week or up to several months. This means we have new people coming to FIAS on a monthly basis and we are doing our best making them feel at home as soon as possible.

Behind all this stands a small, but strong administrative team, organizing everything in the background.

FIAS scientists by research area:





Lasting scientific success is intrinsically linked with the fostering of young talents. At FIAS we support our junior-scientists with an ideal staff-student-ratio, from whom not only our students profit, but our fellows and post-docs as well.

New Fellows 2017

Fellows

Prof. Dr. Armen Sedrakian

Physics

Prof. Dr. Klemens Zink

Physics

Research Fellows

Dr. Tatjana Tchumatchenko

Neuroscience

Dr. Esteban Hernandez-Vargas

Life Sciences

Dr. Jan Steinheimer-Froschauer

Physics

Dr. Nan Su

Physics

Prof. Dr. Rainer Spurzem

Physics

Dr. Kai Zhou

Physics

Adjunct Fellows

Prof. Dr. Thomas Boller, Max-Planck-Institute für extraterrestrische Physik, Garching
Prof. Laslo Csernai, Department of Physics and Technology, University of Bergen, Norwegen
Prof. Dr. Peter Hess, Instituto de Ciencias Nucleares, Universidad Nacional de México, Mexico
Prof. Dr. Peter Jedlicka, NeuroScience Center, Clinical Neuroanatomy, Goethe University
Prof. Dr. Michael Wand, Institut für Informatik, Johannes Gutenberg Universität Mainz

Hartmut

FIAS Senior Fellow Laureatus

Michel

On October 18, 2017, a ceremony was held to mark the appointment of Prof. Dr. Dr. h.c. Hartmut Michel to FIAS “Senior Fellow Laureatus”. This honorary award is given to outstanding international scientists who are not only distinguished by their excellent research work, but are also committed to the scientific community.

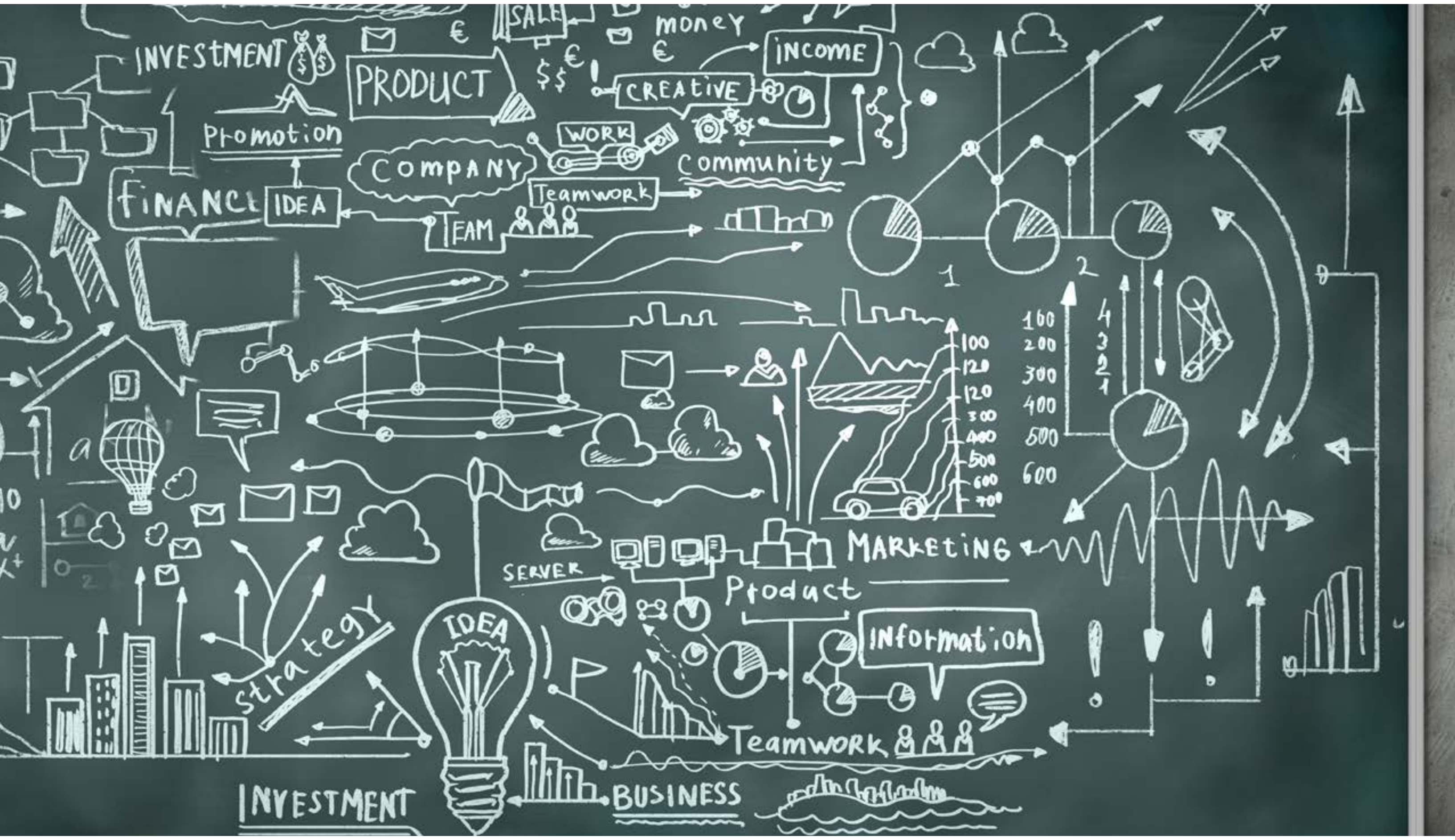
The prizewinner is Prof Dr. Hartmut Michel, Director of the Department of Molecular Membrane Biology at the Max Planck Institute for Biophysics in Frankfurt.

After receiving the honorary fellowship from Senator E.h. Karin Giersch and Senator E.h. Prof. Carlo Giersch, Professor Michel gave a lecture entitled: “The reduction of molecular oxygen and energy conservation by membrane-integrated terminal oxidases”.

Prof. Dr. Hartmut Michel was appointed a FIAS Senior Fellow Laureate by FIAS and the STIFTUNG GIERSCH at a ceremony during the Giersch International Symposium.

FIGSS

Frankfurt International Graduate School for Science



Much of the research at FIAS is performed by our PhD students. The Frankfurt International Graduate School for Science (FIGSS) is the graduate school of FIAS. It provides a framework for structured doctoral education at FIAS and guarantees the interdisciplinary nature of the program for doctoral candidates. The PhD degrees are granted by the departments of Goethe University Frankfurt. The FIGSS PhD students are typically funded by research grants to their advisors and are expected to obtain their PhD degrees within 3 years. Current enrollment is about 60 students with roughly half of them being foreign nationals.

Next to research training, the doctoral education in FIGSS comprises various courses taught by FIAS Fellows such as a base course in Methods for the Study of Complex Systems as well as many specialized courses in the different research areas of the institute. In addition, students can choose from a wide range of transferrable skill courses offered by GRADE, the Goethe Graduate Academy of Goethe University.

A core activity of FIGSS is its weekly interdisciplinary seminar, where FIGSS students and post-docs of the institute report on the status of their research. Special care is taken that the talks are accessible to an interdisciplinary audience. In 2017, presentations ranged from topics like "Proton-proton collisions at the LHC: beyond the Higgs discovery", via the question how to stimulate the brain with electromagnetic coils to presentations of the high performance computing facilities in Hessen.

Events

In October, the participants of the 2nd Giersch International Symposium discussed recent findings on cancer therapy with particle beams.

Hirohiko Tsujii, Director, of iROCK, Kanagawa Cancer Center, Japan. One of the keynote speakers at the 2nd Giersch Symposium

Giersch International Symposium

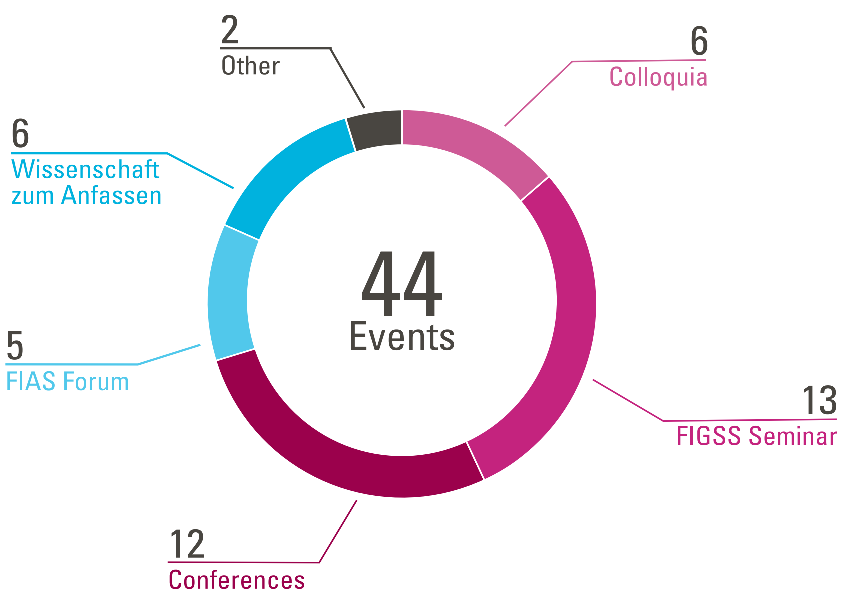
The interconnection of physics and medicine is not a new field, however a field were huge advancements were made in the last decades. Novel radiation techniques help to fight cancer on a whole new level, however all treatment methods need a solid foundation regarding the theoretical understanding. Thus the second Giersch International Symposium bridged the gap between physics and medicine as well as theory and experiment. With their expertise in theoretical modelling FIAS scientists contributed to this world wide effort.

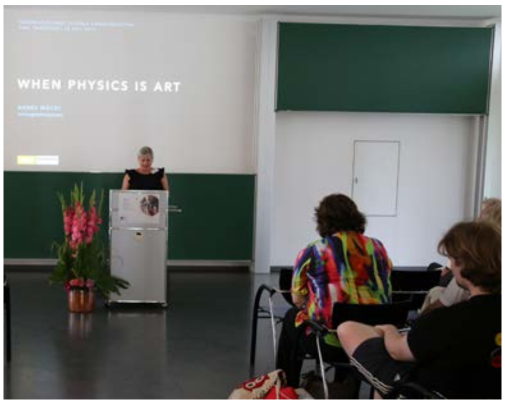
The second Giersch Symposium, was held from October 16-27, at FIAS in Frankfurt with its main focus on cancer therapy with particle beams. With the start of the first clinical facility with dual ion options (protons and carbon) in Heidelberg, Germany, in 2009, the interst in hadrontherapy has been constantly growing. The Symposium brought together leading international experts in the field of hadrontherapy to discuss the present status of the field and to identify the challenges for the future.

Coupled with the Conference, there was a Summer School for young researchers from October 23-27, Under the topic: "Heavy Ion Physics - From Fundamentals to Applications", leading experts taught about the fundamentals and the (medical) applications of heavy ion physics up to applications in areas which one does not expect physics to play a role.

The "Giersch International Symposium" was the second event of this new conference series facilitated by a generous donation by the STIFTUNG GIERSCH.

Overview of all FIAS Events in 2017:





Keynote Lectutre "When physics is art" at the Workshop "Interdisciplinary Science Communication 2017" by Ágnes Mócsy, Pratt University.

Ernst Strüngmann Forum

As in previous years, FIAS was the location for events by the Ernst Strüngmann Forum. In three workshops, international scientists from various disciplines were able to exchange ideas on current topics and work on new concepts. The topics in 2017 were "Interactive Task Learning," and "Manifestations and Mechanisms of Dynamic Brain Coordination over Development".

FIAS International Symposion on Discoveries at the Frontiers of Science

In Rememberance of Walter Greiner, founding father of FIAS, the "FIAS International Symposion on Discoveries at the Frontiers of Science" was hosted in June 2017. Former colleagues and friends of Walter were invited to attend the event and present their recent scientific work.

The participants of the Karl Schwarzschild Meeting in July.

A visit to the Marburg Ion Beam Therapy Centre (MIT) during the Giersch Summer School.

Dr. Berthold Ströter at the Symposium "Machine Intelligence in the Insurance and Finance Industry"

Symposium "Machine Intelligence in the Insurance and Finance Industry"

At the joint invitation of the actuarial firm Bek Clausnitzer Ströter and the Frankfurt Institute for Advanced Studies, insurance companies from all over Germany met with renowned scientists on Thursday July 6, 2017 to discuss the risks, challenges and opportunities that increasingly present machine intelligence brings to the insurance and financial industry.

Interdisciplinary Science Communication 2017

The workshop "Interdisciplinary Science Communication 2017" was held from Juli 10-14, 2017 for the first time. It was its goal to connect experienced science communicators with scientists to exchange knowledge and expand networks.

Karl Schwarzschild Meeting 2017

The 3rd Karl Schwarzschild Meeting on Gravitational Physics and the Gauge/Gravity Correspondence was held at FIAS, from July 24 to 28, 2017. The conference did focus on black holes in astrophysics, quantum gravity, and the gauge/gravity correspondence.

CONNECT 2017

The Symposium "Science and Society" did create a collaborative platform and brougt together young researchers and established scientists from the balkan region. Given the historical background of the region, the group of participants and keynote speakers/lecturers was carefully selected and represented the different ethnical groups as well as the different countries and regions.

Public Relations

June 2017. Boris Rhein (left), Hesse's Minister for Culture and Science with FIAS' Dr. Sascha Vogel (right) are playing a game of "brain football" at the Hessentag in Rüsselsheim.

One of the most important activities within the scientific community apart from research and teaching is the communication of scientific discoveries into the public domain.

Here FIAS established various different formats over the last few years and also in 2017 exceptional activities took place.

The FIAS Forum continued, a series where the general public is invited and presentations about current research is given. Special focus here is that all presentations are understandable not only by scientific audiences, but rather can be understood by non-scientists. In 2016 the speakers were:

- Horst Stöcker - MAGIC - Materie, Gravitationswellen und relativistische Kollisionen - Von schwarzen Löchern und tanzenden Neutronensternen zur FAIR Facility
- Theodor Dingermann - Der lange Arm des Dr. Darwin - Medizin und Pharmazie im Licht der Evolutionstheorie
- Rudolf Steinberg - Scharia und Grundgesetz
- Franziska Matthäus - Im Gleichschritt Marsch - Wie und warum sich (Krebs-) Zellen koordiniert bewegen
- Jan Peters - Wie lernen Roboter? Gehen, Greifen, Tischtennis

Night of Science 2017. A FIAS PhD student explains to a little visitor how one could heal vision problems in the future with VR-glasses.

Especially noteworthy are the activities of the team of the exhibition "Hands-on research", here the team around Sascha Vogel presents science, especially research of FIAS in an hands-on exhibition, where people can operate a particle accelerator, learn how algorithms work and experience what a vacuum does to a chocolate marshmallow. In a cooperation with the initiative "Hessen schafft Wissen" the exhibition travels around Hessen and is presented in schools, at the yearly Hessentag exhibition (with up to 30000 visitors!) and at the Frankfurt Book Fair.

A special honour was the invitation of the Hessian State Government to represent the FIAS at the Hessen Festival in Berlin on Juli 21, 2017.

FIAS also takes part in the Night of Science, which takes place once per year at the Campus Riedberg of the Goethe University. Here the lecture hall is remodelled and the "FIAS Bembelcup" is played. Various robot football teams from all over Germany join us for a chance to win the trophy - the traditional FIAS Bembel.

In the faculty club the newest exhibits of the hands-on research exhibition where displayed and people joined and learned about our science. In addition plenty of FIAS Fellows are involved in giving talks during the nightly program.

Juli 2017. The "Hands-on research" team with Hesse's Prime Minister Volker Bouffier (right),his wife (pink dress) and Minister of State Lucia Puttrich (far left) .

Physics

Optimization of Network building costs:

Due to the increasing share of renewable energies in the electricity grid, there are always grid bottlenecks. Fortunately, there are solutions: new technologies that can quickly compensate for fluctuations, wind turbines with synthetic inertia and better system control. At the moment, network operators usually counter these fluctuations with short-term control measures. The efficient operation and expansion of the transmission grid is therefore an essential part of the integration of renewable energies.

In 2017, a project funded by BMWI was started at FIAS and partner institutions, where the scientists will develop and evaluate algorithms for the distribution of load flows and network costs and then systematically compare them. In addition, the effects of different cost distribution approaches on short-term operating and long-term investment decisions in the German electricity market are examined.

Theoretical physics is the discipline that aims at describing how the world works in terms of fundamental equations. The goal is to abstract explicit phenomena by reducing them to underlying principles that are responsible for many different manifestations in nature. Physical processes are often the basis for other natural sciences, e.g. quantum mechanics is important to understand atoms and therefore chemistry. Establishing knowledge about the microscopic dynamics is crucial to understand macroscopic emergent phenomena. Theoretical physicists at FIAS are working on complex models on very different scales from the elementary particles in the universe to huge objects like neutron stars, two examples of structures governed by the theory of strongly interacting matter.

The properties of such matter under extreme conditions, governed by the theory of Quantum Chromo Dynamics (QCD), are still largely unknown. At high temperatures - accessible in heavy ion collisions - QCD predicts a phase transition from ordinary matter to the Quark-Gluon-Plasma, where the elementary constituents become unconfined. Other interesting new phases of strongly interacting matter, e.g. color superconductivity, at high densities and low temperatures might be realized in the interior of compact stars.

At FIAS, theoretical physicists focus on understanding the properties of strongly interacting matter using a broad range of methods and tools:

Calculations of the equation of state and the phase diagram with effective models based on hadronic and partonic degrees of freedom, e.g. different versions of the relativistic mean field model, chiral models with Polyakov loop and dilaton field, resonance gas model.

- Dynamical modelling of the complex many-body dynamics of heavy-ion collisions, using methods from classical and quantum mechanics, statistical mechanics, transport theory, quantum field theory, and gravity duality. The employed models include e.g. relativistic hydrodynamics and transport theory, employed for example in UrQMD or SMASH.
- Studies on the structure of exotic nuclei away from the band of stability including hypernuclei and antinuclei by solving the corresponding many-body problems. Binding energy and excitation spectra of these nuclei help understand the syntheses of heavy atoms in stellar explosions.
- Also topics like the distribution of renewable energy can be solved using very similar techniques. Various groups at FIAS are thus involved in modelling energy scenarios. Research in physics is also highly interdisciplinary. Collaborations especially with computer scientists are essential for state-of-the-art research in theoretical physics. Theorists at FIAS closely collaborate with their experimental colleagues working at major accelerator centres like GSI (Darmstadt), CERN-LHC (Geneva), BNL-RHIC (Brookhaven) and are closely involved in the preparations for the future FAIR experiments within the program HIC for FAIR.

Group Information

At FIAS
since 2015, Research Fellow

Research Area
Quantum Gravity
General Relativity
Quantum Foundations
Philosophy of Science
Sociology of Science

Team
Ricardo Torromé
Tobias Mistele
Tobias Zingg

Collaborations
Nordita, Stockholm
Perimeter Institute, Canada
SISSA, Trieste

Sabine Hossenfelder

Physicists thought they understood gravity when Einstein completed his theory of general relativity. But the last decades have made increasingly clear, that general relativity is not sufficient to explain the cosmos. To make general relativity fit with the data, astrophysicists have had to conjecture two new constituents: dark matter and dark energy.

We presently do not have evidence that either dark matter or dark energy have a microscopic substructure. That means we do not know whether they are real stuff, or whether they are just fixes that make two sides of an equation agree with each other. What we are missing is either a direct detection of a constituent particle, or an alternative explanation.

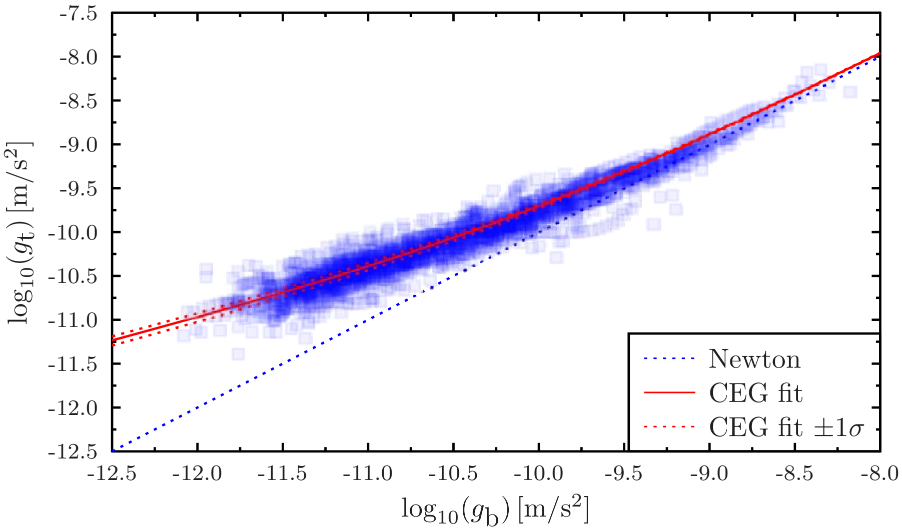
Hossenfelder's group studies the possibility that dark matter and dark energy are not substrates, but that instead the equations of general relativity are only approximately valid and must be amended. Various lines of evidence support this. As emphasized in 2017 work of Hossenfelder and Torromé, deviations from general relativity on long distances can occur of space-time fundamentally is discrete rather than smooth and continuous. The reason is that a discrete space-time would be imperfect much like the lattices of crystals are imperfect. Such imperfections disturb the propagation of matter through space-time, and can therefore make it appear as if our universe contains more stuff than really is the case. However, these "space-time defects," it turns out, are insufficient to make up for dark matter. Their density drops to quickly. They should have played a more important role in the early universe, which is subject of current research.

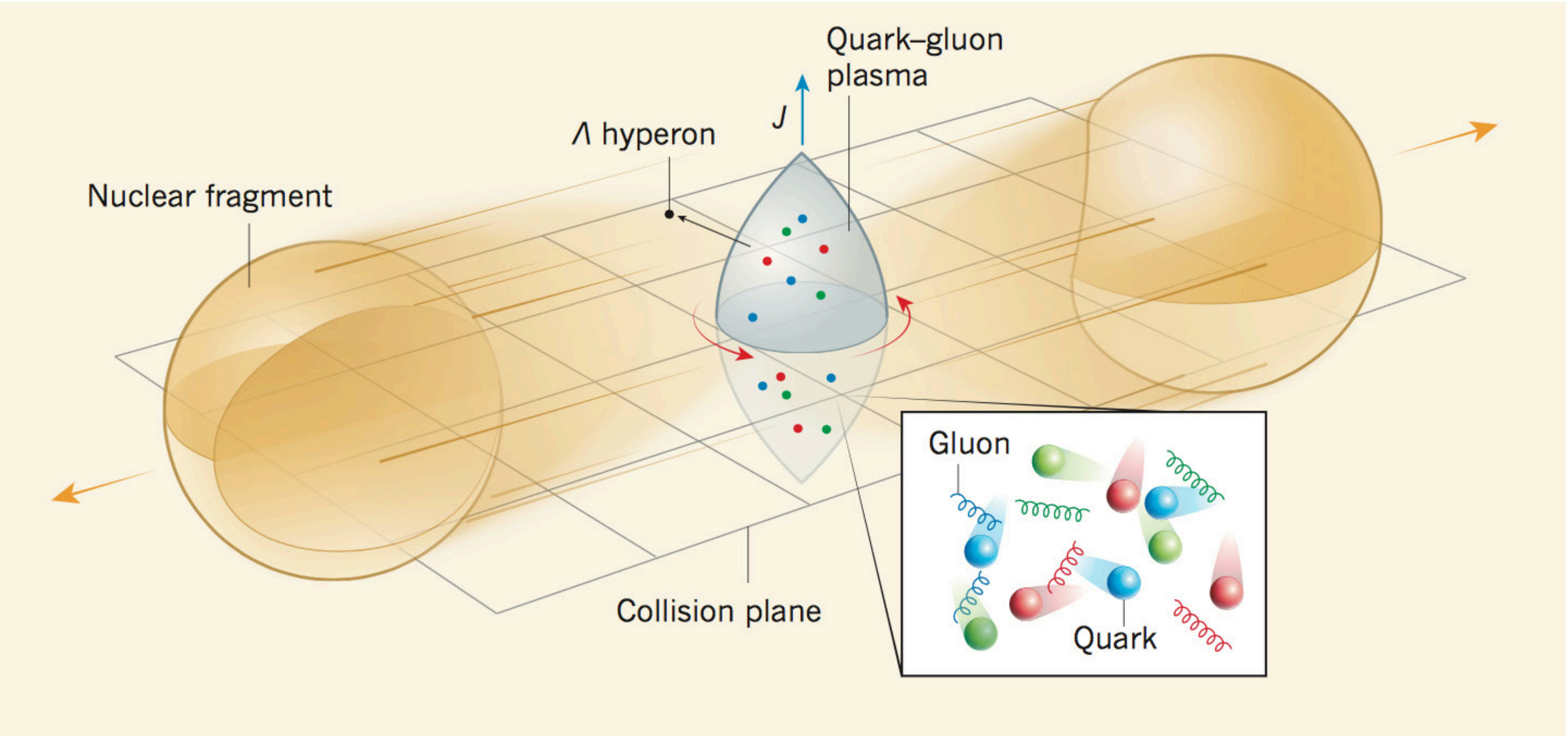
A related idea that however leads to very different results is that space-time does not behave like a rigid body, but that it instead has an elasticity to it. This idea was originally proposed by Erik Verlinde from the University of Amsterdam. In a 2017 work , Hossenfelder showed that Verlinde's approach does not only account for the seeming presence of dark matter in galaxies, but that it moreover also gives rise to dark energy. This is a stunning insight, which Hossenfelder's group is now looking into further. The leading project is that of PhD candidate Tobias Mistele who is studying whether gravitational lensing could be used to distinguish between particle dark matter and an apparent dark matter effect caused by the elasticity of space-time.

These examinations on the interrelations between gravity and condensed matter physics have another, entirely different, range of applicability. It has been known for two decades that certain gravitational theories can be used to study strongly coupled systems, such as the quark gluon plasma or high-temperature superconductors. In collaboration with Tobias Zingg (Stockholm) , Hossenfelder's group has taken this relation one step further and demonstrated that gravity can be used to establish a surprising relation between different types of condensed matter systems. They are now looking into concrete examples that might allow an experimental test of this newly found relation.

Dr. Sabine Hossenfelder

Sabine graduated from Frankfurt in 2003 and was a postdoctoral fellow, among others, at UC Santa Barbara, and the Perimeter Institute in Canada. Before returning to Frankfurt, she held a position as assistant professor at Nordita, in Stockholm, Sweden. Sabine's research is presently supported by the Swedish Research Council, the German Research Foundation, and the Foundational Questions Institute.
Besides her research, Sabine is also active in science communication. She has contributed to several magazines, writes a popular science blog, and will soon publish her first book.





Group Information

At FIAS

since 2012; Fellow

Research Area

Theoretical nuclear physics
Heavy ion collisions
Transport theory and hydro-dynamics

Team

Dr. LongGang Pang
Dr. Juan Torres-Rincon
Dr. Feng Li
Dr. Sangwook Ryu
Dr. Dmytro Oliinychenko
Vinzent Steinberg
Alba Soto-Ontoso
Jean-Bernard Rose
Markus Mayer
Anna Schäfer
Jan Staudenmaier
Christian Schwarz
Jan Hammelmann
Justin Mohs
Jonas Rothermel
Ömür Erkiner
Julia Lienert
Philip Karan

Collaborations

David Blaschke, Univ. Wroclaw
Xin-Nian Wang, LBNL & CCNU
Ulrich Heinz, Ohio State Univ.
Charles Gale, McGill Univ.
Javier Albacete, Univ. of Granada

Hannah Petersen

The major goal of heavy ion research is the exploration of the phase diagram of strongly interacting nuclear matter. In highly relativistic collisions of ions at almost the speed of light, the quark-gluon plasma, the state of matter shortly after the Big Bang, is formed. To learn something about the transition and the properties of the transition from the quark-gluon plasma to the hadron gas phase theoretical models of the dynamics are essential.

In our new hadronic transport approach (SMASH –Simulating Many Accelerated Strongly-interacting Hadrons) the shear viscosity over entropy ratio has been calculated as a function of temperature and baryon chemical potential. By detailed comparisons to available analytic results, the discrepancy between existing results in the literature has been traced back to the influence of finite lifetimes of resonances on the relaxation dynamics. Once the lifetime is of similar magnitude as the mean free time between collisions, the momentum exchange is delayed. To investigate resonance properties in a hot and dense medium as it is created in heavy ion reactions, the dilepton radiation has been studied. Within a detailed comparison to all the available HADES experimental data, it has been demonstrated that explicit medium modifications are necessary in larger collision systems. The contributions of dilepton emission below the hadronic decay threshold yields important contributions in the intermediate mass region.

A question under lively debate in the heavy ion community is, if a quark-gluon plasma can be formed in small systems at very high energies, namely in proton-proton or proton-nucleus collisions at the Large Hadron Collider. To answer these questions anisotropic flow observables are crucial signatures for collective behavior. The explicit sub-structure of the proton is of major importance for quantitative analysis. Correlations between gluonic hot spots (Fig. 2) have been introduced and the consequences on flow observables pointed out. Alba Soto-Ontoso was awarded for her work on this topic with a Flash talk at Quark Matter 2017 and a Giersch Excellence Award. Only with correlations between the constituents of the protons, the 'hollowness effect' and an anti-correlation of elliptic and triangular flow (the most important flow coefficients) can be explained. The 'hollowness effect' denotes the feature, that the proton-proton cross-section is not maximal at zero impact parameter, but at finite impact parameter at LHC energies.

The STAR collaboration has measured for the first time the global rotation of the quark-gluon plasma by observing Lambda polarization in semi-central reactions at low beam energies (see title Fig.). Spin-orbit coupling aligns the spins with the rotation axis of the system. The proton produced in the decay of the Lambda particle preferentially points in the direction of the spin, therefore, it is a self-analysing decay. In the Nature News & Views article this measurement and its implications on the search for the first order phase transition are explained. The quark-gluon plasma is so far the fastest spinning fluid that has been found in nature.

Prof. Dr. Hannah Petersen

Hannah Petersen is leading a Helmholtz Young Investigator Group at FIAS, since October 2012. She obtained her PhD degree at Goethe University in 2009 sponsored by a stipend of the Deutsche Telekom Stiftung and spent 3 years as a Humboldt fellow and visiting assistant professor at Duke University. Her work concentrates on the dynamical description of heavy ion collisions with transport and hydrodynamics.
In 2016, she received the most prestigious award for young scientists in Germany, the Heinz Maier-Leibnitz prize by the DFG and BMBF.

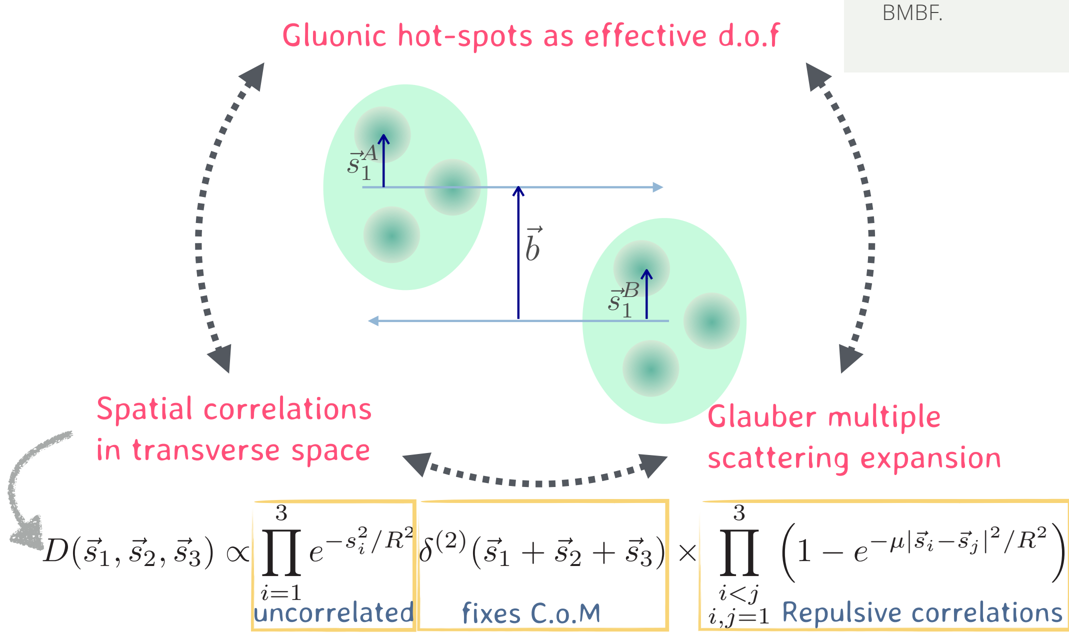
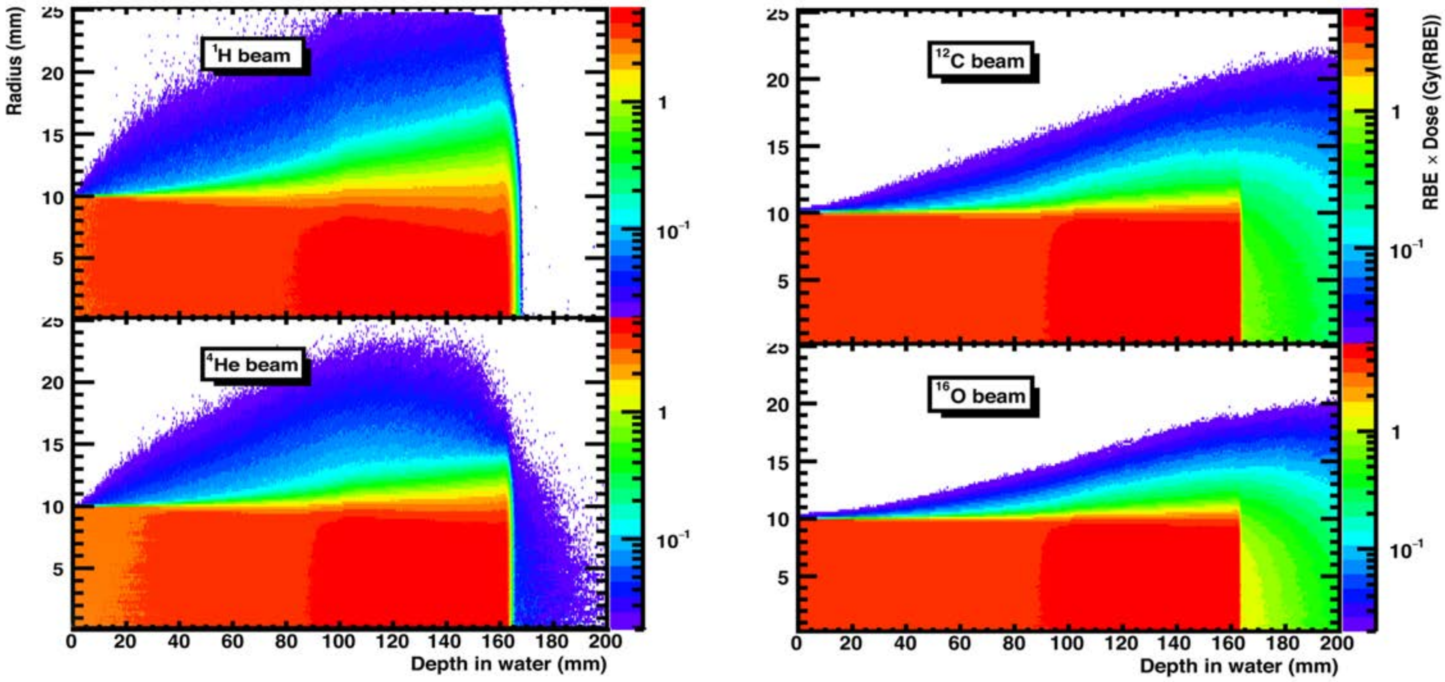


Fig. 2: Schematic picture of introducing correlations into the sub-structure of the proton



Group Information

At FIAS

since 2004; Senior Fellow

Research Area

Equation of state of strongly-interacting matter under extreme conditions
Hydrodynamic modelling of relativistic heavy-ion collisions
Properties of nuclear matter in supernova explosions and compact stars
Modelling Ion-Beam Cancer therapy

Team

Dr. Hub, Leoniid Satarov
Dr. Shun Furusawa
Claudio Ebel
Allesandro Brillante

Collaborations

Dr. Lucas Burigo, DKFZ, Heidelberg
Dr. Hub. Igor Pshenichnov, INR, Moscow
Prof. Dr. Mark Gorenstein
Dr. Hub. Kyrill Bugaev, both B. Inst., Kiev
Prof. Laszlo Csernai, Univ. Bergen

Igor Mishustin

Project 1: Lateral variations of radiobiological properties of therapeutic fields of H-1, He-4, C-12 and O-16 ions studied with Geant4 and microdosimetric kinetic model.

In cancer therapy with ion beams the relative biological effectiveness (RBE) of ions changes in the course of their propagation in tissues. Such changes are caused not only by increasing the linear energy transfer (LET) of beam particles with the penetration depth towards the Bragg peak, but also by nuclear reactions induced by beam nuclei leading to the production of various secondary particles. Although the changes of RBE along the beam axis have been studied quite well, much less attention has been paid to the variation of RBE in the transverse direction, perpendicular to the beam axis. In order to fill this gap, we have performed the comparison of radiation fields produced by various ion beams in water. The simulations have been carried out by means of a Geant4-based Monte Carlo model for heavy-ion therapy (MCHIT), combined with the modified Microdosimetric Kinetic Model (MKM). The main conclusion of this analysis is that the intermediate-mass ion beam (He) could provide an optimum dose distribution.

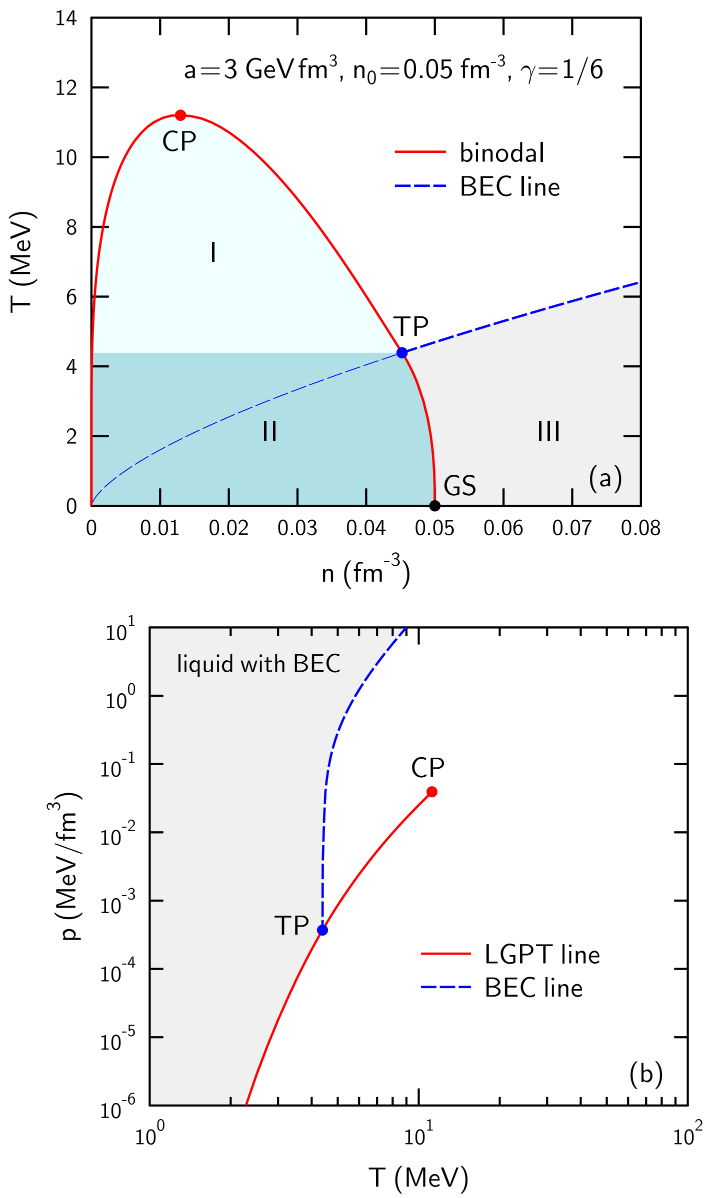
Caption to title Fig.: Calculated radiation fields produced by H-1, He-4, C-12 and O-16 ion beams of 20 cm in diameter in water. The target volume (dark red) is a cylinder of 20 mm in diameter and 70 mm length. H and He beams lead to large dose in the transverse direction (lateral distribution), due to rescattering of light ions. But C and O beams generate large dose in the region behind the tumor, due to nuclear fragmentation reactions.

Project 2: Bose-Einstein condensation and liquid-gas phase transition in α-matter

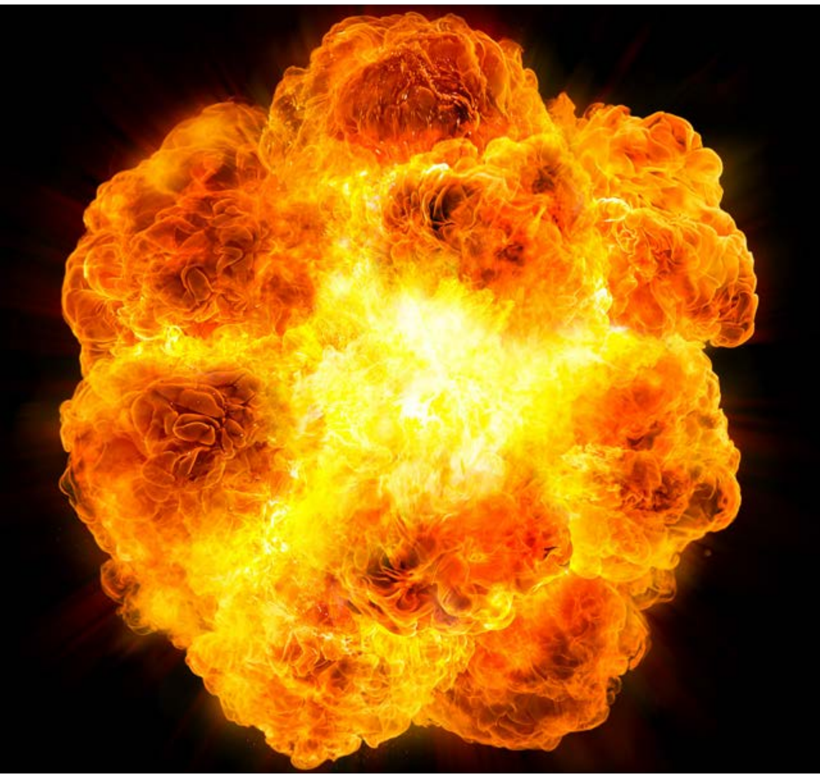
Among nuclear clusters alpha-particles play a special role due to their high binding energy and compact size. It is expected that at subnuclear densities and low temperature the isosymmetric nuclear matter will split into alpha-particles. In this project we have studied systems of alpha-particles with both repulsive and attractive interactions using the Skyrme-like mean-field model. The phase diagram of such systems exhibits two special lines in the chemical potential-temperature plane: one line which represents the first-order liquid-gas phase transition with the critical end point, and another line which represents the onset of Bose-Einstein condensation. The phase diagram of this alpha-clustered nuclear matter is qualitatively similar to that observed for the atomic He4 liquid.

Prof. Dr.
Igor Mishustin

Igor Mishustin studied theoretical physics and astrophysics at the Moscow State University. He obtained his PhD and then the Doctor of Sciences degree (habilitation) at the Kurchatov Institute in Moscow. After long-term stays in the Niels Bohr Institute (Denmark) and the University of Minnesota (USA), he joined the newly-established Frankfurt Institute for Advanced Studies, in 2004. Here he leads the group of theoretical subatomic physics and astrophysics. Over the years he was lecturing graduate and post-graduate courses as well as supervising Diploma and PhD students at several Universities.



Picture 2: Phase diagram of alpha-matter in mu-T (a) and T-p (b) planes.
Solid lines correspond to the Liquid-Gas phase transition and dashed lines to the onset of the Bose-Einstein Condensation. The Critical Point (CP) and Triple Point (TP) are marked by dots. With the parameters used they are located at temperatures 11.2 MeV and 4.39 MeV respectively.



The gauge/gravity duality can relate a system far from equilibrium with an accreting black hole.

Group-Information

At FIAS

since 2010, Research Fellow

Research Area

Classical and quantum gravity
Black hole thermodynamics
Quantum field theory in curved space
Particle theory
Mathematical physics

Team

Dr. Antonia M. Frassino
Alain Dirkes
Marco Knipfer
Sven Köppel
Roman Smit
Athanasios Tzikas
Michael F. Wondrak
Dipanshu Gupta
Tristan Daus
Jiyong Jeong

Collaborations

R. Casadio, Univ. Bologna
M. Kaminski, Univ. Alabama
Maximiliano Isi, Caltech
J. Mureika, LM Univ. Los Angeles
Prof. Dr. Roldao da Rocha, ABC Federal University
Dr. Anais Smailagic, INFN, Trieste
Dr. Euro Spallucci, Univ. Trieste

Piero Nicolini

The physics of fundamental interactions aims to efficiently describe the Universe, its formation, evolution and the properties of matter in it. Despite the importance of the program and some successful theoretical predictions (e.g. the detection of the Higgs particle and gravitational wave signals), there exists a number of unsolved problems that prevent us from reaching a full understanding of the physics governing our Universe. For instance, the role of gravity and its relation with the other fundamental interactions during the Planck era plays a paramount role. An initial attempt to reconcile gravity and quantum mechanics is based on quantum field theory in curved space, a formulation that led to Hawking's discovery about the possibility for black holes to emit thermal radiation. After more than four decades of intense research activity, the situation has to some extent improved and nowadays one can at least speak of an array of candidate theories of quantum gravity. Among the existing formulations, Superstring Theory is probably the major contender to address the issue of the unification of fundamental interactions at quantum level.

The research activity of the group has focused on three major topics that emerge directly or indirectly from string theory: the nonlocal deformation of fields, the modification of black hole metrics at the Planck scale and the AdS/CFT correspondence far from equilibrium.

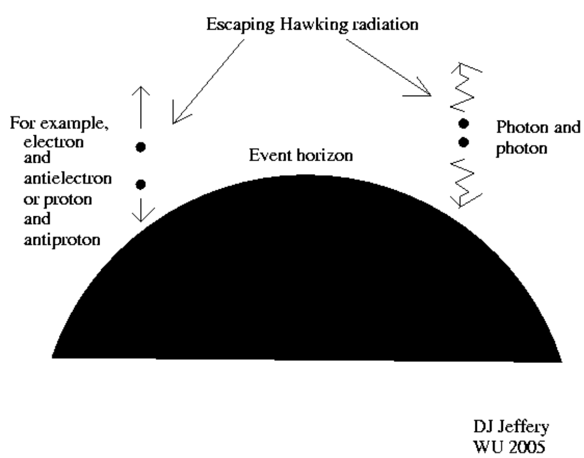
Nonlocal deformations of quantum field theory are a side effect of quantum gravity that show up in disparate circumstances. One of these is the so the called un-particle arena, a conjectured particle sector exhibiting scale invariant properties at a non-trivial infrared fixed point. As a major result, we proposed the Casimir effect as a reliable testbed to uncover unparticle signals. By assuming the coupling of electrons with a U(1) un-field between the plates, we showed that compelling bounds on unparticle parameters can be derived both in the strongly and weakly coupled regimes.

A lot of activity has also been devoted to the analysis and the derivation of quantum gravity corrected black hole metrics. Contrary to previous claims, it has been shown that the regularity of the energy momentum tensor is a sufficient condition to cure curvature singularities. More importantly, the role of a U(1)-black hole hair has been analysed for the first time within the framework of the gravity self-complete paradigm. As a major result, we found that the electric charge drastically modifies the standard scenario based on the Schwarzschild metric. Only quasi-extremal configurations are allowed at the Planck scale with consequent sudden decay via Hawking and Schwinger pair production mechanisms. In parallel to this, black holes have been investigated in a lower dimensional spacetime that naturally uncovers their quantum nature and allows for the study of their phase transitions, namely their "chemistry".

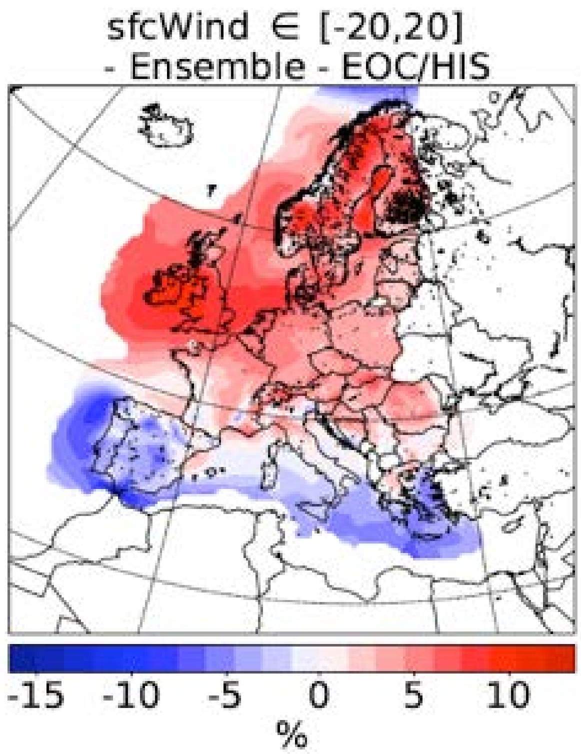
The third research line combines black holes and quantum fields within the so called gauge/gravity duality. The latter refers to the conjectured correspondence between gravitational systems and quantum fields living in a spacetime with one dimension fewer. Despite such a correspondence is mostly known for a specific set up, an Anti-de Sitter space (AdS) and a Conformal Field Theory (CFT), it might disclose universal properties soon at the reach of current heavy ion facilities, including FAIR. A major effort of the group activity has been the extension of the standard AdS/CFT scenario to case of time dependent gravitational systems. This would allow the calculation of shear properties of a strongly coupled plasma in a regime far from equilibrium.

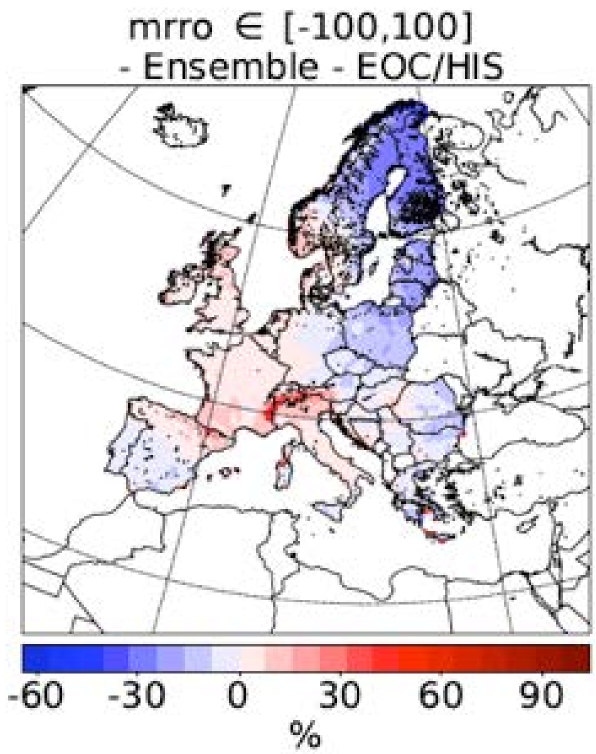
Prof. Dr. Piero Nicolini

Piero Nicolini received his PhD from the University of Bologna in 2002 and his habilitation from the Goethe University in 2013. After postdoctoral positions in Marseille and in Trieste, he is currently a Research Fellow at FIAS and an Apl. Professor at the Goethe University. His research interests cover quantum gravity, quantum field theory, and theoretical particle physics. Prof. Dr. Piero Nicolini is best known for having first proposed noncommutative geometry as a tool for studying evaporating black holes beyond the semiclassical limit.



Hawking radiation, namely a quantum mechanical emission of particles at the event horizon.





Group Information

At FIAS
since 2004, Fellow

Research Area
Nuclear Physics
Astrophysics
Heavy-Ion Physics
Complex Networks

Team
Dr. Thomas Brown
Dr. Alexander Kies
Dr. Rosana Gomes
David Schlachtberger
Jonas Hörsch
Ayon Mukherjee
Fabian Hofmann
Markus Schlott
Clara Steinebach
Dominik Kaufhold
Omar el Sayed
Pia Jakobus

Collaborations
A. Bhatthacharya, Univ. of Calcutta
M. Greiner, Univ. of Aarhus
R. Mallick, IIT Bhopal
F. Weber, UC San Diego
R. Negreiros, Fluminense Univ.
V. Dexheimer, Kent State
C. Vasconcellos, UFRGS
M. Malheiros, ITA Sao Paulo
R. Nandi, TIFR Mumbai

Stefan Schramm

The research of Prof. Schramm's group concentrates on two main topics - (1) strong interaction physics in dense and hot matter and (2) complex networks with emphasis on electricity grids and energy systems.

Addressing the dense matter problem: Strong interaction physics under extreme conditions of temperature, density, as well as isospin are central to a large amount of theoretical and experimental activities, including heavy-ion collision experiments, the study of neutron stars as well as the production of exotic neutron-rich nuclei and hypernuclei. While there are many theoretical calculations investigating separate aspects of this physics regime, very few attempts exist pursuing a unified modelling of the phenomena. To this end we continue the development of a combined description of hadronic and quark degrees of freedom, investigating the phase structure of strong interactions as it relates to heavy ions as well as to neutron and neutron-quark (hybrid) compact stars. In a new improvement of this approach we were able to describe compact star properties that agree with current observations, including the new constraints coming from the recent first measurement of a neutron star merger. Within the same approach we could show how the interplay of two phase transitions in strongly interacting matter, the nuclear liquid-gas and the deconfinement transition to quarks, interfere and can lead to significant measurable effects in ultra-relativistic heavy-ion collisions.

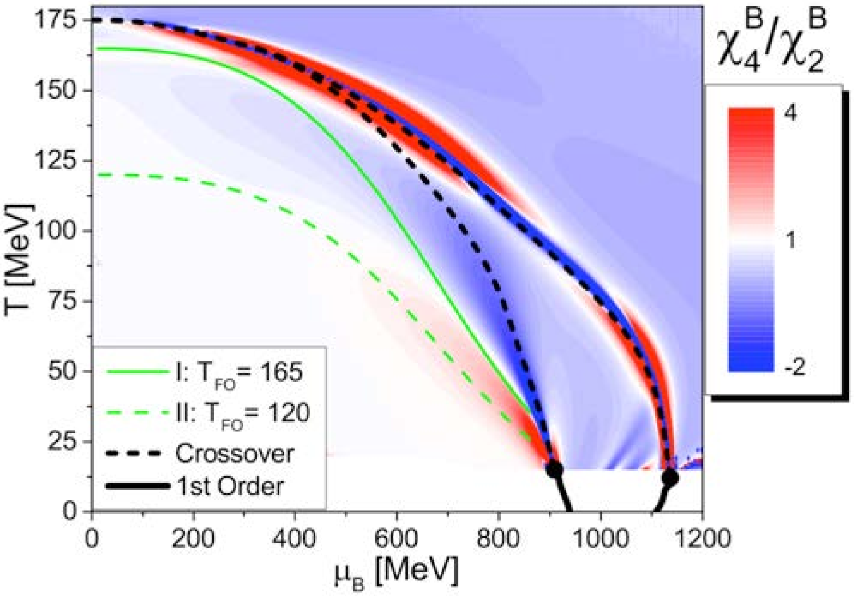
In the field of complex networks, with the backdrop of the "Energiewende" in Germany and the general increased use of renewable energy sources, we investigate the properties and stability of complex network structures. The intrinsic variability of renewable energy production defines a theoretically very interesting system of a network with strongly fluctuating sources, but it generates significant challenges of ensuring a reliable and cost-effective power supply. To study these aspects we continued the development of an open-source software for modelling and optimising electricity grids, including many types of electricity producers, like solar, wind and fossil fuel power stations as well as a variety of energy storage components. Furthermore, explicit coupling to the heating, gas as well as the transport sector, i.e. electric cars have been implemented. The world-wide number of groups using this software is constantly rising.

In one particular project we studied potential adaptions of the energy system triggered by climate change effects. To that end we made use of computed global and regional weather data that assume different rises of the global temperature. On this basis we simulated and optimized the European energy systems up to the year 2100. As one aspect of the results a clear increase in the share of solar energy production in Southern Europe is to be expected, while there is also a significant decrease in the usage of hydro power in various regions in Europe that has to be taken into account in long-term planning strategies.

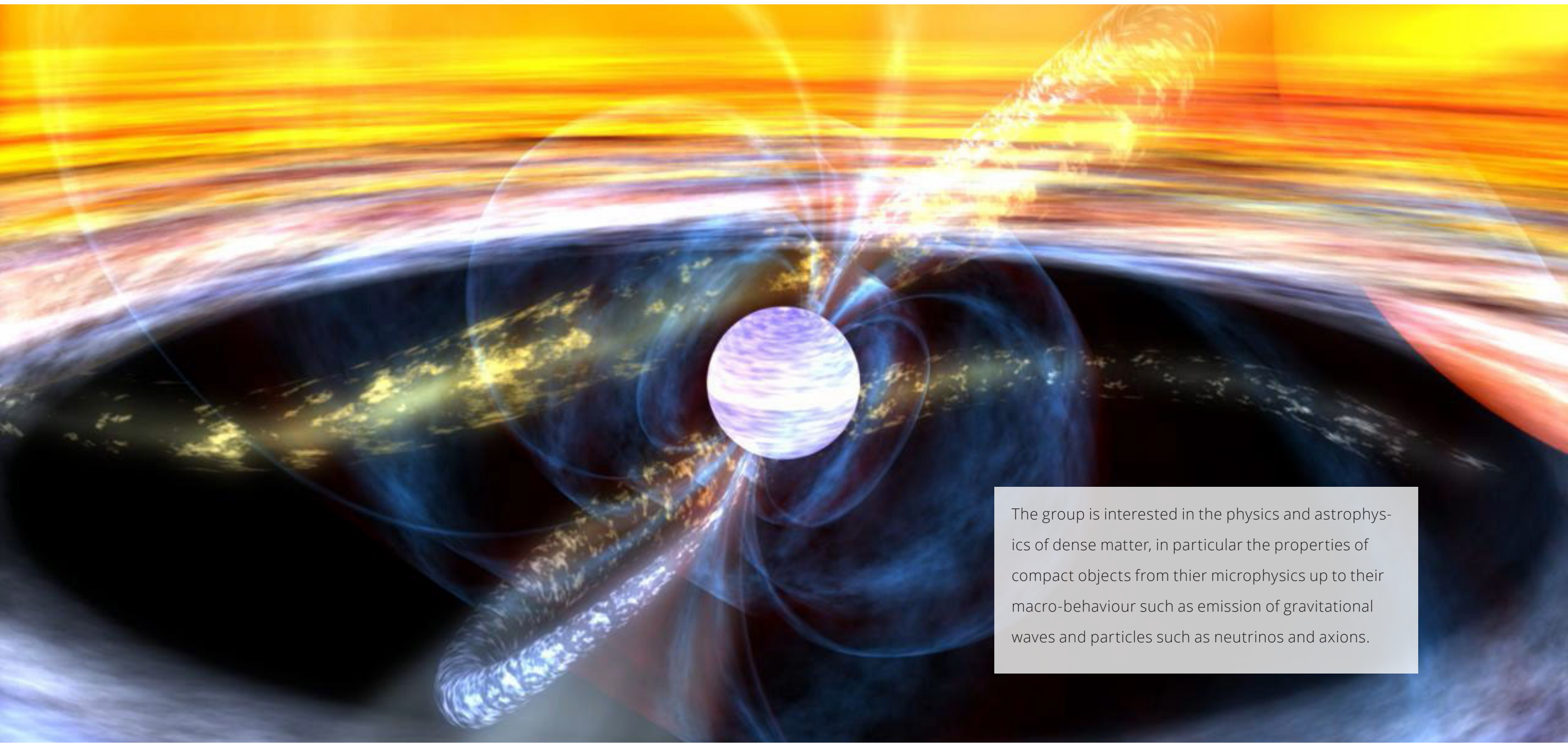
Title picture: Change of spatial correlation lengths for wind (left) and hydro resources (right) using climate simulation data

Prof. Dr.
Stefan Schramm

Prof. Schramm did his PhD at the Goethe University with Walter Greiner on strong-field Quantum Electrodynamics. He was a Postdoctoral Researcher with Steven Koonin at Caltech and Charles Horowitz at Indiana University, working on a variety of astrophysics and nuclear physics problems. As head of the Center of Scientific Computing he was in charge of setting up the first high-performance compute cluster at the Goethe University. His current work covers modelling and simulation of neutron star physics, non-equilibrium effects in heavy-ion collisions as well as the study of large-scale incorporation of renewable energy sources in the electricity grid and the energy system at large.



Susceptibilities that can be measured as fluctuations of produced particle number in heavy-ion collisions. The liquid-gas transition interferes with the deconfinement transition even at high temperatures (red regions).



The group is interested in the physics and astrophysics of dense matter, in particular the properties of compact objects from thier microphysics up to their macro-behaviour such as emission of gravitational waves and particles such as neutrinos and axions.

Group Information

At FIAS

since 2017; Fellow

Research Area

Astrophysics of compact stars
Effective models of QCD
Microphysics of nuclear systems

Team

Dr. Jia-Jie LI
Dr. Arus Harutyunyan

Collaborations

Prof. Mark Alford, Washington Univ.
Prof. David Balschke, Wroclaw Univ.
Prof. Kent Yagi, Virginia Univ.
Prof. Vassileos Paschalidis Univ. of Arizona
Prof. Fridolin Weber, San-Diego State

Armen Sedrakian

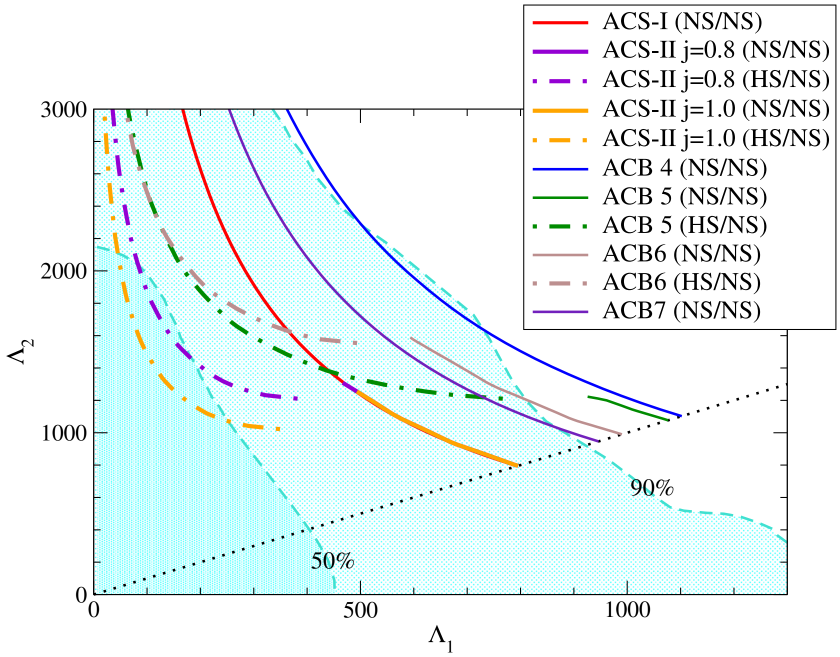
Our work on the compact star physics frontier was concerned with objects that may contain quark matter in their interiors at densities exceeding several times the nuclear saturation density. We explored models of such compact stars, where there are two first-order phase transitions: the first from nuclear matter to a quark-matter phase, followed at higher density by another first-order transition to a different quark matter phase [e.g., from the two-flavor color superconducting (2SC) to the color-flavor-locked (CFL) phase]. We were able to demonstrate that this can give rise to two separate branches of hybrid stars, separated from each other and from the nuclear branch by instability regions and, therefore, to a new family of compact stars, denser than the ordinary hybrid stars. In a range of parameters, one may obtain twin hybrid stars (hybrid stars with the same masses but different radii) and even triplets where three stars, with inner cores of nuclear matter, 2SC matter, and CFL matter, respectively, all have the same mass but different radii.

To study the implications of the gravitational wave observations of GW170817, which placed bounds on the tidal deformabilities of compact stars, we have designed new parametrizations for hybrid hadron-quark equations of state, that give rise to low-mass twin stars. We have tested them against GW170817 data. We found that GW170817 is consistent with the coalescence of a binary hybrid star--neutron star. We also tested and found that the I-Love-Q relations for hybrid stars in the third family agree with those for purely hadronic and quark stars within 3% for both slowly and rapidly rotating configurations, implying that these relations can be used to perform equation-of-state independent tests of general relativity and to break degeneracies in gravitational waveforms for hybrid stars in the third family as well. Our work on the effective models of QCD have concentrated on the computations of the transport coefficients of QCD in the non-perturbative regime within the two-flavor Nambu-Jona-Lasinio model. The Kubo formalism was applied to obtain the thermal and electrical conductivities, bulk viscosity as well as an update of the shear viscosity by evaluating the corresponding equilibrium two-point correlation functions to leading order in the 1 /Nc expansion. The Dirac structure of the self-energies and spectral functions is taken into account as these are evaluated from the meson-exchange Fock diagrams for on-mass-shell quarks. We find that the bulk viscosity dominates the shear viscosity close to the Mott temperature by factors 5 to 20 which should have important implications for hydrodynamics modelling of heavy ion collisions.

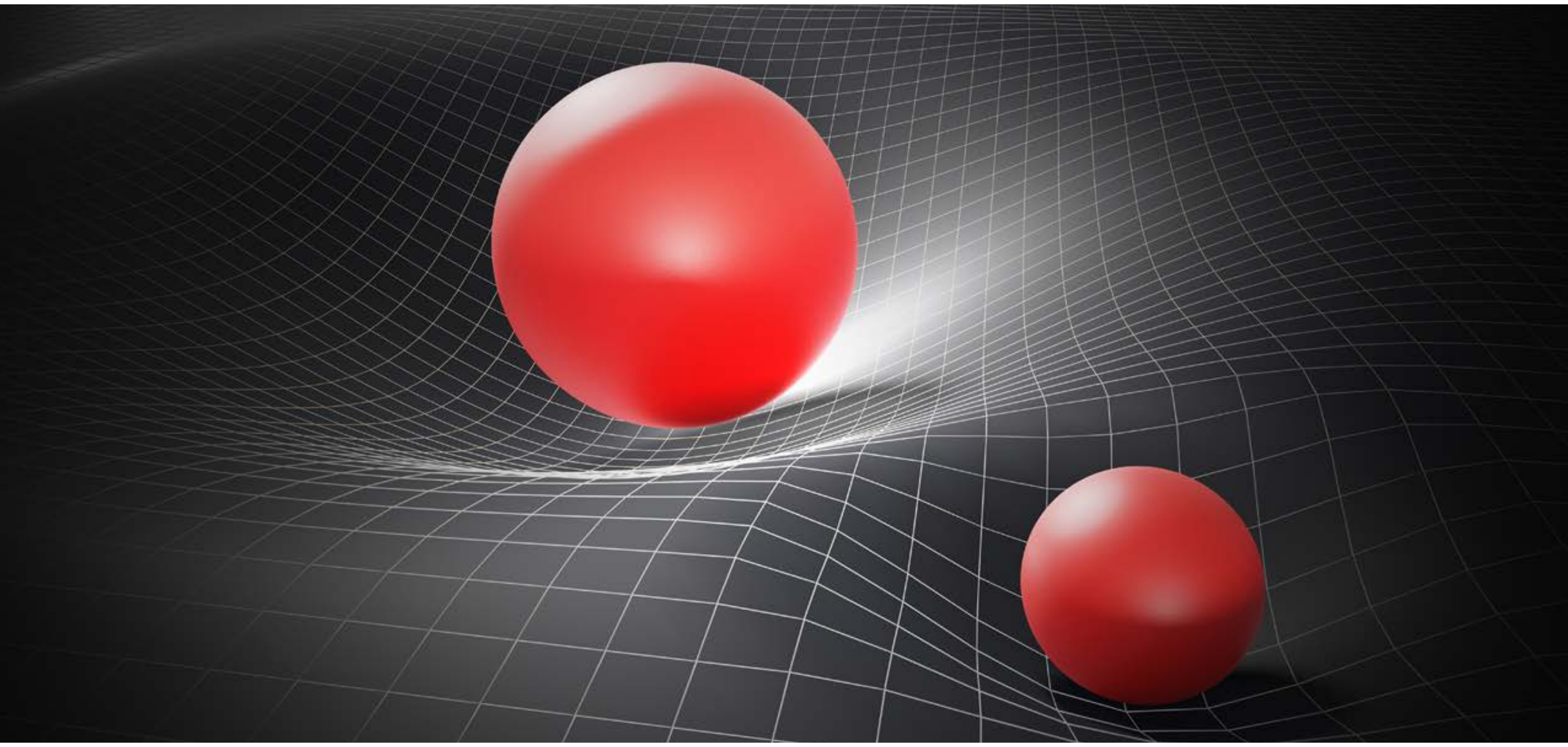
In nuclear physics domain we have studied the composition of dilute warm nuclear matter allowing for the Bose-Einstein condensation of alpha particles. We consider the cases of matter composed of light clusters with mass numbers A≤ 4 and matter that in addition to these clusters contains iron nuclei. In addition we have provided an educational review of the nuclear superfluids for the White Book of "NewCompStar" European COST Action MP1304 and a review on the properties of magnetars – strongly magnetized neutron stars and their superfluid and superconducting properties.

Dr. Armen Sedrakian

Dr. Armen Sedrakian, born in 1965, received his physics degree from the University of Rostock in 1989 and subsequently obtained his doctorate in Theoretical Physics at the Yerevan State University in Armenia in 1992. In 2002, after several post-doc positions around the world, he returned to Germany to work as a research associate and lecturer at the University of Tübingen, where he habilitated in 2006. Since 2007, he teaches at Goethe University at the Institute for Theoretical Physics and holds a professorship at the Department of Physics at the Yerevan State University in Armenia ,since 2011. Since January 1st 2017, he has the position of Fellow at FIAS.



Testing the hypothesis of hybrid stars against the data provided by GW170817 discovery of gravitational waves from the binary neutron star mergers. The axis contains the deforam-bility of the stars (effectively the amount by which they can deform each other by their gravitational fields from spherical shape). The lines show tracks predicted by purely nucleonic stars (solid lines) and quark matter featuring stars (dashed lines).



Group Information

At FIAS

since 2016; Fellow

Research Area

Covariant Hamiltonian Field Theory
Canonical Gauge Theory of Gravitation

Team

David Benisty
Dirk Kehm
Johannes Kirsch
Patrick Liebrich
Johannes Münch
David Vasak

Collaborations

Eduardo Guendelman, Ben-Gurion Univ.
Peter Hess, Univ. Nacional Autonoma

Jürgen Struckmeier

The action principle and the general principle of relativity is the basis of our successful derivation of a Palatini-type gauge theory of gravitation. Using canonical transformation theory ensures, by construction, that the form of the action functional is maintained and thus complies with the General Principle of Relativity. The resulting Hamiltonian system is form-invariant under arbitrary spacetime transformations, and describes both, the dynamics of matter fields and the dynamics of spacetime itself. This way, it is unambiguously determined how spin-0 and spin-1 fields couple to the dynamics of spacetime. Our results imply that Einstein's theory holds only for structureless (spin-0) and massless spin-1 particles. However, massive particles with spin are shown to couple to the torsion of spacetime. The proper source term for the spacetime dynamics is then given by the \emph{canonical} energy-momentum tensor – which embraces also the energy density furnished by the microscopic internal spin.

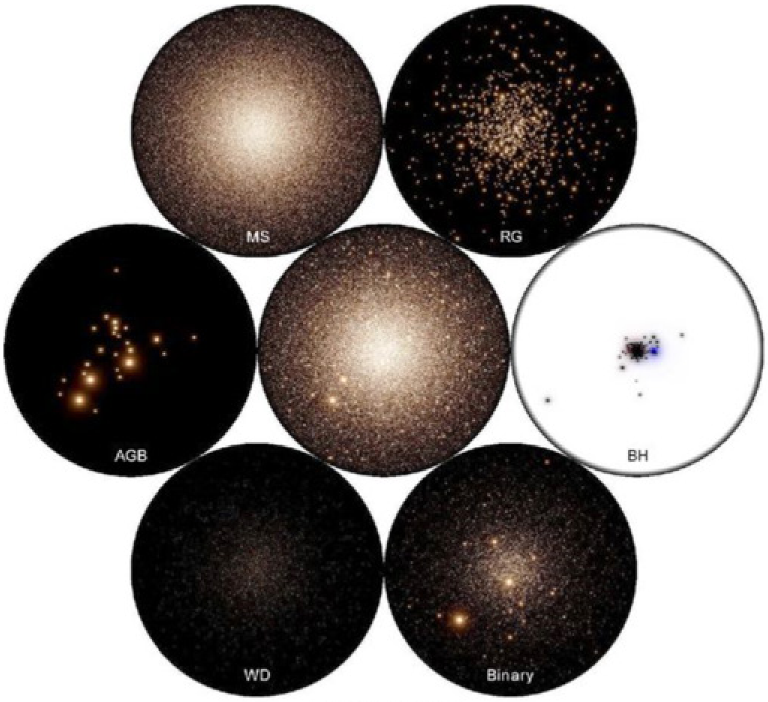
Moreover, the final, generally covariant Hamiltonian must contain a term quadratic in the conjugate momenta of the gauge fields, in order to yield a closed system of field equations --- in complete analogy to all other Hamiltonian descriptions of field theories. The canonical gauge theory of gravity derived here requires that both, quadratic curvature tensors and canonical energy momentum tensors, enter into the field equation for the spacetime dynamics. This leads to a qualitatively new framework for general relativity. The theory is published in Physical

Review D, 95, 124048 (2017). A subsequent paper has been submitted and a third one is actually being prepared for submission.

The Covariant Canonical Gauge Theory of Gravitation (CCGG) introduces an important feature into the theory of gravitation, and adds novel dynamic aspects into cosmology: Einstein's general theory of relativity contains only a linear term, the Ricci scalar, in the Lagrangian. Therefore, spacetime lacks in its description a conjugate momentum field, which is required to enable a dynamical response to deformations of the metric. This is different in the CCGG theory: spacetime itself has a conjugate momentum and thereby a proper dynamical quality of its own. The resulting "restraining force to maximum symmetry" is a reminiscent of a restoring force in analogy to that of a strained string. This changes the description of compact astrophysical objects and of relativistic collapse dynamics, with significant impact on the description of binary neutron star structure, mergers and pulsar dynamics. The CCGG theory developed here also entails important cosmological consequences. It can lead to a new understanding of Friedman cosmology and the cosmological constant problem. Modifications of the Friedman equation, for example, suggest a non-standard running cosmological constant and a new interpretation of Dark Energy, and hence change the standard evolution scenario of the universe. Presence of large curvatures may impact the theory of neutron stars and black holes, and modify the interpretation of gravitational waves. As the CCGG theory unambiguously determines the coupling of spacetime to matter fields, an inflation scenario based on a dynamic "quintessence" field can be implemented.

Prof. Dr. Jürgen Struckmeier

After having passed his physics diploma examination at the Goethe University Frankfurt in 1978, Jürgen Struckmeier got an appointment as staff scientist at the "Gesellschaft für Schwerionenforschung (GSI)" in Darmstadt, which lasted until 2017. Based on his scientific work there, he obtained his PhD in 1985. In 1995, Prof. Struckmeier received the "Particle Accelerator Conference Award" in Dallas (Texas): "For physical and mathematical description of emittance growth phenomena in intense beams". In 2002, his habilitation thesis was accepted at the Physics faculty of the Goethe University Frankfurt. Having worked as a lecturer, he was appointed there as "Extracurricular Professor", in 2010. In 2016, he joined FIAS as "Fellow".



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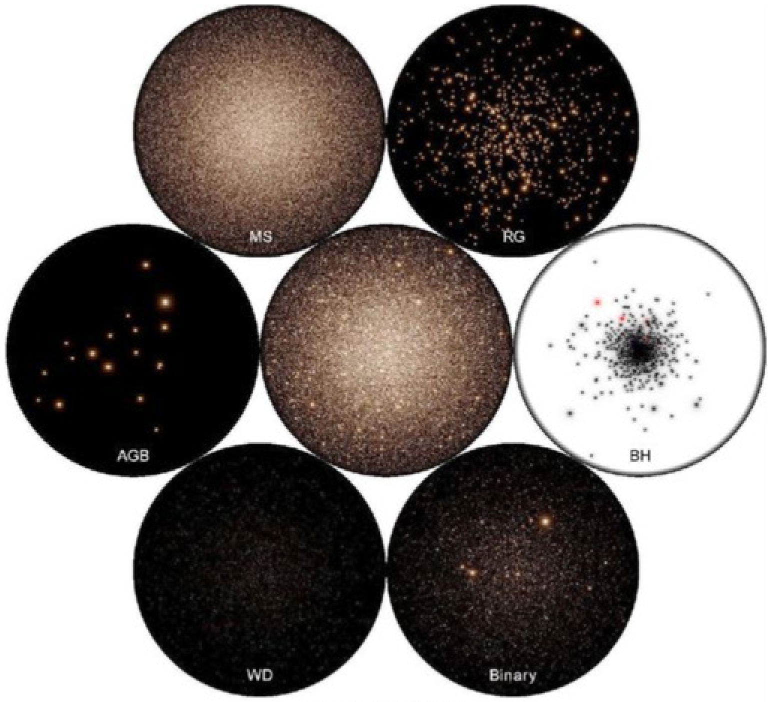

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Group Information

At FIAS

since 2017; Research Fellow

Research Area

Dynamics of Globular Clusters and Galactic Nuclei with Black Holes

Dynamical Evolution of Planetary Systems

Accelerated and Hybrid Parallel Supercomputing

Collaborations

Xian-Jiaotong-Liverpool University at Suzhou (XJTLU);
Fesenkov Astrophysical Observatory, Almaty
Main Astronomical Observatory NASU, Kiev
Max-Planck-Institut for Astrophysics, Garching
Dept. of Physics and Astronomy, Univ. of Rome La Sapienza

Rainer Spurzem

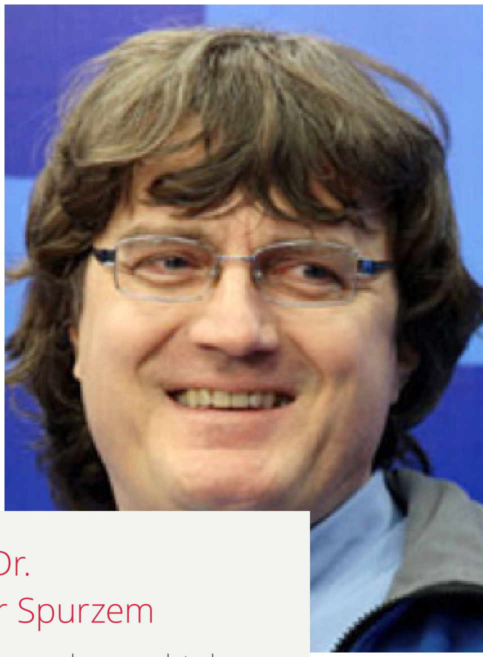
Research Topic 1: Globular Clusters

Globular Clusters are truly enigmatic objects. They are the densest and oldest gravitationally bound stellar systems in the universe consisting of hundreds of thousand luminous stars and their remnants confined to a few tens of parsecs. Their central star densities can reach a million times the stellar density near our sun. About 150 globular clusters orbit the Milky Way but more massive galaxies can have over 10,000 globular clusters. As their stars with various masses have mostly formed at the same time, globular clusters are ideal laboratories for stellar evolution studies. Also, the dynamical evolution of globular clusters is very complex. Unlike in galaxies the stellar densities are so high that stars can interact in close gravitational encounters or even physically collide with each other. The dynamical evolution produces close pairs of massive stars, binaries. The massive stars end their lifetime in a massive supernova explosion, after which only a compact remant remains – a neutron star or black hole. They are invisible for normal electromagnetic observations and, until recently, could only be detected indirectly. But recently gravitational wave emission has been detected from binary black hole coalescences by the LIGO ground based gravitational wave detector. Our Dragon star cluster simulations predict such binary black hole mergers in the supercomputer, as well as some of their key properties to compare with future observations. From our current models, we can already conclude that a globular cluster is a possible origin of some of the recently observed spectacular gravitational wave events (by LIGO).

1990 Japanese scientists proposed to build new supercomputers for the simulation of million-body globular star clusters within ten years (Nature article by D. Sugimoto in 1990). It took much more time, but with the use of the GPU accelerated supercomputer at National Astronomical Observatories at Chinese Academy of Sciences (NAOC) and in collaboration with Peking University and Max-Planck-Institute for Astrophysics in Germany we have succeeded by now. Current and future studies focus on more detailed prediction of gravitational radiation from our globular cluster models (especially in the low frequency range before the objects reach the LIGO band) as well as special electromagnetic sources (like neutron star mergers, white dwarf mergers, X-ray binaries and so-called cataclysmic variables) and on a better coverage of the global initial parameters of globular clusters (mass, density distribution, rotation, multiple stellar populations).

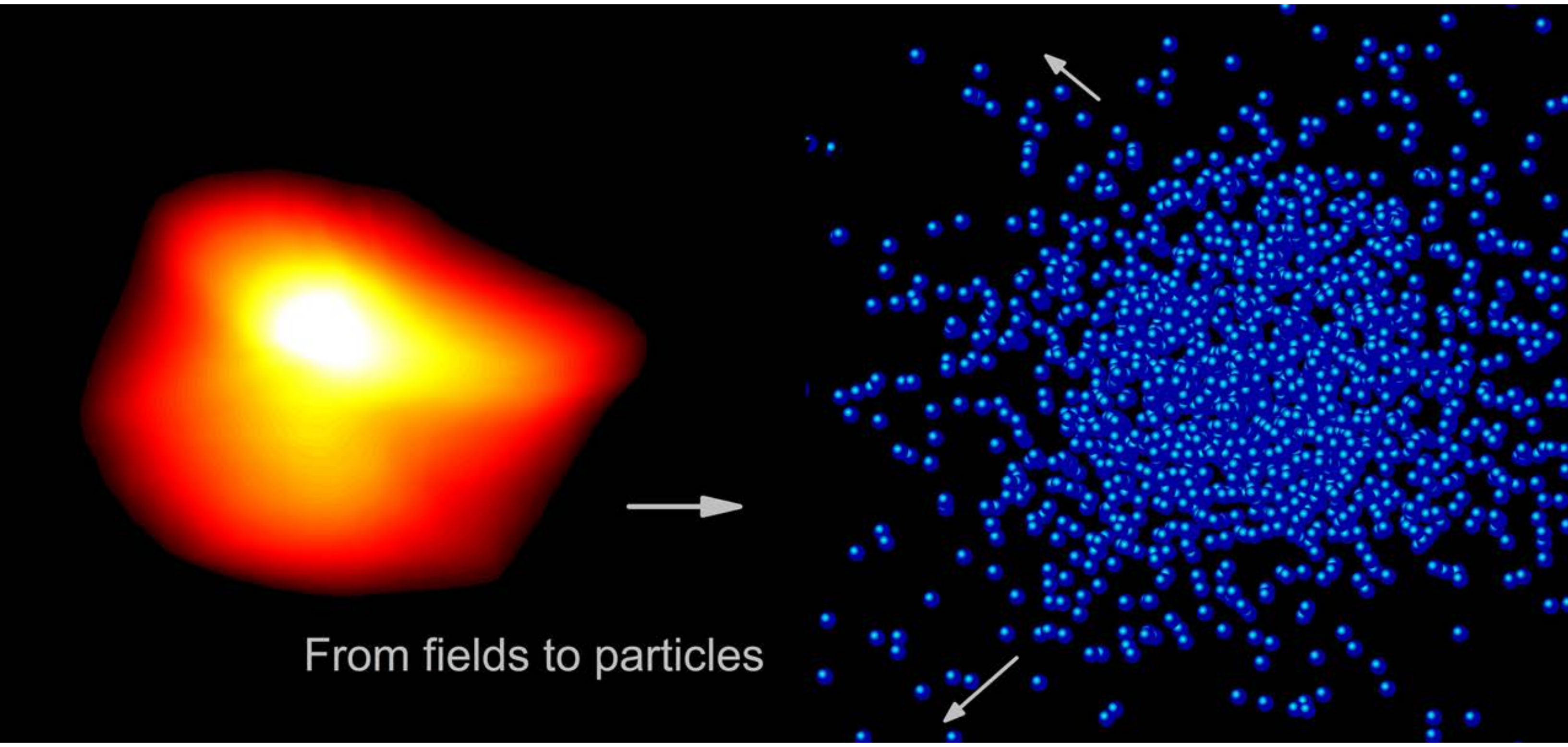
Research Topic 2: Galactic Nuclei

Our current best model of the universe predicts that galaxies form by merging from smaller structures to larger structures. Nearly all galaxies have central supermassive black holes (SMBH), which make up a certain fixed fraction of the mass of the central stellar system. What happens to the nuclei of the galaxies, their SMBH during and after merger? How does the SMBH interact with the central stellar system between the merging events? We have studied these processes in detailed computer simulations on our high performance GPU accelerated supercomputer LAOHU at NAOC. We found that in spherically symmetric nuclei semi-analytic models predicting an empty loss cone are a good approximation, but we also found that small amounts of rotation in the galactic nucleus will enhance the loss cone a lot, and also the corresponding black hole growth. We found that after a galactic merger a SMBH binary forms, with an orbital semi-major axis of about a milli-pc and high eccentricity. It is not long-lived as some people predicted, but will shrink and coalesce in astrophysically short time (few 100 Myr) under emission of strong gravitational waves in the low-frequency band (detectable by future planned space based gravitational wave detectors). We have published detailed evolutionary scenarios from the merger of the galaxies to the coalescence of the black holes, shown that it is a fast process and predicted the theoretical gravitational wave emission from these events. This work is in collaboration with the Institute of Space Technology in Islamabad, Pakistan, the Main Astronomical Observatory of the Ukrainian Academy of Sciences, the University of Heidelberg in Germany and the Swiss Polytechnical Institute (ETH) in Zurich. In current and future work we focus on the interaction of stars and compact objects (white dwarfs, neutron stars, stellar mass black holes, and binaries containing them) with SMBHs (single and binary). Tidal disruption of normal stars produces electromagnetic emission in the X-ray band with a characteristic light curve, while compact objects are accreted onto the SMBH under emission of gravitational waves.



Prof. Dr. Rainer Spurzem

Rainer Spurzem has completed his PhD at the University of Goettingen (Germany) in 1988 with a thesis on stellar systems around supermassive black holes. During the 90s he worked as a researcher and teaching assistant at the University of Kiel (Germany), bringing GRAPE special purpose computers for astro-physical N-body simulations to Europe. After postdocs and visiting fellowships in the UK, Japan and the US, he moved to the University of Heidelberg, Germany, in 1996, where he obtained an honorary professorship in 2003. He was awarded with the GRACE project grant funded by Volkswagen foundation in Germany, which designed the GRACE supercomputer (using GRAPE and FPGA). He is now leading the Silk Road Project as a professor of Chinese Academy of Sciences in Beijing, at the National Astronomical Observatories (while still part time also at the University of Heidelberg), where again large special purpose manycore clusters are built for astrophysical research. His astrophysical research is focused on dynamics of star clusters, galaxies and galactic nuclei, with black holes.



Group Information

At FIAS
since 2017, Research Fellow

Research Area
Physics
Machine learning

Collaborations
Prof. Dr. Jörg Aichelin, CNRS, Univ. de Nantes

Jan Steinheimer-Froschauer

In high energy physics, the collision products of two colliding heavy ions (such as gold or lead) are used to investigate the properties of matter at the highest temperatures possible. At the LHC at CERN, lead nuclei are brought to collisions at speeds that are very close to the speed of light. The product of this collision is a fireball in which the fundamental constituents if matter, the quarks and gluons, are liberated.

To extract the properties of this fundamental form of matter, the so-called quark gluon plasma (QGP), one resorts to fluid dynamical simulations of the hot expansion stage. The important properties of matter, the equation of state and other transport parameters as well as correlations from interactions are then encoded in the fluid dynamical simulation.

Since the fireball is expanding with a large velocity and its size is comparable to a nucleus, it will decouple at a very called time. This process, called freeze-out, describes the transition from a system which is strongly coupled (fluid dynamics) to a system of free streaming particles, ending up in the detector (see also figure 1).

Many models assume that this freeze-out process happens instantaneous and very close to the transition from the QGP to normal „hadronic" matter, therefore the properties of the system of quarks and gluons could be directly measured with the experimental detectors.

In our work [1,2] we used a well-tested fluid dynamical model for the description of heavy ion collisions at the LHC. Instead of assuming an instantaneous freeze-out, we employ the microscopic transport model UrQMD to describe the interactions of hadrons in the late stage of the collision.

We found that the system does not freezes-out instantly after hadronization, but undergoes a lengthy non-equilibrium rescattering phase. The duration of this phase is comparable to the fluid dynamical evolution of the dense QGP. In figure 2 we show the actual last interaction points of pion particles from this hadronic rescattering.

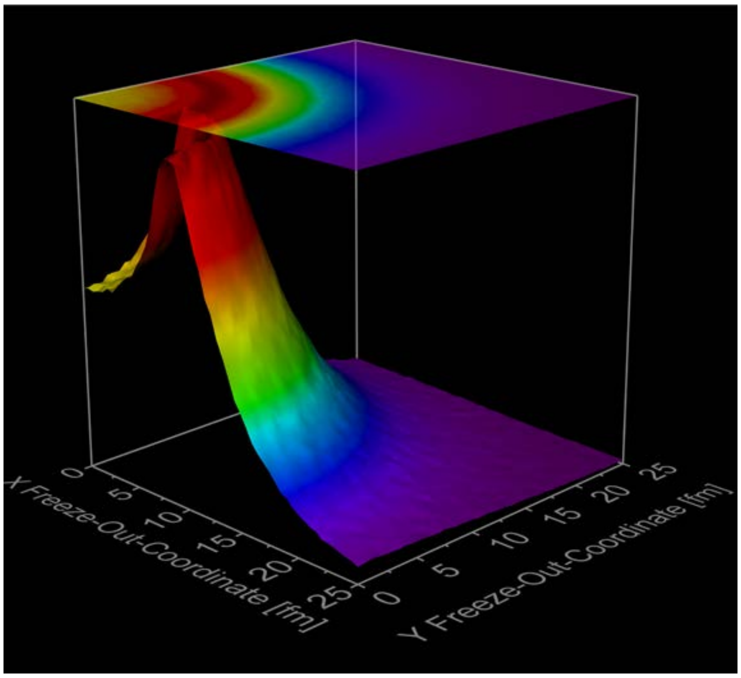
We were able to identify several observables which prove the existence of this rescattering phase, most noteworthy the measured multiplicities of short lived resonance particles. Furthermore we found that essentially every observable of heavy ion collision experiments will change during this hadronic rescattering.

Our observations show that the experimental results cannot assert, or be directly compared to the properties of the system at a conjectured hadronization or chemical freeze-out point.

This makes the microscopic treatment of the final stage of heavy ion collisions mandatory which has now become the state-of-the-art of the field.

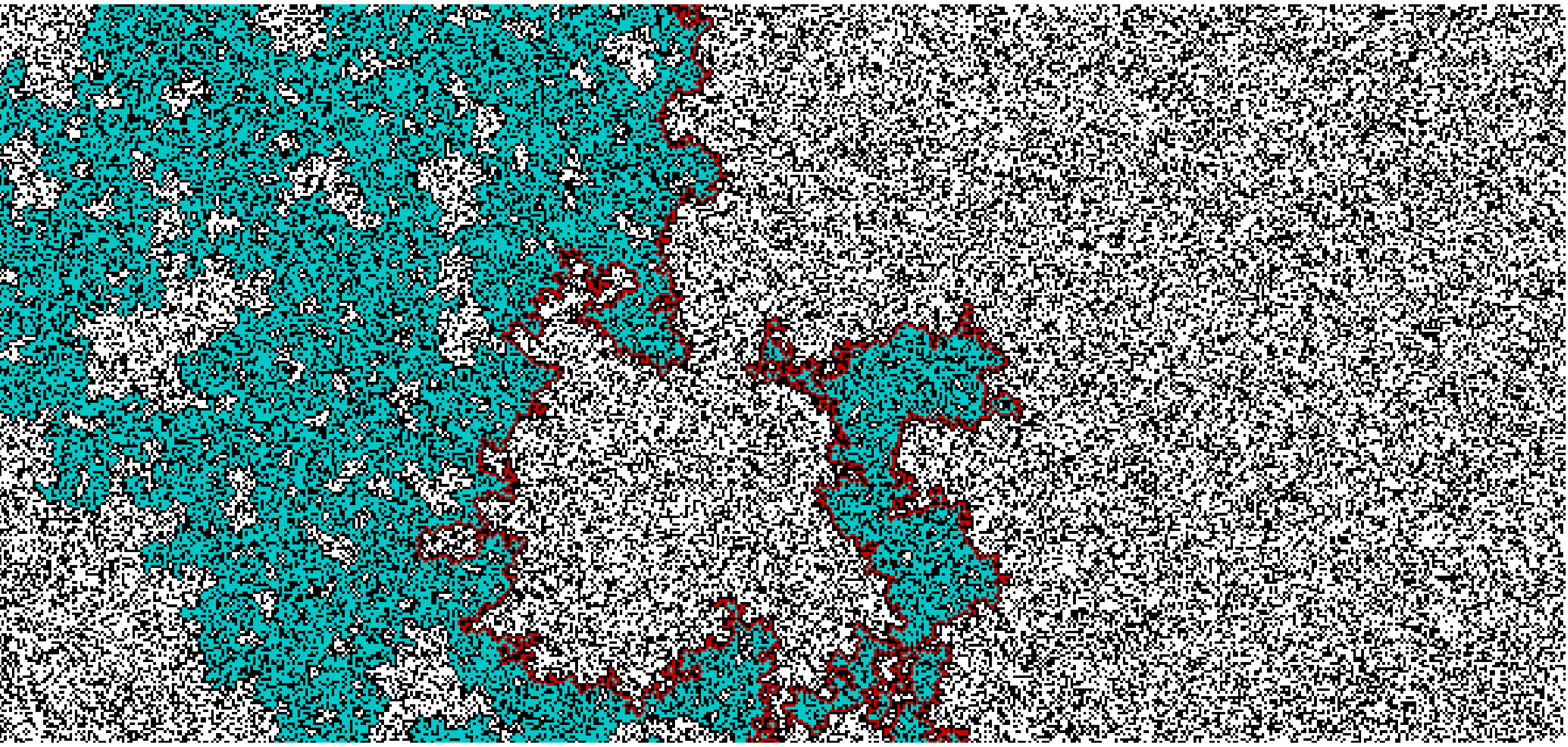
Dr. Jan Steinheimer-Froschauer

Dr. Jan Steinheimer-Froschauer is a research fellow at FIAS since 2017. His main areas of research are high energy physics and machine learning. In 2008 he obtained his Diplom in Physics at the Goethe University in Frankfurt am Main. After a short time at the FIAS he was awarded a Feodor-Lynen research grant to the Lawrence-Berkeley-National-Laboratory in the US. He returned to FIAS in the year 2013 as a Postdoc where he focused his research on the physics of high energy heavy ion collisions, and since 2017 also on the applications of machine learning methods in physics and related areas.



The spatial distribution of pions and their last point of interaction in the transverse plane of a heavy ion collision at the LHC.

[1] J. Steinheimer, J. Aichelin, M. Bleicher and H. Stöcker, Phys. Rev. C 5, no. 6, 064902 (2017)
[2] J. Steinheimer, V. Vovchenko, J. Aichelin, M. Bleicher and H. Stöcker, Phys. Lett. B 776, 32 (2018)



Group Information

At FIAS
since 2017, Research Fellow

Research Area
High energy physics
Complex networks
Machine learning

Collaborations
Prof. Dr. Xiao-Song Chen,
Chinese Academy of Sciences
Mr. Gao-Ke Hu,
Chinese Academy of Sciences
Dr. Konrad Tywoniuk,
CERN
Dr. Andreas Windisch,
St. Louis

Nan Su

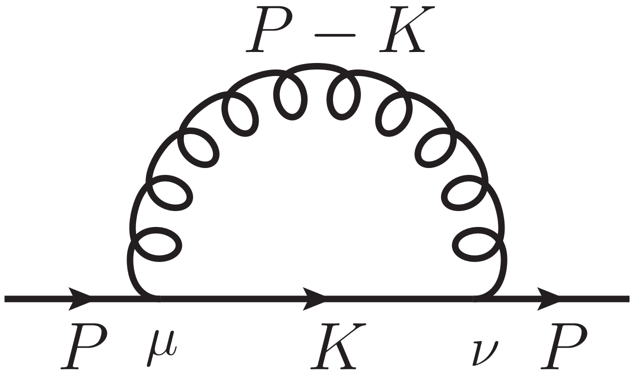
Since the start of the Research Fellow position at the Frankfurt Institute for Advanced Studies in August 2017, my research has been mainly focusing on the following two themes. Firstly, I am continuing my research on theoretical high energy physics, more specifically I am studying the behaviors of quantum chromodynamics (QCD) matter under extreme conditions (e.g., at astronomically high temperatures) utilizing thermal quantum field theory. Secondly, I have been expanding my research activities to the area of machine learning with artificial neural networks since recent years, and I am particularly interested in understanding artificial neural networks from the perspectives of statistical physics and critical phenomena. In the following, I briefly summarized the activities of both themes.

The strongly coupled QCD matter created in ultra-relativistic heavy-ion collisions, which rules out all the theoretical predictions for a weakly coupled one, represents one of the most challenging open questions in fundamental physics. A crucial missing ingredient in the conventional approaches to QCD matter is long-range correlations which would render the system strongly coupled. By generalizing the Gribov-Zwanziger quantization — originally developed for studying color confinement of QCD in the vacuum — to finite temperature, we uncovered a novel massless collective excitation of thermal QCD responsible for inducing long-range correlations in the system [N. Su and K. Tywoniuk, Phys. Rev. Lett. 114, 161601 (2015)]. This mode induces positivity violation in the spectral function that shows a genuine non-Abelian feature. Based on this, we have moved on to carry out a systematic analysis of the spectral function and its associated features. This will unveil more details on the generation of the strongly coupled nature of the QCD matter from the fundamental theory.

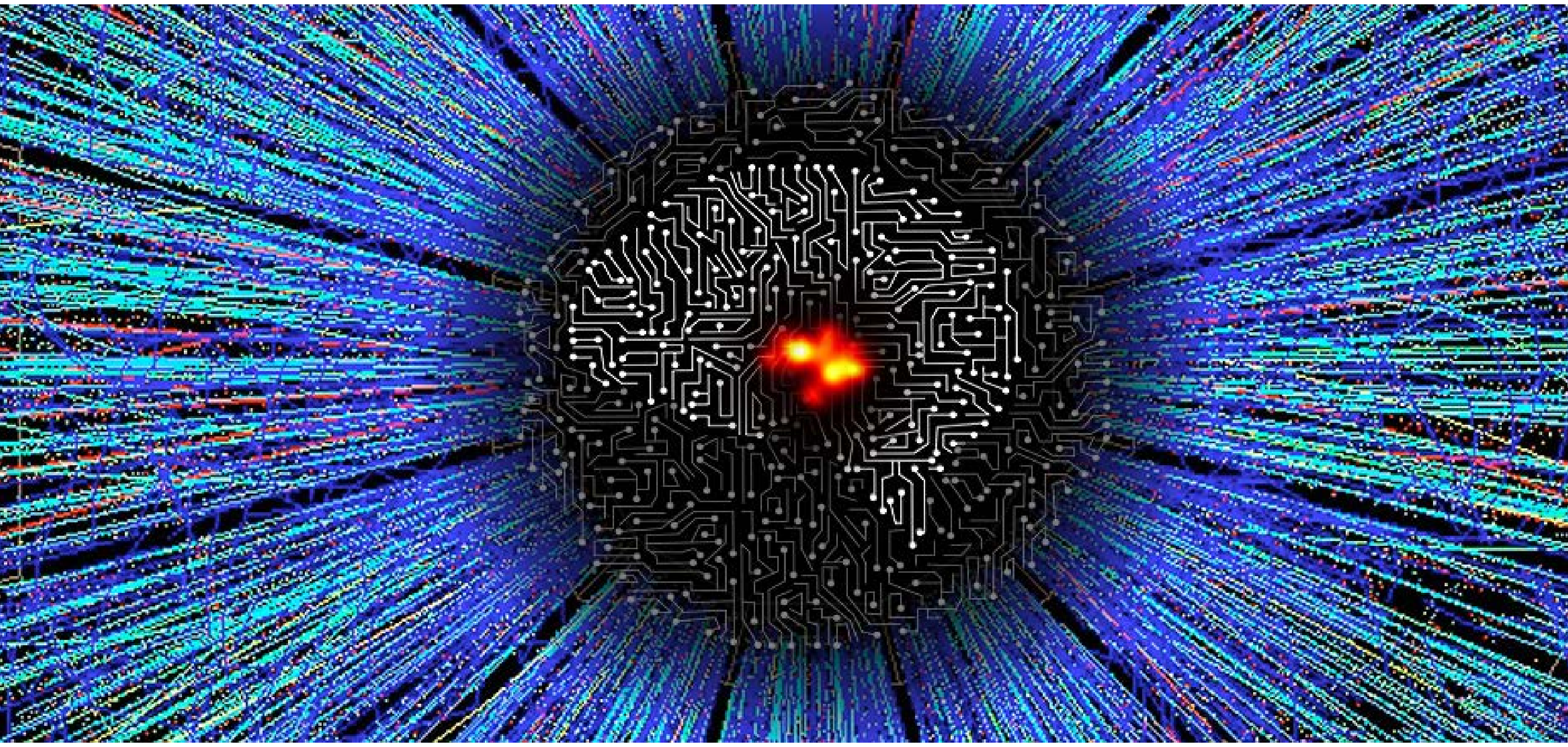
Machine learning based on artificial neural networks has been under rapid development in recent years. There have been novel applications of artificial neural networks in various areas, e.g., science, engineering, medicine, and so on. However we still have a limited understanding about it at a fundamental level. Complex networks play a prominent role in studying a broad range of systems across disciplines, such as the World Wide Web and disease spreading (epidemiology). Due to their simplicity and accessibility, they provide a straightforward test-bench to study the possible mechanisms of artificial neural networks. In this light, we have been carrying out systematic machine learning studies of the percolation transitions of various complex network models. The results may lead to a better understanding of the reasons why artificial neural networks work as they do.

Dr. Nan Su

Dr. Nan Su did his first study in polymer engineering at the University of Science and Technology of China. Afterwards, he moved to Europe and obtained firstly a Master in theoretical physics at Utrecht University, the Netherlands, then a Doctorate in theoretical physics at Goethe University Frankfurt, Germany. He was a Yggdrasil Visiting Scholar at the Norwegian University of Science and Technology, and a Humboldt Fellow at Bielefeld University. He has been a Research Fellow at the Frankfurt Institute for Advanced Studies since August 2017.



Feynman diagram of the leading-order quark self-energy



Group Information

At FIAS
since 2017, Research Fellow

Research Area
Theoretical Physics
Heavy-Ion Collisions
Machine Learning/Deep Learning

Team
Dr.Lijia Jiang
Yi-Lun Du

Collaborations
XinNian Wang, Berkeley & Wuhan
Long-Gang Pang, Berkeley,
Carsten Greiner, GU
Moritz Greif, GU
Gergely Endrődi, GU
Bao-yi Chen, GU and Ti'jin
Zhe Xu, Tsinghua, Beijing
Pengfei Zhuang, Tsinghua, Beijing

Kai Zhou

As a newly constructed group, we mainly focus on interdisciplinary research of artificial intelligence, especially machine learning and deep learning application in physics and industrial problems. Deep learning is a branch of machine learning aiming at understanding big data with high-level of abstraction and is effective in tackling complex non-linear systems with correlations going beyond conventional techniques' exploration. The defeat of the Go human world champion by the deep learning trained computer program AlphaGo developed by Google DeepMind in 2016 have brought out this novel technology to a broader audience, especially due to the fact that winning human in the chess game of Go was considered nearly mission impossible with conventional artificial intelligence methods.

In 2017, our group at FIAS devoted a new method using this deep learning technique to construct an equation-of-state (EoS) meter to better understand QCD matter created from heavy-ion collisions. We showed that for the complex hydro evolution which is mimicking the heavy-ion collisions, even though there are many different physical factors and parameters involved would kinkily influence the final emitted partial spectra and thus hinder a conventional analysis of pinning down the phase structure or transition information during the collision, the deep convolutional neural network (CNN) is capable of disentangling the hidden correlations and find direct efficient mapping from the output particle spectra to phase transition information embedded in the evolution. This thus provides us an useful tool to unveil hidden knowledge from the highly implicit data of heavy-ion experiments. The work has been accepted to publish in Nature Communications later last year and online in January this year. (https://www.nature.com/articles/s41467-017-02726-3, DOI : 10.1038/s41467-017-02726-3)

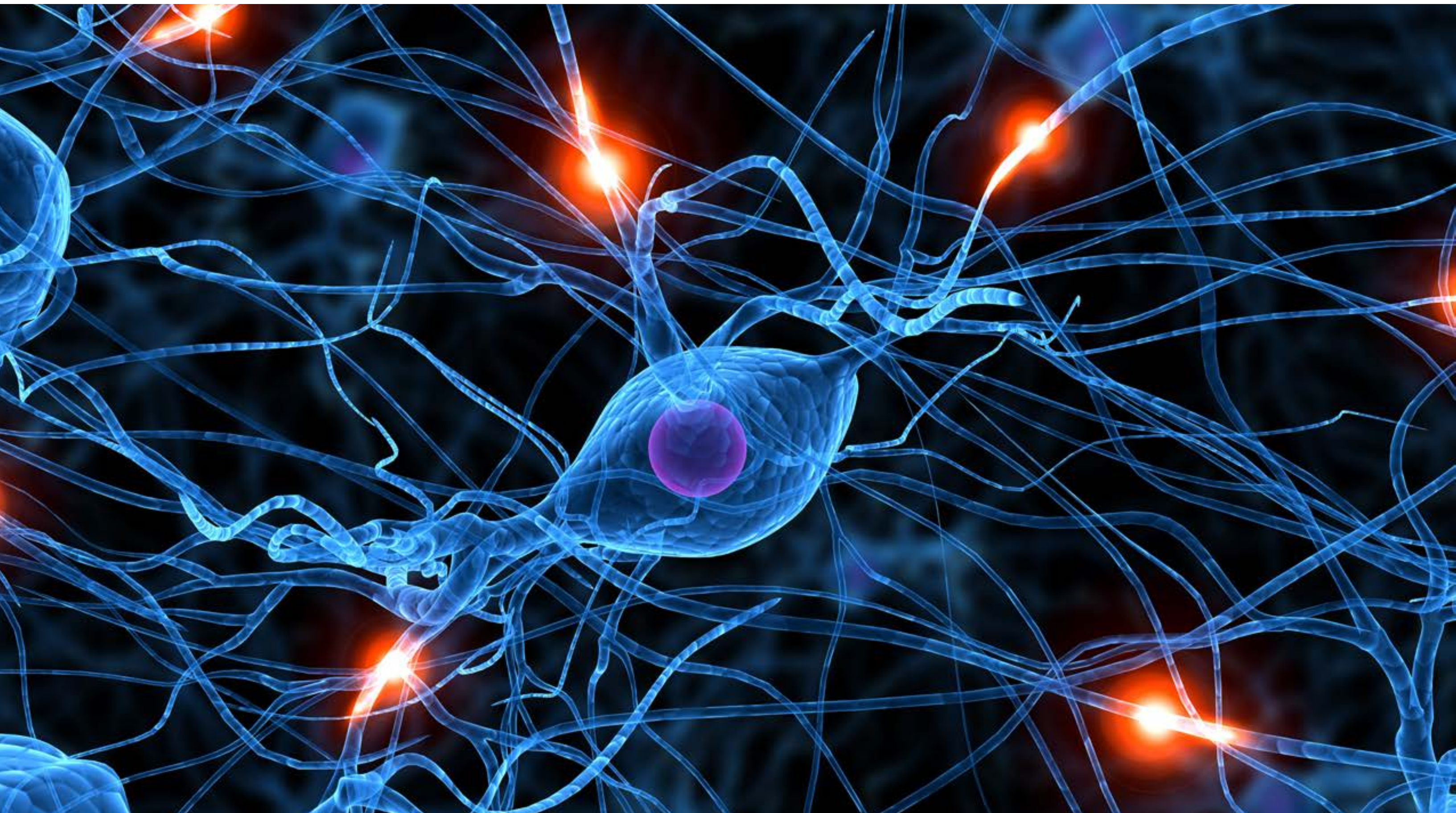
We also made close collaboration with Samson AG in Frankfurt which is with renown in valve manufacturing. Under the same spirit in pursuing the Industrial 4.0 academically, we conducted 'Smart Valve' project which aims at giving normal valve the ability to talk to outside and communicate with each other. In the first step, with close collaboration with the new innovation center at Samson AG, the acoustic signal is recorded with different physical processing parameters and valve states, then we use deep learning to construct a 'brain' for the valve based on the sound signals to tell if there's leakage for the valve, to estimate the flow rate being inside and also the pressure ratio, to detect cavitation/turbulent flow state. This technique would save a lot of manpower and help doing anomaly detection and safety insuring for valve/pipe system like underground or large-scale industrial devise.

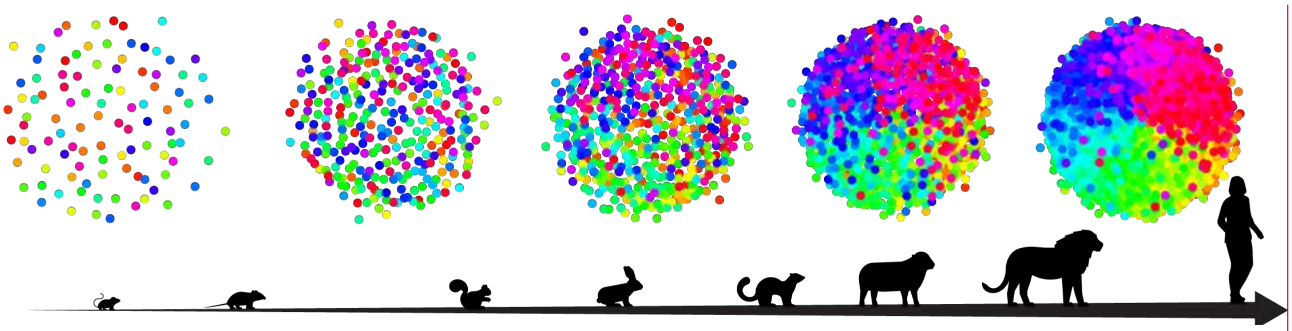
As an application study of deep learning in theoretical physics, we studied neural network regressor and classifier for complex scalar field configurations together with Gergely Endrodi from ITP. In particular, we sucessfully showed the deep convolutional neural network has the ability to recognise phase transition and evaluate physical observable based solely on the raw configuration on a broad range of temperatures, chemical potentials, masses and self-couplings. Most strikingly, with training on limited chemical potential's configurations the algorithm can find the correct way to extend to other unseen chemical potentials for the physical observable evaluation.We further explored the Generative Advaersarial Network (GAN) method to generate new configurations which can bypass the conventional Markov-Chain Monte Carlo process and thus faster and memory light.

Dr. Kai Zhou

Dr. Kai Zhou was born on 1st October 1987 in China. He received the BSc degree in Physics from Xi'an Jiaotong University, in 2009, and his PhD degree in Physics with 'Wu You Xun' Honors from Tsinghua University, in 2014. Afterwards he went to Goethe University Frankfurt to do postdoctoral research work at the Institute for Theoretical Physics (ITP) . Since August 2017, he is a FIAS Research Fellow focusing on Deep Learning (DL) application research, and guides the 'Deepthinkers' group at FIAS as their group leader. Dr. Zhou has a very broad interest in physics and AI/DL application in different fields. Recently with his collaborators he developed a deep learning based strategy to help efficiently extracting essential properties of the very involved dynamical evolution from only final observation, they applied it in Heavy Ion Collisions to construct an Equation-Of-State (EOS) meter which is an ultimate goal for the experiments efforts.

Neuroscience





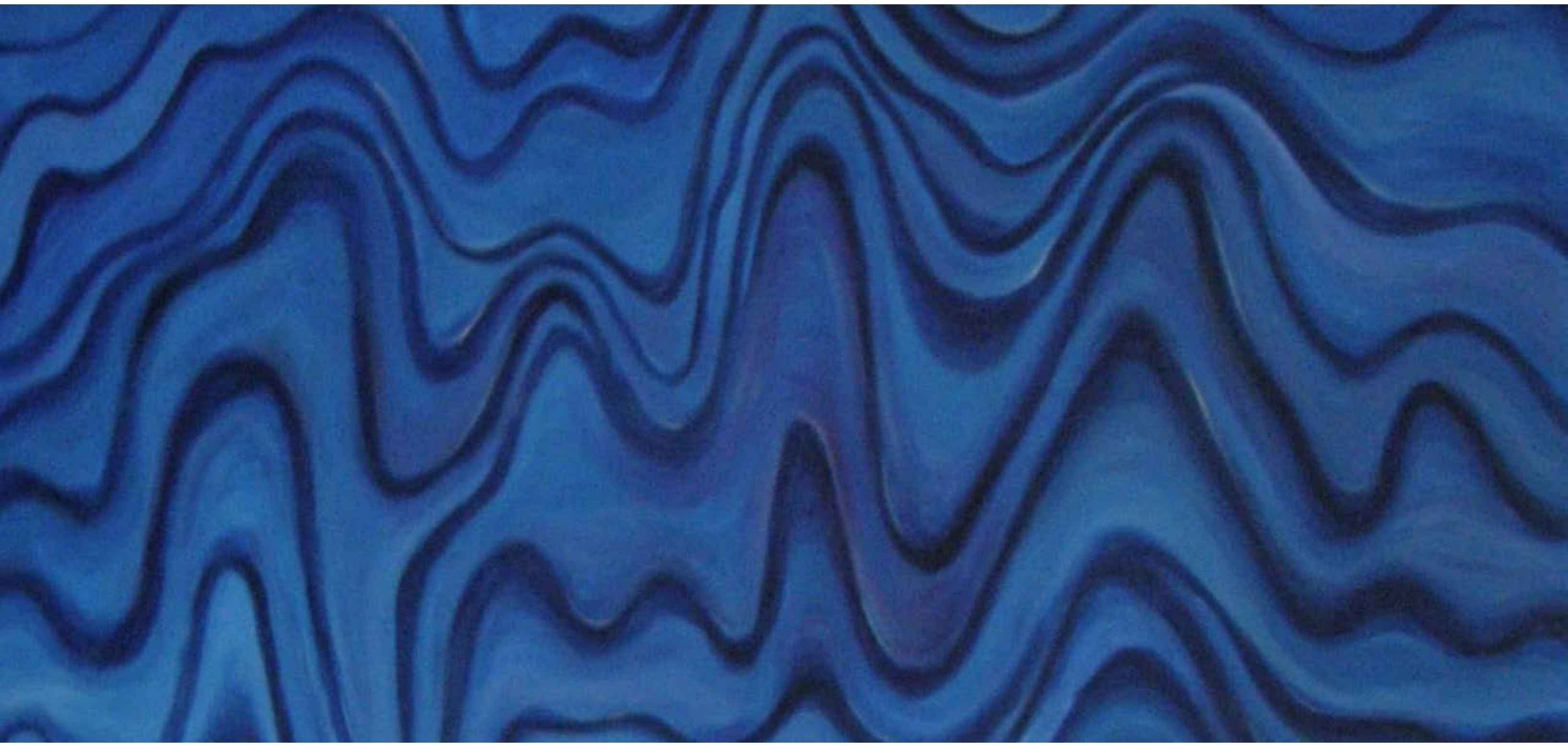
Harmony in Numbers:

The human brain consists of a highly complex network of approximately 85 billion nerve cells (neurons), which continually exchange information with each other. In order for this complex network to function efficiently, it is important that the distances between neurons encoding similar properties remain relatively short. In the human visual system and in that of many mammals, the neurons that respond to objects with similar orientation are indeed located near each other. Interestingly, such an ordered structure cannot be found in rodents. Researchers from the Frankfurt Institute for Advanced Studies, the Max-Planck-Institute for Brain Research and the Ernst-Strüngmann Institute for Neuroscience have studied why such differences between the animal species exist – using two different computer models. Unexpectedly, the researchers found that the existence of this ordered structure is not only determined by the connectivity in the circuit, but also by the total number of neurons. In 2017 the findings of Research Fellow Hermann Cuntz and his colleauges were published in the scientific journal PNAS.

The brain is considered the most complex structure on earth. It is composed of a network of billions of nerve cells. Our goal is to understand how cognitive phenomena can arise from the collective interactions of these many neural elements. We firmly believe that by studying the organizational principles of neural information processing through computational modelling, we can further our understanding of brain function and organization and also make progress towards building a new generation of intelligent artificial information processing systems with potentially profound social and economic implications.

In particular, we investigate how the brain's networks and subsystems can self-organize their information processing capacity to give rise to perception and action. Most of our research focuses on:

- the mathematical analysis of high-dimensional spatio-temporal activity patterns that emerge in defined neuronal networks of animal and human brains during cognitive and executive functions and are provided by the associated experimental institutions,
- the simulation of biologically inspired neuronal networks and
- the implementation of insights gained into mechanisms underlying visual perception, action, and learning in robotic systems.



Group Information

At FIAS
since 2017, Research Fellow

Research Area
Computational
Neuroscience

Collaborations
Prof. Schuman, MPI Brain
Prof. Busse, LMU
Prof. Bittner, Univ. Mainz

Tatjana Tchumatchenko

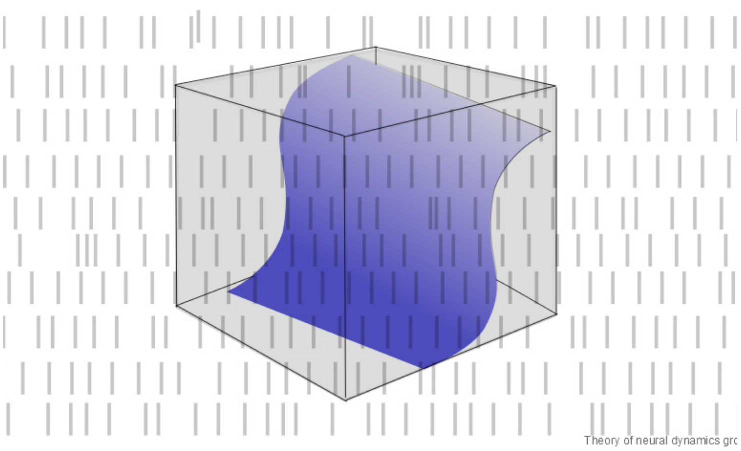
Since 2013, I am the leader of the Theory of Neural Dynamics group at the Max Planck Institute for Brain Research. Since 2017, I am also a FIAS fellow. My team and I have primarily focused on understanding of how neurons process sensory information.

Neurons communicate with each other via spikes, which are stereotypic voltage pulses with fixed amplitude and shape. A single neuron can send spikes along its axon to tens of thousands of neurons. It is currently understood that complex cognitive phenomena like decision-making, attention and emotions emerge from the dynamical interactions between spiking neurons in neuronal network. To better understand neural network dynamics and how it relates to cognition, my group's core aim has been to reduce the complexity of neuronal network by developing an abstract model of a network of neurons and thus making it controllable in computer simulations and accessible for mathematical analysis. Therefore, we have modeled the neurons via interacting point objects that can be excitatory or inhibitory. Only the unique synaptic connectivity of the network, the properties of single neurons, and the external input (stimulus) then define the tasks the neural network can solve. In some instances, the synaptic connectivity can be plastic, because synapses may change their transmission probability depending on past spiking events. Augmenting network models with so-called short term or long-term plasticity, we are able to explain changes in global brain activity and understand learning on timescales of milliseconds up to minutes.

In addition, we have investigated how much information is encoded in the spike response of a neural network about a given input stimulus. We addressed this with information theoretic methods, a field developed by the physicist Claude E. Shannon in 1948. In particular, our major interest has been the understanding how the information depends on the pairwise and higher order correlations between neurons and the statistical properties of the stimulus. In our research, we have tried to understand how synaptic connections can optimize their synergy, meaning that the network response contains more information than the sum of its constituents.

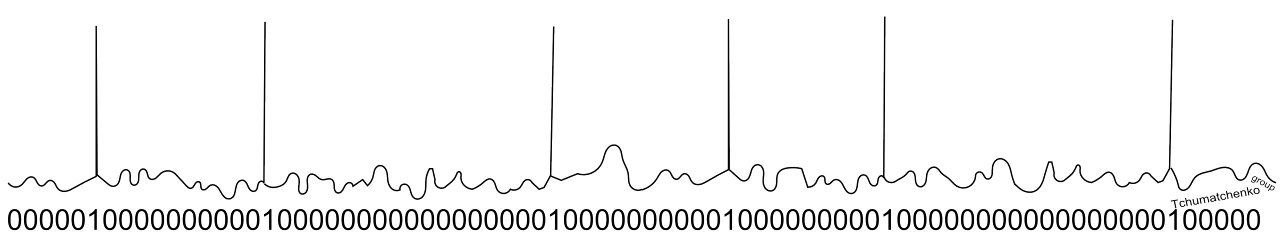
Furthermore, by undertaking joint projects with experimental neuroscience research groups, we have strived to build tractable mathematical models that emulate the recorded spiking activity and subcellular dynamics. One example is an experimental setting where neurons in the brain of a living animal are genetically modified and optically stimulated. Hereby, we have modeled the correlations between the stimulus and the activity of certain neurons.

Over the years, we have emphasized the importance of verifying the results of computational and analytical studies in experiments by always seeking for collaborations with competent experimental colleagues. The MPIBR and FIAS have served as ideal places to pursue this, as it offers us the opportunity to closely interact with some of the worlds most accomplished experimental neuroscientists.



Dr. Tatjana Tchumatchenko

Dr. Tatjana Tchumatchenko is a theoretical neuroscientist whose research focuses on modelling signal processing, synaptic, and subcellular dynamics in biological circuits. After receiving her PhD in Computational Neuroscience from the Göttingen Graduate School for Neurosciences, Biophysics, and Molecular Biosciences (Göttingen University, 2010), she completed a postdoctoral fellowship at the Center for Theoretical Neuroscience (Columbia University, 2011-2013) which was funded by the Volkswagen Computational Sciences fellowship (2011). As of 2013, Dr. Tchumatchenko is a Group Leader at the MPI for Brain Research and she became a FIAS fellow in 2017.



Group Information

At FIAS
since 2010, Research Fellow

Research Area
Computational
Neuroscience

Team
Sebastian Blaes
Alexandros Bouras

Collaborations
Peter de Weerd,
Maastricht University
Ronald Westra,
Maastricht University

Thomas Burwick

The research mission of our group is, on one hand, to analyze and understand the workings of the brain with respect to intelligent information processing and, on the other hand, to use this knowledge for making machines more intelligent.

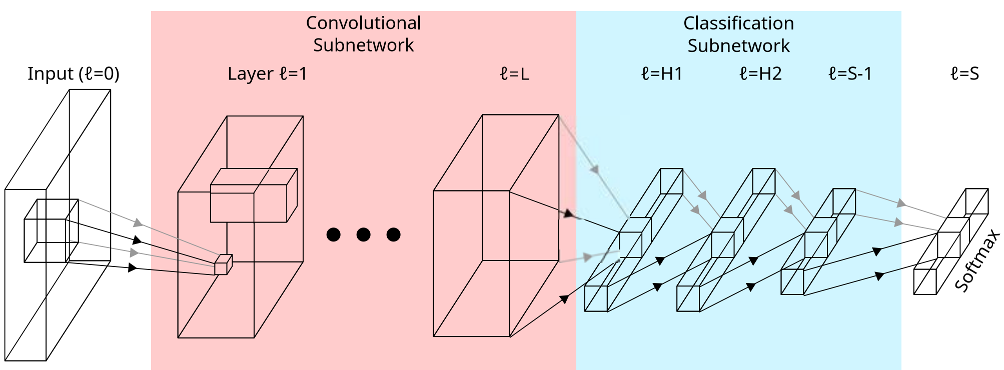
With respect to brain dynamics, we have studied the role of cortical oscillations for the processing of information through the cortex. We took a particularly close look at the microcircuits that connect excitatory and inhibitory neurons and found conditions for gating the information flow based on the attentional context. In particular, we studied the role of frequencies for this attentional gating. As a result, we found that slightly higher frequencies of the sending sites trigger the choice for the attended location or feature by inducing an earlier inhibitory signal in the receiving site which blocks the influence of distractors. In the brain, bottom-up and top-down information flows are different modes of operation. We found that frequencies may trigger the direction of the information flow in favor of the bottom-up or the top-down direction by using a slightly higher frequency of the relevant sending sites and blocking the unwanted direction of flow through inducing the inhibitory oscillatory signals. Our results refer to experimental neurophysiological observations made by Bosman et al. (2012). These confirm a proposal given by Pascal Fries, (2005, 2015), the so-called Communication-Through-Coherence (CTC) hypothesis.

With respect to applications of neural processing in the context of machine learning, we have followed research activity on one of the most relevant open questions: the challenge of learning object categories from only few example. A neural network type which has recently received a lot of attention and which has led to a number of breakthrough discoveries is the Convolutional Neural Network (CNN). This type of networks is inspired, in particular, by the hierarchical architecture of the brains' visual system, beginning with the input to the primary visual cortex and gradually expanding receptive fields as the signals are processed to successive stage of neural units in higher-level visual areas. The drawback of the CNN gradient descent supervised learning of object categories is the necessity of using many (thousands) of examples for the different categories. In contrast, humans are able to learn new categories from only very few examples, occasionally only one. We succeeded in proposing and specifying a new machine learning method which learns new objects categories from only few, sometimes only one example and performs surprisingly well for then correctly categorizing a large portion of object categories. We refer to this method as "Global Prototype Learning" (GPL). It is a generalization and adaption of prototype learning methods which were developed for vector quantization: one or a few input examples for the new object category are used to construct a prototype for the general object class.

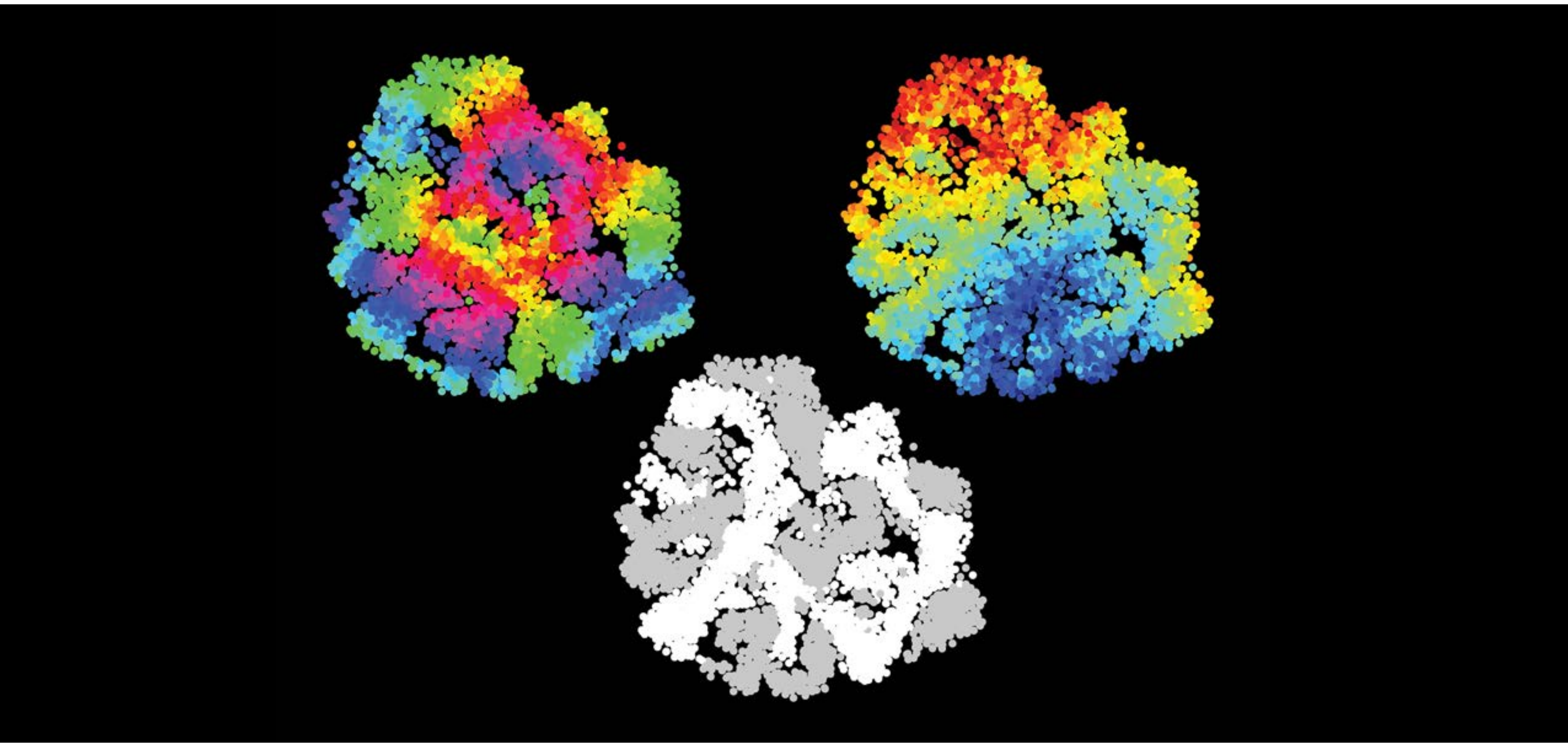
A widely-used model for the study of oscillatory networks is the Kuramoto-model. In its original form, however, it lacks essential properties of what constitutes oscillatory processes in the neural networks of the brain. In a collaboration with the Maastricht University, The Netherlands, we therefore studied extensions of Kuramoto-models that include two properties found in the neurobiological context: Hebbian learning of the weights of the networks and time delays for the signals between the units of the network. We found interesting properties that indicate a development of the networks through the learning process towards so-called small-world network structures.

PD Dr. Thomas Burwick

Thomas Burwick studied mathematics and physics at the ETH Zurich, Switzerland, and at the Université de Paris VI, France. He received his PhD in theoretical physics from the University of Zurich, Switzerland. Subsequently, he was a postdoctoral fellow, working at Stanford University, California, USA. In 1999, he co-founded a software company. In 2012, he has been awarded the German qualification for Professorship (Habilitation) in Theoretical Physics at the Goethe University Frankfurt. He is a Research Fellow at FIAS.



Architecture of the deep neural network that we used for few-shot learning of new categories



Group Information

At FIAS

since 2014, Research Fellow

Research Area

Network modelling
Biophysically realistic models of single cells
Neuroanatomy models

Team

Dr. Felix Effenberger
Dr. Alexander Bird
Dr. Marcel Beining
Marvin Weigand
André Casto
Alexandra Vormberg
Lisa Deters
Adonay Gebrehiwot
Marius Schneider
Moritz Groden

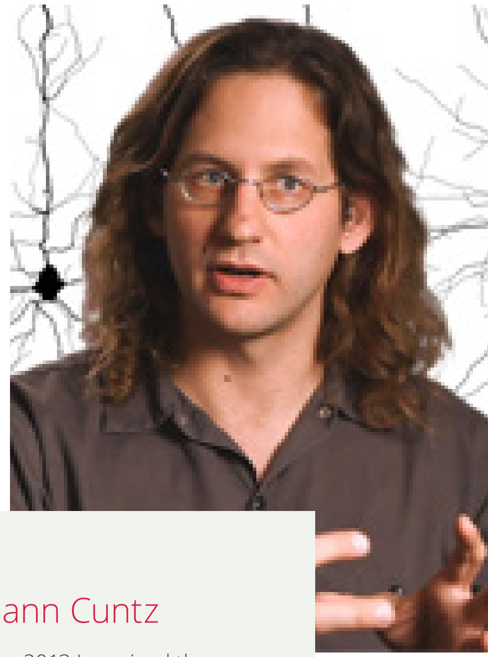
Collaborations

Peter Jedlicka
Gaia Tavosanis
Stephan Schwarzacher
Thomas Deller

Hermann Cuntz

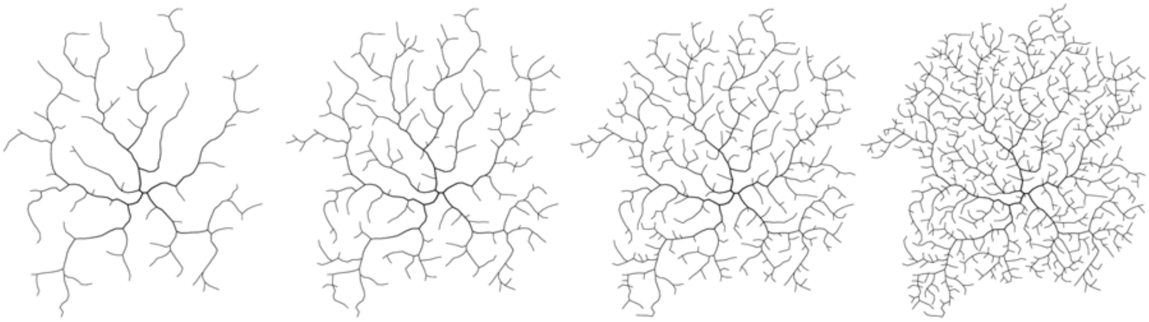
We use generative models based on simple optimisation criteria to predict neuroanatomical structures at various scales. For example, we can predict the branching structures of neuronal dendrites and axons from wiring constraints assuming that neurons minimize conduction times and total amount of material to collect their inputs from other cells. Also, dendritic branch diameters taper toward the tips to optimise the current transfer from distal synapses to the signal summation point in the soma. In a novel complementary approach we can predict neural placement on the premise that neurons with similar connectivity structure should be located near each other to minimize wiring length.

In 2017 we made some significant scientific advances in our understanding of neuronal self-organisation. Alexander Bird dissected the most widely used metric for dendritic branching statistics, the Sholl intersection diagram that measures the number of intersections of a tree with a ball centred on the root of the tree for increasing ball radii (1). He found that it subdivides into a one-dimensional representation of a dendrite's domain, its total length and a new metric the root angle that is instrumental in classifying dendritic trees by cell type. With Lisa Deters, Alex further linked network connectivity to dendritic morphology with a simple equation. Felix Effenberger found that basically all existing branching statistics and their correlations can be predicted from optimal wiring considerations and prepared a manuscript that is about to be submitted (2). His theory suggests a mostly random innervation process that determines dendritic morphology. Marcel Beining finished his PhD and has two important new papers: In the first manuscript published recently in eLife (3), Marcel proposes a new method to constraint compartmental models using morphological models that results in very robust predictions of all existing electrophysiological data for the models that we tested. His model of a dentate granule cell (GC) indicates a universal principle underlying the spiking mechanism that allows him to transform a rat GC into a mouse GC or into an adult born GC model. In his second paper, Marcel shows heterosynaptic plasticity in adult born GCs that integrate into an existing circuit (4). Marvin Weigand found that cortical hypercolumns have fixed neuronal numbers in biology as expected from optimal wiring (5). He is now able to predict complete visual cortex maps including retinotopy, orientation preferences and ocular dominance. Under his supervision, Moritz Groden was able to show that gyrification of the brain is a consequence of optimal wiring and is able to predict a large number of metrics such as fractal dimension, cortical thickness and gyrification frequency with his model. André Castro has dissected the temporal dynamics of the growth process of class I da neurons in the fly larva combining experiments and models. A large paper is in preparation but we also submitted the first paper on dendrite growth for class IV da neurons and found how they are able to optimise wiring throughout development (6). Finally, we studied synaptic plasticity in biophysical models of dendrites and found that including dendrites helps to understand the various responses to plasticity protocols (7).

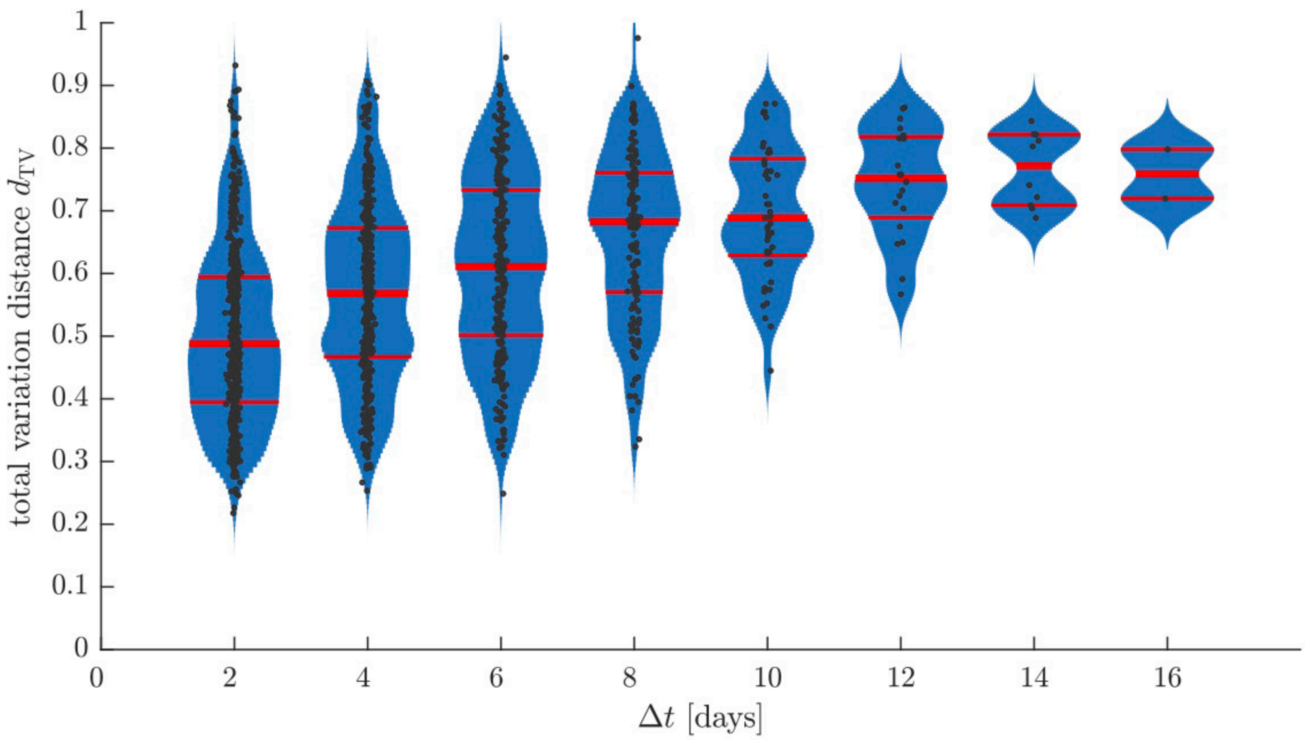


Dr.
Hermann Cuntz

In the year 2013 I received the prestigious Bernstein Award with a prize money of around 1.25 million Euros to establish my group at the FIAS and at the Ernst Strüngmann Institute. In my proposal I play with the idea of approaching cellular neuroanatomy in a similar comparative manner as Santiago Ramón y Cajal one of the founders of the field of Neuroscience. Instead of using pen and paper as in his beautiful drawings we now take advantage of computer models to reproduce dendritic structures from simple general principles.



(1) Bird AD, Cuntz H. Sholl analysis predicted by dendrite spanning fields (submitted).
(2) Effenberger F, Cuntz H. Dendritic branching statistics explained from minimal wiring constraints (in prep).
(3) Beining M, Mongiat LA, Schwarzacher SW, Cuntz H+, Jedlicka P+ (2017). Robust electrophysiological modelling demonstrated for mature and adult-born dentate granule cells of mouse and rat. eLife e26517 (paper of the Month at German Anatomical Society).
(4) Jungenitz T*, Beining M*, Radic T, Deller T, Cuntz H, Jedlicka P+, Schwarzacher SW+. Synaptic integration of newborn dentate granule cells in the adult rat brain (submitted).
(5) Weigand M, Cuntz H. Optimal wiring fixes cortical hypercolumn sizes across species (submitted).
(6) Baltruschat L, Tavosanis G, Cuntz H. A developmental stretch-and-fill process that optimises dendritic space filling (submitted).
(7) Ebner C, Clopath C, Jedlicka P+, Cuntz H+. Toward a unifying synaptic plasticity rule for detailed neuron models (submitted).



Group Information

At FIAS

since 2005, Fellow

Research Area

Functional organization and development of visual cortex
Stability of sensory coding in auditory cortex
Input-output transform and hierarchical motor networks in cuttlefish

Team

Dr. Dmitry Bibichkov
Dr. Enrique Hansen
Bettina Hein
Bastian Eppler
Fatemeh Bagheri
Hanna Kamyshanska

Collaborations

David Fitzpatrick, Max Planck Florida Institute
Simon Rumpel, Univ. Mainz
Gilles Laurent, Max Planck Institute for Brain Research
Kenichi Ohki, Univ. of Tokyo

Matthias Kaschube

Brains are complex dynamical systems comprised of networks that operate across many different temporal and spatial scales. While for several important model systems research in neuroscience has identified many of the relevant players (e.g. proteins, neuron types), we still lack an even basic understanding of how these players act together in networks to establish its functionality. Novel theoretical concepts are necessary to analyse, predict and interpret the multi-level and multi-omics data that current neuroscience and systems biology provide.

We are approaching this issue in a variety of neural systems, focusing on the following general three questions: How is genetic and sensory information dynamically integrated to establish cortical circuits during development? How do the patterns of electrical activity generated by these circuits represent the sensory world? What maintains the functionality of cortical circuits, in light of the observed significant turnover on cellular, subcellular and molecular levels?

During the past year we have tackled these questions in a variety of well-suited and relevant model systems, in tight collaboration with experimental groups in Frankfurt and abroad. Here, I focus on two selected projects that study the organization and functional role of spontaneous cortical activity. In cortical areas processing sensory input the term spontaneous activity commonly refers to neural activity that is not evoked by sensory input. While traditionally often interpreted as noise, more recently we have started appreciating how well structured endogenously generated activity can be prompting questions for its role in development and sensory processing.

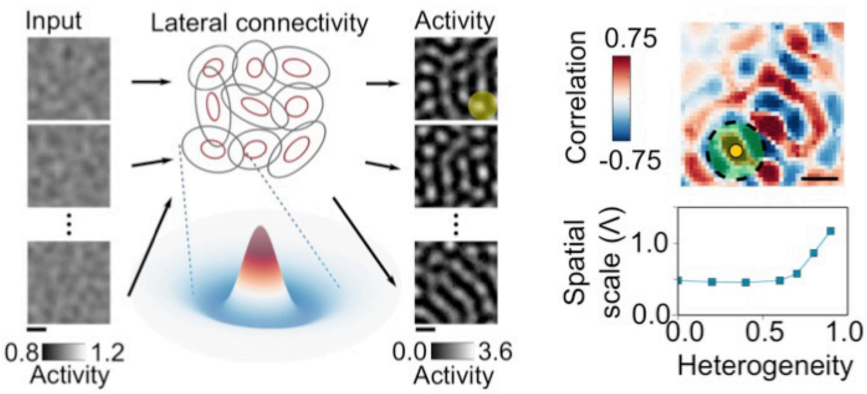
In one project my group has studied the role of spontaneous activity and cortical network interactions in the emergence of long-range order in the early developing visual cortex. Together with neurobiologist David Fitzpatrick at the Max Planck Florida Institute, USA, we found that spontaneous activity shows long-range correlations at an age when anatomical connections are still immature and mostly local in visual cortex. To explain this intriguing finding we proposed a circuit model based on local, heterogeneous connections and showed that heterogeneity reduces the dimensionality of the space of spontaneous activity patterns. This novel mechanism can explain how long-range correlations can arise from only local circuits in the early cortex (Fig. 1). These long-range correlations may provide a scaffold for building long-range anatomical connections over subsequent stages of development.

In another project my group has studied the stability of spontaneous population activity in the auditory cortex of awake mice. The recordings were performed in the group of our collaborator Simon Rumpel, a neurobiologist at the University Mainz. We find that spontaneous activity is typically very structured. However its structure drifts on the time scale of several days, i.e. the distribution of spontaneous activity patterns changes and becomes successively more dissimilar over the time-course of days (Fig. 2). This is an intriguing finding, as one would assume that in adult cortex the circuits that produce these activity patterns are stable. However, it seems the cortical networks are much more dynamic than previously appreciated and it is an important task for the future to explore the significance of these network dynamics.

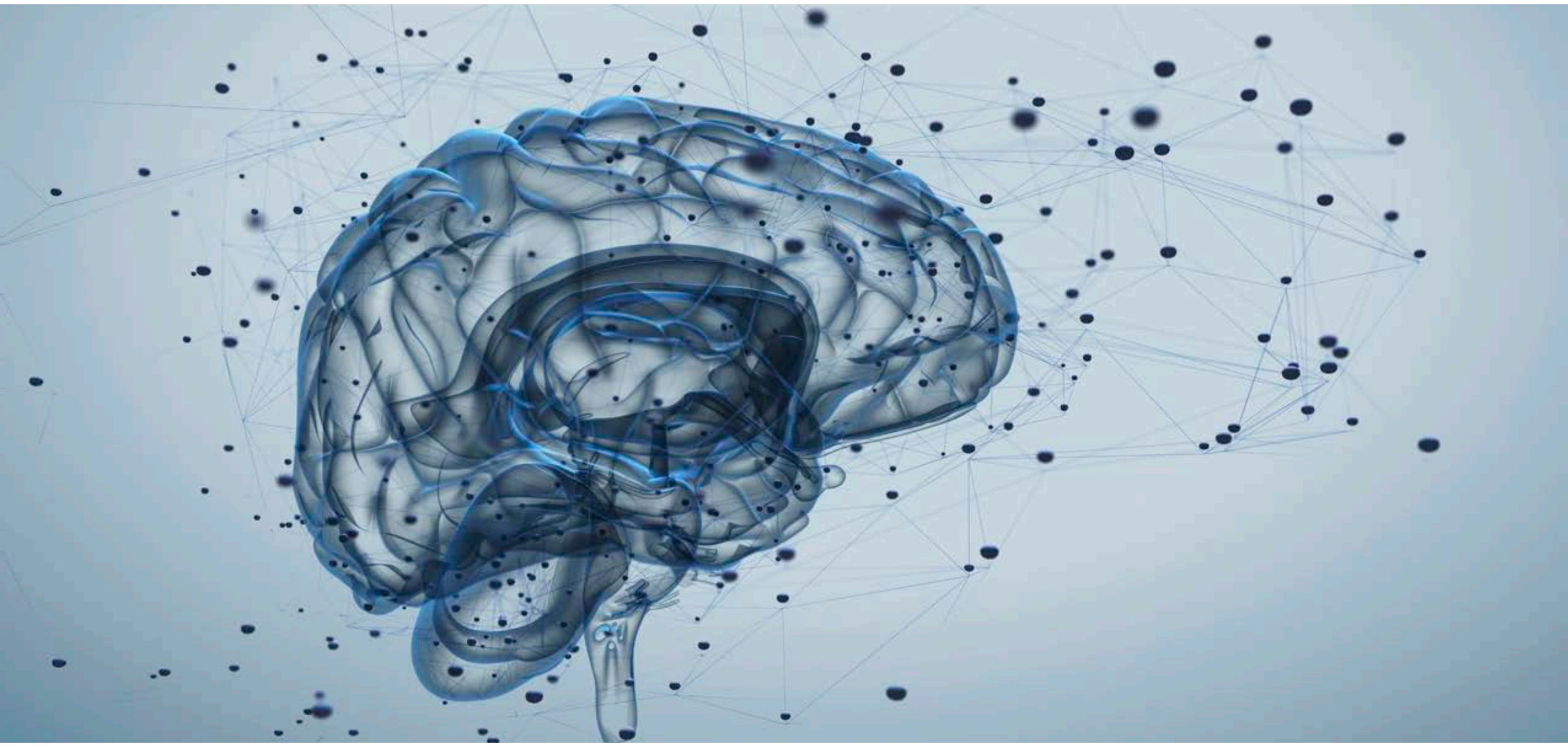
Together these two studies shed new light on the importance of spontaneous cortical activity in development and its structural stability in the adult brain. We are only at the beginning to understand the intricate spatiotemporal dynamics of spontaneous cortical activity and its various roles throughout lifetime.

Prof. Dr. Matthias Kaschube

Matthias Kaschube studied Physics and Philosophy in Frankfurt and Göttingen and obtained his doctoral degree in theoretical physics working with Fred Wolf and Theo Geisel at the Max Planck Institute for Dynamics and Self-Organization. From 2006-2011 he held the position of a Lewis-Sigler Theory Fellow at Princeton University, working on theoretical neuroscience and developmental biology. In 2011 he became a Fellow at FIAS and a Professor for Computational Neuroscience in Computer Science at Goethe University Frankfurt.



Left: A dynamical circuit model of spontaneous activity in the early cortex: a constant input modulated spatially by filtered noise is fed into a recurrent network with short-range, heterogeneous Mexican-hat (MH) connectivity. It produces a set of modular output patterns with typical spatial scale Λ determined by the local lateral connections (average size illustrated by the yellow circle). Right top: The model produces long-range correlations in agreement with experiment (n=100 output patterns, 16% of modelled region shown). Right bottom: The spatial scale of correlations increases with increasing heterogeneity in the lateral connections.



Group Information

At FIAS

since 2003, Senior Fellow

Research Area

Visual cortex, non-linear dynamics, synchrony and oscillations
Plasticity and learning
Recurrent networks

Team

Dr. Andrea Lazar
Yiling Yang

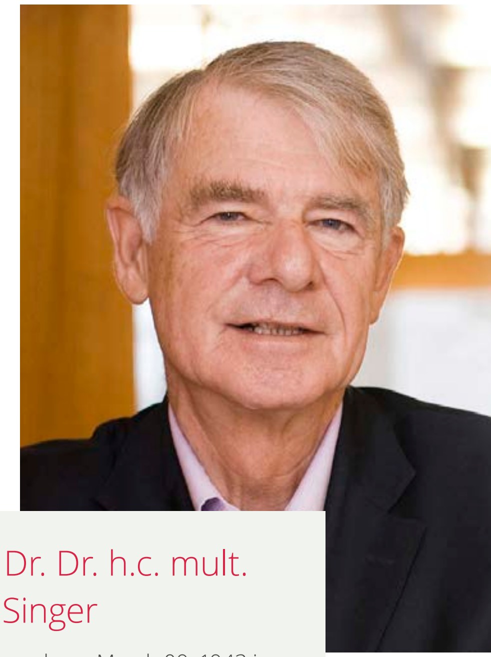
Wolf Singer

Our current understanding of primary visual cortex function comes primarily from studies of individual neurons stimulated with response-tailored visual input (sinusoidal gratings). To this day, it remains unclear how populations of cells act together to perform the computations necessary for processing complex visual scenes. Using chronically-implanted, movable electrodes, we recorded simultaneously population responses (multi-unit activity and local-field potentials) from the primary visual cortex (area V1) of awake rhesus macaques. To enhance aspects of distributed coding, we employed structured visual stimuli (natural scenes or simple visual shapes) and investigated in great detail the variability and covariability of the resulting neural responses.

In particular, we showed that the onset of a visual stimulus causes a reduction in neuronal variability in V1, implying mechanistically that interactions in cortical circuits become more stable when driven. Interestingly, we found that both natural scenes and phase-scrambled controls decreased mean firing variability at the level of the primary visual cortex to a similar extent. However, only the natural scenes generated stimulus specific evoked responses. Inspired by concepts from machine learning, we used a naive Bayesian classifier to decode stimulus identity from both multi-unit population activity and band-limited gamma power. We found that both multi-unit activity and gamma oscillations contained information about the visual stimuli, were modulated by attention and by the type of visual stimulus presented.

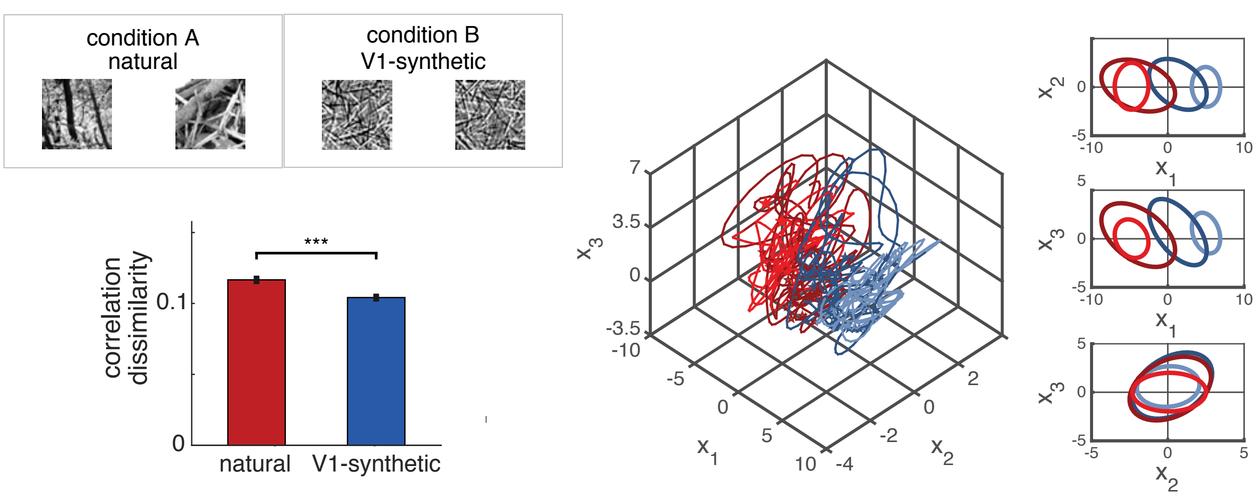
Finally, we studied the fine structure of spike-count correlations and assessed their dependence on stimulus identity and on stimulus statistics. We demonstrated that, as predicted by a hierarchical inference model for visual perception, stimulus-dependent spike-count correlations are characteristic of natural images and that this dependence can be manipulated by controlling the higher-order structure present in visual stimuli (Fig. 1A). In preliminary analysis, we used time-varying latent variable models (e.g. GPFA, Fig. 1B) to extract population dynamics on low-dimensional latent state-space manifolds and studied the time course with which state space trajectories converge and diverge as a function of stimulus structure.

Early theories of perception have suggested that the brain interprets sparse and impoverished input signals on the basis of previously acquired information about the visual environment. In our most recent research efforts, we investigated the encoding, storage, and processing of information that takes place in the high-dimensional state-space provided by the non-linear recurrent dynamics exhibited by primary visual cortex populations.



Prof. Dr. Dr. h.c. mult. Wolf Singer

Wolf Singer, born March 09, 1943 in Munich studied Medicine in Munich and Paris, received his PhD from the LMU Munich and his habilitation at the TU Munich.
He is one of the directors of the MPI for Brain Research and FIAS, as well as founding director of FIAS and the Ernst Strüngmann Institut for Neuroscience.
He currently is the scientific director of the Enst Strüngmann Forum in Frankfurt.
His research is devoted to the exploration of neuronal foundations of cognitive functions. Central to his research is the question over how many brain areas processes are connected to allow for coherent perception.



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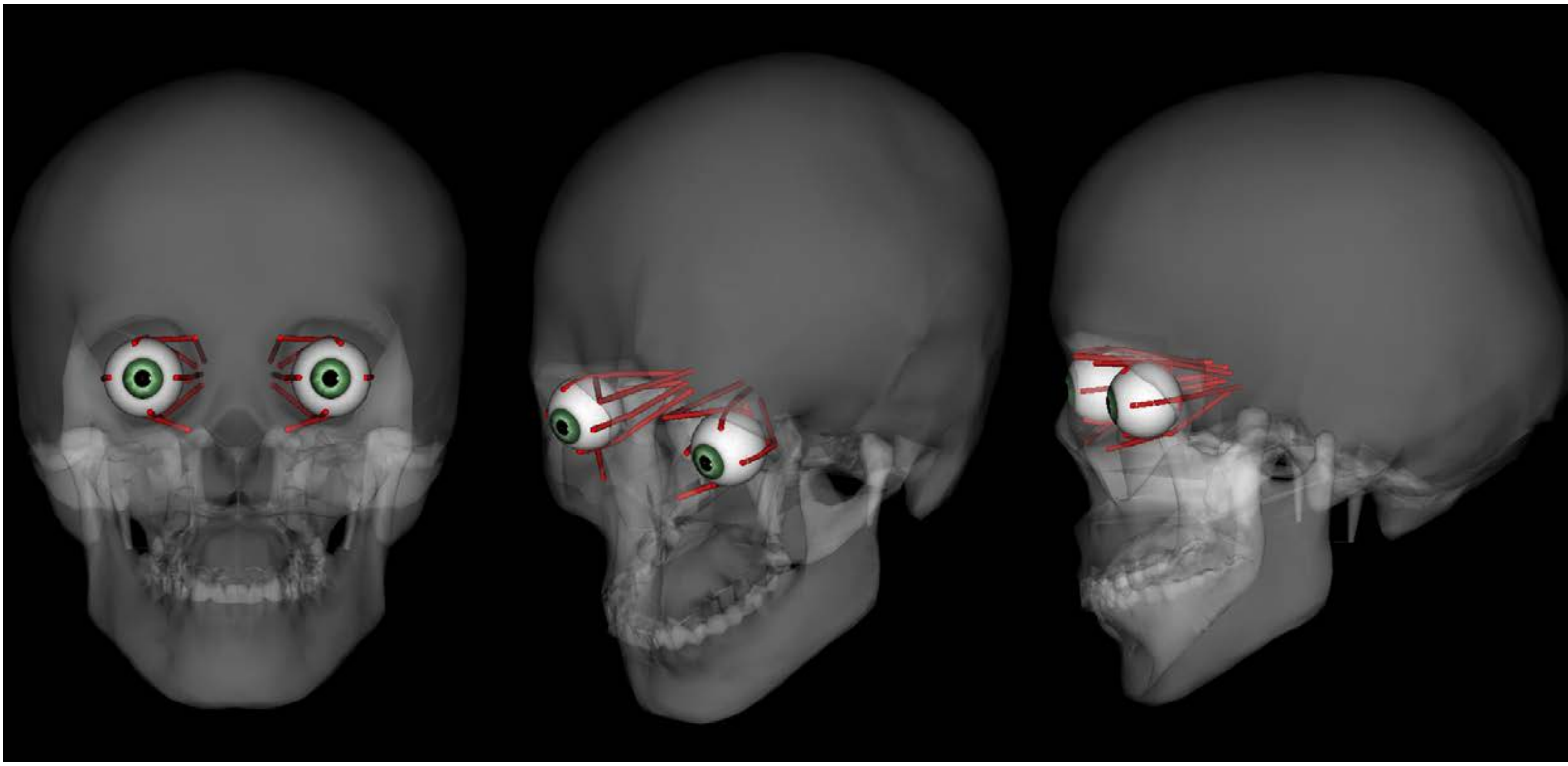


Group Information

At FIAS

since 2005, Senior Fellow

Research Area

Plasticity and Learning in Spiking Neural Networks
Active Efficient Coding
Transcranial Magnetic Stimulation

Team

Samuel Eckmann
Dennis Forster
Felix Hoffmann
Florence Kleberg
Lukas Klimmasch
Alexander Lelais
Alexander Lichtenstein
Diyuan Lu
Max Murakami
Bruno Del Papa
Natalie Schaworonkow
Johann Schneider
Charles Wilmot

Collaborations

Bert E. Shi (Hong Kong)
Maria Fronius (Frankfurt)
Monika Knopf (Frankfurt)
Ulf Ziemann (Tübingen)

Jochen Triesch

Neuroscience is a very dynamic research field. Every year, new and improved methods for recording and manipulating neural activity and reconstructing neural circuits are being developed. Next to providing techniques for data analysis, Computational Neuroscience seeks to reveal the computational principles of brain circuits through the construction of computational models and theoretical analyses. In addition, there is a fruitful interaction with the field of Artificial Intelligence. Despite many advances, however, the field still needs to make fundamental progress at the conceptual level, e.g., regarding the nature of neural codes and the plasticity and learning mechanisms that establish them, or how cognitive processes are implemented in the brain's "wetware."

Studying Plasticity and Learning in Spiking Neural Network Models is a major research topic of our group. We have pioneered the study of spiking neural networks combining different plasticity mechanisms and have achieved a number of noteworthy results regarding the structure and function of such circuits. For instance, we have been working on neural network models explaining the statistics and fluctuations of synaptic connection strengths and predicting the distribution of lifetimes of synapses. Our models have also offered insights into the functional role of spontaneous brain activity suggesting that the brain's coding strategy may be much more efficient than previously thought. Most recently, we have proposed a model of human sequence learning that offers explanations for a number of so-called facilitation and interference effects: how learning one sequence affects and is affected by the learning of other similar sequences.

Going beyond the scale of local circuits to the systems level, our group, together with Prof. B. Shi in Hong Kong, have developed the Active Efficient Coding (AEC) framework. AEC is a generalization of classic efficient coding theories to active perception. In a nutshell, it argues that the brain not only tries to encode sensory information in a particularly efficient manner (classic efficient coding), but that it also uses its motor behavior, e.g., various kinds of eye movements to further improve the coding of sensory information. We have used AEC to build self-calibrating models of active binocular vision and active motion vision and have validated these models in humanoid robots. Most recently, we have been exploring the potential of AEC to explain the mechanisms of developmental disorders of binocular vision such as amblyopia, which affects 4-5% of the population. In this area we are coordinating a European research project with partners working on animal models of amblyopia and partners developing and testing treatment methods for children and adults.

A third major research area is the so-called Transcranial Magnetic Stimulation (TMS) of the brain. In this technique, large magnetic fields are produced with stimulation coils that are positioned close to the head. The magnetic fields are strong enough to activate populations of neurons in the brain in a targeted fashion. Together with neurologist Prof. U. Ziemann and other collaborators, we have developed multi-scale computational models to better understand and explain the mechanisms through which TMS activates neural circuits, laying a foundation for the development of improved stimulation techniques for clinical and basic research settings. In one specific study, we have investigated how spontaneous brain oscillations that can be measured with the help of the electroencephalogram (EEG) modulate the brain's response to TMS. Our findings may be important for optimizing stimulation parameters to achieve desired clinical outcomes, e.g., during the treatment of stroke or depression.

Prof. Dr. Jochen Triesch

is the Johanna Quandt Professor for Theoretical Life Sciences at FIAS. He also holds professorships at the Dept. of Physics and the Dept. of Computer Science and Mathematics at Goethe University Frankfurt. Before joining FIAS in 2005, he was Assistant Professor at UC San Diego, USA. Originally trained as a physicist, he discovered his passion for studying the brain already during his graduate education.

Virtual Reality computer game for the treatment of amblyopia. The contrast in the image presented to the right eye is reduced to avoid suppression of the left eye and facilitate binocular fusion.

Group Information

At FIAS

since 2004, Senior Fellow

Research Area

Modelling of
Brain Function

Team

Dr. Ninad Joshi
Christine Omeira Ibrahim
Jonas Wansch

Collaborations

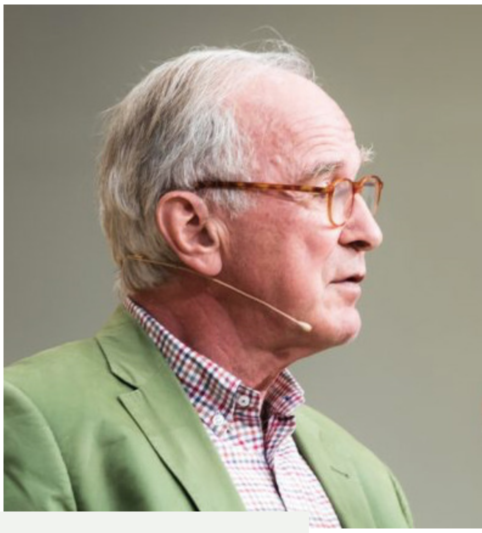
Prof. Irving Biederman, Univ. of Southern California
Prof. Alois Knoll, TU Munich

Christoph von der Malsburg

My approach follows the strategy of trying to emulate typical brain functions in the computer. That attempt has a history of 60 years (if one takes the 1956 Dartmouth Conference on artificial intelligence as the starting point). That field is in a very peculiar historical situation at present. On the one hand, there is great public excitement over the spectacular successes of a method called deep learning, 2017 saw the foundation or sale of near to a thousand companies bent on artificial intelligence (AI), billions are invested, government programs are put up, especially in China, and a flurry of activity is growing around the existential dangers posed by AI for mankind. On the other hand, no essential conceptual progress has been made with AI or understanding brain function (the ideas behind deep learning going back 30 or 40 years, all progress being entirely due to faster computers and network-derived masses of sample data), and the neurosciences are totally concentrated on collecting data, with the help of revolutionary new experimental methods. Some basic conceptual maladaptation is blocking progress. The air smells of a Kuhnian paradigm shift.

My own work is inspired by the conviction that the mental block on the way to understanding the brain has to do with a wrong, or rather insufficient, answer to the question how the neural tissue in our brain expresses the mental content that we experience. From single-cell recordings we know that neurons in our brain act as elementary symbols, for blue light at a particular position in the visual field, for touch at a spot on our arm, for a particular smell, and so on. In the general perception there is, however, a blind spot regarding the mechanism by which our mind assembles from these elementary symbols the vivid representation of the scene surrounding us and indeed of all the complex imaginations and thoughts that we are capable of. All symbol systems mankind has ever conceived of have such mechanisms for constructing complex expressions from elementary symbols -- e.g., words from letters --, and the brain should do without? The consequence of this prejudice is that all neural models, including deep learning, have to live with the dogma that any decision to be taken requires a dedicated neuron: run with an iron ball chained to your ankle!

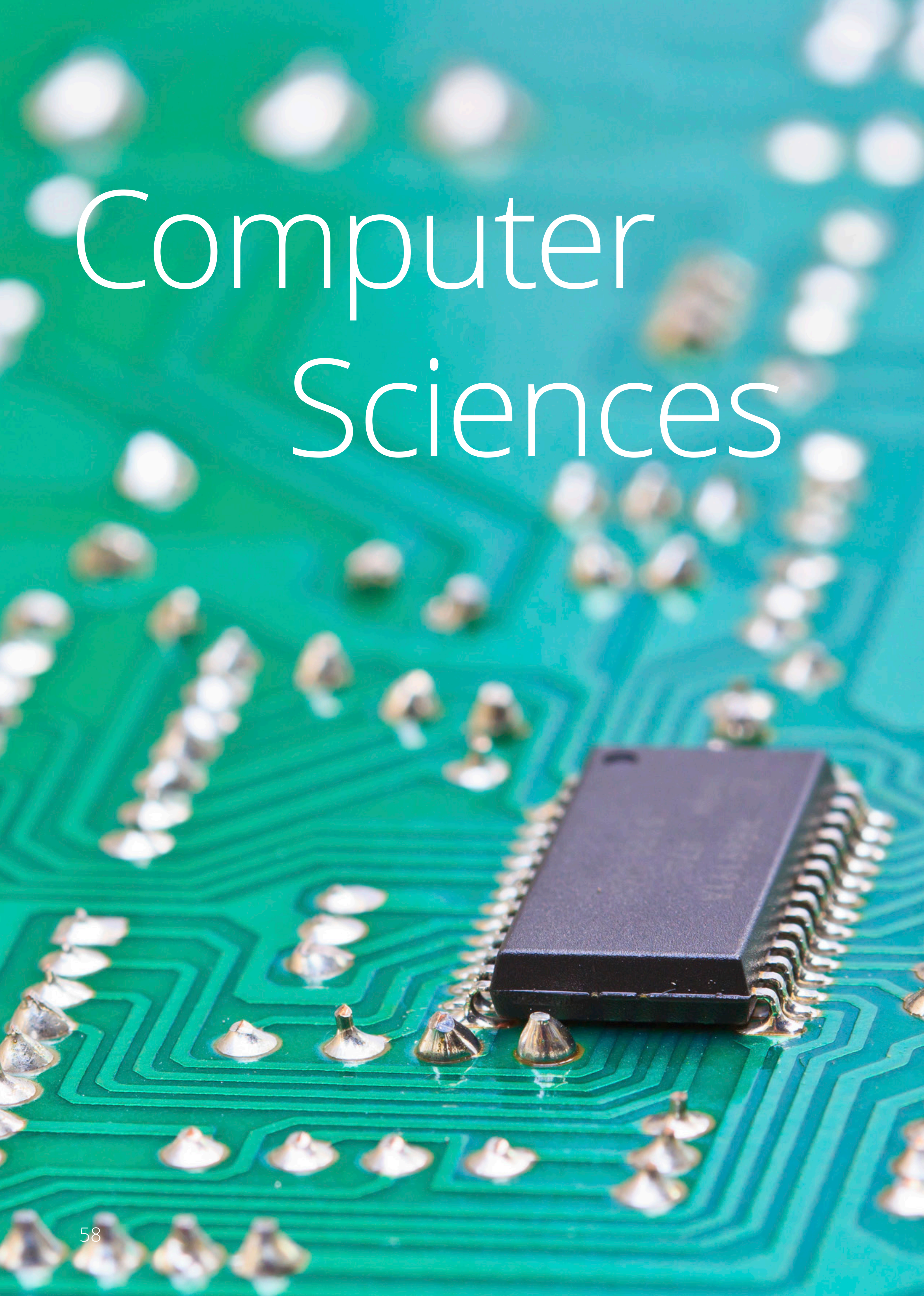
I am proceeding with the idea that the neural equivalent to our mental phenomena are structured networks, nets as I call them. Fragments of such nets are formed in a relatively slow process by what is called network self-organization. This process has been intensely studied both theoretically (to which I have contributed intensely in the past) and experimentally and it is responsible for wiring up our brain (listing of whose connectivity would need a million times more bits than are contained in the genes). Net fragments are the Lego blocks of our mind. They can be activated in fractions of a second, and their assembly is guided by the strict rule that together they form a net stable under self-organization. In 2017 a large part of my work was bent on understanding how network self-organization can be guided by sensory input.



Prof. Dr. Christoph von der Malsburg

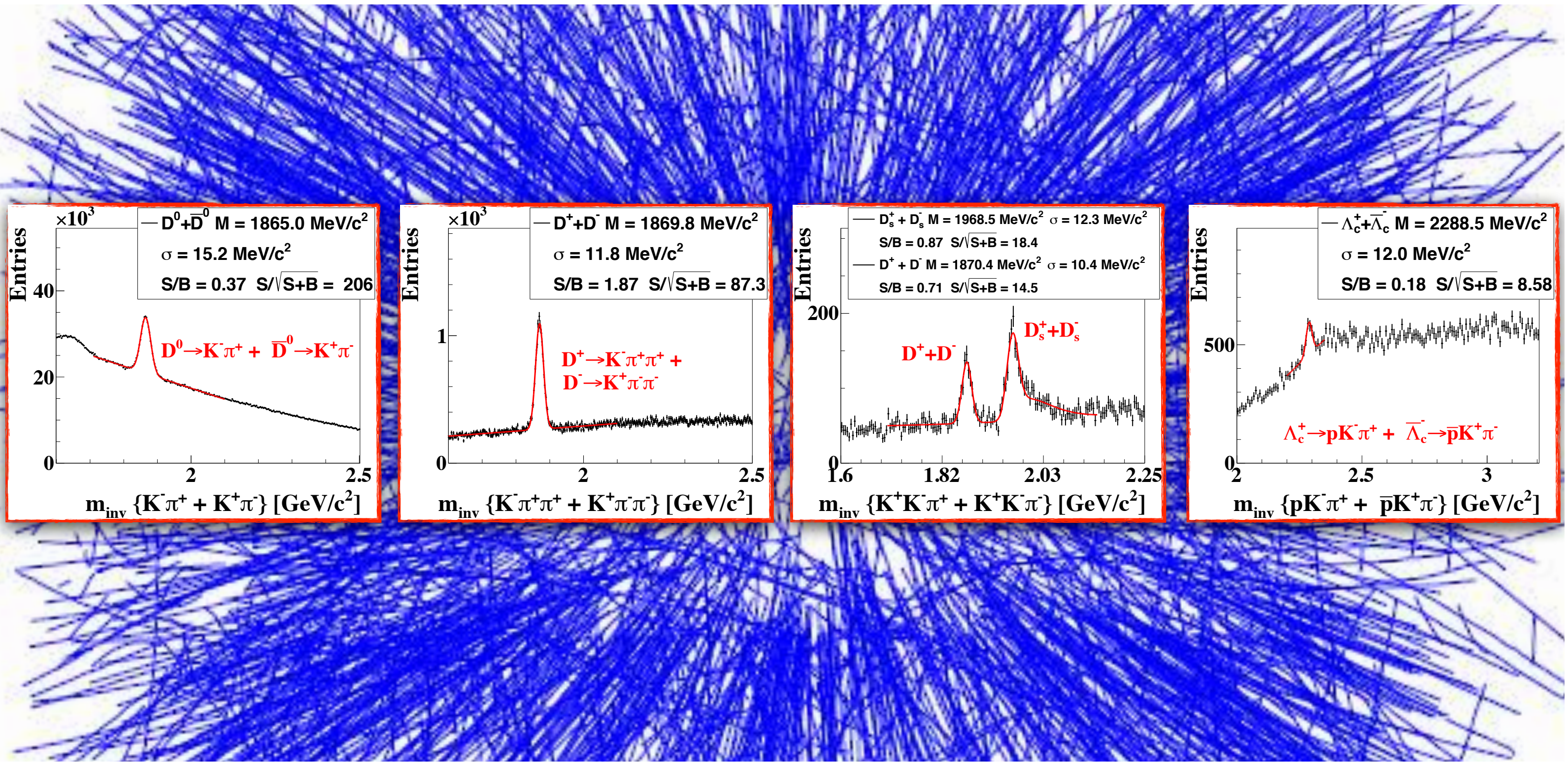
Christoph von der Malsburg is engaged in a long-term quest for a description of the brain as a functional entity. A major focus of his work is the question how the neural tissue of the brain generates the mental content that we experience, how this neural code is generated in development and learning, and how actual brain states are formed. He is working towards demonstrating his solution to those problems in the form of a model visual system.

Computer Sciences



The Green Cube developed by FIAS scientists.

The Computer Science groups at FIAS are interested in High Performance Computing and how to further advance the architecture, the applications and the continued development of high performance computers useful to the natural and life sciences. Our focus is on the selection and analysis of experimental data generated by accelerator facilities such as the GSI Helmholtzzentrum für Schwerionenforschung (Darmstadt, Germany) and CERN (the European Center for Nuclear Research in Geneva, Switzerland). Both of these facilities employ shared, typically massive parallel systems and clusters operating under high-level, real-time and dependability standards. Our task is the research and development of new computer architectures and algorithms to achieve better energy-efficiency. Within the context of shared computing we implement both GRID and virtual technologies as well as cloud computing systems.



Ivan Kisel

Group Information

At FIAS

since 2012, Fellow

Research Area

Supercomputers
Online big data processing
Parallel programming
Heavy-ion physics
CBM, PANDA, ALICE, STAR experiments

Team

Artemiy Belousov
Grigory Kozlov
Mykhailo Pugach

Collaborations

CBM
PANDA
ALICE
STAR

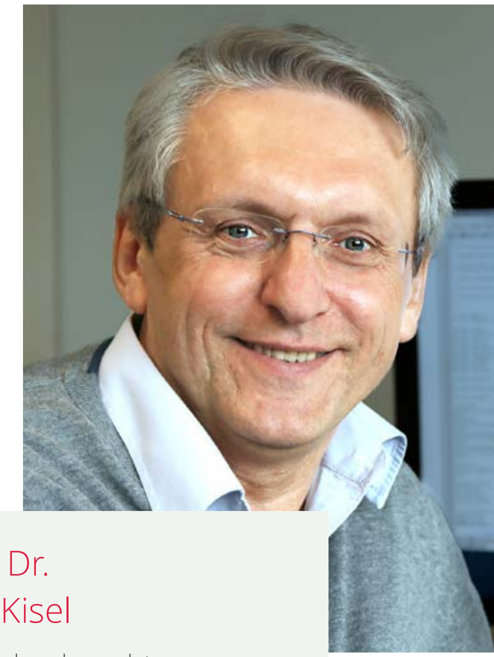
Creation of a little Big Bang in laboratory is of great interest for experiments with heavy ions (^{197}Au and ^{208}Pb nuclei), since it allows one to investigate strongly interacting nuclear matter under the extreme conditions of a hot and compressed quark-gluon plasma, when quarks become asymptotically free. This makes it possible to shed light both on the first microseconds after the birth of the Universe (the ALICE experiment at CERN), and the state of matter at the final stages of the evolution of massive stars, as in the centers of neutron stars (the future CBM experiment at FAIR). In addition, the STAR experiment (BNL) has a unique opportunity to study the phase transition from hadronic matter to a quark-gluon plasma in a wide range of intermediate energies of colliding nuclei.

Among the hundreds and thousands of particles produced in a collision, the most interesting are very rare particles whose quark composition includes heavy quarks, for example, particles with charm quarks, whose mass exceeds the proton mass. Such particles, for example, D^0-mesons and L_c-hyperons, are usually born at the earliest stage of the collision, and therefore can be considered as ideal probes for studying heated and compressed nuclear matter in the state of a quark-gluon plasma. Such particles are rare (about one particle per million collisions) with a very short lifetime (about 10^{-23} seconds), so that they fly no more than a few centimeters and, therefore, cannot be registered in the detector system. Therefore, the search for such particles is an extremely challenging task.

In preparation for the CBM experiment, we have developed the KF Particle Finder software package for the search for and reconstruction of parameters of rare short-lived particles, which are of interest for the study of quark-gluon plasma. At the stage of particle search, the package has to solve the complicated combinatorial problem of analysing of various combinations of hundreds and thousands of registered particles in order to find among them the products of decays of the short-lived (mother) particles of interest. To minimize the time of this combinatorial stage, the algorithms are parallelized in order to use the power of modern many-core computer architectures. In the next stage, the parameters of the found (daughter) particles are used to calculate the parameters of their short-lived mother particles. This is done by using the Kalman Filter (hence KF) method, which also makes it possible to estimate the accuracy of the reconstructed parameters. The application of the package to the search for and study of the decays $D^0 \rightarrow K^- \pi^+$ and $\overline{D}^0 \rightarrow K^+ \pi^-$ in simulated collisions in the CBM experiment showed a signal-to-background ratio of 0.40 and 0.73, respectively, which is a good result for the search for rare short-lived particles in the environment of large particle multiplicities.

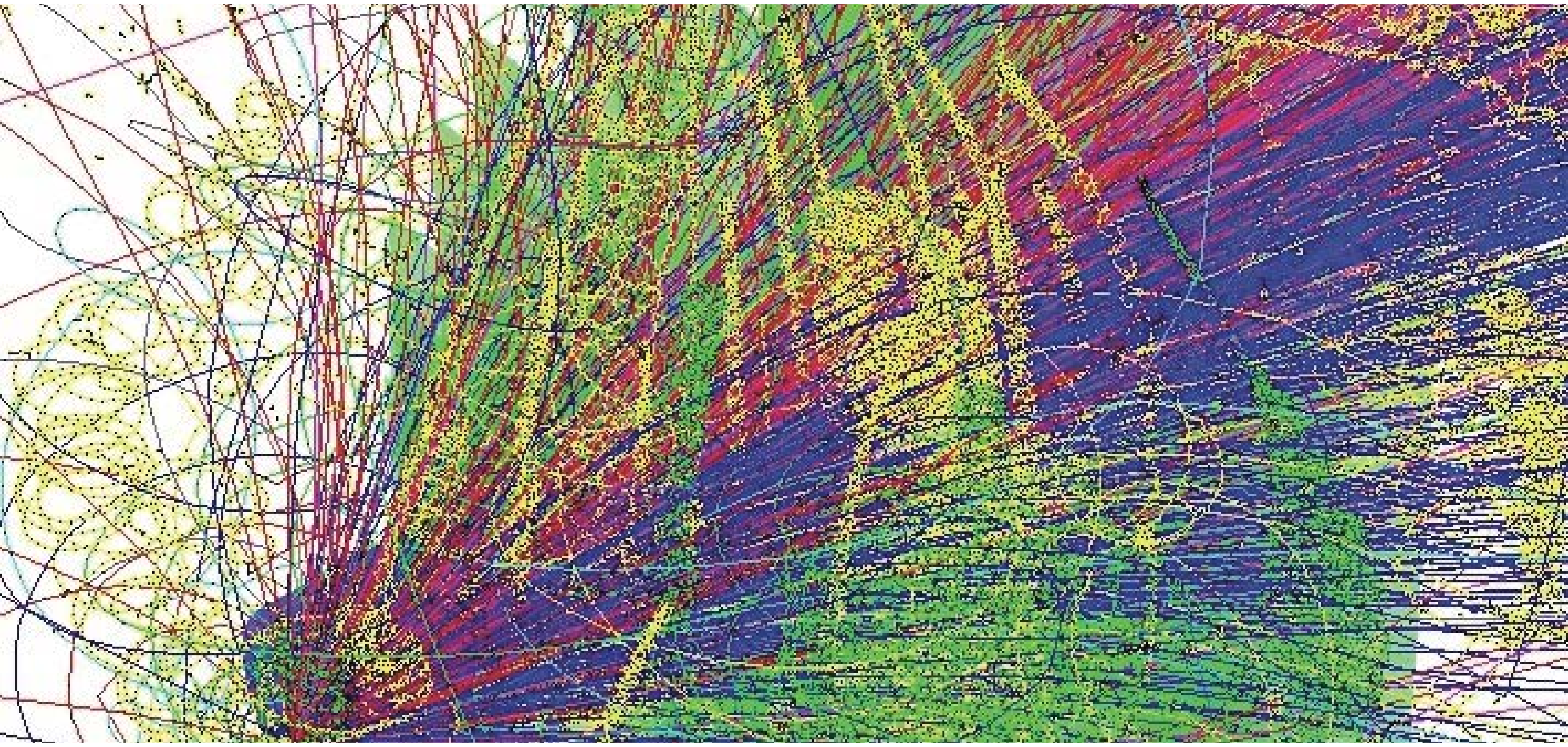
In 2017, within the FAIR Phase-0 program and in collaboration with our GSI and BNL colleagues, the KF Particle Finder package was applied to real data of the STAR (BNL) experiment, collected in 2016. After some adaptation of the selection parameters used in the CBM experiment to the conditions of the STAR experiment, D-mesons and Lc-hyperons were searched for among 1.3 billion collisions of gold-gold nuclei at 200 GeV beam energy. The following values were obtained for the signal-to-background ratio and for the significance calculated as an enhancement of the signal over its standard deviation: $D^0 \rightarrow K^- \pi^+ + \overline{D}^0 \rightarrow K^+ \pi^-$ (0.37/206.0), $D^+ \rightarrow K^- \pi^+ \pi^+ + D^- \rightarrow K^+ \pi^- \pi^-$ (1.87/87.3), $D^+ \rightarrow K^- \pi^+ \pi^+ + D^- \rightarrow K^+ \pi^- \pi^-$ (0.71/14.5), $D^+_s \rightarrow K^+ K^- \pi^+ + D^-_s \rightarrow K^+ \pi^- \pi^-$ (0.87/18.4), and $\Lambda^+_c \rightarrow p K^- \pi^+ + \overline{\Lambda}_c \rightarrow \overline{p} K^+ \pi^-$ (0.18/8.58).

These results are similar to the results obtained by the physics groups of the STAR experiment within their standard approach. This shows the high precision and reliability of the KF Particle Finder package for finding rare short-lived particles in complicated real data conditions and gives confidence in its successful application in the CBM experiment, when it starts to work at the FAIR accelerator complex.



Prof. Dr. Ivan Kisel

Ivan Kisel works on data reconstruction in high-energy and heavy-ion experiments. His approach based on cellular automata allows to develop parallel algorithms for real-time physics analysis using HPC. He received his PhD in physics and mathematics from the Joint Institute for Nuclear Research (Dubna, 1994). Then he worked at the University of Heidelberg, where he gained his habilitation in physics, in 2009, and at the GSI Helmholtz Centre for Heavy Ion Research. Since 2012, he is a professor for software for HPC at the Goethe University and a fellow at FIAS.



Volker Lindenstruth

Group Information

At FIAS

since 2007, Senior Fellow

Research Area

Green-IT
Highly efficient data centers
High performance computing
Real-time event reconstruction
GPU- and FPGA- accelerated tracking
Heavy-ion physics
Algorithm engineering

Team

Jan de Cuveland
Nadine Flinner
Sergey Gorbunov
Dirk Hutter
Stefan Kirsch
Mikolaj Krzewicki
Sarah LaPointe
Johannes Lehrbach
Gvozden Neskovic
David Rohr

Collaborations

CBM
ALICE

With its ever-increasing amount of measured data, fundamental research in large-scale experiments is one of the most demanding applications of high-performance computing. In the field of physics, the upcoming Compressed Baryonic Matter (CBM) experiment will be one of the major scientific pillars of the future Facility for Antiproton and Ion Research (FAIR) in Darmstadt. The goal of the CBM research program is to explore the QCD phase diagram in the region of high baryon densities using high-energy nucleus-nucleus collisions. In order to achieve the required precision, the experiment requires complex online event selection criteria at high reaction rates of up to 10 MHz.

To achieve this, all event selection is performed in a large online processing farm, the “First-level Event Selector” (FLES). This high-performance computing (HPC) system will consist primarily of standard PC components including GPGPUs. It is structured as an entry cluster at the experiment site and a processing cluster at the FAIR Green-IT data center, with both parts being connected by a high-bandwidth InfiniBand network. The data rate at the input to the FLES is expected to exceed 1 TByte/s of time-stamped signal messages from the detectors. The processing cluster will consist of several hundred servers with approximately 60.000 cores to be able to perform the online processing tasks in real-time.

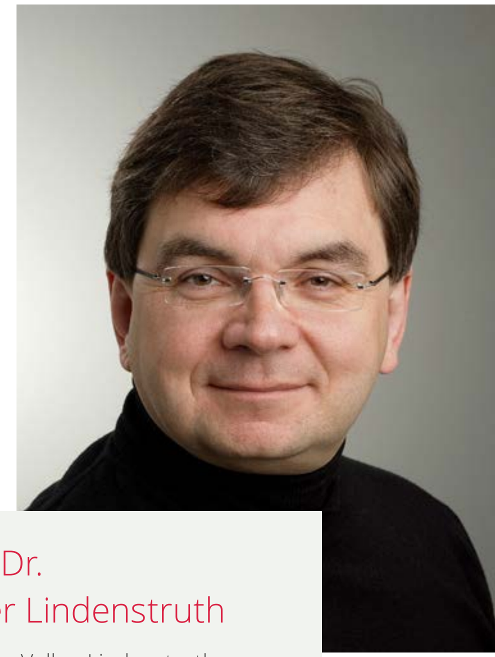
The entry cluster near the experiment comprises custom FPGA-based PCI Express add-on cards, which receive data from the detector through in total approximately 5000 fibers. The current prototype features a

Kintex-7 FPGA and provides up to eight 10 GBit/s optical links. The custom FPGA design developed for this board preprocesses and indexes the incoming detector data and forwards it to the computer's main memory using direct memory access (DMA). The DMA target buffers can efficiently serve as InfiniBand RDMA source buffers without copying the data in memory. By using POSIX shared memory for these buffers, they can be read by multiple processes. This prototype interface card and the accompanying front-end HDL module have been employed successfully in numerous CBM test setups.

To allow efficient event selection, the FLES online data management software first has to perform time slice building. In this process data from all given input links is combined to self-contained, potentially overlapping processing intervals and distributed to compute nodes in the cluster. This allows efficient event selection without the need for inter-node communication during analysis. The current demonstrator implementation builds time slices between an arbitrary number of nodes, supporting various network implementations such as Libfabric and ZeroMQ. It also includes a true zero-copy implementation available on RDMA-enabled networks such as InfiniBand. A sustained time slice building rate of up to 6 GB/s per node was achieved using this implementation.

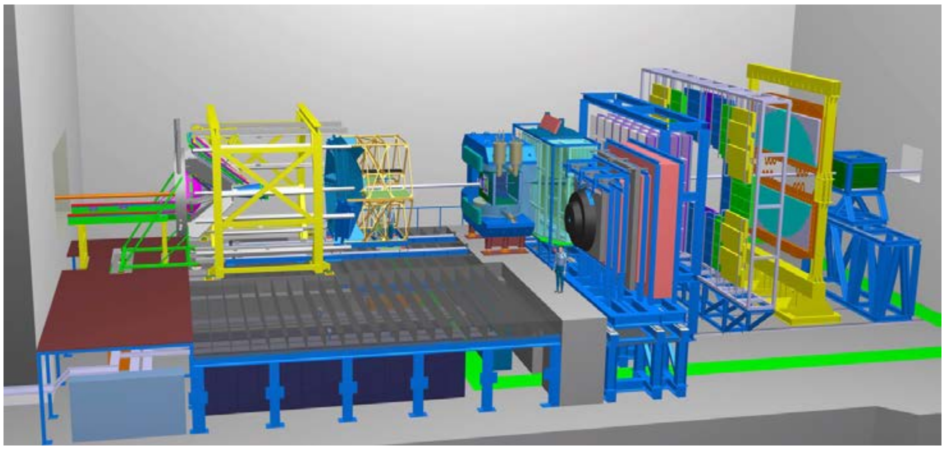
As the continuous all-to-all communication pattern places a high strain on the network, a high-throughput InfiniBand fat-tree architecture is foreseen as the primary network infrastructure. In this application, standard routing patterns exhibit unsatisfactory performance. Using optimized routing schemes on an InfiniBand FDR network, we could achieve excellent performance of more than 5 GB/s per node on a subset of the L-CSC supercomputer.

FLES prototype hardware and software have been successfully enabling CBM detector tests and recording numerous terabytes of time slice data in 2017, including simultaneous data taking with several subdetector prototypes. Concepts and technologies developed for the FLES are being currently adapted for the upcoming Mini-CBM setup and in parallel further developed with respect to performance and scalability for the full CBM experiment at FAIR.



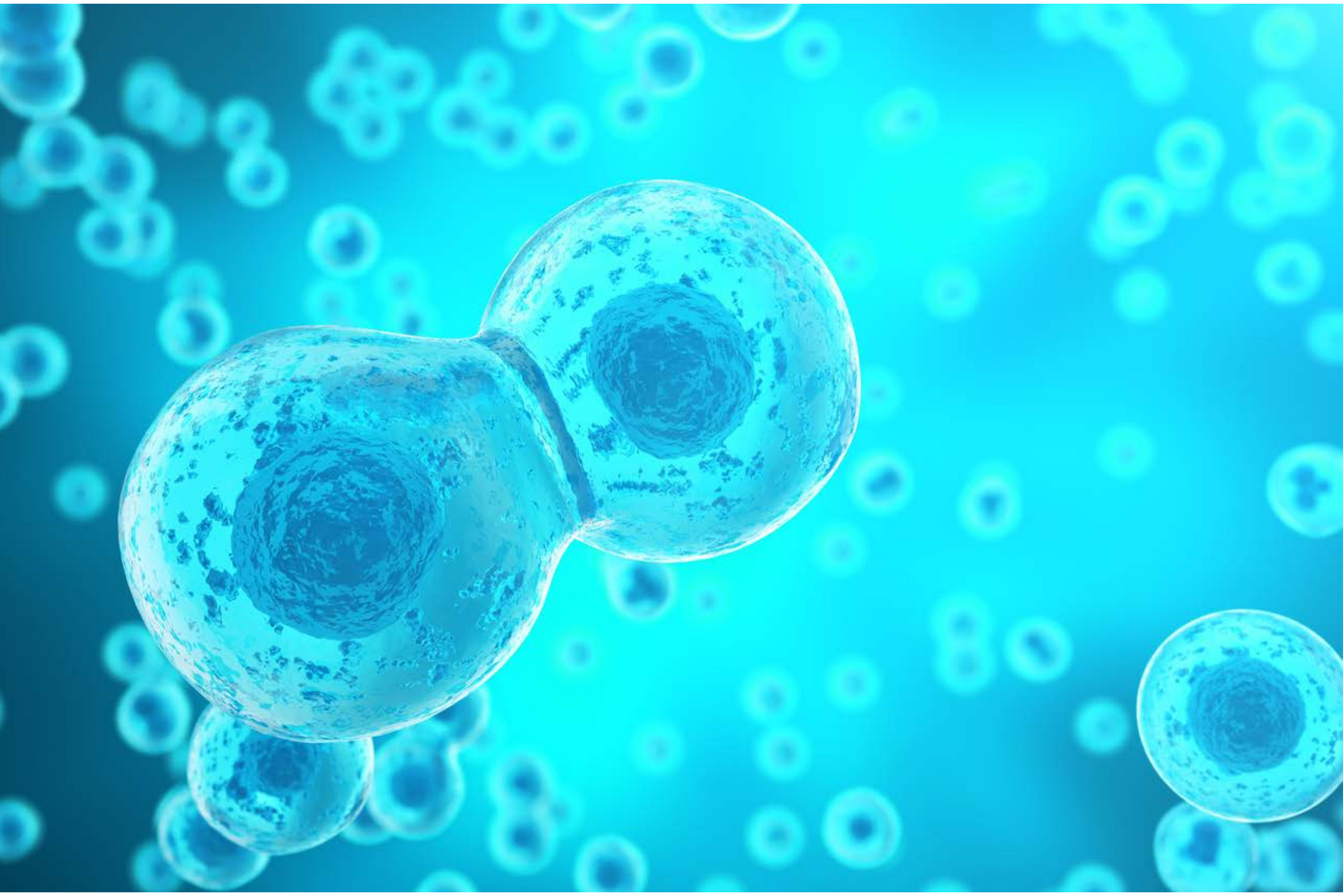
Prof. Dr. Volker Lindenstruth

Professor Volker Lindenstruth studied physics at TU Darmstadt and received his doctorate in 1993 at Goethe University. He spent his Postgraduate years as a Feodor v. Lynen Fellow at LBNL, USA at the UC Space Science Laboratory. In 1998, he returned to Germany as a Professor and department head at the University of Heidelberg. In addition, he has been the head of the ALICE HLT project at the LHC since 2000 and from 2006 to 2007 also a CERN Assosiate. At FIAS he held the position of Fellow since 2007 and became a Senior Fellow soon thereafter. Furthermore the Chair of High Performance Computer Architecture of the Goethe University has been in his care since 2009. Since 2010, Professor Lindenstruth is a part of the board of directors of FIAS, being its chairman since 2012.



3D model of the CBM experiment at FAIR.

Life Sciences



Biological processes are inherently complex as they are not only governed by the interaction of physical and chemical processes but also underlie genetical constraints and evolution. Theoretical biology aims at a quantitative understanding of biological systems, their dynamics and interaction across scales. To this end new analysis approaches are developed to extract relevant information from either tera and petabyte sized data sets, or from very scarce data.

Based on quantitative information provided by experimental data, mathematical models can be formulated in order to abstract and generalize the structure or behavior of a system, and to allow predictions. Mathematical models are a means to identify the level of complexity necessary to explain a given observation, but also represent building blocks to create understanding of the behavior of larger systems.

Model predictions provide guidance for experimental design and clinical studies, reduce the need for animal testing, and help to develop treatment strategies and ecological policies.

Current topics in theoretical biology are the interplay between chemical signaling and biomechanics (forces), decision-making on the cell and systems-level, emergent phenomena, such as collective behavior, or the formation of patterns or structures based on the (inter-)action of small-scale components.

At FIAS, the theoretical life sciences aim at developing efficient pipelines for image processing and analysis, as well as the generation of quantitative mathematical models, simulation and model validation approaches to address, amongst others, the following questions:

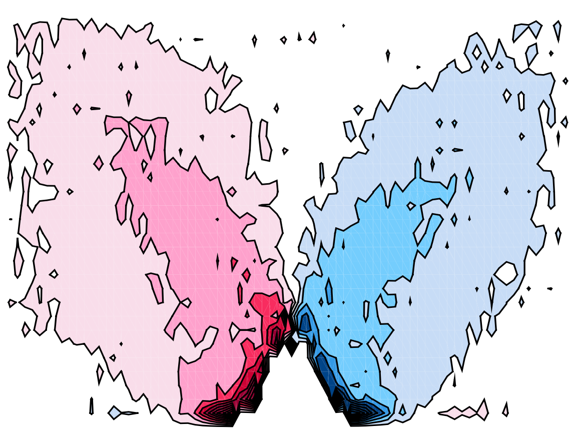
• How can chemical signaling pathways and/or mechanical forces regulate directed movement and collective behavior of small bacterial pathogens?

• Which specific nonlinear interactions between pathogens and immune system components lead to the occurrence of chronic infections? And how can chronic infections be treated?

• How important are mechanical cues and inter-cellular forces for migratory properties of cancer cells, and how are the mechanical properties of cancer cells affected by chemical inhibitors targeted against migration and metastasis?

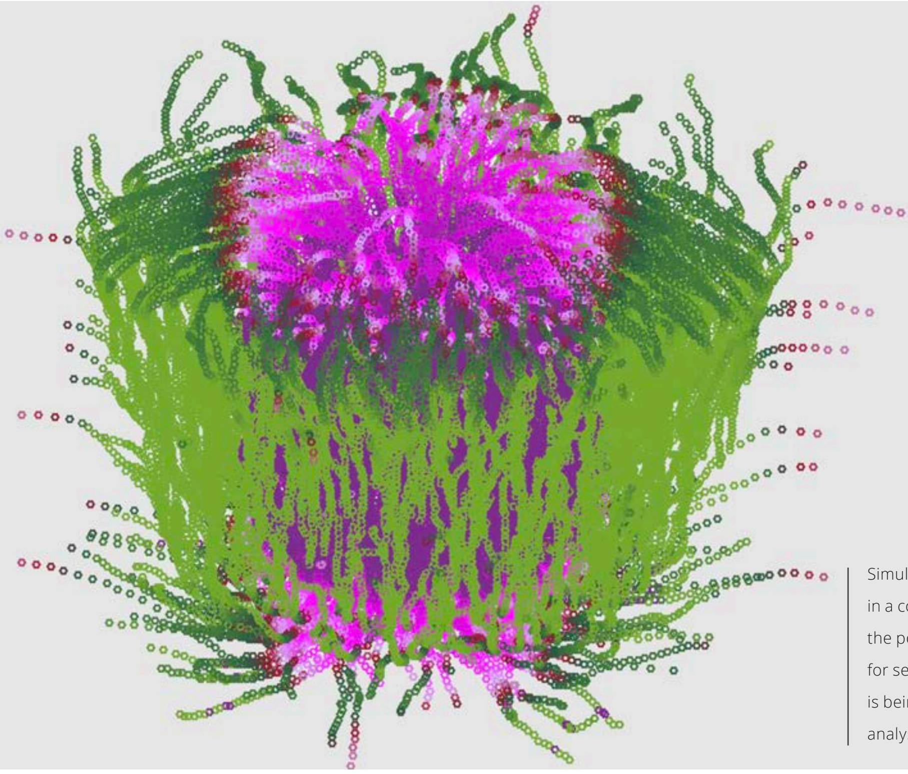
• How are cellular forces and shape changes coordinated across a tissue to achieve morphogenesis?

• How does the interplay of mechanical, chemical or neuronal cues shape and control the development and properties of spatial and spatio-temporal patterns, e.g. skin camouflage patterns in the cuttlefish or the regular pattern of hair follicles during embryonic development?



Quantitative life sciences

The biosciences have transformed into a strongly quantitative science. New technologies are constantly developed and refined to yield quantitative data on biological process across many spatial and temporal scales. One example are imaging approaches. Here two Nobel prizes were awarded in the years 2014 (fluorescence microscopy) and 2017 (cryo-electron microscopy). Another example are the various –omics and sequencing approaches, providing quantitative measurements on the composition and activity of a multitude of components simultaneously and time-resolved.



Simulation of 3D collective cell migration in a confined area. The image shows the positions of all cells superimposed for several time steps. The simulation is being used to test 3D cell migration analysis tools.

Franziska Matthäus

Group Information

At FIAS

since 2016; Fellow

Research Area

Cell motility
Mathematical modelling
Simulation
Data analysis

Team

Kai Kopfer
Armin Drusko
Katharina Becker
Nicklas Riebsamen
Zoë Lange

Collaborations

A. Frangakis, BMLS
E. Stelzer, BMLS, GU
D. Headon, Roslin Inst. Edinburgh
K. Breuhahn, Univ. Hospital Heidelberg
U. Klingmüller, DKFZ Heidelberg
M. Engstler, Univ. Würzburg

Cell motility is an important aspect of developmental processes, tissue regeneration, or the immune response. For all these processes, it is essential that cells respond correctly to external stimuli, given as chemical or mechanical cues. The response is regulated by complex intracellular signaling pathways, involving enzymatic reaction cascades and gene-regulatory processes. Perturbations in these complex pathways can lead to defect immune response, malformation in development, or diseases like cancer.

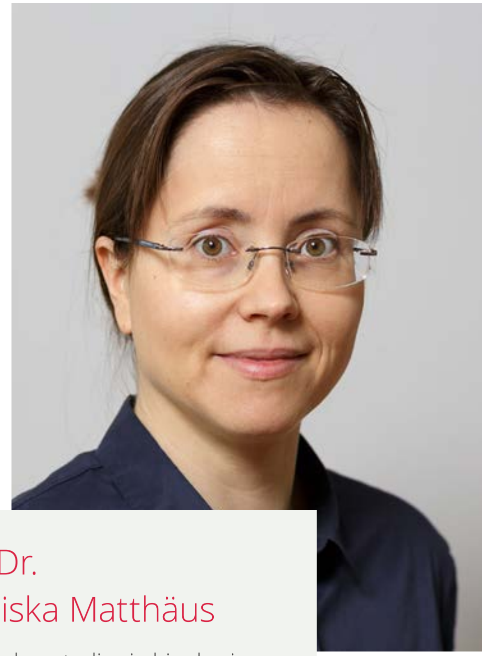
To better understand how intracellular processes, as well as cell-cell interaction, regulate collective cell behavior, like the formation of pattern or shapes, the group of Franziska Matthäus aims at the development of mathematical models coupling intracellular processes, cell-cell interaction mechanisms and the behavior and features of individual cells. Mathematical models are formulated in terms of agent-based approaches or systems of partial differential equations describing the dynamics of the spatially resolved cell density. All mathematical models are developed following an exhaustive analysis of data provided by experimental collaborators. Hereby, image processing tools, such as single cell tracking and particle image velocimetry (PIV) are applied, from which many quantitative spatiotemporal measures, such as velocity distributions, spatial velocity correlation, divergence, or vorticity can be derived.

Based on these quantities, agent-based models are derived, usually given in terms of systems of stochastic differential equations. These models capture motion and migration strategies, mechanics of cell-cell interactions, interactions with and response to external cues.

In 2017, the group finalized a project on the active migration of l neutrophils, cells of the immune system. Here a mathematical model, given as a system of partial differential equations, was developed to describe the interaction of chemical signal processing (symmetry breaking) in the cell with cell mechanics (force generation, membrane tension). The model explains how a chemical pattern, defining the migration direction, with higher concentration of the enzyme Rac at the cell front and a high concentration of the enzyme RhoA at the cell rear can be maintained, but also induced, by membrane tension. The model also accounts for force-generated changes in the cell shape in the course of migration or change in direction.

In further projects we were working on setting up a model for trypanosome motility based on worm-like chains. Trypanosomes are unicellular organisms causing sleeping disease. Apart from human and cattle they live in the Tse-tse fly, where microscopic studies revealed collective movement phenomena. Using our model we aim to study whether mechanical interaction between these organisms might result in movement synchronisation.

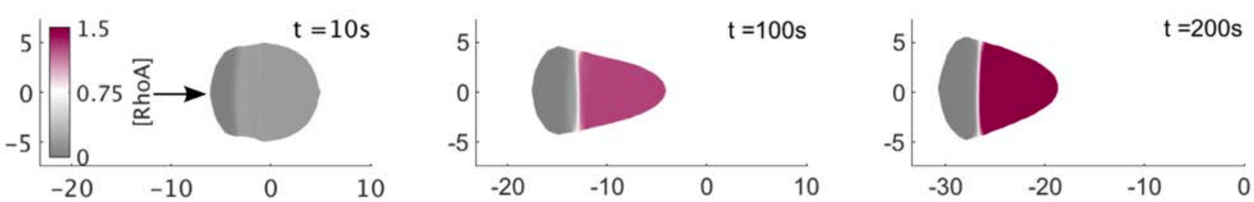
Finally, we are continuing our research on collective cell migration in embryonic systems (e.g. skin patterning in chicken and mice), working towards the development and application of 3D data analysis tools and 3D mechano-chemical agent-based models.

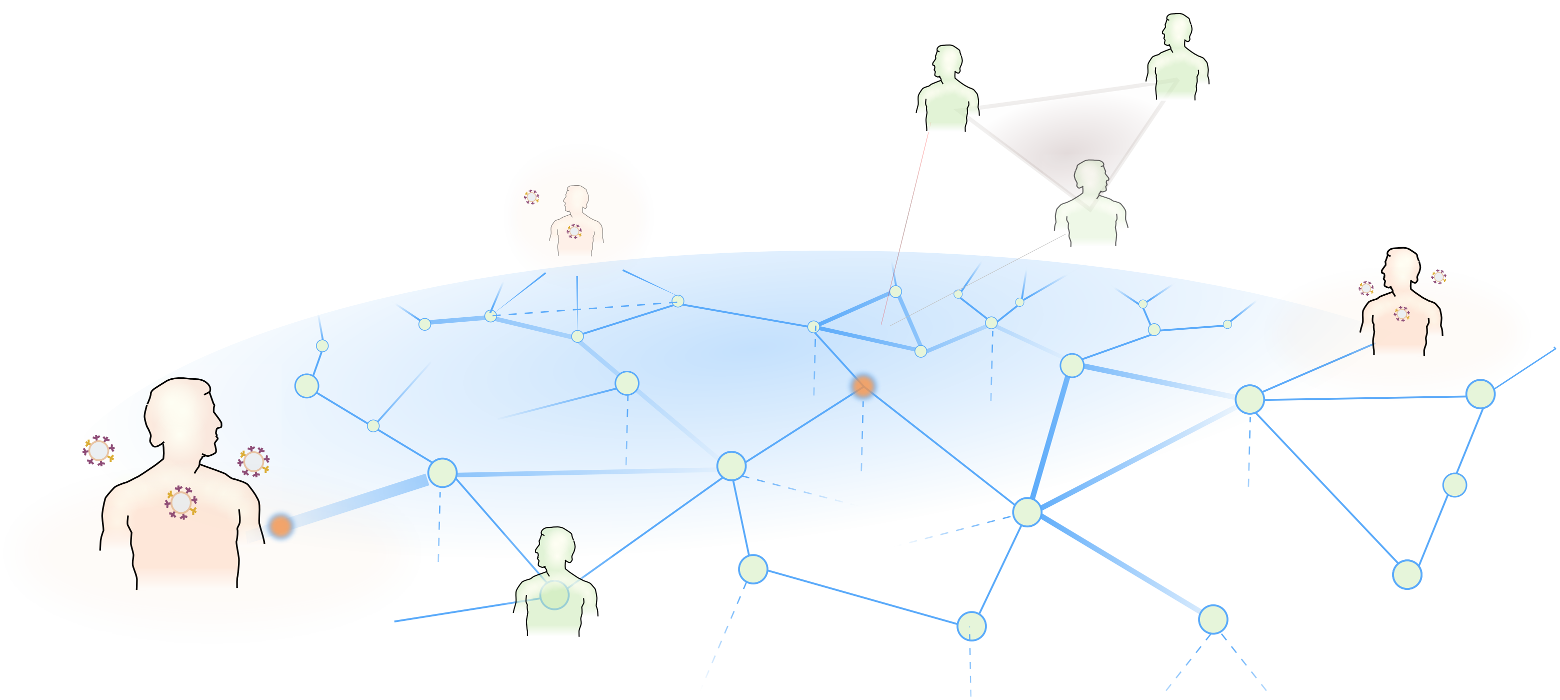


Prof. Dr.
Franziska Matthäus

Following her studies in biophysics at the Humboldt University of Berlin, including one year research stay at UC Berkeley (USA), Franziska Matthäus spent five years in Warsaw (Poland) on her PhD and scientific research. Between 2005 and 2016, she held two postdoc positions and a group leader position at IWR, University of Heidelberg. In 2016, she received a junior professorship at CCTB, University of Würzburg. Since October 2016, she holds a W2 position in bioinformatics, funded by the Giersch-Foundation, at FIAS Frankfurt.

Simulation of migrating neutrophil. The cell is stimulated and develops into the polarized cone shape while moving. Red color indicates high concentration of RhoA in the cell rear.





Group Information

At FIAS

since 2017; Research Fellow

Research Area

Infectious Diseases
Immune System
Mathematical modelling
Simulation
Data analysis
Control Theory

Team

Dr. Van Kinh Nguyen
Dr. Niharika Sharma
Dr. Cesar Parra Rojas
Dr. Alexis Almocera
Gustavo Hernandez-Mejia

Collaborations

Dunja Bruder (HZI)
Veronika von Messling (PEI)
Franklin Toapanta (Maryland University)
Yassine Taoufik (Hôpital Bicêtre)
Alma Alanis (Universidad de Guadalajara)
Frank Pessler (MHH)

Esteban A. Hernandez-Vargas

Throughout history, we have witnessed alarmingly high death tolls derived from infectious diseases around the globe. One of the deadliest natural disasters in human history was caused by a viral infection, the 1918 flu pandemic, which killed approximately 50 million people. Infectious diseases are latent threats to humankind - killing annually 16 million people worldwide. The spread of pathogens between infectious and susceptible hosts can be orchestrated via close physical interactions. Understanding disease transmission remains a central vexation for science as it involves several complex and dynamic processes. The link between the infection dynamics within an infected host and the susceptible population-level transmission is widely acknowledged. However, several technical aspects of the interface of within- and between-host are still in their infancy.

Fusing interdisciplinary activities, the groundbreaking ambition of our research is to apply mathematical modelling and computational simulations to *in vivo* experiments to

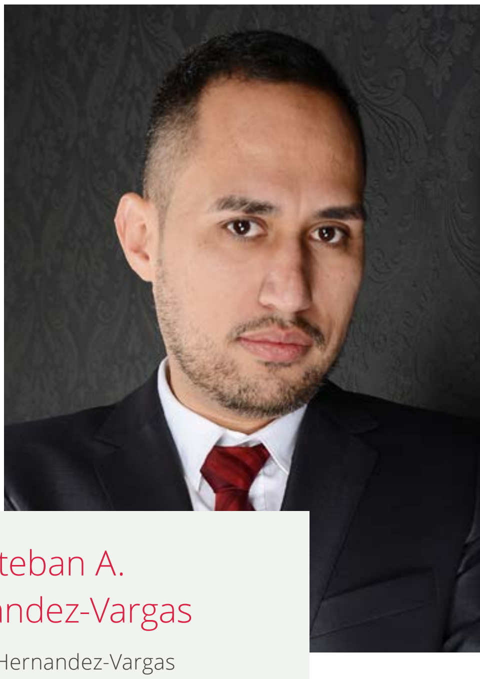
(i) dissect host immune-regulatory mechanisms during acute and chronic infections, and their respective shift in the elderly;

(ii) develop mathematical models for decision making to influence the use of vaccines and drugs; and

(iii) establish the foundations for predictively simulating disease transmission across scales - from the infected host-dynamics to the population level.

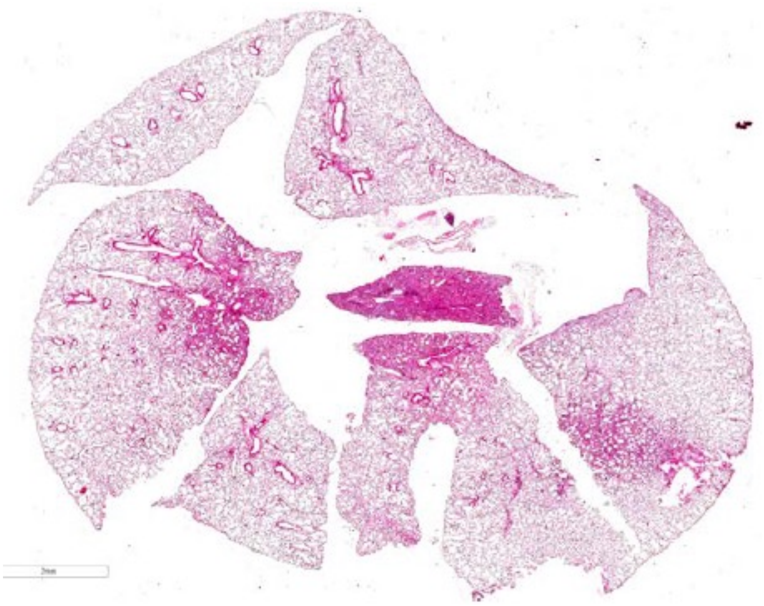
Our research group has a special interest in influenza infection. Up to 20,000 people succumb to the consequences of an influenza disease each year in Germany alone. However, in most cases, it is not the influenza virus that leads to serious complications, but a second bacterial infection acquired by the patient after the onset of influenza. In collaboration with experimental partners at the Helmholtz Centre for Infection Research, Braunschweig, we linked laboratory work with mice, which were infected concurrently with the influenza virus and *Streptococcus pneumoniae*, and computer-based modelling of the infection processes. Based on our results, we are presuming that the immune cells (macrophages) can no longer effectively eliminate the bacteria because of the inflammation response (IFN-γ) of the adaptive immune system to influenza. Our collaborators are testing the simulation predictions in laboratory experiments. With the aid of the established models, it will be possible to predict rational combinations of immune modulators and test them specifically. Thus, it is also conceivable that the insights gained from our research could result in therapeutic alternatives to antibiotics the coming years.

In another project, our group is on the quest for an HIV cure which is a central paradigm in infection research. At present, combined antiretroviral treatment (ART) potently suppresses the virus to undetectable levels in the blood. Nevertheless, virus persistence within different reservoirs and compartments presents a major barrier to eradicate the virus in patients undergoing long-term antiviral combination therapy. The journey towards curing HIV has already started, our group brings together a collaborative approach to assemble the necessary multidisciplinary expertise to advance holistic comprehension of the underlying mechanisms that establish HIV persistence.

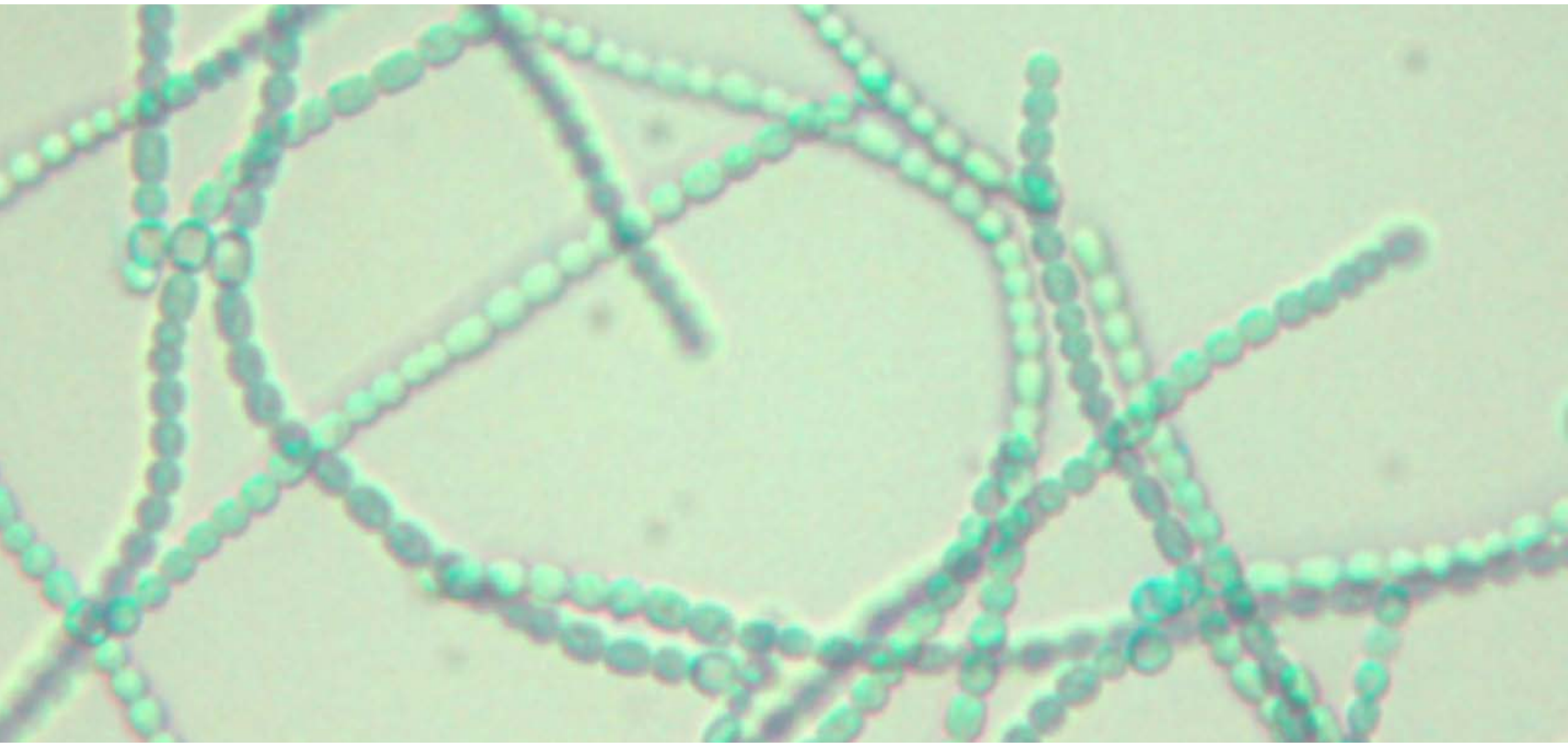


Dr. Esteban A. Hernandez-Vargas

Esteban Hernandez-Vargas obtained a PhD in Mathematics at the National University of Ireland. Esteban held a three-year postdoc position at the Helmholtz Centre for Infection Research, Braunschweig. In the same place, he established the Systems Medicine of Infectious Diseases research group. Since March 2017, he holds a Research Fellow funded by the Alfons und Gertrud Kassel-Stiftung, at FIAS Frankfurt.



Histopathological changes in the lungs of mice infected with influenza



Group Information

At FIAS
since 2017; Senior Fellow

Research Area
Cellular Homeostasis
Next generation sequencing
Big data analysis
Sequence alignments and phylogeny
Structural modelling of molecules
Structural dynamics of molecules
Network identification and modelling

Team
Stefan Simm
Mario Keller
Jannik Berz
Niclas Fester

Collaborations
SPOT-ITN
DynaMem
SFB 807 / 902
Nir Keren,
Hebrew Univ. Jerusalem
Arndt von Haesler, CIBIV, Wien

Enrico Schleiff

Organisms are ensembles of cells, which in eukaryotic systems are highly specialized in their function. Each of the cells are further divided in different subcellular compartments ensuring dissection of molecular and biochemical processes. The differentiation and the molecular networks of cells are highly regulated. The regulation ensures programmed development and responses to alterations of the environmental conditions typically defined as manifestation of tissue dependent interactions and responses to biotic and abiotic stresses. While the individual processes of the cellular program follow defined rules and laws, the behavior of the cellular ensemble and cellular responses have in parts properties of complexity.

In our research group we largely focus on plant systems. Plants are multicellular systems and by that as complex in their development and function as mammals. In addition, they are sessile organisms and thus evolved defense strategies to ensure cellular homoeostasis, cellular dynamics and cellular surveillance. We focus on the deciphering of processes underlying processes and general networks. The latter was exemplified for the metabolism of Arabidopsis thaliana and for the hormone synthesis pathways in plants . We unify experimental and theoretical approaches to define models explaining the global behavior, function and adaptation of plant cells.

For example, in the last two years we have focused on the description of processes of cellular adaptation during heat stress at global level.

On the one hand we discovered general modes of alternative splicing of mRNAs , on the other hand we described the molecular function of involved proteinaceous components. The combination of large scale analysis and description of molecular mechanisms enables us to define the responses to heat stress at different scales. In the recent years, we have also started to target specificities of the network in different cell types as well, however, these approaches are still to be expanded. For example we determined the processes in pollen, a highly specialized cell type, and compared the information to that of tissues generally investigated like leaves. Beside the description of cellular adaptation and surveillance we analyze the processes underlying cellular homeostasis. We aim at understanding the general principles leading to regulation of membrane structures and described a new lipid-transporter in the chloroplast membrane important to define the lipid composition under different environmental conditions. In parallel we formulate the general principles that regulate the biogenesis of the protein synthesis machinery – the ribosome – and that define the intracellular folding and distribution of proteins, both prerequisite for cellular homeostasis.

Beside plant systems we target cyanobacterial systems – bacteria with capability of photosynthesis – as well. On the one hand cyanobacteria are seen as ancestor of the central eukaryotic organelle plastids. Information about the bacterial system are important to understand the organelle function in the eukaryotic cell. In addition, cyanobacteria are important components of the ecosystem. The understanding of their function is prerequisite to develop reliable models of ecosystem behavior. Our main focus is the analysis of the communication of the bacteria with its environment, and thus we aim at understanding the transport mechanism of nutrition's, chemical molecules and proteins. We target the complex network for metabolite, iron, lipid and protein transport (Fig. 1). While we analyze the function of the molecular components of the transport systems we accumulate biochemical and biophysical data in order to obtain quantitative data for modelling, which is a future goal of our group.

In general, our research composed of experimental and theoretical approaches aims at a detailed description of cellular responses ranging from atomistic to organismic scale as well as in short term to long term response. For example, we have just opened a new research area where we aim at developing detection systems for ultrafast responses in plant cells to combine the description at second range with the phenotypic development of plants. One initial point was the analysis on the influence of lipids and proteins based on physicochemical properties on the dynamics within the membrane.

Prof. Dr. Enrico Schleiff

Prof. Dr. Enrico Schleiff, born on November 17, 1971 in Luckenwalde, studied physics at the Charles University in Prague, and later at the Gutenberg University in Mainz and at the University of Basel. In 1999, he did his PhD at McGill University Montreal, Canada. Later he worked at Christian-Albrechts-University zu Kiel, at the Ludwig-Maximilians-University, Munich, lead a junior research group set up by the Volkswagen Foundation. Since 2007, he has held a W3 professorship for Molecular Cell Biology of Plants at the Institute of Molecular Biology at JWG University Frankfurt, where he has been vice president, since 2012. Since 2017, he is also a member of the board of directors at FIAS.

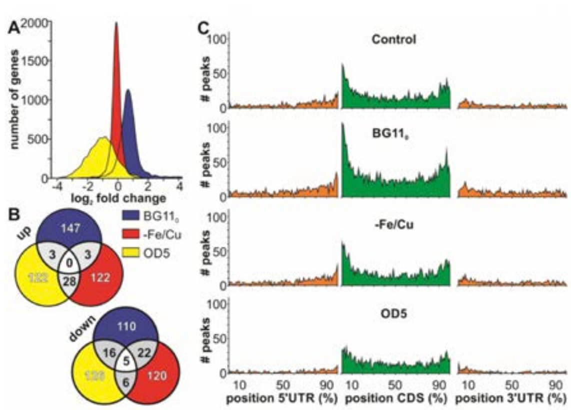


Figure 1.: NGS analysis of Anabaena sp. PCC 7120 response to iron starbation and high cell densities.

Systemic Risk

The latest financial crisis has painfully revealed the importance of a working financial system for the real economy. Many countries are still slowly recovering from the disruption of financial services, not least due to a lack of understanding what caused the near breakdown of financial institutions and how to best counteract the on-going economic downturn.

While practice and research on economic activity and risk management has focused on individual institutions it is only recently widening its view towards systemic interactions. At this level new mechanisms and feedback, some certainly still waiting to be identified, come into play which can threaten the stability of the financial system as a whole. To tackle this problem, our research takes an interdisciplinary approach drawing on expertise from machine learning, information theory and complex systems.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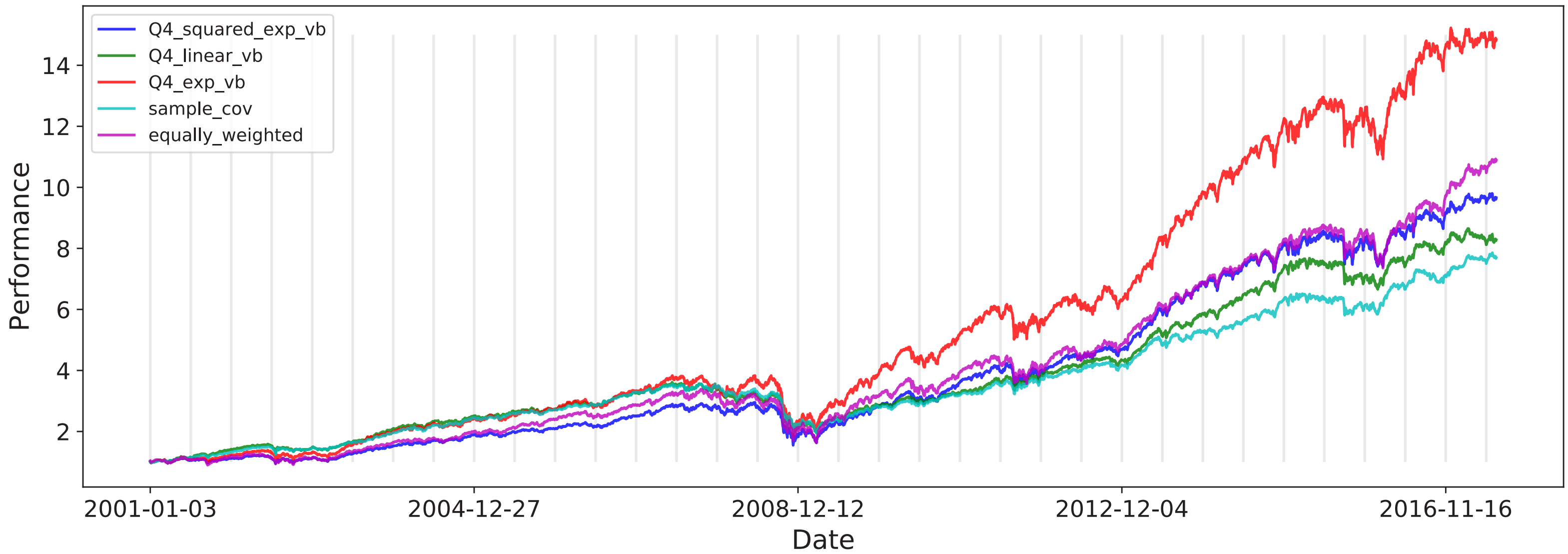


Group Information

At FIAS
since 2015, Fellow

Research Area
Information theory
Complex systems
Financial data analysis
Stochastic volatility models

Team
Rajbir Nirvan
Mirco Parschau

Collaborations
Juergen Jost,
MPI for Mathematics in the Sciences
David Wolpert,
Santa Fe Institute

Nils Bertschinger

Financial theory has long studied how to measure and model market risk. Yet, practice and research on economic activity and risk management has traditionally focused on individual institutions and is only recently widening its view towards systemic interactions. Especially the latest crisis has painfully revealed how apparently small individual risks could be amplified to market wide market distortions. Furthermore, the digital revolution in the form of artificial intelligence (AI) and machine learning (ML) will profoundly change every aspect of our life in the next few years. It starts from mobility, where we will have self driving cars and ends with medical treatments, where robots will take over critical interventions. Also the financial sector is already changing. AI helps us to spot patterns that humans could not spot. It might be fraud detection, credit assessment or just an agent giving advice how to invest your money and what assets to buy.

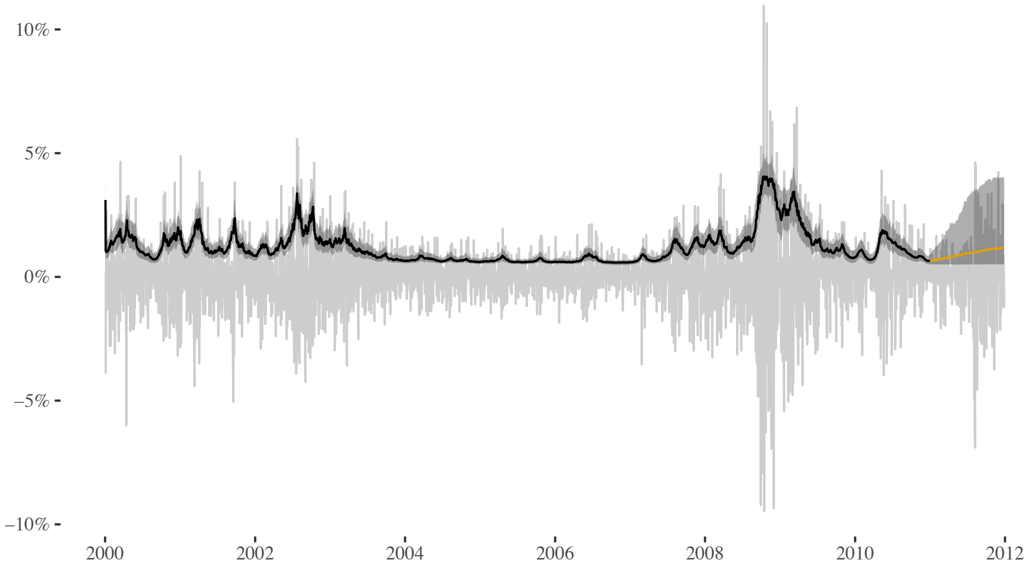
Due to the high success in a lot areas people are starting to allow AI-based machines to make automated decisions without active surveillance. With this, questions about AI-safety are arising, and the demand of AI being aware of its uncertainty is increasing. Bayesian ML methods appear promising in this respect with their focus on probabilistic modelling. Uncertainties are naturally expressed via probabilities and probabilistic models are therefore well suited to incorporate uncertainties as well as express confidence in their predictions. In our interdisciplinary research at FIAS we employ such methods in several ways.

In one of our projects we are working on Gaussian Processes, a kernel based flexible probabilistic model to express non-linear relationships, that allows for uncertainty quantification and makes excellent predictions for the future. Given a set of assets our system learns the correlation structure of the assets from past data. In turn, we use the learned structure to recommend the best investment portfolio that maximizes the return and minimizes the volatility. We evaluated our model on the stocks of S&P500 index and found significant improvements in the performance compared to current state-of-the-art models.

Beyond this purely statistical approach, we examine possible mechanisms that can cause strong market fluctuations. Several mechanisms such as herding behavior of traders or chartist strategies are thought to amplify market fluctuations. Especially in the area of econophysics corresponding models have been developed and each illustrate possible mechanisms and their consequences for the dynamics of prices. Again, by using modern tools from ML we were able to compare several different mechanisms on empirical grounds. In particular, we found strong evidence against one of the proposed mechanisms, essentially ruling it out as an explanation for financial market dynamics.

Prof. Dr. Nils Bertschinger

Nils Bertschinger is Helmut O. Maucher-Stiftungsjuniorprofessor for systemic risk. He studied computer science at RWTH Aachen and received his PhD from the Max-Planck Institute for Mathematics in the Sciences about information processing in complex systems. At FIAS he now applies methods from information theory and machine learning to investigate how systemic risks can develop and spread in financial systems.



Econophysics model with herding behavior among traders fitted to daily returns of the S&P 500 index. Model fit and predictions of market fluctuations are competitive with modern econometric methods.

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