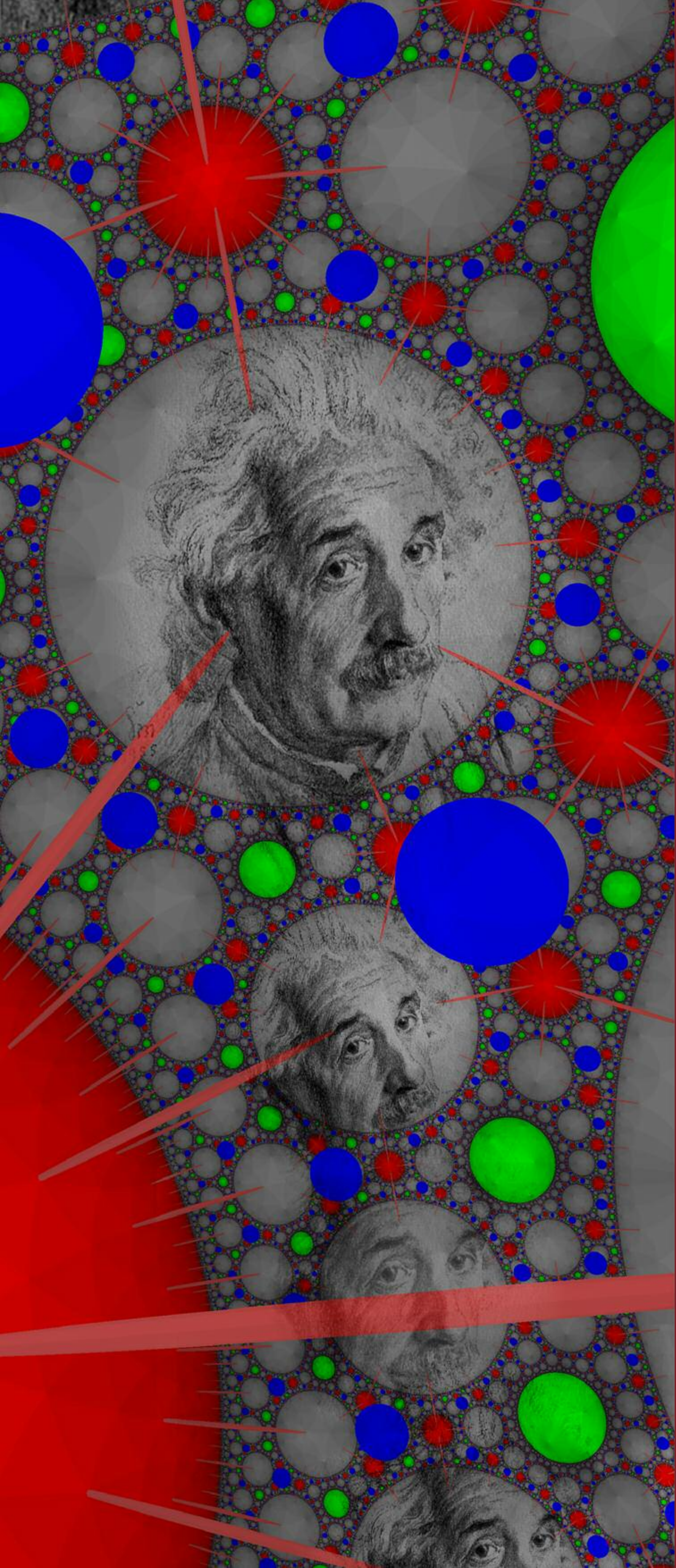


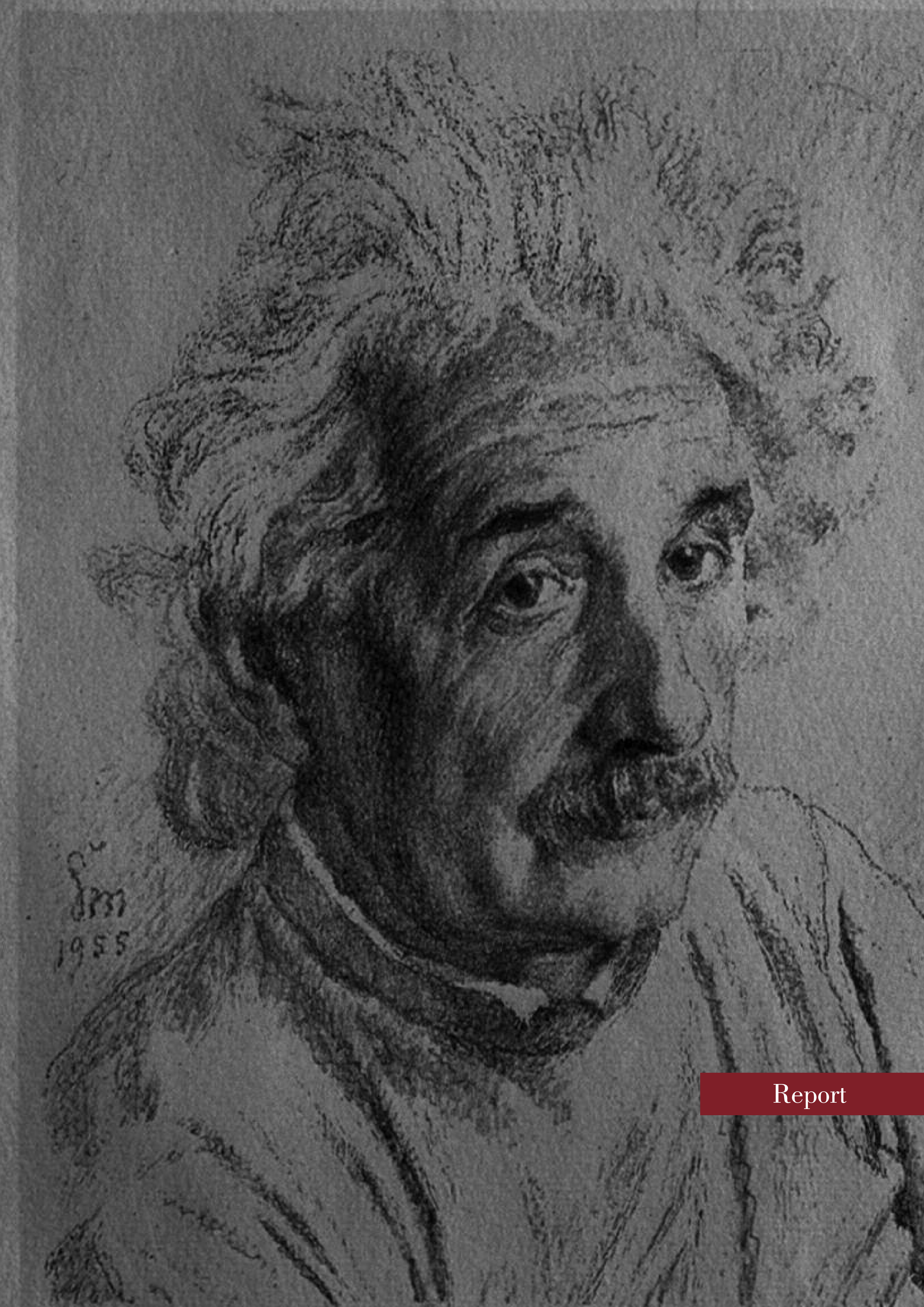
MAX-PLANCK-GESELLSCHAFT

Biennial Report 2008/2009

Max-Planck-Institut für Gravitationsphysik

Albert-Einstein-Institut

Max-Planck-Gesellschaft
zur Förderung der Wissenschaften e. V.



Report

Report by the Managing Director

This report surveys the activities of the Max Planck Institute for Gravitational Physics (Albert Einstein Institute, or AEI for short) during the years 2008-9. The wide range of research now going on at the AEI is a remarkable testimony to the breadth of the impact that Albert Einstein's fundamental work 100 years ago is now having in physics, astronomy, and indeed in everyday life. A small sampling:

- AEI scientists at our branch institute in Hannover have developed the most powerful ultra-stable continuous-wave lasers ever made and are delivering them to our American partners in a worldwide collaboration to detect gravitational waves for the first time; at the same time some of their colleagues in the QUEST Centre of Excellence in Hannover, of which the AEI is a partner, are developing next-generation medical lasers for correcting vision.

- The AEI is building key parts of the LISA Pathfinder space mission, which will introduce a new way of measuring gravity with lasers; at the same time other AEI scientists are preparing to apply this new technology in two kinds of space missions, one to measure gravitational waves emitted by enormous black holes half-way across the known universe, and the other to measure the Earth's gravity and how it changes much more accurately than ever before, with the aim of learning more about the big environmental changes now happening around the globe.

- In our home institute in Potsdam, AEI scientists are grappling with the challenge of unifying Einstein's theory of general relativity with the theory of quantum physics that is the foundation of our understanding of matter; this research investigates the very smallest imaginable structures and yet has deep implications for our understanding of the earliest moments of the entire universe and even of what might have come before the Big Bang.

The AEI is still growing, especially at AEI/Hannover, as the Observational Relativity and Cosmology Department is building towards full strength, as the LISA Pathfinder group has grown, and most notably as the award of the QUEST Centre of Excellence to the University of Hannover and the AEI in 2008 has brought many more scientists into the AEI. There are roughly as many scientists now working at AEI/Hannover as at AEI/Golm.

The QUEST centre is a major research development for the AEI. Germany's federal government initiated a program of supporting particularly strong research groupings with large grants to allow them to consolidate and achieve research leadership in their fields. The only physics award in northern Germany was to the grouping centred on the University of Hannover quantum optics group and the AEI: QUEST (Quantum Engineering and Space Time Research) has brought more than a dozen new professorships to Hannover in addition to research funding. AEI Director Karsten Danzmann is deputy coordinator of the centre, and two other directors (Bruce Allen and myself) are members.

Despite their geographical separation, there are strong working links between AEI/Golm and AEI/Hannover in gravitational wave research, supported by videoconferencing (for meetings and seminars), and by a jointly run International Max Planck Research School (IMPRS) for Gravitational Wave Astronomy. In fact, the Astrophysical Relativity Department has staff on both sites in the field of gravitational wave data analysis. The efforts related to the LISA project are in Golm and those for the ground-based detectors (GEO, LIGO, Virgo) are in Hannover. A research highlight article describes the work on LISA, where the focus now is on developing sensitive data analysis methods that will unravel overlapping signals from thousands of sources throughout the universe.

The numerical relativity group in Golm supports both LISA and the ground-based data analysis efforts, taking advantage of a breakthrough made by former AEI scientists working in the USA that have made it possible finally to run long simulations of black holes orbiting one another without encountering numerical problems. These detailed simulations of mergers of black holes and of neutron stars now routinely predict gravitational waveforms that help improve the sensitivity of the data analysis. One of the research highlight articles below deals with the new results on neutron star mergers that the AEI group has obtained.

Within the Golm institute there is close cooperation between the Quantum Gravity and Geometric Analysis and Gravitation Departments, which jointly run the IMPRS for Geometric Analysis, Gravitation and String Theory. There is also joint research between the numerical relativity group in the Astrophysical Relativity Department and the Geometric Analysis and Gravitation Department, and we have had joint lecture series on equations of motion and on cosmology, which have involved all three Golm Departments.

The Astrophysical Relativity department (Bernard Schutz) has strengthened its research in astrophysics, with work on the stellar environment of the massive black holes in the centres of galaxies. This is described in one of the research highlight articles below.

The Geometric Analysis and Gravitation department has taken a major step toward strengthening our collaboration with Potsdam University. A cooperation agreement was reached to jointly develop a research focus on geometric analysis and geometric evolution equations. This involves two senior appointments at Potsdam University and funding from the Max Planck Society for a five-year independent research group. Two research highlight articles below describe work from this department that deepens understanding of the fundamentals of general relativity.

The Quantum Gravity and Unified Theories department of Hermann Nicolai is one of the leading places in the world where scientists work toward a fundamental unification of gravitation theory and quantum theory; indeed, AEI scientists work both on string theory and on loop quantum gravity, the two most promising avenues. Two research highlight articles below explain the progress that some AEI scientists have made in showing how string theory can help physicists toward the goal of a unified theory.

In Hannover the Laser Interferometry and Gravitational Wave department (Karsten Danzmann) plays a major role in all the important gravitational wave efforts; it is providing ultra-stable high-power continuous lasers to the LIGO project and it is constructing major parts of the payload for the LISA Pathfinder spacecraft. It is also developing related technologies for space measurements of the earth's gravity, which can reveal much about the sub-surface geology, mineralogy, and hydrology. Research highlight articles on both LISA Pathfinder and the department's powerful lasers may be found below. In addition, the department operates the GEO600 detector, which was the only operating detector worldwide for part of the period covered by this report, while other detectors were being upgraded. The department is starting to build a new laboratory interferometer which will be the most advanced facility in the world for developing technologies for third-generation gravitational wave detectors. The AEI is playing a major role in an EU-funded design project for such a detector.

The Observational Relativity and Cosmology department of Bruce Allen has developed the Einstein@Home project into a major data analysis facility for the ground-based network of detectors. Over 100,000 computers around the world donate free computer power to searches for the very weak continuous gravitational waves that are expected from spinning neutron stars. But besides this distributed computer facility, the department has also built the Atlas Cluster, which at the time it began its work was one of the fastest in Germany. Some of the mathematical techniques needed for Einstein@Home are discussed in a research highlight article. Another article shows the importance of geometry for making computer-intensive data searches as efficient as possible.

It is a pleasure to report that members of the AEI continue to receive awards, professorships, and other international recognition for their work:

- *Gerhard Huisken* was awarded the Commemorative Medal of the Faculty of Mathematics and Physics, Charles University Prague, in 2009.

- *Karsten Danzmann* was elected a Fellow of the American Physical Society in 2009.

- *Bernard Schutz* was elected an Honorary Fellow of the Royal Astronomical Society in 2009 for his distinguished leadership in stellar astronomy and gravitational wave research.

- *Matthias Staudacher* received the 2009 Academy Award of the Berlin Brandenburg Academy of Sciences and Humanities, the Academy's most prestigious award after the Helmholtz Medal. Matthias also won the appointment to a Professorship at Humboldt University, which he will take up in 2010.

- *Thomas Thiemann* won a Professorship at Erlangen University, which he took up in October 2009.

- *Niklas Beisert* has won a Chair in Mathematical Physics at ETH Zürich, Switzerland, which he will take up in 2011.

- *Christian D. Ott* has won an Assistant Professor position at the California Institute of Technology in Pasadena, California, where he joins Yanbei Chen, who moved to a similar position from the AEI at the end of 2007.

- *Jan Metzger* was appointed an Associate Professor (W2) at Potsdam University and will continue working closely with Gerhard Huisken and others at the AEI, and *Domenico Giulini* was appointed Associate Professor at ZARM, Bremen, as part of the QUEST center of excellence.

- In 2008 the AEI was named to the InfoWorld 100 list, *InfoWorld*'s highest honour, which recognizes IT projects that exemplify intelligent, creative uses of technology. AEI was one of only two 'Research and Development' winners on the list. The award was for the ATLAS compute cluster, designed and built by *Bruce Allen* and his team at AEI/Hannover.

Bernard F Schutz

Content

Research Highlights (contd.)

Max Planck Institute for Gravitational Physics (Albert Einstein Institute)

The Albert Einstein Institute was founded in 1995 by the Max Planck Society for the purpose of pursuing research into the fundamental laws of gravitation. The Institute was established in Brandenburg as part of the expansion of the Max Planck Society after the reunification of Germany.

The Institute moved from Potsdam to its new building in Golm in 1999. In 2002 the Institute opened a branch at the University of Hannover that specializes in the development of gravitational wave detectors. The GEO600 detector is operated by the Hannover branch.

The AEI was founded in 1995 as a result of the initiative of its founding Director, Jürgen Ehlers. In our previous biennial report we conveyed the very sad news that Professor Ehlers passed away on 20 May 2008, ten years after he retired. The vision that Ehlers displayed in convincing the Max Planck Society to establish the institute has been amply validated by the rapid growth of the AEI over the last fourteen years, including its expansion with the opening of its branch institute in Hannover, devoted to experimental gravitation. During this period it has become the largest research institute in the world devoted to gravitational physics, and it serves as a focal point for scientists working internationally in many areas. More than one three hundred scientists visit each year; the institute regularly hosts workshops and conferences; we publish one of the principal scientific journals in relativity and host community-service websites; and many AEI staff occupy leading positions in big collaborations, external institutions, and in public advisory bodies. We also take satisfaction in the careers of the many former AEI scientists who now occupy leadership positions in research and science management around the world.

The years 2008-9 have been years of consolidation after the large changes in the previous two years, but also further growth. Professor Allen, our latest Director in Hannover, has installed the award-winning Atlas computer cluster, the most powerful cluster in the gravitational wave collaboration and at the time one of the most powerful computers in all of Germany. Our International Max Planck Research School (IMPRS) in Geometric Analysis, Gravitation, and String Theory was reviewed and extended by the Max Planck Society. We gained two new independent research groups in the area of quantum gravity. Our GEO600 gravitational wave detector was the only operating detector while the larger instruments in the USA and Italy were being upgraded. And the AEI began to get involved in Earth geodesy, as a further application of the technologies we are developing for the LISA space-based gravitational wave detector.

Science of the AEI: Relativity in physics and astronomy

The founding of the AEI in 1995 came at a time of enormous expansion of interest in and importance of Einstein's theory of gravitation, general relativity. During the first 50 years after Einstein proposed his theory in 1915, mathematicians and physicists struggled to develop techniques that were capable of unravelling the mysteries of the equations and making sound physical predictions. No physical theory had been as challenging mathematically as general relativity. But elegant and fundamental mathematical work in the 1960's and 1970's put the theory on a sound footing: theorists understood black holes, gravitational waves, gravitational lensing, and cosmology well enough to make confident physical predictions.

This was just in time, because general relativity was becoming important to astronomy. The application of advanced technology to astronomical observing from the ground and in space led to the discovery of many new and exotic phenomena that could be explained only by using relativity. Black holes, gravitational lensing, the cosmological constant – it is a rare conference on astronomy today that does not deal in an almost routine way with some or all of these concepts, which two decades ago were regarded as exotic, if not impossible.

In recent years the most striking technological advances have been in the design and construction of gravitational wave detectors of enormous size, based on the technique of laser interferometry. A worldwide network of such instruments has now completed more than three years of full-time observing, including the AEI's GEO600, a collaboration with British and other European scientists. In the more distant future, the joint European-American space mission LISA will turn gravitational wave astronomy into a field rich in signals and exotic sources. Preparations for LISA include contributing to the LISA Pathfinder mission, due for launch in 2013/14, a technology-proving mission in which AEI scientists in Hannover are playing a leading role. The design of LISA itself, and the setting of its science goals, are also activities in which AEI scientists have leadership positions.

While astronomers were discovering how exotic our universe can be, physicists studying fundamental physics began turning to general relativity as well. By the mid-1970's they had achieved considerable success in understanding, at least in outline, how all the forces of nature except gravitation fit together into a single theory. They were then ready to try to include gravitation into the unified picture that was emerging. Virtual black holes, black hole entropy, the cosmological constant, inflation, wormholes, strings, eleven dimensions – fundamental physicists today work in the exciting border areas between classical gravitation and quantum field theory, searching for the "theory of everything".

Mathematical work in general relativity continues to flower. The theory still presents significant challenges that affect the way it is used in astronomy and particularly in quantum gravity. The field is ever interested in new developments in any field of mathematics that can aid understanding. And, as so often happens in physics, the theory is stimulating the creation of new mathematical concepts and constructs that themselves become interesting research topics.

Structure and research of the Institute

The AEI brings all these threads of research together into a single institute, where scientists working in all these areas can interact with one another, learn from one another, and collaborate with one another. The Institute has five divisions: three in Golm and two in Hannover.

- The Astrophysical Relativity Division (Golm/Schutz) specializes in the applications of relativity in astronomy. It has two main groups, one concerned with the search for gravitational radiation and the other with the computer simulation of the dynamics of black holes and neutron stars. The gravitational radiation group is very heavily involved in the ongoing analysis of the data from the large gravitational wave detectors, and this analysis could at any time make the first direct observations of signals from distant astronomical sources that are carried by the gravitational field itself. The division's numerical relativity group is one of the largest in the world, developing techniques for studying situations that may be important sources of gravitational waves but that are not amenable to analytic calculation or approximation: collisions and mergers of black holes and neutron stars.

- The Geometric Analysis and Gravitation Division (Golm/Huisken) extends the techniques that have unlocked the basic meaning of the theory. The division is a leader in understanding the local and global properties of solutions to Einstein's equations, both those that are dynamical and emit gravitational waves, and those that develop singularities, places where the predictive power of general relativity itself breaks down. The division is broadening its research into areas of geometrical mathematics that have proved powerful in studying general relativity in the past and which show great promise for further progress and for applications in numerical relativity and quantum gravity.

- The Quantum Gravity Division (Golm/Nicolai) studies methods for developing a theory of gravitation that replaces general relativity by making it compatible with quantum mechanics, and if possible unifying gravity with the other forces of nature at the same time. There are two main threads to research in this area around the world, called string theory and canonical quantization, and the AEI is one of the few places in the world where scientists study both. It is in this research area that the most fundamental insights and the most exciting changes in our picture of how Nature is organized can be expected.

- The Laser Interferometry and Gravitational Wave Astronomy Division (Hannover/Danzmann) develops and operates the GEO600 gravitational wave detector, in cooperation with its UK partners in Glasgow and Cardiff. The GEO collaboration is a world leader in detector technology. The optical and mechanical systems they designed for GEO600 are planned to be a key component in the upgrade of LIGO that will finish around 2014. The Division also plays a leading role in the development of the LISA space-based gravitational wave detector, which is competing for a launch by the European Space Agency (ESA) and the US space agency NASA. Danzmann is the European Mission Scientist for LISA. In preparation for LISA, the Division has a major role in the LISA Pathfinder mission, which will be launched by ESA in 2013/14 to test the measurement and control systems designed for LISA.

- The Observational Relativity and Cosmology Division (Hannover/Allen) was established at the beginning of 2007 with the appointment of Bruce Allen from the University of Wisconsin at Milwaukee. Allen had previously been a frequent visitor to the AEI and AEI scientists already had many collaborations with him. The new division will also be active in ground-based gravitational wave data analysis and in developing the interface between data and theory (which is called phenomenology). The overlap with the activities of the Astrophysical Relativity Division is strong at the beginning, but this will change as the Golm division focuses more of its work on space-based gravitational wave detection.

In addition to its permanent research divisions, the AEI hosts three fixed-term independent research groups:

- The Duality and Integrable Structures research group is funded by the Max Planck Society under a grant to its leader, Niklas Beisert, in 2006. Its research focuses on the integrable structures that have recently been identified in gauge and string theories. The aim is to deepen our understanding of these models on which classical and modern particle physics is founded. This group is expected to work for a term of five years.

- In January 2009, Daniele Oriti established the group Microscopic Quantum Structure and Dynamics of Spacetime, a Sofja Kovalevskaja Independent Research Group funded by the A. von Humboldt Foundation. The aim of this research is to examine the implications of current theories of quantum gravity for the structure of space and time on the very smallest scales: is it a continuum, or is it (as is often expected) a complex and continually changing web of lower-dimensional structures? This is one of the most fundamental questions that quantum gravity tries to address.

- Canonical and Covariant Dynamics of Quantum Gravity: this group, led by Bianca Dittrich, started up in September 2009 with funding from the Max Planck Society with an initial duration of 5 years. The research of the group focuses on the construction and examination of quantum gravity models. The aim is to improve current descriptions for the dynamics of quantum gravity in canonical and covariant formulations and in particular to obtain a better connection between these two formulations.

To support this work the AEI provides in Golm an extensive library and one of the best computing environments available to any research institute of its size. The library is a leader in providing electronic access to journals for our scientists. Our computer installation includes not only high-performance workstations and servers, but two teraflop-class cluster computers in Golm and the Atlas cluster in Hannover. In Hannover as well the Institute hosts a very modern and highly capable machine shop that supports both ground-based and space-based experimental activities and it is building a 10-m prototype interferometer to do research on so-called third-generation gravitational wave technologies.

Even more than the physical facilities, the Institute sees the work of its support staff as a key part of its performance: caring for the needs of visitors, maintaining the computer systems and making them accessible to all, ensuring that the library responds to the needs of scientists, supporting scientists who need to administer external research grants – all of these must happen if the research environment is to be productive. Our public outreach and public relations activities are also given a high priority, because there is an especially strong interest among the general public in research associated with Einstein's theories.

The Institute also maintains an extensive guest scientist program. The lists in this report of guest scientists for 2008/9 and of seminars given at the AEI show how rich the intellectual environment is.

QUEST: Partnership in quantum engineering

As the largest research institute of its kind in the world, the AEI occupies a key position not only in world research in relativity but especially in Germany. It has begun to use its special position to assist universities to strengthen their research in gravitational physics and to train new scientists in this exciting and expanding area. The most exciting such development so far is the QUEST Center of Excellence.

QUEST (Centre for Quantum Engineering and Space-Time Research) was awarded in 2007 as the outcome of a competition among many

German universities for funding earmarked for strengthening research in areas where Germany had world-class leadership positions. At the core of QUEST are the AEI/Hannover, the Institute for Quantum Optics of the University Hannover, to which are added a number of partners, including Geodesy, Theoretical Physics and Mathematics Institutes of the University Hannover, the Laser Zentrum Hannover, the Physikalisch-Technische Bundesanstalt Braunschweig, the Centre for Applied Space Technology and Microgravity (ZARM) at the University of Bremen, AEI/Golm, the GEO600 detector, and industrial partners.

QUEST is taking quantum optics out of the realm of pure research and into the new and rapidly emerging applications. Rapid research progress has opened new horizons in quantum metrology for testing fundamental physical laws, reaching unprecedented levels of precision in measurements of space and time, and applying sensors based on these novel quantum technologies in global geodesy, inertial sensing, navigation and laser ranging. The center focuses on four interdisciplinary areas of research: *Quantum Engineering, Quantum Sensors, Space-Time Physics, and Enabling Technologies*. QUEST's funding strengthens its research capabilities and sustainability through the implementation of several new professorships for renowned experts, attractive positions for excellent young researchers and leading postdoctoral positions in junior research groups.

Other initiatives with universities

The AEI participates in at least four further cooperative initiatives with universities in Germany. The first is its long-standing annual vacation course in relativity, offered in cooperation with the University of Potsdam, in which the AEI provides students from all over Germany the opportunity to learn the foundations of general relativity here. Those who want to pursue the subject further may then be able to work at the AEI. The Institute, through its partnerships with Potsdam University, the Humboldt University of Berlin, and the University of Hannover, can supervise work towards advanced degrees of those universities.

A second form of cooperation with universities is the participation of the AEI in three SFBs (*Sonderforschungsbereich* = special research area), in which it collaborates with scientists at German universities in areas of mutual interest. These research grants, which run for many years and can involve hundreds of scientists, are a principal source of support for university research. The SFB TR7 "Gravitational Wave Astronomy" joins the AEI with the Universities of Jena, Hannover and Tübingen and the Max Planck Institute for Astrophysics in Garching in a wide-ranging research program, which is helping to develop a university research community supporting the experimental activities of GEO600 and LISA. For over a decade, the AEI Hannover has been a major player in the SFB 407 "Quantum Measurement", involving scientists from the University of Hannover, the PTB Braunschweig and the Laserzentrum Hannover. This very successful SFB ended in 2009, having reached the maximum permitted 12 years' duration. Both these SFBs have benefited from joint research with members of the QUEST Center in Hannover. In 2005 a new SFB in mathematics and theoretical physics entitled "Space-Time-Matter" started. This SFB is a joint project between the AEI, Potsdam University, Free University and Humboldt University.

The AEI's third and fourth initiatives are its two International Max Planck International Research Schools (IMPRS). The first one, started in 2004 and renewed in 2008, is in Geometric Analysis, Gravitation, and String Theory. It is a cooperation with Potsdam University and the Free University of Berlin. The second, which began in 2006, is in Gravitational Wave Astronomy, and is a cooperation with Hannover University. This, too, benefits from association with QUEST. These two schools not only offer new opportunities to German students to study at the frontiers of physics, but they also bring good students to Germany from many countries. IMPRS's are a very successful recent innovation by the Max Planck Society. They offer instruction through the medium of English and provide students with a "graduate-school" environment in which to study for a Ph.D., something which had been lacking at German universities before.

The AEI naturally also trains many young German and foreign postdoctoral scientists in its research groups. Our recent experience is that when these young scientists leave the AEI they generally go to excellent academic positions, mostly outside Germany. In time, and despite the current serious financial pressures on the German research and education systems, we hope that a larger fraction of our young scientists will enter academic positions at German universities, so that they can offer many more German students the opportunity to learn about and work in the rapidly developing field of research in gravitation.

Another resource that the AEI provides for the university community, both within Germany and outside it, is the internet-based review journal *Living Reviews in Relativity*. This has become a standard reference not only for relativists but for researchers in allied subjects. The quality of the editorial board and of the reviewers has led to very high usage figures on our website, and all of our articles have been downloaded hundreds (in some cases thousands) of times. In recent years we have started up three sisters journals, Living Reviews in Solar Physics, Living Reviews in European Governance, and Living Reviews in Landscape Research. Further journals are expected to join the family in the next year or two. The publishing activities are in association with the newly-established Max Planck Digital Library.

The research vision of the AEI

In a longer view of our research, there are goals and challenges that motivate AEI scientists. We work from day to day, writing papers, holding meetings and other discussions, thinking in quiet isolation, travelling to work with collaborators; but all of this activity accumulates to move research in certain directions and to prepare for certain expected developments. Here is a partial list.

- The first direct detection of gravitational waves will place the AEI at the center of this new branch of astronomy. As a member of the most sensitive network of detectors ever constructed, the GEO600 instrument should participate in these first detections. The data analysis group, our gravitational-wave theorists, and the numerical simulations group will also play key roles in the interpretation of the first observations.

- Software and supercomputers are now powerful enough to do realistic calculations in general relativity: to perform long simulations of black holes and neutron stars merging, to perform somewhat realistic calculations of the formation of neutron stars and black holes, and to begin to explore mathematical questions, such as the development of singularities, that have not been solved analytically so far. This capability opens up tremendous new opportunities for exploring general relativity, as well as for assisting the discovery and interpretation of gravitational waves.

- The launch of new space-based astronomical observatories – not only LISA but also new observatories for the cosmic microwave background radiation, for X-ray astronomy, for cosmological observations in the infrared, and more – and the commissioning of many new sophisticated ground-based telescopes – will not only challenge us with unexpected discoveries about black holes, their relation to the formation of galaxies, and the overall structure of the universe, but they will also provide us with a massive amount of quantitative information about the universe that will be unprecedented in its precision and detail. Gravitational theory will be much in demand for the interpretation of this data.

- Mathematics is advancing rapidly in many areas, especially in those that use computers as an aid to proving theorems, exploring geometrical concepts, and gaining insight into complex situations. Relativity provides an attractive area for the application and even the development of new techniques, offering challenging problems in singularities and in the global structure of solutions. The cross-fertilisation of relativity and other branches of mathematics can lead to fruitful research in the next decade.

- If the optimism of scientists working today in string theory and in loop quantum gravity is justified, then in only a few years we may see the emergence of a coherent but mathematically complex theory that shows how gravity is related to all the other forces of nature. Already exciting and radical ideas are emerging about how these theories might alter our notions of gravity, explain the Big Bang, and predict completely new phenomena. Work to understand the theories and explore predictions that will be testable by experiments and by astronomical observations will require new mathematics and creative young minds. For the first time it may be possible to ask sensible questions – and expect sensible answers – to questions like: what happens inside black holes, what happened "before" the Big Bang, what is space-time like on the very smallest scales, how many dimensions does space really have, and what is time itself?

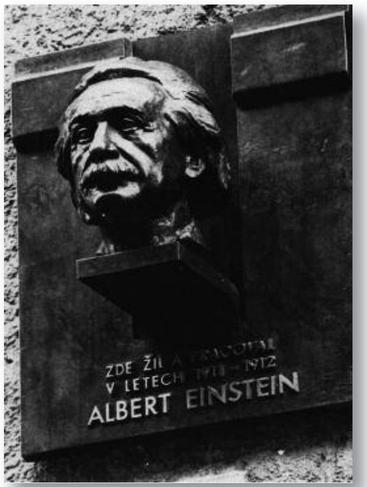
The work of the AEI in 2008/9, as described in these pages, should be seen in the light of these challenges and opportunities. In almost every case, scientists at the AEI are addressing issues that lie at the heart of progress on these questions. A Max Planck Institute is a long-term investment in a research field, and for gravitational physics the prospects for the future are especially exciting. We look forward to many more years of research with optimism and anticipation.

Bernard F Schutz

Einstein in Prague

The price of achievement is toil; and the gods
have ruled that you must pay in advance.
(Hesiod: Days and Works)

In March 1910, Albert Einstein received an offer of a full professorship at the German part of the Karl-Ferdinand University in Prague. One of the recommendation letters came from Max Planck: "…This principle [special relativity] has brought about a revolution in our physical picture of the world that can be compared only to that produced by Copernicus."



In Prague, Einstein and his family lived in Smíchov in what is now Lesnická Street (No.7). A bust was unveiled on the building on the occasion of Einstein's centenary in 1979.

Albert Einstein was appointed full professor for theoretical physics on April 1, 1911: a 100 years ago.[1] He came with his wife Mileva and two young sons. The Einsteins lived in Smíchov, not then considered a fashionable part of the city, but their flat on what is now Lesnická Street (No. 7) was modern and Einstein liked to recall his walks to the Institute over the Vltava (Moldau) River.

How did it happen that Einstein was invited to Prague? The German University in Prague had a section of mathematical physics headed by F. Lippich who was due to retire in the autumn of 1910. In addition, the German University considered it a drawback that it had only a section of mathematical physics rather than the Institute of Theoretical Physics that existed in the Czech University. The professorial staff of the German University therefore decided to establish an Institute of Theoretical Physics and to appoint as its head a professor who would play a full part in the rapidly developing field of theoretical physics. Among three candidates, the professors' first choice was Albert Einstein, associate professor of theoretical physics at the Technical University in Zürich.

The building of the former Faculty of Philosophy of the German University in Viničná Street where Einstein had his office and, in 1912, gave his lectures.

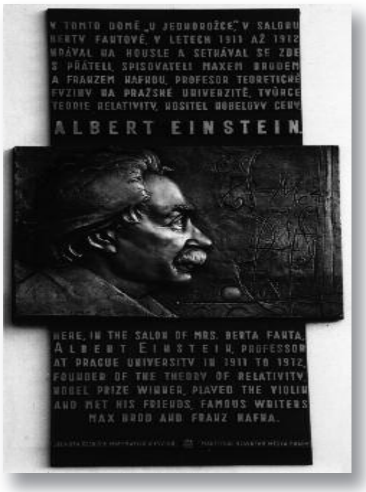
The chief advocate of this proposal was Anton Lampa, professor for experimental physics. Lampa was strongly influenced by Ernst Mach (who was active in Prague for almost 30 years, being, among other things, Rector of the University), and he supposed that Einstein would further develop Mach's ideas in physics. Although the authorities in Vienna moved Einstein to second place among the candidates, Einstein, in the end, obtained the professorship in Prague because G. Jaumann from Brno rejected the offer when he learned that the professorial staff preferred Einstein.

[1] In June 25 - 29, 2012, an international meeting "Relativity and Gravitation - 100 years after Einstein in Prague" will take place at Charles University in Prague. The aim is to summarize the present status of Einstein's theory and its applications. http://ae100prg.mff.cuni.cz

Although in Prague the new Institute with its fine library fully satisfied Einstein, he did not establish as close a rapport with Prague as he had with Zürich. However, he admired historical Prague; for example, in a letter to his friend M. Besso he invites him to Prague with the words: “The city of Prague is very fine, so beautiful that it is worth a long journey for itself.”

While in Prague Einstein was invited to the first of the legendary Solvay congresses where he and F. Hasenöhrl from Vienna were the only representatives of the Austro–Hungarian Empire. Here Einstein met Planck, Lorentz, Madame Curie, Poincaré, Rutherford, most of them for the first time.

Scientists also came to Prague to visit Einstein. One of the most important ones was Paul Ehrenfest who, from the time of his Prague visit, became a close friend of Einstein. Indeed, Einstein chose Ehrenfest as his successor to the chair of the Institute for Theoretical Physics in Prague. However, owing to Ehrenfest’s refusal to state his religious affiliation, this proposal was not brought to fruition and it was eventually Philipp Frank who was nominated to the Einstein post in 1912, keeping it until 1938.



The Albert Einstein memorial tablet on the house “At the Unicorn” in the Old Town Square No. 17.

As a full professor, Einstein gave regular lectures at the German University during his stay in 1911 and 1912. He lectured on mechanics, molecular physics, and thermodynamics; he also organized seminars. While in Prague, he published eleven papers, five of them not concerned with the theory of relativity. The most extensive non-relativistic work is the survey of the theory of specific heats prepared for the Solvay Congress. Another paper and two short remarks deal with Einstein’s favorite problem – the interaction of radiation with matter. However, it was in Prague that Einstein’s intense interest in the quantum theory diminished and his systematic effort to construct a relativistic theory of gravitation began.

What did Einstein learn during the Prague stage for his journey to the general theory of relativity? In his foreword to the 1923 Czech edition of his well-known little book *About the Special and General Theory of Relativity in Plain Terms* he says: “I am pleased that this small book, in which the main ideas of the theory of relativity are explained without mathematical elaboration, should now appear in the native language of the country in which I found the necessary concentration for developing the basic idea of the general theory of relativity which I had already conceived in 1908. In the quiet rooms of the Institute of Theoretical Physics of Prague’s German University in Viničná Street, I discovered that the principle of equivalence implies the deflection of light rays near the Sun by an observable amount, without at that time knowing that a similar result had been derived from Newton’s mechanics and his corpuscular theory of light. In Prague I also discovered the shift of spectral lines towards the red that is not yet completely confirmed. However, the decisive idea of the analogy between the mathematical formulation of the theory and the Gaussian theory of surfaces came to me only in 1912 after my return to Zürich, without being aware at that time of the work of Riemann, Ricci, and Levi-Civita (…). It now appears that it is already possible to evaluate the achievements and limitations of the whole theory. It provides a deep knowledge of the physical nature of space, time, matter and gravity; however, it does not provide sufficient means for solving the problems of quanta and of the atomic constitution of the elementary electric units of which matter is composed."

Einstein does not mention his other relativity papers from Prague except for the famous "Über den Einfluss der Schwerkraft auf die Ausbreitung des Lichtes" ("On the Influence of Gravity on the Propagation of Light"). These other papers contain all that a complete theory of gravity must include: the equations of motion of a particle in a given gravitational field; the influence of a given gravitational field on other physical systems, such as the electromagnetic field; and the field equations which describe the gravitational field due to a given source. From the point of view of a final formulation of general relativity all of these Prague results are remarkable: the equations of motion are derived from a variational principle clearly foreshadowing the variational principle from which the geodesic equation in general relativity is derived; the field equations are non-linear – the gravitational field is also influenced by the energy of the field itself.

Why then did Einstein not achieve the final formulation of the general theory of relativity while he was in Prague? Because he assumed, analogously with the Newtonian theory, in which the gravitational field is characterized by a gravitational potential, that gravity can be described by a single function – the local velocity of light. But this assumption leads to insurmountable difficulties. However, Einstein learned much on his way to general relativity in Prague. He understood the local significance of the principle of equivalence; he realized that the equations describing the gravitational field must be non-linear and invariant with respect to a larger group of transformations than the Lorentz group, and he found that "space-time coordinates lose their simple physical meaning". It was the last point, in particular, which Einstein, in his Autobiographical Notes, later regarded as one of the most difficult to realize; namely that it was not easy to free oneself from the idea that coordinates must have an immediate metrical meaning.

Space does not enable us to provide a more detailed elaboration of Einstein's work on the theory of gravitation in Prague. However, it is to the Prague stage of Einstein's journey to general relativity that Hesiod's words apply: Einstein paid a large installment of 'days and works' in Prague.

Jiři Bičák
Charles University, Prague

Geometric Analysis and Gravitation

The division "Geometric Analysis and Gravitation" is concerned with the physical concepts and mathematical models that allow the description of space and time and gravitational phenomena. In this area of research Analysis, Geometry and Physics interact in fascinating and challenging ways. The methods employed range from differential geometry, nonlinear partial differential equations, calculus of variations and geometric measure theory all the way to discrete approximations and numerical analysis. Special emphasis is given to Einstein's field equations in classical General Relativity modelling phenomena such as isolated gravitating systems and black holes, gravitational waves and cosmology.

The close scientific connections with the other divisions at the AEI and to the nearby Universities in Berlin and Potsdam have been extended. This has been achieved at the individual level through the appointment of scientists with overarching research interests and at the institutional level through collaborative research structures (International Max Planck Research School "Geometric Analysis, Gravitation and String Theory" ("IMPRS"), Special Research Center 647 "Space-Time-Matter" of the German Research Foundation DFG ("SFB647"), Berlin Mathematical School in the DFG "excellence initiative" ("BMS")). The IMPRS has attracted excellent students from around the world and intensified the collaboration between this division and the "Quantum Gravity and Unified Theories" division as well as with Potsdam University and Free University Berlin. Some of its student have in addition become members of the BMS leading to new links with the wider Berlin mathematical community. Joint workshops and seminars between these groups have taken place on subjects such as "Membrane Theory" and "Ricciflow and Renormalisationgroup flows". Both the IMPRS and the SFB647 were very positively evaluated recently and extended for another funding period.

It is envisioned that the collaboration with Potsdam University will be further strengthened in the future: The University of Potsdam has decided to make W3 professorial appointment in the area of "Geometric Analysis" and a W2 professorial appointment in the direction of "Partial Differential Equations", which will hopefully make Potsdam a strong center in that area of research.

International collaboration has taken place in many directions, supported in particular by the guest program of the institute. Funds from the AEI and from the IMPRS and the BMS allowed many students to participate in conferences and to visit partner institutions. The Max Planck partner group led by S. Dain in Cordoba, Argentina, was positively evaluated and extended for another term. Institutional links are also in place with the research group of our external scientific member R. Bartnik at Monash University in Melbourne, Australia. The collaboration with the research group of J. Bičák and his colleagues in Prague was deepened by mutual visits of J. Bičák, G. Huisken and junior researchers.

Helmut Friedrich, who has been a member of the AEI since its foundation, has retired in 2009. His outstanding contributions to Mathematical Relativity and to the AEI were honoured in an international conference "Space, Time and Beyond" at our institute in September 2009. We are fortunate that through the appointment of Lars Andersson to a W2-professorship the expertise of the division in the intersection of analysis, geometry and physics could be maintained. The division is delighted that Hans Ringstroem joined it for an extended period after winning a Bessel-Prize of the Humboldt foundation. During the last two years, while several young scientists have left the division for more senior positions elsewhere, it was possible to attract a team of postdocs in Mathematics and Physics that contributes to a diverse and lively research atmosphere.

Members of the division have taught major courses at Potsdam University, Free University Berlin and Tübingen University. Specialised lecture courses were given at the IMPRS and at special events such as the annual vacation course in collaboration with Potsdam University, which is now being organised by Lars Andersson. Invited research lecture series were given by members of the division a number of other universities and institutes. Members of the division participated in the organization of several international conferences and workshops and helped in the administration and evaluation processes of their research fields.

Concerning specific research projects, major progress was made on the structure of axially symmetric black holes and the relation between their mass and angular momentum. The asymptotic behaviour of gravitational radiation and the relation to static isolated gravitating systems was another important project. Several models of expansion in cosmology were studied and the interaction of gravitation with other matter fields in such models was investigated. Closely related is the study of the singular behaviour of a space-time near a "big bang", which requires a delicate analysis of the nonlinear partial differential equations involved and the time-dependent geometry in such regions.

With a view to numerical simulations of solutions to Einstein's equations geometric concepts for physical quantities such as mass, center of mass and momentum were studied as tools for better quantitative descriptions of such concepts. Scientists from our division interacted closely in this regard with the research group on numerical relativity in the division "Astrophysical Relativity".

Another major direction of research concerns theoretical mathematics that underpins General Relativity and related theories of gravitation: These include geometric variational problems, nonlinear wave equations as well as the deformations of metrics and submanifolds by parabolic geometric evolution equations. Important progress was made in this regard concerning the description of isolated horizons by surfaces of specified mean curvature, where methods from minimal surface theory are combined with the properties of a space-time solution of Einstein's equations. In another difficult subject regularity properties for systems of geometric wave equations were studied at a fundamental level, where similarities between Einstein's equations in classical relativity and other equations such as the membrane equation in string theory become apparent. Here existence of solutions to the Cauchy initial value problem was proved for new classes of equations and criteria for the longtime continuation of such solutions were established. Concerning parabolic evolution equations, both the evolution of hypersurfaces in an ambient manifold with curvature dependent speed and the Ricciflow of Riemannian metrics were investigated. For mean curvature flow generalised solutions involving a surgery procedure were constructed in a similar spirit to the Hamilton-Perelman theory of Ricciflow, while for inverse mean curvature flow new regularity results were established. The research on Ricciflow and mean curvature flow opened new connections to research topics in the section “Quantum Gravity and Unified Theories”, since these equations are approximations to Renormalisationgroup flows. Workshops at the AEI and elsewhere on this topic created new links between the scientists in the respective areas.

Two specific highlights of the research in “Geometric Analysis and Gravitation” are presented further down in the report (see pp. 39–43).

Gerhard Huisken

Astrophysical Relativity

Introduction

Einstein's theory of general relativity plays a central role in the understanding of the fascinating and surprising universe that astronomers have uncovered in the last thirty to forty years. Relativistic objects like black holes and neutron stars dominate much of modern astrophysics, and general relativity provides the arena – the expanding universe – in which astrophysicists are now beginning to understand deeply how our modern universe came to be. In a few years, general relativity will begin to make an important new contribution: when astronomers finally are able to detect and analyze gravitational waves, they will have an important new messenger that is able to bring information from the darkest and most remote parts of the universe.

The Astrophysical Relativity Division of the AEI focuses its work on gravitational waves: how they are generated by black holes and netron stars, how we detect them, and how we will extract information from the waves we detect. Within the GEO project, scientists at AEI/Golm work with their colleagues at AEI/Hannover and our partners elsewhere in Europe and the USA as part of the LIGO Scientific Collaboration (LSC), which analyzes the pooled data taken by the three large LIGO detectors in the USA and the GEO600 detector operated by AEI/Hannover, and which joins with the Italian-French Virgo project to perform a joint analysis including their data as well.

Some of our scientists work with large supercomputers and with the Einstein@Home project (described in the report of Bruce Allen's division) to analyze the data that already exists and to prepare for even more sensitive searches in the future. Other scientists in the Astrophysical Relativity Division perform large supercomputer simulations of the mergers of black holes and neutron stars. Not only are these merger events expected to be among the first gravitational wave sources to be directly detected by the LSC and Virgo detectors, but these events are also intrinsically very interesting because they have much to tell us about general relativity and physics under extreme conditions. Numerical simulations of this kind are a kind of laboratory astrophysics: since we can't experiment directly on neutron stars and black holes, and since they are too complex for us to solve the full Einstein equations for with paper and pencil, our approach is to simulate the evolution of systems we believe exist, using as much physics as we are able to include. The AEI group is now starting to include strong magnetic fields into simulations of neutron-star mergers; we know that neutron stars have such fields, but only recently have computers become powerful enough to include these effects. The interesting highlight article by Bruno Giacomazzo shows what remarkable systems our scientists are now able to study. To support these supercomputer activities we also maintain a small eScience group, developing new tools for performing computations over the internet.

Scientists at AEI/Golm are also increasing their activity in preparing for data from the LISA project, a joint space mission of the European Space Agency and NASA. LISA will be the most sensitive gravitational wave detector ever operated, and the analysis of its data presents special challenges. Unlike the ground-based instruments, where we have to search for signals buried in instrumental noise, LISA will be so sensitive that the signals will be immediately recognizable; but then the reverse problem will challenge us: separating strong, overlapping signals from one another to get the greatest information from all of them. This is described in a highlight article below by Stanislav Babak, the leader of this group.

We have recently established an astrophysics research activity spanning the interests of the data analysis and numerical groups, which studies the star clusters surrounding the massive black holes that astronomers have been finding at the centers of galaxies. A highlight article by Pau Amaro-Seoane gives a good introduction to this work.

Numerical relativity

The highlight article already mentioned, by Bruno Giacomazzo, describes much of the work on neutron stars in this group. The group has also been very productive in studying the mergers of black holes. The dynamics of the merger and the waveforms of the gravitational waves emitted by the merger depend on the spins of the black holes and the ratio of their masses, so there are a large number of systems that must be simulated if we are to understand this problem. The group made progress understanding the mechanism of the "kick", whereby the gravitational waves emitted by merging holes are so anisotropic that they push the final merged product black hole off in the opposite direction at high speed. The group has also worked with the data analysis group in the NINJA project to begin to incorporate numerical waveform predictions in the gravitational wave search templates.

Equally important is that the work we have done has enabled many AEI scientists to advance their careers and leave the AEI for very good positions. Of special mention is that Cecilia Chirenti moved to Brasil and quickly won a grant from the Max Planck Society to set up a Max Planck Partner Group, which will continue our collaboration on neutron stars.

Data analysis

The data analysis activities of the Division take place both in Hannover, where the ground-based activities are led by Maria Alessandra Papa, and in Golm, where Stanislav Babak leads the LISA data group. Dr Papa is the LIGO Scientific Collaboration's co-chair of the international Data Analysis Council, which oversees the entire joint data analysis of the LIGO, GEO, and Virgo detectors. Her own special interest is in searches for spinning neutron stars, or gravitational-wave pulsars, an activity she led for the collaboration until she took over the overall chair. This search is mainly done on the Einstein@Home distributed computer system that was set up and is operated by Bruce Allen, and is described in his report. In Golm, Badri Krishnan is one of the leaders of the NINJA project mentioned above, which helps to bridge between the methods used by numerical relativity groups and the software required for the data analysis methods.

The work of our LISA data analysis group, described by Stanislav Babak in his highlight article, is aimed at developing analysis methods that overcome signal confusion. This is not part of the standard literature on signal analysis, and it involves very sophisticated use of rules that should find the simplest resolution of confusion, since often there is no unique solution. The field has set up the LISA Mock Data Challenges, where a team (including Babak) generates artificial data that is as realistic as possible, containing thousands of signals, and distributes the data to groups worldwide. The groups are not told what signals have been put into the data, so they effectively compete to get the best results. It is pleasing to report that the AEI group has proved very effective and is consistently getting some of the best results.

Regrettably I have to conclude this report on a sad note, because Division scientists Thomas Radke, who had for several years been the leader of the eScience group, died very suddenly and unexpectedly during 2009. He was universally liked and respected, and condolences came to his family from scientists and colleagues from all over the world.

Bernard F Schutz

Quantum Gravity and Unified Theories

Scientists working in this Division of the AEI focus their research on two main topics, namely the search for a consistent theory of quantum gravity reconciling quantum theory and general relativity, and the search for a unified theory of gravity and the elementary particle interactions. The theory of quantum gravity that will one day supersede Einstein's theory, is expected to revolutionize our understanding of space and time, such that classical space-time descriptions emerge from the complete theory only as a limiting case. The unified theory of all interactions should encompass the well-established standard models of elementary particle physics and of cosmology. Over the past few decades several approaches have been developed, ranging from supergravity and superstring theory to canonical approaches, and even attempts to formulate "physics without space and time" in a deep quantum gravity phase.

Over the past two years the division has grown considerably, mainly due to the "accretion" of outside funding, which complements the regular budget of the Division, and which may be viewed as a sign of the growing national and international stature of the group and its research. There are now two independent research groups (Max Planck research groups) funded by the Max Planck Society, namely "Duality and integrable Structures" (headed by Niklas Beisert) and "Canonical and covariant Dynamics of Quantum Gravity" (headed by Bianca Dittrich). A third independent research group "Microscopic Quantum Structure and Dynamics of Spacetime" is funded by the A. v. Humboldt Foundation via a Kovalevskaja Award, and headed by Daniele Oriti. The Division participates in the Sonderforschungsbereich "Raum - Zeit - Materie" linking AEI with Potsdam University, Humboldt University and Free University Berlin. An MPG partner group of the Division now exists at IUCAA in Pune (India) and is directed by a former AEI postdoc Sudarshan Ananth. Additional funding comes from the DFG, and the DIP and GIF Foundations. The Division has been quite successful in recent years with its nominations for the prestigious Humboldt Professorships, which enables internationally known and established scientists to spend longer periods of time at AEI. Recent awardees are Marc Henneaux, Volodya Kazakov, Hirosi Ooguri, Eliezer Rabinovici and Shimon Yankelowics.

Together with the Mathematical Relativity Division, the Division jointly runs the International Max Planck Research School (IMPRS) "Geometric Analysis, Gravitation and String Theory". This is a MPG sponsored program to train PhD students who are recruited nationally and internationally (more than 50% of the current PhD students are from outside Germany). After the first 5-year term, the School was evaluated at the beginning of the year. As a result of the very positive evaluation, the IMPRS has now been extended for another 5-year period.

Synopsis of main research areas

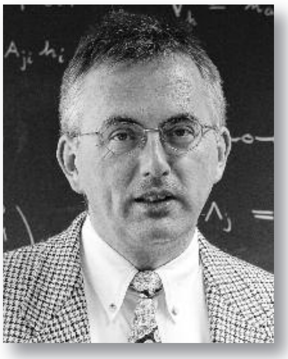
The following is a review of the research activities and highlights during the past two years. The activities of the Independent Research Groups will be covered in separate articles by N. Beisert, B. Dittrich and D. Oriti. In addition, special contributions by T. McLoughlin, I.

Melnikov and P. Vieira will describe in somewhat more detail three research topics of current interest where important progress was made during the last two years. These topics will not be discussed in detail below.

The approach to quantum gravity favored by a majority of researchers continues to be superstring theory, where much of the recent activity (also at AEI) has centered on the so-called AdS/CFT correspondence. String theory grew out of modern particle physics, but differs from standard quantum field theory in that it radically modifies it (and Einstein's theory) at very short distances: its fundamental building blocks are not point-like particles, but one-dimensional extended objects, relativistic strings (or, if fermions are included, superstrings). In modern string theory the framework encompasses also higher-dimensional extended objects ("D branes"), and a non-perturbative extension to supermembrane theory, which in turn leads to M(atrix) theory, a widely discussed proposal for M Theory, the so far elusive non-perturbative formulation of string theory.

The characteristic feature of string theory is the identification of quantized vibrational excitations of the relativistic strings with the different point-particles of conventional quantum field theory – in this way, the multitude of matter particles and their interactions in the standard model of particle physics might be reducible to the physics of just one truly elementary constituent, the fundamental string. While open strings contain massless spin-one excitations, the spectrum of closed strings always contains a massless spin-two particle, whose self-interactions coincide with those of Einstein's theory at the lowest non-trivial (cubic) order (at higher order, Einstein's theory is corrected by terms involving higher powers of the Riemann tensor, however). This is the basis of string theory's claim to being a theory of quantum gravity. With the possible exception of N=8 supergravity (the maximally supersymmetric field theory extension of Einstein's theory), superstring theory is currently the only ansatz that may succeed in removing the inconsistencies of perturbatively quantized general relativity. However, the link (if any) between string theory and real physics is still far from clear. The main task facing string theorists today is to find a non-perturbative formulation of the theory (sometimes referred to as "M Theory"). Research in string theory at AEI covers a wide range of topics: integrability of N=4 Yang Mills theory and string theory in AdS_5 x S^5 (one of the most visible activities at AEI, see the special contribution by P. Vieira); more recent developments concerning the computation of physical amplitudes in quantum field theory following the recent proof of 4-loop finiteness of N=8 supergravity (see the article by T. McLoughlin)); boundary conformal field theories; Calabi-Yau compactification and its many descendants (see the article by I. Melnikov); a general classification of BPS solutions in supergravity; and finally, efforts to develop a proposal for M Theory based on the hyperbolic Kac Moody algebra E_{10}.

A very different approach that continues to thrive proceeds by canonical quantization of Einstein's theory. The modern version of this approach, Loop Quantum Gravity, was pursued at AEI in the past, and much of the groundbreaking in this area was done at AEI. More recently research activities at AEI have shifted to Spin Foam Gravity, a



"covariant" path integral variant of canonical gravity; these topics are reviewed in the contributions by B. Dittrich and D. Oriti. The chief aim of this approach is to find a background independent formulation of quantum general relativity by directly implementing the basic principles underlying Einstein's theory. Just as the absence of background structures in Einstein's classical theory of general relativity forced physicists to re-think old and cherished notions of space and time, these attempts to quantize geometry without reference to any specific space-time background have led to completely new ideas about the structure of space and time at very short distances.

Hermann Nicolai

Laser Interferometry and Gravitational Wave Astronomy

GEO600

In 2008/2009 when the other large gravitational wave observatories in the world have been down for upgrading, our GEO600 gravitational wave detector has taken science data during the so-called Astrowatch period. This data is now being used for triggered burst searchers. In parallel to the Science Run 5 (2006/2007) and Astrowatch activities, we have made tremendous progress in our understanding of the detector noise.

After the end of Astrowatch in July 2009, we have started to prepare for the GEO HF upgrade program for the GEO600 detector. In particular, we have now implemented DC readout and tuned signal recycling, and both are now working in routine operations. This combination of DC readout and tuned signal recycling is employed by no other detector, but it will be an integral part of both Advanced LIGO and Advanced Virgo. A very important step here was the development of a novel technique for the generation of stable alignment control signals in GEO. The GEO600 noise curve is now completely explained and no mystery noise remains.

Laser research

AEI has provided, delivered and installed the Enhanced LIGO 34W lasers both at the Hanford and Livingston observatory sites in 2008. The lasers have shown extremely stable and reliable operations since then. AEI will also provide the Advanced LIGO 200W pre-stabilized laser systems and we are carrying subsystem responsibility for these systems.

Pointing into the future towards 3rd generation gravitational wave observatories and beyond, we also now hold another world record in power sensing in the frequency range 10MHz to 20MHz with a sensitivity of $7 \cdot 10^{-10}/\sqrt{\text{Hz}}$, equivalent to a shot noise limited sensitivity for 700 mA of photocurrent. This was made possible by the development of a novel AC coupling measurement scheme that enables power measurements without destroying the carrier light. We have shown by theoretical analysis that optical AC coupling shows a fundamentally lower quantum shot noise limit than any conventional scheme.

10m Prototype interferometer

To prepare and develop new technologies for future laser interferometric gravitational wave detectors, we have started construction of a 10m arm length prototype interferometer in a UHV vacuum system. In 2008/2009 we have begun to build a team and prepare the prototype lab. The infrastructure work is now complete, the electrics installation is finished, the lab is equipped with optical tables and the control room for the digital control and data system is completed. The full pumping infrastructure and the large scale UHV system has been delivered and installed and is now fully operational with a base pressure in the 10^{-8} mbar range.

The first major experiment to go into the prototype interferometer is a sub - standard quantum limit interferometer. Design proceeded substantially in 2008, was finalized in 2009 and is based on an arm

Albert Einstein Institute Hannover

The AEI Hannover grew out of the gravitational wave group of the Max Planck Institute for Quantum Optics in Garching. It came into proper existence in 2002, with the appointment of Karsten Danzmann as the first director in Hannover. In 2007 we have begun building the second division by appointing Bruce Allen as the second Director.

At AEI Hannover the MPG works closely together with the Leibniz Universität Hannover. The MPG committed to provide stable research funding for both of the planned divisions and the University agreed to provide a new building with 4000 m^2 of lab and office space, equipped with basic scientific inventory.

cavity Michelson interferometer with Khalili cavities in the arms to suppress thermal noise and no power recycling mirror. Construction is proceeding.

Diffractive optics

Future generations of gravitational wave detectors are expected to be limited by thermal noise in the di-electric mirror coatings and mirror substrates. Since several years we have been collaborating with our colleagues in Jena to develop diffractive optical structures that avoid transmission through a substrate and allow to reduce the reflective layer thermal noise. We have demonstrated a diffractive purely reflective 1550 beam splitter and incorporated it in a power recycled interferometer to demonstrate the very low losses and suitability for future interferometers.

Non-classical light

Squeezed non-classical light is expected to be a key ingredient of future generations of gravitational wave detectors. In 2008, we have obtained the first world record in squeezing with more than 10 dB of demonstrated noise reduction. This has in the meantime been improved up to 11,5 dB. This corresponds to a shot noise limited sensitivity improvement needing more than a factor of 10 in laser power, but without the incurred thermal load of the components. This technology has now been employed to construct the source of squeezed light for GEO600 with more than 6dB of usable squeezing which is ready for installation. Squeezing at the AEI has now also been demonstrated for the telecom wavelength of 1550nm, which may be used in future generations of gravitational wave detectors, employing silicon test masses.

Future gravitational wave observatories

A conceptual design study of a 3rd generation gravitational wave telescope, called the Einstein Telescope (ET) is funded by the European Union. Within the ET project AEI studies the technical feasibility of promising quantum non-demolition readout schemes and the potential of using wave guide coatings. In 2009, we have experimentally demonstrated our previously proposed squeezed twin signal recycling interferometry. This combines the advantages of squeezing, detuned signal recycling, and recycling of both signal sidebands and is a promising technology for future generations. High-power high-stability lasers for wavelengths of the traditional 1064nm as well as 1550nm for monolithic silicon optics in ET are expected to be available from Hannover through the combined expertise of the AEI and Laserzentrum Hannover, LZH.

LISA Pathfinder

The LISA pathfinder technology demonstration space mission has been making good progress towards the launch in 2013/14 and flight hardware is now being manufactured by industry.

The most extensive activity involved the development of the flight software of LISA Pathfinder and the preparation for data analysis and mission operation during the actual flight phase. A complete data analysis software environment, called LTPDA, has been developed.

With the software environment complete, we have started to prepare for the online and offline data analysis of the LISA Pathfinder data. So far, two mock data challenges (MDCs) were done, concentrating on various methods for calibration of interferometer outputs to acceleration and non-linear fitting procedures for parameter estimation. This led to the development of complete parametric models of LISA Pathfinder systems.

LISA

At the time of writing (end 2009), the LISA space mission for low frequency gravitational wave observations is in the Mission Formulation phase at ESA and NASA. We have been intensively supporting the Mission Formulation study, both at the level of the industrial formulation contractor EADS Astrium and through various experimental laboratory investigations of key LISA items.

We built a phasemeter laboratory prototype for LISA that reaches the noise requirement. The ranging and data transfer on the laser light has been developed and demonstrated and the weak light phase-lock that is required is also working in our lab. We have developed and tested suitable photo-diode preamplifiers and investigated various fiber lasers with output powers larger than 1W. Extensive experiments and noise modeling are still going on to investigate noise reduction in the back link fiber for laser transfer to the adjacent optical bench required in LISA.

Geodesy space missions

In 2008/2009, our new activity to employ LISA Pathfinder technology for the improvement of future generations of satellite geodesy missions has begun to flourish. In the contents of our Excellence Cluster QUEST we are in intense discussions with JPL and others about a contribution to a future GRACE re-flight or GRACE following mission. We currently study two options, either a fast GRACE copy with a piggy-back laser interferometer located off the optical axis, or a complete new design, optimized for laser interferometry.

Karsten Danzmann

Observational Relativity and Cosmology

The most important research area of this AEI Hannover Division is the development and implementation of data analysis algorithms to search for the four different expected types of gravitational wave sources (burst, stochastic, continuous wave, and inspiral) in data from ground-based gravitational wave detectors. As part of an international data-sharing collaboration, group members have full access to data from the most sensitive five detectors instruments available (3 x LIGO, 1 x Virgo and 1 x GEO).

Searches for weak gravitational wave signals are very compute-intensive. Thus, one of the central activities of the group is to maintain and increase the computing resources available to us. The group operates the ATLAS computing cluster, which is the world's largest and most powerful resource dedicated to gravitational wave searches and data analysis. It also plays a leading role in the Einstein@Home project, which uses computing power donated by the general public to search for gravitational waves.

ATLAS computing cluster

The ATLAS computing cluster is a dedicated computing facility located in Hannover, which provides very large numbers of compute cycles for data-intensive processing. It was officially launched in May 2008 with 1344 quad-core compute nodes. One month later it was ranked number 58 on the June 2008 Top-500 list of the worlds fastest computers. At that time it was the world's fastest computer that used Ethernet as the networking interconnect! This is notable because Ethernet is a relatively inexpensive networking technology. ATLAS received an InfoWorld 100 award for being one of the 100 best IT solutions for 2008.

ATLAS has been expanded to 1680 quad-core nodes (6720 cores total). Additional file servers have been added to bring the total storage capacity to over 2PB, and 66 new Graphics Processor Unit (GPU) systems were installed that will increase the performance of ATLAS by a factor of two to three, at relatively low cost.

The planning for expansion of ATLAS has already begun. The expansion will double the amount of available power, cooling and rack space. We then envision that in 2012 a new state-of-the-art cluster will be installed in this new half of the data centre. The current computing systems will continue to operate for up to another two years, but in a degraded mode, as those systems will then be end-of-life and no longer serviceable.

Einstein@Home

The Einstein@Home project is a volunteer distributed computing project: members of the public sign up for Einstein@Home and donate computer time on their home and office PCs. If it were listed on the Top-500, Einstein@Home would be one of the ten most powerful computers in the world.

Einstein@Home was launched in 2005 and searches for the Continuous Wave (CW) gravitational wave signals that would be emitted by rapidly-rotating neutron stars with small non-axisymetric deformations. In Spring 2009, Einstein@Home launched a new type of distributed search for binary neutron stars using data from the Arecibo Radio Observatory in Puerto Rico. This work is being done by AEI Hannover in collaboration with the Arecibo-based PALFA collaboration, led by Prof. Jim Cordes at Cornell. While this search is intended to find new radio pulsars in sub-hour period binary orbits, it is also sensitive to isolated radio pulsars and to radio pulsars in longer period orbits. By December 2009 this search had already rediscovered 26 known radio pulsars.

An important effort now underway in the Einstein@Home team is the 'porting' of the Einstein@Home search codes to GPU-based hardware that can carry out floating-point operations a factor of ten (or even more!) faster than conventional CPUs. An initial GPU port of both the gravitational wave and the Arecibo radio data search has been completed. With future code development and releases, these should significantly increase the processing power available to Einstein@Home.

New search methods for CW systems

Among the possible potential sources of gravitational waves are rapidly rotating neutron stars which are deformed away from axial symmetry, or undergoing relativistic fluid oscillations. These are called Continuous Wave (CW) sources, since they radiate at all times. The search for CW sources in data is a very challenging analysis problem because the signals are modulated by the motion of the earth around the sun, and by the rotation of the earth.

The key step forward in this research topic was an improved theoretical understanding of the optimal search statistic, and in particular of the geometry of the extremal surfaces. This in turn led to an important technical advance which is expected to lead to a significant increase in the sensitivity of future CW searches – by a factor of up to six in strain! (See p. 73 for more details.)

LISA Pathfinder data analysis system

The Division has the lead responsibility to deliver the data analysis system for the upcoming LISA Pathfinder (LPF) satellite mission, scheduled for launch in 2013/2014. LPF will demonstrate the key new technology elements needed for the LISA gravitational wave detector. The LPF data analysis system will be used to carry out the day-to-day analysis of data from LISA Pathfinder. The output from any analysis can be used as input for further analysis. This capability is extremely important because the experimental program of LISA Pathfinder takes place over a period of less than a single year, and is not entirely determined in advance.

New template placement methods

A common feature of many gravitational wave searches is that they use a 'bank' of templates to search for different waveforms. The optimal way to create such a bank (where to place the grid points in parameter space) has been an important research topic during the past decade.

With a new Monte-Carlo like method the resulting template bank can achieve nearly-optimal coverage. Moreover, by sacrificing a controlled fraction of the coverage, for example by only covering 95% of the parameter space, these random template placement methods can achieve results that use significantly fewer templates than the minimum number needed for 100% coverage. More recent work on 'stochastic' template banks is described in an accompanying article in this report (see p. 70).

Binary inspiral searches

Prof. Sukanta Bose from the University of Washington (USA) together with group members worked on techniques and code to carry out a fully-coherent binary inspiral search, optimally combining data from the gravitational wave detectors. Related work at AEI Hannover included the development of improved Markov-Chain Monte-Carlo (MCMC) methods. These methods can be used to give the best predictions of the parameters of detected astrophysical systems, such as masses, inclination angles, polarizations and arrival times.

Burst searches

Over the past two years, with continued support from Prof. Sergei Klimenko (University of Florida) the group has been carrying out searches for unmodeled gravitational wave bursts in the data from LIGO, Virgo and GEO. Group members led the high-frequency search in the combined S5 LIGO/Virgo/GEO data set. Group members are also leading the Coherent Waveburst blind burst search in the first part of the LSC S6 data run. Additional work is underway to help solve the 'position reconstruction' problem. The challenge is to identify the region of sky from which a burst has come, which is the smallest one containing (for example) 90% of the probability. This is necessary for gravitational-wave data to be combined with data from conventional astronomical observatories and satellites, which have pointing capability.

GEO600

Several members of the group have been contributing to the characterization, calibration and improvement of the GEO600 gravitational wave detector, operated by AEI in Ruthe near Hannover. This includes new methods of calibration such as a photon calibrator, and the replacement of some of the analogue control systems by completely digital control systems developed in collaboration with the LIGO lab for use in Advanced LIGO.

Bruce Allen

Duality and Integrable Structures

This Max Planck Research Group focuses on dualities between gauge and string theories and extended symmetry structures which have recently been identified in this context. The aim is to deepen our understanding of these models on which classical and modern particle physics is founded. The group is led by Niklas Beisert, and funding for five years (2006 – 2011) is provided by the Max Planck Society. It currently hosts three postdoc researchers as well as five doctoral and master students.

Main research areas

Four-dimensional gauge theories provide the theoretical foundation for the standard model of particle physics. Direct computations in these models follow simple and well-defined rules outlined by Feynman. Unfortunately, applying them represents a formidable combinatorial and calculational problem thus putting an upper limit to the precision of feasible computations. Research in this group centres on two methods to improve the situation: dualities and symmetries.

A duality implies an alternative description of some physical model giving insights into regions which are practically inaccessible in the original description. The most actively discussed duality in theoretical particle physics is the AdS/CFT conjecture: It proposes the exact equivalence of particular pairs of gauge and string theories. The duality has far-reaching implications due to the fact that a string theory always contains gravitational interactions. Consequently conventional gauge theories may provide a consistent quantisation of gravitational models, and new insights into the long-standing problem of formulating quantum gravity theories can be gained. Conversely, hard to compute strong-coupling phenomena in gauge theories can be expressed through straight-forward calculations in string theory. This duality is also one of the subjects being investigated in the Quantum Gravity and Unified Theories division of the institute with which close collaborations exist.

Symmetries, on the other hand, relate and constrain the observables of the model. An extremely rich hidden symmetry has been identified in the study of the primary pair of AdS/CFT dual models: Maximally supersymmetric gauge theory and strings on the so-called $AdS_5 \times S^5$ background. This symmetry is called integrability and it constrains the observables to an extent such that full determination becomes very efficient. For example, a specialised method developed in the context of condensed matter theory, the so-called Bethe ansatz, opens a window to the exact spectrum at finite coupling strength. A goal of the research group is to develop further and apply these integrable structures. We also hope to deepen these exciting connections between condensed matter and particle physics.

Activities

A major scientific event during the period under review was the "Conference on Integrability in Gauge and String Theory" (29 June – 3 July, 2009). It is the second time that this conference series was hosted at the Albert Einstein Institute Potsdam. It was organised by the group leader and Matthias Staudacher (Quantum Gravity and Unified Theories division). It brought together 139 physicists from many countries and disciplines, and it had positive resonance much like the previous event at the AEI in 2006. See chapter “Events” for more details.

Additionally, the group engages in teaching: One lecture course with problem sessions was given at Humboldt University. Furthermore a joint seminar is organized to promote discussions and collaborations between the Berlin and Potsdam groups working on related issues. Finally, the group leader and Matthias Staudacher have conducted a two-week student seminar at a summer school of the Studienstiftung des deutschen Volkes.
In terms of third party funding, the group has become part of the DFG Sonderforschungsbereich 647 “Space – Timer – Matter” located in the greater Berlin area. The SFB currently funds one of the postdoctoral researchers. The group leader is also part of the project “String Theory meets Gauge Dynamics” funded by the German Israeli Foundation.

Research highlights

The group has made significant progress in understanding long-range integrable spin chains, which underlie the gauge theory spectrum. While the theory of nearest-neighbour chains is well-established by means of so-called quantum affine algebra, a corresponding theory for long-range chains was largely non-existent. We have discovered a map to promote the nearest-neighbour to a large class of long-range models and thus put all related previous observations onto a solid foundation. This result, as it stands, applies only to a part of the gauge theory spectrum, and two generalizations are still missing: finite-size effects (see the research highlight by Pedro Vieira) and an extension to account for peculiarities of conformal symmetry. Applications of this novel type of long-range spin chain to condensed matter physics also appear plausible. Further work on integrable structures has dealt with supersymmetric quantum affine symmetries, their corresponding R-matrices as well as the application to string vibration modes.

A seemingly unrelated focus of research activities within the group was scattering amplitudes in supersymmetric field theories. Recently, a lot of progress has been made in computing them in a particular limit. Important simplifications in the calculations have been attributed to the appearance of a hidden “dual” conformal symmetry. An important insight that we obtained from string theory is that this dual symmetry is in fact an aspect of the integrability within the model. Making use of integrability in connection with some subtle anomalies of conformal symmetry, we argued that the scattering amplitude is fully determined by symmetry alone. This leads to the interesting prospect that integrability may give some (qualitative) insight into regions of real-world particle scattering experiments, which were hitherto inaccessible to theoretical physics. For a more detailed discussion of these results, please refer to the research highlight by Tristan McLoughlin. Some related work concerned the foundations of three-dimensional gauge theories for which we also investigated scattering processes.

Niklas Beisert

Canonical and Covariant Dynamics of Quantum Gravity

This Max Planck Research Group was newly established in September 2009, with a building up phase from April to August 2009. The group leader is Bianca Dittrich, who previously held positions at the Institute for Theoretical Physics at the University of Utrecht in the Netherlands and at the Perimeter Institute for Theoretical Physics in Canada. The group is funded by the Max Planck Society with an initial duration of 5 years. The research of the group focuses on the construction and examination of quantum gravity models. The aim is to improve current descriptions for the dynamics of quantum gravity in canonical and covariant formulations and in particular to obtain a better connection between these two formulations.

Main research areas

In recent years a number of different approaches to quantum gravity, such as Loop Quantum Gravity, Spin Foam Models, Quantum Regge Calculus and Causal Dynamical Triangulations emerged as serious candidates for successful models of a quantized theory of gravity. These approaches have in common that they do not assume a given space time manifold as a background of the theory. Instead, such a background space time needs to emerge dynamically out of the basic ingredients of the models. This also implies that a notion of space and in particular time itself is not predefined but has to be identified after having established the dynamics. These ideas are connected to diffeomorphism invariance, which is the concept that there are no preferred coordinate systems.

Historically the different approaches to quantum gravity can be divided into covariant ones, based on a path integral quantization, and canonical ones, based on canonical quantization. Covariant frameworks can be seen as providing directly a quantum description of space time, whereas canonical frameworks aim at the construction of the quantum dynamics of space in time. As both frameworks have different strengths and weaknesses, the group pursues both covariant and canonical approaches and aims at a better connection between the two. Whereas the study of diffeomorphism symmetry is typically easier in covariant models, canonical models have the advantage to provide a clean path to quantization, in particular for constrained systems such as general relativity.

Diffeomorphism invariance is indeed the symmetry at the heart of general relativity as it is deeply intertwined with its dynamics. It can be regarded as replacement for the much weaker Poincaré invariance of special relativity. The requirement of Poincaré invariance imposes very stringent restrictions on the allowed dynamics in quantum field theories, the same should hold for diffeomorphism invariance and the dynamics of quantum gravity theories. Taking care of diffeomorphism symmetry comes with the prospect of removing many ambiguities arising in the construction of the models.

Apart from being a very important conceptual question, the fate of diffeomorphism invariance in a theory of quantum gravity will have also a strong impact on its phenomenological predictions, for instance regarding a possible Lorentz invariance breaking.

In the last years much progress has been made that allows for a good understanding of the kinematics of quantum gravity theories, in particular in the field of Loop Quantum Gravity (LQG). These developments also provide the necessary tools to construct the dynamics of the models, which is the main research focus of the group.

Work is progressing on different areas, from improving the classical basics of spin foam models, to developing an alternative quantum representation for LQG. Quantum gravity deals ultimately with quantum geometries. Hence another activity is to investigate the space of all geometries, develop parametrizations and phase space coordinates for this space. In a further step the imposition of possible quantum dynamics will be studied on this space.

Of particular importance is the construction of (quantum) representations for the diffeomorphism group, since such representations are actually equivalent to the definition of the dynamics of the theory.

As diffeomorphism symmetry is a concept from continuum physics, whereas many quantum gravity models involve discrete features, one important question is whether and how these two aspects can be reconciled. As discretization is usually used as a uv cutoff or regulator in the quantization, this is equivalent to asking for a diffeomorphism invariant uv cutoff. This subject requires the consideration of a continuum or large scale limit and involves methods from statistical physics and renormalization theory.

During the so far short existence of the research group a considerable amount of progress has been obtained in understanding this subject, as is reviewed in the Research Highlights.

Another point where discretization plays a role, is the apparent divide between canonical and covariant models. Whereas canonical models often involve continuous time and discretized space, in covariant models both time and space are discretized. This has been a serious obstacle in connecting these two formalism. We therefore developed a canonical framework that exactly reproduces the dynamics and symmetries of the covariant models.

Activities of the group

In October 2009 the first three junior scientist joined the group. These are Benjamin Bahr, previously at Cambridge University, Song He from Peking University and James Ryan joining from Perimeter Institute. In addition one PhD student, Ralf Banisch, and a diploma student, Sebastian Steinhaus, have started in October 2009. Another PhD student, Cosimo Restuccia started in January 2010.

The group works in close collaboration with the independent research group "Microscopic Quantum Structure and Dynamics of Spacetime", and interacts as well with members of the Quantum Gravity and Unified Theories division. To foster exchange and collaboration between the members of the groups we are running a quantum gravity seminar and a more informal quantum gravity discussion series with approximately two events per week focussed on the research interests of the groups. In addition the group takes part in the biweekly International

Loop Quantum Gravity Seminar held via conference phone between the major research centers in LQG. Also a number of visitors have been hosted and collaborated with.

Research of the group has been presented at different conferences and workshops, among them the Marcel Grossmann Meeting in Paris, the Max Born Symposium "The Planck Scale" in Wroclav, the Loops 09 conference in Beijing and the Emergent Gravity meeting in Vancouver. A publication by B. Bahr and B. Dittrich has been chosen for 'IOP Select', comprising articles chosen by IOP editors for their novelty, significance and potential impact on future research.

Bianca Dittrich

Microscopic Quantum Structure and Dynamics of Spacetime

This Independent Research Group is funded by the A. von Humboldt Foundation, through a Sofja Kovalevskaja Prize. It has started its activities in January 2009.

Research area

The research of the group concerns a fundamental unsolved problem in contemporary theoretical physics: Quantum Gravity, that is the construction of a theory of gravitational phenomena valid at all scales of distances and energies, coherent with the basic ideas of General Relativity, and formulated in the language of quantum mechanics. Both theories represented a revolution in physics and a reconciliation of the two would probably lead to another even more profound shift in our picture of the universe. A theory of Quantum Gravity would represent a new universal framework for describing physical phenomena, and it is also needed to fully understand black holes, our current description of which breaks down at the central singularity, and the universe as a whole, including its beginning and possible end, not understandable using the present models. Moreover, a complete quantum gravity theory could shed light for example on astrophysical and cosmological mysteries like the nature of so-called dark matter and dark energy, and on the fate of familiar symmetries like Lorentz and Poincaré symmetry at higher energies.

Our group works in the context of several recent approaches to this problem. In particular, we focus on Group Field Theories, Loop Quantum Gravity, Spin Foam Models, Simplicial Quantum Gravity and Matrix Models, all closely related to each other. These approaches are all background independent, in the sense that they do not assume a fixed background spacetime structure, but deal with how spacetime itself (in both its geometric and topological properties) is dynamically generated from some basic building blocks, and thus describe it as fundamentally discrete.

Loop Quantum gravity, a canonical approach to the quantization of gravity, has identified these building blocks, the states of the quantum gravitational field, as spin networks, graphs labelled by data coming from the representation theory of the Lorentz group. In turn, the dynamics of such states, and thus of quantum spacetime, is described in this approach by spin foams, cellular complexes labelled by the same type of group-theoretic data. Spin foam models define then a purely combinatorial and algebraic path integral or sum over histories dynamics for the fundamental quanta -of- space, in a similar way to what is usually done for particles and fields living -on- a given classical space.

In most models, the cellular complexes that characterize the combinatorics of the interaction processes of these quanta of space, and thus define spacetime itself at the most fundamental level, are simplicial complexes (triangulations) of the same type as those used in simplicial quantum gravity approaches, like Quantum Regge Calculus and Dynamical Triangulations, and the dynamics they define for the building blocks of space is closely related to that defined by the Regge action, a discrete version of the action of General Relativity, on which these simplicial approaches are based. A definition of the dynamics of quantum gravity as a sum over histories, each identified with a simplicial complex, has been shown to be successful in the simpler 2-dimensional case in the context of Matrix Models, which are integrable but very rich systems whose Feynman diagrams are indeed 2d simplicial complexes, and whose Feynman amplitudes can be related to the Regge action for discrete gravity in 2d.

Group field theories (GFT), field theories on group manifolds, are a higher-dimensional generalization of matrix models, characterized by Feynman diagrams having the combinatorial structure of d-dimensional simplicial complexes. The presence of group variables results in the Feynman amplitudes of the theory being spin foam models, based on the same simplicial complexes, and thus in a direct link with canonical quantum gravity. More importantly, it allows a more direct and straightforward use of quantum field theory concepts and methods, in particular to the study of the non-perturbative physics of these models. The fundamental quanta of the theory are, equivalently, spin networks or (d-1)-simplices, labelled by group representations. GFTs define the 2nd quantized dynamics of these quanta. As such GFTs potentially represent a truly unified framework for both loop quantum gravity and simplicial approaches.

All these approaches have obtained important results, in recent years, but still present many aspects in need for a better understanding, and a good part of our research concerns precisely their formal development. Also, we aim at clarifying their mutual links, and try to merge the different insights they provide about space and time at the Planck scale.

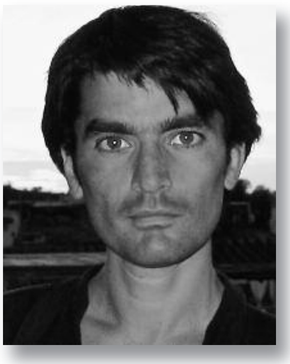
The main questions that all these approaches to quantum gravity have to answer, before being considered as successful, are: if spacetime is fundamentally discrete, where from comes the continuum spacetime we experience at low energies and macroscopic scales? How does such a continuum spacetime emerge from its fundamentally discrete building blocks, and end up being described by General Relativity?

One research direction aiming at addressing the above question is based on the following idea. If space is made out of discrete building blocks, much like atoms forming matter, then there will be situations in which they will behave like a sort of gas, thus manifesting their discrete nature, and there will be other situations in which they will condense, stick to one another so tightly and so uniformly that they will look like a smooth continuum system, like atoms do to form a liquid. It is this very peculiar type of liquid that constitutes the continuum spacetime we experience daily. The above approaches describe properties and dynamics of these fundamental building blocks of space, and so they should allow to describe this process of condensation and the emergence of a continuum spacetime precisely.

Our group, therefore, works actively on the problem of extracting continuum and semi-classical (and General Relativistic) physics from the models of quantum spacetime provided by the above discrete approaches, using also mathematical tools and physical insights coming from other areas of theoretical physics. In particular, we look at analog gravity models in condensed matter physics, for examples of the transition between discrete microscopic and continuum macroscopic realms, and of the emergence of gravity (and matter) from non-gravitational systems.

Bridging the gap between our (tentative) descriptions of quantum spacetime at the Planck scale and the world as we see it, means also constructing effective models of a quantum spacetime and making contact with quantum gravity phenomenology. To this aim, we study the relation between the above-mentioned fundamental approaches and effective non-commutative models of spacetime and matter in the near flat regime, and with non-commutative geometry in general; in fact, they form the basis of much of current quantum gravity phenomenology, focusing on the possibility of quantum gravity-induced deformation of relativistic dispersion relations and scattering thresholds. Finally, part of the group's research is concerned with cosmology. On the one hand, we work on the extraction of simplified quantum gravity models suitable for the description of the universe at large scales; on the other, we aim at obtaining new insights on the role that quantum gravity effects play in the early phases of the evolution of the universe - in particular close to the big bang - , and in the origin of (dark) matter and (dark) energy.

We work in very close collaboration with the other quantum gravity independent research group, led by Dr. B. Dittrich, and interact as well with the Quantum Gravity and Unified Theories division of the AEI, directed by Prof. Nicolai.



Daniele Oriti

Stationary Systems in General Relativity

Einstein's equations represent the core of Einstein's theory of gravitation. They impose restrictions on the possible initial states of space-times, determine the evolution of the physical state in time, and the physical content of the theory is stored in the specific phenomena exhibited by their solutions. To test the predictions of the theory against observations we need an overview of the possible solutions and their distinctive features.

That Einstein's theory removes the dichotomy between background structure and physical fields, which is characteristic for earlier theories is theoretically satisfying, introduces, however, complicated non-linearities into the equations. Only a few solutions have been obtained explicitly and a 'general solution formula', if existent, would require an enormous effort to extract information on the nature of the solutions. Supercomputers allow us to calculate specific solutions and to gain quantitative results but to acquire the desired insights into the manifold of solutions there only remain the methods of abstract analysis.

The specification of an initial state leaves a large freedom to model physically interesting scenarios. A model of particular interest to us is that of an 'isolated self-gravitating system'. It is thought of as describing gravitational fields of subsystems of our cosmos, which are generated by massive sources, that are restricted to a spatially bounded domain, by incoming and outgoing gravitational radiation, and possibly by other long range fields such as electro-magnetic fields. Idealizing these situations, it is assumed that the gravitational field gets weaker and weaker as the distance from the sources increases and approaches in some suitable sense a Minkowski field 'at infinity' so that it becomes 'asymptotically flat'. Remarkably, this idealization has been shown to be consistent with the requirements of the field equations. The most important applications of the resulting theory are related to studies of gravitational radiation phenomena and the calculation of radiation fields for comparison with the projected measurements of gravitational radiation.

Classes of asymptotically flat space-times, which are of considerable interest are given by the stationary solutions to Einstein's field equations. These solutions are distinguished by the fact that they admit families of observers for whom the spacetime does not change at all as time goes by. They include gravitational fields of uniformly rotating stars and such important space-times as the Kerr solutions, which describe fields of black holes. A more special subclass is given by the static solutions, which are distinguished by the existence of observers for whom the space-times look the same even if they look into the past. In other words, these solutions admit distinguished time slices with respect to which the solutions are time reflection symmetric. By this requirement rotation of stars is excluded and from the Kerr family only the Schwarzschild solutions are admitted.

The assumption of stationarity leads to mathematical simplifications because it will be sufficient to know the solution on one time slice.

The field equations then reduce to equations which have the structural properties of Einstein equations coupled to certain 'matter fields' on the three dimensional manifold which represents a chosen time slice. In the case of static solutions the equations simplify even further if a distinguished time slice is assumed.

At first sight solutions, which are stationary everywhere may appear not so important because they lack any gravitational radiation content. But they may still be interesting as describing possible end states of dynamical situations which are approached after all the radiation has escaped to infinity or, in the case of a gravitational collapse, into a black hole. Moreover, as shown recently, there exist rather general classes of highly dynamical space-times, which arise from initial states which are stationary only in some neighbourhood of space-like infinity or which are, in a suitable sense, asymptotically stationary at space-like infinity. By our present understanding such data are likely to play an important role in the detailed analysis and in the calculation of gravitational radiation fields.

For these reasons we have been interested in finding a complete description of the class of data which are asymptotically flat and stationary near space-like infinity. To simplify the task it has been assumed that the solutions will satisfy Einstein's field equations in vacuum. The setting to be analyzed then is that of a three-dimensional manifold on which there are to be constructed gravitational initial data. These data must satisfy the 'stationary vacuum field equations' in an unspecified punctured neighbourhood of a chosen point i which is to represent space-like infinity. In constructing gravitational initial data there is always a freedom in choosing certain 'free data' arbitrarily. The question to be answered here is whether the latter can be prescribed under the present assumptions at the point i and whether this can be done such as to be technically convenient in further studies.

It has been known for a long time that the analogous problems can be solved in the case of Newtonian gravity and static electrodynamics by describing the fields in terms of multipole expansions. In Einstein's theory the answer is much more difficult because fields and background structure are intertwined. Even so, a first general relativistic definition of multipole moments was proposed more than 30 years ago in the static case and this definition was extended later to the case of stationary vacuum fields. These multipole moments consist of two infinite sequences of symmetric trace-free tensors of increasing rank at the point i. In the case of static solutions the multipole moments are given by one sequence only. In the 1980's it has then been shown that the assumptions underlying these definitions could be justified and that any asymptotically flat end of a stationary vacuum solution is determined uniquely, up to isometries, by its multipole moments.

The decisive and technically most demanding question, namely whether there could be given conditions on the sequences of symmetric trace-free tensor fields, which ensure that there actually exist stationary solutions, which assume these sequences as their multipole moments, was left open. Without precise control of these conditions, however, any, possibly quite intricate, application of the theory of gravitational multipoles would stand on shaky foundations and might even lead to empty statements. This situation has changed now.

We have been able to give a complete characterization of all asymptotically flat ends of stationary vacuum initial data. They are constructed from 'free data', which are given by two infinite sequences of symmetric trace-free tensors of increasing rank at the point i.

The data used in these results, which for geometric reasons are called 'null data', are different from the multipole moments referred to above. Again, it can be shown that any asymptotically flat end of a stationary vacuum solution is determined uniquely, up to isometries, by its null data. In fact, on a formal level, at which the question of the existence of solutions is not addressed, there is a one to one relationship between the sequences of null data and the sequences of multipole moments. While the multipole moments show a certain covariance under the admissible gauge transformations, the null data refer to specific gauge conditions and have a more complicated transformation law. But the null data have the advantage of being linear in the curvature tensor and its derivatives while the multipoles referred to above become at each order increasingly non-linear in the curvature and its derivatives. The use of null data thus allowed us to derive estimates on the tensors defining the sequences, which are necessary and sufficient for the existence of stationary solutions, which assume these data. This establishes our result. The estimates obtained for the null data can in principle be translated into corresponding estimates for the multipole moments but this has not be done yet.

This is, however, not the end of the story. As indicated above, solutions which are stationary or asymptotically stationary at space-like infinity are of interest in a much wider range of questions, which are also concerned with studies of gravitational radiation. The linearity of the null data in the curvature can be expected to lead to analytic simplifications if our theory of stationary solutions is applied in this context.

Andrés Aceña, Helmut Friedrich

Shock Waves in General Relativity

Shock waves

Many physical phenomena can be described with the help of quantities which vary smoothly in space and in time. Starting with Isaac Newton it has been realized that it can be preferable to work with relations between rates of change of these quantities instead of trying to describe their variation directly. These relations between rates of change of smooth quantities are partial differential equations. They represent a way of encoding physical laws mathematically. An example of a quantity of this type is the atmospheric pressure, familiar to us all from the weather forecast. The differential equations relating this and other properties of the atmosphere form the basis of the computer models used in modern weather forecasting. To model a given phenomenon it is necessary to find solutions of the differential equations satisfying certain physically motivated conditions. Curiously it turns out that looking for these solutions sometimes leads to cases where the variation of the basic quantities has jumps instead of being smooth. In fluids these are known as shock waves. This seems to contradict the very idea of a differential equation but it turns out that solutions with jumps can be made sense of mathematically and can be very useful in practise. These are known as weak solutions of the equations. In the Earth's atmosphere examples of shock waves are not common in our everyday experience. Those of us who are not too young will remember one - the 'sonic boom' produced by the supersonic airliner Concorde. In contrast, shock waves are common in high energy processes occurring in astrophysics. For instance, the explosions of the stars known as supernovae rely on shock waves.

The typical context in which shock waves arise is that of fluids (gases or liquids). By now many methods have been developed for describing shock waves in fluids on the computer. These often involve a little mathematical theory and a lot of trial and error. Getting precise mathematical results about shock waves has turned out to be extremely difficult, even when the effects of gravity are neglected. Most effort has been concentrated on the one-dimensional case. In other words, the relatively simple case is considered where the quantities describing the fluid, such as pressure or density, only depend on time and one direction in space. Even this model problem presents serious mathematical challenges. Nevertheless a good theory has now been developed. It is important to realize that in many models involving fluids shock waves cannot be avoided. Even if the situation is set up in a smoothly varying initial configuration shock waves will develop at a later time - smoothness is lost.

Incorporating general relativity

In general relativity the gravitational field is described by the Einstein equations. To describe a physical system these equations must be combined with other equations which describe the matter which generates the gravitational field. The choice of the physical system to be modelled affects the choice of matter model used. For instance, if a star is to be modelled then the matter is often treated as a fluid and the equations to be solved are the Euler equations. The combined equations are known as the Einstein-Euler system. If instead gravity is neglected in the description, but relativistic effects taken into account the equations obtained are the special relativistic Euler equations. Under the assumption of a one-dimensional system they belong to the class of equations which can be treated by known theory. When the effects of gravity are incorporated into the model this is no longer the case.

In view of what has just been said it is natural to ask how much changes when a description without gravity is replaced by a more precise one including gravity. Do shock waves still develop as frequently as before? This is important to understand since the formation of shocks causes difficulties which prevent us applying many techniques of the theory of partial differential equations and prevent access to interesting effects we would like to study. It turns out that within general relativity the answer to this question is yes. Shock waves do form from smooth initial configurations in a way similar to that familiar in the absence of gravity. Gravity does not prevent shocks forming. That this is the case is not surprising from the point of view of physical intuition but until very recently this had never been proved mathematically. Now I have been able to develop a proof of this kind in collaboration with Fredrik Stahl, formerly a scientist at AEI.

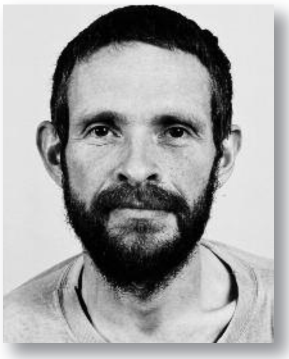
When a shock wave forms in general relativity certain fluid quantities, such as the density, develop jumps. Since these quantities are intimately related to the geometry of spacetime via the Einstein equations the geometry also loses some smoothness. On the other hand this is less drastic than for the fluid and a certain amount of smoothness is retained. The proof of the theorem involves first showing what properties are preserved, guaranteeing a certain similarity of the geometry to that of special relativity, and then using that information to show that other properties are lost. To do so techniques from the area of mathematics known as 'systems of conservation laws' are adapted and generalized.

Living with shock waves

Once it is known that shock waves are unavoidable in solutions of the Einstein-Euler equations the next aim should be to develop techniques which allow us to work with discontinuous solutions. A start in this direction was made by Philippe LeFloch and Bernd Schmidt a few years ago. They obtained some interesting results but further progress was restricted by the occurrence of mysterious types of loss of smoothness they observed which were different from shock waves. More recently LeFloch and I recognized that these were unphysical effects which can be eliminated by setting up the problem correctly. In work in progress we intend to show that solutions of the Einstein-Euler equations of relevance to cosmology can be followed for an unlimited time despite the presence of shocks.

Trapped in one dimension?

All the mathematical results which have been described above are confined to the one-dimensional case. Is it the fate of those wishing to prove general theorems about fluids to be confined to one dimension? Until very recently this appeared to be the case. This has now changed due to the groundbreaking work of Demetrios Christodoulou on the formation of shocks in special relativistic fluids. This work does not include gravity but the approach used is very closely modelled on earlier work on the vacuum Einstein equations and so seems tailor-made to extend to the Einstein-Euler system in due course. Thus we can hope that the dynamics of fluids in general relativity, in the absence of strong restrictions on the allowed configurations, will soon come into reach of mathematical treatment. At the same time, these techniques are likely to have a strong influence on the further development of the theory of hyperbolic partial differential equations and thus feed into a number of existing research directions at AEI.



Alan Rendall

Theoretical Astrophysics of Dense Stellar Environments and Gravitational Waves

One of the most exciting results of modern astronomy is the discovery that most, if not all, nearby bright galaxies harbour a dark, massive, compact object at their centres. The most spectacular case is our own galaxy, the Milky Way. By tracking and interpreting the stellar dynamics at the centre of our galaxy, we have the most well-established evidence for the existence of a massive black hole (MBH).

Many correlations linking the MBH's mass and overall properties of its host spheroid (bulge or elliptical galaxy) have been discovered. The tightest are with the spheroid mass, its velocity dispersion (Mass-sigma relation) and degree of concentration. Consequently, understanding the origin and evolution of these MBHs necessitates their study in the context of their surrounding stellar systems. Claims of detection of “intermediate-mass” black holes (IMBHs, with masses ranging between 100-10,000 solar masses) at the center of globular clusters raise the possibility that these correlations extend to much smaller systems, but the strongest -if not totally conclusive- observational evidences for the existence of IMBHs are ultra-luminous X-ray sources.

The promise of gravitational wave astronomy

In the past years, gravitational wave (GW) astronomy has reached a milestone with the construction of an international network of GW interferometers that have achieved or are close to their design sensitivity. Moreover, the first-generation ground-based detectors LIGO and Virgo will undergo major technical upgrades in the next five years that will increase the volume of the observable universe by a factor of 1000. GRAVITY, as well as Advanced LIGO, is planned to be operational in 2014. The potential detection of IMBHs with these two instruments would allow us to do multi-messenger astronomy.

We have studied the evolution of a binary of IMBHs in a cluster. We find that for reasonable IMBH masses there is only a mild effect on the structure of the surrounding cluster even though the binary binding energy can exceed the binding energy of the cluster. We demonstrate that, contrary to standard assumptions, the eccentricity in the LISA band can be in some cases as large as ~ 0.2 - 0.3 and that it induces a measurable phase difference from circular binaries in the last year before merger. We also show that, even though energy input from the binary decreases the density of the core and slows down interactions, the total time to coalescence is short enough (typically less than a hundred million years) that such mergers will be unique snapshots of clustered star formation [1].

We have also analysed the evolution of a binary of IMBHs in the presence of rotation in the cluster by carrying out a series of direct N-body simulations. The survey indicates that eccentricities and inclinations are primarily determined by the initial conditions of the IMBHs and the influence of dynamical friction, even though they are finally perturbed by the scattering of field stars. A Monte Carlo study indicates that these sources will be detectable by a detector such as LISA with median signal to noise ratios of between 10 and 20 over a three year period, although some events had signal to noise ratios of 300 or greater. Furthermore, one should also be able to estimate the chirp-mass with median fractional errors of 0.0001, reduced mass on the order of 0.001 and luminosity distance on the order of 0.1. Finally, these sources will have a median angular resolution in the LISA detector of about 3 square degrees, putting events firmly in the field of view of future electromagnetic detectors such as LSST [2].

The real promise of detection is next-generation ground-based GW observatories, which will see the ringdown and merger of the process. Recently [3] found that initial LIGO and Virgo are in the position of detecting IMBHs with a signal-to-noise ratio of ~ 10 for systems with total mass between 100 and 500 solar masses situated at a distance of 100 Mpc. Nevertheless, the event rate is too low and the possibility that these signals are mistaken with a glitch is, unfortunately, non-negligible. When going to second- and third-generation detectors, such as Advanced LIGO or the ET, the event rate becomes much more promising (tens per year for the first and thousands per year for the latter) and the signal-to-noise ratio at 100 Mpc is as high as 100 - 1000 and 1000 - 100,000 respectively.

While there is an emerging consensus about the origin and growth of supermassive black holes (with masses larger than a billion solar masses), MBHs with masses up to ten million solar masses, such as our own MBH in the Galactic Centre, are enigmatic. There are many different arguments to explain their masses: accretion of multiple stars from arbitrary directions, mergers of compact objects such as stellar-mass black holes and neutron stars or IMBHs falling on to the MBH, or by more peculiar means such as accretion of dark matter or collapse of supermassive stars. Low-mass MBHs and, thus, the early growth of all MBHs, remain a conundrum.

The main channels of black hole formation and growth are (1) Primordial gas collapse (during the galaxy formation), (2) Accretion of gas in the process of and after galaxy merger, (3) Black hole merger after a galaxy merge, (4) Accumulation of intermediate-mass black holes, (5) Accretion of stars via tidal disruption and accretion of gas produced by stellar collisions. Some of these processes are intertwined with each other and are not readily separable.

Whilst main-sequence stars are tidally disrupted when approaching the central MBH, compact objects (stellar black holes, neutron stars, and white dwarfs) slowly spiral into the MBH and are swallowed whole after some 100,000 orbits in the LISA band. At the closest approach to the MBH, the system emits a burst of GWs, which contains information about spacetime and the masses and spins of the system. We can envisage each such burst as a snapshot of the system. This is what makes EMRIs so appealing: a set of 100,000 bursts of GWs radiated by one system will tell us with the utmost accuracy about the system itself, it will test general relativity, it will tell us about the distribution of dark objects in galactic nuclei and globular clusters and, thus, we will have a new understanding of the physics of the process. New phenomena, unknown and unanticipated, are likely to be discovered. We have addressed these questions and others in a review [4].

Why is this relevant to the evolution of massive black holes?

If the central MBH has a mass larger than ten million solar masses, then the signal of an inspiraling stellar black hole, even in its last stable orbit (LSO) will have a frequency too low for detection. On the other hand, if it is less massive than 10,000 solar masses, the signal will also be quite weak unless the source is very close. This is why one usually assumes that the mass range of MBHs of interest in the search of EMRIs for LISA is between ten million and 10,000 solar masses.

For a binary of an MBH and a stellar black hole to be in the LISA band, it has to have a frequency of between roughly 1 and 0.00001 Hz. The emission of GWs is more efficient as they approach the LSO, so that LISA will detect the sources when they are close to the LSO line. The total mass required to observe systems with frequencies between 0.1 Hz and 0.0001 is of 10,000 - ten million solar masses. For masses larger than ten million solar masses, the frequencies close to the LSO will be too low, so that their detection will be very difficult. On the other hand, for a total mass of less than a thousand solar masses we could in principal detect them at an early stage, but then the amplitude of the GW would be rather low.

On the top of this, the measurement of the emitted GWs will give us very detailed information about the spin of the central MBH. With current techniques, we can only hope to measure MBH spin through X-ray observations, but the numerous uncertainties of this technique may disguise the real value. Moreover, such observations can only rarely be made.

This means that LISA will scrutinize exactly the range of masses fundamental to the understanding of the origin and growth of supermassive black holes. By extracting the information encoded in the GWs of this scenario, we can determine the mass of the central MBH with a ridiculous relative precision of ~ 0.0001. Additionally, the mass of the compact object which falls into the MBH and the eccentricity of the orbit will be recovered from the gravitational radiation with a fractional accuracy of also ~ 0.0001. All this means that LISA will not be "just" the ultimate test of general relativity, but an exquisite probe of the spins and range of masses of interest for theoretical and observational astrophysics and cosmology.

We have addressed the question about the distribution of stellar black holes in galactic nuclei, to the immediate vicinity of the MBH [5], but see also [6], presented N-body realizations that show that the time scales associated with cusp re- growth are shorter than a Hubble time for Milky Way-like galaxies, so that mass segregated, stellar cusps may be common around MBHs in this mass range, contrary to what was thought.

Pau Amaro-Seoane

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Binary Neutron Stars

The study of the inspiral and merger of binary neutron star systems is one of the most important applications of numerical relativity to the description of possible sources of gravitational waves. This is motivated by the fact that these sources, together with binary black holes, are the most promising candidates for the first detection of gravitational waves. Binary neutron star systems are indeed expected to produce signals of amplitude large enough to be relevant for Earth-based gravitational-wave detectors and to be sufficiently frequent sources to be detectable over the timescale in which the detectors will be operative. Recent improved extrapolations to the local group of the estimated galactic coalescence rates predict 1 event per 3-10 years for the first-generation of interferometric detectors and of 10-500 events per year, for the generation of advanced detectors. Moreover the detection of gravitational waves from neutron star binaries will provide a wide variety of physical information on the component stars, including their mass, spin, radius and equations of state (EOS) which cannot be obtained by current electromagnetic observations. These objects are also fascinating since they are thought to be at the origin of very important astrophysical phenomena such as short gamma-ray bursts. After the observational confirmation that gamma-ray bursts have a cosmological origin, it has been estimated that the central sources powering these bursts must provide a large amount of energy ($\sim 10^{51}$ ergs) in a very short timescale, going from one millisecond to one second. It has been then suggested that the merger of neutron star binaries could be a likely candidate for the powerful central source of short gamma-ray bursts. The typical scenario is based on the assumption that a system composed of a rotating black hole and a surrounding massive torus is formed after the merger. If the disc had a mass larger than ~ 0.1 solar masses, it could supply the large amount of energy by neutrino processes or by extracting the rotational energy of the black hole.

For these reasons, results in this field have an impact not only in the community working on the detection of gravitational waves, but it has also a broad impact on the astrophysical and astronomical communities since it could finally unveil the mechanism that is behind the production of short gamma-ray bursts.

Since these objects involve very high densities, relativistic speeds and often high magnetic fields, it is necessary to solve the full set of general relativistic magnetohydrodynamic (GRMHD) equations. Because of their complexity these equations cannot be solved analytically, but require the development of parallel numerical codes. The AEI has a leading role in this field having developed one of the few fully GRMHD codes available up to now. The code, called "Whisky", can solve the full set of GRMHD equations on a dynamical background spacetime and it implements advanced numerical algorithms, such as high-resolutions shock-capturing schemes (HRSC). Moreover it guarantees the divergence free character of the magnetic field by implementing methods such as the constraint transport scheme and the hyperbolic divergence cleaning method. Since it is based on the Cactus framework, this code is highly portable on different clusters and can easily implement Adaptive Mesh Refinement techniques. The code has been extensively validated using several tests in both fixed and dynamical space-times showing to be able to handle situations in which other codes are reported to fail.

With the use of the Whisky code the AEI has been able to compute for the first time the full gravitational wave signal from the merger of equal-mass binary neutron star systems including the signal coming from the ringdown of the black hole that is formed at the end (see Fig. 1). The simulations performed by the numerical relativity group are also the longest performed up to now with some simulations spanning more than 100 ms with a very high level of accuracy with errors on the conservation of quantities such as mass and angular momentum of ~1% or lower.

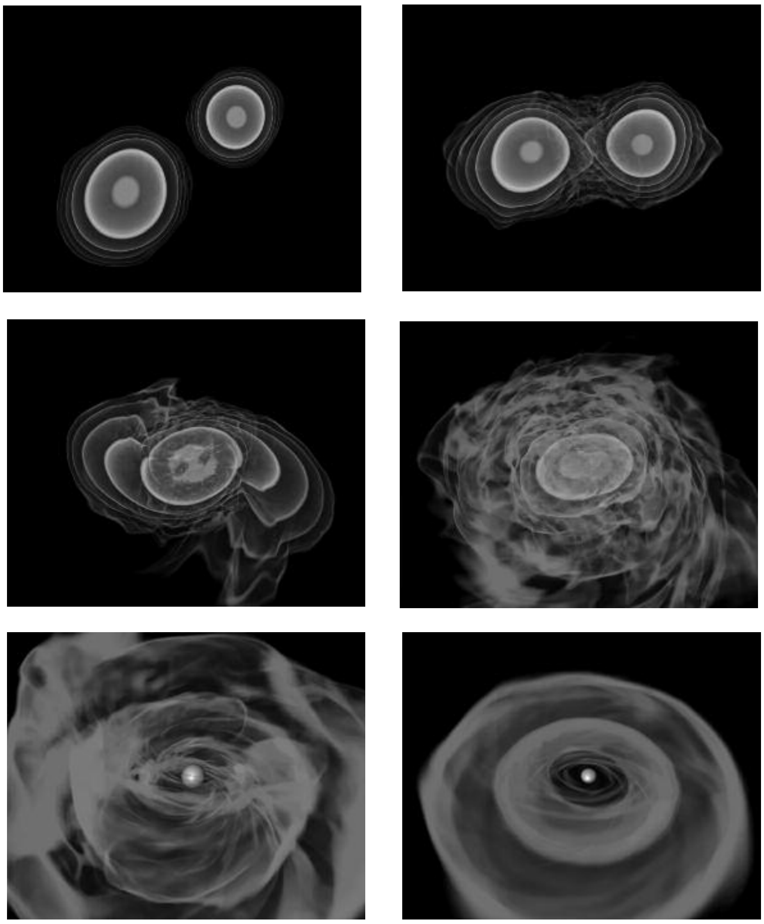


Fig.1: A merger of a neutron star binary to a black hole.

The work has in particular assessed the effect of the mass, of the equation of state and of the magnetic fields on the dynamics of the system and on the gravitational waves. It has been shown indeed that the initial mass of the system and the equation of state have both an important role in the dynamic of the hypermassive neutron star (HMNS) formed after the merger. These objects have indeed masses above the maximum mass for a stable uniformly rotating neutron star (and hence their name “hypermassive”) and they are supported against gravitational collapse by a strong degree of differential rotation. It has been observed that models with a high value for the initial mass of the system and an isentropic (i.e. polytropic) EOS produce a neutron star that collapses promptly to a black hole. When the “cold” polytropic EOS is instead substituted with a more realistic Ideal Fluid EOS that allows for shock heating, the hypermassive neutron star can survive for a time of few milliseconds before collapsing to a black hole. This is due to the extra pressure support due to the heating caused by the strong shocks formed when the two neutron stars merge. The same difference has been observed when using binary systems with a lower total initial mass. In this case the HMNS is able to survive for a longer time even with the polytropic EOS and the survival time has values that range from ~10 ms up to more than 100 ms in the case of an ideal fluid EOS. This long period of time allows the HMNS to develop a bar mode instability in both the cases and to emit a continuous gravitational wave signal at high frequencies (>~2 kHz). These gravitational waves carry away angular momentum from the system until it becomes unstable and collapses forming a black hole surrounded by a disk. One of the important results of this work consisted in showing in detail the differences in the spectra between the gravitational waves emitted by the same initial mass models, but when using a polytropic or an ideal fluid equation of state. While the waveforms emitted during the inspiral are sensible mainly to the compactness of the two neutron stars and so are essentially identical for the same initial model when evolved with a polytropic or with an ideal fluid, the different post-merger dynamics leads to a completely different signal. These gravitational waves though are emitted in the range of frequencies above ~2 kHz where the current detectors have lower sensitivities. Another important result coming from these simulations has been the observation that independently of the initial mass of the binary and of the equation of state a black hole surrounded by a torus is always produced as the final results of the merger. In particular it has been observed that in the case of an ideal fluid equation of state, because of the increase in temperature up to 10^{11} K, a hot and thick torus is formed at the end. Such a thick torus could help in the emission and collimation of the jets necessary to produce short gamma-ray bursts.

The numerical relativity group at the AEI has been also the first to confirm using fully general relativistic simulations that a Kelvin-Helmholtz instability develops in the fluid when the two neutron stars merge together (see Fig. 2). At the merger indeed a vortex sheet is

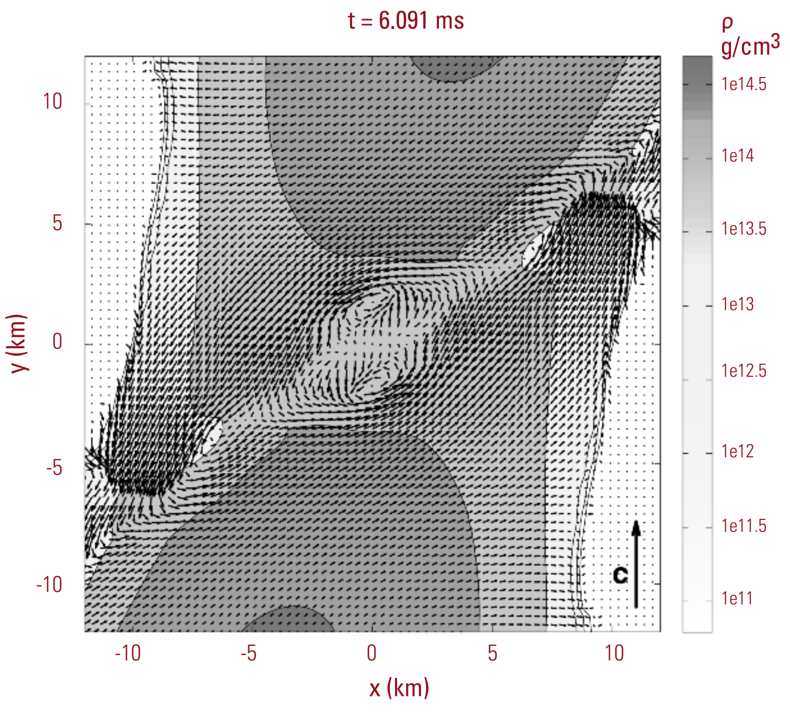


Fig.2: Development of Kelvin-Helmholtz instability during the merger of two neutron stars.

formed when the outer layers of the neutron stars come into contact. This result, which has been shown before only in Newtonian simulations, is very important because it can play a role in the amplification of magnetic fields. Simulations performed at the AEI have indeed shown for the first time in GRMHD that such instabilities curl the magnetic field lines so that, even when starting with a purely poloidal magnetic field, a strong toroidal component is formed and it grows until it reaches values comparable to the poloidal one (see Fig. 3).

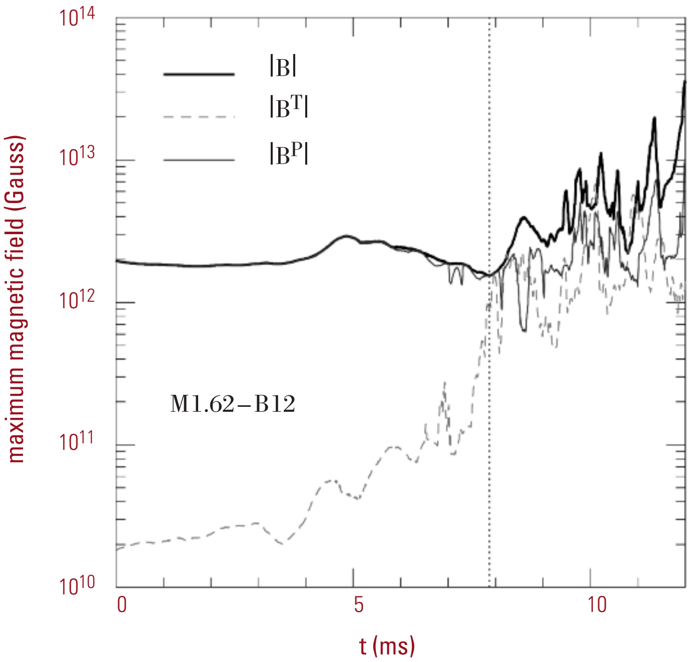


Fig.3: Amplification of the toroidal component (dashed-line) of the magnetic field during the merger (vertical dotted line).

Newtonian simulations in the past have postulated that magnetars, i.e. neutron stars with magnetic field as high as 10^{16} G, can be produced by the merger of binary neutron stars because of this mechanism. But the results obtained at the AEI and, in particular, that a black hole is always the end result of the merger and that the total magnetic field is not amplified of several order of magnitudes, seem to reasonably exclude instead that magnetars could be the result of binary neutron star mergers. Other scenarios should be invoked in order to explain the formation of these objects.

The numerical relativity group has worked in the last year on investigating also the effect that magnetic fields can have on the gravitational wave emitted by inspiralling neutron stars. Since the inspiral part is the one where current gravitational waves detectors are most sensitive it is important to understand if any effect can be detected in this phase. By performing for the first time several simulations with different initial values for the magnetic field it was possible to conclude that effects in the gravitational waves emitted during the last part of the inspiral can be observed only when considering neutron stars with initial magnetic fields of the order of 10^{17} G. Since it is expected from astronomical observations that neutron stars will have magnetic fields much lower than that at the time of the merger, the study performed at the AEI was able to exclude any possibility of detecting magnetic fields in the gravitational waves emitted during the inspiral. Moreover since the magnetic field could have a role instead in the dynamics of the HMNS because of its effect on the angular momentum of the star and since the gravitational waves emitted after the merger have frequencies larger than ~2 kHz, the group has stressed in several occasions the importance that future detectors are built in order to gain higher sensitivities at such high frequencies. Investigations on the effect of magnetic fields on the gravitational signal emitted after the merger are currently in progress and preliminary results have indeed shown that such effects are present.

The results computed up to now by this group have demonstrated a high level of numerical accuracy and the group has been the first to measure the convergence in the waveforms produced by binary neutron stars and in assessing the numerical errors related to the use of different algorithms, resolutions and grid setups. In particular it has been clearly shown, both in the case with and without magnetic fields, that the use of high order schemes, such those implemented in the Whisky code, is of fundamental importance in order to draw robust conclusions. Moreover, in the case of the magnetized binary neutron star mergers, the group has performed the simulations with the highest level of grid resolution used up to now and it has been the first to use in full GRMHD the constraint transport scheme together with mesh refinement being able to keep the divergence of the magnetic field at machine precision for all the duration of the simulations in the region of the domain where the two neutron stars inspiral and merge. More recently the group has extended its study by considering also unequal-mass binary neutron star systems and mixed binary systems with the purpose not only of computing gravitational wave signals, but also of studying the dependence on the initial configuration of the properties of the tori that are formed after the collapse of the HMNS and the application of these models as possible sources of short gamma-ray bursts.

Bruno Giacomazzo

LISA Sources and Data Analysis

The space-based gravitational wave detector LISA is expected to be launched around 2020 as a joint project between the European Space Agency (ESA) and the American space agency NASA. LISA will cover the low frequency band (roughly 10^{-4} to 1 Hz), inaccessible on the ground due to the high level of the seismic noise. Its sensitivity will be so high that it will discover tens of thousands of new sources and return an immense amount of new science: fundamental tests of general relativity, detailed studies of black hole mergers, new insight into the formation of the giant black holes in the centers of galaxies, and a detailed picture of the end-phase of binary stellar evolution.

Ironically, LISA's high sensitivity creates a challenge: signal confusion. Signals have to be extracted from a background dominated by other signals. The loudest signals will obscure those underneath unless they can be very accurately modelled and removed from the data. The primary challenge in LISA data analysis is not the detection of signals (which is an easy task) but the *estimation of the parameters* of the gravitational wave sources. Very accurate modeling of the signal is needed to reduce the systematic error below the statistical. Preparations for LISA data analysis focus, therefore, both on the signal analysis methods and on developing accurate theoretical models for the sources that we expect to detect. Both of these are areas of active research at the AEI. Theoretical modelling of the merger of two massive black holes in a binary system is done in the AEI's numerical relativity group (see the report elsewhere in this volume).

Mock LISA data challenge

The development of the search algorithms for LISA sources is being done mainly within the framework of the international Mock LISA Data Challenge (MLDC), in which simulated data containing blindly injected signals is released to the community, and teams compete to obtain the best performance on signal recovery and parameter estimation. Successive MLDCs, each one more challenging than its predecessor, have the purpose of encouraging and tracking progress in LISA data-analysis development. As a useful by-product, they assist in prototyping the LISA computational infrastructure: common data formats, standard models of the LISA orbits, noises and measurements, software to generate waveforms and to simulate the LISA response, and more. The AEI is deeply involved in the MLDC activity, both as a competitor and in organising the activity. B Schutz is co-chair of the LISA International Science Team's Data and Sources subcommittee, which supervises the activity.

LISA sources and results of the data challenges

LISA's data will contain superposed signals from millions of sources, including all the *binaries in the Galaxy* with orbital periods below five hours and massive-black-hole (MBH) binary coalescences out to $z \sim 20$ or earlier: these would be the earliest individual astronomical systems ever observed. Tens of thousands of sources will be resolvable individually, others will create the *confusion background* dominating over the instrumental noise in a wide frequency range. We also expect few tens to a thousand signals from the inspirals of a compact stellar mass object into a MBH, the so-called *Extreme Mass Ratio Inspirals* (EMRIs).

- **Galactic binaries**

  Galactic binaries radiating in LISA's frequency band are binary systems in our Galaxy containing white dwarfs, naked helium stars, neutron stars or black holes. Such compact binary sources will populate the whole frequency band of the LISA detector. The most common sources are expected to be white-dwarf – white-dwarf binaries emitting gravitational wave signals of nearly constant frequency and amplitude.

  Galactic binaries were targeted in successive MLDCs with increasing complexity of the signal and data. At the AEI we have developed two independent algorithms. R. Prix and J. Whelan have started with the algorithms that are already being used in ground-based gravitational wave searches for continuous gravitational waves. Prix reports elsewhere in this biennial report on work that has made it possible to search the wide range of parameters (possible sky locations and signal frequencies) efficiently. Prix and Whelan have worked to adapt these algorithms to contend with signal confusion. The second algorithm, developed in collaboration between A. Królak (Warsaw), A. Blaut (Wroclaw) and S. Babak, also uses the template grid but constructed in a different way. The main difference between the two algorithms lies in identification of the global maximum among multiple local maxima on the likelihood surface.

The most recent challenge dataset contained signals from over 60 million chirping Galactic binaries. The vast majority of these are too weak to be isolated, and the unresolved component forms a non-stationary confusion noise that adds to the overall noise level. We have detected about 24,000 signals, which is close to the theoretical maximum for this set.

- **Massive Black Hole binaries**
  LISA should detect the merger of two Massive Black Holes (MBHs) in its frequency band essentially anywhere in the Universe. Although many of the signals will be so strong that they will be visible to the eye in the time-series data and in spectrograms, there are nevertheless serious challenges when we want to measure the parameters of the signals well enough to subtract them with high accuracy (parts in 10^4 are needed).

  Early work primarily concentrated on detecting the gravitational wave signal from the inspiralling orbital evolution, before the black holes got too close to one another. After recent breakthroughs in numerical relativity it has become possible to construct a full waveform describing the inspiral, merger and ring-down. However it is not possible to use numerical relativity to generate detection templates because the templates must include a very long inspiral period, and because the parameter space is prohibitively large for these expensive calculations. Instead we (B. Krishnan, F. Ohme, E. Robinson, L. Santamaria) have developed a phenomenological waveform which faithfully represents the signal (as determined by comparing it with numerical relativity waveforms for certain parameter values) and which is fast to generate. Adding merger and ring-down in this way to the original searches improves the estimation of the source parameters considerably.

  However, we expect that most black holes will have significant spin, from the way they form. Spinning MBH binaries are much more challenging sources to model and to remove accurately from the data. Spin affects primarily the end-phase of inspiral and merger, so signals can still be detected, but removal requires accurate measurement of the spins. A. Petiteau, Shang Yu and S. Babak have used a multi-modal genetic algorithm to detect signals and estimate parameters of MBH binaries. They have demonstrated remarkable accuracy in determining the "non-spinning" parameters such as a chirp mass, mass ratio, sky location, distance. The algorithm correctly identified all five MBH signals in the challenge data set, and recovered the direction, masses, and magnitudes of spins with a high precision.

- **Extreme mass ratio inspirals**
  Here the current challenge is in generating accurate templates of waveforms of small black holes falling into large ones. After we can do this we will still have to solve the signal analysis issues of doing searches over these large template family, but today there is still a challenge in computing accurately and rapidly the gravitational waveform for the radiation emitted by such a so-called EMRI, an Extreme

Mass-Ratio Inspiral source. This is basically a study of the equation of motion in general relativity. We describe the inspiral of the small black hole as being due to its self-force, a change in the gravitational field created by its presence and motion. A lot of effort is under way to derive the self-force, which would then give the detailed motion and radiation. Previous reports have described some of the work on this at the AEI. Several approaches led by B. Krishnan, D. Puetzfeld, M. Jasiulek, S. Drasco, S. Babak, Shang Yu are currently being taken at the AEI to model the gravitational wave signal from EMRIs.

We are also working on the signal-search problem, using model waveforms that do not necessarily accurately match real ones but which embody the complexity of the problem and are good testbeds for developing search software. S. Babak in collaboration with J. Gair (Cambridge) have developed an algorithm which allowed us to successfully detect EMRIs embedded in the instrumental Gaussian noise down to a signal-to-noise ratio of 20. The main problems in EMRI data analysis are the numerous maxima on the likelihood surface spread all over the parameter space. The idea behind our detection method was to analyze as many local (secondary) maxima as we could detect. Each maximum carries piece of information about the signal, then we can use this information to direct the search toward the global maximum.

- **Stochastic background**
  LISA is expected to see many stochastic signals, most prominently the anisotropic foreground radiation generated by the Galactic population of double white dwarfs. We also expect that LISA will observe many isotropic stochastic signals, of which there are expected to be various sources. We expect to see astrophysical foregrounds: extra-galactic populations of close stellar-mass compact objects or by stellar-mass compact objects captured by massive black holes in galactic nuclei, and/or primordial backgrounds produced by a variety of processes in the early universe. The standard search for anisotropic backgrounds is to use data combinations that are equivalent to noise-orthogonal unequal-arm Michelson interferometers, rotated at 45 deg to each other. The two data sets are sensitive to orthogonal polarizations of gravitational waves (GWs), and therefore they are insensitive to the isotropic component of the background. We have thus been investigating new methods by which to detect the isotropic component of the stochastic background in the LISA band. The most promising method under investigation is to use a signal-suppressed data set as a noise monitor for a variable in which both signal and noise are present.

Here isotropic stochastic backgrounds can be characterized by a single dimensionless quantity, Ω_{gw} (f), which is a ratio of the energy density in GWs (per logarithmic frequency range) to the critical energy density required to close the universe. In the most recent MLDC round, Ω_{gw} was taken to be constant across frequencies. The analysis of this data was performed by E. Robinson in collaboration with A. Vecchio (Birmingham). They analyzed the data using a Markov Chain Monte Carlo search method. The GW signal was successfully recovered with an accurate estimation of the GW strain.

Stanislav Babak

Scattering Amplitudes in Supersymmetric Theories

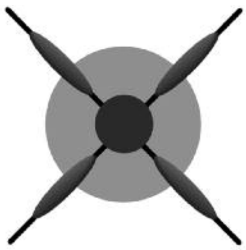


Fig.1: Two gluons scattering into two gluons can be pictured as four external legs, each thickened to represent the gluon self interaction. The legs interact via additional low energy gluons, the outer disk, before meeting in a short distance interaction, the darker core.

Scattering experiments have long been the tool of choice for physicists studying the properties of nature on the smallest scales. At the beginning of the last century the Rutherford experiment, which scattered helium nuclei against gold atoms, led to the modern view of the atom as a massive nucleus consisting of protons and neutrons surrounded by orbiting electrons. Throughout the last century physicists probed ever shorter distances finally leading to one of the crowning achievements of contemporary physics, the standard model, which describes all known particles and forces except for gravity. One key step, provided by particle colliders in the middle of the last century, was the discovery of point-like quarks and gluons which are bound together by strong interactions to form protons and neutrons. Today we are on the cusp of a new era in scattering experiments as the Large Hadron Collider (LHC) at CERN has started conducting experiments, which will hopefully reveal an even deeper layer of structure. As theorists we thus wish to calculate amplitudes, which give the probabilities of specific scattering processes (see Fig. 1) and tell us nearly everything we need to understand events at colliders. From a more conceptual point of view, amplitudes are interesting as gedanken, or thought, experiments which give insight into the properties of particle interactions.

Just as electrons carry electric charge and interact via photons, as described by the theory of quantum electrodynamics (QED), quarks and the force carrying gluons carry “color” charge. This comes in three types – red, green, and blue – and the theory which describes these interactions is called quantum chromodynamics (QCD). While this theory is superficially similar to QED, because the force carrying particles are themselves charged, and so self interact, the dynamics are significantly more complicated. At high-energies the theory becomes weakly coupled, this is the famous “asymptotic freedom”, so that one can use perturbation theory and prove that QCD is indeed the correct theory of strong interactions. Unfortunately at low energies the theory is strongly coupled, rendering perturbation theory useless, and understanding the theory at these energies remains one of the great outstanding problems in theoretical physics.

Supersymmetric gauge theory

Given the difficulties in understanding QCD, theorists have turned to studying QCD-like theories to develop tools and intuition. Supersymmetric gauge theories, which have a novel symmetry relating particles with integer spin to those with half integer spin, are a particularly useful class of theories. Supersymmetry may in fact exist in nature at high energies, and searching for its signature is one of the goals of the LHC, but as a theoretical tool its value is already beyond doubt. Perhaps the simplest cousin of QCD, one for which there are already many beautiful results, is the gauge theory with the maximum allowed amount of supersymmetry: N=4 super-Yang-Mills theory (SYM). Although this theory has many special properties, for example it is invariant under so-called superconformal transformations such as simultaneously rescaling all coordinates, it shares many non-trivial features with QCD.

For the practical issue of perturbatively calculating scattering amplitudes QCD can be split into several parts, the simplest of which is just N=4 SYM. However, even for this most symmetric of theories, carrying out perturbative calculations beyond the lowest orders rapidly becomes intractable using standard methods. This is in part because the usual methods make use of a redundant "off-shell" description, which masks the underlying simplicity. In recent years there have been great advances in developing more efficient "on-shell" techniques such as the unitarity method (see Fig. 2).

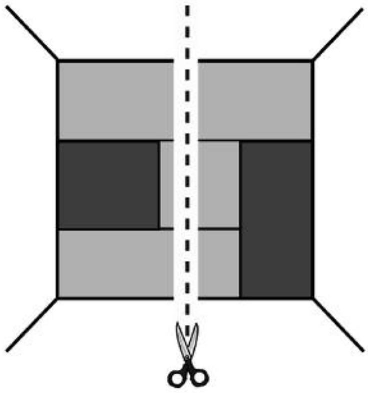


Fig.2: Standard perturbation theory, pictorially represented by Feynman diagrams, organizes the expansion by the number of closed loops. The unitarity method allows us to express a given contribution in terms of products of diagrams with fewer loops by "cutting" it in a specific way.

While these methods have led to improved calculations in QCD, in N=4 SYM they reveal their full potential and have given, for example, all loop answers for the scattering of four and five gluons in the limit of a large number of colors. One topic AEI researchers have worked on, is developing a better understanding of the symmetries of amplitudes which is almost certainly necessary for further progress. Even for the well known superconformal symmetries at the lowest orders in perturbation theory, the action on the amplitudes is subtle and gives rise to an intricate pattern of relations between different amplitudes.

AdS/CFT duality

However, undoubtedly the most prominent reason for the interest in N=4 SYM is the role it plays in the conjectured AdS/CFT duality. This correspondence is a concrete realisation of the old observation that the low energy behavior of strongly interacting particles is in fact string-like. While no one has yet found a string theory which produces three color QCD, in 1997 Juan Maldacena proposed a string theory corresponding to N=4 SYM. An important feature of this theory is that the strings do not move in four dimensions but in a higher dimensional curved space with a boundary (see Fig. 3). These strings provide an alternate, but equivalent, description of the four dimension gauge theory which lives on this boundary. Most excitingly the correspondence relates the weakly interacting regime of one theory to the strongly coupled regime of the dual theory. While this makes proving the duality rather difficult, it means that we can understand the strongly interacting gauge theory by considering weakly interacting strings.

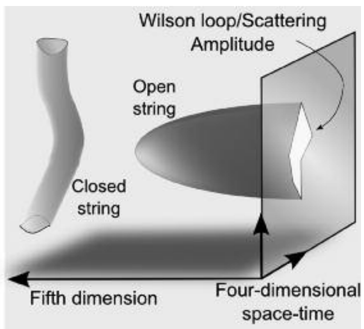


Fig.3: As a closed string moves through the higher dimensional bulk it will sweep out a tube while an open string will form a surface whose end points are on the boundary. Because of the space-time curvature the surface is pulled away from the boundary into the fifth dimension.

One discovery, in which many members of AEI have played key roles, is that this duality seems to be integrable in the limit of a large number of colors. That is to say, there are an infinite number of hidden symmetries, which in turn tells us that there are an infinite number of conserved quantities similar, in a fashion, to the conservation of energy. The existence of these hidden symmetries greatly constrains the theory, allowing us to calculate many interesting quantities exactly (see reports of previous years).

There has recently been great progress, in which members of AEI have been actively involved, in understanding the string description of scattering amplitudes in this limit of a large number or colors. An important step in the calculation involves making use of a property of string theories, called T-duality and its recently discovered analogue fermionic T-duality, to map the problem of calculating scattering amplitudes into that of calculating certain extended objects called Wilson loops. From the string point of view the problem reduces to a generalization of the classical problem of finding a soap bubble surface with a given boundary (see Fig. 3); the area of the bubble is essentially the logarithm of the scattering amplitude. Here again the symmetries of the theory, the conformal symmetry and integrability, are essential in solving the problem and it has already been shown that the full four- and five-leg amplitudes are uniquely determined by the symmetries alone. It is quite plausible that the integrable structure will allow us to completely determine all scattering amplitudes to all-orders; a remarkable achievement if possible.

Supergravity scattering amplitudes

In the realm of quantum gravity the improvements in perturbative methods have also led to some intriguing results. It has been long known that Einstein's theory of gravity cannot be naively used as a quantum theory due to infinities which appear at two-loops and which cannot be removed in a sensible fashion because the coupling parameter, Newton's constant, is dimensionful. Furthermore, while supergravity theories, that is gravitational theories with particular types of matter and couplings determined by supersymmetry, are better behaved, it was long believed that at some sufficiently high order in the loop expansion the same infinities would appear. These divergent terms had, however, never been explicitly calculated and it is only recently that such calculations have become feasible. While it may be slightly surprising, it is often useful to study the scattering of strings from which one can extract the field theory answers as a low energy limit. One important relation originating in string theory (see Fig. 4), allows the recycling of the calculation of amplitudes in N=4 SYM into those of the maximally supersymmetric gravity theory, N=8 supergravity.

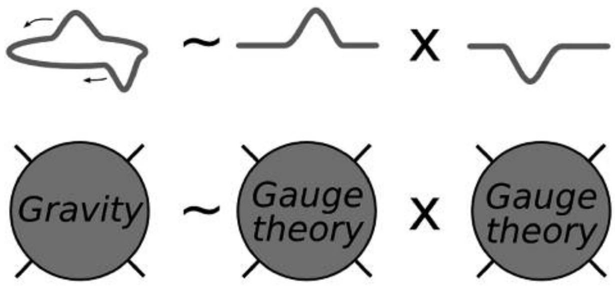
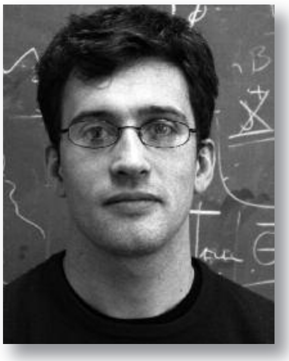


Fig.4: The excitations of a closed string can be split into two sets, each corresponding to the excitations of an open string. This implies relations between the scattering of closed strings, which become gravitons at low energies, and open strings, which become gluons.

Thus the progress in understanding gauge theory amplitudes can be used in understanding the perturbative expansion of gravity. Remarkably, explicit calculations have shown that there are no divergences up to the fourth order. Even more strikingly, the subtle cancellations amongst diagrams at low orders propagate to higher orders and suggest that the theory may in fact be finite to all orders, thus providing us with a perturbatively consistent quantum field theory of gravity. It is fair to say that the origin of these cancellations is currently far from clear. Understanding the consequences of just simply the supersymmetry remains an issue in which new progress is being made at the AEI. However, if the cancellations do indeed persist to all orders they cannot be due to supersymmetry alone but would rather suggest additional hidden symmetries or a new dynamical principle of field theory.

While perturbation theory cannot settle the issue of finiteness, at least not without some deep new insight, the study of amplitudes can reveal hidden structures. For example, it is well known that N=8 supergravity has an invariance with respect to the exceptional Lie group E_7 which is difficult to see in the usual description of the theory. Many aspects of this hidden symmetry have been actively studied by members of the institute, for example it has already been partially analyzed at the level of amplitudes. However, understanding its full implications for the finiteness of the theory remains work for the future.

Tristan McLoughlin



The Stringy Geometry of the Heterotic String

The notion of stringy geometry

What is the geometry of spacetime? On macroscopic scales Einstein's theory of relativity gives a precise and well-tested answer to this question: spacetime geometry and background matter fields obey Einstein's equations. The structure of spacetime on microscopic scales remains more mysterious, and most approaches to quantum gravity suggest that on scales near the Planck length of 10^{-35} cm a conventional notion of spacetime geometry based on manifolds of fixed topology and probe objects following geodesics will not yield a useful description. Does this mean that to describe the microscopic structure of spacetime we must abandon our well-honed geometric tools and hard-won insights? In the final reckoning it may well be so. However, the utility of these tools and dearth of substitutes suggest that we do so gradually, identifying which geometric aspects may be safely kept, which modified, and which must be entirely discarded. In string theory, the resulting set of ideas constitutes the notion of "stringy geometry."

In string theory, the question of spacetime structure receives a new twist since the string length provides an additional scale in the problem. If the Planck length is much smaller than the string length – the regime where the strings are weakly coupled – then strings are a natural set of objects for probing spacetime geometry, and it is sufficient to study a first-quantized formulation of the theory. This formulation is a generalization of the path-integral describing the quantum evolution of a point particle in a fixed background: the world-line is replaced by a two-dimensional space, known as the worldsheet, and the point particle action is replaced by a two-dimensional quantum field theory of maps from the worldsheet to spacetime. When the spacetime is flat, the two-dimensional theory is free; more generally, the strength of quantum corrections is governed by the scale of curvatures of spacetime fields in units of the string length.

Invariance of the theory under worldsheet reparametrizations requires the worldsheet theory to be a conformal field theory with a certain central charge. In supersymmetric string theories, when the spacetime curvatures are small, this implies that the spacetime must be ten dimensional, and the metric and other massless background fields must obey a ten-dimensional generalization of Einstein's equations. When the curvatures become large, this geometric interpretation must be replaced by properties of abstract conformal field theory. This quantum regime is the realm of stringy geometry. To study this regime quantitatively, it is useful to concentrate on a class of solutions with enough symmetry to make the problem tractable but not so much as to make it trivial. Such a class is provided by minimally supersymmetric four-dimensional compactifications of the heterotic string.

Heterotic string backgrounds and their moduli

The massless fields of the ten-dimensional heterotic string in a weakly curved background constitute a minimal supergravity coupled to super Yang-Mills theory with gauge group $E_8 x E_8$ (or SO(32)). To construct a solution with four-dimensional Poincaré invariance, a six-dimensional compact manifold replaces six of the spacetime dimensions. The consistency conditions that restrict the possible gauge groups to two choices also imply that a typical compactification geometry requires a non-trivial background gauge field. Geometrically this amounts to a choice of a vector bundle over the six-dimensional manifold obeying certain topological conditions. The simplest solution that preserves minimal supersymmetry in four dimensions selects the compactification geometry to be a Ricci-flat Kähler manifold with finite fundamental group – a space known as a Calabi-Yau manifold. In this case, the Yang-Mills vector bundle must be set equal to the tangent bundle of the Calabi-Yau space. This construction is known as the "standard embedding."

As described so far, the standard embedding solution satisfies the string consistency conditions to first order in the background curvature. Does the background continue to make sense in the full quantum worldsheet theory? There is by now overwhelming evidence that it does. The case for this assertion rests on two important properties of the worldsheet theory. The first is (2,2) supersymmetry, a property preserved by quantum corrections. The second is that the solution depends on a number of parameters that describe the size and shape of the Calabi-Yau manifold. These parameters are known respectively as Kähler moduli and complex structure moduli. Quantum corrections depend on the former set of moduli and are independent of the latter set. By tuning the Kähler moduli so that the Calabi-Yau curvature is small in units of the string length, the quantum corrections can be made arbitrarily small; moreover, by using properties of (2,2) supersymmetry and the geometry, it is possible to show that the background can be adjusted to solve the consistency conditions to all orders in perturbation theory. Arguments can be given that extend this result beyond perturbation theory, with one of the strongest based on mirror symmetry, a remarkable feature of stringy geometry.

Mirror symmetry is the property that two topologically distinct Calabi-Yau manifolds **M** and **W** can give rise to isomorphic conformal field theories and thus exactly the same heterotic string compactification. Moreover, the isomorphism maps the Kähler moduli of **M** to the complex structure moduli of **W** and vice-versa. This exchange allows control of quantum corrections in both the **M** and **W** descriptions and provides a clear example of emergent geometry: the string probe does not distinguish between two topologically distinct geometries; the choice of one versus the other is simply one of computational convenience! A basic lesson for stringy geometry is that while the space-time geometry is an ambiguous notion, the geometry of the Kähler and complex structure moduli spaces remains well defined. The moduli have a natural geometric structure, determined for instance by the Zamolodchikov metric of the conformal field theory. The associated geometric quantities, such as the Riemann curvature, describe the moduli dependence of terms in the effective action governing the scattering of massless string states. The (2,2) supersymmetry ensures that the moduli space splits as a product of Kähler and complex structure moduli spaces and constrains the possible quantum corrections: while the metric on the former receives an infinite sum of non-perturbative corrections, the classical metric on the latter is exact. Mirror symmetry allows both to be determined exactly by using the pair **M** and **W**, as opposed to just one of the manifolds.

Although the moduli are a boon for understanding the stringy geometry of the heterotic string, they are also the source for its great shortcoming as a viable phenomenological framework. In the standard embedding scenario, the low energy four-dimensional theory is a minimal supergravity coupled to supersymmetric gauge theory with gauge group E_6xE_8 and a chiral spectrum of matter fields charged under the E_6 gauge group and neutral under the E_8. In addition to these desirable features, each modulus of the worldsheet theory yields in the four-dimensional theory a neutral scalar field with vanishing potential. Such "fifth-force" carriers are largely ruled out by observations.

The last five or six years have seen much effort to find mechanisms by which these undesirable moduli can obtain sufficiently large masses. The work has mostly concentrated on type II superstrings, and notions of stringy geometry and mirror symmetry have played important roles in that program. It would be very useful to apply similar ideas in the context of the heterotic string, where many features of the worldsheet theory are actually under better control than in general type II backgrounds. There is, however, a significant obstacle that must be overcome: we still lack a full description of the heterotic moduli space!

Reducing worldsheet supersymmetry

We described the Kähler and complex structure moduli and claimed that (2,2) supersymmetry and mirror symmetry lead to a quantitative description of the moduli space geometry. What is lacking? The trouble is that the background typically has additional moduli associated with the Yang-Mills bundle. Turning on these moduli necessarily renders the six-dimensional metric non-Kähler and breaks half of the (2,2) worldsheet supersymmetry, leaving a less restrictive (0,2) supersymmetry. These moduli are typically not lifted by quantum corrections.

What is the full moduli space? How does mirror symmetry exchange the bundle moduli on M with those on W? What are the implications for stringy geometry? Can the moduli space metric be computed? There is one important reason to suspect that progress can be made on these issues: although the two-dimensional theory seems to be drastically modified by the bundle moduli, the four-dimensional spacetime physics is not much altered: for small but finite deformations the theory retains exactly the same spacetime supersymmetry, gauge group, and spectrum of charged matter fields. A closer look at the worldsheet theory suggests that perhaps the modifications are less drastic than they first appear. In the last few years, a number of groups have been using the experience with (2,2) theories and their various cousins such as gauged linear sigma models, topological field theories, and Landau-Ginzburg theories, to study the more general theories with (0,2) supersymmetry.

By use of additional structures in the theory it is possible to generalize a number of (2,2) results to (0,2) theories. For example, in collaboration with J. McOrist (Cambridge University), the author was able to derive non-renormalization theorems that generalize the splitting of the geometric moduli, as well as to compute the dependence of four-dimensional Yukawa couplings on the bundle and geometric moduli. Currently, in collaboration with McOrist and M.R. Plesser (Duke University), the author is pursuing a detailed study of the moduli spaces with the goal of generalizing mirror symmetry to include the bundle moduli. We have identified a class of models where this identification can be naturally made in the context of toric geometry and are now attempting to construct an explicit mirror map.

Despite being a textbook classic of string theory, heterotic compactification with standard embedding still offers important lessons. The most interesting of these relate to generalizations of stringy geometry and mirror symmetry. The lessons learned in these reasonably simple examples will have applications to a much wider class of heterotic solutions, and they are likely to shed light on the nature of spacetime from the point of view of the string.

Ilarion Melnikov

LISA Pathfinder Data Analysis

The planned gravitational wave observatory, LISA, is a very demanding space mission in scientific as well as technological terms. Since some technologies cannot be examined on ground, they will be tested in the precursor mission called LISA Pathfinder (LPF).

The main measurement concept of LISA is based on the ability to put a test mass in free fall and account for all residual forces that may act on it. LISA Pathfinder aims to develop the corresponding technologies and verify this concept. An interferometer measures the distance between two free-falling test masses with pico-meter accuracy in the milli-hertz range.

The LISA Pathfinder mission time is strictly limited. Experiments must be prepared in detail prior to the mission in order to maximise the mission's science output. The task of planning everything in advance becomes even more challenging when taking into account that the experiments are not independent from each other, but the result of one is likely to affect following experiments.This situation leads to special demands on the data analysis activities, as only a robust and carefully tested tool shall be used for the quasi-online data analysis whose results affect decisions for the experiments to follow. It becomes evident that the LISA Pathfinder mission needs a robust and flexible data analysis tool, which enables scientists to carry out the complete data analysis of the mission.

In late 2006 the development of such a data analysis tool started, and the idea of an object-oriented LTPDA (LISA Technology Package Data Analysis) MATLAB toolbox formed. The task was to develop a data analysis environment, which contains all analysis algorithms necessary to completely characterise the LISA Pathfinder experiment. Another major aim was to develop it such that every analysis would be completely traceable back to the raw data used, and fully reproducible. This concept has paved the way for LTPDA to become the official analysis software tool for the entire mission, and as such, it is tested according to ESA standards.

It so happens that the requirements placed on LTPDA concur with what most scientists wish their data analysis software to be. In turn this formed a very good starting situation for the development of a comprehensive software tool appealing to many scientists from the beginning. Thanks to this agreement, the expertise from GEO data analysis and commissioning team, and the good design of the tool, LTPDA quickly became the main software tool in the LISA and LISA Pathfinder groups of the AEI. These numerous users, especially the scientists, working in the lab on LPF experiments, greatly accelerated the development process.

The popularity of LTPDA is mainly the result of the new object oriented concept of so-called Analysis Objects (AOs) which greatly simplifies typical analysis pipelines. An AO is a structure, in which all kinds of information can be stored. Figure 1 illustrates the structure underlying an AO. In LTPDA every data analysis result is one AO. Within the environment of LTPDA a result is not only data or a plot but with the AO comes important information like units and data type. This concept enables scientists to share their results, which automatically include all important information on the analysis details. Results stored as AOs can be easily understood, redone or extended by anyone who uses LTPDA.

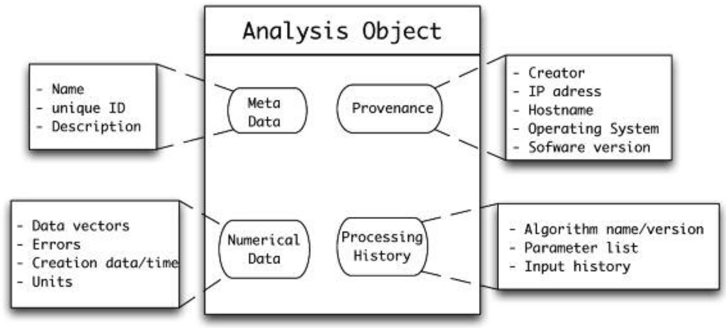


Fig.1: Illustration of the structure of an Analysis Object. The top layer and some details from the underlying structure are shown.

The heart of this structure is a so-called history field, in which all names and versions of the functions that have been used for the analysis, as well as a pointer to the raw data, are kept. This information makes every scientist using LTPDA able to trace back any analysis done, not only by her or himself, but by every other scientist using LTPDA.

Keeping track of each analysis step requires every single algorithm to add what we call 'history' information to the processed AO as well as to pass on the given input history object. In Figure 2 this behaviour of the algorithms of LTPDA is visualised. The information necessary to make a result reproducible at every stage of the analysis are:

- the algorithm name and version,
- the parameters given to the algorithm,
- the names of the input objects and
- the input history.

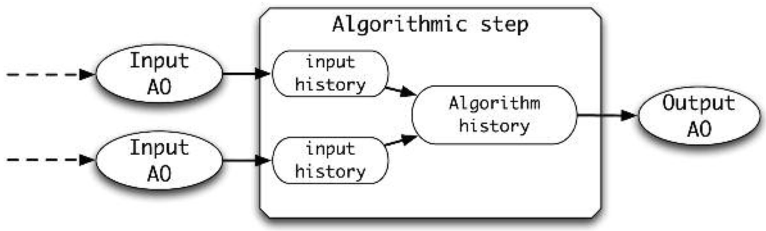


Fig.2: Schematic of the history processing of an LTPDA algorithm. Each algorithm unwraps the input AOs to store their history objects together with its own history object in the structure of the output AO.

Many standard MATLAB functions have been 'wrapped' to correctly process history information and many new algorithms have been developed following this principle. Figure 3 shows an example of a history tree evolved from a complex analysis. These schematics are generated automatically executing one simple command in LTPDA.

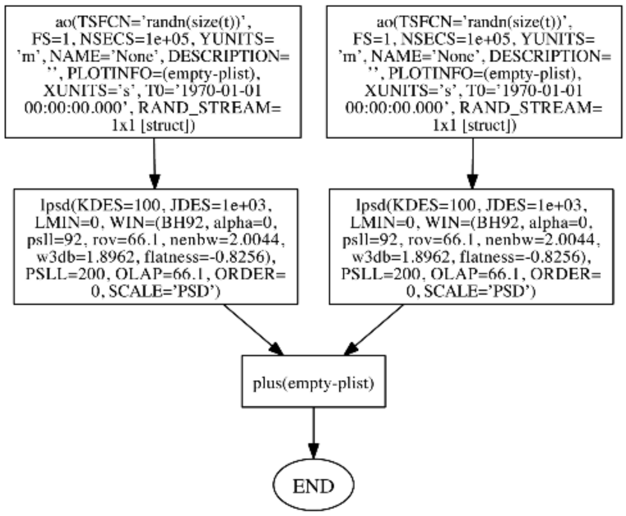


Fig.3: History tree of an Analysis Object. Visualising the processing path leading to the obtained result including important information about algorithms and their user defined parameters. The history object shown, originates from the result of a simple analysis procedure: the spectra of two time series are computed and then added together.

Mock data challenges

For the LPF data analysis, all the required functionality must be implemented and completely tested before the mission. Daily use of LTPDA during hardware development and testing on ground is necessary to assure the reliability of the software tool. However, this alone is not enough to ensure all necessary parts needed for the analysis of the mission will be in place. For this reason so called Mock data challenges (MDCs) simulating some of the experiments performed aboard LISA Pathfinder are carried out.

In the Mock Data Challenges, simulated data is generated according to a certain model of the experiment and this mock data is then analysed using the actual tools, which in our case is LTPDA (see Figure 4). These MDCs have proven to be a good instrument for driving the development of the analysis tools, as well as forcing a common understanding of the experiment on all scientists involved. So far two of these MDCs have been performed successfully. They were both based on a simplified model of the LPF system. With every MDC this model will become more advanced and the analysis outputs will be used as reference data during the mission.

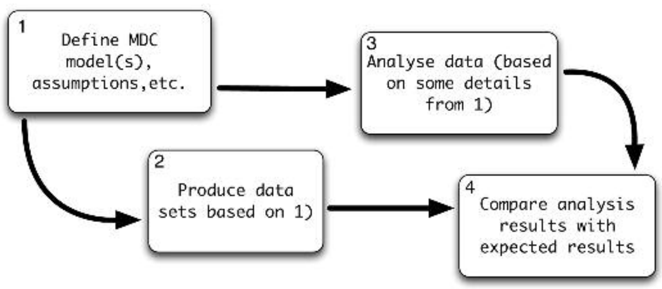


Fig.4: Flow chart illustrating the procedure of the first two LTP Mock Data Challenges.

The first MDC was focused on verifying the correct model matching the assumptions made. For this, data was generated by Team A and analysed by Team B. Team B derived the acceleration of the test masses from their position given by the simulated data according to their understanding of the underlying experiment. The 'correct answer', according to the model used for the data generation was provided by Team A. A comparison of the analytical model with the results derived from the mock data by the data analysis team is plotted in Figure 5.

Finally MDC1 resulted in finding the correct model, which every member of the LISA Pathfinder data analysis group agrees on. All MDCs to follow will be based on expansions of this model.

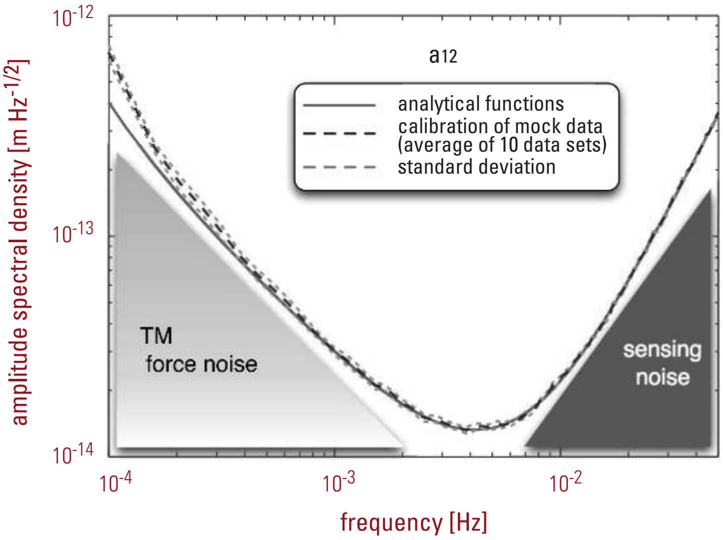


Fig.5: Result from MDC1: Conversion from simulated interferometer output to test mass acceleration including the noise sources that dominate the corresponding frequency regions: Differential acceleration between the two test masses in free-fall. The average of the analysis of 10 simulated data sets is plotted, and the resulting standard error represented by an upper and lower bound of the curve.

MDC2 has just been closed. Here the expansion from MDC1 does not lie in the model (which is the same as in MDC1) but in including some unknown parameter values. The data analysis team is provided with a set of simulated data, which contains a number of injected signals. Some parameters of the model are not communicated and instead have to be estimated from the signal injections by appropriate fitting routines. As a result, MDC2 drove the development and investigation of a variety of fitting routines.

The development of MDCs, and the analysis tools in general, is closely connected to the design of the experiments. The complexity of the simulated experiments is increased stepwise, such that the MDCs will become increasingly realistic and all mission experiments can be tested using realistic MDC models. The second version of LTPDA has been delivered to ESA and passed numerous testing procedures including unit tests, systems tests and acceptance tests. It contains many routines written for the Mock Data Challenges, daily data analysis issues (useful for various scientists), as well as for use in the LISA Pathfinder hardware test campaign, which has just started at the AEI in Hannover. The third version contains all tools necessary to analyse the mission data and was delivered in 2010.

Finally, what started as the development of a robust tool for the online data analysis of LISA Pathfinder has become a comprehensive, reliable and as such a powerful and popular tool for a more general data analysis. It is already used extensively not only for the data analysis of the LISA Pathfinder component tests but for all kinds of laboratory experiments throughout scientific groups around Europe.

Anneke Monsky

New Concepts and Results in Laser Power Stabilization

A key technology of interferometric ground-based gravitational wave detectors is an extremely stable, high-power laser system. Even a small amount of laser noise that is coupling to the gravitational wave readout channel could mask the faint gravitational wave signals. Therefore stringent, comprehensive laser stabilization is required to achieve the ambitious sensitivity of future detectors.

Advanced LIGO pre-stabilized laser system

The AEI is developing the pre-stabilized laser system for the second generation gravitational wave detector Advanced LIGO, which is going to replace the currently operating LIGO detector in a few years. The laser itself, with an output power of 200W at a wavelength of 1064nm, is developed by the Laser Zentrum Hannover e.V., and the latest laser prototype has been delivered to the AEI in May 2009. A unique and dedicated testbed for the pre-stabilized laser system has been set up during 2009 at the AEI. It is used to characterize and stabilize the laser, develop the interface to the Advanced LIGO computer control and to perform integrated tests of the whole system. The comprehensive stabilization includes a reduction of fluctuations of the output power, the laser frequency, and the beam pointing, as well as an improvement of the spatial beam quality. This laser stabilization effort is probably the most demanding one as of today.

A critical aspect of this stabilization is the laser power stabilization. Power fluctuations couple to the gravitational wave readout channel via radiation pressure and directly in the photo-detection process. The laser output power of about 200W will be enhanced by optical resonators in the interferometer to an expected circulating power of about 815kW. This laser beam will be reflected at test masses suspended with multi-stage pendulums and will cause radiation pressure. The distances between these test masses have to be measured to a precision of a fraction of a proton diameter in order to detect gravitational waves. Small fluctuations of the laser power cause radiation pressure fluctuations acting on the test mass, which leads to length changes of the interferometer arms. Asymmetries can cause slightly different power levels in the interferometer arms such that power fluctuations cause a differential length change that cannot be distinguished from length changes due to gravitational waves. By this effect, laser power fluctuations couple to the gravitational wave channel and thus an active power stabilization of the laser is essential in the detection frequency band from about 10Hz to 10kHz.

Several precursor laser power stabilization experiments, among others at the AEI and the MIT, were performed specifically for Advanced LIGO, and although their results were the best ones worldwide at the time of publication, the stability required by Advanced LIGO could not be demonstrated in these experiments. A high-sensitivity photodetector, transforming the laser power into an electrical signal, turned out to be the crucial component to reach the required relative power stability in the 10^{-9} range. Furthermore, laser power stabilization is crucial not only for Advanced LIGO, but also leads the way in the development of high-sensitivity photodetectors, which are essential for nearly all optics experiments. Photodetectors are fundamentally limited by quantum noise – called shot noise in this context – caused by the statistically independent arrival time of the photons at the detector. In order to improve the quantum-noise-limited sensitivity of the photodetectors, the detected laser power has to be increased. However, the maximum power handling capability of photodetectors commonly used has already been reached. As described in the following, two different, complementing approaches were taken in the last two years at the AEI to successfully increase the effective detected laser power and with it the sensitivity of the power detector.

High-sensitivity photodiode array

The first approach was to increase the total detected power by scaling the number of photodiodes. An array of four photodiodes was used to measure the power fluctuations of the laser, which were subsequently compensated with a power actuator to stabilize the laser. This power detector was specifically developed for Advanced LIGO and stands out due to its vacuum compatibility, a low-noise readout electronics, and a low scattering optical design (Fig. 1). Furthermore, we were able to operate the readout electronics outside of the vacuum tank, which allowed quick modifications of the electronics without time consuming venting. A second identical photodiode array was used to independently measure the residual power fluctuations downstream of the stabilization to verify the power stability achieved.

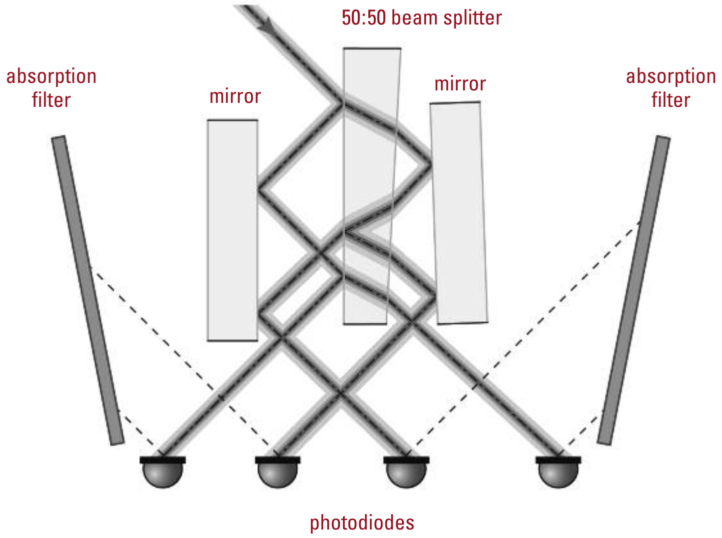


Fig.1: Optical layout and beam paths of the photodiode array.

The best power stability so far in the frequency range from 10Hz to 1kHz was achieved with this photodiode array (Fig. 2). This was the first experiment in this power stability range for which the limiting noise sources were identified, which was closer than 1dB (corresponds to about 12%) to the expected fundamental quantum noise limit, and which fulfilled the Advanced LIGO requirements. These power stabilization results set a new record and are a factor of two better than the previous best power stability, which was achieved at the AEI in 2006. Currently the next version of the photodiode array is being engineered and will be used for the power stabilization in Advanced LIGO.

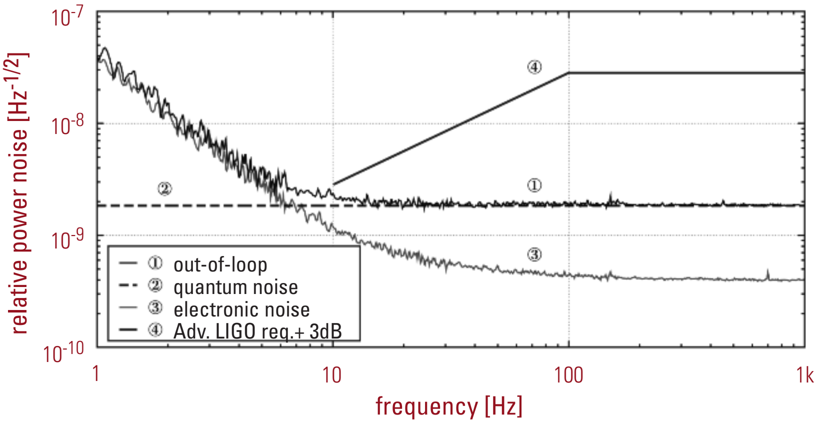


Fig.2: Independently measured residual power noise (out-of-loop), limiting noise sources (quantum and electronic noise), and Advanced LIGO requirements.

Optical ac coupling

The second approach was to use an optical resonator to increase the sensitivity of a photodetector. We called this novel, innovative detection method for power fluctuations "optical ac coupling". It is based on photo-detection in reflection of an optical resonator with a specific impedance matching.

In the traditional detection technique, commonly used until now, the high beam power at the photodetector causes most technical problems. Almost the complete beam power can be attributed to the large light field carrier, although only the small fluctuation sidebands contain the actual information about the power fluctuations to be measured. In the optical ac coupling, the optical resonator is used to suppress the carrier while preserving the fluctuation sidebands. Therefore the average power on the photodetector in reflection of the resonator can be reduced while keeping the same quantum-noise-limited sensitivity of power fluctuations. Taking current technical limits into account, it is possible to increase the sensitivity of a photodetector by about 20dB (corresponds to a factor of ten). To achieve the same effect in a traditional detection setup, one would have to increase the detected laser power by a factor of 100 – which is in many cases impossible due to the maximum power handling capability of photodetectors. In an experiment at the AEI a sensitivity for relative power noise in the upper 10^{-10} range in the radio frequency band was demonstrated, also setting a new record at these frequencies (Fig. 3).

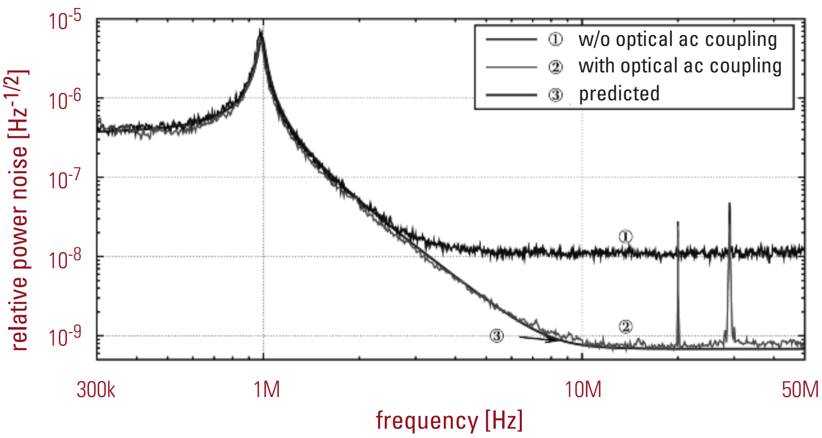


Fig.3: Measured power noise of a laser at radio frequencies with and without the optical ac coup-ling technique.

Besides these technical advantages, this technique allows new power stabilization concepts, which we studied theoretically and experimentally. Thus a power stabilization with optical ac coupling allows one to beat the quantum-limit of traditional power stabilizations by up to 6dB (corresponds to a factor of two). Furthermore these new concepts are compatible with ground-based gravitational wave detectors and might be used in the future to significantly improve the power stability of the laser beam injected into the interferometer.

Both experiments set milestones in the power stabilization of high-power laser systems. The new power stabilization results achieved with the high-sensitivity photodiode array are a big step forward in the laser stabilization for Advanced LIGO. In addition the optical ac coupling technique and the new stabilization concepts open a whole new range of attainable power stabilities that seemed to have been inaccessible due to technical limits before.

Patrick Kwee

Random and Stochastic Template Banks for Gravitational-Wave Searches

The past two years have seen tremendous progress in the construction of improved template banks for gravitational-wave searches, with a large contribution from groups at the AEI. In particular the — somewhat counter-intuitive — idea of placing templates *randomly* has proved to be surprisingly fruitful when facing a large number of unknown signal parameters ("dimensions"). This idea has resulted in two slightly different approaches, termed *random* and *stochastic* template banks, respectively.

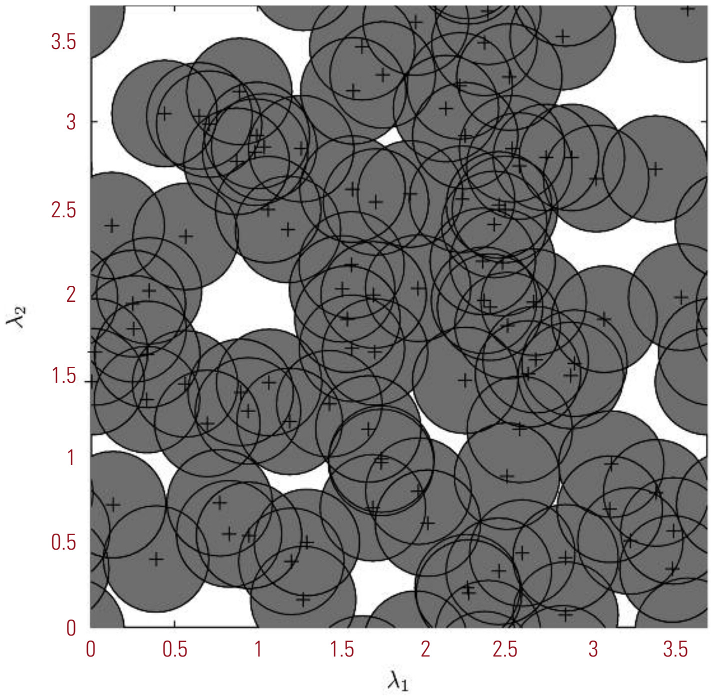


Fig.1: Example random template bank in two dimensions, with covering confidence of 90%.

Many gravitational-wave searches are based on *matched filtering*, where the observed data from gravitational-wave detectors are correlated with signal *templates*. The degree of correlation between the data and any given template determines the probability that this signal is actually present in the data. Examples are searches for binary inspirals and for (quasi-)periodic signals from spinning neutron stars using ground-based detectors, and searches for white-dwarf binary systems and supermassive black-hole binaries in LISA data.

The templates are usually parametrized by a number of unknown signal parameters, such as the frequency of a periodic signal, the sky-position of the emitting source, or the masses of a coalescing binary system. Typically the number of unknown parameters in most current searches falls in the range $2-4$, but could be as high as six or more, for example if searching for periodic signals from spinning neutron stars in binary systems. In the case of LISA there are certain signal classes with more than ten parameters, and some techniques require searching for a large number of signals *simultaneously*, which can bring the number of unknown parameters into the tens of thousands.

A general problem for any template-based search is the proper sampling of the multi-dimensional parameter space. There are two competing requirements: obviously one wants to sample the parameter space as finely as possible, in order to avoid missing a signal that might otherwise "slip through the net". On the other hand, each template requires computing its correlation with the data. Therefore the total computing cost of a search is directly proportional to the number of templates searched. In many cases the resulting computing cost is a limiting factor of what searches are even possible to perform, and what sensitivity can be reached. Therefore it is very important to find *efficient* template banks, which reconcile these demands by achieving a high probability of catching any signal with an affordable number of templates.

The matched-filtering correlation provides a natural distance scale in parameter space, namely the degree of correlation between two templates determines whether they are "close" or "far". This natural matched-filtering *metric* encodes the relevant geometry of the template parameter space. Depending on the signal family and the dimensionality of the parameter space, the metric can be very hard to compute explicitly, and generally depends on the position in parameter space, corresponding to a curved geometry. Not surprisingly, such curvature substantially complicates the problem of building an efficient template bank.

Using this natural distance scale, we can visualize each template as covering a *sphere* in parameter-space, e.g. see Fig. 1. The sphere radius corresponds to the maximal acceptable loss in correlation between a signal and a template, which depends on the requirements of the particular analysis. An *optimal* template bank should cover all (or most) of the parameter space with the smallest possible number of template spheres. This corresponds to a long-standing mathematical question known as the "sphere covering problem", which has only been solved for low dimensions (less than 6) and for flat metrics.

Traditionally, template-bank sampling was based on laying regular grids, or *lattices*, in parameter space. The simplest example would be a (hyper-) cubic lattice of templates (denoted as $\mathbb{Z}_n$). Unfortunately the hypercubic lattice results in a particularly inefficient covering, especially as the number of dimensions increases. On the other hand, the so-called A_n^* lattice, which generalizes the two-dimensional hexagonal ("honeycomb") lattice to higher dimensions, is a highly efficient covering lattice. Namely, an A_n^* template bank requires dramatically fewer templates than the hypercubic $\mathbb{Z}_n$ lattice [1], as can be seen in Fig. 2.

However, the lattice-based approach suffers from a number of practical difficulties: even the best covering lattices become *intrinsically* quite inefficient at higher dimensions (see Fig. 2), where overlap between neighbouring template spheres increasingly dominates over the actual space covered. Secondly, many signal types yield a curved parameter-space geometry, which makes constructing a lattice-based template bank nearly impossible.

This is where random and stochastic template placement shines. Both methods have in common that templates are placed randomly, but in

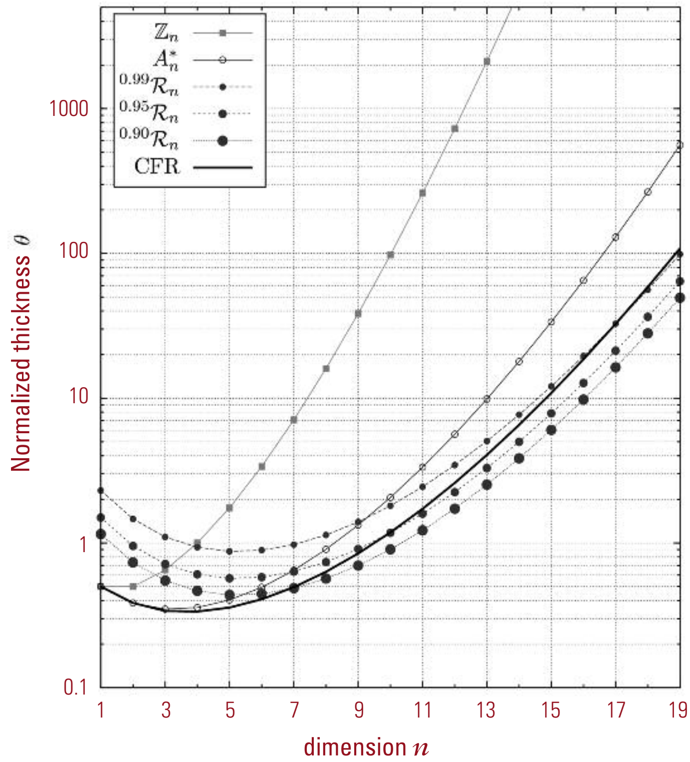


Fig.2: Template density θ as function of dimension n for different template banks. $\mathbb{Z}_n$ denotes the hyper-cubic lattice, A_n^* is the generalized hexagonal lattice, and R_n^η denotes random template banks with different covering confidences, $\eta < 1$. The curve labelled 'CFR' is the theoretical lower limit for any *complete* covering.

the case of *stochastic template banks*, any new randomly-picked template is first checked for overlap against all previous templates and is only retained if it does not overlap by too much. This process is continued iteratively until no new "hole" can be found for a new template in a given number of trials. The AEI has played a key role in the development and application of this method [2, 3].

Random template banks, which were first studied at the AEI [4], contain no such "pruning" step. This considerably simplifies analysis of the resulting covering properties. In particular, it allows to analytically compute the number of templates required for a given desired covering confidence. If the underlying template space has a curved geometry, one can adapt the method by randomly sampling proportionally to the "metric density".

Apart from the obvious gain in simplicity of these random methods, a very surprising result was found in the analytic study [4]: the relative efficiency of random template placement compared to lattices grows rapidly as a function of parameter-space dimension n. In fact, random banks outperform *any* lattice-based approach in higher dimensions, and this transition typically happens around dimensions $n \sim 4 - 9$ (see Fig. 2), and is therefore of great practical relevance.

Note that contrary to classical lattice banks, neither random nor stochastic template banks guarantee *complete* coverage of the parameter space. One can only give a certain statistical confidence < 100% that a signal will be covered. This is a key feature of these methods, which allows them to be so efficient at higher dimensions, where it becomes increasingly expensive to cover "the last few percent". By giving up a small fraction of parameter space in a statistically controlled way, massive efficiency gains become possible. Note that this also held an important lesson for lattice-based coverings: one can construct "relaxed lattices" that are more coarsely sampled than would be required for full coverage. This substantially improves the efficiency of lattice template banks, and makes them competitive again with random banks for dimensions up to $n \sim 11$. In higher dimensions, however, random-based template banks again are more efficient than even relaxed lattices.

Stochastic template banks improve the covering efficiency of pure random placement by pruning any unneeded templates, which is useful especially at lower dimensions, but this pruning process can itself become costly for a large number of templates. However, stochastic template banks have a major advantage over other approaches when the underlying metric geometry is strongly curved, unknown or difficult to compute. Contrary to the other methods, stochastic placement does not need any explicit knowledge about the parameter-space metric, all it requires is computing direct correlations between different templates. As long as this latter step is not computationally prohibitive, stochastic template banks can deal with even the most complicated parameter-space structures in a highly efficient way.

In recent years there has been a lot of progress in our understanding of different template placement strategies, starting from classical lattice coverings, to the newer random and stochastic placement methods and relaxed lattices, with a strong AEI component in all of these developments. As a result of this, a good arsenal of methods is now available, with the respective strengths and weaknesses well understood. This allows gravitational-wave data analysts to make well-informed choices and to pick the most suitable template-bank approach for any given search, which has increased our overall chances of detecting gravitational waves.

Reinhard Prix

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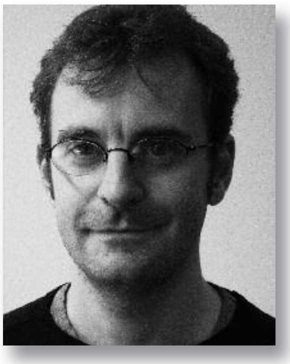


All-Sky Surveys for Continuous Gravitational-Wave Sources: On the Solution of the Semicoherent Combination Problem

Prime target sources of continuous gravitational waves (CW) for current Earth-based laser-interferometric detectors are rapidly spinning compact objects, such as neutron stars, with nonaxisymmetric deformations. The most promising searches are for previously unknown CW sources. As most neutron stars are electromagnetically invisible, gravitational-wave observations might allow to reveal completely new populations of neutron stars. Only recently, CW searches have started to invade the parameter space of astrophysical interest for the first time by any kind of observation. This is particularly important since there are enormous uncertainties in the predicted parameters. Therefore, a CW detection could potentially be extremely helpful for neutron-star astrophysics. Even the null results of today's search efforts, yielding observational upper limits, already constrain the physics of neutron stars.

The expected CW signals are extremely weak, and deeply buried in the detector instrument noise. Thus, to extract these signals sensitive data analysis methods are essential. A powerful method is coherent matched filtering, where the signal-to-noise ratio (SNR) increases with the square root of observation time. Hence, detection is a matter of observing long enough, to accumulate sufficient SNR.

The CW data analysis is complicated by the fact that the terrestrial detector location Doppler-modulates the amplitude and phase of the waveform, as the Earth moves relative to the solar system barycenter (SSB). The parameters describing the signal's amplitude variation may be analytically eliminated by maximizing the coherent matched-filtering statistic. The remaining search parameters describing the signal's phase are the source's sky location, frequency and frequency derivatives. The resulting coherent detection statistic is commonly called the F-statistic.

However, what ultimately limits the sensitivity of all-sky surveys for unknown CW sources using the F-statistic is the finite computing power available. Such searches are computationally very expensive, because for maximum sensitivity one must convolve the full data set with many signal waveforms (templates) corresponding to all possible sources. But the number of templates required for a fully coherent F-statistic search increases as a high power of the observation time. For a year of data, the computational cost to search a realistic range of parameter space exceeds the total computing power on Earth. Thus a fully coherent search is limited to much shorter observation times.

Searching year-long data sets is accomplished by less costly hierarchical semicoherent methods. The data is broken into segments of duration T, with T being much smaller than one year. Each segment is analyzed coherently, computing the F-statistic on a coarse grid of templates. Then the F-statistics from all segments (or statistics derived from F) are incoherently combined using a common fine grid of templates, discarding phase information between segments.

Among previous semicoherent strategies, the so-called Stack-Slide method sums F values along putative signal tracks in parameter space across segments. The Hough transform method sums ones or zeros across segments, depending upon whether the F-statistic exceeds a predefined threshold in a given segment. This latter technique has also been used by the public distributed computing project Einstein@Home, carrying out the most sensitive all-sky CW searches.

A central long-standing problem in these semicoherent methods was the design of, and link between, the coarse and fine grids. Previous methods, while creative and clever, were arbitrary and ad hoc constructions. In most recent work at the AEI [1], the optimal solution for the incoherent combination step has been found. The key quantity is the fractional loss, called mismatch, in expected F-statistic (or sum of F-statistics in the incoherent step) for a given signal at a nearby grid point. Locally Taylor-expanding the mismatch (to quadratic order) in the differences of the coordinates defines a positive definite metric. Previous methods considered parameter correlations in the F-statistic to only linear order in coherent observation time T, discarding higher orders in T from the metric. The F-statistic has strong "global" (large-scale) correlations in the physical coordinates, extending outside a region in which the mismatch is well-approximated by the metric. In a recent study at the AEI [2], an improved understanding of the large-scale correlations in the F-statistic has been found. Particularly, for realistic values of T (a day or longer) it turned out to be also crucial to consider the fractional loss of F to second order in T.

Exploiting these large-scale correlations in the coherent detection statistic F has lead to a significantly improved semicoherent search technique for CW signals. This novel method is optimal if the semicoherent detection statistic is taken to be the sum of one coarse-grid F-statistic value from each data segment, and makes a number of important improvements.

First, the improved understanding of large-scale correlations yields new coordinates on the phase parameter space. The metric in these coordinates accurately approximates the mismatch in each segment. Hence, the optimal (closest) coarse-grid point from each segment can be determined for any given fine-grid point in the incoherent combination step.

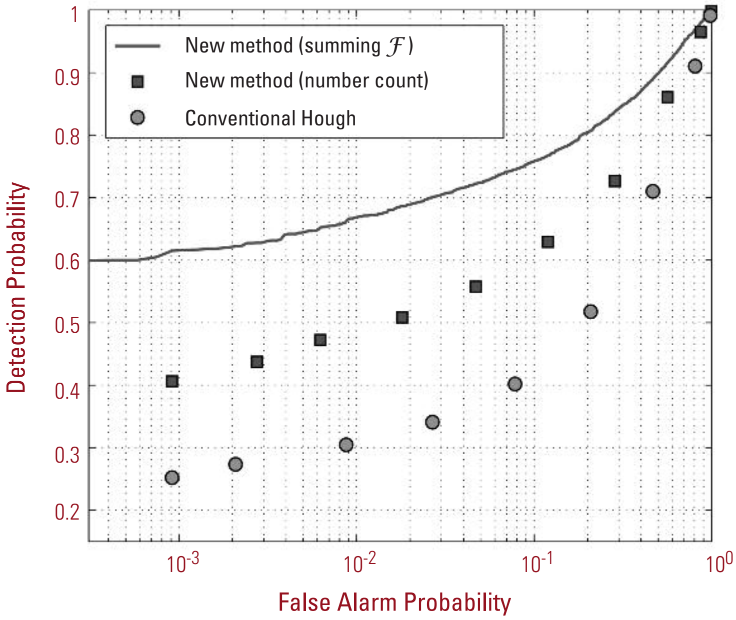
Second, in the new coordinates the first analytical metric for the semicoherent combination step has been found to construct the optimal fine grid (minimum possible number of points). Previous ad hoc approaches obtain the fine grid by refining the coarse grid in three dimensions. The explicit semicoherent-step metric shows that refinement is only needed in one dimension. This greatly reduces the computational cost at equal detection sensitivity.

Third, existing techniques combined the coherent results less effectively, because they did not use metric information beyond linear order in T. Thus, the new method leads to a higher sensitivity at equal computational cost.

Fourth, the new technique can simultaneously operate in a Stack-Slide-like and a Hough-like mode, with a lower total computational cost than either one of these methods individually.

Figure 1 illustrates the improved performance of an implementation of this new method in comparison with the conventional Hough transform technique, based on Monte Carlo simulations. Providing a realistic comparison, simulated data covered the same time intervals as the input data of the recent (S5R5) Einstein@Home search, which employed the conventional Hough transform technique. Those data, from LIGO Hanford (H1) and LIGO Livingston (L1), included 121 data segments of 25-hour duration. The false alarm probabilities were obtained using many simulated data sets with different realizations of stationary Gaussian white noise. To find the detection probabilities, different CW signals with fixed source strain amplitude were added. Source parameters were randomly drawn from uniform distributions.

The bottom panel of Figure 1 shows the detection efficiencies for different values of source strain amplitude, at a fixed 1% false alarm probability. In both modes of operation, the new technique performs significantly better than the Hough method. For instance, 90% detection probability with the new method (in number-count operation



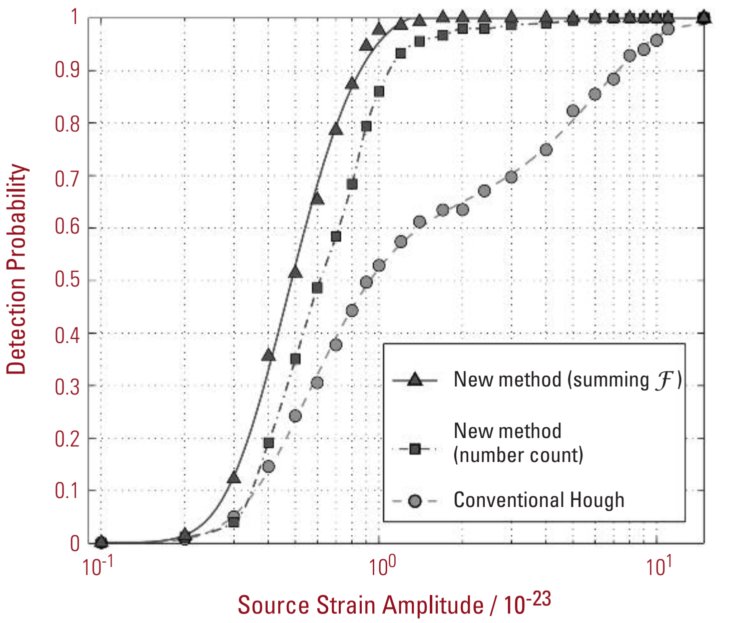


Fig.1: Performance demonstration of the new search method.

Top panel: Receiver operating characteristic curves for fixed source strain amplitude.

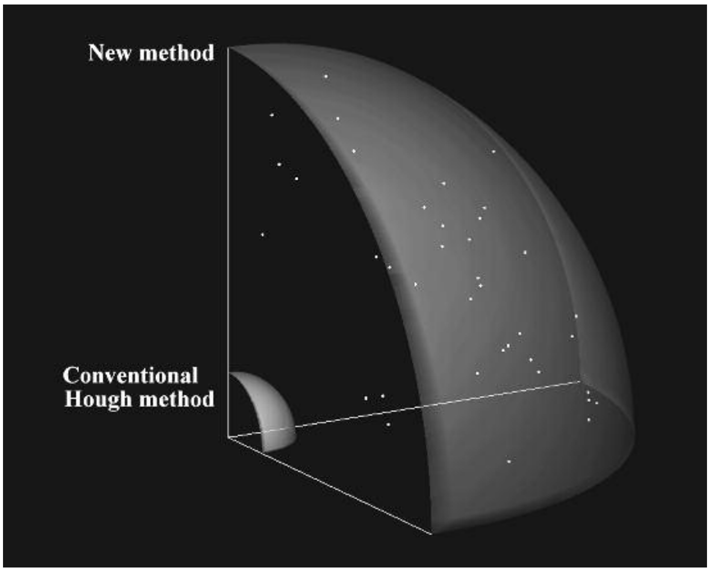
Bottom panel: Detection probability as a function of source strain amplitude, at 1% false alarm probability. The new method performs substantially better than the conventional Hough technique.

mode) is obtained for a value of source strain amplitude about 6 times smaller as needed by the Hough method: the "distance reach" of the new technique is about 6 times larger. This increases the number of potentially detectable sources by more than 2 orders of magnitude, since the "visible" spatial volume increases as the cube of the distance, as illustrated in Figure 2 (overleaf).

In addition, the new method has lower computational cost, which in turn could also be reinvested to even further improve the sensitivity.

It is hoped that this method should be extendible to search for CW sources in binary systems, as well as to space-based detectors. The method also has applicability in radio, X- and γ-ray astronomy (searches for weak radio or γ-ray pulsars, or pulsations from X-ray binaries).

Fig.2: Illustration of increased "visible" spatial volume due to the novel search technique.



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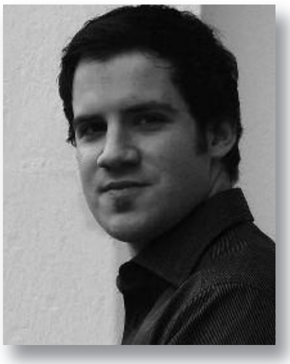

The LIGO Scientific Collaboration is currently working towards using this technique in the Einstein@Home project, eventually beginning with future LIGO S6 data. The combination of a better search technique, and more sensitive data, greatly increases the chance of making the first gravitational wave detection of a CW source. In the long run, the detection of CW signals will provide new means to discover and locate neutron stars, and will eventually provide unique insights into the nature of matter at high densities.

Holger J. Pletsch

Duality and Integrable Structures
Max Planck Research Group

Exact AdS/CFT Planar Spectrum

Gauge/Gravity dualities

In 1997 Maldacena provided the first concrete realization of the so called *Gauge/Gravity dualities*. He conjectured that a very particular particle theory called N=4 super Yang-Mills theory (N=4 SYM) was equivalent to a supersymmetric string theory on a curved space-time (denoted by AdS_5 x S^5). Over the last twelve years evidence for this duality grew spectacularly (so far, after thousands of papers of scrutiny, there is no indication of failure!) and the consequences of such remarkable correspondence are being intensively explored. In particular, there are two major open questions in human knowledge which might be answered or at least much better understood by means of such dualities:

The first question concerns the unification of two seemingly irreconcilable theories: relativistic quantum field theories, governing the subatomic world, and the theory of general relativity, which describes astrophysical phenomena. In general the domain of applicability of these theories is quite distinct and their immiscibility is not an urgent concern. However, when considering some problems in cosmology, such as the Big Bang when the universe was both very small and very curved, we *do* need to deal with quantum mechanics and gravity at the same time. String theory is the most promising candidate for the unified theory of quantum gravity.

The second open question concerns the dynamics of strongly coupled quantum chromodynamics (QCD), the physical theory which best describes the properties of constituents of atomic nuclei. At extremely high energies the quarks and gluons are weakly coupled and we have a good physical description of their behaviour. On the other hand, at lower energies, they become strongly coupled and our current computational techniques – except in some cases for lattice QCD – are not suitable.

The Gauge/Gravity dualities mentioned above seem to indicate that these two questions might actually be very tightly related! Furthermore, as explained above, there is by now mounting evidence that the theories related by this correspondence are actually exactly solvable at least in some particular limit! Of course this should be taken with a grain of salt since N=4 SYM is not the theory, which describes particles in the real world. However the importance of providing a complete solution of this interacting four-dimensional gauge theory and of the corresponding gravity dual can not be overestimated. As an historical example, the 1944 Onsager solution of the two dimensional Ising model gave rise to an outstanding improvement of our description of two-dimensional classical models. Many other more realistic models, seemingly much more complicated than the Ising model, were solved soon after Onsager's discovery and nowadays our description of 2D classical models is extremely complete. It is very likely that we will observe a similar revolution in our understanding of gauge theories if we exactly solve a first nontrivial example such as N=4 SYM.

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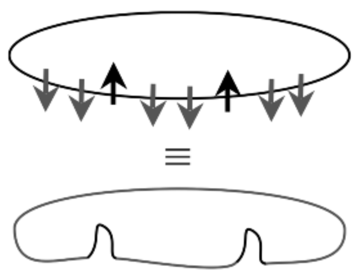


Fig.1: Composite operators in N=4 SYM can be thought of as one dimensional integrable spin chains which are dual to single string states according to the Gauge/Gravity duality.

Integrability in Gauge/Gravity dualities

In the planar limit introduced by 't Hooft, integrable structures – so dear to condensed matter physicists – arose in both theories related by Maldacena Gauge/Gravity duality also called AdS/CFT duality. In N=4 SYM the objects which correspond to single closed strings under the Gauge/Gravity dictionary are composite objects made out of several fundamental fields lined up in a circle. This circle is the analogue of the string loop. In string theory we can have string excitations propagating in the loop and scattering among themselves; similarly, in N=4 SYM some fundamental fields in the circle mentioned above can also move and scatter with other fundamental fields. The remarkable feature of these theories – integrability – arises when we analyze the scattering of these excitations. It turns out that if we consider the scattering of one of the excitations with all the other excitations we observe that the net effect of this many-body scattering process is the same as if this particle would only interact in a pair-wise fashion with each of the other particles. This is what defines a theory to be integrable!

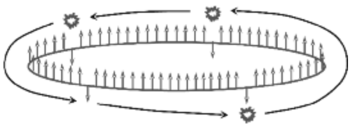


Fig.2: Integrable models: The scattering of one particle with all other particles can be though of as a sequence of pair-wise scattering events.

As described in detail in the reports of the previous years, Beisert, Staudacher and their collaborators were world leaders in understanding to which extent integrability was present in both theories and how to describe them in a unified set-up: the Beisert-Staudacher Bethe equations based on the Beisert-Eden-Staudacher scattering phase. These equations describe what happens to an excitation when it goes around the circle and comes back to the same position scattering in pair-wise fashion with all other excitations.

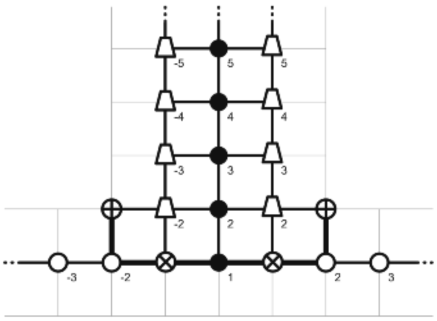


Fig.3: The Y-system is a set of functional equations for functions $Y_{as}(u)$ where the indices take values in a T-shaped lattice. The solution to these equations, supplemented by appropriate boundary conditions, is conjectured to yield the exact spectrum of planar AdS/CFT.

The domain of applicability of the Bethe ansatz grows with the size of the circle we consider. This is because, in order for the above picture to hold, we need free asymptotic particles moving in the circle and scattering with each other in localized regions. As we go to higher orders in perturbation theory the excitations develop longer range interactions and therefore, if the circle is too small, the Bethe ansatz description breaks down (for the smallest operators in N=4 SYM the breakdown of the asymptotic Bethe ansatz only happens at four loops). If we consider composite operators made out of a large number of fundamental fields or, in the dual picture, if we focus on strings with very large angular momentum then we can describe the spectrum with arbitrary precision; because of this property these Bethe equations are called *asymptotic*. Obviously, to solve the spectral problem, we want to be able to treat any state irrespective of its size.

Thermodynamic Bethe Ansatz in Gauge/Gravity dualities

In 2009 P. Vieira and collaborators N. Gromov (Hamburg University) and V. Kazakov (Ecole Normale Superieure) proposed a set of equations, dubbed Y-system, which are supposed to describe the exact planar spectrum of N=4 SYM and of the dual string theory. They are based on the string world-sheet approach and on the thermodynamic Bethe ansatz trick.

Fig.4: Thermodynamic Bethe ansatz trick: Exchanging space and time allows us to relate the ground state energy in finite volume with the free energy at infinite volume.

Suppose we want to compute the ground state energy of some integrable field theory with compact spatial direction. We would perform the partition function path integral in a torus with one of the circles being finite (the spatial direction) while the other circle (euclidean time direction) is taken to be huge so that the path integrals picks up the ground state. If we now re-interpret this path integral by exchanging the role of time and space we end up with a huge spatial direction times a finite time circle. Since the spatial circle is huge the asymptotic description of Beisert and Staudacher alluded above is valid while the finite time circle simply means we need to consider finite temperature. By this trick we can compute the exact ground state energy of an integrable system put in any circle, no matter how small it might be. Analytically continuing the ground state thermodynamical Bethe ansatz equations one can incorporate the excited states. The resulting integral equations, proposed by P. Vieira and collaborators in a series of papers in 2009, are a major accomplishment in the field since they are a proposal for the solution to the spectral problem in planar AdS/CFT, a goal which was being actively pursued by the community. So far they reproduce all known data and have passed a few tests beyond.

The Y-system equations were solved numerically for the simplest operator in N=4 SYM, the Konishi state. This involved about 1000 hours of computer time and allowed to compute its exact anomalous dimension up to very large values of the coupling (see figure 5). This was the first time ever that an anomalous dimension in a non-trivial four-dimensional gauge theory was computed for generic coupling. It should be possible to develop even more efficient and elegant techniques to solve these equations. In the context of the somewhat simpler SO(4) non-linear sigma model this was successfully done by P. Vieira and collaborators in late 2008. For this model the corresponding infinite number of Y-system equations were reduced to a single integral equation, thus enormously simplifying the computation of the exact spectrum of this model.

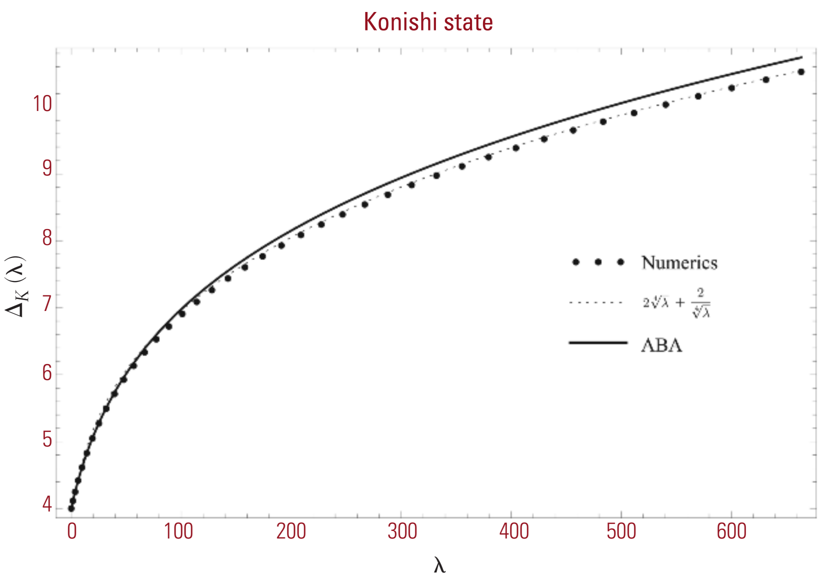


Fig.5: Numerical plot of the dimension of the Konishi operator as a function of the coupling.

Despite the enormous successes of the last years it is still fair to say that very little is understood concerning why is integrability present in N=4 SYM. The derivation discussed above relies very strongly on string theory and on the validity of the AdS/CFT correspondence; an alternative derivation of the Y-system based on N=4 SYM alone would be extremely important. Altogether, there are still extremely interesting questions to be understood in the very exciting field of integrability in Gauge/Gravity duality.

Pedro Vieira

Canonical and Covariant Dynamics of Quantum Gravity Max Planck Research Group

Continuum Symmetries in Discretized Theories?

Many quantum gravity models, such as spin foams, quantum Regge calculus or canonical lattice models, utilize a discretization of the underlying space time manifold as a regularization method. This is one method to avoid divergencies, however this method endangers the fundamental symmetry of general relativity, which is diffeomorphism symmetry. Indeed systems with symmetry, either global or local gauge symmetries, very often lose that symmetry upon discretization. While e.g. the introduction of a lattice in Yang-Mills theory can be done without harming the local gauge symmetry, it usually breaks invariance under global Poincaré transformation, which results in severe problems for lattice quantum chromo dynamics.

In the same way the introduction of a triangulation in Regge calculus or in spin foam approaches breaks local diffeomorphism symmetry. This is a problem for quantization as keeping symmetries in the theory is essential to avoid otherwise ubiquitous quantization ambiguities and to obtain general relativity in the semi-classical limit of the quantum theory. We will discuss whether discretization leads always to a breaking of diffeomorphism invariance or whether this can be avoided. The latter case would provide us a diffeomorphism invariant cut off method and hence be extremely valuable for the construction of quantum gravity theories.

Are there any symmetries?

The issue of diffeomorphism symmetry in discretized gravity theories is quite involved. In the continuum diffeomorphism symmetry is connected to the free choice of space-time coordinates. Many discretized models do however not use any coordinates, but deal directly with geometric quantities, such as the length of the edges in the discretized geometry. Therefore it was often argued that there is no notion of diffeomorphism symmetry for discrete models.

In particular Regge calculus, which is the classical theory underlying for instance spin foams, operates directly with the length of the edges of the discretized space time (usually a triangulation). Although it does not involve any coordinates, Rocek and Williams in 1981, found that the linearization of the theory around a flat background has gauge modes, which can be connected to the gauge modes of the continuum theory arising from coordinate invariance of the continuum action. These findings imply that diffeomorphism symmetry should play a role also in discretized models. Nevertheless opinions were divided on the significance of these results and whether gauge modes should appear also on curved backgrounds.

Perfect actions

Bahr and Dittrich showed in 2009 explicitly that for a curved solution the gauge modes of the flat background do not appear. Nevertheless there are pseudo gauge modes, which behave dynamically very differently from the true physical modes. Indeed, in a continuum limit these pseudo gauge modes have to be converted to true gauge modes in order to re-obtain the correct long distance physics.

Hence there is a notion of diffeomorphism symmetry for discretized geometries, which in most cases happens to be only an approximative one. Whether one encounters exact or approximate gauge symmetries depends on the chosen discretization of the action. Indeed for three-dimensional discretized gravity with a cosmological constant the standard Regge action – based on discretizing space-time with a piecewise flat manifold – has only approximate symmetries. There is however an alternative discretization – proposed by Bahr and the author in 2009 – that uses piecewise homogeneously curved manifolds. This action displays exact gauge modes and although being a discretized action mirrors exactly the continuum physics.

Discretized actions that exactly describe the dynamics and hence gauge symmetries of the continuum theory are known under the name 'perfect actions'. Wilson's renormalization approach allows us to construct such actions: if we start with a very fine grained lattice and integrate out the fine grained degrees of freedom the resulting effective theory – although defined on the coarse grained lattice – delivers the predictions of the fine grained theory. Taking the limit of the fine graining to the continuum, resulting in a 'block transformation from the continuum' we obtain a theory on a lattice that exactly reflects the predictions of the continuum theory. Note that the predictions derived from a discrete action of this type should be also independent of the details of the triangulation, as such an action reflects the continuum physics. Hence the restoration of diffeomorphism invariance is connected to the independence of the chosen regulation, which in this case is provided by a triangulation. Bahr and the author could show that this scenario can be realized in the case of 3d gravity with a non-vanishing cosmological constant and some special cases of 4d gravity with a cosmological constant.

Canonical framework

Covariant models can be understood as describing space-time states, whereas canonical formulations of gravity describe the evolution of space in time. The gauge symmetries of the action lead in the canonical formulation to so-called constraints, that in gravity are essential to define the canonical dynamics of the system.

Also in the canonical framework lattices and more general discretizations can be used as a regulator. However almost always one encountered the problem of an anomalous constraint algebra, leading to an inconsistent dynamics. This has been a huge obstacle in the development of canonical lattice models. Furthermore typically such models did not treat space and time symmetrically. Whereas space was discretized, time remained continuous. Therefore it was very uncertain whether the symmetries of general relativity could be preserved in such a framework and moreover a connection to the covariant models, which involve both space and time discretization very unclear.

A first task was therefore to develop a canonical formalism that would lead to exactly the same solutions – with discretized space and discretized time – as in the covariant formalism. Such a formalism for gravity has been developed in papers by Bahr and the author and another paper by Höhn and the author using earlier ideas of Gambini, Pullin et al., known as consistent discretization, and Sorkin et al. for an initial value formulation of Regge calculus.

It has been shown that within this new canonical formalism the appearance and consistency of constraints is tied to the existents of exact gauge symmetries in the action. Hence constructing an anomaly free discretization of the constraints is possible if one can construct the perfect action. Moreover in case that diffeomorphism symmetry can be implemented in this way into the discrete models one automatically obtains also an infinitesimal version of time evolution whose integration coincides with the evolution in discrete time. In other words the choice of discretization steps in time (and in space) does not matter for the prediction of the theory. This is in analogy to diffeomorphism symmetry in the continuum, that ensures that the choice of time and spatial coordinates does not matter for the predictions of the theory.

Perturbative expansion

The method described above for constructing the perfect action requires to partially solve the dynamics of the theory. For 4d Regge gravity (as for continuum gravity) this is unfortunately impossible to do in full generality. A perturbative expansion around flat space is however feasible and should provide us with information about structural properties of the perfect action.

Such a perturbative expansion and its canonical analogue has been performed by the author and Höhn. The results very nicely underline the previous findings: The lowest (linear) order inherits the exact gauge symmetries of the flat background. The linear constraints are consistent and form an anomaly free (Abelian) algebra. At the lowest non-linear order the gauge symmetries are broken. This breaking leads to a consistency requirement that allows only for an expansion with specific choices of the background gauge – which basically determines how the flat background is discretized. Interestingly the consistency requirement is such, that it minimizes the dependence of physical predictions on the choice of discretization. In a way the first non-linear order selects a preferred discretization of the background space-time.

In summary although discrete theories of four-dimensional gravity seem to generically break diffeomorphism invariance there is a possibility to construct discretizations that display exact diffeomorphism invariance.

Even if it is calculationally not possible to obtain the exact perfect action, a systematic investigation of the approximate symmetries and constraints under refinement of the triangulation – or change of scale – is paramount for the question of the fate of diffeomorphism symmetry in the discretized setting and therefore in quantum gravity.

Bianca Dittrich

Microscopic Quantum Structure and Dynamics of Spacetime Research Group

Group Field Theory Models for Quantum Gravity

A main focus of the research activities of the group are so-called group field theory models for quantum gravity. They are an attempt to define quantum gravity in terms of combinatorially non-local quantum field theories on group manifolds, related to the Lorentz group. Quantum field theory (QFT) is the best formalism we have for describing physics at both microscopic and mesoscopic scales. Therefore it is natural to look for a formulation of quantum gravity as a QFT. However, a good theory of quantum gravity should be background-independent, as it should explain origin and properties of spacetime itself, while we know how to formulate quantum field theories only on fixed background spacetimes.

Therefore, if a QFT it should be, quantum gravity can only be a QFT on some internal or "meta-space". In General Relativity one background structure is the local symmetry group of the theory, the Lorentz group. Another one is its configuration space: the (meta-)space of (spatial) geometries on a given (spatial) topology, coined "superspace" by Wheeler. Also, as we have learned from loop quantum gravity, the set of possible geometries, at the quantum level, can be characterized in terms of (Lorentz) group elements, parallel transports of the gravity connection. All this motivates the use of the Lorentz group as the background space on which to define a field theory of quantum geometry, in the form of a group field theory (GFT). This QFT for the microstructure of space represents the quanta of space itself as spin network vertices or, equivalently, fundamental simplices and in doing so it incorporates ideas from both loop quantum gravity and simplicial quantum gravity.

The fact that Feynman diagrams (describing possible interaction histories) of usual particle or field theories are simple graphs (see Fig.1) follows from 1. the point-like nature of the particles (the quanta of the field), and 2. the locality of the corresponding interaction. Matrix models move one step up in dimension (see Fig.2). Instead of point particles, they consider 1d objects that could be represented graphically by a line, with two end points to which the indices of the matrix refer. The interaction of such 1d objects is chosen to be of a peculiar combinatorially non-local nature, such that the corresponding Feynman diagrams are 2-dimensional simplicial complexes of arbitrary

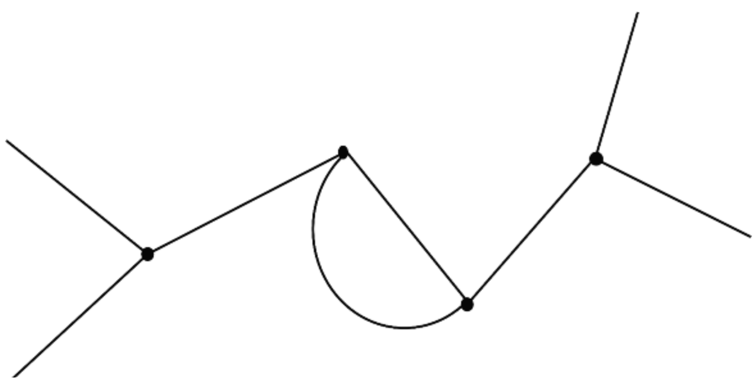


Fig.1: A piece of a Feynman diagram for an ordinary field theory.

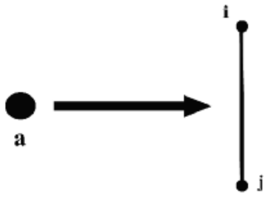


Fig.2: The step from point particles to 1d objects in matrix models and 2d GFTs.

topology (see Fig.3). These are interpreted as discrete spacetimes. Matrix models have been quite successful in describing 2d quantum gravity, the key results being that the Feynman amplitudes of the model can be related to discrete gravity path integrals on the corresponding simplicial complexes, and that the sum over topologies and over different triangulations for a given topology can be kept under control.

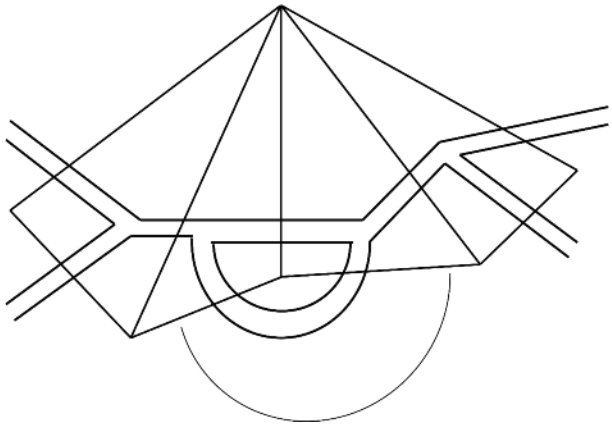


Fig.3: A piece of a Feynman diagram for a matrix model and a 2d GFT, with the dual simplicial complex.

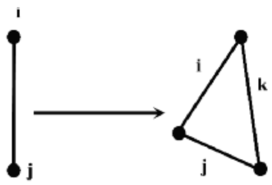


Fig.4: The step from 1d to 2d objects in going to 3d tensor models and GFTs.

There is no obstruction to keep moving upward in dimension. We can move from 1d objects represented by matrices, with indices labeling the end points of the line, to d-dimensional simplices (see Fig.4, for the d=3 case), represented by tensors, with indices labeling their boundary (d-1)-dimensional faces. Correspondingly, the Feynman diagrams of the theory are now given by (d+1)-dimensional simplicial complexes (triangulations) interpreted as discrete spacetimes (see Fig.5, for the d=3 case). Moreover, we can add degrees of freedom and define corresponding field theories, in which the tensor indices are replaced by variables taking values in appropriate domain spaces. Choosing these spaces to be group manifolds, we obtain group field theories with their associated non-trivial Feynman amplitudes given by spin foam models. Crucially, these amplitudes can also be directly related to discrete quantum gravity path integrals. We thus have discrete spacetime emerging as a virtual construct and weighted by a discrete and algebraic path integral.

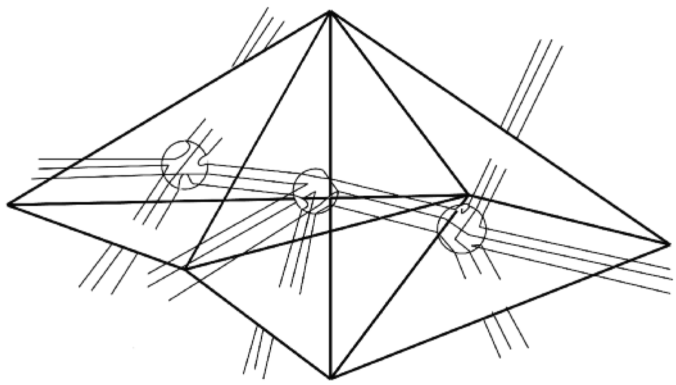


Fig.5: A piece of a Feynman diagram for a 3d tensor model or a 3d GFT, with the dual simplicial complex.

An important area of recent developments in this approach, in which the AEI has played a crucial role, has been the application of quantum field theory techniques to GFTs, to gain a better understanding and control over its perturbative expansion in Feynman diagrams, using tools from (perturbative) renormalization theory.

GFTs define a sum over simplicial complexes/discrete spacetimes 1) of arbitrary topology and 2) that correspond, in general, to pseudo-manifolds, i.e. contain conical singularities at the vertices. Our classical spacetime, at macroscopic scales, seems to possess a trivial topology and a smooth manifold structure, at least to a very good approximation. Therefore the problem occurs of how these observed two features of our universe arise from a theory in which these "nice" configurations are but one among infinite many other "pathological" ones. In the simpler matrix models context, it has been shown that diagrams of trivial topology dominate the perturbative sum, in the so-called large-N, corresponding to matrices of very large dimension. The issue of controlling the relative weight of manifolds and pseudo-manifolds in the perturbative sum arises instead only in dimensions $D > 2$ and it has represented an obstacle to the development of tensor models. A third issue is to identify and control the divergences that arise in this perturbative expansion, which are of two types: a) divergences in the sum over (pre-)geometric data (group elements or group representations) for each amplitude associated to a given simplicial complex; b) the divergence of the entire sum over simplicial complexes.

In collaboration with L. Freidel and R. Gurau of the Perimeter Institute for Theoretical Physics, Waterloo, Canada, we have made the first steps toward solving these issues, and started a systematic study of GFT perturbative renormalization, in the context of the Boulatov model for 3d (Riemannian) quantum gravity. The divergences of this model are related to the topology of the bubbles (3-dimensional cells), dual to vertices of the simplicial complex, in the Feynman diagrams. But it is difficult to establish which diagrams need renormalization in full generality, mainly due to the very complicated topological structure of 3D simplicial complexes. What we achieved is the following:

1. a detailed algorithm is given for identifying bubbles (3-cells) in the Feynman diagrams of the model, together with their boundary triangulations, which in turn can be used to identify the topology (genus) of the same boundary. This topological information is directly relevant to the degree of divergence of the corresponding Feynman diagram.

2. using this algorithm, we were able to identify a subclass of Feynman diagrams which allow for a complete contraction procedure. Thus the ones that allow for an almost standard renormalization; this class of graphs, dubbed "type 1" have then be shown to be a natural generalization of the 2d planar graphs of matrix models, thus suggesting that they can play a similarly crucial role in GFTs.

3. for this class of diagrams, an exact power counting of divergences has been proven, according to which their divergence is of the order of the number of bubbles in the Feynman diagram.

On the basis of these results, it is then possible to put forward two main conjectures, obviously confirmed in all examples considered: 1) that all "type 1" diagrams correspond to manifolds of trivial topology; and 2) that an appropriate generalization of the usual scaling limit (large-N) of matrix models to these GFT would lead to the relative suppression of all the "non-type 1" diagrams. Thus these GFT leave us with: only type 1 diagrams in need for renormalization, and only manifolds of trivial topology in the theory. Clearly, if this is confirmed, the natural suggestion would be that it is in the same range of parameters that characerise this sector of the theory that one should look for an effective GFT dynamics from which the usual general relativistic dynamics of classical spacetime can be derived.

Another set of interesting steps in the direction of bridging the gap between the microscopic GFT description of quantum space and macroscopic continuum physics, including usual quantum field theories for matter, has been taken by the group along a different line of investigation.

One would expect a generic continuum spacetime to be formed by zillions of Planck size building blocks, and thus to be, from the GFT point of view, a many-particle system whose microscopic theory is described by some fundamental GFT action. This suggests us to look for ideas from condensed matter theory, and to try to apply them in a GFT context. E.g. condensed matter theory provides examples of systems in which the effective dynamics of perturbations (quasi-particles) takes the form of matter field theories in curved spacetimes, with the effective background geometry being a function of the background configuration chosen for the fluid. Inspired by these results, we ask: assuming that a given GFT model describes the microscopic dynamics of the discrete building blocks of quantum spacetime, 1) can we obtain an effective macroscopic continuum field theory for matter fields from it? And if so, 2) what is the effective spacetime and geometry that these emergent matter fields see?

It is indeed possible to obtain effective continuum field theories for matter fields from GFTs, and these turn out to be QFTs on non-commutative spaces of Lie algebra type. More precisely, if we have a non-commutative spacetime of Lie algebra type, the corresponding momentum space is naturally identified with the corresponding Lie group, in such a way that the non-commutative coordinates act on it as (Lie) derivatives. This is the key feature that makes the derivations of such field theories from GFTs rather straightforward. Recently, this has been achieved in the context of the Boulatov group field theory for 3d Riemannian gravity, by the quantum gravity group in Lyon (W. Fairbairn and E. Livine). One considers two-dimensional variations around a class of GFT classical solutions (which can be interpreted as quantum flat space on some a priori non-trivial topology), and computes the effective action for these collective excitations of the GFT field. What one finds is that the effective action is that of a noncommutative quantum field theory, living on a non-commutative space whose coordinate algebra is the Lie algebra of SU(2), invariant under the quantum double of SU(2) (which provides a quantum deformation of the 3d Riemannian Poincaré group ISU(2)).

Similar results have then been obtained by members of the AEI group, in collaboration with E. Livine of the ENS in Lyon, and with F. Girelli of the University of Sydney, Australia, in the more physically interesting (and mathematically more challenging) 4d Lorentzian context. It has been shown that from GFT models (indirectly) related to 4d quantum gravity, and describing SO(4,1) BF theory, it is possible to derive effective non-commutative matter field theories of "deformed special relativity" type. They are based on momentum group given by AN(3) and are living on a noncommutative k-Minkowski spacetime, characterized by an isometry group being a deformation of the usual Poincaré group of special relativity. These field theories are of direct physical interest because they form the basis for much current work in the area of quantum gravity phenomenology, focusing on the possibility of quantum gravity-induced deformations of spacetime symmetries.

Work in this direction, therefore, is a step in bridging the gap between a fundamental discrete quantum theory of spacetime and a continuum description of spacetime and of matter living on it, and thus bringing this class of models a bit closer to experimental falsifiability.

Daniele Oriti

Activities and Highlights of the IT Department in 2008 and 2009

During the past years a strong focus was laid on efficiency: Efficiency as it is addressed by the buzz word Green IT: efficiency in communication, in presenting and retrieving information, and efficiency that results from high motivation and excellent skills of the IT staff.

Green IT

The reduction of hardware by virtualizing the servers led to a reduction of power consumption and at the same time the requirements for cooling were decreased. Already in 2008 two identical virtual centres were set up that house the most important virtual machines.

By replacing dual core systems by quad core or even higher multi core systems a better ratio of CPU-power to power consumption was gained. We have doubled the number of cores in the desktop systems without any increase in power consumption.

Communication and information

The relevance and acceptance of video conferencing systems – not only amongst the two sites – is still growing. Therefore at AEI Potsdam another seminar room was recently equipped with additional beamers and video cameras for operating video conferences.
The scientists in Hannover use the collaboration tool EVO (Enabling Virtual Organizations) very frequently. In the seminar rooms fixed setups are installed, in order to easily arrange ad hoc meetings with collaborators all over the world.

For lectures of all kind IT staff has installed smart boards in the seminar rooms. These smart boards enable the lecturer to write on a PC tablet instead of a whiteboard. The advantage of a smart board is that the lecturer can use handwriting but can also run normal PC programs. The data from the smart board can also be transmitted via video conference systems or tools like EVO. Within the series of lectures for the IMPRS students such a set up has successfully been used.

Good search tools on web pages are very helpful to retrieve information easily. For the web pages of the AEI the OpenSource Search Engine swish-e has been installed for this purpose. This engine supports multilingual pages and also retrieves information from inbounded files of various types.

The past years much effort was put into the design of the web pages of the various groups and projects of the Institute, and also into the development of web pages for conferences and other events. Databases and other back office tools have made life easier for the participants and organizers of the event. Examples for this kind of events in 2009 are:

- The conference "Integrability in Gauge and String Theory" (INT09)
- The "Numerical Relativity and Data Analysis Meeting" (NRDA09)
- The conference "Space, Time and Beyond"

High Performance Computing

Even though the high performance compute clusters Damiana and Morgane (supercomputers.aei.mpg.de) did not grow much in respect of number of nodes or storage space, they are still important working tools for the scientific communities.

Worth to mention is the transition to a different file system that was made on Damiana. As the performance of the Network File System on the Damiana HPC was not satisfying we tested several other software and finally installed the Open Source file system LUSTRE. Since 2008 LUSTRE runs the applications of the numerical relativity group very stable and with high efficiency.

For further reading please have a look at the scientific chapters of the numerical relativity group for more information of the usage of Damiana and the chapter of the gravitational waves group for Morgane.

New techniques

In order to simplify communication during travels IT provides smart phones and the tools needed to enter the mailing system of the AEI (e.g. with the Lotus Notes Travel program).

The investigations members of the IT made on systems with GPUs (Graphic Processor Units) led to purchasing a system with two GPUs of type nVidia FX370. Additionally the Linux distribution Ubuntu with a cuda environment was installed. Scientists of the Astrophysical Relativity division adopted their applications where necessary and found the GPU system performing excellently.

A new visualization system has also been purchased. This system has 32 GByte of memory and 8 Intel processors. As it is integrated into the LUSTRE file system of the HPC cluster Damiana the scientists can directly use data from the simulations for visualization without copying files from one place to another.

Most of the services are dependent of a stable and secure network. In 2009 redundant network cable tracks were installed between the GNZ („Gemeinsames Netzwerkzentrum für die Berliner und Brandenburger Max-Planck-Institute“) and the Max Planck Campus in Potsdam. Thus, the risk of data network interruption by damage of a cable or a network device has become very low.

Events organized by the IT department in 2009

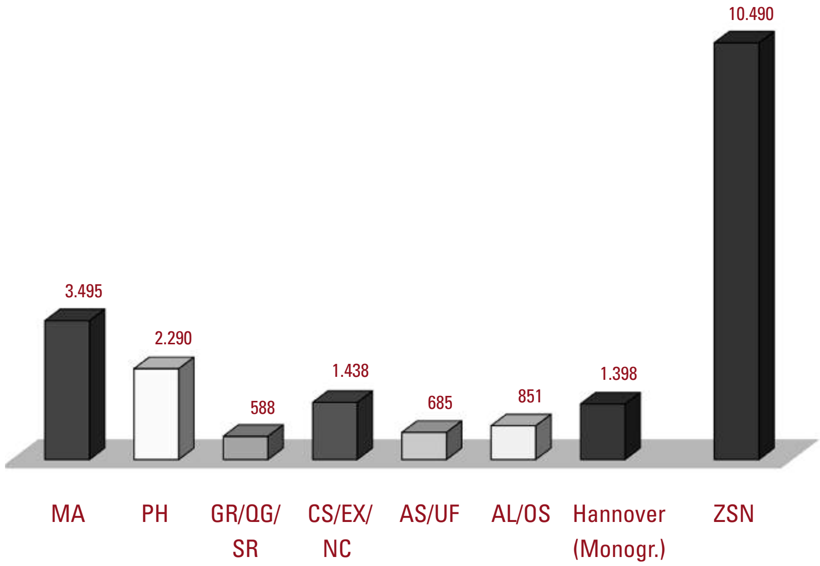
- Cluster-Day 2009@AEI: exchanging experiences and knowledge in high performance computing cluster techniques (participants: research institutes and universities from the area Brandenburg/Berlin and invited companies)
- Data Protection and IT security workshop in Hannover (participants: data protection and IT security officers of the Max Planck Society and of Leibniz Universität Hannover, scientific and non scientific members of AEI, including staff from Potsdam who took part via video link)
- Workshop Introduction to Lotus Notes (participants: experts from IBM, scientific and non scientific staff from AEI Hannover)
- 2009 Annual meeting of the employers of the IT of the Max Planck Society in Berlin

Christa Hausmann-Jamin

Activities and Highlights of the Library in 2008 and 2009

The library is a specialized library offering services primarily to scientists working at the Institute in Golm and Hannover. Scientists from outside are welcome and usage is possible on appointment. Two librarians manage the library: Mrs. Elisabeth Schlenk (head of the library) and Mrs. Anja Lehmann.

The collection increases continuously. By the end of 2009 our catalogue listed 10.745 monographs and conference reports, 10.490 bound journal volumes, 140 printed journal subscriptions and online access to journals covered by the Grundversorgung, i.e. the Max Planck Society (MPG) secured a permanent right to full text access for more than 32.000 journal titles.



AL: General, **AS:** Astronomy, Astrophysics, Cosmology, **CS:** Computer Subjects, **EX:** Exp. Methods Measurements, **GR:** Gravitation & Relativity, **MA:** Mathematics, **NC:** Numerics & Computation, **OS:** Other Sciences, **PH:** Physics, **QG:** Quantum Gravity, **SR:** Special Relativity, **UF:** Unified Field Theory & Other Theories of Gravitation, **ZSN:** journal volumes

In addition to the usual tasks of librarians, we are constantly looking for new ways to facilitate and optimize the use of the library for the scientists at AEI.

After numerous discussions we have taken responsibility for the management for the institute's scientific publications. To implement this activity we are using the eDoc server (http://edoc.mpg.de). The intention of this electronic document server is to increase the visibility of the intellectual output of the MPG and to add to the world-wide virtual repository of high-quality scientific information.

In this context the AEI also participates in a new pilot project called 'Publication Management' (PubMan). Under the leadership of the AEI library the three libraries on Campus are setting up a 'PubMan Cluster'. This allows for networking synergies and creates an optimal testbed for the adaption by other Max Planck Institutes. This project was supported by a third librarian, who was working on a two-year contract.

PubMan (http://pubman.mpdl.mpg.de) has replaced eDoc and since the beginning of 2010, Pubman is the only platform for storing old and new publications of the Institute.

In 2008 we started to sort through the late Prof. Ehlers' scientific papers, personal notes, and correspondance. This is done in close collaboration with the archives of the Max Planck Society and with the help of an archivist whom we hired for this purpose. This project is still in progress.

While our first priority is to provide an excellent service for AEI scientists, we also actively support various activities (Catalogue Enrichment, e-Books, Virtual Library, Open Access, Document Ordering, Electronic Resource Management) of the MPDL (Max Planck Digital Library).

Elisabeth Schlenk

Events

GEO General Meeting, AEI Hannover, 23 – 24 November 2009

During this meeting the whole GEO collaboration from UK and Germany gets together to review progress and discuss future research directions. The program included short talks from each project. A main point of discussion was the future of GEO600 – the extension of the observation range to higher frequencies (GEO-HF) and the ability to perform continuous observations during the upgrades of the other detectors (Astrowatch). After the successful generation of squeezed light in the lab, it was decided to implement such a light source into GEO600 in order to feed squeezed vacuum into the interferometer output. This requires alterations in the central building, but it is expected thus to improve the sensitivity by factor of 2 or 3.

Peter Aufmuth

Workshop „Equations of motion“, AEI Golm, 04 November 2009

To understand the behaviour of isolated gravitating systems such as stars, black holes and binaries it is necessary to carefully understand the relation between the time development predicted by Einstein’s equations in General Relativity and the classical equations of motion from Newtonian theory.

The workshop brought together mathematicians and astrophysicists for lectures and discussions on Postnewtonian approximations, concepts of Newtonian limits and self-force phenomena in electrodynamics and gravitation.

More information can be found on the AEI web site at
http://www.aei.mpg.de/~dpuetz/eomworkshop.html

Gerhard Huisken

Workshop on "Membranes, Minimal Surfaces and Matrix Limits", AEI Golm, 19 – 21 October 2009

The fascinating interplay between mathematics and physics in the context of Membrane Theory has been explored over the last 30 years. However, the organized meetings focusing on this interplay have been few. The aim of the workshop was to bring together mathematicians and physicists working in areas related to Membrane Theory, and to establish connections between the mathematical and physical questions. In focus were the relations of membranes and matrix regularizations to minimal surfaces and noncommutative geometry. Out of the 13 invited speakers, approximately 2/3 were physicists and 1/3 were mathematicians, and the total number of participants (both local and external) was around 25.

All talks were 45 minutes long, giving enough time to explain some concepts in detail, and the speakers were asked to prepare their talks with the mixed audience of mathematicians and physicists in mind.

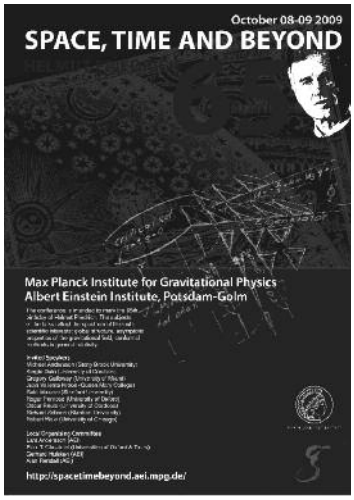
The workshop was organized within the "Quasilinear Wave Equations, Membranes, and Supermembranes (SFB647/A4)" project, financed by the SFB 647 and held at the Max Planck Campus in Golm.

More information can be found on the AEI web site at
http://www.aei.mpg.de/~arnlind/m3/

Joakim Arnlind

Conference "Space, Time and Beyond", AEI Golm, 08 – 09 October 2009

This conference at AEI Potsdam-Golm, organized by Lars Andersson, Piotr Chrusciel, Gerhard Huisken and Alan Rendall was intended to mark the 65th birthday of Helmut Friedrich. There were talks by eight invited speakers who had been chosen to reflect the spectrum of Helmut's scientific interests: global structure, asymptotic properties of the gravitational field and conformal methods in general relativity. Three of the speakers, Sergio Dain, Juan Valiente Kroon and Oscar Reula had spent extended periods working with Helmut before pursuing their careers in other parts of the world. They are now contributing to the global influence of ideas developed at AEI.



The recognition which Helmut's work has received in the research community is witnessed by the other eminent speakers who came to give talks: Michael Andersson, Gregory Galloway, Rafe Mazzeo, Roger Penrose and Richard Schoen. The conference was attended by over sixty participants.

More information can be found on the AEI web site at
http://spacetimebeyond.aei.mpg.de/

Alan Rendall

Workshop on "Variational Problems of Higher Order in Geometry", AEI Golm, 16 – 18 September, 2009

During the last twenty years, there has been increasing interest in higher order differential equation to describe the geometric motion of fluid interfaces, materials, and biological membranes, and in image restoration.

This three day workshop brought together geometers, analysts, and numerical analysts working in this challenging field of research. It gave the participants an overview of the current state of research. The topics of the talks ranched from quantizations effects for polyharmonic maps over new numerical and analytic results on Willmore surfaces and especially Lawsons conjecture, Willmore flow and surface diffusion flow to foliations of assymptotically flat spacestimes.

The event took place at the Zuse Institute in Berlin. It was a joint project of the Max Planck Institute for Gravitational Physics, the SFB 647 "Raum-Zeit-Materie", and the Free University Berlin.

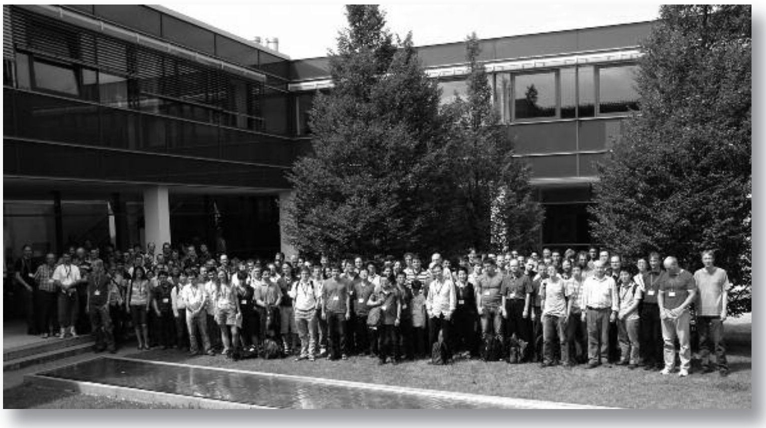
The workshop consisted of three to four one-hour lectures per day by invited speakers leaving generous breaks between talks for questions and informal scientific interaction.

More information can be found on the AEI web site at *http://www.aei.mpg.de/~sblatt/workshop/*

Simon Blatt

Conference "Integrability in Gauge and String Theory", AEI Golm, 29 June - 03 July 2009

This conference is the already fifth edition of a very successful European workshop series started in 2005 by Niklas Beisert and Matthias Staudacher of the AEI, and Volodya Kazakov of the ENS in Paris. It took place once before in Potsdam (in 2006, see Biennial Report 2006/07). The general topic is the study of exactly solvable instances of gauge-string dualties. In the course of the last seven years it has been established that exact integrability, previously believed to be confined to one- or two-dimensional models, appears also in some four-dimensional gauge theories. Likewise, various intricate superstring models on special, curved backgrounds are also exactly solvable. What is more, the gauge- and string theories are conjectured to be connected by the so-called AdS/CFT correspondence, and the exact solvability allows for a direct analysis of this correspondence. The purpose of this conference series is to create a discussion platform for this rapidly evolving field, and to offer an interdisciplinary forum for scientists interested in gauge theory, string theory, condensed matter theory and mathematics. The hallmark of the series is a program which is balanced between a number of broad overview talks on all relevant aspects of this research area, and more specialized contributions reporting the latest research developments.



The conference was attended by 140 participants.

The overview talks discussed such diverse topics as various methods in integrable models (Bazhanov, Bobenko, Gaiotto, Saleur, Shatashvili), Euler sums and Zeta functions (Vermaseren), and string theory (Roiban, Tseytlin). The more specialized talks included work on integrablity in lower-dimensional gauge theories (Nepomechie, Rey, Sieg, Zarembo), on solvable structures in gluon amplitudes (Arkani-Hamed, Korchemsky, Lipatov, Maldacena, McLoughlin, Plefka), and on finite size corrections of the AdS/CFT spectral problem (Bajnok, Frolov, Gromov, Janik, Kazakov). For the scientific background of the last two topics, which have recently seen enormous progress, please refer to the contributions of Tristan McLoughlin and Pedro Vieira in this report. The conference summary was given by former AEI member Gleb Arutyunov (Utrecht).

A good indicator for the quality and the successful design of the conference series is the ever growing number of participants, which reached 140 this year. Particularly encouraging is the large number of younger participants, including many graduate students and beginning postdocs. Another positive sign, which distinguishes the workshop from many other similar international events, is the very large participant attendance rate of all scientific presentations: The week-long conference indeed takes place both inside as well as outside the lecture hall, the latter in the form of very animated discussions! This is achieved by an attractive and diverse mix of just five 50 minute talks per day, which leaves ample time for exchange and collaboration among the conferees.

More information can be found on the webpage of the conference http://int09.aei.mpg.de/ which also provides links to the earlier workshops of the series.

Niklas Beisert & Matthias Staudacher

Astro-GR Meetings

Since 2006 Pau Amaro-Seoane is organising regular meetings, which bring together scientists working on different fields related to Gravitational Waves. These meetings proved to be very fruitful. "Astro-GR@X" represents a series of meetings, which take place at X. The workshops aim to bring together astrophysicists, cosmologists, relativists and data analysts, with the goal of building new collaborative relationships - as well as strengthening existing ones - focused on the interpretation of gravitational wave observations as a tool of astronomical discovery and a probe of the fundamental physics of gravity.

Astro-GR@Como in 2008.

The Five Golden Rules of Astro-GR are to...
1. bring together Astrophysicists, Cosmologists, Relativists and Data analysts
2. motivate new collaborations and projects
3. be run in the style of Aspen/ITP/Newton Institute/Modest meetings, with plenty of time for discussions
4. grant access to the slides in a cross-platform format, as e.g. pdf or odt and, within reason, to the recorded movies of the talks
And, of course:
5. keep it simple and spontaneous, which means there no registration fee, nor poster presentation, nor proceedings.

Past and future
The first one was at the AEI in 2006, followed by another one after one-a-half years gap in Como and then, in the same year, again at the AEI. The next one was in Barcelona in September 2009

The 2010 meeting took place in Paris in October, as announced in Sep. 2009 by Ed Porter, and was hosted at the APC. George Smoot gave the first talk there.
The next meetings will take place in Mallorca (2011), Lundt, Sweden (2012), and Cambridge, UK (2013).

For further information, please visit:
http://www.aei.mpg.de/~pau/LISA_Astro-GR@AEI (Sep. 2006)
http://www.aei.mpg.de/~pau/LISA_Astro-GR@Como (Feb. 2008)
http://www.aei.mpg.de/~pau/2W@AEI (Sep. 2008)
http://www.aei.mpg.de/~pau/LISA_Astro-GR@BCN (Sep. 2009)
http://www.aei.mpg.de/~pau/LISA_Astro-GR@Paris (Sep. 2010)

Pau Amaro-Seoane

Numerical Relativity and Data Analysis Meeting (NRDA), AEI Golm, 06–09 July, 2009
The NRDA meeting was the third in an annual series of meetings seeking to build bridges between numerical relativists and gravitational wave data analysts. These meetings have become increasingly well attended, and there were 84 officially registered participants. The contributions in a special edition of Classical and Quantum Gravity provide a flavor of the talks and discussions at the meeting. The meeting featured talks on topics ranging from gauge conditions in numerical relativity, the astrophysics of binary systems, and all the way to parameter estimation accuracies in data analysis pipelines. An important feature, unlike the previous NRDA meetings, was the significant presence of numerical relativists modeling neutron stars and supernovae.

This meeting took place at an important time. The first NINJA project had been successfully completed and the time was ripe for bringing numerical relativists yet closer to the LIGO and Virgo collaborations. There was an extended discussion session on the last day of the meeting devoted to expanding on the issues in this interaction. It would be fair to say that this meeting significantly deepened the interaction between numerical relativists and gravitational wave data analysts, and laid the groundwork for future NINJA projects.

For further information, please visit:
https://nrda2009.aei.mpg.de/

Badri Krishnan

Workshop on (0,2) Mirror Symmetry and Quantum Sheaf Cohomology, AEI Golm, August 17-21, 2009

The last few years have seen important progress in the understanding of the physics and mathematics of heterotic string backgrounds. On the mathematics side this has involved constructing stable holomorphic vector bundles over Calabi-Yau manifolds, explicitly describing the moduli spaces of these bundles, and defining certain natural product structures of various sheaf cohomology groups. From the physics perspective, new techniques have become available to study two-dimensional (0,2) superconformal theories that are naturally associated to the geometries just described. These (0,2) theories provide a "quantum" or "stringy" geometry, which in a certain limit reduces to the classical geometry of the vector bundles. Away from this limit, the quantum geometry can be significantly different: for instance, a classically singular bundle can lead to a perfectly smooth quantum geometry, and the classical product on sheaf cohomology is deformed to a quantum product. Moreover, there are suggestions that there is a generalization of the familiar phenomenon of "mirror symmetry," where a bundle E->M and a mirror bundle F->W, two classically distinct bundles on topologically distinct spaces, lead to equivalent quantum geometry. This is the notion of (0,2) mirror symmetry.

The central aim of the workshop was to bring together the mathematicians and physicists working on aspects of the geometry/heterotic supergravity with those developing the world-sheet techniques of (0,2) superconformal theory. In addition, it was important to have input from scientists pursuing aspects of mirror symmetry in other contexts, such as D-branes in type II string theories. The meeting brought together twenty-five participants, ranging from pure mathematicians to physicists pursuing phenomenological model building. The lectures were organized to provide thorough overviews of the different approaches, and they often led to fruitful discussions during and after the seminar. In addition to the invited lectures, the workshop also had lectures on several topics chosen by the participants during the conference.

The workshop was productive and led to a number of new interactions and collaborations. A follow-up workshop has been held at the Banff research station in March 2010, and additional follow-ups are being planned. The workshop was supported by the Max Planck Society, as well as by the SFB 647 - Space, Time, Matter.

For further information, please visit:
http://www.aei.mpg.de/~ilarion/MirrorConf/HetMir.html

Ilarion Melnikov

LISA Technology Package Meetings at AEI Hannover

The LISA Technology Package (LTP) aboard the LISA Pathfinder mission is dedicated to demonstrate and verify key technologies for LISA, in particular drag free control, ultra-precise laser interferometry and gravitational sensors.

LTP NPM Meeting #17, AEI Hannover, 01 – 02 July 2008

The NPM Meeting is a meeting of the national project managers. Each national team or each national space agency has a national project manager, who is responsible for the successful realisation of the corresponding national program and for the national supply to the whole project. During this meeting each NPM gives a presentation of the status of the progress. Later on possible solutions are discussed and decisions are made.

LTPDA Developers Meeting, AEI Hannover, 10 – 11 February 2009

LTPDA is the official software environment for the data analysis of the flight data from the LISA Technology Package on the LISA Pathfinder mission. It has to be ESA space certified and has to undergo close scrutiny. The software developers get together periodically to synchronize future developments.

LISA BB Progress Meeting, AEI Hannover, 02 September 2008

LISA breadboarding is the ground-based technology preparation for the LISA mission space mission. It is supported by the German space agency DLR and progress is reviewed on a regular basis.

Jürgen Ehlers Spring School "Gravitational Physics" 2008 and 2009

The 2 weeks vacation course on Gravitational Physics, which is meant for third year students, was started by the AEI together with the University of Potsdam in 1999. It has since then become a regular activity of the Institute. The students have lectures in the mornings and use the afternoons for discussions and for working on the lecture content. The courses take place in the lecture hall of the Max Planck Campus in Potsdam-Golm.

In 2008, Lars Anderson and Marcus Ansorg gave an "Introduction to Gravitational Field Theory". Two other lecture series were given by Luciano Rezzolla on "Modelling compact objects: from perturbative to nonlinear regimes" and by Badri Krishnan on "Fundamentals of gravitational wave astrophysics".

In 2009 we have renamed the vacation course the "Jürgen Ehlers Spring School Gravitational Physics"".

The first course in 2009 again was the “Introduction to Gravitational Field Theory” (Nikodem Szpak and Marcus Ansorg). The other lecture series was given by Kristina Giesel on “Canonical Formulation of General Relativity and Introduction to Loop Quantum Gravity”.

In 2008, 55 participants attended the vacation course: 13 came from the Berlin-Potsdam area and another 42 from all over Germany. In 2009 we had 19 from the Berlin-Potsdam area and another 46 from all over Germany.

More information about the Jürgen Ehlers Spring School can be found at *http://www.aei.mpg.de/english/contemporaryIssues/seminarsEvents/events/springschool2010/index.html*

Through the Eyes of a Visitor

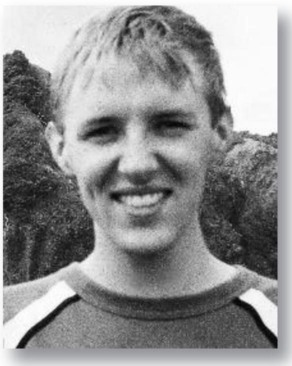
During my time as a PhD student at The Australian National University, I was very fortunate to have visited the Albert Einstein Institute in Hannover on two occasions. My first visit began with the LSC-Virgo meeting, held in Hannover, in October 2007, after which I stayed until the end of November. In 2008, I returned for a longer stay, from the end of May through November, during which I attended the June LSC-Virgo meeting in Paris, and the September meeting in Amsterdam.

I thoroughly enjoyed my time at the AEI. The Institute has a stimulating atmosphere and is an excellent environment in which to work. Prof. Bruce Allen holds weekly meetings where members of his group present and discuss their scientific work. Being used to working by myself, I found these meetings a little intimidating at first! But I soon saw the benefits to learning to present my work to my colleagues, and it was always interesting to hear about the work of others in the group. My PhD work involved analysing data from the LIGO gravitational wave detectors in search of continuous gravitational waves, in particular from the suspected neutron star at the centre of the young supernova remnant Cassiopeia A. This branch of gravitational wave data analysis is a particular strength of Prof. Allen's group. Many members of the group are active participants in the activities of the LSC Continuous Wave Working Group, and are co-authors of many of the key software used by the LSC to search for continuous gravitational wave signals. An important component of the group's activities is the Einstein@Home project, lead by Prof. Allen, which uses time on computers volunteered by the public to search for continuous gravitational waves in LIGO data. As a student still learning the ropes, my time at the AEI was a great opportunity for me to present and discuss my work with some of the leading researchers in my field, and to benefit for their extensive experience in LIGO data analysis. I am particularly grateful for interesting discussions with Bruce Allen, Maria Alessandra Papa, Reinhard Prix, and Chris Messenger.

In addition to the collegial atmosphere, the AEI provides you with everything a working scientist requires, including a desk, a comfortable chair, Internet, and a plentiful supply of coffee, spring water, and computing power - the latter courtesy of the ATLAS supercomputer located in the Institute's basement. For the workaholically inclined, the electronic key fob will get you in and out of the building at any time, day or night! The friendly and efficient administrative staff, in particular Karin Salatti-Tara and Hannah Arpke, can help you with anything from arranging accommodation and travel to conferences, to extending your stay by another few weeks. When it's time for lunch, there are many nearby options to choose from: from the excellent baguettes, bagels and coffee at Campus Suite, to a sit-down hot meal at the Leibniz University's Hauptmensa. If you can't decide, never fear; Reinhard Prix's Lunch Daemon will make a random selection for you, based on a full Bayesian analysis of your preferences! Special occasions, such as farewelling a colleague or celebrating a student completing his or her PhD, are marked with food, drink, and merriment in the atrium, which features a large cardboard cut-out of Albert Einstein!
The Institute is situated in a quiet suburb of Nordstadt in north-west

Hannover, nearby to the Leibniz University campus. Getting from the Institute to and from the centre of the city is quick and easy on the tram. There are a number of accommodation options close to the Institute. If you are a long-term visitor, you may find yourself staying in one of the cheap and cheerful guest rooms of Herr Franke, who can sometimes be seen driving around the streets of Nordstadt in a golf cart. Along Engelbosteler Damm, there are a number of good restaurants, including at least six different kebab shops. I particularly liked the small bistro which serves toasty French baguettes and crepes, and Coke in old-fashioned glass bottles.

Hannover may strike the first-time visitor as a rather sleepy town – but don't be fooled! It all kicks off during the summer months, starting with the Schützenfest: beer, riesenbratwurst and fun rides. There's usually something going on somewhere, whether it's an athletics and martial arts demonstration by Leibniz University students, followed by beer and 80s classic hits from Peppermint Petty; or beer and Swedish acoustic rock covers from Sugarplum Fairy down on the shores of the Maschsee. I witnessed the German finals of the Battle of the Year break-dancing competition, and stood in a crowd of thousands of flag-waving German football supporters watching "die Nationalelf" play in the final of the 2008 European championship – which, to the crowd's disappointment, was won by Spain. That I so enjoyed my time in Hannover is equally due to the interesting and fun people I met during my stay. On Fridays, a group of us would usually head off to spend the evening at the pub: first to the nearby Kuriosum for beer and free peanuts, then across the road to Kaiser's for schnitzel, more beer, and maybe a whisky or two.



Having now finished my PhD, I am looking forward to once again returning to the AEI – this time to take up a post-doctoral position beginning in 2010.

Karl Wette
The Australian National University

Short Notices

Visit of Prime Minister and Delegation from South Korea, AEI Hannover, 20 April 2009

A delegation from South Korea including the Prime Minister, Han Seung-Soo, high ranking delegates of the South Korean government and of the Pohang Institute of Science and Technology came for an informational visit to AEI. Here they met the President and Vicepresident of the Max Planck Society and the Directors of the AEI to discuss future possibilities for a closer collaboration. Prof. Dr. Peter Gruss said: "We have already very good connections to South Korea, e.g., via Max Planck trainees at Korean Universities. For the future, we are going to improve the scientific collaboration even further." The Korean delegation viewed the prototype of the next generation of gravitational wave detectors developed at AEI.

Scienceface: Films and Webpage

www.scienceface.org: Scienceface was selected as a global Special Project for the International Year of Astronomy in 2009.

In 2007 Bernard Schutz and Milde Science Communication initiated the production of a series of 15 short interviews with distinguished scientists from all over the world, for whom black holes are their work and their passion. Scienceface is a joint project of AEI and Milde Science Communication. The films address young people in the age bracket of 15-21, many of whom are looking for information mainly on the internet. The Scienceface films include interviews with Joan Centrella, Reinhard Genzel, Günter Hasinger, Stefanie Komossa, Badri Krishnan, Christian Ott, Jürgen Renn, Ed Seidel, Kip Thorne, and Cliff Will. A dedicated website offering further information about black holes and the interviewees has been launched and eight film clips are already posted there, at http://www.scienceface.org/. More Scienceface clips will be posted on the website in the near future and subtitles will be integrated in the films.

German Year of Mathematics in 2008

For the exhibition ship 'MS Wissenschaft' the AEI produced several mathematical hands-on exhibits, e.g. on topology, group theory, minimal surfaces, the brachistochrone and the cycloid. The exhibition toured on the German waterways in 2008, stopped in 31 cities and had 118.000 visitors. We later used the exhibits for our open day in 2009 and for other public outreach events.

Hands-on mathematical exhibits were very popular with young visitors.

Girls Day

Encouraging girls and young women to undertake studies in science is regarded as the first opportunity to increase interest in scientific careers. The AEI takes part in the German 'Girls Day' and in other measures that aim at increasing the number of female scientists, such as BrISaNT, a Brandenburg initiative funded by the European Commission. At the occasion of the Girls Day and the visits of school girls coming to the AEI in the BrISaNT framework we not only focus on getting our visitors interested in our science, but introduce them to female AEI scientists in order to provide them with role models for possible future careers in science.

Max Planck Exhibition

The AEI participated in the exhibition about Max Planck that was shown at the Technikmuseum in Berlin in 2008, providing a film and interactive exhibit about squeezed light and gravitational wave detection. *http://www.planck-ausstellung.de/*

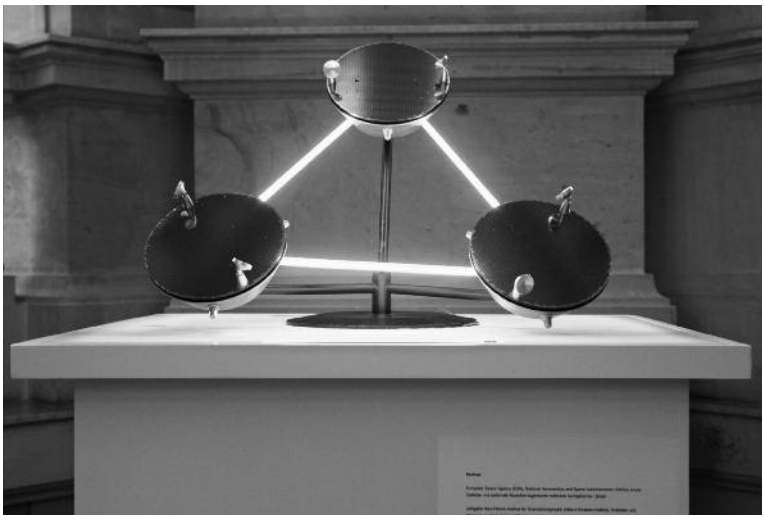
Hands-on exhibit at the Max Planck exhibition in Berlin.

Highlights der Physik

The AEI Hannover participated in the Highlights of Physics exhibition in Halle (2008) and Köln (2009), presenting gravitational wave exhibits.

International Year of Astronomy (IYA2009)

AEI participated in the German IYA2009 launch on January 20th, 2009, at the Museum for Communication in Berlin. On the occasion of this event a large LISA satellite model and sequences from the LISA film were shown.



The LISA three-satellite model at the Museum of Communication in Berlin.

For the IYA2009 AEI produced an exhibition entitled 'From Galileo Galilei to Gravitational Wave Astronomy', which showcases what astronomers see with the different astronomical methods that have been developed so far, and how gravitational wave astronomy will expand our knowledge about the universe. The exhibition was shown on the occasion of our open day, at the Night of Astronomy at the town hall in Hannover and – together with the new LISA satellite model – at the Brandenburg IYA2009 closing event. This closing event was a joint crossover music/art/astronomy project of AEI together with the University of Potsdam, the Astrophysical Institute Potsdam and the

Nikolaisaal (a concert hall in Potsdam). Bernard Schutz together with MildeMarketing developed a multimedia talk about gravitational wave astronomy (‘*Music of the Spheres*’) for this event, which he since then gave a couple of times in Germany, Portugal, India and China (with Chinese subtitles). Sascha Skorupka from ARTEWIS/AEI Hannover staged a show with experiments on energy and fire.

The exhibition at the Nikolaisaal for the IYA2009 closing event.

Felicitas Mokler together with Anita Schael (Max Planck Institute for Extraterrestrial Physics) organized the competition AstroKlasse dedicated to the subject of astronomy at school. This competition was open to all kinds and levels of schools in Bavaria. The pupils should have the opportunity to explore the interesting field of astronomy on an interdisciplinary basis during teamwork. Various creative projects were realized, e.g. a hands-on model of the planetary system, exhibitions on the history of astronomy or a couple of astronomical board games that are highly educational themselves. Thanks to generous sponsoring, astronomical prizes such as an amateur telescope, astronomy books or magazines could be awarded for the best projects.

GEO600 as well as LIGO, Virgo, TAMA and AIGO participated in the 100 hours of astronomy around the world in 80 telescopes a webcast project organized by ESO in April 2009: http://www.100hoursofastronomy.org/component/content/article/149

A full-size LISA model was sent to the 213th American Astronomical Association meeting in Long Beach, CA, in January 2009. LISA acted as a real model and many visitors took photographs of themselves together with the satellite.

AEI donated another full-size LISA model to the ‘Cosmos and Culture’ exhibition, launched at the London Science Museum in July 2009. This exhibition, which celebrates 400 years of observational astronomy, features several gravitational wave exhibits. The exhibition ran until the end of 2010.

The AEI participated in the exhibition ‘Gravitational Wave Astronomy’ at the planetarium in Mannheim and in the exhibition ‘Space for Kids’ at Potsdam Central Station. At these exhibitions the AEI displayed

models, interactive exhibits and animations. For an exhibition in Tübingen the AEI provided several exhibits on gravitational waves (laser interferometer, model of the LISA satellites, films about GEO600 and LISA). Amongst other gravitational wave exhibits the LISA model was also displayed at the Night of Astronomy at the town hall in Hannover. With a model of the LISA satellites, the AEI participated in the Science Express, an exhibition train that travelled to 62 railway stations all over Germany and had 260.000 visitors.
http://www.expedition-zukunft.org

DFG Science TV

The AEI is part of the Cluster of Excellence QUEST (Quantum Engineering and Space Time Research). QUEST received money from the Deutsche Forschungsgemeinschaft (DFG) to finance a film about gravitational wave research. Doctoral students at AEI Hannover did the filming of the research diary and wrote the texts for 10 episodes about 'The Wave Hunters':
http://www.dfg-science-tv.de/en/projects/the-wave-hunters

Activities at Public Schools

The AEI often works together with public schools, either by giving talks at the school or by performing a fortnight's practical training at the AEI. Since many years Peter Aufmuth gives lectures about general relativity and gravitational waves at the Gymnasium Andreanum in Hildesheim and the Schillerschule in Hannover, each followed by a guided tour of GEO600. In 2008 and 2009 he also gave talks at the Marie Curie Schule in Ronnenberg and the Kaiser-Wilhelm- und Ratsgymnasium in Hannover. He even gives lectures at primary schools (3rd class), e.g., at the Grundschule Stelingen (on time and relativity) and the Grundschule *Auf dem Loh* at Hannover (on astronomy and cosmology). The AEI Hannover also participated in projects and exhibitions addressing pupils like TecToYou, IdeenExpo 2009, and the Sommeruniversität Rinteln.

Living Reviews in Relativity

To mark Living Reviews in Relativity's 10th anniversary, we organized a lecture series with distinguished authors of the journal. Public lectures in Potsdam and Berlin were held by Abhay Ashtekar, Luc Blanchet, Martin Bojowald, Marc Henneaux, Dimitrios Psaltis, and Clifford Will. Our aim was to promote the journal and the research field to a wider audience. Especially, Martin Bojowald generated much interest also with the press, which was supported by Milde Marketing.

A user survey was conducted from September 2008 to February 2009. The survey aimed to find out where readers come from, their professional background and their reading and download habits. The analysis is based on 80 completed questionnaires, 60 by readers with a scientific background, and 20 by non-scientists. The largest group of readers who took part in the survey came from Europe, the second largest from the United States, and third one from India. A very satisfactory result is that more than half visit Living Reviews in Relativity at least once a month.

At the time of writing (December 2009), Living Reviews in Relativity maintains 65 different articles online, of which 18 have been updated at least once by a major revision. Altogether, 91 reviews have been published since 1998. Within the report period (2008 to 2009), we have processed 10 new articles and 6 major updates. Living Reviews' searchable reference database now contains more than 17,000 reviewed records from our publications. With over 3,000 downloads of PDF article versions per month, and 700 subscriptions to our newsletter, we have become a major resource for scholars not only in the gravitational physics community.

Scientific impact

The success of our journal is most clearly visible by its enormous increase of citations within the last couple of years. By 2009, more than 4,800 refereed journal articles have been referencing Living Reviews in Relativity. Our annual citation analysis in Web of Science

(09/2009) showed that the five most cited reviews of the journal are cited more than 300 times each:

- C.M. Will: "The Confrontation between General Relativity and Experiment" – 315 + 174 (the 2006 update has been cited 174 times.)
- S. Carroll: "The Cosmological Constant" – 460
- R. Maartens: "Brane-World Gravity" – 349
- K.D. Kokkotas & B.G. Schmidt: "Quasi-Normal Modes of Stars and Black Holes" – 345
- C. Rovelli: "Loop Quantum Gravity" – 303

In August 2008, Thomson Reuters selected the journal for coverage in their information services. Since April 2009, the journal is indexed and abstracted in SCI, JCR and Current Contents. Thus, it will be listed with a Journal Impact Factor in the 2009 JCR edition, to be released in June 2010. Living Reviews are now also index by EBSCO Information Services in their subscription-based bibliographic databases Academic Search Complete and Academic Search Premier, covering our publications since 2007.

Digital editions

Living Reviews' collaboration with the Max Planck Digital Library (MPDL) has not only provided us with further software development and technical support, but also involved us in other activities. *The World Atlas of Language Structures Online* (WALS Online), a joint project of the MPDL with the MPI for Evolutionary Anthropology in the field of comparative linguistics has been a great success. While mostly a unique web application, WALS Online is also reusing components from the Living Reviews project, e.g. its reference database. This project engaged all team members and gave us the opportunity to explore the possibilities of web publishing based on office document formats. In addition, Andre Wobst dedicated his time to the organization and web site of the Dublin Core 2008 conference, co-organized by the MPDL.

The concept of regularly updated, high-quality online review journals has been successfully transferred to other fields of science. The Living Reviews family is growing and gaining reputation especially in the field of political science. A new journal, Living Reviews in Democracy (LRD) was launched in March 2009. It is published by the National Center of Competence in Research (NCCR) Democracy, an interdisciplinary research program launched by the Swiss National Science Foundation, and the Center for Comparative and International Studies, a joint venture of the ETH Zurich and the University of Zurich. In its fourth year of publication, Living Reviews in European Governance (LREG) is a joint winner of the European Information Association's 2009 "Awards for European Information Sources".

Frank Schulz

Cooperations and Outside Funding

The Institute's research is characterized by worldwide collaborations with universities and research institutes. In 2008/2009 research projects were funded by the following foundations and institutions:

Alexander von Humboldt-Stiftung - AvH (Humboldt Foundation)
The AEI hosted three AvH-laureates, Hirosi Ooguri (Humboldt-Award), Hans Ringström and Ruben Minasian (both Friedrich Wilhelm Bessel Research Award), and seven AvH-Fellows (Stefan Danilishin, Teresia Mansson, Cecilia Chirenti, Andres Anabalon, Oscar Varela, Jose-Luis Jaramillo and Alex B. Nielsen).

At the end of 2008 Yanbei Chen finished his research work at AEI which was supported by the Sofja Kovalevskaja Award. A new laureate of that prestigious prize, Daniele Oriti, started his research group on "Microscopic Quantum Structure and Dynamics of Spacetime" at the AEI in 2009.

Bundesministerium für Bildung und Forschung (Federal Ministry for Education and Research - BMBF) / Deutsches Zentrum für Luft- und Raumfahrt (DLR)
The German Aerospace Center (DLR) funds the technology demonstration space mission for *LISA, LISA Pathfinder*. The AEI-Hannover serves as Co-PI within the LISA technology package (LTP) architect team, and is largely responsible for the laser system and interferometry layout.

The German D-Grid Initiative is going to build a general and sustainable Grid-infrastructure that will be available for all German scientists in Germany.

The AEI is involved in three projects of that initiative and gets financial support for its work on the *German Astronomy Community Grid (GACG)*, the *Horizontal Integration of Resource- and Service Monitoring in D-Grid (D-MON)* and the *D-Grid Integration Project-2 (DGI-2)*.

The core task of the *GACG* was developing a framework and appropriate standards for collaborative management of astronomy-specific grid resources within the required infrastructure.

D-MON's vision is to realize a Grid wide monitoring architecture across several underlying, heterogeneous systems taking in consideration multiple resource providers and virtual organisations.

In 2008 the *DGI-2*, a follow-up project of the *DGI* (see last report), started. It intends to put the sizable grid infrastructure, created in *DGI*, on a sustainable basis for long-term use. The AEI is involved in two work packages of this project.

The BMBF/DLR also supports the German Israeli Project (DIP) *Applications of string theory to particle physics and to Gravity*, a binational center for the study of string theories. It also promotes a bilateral cooperation in education and research between the University of South Africa and the AEI.

Deutsch-Akademischer Austauschdienst – DAAD
(German Academic Exchange Service)
The DAAD supports the collaboration between the NumericalRelativity Group of the AEI and the Universidad de les Illes Balears (UIB). By funding the travel costs to Mallorca several times a year the programme allows the researchers from AEI and UIB to maintain a steady exchange.

Deutsche Forschungsgemeinschaft (DFG)
German Research Foundation

- Special Research Centers ("Sonderforschungsbereiche" (SFB)):
  SFB Transregio 7 *Gravitationswellen-Astronomie*: Gravitational wave activities in Germany are funded by the Deutsche Forschungsgemeinschaft (DFG) through the Sonderforschungsbereich Transregio (SFB/TR 7) "Gravitational Wave Astronomy" comprising the Universities of Tübingen, Jena, and Hannover and the Max Planck Institutes for Gravitational Physics and Astrophysics. It is running up to twelve years.

  SFB 647 *Raum-Zeit-Materie*: The special research area entitled "Space-Time-Matter" funded by the Deutsche Forschungsgemeinschaft (DFG) is a collaboration between the divisions 'Geometric Analysis and Gravitation' and 'Quantum Gravity and Unified Theories' of the AEI, the Humboldt University and the Freie Universität in Berlin, and the University of Potsdam. In this project mathematicians and physicists explore the exciting research field where theoretical physics, geometry and analysis meet.

  The SFB 407 *Quantenlimitierte Messprozesse* was concluded in 2009.

- Leibniz-Programme
  In 2003 the Leibniz Prize – the most prestigious German research prize – was awarded to Prof. Gerhard Huisken. The prize-money can be spent for personnel and travel over a period of seven years. Currently five scientists are paid by these funds.

- Bilateral Cooperations
  The DFG supports international mobility of scientists especially the initiation and intensification of bilateral cooperations. In 2009 they funded a visit of Prof. Luciano Rezzolla in Uzbekistan.

- Excellence Initiative
  Within the Excellence Initiative which aims to promote top-level research and to improve the quality of German universities and research institutions in general the Cluster of Excellence QUEST (Centre for Quantum Engineering and Space-Time Research) is funded by the DFG.

  Until 2012 QUEST will concentrate on the advancement of quantum engineering and spacetime research to gain a better understanding of the underlying physics and to improve or utilise resulting innovative methods in fundamental physics and applied fields. Accordingly, the activities of QUEST focus on four areas of research: Quantum Engineering, Quantum Sensors, Space-Time Physics, and Enabling Technologies.

In total QUEST will be supporting 14 graduate students and 4 Post-docs at AEI.

European Gravitational Observatory – EGO

EGO is currently funding a postdoctoral fellowship for the study on *Signature of Spins in Gravitational Waves from binary black-hole evolutions and construction of accurate and complete template banks.*

European Commission (EC)

In 2008/09 three Framework Programme 6 EC-projects (*Superstrings, Forces Universe* and *ILIAS*) were finished.

- Superstrings (*Superstring Theory*) was a four year follow-on to the former EC Research Training Network Superstrings and aimed at further developing string theory as a unified theory of the physical forces in order to understand its physic implications.

- Forces Universe (*Constituents, Fundamental Forces and Symmetries of the Universe*) aimed at gaining further insights into the fundamental structure of the universe, namely its basic constituents, the forces mutually acting on them and the symmetries which underlie its theoretical description.

- ILIAS (*Integrated Large Infrastructures for Astroparticle Science*) was an Integrated Infrastructure Initiative that pulled together all of Europe's leading infrastructures in Astroparticle Physics to produce a focused, coherent and integrated project in order to improve the existing infrastructures.

In Framework Programme 7 a new project started in May 2008: *ET (Einstein Telescope)* is a Design Study project. It concerns the study and the conceptual design for a new research infrastructure that will bring Europe to the forefront of the most promising new development in our quest to understand the history and future of the Universe, the emergence of the field of Gravitational Wave Astronomy.

From June 2010 on an International Reintegration Grant will be funded by the European Commission. Dr. Eloisa Bentivegna, currently at the Louisiana State University in Baton Rouge, U.S., will start working at AEI on her project *Computing in the dark sector: a Cactus toolkit for modified-gravity cosmologies.*

A proposal for the prestigious Starting Grant was positively evaluated by the European Research Council in 2010.

ESA and NASA

In 2008/2009 the Laser Interferometer Space Antenna (LISA) was funded jointly by ESA and NASA. The mission studies the mergers of supermassive black holes, tests Einstein's Theory of General Relativity, probes the early Universe, and searches for gravitational waves – its primary objective. Three of the ten European members of the LISA Science Team are from the AEI.

German-Israeli Foundation for Scientific Research and Development (GIF)

The German-Israeli Foundation is currently funding a proposal for a joint research project of the Quantum Gravity Division together with the University of Tel Aviv entitled *String Theory Meets Gauge Dynamics.*

INTAS

The International Association for the promotion of co-operation with scientists from the New Independent States of the former Soviet Union is funding the project *Current Topics in String Theory.* It deals with string and field theoretic aspects of supersymmetric theories, in particular targeting at the aim to learn about field theory beyond perturbation theory and about string theory in non-trivial backgrounds.

Volkswagen-Stiftung (VW Foundation)

The VW foundation supported the laser development for GEO600 and is funding the R&D programme *Advanced LIGO*. The objective of that project is the development and delivery of high-power pre-stabilized laser systems for the Advanced LIGO gravitational wave detectors. It is jointly conducted by the AEI laser group and the Laser Zentrum Hannover.

Perimeter Institute (PI)

The Perimeter Institute is providing an award to a student of the AEI in the area of theoretical physics who will visit PI for research.

Constance Münchow

Appraisals and Prizes

Karsten Danzmann was elected a Fellow of the American Physical Society in 2009 for his innovation and leadership in gravitational wave detection across its full spectrum and for promoting collaboration across national boundaries.

Gerhard Huisken was awarded the Commemorative Medal of the Faculty of Mathematics and Physics, Charles University Prague, in 2009.

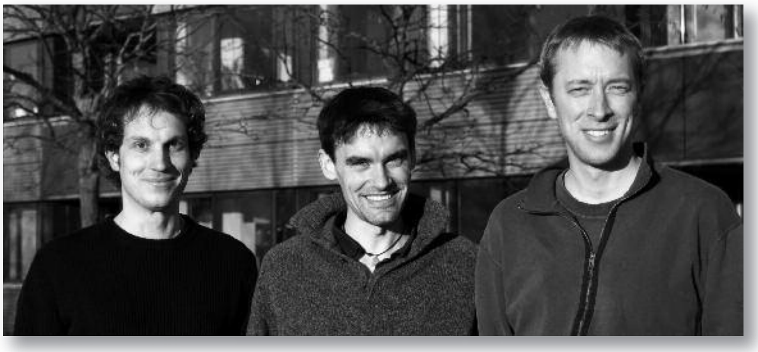
Bernard Schutz was elected an Honorary Fellow of the Royal Astronomical Society in 2009 for his distinguished leadership in stellar astronomy and gravitational wave research.

Matthias Staudacher received the 2009 Academy Award of the Berlin Brandenburg Academy of Sciences and Humanities, the Academy's most prestigious award after the Helmholtz Medal. Matthias Staudacher also won the appointment to a Professorship at Humboldt University, which he took up in April 2010.

Henning Vahlbruch won the 2008 GWIC Thesis Prize for his PhD thesis "Squeezed Light for Gravitational Wave Astronomy".

Hidehiko Shimada received the Seitaro-Nakamura Medal for 2008, for his paper „Beta-deformation for the matrix model of M-theory", Nucl.Phys.B813:283-314, 2009.

In 2008 the AEI was named to the InfoWorld 100 list, InfoWorld's highest honour, which recognizes IT projects that exemplify intelligent, creative uses of technology. AEI was one of only two 'Research and Development' winners on the list. The award was for the ATLAS Compute Cluster, designed and built by Bruce Allen and his team at AEI/Hannover.



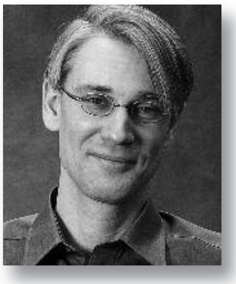
Niklas Beisert, Till Bargheer and Florian Loebbert (from right to left) were awarded the 2008 JSTAT (J. of Statistical Mechanics) prize for young scientists.

Carla Cederbaum (right) and Elke Müller (left) won the German National Competition "Wissenschaft interaktiv" in the 2009 Wissenschaftssommer with their outreach project "From Newton to Einstein: Travelling through Space and Time".

Academic Achievements

Professorships at AEI and abroad

Roman Schnabel was appointed as professor at Leibniz Universität Hannover in 2008.



Matthias Staudacher won the appointment to a professorship at Humboldt University, which he took up in April 2010.

Thomas Thiemann won a professorship at Erlangen University, which he took up in October 2009.

Jan Metzger was appointed an Associate Professor at Potsdam University.

Domenico Giulini was appointed Associate Professor at ZARM, Bremen, as part of the QUEST center of excellence.

Lars Andersson was appointed to a W2-professorship in Gerhard Huisken's division at AEI.

Habilitation Theses

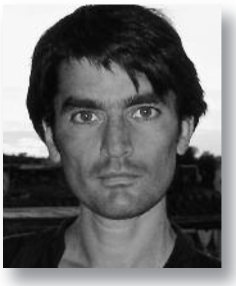
Gerhard Heinzel finished his habilitation thesis on "Präzisionsinterferometrie für Gravitationswellendetektoren" and was habilitated by Leibniz Universität Hannover in 2009.

Benno Willke finished his habilitation thesis on "Stabilisierte Festkörperlaser hoher Leistung für Gravitationswellenmessungen" and was habilitated by Leibniz Universität Hannover in 2009.

New Max Planck Research Group at AEI

Bianca Dittrich was awarded a special grant from MPG to set up a Max Planck Research Group on "Canonical and Covariant Dynamics of Quantum Gravity" at AEI. Since 1969 the Max Planck Society has been supporting gifted, young scientists and researchers through these independent junior research groups, which run for a limited period of time.

New Independent Research Group at AEI



Daniele Oriti won one of the Sofja Kovalevskaja Awards of the Alexander von Humboldt Foundation in 2008. The prize enabled him to establish an independent research group on "Microscopic Quantum Structure and Dynamics of Spacetime" at AEI.

Doctoral Theses

Ernazar Abdikamalov has finished his doctoral thesis on "The gravitational wave signature of stellar collapse and dynamics of compact stars" under the supervision of Prof. Luciano Rezzolla. He was awarded his PhD from SISSA (Italy) in 2009.

Andres Aceña was awarded his Dr. rer. nat. from Potsdam University in 2009. He wrote his doctoral thesis on "Convergent null data expansions at space-like infinity of stationary vacuum Solutions" under the supervision of Prof. Helmut Friedrich.

Benjamin Bahr has finished his doctoral thesis on "Analysis of the Loop Quantum Gravity dynamics with coherent states and categories" under the supervision of Prof. Thomas Thiemann. He was awarded his PhD from Potsdam University in 2008.

Enrico Barausse has finished his doctoral thesis on “Exploring Gravity Theories with Gravitational Waves and compact Objects” under the supervision of Prof. Luciano Rezzolla. He was awarded his PhD from SISSA (Italy) in 2008.

Roger Bieli was awarded his Dr. rer. nat. from Free University Berlin in 2008. He wrote his doctoral thesis “On the Late-Time Asymptotics of the Non-Minimally Coupled Einstein-Scalar Field System” under the supervision of Prof. Alan Rendall.

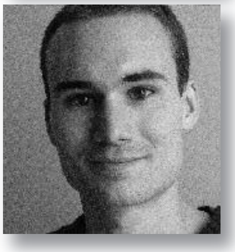
Alexander Franzen was awarded his Dr. rer. nat. from the Leibniz Universität Hannover in 2008. He wrote his doctoral thesis on “Präparation von destillierten und purifizierten gequetschten Zuständen“ under the supervision of Prof. Roman Schnabel.

Felipe Guzmán Cervantes has finished his doctoral thesis on “Gravitational Wave Observation from Space: optical measurement techniques for LISA and LISA Pathfinder” under the supervision of Prof. Gerhard Heinzel. He was awarded his Dr. rer. nat. from the Leibniz Universität Hannover in 2009.

Christian Hillmann was awarded his Dr. rer. nat. from Humboldt University in 2008. He wrote his doctoral thesis on “E7(7) and d = 11 supergravity” under the supervision of Prof. Hermann Nicolai.

Olaf Milbredt has finished his doctoral thesis on “The Cauchy Problem for Membranes” under the supervision of Prof. Gerhard Huisken. He was awarded his Dr. rer. nat. from Free University Berlin in 2008.

Helge Müller-Ebhardt was awarded his Dr. rer. nat. from the Leibniz Universität Hannover in 2008. He wrote his doctoral thesis on “On quantum effects in the dynamics of macroscopic test masses” under the supervision of Prof. Roman Schnabel.



Jakob Palmkvist was awarded his PhD from Göteborg University in 2008. He wrote his doctoral thesis on “Exceptional Lie algebras and M-theory” under the supervision of Prof. Hermann Nicolai.

Holger Pletsch was awarded his Dr. rer. nat. from the Leibniz Universität Hannover in 2009. He wrote his doctoral thesis on "Data Analysis for Continuous Gravitational Waves" under the supervision of Prof. Bruce Allen.

Henning Rehbein was awarded his Dr. rer. nat. from the Leibniz Universität Hannover in 2008. He wrote his doctoral thesis on "On the enhancement of future gravitational wave laser interferometers and the prospects of probing macroscopic quantum mechanics" under the supervision of Prof. Roman Schnabel.

Adam Rej has finished his doctoral thesis on "Integrabilität der N = 4 SYMt und die AdS/CFT Korrespondenz" under the supervision of Dr. Matthias Staudacher. He was awarded his Dr. rer. nat. from Humboldt University in 2008.

Frank Seifert was awarded his Dr. rer. nat. from the Leibniz Universität Hannover in 2009. He wrote his doctoral thesis on "Power Stabilization of High Power Lasers for Second Generation Gravitational Wave Detetors" under the supervision of Dr. Benno Willke.

Frank Steier was awarded his Dr. rer. nat. from the Leibniz Universität Hannover in 2008. He wrote his doctoral thesis on "Interferometry techniques for spaceborne gravitational wave detectors" under the supervision of Dr. Gerhard Heinzel.

André Thüring has finished his doctoral thesis on "Investigations of coupled and Kerr non-linear optical resonators" under the supervision of Prof. Roman Schnabel. He was awarded his Dr. rer. nat. from the Leibniz Universität Hannover in 2009.

Henning Vahlbruch was awarded his Dr. rer. nat. from the Leibniz Universität Hannover in 2008. He wrote his doctoral thesis on "Squeezed Light for Gravitational Wave Astronomy" under the supervision of Prof. Roman Schnabel.

Diploma Theses

Stefan Ast graduated in physics from the Leibniz Universität Hannover in 2009. He wrote his diploma thesis "Erzeugung gequetschter Lichtfelder mit einer Bandbreite über 1 GHz" under the supervision of Prof. Roman Schnabel.

Robin Bähre graduated in physics from the Leibniz Universität Hannover in 2009. He wrote his diploma thesis "Suppression of correlated laser power noise in a single-mode pumped non-planar ring oscillator" under the supervision of Dr. Benno Willke.

Simon Barke graduated in physics from the Leibniz Universität Hannover in 2008. He wrote his diploma thesis "Inter-Spacecraft Clock Transfer Phase Stability for LISA" under the supervision of Dr. Gerhard Heinzel.

Berit Behnke graduated in physics from Hamburg University in 2008. She wrote her diploma thesis on "Stabilization of the H2 LIGO detector in high power operation" under the supervision of Dr. Maria Alessandra Papa.

Nicolas Behr graduated in physics from Humboldt University in 2008. He wrote his diploma thesis on "Matrix factorizations in Kazama-Suzuki-models" under the supervision of Dr. Stefan Fredenhagen.

Nikolaus Berndt graduated in physics from Humboldt University in 2008. He wrote his diploma thesis "Dynamik von kosmologischen Modellen in verallgemeinerten Relativitätstheorien" under the supervision of Prof. Alan Rendall.

Yurij Davygora graduated in physics from Erlangen University in 2009. He wrote his diploma thesis on "Kanonische Formulierungen der Gravitationstheorien" under the supervision of Prof. Thomas Thiemann.

Christian Diekmann graduated in physics from the Leibniz Universität Hannover in 2008. He wrote his diploma thesis „Phasenstabilisierung und -auslesung für LISA" under the supervision of Dr. Gerhard Heinzel.

Johannes Eichholz graduated in physics from the Leibniz Universität Hannover in 2009. He wrote his diploma thesis "Inter-Spacecraft Optical Ranging and Data Transfer for LISA" under the supervision of Dr. Gerhard Heinzel.

Filippo Galeazzi graduated in physics from the University of Padua in 2008. He wrote his diploma thesis on "Modelling fluid interfaces in numerical relativistic hydrodynamics" under the supervision of Prof. Luciano Rezzolla.

Arne Gödeke graduated in physics from Free University Berlin in 2009. He wrote his diploma thesis on "Long-term behavior of higher dimensional spatially homogeneous cosmological models" under the supervision of Prof. Alan Rendall.

Christian Gräf graduated in physics from the Leibniz Universität Hannover in 2008. He wrote his diploma thesis "PPKTP-Quetschlichtquelle und Twin Signal Recycling" under the supervision of Prof. Roman Schnabel.

Michael Jasiulek graduated in physics from Humboldt University in 2008. He wrote his diploma thesis on "Spin Measures on Isolated and Dynamical Horizons in Numerical Relativity" under the supervision of Prof. Luciano Rezzolla.

Oliver Kranz graduated in physics from the Leibniz Universität Hannover in 2009. He wrote his diploma thesis "Suspension Platform Interferometer" under the supervision of Dr. Gerhard Heinzel.

Sebastian Krug graduated in physics from Humboldt University in 2009. He wrote his diploma thesis on "Geometric aspects of renormalization group flows in SU(2) related models" under the supervision of Dr. Stefan Fredenhagen.

David Link graduated in physics from Humboldt University in 2009. He wrote his diploma thesis "On the Final State of Inspiralling Neutron Stars: Investigation of the Properties of Accretion Tori Produced in Binary Neutron Star Mergers" under the supervision of Prof. Luciano Rezzolla.

Christoph Mahrdt graduated in physics from the Leibniz Universität Hannover in 2008. He wrote his diploma thesis "Rauschprojektion höherer Ordnung" under the supervision of Dr. Martin Hewitson.

Thomas Marquardt graduated in mathematics from TU Dresden in 2008. He wrote his diploma thesis "Randwertprobleme für Hyperflächen vorgeschriebener, anisotroper, mittlerer Krümmung" under the supervision of Prof. Gerhard Huisken.

Philipp Mösta graduated in physics from Kassel University in 2008. He wrote his diploma thesis on "Puncture evolutions within the harmonic framework" under the supervision of Prof. Luciano Rezzolla.

Ernesto Nungesser graduated in physics from Free University Berlin in 2008. He wrote his diploma thesis on "Strong cosmisc censorship in polarized T3-Gowdy symmetric spacetimes with a Maxwell field" under the supervision of Prof. Alan Rendall.

Markus Otto graduated in physics from the Leibniz Universität Hannover in 2008. He wrote his diploma thesis "Simulation und Messung des stochastischen Hintergrundes" under the supervision of Dr. Martin Hewitson.

Stefan Pfenninger graduated in physics from ETH Zurich in 2009. He wrote his diploma thesis on "D-brane dynamics in coset models: a case study" under the supervision of Dr. Stefan Fredenhagen.

Jan Hendrik Pöld graduated in physics from the Leibniz Universität Hannover in 2009. He wrote his diploma thesis "Stabilization of the Advanced LIGO 200 W Laser" under the supervision of Dr. Benno Willke.

David Radice graduated in physics from Milan University in 2009. He wrote his diploma thesis on "Numerical Simulations of Critical Phenomena in Neutron Star Collapse" under the supervision of Prof. Luciano Rezzolla.

Henning Ryll graduated in physics from the Leibniz Universität Hannover in 2008. He wrote his diploma thesis "Transmission hoher Laserleistung durch optische Fasern" under the supervision of Dr. Benno Willke.

Sebastian Steinlechner graduated in physics from the Leibniz Universität Hannover in 2008. He wrote his diploma thesis "Gequetschtes Licht bei 1550 nm" under the supervision of Prof. Roman Schnabel.

Henrik Tünnermann graduated in physics from the Leibniz Universität Hannover in 2009. He wrote his diploma thesis "Intrinsische Reduktion der Depolarisation in Nd:YAG Kristallen" under the supervision of Peter Weßels.

Tobias Westphal graduated in physics from the Leibniz Universität Hannover in 2009. He wrote his diploma thesis "Optomechanische Kopplung in Michelson-Sagnac-Interferometern" under the supervision of Prof. Roman Schnabel.

Holger Wittel graduated in physics from the Leibniz Universität Hannover in 2009. He wrote his diploma thesis "Compensation of thermal lensing in the GEO600 beam splitter" under the supervision of Dr. Harald Lück.

Herman Witzel graduated in physics from Potsdam University in 2009. He wrote his diploma thesis on "Curvature of the refined spacetime geometry probed by photons" under the supervision of Dr. Frederic Schuller.

Bernhard Wurm graduated in physics from Bonn University in 2008. He wrote his diploma thesis on "Twistor String Theories" under the supervision of Prof. Stefan Theisen.

Master Thesis

Cosimo Restuccia graduated in physics from Florence University in 2009. He wrote his master thesis on "Geometric approach to branes on Wess-Zumino-Witten models" under the supervision of Dr. Stefan Fredenhagen.

Bachelor Thesis

Christoph Witte has finished his bachelor thesis on "Algebraic classification and causal structure of four-dimensional area" under the supervision of Dr. Frederic Schuller. He received his bachelor degree from Humboldt University in 2009.

The Fachbeirat of the AEI

The Fachbeirat is the Institute's scientific advisory and assessment board, made up of internationally renowned physicists and mathematicians. The Fachbeirat advises the President of the Max Planck Society (MPG) on how effectively the Directors are managing the work of the Institute. Their advice helps the Directors to establish priorities and improve their management. The Fachbeirat is the main tool used by the MPG to evaluate its research institutes to ensure appropriate and effective development of funds. Every two years the members of the Fachbeirat meet for several days to evaluate the Institute and to prepare a report to the President of the MPG.

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Thomas Marquardt (AEI Golm)
Giulio Mazzolo (AEI Hannover)
Moritz Mehmet (Leibniz Universität Hannover)
Tobias Meier (Leibniz Universität Hannover)
Carlo Meneghelli (AEI Golm)
Anneke Monsky (Leibniz Universität Hannover)
Kristen Moore (AEI Golm)
Philipp Mösta (AEI Golm)
Michael Munzert (AEI Golm)
Thilo Notz (AEI Golm)
Ernesto Nungesser (AEI Golm)
Frank Ohme (AEI Golm)
Markus Otto (Leibniz Universität Hannover)
Rodrigo Panosso Macedo (AEI Golm)
Stefan Pfenninger (AEI Golm)
Jan Hendrik Pöld (AEI Hannover)
Alexander Post (AEI Hannover)
Mirko Prijatelj (Leibniz Universität Hannover)
Matti Raasakka (AEI Golm)
David Radice (AEI Golm)
Dennis Rätzel (AEI Golm)
Cosimo Restuccia (AEI Golm)
Sergio Rivera (AEI Golm)
Constanze Rödig (AEI Golm)
Pablo Antonio Rosado Gonzalez (AEI Hannover)
Aiko Samblowski (Leibniz Universität Hannover)
Lucia Santamaria Lara (AEI Golm)
Burkhard Schwab (AEI Golm)
Miroslav Shaltev (AEI Hannover)
Yu Shang (AEI Golm)
Dmitry Simakov (Leibniz Universität Hannover)
Jessica Steinlechner (AEI Hannover)
Sebastian Steinlechner (Leibniz Universität Hannover)
Johannes Tambornino (AEI Golm)
Aaryn Tonita (AEI Golm)
Yan Wang (Leibniz Universität Hannover)
Alexander Wanner (Leibniz Universität Hannover)
Gudrun Wanner (AEI Hannover)
Tobias Westphal (Leibniz Universität Hannover)
Holger Wittel (AEI Hannover)
Stefan Zieme (AEI Golm)

Diploma, Bachelor and Master Students

Kais Abdelkhalek (Leibniz Universität Hannover)
Vitus Händchen (Leibniz Universität Hannover)
Björn Hemb (Leibniz Universität Hannover)
David Mesterhazy (AEI Golm)
Vitali Müller (Leibniz Universität Hannover)
Amrit Pal-Singh (Leibniz Universität Hannover)
Jan Rybizki (Leibniz Universität Hannover)
Clemens Schäfermeier (Leibniz Universität Hannover)
Axel Schönbeck (Leibniz Universität Hannover)
Emil Schreiber (Leibniz Universität Hannover)

Scientists and Support Staff (Potsdam & Hannover) at the AEI and the Leibniz Universität Hannover – based on 1st June 2010

Daniela Schulze (Leibniz Universität Hannover)
Dirk Schütte (Leibniz Universität Hannover)
Martin Sommerfeld (Leibniz Universität Hannover)
Sebastian Steinhaus (AEI Golm)
Vaclav Tlapak (AEI Golm)
Daniel Wahlmann (Leibniz Universität Hannover)
Maximilian Wimmer (Leibniz Universität Hannover)
Bernhard Wurm (AEI Golm)

Research Programmers

Dr. Carsten Aulbert (AEI Hannover)
Dr. Alexander Beck-Ratzka (AEI Golm)
Oliver Bock (AEI Hannover)
Ingo Diepholz (AEI Hannover)
Dr. Henning Fehrmann (AEI Hannover)
Dr. Steffen Grunewald (AEI Golm)
Uwe Kronholm (AEI Golm)
Alexander Koholka (AEI Golm)
Bernd Machenschalk (AEI Hannover)

Support Staff

Kathrin Altmann – Travel Expenses Referee (AEI Golm)
Robin Bähre – Student Assistant (Leibniz Universität Hannover)
Almuth Barta – Database Administrator (AEI Golm)
Christoph Baune – Student Assistant (Leibniz Universität Hannover)
Karina Beiman – Trainee (AEI Golm)
Maximilian Beyer – Precision Mechanic (Leibniz Universität Hannover)
Sarah Blum – Student Assistant (AEI Golm)
Mara Blümel – Personnel Administrator (AEI Golm)
Jens Breyer – Technician (AEI Hannover)
Marc Brinkmann – Operator GEO600 (AEI Hannover)
Thomas Brockt – Student Assistant (Leibniz Universität Hannover)
Nico Budewitz – HPC System Administrator (AEI Golm)
Dr. Iouri Bykov – Electronic Technician (AEI Hannover)
Guido Conrad – System Administrator (AEI Hannover)
Andreas Donath – System Administrator (AEI Golm)
Thomas Feg – System Administrator (AEI Golm)
Marco Gajardo – Web Programmer (AEI Golm)
Brigitte Gehrmann – Administrative Assistant LISA (AEI Hannover)
Gina Gerlach – Administrative Assistant (AEI Hannover)
Christine Gottschalkson – Secretary (AEI Golm)
Daniel Gregorek – Student Assistant (Leibniz Universität Hannover)
Marius Hartmann – Student Assistant (AEI Hannover)
Olaf Hartwig – Student Assistant (AEI Hannover)
Melanie Hase – Coordinator IMPRS (AEI Golm)
Brigitte Hauschild – Assistent of Head of Administration (AEI Golm)
Christa Hausmann-Jamin – Head of IT Department (AEI Golm)
Katharina Henke – Administrative Assistant (AEI Golm)
Tejun Heo – Programmer (AEI Hannover)
Stephan Herdam – System Administrator (AEI Hannover)
Hans-Jörg Hochecker – Electronic Technician (AEI Hannover)
Susanne Holldorf – Personnel Administrator (AEI Golm)
Katharina-Sophie Isleif – Student Assistant (AEI Hannover)
Lars Jacob – Student Assistant (AEI Golm)
Marvin Keller – Student Assistant (AEI Golm)
Philipp Kormann – Electronic Technician (AEI Hannover)
Volker Kringel – Operator GEO600 (AEI Hannover)
Ralf Kuschel – Student Assistant (AEI Golm)

Scientists and Support Staff (Potsdam & Hannover) at the AEI and the Leibniz Universität Hannover – based on 1st June 2010

Anne Lampe – Secretary (AEI Golm)
Anja Lehmann – Librarian (AEI Golm)
Danara Martinez Saiz – Student Assistant (AEI Hannover)
Mike Marwede – Student Assistant (AEI Hannover)
Jonas Matthias – Lecture Assistant (Leibniz Universität Hannover)
Dr. Felicitas Mokler – Press Officer AEI Hannover (AEI Hannover)
Dr. Elke Müller – Scientific Coordinator (AEI Golm)
Constance Münchow – Third-Party Funds Manager (AEI Golm)
Ronny Nickel – Trainee (AEI Golm)
Vera Osswald – Database Manager Back Office Living Reviews (AEI Golm)
Christina Pappa – Cleaning Lady (AEI Golm)
Holger Petzholdt – Student Assistant (AEI Hannover)
Christian Pfennig – Student Assistant (Leibniz Universität Hannover)
Dr. Markus Pössel – Adjunct Public Outreach Scientist (AEI Golm)
Susann Purschke – Referee Guesthouse and Cashier (AEI Golm)
Dr. Jens Reiche – LISA Pathfinder Project Manager (AEI Hannover)
Roderik F. P. Rintisch – Student Assistant (AEI Golm)
Christoph Rollwagen – Student Assistant (AEI Golm)
Christiane Roos – Head of Administration (AEI Golm)
Jan Scharein – Web Developer (AEI Golm)
Elisabeth Schlenk – Head of the Library (AEI Golm)
Matthias Schlenk – Lecture Assistant (Leibniz Universität Hannover)
Ute Schlichting – Secretary (AEI Golm)
Mirko Schmidt – Student Assistant (AEI Golm)
Manuela Schneehufer – Personnel Administrator (AEI Golm)
Babett Schöppe – Bookkeeper (AEI Golm)
Frank Schulz – Manager Back Office Living Reviews (AEI Golm)
Beatrice Schütze – Travel Expenses Referee (AEI Golm)
Thomas Schwarze – Student Assistant (Leibniz Universität Hannover)
Marcus Thienert – Web Developer (AEI Golm)
Arthur Varkentin – Student Assistant (AEI Hannover)
Gerrit Visscher – Student Assistant (AEI Hannover)
Michael Weinert – Operator GEO600 (AEI Hannover)
Ramona Wittwer – Bookkeeper (AEI Golm)
Dietlind Witzger – Cleaning Lady (AEI Golm)
Manfred Zimpel – Administrative Consultant (AEI Hannover)

Guest Scientists in Potsdam-Golm (2008)

Aastrup, Johannes – Universität Münster
Abdikamalov, Ernazar – SISSA, Trieste
Ahmedov, Bobomurat – Uzbekistan Academy of Sciences
Ahn, Changrim – Ewha Womens University, Seoul
Ahrens, Sven – Landessternwarte, Heidelberg
Aichelburg, Peter Christian – Universität Wien
Akhmedov, Emil – ITEP, Moscow
Alexander, Tal – Weizmann Institute, Rehovot
Allen, Paul T. – University of Washington, Tacoma
Ansorg, Marcus – Helmholtz Zentrum, München
Ashtekar, Abhay – Pennsylvania State University

Baiotti, Luca – Tokyo University
Balasin, Herbert – Technische Universität, Wien
Bander, Myron – University of California, Irvine
Banerjee, Nabamita – Utrecht University
Bao, Ling – Chalmers University
Barack, Leor – University of Southampton
Barausse, Enrico – University of Maryland
Barranco, Juan – UNAM, Mexico
Bartnik, Robert – University of Canberra
Bastianelli, Fiorenzo – University of Bologna
Bazhanov, Vladimir – Australian National University, Canberra
Beccaria, Matteo – Lecce University
Bergshoeff, Eric – University of Groningen
Bernal, Argelia – University Michoacana, Morelia
Bernhardt, Mike – Universität Heidelberg
Beyer, Horst – Louisiana State University
Bičák, Jiři – Charles University, Prague
Bishop, Nigel – Rhodes University
Bizon, Piotr – Cracow University
Blanchet, Luc – Observatory Paris-Meudon
Blaut, Arkadiusz – University of Wroclaw
Blue, Pieter – University of Edinburgh
Bojowald, Martin – Pennsylvania State University
Boschitz, Edmund – Bejing University
Botvinnik, Boris – University of Oregon
Boulanger, Nicolas – University of Pisa
Brendle, Simon – Princeton University
Brink, Lars – Chalmers Technical University
Burchard, Almut – University of Toronto

Cao, Huai-Dong – Lehigh University
Caputo, Maria-Cristina – University of Texas
Carqueville, Nils – King's College London
Chatterjee, Debarati – Saha Institute of Nuclear Physics, Kolkata
Chen, Chiang-Mei – National Central University, Taiwan
Chen, Sophie Szu-Yu – University of Berkeley
Chirenti, Cecilia – University of Sao Paulo
Choptuik, Matthew – University of British Columbia, Canada
Christodoulou, Demetrios – ETH, Zürich
Chung, Christine – University of Melbourne
Corvino, Giovanni – Parma University
Cremascini, Claudio – University of Trieste
Cutler, Curt – Jet Propulsion Laboratory, Pasadena

Dain, Sergio – University of Cordoba, Argentina
Davies, Melvyn B. – Lund Observatory
Dehne, Christoph – Universität Leipzig
Deser, Stanley – California Institute of Technology, Pasadena
Dias, Marcelo – University of Massachusetts
Diener, Peter – Louisiana State University
Dixon, Lance – SLAC, Stanford

Guest Scientists in Potsdam-Golm (2008)

Dönmez, Orhan – Nigde University
Donninger, Roland – University of Vienna
Döring, Andreas – Imperial College, London
Durhuus, Bergfinnur – University of Copenhagen
Dutta, Suvankar – Swansea University

Eden, Burkhard – Universität Leipzig
Engle, Jonathan – University of Marseille
Eriguchi, Yoshiharu – University of Tokyo

Faraoni, Valerio – Bishop s University, Sherbrooke
Feingold, Alex – State University of New York at Binghamton
Filter, Robert – Universität Jena
Fischbacher, Thomas – University of Southampton, UK
Font, Anamaria – UAM, Madrid
Font-Roda, José Antonio – University of Valencia
Frauendiener, Jörg – University of Otago, New Zealand
Frolov, Sergey – Trinity College, Dublin
Fulde, Peter – MPI für Physik komplexer Systeme

Gair, Jonathan – University of Cambridge, UK
Garcia del Moral, Maria Pilar – Turin University
Garecki, Janusz – University of Szczecin
Garrett, Travis – Louisiana State University
Gholami, Iraj – Hahn-Meitner-Institut
Ghoshal, Debashis – Jawaharlal Nehru University, New Delhi
Giacomazzo, Bruno – University of Maryland
Giazotto, Adalberto – National Institute of Nuclear Physics, Frascati
Giesel, Kristina – NORDITA, Stockholm
Glowna, Frank – Universität Jena
Goetz, Evan – University of Michigan
Govindarajan, Tupil Rangachari – Institute of Mathematical Science, Chennai
Gowdigere, Chethan – ICTP, Trieste
Gregory, Ruth – Durham University
Grimstrup, Jesper – Niels Bohr Institute, Copenhagen
Grotowski, Joseph – University of Brisbane
Gualtieri, Leonardo – University of Rome „Sapienza"
Guilfoyle, Brendan – Institute of Technology, Tralee
Gundlach, Carsten – University of Southampton
Gupta, Nitin – Indian Institute of Technology, Kharagpur
Gutierrez, Benjamin – University of British Columbia, Canada

Halpern, Martin – University of California
Hamber, Herbert – University of California, Irvine
Hanada, Masanori – Weizmann Institute, Rehovot
Hanany, Amihay – Massachussets Institute of Technology
Hannam, Mark – Universität Jena
Harfst, Stefan – University of Amsterdam
Herbst, Manfred – CERN, Geneva
Hernandez, Hector – Autonomous University of Chihuahua, Mexico
Hillmann, Christian – Institute des Hautes Etudes Scientifiques, Paris
Hohm, Olaf – University of Groningen
Hopman, Clovis – Leiden Observatory
Hoppe, Jens – Royal Institute of Technology, Stockholm
Hryczuk, Andrzej – University of Warsaw
Hung, Ling-Yan – DAMTP, Cambridge

Isidro, Jose – University of Valencia

Kajtar, Jules – Monash University
Kazakov, Vladimir – ENS, Paris
Kazama, Yoichi – University of Tokyo

Guest Scientists in Potsdam-Golm (2008)

Keller, Christoph – ETH, Zürich
Kim, Jinho – Seoul National University
Kisielowski, Marcin – University of Warsaw
Klein, Christian – MPI für Mathematik in den Naturwissenschaften
Kleinschmidt, Axel – University of Brussels
Klingenberg, Wilhelm – Durham University, UK
Kluson, Josef – University Brno
Knopf, Dan – University of Texas at Austin
Kofron, David – Charles University, Prague
Kojima, Yasufumi – Hiroshima University
Komossa, Stefanie – MPI für Extraterrestrische Physik Garching
Kong, De-Xing – Hangzhou University
Koroteev, Peter – ITEP, Moscow
Kostov, Ivan – CEA, Saclay
Kotikov, Anatoly – Joint Institute for Nuclear Research, Dubna
Kozak, Andrii – ENS, Paris
Krolak, Andrzej – Academy of Sciences, Warsaw
Kroyter, Michael – Tel Aviv University
Kumar, Prayush – Birla Institute of Technology and Science
Kumar, Rahul – Indian Institute of Technology, Kanpur

Lambert, Neil – King's College, London
Lavrelashvili, George – A. Razmadze Mathematical Institute, Tbilisi
LeFloch, Philippe – University Pierre and Marie Curie, Paris
Lehner, Luis – Louisiana State University
Lipatov, Lev – Universität Hamburg
Liu, Fukun – Beijing University
Llinares, Claudio – Astrophysikalisches Institut, Potsdam
Löffler, Frank – Louisiana State University –
Lousto, CarlosUniversity of Rochester
Luan, Jing – Beijing University
Lukas, Andre – University of Oxford
Lukierski, Jerzy – Wroclaw University

Madore, John – University of Paris (South)
Magro, Marc – ENS, Lyon
Mahapatra, Swapna – Utkal University, Bhubaneswar
Mandel, Ilya – Northwestern University
Martin-Benito, Mercedes – Institute of structure of the matter, Madrid
Martin, Isabelia – Simon Bolivar University, Caracas
Meissner, Krzysztof – University of Warsaw
Melatos, Andrew – University of Melbourne
Menou, Kristen – Columbia University
Minasian, Ruben – CEA, Saclay
Moncrief, Vincent – Yale University
Mundim, Bruno – University of British Columbia, Canada

Nagar, Alessandro – Institute des Hautes Etudes Scientifiques Paris
Neilsen, David – Brigham Young University, Provo
Nerozzi, Andrea – Portsmouth University
Nicolo, Francesco – University of Rome
Nuyts, Jean – University of Mons-Hainaut

Okolow, Andrzej – University of Warsaw
Oliynyk, Todd – Monash University, Australia
OMurchadha, Niall – University College, Cork
Ott, Christian – Steward Observatory, Tucson
Özel, Feryal – University of Arizona
Oz, Yaron – Tel Aviv University

Palmkvist, Jakob – University of Brussels
Penner, Jason – University of British Columbia, Canada

Guest Scientists in Potsdam-Golm (2008)

Perego, Albino – University of Milano
Perelomov, Askold – ITEP, Moscow
Perez, Alfredo – University of Concepcion, Chile
Petroff, David – TPI, FSU Jena
Pfister, Herbert – Universität Tübingen
Plefka, Jan – Humboldt-Universität, Berlin
Pollney, Denis – University of the Balearic Islands, Mallorca
Popov, Sergei – Sternberg Astronomical Institute, Leiden
Porter, Edward – APC, University Paris 7
Porto, Rafael – University of California, Berkeley
Preto, Miguel – Astronomisches Recheninstitut, Heidelberg
Psaltis, Dimitrios – University of Arizona

Rej, Adam – Imperial College, London
Restuccia, Alvaro – University of Caracas
Rey, Soo-Jong – Seoul National University
Ringström, Hans – Royal Institute of Technology, Stockholm
Rinne, Oliver – University of Cambridge UK
Roberts, Mark – IHES, France
Roiban, Radu – Pennsylvania State University

Sadler, Wendy – Cardiff University
Saez, Mariel – Catholic University of Chile
Sahoo, Bindusar – Harish Chandra Research Institute, Allahabad
Samsonov, Igor – Universität Hannover
Samtleben, Henning – ENS, Lyon
Sancho de la Jordana L., L. – University of the Balearic Islands, Mallorca
Sarkar, Sudiptal – UCAA, Pune
Schätzle, Rainer – Universität Tübingen
Schmidt, Bernd – München
Schnetter, Erik – Louisiana State University
Scholtz, Martin – Charles University, Prague
Schoutens, Kareljan – University of Amsterdam
Schroer, Bert – Freie Universität Berlin
Schubert, Christian – University Michoacana, Morelia
Schwimmer, Adam – Weizmann Institute, Rehovot
Serban, Didina – CEA, Saclay
Sinestrari, Carlo – University of Rome II
Sintes Olives, Alicia – University of the Balearic Islands, Mallorca
Sivakumar, Muthuswamy – University of Hyderabad
Smilga, Andrei – University of Nantes
Sopuerta, Carlos – Institute of Space Sciences, Barcelona
Sorokin, Dimitri – University of Padua
Spurzem, Rainer – Astronomisches Recheninstitut, Heidelberg
Stamatescu, Ion-O. – Universität Heidelberg
Stavrov, Iva – Clark University
Stelle, Kellogg – Imperial College, London
Szekelyhidi, Laszlo – Universität Bonn

Tchapnda, Sophonie Blaise – University of Yaounde
Thornburg, Jonathan – Indiana University
Trias Cornellana, Miquel – University of the Balearic Islands, Mallorca
Tsimpis, Dimitris – LMU, München

Ullmer, Brygg – Louisiana State University
Uruchurtu, Linda – DAMTP, Cambridge

Valtonen, Mauri – Tuorla Observatory, Turku
Van Meter, James – Goddard Space Flight Center
van Putten, Maurice – University of Orleans
Vasiliev, Misha – Lebedev Institute, Moscow
Velizhanin, Vitaly – Petersburg Nuclear Physics Institute

Guest Scientists in Potsdam-Golm (2008)

Vicedo, Benuit – ENS, Paris
von der Luehe, Oskar – Kiepenheuer-Institut für Sonnenphysik, Freiburg
Vulcanov, Dumitru – Timisoara University

Wald, Robert – University of Chicago
Wang, Guofang – Universität Magdeburg
Wang, Mu-Tao – Columbia University
Wapler, Matthias – Perimeter Institute
White, Simon – MPI für Astrophysik, Garching
Wiegmann, Paul – Chicago University
Will, Clifford – Washington University
Williams, Ruth – DAMTP, Cambridge
Wiltshire, David – University of Canterbury, New Zealand
Winicour, Jeffrey – University of Pittsburgh
Wise, John – Goddard Space Flight Center

Yankielowicz, Shimon – Tel Aviv University

Zagermann, Marco – MPI für Physik
Zanotti, Olindo – University of Notre Dame, Indiana
Zayakin, Andrei – Universität München
Zenginoglu, Anil – Universität Wien
Zink, Burkard – Louisiana State University
Zoubos, Konstantinos – Niels Bohr Institute , Copenhagen
Zoupanos, George – University of Athens

Guest Scientists in Potsdam-Golm (2009)

Abdikamalov, Ernazar – SISSA, Trieste
Abramowicz, Marek – Gothenborg University
Ahmedov, Bobomurat – Uzbekistan Academy of Sciences
Akhmedov, Emil – ITEP, Moscow
Alexander, Tal – Weizmann Institute, Rehovot
Alexandrov, Sergei – University Utrecht
Allen, Paul T. – University of Washington, Tacoma
Aloy Torás, Miguel – University of Valencia
Anderson, Matt – Louisiana State University
Andersson, Nils – Southampton University
Ansorg, Marcus – Helmholtz Zentrum, München
Aoudia, Sofiane – Paris Observatory
Arutyunov, Gleb – Utrecht University
Athanassenas, Maria – Monash University, Australia

Bagchi, Arjun – Harish Chandra Research Institute, Allahabad
Baiotti, Luca – Tokyo University
Bai, Shan – Chinese Academy of Sciences, Beijing
Baker, Charles – ANU, Canberra
Banados, Maximo – University of Santiago, Chile
Banerjee, Nabamita – Utrecht University
Barbour, Julian – University of Oxford
Barcelo Seron, Carlos – Astrophysical Institute of Andalusia
Barranco, Juan – UNAM, Mexico
Bastianelli, Fiorenzo – University of Bologna
Baumgardt, Holger – Universität Bonn
Bazhanov, Vladimir – Australian National University, Canberra
Benedetti, Dario – Perimeter Institute
Ben Geloun, Joseph – National Institute for Theoretical Physics, Stellenbosch
Bentivegna, Eloisa – Louisiana State University
Bernal, Argelia – University Michoacana, Morelia
Bičák, Jiři – Charles University, Prague

Guest Scientists in Potsdam-Golm (2009)

Bishop, Nigel – Rhodes University
Bizon, Piotr – Cracow University
Blaut, Arkadiusz – University of Wroclaw
Blue, Pieter – University of Edinburgh
Blumenhagen, Ralph – MPI für Physik
Bona, Carles – University of the Balearic Islands, Mallorca
Bonzom, Valentin – ENS, Lyon
Botvinnik, Boris – University of Oregon
Boutlokos, Stratos – University of Maryland
Brink, Lars – Chalmers Technical University
Buric, Maja – University of Belgrade

Canizares, Priscilla – University of Barcelona
Caputo, Maria-Cristina – University of Texas
Catino, Giovanni – SISSA, Trieste
Cécere, Mariana Andrea – FAMAF, Cordoba, Argentina
Chatterjee, Ayan – Saha Institute of Nuclear Physics, Kolkata
Chen, Chiang-Mei – National Central University, Taiwan
Chirenti, Cecilia – University of Sao Paulo
Chrusciel, Piotr – Oxford University
Corvino, Giovanni – Parma University
Creighton, Teviet – California Institute of Technology
Creutzig, Thomas – DESY, Hamburg
Cutler, Curt – Jet Propulsion Laboratory, Pasadena

Dahl, Mattias – Royal Institute of Technology, Stockholm
Daskalopoulos, Panagiota – Columbia University
Das, Sudipta – Harish Chandra Research Institute, Allahabad
Del Zanna, Luca – University of Florence
Dey, Anindya – University of Texas at Austin
Dhurandhar, Sanjeev – IUCAA, Pune
Diener, Peter – Louisiana State University
Dönmez, Orhan – Nigde University
Dotti, Gustavo – FAMAF, Cordoba, Argentina
Dowdall, Richard – University of Nottingham
Drummond, James – LAPTH, Annecy
Dumbser, Michael – University of Trento

Ecker, Klaus – Freie Universität, Berlin
Eichmair, Michael – MIT, Cambridge MA
Ellwanger, Ulrich – LPTh, Orsay
Engle, Jonathan – University of Marseille
Espinar, Jose – University of Granada

Finn, Lee Samuel – Pennsylvania State University
Fisher, Mark – Monash University, Australia
Fiziev, Plamen – University of Sofia
Font, Anamaria – UAM, Madrid
Foster, Brendan – University of Oxford
Fox, Daniel – University of Oxford y
Frauendiener, Jörg – University of Otago, New Zealand
Fredenhagen, Klaus – Universität Hamburg
Freund, Peter – University of Chicago
Frolov, Sergey – Trinity College, Dublin

Gabach Clement, Maria E. – University of Cordoba, Argentina
Gair, Jonathan – University of Cambridge, UK
Garcia Parrado, Alfonso – University of Gent
Garecki, Janusz – University of Szczecin
Ghoshal, Debashis – Jawaharlal Nehru University, New Delhi
Giacomazzo, Bruno – University of Maryland
Gielen, Steffen – DAMTP, Cambridge

Guest Scientists in Potsdam-Golm (2009)

Giesel, Kristina – NORDITA, Stockholm
Girelli, Florian – University of Sidney
Glampedakis, Kostas – SISSA, Trieste
Glowna, Frank – Universität Jena
Gondek-Rosinska, Dorota – University of Warsaw University
Gopakumar, Rajesh – Harish Chandra Institute, Allahabad
Gopala Krishna Murty, Kappagantula – Institute of Mathematical Sciences, Chennai
Govindarajan, Tupil Rangachari – Institute of Mathematical Science, Chennai
Grimm, Thomas – Universität Bonn
Gromov, Nikolay – ENS, Paris
Gross, David – University of Santa Barbara
Guerlebeck, Norman – Charles University, Prague
Gurau, Razvan – Perimeter Institute

Hanada, Masanori – Weizmann Institute, Rehovot
Hannam, Mark – Universität Jena
Heinzle, Mark – Institut für Theoretische Physik, Wien
Hellmann, Frank – University of Nottingham
Henneaux, Marc – University of Brussels
Hogan, Craig – Fermilab, University of Chicago
Hoppe, Jens – Royal Institute of Technology, Stockholm
Hossenfelder, Sabine – Nordita, Stockholm

Iazeolla, Carlo – Scuola Normale Superiore, Pisa
Imbimbo, Camillo – University of Genova

Jani, Karan Pankaj – Pennsylvania State University
Jezierski, Jacek – University of Warsaw University

Kandanaarachchi, Sevvandi – Monash University, Australia
Kapouleas, Nikolaos – Brown University, Providence
Kazakov, Vladimir – ENS, Paris
Kelly, Bernard – Goddard Space Flight Center
Kennedy, Gareth – University of Barcelona
Khalatnikov, Isaak – Landau Institute for Theoretical Physics, Moscow
Kiefer, Claus – Universität Köln
Kleinschmidt, Axel – University of Brussels
Klimenko, Sergey – University of Florida
Klioner, Sergei – Technische Universität, Dresden
Kluson, Josef – Masaryk University, Brno
Knippel, Bettina – Universität Frankfurt
Kofron, David – Charles University, Prague
Konechny, Anatoly – University of Edinburgh
Korobkin, Oleg – Louisiana State University
Kostov, Ivan – CEA, Saclay
Kotikov, Anatoly – Joint Institute for Nuclear Research, Dubna
Kouchner, Antoine – APC, University Paris 7
Kowalska, Izabela – University of Warsaw University
Kowalski-Glikman, Jerzy – University of Wroclaw
Ko, Yumi – Sogang University, Seoul
Krolak, Andrzej – Academy of Sciences, Warsaw
Kroyter, Michael – Tel Aviv University
Kubiznak, David – DAMTP Cambridge

Landis, Tyler – Louisiana State University
Lavrelashvili, George – A. Razmadze Mathematical Institute, Tbilisi
Lee, Ho – Seoul National University
Lessel, Bernadette – Universität Marburg
Leung, Conan – University of Hongkong
Leurent, Sebastian – ENS, Paris
Liebendörfer, Matthias – Universität Basel
Lindblad, Hans – University of California, San Diego

Guest Scientists in Potsdam-Golm (2009)

Lipatov, Lev – Universität Hamburg
Livine, Etera – ENS, Lyon
Löffler, Frank – Louisiana State University
Lopez, Francisco – Astrophysical Institute, Granada
Lousto, Carlos – University of Rochester
Lukierski, Jerzy – University of Wroclaw
Lukowski, Tomasz – Jagellonian University, Krakow
Lüst, Dieter – MPI für Physik, München

Ma, Yongge – Beijing Normal University
Machado, Pedro – Utrecht University
Madore, John – University of Paris (South)
Magro, Marc – ENS, Lyon
Mandel, Ilya – Northwestern University
Martin-Benito, Mercedes – Institute of structure of the matter, Madrid
Martins, Marcio – University of Sao Carlos, Brazil
Matsuura, So – Jagellonian University, Krakow
Mazzeo, Rafe – Stoney Brook University
Meissner, Krzysztof – University of Warsaw University
Minasian, Ruben – CEA, Saclay
Miskovic, Olivera – Catholic University of Valparaiso, Chile
Moncrief, Vincent – Yale University
Musco, Ilia – University of Oslo

Nastase, Horatiu – Global Edge Institute, Tokyo
Neilsen, David – Brigham Young University, Provo
Newman, Ezra Ted – University of Pittsburgh
Nicolini, Piero – University of Trieste

Obukhov, Yuri – Moscow State University
Olea, Rodrigo – University of Valparaiso
Oliynyk, Todd – Monash University, Australia
Ooguri, Hirosi – California Institute of Technology
Oz, Yaron – Tel Aviv University

Palmkvist, Jakob – University of Brussels
Panosso Macedo, Rodrigo – University of Sao Paulo
Parameswaran, Ajith – California Institute of Technology
Parisi, Florencia – FAMAF, Cordoba, Argentina
Pawellek, Michael – Universität Nürnberg-Erlangen
Penrose, Roger – University of Oxford, UK
Perelomov, Askold – ITEP, Moscow
Perez, Alfredo – University of Concepcion, Chile
Plefka, Jan – Humboldt-Universität, Berlin
Pollney, Denis – Universitat de les Illes Balears, Mallorca
Porter, Edward – APC, University Paris 7
Prabhu, Kartik – Indian Institute of Technology, Kharagpur
Premont-Schwarz, Isabeau – Perimeter Institute
Preto, Miguel – Astronomisches Recheninstitut, Heidelberg

Quella, Thomas – University of Amsterdam
Quintavalle, Sara – University of Camerino

Rabinovici, Eliezer – The Hebrew University, Jerusalem
Racioppi, Antonio – University of Rome
Rangamani, Mukund – Durham University
Reisenberger, Michael – University of the Republic, Montevideo
Rej, Adam – Imperial College, London
Reula, Oscar – University of Cordoba, Argentina
Rey, Soo-Jong – Seoul National University
Ringström, Hans – Royal Institute of Technology, Stockholm
Rodriguez, Maria – University of Barcelona

Guest Scientists in Potsdam-Golm (2009)

Rosquist, Kjell – Stockholm University
Rostworowski, Andrzej – Cracow University

Sadoyan, Avetis Abel – Yerevan State University
Saez, Mariel – Catholic University of Chile
Sakovich, Anna – Royal Institute of Technology, Stockholm
Schikorra, Armin – RWTH, Aachen
Schmidt, Bernd – München
Schnetter, Erik – Louisiana State University
Schödel, Rainer – Astrophysical Institute of Andalusia
Scholtz, Martin – Charles University, Prague
Schrörs, Bernd – University of Edinburgh, UK
Schubert, Christian – University Michoacana, Morelia
Schwartz, Fernando – University of Warwick
Schwimmer, Adam – Weizmann Institute, Rehovot
Sedrakian, Armen – Universität Tübingen
Sekiguchi, Yuichiro – National Astronomical Observatory Tokyo
Serban, Didina – CEA, Saclay
Shaposhnikov, Mikhail – EPFL, Lausanne
Sinestrari, Carlo – University of Rome II
Skinner, David – Mathematical Institute, Oxford
Smilga, Andrei – University of Nantes
Sonnenschein, Jacob – Tel Aviv University
Sopuerta, Carlos – Institute of Space Sciences, Barcelona
Steinacker, Harold – Universität München
Steinhoff, Jan – Universität Jena
Stelle, Kellogg – Imperial College, London
Sudarsky, Daniel – UNAM, Mexico
Suszek, Rafal – King's College, London
Svedberg, Christopher – Royal Institute of Technology, Stockholm

Teryaev, Oleg – Joint Institute for Nuclear research, Dubna
Then, Holger – Universität Oldenburg
Thornburg, Jonathan – Indiana University
Tod, Paul – Oxford University
Tomàs Bayo, Ricard – Universität Hamburg
Trzetrzelewski, Maciej – Cracow University
Tseytlin, Arkady – Imperial College, London

Valenzuela, Mauricio – University of Tours
Valiente Kroon, Juan Antonio – Queen Mary College, London
van Putten, Maurice – Massachusetts Institute of Technology
Vardarajan, Suneeta – University of Alberta, Canada
Villani, Cedric – ENS, Lyon
Villan, Loic – Oberservatory Paris_Meudon
Volin, Dmytro – CEA, Saclay

Weinfurtner, Silke – University of British Columbia
Weyher, Christina – Max Planck Digital Library
Wheeler, Glen – University of Wollongong, Australia
Winicour, Jeffrey – University of Pittsburgh
Wise, Derek – University of California, Davis

Yankielowicz, Shimon – Tel Aviv University
Yildirim, Erkan – University College, London

Zanotti, Olindo – University of Notre Dame, Indiana
Zink, Burkard – Louisiana State University
Zschoche, Jan – Universität Jena
Zumbusch, Gerhard – Universität Jena

Guest Scientists in Hannover (2008)

Blaut, Arkadiusz – University of Wroclaw
Bork, Rolf – California Institute of Technology
Bose, Sukanta – Washington State University
Breitbart, Jens – Universität Kassel
Buonanno, Alessandra – University of Maryland

Chelkowski, Simon – University of Birmingham
Cordes, James – Cornell University
Creighton, Jean – University of Wisconsin, Milwaukee
Creighton, Jolien – University of Wisconsin, Milwaukee

d'Arcio, Luigi – Leiden Observatory
Danilishin, Stefan – Moscow State University
de Salvo, Riccardo – California Institute of Technology

Fairhurst, Stephen – Cardiff University
Ferraioli, Luigi – University of Trento
Frede, Maik – Laserzentrum Hannover

Giampanis, Stefanos – University of Rochester
Gopakumar, Achamveedu – Universität Jena
Große, Nicolai – Australian National University
Grynagier, Adrien – IFR, Stuttgart

Hogan, Craig – Fermilab
Hueller, Mauro – University of Trento

Khalili, Farid Yavdatovich – Moscow State University
Kiesel, Thomas – Universität Rostock
Klimenko, Sergey – University of Florida
Kondrashov, Ivan Sergeevich – Moscow State University
Koranda, Scott – University of Wisconsin, Milwaukee
Korpela, Eric – University of California, Berkeley
Krolak, Andre – Polish Academy of Sciences

Leong, Jonathan – Case Western Research University

Marecki, Piotr – Universität Leipzig
Mattioli, Andrea – University of Trento

Pareja, Maria Jesus – Universität Tübingen
Pitkin, Matthew – University of Glasgow
Puncken, Oliver – Laserzentrum Hannover

Robinson, Emma – University of Birmingham
Romano, Joe – Stanford University

Salconi, Livio – European Gravitational Observatory
Salemi, Francesco – University of Trento
Schulz, Bastian – Laserzentrum Hannover
Siemens, Xavier – University of Wisconsin, Milwaukee
Sigg, Daniel – California Institute of Technology
Simakov, Dimitry Andreevich – Moscow State University

Tateo, Nicola – University of Trento
Tessmer, Manuel – Universität Jena
Thorne, Keith – Pennsylvania State University

Ung-Dai, Ko – University of Texas, Austin

van den Broek, Chris – Cardiff University
Veitch, John – University of Birmingham

Guest Scientists in Hannover (2008)

Veltkamp, Christian – Laserzentrum Hannover
Vogel, Werner – Universität Rostock

Wette, Karl – Australian National University
Whelan, John T. – Rochester Institute of Technology
Wiele, Stephanie – University of Texas, Austin
Winkelmann, Lutz – Laserzentrum Hannover

Yamamoto, Kazuhiro – National Astronomical Observatory of Japan

Guest Scientists in Hannover (2009)

Ackley, Kendall – University of Florida, Gainesville
Anderson, Malcolm – University of Brunei, Darussalam
Audley, Heather – University of Birmingham
Aylott, Ben – University of Birmingham

Bachem, Eberhard – Deutsches Zentrum für Luft- und Raumfahrt
Barlage, Bernhard – EADS Astrium
Bartos, Imre – Columbia University
Bell, Angus – University of Glasgow
Bojowald, Martin – Pennsylvania State University
Bork, Rolf – California Institute of Technology
Bose, Sukanta – Washington State University
Brady, Patrick – University of Wisconsin, Milwaukee
Brand, Uwe – Physikalisch-Technische Bundesanstalt Braunschweig

Cesa, Marco – ESA-Estec
Chelkowski, Simon – University of Birmingham
Colas, Jaques – European Gravitational Observatory
Corsi, Alessandra – University of Rome "La Sapienza"
Creighton, Teviet – University of Texas, Brownsville
Cutler, Curt – Jet Propulsion Laboratory

Dhurandhar, Sanjeev – Inter-University Centre for Astronomy and Astrophysics, Pune
Diaz Aguilo, Marc – Polytechnic University of Catalonia

Ehret, Klaus – DESY, Hamburg

Fidecaro, Francesco – European Gravitational Observatory
Flury, Jakob – Leibniz Universität Hannover
Frede, Maik – Laserzentrum Hannover
Freise, Andreas – University of Birmingham

Genzel, Reinhard – University of California, Berkeley
Gerardi, Domenico – EADS Astrium
Ghazaryan, Samuel – DESY, Hamburg
Ghosh, Shaon – Washington State University
Gianolio, Alberto – ESA
Goeklue, Ertan – ZARM, Bremen
Grynagier, Adrien – IFR, Stuttgart
Guangyu, Li – Purple Mountain Observatory
Gusev, Yuri – Simon Fraser University

Hallam, Jonathan – University of Birmingham
Hammer, David – University of Wisconsin, Milwaukee
Harry, Ian – School of Physics and Astronomy, Cardiff
He, Chi – Technische Universität München
Hechenblaikner, Gerald – EADS Astrium
Hild, Stefan – University of Birmingham

Guest Scientists in Hannover (2009)

Hogan, Craig – Fermilab
Hough, James – University of Glasgow

Jackson, Mark – Fermilab
Jennrich, Oliver – ESA
Johann, Ulrich – EADS Astrium

Kalogera, Vicky – Dearborn Observatory
Katsanevas, Stavros – CNRS/IN2P3, Paris
Khanna, Gaurav – University of Massachusetts
Kiesel, Thomas – Universität Rostock
Kim, Chunglee – Lund Observatory
Klimenko, Sergey – University of Florida
Knabbe, Ernst-Axel – DESY, Hamburg
Koranda, Scott – University of Wisconsin, Milwaukee
Korobkin, Oleg – Louisiana State University
Kramer, Michael – MPI für Radioastronomie
Krolak, Andrzej – Polish Academy of Sciences

Lämmerzahl, Claus – ZARM, Bremen
Langellier, Nicholas – University of Florida, Gainesville
Lau, Yun-Kau – Academy of Mathematics and System Science, Beijing
Lindner, Axel – DESY, Hamburg
Lommen, Andrea – Franklin & Marshall College, Lancaster
Lorek, Dennis – ZARM, Bremen
Lützow-Wentzky, Peter – EADS Astrium

Mammut, Letizia – University of Melbourne
Márka, Szabolcs – Columbia University
Márka, Zsuzsanna A. – Columbia University
Mattioli, Andrea – University of Trento

Nesterov, Vladimir – Physikalisch-Technische Bundesanstalt, Braunschweig
Numata, Kenji – NASA Goddard Space Flight Center

Ottewill, Adrian – University College Dublin
Owen, Benjamin – Pennsylvania State University

Patel, Pinkesh – California Institute of Technology
Pinead, Carlos Francisco – Universität Potsdam
Plagnol, Eric – University Paris 7
Porter, Edward – University Paris 7
Pulido Patón, Antonio – Purple Mountain Observatory
Puncken, Oliver – Laserzentrum Hannover

Quetschke, Volker – University of Texas, Brownsville

Ransom, Scott – National Radio Astronomy Observatory
Reagor, Matthew – University of Florida, Gainesville
Rollins, Jameson – Columbia University
Rowan, Sheila – University of Glasgow

Savage, Rick – California Institute of Technology
Schulz, Bastian – Laserzentrum Hannover
Shankaranarayanan, Subramaniam – University of Portsmouth
Shawhan, Peter – University of Maryland
Siemens, Xavier – University of Wisconsin, Milwaukee
Sneeuw, Nico – Universität Stuttgart
Somiya, Kentaro – California Institute of Technology
Sperling, Jan – Universität Rostock
Stergioulas, Nikolaos – Aristotle University of Thessaloniki
Sutton, Patrick – Cardiff University

Guest Scientists in Hannover (2009)

Tarabrin, Sergey – Moscow State University
Tateo, Nicola – University of Trento
Thorpe, James Ira – Goddard Space Flight Center

van Haasteren, Rutger – University of Leiden
Veltkamp, Christian – Laserzentrum Hannover
Vitale, Stefano – University of Trento
Vogel, Werner – Universität Rostock
Vollmer, Günther – EADS Astrium

Wand, Vinzenz – EADS Astrium
Wang, Yan – Nanjing University
Ward, Harry – University of Glasgow
Weise, Dennis – EADS Astrium
Weßels, Peter – Laserzentrum Hannover
Winkelmann, Lutz – Laserzentrum Hannover
Woan, Graham – University of Glasgow

Yamamoto, Kazuhiro – National Astronomical Observatory of Japan

Zadrozny, Adam – Andrzej Soltan Institute for Nuclear Studies

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B. Abbott, The LIGO Scientific Collaboration, "Beating the spin-down limit on gravitational wave emission from the Crab pulsar", Astrophysical Journal Letters 683 (1), L45-L49 (2008). http://iopscience.iop.org/1538-4357/683/1/L45

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Tomomi Akutsu, Masaki Ando, Tomiyoshi Haruyama, Nobuyuki Kanda, Kazuaki Kuroda, Sinji Miyoki, Masatake Ohashi, Yoshio Saito, Nobuaki Sato, Takakazu Shintomi, Toshikazu Suzuki, Hideyuki Tagoshi, Hirotaka Takahashi, Daisuke Tatsumi, Souichi Telada, Takayuki Tomaru, Takashi Uchiyama, Akira Yamamoto, and Kazuhiro Yamamoto, "Search for continuous gravitational waves from PSR J0835-4510 using CLIO data", in Classical and Quantum Gravity, (2008), Vol. 25.

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Hidden symmetries and the wave equation on Kerr
CADS IV, Nahariya, Israel

Andersson, L. / 04 June 2009
Hidden symmetries and decay for waves on Kerr
CQG Scientific Meeting, London, UK

Andersson, L. / 21 July 2009
Hidden symmetries and the wave equation on Kerr
Lorentzian geometry, Greifswald, Germany

Andersson, L. / 04 November 2009
Hidden symmetries and linear fields on Kerr
Mathematical methods in general relativity and quantum field theories

Arnlind, J. / 14 June 2008
Representation Theory for C-algebras of Spheres and Tori via Graphs and Dynamical Systems
Algebraic and Geometric Aspects of Lie Algebras, Mulhouse, France

Arnlind, J. / 17 November 2008
Representation Theory of C-algebras for Spheres and Tori
Nordic - Oresund Symposium INANGA, Lund, Sweden

Aufmuth, P. / 16 May 2008
Empfang von Gravitationswellen mit Laserinterferometern
Symposium "Ultrapräzisionsmessungen" der Deutschen Gesellschaft für angewandte Optik, Esslingen, Germany

Aufmuth, P. / 30 July 2009
Gravitationswellen - Die Zukunft der Astronomie
8. Internationale Astronomiewoche, Arosa, Switzerland

Aulbert, C. / 17 June 2008
Atlas - How to build a top100/fastest purely ethernet based cluster with good price to performance ratio
ISC 2008, Dresden, Germany

Baratin, A. / 05 March 2008
Spin foam structures for field theory
Workshop "Loops and foams 08", Zakopane, Poland

Invited Conference Talks given by AEI members

Baratin, A. / 19 September 2009
2-Groups Representations for Spin Foams
2nd School and Workshop on Quantum Gravity and Geometry, European Institute for Sciences and their Applications, Corfu, Greece

Beisert, N. / 03 January 2008
The Worldsheet S-Matrix of Planar N=4 Gauge Theory
German-Japanese Workshop "Strings, Non-Commutativity and all that", Hannover, Germany

Beisert, N. / 19 March 2008
Integrability in N=4 SYM
"30 Years of Mathematical Methods in High Energy Physics", RIMS, Kyoto, Japan

Beisert, N. / 10 April 2008
Integrability in AdS/CFT, the Hubbard Model and Quantum Algebra
ICFT08, Edinburgh, UK

Beisert, N. / 22 April 2008
Algebraic Aspects of AdS/CFT Integrability
"Non-Perturbative Methods in Strongly Coupled Gauge Theories", GGI, Firenze, Italy

Beisert, N. / 18 June 2008
The Classical Worldsheet Scattering Matrix of AdS/CFT
Cinquantenaire de l IHES, Bures-sur-Yvette, France

Beisert, N. / 25 June 2008
Wonderful Conjectures on Planar N=4 Gauge Theory
"Wonders of Gauge theory and Supergravity", Saclay IPhT, France

Beisert, N. / 11 August 2008
Boosting Nearest-Neighbour to Long-Range Integrable Spin Chains
Integrability in Gauge and String Theory 08, Utrecht, Netherlands

Beisert, N. / 14 September 2008
Integrability in the AdS/CFT Correspondence
RTN Forces Universe Workshop, Varna, Bulgaria

Beisert, N. / 10 November 2008
Fermionic T-Duality, Dual Superconformal Symmetry and Integrability in AdS5xS5
"Workshop on Applied 2d Sigma Models", DESY Hamburg, Germany

Beisert, N. / 17 February 2009
Dual (Super) Conformal Symmetry and Integrability in AdS5xS5
Workshop Fundamental Aspects of Superstring Theory, Kavli Institute for Theoretical Physics, University of California, Santa Barbara, USA

Beisert, N. / 02 April 2009
Integrability in Perturbative N=4 SYM
International Workshop on Gauge and String Amplitudes, Durham University, UK

Beisert, N. / 23 April 2009
AdS/CFT Integrability: Spacetime Scattering Amplitudes
Workshop "New Perspectives in String Theory", GGI Firenze, Italy

Beisert, N. / 18 May 2009
Dynamic N=4 Superconformal Symmetry
4th International Sakharov Conference, Lebedev Institute Moscow, Russia

Beisert, N. / 21 July 2009
Dynamic N=4 Superconformal Symmetry
6th International Symposium on Quantum Theory and Symmetries, University of Kentucky, USA

Invited Conference Talks given by AEI members

Beisert, N. / 21 August 2009
Dynamic N=4 Superconformal Symmetry
33rd Johns Hopkins Workshop on Maximal Supersymmetry, Göteborg, Sweden

Beisert, N. / 23 September 2009
Symmetries for Local Operators and Scattering Amplitudes in N=4 SYM
Workshop A New Year of String Theory, Tel Aviv, Israel

Blatt, S. / 16 September 2008
Higher Dimensional Nontrivial Knots are not flat
DMV Tagung, Erlangen, Germany

Calcagni, G. / 06 November 2009
Horava-Lifshitz gravity: Whats the matter?
Perimeter Institute, Waterloo, Canada

Cederbaum, C. / 04 November 2009
The Newtonian limit of static vacuum general relativity
Workshop "Equations of motion", AEI Potsdam, Germany

Danzmann, K. / 19 February 2008
Der Klang des Universums
EMV 2008, Düsseldorf, Germany

Danzmann, K. / 05 March 2008
Multiwave Length Gravitational Wave Astronomy: A dream will soon be reality
DPG Frühjahrstagung 2008, Freiburg, Germany

Danzmann, K. / 13 June 2008
LISA und LISA Pathfinder
Symposium Grundlagenforschung im Weltraum, Munich, Germany

Danzmann, K. / 16 June 2008
The status of LISA
7th International LISA Symposium, Barcelona, Spain

Danzmann, K. / 07 July 2008
Listening to the universerse with gravitational waves
Quantum to Cosmos II, Washington, USA

Danzmann, K. / 15 October 2008
Laserinterferometry in Space
International Conference on Space Optics, Toulouse, France

Danzmann, K. / 12 November 2008
LISA: The science and the mission
1st LISA DECIGO Symposium, Tokyo, Japan

Danzmann, K. / 21 June 2009
Space Antennas and their science reach
8th Eduardo Amaldi Meeting, New York, USA

Danzmann, K. / 21 July 2009
Listening to the Universe
EPS-HEPS Symposium, Krakau, Poland

Danzmann, K. / 21 September 2009
Gravitational Wave Detection in Space
Quantum to Cosmos IV, Bremen, Germany

Di Palma, I. / 26 November 2009
Search for GW Bursts associated with GRBs using LIGO and Virgo
Antares Collaboration Meeting, Gandia, Spain

Invited Conference Talks given by AEI members

Dittrich, B. / 03 August 2009
Diffeomorphism symmetry and discreteness in quantum gravity
International Conference on Quantum Gravity, Loops 09, Beijing, China

Dittrich, B. / 28 August 2009
The fate of diffeomorphism symmetry in quantum gravity models
Conference Emergent Gravity IV, Vancouver, Canada

Drasco, S. / 10 November 2009
How well can LISA observe EMRIs?
LISA-France meeting, Centre Universitaire Méditerranéen, Nice, France

Drasco, S. / 14 December 2009
Parameter estimation errors for radiating binaries with non-trival mass ratios
Stars and Singularities Workshop, Weizmann Institute of Science, Rehovot, Israel

Fehrmann, H. / 17 June 2008
Atlas - How to build a top100/fastest purely ethernet based cluster with good price to performance ratio
ISC 2008, Dresden, Germany

Forini, V. / 12 December 2008
Reciprocity in AdS/CFT
FRIF workshop N = 4 SUSY and QCD, LPTHE Jussieu, Paris, France

Forini, V. / 18 May 2009
Reciprocity in AdS/CFT
4th International Sakharov Conference, Lebedev Institute Moscow, Russia

Fredenhagen, S. / 10 April 2008
D-branes and matrix factorisations in coset models
Workshop "String theory: From theory to experiment", Jerusalem, Israel

Fredenhagen, S. / 13 May 2008
Matrix factorisations in supersymmetric coset models
Workshop "Matrix factorizations in physics and mathematics", Banff, Canada

Fredenhagen, S. / 10 September 2008
Branes and matrix factorisations in coset models
39th International Symposium Ahrenshoop, Wernsdorf, Germany

Fredenhagen, S. / 30 November 2009
Boundaries and defects in perturbed minimal models
Workshop "Interfaces and Wall-crossings", Munich, Germany

Friedrich, H. / 12 April 2008
One-parameter families of conformally related, asymptotically flat, static vacuum data
"Mathematical Aspects of General Relativity", Niels Bohr International Academy, Copenhagen, Denmark

Friedrich, H. / 19 June 2008
The initial boundary value problem for Einstein's field equations and geometric uniqueness
"Hyperbolic equations in relativity", Mathematical Institute of Bordeaux, France

Friedrich, H. / 20 August 2008
The initial boundary value problem for Einstein's field equations and geometric uniqueness
Conference "Developments in Mathematical Relativity", ESI, Wien, Austria

Friedrich, H. / 25 August 2008
Regularity at null infinity and asymptotic staticity
Conference "Geometry and Analysis", KTH Stockholm, Sweden

Friedrich, H. / 08 September 2008
Global structure of spacetime in general relativity
414. WE-Heraeus-Seminar, Bad Honnef, Germany

Invited Conference Talks given by AEI members

Friedrich, H. / 14 April 2009
Initial boundary value problems for Einstein's field equations and geometric uniqueness
Grav09, Cordoba, Argentina

Grote, H. / 16 March 2009
GEO600 status
LSC-Virgo meeting, Pasadena, USA

Grote, H. / 23 June 2009
The Status of GEO600
8. Amaldi Conference, New York, USA

Grote, H. / 21 September 2009
GEO600 Status
LIGO-Virgo meeting, Budapest, Hungary

Head, J. / 19 March 2009
Mean Curvature Flow with Surgery
Workshop on non-linear analysis, ANU, Canberra, Canada

Head, J. / 16 October 2009
Mean Curvature Flow with Surgery
AMS Sectional Meeting, Baylor University, Texas, USA

Heinzel, G. / 16 April 2008
LTP: The LISA Technology Package aboard LISA Pathfinder
6th DECIGO workshop, Tokyo, Japan

Heinzel, G. / 22 May 2008
Interferometric measurement of Drag-Free proof masses in LISA Pathfinder
Satellite Dynamics Modelling, Calibration, Processing Conference, ZARM, Bremen, Germany

Heinzel, G. / 19 June 2008
LISA interferometry breadboarding
6th LISA Symposium, Barcelona, Spain

Heinzel, G. / 16 July 2008
LISA breadboarding at AEI Hannover
COSPAR Scientific Assembly, Montreal, Canada

Heinzel, G. / 27 October 2008
LISA technology for gravity field missions
Xiangshan meeting on future gravity missions, Beijing, China

Heinzel, G. / 12 November 2008
The LISA Pathfinder Interferometer
International LISA-DECIGO workshop, Sagamihara, Tokyo, Japan

Heinzel, G. / 08 January 2009
Update on AEI activities
LISA Science team meeting, Pasadena, USA

Heinzel, G. / 30 September 2009
LISA technology for gravity field missions
Workshop on Future Satellite Gravity Missions, Graz, Austria

Hennig, J. / 16 July 2009
Non-existence of stationary two-black-hole configurations
12th Marcel Grossmann Meeting, Paris, France

Henning, H. V. / 10 August 2009
Squeezed Light For Gravitational Wave Astronomy
Amaldi conference, New York, USA

Invited Conference Talks given by AEI members

Hinder, I. / 06 July 2009
Binary Black Hole Simulations in Numerical Relativity
Numerical Relativity and Data Analysis conference, AEI Potsdam, Germany

Huisken, G. / 06 March 2008
An isoperimetric concept for the mass and energy of isolated systems
DFG -Frühjahrstagung, Freiburg, Germany

Huisken, G. / 02 May 2008
Isoperimetric inequalities and the mass in general relativity
The seventh conference on Geometry and Topology, Harvard University, Cambridge, USA

Huisken, G. / 24 June 2008
Isoperimetric inequalities and Willmore energy
Ricci flow and related topics, IHP, Paris, France

Huisken, G. / 28 August 2008
The isoperimetric inequality in General Relativity
KTH Stockholm, Sweden

Huisken, G. H. / 31 August 2008
Curvature inequalities via geometric evolution equations
Harvard University, Cambridge, USA

Huisken, G. / 08 September 2008
A sharp lower bound for the integral of mean curvature on closed hypersurfaces
Workshop Global Analysis on Manifolds, Rome University, Italy

Huisken, G. H. / 25 September 2008
New estimates for mean curvature flow with surgery
Yamabe Symposium, University of Minnesota, USA

Huisken, G. / 25 November 2008
Mean curvature flow, inverse
Workshop on Field Theory and Geometric Flows, Ludwig Maximilians Universität, Munich, Germany

Huisken, G. / 18 November 2009
Monotonicity and Rigidity Estimates for the Evolution of Hypersurfaces
Workshop on GR, Simons Center for Geometry and Physics, Stony Brook State University of New York, USA

Krishnan, B. / 09 January 2008
Using numerical relativity waveforms is gravitational wave searches
Miniprogram: Interplay between Numerical Relativity and Data Analysis, Kavli Institute for Theoretical Physics, University of California, Santa Barbara, USA

Lück, H. / 17 June 2008
ET (Einstein GW Telescope) and the European ground based GW detector road map
Astronet Symposium, Liverpool, UK

Lück, H. L. / 07 October 2009
Interferometrische Messverfahren zum Nachweis von Gravitationswellen
Lehrer Herbstakademie, Leibniz Universität Hannover, Germany

Lück, H. L. / 04 December 2009
Science with gravitational-wave detectors
12th Dutch Astroparticle Physics Symposium, Amsterdam Science Park, Netherlands

Mafra, C. R. / 14 August 2009
Pure Spinor Superspace and Superstring Scattering Amplitudes
Workshop "Hidden Structures in Field Theory Amplitudes 2009", Niels Bohr International Academy, Copenhagen, Denmark

Metzger, J. / 08 July 2008
Foliations of asymptotically flat manifolds by surfaces of Willmore type
Calculus of Variations, Oberwolfach, Germany

Invited Conference Talks given by AEI members

Metzger, J. / 27 August 2008
Marginally outer trapped surfaces and apparent horizons
Geometry, Analysis and General Relativity meeting in Stockholm, Sweden

Metzger, J. / 18 September 2009
Foliations of asymptotically flat manifolds by surfaces of Willmore type
Workshop "Variational Problems of higher Order", Berlin, Germany

Nicolai, H. / 31 January 2008
Quantum gravity: challenges and perspectives
Southern African Relativity Society Conference, Cape Town, South Africa

Nicolai, H. / 07 April 2008
Canonical constraints and the E10/K(E10) sigma model
String Theory: from Theory to Experiment, IAS, Hebrew University, Jerusalem, Israel

Nicolai, H. / 25 April 2008
Low energy supersymmetry: to be or not to be?
KellyFest, Imperial College, London, UK

Nicolai, H. / 20 June 2008
Hyperbolic Weyl groups, the four division algebras, and new modular groups
50th Anniversary Conference, I.H.E.S., Bures-sur-Yvette, France

Nicolai, H. / 23 June 2008
Wonders of E10 and KE10
Wonders of Gauge Theory and Supergravity, Paris, France

Nicolai, H. / 11 September 2008
Space-time, singularities and symmetries
"Space and time 100 years after Minkowski", Physikzentrum Bad Honnef, Germany

Nicolai, H. / 22 September 2008
Quantum phenomena and gravity
"Foundations of Quantum Physics", Physikzentrum Bad Honnef, Germany

Nicolai, H. / 26 September 2008
Divsion algebras and hyperbolic Weyl groups as modular groups
Superstrings@Cyprus, Ayia Napa, Cyprus

Nicolai, H. / 06 December 2008
The E10/K(E10) sigma model: searching for a fundamental symmetry of physics
Supersymmetry and Noncommutative Quantum Field Theory: Workshop in Honour of Julius Wess, ESI, Vienna, Austria

Nicolai, H. / 15 May 2009
Cosmological singularities, higher order corrections, and the hyperbolic algebra E10
Solvay Workshop "Cosmological frontiers in fundamental physics", Brussels, Belgium

Nicolai, H. / 29 June 2009
Conformal standard model and the Planck scale
"The Planck Scale", Wroclaw, Poland

Nicolai, H. / 13 August 2009
The hyperbolic algebra E10: searching for a fundamental symmetry of space-time-matter
"Foundations of space and time: reflections on quantum gravity", Cape Town, South Africa

Nicolai, H. / 14 September 2009
Hidden symmetries: from Grassmann to maximal (N=8) supergravity
Grassmannian Conference in Fundamental Cosmology, Szczecin, Poland

Nicolai, H. / 17 September 2009
Quantum Gravity
XXX Encontro Nacional de Fisica, Passo Quatro, Brasil

Invited Conference Talks given by AEI members

Norton, A. H. / 04 November 2009
On the use of mass renormalization in calculating the self-force on a radiating system
Workshop "Equations of Motion", AEI Potsdam, Germany

Oriti, D. / 30 March 2009
Group field theories: some recent results
"Algebraic and combinatorial methods in quantum field theory" conference, Cargese, France

Oriti, D. / 02 July 2009
The group field theory approach to quantum gravity: some recent results
"XXV Max Born symposium: The Planck Scale", Wroclaw, Poland

Oriti, D. / 10 July 2009
The group field theory approach to quantum gravity: a QFT for the microstructure of spacetime
2nd FQXi international conference, Ponta Delgada, Azores, Portugal

Oriti, D. / 03 August 2009
Group field theory for Quantum Gravity
"Loops 09" conference, Beijing Normal University, Beijing, China

Oriti, D. / 10 August 2009
Group field theory: a candidate description of the atoms of space
George Ellis Fest "Foundations of Space and Time", Stellenbosch, South Africa of Space and Time",
Stellenbosch Institute for Advanced Studies, South Africa

Oriti, D. / 26 August 2009
Group field theory: microscopics of quantum space and emergent (non-commutative) matter
"Emergent Gravity IV" conference, University of British Columbia, Vancouver, Canada

Petiteau, A. / 09 November 2009
Spinning black hole binaries in LISA data Analysis
LISA France 2009, Nice, France

Read, J. S. / 25 March 2009
Physics from binary neutron star coalescences.
Einstein Telescope Working Group 4 Meeting

Rendall, A. D. / 07 April 2008
The interface between mathematics and astrophysics in the study of cosmic acceleration
Conference at Niels Bohr Institute, Copenhagen, Denmark

Rendall, A. D. / 16 June 2008
Loss of regularity in solutions of the Einstein-Euler system
Conference "Hyperbolic equations in relativity", Bordeaux, France

Rendall, A. D. / 26 August 2008
Cosmological perturbation theory
Conference "Geometry and Analysis", KTH Stockholm, Sweden

Rendall, A. D. / 02 April 2009
Cosmic censorship: an introduction and status report
University of Edinburgh, UK

Rendall, A. D. / 18 June 2009
Dynamics of linearized cosmological perturbations
Conference "Mathematical Relativity", Lisbon, Portugal

Rendall, A. D. / 21 July 2009
The Einstein-Maxwell equations and the complex hyperbolic plane
Summer Academy Lorentzian Geometry, Greifswald, Germany

Invited Conference Talks given by AEI members

Rendall, A. D. / 14 September 2009
The characteristic initial value problem in general relativity
Conference "Hot Topics: Black Holes in Relativity", Mathematical Sciences Research Institute, Berkeley, California, USA

Rendall, A. D. / 05 November 2009
Relations between Gowdy and Bianchi spacetimes
Conference "Mathematical methods in general relativity and quantum field theories", Paris, France

Rezzolla, L. / 01 February 2008
Modelling the merger of binary neutron stars
First Workshop of Compstar, Ladek Zdroj, Poland

Rezzolla, L. / 02 February 2008
On the final spin from binary black hole mergers
LISA@Como, Como, Italy

Rezzolla, L. / 01 March 2008
Numerical modelling of sources of gravitational waves
ILIAS Winter meeting, Hamburg, Germany

Rezzolla, L. / 02 June 2008
Modelling binary neutron stars
7th LISA Symposium, Barcelona, Spain

Rezzolla, L. / 01 September 2008
Dynamics of binary neutron stars
The Modern Physics of Compact Stars, Yerevan, Armenia

Rezzolla, L. / 02 September 2008
Collapse to BHs: equilibrium models and binary systems
Numerical modelling of astrophysical sources of gravitational waves, Valencia, Spain

Rezzolla, L. / 01 November 2008
Binary mergers for ET
ET-ILIAS Meeting, Cascina (PI), Italy

Rezzolla, L. / 02 November 2008
Modelling binaries as sources of gravitational waves
JGRG18, 18th Japanese General Relativity and Gravitation Meeting, Hiroshima, Japan

Rezzolla, L. / 01 February 2009
Predicting the final spin vector from binary black hole mergers
LISA@Paris, Paris, France

Rezzolla, L. / 01 March 2009
On the properties of the final black hole
Observational Signatures of Black hole mergers, Space Telescope Science Inst., Baltimore, USA

Rezzolla, L. / 01 May 2009
Modelling the Inspiral and Merger of Binary Neutron Stars
APS April Meeting 2009, Denver, Colorado, USA

Rezzolla, L. / 01 July 2009
Modelling the final spin and EM counterparts from binary black hole coalescences
Massive Black Hole Binaries and Their Coalescence in Galactic Nuclei, Bejing, China

Rezzolla, L. / 01 August 2009
Simulations of binary neutron stars: results, difficulties and prospects
Microphysics in Computational Relativistic Astrophysics (Micra) 2009, Copenhagen, Denmark

Rezzolla, L. / 01 September 2009
Simulations of binary neutron stars: results, difficulties and prospects
Neutron stars - The crust and beyond, Nordita Stockholm, Sweden

Invited Conference Talks given by AEI members

Rezzolla, L. / 01 October 2009
Modelling the Inspiral and Merger of Binary Neutron Stars: results and difficulties
Computational Relativistic Astrophysics: 2009-2010, Princeton, NJ, USA

Rezzolla, L. / 01 November 2009
What we know about the Inspiral and Merger of Binary Neutron Stars
CoCoNuT meeting 2009, Valencia, Spain

Rezzolla, L. / 01 December 2009
Astrophysics of binary BH mergers: properties of the final BH and EM counterparts
Stars and Singularities, Tel Aviv, Israel

Rodriguez, M. J. / 16 July 2009
On the Black Hole Species (by means of natural selection)
12th Marcel Grossmann Meeting 2009, Paris, France

Roura, A. / 25 June 2009
Analytical results for the master equation of QBM models and their solutions
Peyresq Cosmology Meeting, France

Roura, A. / 21 December 2009
Analytical results for the master equation of QBM models and their solutions
Theoretical Physics Christmas Meeting, University of Barcelona, France

Rüdiger, A. / 22 June 2009
Detecting gravitational waves with Earth-bound laser interferometers
ICGA9 & Summer School, Wuhan, China

Rüdiger, A. / 23 June 2009
Detecting gravitational waves with Earth-bound laser interferometers
ICGA9 & Summer School, Wuhan, China

Rüdiger, A. / 24 June 2009
LISA Pathfinder
ICGA9 & Summer School, Wuhan, China

Rüdiger, A. / 30 June 2009
LISA – Laser Interferometer Space Antenna for gravitational wave detection
ICGA9, Wuhan, China

Rüdiger, A. / 30 June 2009
What we can learn from the LISA Pathfinder
ICGA9, Wuhan, China

Schnabel, R. / 21 February 2008
The SQL and Test Mass Entanglement via Squeezed Light
Gordon Research Conference, Ventura, USA

Schnabel, R. / 16 May 2008
Squeezed Light for GEO600 Upgrade
GWADW, Elba, Italy

Schnabel, R. / 15 September 2008
Efficient Generation of Squeezed Light and its Application for Quantum Optics and Interferometry
EMALI, Niels Bohr Institute, Copenhagen, Denmark

Schnabel, R. / 15 September 2008
Efficient generation of squeezed light and its application for quantum optics and interferometry
QAP EU Integrated Project Workshop, Copenhagen, Denmark

Schnabel, R. / 12 February 2009
Squeezed Quantum Noise
Leibniz Universität Hannover, Germany

Invited Conference Talks given by AEI members

Schnabel, R. / 18 June 2009
Squeezed Light for Gravitational Wave Detection
CLEO Europe-EQEC 2009, Munich, Germany

Schnabel, R. / 19 July 2009
Squeezed Quantum Noise
WE-Heraeus-Seminar on Quantum Optics of Nano- and Micro-Mechanical Systems, Bad Honnef, Germany

Schutz, B. F. / 13 May 2008
Sources of Gravitational Waves for 3G Detectors
Gravitational Wave Advanced Detector Workshop, Elba, Italy

Schutz, B. F. / 19 June 2008
Fundamental Physics with LISA
Seventh International LISA Symposium, Barcelona, Spain

Schutz, B. F. / 07 October 2008
From Classical Theory to Quantum Gravity
Workshop on the Nature of Gravity, ISSI, Bern, Switzerland

Schutz, B. F. / 29 March 2009
Science Frontiers of the World-Wide Gravitational Wave Network
Japanese Physical Society Meeting, Tokyo, Japan

Schutz, B. F. / 29 April 2009
Astrometric and Timing Effects of Gravitational Waves
IAU Symposium 261, Virginia Beach, Virginia, USA

Schutz, B. F. / 27 May 2009
Capabilities of a Gravitational Wave Network
Fujihara Seminar, Tokyo, Japan

Schutz, B. F. / 22 June 2009
Multimessenger and Multiwavelength Gravitational Wave Astronomy
8th Amaldi Meeting, Columbia University, New York, USA

Schutz, B. F. / 11 August 2009
LISA Sources and Science
IUCAA, Pune, India

Schutz, B. F. / 15 October 2009
A Scientist's View of Open Access
Association of Research Libraries Conference, Washington, USA

Schutz, B. F. / 26 October 2009
Enhanced Science from Advanced Detectors in Asia
First Galileo-Xu Guangqi Meeting, Shanghai, China

Schutz, B. F. / 08 November 2009
Mergers Involving Black Holes and Neutron Stars in an ADM Landscape
ADM-50 Meeting, Texas A&M University, USA

Sesana, A. / 08 December 2009
Enhanced tidal disruption rates of bound stars from MBH binaries
Conference "Stars and Singularities The physics of dense cusps around massive black holes", Weizmann Institute, Rehovot, Israel

Smulevici, J. / 17 October 2009
Structure of singularities in cosmological spacetimes with symmetry
Mathematical Aspects of General Relativity, Mathematisches Forschungsinstitut Oberwolfach, Germany

Smulevici, J. / 18 November 2009
Structure of singularities in cosmological spacetimes with symmetry
Institut für Mathematik, Technische Universität Berlin, Germany

Invited Conference Talks given by AEI members

Vahlbruch, H. V. / 10 August 2009
Squeezed Light For Gravitational Wave Astronomy
Amaldi conference, New York, USA

Wanner, A. / 22 April 2008
The 10 Meter Prototype Interferometer
EGC-Seminar, Hannover, Germany

Wanner, A. / 08 December 2009
Seismic Attenuation of the 10 Meter Prototype
EGC Seminar, Hannover, Germany

Lectures and Lecture Series given by AEI members

Arnlind, J. / 23 September 2008
Quantization and L -quasilimits
Lund, Sweden

Arnlind, J. / 04 November 2008
Representation Theory for C -algebras of Spheres and Tori via Graphs and Dynamical Systems
University of Geneva, Switzerland

Arnlind, J. / 10 February 2009
Noncommutative surfaces and graphs
IHES Paris, France

Arnlind, J. / 27 August 2009
Noncommutative algebras related to Poisson structures on the intersection of hypersurfaces
Stockholm University, Sweden

Arnlind, J. / 16 September 2009
Geometry and Topology in the Matrix Regularization of Membrane Theory
Dept. of Physics, KTH Stockholm, Sweden

Aufmuth, P. / 13, 14, 15 October 2008
Gravitationswellen (3 lectures)
Schule für Astroteilchenphysik, Obertrubach-Bärnfels, Germany

Aufmuth, P. / 12 November 2008
An der Schwelle zur Gravitationswellenastronomie
Studium Generale, Universität Marburg, Germany

Aufmuth, P. / 08 December 2008
An der Schwelle zur Gravitationswellenastronomie
Physikalisches Kolloquium, Bergische Universität Wuppertal, Germany

Aufmuth, P. / 28 May 2009
An der Schwelle zur Gravitationswellen-Astronomie
Ringvorlesung zum Internationalen Jahr der Astronomie, Universität Bonn, Germany

Aufmuth, P. / 06 October 2009
Interferometrische Messverfahren zum Nachweis von Gravitationswellen
Herbstakademie für Lehrerinnen und Lehrer, Hannover, Germany

Babak, S. / 31 March 2008
Gravitational Wave Astronomy
Spring course AEI Potsdam, Germany

Beisert, N. / 15 October 2008
Einführung in die Supersymmetrie (winter term 2008/2009)
Humboldt University Berlin, Germany

Lectures and Lecture Series given by AEI members

Danzmann, K. / winter term 2007/2008
Physik I mit Experimenten
Leibniz Universität Hannover, Germany

Danzmann, K. / summer term 2008
Physik II
Leibniz Universität Hannover, Germany

Danzmann, K. / 05 May 2008
Gravitational Wave Astronomy
Max Planck Institute for Quantum Optics, Garching, Germany

Danzmann, K. / 26 August 2008
The history of GEO
AEI Hannover, Germany

Danzmann, K. / 01 October 2008
QUEST: Forschung am Quantenlimit
Leibniz Universität Hannover, Germany

Danzmann, K. / winterterm 2008/2009
Gravitationsphysik
Leibniz Universität Hannover, Germany

Danzmann, K. / 20 November 2008
Listening to the universe with gravitational waves
RWTH Aachen, Germany

Danzmann, K. / 12 January 2009
Research in QUEST, Research Area B
Leibniz Universität Hannover, Germany

Danzmann, K. / 09 March 2009
SFB 407: Brechungsindex Manipulation in atomaren Ensembles
Leibniz Universität Hannover, Germany

Danzmann, K. / 02 April 2009
LISA Technology
AEI Hannover, Germany

Danzmann, K. / summer term 2009
Gravitationsphysik II
Leibniz Universität Hannover, Germany

Danzmann, K. / 28 April 2009
Quantum sensors
QUEST Symposium, Bad Pyrmont, Germany

DiGuglielmo, J. / 12 February 2008
Squeezing and Entanglement at the Albert Einstein Institute
Palacky University, Olomouc, Czech Republic

Drasco, S. / 06 July 2009
Relativity and Gravitational Waves
Fourth International Summer School on Gravitational-Wave Astronomy, Yunnan University, Kunming, China

Drasco, S. / 07 July 2009
Detectors and Sources
Fourth International Summer School on Gravitational-Wave Astronomy, Yunnan University, Kunming, China

Drasco, S. / 19 July 2009
Introduction to Extreme Mass Ratio Inspiral Waveforms
Fourth International Summer School on Gravitational-Wave Astronomy, Yunnan University, Kunming, China

Lectures and Lecture Series given by AEI members

Fredenhagen, S. / 16 April 2008
Einführung in die Stringtheorie
Humboldt University Berlin, Germany

Fredenhagen, S. / 29 September 2008
Conformal Field Theory
String-Steilkurs 2008, AEI Potsdam, Germany

Fredenhagen, S. / 17 April 2009
Einführung in die Stringtheorie
Humboldt University Berlin, Germany

Friedrich, H. / 10 March 2008
Die Grundlagen der Allgemeinen Relativitätstheorie
Frühjahrskurs, AEI

Grigorian, S. / 05 January 2009
Geometry of G2-manifolds
Institute of Mathematical Sciences, Hong Kong, China

Grote, H. / 30 June 2008
Gravitational Wave Detectors
European Graduate College, Paris, France

Heinzel, G. / 01 July 2008
Interferometrie im Weltraum: LISA und LISA Pathfinder
Mathematisch-Physikalisches Kolloquium, Hannover, Germany

Heinzel, G. / 17 June 2009
Physikalische Grenzen der Genauigkeit von GPS und Galileo
Leibniz Universität Hannover, Germany

Heinzel, G. / 28 August 2009
Elektronik für physikalische Experimente
Mardorf, Germany

Heinzel, G. / 03 November 2009
Laserinterferometer auf Satelliten und ihre Anwendung in der Gravitationsphysik
Leibniz Universität Hannover, Germany

Huisken, G. / 18 April 2008
Geometric Variational Problems in General Relativity
Aisenstadt Lectures, CRM Montreal, Canada

Huisken, G. / 21 April 2008
Mean Curvature Flow and Isoperimetric Inequalities
Aisenstadt Lectures, CRM Montreal, Canada

Huisken, G. / 22 April 2008
Inverse Mean Curvature Flow
Aisenstadt Lectures, CRM Montreal, Canada

Huisken, G. / 23 April 2008
An Isoperimetric Concept for the Mass in General Relativity
Aisenstadt Lectures, CRM Montreal, Canada

Huisken, G. / 09 May 2008
Ausgewählte Resultate der Geometrischen Analysis
Universität Tübingen, Germany

Huisken, G. / 14 October 2008
Ricci-Curvature and Geometric Analysis, Differentialgleichungen III
Freie Universität Berlin, Germany

Lectures and Lecture Series given by AEI members

Huisken, G. / 11 December 2008
Mean curvature flow with surgeries
Ritt Lectures, Columbia University, USA

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Inverse mean curvature flow and isoperimetric inequalities
Ritt Lectures, Columbia University, USA

Huisken, G. / 18 March 2009
Mean Curvature Flow with Surgeries
Marston Morse Memorial Lectures, Princeton University, USA

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Inverse mean curvature flow and isoperimetric inequalities
Marston Morse Memorial Lectures, Princeton University, USA

Huisken, G. / 20 March 2009
An isoperimetric concept for the mass in General Relativity
Marston Morse Memorial Lectures, Princeton University, USA

Huisken, G. / 17 April 2009
Partielle Differentialgleichungen II
Universität Tübingen, Germany

Huisken, G. / 08 May 2009
Ricci-Curvature und Geometrie Riemannscher Mannigfaltigkeiten
Universität Tübingen, Germany

Huisken, G. / 06 October 2009
Introduction to Ricci Flow
Freie Universität Berlin, Germany

Huisken, G. / 17 October 2009
Ricci-Curvature und Geometrie Riemannscher Mannigfaltigkeiten
Universität Tübingen, Germany

Huisken, G. / 23 October 2009
Aspekte des Ricci-Flow
Universität Tübingen, Germany

Knispel, B. / 07 May 2008
Einführung in die Astronomie
Volkshochschule Hannover (Kurs in der Volkssternwarte Hannover), Germany

Knispel, B. / 29 October 2008
Einführung in die Himmelsbeobachtung
Volkshochschule Hannover (Kurs in der Volkssternwarte Hannover), Germany

Knispel, B. / 13 May 2009
Einführung in die Astronomie
Volkshochschule Hannover (Kurs in der Volkssternwarte Hannover), Germany

Melnikov, I. / 23 July 2009
Lectures on Stringy Geometry
International Advanced Summer School, Dubna, Russia

Melnikov, I. / 28 September 2009
Lectures on Stringy Geometry
String Steilkurs 2009, AEI Golm, Germany

Mokler, F. / 27 December 2009
LISA – Auf der Suche nach Gravitationswellen
CUSANUS-Stiftung, Gernsheim, Germany

Lectures and Lecture Series given by AEI members

Nicolai, H. / 21, 23, 24 February 2008
Einführung in die Supersymmetrie (5 lectures)
Humboldt Universität, Berlin, Germany

Nicolai, H. / 06 March 2008
Mini-Einführung Supersymmetrie
Leibniz Universität Hannover, Germany

Nicolai, H. / 04 April 2008
Introduction to Kac - Moody algebras
Weizmann Institute, Rehovot, Israel

Nicolai, H. / 02 February 2009
Konforme Invarianz in der Quantenfeldtheorie
Blockkurs, Leibniz Universität Hannover, Germany

Nicolai, H. / 27 July 2009
Introductory quantum gravity
IMPRS Excursion, Bollmannsruh, Germany

Nicolai, H. / 31 August 2009
Infinite dimensional Lie algebras in Physics
Doktorandenschule Saalburg "Foundations and new methods in Theoretical Physics", Wolfersdorf, Germany

Nicolai, H. / 19 September 2009
E10 and M Theory: an introductory survey
IFT, UNESP, Sao Paulo, Brasil

Nicolai, H. / 30 November 2009
Konforme Quantenfeldtheorie (4 lectures)
Leibniz Universität Hannover, Germany

Oriti, D. / 26 July 2009
Group Field Theories and their relation with spin foam models
The BNU International Summer School on Quantum Gravity", Beijing Normal University, Beijing, China

Oriti, D. / 15 October 2009
An introduction to the group field theory approach to quantum gravity
AEI Potsdam, Germany

Puetzfeld, D. / 21 November 2008
The problem of motion and the use of approximation schemes in relativistic astrophysics
Dept. of Physics and Astronomy, Iowa State University, USA

Puetzfeld, D. / 01 December 2008
Probing the nature of space and time
Department of Physics and Astronomy, University of Iowa, USA

Puetzfeld, D. / 05 December 2008
Multipolar approximation techniques and their use in astrophysics and cosmology
Department of Physics, University of Utah, USA

Puetzfeld, D. / 20 July 2009
Multipolar approximation schemes and the motion of extended bodies in General Relativity
Institute of Theoretical Physics, University of Cologne, Germany

Puetzfeld, D. / 28 October 2009
Motion of extended bodies in General Relativity
ZARM, University of Bremen, Germany

Rendall, A. / 15 April 2008
Einführung in die Allgemeine Relativitätstheorie
Freie Universität Berlin, Germany

Lectures and Lecture Series given by AEI members

Rendall, A. / 14 April 2009
Kinetic equations
Freie Universität Berlin, Germany

Schnabel, R. / winterterm 2007/2008
Quantum Optics
Leibniz Universität Hannover

Schnabel, R. / summer term 2008
Experimentalphysik II
Leibniz Universität Hannover, Germany

Schnabel, R. / winterterm 2008/2009
Experimentalphysik I
Leibniz Universität Hannover, Germany

Schnabel, R. / winterterm 2008/2009
Quantenoptik
Leibniz Universität Hannover, Germany

Schnabel, R. / summer term 2008
Experimentalphysik II
Leibniz Universität Hannover, Germany

Schnabel, R. / 06 November 2009
Quantum Noise
IMPRS Lecture Week, AEI, Wandlitz

Schutz, B. / 05 June 2008
Physics and Astrophysics of Gravitational Waves
Postgraduate Lecture Course, Southampton University, UK

Schutz, B. / 03 November 2008
Gravitational Waves
IMPRS Gravitational Waves Lecture Series, AEI, Germany

Schutz, B. / 24 August 2009
Gravitational Waves
IMPRS Gravitational Waves Lecture Series, AEI, Germany

Schutz, B. / 11 December 2009
Current and Future Gravitational Wave Experiments
VIII School of Gravity and Mathematical Physics, Playa del Carmen, Mexico

Szpak, N. / 16 March 2009
Einführung in die Allgemeine Relativitätstheorie
Jürgen Ehlers-Frühjahrsschule "Gravitationsphysik", AEI Potsdam, Germany

Willke, B. / 31 August 2008
Stabilized high-power single frequency solid-state lasers for gravitational wave measurements
Europhoton Conference - summer school, Paris, France

Willke B. / 30 January 2009
Thermodynamische Effekte in Festkörpern als Grenze von Präzisionsmessungen
Habilitation, Leibniz Universität Hannover, Germany

Willke, B. / 05 May 2009
Kernfusion - Erzeugung und Kontrolle von Materie in extremen Zuständen
Leibniz Universität Hannover, Germany

Willke, B. / 17 June 2009
Optical Technologies and Laser Systems
QUEST Ring Vorlesung, Leibniz Universität Hannover, Germany

Lectures and Lecture Series given by AEI members

Willke, B. / 24 June 2009
Optical Technologies and Laser Systems
QUEST Ring Vorlesung, Leibniz Universität Hannover, Germany

Willke, B. / 26 August 2009
Laser stabilization and control
IMPRS Lecture week, Mardorf , Germany

Popular Talks given by AEI members

Aufmuth, P. / 28 January 2008
Nachweis von Gravitationswellen mit GEO600
Schillerschule, Hannover, Germany

Aufmuth, P. / 14 February 2008
Wie die Zeit vergeht - Uhren, Zeit und Einstein
Grundschule Stelingen, Garbsen, Germany

Aufmuth, P. / 11 March 2008
Astronomie mit Gravitationswellen
Sternwarte, Solingen, Germany

Aufmuth, P. / 21 April 2008
Wie die Zeit vergeht - Uhren, Zeit und Einstein
TecToYou, Hannover Messe, Hannover, Germany

Aufmuth, P. / 22 April 2008
Einsteins Wellen - Gravitationswellen und ihr Nachweis
TecToYou, Hannover Messe, Hannover, Germany

Aufmuth, P. / 23 April 2008
Einsteins Universum - Das kosmologische Standardmodell
TecToYou, Hannover Messe, Hannover, Germany

Aufmuth, P. / 24 April 2008
Quantenschaum und Parallelwelten - Quantengravitation & Stringtheorie
TecToYou, Hannover Messe, Hannover, Germany

Aufmuth, P. / 04 June 2008
Krummes Licht, kollabierende Sterne, kosmische Wellen - Einstein und die Gravitation
Planetarium am Insulaner, Berlin, Germany

Aufmuth, P. / 08 July 2008
GEO600 - der deutsch-britische Gravitationswellendetektor
Marie Curie Schule, Ronnenberg, Germany

Aufmuth, P. / 14 July 2008
Einführung in den Studiengang Physik
Sommeruniversität, VHS Schaumburg, Rinteln, Germany

Aufmuth, P. / 14 July 2008
Gravitationswellenforschung in Hannover
Sommeruniversität, VHS Schaumburg, Rinteln, Germany

Aufmuth, P. / 08 August 2008
Wie klingt das Universum?
SommerCampus, Hannover, Germany

Aufmuth, P. / 20 September 2008
Visionen von Raum & Zeit - Vom Urknall zum Paralleluniversum
Galerie nr. 1, Warmse, Germany

Aufmuth, P. / 21 September 2008
“Mehr Licht!” - Vom Brockengespenst zum Quantenspuk
Galerie k9 aktuelle Kunst, Hannover, Germany

Aufmuth, P. / 13 November 2008
Wie die Zeit vergeht - Uhren, Zeit und Einstein
November der Wissenschaft, Hannover, Germany

Aufmuth, P. / 18 November 2008
Einsteins Wellen - Gravitationswellen und ihr Nachweis
November der Wissenschaft, Hannover, Germany

Aufmuth, P. / 20 November 2008
Einsteins Universum - Das kosmologische Standardmodell
November der Wissenschaft, Hannover, Germany

Aufmuth, P. / 27 November 2008
Quantenschaum und Parallelwelten - Quantengravitation & Stringtheorie
November der Wissenschaft, Hannover, Germany

Aufmuth, P. / 26 January 2009
Relativitätstheorie und Gravitationswellen - Forschung an der Leibniz Universität Hannover
Kaiser-Wilhelm- und Ratsgymnasium, Hannover, Germany

Aufmuth, P. / 03 March 2009
Astronomie mit Gravitationswellen
Planetarium Mannheim, Germany

Aufmuth, P. / 17 March 2009
Weißt Du wie viel Sterne stehen?
Grundschule Auf dem Loh, Hannover, Germany

Aufmuth, P. / 21 April 2009
Das Universum - unendliche Weiten?
Grundschule Auf dem Loh, Hannover, Germany

Aufmuth, P. / 11 May 2009
Mit LISA zum Urknall - Gravitationswellen erschüttern das Universum
Max-Planck-Schüler-Kollegium, Hannover, Germany

Aufmuth, P. / 12 May 2009
Mit LISA zum Urknall - Gravitationswellen erschüttern das Universum
Max-Planck-Schüler-Kollegium, Hannover , Germany

Aufmuth, P. / 27 May 2009
Gravitationsphysik in Hannover
Schillerschule, Hannover, Germany

Aufmuth, P. / 27 May 2009
Die dunkle Seite des Universums - Kosmologie heute
Robert-Koch-Schule, Hannover, Germany

Aufmuth, P. / 03 June 2009
Der Gravitationswellendetektor GEO600
Schillerschule, Hannover, Germany

Aufmuth, P. / 22 July 2009
Astronomie mit Gravitonen
Mittwochsakademie Siegen, Hannover, Germany

Aufmuth, P. / 31 July 2009
Der Klang des Universums - Neutronensterne, Pulsare, Schwarze Löcher und der Urknall
8. Internationale Astronomiewoche, Arosa, Switzerland

Popular Talks given by AEI members

Aufmuth, P. / 05 September 2009
Landschaften & Wege im Universum
Galerie nr.1, Warmse, Germany

Aufmuth, P. / 06 September 2009
Die Welt vor der Welt - Was war vor dem Urknall ?
Galerie k9 aktuelle Kunst, Hannover, Germany

Aufmuth, P. / 10 September 2009
Blitzschnell durch den Kosmos? - Reisen zu anderen Planeten, zu Sternen und zu Schwarzen Löchern
IdeenExpo 2009, Hannover, Germany

Aufmuth, P. / 11 September 2009
Blitzschnell durch den Kosmos? - Reisen zu anderen Planeten, zu Sternen und zu Schwarzen Löchern
IdeenExpo 2009, Hannover, Germany

Aufmuth, P. / 11 September 2009
Wie klingt das Universum?
IdeenExpo 2009, Hannover, Germany

Aufmuth, P. / 19 September 2009
Von Galileo Galilei zur Gravitationswellenastronomie
Tag der offenen Türen, AEI Potsdam, Germany

Aufmuth, P. / 24 November 2009
Gravitationswellen - Die Zukunft der Astronomie
Lions Club, Hildesheim, Germany

Beisert, N. / 01 September 2009
Was ist Stringtheorie?
Sommerakademie VIII 2009 der Studienstiftung des deutschen Volkes, Rot an der Rot, Germany

Cederbaum, C. / 04 July 2008
Was ist Krümmung?
Life Science Lab, Heidelberg, Germany

Danzmann, K. / 19 May 2008
Auf der Suche nach Einsteins Gravitationswellen
Jena, Germany

Danzmann, K. / 27 October 2008
Der Klang des Universums
Keppler Gymnasium Garbsen, Germany

Danzmann, K. / 14 July 2009
Gravitationswellenastronomie: Das Universum hören mit Albert Einstein
Tübingen, Germany

Danzmann, K. / 01 September 2009
Das Universum hören mit Albert und Herbert
Magnus Haus, Berlin, Germany

Danzmann, K. / 13 November 2009
Das Universum hören mit Gravitationswellen - Die Quantenphysik hilft der Astronomie
"Nacht der Astronomie", Rathaus Hannover, Germany

Fredenhagen, S. / 08 February 2008
Von Licht und schwarzen Löchern
Gymnasium Wolkenberg, Michendorf, Germany

Fredenhagen, S. / 09 January 2009
Quantenphysik schwarzer Löcher
Bruno-Bürgel-Sternwarte, Berlin, Germany

Popular Talks given by AEI members

Huisken, G. / 10 March 2008
Mathematik als Sprache der Natur:
Urania Berlin, Germany

Huisken, G. / 05 June 2008
Geometrie und Graviation
Akademie der Wissenschaften und der Literatur, Mainz, Germany

Knispel, B. / 08 May 2008
Asteroiden
Monatsvortrag Volkssternwarte Hannover, Germany

Knispel, B. / 09 October 2008
GPS - Einstein auf dem Beifahrersitz
Monatsvortrag Volkssternwarte Hannover, Germany

Knispel, B. / 19 March 2009
GPS - Einstein auf dem Beifahrersitz
Deutscher Hochseesportverband Hansa, Hannover, Germany

Knispel, B. / 07 May 2009
GPS - Einstein auf dem Beifahrersitz
Deutscher Amateur-Radio-Club, Hannover, Germany

Knispel, B. / 14 May 2009
Geschichten aus dem Reich der Schweifsterne
Monatsvortrag Volkssternwarte Hannover, Germany

Knispel, B. / 13 August 2009
Eine Reise durch das Sonnensystem
Monatsvortrag Volkssternwarte Hannover, Germany

Knispel, B. / 10 September 2009
Das Arecibo-Radioteleskop - Astronomie im Urwald
Monatsvortrag Volkssternwarte Hannover, Germany

Knispel, B. / 05 November 2009
Das Arecibo-Radioteleskop
Deutscher Amateur-Radio-Club, Hannover, Germany

Lück, H. / 03 April 2009
Live Webcast GEO600
100h of astronomy, Hannover, Germany

Nicolai, H. / 12 September 2008
Die Vereinheitlichung der Physik: von Minkowski zur M-Theorie
Fachhochschule Köln, Germany

Nicolai, H. / 12 November 2009
Gravitation und Quantentheorie: an den Grenzen von Raum und Zeit
Akademie der Wissenschaften, Hamburg, Germany

Nicolai, H. / 02 December 2009
Den Urknall verstehen: Physik in kosmischen Extremsituationen
URANIA Potsdam, Germany

Nicolai, H. / 04 December 2009
Quantentheorie und Gravitation: an den Grenzen von Raum und Zeit
Sternwarte Spandau, Berlin, Germany

Schnabel, R. / 12 January 2008
Gequetschtes Licht
Saturday Morning Lecture, Leibniz Universität Hannover, Germany

Popular Talks given by AEI members

Schnabel, R. / 20 May 2008
Quantenphysik im Kleinen und im Großen
University, Hamburg, Germany

Schnabel, R. / 25 November 2008
Squeezed light and its application for quantum optics and interferometry
University, Potsdam, Germany

Schnabel, R. / 01 December 2008
Verschränkung von Testmassen und das Standard-Quanten-Limit der Laserinterferometrie
Jena University, Germany

Schnabel, R. / 25 May 2009
Squeezed Quantum Noise
Stuttgart University, Germany

Schutz, B. / 04 December 2009
Schwerkraftwellen – Sphärenmusik tatsächlich hören!
Nikolaisaal, Potsdam, Germany

Tröbs, M. / 29 January 2009
Spurensuche im Weltall
Schillerschule, Gymnasium, Hannover, Germany

Guided Tours at GEO600

Aufmuth, P., Grote, H., Lück, H.

Appr. 310 visitors

"GEO600: The German-British Gravitational-Wave Detector"
Introductory talk and guided tour

30 January 2008 / 10 June 2008 / 11 June 2008 / 19 June 2008 / 9 July 2008 / 28 July 2008 / 7 August 2008 / 14 August 2008 / 14 November 2008 / 17 November 2008 / 30 January 2009 / 2 February 2009 / 9 February 2009 / 18 February 2009 / 25 February 2009 / 5 March 2009 / 27 April 2009 / 18 June 2009 / 29 June 2009 / 30 June 2009 / 22 July 2009 / 1 September 2009 / 3 September 2009 / 1 October 2009 / 6 October 2009 / 7 October 2009 / 22 October 2009 / 17 December 2009

The Max Planck Society: Profile and Organisation

The Max Planck Society for the Advancement of Science is an independent, non-profit research organization. It was founded on February 26, 1948, and is the successor organization to the Kaiser Wilhelm Society, which was established in 1911. The primary goal of the Max Planck Society is to promote research at its own institutes.

The research institutes of the Max Planck Society perform basic research in the interest of the general public in the natural sciences, life sciences, social sciences, and the humanities. In particular, the Max Planck Society takes up new and innovative research areas that German universities are not in a position to accommodate or deal with adequately. These interdisciplinary research areas often do not fit into the university organization, or they require more funds for personnel and equipment than those available at universities. The variety of topics in the natural sciences and the humanities at Max Planck Institutes complement the work done at universities and other research facilities in important research fields. In certain areas, the institutes occupy key positions, while other institutes complement ongoing research. Moreover, some institutes perform service functions for research performed at universities by providing equipment and facilities to a wide range of scientists, such as telescopes, large-scale equipment, specialized libraries, and documentary resources.

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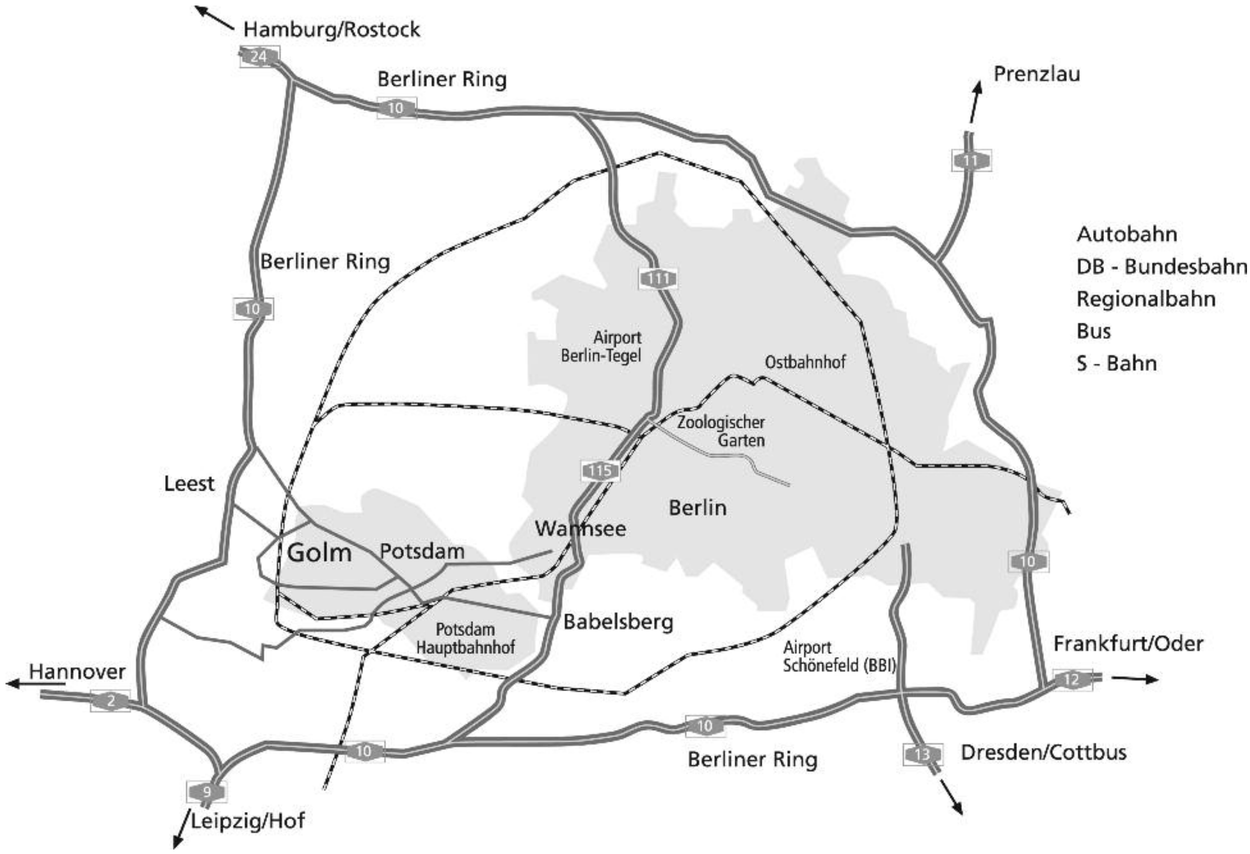
Take the S-Bahn no. 5 to the Central Station ("Hauptbahnhof"). Leave the Central Station direction "City"; walk along the Bahnhofstraße to the subway station "Kröpcke" (at the "Kröpcke" square); take subway no. 4 direction "Garbsen" or no. 5 direction "Stöcken". Leave the train at the fourth stop "Schneiderberg/Wilhelm-Busch-Museum"; cross the Nienburger Straße, walk along the Schneiderberg; after the refectory (Mensa) turn left into the Callinstraße; no. 38 at the right hand side is the AEI.

By train:
Leave the Central Station direction "City" and follow the above directions.

By car:
Take the highway A2; exit "Hannover-Herrenhausen", follow the sign "Zentrum"; drive along the B6 (Westschnellweg), exit "Herrenhausen"; take the Herrenhäuser Straße to the right; pass the Great Garden; at the fork to the right into the Nienburger Straße; the second left is the Callinstraße; no. 38 at the left hand side is the AEI.



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From the airports:
Tegel: Take the bus X9 to train station "Zoologischer Garten"
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then take S-Bahn or Regionalbahn to train station "Potsdam Hauptbahnhof" and take Bus 605 or 606 straight to the Max Planck Campus („Wissenschaftspark Golm").

By train:
Take any train going to "Potsdam Hauptbahnhof", then follow the above directions.

By car:
From Berlin: leave Autobahn A115 at exit "Potsdam-Babelsberg", go in the direction "Potsdam-Zentrum".

Follow signs "Autobahn Hamburg" until Golm is indicated.

Other routes: leave Autobahn A10 at exit "Leest", go in the direction "Potsdam", pass Leest and Grube to reach Golm.

Masthead

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The front cover shows the view into a Kaleidoscope in a curved space: Five differently colored objects are reflected ad infinitum by four mirror plates. In our case, curvature manifests as an apparent bending of straight lines (light red) away from the viewer.
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pp 14,15: Courtesy of the Union of Czechoslovak Mathematicians and Physicists
p 48: Numerical simulation: B. Giacomazzo, L. Rezzolla (AEI), scientific vizualisation: R. Kähler (AEI/Zuse Institute Berlin) | p 104 (top): N. Junkes (MPI for Radioastronomy)
pp 113 (Danzmann, Schutz, Staudacher) | 114 (top), 116 (Willke): N. Michalke
p 115 (Metzger): K. Fritze | p. 116 (Heinzel): Pressestelle der Leibniz Universität Hannover

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Note: Academic Achievements: This page shows Albert Einstein's results in his final school exams. A"6" is the highest possible grade in the Swiss system!

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