MAX-PLANCK-GESELLSCHAFT

Biennial Report 2004/2005

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, AEI) in the years 2004 and 2005. The 10th anniversary of our institute last year and the coinciding 100th anniversary of Einstein's annus mirabilis has focused attention of both the scientific community and the general public onto the research areas of the institute: From the geometrical and analytical aspects of General Relativity, String Theory and other unified theories to the astrophysics of gravitational waves and to the laser interferometry and quantum optics used to detect them, Einstein's heritage is present in much of the current research of the institute.

The two years covered by this report have seen scientific advances in all sections of the institute that are detailed in the reports of the individual sections. They have also brought a further strengthening of the international role and recognition of the institute: We are very pleased that several recipients of prizes from the Alexander von Humboldt Foundation chose the AEI as host institution for their research. I also mention the conference on "Geometry and Physics after 100 years of Einstein's Relativity" in Golm in April 2005 where a distinguished group of speakers covered all aspects of gravitation in front of an international audience of leading researchers and younger scientists, see the detailed report in this volume.

Several specific new developments have taken shape. The International Max Planck Research School in "Geometric Analysis, Gravitation and String Theory" has already attracted many new graduate students from around the world to the AEI and the participating university research groups. A second International Max Planck Research School in "Gravitational Wave Astronomy" in cooperation with Hannover University started at Hannover and Potsdam-Golm in January 2006. A new "Special Research Center" (SFB) of the German Research Foundation (DFG) in mathematics and theoretical physics with the title "Space-Time-Matter" started in 2005 jointly between the AEI, Potsdam University, Free University and Humboldt University, strengthening the links between the AEI and nearby universities further and widening the course and seminar offerings to our PhD students. Additional research projects in string theory were launched within the newly established EU-networks "Superstrings" and "Forces Universe", which came out on top among more than 600 other applications.

In 2004 Yanbei Chen won the Kovalevskaja-Prize of the Humboldt foundation enabling him to establish his research group on "Theoretical Gravitational Wave Physics" in the Astrophysical Relativity division of the AEI. This research will complement other efforts towards the detection of gravitational waves such as the analysis of data from the detectors GEO600 in Hannover and LIGO in the USA on the Merlin cluster. A regular new lecture series by prominent researchers on recent astrophysical developments was also started in this division. The AEI continues its close partnership with both the LIGO gravitational wave detector in the US and the planned space based project of ESA-NASA called LISA: Following joint data-taking runs of GEO600 and LIGO in the current report period the AEI has assumed important tasks concerning both the data analysis and the construction of Advanced LIGO. The AEI is closely involved in the mission formulation phase of the LISA Pathfinder mission that was entered in 2005, with a planned launch in late 2008. The division in Hannover is co-PI for the experimental aspects of this mission.

The institute was able to make several senior level appointments during the last two years: Lars Brink (Stockholm), Robert Bartnik (Melbourne) and Kenneth Strain (Glasgow) have joined the institute as external scientific members. The AEI is very pleased to have secured the regular scientific collaboration of these distinguished colleagues which will greatly benefit the scientific work of the institute. With the help of additional funds provided by the Leibniz program of the German Research Foundation it was possible to make a temporary senior appointment in the division “Geometric Analysis and Gravitation”: Lars Andersson from the University of Miami has joined the division for four years as a visiting professor and will provide additional expertise on analytical and geometrical aspects of Einstein’s equations.

The institute cooperates nationally and internationally with many other research institutions and individual scientists through a number of activities: Longterm institutionalized cooperation agreements, honorary professorships at neighbouring universities, joint special research centers, graduate schools and networks with other scientists as well as, very importantly, small research projects between individual scientists. Conferences, workshops and a regular visitor program provide further opportunities for young scientists to forge links with the scientific community.

Some members of the AEI have accepted offers elsewhere while new members have been attracted to the AEI: Curt Cutler has moved to a more senior position at the California Institute of Technology in autumn 2005 and in the same year Jan Plefka received a Lichtenberg-professorship established by the Volkswagen Foundation at Humboldt University. Thomas Thiemann has returned to the division “Quantum Gravity and Unified Theories” of the AEI in 2004.

Following the move of Ed Seidel to a senior position at LSU in Baton Rouge the institute is very pleased to have attracted Luciano Rezzolla from Trieste to head the numerical relativity group in the division Astrophysical Relativity which is currently located in offices in Potsdam-Babelsberg. The Peyote computing cluster provides an excellent computing environment for this group and will be upgraded in 2006 following the successful application to the computing committee of the Max Planck Society.

The physical buildup of the institute has reached an important stage with the completion of the new laboratories and offices in Hannover and the fast progress on the extension building in Golm. It is expected that this extension building will be completed within the next months so that all Potsdam based research groups of the AEI will be reunited in Golm by autumn 2006, compare the detailed report in this volume (see page 96). The move into the extension building in Potsdam will require an extra effort by both scientists and service sections of the institute.

The institute gratefully acknowledges the continued support for the build-up of the AEI by the Max Planck Society. Apart from the building investments it has also secured the basic funding for the future operation and upgrading of GEO600. Outside funding of the institute has been boosted by the start of several new research programs funded by a great variety of national and international sources: The German Research Foundation (projects in three Special Research Centers, Leibniz-Program), the EU (four separate projects), ESA/NASA (funding for LISA) and “Deutsches Zentrum für Luft- und Raumfahrt” (DLR) with funding for the LISA Pathfinder (for a detailed report on cooperations see page 99).

Challenges for the immediate future include the start of the second division in the Teilinstitut Hannover where we hope to successfully complete the appointment of the fifth director of the AEI. This would allow the new section to become operational in the second half of 2006. The new research group could then focus on data analysis and the observation of gravitational waves, complementing the existing experimental research.

The institute was visited and thoroughly evaluated concerning the quality and effectiveness of its scientific work by its "Fachbeirat" in September 2005. The report of the Fachbeirat to the Max Planck Society was very positive and supportive of the research strategies of the AEI and offered very helpful advice for its future development. The Kuratorium of the AEI met in September 2005 in a historical building in the center of Berlin and offered additional advice to the institute how to communicate its research to a broad public audience, see the detailed reporting this volume. The meeting also took advantage of the central Einstein Year exhibition in Berlin concerning the science and life of Albert Einstein where several exhibits of the AEI were present.

The Einstein Year 2005 provided a unique opportunity for the institute to involve the general public and in particular the young generation in its research. Elke Müller and Peter Aufmuth were supported by Markus Pössel to plan and coordinate the many activities of the AEI this year as described in a separate article. I particularly like to mention here the new website Einstein-Online with its multi-level introduction into relativity which will remain an important point of contact for the general community. The institute continues to provide a multitude of lectures for the general public, teacher and student educational lectures, open day talks and popular science lectures at the Urania in Berlin. The institute is particularly grateful to Jürgen Ehlers for his continuing enthusiasm in publicly representing the institute on many such occasions.

Nearing the end of my term as managing director I would like to thank all the scientists and all the support staff of the AEI for their continued support and enthusiasm: The building projects and the Einstein Year have provided challenges and extra workloads. I was lucky to have found so much help and support in all sections of the institute – the library, IT-section, scientific coordination/public relations as much as in the secretariat and the administration. It will be exciting to work in such an excellent research environment in a reunited and fully extended AEI during 2006.

Gerhard Huisken

The Institute

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The Institute

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. Its establishment was an initiative of its founding Director, Jürgen Ehlers, who retired at the end of 1998. The Institute moved from Potsdam City to its new building in Potsdam-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.

In 2005 the AEI celebrated ten years of existence. It was able to look back on a decade of very rapid growth, including the founding of its branch institute in Hannover, devoted to experimental gravitation. During this period it has become the largest research institute devoted to gravitational physics, and it serves as a focal point for scientists working internationally in many areas. More than one hundred scientists visit each year; the institute regularly hosts workshops and conferences; we publish one of the principal scientific journals in relativity; and many AEI staff occupy leading positions in big collaborations, external institutions, and in public advisory bodies. Even after only ten years, former AEI scientists occupy permanent positions and in some cases leadership positions in many of the important relativity research groups around the world.

The AEI prospered in 2004/5. The earlier funding restrictions in the Max Planck Society eased, an extension building providing much-needed office space was begun, funds were awarded for a new cluster supercomputer, resources for opening a second division in our Hannover branch were approved, and the Max Planck Society also endorsed and funded our ambitious long-range plans in gravitational wave detection for an upgrade of the GEO600 detector and for collaborative work with our international partners.

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 is entering full-time observing, including the AEI's own 600 m detector, GEO600, a collaboration with British and other European scientists. These experiments could soon directly observe signals from distant astronomical sources that are carried by the gravitational field itself.

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 in 2004/5 had four divisions: three for theoretical research in Potsdam-Golm, and the first of two planned experimental physics divisions 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 black holes and their dynamics. The gravitational radiation group analyzes data from the GEO600 gravitational wave detector and its international partners and performs theoretical studies to understand sources of gravitational waves. The 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 take place at the end of this decade. The Division also plays a leading role in the development of the LISA space-based gravitational wave detector, which is planned to be launched in 2015 jointly by the European Space Agency (ESA) and the US space agency NASA. Danzmann is the European Project 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 2009 to test the measurement and control systems designed for LISA.

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 dedicated to specific research areas.

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 2004/5 and of seminars given at the AEI show how rich the intellectual environment is.

The AEI and Universities

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. Despite the fact that general relativity was created in Germany, research in mathematical and astrophysical general relativity is unfortunately not strongly supported at most German universities. Apart from the contributions of a strong group at the Max Planck Institute for Physics and Astrophysics (which became the core of the AEI when it was established) and of a few individuals and small groups at German universities, the focus of the development of classical relativity in the 1960‘s through the 1990‘s was outside Germany. Today, increasing numbers of German students are going abroad to study the subject at an advanced level.

In order to help to make Germany attractive to young students, the AEI participates in at least four different cooperative initiatives. 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 two 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. One SFB 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 in gravitational wave astronomy, which will help to develop a university research community supporting the experimental activities of GEO600. 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, is in Geometric Analysis, Gravitation, and String Theory. It is a cooperation with Potsdam University and the Free University of Berlin. The second, which started in 2006, is in Gravitational Wave Astronomy, and is a cooperation with Hannover University. These 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. The editorial staff of the journal are now supported by the Heinz-Nixdorf Center for Information Management (ZIM) of the Max Planck Society, and in recent years we have started up two sisters journals, Living Reviews in Solar Physics and Living Reviews in European Governance. Further journals are expected to join the family in the next year or two.

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.
- Very soon, supercomputers will be large enough to do realistic calculations in general relativity, to perform long simulations of black holes and neutron stars merging, possibly to perform realistic calculations of the formation of neutron stars and black holes, and probably to explore mathematical questions, such as the development of singularities, that have not been solved analytically so far. This work will aid in the discovery and interpretation of gravitational waves and should also raise new questions in mathematical relativity, offering new opportunities for research there.
- 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 – 8-meter-class optical telescopes, optical interferometers, and survey instruments – 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 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 2004/5, 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 our next ten years with optimism and anticipation.

Bernard F. Schutz

Einstein, the Photoelectric Effect and the Nobel Prize

ANNALEN

DER

PHYSIK.

VIERTE FOLGE.

BAND 17.

KURATORIUM:
F. KOHLRAUSCH, M. PLANCK, G. QUINCKE,
W. C. RÖNTGEN, E. WARBURG.

M. PLANCK

PAUL DRUDE.

LEIPZIG, 1905.
VERLAG VON JOHANN AMBROSIUS BARTH.

In 2005, the 100th anniversary of Einstein's miraculous year 1905, numerous meetings were held to review Einstein's path-breaking ideas, to put them in perspective and to assess the extent to which the questions then raised have by now been answered.

Einstein's fame is mostly associated with his two relativity theories which radically changed the physicist's conceptions of time, space, causality and gravitation. In view of this it is surprising that the Nobel Prize for 1921 was awarded to him not for these outstanding accomplishments, but "for his services to theoretical physics, and especially for his discovery of the law of the photoelectric effect". When the prize was announced in 1922, seven years had passed since the completion of the General Theory of Relativity and its beautiful explanation of the anomalous advance of the perihelion of Mercury's orbit, and three years ago the light deflection measurements had made Einstein a world celebrity. So, why the photoelectric effect?

The circumstances which led to the decision of the Nobel committee have been related in detail by Abraham Pais (Subtle is the Lord, chapter 30). Here I mention only that Einstein had been nominated several times, for the Special Theory, the General Theory, and for his statistical and quantum researches. In both relativity cases, doubts concerning experimental tests had been voiced, so the committee, lacking a knowledgeable relativist, apparently was happy when Carl Wilhelm Oseen argued in favour of the photoelectric effect – that had been verified thoroughly, and it certainly was important.

In hindsight, the choice of the committee may after all be considered most appropriate. One good reason may be seen in the fact that when Einstein announced his 1905 papers to his friend Conrad Habicht, he described as "very revolutionary" only the light quantum paper, which has the peculiar title "On a heuristic point of view concerning the generation and conversion of light". Indeed, this work constitutes the second step into the quantum world after Max Planck's discovery of 1900. It explains, inter alia, the photoelectric effect, the first instance of an elementary interaction of radiation and matter governed by Planck's constant, and it introduces the wave-particle dualism.

Before returning to the light quantum paper I briefly describe the history of the photoelectric effect. In 1887 Heinrich Hertz noticed, during his famous experiments which established the existence and properties of electromagnetic waves, that ultraviolet radiation emitted from electric sparks induced similar sparks when hitting metal. In the following year Wilhelm Hallwachs found that during such a process the irradiated metal plate becomes positively charged. Ten years later, after his discovery of the electron, J.J. Thomson found in 1899 that ultraviolet light causes electrons to be ejected from metals; this phenomenon then became known as the photoelectric effect. In 1902, Philip Lenard found a very surprising property of this effect: even an increase of the intensity of the incident radiation by a factor of a thousand does not change the energy of the emitted electrons in the slightest. Also, he noted that raising the frequency of the light also raises the electron energy, in a qualitative way. This was the state of knowledge when Einstein wrote his light quantum paper, which he submitted to the Annalen der Physik on March 17, 1905.

Einstein begins his revolutionary paper by contrasting the prevailing views on matter and radiation. Matter was represented as consisting of discrete localized particles, radiation was considered as a continuous wave process. Having recalled the successes of the wave theory of light, Einstein boldly continues: “It is nevertheless conceivable that the theory which operates with continuous space functions leads to contradictions with experience if one applies it to the phenomena of the production and transformation of light”, and he lists some phenomena that “can be understood better by assuming that the energy of light is distributed in space discontinuously” – this is his heuristic hypothesis.

6. *Über einen die Erzeugung und Verwandlung des Lichtes betreffenden heuristischen Gesichtspunkt;*

von A. Einstein.

Zwischen den theoretischen Vorstellungen, welche sich die Physiker über die Gase und andere ponderable Körper gebildet haben, und der Maxwellschen Theorie der elektromagnetischen Prozesse im sogenannten leeren Raume besteht ein tiefgreifender formaler Unterschied. Während wir uns nämlich den Zustand eines Körpers durch die Lagen und Geschwindigkeiten einer zwar sehr großen, jedoch endlichen Anzahl von Atomen und Elektronen für vollkommen bestimmt ansehen, bedienen wir uns zur Bestimmung des elektromagnetischen Zustandes eines Raumes kontinuierlicher räumlicher Funktionen, so daß also eine endliche Anzahl von Größen nicht als genügend anzusehen ist zur vollständigen Festlegung des elektromagnetischen Zustandes eines Raumes. Nach der Maxwellschen Theorie ist bei allen rein elektromagnetischen Erscheinungen, also auch beim Licht, die Energie als kontinuierliche Raumfunktion aufzufassen, während die Energie eines ponderabeln Körpers nach der gegenwärtigen Auffassung der Physiker als eine über die Atome und Elektronen erstreckte Summe darzustellen ist. Die Energie eines ponderabeln Körpers kann nicht in beliebig viele, beliebig kleine Teile zerfallen, während sich die Energie eines von einer punktförmigen Lichtquelle ausgesandten Lichtstrahles nach der Maxwellschen Theorie (oder allgemeiner nach jeder Undulationstheorie) des Lichtes auf ein stets wachsendes Volumen sich kontinuierlich verteilt.

Die mit kontinuierlichen Raumfunktionen operierende Undulationstheorie des Lichtes hat sich zur Darstellung der rein optischen Phänomene vortrefflich bewährt und wird wohl nie durch eine andere Theorie ersetzt werden. Es ist jedoch im Auge zu behalten, daß sich die optischen Beobachtungen auf zeitliche Mittelwerte, nicht aber auf Momentanwerte beziehen, und es ist trotz der vollständigen Bestätigung der Theorie der Beugung, Reflexion, Brechung, Dispersion etc. durch das

The main, very subtle reason which led Einstein to introduce quanta of light energy was neither the photo effect nor any of the other effects considered in the last three paragraphs of his paper. It was his recognition that neither classical mechanics nor classical electrodynamics can account for the fluctuation phenomena which are implied by Planck’s law (1900) for the spectral distribution of thermal radiation, a law which was well supported by measurements but not at all understood theoretically by 1905. Lacking a fundamental theory of either mechanics or radiation, Einstein ingeniously combined Wilhelm Wien's asymptotic form of the radiation law for high frequencies (1896, $h\nu > kT$), a theorem by the same author for the thermodynamics of radiation (1894), and Ludwig Boltzmann's "principle" (1877) which relates the entropy of a system to the probability assigned to its state. From these quite different ingredients he was able to deduce:

Quasi-monochromatic radiation of low energy density behaves with respect to its fluctuating spatial energy distribution as if its energy consisted of independent point like quanta $h\nu$. It was this startling conclusion contradicting the classical theory of radiation that led Einstein to look for specific observed phenomena which would support his light quantum picture. Of these, the photoelectric effect became the best known, since it provided a quantitative law which could be checked experimentally. Einstein assumed that in that process the energy $h\nu$ of each light quantum is converted, inside the metal, into kinetic energy of an electron. Some of these electrons will then be expelled from the metal after having lost at least that part P of their energy which is necessary for it to escape from the metal. Thus, the maximal energy E of the ejected electrons will be given by the photoelectric equation

$$E = h\nu - P.$$

In a review in 1949 Robert Andrews Millikan wrote: "I spent 10 years of my life testing that 1905 equation of Einstein's and contrary to all my expectations I was compelled in 1915 to assert its unambiguous verification in spite of its unreasonableness, since it seemed to violate everything we knew on the interference of light."
So much for Einstein's Nobel Prize.

Jürgen Ehlers

Research Overview

Geometric Analysis and Gravitation Division

The description of astronomical objects by means of mathematics is one of the oldest human endeavours. To forecast the motion and appearance of the moon, the planets and the stars Greek mathematicians developed the first basic concepts of geometry still valid today, their theory of conic sections was used centuries later by Kepler to formulate his laws of motion for the planets. Following the discovery of infinitesimal calculus in the 17th century the development of analysis made it possible to formulate laws of equilibrium and laws of motion in terms of variational principles, culminating in particular in the variational interpretation of the Einstein field equations in General Relativity by David Hilbert.

The second half of the 20th century has seen tremendous progress both in gravitational physics and in mathematics: On the side of physics black holes have developed from a theoretical and mathematical curiosity to very real objects of observation, gravitational lensing has become an important observational tool, cosmological models interact with particle physics, and gravitational waves are within reach of modern detectors. On the other hand mathematical analysis has developed a deep understanding of nonlinear elliptic and parabolic partial differential equations arising from geometric variational problems, differential geometry has developed methods to link local curvature properties of surfaces and spaces to global properties of their shape, and numerical simulations allow detailed quantitative predictions from complex mathematical models. A main task for the Division “Geometric Analysis and Gravitation” is the pursuit of basic research on mathematical methods relevant for the modelling of gravitation and the investigation of specific models for concrete physical phenomena using modern mathematical techniques.

Since Galilei, Brahe and Kepler the theory of gravitational attraction between celestial bodies has benefited from lively interaction between astronomical observation, theoretical physics and mathematical modelling. In recent years the search for unified theories and new developments in String Theory and M-Theory have suggested many new connections between mathematics and physics, the interpretation of observations in astrophysics and gravitational wave experiments require new methods in theoretical and numerical analysis. The other divisions of the Albert Einstein Institute have made great advances in their areas and provide continuous exposure to these developments and benefit in turn from the mathematical expertise offered here.

The Role of Mathematics in the Description of Gravitation

Newton’s theory of gravitation is usually formulated in the language of differential equations. It had tremendous impact on the mathematical theory of dynamical systems, potential theory and partial differential equations, but also on the calculus of variations, hamiltonian mechanics and symplectic geometry. From a physical point of view Newton’s theory of gravitation is accurate enough in many situations and for many purposes - only in extreme situations where very strong forces or high velocities occur, or where extreme accuracy is required Einstein’s theory of gravitation has to be used. The mathematical formulation of Einstein’s theory of gravitation uses both differential equations and geometry, since the background where the differential equations have to be formulated and solved is no longer Euclidean space but a curved four-dimensional space-time. In fact, the equations proposed by Einstein have to be interpreted as a balance between curvature and physical non-gravitational fields, as a variational equilibrium between geometry and matter. This intrinsic linkage of analysis, geometry and physics in Einstein's general theory of relativity leads to beautiful and challenging mathematical concepts and models which lie at the heart of the work of the Division "Geometric Analysis and Gravitation".

After the main framework of Einstein's theory has been established during the last decades it has now become possible to ask specific questions about characteristic phenomena of general relativity like rotating neutron stars, collapse of stars into black holes, gravitational waves emanating from the collision of heavy objects, or conditions in the early universe. Such specific questions make it necessary to identify and study new mathematical structures representing classical physical concepts, for example mass, energy and momentum, in the geometric setting of general relativity, both in a global and in a localised context. Moreover, the difficulties arising from the questions posed often make it necessary to invoke sophisticated mathematical tools such as weak solutions of differential equations or concepts from geometric measure theory allowing generalised surfaces with possible singularities. In other situations it may be advantageous to reformulate the original mathematical description in a more natural way, for example with the help of conformal equivalences. Difficult mathematical problems arise in particular concerning the solvability of nonlinear wave equations and related stability questions, the description of physically consistent initial data in the framework of three-dimensional differential geometry, differential equation models for matter coupled to the Einstein equations, formation of singularities, and concerning the relation of Einstein's theory to the classical theory of Newton in the limit of weak fields.

Research projects 2004-2005

The reporting period included the Einstein year 2005 where the members of the division were heavily involved both in scientific events and in outreach projects to the interested community. All research projects of the division benefited from this heightened activity:

Geometric Evolution Equations

As our understanding of partial differential equations (PDEs) advances, more and more connections between elliptic, parabolic and hyperbolic partial differential equations become apparent, both in terms of phenomena and methods. Beside the hyperbolic Einstein field equations of General Relativity research into elliptic and parabolic geometric PDEs therefore has been an important component of our work. In the past two years the deformation of curved spaces by a parabolic evolution equation was studied from several different points of view:

Hamiltons Ricciflow of metrics was investigated in its relation to the geometrisation of 3-manifolds and the renormalisation group flow. Recent results of Perelman were extended to show that the renormalisation group flow is a gradient flow to lowest order in the loop expansion, concretising an interesting link between Ricciflow and quantum field theory (Oliynyk). A special Mini-Workshop on Perelmans recent work on Ricciflow was organised at the Mathematical Sciences Research Institute Oberwolfach (2005, Huisken) with strong participation from the AEI. An extended version of the Ricciflow linking it to static solutions of the Einstein equations was proposed and investigated in a PhD thesis (List). It appears that the insights of Hamilton and Perelman in Ricciflow open the door to many deep relations between structures in analysis, geometry and theoretical physics.

Another analytical project concerned the conformal deformation of Riemannian metrics by their scalar curvature, the so called Yamabe flow. In this flow the longtime behaviour of solutions and the possible formation of singular bubbles in infinite time was investigated for manifolds of arbitrary dimension. The analysis of this longtime behaviour of the Yamabe flow is closely linked to the concept of mass in General Relativity and the York-method for the construction of initial data sets satisfying the constraint equations (Grüneberg).

The evolution of hypersurfaces by their mean curvature was studied both in the Riemannian and in the Lorentzian setting, specific projects concerned the surgery procedure for the flow of 2-convex surfaces (Huisken-Sinestrari) and the flow of asymptotically hyperbolic surfaces in Minkowski space: In a PhD project (Aarons) it was shown that asymptotically hyperbolic constant mean curvature surfaces in Minkowski space can be constructed as the longtime asymptotic limit of a suitable mean curvature flow. In another PhD project (Hein) the weak solution of inverse mean curvature flow was constructed as the parabolic limit of a mean curvature flow with appropriate forcing term.

In a further new project, the relation of mean curvature flow with the Ginzburg-Landau equation is explored, allowing the representation of solutions to mean curvature flow as limits of interfaces of solutions to the Ginzburg-Landau equation. Advances have been made on the ambitious goal to represent trioids evolving by curve-shortening flow in terms of vector valued Ginzburg-Landau equations (Saez). Further relations of mean curvature flow to singular and degenerate elliptic PDEs occur in relation to the p-Laplacian and the infinity Laplacian (Saez).

When using a Hamiltonian formulation of general relativity, where space-time is considered in a suitable (3+1)-splitting of space and time, the Einstein equations give a prescription for the evolution of a three-dimensional curved space in time, driven by its own geometry and the matter fields present in the system. The geometric evolution equations described above can be used to construct optimal (3+1)-splittings of spacetime and serve to control the geometry of the 3-dimensional spatial slices. In a new PhD project combining the expertise of this division with the expertise of the “Quantum Gravity” division, the Cauchy problem for d-branes involving the time-like minimal durface equation is studied in the context of quasilinear hyperbolic systems, leading to a space-time splitting of the d-brane equation similar to the (3+1)-Hamiltonian formalism employed in Einstein’s equations (Milbredt). It can be argued that the timelike minimal surface equation is the most natural hyperbolic equation for a vibrating membrane from a geometric point of view.

Geometric Variational Problems

Since the calculus of variations was initiated by Newton, Leibniz and the Bernoulli brothers and since Huygens demonstrated the power of variational principles in the foundations of geometrical optics, variational principles for geometrical structures have governed large parts of physics. In general relativity they become apparent not only in the Hilbert action for the Einstein equations and the variational properties of geodesics, but also in the Hamiltonian formulation of the Cauchy problem and in the construction of optimal gauges with the help of maximal or constant mean curvature slices as well as harmonic maps. Needless to say, variational principles are also present in the formulation of various models of matter.

In the reporting period variational principles were important in the study of Cauchy data on a three-dimensional Riemannian manifold representing a spatial slice of an isolated gravitating system: One unexpected result establishes a new integral invariant of initial data sets characterising the distance of given initial data from stationary data. Such an invariant may become an important tool in constructing physically meaningful initial data without introducing spurious radiation into the system. The study of this problem is closely linked to certain elliptic systems of partial differential equations and has led to the establishment of a new 'Korns inequality' related to conformal Killing vector fields (Dain).

As minimisers of the isoperimetric variational problem constant mean curvature surfaces (cmc-surfaces) are some of the oldest geometrical structures. They appear naturally in General Relativity when constructing well adapted time gauges in Lorentzian manifolds or when constructing optimal radial gauges in asymptotically flat initial data sets serving as center of mass. Much progress was made on the existence and stability of cmc-curfaces and their generalisations in initial data sets for isolated systems (Metzger). In Euclidean space an extension of the isoperimetric problem concerns the separation problem for multiple volumes and leads to the so called double bubble conjecture for the shape of two attached soapbubbles, where significant progress was made (Daily).

Another natural variational problem concerns elastic bodies in rigid rotation, both relativistically and nonrelativistically. It was established that for a body which is in its natural state in the absence of rotation, there exist solutions to the elastic field equations for small angular velocity (Schmidt, Beig, Andersson).

Asymptotically Flat Spacetimes

Asymptotically flat space-times provide the most important model for analysing phenomena occurring in fields of self-gravitating isolated systems such as one or several stars, black holes or even galaxies. They are particularly important for discussing problems concerning gravitational radiation. To get control on the behaviour of asymptotically flat solutions to the Einstein equations both in a vacuum setting and in the presence of matter, methods from differential geometry, analysis and numerical mathematics have been employed in several projects of our division:

Asymptotically flat initial data were studied in the presence of horizons representing the boundary of a black hole and it was shown that various boundary conditions for such initial data are well posed. These results provide new ways to calculate numerically black hole data (Dain).

The mathematical description of black hole boundaries in asymptotically flat spacetimes was pursued in the study of prescribed mean curvature 2-spheres modelling marginally trapped surfaces. A notion of stability for such 2-spheres was developed (Andersson, Mars, Simon) and used in the study of dynamical horizons. In further work curvature estimates and smoothness properties were established that should be important for the understanding of dynamical horizons (Metzger, Andersson).

The formation of black holes through critical collapse was also studied in higher dimensions: It was shown that the (4+1)-dimensional vacuum Einstein equations admit gravitational waves with radial symmetry. The dynamical degrees of freedom correspond to deformations of the three-sphere orthogonal to the time and radial coordinates. Gravitational collapse of such waves was studied numerically and shown to exhibit so called discretely selfsimilar Type II behaviour at the threshold of black hole formation (Bizon, Chmaj, Schmidt).

Vacuum gravitational collapse was also studied for two-cohomogeneity solutions of the nine dimensional Einstein equations: Using combined numerical and analytical methods evidence was given that within this model the Schwarzschild-Tangherlini black hole is asymptotically stable and the critical behaviour at the threshold of black hole formation was studied (Bizon, Chmaj, Rostworowsky, Schmidt).

For stationary, spherically symmetric solutions to the Vlasov-Poisson system motivated from astrophysics improved criteria for the finiteness of the radius of the configuration were developed (Heinzle, Rendall). Global smooth solutions of a 2d-Nordström-Vlasov system were shown to exist without any smallness assumption and the non-relativistic limit of the Nordström-Vlasov system was analysed (Lee, Calogero).

The non-relativistic Newtonian limit was also studied from a completely different point of view in the context of perfect fluids, where a precise notion of convergence was rigorously established in an appropriate class of function spaces. These results make use of singular limits of symmetric hyperbolic systems and can be extended to higher order expansions (Oliynyk).

The analysis of gravitational radiation emanating from catastrophic astrophysical processes is strongly concerned with the asymptotic behaviour of certain gravitational fields. Recent insights suggest that a full understanding of static asymptotically flat solutions to the Einstein Vacuum field equations is necessary for that analysis of gravitational radiation and major progress was made in this direction by investigating the underlying quasi-linear, gauge-elliptic tensorial PDE system: A new class of asymptotic quantities was studied and their relation to multipole moments and asymptotic expansions was established. This provides a complete characterisation of all static vacuum solutions in terms of these quantities and brings this major longterm project to a conclusion that can serve as a basis for the further investigation of gravitational radiation (Friedrich).

To be able to compare gravitational radiation with other more linear radiation phenomena, in another project electromagnetic radiation emanating from charged matter was investigated. This work resulted in a dipole formula for a self-consistent system of charged matter and radiation (Bauer, Kunze, Rein, Rendall). The gravitational radiation emanating from a rotating black hole is modelled by quasi-normal modes (QNMs), which are expected to yield an accurate expansion of the gravitational field in certain regions of spacetime. The mathematical description of (QNMs) in wave equations is a difficult analytical problem (Szpak).

Cosmological Spacetimes

A crucial model for modern cosmology is the Friedman-Lemaitre model, describing a universe that is homogeneous, isotropic and has (under reasonable conditions) a big-bang singularity. As increasingly high precision data become available it will no longer be possible to treat deviations from the Friedman model by perturbation theory and as a consequence the field of cosmology will inevitably be confronted with the truly nonlinear features of the general relativity. Two asymptotic regimes are of particular importance: The understanding of the asymptotic behaviour of solutions to the Einstein equations at cosmological singularities is of importance for models of the early universe while the asymptotic behaviour of such solutions at late times is important for models of the universe at present.

Numerical and formal methods were used to study cosmological spacetimes with symmetry, supporting the strong cosmic censorship hypothesis of Penrose and the more detailed conjecture of Belinski, Khalatnikov and Lifshitz (Andersson, Lim, Uggla, Van Elst). A large class of cosmological models including higher dimensional models from string/M theory was investigated with respect to their nonlinear stability properties (Andersson, Moncrief).

Accelerated cosmic expansion is one of the pressing issues in the field of cosmology and many different mechanisms were proposed during the last few years to explain it. The simplest class of models, known as quintessence, allows the choice of a free function V, the potential. It was studied how the choice of V affects the dynamics and rigorous proofs for properties of these models were given, including a clarification of the so called slow-roll-approximation used in applications (Rendall). In the special case known as power-law inflation control of the global dynamics was obtained for solutions with general spatial dependence (Heinzle, Rendall).

In a PhD project expansion models with complex scalar fields were investigated in a non-symmetric setting, leading to full asymptotic expansions of late-time inflating solutions and a corresponding detailed description of the corresponding solutions (Bieli).

In the Einstein-Vlasov model with a nonlinear scalar field or with a positive cosmological constant the expansion behaviour could be characterised as to “power-law” or “exponential” behaviour (Lee). The Einstein-Vlasov system in inhomogeneous spacetimes with a toroidal symmetry is also being investigated in this context (Lee, Tchapnda). Additional difficulties occur when the particles of the collisionless matter are charged, leading to the Einstein-Vlasov-Maxwell system, where longtime existence of solutions was established and the asymptotic behaviour of the electromagnetic field was characterised (Tchapnda).

An important connection between black hole collapse and cosmology was discovered in a different project: In the spherical collapse of collisonless matter the occurrence of a trapped surface implies that of a black hole. When studying the interior of a such a black hole connections with cosmology appear leading to new insights into singularities of symmetric cosmological models (Dafermos, Rendall). The occurrence of big-bang and big-crunch singularities in certain Einstein universes was also established (Heinzle, Röhr, Uggla). Constant mean curvature slicings, which play an important role in the study of cosmological spacetimes, were studied in detail in the Kottler-Schwarzschild-de Sitter family of spacetimes, providing another link between models of isolated systems and cosmological models (Heinzle, Rendall).

Numerical Relativity

Given the strong interplay between astrophysical phenomena and mathematical methods and models, there is a strong need to make detailed quantitative predictions for specific initial conditions for Einstein’s equations.

In view of the nonlinear structure and geometric invariance of these equations in spacetime the development of stable and justifiable numerical algorithms is a tremendous challenge both from a theoretical and implementational point of view. The division "Geometric Analysis and Gravitation" has chosen a few specific projects for its numerical investigations where it seems that new mathematical input can lead to considerable progress.

One project is concerned with the use of the conformal field equations in calculating numerically radiation fields of isolated self-gravitating systems. In a PhD project the conformal field equations were implemented in a 3-dimensional evolution code based on a cartesian grid. Stability tests and studies of axially symmetric examples in an asymptotically flat setting have been carried out successfully, with future work aiming at hyperboloidal initial data (Zenginoglu). The initial value problem for the conformal field equations is also studied analytically and numerically in a second PhD project aiming to understand global properties of solutions to the past and towards the future. Of particular interest here are relations between the given initial data and asymptotically simple ends and singularities of the space time which are studied with in the context of the conformal field equations (Beyer).

Another PhD project is concerned with the problem of "constraint violation", where admissible initial data for the Einstein equations leave this class at an exponential rate during the numerical evolution. The project demonstrates how to obtain stable constraint propagation by suitable choice of gauges in the context of Maxwell's equations (Vogel).

Another important project concerns the numerical description of black holes. Stationary Ring-Black hole systems are investigated with a highly accurate numerical scheme based on spectral methods: The scheme is able to calculate the general relativistic gravitational field of an axisymmetric and stationary two-body system consisting of a central black hole and a surrounding fluid toroid. An important result of this joint project with the SFBTransregio7 of the DFG is that there is no upper bound for the ratio of the total angular momentum of the black hole to the square of it Komar-mass (Ansorg, Petroff).

To solve the constraint equations for binary black holes a new multidomain pseudo-spectral method was developed. The numerical accuracy obtained approaches machine precision even in limiting cases such as when very large distances or mass ratios of the black holes occur (Ansorg).

Gerhard Huisken

Astrophysical Relativity Division

The scientists in the Astrophysical Relativity Division focus their research on how Einstein's theory of gravity, general relativity, helps us to understand the Universe that astronomers see around us. Modern astronomical observatories have revealed a rich variety of phenomena that need relativistic gravitation for their explanation: black holes, neutron stars, gravitational lenses, and the acceleration of the expansion of the Universe itself. Among these phenomena, the AEI's scientists work in two related areas where the potential for scientific progress is especially promising: the detection of gravitational waves and the numerical study of the emission of gravitational waves by the formation and collision of black holes and/or neutron stars.

A particularly important development for our work was the award of a prestigious Sofja Kovalevskaja Award from the Alexander von Humboldt Foundation to young AEI scientist Yanbei Chen, who arrived in late 2004. The award took effect from the beginning of 2005 and allows Chen to build up an independent research group. Chen's interests in the design of advanced detectors for gravitational waves (including the quantum theory of these immense detectors) and in the development of novel ways of searching for gravitational waves will both be served by this award. Chen has written a report on the first year of his group's activity later in this volume.

Gravitational Wave Detection

The AEI's Laser Interferometry and Gravitational Wave Astronomy Division is developing and operating the GEO600 gravitational wave detector, located near Hannover. Details of this detector and of associated collaborations on technology development with the American LIGO project can be found in the report of that division. In the Astrophysical Relativity Division, our scientists analyze the data from the GEO600 and LIGO detectors and work to understand potential sources of gravitational waves.

On data analysis, we work with our partners in the GEO600 project in Britain (at Glasgow, Cardiff, and Birmingham Universities) and in Spain (at the University of the Balearics). In addition, we contribute our data to the LIGO Scientific Collaboration (LSC), within which a large team of scientists looks for various gravitational wave sources in the data from all four detectors in both projects.

The period 2004-5 saw the continued improvement in the sensitivity of all the detectors, and repeated periods of data-taking (science runs) in which the analysis teams got more and more experience in how to process the data effectively and efficiently. Working together is not easy when members of the teams span 10 or more time zones. Scientists of our group have spent many unsocial hours in regular telephone conference calls, and on trips to the joint team meetings that are held at least four times a year. Later in this volume there is a report that gives more details of this analysis. By the end of 2005, the LIGO detector had entered the fifth observing run (S5) at full design sensitivity, and the data analysis teams were preparing to study data in which there is at last a real (although still small) chance of finding gravitational wave signals.

According to present plans, the detectors will continue to observe for some years, gradually improving their sensitivity. The network will soon be joined by the VIRGO detector, an Italian-French cooperation. At the end of the decade, major upgrades and refits of the detectors will produce a quantum jump in sensitivity, but the team hopes that the first detections will happen before then. The business of gravitational wave detection requires a steadfast commitment to careful experimental work and painstaking data analysis.

Two highlights of our data analysis development were the release of our Hough transform code and the introduction of Einstein@Home, a joint work with our LIGO partners, led by Bruce Allen at the University of Wisconsin at Milwaukee. Einstein@Home is a screen-saver program, which can be installed on any home computer, and which does real data analysis for the LSC while the computer would otherwise be idle. With a steadily increasing population of users that exceeded 50,000 by the end of 2005, Einstein@Home is delivering many teraflops of computing power and is the most important "computer" available to the LSC. The Hough transform is a method devised at the AEI for doing wide-area searches for gravitational wave pulsars; it uses available computer power in a highly efficient way. It has begun to work on LSC data and will be introduced to the Einstein@Home network during 2006.

While much of the division's work on gravitational waves is devoted to data analysis, we also maintain a strong research activity in theoretical questions, because theory and observation are closely connected in this field. Indeed, our postdoctoral research scientists who work on data analysis are also expected to work on theoretical questions for half of their research time. A number of such results deserve mention here. Badri Krishnan, our Hough Transform expert, is also an expert on "dynamical horizons", a method of defining black holes in dynamical situations where the strict definitions usual in general relativity don't apply; he has published important papers with Penn State University's Abhay Ashtekar, and he has worked to apply the method to the numerical studies of black holes performed by our computational physicists (below). Reinhard Prix has steered our searches for gravitational wave pulsars and he has also broken new ground in the study of the interiors of neutron stars; working with UK collaborators, Prix has studied the complex and fascinating physics of neutron stars that have superfluid interiors and normal-matter crusts. Yosuke Itoh worked on pulsar searches as well, and also developed the post-Newtonian approximation for the motion of binary stars to a high order using a method very different from other approaches, showing that the various assumptions underpinning the different methods lead to consistent (hence reliable) equations of motion. Linqing Wen worked with Schutz on the theory of data analysis for gravitational wave detector networks, and she also continued her earlier work in X-ray astronomy.

Of increasing importance is our work for the LISA space-based gravitational wave detector, a collaboration between ESA and NASA, expected to be launched around 2015. Cutler and division director Prof Bernard Schutz are members of the LISA International Science Team, which oversees the development of this project. We have been working to initiate early planning for data analysis for LISA, because LISA presents several unique data analysis challenges that the ground-based detectors do not. We have also been working hard to understand and resolve one or two of these challenges.

One of the most challenging of signals for LISA is the gravitational radiation from a compact object (such as a black hole formed from the collapse of a giant star) as it spirals around and eventually into a massive black hole in the center of a distant galaxy. We know that our own Milky Way has a black hole with the mass of 2.6 million suns, and astronomers believe that this is fairly typical. During the LISA mission we expect every year that there will be perhaps dozens of signals from such events involving similar black holes within the volume of space LISA can search. But picking these signals out of the noise background will be a challenge because they have a very complex form. The work at the AEI on this problem has been described in the gravitational-wave article below.

The period 2004-5 has seen important changes in the personnel of the division. Curt Cutler, who led the gravitational wave work, moved in mid-2005 to the Jet Propulsion Laboratory in California, to work within the American LISA team. Maria Alessandra Papa, who leads the pulsar analysis work, has reduced to part-time in mid-2005 and moved (we hope temporarily) to Milwaukee for family reasons. Itoh left the group but we have been joined by S Babak, who has taken on some of the group leadership functions, assisted by Yanbei Chen.

Numerical Solutions of Einstein's Equations

The other major activity in the Astrophysical Relativity Division is the effort to solve Einstein's equations on a computer in order to study situations that are not amenable to analytic solution. One problem in particular is especially important from the point of view of the gravitational wave detectors: the merger of two black holes and/or neutron stars as they spiral together from a circular binary orbit. While rare, these events are expected to be seen both by ground-based detectors and by LISA, and an adequate theoretical understanding of the gravitational wave signature of these events will greatly assist their detectability.

In our last report we mentioned the departure of the founder and leader of this group, Prof Edward Seidel, to LSU in the USA. During an interim period, Dr Denis Pollney ably stepped in as acting group leader and continued the work of this large and diverse group. I am particularly pleased to welcome Prof Luciano Rezzolla, who joined us late in 2005 as the permanent replacement for Seidel. Rezzolla comes to us from SISSA in Trieste, where he had been a partner of ours in the EU-funded Gravitational Wave Network. He is particularly well known for having developed the Whisky Code, a highly advanced and accurate software package for hydrodynamics within general relativity. With his code we are able to broaden our research from simulations involving black holes to those involving neutron stars as well.

Nevertheless, simply representing on a computer two black holes orbiting about one another is already a challenge. It requires a large supercomputer with enough memory and speed to approach solving the problem, and it requires software that solves Einstein's equations with accuracy and stability. With our Peyote supercomputer cluster and its upgrade Belladonna, we have the computer power to address these problems realistically. But we are still limited by software: through a process of trial and error, scientists at the AEI and around the world are gradually learning what is required to simulate black holes in orbit over long periods of time. The year 2005 was a breakthrough year for this study: around the world several groups including our own managed for the first time to run stable simulations of orbiting black holes for more than one orbit. This is an indication that in the next year or so one can expect rapid progress and the development of a consensus on what gravitational radiation black hole mergers produce, at least in the case of equal-mass non-spinning holes. But this is only the beginning, and we look forward to considerable activity on this problem in the future.

Another major change in the numerical area has been the restructuring of our efforts in computational techniques. The AEI has a distinguished history of software development, at the frontier of modern computing techniques. Our Cactus Computational Toolkit broke new ground in its ability to allow collaborators in diverse environments to work together and pool their expertise. Our work on Grid technology, including the Grid Application Toolkit and on web portals for interfacing to Grid applications, has been incorporated into emerging standards in the field of Grid computing. With the ending of the EU-supported Gridlab project and the advent of national German funding for Grid activities (D-Grid), we have re-oriented our work. We are focussing on developing portals and grid-enabling computer applications in astronomy, including of course Cactus. The report later in this volume from Thomas Radke describes these developments in detail.

Conclusion

The AEI celebrated its tenth anniversary in 2005, and that is a time for looking both backwards and forwards. The rapid growth of the institute in its first decade established it as a major center for research in all its core areas, including gravitational waves and numerical relativity. The investment in infrastructure, in people, and in research collaborations has in turn opened many opportunities for future research. The international gravitational wave network is well funded for the next ten years, and will be producing data – and eventually detections – abundantly. The unabated rapid improvement in computing power and in our understanding of techniques appropriate to solving Einstein's equations will soon bring very realistic and reliable results. We can look forward to increasing cooperation and interaction between the two main activities in this department as data analysts look to numerical relativists for guidance as to what to look for in their data, and as the numerical specialists tune their work to address the problems of greatest interest for gravitational wave detection. The next decade will, I hope, see the exciting harvest of the hard work that AEI scientists have invested during the first ten years.

Bernard Schutz

Quantum Gravity and Unified Theories

Research in the division "Quantum Gravity and Unified Theories" focuses on two main topics, which are quite possibly related. The first is the search for a consistent theory of quantum gravity, which reconciles the elegant geometry of general relativity with the probabilistic world of quantum physics. The second is even more ambitious - the search for a unified theory of all interactions, including gravity. Such a unified theory should encompass the well-established standard models of elementary particle physics and of cosmology.

These two searches - which, in the end, might turn out to have the same goal! - represent the greatest challenges currently faced by theoretical physics, with major conceptual and mathematical problems still waiting to be solved. So far, there is no clear favourite among the different candidate models that have been proposed - no model that can justly lay claim to being the theory of quantum gravity. Hence, the strategy of our division has long been to keep all viable options open, and to pursue a variety of different approaches. Diversity is actively encouraged, and we are one of only a few research groups world-wide in which all major approaches are represented, most notably superstring and supermembrane/M-Theory (candidates both for quantum gravity and for a unified theory) as well as canonical quantum gravity (loop and spin foam quantum gravity).

Main Research Areas of Scientific Work

Presently, the approach to quantum gravity that has the most adherents within the scientific community is superstring theory, with its extensions supermembrane and M(atrix) theory. It is a descendant of modern particle physics, but where particle theories run into insurmountable problems in the description of gravity, string theory proposes a radical modification at short distances: In this theory, the fundamental building blocks are not point-like particles, but one-dimensional extended objects called relativistic strings (or, if fermions are included, superstrings) or even supersymmetric extended objects with two spatial dimensions, called supermembranes.

What makes the theory a compelling candidate for a unified theory is the identification of quantized excitations of the relativistic strings with the different point-particles of conventional quantum field theory - in this way, the bewildering diversity of matter particles and interactions in the standard model of particle physics could be reduced to the physics of just one truly elementary constituent, the string. Also, in any string theory containing closed strings, this particle spectrum will contain a massless spin-two particle, whose self-interactions coincide with those of Einstein‘s theory at the lowest non-trivial (cubic) order. This is the base of string theory‘s claim to being a theory of quantum gravity. Still, while superstring theory is currently the only ansatz that succeeds in removing the inconsistences of perturbatively quantized general relativity, the connection with "real physics" is still far from clear.

The main task facing string theorists today is to find a non-perturbative formulation of the theory (which is sometimes dubbed "M Theory"). This problem, together with its many ramifications, has defined one of the main and most successful areas of activity of the Division.

A very different approach to finding a theory of quantum gravity is canonical gravity, or more specifically, Loop Quantum Gravity. Here, the aim is to find a background independent theory of quantum general relativity by directly implementing the basic principles underlying Einstein‘s theory, thus avoiding problems faced by perturbative approaches like string theory. Just as the absence of background structures in Einstein's classical theory of general relativity has forced physicists to re-think age-old and cherished notions of space and time, the attempts to quantize geometry without reference to any specific spacetime background have led to completely new ideas about the structure of space and time at very short distances. Much of the groundbreaking work in this field over the past few years has been done at AEI. Most recently, the formalism has been applied to cosmology, where it has spawned an entirely new field of research now called "Loop Quantum Cosmology". During the last year, this has become one of the most active fields of research at AEI. However, true to its aim of fostering diversity, AEI researchers have been involved in other aspects of canonical gravity as well, in particular in the physics and mathematics of classical and quantum gravity in (2+1) spacetime dimensions.

In the following, some research highlights and results obtained in the period 2004--2005 will be described, omitting two topics that will be presented elsewhere in this report in more detail, to wit, Kasper Peeters' account of the applications of AdS/CFT duality to hadronic physics (page 69) and Sebastian de Haro's contribution tracing the connections between the theory of Brownian motion (one of Einstein's groundbreaking publications in his miracle year 1905!) and modern string and gauge theory (page 66).

Research Highlights

Current activities in the quantum gravity division at AEI reflect the diversity of the major approaches. Needless to say, much of this work is the result of fruitful collaborations between AEI scientists and scientists from other institutions (whom will not all be named in this brief report), many of whom have spent extended periods of time as visitors at AEI during the past year.

ADS/CFT Duality and Integrability

Some of the most impressive recent results in string theory concern unexpected interconnections called dualities. In particular, the duality between gauge theories and string theory continues to fascinate theoretical physicists worldwide - and understandably so: the quantum field theories that are at the basis of elementary particle physics are gauge theories, so the gauge theory/string theory duality constitutes an unexpected, if tenuous connection between the exotic realm of quantum gravity and the down-to-earth physics currently being tested with particle accelerators!

Recent years saw a further increase in interest, as so-called integrable structures were discovered in the simplest example for such a duality, the AdS/CFT correspondence. The significance of this is as follows: Finding the fundamental equations of particle physics, or of string theory, is only half of the answer. In order to construct models (and thus to make connections with the real world!), physicists have to find solutions to their equations. Typically, this proves very difficult, and approximation schemes like perturbation theory or numerical calculations are the only way out. But matters are different in special cases when the equations in question exhibit an especially rich structure - these equations are called integrable, and with integrability, it is frequently possible to construct exact solutions!

Until recently, it seemed impossible that physicists would ever find nontrivial exact solutions in theories as complex as the four-dimensional quantum field theories of particle physics, or superstring theories on curved space-times. But with the new discoveries, this goal has suddenly come within realistic reach. Researchers at the AEI have made key contributions to these novel and surprising developments, and it might even be justified to claim that the Institute has set the pace in this rapidly evolving field in the last couple of years.

More concretely, quantum integrability is essentially equivalent to the existence of a Bethe ansatz. This technique was invented in 1931, i.e. just after the creation of quantum mechanics, by Hans Bethe, and it leads to equations that describe the exact spectrum of a quantum mechanical system. However, success is not automatic: for the ansatz to work, a crucial requirement is the presence of certain hidden symmetries. In one of the most thrilling recent developments in string theory, evidence has mounted that this is indeed the case in the AdS/CFT system!

In particular, Beisert, Dippel and Staudacher have found a Bethe ansatz which applies to the spectrum of the gauge part of AdS/CFT. The validity of this ansatz has already been proven at three-loop order in perturbation theory. An important element of the proof was an involved Feynman diagram calculation due to Eden, Jarczak and Sokatchev, and an independent calculation involving the computer-aided evaluation of approximately 1000 Feynman diagrams. Furthermore, Arutyunov, Frolov and Staudacher have proposed a similar ansatz for the string part of the correspondence. While structurally similar to the gauge case, the two ansätze also differ in a subtle fashion; however, the issue has not yet been resolved and promises deep insights into the nature of gauge-string dualities in the future. The above Bethe ansätze were initially derived for only a part of the full spectrum. Recently they were extended by Beisert and Staudacher to the general case.

Furthermore, interesting cross-connections between the gauge ansatz and a well known model of condensed matter theory, the so-called Hubbard model, have been exposed by the work of Rej, Serban and Staudacher. This indicates that not only is there an intricate connection between quantum string and gauge theory, but, even more suprisingly, these two are also related to sophisticated solid state models of a type relevant for the description of high temperature superconductivity!

In the context of this research topic N.Beisert wrote his dissertation "The dilatation operator of N=4 super Yang-Mills theory and integrability" (advisor: M. Staudacher). As an indicator of the remarkable impact of this work, this thesis was recently published in its entirety in the prestigious review journal Physics Report - an unprecedented occurence.

The string Bethe equations just mentioned pass a number of important tests. In order to test genuine quantum string features of these equations, we have recently performed a detailed comparison between the predictions for the quantum corrections of the string energies following from the Bethe equations and the results obtained by a semiclassical quantisation of string solitons (M. Zamaklar, S.Schafer-Nameki, K.Zarembo). As it turns out, the Bethe equations correctly and reproduce the results which have direct counterparts in gauge theory - a highly non-trivial test of their validity. However, they miss a whole tower of terms non-analytic in the coupling, which is a clear indication that the final form of the quantum string Bethe equations has not yet been found. What form the modification should take to bring the Bethe equations in line with semiclassical string results is still an open question which is under active investigation.

Integrability is present only for free strings, which correspond to the so-called planar limit of the gauge theory. However, for a solid understanding of the AdS/CFT correspondence, free strings are not enough - one must include genuinely dynamical processes involving string interactions. To this end, we focused on studying simple toy examples for splitting macroscopic spinning strings in AdS space. By constructing an appropriate, explicit, time-dependent gauge theory solution, they have been able to identify the resulting decay products and compare them to the string theory calculations. Their study has led to new predictions for correlators in gauge theory, and to an interesting suggestion for how integrability might "survive" the transition from free strings to non-zero coupling: While it is known that non-planar processes break integrability, we were able to show that correlators dual to the the most dominant string decay processes should still preserve it (Peeters, Plefka, Zamaklar).

In another interesting development, Peeters and Zamaklar in collaboration with J. Sonnenschein have initiated a promising program to establish the connection between modern string theory and a phenomenologically successful model for the strong interactions - the Lund model.

Last but not least, I must mention the research of S. Frolov, who has recently joined the AEI as a long-term staff member. It includes seminal work on certain natural deformations of the original AdS/CFT correspondence, in particular a non-supersymmetric example for this kind of duality. Taking the duality beyond supersymmetric models is of crucial importance if string theory is to teach us anything about the gauge theories at the core of the standard model of elementary particles, more concretely: if we intend to find a string theory dual to the (non-supersymmetric) theory of strong nuclear interactions, quantum chromodynamics. Judging by results that Frolov obtained after joining our division, the impressive agreement between gauge theory and semiclassical strings in the original AdS5 x S5 geometry is merely one part of a larger, much more general picture.

Finally, Frolov has successfully continued his joint work with former AEI staff member Arutyunov (now a professor at Utrecht University) on the direct quantization of the string side of the string theory/gauge theory correspondence. It is hoped that their approach will eventually lead to a derivation of the correct Bethe equations from first principles.

Loop Quantum Gravity

Where string theory approaches the problem of quantum gravity from the direction of particle physics, Loop Quantum Gravity (LQG) chooses a more direct line of attack, facing squarely up to the conceptual difficulties resulting from the fact that gravity is not just another interaction, but intimately connected with the geometry of space and time. As a result, LQG is one of the few approaches which by its very definition is not in conflict with Einstein's equations, but instead incorporates the dictum that geometry is not a given, but must be determined dynamically in interaction with the prevailing matter according to Einstein's equations. Much of the progress in this field over the past two years is due to work done at AEI, most notably by T. Thiemann and M. Bojowald, and their collaborators.

In order to combine general relativity and quantum theory, Loop quantum gravity researchers had develop a wealth of new mathematical tools. Their effort was rewarded by the emergence of a new picture of space and time. It replaces the space-time continuum of Einstein's theory by a discrete structure - at small length scales, space and time turn out to behave very differently from what general relativity predicts. While these scales are currently not accessible to direct observations, the modified properties should have consequences for the physics of the very early

universe and in the vicinity of black holes.
The corner stone of quantized general relativity are the quantum Einstein equations, an infinite set of Schrödinger type of equations. However, while a simple prototype for this kind of equation is readily written down, the highly complicated structure of Einstein's equations makes it very difficult to formulate their quantum version in a mathematically rigorous manner and to prove the existence of solutions. Within the LQG approach, research undertaken at AEI in recent years has led to substantial progress in this regard (T. Thiemann and B. Dittrich).

With the existence of solutions proven, one focus of current research addresses a more specific question: What are the solutions of physical interest? In particular, what are the solutions corresponding to cosmological models - solutions that could eventually be tested against recent high precision observations, such as the measurements of the WMAP satellite?
In finding a general answer to these questions, one major complication is the fact that general relativity involves an infinite number of degrees of freedom - at every point in space, curvature and distortion can vary as part of the dynamical evolution. An obvious simplification is to begin with drastically simplified models in which all but a finite number of degrees of freedom is switched off. An especially simple example would be a universe that is completely isotropic and homogeneous, whose evolution depends on a single scale factor governing that universe's expansion or collapse. Quantizing such toy models with the methods of LQG leads to what is called "Loop Quantum Cosmology", another major research area at AEI. Using Loop Quantum Cosmology models, researchers have been able to verify a number of intuitive expectations, especially regarding the occurrence and nature of singularities.

Singularities are an awkward feature of general relativity - regions at which spacetime comes to an abrupt end, usually while quantities like energy density and spacetime curvature take on unphysical infinite values. It is a long-held hope that the transition from classical to quantum gravity will somehow resolve these highly problematic features of spacetime. Indeed, this hope was realized several years ago in the most highly symmetric cosmological models which are homogeneous and isotropic. As it turned out, no singularities arise in isotropic loop quantum cosmology. In those space-time regions where classical evolution would break down, as shown by the presence of a singularity, quantum evolution continues undisturbed. This is a direct consequence of the discrete nature of space and time.

The last two years have seen much progress in an extension of these results to less special models - some of them even including inhomogeneities. In particular, it has been shown that not only can cosmological singularities be avoided, but also the singularities characteristic for classical black hole solutions - both under stringent symmetry assumptions and when some inhomogeneities are permitted. Taken together, for the most typical classical examples of singular space-time structure, there are now corresponding non-singular results from Loop Quantum Cosmology (M. Bojowald and collaborators).

There is, however, a weighty caveat. Loop Quantum Cosmology is not to be confused with the application of full LQG to cosmology - to start with a simplified model universe and then apply quantization methods to obtain a quantum universe will not necessarily lead to the same result as to start with a full theory of gravity, namely LQG, and then construct simplified solutions of that full theory. Thus, it is very important to study in how far the drastic simplification represented by Loop

Quantum Cosmology does indeed lead to physically meaningful results. This is one of the questions that have been under intense study at AEI in the last two years. While the general singularity structure remains to be understood, recent work in full LQG has yielded interesting preliminary results, and identified the mathematical hurdles still barring a more general analysis. In consequence, it is now possible to compare results of symmetric models with some properties in the full theory, and so far none of the comparisons has led to any inconsistency. Instead, crucial aspects of more general geometrical configurations have been uncovered which will play a role in shedding more light on the singularity structure. In parallel, the program of deriving symmetric models from the full theory has made considerable progress. In view of these developments, there is now cautious optimism that a crucial milestone may be reached during the next years: the derivation of solid and reliable predictions to be tested by cosmological observations.

Among the more mathematical aspects of LQG that are under study at AEI are so-called spin foam models. They can be regarded as "covariant" versions of (canonical) loop quantum gravity - structures that embody Einstein's relativistic dictum that, as far as the laws of physics are concerned, all observers are on an equal footing, and all coordinate systems equally suitable for describing the universe. Once more, there is a highly interesting mathematical connection, this time with the so-called topological quantum field theories (TQFT). TQFT are very simple models that combine the rules of quantum theory with the symmetry corresponding to observer equality ("symmetry under general coordinate transformations"). Since, in this respect, they have the properties that can be expected of a more complete theory of quantum gravity, they can serve as useful toy models.

It turns out that for TQFTs in 1+1 space-time dimensions (unrealistic, since our own universe has 3+1 dimensions), there exists a complete mathematical classification scheme. For TQFTs in 2+1 space-time dimensions (still unrealistic), it is not known whether they can be classified, but one can systematically construct families of interesting examples. For the most interesting case of 3+1 space-time dimensions, however, there is a huge gap in our mathematical understanding - only very few examples are known, and none of the holds much interest for physics. The paucity of examples directly reflects the deficiencies of the known mathematical techniques for dealing with this type of theory.

Part of the research undertaken at AEI is aimed at making progress in this particular area. The objects under study include novel (and rather fancy!) mathematical structures such as "Hopf categories" and "monoidal 2-categories", which promise to bridge the gap between our understanding of lower-dimensional TQFTs and the crucial 3+1-dimensional case. Among the more recent results obtained in this direction is the classification of TQFTs in 1+1 dimensions to spaces that can have certain boundaries. Coincidentally, this result is also of relevance to string theory, as the space-times that appear in this sort of TQFT are precisely the surfaces swept out by propagating open and closed strings, and their boundary conditions describe what string theorists call "D-branes" (H. Pfeiffer).

Black Holes and String Theory

Black holes are fascinating objects for the layman as well as for the expert and an important testing ground for any proposed theory of quantum gravity, such as string theory. Since the 1970s, it is known that black holes are thermodynamic objects - for instance, one must assign to a black hole both a temperature and an entropy. However, in ordinary thermodynamics, entropy is, roughly speaking, directly related to the disorder of the system in question. For a gas, the number of different ways in which the molecules can zip back and forth producing the observed pressure and temperature is a direct measure of the entropy. What, then, if anything, is the microscopic structure behind black hole entropy?

To part of this question, string theory has given a surprising answer. String theory is most naturally formulated in ten space-time dimensions. It can, however, be used to describe a universe like ours in which there are only four large dimensions (three of space and one time dimension), while the additional six space dimensions are rolled up on a tiny length scale, so as to be unnoticable in everyday life. With the help of these extra dimensions, as well as of extended objects called "branes" that are another ingredient of the theory, it is possible to describe four-dimensional supersymmetric black holes as branes wrapped around the compactified extra dimensions (a higher-dimensional and more complicated analogue of wrapping a donut with shrink-wrap). Microscopically, such configurations are characterized by a set of quantum numbers (such as winding and flux quanta).

This is what provides the microscopic description of black hole entropy. The connection with the classical results can be made when the quantum numbers are sufficiently large - a phenomenon typical for quantum theory and similar to the transition in which a collection of a large number of quantum objects like atoms can be viewed as an ordinary, classical piece of matter. These brane configurations with large quantum numbers can be regarded as black hole solutions of a corresponding effective low-energy gravity theory. In the four-dimensional gravity description, the wrapped branes enter as sources and carry the microscopic quantum numbers as electric and magnetic charges.

In the mid-nineties it was found that to leading order (in the limit of large charges) the microscopic entropy precisely reproduces the Bekenstein-Hawking area law for black hole entropy. But the Bekenstein-Hawking law is itself the result of a semi-classical calculation. How does the correspondence between brane configurations and black holes hold up when quantum gravity is taken into account more fully - in particular the corrections that can be derived from string theory or its even more fundamental kin, M-theory? This is a question on which substantial progress has been made in recent AEI research.

Beyond the semi-classical picture, there are, first of all, subleading corrections to the microscopic degeneracy of states, which are explicitly known in various setups such as M-theory compactifications. Recent progress has culminated in the proof that in the effective gravity description, these subleading corrections are fully accounted for by including a certain class of higher-derivative interactions involving terms quadratic in the Weyl tensor and supersymmetrizations thereof. Such terms are particular quantum string corrections and can be traced back to the quantum corrections of ten-dimensional string or M-theory. The four-dimensional correction terms are multiplied by functions depending on the compactification parameters, which in turn can be calculated using methods of topological string theory (J. Käppeli, P. Prester).

When including such higher-derivative interactions the analysis of black hole solutions and their entropy becomes very complicated. Nevertheless many of the key features of the unperturbed black hole solutions, such as the socalled attractor mechanism, can be proved to still be valid. Taking the various complications into account one precisely reproduces the subleading corrections of the microscopic entropy. Even under these highly non-trivial extensions, the correspondence holds true (J. Käppeli).

This analysis has recently been extended to dyonic black holes (i.e. black holes with electric and magnetic charges) of N=4 string theory, for which the microscopic degeneracy of states are encoded in certain explicitly known mathematical entities called modular forms. It was demonstrated that the subleading corrections to the black hole entropy are captured precisely by the asymptotics of this state degeneracy. Furthermore, a conjecture about the relation between the black hole partition function obtained from the microscopic degeneracies and the partitional function of the topological string could be shown to agree at leading order. At the subleading order the partition functions of black holes and of topological strings are related if certain measure factors are included. These factors can be derived based on arguments of electric-magnetic duality covariance.

While black holes in four dimensions are those relevant for our universe, some details of black-hole physics are more easily accessible for their three-dimensionsal cousins. To this end, AEI researchers have studied three-dimensional black holes in theories with gravity coupled to scalar fields and gauge fields, so-called hairy black holes. This has led to a remarkable discovery: Once one has adapted the equations to the black-hole environment, the system posesses a scaling symmetry, regardless of which potential is chosen for the scalar field. By Noether‘s theorem, such a symmetry leads to a conserved charge: an expression constructed from the black-hole solution which does not change as one moves radially away from the black hole. Making use of this charge, it was possible to derive relations between the entropy, mass, angular momentum and electric charge of the black hole, neatly connecting those properties of the black hole defined directly at the horizon (the “edge” of the black hole) and those properties defined at infinity. Remarkably, these relations are independent of the precise form of the potential, the only condition being that the equations of motion allow for black hole solutions. For this reason one can also discuss under which conditions this symmetry survives a generalization to higher dimensions (S. Theisen).

Finally, black holes have an intimate connection with the AdS/CFT correspondence mentioned in the previous section. In this regard, previous investigations of so-called holographic anomalies were continued during the past two years. So-called Chern-Simons gravity theories, which can be formulated in any odd dimensional space-time, possess Anti-de-Sitter solutions and are thus an interesting arena for the AdS/CFT correspondence. They are also particular examples of higher-derivative gravity theories about which little is known in the context of the correspondence but which are relevant for the duality between string theories and interesting conformal field theories on the gauge theory side - such as supersymmetric Quantum Chromodynamics in its conformal window which, as has been suggested, could be described by a non-critical string theory. For Chern-Simons gravity one can then compute the Weyl anomaly in any dimension and construct the corresponding stress-energy tensor for the dual partner theory. The extension to more general higher derivative theories is still an open problem, and probably requires a case-by-case analysis (S. Theisen).

BKL Dynamics, Cosmological Billiards and Hidden Symmetries

As mentioned before, the existence of singularities in many physically realistic solutions of Einstein‘s field equations is a central problem in general relativity. The most prominent of these is the “big bang” singularity that is part and parcel of the classical cosmological models used to describe the evolution of our universe.

In all generality, the dynamics of a physical system like the very early universe, filled with inhomogeneities and with a strong coupling between geometry and matter, is impossible to describe. But remarkably enough, more than 30 years ago, an ingeneous method was devised by Belinski, Khalatnikov and Lifshitz (=BKL) to study the behaviour of such a universe very close to its initial singularity. Extending their early analysis of cosmological singularities in Einstein's theory, and generalizing it by including new kinds of matter, a new description has been developed by T. Damour (I.H.E.S., Bures), M. Henneaux (Brussels University) and H. Nicolai (AEI). The new description relies on the reformulation of the problem in terms of a "relativistic billiard" that can serve as a very general framework for the analysis of such singularities.

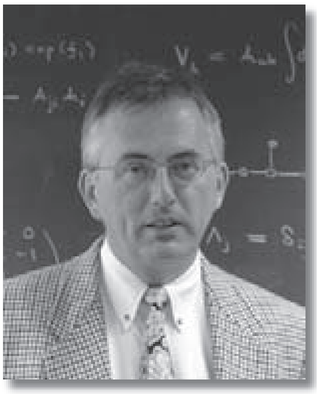
For this analysis, one considers a universe that began with an initial singularity (in technical terms, a space-time with an initial singular space-like hypersurface at cosmic time t=0). According to the BKL hypothesis, Einstein's equations will simplify drastically in the vicinity of this singularity. Ordinarily, these equations depend in a complex way on how geometry and matter properties change from point to point in space. In the vicinity of this singularity, spatial changes (that is, changes "along" the singular hypersurface) become less and less important compared with time derivatives. This intuitive picture can be made more precise by showing two things: First of all, the infinite possibilities of variations from point to point in space (the infinite number of degrees of freedom encoded in the spatially inhomogeneous metric, and in other fields) are drastically reduced - they are frozen in the sense that all spatial variations tend towards some finite limits near the singularity. Secondly, the dynamics of the remaining "active" degrees of freedom tend towards a surprisingly simple description: Asymptotically, it can be described in terms of a simple "billiard dynamics". In a simplified game of billiards, a single ball rolls around a table with constant speed, changing its direction only when it hits one of the borders and is reflected. The evolution of the simplified early universe near the singularity is very similar - it moves freely within a higher-dimensional configuration space, except when it is reflected at one of a number of "walls" located within this space.

As if this transition were not remarkable enough already - from a chaotic, intractable early universe to the supremely simple dynamics of billiards - the walls themselves have a profound relation to much more abstract mathematics. Mathematicians have a keen interest in classifying all instances of a given mathematical structure. For Lie algebras - structures similar to the mathematics that can be used to describe rotations in three-dimensional space -, there exists a sophisticated classification scheme. It makes use of ingenious methods for recasting a given algebra in the form that shows best its role within the general classification. Part of this recasting are so-called "Weyl-chambers", and true to their name, these Weyl chambers can be pictured as regions enclosed by walls. Here is the profound relation: In many interesting physical theories, the "billiard table" encoding the dynamics of the active degrees of freedom of the early universe is not just any arbitrary collection of walls. It can be identified with the Weyl chamber relevant for a certain class of (infinite dimensional) Lie algebras called indefinite Kac Moody algebras.

In their turn, a number of these algebras turn out to be related to the concept of supersymmetry - the way to treat the bosons and fermions of a field theory on an equal footing, and a central ingredient of string theory. Of particular interest in this context is the maximal hyperbolic Kac Moody algebra E10 related to maximal supergravity in D=11. As first shown by Damour, Henneaux and Nicolai, one can make a precise identification between the quantities obtained from a geodesic action on a certain infinite dimensional manifold (coset space) possessing E10 as an 'isometry', and the fields of D=11 supergravity and their spatial gradients evaluated at a given spatial point. So far, this correspondence works for suitably truncated versions of both models, but there are indications that it extends to higher order spatial gradients, indicating that the full geometrical data of the (super)gravity theory in question can be mapped onto a geodesic motion on the group theoretically defined abstract space of infinite dimension.

Recent work at AEI (Kleinschmidt, Nicolai) has been concerned with obtaining a more uniform view of the E10 model, and with the study of various other truncations of this model related to type IIA and typeIIB supergravity in D=10. To obtain the equivalence map, one first needs to compute a part of the generators and structure constants and determine the corresponding coset equations of motion. This can be done using specifically designed computer programs. On the supergravity side the equations of motion have to be truncated in such a way that one retains only first order spatial gradients of the fields. The result of these investigations is that the E10 model then can be matched exactly not only with the maximal eleven-dimensional theory, but also with the massive IIA and chiral IIB supergravity theories. This is all the more striking because the E10 model is essentially unique; simply by grouping the same generators differently one can make contact with all maximal supergravity theories, displaying a remarkable adaptability of the E10 model. Present work in progress deals with extending these results to include more degrees of freedom, i.e. relaxing the truncation criteria, and with matching the E10 root lattice with the higher order corrections in the Riemann tensor and four-form field strenghts predicted by string theory (T. Damour, A. Kleinschmidt, H. Nicolai).

Most recently, the incorporation of fermions into this scheme has been studied, identifying a new type of hidden symmetry acting on the fermions (which might be called 'R symmetry' in analogy with similar symmetries occurring in supersymmetric models of a more standard type). This result is important because it demonstrates that the suspected hidden symmetry of supergravity as part of a unifying theory (like string theory) is compatible with supersymmetry that is it acts both on the fermions and on the bosons in a compatible manner. In the course of these investigations many interesting facts about these infinite dimensional symmetries have been discovered. In particular, it has become clear that the 'R symmetry' acting on the fermions is of a rather unusual type, such that many of the standard mathematical tools and techniques for analysing it are not available. Since the advent of supergravity almost thirty years ago it has been repeatedly demonstrated that supersymmetry is a highly constraining and therefore very powerful property of the theory. Because the basic compatibility of supersymmetry with the infinite dimensional E10 symmetry has now been established, one can hope that there is more to be learned from studying the supersymmetric aspects of these models.



Hermann Nicolai

Laser Interferometry and Gravitational Wave Astronomy

Since January 1st of 2002, experimental gravitational research has a permanent home in the enlarged Albert Einstein Institute. In addition to the three theoretical divisions in Potsdam-Golm, the Teilinstitut Hannover will comprise two divisions, concentrating on experimental aspects, detector characterization and observations. Currently, one division is fully staffed in Hannover and we expect the second division to become operational during 2006. All activities in Hannover are a joint undertaking of the Max Planck Society and the University of Hannover.

All laboratories and experiments of the AEI in Hannover were moved into a new laboratory building after construction had finished in the fall of 2003. At the same time, all offices were moved into temporary quarters for complete remodelling of the office building. Construction was finished in early 2005 and by the end of April 2005 we have moved into our completely remodelled office building, providing excellent working conditions to all members of the AEI in Hannover.

The central focus of all our work is the development of multi-wavelength gravitational wave astronomy as a new field of science to study the universe. This involves the development and operation of large-scale facilities and observatories on the ground as well as in space, but also a full range of fundamental experimental work in quantum optics and classical optics, atomic physics and laser science.

Our ground-based gravitational wave detector GEO600 was built as a German-British collaboration comprising the Max Planck Institute for Gravitational Physics, the Max Planck Institute for Quantum Optics, the University of Hannover, Laserzentrum Hannover (LZH), University of Glasgow, Cardiff University, University of Birmingham and University of Palma de Mallorca. We are part of the LIGO Science Collaboration (LSC), participating in the initial LIGO observations with GEO600 under a reciprocal data sharing agreement and we are actively participating in the design and realisation of the second generation upgrade of the LIGO observatory (Advanced LIGO). We are collaborating with the French-Italian VIRGO project through the EGO (European Gravitational Observatory) Consortium in the framework of the EC funded Integrated Infrastructure Initiative ILIAS in a Joint Research activity on thermal noise and in a Networking Activity with working groups on detector commissioning, advanced detector development and data analysis.

Gravitational wave activities in Germany are funded by the Deutsche Forschungsgemeinschaft (DFG) through the Sonderforschungsbereich TR7 “Gravitationswellenastronomie”, comprising the universities of Tübingen, Jena and Hannover and the Max Planck Institutes for Gravitational Physics and Astrophysics. Our quantum optics activities are funded by the DFG Sonderforschungsbereich 407 (Quantum Measurement), comprising the University of Hannover, the Physikalisch-Technische Bundesanstalt (PTB) and Laserzentrum Hannover (LZH).

For the space detector LISA we are part of an international collaboration of ESA and NASA, with payload contributions from European national member states. In particular, for LISA Pathfinder (formerly SMART II), the technology demonstration space mission for LISA, to be launched by ESA in 2009, we serve as Co-PI and are responsible for the supervision of the industrial architect to coordinate the complete multinational consortium providing the LISA Technology Package, funded by Deutsches Zentrum für Luft- und Raumfahrt (DLR). For the LISA mission itself, to be launched in 2015, the AEI in Hannover carries responsibility for the Co-Chair of the joint ESA/NASA LISA International Science Team (LIST) and in Potsdam-Golm for the Co-Chair of the LISA theory working group.

On January 1st 2006, the International Max-Planck Research School on Gravitational Wave Astronomy at the University of Hannover started operating. The IMPRS will exploit the unique environment provided by the close collaboration between the AEI in Hannover and Potsdam and the University of Hannover with its institutes for gravitational physics, quantum optics and theoretical physics and the Laserzentrum Hannover. The education provided in this IMPRS will cover the complete scope of the field from classical interferometry over non-classsical light, laser sources, matter waves, to source modelling, observations and data analysis. So far, no graduate study program tailored to the specific needs of this field exists anywhere in the world.

GEO 600 - A Ground-Based Gravitational Wave Detector

At this time (February 2006), we see GEO600 operating in close to its final configuration. We have made several improvements and changes that made it possible to operate GEO600 as the first kilometre-sized power and signal recycled laser interferometer. Over the last two years, the sensitivity at 100 Hz has been improved by over a factor of a thousand and at 500 Hz by more than a factor of one hundred. We have participated in the S3 science data-taking run December 2003 to January 2004 in coincidence with the two LIGO observatories, the S4 data-run in February and March 2005, and in January 2006 we have joined in night and weekend mode the long S5 data run started by LIGO in November 2005. In May 2005 this data taking was extended to 24 hour operation.

The lock acquisition is now greatly facilitated by the installation of a high performance active vibration isolation system for low frequencies. A major breakthrough was the development and implementation of a new lock acquisition topology for the signal recycling, based on offset locking to power in a sideband. Fine tuning of the interference quality in the Michelson Interferometer is now achieved by adaptive optics technology, based on differential mirror heating. This slightly distorts the mirrors to adjust the radius of curvature of the reflected optical wavefront for best interference. The complete GEO600 interferometer is under control of an interferometric autoalignment system for all

degrees of freedom, including the signal recycling. The system is so stable that under normal operating conditions it will always autonomously recover from a disturbing event within a few minutes without any operator intervention. An active feed forward system for mirror alignment assists this process. This remarkable stability was demonstrated during the S4 data-run, while GEO600 was operating over 31 days with better than 97% duty cycle.

The commissioning and noise hunting for GEO600 has been made possible by detailed modelling calculations, both in the time and the frequency domain. These permit noise projections from the various potential input noise sources into the apparent strain noise of the interferometer. This way the complete spectral sensitivity distribution for GEO600 can be analysed as a function of the various control sideband resonances on the laser light. Our interferometer modelling environment FINESSE makes it possible to optimize the various length parameters and, in particular, the demodulation phases for signal recycling and Michelson control. A detailed look-up table for the interferometer control parameters is thus generated for a stepwise microscopic position shifting of the signal recycling mirror to tune the interferometer sensitivity curve to lower frequencies after the first lock acquisition has been achieved at 2.5 kHz detuning.

The absolute strain sensitivity of GEO600 is now routinely obtained on-line by an extension of the old time domain calibration of the power recycled GEO to a calibration system for both output quadratures of dual recycled GEO600. By appropriate waiting of the two output quadratures, an optimal calibration of the sensitivity of GEO600 is achieved. An alternate calibration method by periodic radiation pressure actuation of a mirror with a modulated laser diode is available and agrees with the standard calibration to better than 15%. The GEO600 data system is stable and reliable, several veto strategies have been developed for spurious events and an online monitoring pipeline of the GEO600 data is running routinely to generate GEO600 summary reports accessible on the web. A robust veto strategy has been formulated to veto spurious instrumental burst events appearing in the GEO600 data by making use of the measured coupling between detector subsystem behaviour and the main detector output through noise projection with measured transfer functions.

All these efforts enabled us in January 2006 to join the long S5 data taking run started by the LIGO observatories in November 2005. GEO600 is now operated in close to final configuration with signal recycling tuned to 332 Hz. This results in a peak sensitivity of $4 \times 10^{-22}/\sqrt{Hz}$ in broad band operation. The sensitivity stays better than $10^{-21}/\sqrt{Hz}$ from 170 Hz up to 2 kHz. We are operating the interferometer with half the maximum available laser power and the laser power build-up in the power recycling cavity is more than a factor of thousand. We are currently participating in the S5 run in a night and weekend mode with commissioning continuing during the daytime. After we reach design sensitivity later this year, we will join S5 in 24 hour operation.

Advanced LIGO, EGO and Advanced Interferometry

The first generation of large gravitational wave detectors is going into operation now. The experimental sensitivity is approaching the design sensitivity rapidly, but it will not necessarily be sufficient for serious astronomical observations and maybe not for a first detection. The observatories were always foreseen to go through a series of well planned upgrades with ever increasing sensitivity.

We have been actively participating in the design of Advanced LIGO, the second generation upgrade of LIGO. The systems design has now been finished and it incorporates several GEO600 technologies like multiple pendulum vibration isolation, monolithic suspensions, signal recycling and resonant sideband extraction. We are proposing to contribute to the construction of Advanced LIGO and participate in the observations with the advanced instrument, which are now expected to commence in 2013. In Europe, we have intense interactions between GEO and the VIRGO project, which is now under the umbrella of EGO, the European Gravitational Observatory Consortium. These interactions range from Joint Commissioning to design and technology development for third generation gravitational wave detectors and are coordinated under the EC Integrated Infrastructure Initiative ILIAS. GEO600 itself will be operated after reaching its design sensitivity for at least two years in data-taking mode and will then go through a series of incremental upgrades to improve the sensitivity at high frequencies in particular, by incorporating higher power lasers, new optics and non-classical light (GEO-HF).

The Garching 30m-prototype in the basement of the Max-Planck-Institute for Quantum Optics was closed down at the end of the year 2003, but in the last few months of its life it provided the first demonstration of variable bandwidth signal recycling by using a thermally tuneable solid Fabry-Perot etalon as a signal recycling mirror in a fully suspended interferometer. This technique has then been further developed in Hannover on a prototype of a thermally tuneable etalon with GEO600 optics parameters and suitable for later use in the GEO600 interferometer.

Laser development and stabilization is continuing to be a major effort in our research programme for a next generation gravitational wave detector. Correlations of the various noise processes in monolithic miniature diode pumped Nd:YAG lasers (non-planar ring oscillators, NPROs) are now well understood and simultaneous reduction of both amplitude and frequency noise can be reliably achieved by feedback to only one parameter. Particular attention received the current lock technique, where feed back to the pump diode current is used to control the NPRO output frequency. Very high gains have been possible by increasing the unity gain frequency up to 200 kHz. Cross coupling of Schawlow-Townes noise has been identified as a limiting factor in simultaneous frequency and amplitude stabilization.

Current efforts together with the LZH are aimed at the development of a very stable 200W laser system for future detectors. The work is largely driven by our responsibility as chair of the LSC laser working group, but the developments will be useful for all future gravitational wave observatories. Currently an output power of 197 W in polarized single frequency operation, injection-locked to a 12W intermediate master laser, can be achieved. Intensity noise levels in the range of $10^{-9}/\sqrt{Hz}$ can be achieved for this laser system at Fourier frequencies above 10Hz, and work is going on to understand in particular the discrepancies between in-loop and out-of-loop measurements. An important part of this investigation is a study of the geometrical mode content of the laser beam and its temporal stability.

New interferometer layouts may be necessary for future generations of gravitational wave observatories. We have been studying three- and four-mirror coupled cavity layouts for such detectors. Three-mirror cavities were studied experimentally and theoretically as a first step towards more complicated arrangements. It could be shown that reliable locking schemes can be generated. For four-mirror cavities, the multi-dimension parameter space has been characterised using an analytic sensitivity description as an input to numerical parameter studies. It could be shown that a wide variety of sensitivity curves can easily be generated this way, but no particular sensitivity advantage over the currently foreseen Advanced LIGO configuration could be achieved.

Thermal noise is expected to be a serious hurdle for the sensitivity improvements on future generations of gravitational wave detectors. Thermal noise in suspensions and mirror substrates has been studied for some time, it now seems that thermal noise in the dielectric multi-layer mirror coatings may be a particularly hard problem to deal with. We are attempting to study coating thermal noise, using a specially designed dielectric stack that incorporates a short Fabry-Perot etalon, buried inside a multi-layer dielectric coating using a read-out scheme based on our previous work on three-mirror linear cavities.

Diffractively coupled interferometers may be an important way to avoid problems for thermal noise, thermal loading and wavefront distortion in transmitted optical components. We have begun a collaboration with the University of Jena to develop and study very low loss diffraction gratings, useable as cavity couplers and beam splitters in gravitational wave detectors. As a first step, we have concentrated on diffraction gratings as cavity coupling devices, both in a high diffraction efficiency and in a low diffraction efficiency version. We could demonstrate an all-reflective cavity with a finesse of 1600, using a grating with 99.6% first order diffraction efficiency in first order Littrow geometry. We have also been able to demonstrate a new cavity coupling concept, using a low diffraction efficiency grating that was generated by overcoating a shallow binary grating written into the mirror substrate with a low-loss dielectric stack. A finesse of 400 was obtained for a second order Littrow coupling geometry in excellent agreement with our theoretical analysis of the phase relations at a generic three-port device applied to Fabry-Perot cavities. The work is now extended towards more general three-port coupled interferometric topologies and experimentally towards even higher finesse.

Strongly dispersive media may be useful for a variety of interferometric applications to slow down and store light, to realize superluminal group velocities, or to realize broad-band optical cavities. We have concentrated our experimental investigation of degenerate closed atomic two-level systems on the F=2 to 3 and F=4 to 5 hyperfine transitions in the Caesium D_2 line. In the second case, the absorption signal of the probe shows electromagnetically induced absorption, while simultaneously the pump exhibits electromagnetically induced transparency. Also, the potentially useful Kerr non-linearity in the second case is much higher than in the first. We have achieved and measured very large higher order non-linear components of the refractive index, were both, n_2 and n_4 are approaching values of 10^{-3} (in units of mW/cm), thus being 10 orders of magnitude larger than optical Kerr coefficients for optical glasses.

In the same system we could obtain light-induced birefringence because the spontaneous decay of the differently populated Zeeman levels creates an alignment which makes the atomic sample anisotropic. To obtain these measurements, a new diode laser was developed that combines the advantages of grating coupled diode lasers and diode lasers with a resonant optical feedback.

In a separate theoretical study, we have compared potential schemes to realize a white-light cavity and could show that the system using two closely spaced gain lines may provide a number of advantages over the previously considered strongly driven two-level system, in particular a lower driving field strength, larger dispersion and adjustable frequency range for the negative dispersion. This white light cavity using a gain doublet achieves transparency and l-compensation by off-resonant pumping on the Caesium D_2-line.

The standard quantum limit for the sensitivity of laser interferometers will soon be reached by second generation gravitational wave detectors. Fortunately, it is now clear that this no longer has to be regarded as a fundamental limit and we have started a research program on non-classical interferometry. Already our first studies on opto-mechanical effects in interferometers show that any interferometer using detuned signal recycling can show sensitivity curves that go below the standard quantum limit. This analysis has since been refined and extended to include beamsplitters with finite mass and optical and opto-mechanical resonances with three-mirror and four-mirror cavities. In addition to these mechanical Kerr non-linearities due to radiation preasure driven motion of the mirrors, the effects of introducing an optical Kerr medium in the arms of an interferometer have been analysed in a linearized treatment, the transfer function of the Kerr-interferometer calculated and the resulting intra-cavity squeezing shown.

A general analysis of interferometer schemes with detuned signal recycling cavity has been performed to compare Michelson and Sagnac Interferometers. In the Sagnac Interferometer no additional opto-mechanical resonance is obtained, due to the speed meter properties of the Sagnac, but instead optical inertia of the test masses at low frequencies is predicted.

To find a better squeezer design, the phase relations of fundamental and frequency doubled wave in a non-linear cavity have been calculated and second harmonic generation squeezing has been demonstrated. A major break-through was the success in setting up a bench-top dual-recycled interferometer that achieved a broad-band sensitivity improvement of several dB, using squeezed light with the frequency dependent squeezing angle.

The benefits of using squeezed light in interferometric measurements have been investigated by analysing several configurations that lead to a sensitivity improvement in interferometric measurements. In particular, the effects due to frequency dependent squeezing, achievable through filter resonators, were shown and their applicability for shot-noise dominated interferometers predicted.

The experimental squeezing effort using optical parametric amplifiers has been directed at achieving larger degrees of squeezing at lower frequency. After first experiments showed squeezing of 0.5 dB, we now routinely achieve 3.5 dB of squeezing and 6 dB seem very feasible. In stably locked operation we have achieved squeezing all the way down to frequencies of 80 kHz, and lately have observed squeezing down to 3 kHz, while trying to push the limit even further down into the gravitational wave frequency band. The quantum state of the produced light field can by stably and reliably characterized by a quantum tomographic analyser that employs a stably controlled phase at the homodyne beamsplitter. The predicted generation of squeezed light with a frequency dependent rotation of the squeezing phase by reflection from a detuned Fabry-Perot cavity could be demonstrated this way.

LISA and LISA Pathfinder, Laser Interferometers in Space

LISA is a collaborative ESA/NASA project for a gravitational wave detector in space with 5 Mio. km armlength, comprising three spacecraft at the corners of an equilateral triangle. The launch is currently foreseen for 2015. The AEI has been involved in the LISA mission since its very inception, being among the original proposers to ESA in 1992. In early 2005, LISA has made a major step forward by entering into the so called mission formulation phase. The AEI in Potsdam-Golm and Hannover is closely involved in this formulation phase, providing the European Co-Chair of the LISA International Science Team (LIST, appointed by ESA and NASA) and the European Co-Chair of the LISA theory working group.

We have also performed laboratory and breadboarding activities to accompany experimentally the progress of the theoretical mission formulation phase. We have in particular looked at the feasibility of cavity stabilization of lasers in the environment and over the time scales relevant for the LISA Mission. It could be demonstrated that two independently stabilized LISA type diode-pumped Nd:YAG lasers stabilized to independent cavities can reach a frequency noise below 30 Hz/√Hz at 1 mHz, falling off as 1/f at higher frequencies, thus reaching the LISA goal for laser pre-stabilization. A detailed investigation of the various noise coupling effects has been performed, showing that in addition to the obvious temperature dependence, several cross-coupling effects have to be taken to account that depend on laser power, longitudinal and transverse beam position fluctuations, electronic off-set drifts, inhomogeneous diode response, and frequency noise at high frequencies up to 10 kHz.

For the second step of the LISA frequency stabilization we have demonstrated in the lab that the direct stabilization of lasers on board of the LISA mission to the average LISA armlength will be feasible with the controlled bandwidth much larger than the inverse light time along the LISA arms. For this laboratory demonstration the 30 sec round-trip delay for optical frequencies along the LISA arm was simulated by scaling the frequency to the radio-frequency range and using a cable drum for the optical delay.

First experimental work on the LISA phase measurement system has started, concentrating on the synchronise data communication based on binary phase shift keying for simultaneous data and clock transfer along the LISA arms, leading to the design and test of a first prototype based on FPGAs.

Most of our activity over the last two years was devoted to LISA Pathfinder (formerly SMART II), the technology precursor mission for LISA, with a planned launch date at the end of 2009. As part of the LISA Technology Package Architect Team we were largely responsible for the interferometry and read-out design and trade-off. In early 2005, LISA Pathfinder has entered into the final phase of realization, the mission implementation phase, in which the actual flight hardware is provided and launched into space. We are involved as Co-PI (Principal Investigator) and are responsible for the supervision of the Industrial Architect that is in charge of Systems Engineering, Integration and coordination of the European multinational conglomerate providing the various pieces of flight hardware that have to come together in the LISA Technology Package (LTP) to be flown on board of LISA Pathfinder.

After the design of the complete interferometry of LISA Pathfinder we have performed an optical bench test campaign at the AEI, but also using the facilities of the University of Glasgow and TNO in Holland. Environmental testing of the optical bench engineering model has been performed at TNO and passed successfully. Extensive noise investigations on the LTP interferometer have been performed, both theoretically and experimentally in collaboration with colleagues in Glasgow. Non-linearities of the phase read-out could be identified, explained and suppressed. The LTP interferometer is now much better than the flight requirements, as verified by laboratory testing. A new FPGA base phasemeter has been developed, and shows a laboratory performance more than a 100 times better than required. The breadboard developments were transfered to industry for flight model implementation.

In collaboration with colleagues at the IEEC in Spain, extensive thermal optical measurements on LTP components like optical windows, thermal sensors and heaters were performed. A real time spatially resolved phasemeter with subnanometer resolution was developed to support the optics integration of the LTP. The optical on-board alignment procedure was developed and tested in the lab with the optical bench EM.

Currently, in collaboration with colleagues from Trento, the experiment master plan for a complete mission and test sequence is being developed.

Karsten Danzmann

Research Highlights

Geometric Analysis and Gravitation Division

Geometric Aspects of Mass and Momentum

The Einstein Equations

The Einstein equations of general relativity are used to predict the future development of an initial state. Such an initial state could describe single or multiple stars or black holes. It is given by prescribing a curved three dimensional space. We will concentrate on systems in which the matter and energy initially is contained in a bounded region, so called isolated systems. In such systems there exist quantities like the total mass, the total energy, and linear momentum, which are conserved by the evolution. These quantities can be extracted directly from the initial data set, but there are some major problems. Although there is a well defined notion of energy density, it is not clear from the theory how one would associate an energy to a bounded region in space. The theory does provide us with the energy at a single point and the total energy of an isolated system, that is the whole space. Yet, it is unclear how to associate an energy to an extended body for example. This is in sharp contrast to classical mechanics, where one could just integrate the respective density on the body in question.

To see the true extent of this problem, recall that the force acting on a body is defined as the rate of change of the momentum of the body. Since it is not possible to compute the momentum of an extended body, the rate of change is also not known. Therefore, there is no natural notion of force.

Quasi-local Quantities

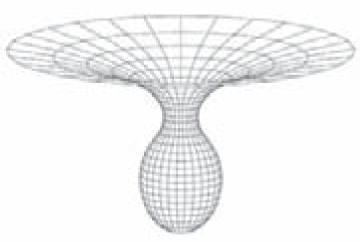
Multiple ways out of this situation have been suggested. One proposal is to assign the respective quantities not to regions in space-time, but to two dimensional surfaces. This leads to quasi-local definitions of mass, energy, or momentum. However, all the definitions proposed up to date are either not meaningful on arbitrary surfaces or very hard to compute.

We will focus on the former kind of such definitions. That is, it we will accept that they do not make sense on arbitrary surfaces. Then the natural question arises whether these definitions have nice properties on a carefully selected subset of all surfaces. For example, from a quasi-local mass definition one would expect non-negativity. That is, no surface in the class to be selected should be assigned a negative quasi-local mass. This requirement is based on the fact that in real world no negative mass has been observed up to date. The other requirement is monotonicity. Namely, if a given surface encloses a region which contains a second surface, then it should have bigger or equal quasi-local mass than the enclosed surface. This captures the idea that enclosing more space should result in a bigger quasi-local mass if the matter density is everywhere non-negative.

There are also compatibility conditions which, for example, ensure that in flat space the mass is zero. Here, flat space corresponds to an initial state which contains neither mass nor energy. It is not surprising that the requirement of non-negativity and the fact that the mass should be zero in flat space are complementary assumptions.

Foliations

A starting point for selecting good surfaces to compute quasi-local quantities is to require that they form a foliation of the initial data set. Here, a foliation means a collection of surfaces that do not intersect, but cover the whole initial data set. The fact that they do not intersect is very useful since one surface is then always completely contained in the region bounded by the other - or vice versa. The fact that they cover the entire data set in particular means that there are no gaps between the surfaces and that we can find arbitrarily large surfaces.

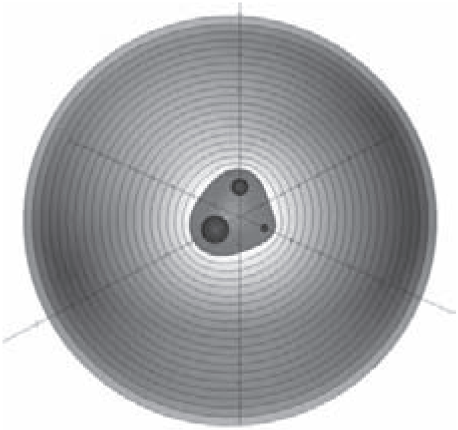

A two dimensional model of a space containing a minimal surface.

Consider for example the figure in the margin. Here we have tried to illustrate a three dimensional example by a two dimensional surface. We assume that it is rotationally symmetric. Then you can see that for each radius there is a circle (in the three dimensional picture this would be a sphere) at precisely that distance from the center of the dip. Increasing the radius gives a family of surfaces that sweep the whole shape without gaps. In other situations, where there is no symmetry, this procedure is not possible since in the first place it is not clear where the center would be.

Thus we have to find means of prescribing the properties of the surfaces in question to uniquely determine the foliation. The most important point here is that these prescriptions only refer to the geometry of the initial data set, and not to unphysical properties like specific coordinates. Obviously, if we take into account unphysical data then we can not expect the outcome, that is the value of the quasi-local quantity, to have physical meaning.

Surfaces of Constant Mean Curvature

A first result in this direction is motivated by the observation that the Hawking mass is non-negative on stable surfaces of constant mean curvature. The Hawking mass is a quantity computed with respect to the curvature of the surface. Surfaces of constant mean curvature are critical points of the isoperimetric problem, which is the problem of looking for a surface bounding a set of given volume with least area. If we fix such a surface and demand that the next surface enclose a fixed amount of volume more than this one, and again minimize area, we will find a nice surface outside of the initial surface. This is similar to blowing up a soap bubble in a curved space. A numerically computed picture of the foliation created by this process for a particular initial data set is displayed below.


A numerical computed family of constant mean curvature surfaces. The innermost surfaces are minimal.

Huisken and Yau proved that such foliations exist outside of a bounded region. As observed by Bray, the Hawking mass is indeed monotonic in such foliations.

In conclusion, the constant mean curvature foliations are the right surfaces on which to compute the quasi-local Hawking mass. In the above picture, all leaves of the foliation become more and more spherical and centered when their radius is growing. This is no coincidence. Indeed, the center of mass of an isolated system can be defined to correspond to such a foliation, as was shown by Huisken and Yau.

Capturing Linear Momentum

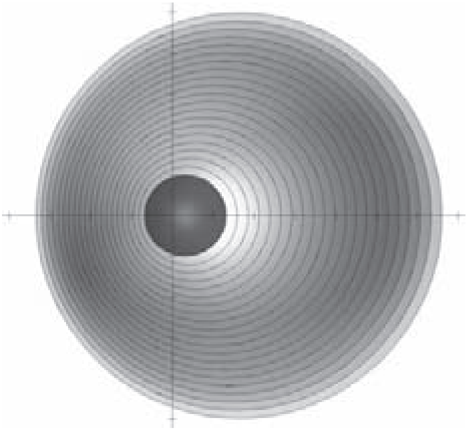
We now want to extend the prescription rule of the surfaces to capture the linear momentum. In the case of the constant mean curvature surfaces, this is not possible since they do not depend on the part of the initial data which contains the linear momentum density.

However, we wanted to keep the nature of the equation for the surface, which is a prescribed mean curvature equation. To explain the analogy to the constant mean curvature case, we have to explain what it geometrically means for a surface to have constant mean curvature. If you take a small piece of the surface, and push it outward in the normal direction, then the mean curvature turns out to be the infinitesimal rate of change of the area. Thus constant mean curvature means that infinitesimally the area of the surface changes everywhere at the same rate when pushing outward.

Now recall that we are actually dealing with initial data sets for the Einstein equations. These equations can be used to generate a piece of four dimensional space-time which contains the initial data set as initial slice. Instead of looking at the variation of area into the normal direction in the initial data set, we consider variations of the surface in light-like directions in the space-time and demand that the infinitesimal rate of change of the area in such directions be constant. There is an ambiguity here since the null directions of a surface are not uniquely determined. Here, it should suffice to say that the precise embedding of the surface and the initial data set into the space-time makes the choice almost unique. The remaining freedom lies in the question if one wants to consider future or past directed light-like directions.

In our work, we proved that outside of a bounded region such foliations exist provided the total mass is positive. We had to assume rather weak conditions on the asymptotics of the initial data set for the proof to work.

Interestingly, it turns out that the geometry of these foliations is different from the constant mean curvature foliations constructed by Huisken and Yau. When going outward, the surfaces become round, but they do not have a common center as can be seen from the following picture.



A numerically computed family of surfaces of constant expansion.

When the surfaces become large, the approximate centers of the surfaces move outward. We showed that the direction of this movement agrees with the direction of the total linear momentum of the system, and that the velocity is related to the absolute value thereof.

This observation leads us to believe that the intermediate leaves of the foliation can be used to define a quasi-local version of the linear momentum.

Jan Metzger

The Newtonian Limit

General relativity is presently the most accurate theory of gravity. In general relativity, the Einstein field equations must be solved to completely determine the gravitational field. These equations are extremely complex and, outside of a small set of idealized situations, they are at present impossible to solve directly. However, to make physical predictions or understand physical phenomena, it is often enough to find approximate solutions that are governed by a simpler set of equations. For example, Newtonian gravity approximates general relativity very well in regimes where the typical velocity of the gravitating matter is small compared to the speed of light. Indeed, Newtonian gravity successfully explains much of the behaviour of our solar system and is a simpler theory of gravity that is less difficult to solve. Therefore the expectation is that Newtonian gravitational solutions can be used as a starting point for approximating general relativistic ones. This expectation has spawned a large body of research that goes by the name of the *Newtonian limit* which is defined as the study of gravitating matter systems which obey the Einstein field equations in the regime where a characteristic velocity scale associated to the matter is small compared to the speed of light. Many researchers have examined this problem from different points of view and although a lot has been understood, it is still surprising that after so long there are so few rigorous results on the precise relationship between solutions to Newtonian gravity and solutions to general relativity. The main reason for this can be explained as follows: let v be a characteristic velocity associated to the gravitating matter and c be the speed of light. If v is small compared to c, then the ratio v/c will be close to zero. Consequently, to understand the Newtonian limit, solutions of general relativity must be examined in the limit that v/c goes to zero. The difficulty with this limit is that the Einstein field equations become *singular* as v/c goes to zero; by singular we mean that as v/c becomes arbitrarily small, certain terms in the Einstein field equation appear to become arbitrarily large. This makes the analysis of the Newtonian limit particularly difficult as one must find ways to control the large terms.

I. The Stationary Limit

A special case in the analysis of the Newtonian limit occurs when the matter is moving with a constant speed. The analysis of the stationary limit turns out to be easier than the fully dynamical case where speed of the matter is changing. This is due to the existence of a special combination of the field variables, discovered by Jürgen Ehlers, for which the Einstein field becomes regular in the stationary setting. In other words, there is no longer a problem with terms in the equation becoming arbitrarily large as v/c goes to zero. These special variables were employed by Uwe Heilig to prove the existence of a family of solutions to the full Einstein field equations that represent slowly rotating stars and moreover, converge to a solution of Newtonian gravitational equations in the limit v/c vanishes. The method developed by Heilig is an important method for constructing stationary solutions with well defined Newtonian limits and also works for other gravitating matter systems. For example, I proved the existence of a family of gravitating BPS monopole solutions of Einstein-Yang-Mills theory using Heilig‘s method. This family of solutions also has a well defined Newtonian limit and reduces to the standard BPS monopole solution of Yang-Mills theory in the limit v/c vanishes.

II. The Dynamical Limit

To analyze the fully dynamical Newtonian limit where the speed of the matter is not constant, two problems must be overcome. First one must solve the constraint equations to get initial data which is needed as input to solve the Einstein field equations. This turns out to be a singular problem when analyzed in the limit v/c goes to zero. Fortunately, as shown by Martin Lottermoser and Alan Rendall, this problem can also be regularized by an appropriate choice of variables as in the stationary case and solutions that are regular in the limit v/c vanishes can be constructed. This provides initial data with a well defined Newtonian limit. The second, and more difficult problem, is that for the fully dynamical situation the singular terms cannot be removed from the field equations by a clever choice of variables. Instead, one must invent techniques to analyze the singular parts of the equations and show that they do not cause the solutions to become unbounded as v/c goes to zero. The first general result showing this was by Alan Rendall for the gravitating Vlasov system which describes gravitating collisionless particles. He showed that this system has a wide class of solutions with a well defined Newtonian limit. Recently, I showed, using a different method, how to analyze the problem for gravitating perfect fluids and I was able to establish the existence of a large class of solutions representing gravitating fluid bodies (e.g. stars) that have a regular Newtonian limit. To my knowledge, these are the only rigorous results on the Newtonian limit where no simplifying assumptions, such as spherical symmetry, have been made.

III. Post-Newtonian Expansions

The post-Newtonian expansion is an approximation scheme that uses Newtonian solutions as the starting point. A regular Newtonian limit can be thought of as saying that the lowest order term in the post-Newtonian expansion is a good approximation to a general relativistic solution for small v/c. More precisely, the post-Newtonian expansion is a scheme that seeks to represent solutions to the Einstein field equations in the following form

$$u=u_0+(v/c)u_1+(v/c)^2u_2+(v/c)^3u_3+\dots$$

where u represents the combined gravitating and matter fields, u_0 is a Newtonian solution, u_1 is the first post-Newtonian correction, u_2 is the second post-Newtonian correction, and so on. The point is that u_1 can be determined by solving an equation that depends only on u_0, u_2 can be determined by solving an equation that depends only on u_0 and u_1, and so on. In this way, any finite number of terms u_1 up through u_n (n is any integer) can be generated by solving a series of equations that are easier to solve than the full Einstein field equations. The hope is that by calculating each successive term in expansions, better and better approximations to the true solution are determined. In the most favourable case, this series would be convergent and then it would be possible to calculate the true solution to any desired accuracy by only computing a finite number of terms in the series. Unfortunately, in general relativity little is known of the nature of the post-Newtonian expansion and in what sense it approximates true solutions of general relativity. However, there does exist formal computational schemes for the post-Newtonian approximations and these are in wide use by physicists. In fact, these post-Newtonian computational schemes are one of the most important techniques in general relativity for calculating physical quantities for the purpose of comparing with experiment. For example, the post-Newtonian expansions are used to calculate gravitational wave forms that are emitted during gravitational collapse. These wave forms are of crucial importance for the search for gravitational waves which is now in progress using gravitational wave detectors. Due to the importance of the post-Newtonian approximation scheme for computing physical predictions, it would be highly desirable to rigorously understand in what sense the post-Newtonian expansion is a valid approximation method, because without this knowledge it is difficult to trust any of the results derived from it.

My work on the Newtonian limit for perfect fluids shows that such an approximation scheme is valid at the lowest order. Moreover, the techniques I employ can be used to show that a convergent expansion exists. However, the convergent expansion differs from the standard computational expansions and it is unclear to me at the moment how the two are related. Also my results say nothing about the long time behaviour of the expansion which is needed to answer questions about radiation. These are difficult and interesting problems which I plan to return to in the future.

Todd Oliynyk

Astrophysical Relativity Division

The Gravitational Wave Group

The astrophysical relativity division has a group of about 10 members who do research on gravitational waves (GW's); we work on the theory of wave generation, develop codes to analyze data from GW experiments, and help analyze the data. We are part of the GEO gravitational wave collaboration, which supports the GEO600 detector, operated by the Hannover branch of the AEI. The data from this detector is pooled with that of the American LIGO detectors as part of our membership of the LIGO Scientific Collaboration (LSC). Scientists of our division play important roles within the LSC's data analysis teams. We also enjoy close ties to the LISA mission, a joint ESA/NASA project to fly a laser interferometer GW detector in space; its launch is currently planned for 2015.

Science Data from GEO and LIGO

Thanks to the complete data sharing agreement between GEO and LIGO, the data analysis is performed jointly by teams of scientists across the two projects and is managed by the LSC. Different search techniques are employed for different astrophysical sources. Four teams have been set up to coordinate searches for the four general types of sources: coalescing compact binaries, where neutron stars (NS) and/or black holes (BH) merge together at the end of a long-lived inspiralling orbit; continuous gravitational waves from rapidly rotating deformed NSs; short bursts (lasting of order milliseconds) of GWs from, e.g., supernovae or hypernovae, or from unexpected sources; and a stochastic GW background generated in the very early universe. Each of the four groups has two chairpersons, an experimentalist and a theorist, who coordinate the activities of the group and are ultimately responsible for delivering correct, high-quality scientific papers. Dr Maria Alessandra Papa co-chairs the search for continuous waves, and other group members participate in the searches for continuous waves and inspiral signals. Both searches are described below.

LIGO/GEO Results from 2004-05

During 2004 and 2005, the LIGO and GEO detectors alternated between short periods of data taking, called science runs, and longer periods of commissioning work, where their sensitivity was being improved. The data analysis teams have produced a number of papers from these early runs, setting upper limits on the strengths of gravitational waves. Since the detectors had not yet reached design sensitivity, no detections were expected, and none were made. But the upper limits so obtained are the most sensitive direct limits so far available. As described in more detail below, limits have been placed on the smoothness of neutron stars, for example: they cannot be more than one one-hundredth of one percent out of round. Said another way, a 15-km diameter neutron star cannot deviate from circularity by more than an average of 15 cm.

Data Taking at Design Sensitivity

The LIGO detectors recently reached their design sensitivity near the end of 2005, and they have entered their first full-sensitivity observing run. Called S5 (the 5th science run), it will run for roughly 2 years. The first GW detections may occur in this time frame. After the S5 an upgrade is planned that will improve the detectors' sensitivity by more than an order of magnitude. This will increase the volume of space that is searched, and so the detection rate, by more than a factor of 1000.

The Search for Continuous GWs from Rotating Neutron Stars

The AEI plays a central role in these analyses, leading the efforts of the continuous waves group. In this group, two different analysis approaches are being used. To search for GWs from previously known NSs, the University of Glasgow has developed a time-domain technique employing Bayesian statistics. The AEI has developed a complementary, frequency-domain technique that uses frequentist statistics. The AEI's code can be used both to search for GW's from known NSs and to conduct an all-sky search for GWs from unknown NSs. The data from the S2 run (second science run) was analyzed during 2004. Using data from radio telescopes to give precise information about the expected frequency of the gravitational waves, the analysis set upper limits on the strength of GWs from all known isolated pulsars; this paper was published in the prestigious journal Physical Review Letters. The group also performed a wide-frequency, all-sky search for GWs from previously unknown NSs, and a targeted search for a GW signal from the binary system Sco-X1. The all-sky search used a new technique (new, that is, to the GW community) to cover long observation times, large portions of the sky and spin-down parameter ranges: the Hough transform. The Hough transform is widely used in pattern recognition in digital image processing. At the AEI we have adapted this method to search for tracks of possible continuous wave signals in the time-frequency plane composed of GW spectra from successive data segments.

Since the GW's from rapidly rotating neutrons stars are expected to be quite weak (even compared to other GW sources), roughly year-long integration times will be necessary to dig them out of the detector noise. Moreover, though the wave patterns are sinusoidal at any instant, the sinusoids are modulated by the motion of the detector (as it is dragged about by the Earth's rotation and its motion around the Sun) and by the spinning down of the neutron stars. For neutron stars with known positions and spin rates, it is straightforward to account for these modulations, but the search for previously unknown neutron stars is highly computationally intensive. Indeed, the search for unknown GW pulsars is by far the most computationally challenging of all the LIGO/GEO data analysis efforts. To meet this challenge, the AEI and its partners have been pushing forward on several fronts:

(1) Development of New Algorithms - The Hough Transform

Since it is computationally prohibitive to perform one-year Fourier transforms for each different resolvable location on the sky, we adapted the Hough transform to search for signals using shorter transforms. Fourier transforms of data sets of length 30 minutes to 24 hours are much easier to construct. While they will not clearly show the signal within the noisy GW spectra, the frequencies where signals do exist are likely to be a little stronger than average. The Hough transform looks for sequences of these stronger frequencies that follow exactly the pattern expected over days and months for the modulation of the frequency described above. This is a far more cost-effective, and hence ultimately more sensitive, method than full Fourier transforms. This algorithm was desiged at the AEI and our scientists have worked since 2000 to produce an efficient working code. The full paper describing the code was published in 2005 (by authors B. Krishnan, A. Sintes, M.A. Papa, B. Schutz, S. Frasca, and C. Palomba), and the code is now being applied to science run data.

The Hough transform can be used for other purposes than GW astronomy. For his Ph.D. thesis, AEI graduate student Carsten Aulbert adapted the basic method to search data from radio telescopes for radio pulsars in binary systems. Such searches are also computationally limited because the motion of the NS about its companion modulates the frequency strongly, so that the pulsar may not be visible in the radio spectra produced by the telescopes. It appears that Aulbert's software is at least competitive with the best other methods for finding binary radio pulsars, and we expect in the future to collaborate with radio astronomers to do deep searches.

(2) Upgrade of Merlin Cluster

Our Merlin cluster is crucial to our data analysis work. Since its upgrade in 2003, Merlin is a 356-CPU teraflow-class computing facility. Its overall design, and indeed every component, were specified by AEI scientists after extensive benchmarking and testing of commodity parts. This allowed us to achieve a formidable price to computing power ratio. The cluster is completely managed by AEI staff. It not only provides computing power, but also constitutes the main European storage facility for fast retrieval of GEO and LIGO data. Several tens of TB of data are redundantly distributed across the nodes of the cluster ensuring fast access during the analysis and a robust and cheap archival system. (More generally, Merlin system manager S. Grunewald manages the transfer of GEO data from Hannover, where the data files are produced, to our partners in GEO and LIGO and to the large tape facility at ZIB, where the data are permanently archived.) But Merlin is becoming obsolete. Its components are starting to wear out and cannot be replaced, because they have been superseded by improved parts. Merlin has been the most heavily used computer in the entire LSC and has underpinned the work particularly of the CW group. We hope in 2006 to obtain funds to replace this important machine with a modern version.

(3) Einstein@Home

The most unusual and exciting development in GW data analysis was the introduction in 2005 of the screen-saver data analysis program Einstein@Home. Modelled on the popular SETI@Home project, and using some of the same software, Einstein@Home was developed by scientists in LIGO and at the AEI, under the leadership of Professor Bruce Allen of the University of Milwaukee. The project was launched as part of the American Physical Society's activities for the Einstein Year. (See elsewhere in this report for a description of the whole range of activities the AEI was involved in for this anniversary year.) Einstein@Home has proved to be a hit with the general public. During 2005 user number climbed well above 50,000, and the distributed "computer" became by far the most powerful computing resource available to the LSC for its data analysis. The system works by downloading small amounts of data onto remote computers and then, when they are idle, searching the data for evidence of continuous wave signals from pulsars. The top candidates are returned to central server computers in the USA and at the AEI, and are further tested for significance. It is a remarkable service that thousands of interested citizens are performing for free.

(4) Development of Hierarchical Search Strategies

Because of the overwhelming computational demands of continuous-wave searches, the most efficient search strategies are probably hierarchical and multi-stage. In the first stage of a multi-stage search, one might use the Hough Transform method to search the entire sky (as well as some range of neutron star spin-down parameters), but using only a rather limited span of data. One would pick out regions of the sky that seemed promising, and search only in those in the second stage, but using more data. This would produce a shorter list of candidates, which would be re-examined using even more data, and so on. The optimal way of organizing such a hierarchical search was worked out at the AEI by C. Cutler, B. Krishnan, and I. Gholami, using somewhat idealized assumptions (and building on earlier work by Brady and Creighton). Krishnan is now implementing these ideas – writing a hierarchical, multi-stage Hough code that will run on Einstein@Home and be used to analyze S5 data.

(5) Optimally Combining Data from Different Detectors

One can substantially decrease the integration time required to detect any given GW pulsar by optimally combining the data from all the working detectors. (For N equally sensitive detectors, the time required for detection would be expected to decrease by 1/N.) Cutler and B. Schutz worked out, analytically, the optimal way of combining data from several detectors. The code to do implement this multi-detector analysis is now being written by AEI graduate student Iraj Gholami.

Short Bursts of Gravitational Waves

Searching for GWs from Inspiralling Binaries

Among the promising GW sources for the ground based detectors are close binary systems. Those systems consist of two compact objects (binary Neutron Stars (BNS), binary Black Holes (BBH), ...) orbiting around each other in an inspiralling trajectory due to loss of orbital energy and angular momentum through gravitational radiation. Here at AEI we conduct search for GW's emitted by BNS in the LIGO-GEO and in LIGO-TAMA detectors network. (TAMA is a detector in Japan.) This search is conducted with the hierarchical pipeline which can analyze the data from up to four detectors running in coincidence. The paper on results of LIGO-TAMA analysis of S2 data (the second LSC science run) is submitted for publication in Physical Review D and the analysis of GEO-LIGO S3 data is approaching the final stage. The detectors‘ noise is still far from the ideal Gaussian-distributed model which our data analysis methods expect. This is very well reflected at the output of the matched filtering. Noise-generated broad band transient events (so called “glitches”) cause a large signal-to-noise ratio triggers (false alarms) which we need to veto out without dismissing the possible true gravitational wave signal. AEI in Golm and in Hannover work on developing and testing data quality flags for the data obtained by GEO600 detector. The data quality flags help to remove the contaminated data but do not solve the problem fully. Therefore we use the signal-based consistency checks such as the chi-squared veto in order to reduce number of false alarms. This discriminator checks the consistency of the candidate event with the time-frequency structure of the signal we are looking for. S. Babak (AEI) has suggested the method for tuning this vetoing statistic and proposed a few other signal-based vetoes. Besides analyzing the data, the AEI is also working on the theoretical aspects of the data analysis. In collaboration with Cardiff University we work on the designing the banks of the templates which are used in the search. Yanbei Chen (AEI) and his group is also involved in the designing the phenomenological and semi-physical (semi-phenomenological) template family for spinning binaries. Phenomenological waveform aim to reduce the number of parameters we need to search for and cover possible inaccuracy in the theoretical model of GW signals at the expense of allowing phenomenological parameters to take unphysical values. See the report by Chen elsewhere in this volume for more detail.

Vetoes for Networks of Detectors

B. Schutz and L. Wen have worked on methods to discriminate between real signals and bursts of noise in detectors, such as those that were mentioned above, when they occur simultaneously (and at random) in different detectors. Our main discrimination is the demand that the bursts happen almost simultaneously in two, three, or four detectors. But this does happen sometimes, and it limits our sensitivity. Schutz and Wen devised the “null-stream veto”, a method that tests the consistency of the response of the various detectors, on order to eliminate non-GW events. Two perfectly aligned detectors, or any network of three detectors, have some redundancy in their responses, and this can be looked for by constructing a combination of their data that should contain no GW signal. If this combination nevertheless contains a burst, then the burst can be assumed to be detector noise, and can be vetoed. If on the other hand the data streams contain apparent bursts and the “null stream” does not, then this is a strong candidate for a real GW. The LSC is beginning to implement this veto in its data analysis.

Research on LISA Sources

LISA is a major interest of the AEI. In the Hannover branch, Prof Danzmann leads the European development team and makes a major contribution to the LISA precursor mission, LISA Pathfinder, which will launch in 2009. (See the Hannover report in this volume for more detail.) In Golm, both Prof Schutz and Prof Curt Cutler are members of the LISA International Science Team (LIST). (Cutler left the AEI in August 2005, to work primarily on LISA at NASA‘s Jet Propulsion Lab.) Schutz, Papa and S. Babak are together helping put together a European effort to develop all the tools necessary for LISA data analysis, before LISA flies.

LISA and Confusion Noise from “Too Many Sources”

Unlike the ground-based detectors, LISA is guaranteed to see GW sources from almost the moment it becomes operational. Indeed, LISA will almost suffer from an embarrassment of riches. Our Galaxy contains roughly one hundred million white-dwarf binaries that are radiating GW‘s in the LISA band. These sources are all “on” simultaneously. At low frequencies (below about 2 milli-Hz), these binaries are too closely packed in frequency for them to be individually resolved. Above about 2 milli-Hz, they can be teased apart, and about ten thousand will be individually identified. The sum of the GW signals from the unidentified white dwarf binaries will actually impede somewhat our ability to detect other kinds of interesting sources, such as stellar-mass compact objects (COs -- these could be stellar black holes, neutron stars, or high-mass white dwarfs) inspiralling into supermassive black holes (SMBHs) at the centers of distant galaxies. This “confusion noise” from unidentified white-dwarf binaries actually dominates over LISA‘s instrumental noise, over much of the LISA sensitivity band.

LISA may observe hundreds to thousands of such CO-captures by supermassive black holes. Cutler and former AEI postdoc L. Barack considered the question of whether CO-captures are “self-confusing”, in the sense that any one of them effectively gets buried in the signals from all the others. Fortunately, they found that the confusion noise from CO-noise captures is several times smaller than other noise sources, and so self-confusion will not be a serious problem for these sources.

A possible “follow-on” mission to LISA, called the Big Bang Observer (BBO), is also been studied. BBO‘s primary goal would be to search for primordial GW‘s generated during an inflationary epoch in the very early universe. BBO would be sensitive in the band 0.1 - 1 Hz, where the dominant “noise,” obscuring the primordial background, would be a foreground of GW’s from all the merging neutron star binaries in the universe. For BBO to work, all these merging-binary signals would first have to be subtracted out of the BBO data stream. A key question is whether self-confusion from all the binaries spoils one‘s ability to do the subtraction (at the required, nearly perfect level). Cutler and AEI-Hannover graduate student Jan Harms examined this question in detail, and concluded that the subtraction is probably possible, but only if BBO‘s actual performance is quite close (within a factor 2) to the current design goal.

Testing GR with CO Captures

Accumulated astrometric observations provide strong support in favour of the existence of a very massive dark compact object in the core of almost every galaxy for which the central parsec region can be resolved. With masses ranging between a million and several billion solar mass these objects are believed to be supermassive black holes (SMBH). Encounters between stars in the stellar population surrounding these SMBHs can put stellar mass compact objects onto orbits that come sufficiently close to the central black hole that the object is captured and spirals in by the emission of gravitational waves. Those extreme mass ratio inspirals (EMRIs) are one of the most interesting of all anticipated source for LISA.

Here at AEI we study many aspects of these sources. One of them is the astrophysics of galactic centers. P. Amaro Seoane in collaboration with Prof R. Spurzem (Heidelberg) and Dr. M. Freitag (Cambridge) study two problems: evolution of two comparable mass SMBHs in galactic nuclei and capture of the compact mass objects by SMBHs, using computer simulations of clusters of millions of stars. In this approach they study the dynamics of systems consisting of many masses under mutual gravitational forces (including post-Newtonian effects of general relativity). This is a computationally expensive task and require computers of special architecture (GRAPE) to conduct simulations with large (realistic) number of particles (each particle represent a star or a BH). These simulations will yield an accurate estimation of the orbital parameters (for SMBH binary and for EMRIs) of systems detectable by LISA. This should help to estimate the expected event rate and parameter space which we need to search through.

S. Babak at the AEI, in collaboration with K. Glampedakis, J. Gair, S. Hughes and H. Fang, works on designing the template family for detecting GW signals from EMRIs. Those templates (so called numerical kludge waveforms), though constructed in an approximate way, capture the main essence of true GW signal. The main advantage of these waveforms is that they are relatively quick to generate and they give a very good (overlap above 95%) agreement with physical templates constructed using the exact (so-called Teukolsky) approach. However here we strongly rely on the currently available description of the orbital evolution, which is itself approximate. To get the orbital evolution we need to derive and incorporate “self-force” (force acting on the test mass due to gravitational radiation and due to coupling of its own gravitational field with the background curvature).

D-H Kim (AEI), in collaboration with scientists at Penn State University and the University of Florida, is involved in the effort on the computing the self-force. Another branch of our research is to investigate time-frequency methods for detecting some of EMRIs. L. Wen from AEI and J. Gair (Cambridge) considered excess power method for detecting EMRIs in time-frequency plane. They found that this method allows to detect a typical source 2 Gpc away with ~55% efficiency and false alarm ~1%. Other time-frequency search methods are also currently under investigation (in collaboration with Cardiff University); one that could be especially promising is the chirplet based method suggested by Archana Pai (AEI) and former AEI postdoc E. Chassande-Mottin (Nice). All these methods search for the excess of power in the time-frequency representation of the noise with signal, but they differ in the way they identify and accumulate the total excess of power. The time-frequency based search could be the first step in the hierarchical search for EMRIs, which could be followed by semi-coherent method described above.

According to general relativity, the very massive objects in the galactic nuclei should be Kerr BHs. This belief (so far) is based on our faith to General Relativity itself rather than on direct evidence from the objects. Indeed, the best way of getting direct evidence about the central objects is through gravitational radiation. It is expected that using observations from LISA, we will be able to "map" the geometry around the supermassive object by extracting its multipolar structure from the GW signal generated by EMRI. The main idea behind this is that the space time of Kerr BH depends only on two parameters: its spin and mass. If the central object is not a Kerr BH, then this will not be true. S. Babak (AEI) and K. Glampedakis (Southampton) suggested a practical scheme for mapping a space time which deviates only slightly from Kerr. Further work on this problem is described in the report by Y. Chen in this volume.

Maria Alessandra Papa, Curt Cutler, Stas Babak, Bernard Schutz

Highlights from the Numerical Relativity Group

Einstein's General Theory of Relativity represents one of the cornerstones of our modern understanding of physics. Yet, because based on a highly nonlinear system of equations, our understanding of the mathematical properties of the Einstein equations is still far from being complete. Indeed, solutions to these equations are known analytically only in very few and special cases, when particular symmetries and simplifications can be exploited. Under more general conditions, however, analytic solutions have not been found, forcing the use of numerical techniques to investigate General Relativity in regimes in which the behaviour of the equations is not well understood. It is not surprising, therefore, that the numerical solution of the Einstein equations is often a daunting task, a dangerous terrain to explore and in which both numerical and mathematical difficulties can appear to spoil the solution.

Fortunately, a number of long-standing problems have been solved in recent years and the numerical solution of the Einstein equations under generic, four-dimensional spacetimes has never been as accurate and stable. This progress comes as a timely response to the need of providing a theoretical input for the calculation of the gravitational waveforms needed by the numerous detectors now in operation or construction (e.g. GEO600, LIGO, Virgo, etc.). This input will be essential not only for the detection of the gravitational wave emission from compact objects but, most importantly, for the extraction of the physical information these waveforms carry.

The numerical relativity group at the Albert Einstein Institute (AEI) has played an important role in this recent progress and this is in great part related to the development of a general numerical infrastructure (i.e. the "Cactus Computational Toolkit") to solve the Einstein equations in Cartesian coordinates on massively parallel supercomputers. This infrastructure, which has been built and tested in close collaboration with scientists at the Louisiana State University in Baton Rouge (USA), has seen some recent important developments. Among these is the construction of the "Whisky" code for the solution of the relativistic hydrodynamics equations in generic curved spacetimes and which allows for the calculation of the emission of gravitational waves from the dynamics of compact stars. This represents the first extension to non-vacuum spacetimes of the research traditionally carried out by the numerical relativity group at the AEI.

An equally important achievement of the last couple of years is represented by the "Carpet" code, which has provided the long-awaited possibility of using adaptive-mesh refinements (AMR) techniques within the Cactus Toolkit. These techniques, implemented only seldom in numerical relativity, allow for a more efficient use of the computational resources as well as the for the possibility of placing the outer boundaries at sufficiently large distances from the sources where gravitational wave information can be collected.

Exploiting these two new "tools" and with a better insight on the properties of the numerical solution of the Einstein equations, the group has made considerable progress on several among the most pressing problems in gravitational physics: the solution of the two-body problem for an inspiralling pair of binary black holes, the collapse of a neutron star to a rotating black hole and the birth of a neutron star as a result of a stellar-core collapse. In what follows we briefly discuss the most essential aspects of these researches.

(1) Binary Black Holes Simulations

Starting from initial data representing a pair of black holes at a separation near the "innermost stable circular orbit" (i.e. a separation at which the radial motion becomes significant and the black holes start to plunge), the group has solved the full set of Einstein equations exploiting the advantages of newly developed gauge conditions which are dynamically enforced and adapted to the motions of the horizons within the spatial grid. In addition, the use of a co-rotating reference frame, in which the black holes simply move on a linear trajectory toward each other as they inspiral, is particularly helpful to maintain the evolution accurate. The orbital motion of the two black holes can be then reconstructed by transforming the results into a frame which is non-rotating and hence similar to the one of an observer at a large distance from the binary.

This is shown in *Fig. 1*, where the red circles represent the apparent horizons of one of the black holes at different times during the inspiral. As the inspiral proceeds and the merging approaches, the black holes come closer together until a common apparent horizon first appears (this is shown as the oblate dashed line in *Fig. 1*) which incorporates both black holes. The evolution of the final black hole can be followed far beyond merger, with the resulting solution corresponding to a black hole which oscillates according to the predicted quasi-normal modes of a perturbed, Kerr black hole.

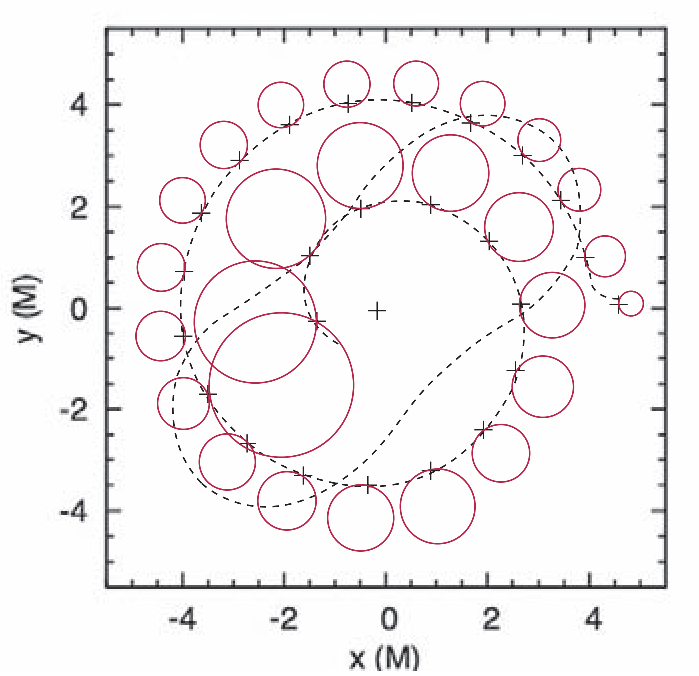


Fig. 1

(2) Gravitational Collapse to Rotating Black Holes

A second important result obtained by the numerical relativity group is the calculation of the gravitational wave emission from the birth of a rotating black hole. As mentioned above, this has been possible because over the last couple of years, the group has developed, in collaboration with several other European institutes and in particular with scientists at SISSA (Trieste), a new code for the solution of the relativistic hydrodynamics equations in a generic and curved background spacetime. The Whisky code uses state-of-the-art techniques in the solution of the hydrodynamic equations, is fully integrated with the other components of the Cactus code and thus provides the opportunity of investigation the solution of the Einstein equations in realistic, non-vacuum spacetimes.

As a first application of the code the group has considered the gravitational collapse to a rotating black hole, a basic prediction of General Relativity and one of the most intriguing phenomena in physics. Interest in this process is not just academic since the collapse of a compact star to a black hole also is among the most intense sources of electromagnetic and gravitational radiation. Despite this, the problem is very challenging from a numerical point of view and progress in the calculation of the waveforms produced has been rather slow over the years, with a single previous calculation performed in two spatial dimensions (2D) and almost twenty years ago (Stark and Piran, 1985). The reasons for this are numerous but mainly that, in the absence of non-axisymmetric instabilities, the conversion of the binding energy to gravitational radiation is very inefficient (only a few parts in a million of the initial energy of the system are carried away by gravitational waves) and thus the calculation of the waveforms requires a very accurate solution. Furthermore, the extraction of gravitational waves imposes not only the dynamics of the matter and of the trapped surfaces to be resolved accurately, but also the computational domain to have boundaries sufficiently far from the source where the waves attain their asymptotic form. Exploiting a series of new developments to treat and study the formation of the various trapped surfaces produced during the collapse (*Fig.* 2) and the use of AMR techniques, it was possible for the first time to calculate the gravitational radiation produced from a fully 3D calculation, filling in the gap with the previous results in 2D. The waveforms computed in this way (*Fig.* 3) provide more precise and stringent estimates on the gravitational wave efficiency, thus better assessing the detectability of these sources. In particular, they have revealed that while the birth of a black hole may be detected by the present interferometric detectors if it occurs very close to us, it will have to wait for the construction of the next-generation interferometers for a likely detection from within the Galaxy.

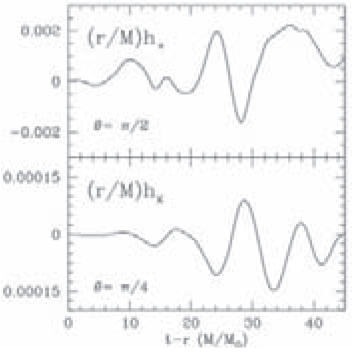


Fig. 3

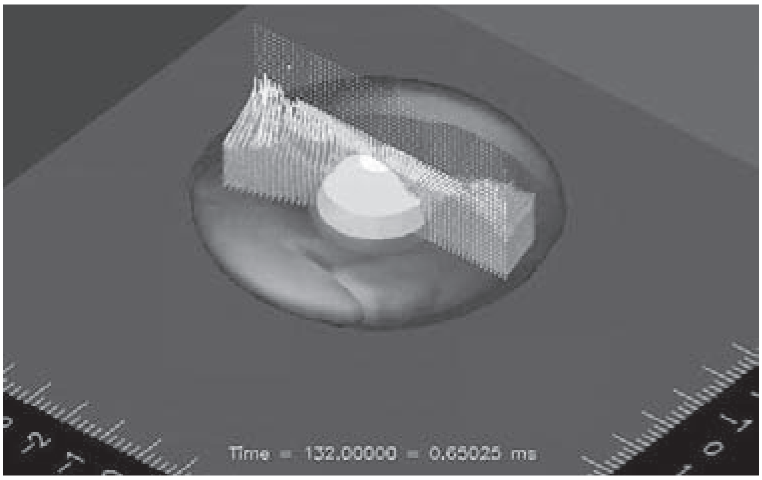
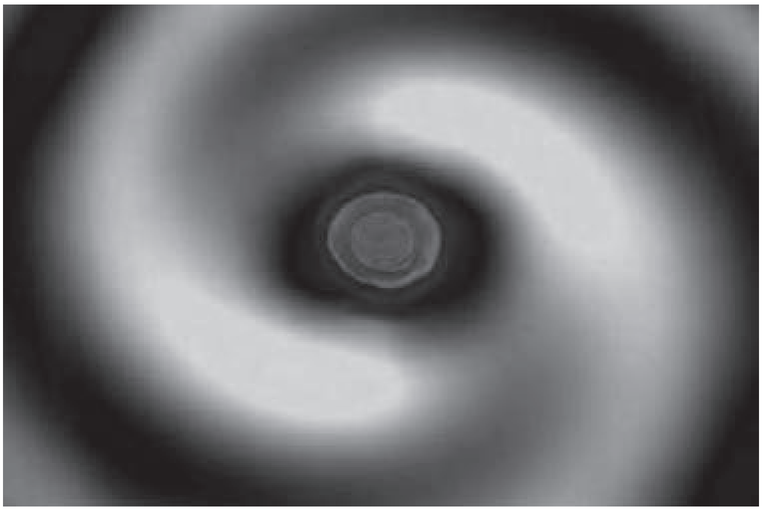


Fig. 2

(3) Stellar-Core Collapse to Neutron Stars

Supernova explosions mark the dramatic ends of stellar lives and are among the most energetic events in the Universe. Despite many decades of work in this area, one key problem remains the complete understanding of how the gravitational binding energy of the collapsed core can be tapped efficiently to produce a supernova explosion. During the past couple of years a considerable effort at the AEI has been devoted to the application of the Cactus/Whisky codes to perform large-scale simulations of stellar core-collapse and of the post-bounce epoch in full General Relativity. This represents a major development in a research line in which the dynamics of the collapse has been mostly treated within a Newtonian approximation of gravity. The results obtained so far have highlighted that the corrections introduced by General Relativity can indeed be important and cannot be neglected in any realistic simulation. Special attention has also been paid to the development of non-axisymmetric structures in the collapsed cores as a result of a dynamical instability triggered by the excess of rotational energy. While not generic, these instabilities are exciting as they can lead to a copious emission of gravitational waves and thus provide important clues on the physics of this complex process (*Fig.* 4). Clearly, the study of supernova physics is by no means an easy task. Together with an accurate treatment of gravity, in fact, a realistic simulation of core-collapse must include a detailed description of the relevant physics on both a microscopic level (by including neutrino radiative transfer and corrections coming from nuclear and weak interactions physics) and on a macroscopic one (including a realistic equation of state and the energetic contribution provided by electro-magnetic fields). Clearly, all of these aspects raise considerably the complexity of the numerical simulations, which will need to improve as more refined description of the physics are progressively incorporated. Overall, numerical evolutions in full general relativity are now beginning to overcome some of the problems and instabilities which limited their lifespan and prevented a thorough physical investigation. Simulations such as the ones carried out at the AEI in recent years represent important milestones opening new opportunities for the use of Einstein equations to unveil the complex physics behind black holes and neutron stars.

Fig. 4



Upcoming Events:

"New Frontiers in Numerical Relativity"

A workshop on the "New Frontiers" of numerical relativity will take place from July 17th to July 21st 2006 at the AEI in Golm. In a period of important novel results in numerical relativity, the workshop is meant as an opportunity to bring together scientists working in numerical relativity to present and discuss the techniques in use or under development to tackle among the most challenging problems in relativity.

Luciano Rezzolla

Applied e-Science Research

Many of the Physics research highlights described in the previous section would probably have taken much longer to achieve without the AEI Numerical Relativity group's long-standing tradition of applied research in the field of advanced Computer Science and Grid Computing. Such work is pursued by a small number of computer scientists and engineers who's structure recently has been reorganised to form their own e-Science group within the Astrophysical Relativity division at AEI.

As one point of emphasis, the already mentioned Cactus code has been extended by the physicists not only with implementations of new numerical schemes and Physics formulations but also constantly enhanced by the e-Science group to integrate the latest changes in software technology: the Cactus computational toolkit as a standardised, easy and flexible to use software environment to design, code, debug, test, and optimise new Cactus components; high-end scientific visualisation methods for the analysis of large-scale simulation datasets; GridScreen as open-source monitoring tool for high-performance computing resources (such as AEI's Linux cluster Peyote), with sensors for low-level hardware information as well as composite high-level sensors for resource and application monitoring; tailored software components to monitor and interactively steer running Cactus simulations via standardised interfaces such as a browser-based Cactus portal. All these enhancements, developed and maintained at AEI in close collaboration with the Cactus groups at CCT (Louisiana State University) and Cardiff, make sure that the open source Cactus framework remains one of the most advanced problem-solving software environments, primarily to be used by astrophysicists in AEI's Numerical Relativity group and their collaboration partners at CCT, SISSA, and Southampton as well as by scientists in other research areas who are all joined together in the global Cactus community.

Catching a Wave with the Research Net

Another major research topic in the e-Science group is Grid Computing. After a number of successfully finished DFN-funded Grid projects in the years before, the AEI had been committed from 2001 until 2004 in GridLab, a European-wide research project of 11 universities and research institutions in 8 different countries, complemented by 3 collaboration partners in the U.S. As one of the central components of the GridLab project, the AEI signed responsible for the development of the Grid Application Toolkit (GAT) which provides application developers with a standardised interface for leveraging many different Grid services. This GAT API has also led to the creation of a Grid Application Programming Interface working group (SAGA) at the Global Grid Forum (GGF). GridSphere, a Grid portal development framework, is the other major product that has been developed at AEI within GridLab. Like the GAT, the GridSphere framework set standards in the research area of Grid Computing and has since been adopted by a number of other Grid and application projects around the world. The final GridLab review took place in Brussels in April 2005 where a demonstration of a grid-enabled Cactus simulation using the GAT and GridSphere was shown. The EU reviewers have evaluated GridLab among of the most successful projects of the 5th Framework program funded by the European Union.

Besides their well-acknowledged contributions to various European and international Grid projects and their commitment in the GGF over the past decade, our e-Science group became actively involved again in Grid research also within Germany itself. Starting in the fall of 2003, the AEI joined the just founded D-Grid initiative, a promotion activity of the leading German academic science communities who already gathered advanced theoretical knowledge and practical experiences in the Grid Computing and e-Science research area. The intention of D-Grid in its first phase is to combine the many already existing Grid Computing testbeds and Grid middleware components of individual science communities into a common, self-sustaining Grid infrastructure stretching all across Germany. Based on such a shared Grid infrastructure, the scientific communities joined together in the D-Grid initiative will then be able to deploy their applications on a much broader base and run them in a true “Grid” context, resulting in better throughput and more efficient use of resources. After several iterations of writing a coordinated project proposal and negotiations about D-Grid‘s organisational structure, five science communities and an integration platform project were finally selected to be funded by the Bundesministerium für Bildung und Forschung (BMBF) for a period of 3 years, starting in September 2005. The AEI is well represented within the D-Grid initiative as a member of both the German AstroGrid Community Grid project (GACG) and the D-Grid Integration Project (DGI).

With D-Grid, a solid basis is laid for the coming years in which our e-Science group will continue its work to provide tailored software solutions to the physicists and pave the road for them into new and exciting world of Grid computing.

Thomas Radke

Theory of Advanced Gravitational Wave Detectors

The newly-established research group led by Yanbei Chen is supported by Alexander von Humboldt Foundation‘s Sofja Kovalevskaja Award, which provides a funding of 900,000 EUR (financed by the German Federal Ministry of Education and Research) over a period of 4 years (January 2005 - December 2008). This group does theoretical research in advanced gravitational wave interferometers, quantum measurement theory, and physics of gravitational wave sources and data analysis. This is a research area new to the Astrophysical Relativity Division, which is being carried out by Chen, Mueller-Ebhardt and Somiya. Our research is carried out in close collaboration with Roman Schnabel‘s research group in AEI-Hannover. Our research in this area can be divided into three categories:

Quantum Measurement Theory and its Application to Designs of Gravitational Wave Interferometers.

Interferometric gravitational wave detectors (interferometers for short) use light to monitor motions induced by gravitational waves on mirror-endowned test masses. Improving sensitivities of interferometric gravitational wave detectors beyond the second generation (e.g., Advanced LIGO, scheduled for 2012, whose design has largely been determined) requires us to design configurations that surpass the so-called Standard Quantum Limit (SQL), which was discovered theoretically by Braginsky in the 1960s. The SQL arises due to the non-vanishing commutatos between the (Heisenberg-picture) test-mass displacement operators at different times -- in other words, quantum uncertainty in macroscopic test masses, albeit very tiny, may create a barrier to improvements of interferometer sensitivities! Experimentally, if we "sense" our test-mass to "strongly", then the quantum back-action noise imposed by Heisenberg Uncertainty Principle may be higher than our sensing noise, and could limit the overall sensitivity. As was soon realized, the SQL only exists when the Heisenberg Uncertainty Principle is applied naively. The SQL can be surpassed, when both the measurement device (the optical field) and the test mass are treated consistently with quantum mechanics -- if quantum correlations are appropriately employed in the measurement scheme -- and such schemes are called Quantum Non-Demolition (QND) schemes.

Originally, it was thought that QND schemes are very difficult to devise. However, over the past three decades, theoretical concepts of QND schemes have been put forward. In the past five years, several concepts have been put into forms rather plausible for implementation in the coming decade, including: using optical filters to employ quantum correlations, modifying interferometer optical response and constructing "speed meters", and modifying interferometer mechanical response and constructing "optical springs". These are theoretical "tools" one can use to "assemble" third-generation designs.

In the past two years, our group has been continuing the analysis of QND interferometer configurations, which offer improvements to interferometer sensitivity. In particular, we have explored further the use of Sagnac Interferometers for gravitational wave detection. Sagnac Interferometers are different from Michelson Interferometers in that they measure mirrors "less strongly" at lower frequencies -- this suppresses quantum back-action noise, which for Michelson Interferometers dominates at such frequencies. At the same time, Sagnac Interferometers could sense mirror motions "more strongly" at higher frequencies, which is desired.

Looking more into the future, even if the SQL can be surpassed, most QND schemes will still require huge optical power in order to lower quantum noise. In collaboration with S. Danilishin, F. Khalili, and S. Vyatchanin, we have started research in the so-called intra-cavity readout schemes. Originally proposed conceptually by Braginsky and Khalili, such schemes use the long arm of gravitational wave interferometers as optomechanical transducers, and allows, in principle, the use of limited optical powers to achieve significant improvements in sensitivity. Much further theoretical work are still required in order to bring such conceptual schemes into practical.

In addition to applying Quantum Measurement Theory to improving sensitivities to gravitational waves, one should also be able test quantum theory using SQL-limited gravitational wave detection experiments, which involve truly macroscopic test masses -- because non-trivial quantum correlations must be involved when the SQL is suppressed. In collaboration with Kip Thorne's group at Caltech, we are currently formulating possible tests of quantum theory (or possible deviations from it, e.g., the Objective Reduction proposed by R. Penrose) that one could perform on such experiments.

Modeling of Practical Advanced Interferometer Configurations

In order to successfully build QND interferometers, we must also consider important "technical issues", for example classical optical configurations, classical optical noises, thermal noises, etc. In the past two years, we have carried out the following research in this category:

Simulations of QND interferometers. In order to study the tolerance of QND schemes to optical imperfections and technical noises, a computer program capable of simulating generic full-scale interferometer configurations, taking into account quantum correlations, is necessary. Such a program has first been written by T. Corbitt at MIT. We took part in providing some of the theoretical foundations for this program, and in its validation.

Modeling of a proposed Ponderomotive Squeezing experiment at MIT. Generation of squeezed vacuum in acoustic band is an important tool for improving sensitivities of gravitational wave interferometers. Aside from using non-linear optical processes, squeezed vacuum can also be generated when optical field is coupled to a mechanical oscillator, such a process is called ponderomotive squeezing. The experimental program is being carried out at MIT, lead by N. Mavalvala and T. Corbitt. We took part in the theoretical modeling of this experiment.

In addition, together with P. Savov, J. Agresti and D'Ambrosio at Caltech, we studied spatial optical modes of Fabry-Perot Interferometers, proving a duality relation between cavities with nearly flat mirrors and those with nearly concentric mirrors; such a duality is useful in guiding the design of advanced interferometer optics. Together with N. Mio from University of Tokyo and S. Kawamura from National Astronomical Observatory of Japan, we are finishing a semi-analytical study of laser-noise transfer functions in the detuned RSE interferometer topology (which is going be used in Advanced LIGO and the future Japanese gravitational wave detector, LCGT), which aims at providing experimentalists with an intuitive understanding of laser-noise coupling in this topology.

Finally, as an ongoing research, we are scoping out plausible design parameters for the planned 10-meter prototype interferometer in Hannover, such that it could observe quantum back-action noise, or even the SQL.

Exploration of Dramatically Different Gravitational Wave Detection Strategies

Recently, S. Kawamura proposed a scheme of gravitational wave detection that cancels test-mass displacement noise, based on the insight that gravitational waves and test-mass motions influence differently the time delays experienced by optical signals traveling between members of an array of test masses -- if the gravitational wave have non-zero frequency, in particular if the gravitational wavelength is not much smaller than the size of the array. Together with Kawamura, we provided a rigorous theoretical analysis of his scheme, and generalized into schemes in which both timing- and displacement-noises can be cancelled -- such schemes can in principle be implemented using laser-noise free interferometry. Such schemes are possible, because an array of N detectors provides O(N2) signals, while susceptible to only on O(N) timing and displacement noises. Having derived the mathematical conditions for such arrays and configurations, we are currently looking for ones that are easy to implement and have practical advantage over conventional detection strategies.

Yanbei Chen

Quantum Gravity and Unified Theories Division

Brownian Motion, QCD and Topological Strings

Reviewing current excitement in string theory, Edward Witten wrote in a recent Nature essay: “All this suggests that string theory is on the right track; otherwise, why would it generate so many unexpected ideas? And where critics have had good ideas, they have tended to be absorbed as part of string theory, whether it was black-hole entropy, the holographic principle of quantum gravity, noncommutative geometry, or twistor theory” [*Nature*, vol. 438 22/29 (2005)]. Einstein did not live long enough to have a chance to become a string theory critic, but it is certainly true that many of his ideas “have tended to be absorbed as part of string theory”. The last one resisting absorption in string theory seems to be the idea of underlying determinism in quantum mechanics, beautifully illustrated by the EPR experiment, although – if we are to believe Gerard ‘t Hooft – also this one will one day become part of string theory lore. Or the other way way around, string theorists might one day agree with Einstein. Whichever way string theory chooses on determinism – Brownian motion and its intrinsic diffusive, non-deterministic nature most definitely has a place and interesting applications in string theory and gauge theories, including QCD.

Brown observed that pollen grains suspended in water have an atypical zig-zag-like behavior. Einstein understood that this effect confirmed the existence of atoms of definite size, as the suspended particles are continuously bombarded by the impact of other molecules in the liquid and so feature random trajectories on the surface of the liquid. Generally speaking, Brownian motion describes the random trajectories of particles in a diffusive medium. Bringing order to and modeling this random behavior is an important and very universal problem, as it is exhibited by many systems ranging form biology to high-energy physics: it is one of the most fundamental properties of matter. In high-energy physics, Brownian motion appears for a good reason: quantum mechanical systems are intrinsically random, and quantum mechanical indeterminacy can be modeled by stochastic processes.

Screening in QCD and Random Fluxes

Confinement is the phenomenon of the absence of free color charges in nature. Whereas electrons can travel freely – a fact that most of our technology is based on – this is not so for color charged particles like quarks. Quarks are always confined together – a fact that holds the nucleus of atoms together. The behavior of a quark-antiquark pair is indeed quite different from that of an electron-anti-electron pair. The Coulomb attraction between an electron and an anti-electron decreases as we pull them apart: at long enough distances, they don’t feel each other. The attraction between a quark and an antiquark, on the other hand, *increases* if we pull them apart: the potential between the quarks grows linearly. We can think of this linear potential as being produced by a string stretched between the quarks. If we increase their separation, however, it will be energetically more favorable to pair-create quarks in the middle: hence the string will break, and we are left with two bound states of quarks. Before string breaking takes place, the quarks will be screened by the virtual pairs. An important problem here is to identify the properties of the strings between the quarks: at large distances, not every string excitation will be able to hold quarks together, but only the so-called k-strings, that is strings that have certain color charge properties. Predicting the stability and describing the dynamics of these k-strings from a Brownian motion model was the main result of my recent work with Arcioni and Peng.

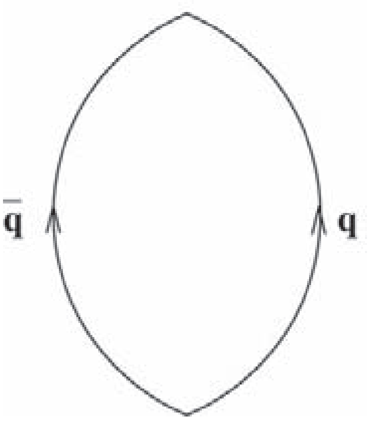


Fig. 1
The Wilson loop can be thought of as a quark-antiquark pair being created and annihilated in vacuum.

In analogy with condensed matter systems, it is important to have order parameters that allow to detect the presence of a confining phase. Wilson loops are such observables: we can think of them as a quark-antiquark pair going around the loop (see Figure 1). For linearly confining potentials, the Wilson loop will decay exponentially like the area of the enclosed surface; on the other hand, in the presence of screening the loop will decay exponentially like the perimeter of the surface, that is, with the length of the loop. Thus, area scaling of Wilson loops can be used to detect confinement. It has been known since the 1980's that if one has confinement in the sense of Wilson's area law, then the magnetic flux is random. Also, one can show that the assumption of the presence of a random magnetic flux in the vacuum gives rise to area behavior. It is here where we used the Brownian motion description – not to explain why the QCD vacuum has random magnetic flux, but to model it. Indeed, it was known that the confining behavior of the quarks can be reproduced by the random diffusion of a particle on a particular space – a so-called "group manifold". With Arcioni and Gao, and adapting a previously existing model, we were able to reproduce some of the important physics in the screening phase as well. The diffusion process is now subject to a universal potential. The crucial point is that a discrete rotational symmetry of the potential acts as a superselection rule that predicts the only stable strings to be the k-strings. Thus, k-strings emerge naturally from a symmetry requirement on the diffusion model. Although the k-strings are the only stable objects for large separation between the quarks, at smaller distances many other types of virtual strings can contribute. Our model was able to predict this behavior as well. We analyzed in detail which intermediate states will contribute, found their wave-functions, and computed their energy levels. Again, the correct superselection rule appears for the intermediate states, but the values of the energy levels are no longer universal and depend on some of the details of the potential, and at this point it is convenient to fit the model with simulation data. To this end we are currently in contact with phenomenologists.

Knots and Topological Strings

Superstrings are very complicated objects: their low-energy spectrum contains massless particles like photons and gravitons as different vibration modes of the string, but it also contains an infinite tower of massive particles. This makes it hard to perform exact, non-perturbative computations because at high energies the massive string modes interact with the light ones. So, in the quest for a non-perturbative version of string theory, one can ask whether there are simpler versions of string theory where the non-perturbative aspects can be made explicit. However simple this theory might be, consistent quantum gravity theories are scarce, so we better study it carefully if we find one. Also, the simpler "toy model"-theory deals with non-perturbative effects and might in fact end up being at the core of the full theory. The so-called *topological string* is such an example. It is a simplified, 6-dimensional version of the full superstring – the latter lives in 10 dimensions. By now it is clear that it is more than a toy model, as it describes a sub-class of observables of the full superstring. Among other things, it describes 4-dimensional black holes (the 4 stemming from the fact that 4+6=10...).

Just like the ordinary superstring, the topological string contains three-dimensional membranes called D-branes. The effective string theory describing them is called Chern-Simons theory: a 3-dimensional topological quantum field theory living on the surface of the D-branes. We can let the D-branes intersect each other along a common closed curve. This curve can be non-trivial, it can be knotted in a complicated way as in Figure 2. The Chern-Simons observable associated to the knot is a Wilson loop, where the loop winds around the knot. Recall how we encountered Wilson loops in QCD, and indeed Chern-Simons theory is a three-dimensional cousin of QCD, so we can think of the Wilson loop as the trajectory of a quark-antiquark pair that is created and then disappears in the vacuum. In QCD, Wilson loops depended on the area and the length of the loop, and area scaling was a signal of confinement. In Chern-Simons, there is no dependence on the area at all! Chern-Simons Wilson loops only depend on the topological configuration of the knot (its amount of ‚knottedness'): we can stretch or shrink the knot a little bit – as long as we don't break it, the expectation value of the Wilson loop remains invariant.

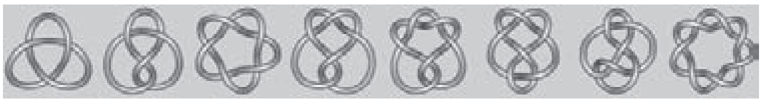


Fig. 2
Some examples of knots.

In a paper with Tierz, we found that there is a very simple Brownian motion description of Wilson loop observables in Chern-Simons theory. The Brownian motion system in question is as follows. Consider a system of particles moving randomly on a line. We demand that they move for a certain period of time, and impose the additional condition that their trajectories do not intersect during the whole motion. We compute the probability that, starting with a configuration where the particles are sitting at constant distance from each other on the line, they end up in the same configuration after the elapsed time. It turns out that the logarithm of this probability is exactly the free energy of Chern-Simons theory on a three-dimensional sphere. If instead of taking the initial and final positions of the motion to be constants, we let them vary, we get the knot invariants of various Wilson loops in Chern-Simons! In fact, Brownian motion gives a remarkably simple description of various other Chern-Simons quantities and a way to evaluate them explicitly. As an application of this, I showed how Chern-Simons Wilson loops can also be computed from two-dimensional QCD. QCD in two dimensions is confining and has area behavior, whereas as mentioned before Chern-Simons depends only on the topology of the loop. How can they be equal to each other? The resolution of this puzzle was that the correspondence only works if the areas are quantized. So in fact the two-dimensional QCD with quantized areas is equivalent to three-dimensional Chern-Simons, and the quantized values of the areas encode topological information about the extra dimension!

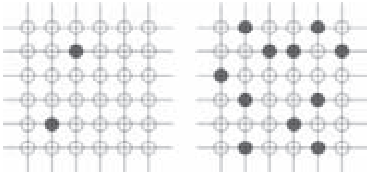
The relation between Chern-Simons and two-dimensional QCD has an interesting application in topological strings and black holes which is currently under study. I mentioned above that Chern-Simons describes topological strings in a certain six-dimensional space; QCD in two dimensions turns out to describe topological strings in a *different* six-dimensional space. So their relation tells us that topological strings in one space is equivalent to topological strings in a different space (and with different configuration of D-branes). This is another example of a string "duality": the string has a Chern-Simons or a QCD description depending on the space it moves in. Hopefully this type of Gedankenexperiment will bring us a little bit closer to a formulation of string theory which does not depend too much on the background space-time we choose. These are exciting times for string theory. Experiment will some day decide whether it is the right theory, but meanwhile there is good evidence that it cannot be totally wrong...

Sebastian de Haro

Gravity Tools for Meson Physics

Identical yet Different

A most fascinating aspect of theoretical physics is that the same simple and elegant concepts show up over and over again, but often in completely different settings or problems. One concept for which this is certainly true is that of order/disorder duality. This concept is known since at least 1931, when Kramers and Wannier first discovered it in the description of ferromagnets. The interaction of the individual spins that make up a magnet are described by the Ising model. There are two natural regimes in which one can study this model: the low-temperature regime, in which the spins are on average aligned in large, connected regions, and the high-temperature regime, in which the spins are fluctuating violently. Two natural perturbation series thus suggest themselves, one in powers of the temperature and one in powers of the inverse temperature. Surprisingly, the coefficients of these two series expansions are "the same": roughly speaking, if you invert the temperature in the series which is valid for small temperatures, you end up with the series for large temperatures.



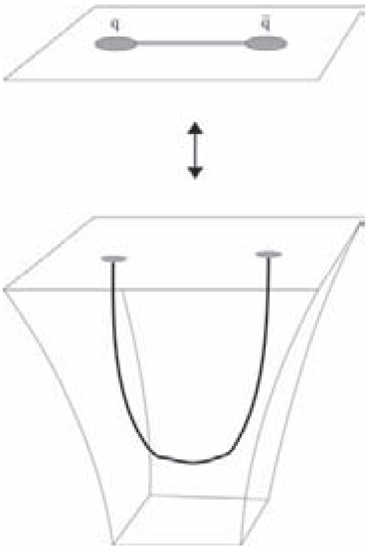
Snapshots of the low (left) and high temperature (right) Ising models: completely different behaviour of the spins, yet the coefficients of the free energy series expansions are identical.

Little did Kramers and Wannier know about the central role which their observation, now more commonly known under the name of strong/weak coupling duality or "S-duality", would come to play in modern quantum field theory and string theory. While the Ising model eventually turned out to be exactly solvable, and we therefore do not really need the perturbative expansions anymore, there are many other physical systems for which we are not so lucky. The strongly coupled regime of gauge field theories, dominated by ill-understood dynamics of hadrons, is such a system. Instead of analysing gauge field theories perturbatively and being restricted to weak coupling, is it perhaps possible to find a dual description, equally fundamental, yet better suited to describe strongly coupled phenomena?

A Gravitational Description of Hadrons

A key surprise which has made dualities so important is that, quite generally, the degrees of freedom which are "natural" at strong and at weak coupling are completely different. The perturbative expansions of two systems may a priori look completely different, yet turn out to be related by a simple inversion of their respective coupling constants. This is perhaps not yet very striking in the case of the Ising model. But it becomes truly amazing in the context of the Maldacena correspondence, which relates the observables of a *gauge* theory to those of a quantum *gravity* theory. In this latest extension of the duality concept, the two theories furthermore do not even live in the same number of dimensions. The gauge theory lives on a four-dimensional screen, on which the dynamics of the higher-dimensional gravity theory (or better put, string theory) is encoded like in a hologram. And again, when the gauge theory coupling is strong, the dual string theory is in fact weakly coupled and relatively easy to analyse. Many intriguing tests of this duality have been reviewed in previous editions of the AEI annual report. In the 8 years since Maldacena first proposed it in the context of a particular, highly supersymmetric gauge field theory and a string theory on an equally special gravitational background, many results have been obtained which show an impressive agreement between these completely different theories. At the AEI and elsewhere in the world, various observables have been compared in cases where we have sufficient control over the strong-coupling regime on one of the two sides, so that a comparison can actually be made. While the last word on this special string/gauge duality has certainly not been said yet, a logical next question is to wonder whether a similar duality can perhaps be used to learn about the gauge theory of QCD, which describes the real world.

In order to "build" a string theory which is dual to real world gauge theories such as QCD, one needs to find an appropriate dual geometry on which the string theory can live. Several such geometries have been discovered during recent years. Although the gauge theories which they describe do not yet look like QCD when you examine them at short distance scales (i.e. in the ultraviolet), they approximate the real world better and better when you consider larger distances. These are the distances at which hadrons (rather than individual quarks and gluons) dominate, and this is where conventional perturbative methods do not apply any longer.



The bound state of a quark and an antiquark corresponds to the "projection" of a string, living in a higher-dimensional curved spacetime, onto our four-dimensional world.

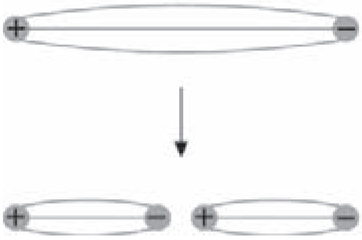
Hadrons are peculiar objects. They are bound states of quarks, which exist through effects of gauge theories which are impossible to calculate in perturbation series. When you try to separate two quarks from each other more and more, the force does not become weaker. Instead, the system behaves more like an elastic band, with a force which remains constant as the quarks are separated further and further. The problem with this intuitive picture is, however, that it is extremely hard to turn it into a physical theory. But the Maldacena correspondence has changed this completely.

What do composite, bound states such as hadrons look like in the dual picture? The proper way to think about the force which binds two quarks, is to see it as a string, not in the gauge theory itself, but rather in the *dual* gravitational theory. In this picture, a quark/antiquark bound state is described as a string which starts and ends on the four-dimensional screen, but extends into the higher-dimensional spacetime. The vertical parts of the string, which are nothing special from this point of view, correspond to masses of the quark and antiquark. In this dual, string theory description, the properties of hadrons are subtly encoded in the geometry of the curved spacetime on which the string lives. The meson mass spectrum, for instance, which can otherwise only be computed using elaborate computer simulations of lattice gauge theory, comes out surprisingly easily from the dual gravity computations.

What is even better, these spectra actually show an impressive qualitative agreement, not perfect yet, but intriguingly close to what is known from the real world or from numerical simulations. These agreements, together with the much more firmly established agreement in Maldacena's original correspondence, have recently been the inspiration to look yet further. Instead of trying to learn mainly about kinematical features of hadrons, such as their mass spectrum, the focus has now shifted to a study of truly dynamical properties of strongly coupled gauge theories.

Meson Decay from String Fluctuations

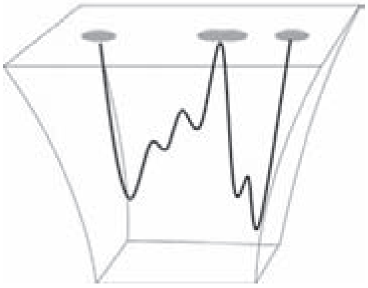
At the AEI, we have addressed one of the long-standing problems of hadron physics: how to derive, from first principles, the decay rates of mesons and other bound states of quarks. There exists a 30 year old, intuitive picture of such decay processes, which makes use of the idea of particle pair production in an electric field, first calculated by Schwinger in 1951. If we view the quark-antiquark system as a pair of colour charges connected by a chromo-electric flux tube, the decay of this bound state can be seen as the production of a virtual quark-antiquark pair inside the tube. The two newly-created particles reconnect to the existing two particles, and a system of two mesons is the result.



Intuitive gauge theory picture: a strong electric field may lead to the pair-production of a particle-antiparticle pair.

Unfortunately, this intuitive picture is of little use when it comes to actually calculating the decay rate of mesons from first principles. The reason is that the force inside this flux tube is extremely strong, certainly much too strong to be treated in a perturbative expansion around freely interacting quarks. The best one could do until now is to write down a phenomenological model which "parametrises" all possible results compatible with the flux tube idea. Such a model was proposed by a group at Lund University in the early '80s. Even though it works surprisingly well (and is in fact being used for the analysis of particle collider data while you read this), its connection to QCD remains as unclear as ever. Is there a way in which a strong/weak duality can help?

The answer turns out to be firm "yes". In order to understand how this works, let us return to the description of a meson as a U-shaped string in a higher-dimensional curved spacetime. This picture is only a first approximation to the full story. As with any quantum mechanical system, this string undergoes quantum fluctuations. There is a certain nonzero probability that, due to such a fluctuation, the string actually touches the four-dimensional screen. When this happens, the string is allowed to split into two smaller segments. Each of these segments will have both ends connected to the four-dimensional screen, and when this result is translated back to the gauge theory, one obtains a system of two mesons.



String or gravity picture: the U-shaped string undergoes quantum fluctuations which may make it touch the four-dimensional screen, after which it can break and end up as two separate U-shaped strings.

Rather interestingly, it turns out to be possible to compute both ingredients in this process. Firstly, the fluctuation probability of the string in the gravitational background can be computed, and turns out to agree, at leading order in the mass of the mesons, with the pair production probability discussed above. Secondly, it is possible to compute, using standard relativistic quantum string splitting calculations, the probability that the string will actually cut in two at the point where it touches the screen. Together, these two ingredients nicely reproduce the results of the phenomenological Lund model. The intuitive "flux tube" picture thus gets replaced by a new, entirely geometrical one. And in full analogy with the Kramers-Wanner duality, the new geometrical picture is equally fundamental as the gauge field theory we started with, but written in terms of degrees of freedom which are much more natural to describe meson physics.

Meanwhile, the consequences of the dual string picture of mesons reach much further. When one looks more carefully at the fluctuation probability, one sees that there are various interesting correction terms which arise because the string space is not flat, but *curved*. The geometrical properties of the background in which the string moves encode, in an intriguing way, the properties of meson decays. In fact, a detailed analysis shows that the curvature leads to predictions for rather specific corrections to the currently used models of meson decay processes. With more precise data on the dynamics of quark/antiquark bound states, such unusual predictions of gravity and strings may perhaps become measurable in the near future.

Kasper Peeters

Laserinterferometry and Gravitational Wave Astronomy Division

Space Borne Gravitational Wave Detection: LISA and LISA Pathfinder

The Laser Interferometer Space Antenna (LISA) is a joint ESA/NASA mission designed to observe gravitational waves in the frequency range from 0.1 mHz to 1 Hz. At these low frequencies, the sensitivity of ground based detectors such as GEO, LIGO or VIRGO is limited by terrestrial noise, so that LISA widens the spectrum of observable sources down to the millihertz where the high energetic events are expected.

LISA consists of three identical spacecraft separated by 5 million kilometer carrying a total of six free flying test masses in heliocentric drag-free orbit. They form an equilateral triangle as shown in *Fig.1*. Relative changes in a LISA arm (this is the 5 million km separating two test masses located in different satellites) are measured by laser interferometry with picometer precision.

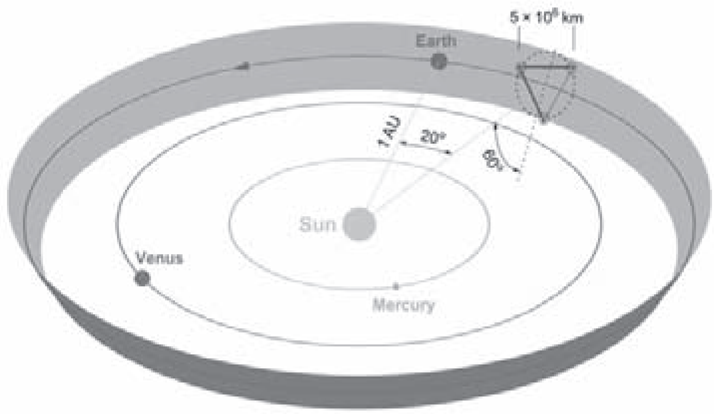


Fig.1: The three LISA satellites orbit the sun 20 degrees behind the earth in an equilateral triangle formation.

LISA Pathfinder (LPF) is a demonstration mission to be launched five years before LISA. It will test several key technologies for LISA that are impossible to test on ground:

- the drag-free control system to keep the test masses floating inside the satellite free from residual accelerations to a level of 30×10^{-15} N/√Hz.
- micro-newton thrusters that actuate the satellite around the test mass as part of the drag-free control system.
- ultra-stable interferometry in space.

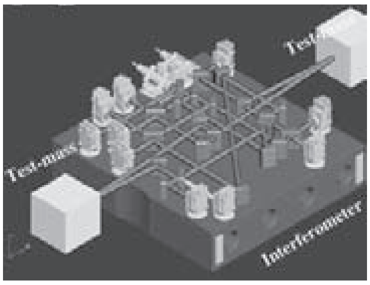
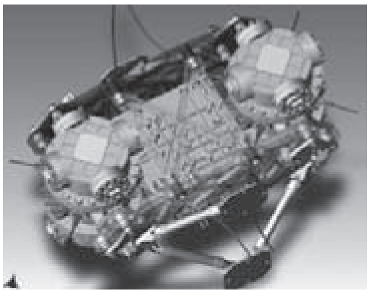


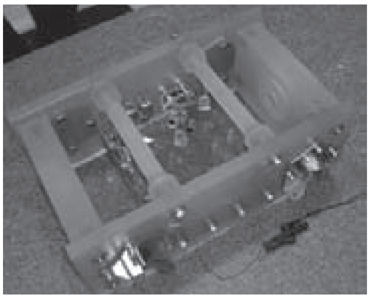
Fig.2a: LPF interferometric concept.

To this end, two LISA-like test masses are enclosed inside the LPF satellite and fluctuations in the separation between them (30 cm instead of 5 million km) are interferometrically monitored. This concept is shown in *Fig.2a* with the two test masses acting as mirrors of the interferometer. *Fig.2b* shows the actual design of the experiment with the test masses inside their vacuum enclosures, the optical bench between them and two side slabs holding the structure. *Fig.2c* shows the Engineering Model (EM) of the optical bench with two gold coated mirrors acting as dummy test masses for ground testing.



2b: Actual mechanical design of the experiment.

Several people in the Hannover group are working on the design and implementation of the LISA and LPF interferometry and phase measurement, applying the wide heritage of the institute regarding laser



2c: Engineering model of the optical bench.

interferometry for gravitational wave detection to the new challenges of the low frequency range and space environment, where almost no commissioning is possible.

The LISA Pathfinder Interferometer and Phasemeter

Both the LISA and LPF interferometer are based on a heterodyne design, where position fluctuation of the test masses are detected as phase fluctuations of a beat note at the interferometer output. The functionality of both the interferometer and phasemeter design for LPF had been tested in Hannover with breadboard prototypes before 2004, allowing debugging of the phasemeter and identification of several noise sources.

In February 2004 our prototype phasemeter was tested for the first time with an ultra-stable monolithic optical bench at the Institute for Gravitational Research (IGR) in Glasgow, and the low-noise requirements at the millihertz range were achieved, as shown in the second sensitivity curve of *Fig.3*.

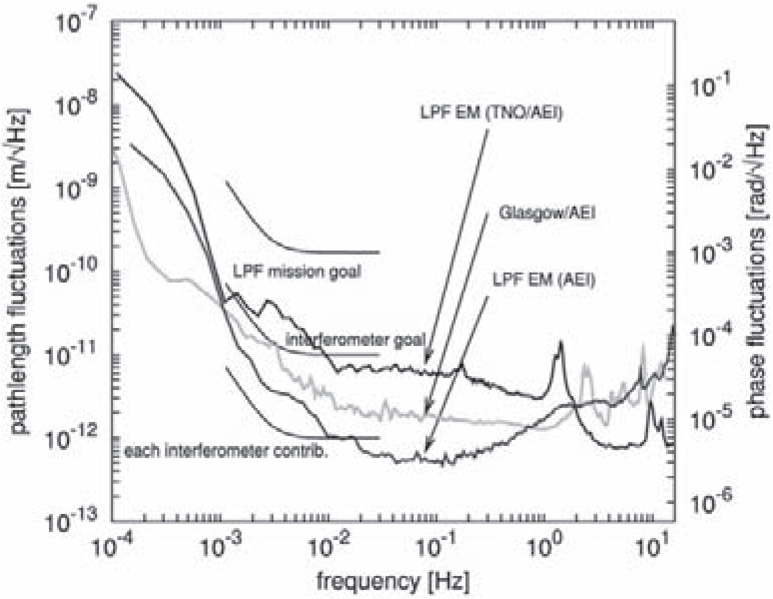


Fig.3: Sensitivity of the interferometer and phasemeter system to longitudinal test mass displacement.

One month later, the same phasemeter prototype was used during the successful environmental testing campaign of the engineering model (EM) of the LPF optical bench (*Fig.2b*) at TNO, the Netherlands Organisation for Applied Scientific Research. This optical bench was manufactured at the Rutherford Appleton Laboratory (RAL) with scientific support from IGR, AEI, University of Birmingham and integrated by Astrium Germany, thus representing the successful international collaboration of the team. The noise level measured during the campaign is shown by the upper curve in *Fig.3*.

Finally, the EM was brought to the new AEI laboratory facilities, where it has since then undergone a variety of functional and sensitivity tests. A new phasemeter prototype based on the hardware design to be implemented on LPF has been assembled and set-up during an extensive noise investigations campaign that has resulted in a theoretical explanation of the noise sources affecting the LPF interferometer/phasemeter design and an optimisation of the sensitivity (lower curve in *Fig.3*).

The on-going collaboration with Glasgow has also made possible the manufacturing and investigation with monolithic optical benches in the new AEI clean-room facilities.

LISA

More and more manpower is being focused on the LISA interferometry, together with the experience gained with the pathfinder. The differences mentioned before make of LISA a much more challenging project: not only are the requirements typically more stringent but also the 5 million km arms result in many technical challenges:

- The arm length differences require laser frequency stability never met before at low frequencies. A "prestabilization" scheme tested in Hannover has demonstrated 30 Hz/√Hz at the millihertz. Furthermore, a "proof of principle" hardware demonstration of a complementary frequency stabilization technique called "arm-locking" has also been shown.
- The heterodyne frequency by LISA will be in the MHz range instead of kHz by the pathfinder, thus requiring a different kind of phasemeter. Breadboard implementation of such a "fast" phasemeter has begun.
- Offset phase locking at low frequencies has also been implemented, together with an ultra-stable optical bench for LISA interferometry tests.
- Development and characterization of laser prototypes for space borne gravitational wave interferometry is also being done at the AEI.

Both LISA and LISA Pathfinder have experienced major advances in the last two years. The pathfinder has entered its implementation phase and no more "proof of principle"-experiments are needed. The challenge now consists in offering scientific support with the exact definition of each subsystem and procedure. This gives a young scientist the rare chance to work along with industrial partners in the development of a space project.

Antonio Francisco García Marín

All-Reflective Interferometry with Nano-Structured Optics

While the first generation of gravitational wave (GW) interferometers are prepared for long term scientific data runs, research and development on many different aspects of future generations of detectors are underway. Together with the University of Jena, our group investigates a new approach to laser interferometry. The goal is to replace transmissive optical components by reflection gratings thereby allowing for much higher laser powers as well as new optical materials, and ultimately for an increased interferometer sensitivity.

Conventional GW-detectors are based on Michelson interferometers, in which the laser power is split and recombined with a partly transmissive mirror (beam splitter) as shown in *Fig.1*. Half the light has to go through a mirror substrate. Although the substrates are made of extremely pure materials some amount of energy of the transmitted light is absorbed, which leads to heating and hence deformation of the substrates. The deformation increases with increasing light power.

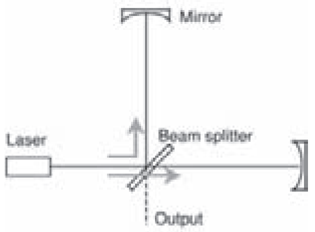


Fig.1: Conventional Michelson interferometer with a transmissive beam splitter.

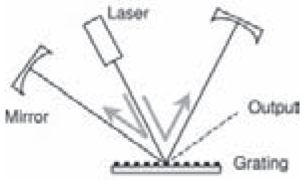


Fig.2: All-reflective Michelson interferometer with a grating beam splitter.

GEO600 already has a circulating laser power of several kW. Future detectors will have orders of magnitude higher power levels so that the deformations of the substrates will limit the sensitivity of the detectors. It is therefore desirable to avoid transmission through optical

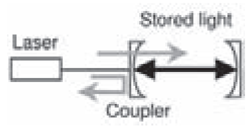


Fig.3: A conventional optical cavity with a transmissive coupler.

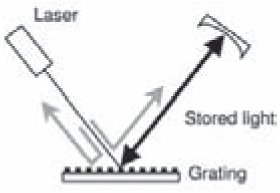


Fig.4: A grating cavity coupler with two diffraction orders.

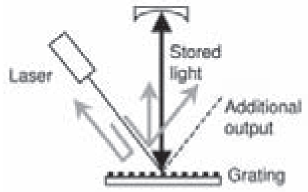


Fig.5: A grating cavity coupler with three diffraction orders.

substrates. Instead of using the transmitted and reflected light paths of a mirror we only want to use reflected paths to split and recombine laser beams. Conventional mirrors just reflect light into one path hence splitting in reflection does not seem to be possible. However, the situation changes if the phenomenon of diffraction is taken into account. Light incident to a periodically corrugated structure (a grating) can be diffracted into more than one path, so-called diffraction orders. The grating parameters can be chosen to allow only two diffraction orders therefore allowing the all-reflective analogue to a conventional beam splitter. *Fig.2* depicts schematically an all-reflective Michelson interferometer built with such a diffractive 50/50 beam splitter.

There are more optical elements inside the interferometer which are used in transmission and can cause thermal problems, for example cavity couplers. A cavity is used to store light and consists in the simplest case of two opposing partly transmissive mirrors as depicted in *Fig.3*. The amount of light that can be stored inside a cavity grows with increasing power reflectivity of the mirrors. In contrast to the central 50/50 beam splitter, cavity couplers typically have splitting ratios of 99/1 or more. Transmissive cavity couplers can also be replaced by reflection gratings. A grating with two diffraction orders (*Fig.4*) can act as an all reflective coupler. For this concept high diffraction efficiency is needed if high power buildup inside the cavity is desired. Another coupling concept can be realized with gratings having three diffraction orders as shown in *Fig.5*. It has the advantage that only low diffraction efficiency and therefore only weakly corrugated mirror surfaces are needed for high buildup.

The requirements for GW interferometer mirrors with respect to power reflectance and surface quality are extreme. Although diffraction gratings have been known and used over many years for various applications none of the commercially available gratings can fulfill them. The project goal is to develop diffraction gratings with well defined and controllable diffraction efficiencies in every reflection order and test them in interferometric applications. Furthermore, the residual transmission and scattering from the gratings must be minimized to a level that can be tolerated by laser interferometric GW detectors.

High reflectance of conventional interferometer mirrors is achieved by applying alternating thin layers of two different dielectric materials. Multiple interference between these layers leads to the desired mirror properties. The thickness of layers usually corresponds to a quarter of the wavelength of the light being used. For lasers used in GW detectors the wavelength is roughly 1 µm. We use a combination of such multi-layer coatings with periodic structures, so-called dielectric gratings. The length of the grating period is around 1 µm whereas the depth of the structures can be as small as 40 nm. The challenge is to manufacture such small structures uniformly over the surface of the whole substrate which is of the size of several centimeters. We use electron beam lithography - a technology known from microchip production - to fabricate the small structures.

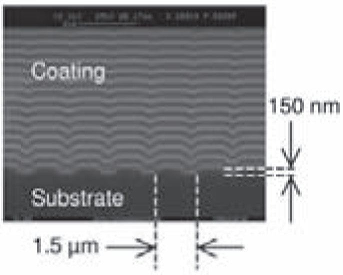
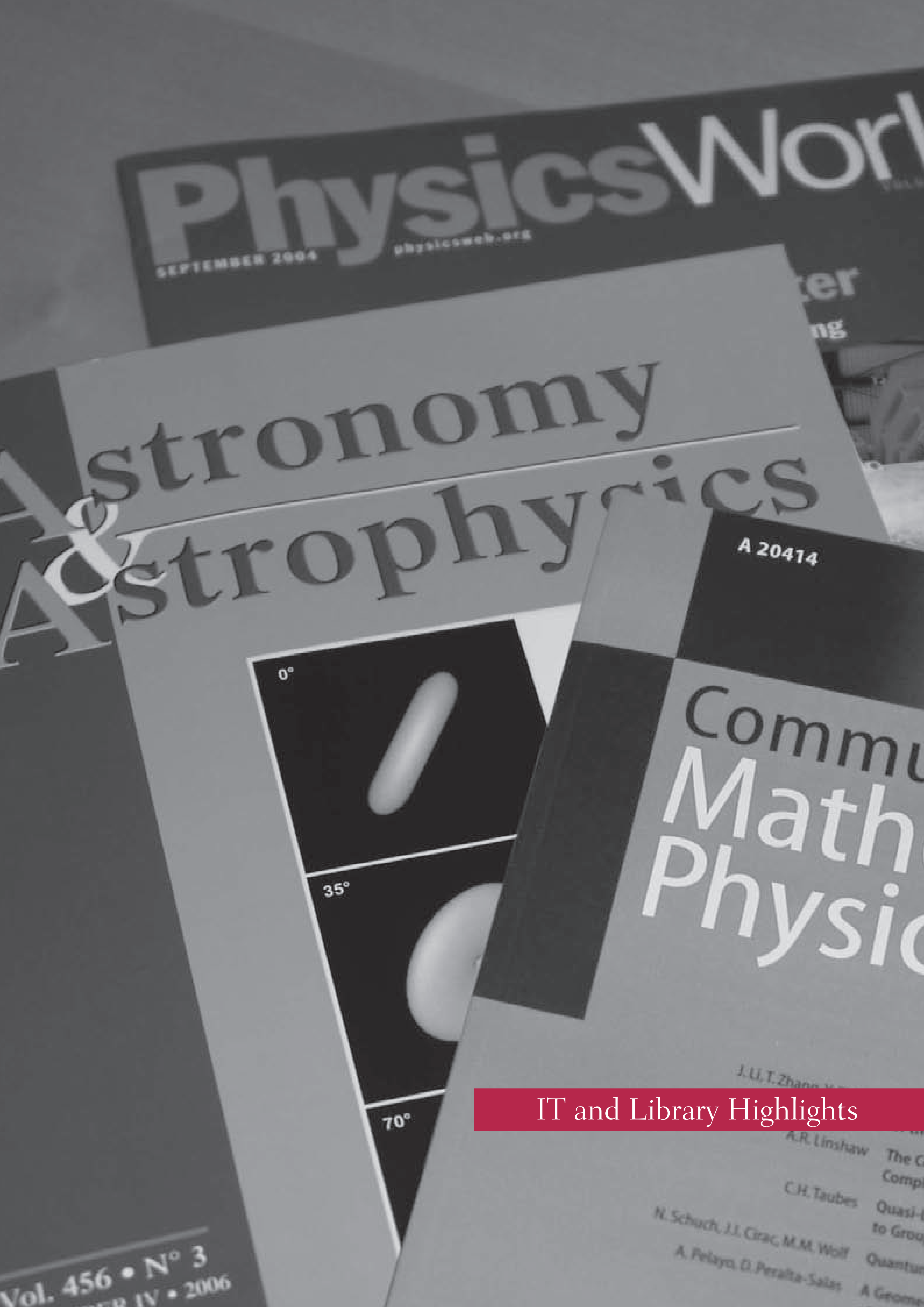


Fig. 6
Cross section of an over-coated diffraction grating (Scanning electron microscope image) suitable for low scattering and low diffraction efficiency gratings.

We pursue two different approaches to dielectric gratings. For the 50/50 beam splitter and the cavity concept in *Fig.4* we etch the grating into the topmost layer of the coating. Interferometric measurements revealed an unprecedented high diffraction efficiency of 99.62 % for our cavity coupler. Another approach is to etch the grating directly into the substrate and apply the coating onto it. With every coating layer the grating ridges get shallower and hence the flatness of the surface increases as shown in *Fig.6*. With this technique we could demonstrate extremely low diffraction efficiency gratings combined with low scattering and low transmission. With these gratings we could demonstrate the coupling concept of *Fig.*5 for the first time. The demonstration revealed new cavity features that are due to the fact that three light paths interfere instead of two as it is the case for conventional cavities. We could explain these features by theoretical investigations of generic three port devices and thereby generalizing cavity theory.

Our research program has shown that custom designed and fabricated diffractive optics has the potential to be implemented in future GW detectors. The transition from table-top interferometers to large-scale prototypes is already planned with the set up of a fully suspended 10 m all-reflective cavity within the GEO600 collaboration in Glasgow by the end of 2006.

Alexander Bunkowski



IT and Library Highlights

Activities and Highlights of the IT Department in 2004 and 2005

General Infrastructure

At the root of the computer infrastructure are the mail server, the file servers and nowadays also the WEB servers, all linked through a stable and secure network. Major improvements have been made in all these areas during the last two years, apart from the necessary upgrades on the various platforms (migrate from MS Win NT to MS Win 2003, upgrade Fedora Core 2, upgrade from MAC OS 9 to MAC OS 10).

Changing a mail server for example is very crucial and could affect the productivity of the scientists very much. The system administrator succeeded in managing the migration to another mailing system without significant downtimes. The new mail server provides web-mail access and integrated Spam/virus filtering. The web-mail facilities in particular improve accessibility for AEI scientists if they are working in another environment. They now only need a web browser and can access the inbox at AEI without setting up a special profile on their current computer. A big relief in handling the daily mails was achieved by the installation of a powerful spam-filter on the mail server.

The transitions to new file and WEB servers have taken place in a similarly satisfying manner. The Institute is currently running five file servers with a total capacity of about 5 TerraBytes.

More than five servers are installed to allow the general public access to detailed information about the institute. Worthy of mention is the relaunch of the AEI web site (*www.aei.mpg.de*), which can now be maintained via a content management system (NPS, infopark). For the internal users, another important relaunch has taken place: *help.aei.mpg.de* now offers an “AEI Virtual Computer Support Office”. On these pages, AEI users can find useful information about the IT infrastructure, responsibilities of the IT staff and rules that have to be taken into account during daily work. Most frequented are the topics “Known Issues” and “How To”.

In the last years mobile computing has become common and the IT department is keeping track with these developments. UMTS allows scientists to go on-line in nearly every corner of the world. Mobile computing also needs special attention in respect of security. VPNs (Virtual Private Networks) are installed for all remote and/or wireless activities. We‘d like to emphasize that the Hannover branch of the institute is connected to the AEI in Potsdam-Golm via a special VPN bridge since 2005.

High Performance Computing

Since the end of 2002/beginning of 2003 the AEI is running high performance compute clusters for jobs too big for ordinary desktop systems. Both high performance clusters, MERLIN and PEYOTE, have been extended in 2004 and 2005. The MERLIN cluster is operated by the gravitational wave group and is exclusively designed and dedicated to the job of data analysis of LIGO and GEO600 data.

The Institute is very pleased to have access to the dedicated high speed data link of the HLRN (Norddeutscher Verbund für Hoch- und Höchstleistungsrechnen) since December 2004. The HLRN system consists of two identical parts which are installed at Konrad-Zuse-Zentrum (ZIB) and the Regionales Rechenzentrum für Niedersachsen

(RRZN) at the University of Hannover. Both sides are linked by a dedicated fiber network with a bandwidth of 2.4Gbit/s. This link provides a direct and inexpensive route for bringing data from the GEO600 detector in Hannover to its archive at ZIB. The technical details of Merlin may be found on *pandora.aei.mpg.de/merlin*.

The PEYOTE cluster is the main in-house computing resource of the AEI. Peyote was designed for calculating the closely linked problems set by the scientists in a highly parallel way. The size of the cluster has grown continuously and currently consists of 176 nodes.

LAGAVULIN is the third cluster that the AEI houses. Infiniband is installed as interconnect network. This cluster is placed at Benzstraße, an outpost of the Institute, and allows the scientists there to run smaller jobs and to test their code. Technical details on PEYOTE and LAGAVULIN can be found on *numrel.aei.mpg.de/Research/Peyote/*.

Graphics

For presenting results, scientists normally use graphic output. This may be either in the form of 2D graphs but sometimes also in 3D or even in movies. For daily calculations and graphical output the Dual CPU individual workstations systems are adequate for the requirements of the scientists. For special purposes such as the creation of 3D animated movies and visualization of results in a sophisticated manner, a special graphic workstation is needed. At the end of 2004 the Institute purchased a Fujitsu Siemens Celsius V810 with the following components: 2xAMD Opteron 250 (2.4 GHz), 16 GB RAM, nVidia QuadroFX 3000 (256 MB), DVD, 1TB disc space. This configuration works very well together with the AMIRA software which is the main visualization tool used for both 3D output and movies.

Movements

An extra challenge for the IT members in 2004 was to set up a reliable network connection between the AEI-Golm and the new branch in Benzstraße. Most of the members of the numerical relativity group moved to Benzstraße. The need of a data line with sufficient capacity to transfer hundreds of GigaBytes of data from the Peyote cluster to the local systems was obvious. With the help of a local provider we could release a 100Mbit/s line at the beginning of December 2004.

To integrate the Benzstraße branch as much as possible into the AEI parent institute in Golm, we have opted for very modern technology. For an adequate telephone and fax connection to the AEI we decided to go for VoIP (Voice over IP). This technology was rather new then and not in use in many places. But it acquitted itself very well. Ever since the data line was set up, data and speech were transferred perfectly into all directions of the world. Calls between AEI members, no matter whether they are located in Golm or in Benzstraße, are in-house calls.

In order not to be too dependent on the network and power in case of an emergency, an additional standard telephone line with DSL (Digital Subscriber Line) has been installed to be able to do emergency calls.

Events and contact

In 2005, the Einstein Year was celebrated. The IT was involved in very many events. Setting up computer equipment in places where special exhibitions were taking place and keeping the systems running was a very exciting task. But the biggest challenge was the conference “Geometry and Physics after 100 Years of Einstein‘s Relativity” which was held at the Institute in Golm. The IT was responsible for all infrastructure necessary to WEBcast the whole conference to interested people all over the world. The streams are archived and can be accessed by a general WEB browser on the WEB pages of the AEI (*www.aei.mpg.de » Seminars & Events » Conferences*)

Also worth mentioning is the institutes Loops 2005 conference. The IT set up technical equipment for recording all talks of the conference. Further details can be found under topic "Programme" of *loops05.aei.mpg.de*.

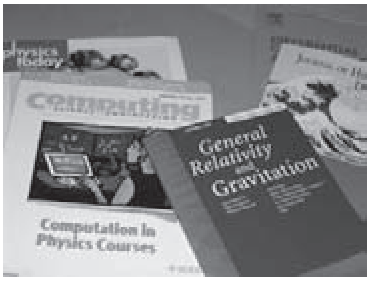
Other events have taken place, most of them using video conference techniques, either AGN (Access Grid Node) or Standard H.323. The scientific cooperation between the AIP (Astrophysical Institute Potsdam) and the AEI has led to the idea to investigate the opportunities offered through a better network connection of the two institutes. AEI IT members are looking for a good and inexpensive solution to set up a dedicated line between AEI and AIP together with the IT staff of the AIP and the University of Potsdam. A 10 Gbit/s line is currently being tested and there is good hope for putting the line in operation in March 2006.

Education

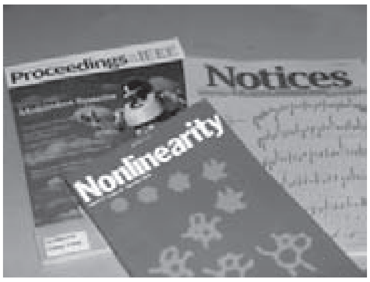
In 2004, two members of the IT department have successfully finished their training as IT specialists. One has become systems integrator, the other application developer.

Christa Hausmann-Jamin

Activities and Highlights of the Library in 2004/2005



The library is a specialized library offering services first of all to scientists working at the institute in Golm, the satellite office at Benzstraße, Potsdam-Babelsberg, and the Teilinstitut in Hannover. Scientists from outside are welcome and usage is then possible by making an appointment. Scientists and students working at the two other Max Planck Institutes on the campus or at the University of Potsdam located in Golm can use the library in the same way as the scientists at the institute, but they cannot participate in the library loan service. Two librarians manage the library: Mrs. Elisabeth Schlenk, the head of the library, and Mrs. Anja Lehmann.



The holdings increase continuously and at the end of 2005 our holdings list 7.982 monographs and conference reports, 9.676 bound journal volumes, 140 printed journal subscriptions and online access to journals covered by the Grundversorgung, i.e. the Max Planck Society secured a permanent right to full text access for at least 17.834 journal titles. The search in online databases (Web of Knowledge, INSPEC, Current Contents etc.) through the host OVID is also part of the Grundversorgung and offered by the library. Besides this the membership in the North Rhine Westphalia Consortium, Bielefeld, which we joined in 2002 to get online access to MathSciNet was renewed as well as the membership in the Zentralblatt MATH-Konsortium to support the German and European Mathematical Societies.

The e-only decision is still in progress and a kind of ultimate solution regarding local or agency hosting, stand-by-archive, Articles in Press, Springer First etc. needs more discussions not only with the publishers but also within the society. Nevertheless the policy of our library is to place electronic access at the scientists‘ disposal irrespective of usage. We know that there are electronic resources and the scientists should have the possibility to use them whenever they need them.

The members of the Library Committee are Prof H. Friedrich (Chairperson), Dr. M. Ansorg and Dr. M. Staudacher. They check the publisher's catalogues, brochures and new title announcements for relevant titles of monographs which have to be ordered, they study sample copies of new journal titles for possible subscription, they classify the new books and they discuss in regular meetings new developments or necessary changes regarding the demands of the library. Mrs. Hausmann-Jamin, Prof Theisen and Prof Huisken support the library committee in terms of the selection of new books and other relevant media.

Besides the classical services, namely the supply of the library holdings, the procurement of literature for the scientists at the institute is another main task of the library. In general we do this by ordering the requested journal articles or monographs via the internet server (SUBITO) located at the University Library in Göttingen. Other libraries from which to get requested literature are not only those of the various Max Planck Institutes, but also those of the universities in Vienna, Berlin and Potsdam, of the Astrophysical Institute in Potsdam, and the National Library Preussischer Kulturbesitz in Berlin.

We are still one of the institutes supporting the electronic document server (eDoc) of the Max Planck Society. This server provides a unique entry point to the accumulated research output of the Max Planck Society. Via eDoc, scientists can make their work openly accessible online with the technological and institutional backing of the Max Planck Society. Therefore we are registering the institute publications adding links for online versions and abstracts not only in our OPAC (Online Public Access Catalog) but also in the eDoc Server and up to now the metadata and full texts of 2214 documents (articles, conference papers, talks, etc.) have been collected.

The phrase 'everything is electronic and the scientists can manage it by themselves' is used very often from various decision makers. A survey showed, however, that in nearly all MPG libraries the classical work of the librarians is still required and that the new media are additional fields of activity.

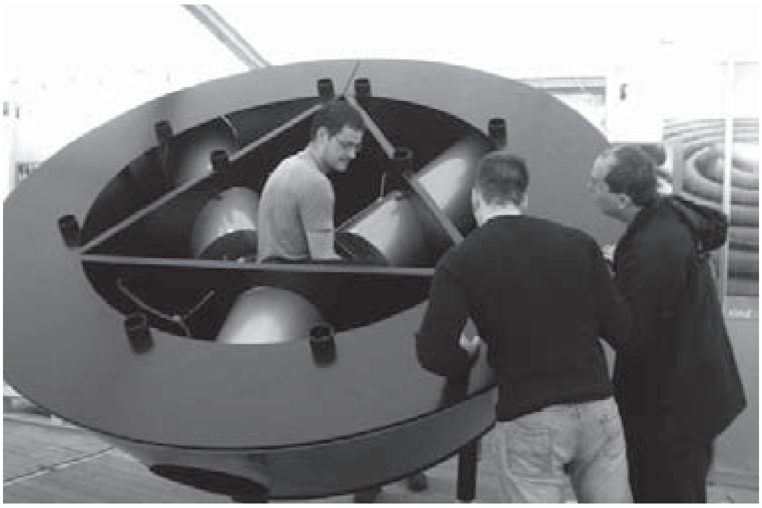
Elisabeth Schlenk

The Einstein Year 2005

The Einstein Year 2005: Einstein's Legacy and the Public

The International Year of Physics 2005 was devoted to the 100th anniversary of Einstein's miracle year. In 1905 Einstein did not only publish his revolutionary Special Theory of Relativity, including the famous formula E=mc^2, but he also provided an explanation for the photo effect (for this achievement he was awarded the Nobel Prize in 1921), and proved the existence of atoms by studying Brownian Motion and – last not least – by finishing his doctoral thesis on a new method to determine the dimension of molecules.

The Einstein Year offered a unique opportunity for showing the importance of relativity today and for communicating research in Einstein's footsteps to a broader public. Our aim was two-fold: First of all, we wanted to focus not on the history, but on Einstein‘s scientific legacy – on the fact that, despite its respectable age of one hundred years, relativity is still an area of fascinating, cutting-edge research. Secondly, we took a long-term perspective: We wanted to create sustainable projects from which AEI outreach could profit far beyond 2005. With these aims in mind, the public relations department concentrated on building the new web portal 'Einstein-Online', on producing film sequences and animations, as well as on constructing exhibits and hands-on experiments. The latter were mainly built by the experts in the institute's own workshops in Hannover. Jens Reiche and Sascha Skorupka from the AEI in Hannover provided a lot of brilliant ideas for hands-on exhibits and took care of the realisation together with the workshop staff: Special thanks to Stefan Bertram, Lars Brunnermeier, Jan Diedrich, Hans-Joachim Melching, Philipp Schauzu, Andreas Weidner, and Heiko zur Mühlen!



Sascha Skorupka, Michael Augustin and Markus Pössel assembling a life-sized model of a LISA satellite for the science summer.

Exhibiting Einstein

Both within Germany and abroad, there was a multitude of exhibitions focussing on different aspects of Einstein‘s life and work. Our institute contributed to the exhibitions in Berlin, in the Deutsches Museum in Munich, in Mannheim, Bern, and Ulm, as well as to the floating exhibition on the "Einstein Ship" that toured Germany's waterways. For the central exhibition in Berlin, which was organized by the Max Planck Institute for the History of Science, we provided several exhibits and hands-on experiments as well as computer simulations and films about LISA, GEO600 and string theory. Also, Markus Pössel, a postdoctoral researcher and outreach specialist who was hired specifically to support our Einstein Year activities, joined the scientific team preparing the exhibition and assisted with the planning, organization

and presentation of the section dealing with Einstein's legacy for modern physics, 'Worldviews of Modern Science'.

Einstein-Online

Our new web portal 'Einstein-Online' (conception and realisation: Markus Pössel) provides a presentation of Einstein's theories of relativity aimed at the general public. Visitors of the portal can find out about the basics of relativistic physics in "Elementary Einstein" or explore its ramifications and modern relativity research in the "Spotlights on Relativity". The German version of the webpages went online in January 2005, while the English version was released in June. An offline version on CD was included with the November edition of "Physik in unserer Zeit" (the German analogue to "Physics Today"). The web-site was reviewed favourably in the media, and it was featured in the Netwatch section of the journal Science in November 2005.

Einstein-Online scored 2.5 million hits (corresponding to 85,000 visits) within the first month of its publication, and has now settled down to a regular average of about 200,000 hits (15,000 visits) per month. Starting in late 2005, it has also evolved from an institute project into a community project: Several "Spotlights on Relativity" have been contributed by scientists from other institutes, and it is planned to intensify this cooperative aspect even further in the future. All in all, Einstein Online has developed into a core project of the outreach activities of the Institute.

Einstein@Home

Another major web-based project for the World Year of Physics is Einstein@Home, which was created both at the University of Wisconsin, Milwaukee (UWM), with Bruce Allen as project leader, and at the AEI. Where Einstein-Online aims at explaining relativity to laymen, Einstein@Home actively involves the public in the search for gravitational waves: With the help of their personal computers, participants help in the analysis of data from the gravitational wave detectors LIGO and GEO600 aimed at the detection of signals from spinning neutron stars (pulsars). Such analysis requires an enormous amount of computing power, but such power can be achieved by distributing the data among the personal computers of a great number of participants. Joining Einstein@Home is easy: Those who want to dedicate a portion of their personal computers' time to the project can simply go to the Einstein@Home web page and download a software called Boinc, which was developed for the administration of such distributed computing projects. Once installed, the software initiates downloads of LIGO and GEO data from a central server. Whenever the PC is not in use, the program than searches the data for gravitational wave signals, while, in parallel, a screensaver image showing the celestial sphere and indicating the region currently being searched is displayed.

Festivals, Talks and all the Rest

In addition to the aforementioned activities, AEI took part in a great number of other Einstein Year events. Close to home was the "Science Summer" festival in Potsdam and Berlin, in which the institute was represented with a whimsical "elementary particle zoo" as well as exhibits about gravitational waves. Peter Aufmuth and Sascha Skorupka joined the AEI Potsdam team and spent one week giving talks and entertaining the public. In addition, there was a plethora of popular talks given by individual AEI scientist not only all over Germany – from the International Literary Festival Berlin to the Zinnober Art Festival at Hannover, but also abroad, for instance, in Switzerland, Austria, and at the International Science Festival in Luxemburg, even at the Public Outreach Meeting of the Australian Physical Society in Canberra (Australia). A number of events were targeted explicitly at high school or even elementary school students – for example, AEI contributed to the "Einstein Day for Schools" in Jena (in cooperation with the SFB Transregio Gravitational Wave Astronomy) and to the first Children's University of the GKSS research center, Geesthacht. Hoping to improve the quality of tuition AEI scientists participated in several courses devoted to the training of teachers.

For science communication the Einstein Year 2005 was a great success and we are now looking forward to 2015 – the 100th anniversary of General Relativity!

Elke Müller & Peter Aufmuth

Open Day at the Research Campus Golm

It was a warm and sunny Saturday in late August, 2005, when the fifth Open Day of the Campus Golm was held. It was organized by the three Max Planck Institutes, the Fraunhofer Institutes for Applied Polymer Research and for Biomedical Engineering, and the University of Potsdam. While in 2004 the Max Planck and Fraunhofer Institutes were guests at the campus of the University's Faculty of Mathematics and Sciences, in 2005 the Open Day took place at the Max Planck Campus again.

There was a wide spectrum of attractions for the young and the young at heart, covering topics in physics, chemistry and biology. The choice of activities ranged from talks about Einstein, genetic engineering, or solar cells made of polymers, to guided tours of the institutes and to demonstrations of black hole simulations or the three-dimensional structure of bones. Special highlights were the research area for children and the nanoTruck of the Federal Ministry of Education and Research. In the central building the exhibition "Bilder aus der Wissenschaft" (Science in Pictures) of the Max Planck Society could be seen.

The AEI presented its new projects from 2005: Einstein online, a website explaining Einstein's theories of relativity, and Einstein@Home, a screen saver searching for gravitational waves. A full-scale satellite model of the LISA mission was an impressive eye-catcher, and Sascha Skorupka and Peter Aufmuth from Hannover explained the operating mode of interferometric gravitational wave detectors to the visitors. Also, there was a virtual tour of the gravitational wave detector GEO600, an introduction to relativity, given by Markus Pössel, and other talks of AEI members.

In the children's research area the AEI showed an elementary particle zoo. Its inhabitants were not only the familiar ones of the standard model like quarks, gluons or neutrinos, but also some that have not been seen so far like the Higgs boson, the graviton and even the tiny strings (which felt quite at home at the AEI) and the mysterious dark matter. Next to the zoo the children could act as young researchers and explore why leaves are green, experiment with colours or experience with their own body the angular-momentum conservation law. And now the children probably know more than the reader about at least one question: Why don't plants eat chocolate?

Dörte Blischke

Events

Conference "Geometry and Physics 100 Years After Einstein's Relativity" and 10th Anniversary Celebration, April 4-8, 2005, in Golm

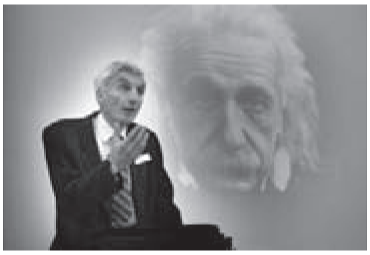
Speakers:
Ashtekar (PennState University), Barry C. Barish (California Institute of Technology), V. Braginsky (Moscow State University), Robert Brandenberger (Brown University), J. P. Bourguignon (IHÉS), T. Damour (IHÉS), R. Genzel (MPI Garching), M. B. Green (University of Cambridge), J. Hartle (University of California, Santa Barbara), T. Prince (California Institute of Technology), M. Rees (University of Cambridge), R. Schoen (Stanford University), M. Staudacher (AEI), M. Struwe (ETH Zürich), M. S. Turner (University of Chicago), C. Wetterich (Universität Heidelberg), C. Will (Washington University), S.-T. Yau (Harvard University).

In the International Year of Physics 2005 the Albert Einstein Institute celebrated its 10th anniversary with a special event and by organising a conference on modern developments in geometry and physics a century after Einstein's relativity.

On 4th April 2005 the president of the Max Planck Society, Peter Gruss, attended the special celebration on occasion of the 10th anniversary of the AEI and recognised the research undertaken at our institute. P. Gruss and Ministerialdirgent J. Glombik representing the state of Brandenburg asserted the importance of basic scientific research in a wider context and expressed their continued support for the AEI. After Norbert Straumann (Zürich) gave an inspiring overview of modern research on gravitational phenomena the setting of a foundation stone for the new extension building provided an outlook to an exciting future for the AEI.

The conference brought together mathematicians, theoretical and applied physicists from all areas of Gravitational Physics and provided a thorough snapshot of the state of the art in this field. The program consisted of eighteen plenary lectures that were attended by about two hundred participants in Golm and up to three thousand viewers connected via the internet. The speakers from all over the over world represent the wide ranging national and international collaboration of the AEI in the research areas relevant to gravitation

All speakers made an extra effort to speak to the wide range of scientists in the audience making possible a lively interaction between scientists in different specialties ranging from differential geometry and string theory all the way to astrophysics and laserinterferometry. The conference showed how intensely many formerly different areas of science have to interact to provide an understanding of the complex phenomena observed in the universe. Their lectures and slides are available on the homepage of the AEI.



Martin Rees gave an inspiring evening lecture

For the general public Martin Rees gave an inspiring evening lecture in the festive main lecture hall of Potsdam University describing the latest discoveries in astronomy and their impact on our modern view of the world.

Gerhard Huisken

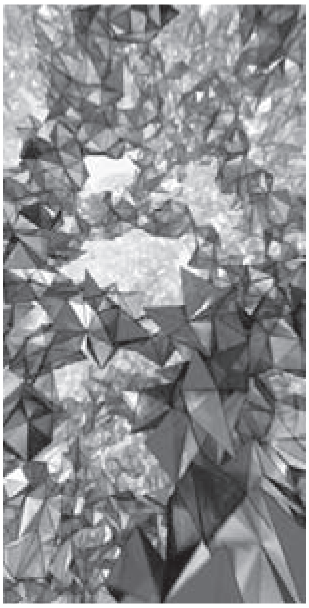
Loops'05 at the AEI

In the Einstein year, the almost annual conference on background independent approaches to quantum gravity took place at the Albert Einstein Institute. The official title of the conference was 'Loops 05', however, not only Loop Quantum Gravity (LQG) researchers were present but also practitioners of the other non-perturbative approaches.

Plenary talks were distributed among the following topics:

1. Asymptotically Safe Quantum Gravity (Reuter)
2. Causal Sets (Sorkin and Dowker)
3. Dynamical Triangulations (Loll)
4. Generally Covariant Algebraic Quantum Field Theory (Verch) and
5. Loop Quantum Gravity (Ashtekar, Baez, Barrett, Corichi, Freidel, Gambini, Lewandowski, Perez, Pullin, Rovelli and Smolin)

The well-known names associated with the topics indicate that almost all the leaders in those fields were present at the conference.



Quantum spin dynamics seen through the eyes of an artist.

There were also talks on background independent aspects of string theory (Dijkgraaf and Theisen), Supergravity (Julia), Emergent Quantum Gravity (Morales - Tecotl) and Quantum Cosmology (Maartens). There were 20 plenary talks and 63 afternoon talks which, for the first time, had to be distributed over two parallel sessions. We had more than 150 official registrations but the lecture theatre was sometimes filled close to capacity (210 seats). This was certainly the biggest quantum gravity conference focussing on background independent approaches so far. It is pleasing to observe that the number of participants at this kind of meetings is rapidly increasing. From my own memory I recall the following conferences and rough participant numbers respectively: Banach Center, Warsaw, Poland, 1995 (50); Punta Del Este, Uruguay, 1996 (40); ESI, Vienna, Austria, 1997 (60); Banach Center, Warsaw, Poland, 1997 (60); ITP, Santa Barbara, USA, 1999 (70), Banach Center, Warsaw, Poland, 2001 (60); IGPG, State College, USA, 2003 (90); CPT, Luminy, France, 2004 (110).

The conference was subsidised by the Max Planck Society (MPS) and The Perimeter Institute for Theoretical Physics (PI). While PI sponsored the conference poster, the money from the MPS and about 60% of the conference fee (EUR 150), which was cashed only from non-students, was solely used in order to enable students to participate. I would like to take the opportunity to thank the plenary speakers once again for not asking for reimbursement which would have downsized the student participation by an order of 40 people.

Due to the help of the science communication company ‘Milde Marketing’, the conference also had quite some impact on the German press. Major articles appeared for instance in the Frankfurter Allgemeine Zeitung and the television company RBB interviewed some of the participants and intends to broadcast parts of the conference. Also, Lee Smolin spoke in the ‘Urania’, a world famous institution in Berlin, which focuses on mediating science to the public through popular talks. The scientific contributions to the conference can be downloaded, in many cases both audio and video, from the conference website *http://loops05.aei.mpg.de/*. It is difficult to single out particular highlights but maybe one of the lessons to take home from the conference is that all afore mentioned approaches start deriving results relevant for quantum cosmology which is very important in view of the fact that precision cosmological measurements such as WMAP and later PLANCK might be able to detect quantum gravity fingerprints in the cosmic microwave background.

Thomas Thiemann

Through the Eyes of a Visitor

Through the Eyes of a Visitor

I was visiting AEI as a Humboldt professor for few of month in the Fall 2004 and then Summer 2005. Prior to this I was at AEI for short visits at workshops.

The Institute is located in the rural setting. One may expect that the place is isolated. I did not find this to be a problem: I had many problems to work on. But most importantly, I had very interesting discussions with members of the institute and visitors: with G. Arutyunov, N. Beisert, H. Nicolai, M. Staudacher, S. Theisen, and others.

The library at the institute is an example of a wonderfully selected collection of publications. Since I was staying at the guest house which is close to the institute, some time in the evening I would browse the library‘s bookshelves and read books which I always wanted to read but never had time.

The computing support was effective and all questions that I had were quickly resolved. I came with a laptop which was almost immediately connected to the net in the Guesthouse and in my office.

The cafeteria offers breakfast and lunch. In both cases there is a reasonable variety and usually one can choose something good. It is not a fancy place to have lunch but if compared with other cafeteria of similar nature I would give it a good rating. When I was tired of the cafeteria food, I would bring something or would have my own lunch at the Guesthouse.

The Guesthouse has apartments and rooms. Most of the rooms have private bathrooms. For a couple of weeks I was staying at a room with private bathroom sharing the kitchen with other visitors on the second floor. The kitchen is spacious and convenient, it has plenty of space to cook and eat. It was an interesting social experience. Then I moved to an apartment. It had a balcony, bedroom and living room with a small kitchenette, and it was comfortable. On one of the first days of my visit S. Theisen kindly offered me a bike which I was using a lot. There are many picturesque paths to walk or to bike in the vicinity of Golm.

The institute is conveniently close to Potsdam and in particular to the beautiful park Sanssouci. There is a very pleasant walk from the institute past the train station and then via Lindenallee to the park. It is about a few kilometers and it is ideal for an early evening or a weekend walk. It can be continued through the park and to Potsdam, where one can easily find good dinner.

I was going frequently to TU, Berlin. The AEI is in a reasonably convenient proximity to Berlin. In order to have a rapid commute to the Zoo station in Berlin one has to be a bit organized to follow the schedule of trains, but the ride itself is comfortable and takes about the same time as a ride by BART from the East Bay to San Francisco.

The visits were both productive and stimulating. I had many very interesting discussions with N. Beisert and M. Staudacher from which I learned a lot on latest developments in integrable systems and the string theory. It appeared that the techniques developed for computing the spectrum of Hamiltonians of quantum spin chains can be used to compute the spectrum of conformal dimensions of certain composite operators. In particular, Bethe ansatz can be applied when the spin chain corresponding to the composite operator is integrable. We had a number of productive discussions with G. Arutyunov about quantum "nonlinear" spin Callogero-Moser systems. One of the key ingredients of the "exact" solution of dimer models on planar (surface) graphs is the so-called Kasteleyn operator. This operator(s) can be regarded as a discrete version of the Dirac operator. With H. Nicolai we had a number of interesting discussions on discrete supersymmetry. The theory of random matrices known in physics as matrix integrals is very important in statistical mechanics, two-dimensional gravity, and other branches of theoretical and mathematical physics. With M. Staudacher and V. Kazakov we had very interesting discussions of dimer models on random graphs.

I am planning to visit AEI again in summer 2006 and to participate in the workshop "Integrability in Gauge and String Theory".

Nicolai Reshetikhin
Berkeley University

News Items

News Items

High-End Visualisation Workshops in Obergurgl, Austria

Initiated by Werner Benger, the visualisation expert at ZIB/AEI, a series of annual workshops on high-end visualisation methods and techniques has been launched in Winter 2004. These workshops, organised by the AEI numerical relativity group, ZIB, and the University of Innsbruck (UIBK), focussed on issues surrounding the visualisation and interpretation of data resulting from supercomputer simulations. They offered an opportunity for scientists working with data to interact with specialists in the field of computer graphics and data visualisation.

Besides the very interesting talks and demonstrations that were given, the UIBK organisers also made sure that there was enough time left for fruitful informal discussions to knit new interdisciplinary contacts between physicists and computer scientists.

Vacation Courses at AEI in March 2004 and 2005

The 2 weeks vacation course on "Gravitational Physics", which the AEI started in 1999 together with the University of Potsdam has become a regular activity of the AEI. It is meant for students who have done their "Vordiplom". The structure of the courses was, as in the years before, two lectures in the mornings and the afternoons to go through the material of the lectures. The courses took place in the lecture hall of the Max Planck Campus in Golm.

In 2004, as already the years before, Jürgen Ehlers and Bernd Schmidt gave an "Introduction into General Relativity". The second lecture series was this time given by Gerhard Huisken on "Variational Problems in Geometry and Physics".

In 2005 the first course was "Introduction into General Relativity" (Jürgen Ehlers, Bernd Schmidt). The second course, led by Reinhard Prix, was "Introduction to the Physics of Neutron Stars". In 2004 about 24 students from the Berlin-Potsdam area and another 44 from all over Germany participated. In 2005 we had 8 from Berlin, 44 from all over Germany. Once more the AEI could provide some financial support.

The courses were again greatly appreciated such that continuation is planned.

Workshop on Quantum limited Atom Optics at AEI Hannover

In March 2004 the workshop of an international network with the topic "Quantum limited Atom Optics" was held in Hannover. The network is formed by leading French, Australian and German scientist in the field of quantum-limited high-precision measurements with light and atoms. The workshop was organized by the Sonderforschungsbereich 407, the Australian Research Centre of Excellence for Quantum-Atom Optics, the Groupement de Recherche "Optique atomique integrée et nanostuctures" du CNRS, the Institute for Theoretical Physics, University Hannover, and the Institute of Physics, University Potsdam.

About 50 scientist and graduate students were attending this workshop. The program was organized in talks followed by long discussion periods and lab and site visits. The talks were experimental and theoretical in nature and covered the whole field of interaction of light and mater in the quantum regime. Technical aspects as for example high precision measurement techniques with lasers and interferometers were discussed as well as fundamental limits on the measurement of atomic constants. A large fraction of the workshop was devoted to ultra-cold atoms and molecules and Bose-Einstein condensates. Especially the close interaction with graduate students and world-class physicists and the intense discussions after the talks and during the breaks made this workshop to a great success. The attendants of the workshop agreed to have similar workshops in France and Australia.

Workshop on "Scoping out LISA Data Analysis" 22-24 March 2004

The AEI hosted a workshop of about 30 participants from the USA and Europe to discuss the problem of planning for LISA data analysis. The participants were a mixture of people with experience of ground-based gravitational wave data analysis and experience of planning the LISA mission and its capabilities. Also attending, at our invitation, was Dr Michael Perryman of ESA, who was mission scientist for Hipparcos and is now leading the development of the GAIA mission. Both missions have data analysis requirements that have similarities to those of LISA, so his advice was very welcome.

The discussion covered technical issues, right down to trying to estimate the manpower required for a data center and the schedule of development needed for different components. The meeting agreed that the problem was not well understood yet, and much work needed to be done on the scientific underpinnings of searching for gravitational waves against confusion noise, as well as the appropriate data handling organization, one that would allow LISA to meet its scientific goals and at the same time satisfy the community‘s wish to be involved in data analysis and to have access to data for their own work.

The workshop was a significant step in the process of LISA data analysis development, which is being coordinated by the LIST. As a concrete result, LIST recommended that ESA and NASA establish as quickly as possible a design team for the data analysis architecture, which would coordinate work among scientists in the community. The establishment of these teams on either side of the Atlantic is now going on.

Cactus Retreat in Louisiana

In April 2004 the first Cactus Retreat was held at CCT in Baton Rouge. AEI‘s Cactus team was helping to organize this meeting which brought together Cactus users and application developers not only from AEI‘s and CCT‘s Numerical Relativity groups but also physicists of other research disciplines as well as computer scientists and Grid computing experts. The workshop, with its presentations and a practical Cactus tutorial for beginners, gave an exciting expression of how the Cactus code, since its first days at AEI a decade ago, has steadily grown into a widely used collaboration framework for a variety of scientific applications. The second Cactus Retreat is planned to take place in Spring 2006.

Meeting of the SFB/Transregio 7, April 23 – 24, 2004, in Golm

The Sonderforschungsbereich-Transregio 7 hold its spring meeting on April 23-24 2004 at the AEI, Golm. The two main topics of the meeting were black hole binary systems and gravitational collapse of astrophysical objects. The speakers provided an introduction to their subject and pointed out clearly the open problems. The meeting was important to improve the collaborations between the different sections of the project. The program of the meeting is available on the web:

http://www.tpi.uni-jena.de/SFB/golm_23_24_april_2004/golm2324april2004.html

EU Network Kick-off Meeting

In the week of 24 April 2005 AEI hosted the inaugural ("kick-off") meeting of the EU Network "Superstrings", in which AEI participates as a node (this network was rated as the first among more than 600 proposals in the corresponding round of applications to the EU). While many participants have been known to each other for a long time from previous networks and collaborations, one key objective of the meeting was to welcome the new members from Eastern Europe (Brno and Budapest). Another was the exposition of the main research topics of the network by the node leaders, in view of exploring the possibilities for further intra-European collaboration. These talks gave rise to lively discussions among all participants, which vividly demonstrated the emergence of a European sense of identity among the members of the network.

Cluster Grid Days in May 2004 and September 2005 in Golm

The annual Cluster Grid day is a regular meeting organized by and at AEI. Scientists from AEI and other local research institutes in the Brandenburg and Berlin area are invited to present their research and demonstrate practical solutions with special focus on cluster and Grid Computing. The previous two events, which took place in May 2004 and September 2005, were used as an opportunity to present an overview of AEI's activities and results in various Grid projects such as GridLab and D-Grid.

Workshop QHG 2004 "Towards the quantum geometry of hyperbolic 3-manifolds", June 28 - July 2, 2004 in Golm

The workshop was organized by K. Krasnov, H. Nicolai both of AEI and J. Teschner of Freie Universität Berlin. The idea was to bring together a small (~20) group of world-class experts in the areas of classical and quantum gravity in 2+1 dimensions, Liouville theory, Teichmuller theory and hyperbolic geometry to share expertise and boost progress in all these related fields.

Over the last decade or so the theory of negative cosmological constant quantum gravity in 2+1 dimensions has been developing rather rapidly, in particular due to its connections with the AdS/CFT correspondence of string theory. As a result of these developments it has became clear that this theory provides a bridge between several areas of mathematics and mathematical physics such as the classical and quantum Liouville theory, the classical theory of uniformization of Riemann surfaces, the classical and quantum Teichmuller theory, the geometry of hyperbolic

3-manifolds, topological (Chern-Simons) theory. One of the goals of the workshop was to clarify all the existing links between the above mentioned fields and their corresponding relations to 2+1 (quantum) gravity. This was aimed as a step towards a complete solution of quantum gravity in 2+1 dimensions.

The scientific highlights of the workshop were: description by Kashaev of flat PSL(2,R) connections on bundles other than of maximal Euler class; presentation by Teschner of his recent work relating quantum Liouville theory to quantization of Teichmuller spaces and proving an old conjecture by Verlinde; description by Freidel of a new set of duality formulas for quantum 6j symbols; description by Bonsante of an "analytic continuation" procedure that relates spaces of different signatures and different signs of the curvature; description by Fock of a new class of classical solutions of 2+1 gravity parameterized by projective structures on a Riemann surface.

To summarize, the workshop was very successful in that it fulfilled its goal of sharing expertise and bridging between different areas of mathematical physics. It resulted in many new interesting ideas and a few collaborations.

WHISKY retreat workshops, 2004 and 2005, in Golm

One of the many successes of the EU Research Training Network on Gravitational Wave Sources was a Europe wide collaboration on relativistic hydrodynamics. The collaboration was based around a code written by people at the AEI and SISSA (Italy) with considerable help from collaborators from Spain and Greece.

On July 16/17th, 2004 a meeting was held in Potsdam to discuss the progress of this rapidly expanding collaboration. The meeting was attended by researchers from Germany (AEI, Tübingen, Garching), Spain, Italy, the US and the UK. After talks describing previous successes in simulating gravitational collapse of iron cores and of neutron stars to black holes the discussion moved to ideas for future work including investigations of bar mode instabilities, the introduction of magnetic fields through GRMHD, and non-ideal hydrodynamics. The broad range of investigations indicates the success of this collaboration and the EU Network that brought it about.

In the summer 2005 the numerical relativity group organized the follow-up meeting dedicated to the Whisky code. Both meetings have represented excellent opportunities to present recent and unpublished results as well as to plan the development of new aspects of the code.

More information about the WHISKY code can be found on the AEI web-site at: *http://www.aei.mpg.de/~hawke/Whisky.html*

School on "Structure and dynamics of compact objects", September 20 - 25, 2004

The Albert Einstein Institute has hosted a summer school on the physics of compact objects, with emphasis on the modeling of gravitational wave sources from September 20-25 2004.

The school has been organized by Jörg Frauendiener, Stratos Boutloukos (both University of Tübingen) and Sascha Husa (AEI), as a common activity of the German transregional research network SFB/TR7 "Gravitational Wave Astronomy", the European Network of Theoretical Astroparticle Physics (ENTAPP) within ILIAS and the Albert Einstein Institute.

Local organisation was provided by numerous members of the AEI numerical relativity group (note that this includes members of two AEI divisions these days).

The scientific program was addressed to post-graduate scientists around the world and covered selected issues clustered around the modeling of gravitational wave sources with an emphasis on the physics of neutron stars. The program consisted of lectures on selected topics by invited speakers, with ample time for discussions. A computer-lab devoted to numerical relativity and a poster session have given opportunities for active participation. In addition to the program slides from lectures the school website also includes links to the numerical relativity tutorials and codes, and an extensive photo gallery (including shots from the conference dinner that eventually turned into another AEI dance party). Several of the participants got so excited about the location that they turned in applications for PhD or postdoc positions at AEI immediately after or even during the school.

More information can be found on the AEI web-site at:
http://sfb.aei.mpg.de/School04/

Steilkurse in Stringtheorie

The "Steilkurs in Stringtheorie" is an initiative of the German string theory community to offer compact lectures series in string theory to interested students from Germany and abroad.

In 2004 and 2005 the courses were organized by the AEI. From 27.9.-1.10.2004 more than 60 students were following the lectures by Jan Plefka (introduction to supersymmetry and supergravity), Ingo Runkel (introduction to conformal field theory) and Stefan Theisen (introduction to string theory).

Roughly the same number of students, partially those who were infected by the previous year‘s lectures, partially newcomers, came for the last week of September 2005 to Golm to listen to the lectures by Gleb Arutyunov (Utrecht, formerly AEI), Ben Craps (Amsterdam), Johanna Ergmenger (MPI Munich) and Marco Zegermann (Stanford) on advanced topics in string theory.

The participating students were financed by the priority program ‘Stringtheory’ of the DFG. The University of Potsdam, which listed the courses as part of their curriculum, helped with the organization of student accomodations. As in previous years, the Steilkurse 2004 and 2005 can be considered as great successes.

HERMES workshop "Hermes and Semantic Authoring with TeX and MathML" October 26 – 27, 2004, in Golm

The workshop was focused on existing semantic authoring tools for scientists. The workshop brought together delegates of 10 organizations ranging from universities to publishers. It was an opportunity to describe to all the interested parties what Hermes does and how, and also an opportunity to gather further functionality requirements. Some (happy) users described their experience with Hermes (ZentralBlatt für Mathematik, Berlin, Germany and Eötvös Loránd University, Budapest, Hungary).

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

Optical Readout Meeting

In June 2005 a meeting in Hannover was held to discuss a possible optical readout for the LISA test masses. All six groups that are working on this subject in Europe participated and presented their results and plans. Apart from the presentations, lively scientific discussions took place, and a follow-on meeting in 2006 is planned.

A programme on ‚Global Problems in Mathematical Relativity' at the Isaac Newton Institute

Helmut Friedrich organized together with Piotr Chrusciel (Tours) and Paul Tod (Oxford) a programme on ‚Global Problems in Mathematical Relativity' at the Isaac Newton Institute for Mathematical Sciences, Cambridge UK during August 8 - December 23, 2005. The aim was to discuss recent progress and open problems of Mathematical GR and to stimulate collaborations across the various subfields. The programme included: a Euroconference on ‚Global General Relativity' August 22 - 26, a satellite conference on ‚New Directions in Numerical Relativity' in Southampton, organized by Helmut Friedrich and Carsten Gundlach, a LMS Spitalfields day ‚Einstein and Beyond' on November 7 with talks directed to a general mathematical audience, which was organized by Paul Tod, and a conference on the ‚Einstein Constraint Equations' December 12 - 16, which was organized by Piotr Chrusciel and Jim Isenberg. All the talks of the meetings were of very high quality, they were well-attended and in some cases the number of applications went well beyond the capacity of the rooms available.

Besides these conferences there have been organized emphasis weeks devoted to specialized topics, which were attended by invited participants. The topic discussed in the daily seminar talks included: hyperbolic and numerical problems, black holes, dynamics with (and without) symmetries, Riemannian geometry and GR, Lorentzian geometry and GR, global techniques, quantum aspects of GR, asymptotic structure, inverse scattering methods and integrability, static and stationary solutions, the constraint equations. These weeks have been organized by the main organizers together with specialists in the field.

The whole programme was attended by 61 long stay participants and 91 short stay ones. It was generally considered as extremely stimulating. Various new collaborations have been started and old ones renewed. By the end of 2005 the participants of the programme have submitted twenty-six papers to the Newton Institut preprint series and more are expected to come. In some of these articles long standing problems have been solved. Several participants pointed out that the programme has considerably affected their research and there are indications that the programme will have a lasting impact on the field.

More detailed information on the programme can be found under *http://www.newton.cam.ac.uk/programmes/GMR/index.html* accessible via the home page of the Isaac Newton Institute.

IMPRS on Gravitational Wave Astronomy

At the end of 2005 the Max Planck Society granted a new International Max Planck Research School on Gravitational Wave Astronomy. The School is a collaboration between the AEI, the University of Hannover, and the Laser Centre Hannover. It aims at educating a new generation of researchers in the emerging field of gravitational wave astronomy. The education will cover the whole field from classical interferometry on the ground and in space, over to advanced and nonclassical interferometry, source modelling, and data analysis. The lectures will begin in Fall 2006, for further information please see: *http://imprs-gw.aei.mpg.de*.


The Kronprinzenpalais draped with the *Leitmotiv* of the exhibition.

Meeting of the Institute's Kuratorium

End of August 2005 the Kuratorium of the AEI met at the Magnus Haus in Berlin, just around the corner of Kronprinzenpalais where the exhibition "Albert Einstein – Chief Engineer of the Universe" was shown at this time. Dr. Wilhelm Krull was welcomed as a new member of the Kuratorium, strengthening the Institute's link to the Volkswagen Foundation that he chairs.

After a discussion about the Institute's development, funding and the public relations activities during the Einstein Year, Barbara Bludau, Secretary General of the Max Planck Society (MPS) gave an overview on recent developments within the Society. A survey concerning name recognition sees MPS on the top of the science funding organisations. As only 10% of the interviewees gain information about the MPS from the world wide web, the general administration in Munich plans to enlarge the web sites and the visibility of the Society.

The meeting was completed by a guided tour through the Einstein exhibition. Jürgen Renn, director at the Max Planck Institute for the History of Science, showed his masterpiece to the participants of the meeting.

Annual Meeting of the Max Planck Librarians at the AEI

For the second time Elisabeth Schlenk and Anja Lehmann organized the Annual Meeting of the Max Planck Librarians (105 participants) which took place from the 9th until the 11th of May 2005. One of the highlights was the panel discussion entitled 'Alles bleibt anders: Stabilität und Wandel in der wissenschaftlichen Informationsversorgung durch Bibliotheken' and the talk of Alice Keller, Bodeleian Library, Oxford dealing with the relationship between libraries and publishers. Five workshops, a poster session and company presentations enhanced the program. More information can be found under:

http://elzar.aei.mpg.de/library/index.html

AEI at CeBIT and Hannover Fair in 2005

Minister Edelgard Bulmahn at the AEI booth (Hannover Fair 2005).

In 2005 the AEI had the opportunity to show up at two important fairs in Hannover: At the world's largest computer fair "CeBIT" we presented the Einstein@Home project and Grid computing at the stall of the German Government. At the Hannover Industry Fair we were part of the stall of the Federal Ministry for Research and Education and displayed high tech laser interferometry for GEO600 and LISA.

New Rooms for the AEI Hannover

At long last, the Institute of Atomic and Molecular Physics of the University of Hannover, cooperating with the AEI Hannover under the name of 'Centre for Experimental Gravitational Physics', could be aptly renamed in Institute for Gravitational Physics (IGP). This was made easier because the University of Hannover has been restructured, changing from Departments to Faculties. The new name was accompanied by new quarters: Finally, the reconstruction of the former AEI building Appelstr. 38 has been completed, so the members of AEI and IGP moved into their new offices in April 2005. The costs of about 12.8 Mio. Euro include new basic equipment. They have been paid by the state of Lower Saxony while the Max Planck Society now pays a rent for the use of the buildings. A covered footbridge links the office building to the new lab building on the other side of the street that is in use since the end of 2003. So all the members of both Institutes now have optimal working conditions.

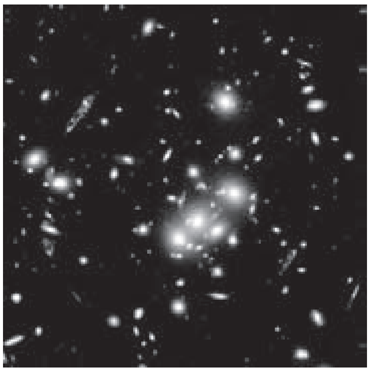
New AEI Building in Golm

After several years of planning and postponing, on April 4, 2005, the corner stone to the extension of the East wing of the institute building was finally laid in a ceremony which was part of the tenth anniversary celebration of the institute. Since then the construction has progressed at a rapid pace. The completion of the structural work, which also meant the end of the 'noisy period', was celebrated jointly with the construction workers, the architects and the institute.

As of now, the construction proceeds within schedule. Unless a long and cold Winter will cross our plans, the moving of the numerical relativity group from Benzstraße to the new offices is planned for November 2006.

Living Reviews

Living Reviews in Relativity

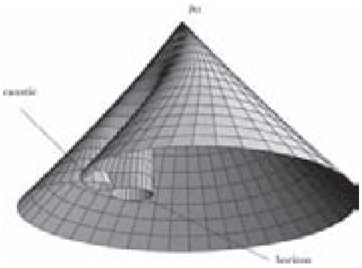

"Gravitational Lens Captures Image of Primeval Galaxy", from Joachim Wambsganss, Gravitational Lensing in Astronomy (lrr-1998-12)

The Concept

Since its first publications in 1998, Living Reviews has become more than just a successful physics journal, providing readers with free review articles by leading experts on the web. It has drawn wide attention to its concept of a unique open access online journal. Living Reviews uses the web format not only to enhance traditional papers with the possibilities of electronic media, but also allows our authors to publish regular updates, and thus maintain their reviews to follow the current state of research. The revisions and amendments that keep the articles ‚alive' are our major advantage in respect to other print journals. The online presentation of Living Reviews articles offers an unlimited amount of text, images, movies and links to the other resources on the web, and is enhanced by features that make navigation very comfortable for readers.

The Journal

As of December 2005, the journal has published and maintains 49 review articles by 63 authors in all areas of the field. In 2004 and 2005, we increased our publication output by more than 50 percent, having 12 resp. 10 new articles and updates published. That is an equivalent of more than 1,800 print pages and 4,300 processed references. Currently, we have a monthly average of 85,800 html page requests. Article download numbers amount to about 4,500 downloads per month. In our online reference database one can search through more than 10,500 reviewed records. Living Reviews articles are well known and highly regarded within the community, as web visibility and citation numbers prove (our articles are referenced by more than 1,300 journal papers). 750 readers are subscribed to our mailing list, getting information on the latest publications. Living Reviews has also been a sponsor and present with an info desk at GR17 in Dublin, Ireland in July 2004.



"Past light cone in the Schwarzschild spacetime", from Volker Perlick, Gravitational Lensing from a Spacetime Perspective (lrr-2004-9)

The Editorial Board of Living Reviews in Relativity held a meeting in Golm in November 2004, bringing together Robert Beig, Bala Iyer, Renate Loll, Jorge Pullin, Bernard Schutz, and Joachim Wambsganss to discuss further article topics and possible authors. Jorge Pullin of LSU replaced Ed Seidel as subject editor for Numerical Relativity, while Don Marolf of UCSB accepted an invitation to join the board as a subject editor for String Theory and Gravitation.

The Family

The concept of an electronic open access Living Reviews journal was born at the AEI and first carried out in the field of gravitational physics with Living Reviews in Relativity. Its twofold success as both an independent physics and open access journal encouraged us to spread the idea within and outside the Max Planck Society. We have been developing a unique open source publishing toolkit, including our article conversion software (LaTeX to HTML and PDF), a web content management system, and a reference database (BibTeX and XML). Furthermore, we are going to offer our own web based editorial information management system to interested users.

In 2004, we have celebrated the birth of a first sister journal - Living Reviews in Solar Physics, published by the MPI for Solar Systems Research in Katlenburg-Lindau in cooperation with the Living Reviews BackOffice in Potsdam. Meanwhile, ten review articles have been published in this new journal. A first step has been taken to carry the Living Reviews concept outside the physics world: a Living Reviews in

European Governance issued first article invitations in 2005. This is a joint EU funded project within the CONNEX and NewGov frameworks. For further journals we are in discussion with other institutes and research networks.

To cope with the growing journal family and concentrate forces, the Living Reviews project has been restructured. The BackOffice in Potsdam is currently maintaining the two physics journals, while further research and development is done by the group affiliated with the Center for Information Management (ZIM) of the Max Planck Society in Garching. We have now set up a central web and data base server at the ZIM to host all Living Reviews journals. The idea to expand the concept into other fields of research and start new journals has convinced the Heinz Nixdorf Foundation to extend their funding of the project until 2008.

Hermes

Romeo Anghelache has successfully finished his tasks for the EU funded MoGWLI project, in which Living Reviews participated as a use-case. He developed a software package called Hermes that allows a direct conversion of scientific documents written in LaTeX into presentation and content XML/MathML. This format not only allows an easier distribution and display of scientific articles on the web, but allows authors and publishers to enrich their documents semantically and thus prepare them for deeply searchable electronic archiving. A complete test conversion of all Living Reviews volumes has already been generated, promising another innovative potential of scientific publishing incorporated by our journal. Hermes has attracted considerable attention from the electronic publishing community and was the focus of a workshop at the AEI in November 2004.

Frank Schulz

Cooperations

Cooperations and Outside Funding

The AEI's work is especially collaborative. We have close links with universities and research institutes in many countries. Research projects are funded by the following institutions and foundations:

European Commission (EU)

The institute currently participates in three EU-projects: Superstrings, Forces Universe and ILIAS.

- *Superstrings* (Superstring Theory) is a four year follow-on to the former EU Research Training Network Superstrings and aims 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) aims 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) is an Integrated Infrastructure Initiative that has 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.

The EU-funded Research Training Networks *Sources of Gravitational Waves, MoWGLI, Superstrings* and *Quantum Spacetime* as well as the Information Society Technologies (IST)-project *GridLab* were finished in 2004.
Proposals for another Research Training Network and for two new IST-projects are currently under review.

ESA and NASA

The Laser Interferometer Space Antenna (LISA) is 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 Institute.

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

The German-Israeli foundation currently funds a joint research project of the Quantum Gravity Division together with the University of Tel Aviv entitled *Learning from each other: The String Theory – Gauge Theory Connection*. It is investigating the connection between gauge fields and strings.

The GIF-funded project *Field Theory, String Theory and their Interrelations* was finished in 2004.

Deutsche Forschungsgemeinschaft (DFG)

Special Research Centers ("Sonderforschungsbereiche" (SFB)):

- *SFB Transregio 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 for at least four and up to twelve years.

- *SFB 407 Quantenlimitierte Messprozesse*: the Laser Interferometry and Gravitational Wave Astronomy Division participates in this project which the Laser Zentrum at Hannover, the Physikalisch-Technische Bundesanstalt at Braunschweig and the Institute for Quantum Optics at Hannover University are also involved in.

- *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 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.

Leibniz-Programme

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

Deutsches Zentrum für Luft- und Raumfahrt (DLR)

The German Aerospace Center 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.

Deutsches Forschungsnetz (DFN-Verein)

During the reporting period the DFN-Verein supported a project in the Numerical Relativity Group called *GriKSL* (Grid-basierte Simulation und Visualisierung) which has developed Grid based simulations and visualisations.

Volkswagen-Stiftung (VW Foundation)

The VW foundation supports the laser development for GEO600. It also funded a research project between the Geometric Analysis and Gravitation Division and the University of Yaoundé, Cameroon, called *Global Dynamics of Kinetic Matter in General Relativity*.

Alexander von Humboldt-Stiftung (Humboldt Foundation)

In the years 2004/2005 the AEI hosted two Friedrich Wilhelm Bessel-Award laureates: B. Allen (University of Wisconsin, Milwaukee) and S. Rey (Seoul National University, Korea) as well as four Humboldt-Prize laureates (A. Ashtekar, N. Reshetikhin, A. Schwimmer, and L. Simon). Another Humboldt-Prize laureate, E. Rabinovici, is supposed to come to the Institute in 2006.

In October 2004 the prestigious Sofja Kovalevskaja-Prize was awarded to Y. Chen. The award enables him to establish an independent research group on Theoretical Gravitational Wave Physics at the AEI which collaborates closely with the divisions of Astrophysical Relativity and Laser Interferometry & Gravitational Wave Astronomy.

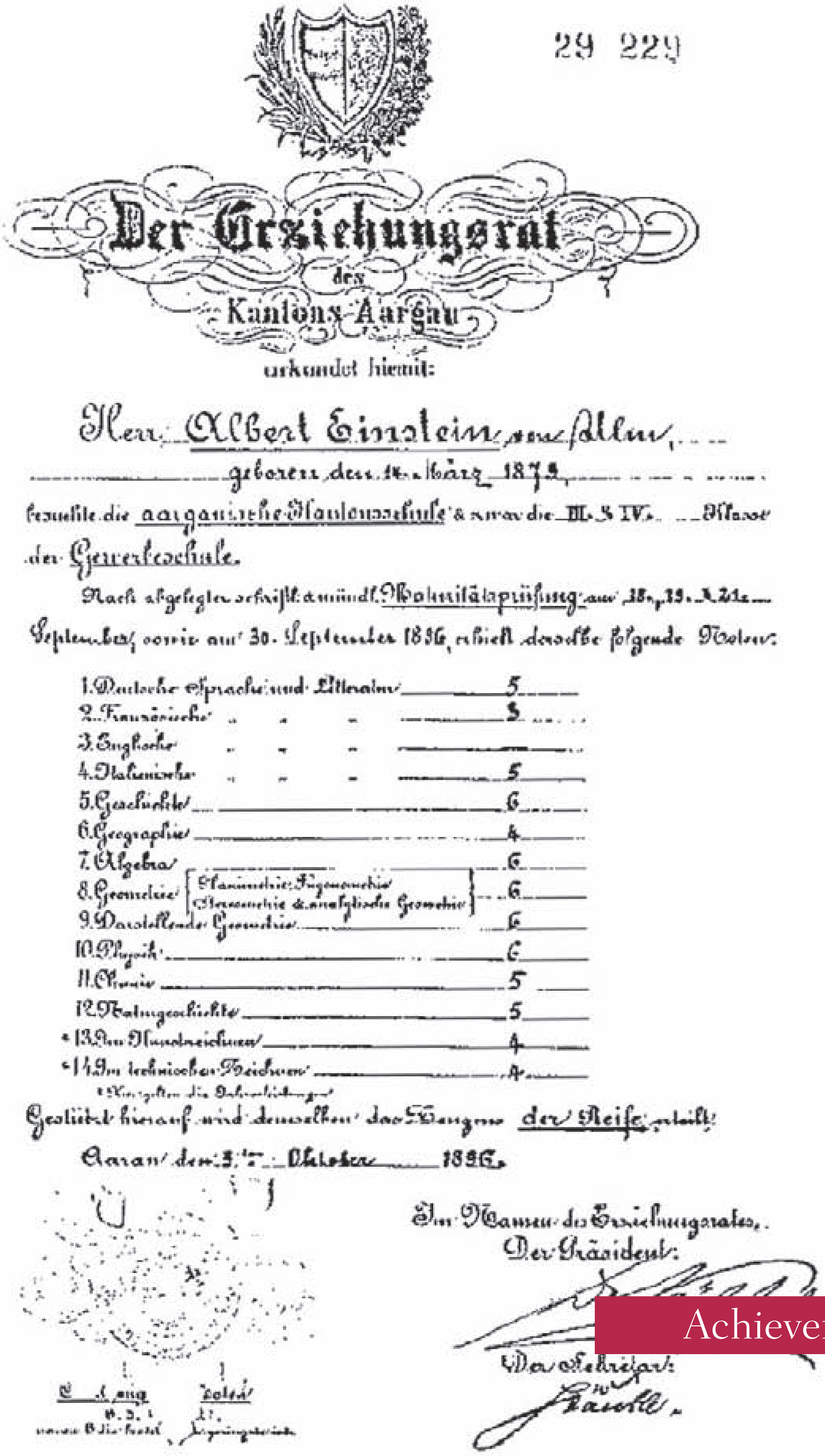
Bundesministerium für Bildung und Forschung (Federal Ministry for Education and Research - BMBF)

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 two projects of that initiative and gets funding for its work on one of the community projects, the *German Astronomy Community Grid* (GACG), and for its work on the *D-Grid Integration project* (DGI) which integrates the infrastructure, middleware tools and e-Science methods developed in the different community projects in one common D-Grid platform.

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

Constance Münchow



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Der Erziehungsrat
des
Kantons Aargau
urkundet hiemit:

Herr Albert Einstein von Ulm,
geboren den 14. März 1879,
besuchte die aargauische Kantonsschule & zwar die III. & IV. Klasse
der Gewerbeschule.

Nach abgelegter schriftl. & mündl. Maturitätsprüfung am 18., 19. & 21. September, sowie am 30. September 1896, erhielt derselbe folgende Noten:

1. Deutsche Sprache und Litteratur	5
2. Französische " " "	3
3. Englische " " "	
4. Italienische " " "	5
5. Geschichte	6
6. Geographie	4
7. Algebra	6
8. Geometrie [Planimetrie, Trigonometrie, Stereometrie & analytische Geometrie]	6
9. Darstellende Geometrie	6
10. Physik	6
11. Chemie	5
12. Naturgeschichte	5
*13. Im Kunstzeichnen	4
*14. Im technischen Zeichnen	4

*Hier gelten die Jahresleistungen.

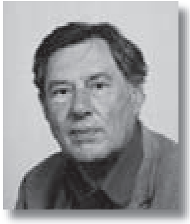
Gestützt hierauf wird demselben das Zeugnis der Reife erteilt.

Aarau, den 3.ten Oktober 1896.

Im Namen des Erziehungsrates,
Der Präsident:

Der Sekretär:

Appraisals and Prizes



Volta Medal for Jürgen Ehlers

The University of Pavia in Italy has awarded the golden Volta Medal to Jürgen Ehlers, the founding director of the AEI. Ehlers was honoured for his life's work, consisting in major contributions to general relativity, and his strong influence on current research in this field. The medal was awarded during the international conference "Spacetime in Action" in March 2005. In his honorific speech, professor Sergio Ratti compared Ehlers to Alessandro Volta, the Italian physicist the medal is named after, calling them both great scientists and respectable academic teachers.

Jürgen Ehlers new Honorary Fellow of the IUCAA

The Inter-University Centre for Astronomy and Astrophysics (IUCAA) in India appointed Jürgen Ehlers as Honorary Fellow at the end of 2005. Naresh Dadhich, director of the IUCAA, greatly appreciated Ehlers' long association and support to the Centre. The IUCAA is an autonomous institution which aims to promote nucleation and growth of active groups in astronomy and astrophysics in Indian universities.

Gerhard Huisken has become Member of the Leopoldina

The German Academy of Sciences Leopoldina has elected Gerhard Huisken as a new member of the mathematical section in February 2004. The Leopoldina is the oldest scholars' society of the natural sciences in Germany, founded in 1652. Its mission follows the founder's motto of exploring nature to the benefit of the human being. The Leopoldina's more than 1200 members are outstanding scientists in their specific disciplines, coming from more than 30 countries. Becoming a member of the Leopoldina is one of the highest awards for scientists in Germany.

Bernard F. Schutz Member of the Royal Society of Sciences of Uppsala

The Royal Society of Sciences of Uppsala admitted Bernard F. Schutz as a Foreign Member in May 2005. Schutz thereby joins such famous scientists as Albert Einstein, Max Planck, and John A. Wheeler. The society, founded in 1710, is the oldest royal academy in Sweden.

Otto Hahn Medals for AEI PhD students in 2004 and 2005

Thomas Fischbacher was awarded the Otto Hahn Medal in 2004. The Max Planck Society honours with this medal outstanding achievements of young scientists. Thomas Fischbacher obtained the Otto Hahn Medal for the development of highly efficient new technologies to cope with large exceptional symmetry groups that abound in supergravity and superstring theory, and for the detailed systematic investigation of the vacuum structure of a large class of low-dimensional gauged extended supergravity models by application of these methods.

Niklas Beisert obtained the Otto Hahn Medal in 2005 for the groundbreaking discovery of integrable structures in four-dimensional conformal Gauge theories. He proved that the complete spectrum of the maximally superconformal Gauge theory can be obtained from an integrable Hamiltonian which he constructed to leading order of perturbation theory. He then showed that the integrable features extend to higher orders leading to deep insights into the structure of Gauge field and string theories as well as their interconnecting dualities.

Academic Achievements

New Leader of Numerical Relativity Group

Luciano Rezzolla accepted the position of the leader of the Numerical Relativity Group at AEI in 2005. He has a long experience in relativistic astrophysics and particularly in computational studies of general relativistic hydrodynamics and magnetohydrodynamics applied to the modelling of gravitational-wave sources. He is an expert in perturbative studies of compactobjects, such as black holes and neutron stars and in the investigation of the instabilities they may be subject to. He is presently an adjunct Associate Professor at the Department of Physics of the Louisiana State University in Baton Rouge (USA) and member of the editorial board of Classical and Quantum Gravity. He was previously Associate Professor and Director of the Computing Centre at SISSA (Italy) and still maintains a position there to facilitate the connections with scientists and students at SISSA where he also keeps regular lectures.

New Junior Research Group at AEI

Yanbei Chen won one of the Sofja Kovalevskaja Awards of the Alexander von Humboldt Foundation in 2004. The prize enables him to establish an independent research group on Theoretical Gravitational wave Physics at the AEI. Yanbei Chen's group collaborates closely with the divisions of Astrophysical Relativity and Laser Interferometry and Gravitational Wave Astronomy.

Habilitation

Jan Plefka finished his Habilitation thesis on "Aspects of Supermembrane and Matrix Theory" in February 2003.
In July 2005 he received a Lichtenberg-Professorship of the Volkswagen Foundation for a W2 (associate professor) position at the Humboldt Universität Berlin, which he took up on February 2006.

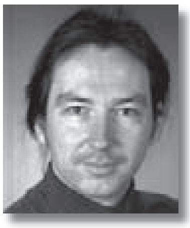
Doctoral Thesis

Mark A.S. Aarons finished his doctoral thesis on "Mean curvature flow with a forcing term in Minkowski Space" supervised by Prof Gerhard Huisken. He was awarded his PhD from the Freie Universität Berlin in 2004.

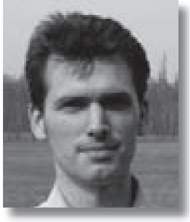
Doctoral Thesis

Niklas Beisert finished his doctoral thesis on "The Dilatation Operator of N=4 Super Yang-Mills and Integrability" supervised by Dr. Matthias Staudacher. He was awarded his PhD from the Humboldt-Universität Berlin in 2004.

Doctoral Thesis



Werner Benger was awarded his PhD from the Freie Universität Berlin in 2005. He wrote his doctoral thesis on "Visualization of General Relativistic tensor Fields via a Fiber Bundle Data Model" supervised by Prof Peter Deuflhard (ZIB) and Prof Edward Seidel (AEI).



Doctoral Thesis

Peer Burdack has finished his doctoral thesis on "Einfrequenter monolithischer Ringlaser für Weltraumanwendungen" supervised by Dr. Gerhard Heinzel. He was awarded his Dr. rer. nat. from the Universität Hannover in 2004.

Doctoral Thesis

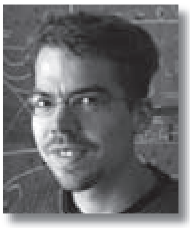
Florian Conrady finished his PhD thesis on "Semiclassical analysis of loop quantum gravity" supervised by Prof Thomas Thiemann. He was awarded his PhD from the Humboldt-Universität Berlin in 2005.

Doctoral Thesis

Bianca Dittrich completed her doctoral thesis on "Aspects of Classical and Quantum Dynamics of Canonical General Relativity" supervised by Prof Thomas Thiemann. She was awarded her PhD from the Universität Potsdam in 2005.

Doctoral Thesis

Stefan Goßler has finished his doctoral thesis on "The suspension systems of the interferometric gravitational-wave detector GEO600" supervised by Dr. Harald Lück. He was awarded his Dr. rer. nat. from the Universität Hannover in 2004.



Doctoral Thesis

Frank Herrmann was awarded his PhD from the Universität Potsdam. He wrote his doctoral thesis on "Evolution and Analysis of Binary Black Hole Spacetimes" supervised by Prof Edward Seidel (2005).

Doctoral Thesis

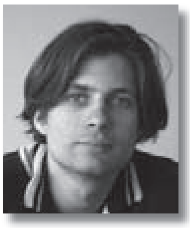
Michèle Heurs has finished her doctoral thesis on "Gravitational waves in a new light: Novel stabilisation schemes for solid-state lasers" supervised by Dr. Benno Wilke. She was awarded her Dr. rer. nat. from the Universität Hannover in 2004.

Doctoral Thesis

Michael Hunnekuhl has finished his doctoral thesis on "Entwicklung weit frequenzabstimmbarer, einfrequenter Laserstrahlquellen für Raumfahrtanwendungen". He was awarded his Dr. rer. nat. from the Universität Hannover in 2004.

Doctoral Thesis

Ralf Kähler finished his PhD thesis on "Accelerated Volume Rendering on Structured Adaptive Meshes" supervised by Prof Peter Deuflhard (ZIB) and Prof Edward Seidel (AEI). He was awarded his PhD from the Freie Universität Berlin in 2005.



Doctoral Thesis

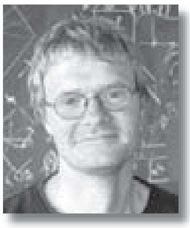
Thomas Klose completed his doctoral thesis on "Plane Wave Matrix Theory: Gauge Theoretical Origin and Planar Integrability" supervised by Prof Jan Plefka. He was awarded his PhD from the Humboldt-Universität Berlin in 2005.

Doctoral Thesis

Karsten Kötter has finished his doctoral thesis on "Data Acquisition and Data Analysis for the Gravitational-Wave Detector GEO600". He was awarded his Dr. rer. nat. from the Universität Hannover in 2004.

Doctoral Thesis

Michael Koppitz completed his doctoral thesis on "Numerical studies of Black Hole initial data" supervised by Prof Edward Seidel. He was awarded his PhD from the Universität Potsdam in 2004.



Doctoral Thesis

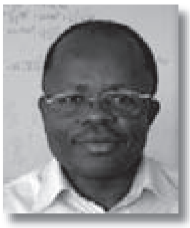
Gerrit Kühn has finished his doctoral thesis on "Aktive und passive Plasmaspektroskopie im Kathodenbereich eines freibrennenden Lichtbogens". He was awarded his Dr. rer. nat. from the Universität Hannover in 2005.

Doctoral Thesis

Volker Leonhardt has finished his doctoral thesis on "Displacement measurements on suspended mirrors for off-resonant thermal noise detection" supervised by Dr. Harald Lück and Dr. Benno Wilke. He was awarded his Dr. rer. nat. from the Universität Hannover in 2004.

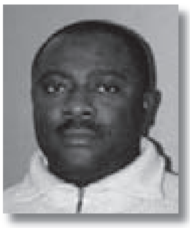
Doctoral Thesis

Jan Metzger finished his doctoral thesis on "Blätterungen asymptotisch flacher Mannigfaltigkeiten durch Flächen vorgeschriebener mittlerer Krümmung" supervised by Prof Gerhard Huisken. He was awarded his PhD from the Universität Tübingen in 2004.



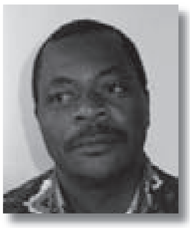
Doctoral Thesis

Pierre Noundjeu completed his doctoral thesis on “The Einstein-Vlasov-Maxwell system with spherical symmetry” supervised by Prof Alan Rendall. He was awarded his PhD from the Technische Universität Berlin in 2005.



Doctoral Thesis

Sophonie Blaise Tchapnda finished his doctoral thesis on “On the Einstein-Vlasov System with cosmological constant” supervised by Prof Alan Rendall. He was awarded his PhD from the Technische Universität Berlin in 2004.



Doctoral Thesis

David Tegankong was awarded his PhD from the Technische Universität Berlin. He wrote his doctoral thesis on “Cosmological solutions of the Einstein-Vlasov-scalar field system” supervised by Prof Alan Rendall (2005).

Doctoral Thesis

Michael Tröbs has finished his doctoral thesis on “Laser development and stabilization for the spaceborne interferometric gravitational wave detector” supervised by Dr. Gerhard Heinzel. He was awarded his Dr. rer. nat. from the Universität Hannover in 2005.

Doctoral Thesis

Uta Weiland has finished her doctoral thesis on “Preparing for gravitational wave astronomy: A verification of the GEO600 detection chain by generation, injection and extraction of continuous signals” supervised by Dr. Gerhard Heinzel. She was awarded her Dr. rer. nat. from the Universität Hannover in 2004.

Diploma Thesis

Johanna Bogenstahl graduated in physics from the Universität Hannover in July 2005. She wrote her diploma thesis under the supervision of Dr. Gerhard Heinzel on “Interferometer zur Charakterisierung von optischen Komponenten”.

Diploma Thesis

Oliver Burmeister graduated in physics from the Universität Hannover in January 2005. He wrote his diploma thesis at the AEI under the supervision of Jun.-Prof Dr. Roman Schnabel on “Fabry-Perot Resonatoren mit diffraktiven Einkopplern”.

Diploma Thesis

Gudrun Diederichs graduated in physics from the Universität Hannover in May 2005. She wrote her diploma thesis at the AEI under the supervision of Jun.-Prof Dr. Roman Schnabel on "Spektrale Rauschdichten optomechanisch gekoppelter Oszillatoren".

Master Thesis

Felipe Guzmán Cervantes graduated in physics from the Universität Oldenburg in December 2004. He wrote his Master of Science thesis at the Universität Oldenburg under the supervision of Dr. Gerhard Heinzel on "Real-Time Spatially Resolving Phasemeter for LISA".

Diploma Thesis

Boris Hage graduated in physics from the Universität Hannover in July 2004. He wrote his diploma thesis under the supervision of Jun. Prof Dr. Roman Schnabel on "Quantentomographische Charakterisierung gequetschter Zustände".

Diploma Thesis

Philipp Höffer zu Loewenfeld graduated in physics from the Technische Universität München in 2004. He wrote his diploma thesis under the supervision of Prof Bernd Schmidt on "Linearisierte Störungen rotierender Flüssigkeitszylinder in der Einsteinschen Gravitationstheorie".

Diploma Thesis

Philipp Huke graduated in physics from the Universität Hannover in October 2004. He wrote his diploma thesis under the supervision of Dr. Rolf-Hermann Rinkleff on "Stabilisierung eines Lasers mit optischer Rückkopplung".

Diploma Thesis

Patrick Kwee graduated in physics from the Universität Hannover in September 2005. He wrote his diploma thesis at the AEI under the supervision of Dr. Benno Willke on "Charakterisierung von Lasersystemen für Gravitationswellendetektoren".

Diploma Thesis

Nico Lastzka graduated in physics from the Universität Hannover in July 2005. He wrote his diploma thesis under the supervision of Jun.-Prof Dr. Roman Schnabel on "Analyse nichtlinearer Resonatoren".

Diploma Thesis
Tobias Meier graduated in physics from the Universität Hannover in August 2005. He wrote his diploma thesis under the supervision of Dr. Benno Willke on "Current Lock mit hoher Bandbreite - Kopplungen zwischen Frequenz und Leistung bei nicht-planaren Ringoszillatoren".

Diploma Thesis
Henning Rehbein graduated in physics from the Universität Hannover in May 2004. He wrote his diploma thesis under the supervision of Jun.-Prof Dr. Roman Schnabel on "Optische Bistabilität und gequetschtes Licht in einem Kerr-Interferometer".

Diploma Thesis
Frank Steier graduated in physics from the Universität Hannover in June 2004. He wrote his diploma thesis at the AEI under the supervision of Dr. Gerhard Heinzel on "Messmethoden zur thermo-optischen Charakterisierung optischer Komponenten".

Diploma Thesis
André Thüring graduated in physics from the Universität Hannover in January 2004. He wrote his diploma thesis under the supervision of Dr. Harald Lück on "Lineare mehrfach Spiegel-Resonatoren für Gravitationswellendetektoren".

Diploma Thesis
Henning Vahlbruch graduated in physics from the Universität Hannover in January 2004. He wrote his diploma thesis at the AEI under the supervision of Jun. Prof Dr. Roman Schnabel on "Gequetschtes Licht bei kleinen Seitenbandfrequenzen".

Bachelor Thesis
Rowena Fermi graduated in physics from the Universität Hannover in December 2005. She wrote her bachelor thesis at the AEI under the supervision of Andreas Weidner on "Entwicklung eines DDS-Signalgenerators".

The Fachbeirat of the AEI

The Fachbeirat is the Institute's scientific advisory and assessment Board, made up of internationally renowned physicists. The Fachbeirat advises the President of the Max Planck Society (MPS) 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 MPS 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 MPS.

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Prof Dr. Luciano Rezzolla (AEI Golm)
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Albrecht Rüdiger (AEI Hannover)
Roland Schilling (AEI Hannover)
Prof Dr. Bernd Schmidt (AEI Golm)
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Prof Dr. Thomas Thiemann (AEI Golm)
Dr. Jonathan Thornburg (AEI Golm)
Dr. Benno Willke (University of Hannover)
Dr. Walter Winkler (AEI Hannover)

Junior Scientists (Funding Source)

Dr. Pau Amaro Seoane (AEI Golm/DFG)
Dr. Sudarshan Ananth (AEI Golm)
Dr. Luca Baiotti (AEI Golm)
Dr. Markus Berg (AEI Golm/EU)
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Dr. Sergio Dain (AEI Golm/DFG)
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Dr. Hayoung Lee (AEI Golm)
Dr. Jan Metzger (AEI Golm)
Dr. Todd Oliynyk (AEI Golm/DFG)
Dr. Archana Pai (AEI Golm/AvH)
Dr. Kasper Peeters (AEI Golm)
Dr. Hendryk Pfeiffer (AEI Golm)
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Dr. Kentaro Somiya (AEI Golm/AvH)
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Dr. Sophonie Blaise Tchapnda (AEI Golm)
Dr. Michael Tröbs (AEI Hannover)
Oliver Wehrens (AEI Golm/BMBF)
Dr. Linquing Wen (AEI Golm)
Steve White (AEI Golm)
Dr. Marija Zamaklar (AEI Golm)

PhD Students (Funding Source)

Carsten Aulbert (AEI Golm)
Benjamin Bahr (AEI Golm)
Florian Beyer (AEI Golm)
Roger Bieli (AEI Golm)
Johanna Bogenstahl (University of Hannover)
Till Brönnle (AEI Golm/DFG)
Johannes Brunnemann (AEI Golm)
Alexander Bunkowski (University of Hannover/DFG)
Oliver Burmeister (AEI Hannover)
Simon Chelkowski (University of Hannover/DFG)
Mihaela Chirvasa (AEI Golm)
Aydin Demircioglu (AEI Golm)
Gudrun Diederichs (AEI Hannover)
Robert Engel (AEI Golm)
Alexander Franzen (University of Hannover/DFG)
Antonio Francisco Garcia Marin (AEI Hannover)
Iraj Gholami (AEI Golm)
Kristina Giesel (AEI Golm)
Felipe Guzmán Cervantes (University of Hannover/DFG)
Boris Hage (University of Hannover/DFG)
Jan Harms (University of Hannover/DFG)
Bruno Hartmann (AEI Golm)
Stefan Hild (AEI Hannover)
Christian Hillmann (AEI Golm)
Torsten Kellermann (AEI Golm)
Andreas Knoche (University of Hannover)
Amos Nathan Koeller (AEI Golm)
Patrick Kwee (AEI Hannover)
Nico Lastzka (University of Hannover/DFG)
Bernhard List (AEI Golm)
Michaela Malec (AEI Hannover)
Tobias Meier (University of Hannover/DFG)
Olaf Milbredt (AEI Golm)
Helge Müller-Ebhardt (AEI Hannover/AvH)
Christian Ott (AEI Golm)
Jakob Palmkvist (AEI Golm)
Ajith Parameswaran (AEI Hannover)
Henning Rehbein (University of Hannover/DFG)
Adam Rej (AEI Golm)
Bernd Reimann (AEI Golm)
Luciano Ribichini (AEI Hannover)
Frank Seifert (University of Hannover/DFG)
Jennifer Seiler (AEI Golm)
Aureliano Skirzewski Prieto (AEI Golm)
Sascha Skorupka (AEI Hannover)
Joshua Smith (AEI Hannover)
Luca Spani Molella (AEI Hannover)
Frank Steier (AEI Hannover)
André Thüring (University of Hannover/DFG)
Davis Treeby (AEI Golm)
Henning Vahlbruch (AEI Hannover/DFG)
Tilmann Vogel (AEI Golm)
Vinzenz Wand (AEI Hannover)
Anil Colpan Zenginoglu (AEI Golm/DFG)

Diploma Students

Johannes Brödel (AEI Golm)
Marina Dehne (University of Hannover)
James DiGuglielmo (University of Hannover)
Jessica Dück (University of Hannover)
Roland Fleddermann (University of Hannover)
Daniel Friedrich (University of Hannover)
Philine Hüttig (AEI Golm)
Moritz Mehmet (University of Hannover)
Vera Spillner (AEI Golm)
Steffen Stern (AEI Golm)

Support Staff (Funding Source)

Michael Augustin	Technical Helpforce (AEI Golm)
Simon Barke	Technical Helpforce (AEI Hannover)
Almuth Barta	System Administrator (AEI Golm)
Alexander Beck-Ratzka	Research Programmer (AEI Golm/BMBF)
Stefan Bertram	Precision Mechanic (Univ. Hannover)
Olaf Beyer	Technical Helpforce (University of Hannover)
Dörte Blischke	Public Relations Assistant (AEI Golm)
Librawin Bong Levin	Technical Helpforce (AEI Hannover)
Elisabeth Börner-Schlenk	Librarian (AEI Golm)
Dorothee Böhme	Secretary Assistant (AEI Golm)
Alexander Brensing	Technical Helpforce (University of Hannover)
Lars Brunnermeier	Technician (AEI Hannover)
Diana Caspar	Secretary (AEI Golm)
Marina Dehne	Technical Helpforce (AEI Hannover)
Jan Diedrich	Precision Mechanic (University of Hannover)
Andreas Donath	System Administrator (AEI Golm)
Claus Ebert	System Administrator (AEI Hannover)
Marco Ehlert	Network and Cluster Administrator (AEI Golm)
Ronny Esterluß	Technical Helpforce (AEI Golm)
Henryk Feider	Peyote Cluster System Administrator (AEI Golm)
Rowena Fermi	Technical Helpforce (AEI Hannover)
Marco Pino Gajardo	Technical Helpforce (AEI Golm)
Christine Gottschalkson	Secretary (AEI Golm)
Christian Gräf	Technical Helpforce (AEI Hannover)
Walter Grass	Technician (AEI Hannover)
Klaus-Dieter Haupt	Electronic Technician (University of Hannover)
Brigitte Hauschild	Secretary (AEI Golm)
Christel Hausmann-Jamin	Head of IT Department (AEI Golm)

Johannes Heinze	Technical Helpforce (AEI Hannover)
Kevin Heiß	Trainee (AEI Golm)
Katharina Henke	Administrative Assistant (AEI Golm)
Lilli Karatunov	Technical Helpforce (AEI Hannover)
Claudia Köhler	Secretary (AEI Golm)
Vladimir Kossovoi	Scientific Helpforce (AEI Hannover)
Heidi Kruppa	Procurement (AEI Hannover)
Anne Lampe	Secretary (AEI Golm)
Anja Lehmann	Library Assistant (AEI Golm)
Hartmut Lehmann	Precision Mechanic (University of Hannover)
Bernd Machenschalk	Research Programmer (AEI Golm)
Gillian Mayer	Technical Helpforce (University of Hannover)
Hans-Joachim Melching	Precision Mechanic (University of Hannover)
Azadeh Moradi	Technical Helpforce (University of Hannover)
Konrad Mors	System Administrator (AEI Hannover)
Dr. Elke Müller	Scientific Coordinator (AEI Golm)
Kathleen Müller	Human Resources (AEI Golm)
Constance Münchow	Third Party Funds Manager (AEI Golm)
Kirsten Naceur	Secretary (University of Hannover)
Vera Oßwald	Data Base Manager Back Office Living Reviews (AEI Golm)
Christina Pappa	Cleaning Service (AEI Golm)
Markus Paul	Trainee (AEI Golm)
Sebastian Philipp	Technical Helpforce (University of Hannover)
Michaela Pickenpack	Lecture Assistant (University of Hannover)
Dr. Markus Pössel	Public Outreach (AEI Golm)
Malte Prieß	Technical Helpforce (University of Hannover)
Susann Purschke	Guest House Manager (AEI Golm)
Norbert Rainer	Operator GEO600 (AEI Hannover)
Christiane Roos	Head of Administration (AEI Golm)
Sabine Ruhmkorf	Secretary (University of Hannover)
Aiko Samblowski	Scientific Helpforce (University of Hannover)
Philipp Schauzu	Precision Mechanic (University of Hannover)
Jonathan Schenk	Precision Mechanic (University of Hannover)
Matthias Schlenk	Lecture Assistant (University of Hannover)
Ute Schlichting	Secretary (AEI Golm)
Manuela Schneehufer	Human Resources (AEI Golm)
Lars Schneider	Technical Helpforce (AEI Golm)
Babett Schöppe	Accounting (AEI Golm)
Frank Schulz	Manager Back Office Living Reviews (AEI Golm)
Julia Springer	Web Programmer (AEI Golm)
Andreas Weidner	Electronic Technician (AEI Hannover)
Ole Weidner	Technical Helpforce (AEI Golm)
Susanne Witte	Human Resources (AEI Golm)
Ramona Wittwer	Accounting (AEI Golm)
Dietlind Witzger	Cleaning Service (AEI Golm)
Heiko zur Mühlen	Electronic Technician (University of Hannover)
Karl-Heinz Zwick-Meinheit	Electronic Technician (University of Hannover)
Roland Zymelka	Precision Mechanic (University of Hannover)

Guest Scientists in Potsdam-Golm (2004)

Ahmedou, Mohameden O.	Universität Tübingen	05/12/2004-09/12/2004
Alcubierre, Miguel	Universidad Nacional Autonoma de Mexico	18/02/2004-29/02/2004
Alic, Daniela	West University of Timisoara	01/01/2004-31/08/2004 01/11/2004-13/11/2004
Allen, Bruce	University of Wisconsin	22/02/2004-29/02/2004
Arcioni, Giovanni	Racah Institute of Physics, Jerusalem	01/11/2004-09/11/2004 02/12/2004-31/12/2004
Ashtekar, Abhay	Pennsylvania State University	07/06/2004-31/07/2004
Athanassenas, Maria	Monash University, Australia	28/06/2004-11/07/2004 21/11/2004-12/12/2004
Aznar Cuadrado, Regina	MPI für Sonnensystemforschung, Katlenburg-Lindau	22/11/2004-23/11/2004
Banados, Maximo	University of Santiago, Chile	12/07/2004-23/07/2004
Barack, Leor	University of Southampton	20/03/2004-28/03/2004 13/06/2004-11/07/2004 18/08/2004-27/08/2004
Barbot, Thierry	CNRS, Moscow Laboratory	27/06/2004-03/07/2004
Barrett, John	University of Nottingham, UK	27/06/2004-03/07/2004
Bartnik, Robert	University of Canberra	10/10/2004-20/12/2004
Baseilhac, Stephane	University of Grenoble, France	27/06/2004-03/07/2004
Bastianelli, Fiorenzo	University of Bologna	06/06/2004-12/06/2004
Becerril, Ricardo	University of Michoacana, Mexico	19/07/2004-29/07/2004

Beig, Robert	Universität Wien	19/04/2004-30/04/2004 31/08/2004-19/09/2004 04/11/2004-07/11/2004
Beisert, Niklas	Princeton University	04/04/2002-30/09/2004
Benincasa, Paolo	University of Bologna	02/12/2004-04/12/2004
Bergamin, Luzi	Technische Universität Wien	25/04/2004-29/04/2004
Bernal, Argelia	CINVESTAV, Mexico	23/07/2004-01/08/2004
Bicak, Jiri	Charles University, Prague	28/05/2004-30/06/2004 01/09/2004-20/12/2004 07/10/2004-20/12/2004
Bishop, Nigel	University of South Africa	06/04/2004-27/04/2004
Bizon, Piotr	Cracow University	01/02/2004-30/06/2004
Bonsante, Francesco	University of Pisa	27/06/2004-03/07/2004
Calabrese, Gioel	Louisiana State University	15/06/2004-19/06/2004
Chaudhuri, Shyamoli	Bellefonte, USA	25/05/2004-31/05/2004
Chekhov, Leonid	Steklov Institute, Moscow	27/06/2004-11/07/2004
Chermisi, Milena	University of Rome	01/06/2004-31/08/2004
Choi, Dale	NASA Goddard Space Flight Center	25/07/2004-29/07/2004
Choptuik, Matthew	University of British Columbia, Canada	29/04/2004-31/05/2004
Christensen, Carl	Oxford University	21/11/2004-22/11/2004 01/12/2004-31/12/2004
Chrusciel, Piotr	Tours University	21/04/2004-02/05/2004 04/11/2004-06/11/2004
Creighton, Teviet	California Institute of Technology	12/11/2004-22/11/2004
Daskalopoulos, Panagiota	Columbia University	12/11/2004-17/11/2004
Date, Ghanashayam	The Institute of Mathematical Sciences, Chennai	20/09/2004-01/11/2004 27/11/2004-14/12/2004
David, Justin R.	ICTP, Trieste	29/02/2004-06/03/2004
De Lellis, Camillo	Universität Zürich	22/09/2004-18/10/2004
De Pietri, Roberto	Parma University	16/07/2004-18/07/2004
de Wit, Bernard	Utrecht University	21/03/2004-02/04/2004 23/05/2004-28/05/2004 27/08/2004-28/08/2004
Diener, Peter	Louisiana State University	15/02/2004-21/02/2004 18/05/2004-26/05/2004 24/11/2004-02/12/2004
Domagala, Marcin	Warsaw University	04/07/2004-14/07/2004
Dooley, Ryan	Louisiana State University	10/05/2004-16/05/2004
Dorband, Nils	Louisiana State University	16/02/2004-27/02/2004 23/06/2004-17/07/2004
Dunajski, Maciej	DAMTP Cambridge, UK	17/02/2004-19/02/2004
Elashvili, Alexander	Mathematical Institute, Academy of Science, Tbilisi	14/12/2004-15/12/2004
Feingold, Alex	State Univ. of New York at Binghamton	14/07/2004-25/07/2004
Fischer, Arthur	University of California	01/08/2004-16/08/2004
Fock, Vladimir	ITEP, Moscow	27/06/2004-03/07/2004
Font, Anamaria	UNAM, Madrid	29/07/2004-14/08/2004 20/12/2004-08/01/2005
Frauendiener, Jörg	Universität Tübingen	19/09/2004-25/09/2004
Freedman, Daniel	MIT, Cambridge, USA	18/06/2004-24/06/2004
Freidel, Laurent	Perimeter Institute, Waterloo	27/06/2004-03/07/2004
Freitag, Marc	Universität Heidelberg	29/04/2004-01/05/2004
Fuchs, Jürgen	Karlstad University	07/01/2004-14/01/2004
Gair, Jonathan	Cambridge University	15/11/2004-24/11/2004
Garecki, Janusz	University of Szczecin	06/09/2004-11/09/2004
Gopakumar, Achamveedu	Universität Jena	13/05/2004-18/05/2004 17/10/2004-19/10/2004
Govindarajan, T. R.	Institute of Mathematical Sciences, Chennai	25/10/2004-21/11/2004
Gukov, Sergei	Harvard University	27/06/2004-03/07/2004
Gundlach, Carsten	University of Southampton, UK	22/08/2004-28/08/2004
Gupta, Kumar S.	Saha Institute of Nuclear Physics, Calcutta	15/05/2004-19/05/2004
Guzman, Francisco	Louisiana State University	24/07/2004-09/08/2004
Guzzi, Jerome	ETH Zürich	11/05/2004-13/05/2004
Harada, Tomohiro	Queen Mary College, London	24/09/2004-30/09/2004
Hawke, Ian	University of Southhampton	01/10/2003-30/09/2004 08/11/2004-18/11/2004
Hein, Bernhard	Universität Tübingen	01/02/2004-08/02/2004
Heng, Ik Siong	University of Glasgow	11/06/2004-14/06/2004
Hinder, Ian	University of Southampton	15/06/2004-19/06/2004
Hofmann, Stefan	Stockholm University	12/12/2004-18/12/2004
Hoppe, Jens	Royal Institute of Technology, Stockholm	02/01/2004-12/01/2004 15/06/2004-20/06/2004 20/12/2004-20/01/2005

Hossain, Golam Mortuza	The Institute of Mathematical Sciences, Chennai	03/09/2004-29/10/2004
Isaev, Alexey	Joint Institute for Nuclear Research, Dubna	14/12/2004-14/12/2004
Isidro, Jose	University of Valencia	01/07/2004-31/07/2004
Iyer, Bala	Raman Research Institute, Bangalore	03/11/2004-07/11/2004
Jaramillo, Jose	Observatoire de Paris	21/06/2004-25/06/2004 04/10/2004-06/10/2004
Jezierski, Jacek	Warsaw University	25/04/2004-15/05/2004
Jorjadze, George	A. Razmadze Mathematical Institute, Tbilisi	01/05/2004-01/06/2004
Kadar, Zoltan	Spinoza Institute, Utrecht	27/06/2004-03/07/2004
Karadi, Matyas	DAMTP, Cambridge, UK	27/06/2004-03/07/2004
Karlovini, Max	Stockholm University	30/01/2004-05/02/2004
Kashaev, Rinat	University of Geneva	27/06/2004-03/07/2004
Kastrup, Hans	DESY, Hamburg	25/04/2004-29/05/2004
Kim, Nakwoo	Seoul National University	26/09/2001-20/02/2004
Klein, Andreas	Humboldt Universität Berlin	05/01/2004-31/03/2004 18/04/2004-21/04/2004 31/08/2004-02/09/2004 15/12/2004-20/12/2004
Klemm, Albrecht	University of Wisconsin	01/06/2004-30/06/2004
Klitz, Alexander	Universität Bonn	27/06/2004-03/07/2004
Knopf, Dan	University of Texas at Austin	10/10/2004-15/10/2004
Kobras, Daniel	Universität Tübingen	16/07/2004-18/07/2004
Korotkin, Dimitrii	Concordia University, Montreal	24/06/2004-03/07/2004 18/12/2004-23/12/2004
Krauth, Werner	ENS, Paris	24/07/2004-29/07/2004
Krolak, Andrzej	Academy of Sciences, Warsaw	06/09/2004-05/09/2005 08/12/2004-14/12/2004 18/12/2004-20/12/2004
Kroyter, Michael	Tel Aviv University	13/05/2004-27/05/2004
Krtous, Pavel	Charles University, Prague	10/11/2004-27/11/2004
Kulshrestra, Archid	Louisiana State University	22/07/2004-06/08/2004
Kuzenko, Sergei	University of Western Australia	01/06/2004-15/07/2004
Lamm, Tobias	Universität Freiburg	31/01/2004-31/03/2004
Lattimer, James	Stony Brook University, New York	27/03/2004-02/04/2004
Lavrelashvili, George	A. Razmadze Mathematical Institute, Tbilisi	20/02/2004-05/03/2004
Lehner, Luis	University of British Columbia, Vancouver	13/01/2003-18/01/2004
Leski, Szymon	PAN, Warsaw	21/04/2004-29/04/2004
Lewandowski, Jerzy	Warsaw University	07/06/2004-15/07/2004 15/07/2004-16/07/2004
Lindner, Peggy	Universität Stuttgart	19/01/2004-22/01/2004
Lobanov, Igor	Humboldt-Universität	05/01/2004-31/03/2004
Loll, Renate	Utrecht University	04/11/2004-05/11/2004
Louko, Jorma	University of Nottingham	22/03/2004-29/03/2004
Martin Garcia, José Maria	CSIC, Madrid	18/10/2004-13/11/2004
Meissner, Krzysztof	Warsaw University	04/07/2004-17/07/2004
Memmesheimer, Raoul	Universität Jena	06/06/2004-08/06/2004
Merzky, André	Free University, Amsterdam	13/12/2004-17/12/2004
Minasian, Ruben	CEA, Saclay	09/01/2004-14/01/2004 14/07/2004-01/08/2004
Mingireanu, Florin	Louisiana State University	12/12/2004-21/12/2004
Mironov, Andrei	ITEP, Moscow	19/08/2004-22/08/2004
Mohaupt, Thomas	Universität Jena	31/03/2004-02/04/2004
Moncrief, Vincent	Yale University	28/04/2004-02/09/2004 13/12/2004-09/01/2005
Mugnai, Luca	University of Pisa	01/03/2004-31/05/2004
Mukherjee, Soma	University of Brownsville, Texas	01/07/2004-31/07/2004
Murakami, Jun	Waseda University, Japan	27/06/2004-03/07/2004
Narlikar, Jayant	IUCAA, Pune	24/03/2004-30/03/2004
Nerozzi, Andrea	Portsmouth University	18/01/2004-31/01/2004 12/07/2004-17/07/2004
Nirov, Khazret	Russian Academy of Sciences, Moscow	01/10/2004-28/12/2004
Nollert, Hans-Peter	Universität Tübingen	23/04/2004-24/04/2004
Noundjeu, Pierre	University of Yaounde	01/09/2004-27/11/2004
Noutchegueme, Norbert	University of Yaounde	25/06/2004-03/07/2004
Olea, Rodrigo	CECS Valdivia, Chile	14/11/2004-10/12/2004
Pürrer, Michael	Universität Wien	01/05/2004-15/05/2004
Palenzuela, Carlos	Universitat de les Iles Balears, Mallorca	18/02/2004-21/02/2004 25/02/2004-26/02/2004
Pankiewicz, Ari	University of Washington	12/04/2004-12/05/2004 06/09/2004-01/10/2004
Park, Jeong-Hyuck	IHES, Bur-sur-Yvette	31/10/2004-05/11/2004
Pawlowski, Tomasz	Warsaw University	01/07/2004-14/07/2004
Peitz, Jochen	Universität Tübingen	16/07/2004-18/07/2004
Penner, Robert	University of California, Los Angeles	27/06/2004-03/07/2004

Pfeiffer, Hendryk	DAMTP Cambridge, UK	12/12/2004-19/12/2004
Pfister, Herbert	Universität Tübingen	10/10/2004-22/10/2004
Piontek, Tomasz	Supercomputing Center, Poznan	19/01/2004-21/01/2004
Policastro, Giuseppe	DAMTP Cambridge, UK	04/07/2004-07/07/2004
Prokopec, Tomislav	Universität Heidelberg	01/02/2004-31/03/2004
Pullin, Jorge	Louisiana State University	05/05/2004-07/05/2004
Reshetikhin, Nicolai	University of California, Berkeley	27/06/2004-03/07/2004
		15/09/2004-11/11/2004
Rezzolla, Luciano	SISSA/ISAS, Trieste	27/06/2004-22/08/2004
Ringström, Hans	Royal Institute of Technology, Stockholm	01/11/2002-30/10/2004
Rinne, Oliver	University of Cambridge, UK	09/08/2004-23/08/2004
Roche, Philippe	LPMP, Montpellier	27/06/2004-03/07/2004
Sahlmann, Hanno	Pennsylvania State University	08/07/2004-20/07/2004
Samtleben, Henning	DESY, Hamburg	25/01/2004-29/01/2004
		12/05/2004-13/05/2004
		24/06/2004-25/06/2004
Sarkar, Swarnendu	Institute of Mathematical Sciences, Chennai	21/07/2004-30/07/2004
Sathyaprakash, Bangalore	Cardiff University	12/11/2004-15/11/2004
		05/12/2004-07/12/2004
Saueressig, Frank	Universität Jena	31/03/2004-02/04/2004
Schmidt, Michael G.	Universität Heidelberg	16/02/2004-19/02/2004
Schnakenburg, Igor	Hebrew University, Jerusalem	26/03/2004-26/03/2004
Schoen, Richard	Stanford University	01/07/2004-15/07/2004
Schreiber, Urs	Universität Essen	13/04/2004-16/04/2004
Schroer, Bert	Freie Universität, Berlin	26/07/2004-06/08/2004
Schroers, Bernd	Heriot-Watt University, Edinburgh	27/06/2004-03/07/2004
Schubert, Christian	University of Texas-Pan American, Edinburgh	01/06/2004-30/06/2004
Schwimmer, Adam	Weizmann Institute, Rehovot	14/07/2004-29/07/2004
Seiler, Jennifer	Cornell University	04/06/2004-04/08/2004
Selberg, Sigmund	University of Trondheim	25/05/2004-08/06/2004
Sesum, Natasa	Courant Institute of Mathematical Sciences, New York	26/06/2004-03/07/2004
Shadchin, Sergej	IHES, Paris	15/12/2004-16/12/2004
Siemens, Xavier	University of Wisconsin	03/10/2004-09/10/2004
Simon, Leon	Stanford University	01/07/2004-30/08/2004
Sinestrari, Carlo	University of Rome II	21/03/2004-04/04/2004
		18/04/2004-04/07/2004
Singh, Parampreet	IUCAA, Pune	18/04/2004-02/05/2004
		21/09/2004-15/10/2004
Sintes Olives, Alicia	University of the Balearic Islands, Mallorca	05/02/2004-07/02/2004
		23/02/2004-31/08/2004
		07/11/2004-15/11/2004
Smilga, Andrei	University of Nantes	28/02/2004-03/03/2004
Sokatchev, Emery	Theoretical Physics Laboratory of Annecy-Le-Vieux	16/08/2004-22/08/2004
		19/10/2004-06/11/2004
		01/12/2003-04/01/2004
Solodukhin, Sergej	LMU, München	18/01/2004-25/01/2004
Southwood, David	European Space Agency	14/06/2004-15/06/2004
Sperhake, Ulrich	Pennsylvania State University	09/08/2004-13/08/2004
Stahn, Christian	DAMTP, Cambridge, UK	01/02/2004-06/02/2004
Starodubtsev, Artem	Perimeter Institute, Waterloo	10/10/2004-14/10/2004
Stefanski, Bogdan	Cambridge, UK	09/02/2004-13/02/2004
Steinacker, Harold	Universität München	15/03/2004-17/03/2004
Stelle, Kellogg	Imperial College, London	12/08/2004-22/08/2004
Stergioulas, Nikolaos	Thessaloniki	15/09/2004-26/09/2004
Sthanumoorthy, Neelakanta	University of Madras	04/07/2004-02/08/2004
Strobl, Thomas	Universität Jena	01/12/2004-05/12/2004
Takahashi, Ryoji	Theoretical Astrophysics Center, Copenhagen	24/07/2004-09/08/2004
Tegankong, David	University of Yaounde	07/09/2004-27/11/2004
Teo, Lee-Peng	Chiao Tung University, Taiwan	27/06/2004-04/07/2004
Thurston, Dylan	Harvard University	27/06/2004-05/07/2004
Tierz, Miguel	University of Barcelona	08/03/2004-14/03/2004
		14/06/2004-30/06/2004
Tiglio, Manuel	Pennsylvania State University	18/02/2004-20/02/2004
		25/02/2004-05/03/2005
Tilman, Vogel	Universität Tübingen	28/03/2004-30/03/2004
Tod, Paul	Oxford University	04/11/2004-06/11/2004
Tohline, Joel	Louisiana State University	13/07/2004-18/07/2004
Topping, Peter	University of Warwick	11/10/2004-15/10/2004
Trudinger, Neil	ANU, Canberra	18/04/2004-15/05/2004
Uggla, Claes	Karlstad University, Sweden	18/08/2004-25/08/2004
Urena, Luis	Sussex University	19/07/2004-28/07/2004
Valiente Kroon, Juan Antonio	Universität Wien	14/06/2004-25/06/2004
Ventrella, Jason		18/02/2004-20/02/2004

		25/02/2004-26/02/2004
Vulcanov, Dumitru	Timisoara University	10/01/2004-20/02/2004 02/05/2004-15/06/2004 01/11/2004-14/11/2004
Wambsganss, Joachim	Universität Heidelberg	03/11/2004-07/11/2004
Whelan, John	Loyola University, New Orleans	07/07/2004-11/07/2004
Wickramasekera, Neshan	Massachusetts Institute of Technology	03/06/2004-04/08/2004
Winicour, Jeffrey	University of Pittsburgh	01/01/2004-31/03/2004 01/11/2004-31/01/2005
Winklmann, Sven	Universität Duisburg/Essen	22/11/2004-26/11/2004
Wosiek, Jacek	Jagellonian University, Krakow	22/11/2004-27/11/2004
Yokota, Yoshiyuki	University of Tokyo	27/06/2004-03/07/2004
Zagermann, Marco	Stanford University	26/07/2004-26/07/2004
Zanelli, Jorge	Centro de Estudios Cientificos de Santiago, Chile	13/09/2004-23/09/2004
Zarembo, Konstantin	Uppsala University	08/08/2004-22/08/2004
Zink, Burkard	MPI für Astrophysik, Garching	01/02/2004-05/02/2004 13/07/2004-17/07/2004

Guest Scientists in Potsdam-Golm (2005)

Agarwal, Abishek	University of Rochester	27/05/2005-19/06/2005
Akhmedov, Emil	ITEP, Moscow	01/02/2005-01/03/2005 01/08/2005-31/08/2005
Alday, Fernando	Utrecht University	05/06/2005-10/06/2005
Alexandrov, Sergei	Utrecht University	16/05/2005-21/05/2005
Alic, Daniela	West University of Timisoara	26/02/2005-13/03/2005
Allen, Bruce	University of Wisconsin	07/06/2005-31/08/2005
Ammann, Bernd	Institut Elie Cartan, Nancy	03/07/2005-23/07/2005
Anderson, Matt	Louisiana State University	12/01/2005-20/01/2005
Anderson, David	University of California, Berkeley	03/07/2005-28/07/2005
Andersson, Nils	Southampton University	20/11/2005-26/11/2005 29/11/2005-06/12/2005
Arcioni, Giovanni	Racah Institute of Physics	29/03/2005-08/04/2005 20/11/2005-25/11/2005
Arutyunov, Gleb	Utrecht University	23/01/2005-25/01/2005 25/09/2005-01/10/2005
Ashtekar, Abhay	Pennsylvania State University	15/06/2005-01/08/2005
Babiuc, Maria	University of Pittsburgh	16/11/2005-31/01/2006
Banados, Maximo	University of Santiago, Chile	01/05/2005-08/05/2005 02/11/2005-10/11/2005
Barack, Leor	University of Southampton	04/04/2005-12/04/2005 19/12/2005-27/12/2005
Barausse, Enrico	SISSA, Trieste	24/10/2005-05/11/2005
Bastianelli, Fiorenzo	University of Bologna	01/07/2005-30/07/2005
Baumgardt, Holger	Universität Bonn	31/07/2005-03/08/2005
Bazhanov, Vladimir	Australian National University, Canberra	01/08/2005-07/08/2005
Beisert, Niklas	Princeton University	10/01/2005-14/01/2005 05/07/2005-07/08/2005 26/10/2005-28/10/2005
Bekaert, Xavier	IHES, Bures-Sur-Yvette	31/10/2005-06/11/2005
Benincasa, Paolo	University of Bologna	18/07/2005-25/07/2005
Benlagra, Adel	ENS, Paris	25/02/2005-31/08/2005
Bicak, Jiri	Charles University, Prague	03/04/2005-20/04/2005 27/05/2005-28/05/2005 04/09/2005-20/12/2005
Bishop, Nigel	University of South Africa	05/01/2005-19/01/2005 04/04/2005-16/04/2005 22/08/2005-09/09/2005 08/12/2005-17/12/2005
Blumenhagen, Ralph	MPI für Physik, München	02/05/2005-04/05/2005
Bohm, Arno	University of Texas at Austin	29/06/2005-30/06/2005
Bona, Carles	University of the Balearic Islands, Mallorca	12/01/2005-20/01/2005
Bose, Sukanta	Washington State University	01/07/2005-23/07/2005
Brandenberger, Robert	Mc Gill University, Montreal	24/07/2005-30/07/2005
Brandhuber, Andreas	Queen Mary and Westfield College, London	24/04/2005-28/04/2005
Brendle, Simon	Princeton University	10/07/2005-23/07/2005
Brink, Lars	Chalmers Technical University	14/02/2005-22/02/2005 05/04/2005-09/04/2005 06/09/2005-11/09/2005
Brügmann, Bernd	Universität Jena	10/05/2005-11/05/2005
Buonanno, Alessandra	Institut d´Astrophysique de Paris	27/02/2005-04/03/2005
Calabrese, Gioel	Louisiana State University	15/06/2004-19/06/2005

Cederwall, Martin	Chalmers Technical University	10/10/2005-20/10/2005
Chesterman, Michael	Karlstad University	01/07/2005-08/08/2005
Chrusciel, Piotr	Tours University	22/12/2005-24/12/2005
Comer, Gregory	Saint Louis University	20/11/2005-26/11/2005
Craps, Ben	University of Amsterdam	25/09/2005-30/09/2005
Dafermos, Mihailis	University of Cambridge, UK	28/03/2005-09/04/2005
David, Justin R.	ICTP, Trieste	11/08/2005-12/08/2005
de Gosson, Maurice	Blekinge Inst. of Technology, Sweden	07/02/2005-28/02/2005
Dehne, Christoph	Universität Leipzig	31/01/2005-02/02/2005
Denef, Frederik	Rutgers State University of New Jersey	06/06/2005-10/06/2005
de Pietri, Roberto	University of Parma	07/06/2005-12/06/2005
		08/11/2005-12/11/2005
Diener, Peter	Louisiana State University	06/01/2005-20/01/2005
		20/11/2005-26/11/2005
Dietz, Alexander	Louisiana State University	21/06/2005-25/06/2005
Dittrich, Bianca	Perimeter Institute, Waterloo	01/08/2004-31/08/2005
Dorband, Nils	Louisiana State University	08/01/2005-24/01/2005
Drukker, Nadav	Niels Bohr Institute, Copenhagen	04/09/2005-11/09/2005
		31/07/2005-06/08/2005
Drury, Luke	Dublin Institute for Advanced Studies	27/09/2005-29/09/2005
Duran, Pablo Cerda	University of Valencia	07/06/2005-11/06/2005
Englert, Francois	University of Brussels	31/07/2005-06/08/2005
Erdmenger, Johanna	MPI für Physik, München	26/09/2005-30/09/2005
Everitt, Francis	Stanford University	25/02/2005-26/02/2005
Ewerz, Carlo	University of Milano	13/03/2005-22/03/2005
Font, Anamaria	UNAM, Madrid	20/12/2004-08/01/2005
		26/04/2005-02/05/2005
		25/07/2005-31/08/2005
		21/12/2005-10/01/2006
Freitag, Marc	Cambridge University	01/10/2005-31/01/2006
Futamase, Toshifumi	Tohoku University, Sendai	01/03/2005-16/03/2005
Gair, Jonathan	Cambridge University	16/10/2005-23/10/2005
Garecki, Janusz	University of Szczecin	12/09/2005-17/09/2005
Ghoshal, Debashis	Harish-Chandra Research Institute, Allahabad	15/06/2005-15/07/2005
Giacomazzo, Bruno	SISSA Trieste	07/06/2005-11/06/2005
		13/11/2005-26/11/2005
		11/12/2005-17/12/2005
		19/12/2005-23/12/2005
Glampedakis, Kostas	University of Southampton	07/03/2005-14/03/2005
Göhmann, Frank	Universität Wuppertal	22/08/2005-24/08/2005
Grumiller, Daniel	Universität Leipzig	16/03/2005-19/03/2005
Hahn, Atle	Universität Bonn	03/01/2005-06/01/2005
		17/01/2005-21/01/2005
		16/05/2005-20/05/2005
Hawke, Ian	University of Southampton	07/06/2005-11/06/2005
Helling, Robert	International University, Bremen	18/07/2005-24/07/2005
Heng, Ik Siong	Glasgow University	17/04/2005-20/04/2005
Hoppe, Jens	Royal Institute of Technology, Stockholm	20/12/2004-20/01/2005
		03/04/2005-08/04/2005
		17/12/2005-16/01/2006
Houart, Laurent	University of Brussels	31/07/2005-06/08/2005
Humbert, Emmanuel	Nancy University	03/07/2005-08/07/2005
Husa, Sascha	University of Pittsburgh	05/09/2000-31/08/2005
		15/12/2005-20/12/2005
Hutanu, Andrei	Louisiana State University	08/05/2005-15/05/2005
		25/04/2005-30/04/2005
Hwang, Hyung Iu	Duke University, Durham, USA	31/07/2005-02/08/2005
Ishimoto, Yukitaka	RIKEN, Japan	25/08/2005-27/08/2005
Isidro, Jose	University of Valencia	02/10/2005-16/10/2005
Jaramillo, Jose	Observatoire de Paris	26/06/2005-01/07/2005
Jones, Gareth	Cardiff University	16/10/2005-23/10/2005
Jorjadze, George	A. Razmadze Mathematical Institute, Tbilisi	10/06/2005-10/08/2005
Julia, Bernard	ENS, Paris	09/10/2005-14/10/2005
Karino, Shigeyuki	SISSA Trieste	05/12/2005-10/12/2005
Kastaun, Wolfgang	CPT, Tübingen	08/08/2005-13/08/2005
Kastrup, Hans	DESY, Hamburg	29/05/2005-16/07/2005
Kazakov, Vladimir	ENS, Paris	23/07/2005-07/08/2005
Kerstan, Sven	University of Groningen	21/06/2005-25/06/2005
Khalatnikov, Isaak	Landau Institute for Theoretical Physics, Moscow	04/04/2005-04/05/2005
Kiefer, Claus	Universität Köln	01/11/2005-31/01/2006
Kim, Nakwoo	Seoul National University	27/01/2005-08/02/2005
Kobras, Daniel	Universität Tübingen	07/06/2005-11/06/2005
Korzynski, Mikolaj	Warsaw University	01/07/2005-20/07/2005
Kostov, Ivan	CEA, Saclay	24/07/2005-05/08/2005
Kotikov, Anatoly	Joint Institute for Nuclear Research, Dubna	01/08/2005-02/08/2005

Kramer, Michael	University of Manchester	22/01/2005-29/01/2005
Kraus, Margarita	Universität Regensburg	02/02/2005-16/02/2005
Krolak, Andrzej	Academy of Sciences, Warsaw	03/01/2005-14/01/2005
		06/09/2004-31/08/2005
		01/09/2005-31/01/2006
Krtous, Pavel	Charles University, Prague	06/11/2005-24/11/2005
Kukreja, Lalit	Centre for Advanced Technology, Indore	10/02/2005-12/02/2005
Kupi, Gabor	Astronomisches Recheninstitut, Heidelberg	29/11/2005-09/12/2005
Kuzenko, Sergei	University of Western Australia	17/10/2005-17/11/2005
Lai, Chi Wai	University of South Africa, Pretoria	22/08/2005-09/09/2005
Lau, Yun-Kau	Chinese Aademy of Sciences, Bejing	16/08/2005-15/09/2005
Lauda, Aaron	DPMMS Cambridge, UK	06/12/2005-21/12/2005
Lechner, Christiane		01/02/2005-31/03/2005
		01/05/2005-01/07/2005
Lee, Sangmin	Imperial College, London	18/07/2005-20/07/2005
Lehner, Luis	University of British Columbia, Vancouver	13/01/2005-18/01/2005
Madore, John	University of Paris (South)	01/06/2005-22/07/2005
Malec, Edward	Cracow University	27/06/2005-23/07/2005
Manca, Gian Mario	University of Parma	07/06/2005-14/06/2005
		08/11/2005-12/11/2005
Matsuo, Toshihiro	RIKEN, Japan	14/11/2005-01/12/2005
Mayr, Peter	LMU, München	15/02/2005-16/02/2005
Meissner, Krzysztof	Warsaw University	30/03/2005-12/04/2005
		27/06/2005-12/07/2005
Meusburger, Catherine	Perimeter Institute, Waterloo	01/12/2005-28/02/2006
Minasian, Ruben	CEA, Saclay	10/07/2005-17/07/2005
Mishima, Takashi	Nihon University, Japan	28/02/2005-19/03/2005
Miskovic, Olivera	University of Santiago, Chile	07/06/2005-01/07/2005
Misner, Charles	University of Maryland	23/03/2005-08/06/2005
Mizoguchi, Shunya	High Energy Accelerator Research Organization	22/08/2005-13/09/2005
Moncrief, Vincent	Yale University	13/12/2004-09/01/2005
		24/04/2005-25/06/2005
		11/07/2005-04/08/2005
Mukherjee, Soma	University of Brownsville, Texas	04/04/2005-11/04/2005
Müller, Ewald	MPI für Astrophysik, Garching	08/11/2005-10/11/2005
Nagar, Alessandro	University of Parma	04/06/2005-10/06/2005
Nelemans, Gijs	Radboud University Nijmegen	24/04/2005-28/04/2005
Noundjeu, Pierre	University of Yaounde	10/04/2005-18/04/2005
Olea, Rodrigo	CECS Valdivia, Chile	07/11/2005-30/11/2005
OMurchadha, Niall	University College, Cork	17/04/2005-23/04/2005
Palenzuela, Carlos	Universitat de les Iles Balears, Mallorca	12/01/2005-20/01/2005
Pawelczyk, Jacek	Warsaw University	04/04/2005-30/04/2005
Peitz, Jochen	Universität Tübingen	08/06/2005-10/06/2005
Perelomov, Askold	ITEP, Moscow	29/11/2005-02/01/2006
Perez, Alexandro	CNRS, Marseille	17/04/2005-25/04/2005
Petkou, Anastasios	University of Crete, Heraklion	20/02/2005-27/02/2005
Petroff, David	Universität Jena	26/07/2005-28/07/2005
Pottier, Antonin	Ecole Normale Superieure, Paris	14/02/2005-24/06/2005
Prester, Predrag	Zagreb University	01/09/2004-28/02/2006
Pretorius, Frans	California Institute of Technology	20/05/2005-26/05/2005
Pullin, Jorge	Louisiana State University	03/04/2005-09/04/2005
Quella, Thomas	King's College, London	16/12/2005-23/12/2005
Rajeev, S.G.	University of Rochester, USA	01/08/2005-06/08/2005
Ramgoolam, Sanjaye	Queen Mary and Westfield College, London	26/06/2005-29/06/2005
		14/11/2005-19/11/2005
Rani, Raffaele	Universität Tübingen	07/04/2005-02/05/2005
Reiris, Martin	Stony Brook University	17/12/2005-22/12/2005
Reshetikhin, Nicolai	Univ. of California, Berkeley	05/07/2005-28/07/2005
Reuter, Martin	Universität Mainz	23/02/2005-25/02/2005
Rey, Soo-Jong	Seoul National University	20/07/2005-31/08/2005
Riccioni, Fabio	DAMTP Cambridge, UK	20/11/2005-22/11/2005
Rideout, David	Hamilton College, Clinton	07/10/2005-31/10/2005
Ringstrøm, Hans	KTH, Stockholm	03/04/2005-10/04/2005
Rinne, Oliver	University of Cambridge, UK	22/05/2005-28/05/2005
Rosales, Leobardo	Stanford University	09/08/2005-12/12/2005
Roszkowski, Krzysztof	Krakow University	24/07/2005-31/07/2005
Röhr, Niklas	University of Karlstad	29/08/2005-06/09/2005
Samtleben, Henning	DESY, Hamburg	09/02/2005-11/02/2005
		20/07/2005-29/07/2005
		23/11/2005-25/11/2005
Sancho de la Jordana Llabres, Llucia	University of the Balearic Islands, Mallorca	03/07/2005-20/08/2005
Schubert, Christian	University of Texas-Pan American, Edinburgh	24/07/2005-24/08/2005
Schwimmer, Adam	Weizmann Institute, Rehovot	01/10/2005-30/11/2005

Serban, Didina	CEA, Saclay	20/04/2005-26/04/2005 24/07/2005-04/08/2005
Sesum, Natasa	New York University	04/06/2005-18/06/2005
Shojai, Ali	University of Tehran	24/06/2005-23/09/2005
Shojai, Fatimah	University of Tehran	24/06/2005-23/09/2005
Shovkovy, Igor	Universität Frankfurt	31/10/2005-04/11/2005
Silk, Joe	Oxford University	25/10/2005-27/10/2005
Simon, Leon	Stanford University	07/05/2005-20/12/2005
Sinestrari, Carlo	University of Rome II	06/03/2005-20/03/2005 17/07/2005-24/07/2005
Sintes Olives, Alicia	Universitat de les Illes Balears, Mallorca	01/03/2005-31/08/2005
Skenderis, Kostas	University of Amsterdam	23/04/2005-26/04/2005
Smyth, Paul	Catholic University, Leuven	07/03/2005-11/03/2005
Sokatchev, Emery	Theoretical Physics Laboratory of Annecy-Le-Vieux	09/02/2005-20/02/2005
Sonnenschein, Jacob	Tel Aviv University	21/08/2005-01/09/2005
Sorkin, Rafael	Syracuse University	05/10/2005-15/10/2005
Spurzem, Rainer	Astronomisches Recheninstitut, Heidelberg	27/06/2005-28/06/2005
Stamatescu, Ion-O.	Universität Heidelberg	27/06/2005-10/07/2005
Starinets, Andrei	Perimeter Institute, Waterloo	15/09/2005-22/09/2005
Steinmetz, Matthias	Astrophysikalisches Institut, Potsdam	18/05/2005-18/05/2005
Stergioulas, Nikolaos	University of Thessaloniki	08/06/2005-11/06/2005
Ståhl, Fredrik	Mid Sweden University, Östersund	17/03/2005-24/03/2005
Szabados, Laszlo	Research Institute for Particle and Nuclear Physics, Budapest	25/04/2005-07/05/2005
Taylor, Marika	University of Amsterdam	23/04/2005-26/04/2005
Tegankong, David	University of Yaounde	15/05/2005-22/05/2005
Tiglio, Manuel	Pennsylvania State University	13/01/2005-20/01/2005 27/02/2004-05/03/2005
Topping, Peter	University of Warwick	18/10/2005-17/04/2006
Tozzi, Paolo	INAF Osservatorio Astronomico de Trieste	04/07/2005-11/07/2005
Trias Cornellana, Miquel	University of the Balearic Islands, Mallorca	03/07/2005-20/08/2005
Tsujikawa, Shinji	Gunma National College of Technology, Japan	23/08/2005-27/08/2005
Uggla, Claes	Karlstad University, Sweden	18/05/2005-25/05/2005
Ungarelli, Carlo	University of Birmingham	29/03/2005-22/04/2005
Valiente Kroon, Juan Antonio	University of Vienna	03/04/2005-10/04/2005 01/05/2005-31/05/2005
Vandersloot, Kevin	Pennsylvania State University	21/02/2005-16/05/2005
Vandoren, Stefan	Utrecht University	24/07/2005-28/07/2005
Vanhove, Pierre	CEA, Saclay	06/03/2005-10/05/2005
Volkov, Michael	University of Tours	01/03/2005-31/03/2005
Vulcanov, Dumitru	Timisoara University	10/01/2005-16/02/2005 21/09/2005-30/10/2005
Wambsganss, Joachim	Astronomisches Recheninstitut, Heidelberg	20/04/2005-24/04/2005
Watson, Alan	University of Leeds	18/10/2005-21/10/2005
West, Peter	King's College, London	23/04/2005-29/04/2005
Wickramasekera, Neshan	Massachusetts Institute of Technology	03/07/2005-28/08/2005
Wiegmann, Paul	Chicago University	01/08/2005-06/08/2005
Winicour, Jeffrey	University of Pittsburgh	01/11/2005-31/01/2006
Winklmann, Sven	Universität Duisburg/Essen	01/08/2005-02/09/2005
Wohlfarth, Mattias	DESY, Hamburg	13/12/2005-14/12/2005
Wood, Gavin	IT Centre, York Science Park, UK	13/02/2005-17/02/2005
Woolgar, Eric	University of Alberta	20/09/2005-25/09/2005
Yankielovich, Shimon	Tel Aviv University	23/08/2005-01/09/2005
Zabzine, Maxim	University of London	21/06/2005-25/06/2005
Zagermann, Marco	MPI für Physik, München	25/09/2005-30/09/2005
Zapata, Oswaldo	University Rome II	07/02/2005-15/02/2005 20/09/2005-20/12/2005
Zink, Burkard	MPI für Astrophysik, Garching	05/06/2005-12/06/2005
Zofka, Martin	Prague University	17/10/2005-28/10/2005

Guest Scientists in Hannover (2004-2005)

Allen, Bruce	University of Wisconsin	22/09/2004-25/09/2004
Adhikari, Rana	MIT, Cambridge	23/08/2005-23/09/2005
Beyersdorf, Peter	National Astronomical Observatory (Japan)	12/04/2004-07/05/2004
Brindisi, Angela	Università di Napoli	15/05/2004-18/05/2004
Casey, Morag M.	University of Glasgow	01/11/2004-10/12/2004
Ciani, Giacomo	Università di Pisa	04/12/2005-11/12/2005
Clark, James	University of Glasgow	22/08/2005-28/09/2005
Daw, Edward	University of Sheffield	21/03/2005-23/03/2005
Fiurasek, Jaromir	Université Libre de Bruxelles	11/07/2005-15/07/2005
Grosse, Nicolai	Australian National University	01/01/2004-29/02/2004
Grosse, Nicolai	Australian National University	01/05/2005-30/09/2005
Heng, Ik Siong	University of Glasgow	23/11/2004-30/11/2004
		23/01/2005-30/01/2005
		15/05/2005-19/05/2005
		29/05/2005-01/06/2005
		25/07/2005-01/08/2005
Hough, James	University of Glasgow	11/10/2004-22/10/2004
Jennrich, Oliver	ESA/ESTEC	25/07/2005-01/08/2005
Nofrarias, Miguel	Institut D'Estuds Espacials de Catalunya	09/11/2005-11/12/2005
Sathyaprakash, Bangalore	Cardiff University	11/03/2005-11/03/2005
Strain, Kenneth A.	University of Glasgow	27/10/2004-09/11/2004
		06/04/2005-09/04/2005
		09/05/2005-20/05/2005
		13/06/2005-24/06/2005
.		01/08/2005-12/08/2005
		12/09/2005-23/09/2005
		22/10/2005-08/11/2005

Publications by the Institute

Max-Planck-Institut für Gravitationsphysik (Ed.)	Living Reviews in Relativity, Living Reviews in Relativity 7 (2004), 8 (2005) *http.//www.livingrewiews.org*

Publications by AEI Members and Guest Scientists

Abbott, B. for the LIGO Scientific Collaboration (author list S1, S2)	Detector description and performance for the first coincidence observations between LIGO and GEO. Nucl. Instr. Methods Phys. Res. A 517 (2004) 154-179
Abbott, B. for the LIGO Scientific Collaboration (author list S1, S2)	Setting upper limits on the strength of periodic gravitational waves from PSR J1939 + 2134 using the first science data from the GEO 600 and LIGO detectors. Phys. Rev. D 69 (2004) 082004
Abbott, B. for the LIGO Scientific Collaboration (author list S1, S2)	Analysis of first LIGO science data for stochastic gravitational waves. Phys. Rev. D 69 (2004) 122004
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Abbott, B., R. Abbott, R. Adhikari, J. Agresti, P. Ajith, B. Allen, J. Allen, R. Amin, S. B. Anderson, W. G. Anderson, M. Araya, H. Armandula, M. Ashley, C. Aulbert, S. Babak, R. Balasubramanian, S. Ballmer, B. C. Barish, C. Barker, D. Barker, M. A. Barton, K. Bayer, K. Belczynski, J. Betzwieser, B. Bhawal, I. A. Bilenko, G. Billingsley, E. Black, K. Blackburn, L. Blackburn, B. Bland, L. Bogue, R. Bork, S. Bose, P. R. Brady, V. B. Braginsky, J. E. Brau, D. A. Brown, A. Buonanno, D. Busby, W. E. Butler, L. Cadonati, G. Cagnoli, J. B. Camp, J. Cannizzo, K. Cannon, L. Cardenas, K. Carter, M. M. Casey, P. Charlton, S. Chatterji, Y. Chen, D. Chin, N. Christensen, T. Cokelaer, C. N. Colacino, R. Coldwell, D. Cook, T. Corbitt, D. Coyne, J. D. E. Creighton, T. D. Creighton, J. Dalrymple, E. D'Ambrosio, K. Danzmann, G. Davies, D. DeBra, V. Dergachev, S. Desai, R. DeSalvo, S. Dhurandar, M. Diaz, A. Di Credico, R. W. P. Drever, R. J. Dupuis, P. Ehrens, T. Etzel, M. Evans, T. Evans, S. Fairhurst, L. S. Finn, K. Y. Franzen, R. E. Frey, P. Fritschel, V. V. Frolov, M. Fyffe, K. S. Ganezer, J. Garofoli, I. Gholami, J. A. Giaime, K. Goda, L. Goggin, G. Gonzalez, C. Gray, A. M. Gretarsson, D. Grimmett, H. Grote, S. Grunewald, M. Guenther, R. Gustafson, W. O. Hamilton, C. Hanna, J. Hanson, C. Hardham, G. Harry, J. Heefner, I. S. Heng, M. Hewitson, N. Hindman, P. Hoang, J. Hough, W. Hua, M. Ito, Y. Itoh, A. Ivanov, B. Johnson, W. W. Johnson, D. I. Jones, G. Jones, L. Jones, V. Kalogera, E. Katsavounidis, K. Kawabe, S. Kawamura, W. Kells, A. Khan, C. Kim, P. King, S. Klimenko, S. Koranda, D. Kozak, B. Krishnan, M. Landry, B. Lantz, A. Lazzarini, M. Lei, I. Leonor, K. Libbrecht, P. Lindquist, S. Liu, M. Lormand, M. Lubinski, H. Lück, M. Luna, B. Machenschalk, M. MacInnis, M. Mageswaran, K. Mailand, M. Malec, V. Mandic, S. Marka, E. Maros, K. Mason, L. Matone, N. Mavalvala, R. McCarthy, D. E. McClelland, M. McHugh, J. W. C. McNabb, A. Melissinos, G. Mendell, R. A. Mercer, S. Meshkov, E. Messaritaki, C. Messenger, E. Mikhailov, S. Mitra, V. P. Mitrofanov, G. Mitselmakher, R. Mittleman, O. Miyakawa, S. Mohanty, G. Moreno, K. Mossavi, G. Mueller, S. Mukherjee, E. Myers, J. Myers, T. Nash, F. Nocera, J. S. Noel, B. O'Reilly, R. O'Shaughnessy, D. J. Ottaway, H. Overmier, B. J. Owen, Y. Pan, M. A. Papa, V. Parameshwaraiah, C. Parameswariah, M. Pedraza, S. Penn, M. Pitkin, R. Prix, V. Quetschke, F. Raab, H. Radkins, R. Rahkola, M. Rakhmanov, K. Rawlins, S. Ray-Majumder, V. Re, T. Regimbau, D. H. Reitze, R. Riesen, K. Riles, B. Rivera, D. I. Robertson, N. A. Robertson, C. Robinson, S. Roddy, A. Rodriguez, J. Rollins, J. D. Romano, J. Romie, S. Rowan, A. Rüdiger, L. Ruet, P. Russell, K. Ryan, V. Sandberg, G. H. Sanders, V. Sannibale, P. Sarin, B. S. Sathyaprakash, P. R. Saulson, R. Savage, A. Sazonov, R. Schilling, R. Schofield, B. F. Schutz, P. Schwinberg, S. M. Scott, S. E. Seader, A. C. Searle, B. Sears, D. Sellers, A. S. Sengupta, P. Shawhan, D. H. Shoemaker, A. Sibley, X. Siemens, D. Sigg, A. M. Sintes, J. Smith, M. R. Smith, O. Spjeld, K. A. Strain, D. M. Strom, A. Stuver, T. Summerscales, M. Sung, P. J. Sutton, D. B. Tanner, R. Taylor, K. A. Thorne, K. S. Thorne, K. V. Tokmakov, C. Torres, C. Torrie, G. Traylor, W. Tyler, D. Ugolini, C. Ungarelli, M. Vallisneri, M. van Putten, S. Vass, A. Vecchio, J. Veitch, C. Vorvick, S. P. Vyachanin, L. Wallace, H. Ward, R. Ward, K. Watts, D. Webber, U. Weiland, A. Weinstein, R. Weiss, S. Wen, K. Wette, J. T. Whelan, S. E. Whitcomb, B. F. Whiting, S. Wiley, C. Wilkinson, P. A. Willems, B. Willke, A. Wilson, W. Winkler, S. Wise, A. G. Wiseman, G. Woan, D. Woods, R. Wooley, J. Worden, I. Yakushin, H. Yamamoto, S. Yoshida, M. Zanolin, L. Zhang, N. Zotov, M. Zucker and J. Zweizig

Institute Colloquium 2005 at AEI Potsdam-Golm

Reinhard Genzel (Max-Planck-Institut für Extraterrestrische Physik, Garching)	The massive black hole at the center of the milky way / 13 January 2005
Michael Kramer (University of Manchester and Jodrell Bank Observatory)	The double pulsar system: a unique gravity lab / 26 January 2005
Günther Hasinger (Max-Planck-Institut für Extraterrestrische Physik, Garching)	The growth of supermassive black holes in the universe / 16 February 2005
C.W. Francis Everitt (W.W. Hansen Experimental Physics Laboratory, Stanford University, Stanford, CA)	Space, Einstein & Technology: The NASA-Stanford Gravity Probe B mission / 25 February 2005
Heino Falcke (Radio Observatory Westerbork)	The future of Radio Astronomy / 3 March 2005
Joachim Wambsganss (Universität Heidelberg)	Gravitational Microlensing: Light deflection as a tool to investigate Halo Dark Matter, Quasar Structure and Exoplanets / 21 April 2005
Gijs Nelemans (Radboud University Nijmegen)	Ultra-compact binaries: doing astrophysics with gravitational wave measurements / 25 April 2005
Bernd Brügmann (Universität Jena)	Almost orbiting black holes / 11 May 2005
Matthias Steinmetz (Astrophysikalisches Institut Potsdam)	Cosmology with the Milky Way / 18 May 2005
Charles Misner (University of Maryland)	Will LISA need finite size effects for white dwarf orbits in the post-Newtonian domain? / 25 May 2005
Paolo Tozzi (Astronomical Observatory, Trieste, Italy)	The multiwavelength survey of the Chandra Deep Field South / 7 July 2005
Luke Drury (Dublin Institute for Advanced Studies)	The other anniversary in 2005: Bicentenary of William Rowan Hamilton / 28 September 2005
Alan Watson (Leeds University)	Status of Observations on the Highest Energy Cosmic Rays / 19 October 2005
Joseph Silk (Oxford University)	Dark Matter and Galaxy Formation / 26 October 2005
Stefan Rahmsdorf (Potsdam Institut für Klimafolgenforschung)	Climate change: what do we really know? / 2 November 2005
Ewald Müller (Max-Planck-Institut für Astrophysik, Garching)	Looking into the heart of a supernova / 9 November 2005
Nils Andersson (University of Southampton)	LMXBs as gravitational-wave sources / 1 December 2005

Invited Conference Talks Given by AEI Members

Andersson, L.	The BKL proposal and cosmic censorship / 16 April 2005 / American Physical Society meeting, Tampa (USA)
Andersson, L.	Asymptotic silence of inhomogenous cosmological singularities / 30 May 2005 / Workshop “Nonlinear Evolution Problems”, Oberwolfach (Germany)
Andersson, L.	On the interaction of mathematical and numerical general relativity / 16 August 2005 / Workshop “Global Problems in Mathematical General Relativity” Newton Institute, Cambridge (UK)
Andersson, L.	Constant mean curvature foliations of flat spacetimes / 6 September 2005 / Conference “Classical and quantum gravity in 3 dimensions”, Centro Di Ricerca Matematica Ennio De Giorgi, Pisa (Italy)
Andersson, L.	Future asymptotics of cosmological spacetimes / 16 September 2005 / Workshop “Global Problems in Mathematical General Relativity” Newton Institute, Cambridge (UK)
Anghelache, R.	Scientific Content on the Web, MathML, Hermes / 10 November 2005 / Workshop on Web Enabling Technologies and Strategies for Scientific e-Learning, ICTP Trieste (Italy)
Anghelache, R.	LateX, XSLT to XHTML + MathML / 11 November 2005 / Workshop on Web Enabling Technologies and Strategies for Scientific e-Learning, ICTP Trieste (Italy)
Aufmuth, P.	Gravitationswellen - Theorie, Quellen, Detektoren / 15 October 2004 / Schule für Astroteilchenphysik, Universität Erlangen-Nürnberg, Obertrubach-Bärnfels (Germany)
Beisert, N.	Higher-loop integrability in N=4 gauge theory / 1 July 2004 / Strings 2004, Paris (France)
Beisert, N.	SU(2) spin chains in AdS/CFT / 6 September 2004 / RTN and EXT Workshop 2004, Kolymbari, Crete (Greece)
Bojowald, M.	Loop Quantum Cosmology: Recent Progress / 10 January 2004 / ICGC 04, Cochin (India)
Bojowald, M.	Phenomenological Aspects of Loop Quantum Cosmology / 15 January 2004 / Workshop on Braneworlds and Quantum Cosmology, IUCAA, Pune (India)
Bojowald, M.	Loop Quantum Cosmology / 15 March 2004 / Hauptvortrag, Fachverband Gravitation, DPG-Tagung Ulm (Germany)
Bojowald, M.	Loop Quantum Cosmology / 6 May 2004 / Non-Perturbative Quantum Gravity: Loops and Spin Foams, Marseille (France)
Bojowald, M.	Loop Quantum Cosmology / 26 November 2004 / 6th Mexican School on Gravitation and Mathematical Physics: Approaches to Quantum Gravity, Playa del Carmen, Quintana Roo (Mexico)
Bojowald, M.	Quantum Geometry of Black Holes and Cosmology / 31 March 2005 / Spacetime in Action: 100 Years of Relativity, University of Pavia (Italy)
Bojowald, M.	Background Independence and the Small-Scale Behavior of Gravity / 28 April 2005 / Quantum Gravity Workshop, University of New Brunswick, Fredericton (Canada)
Bojowald, M.	Loop Quantum Cosmology / 6 July 2005 / Cape Town Cosmology Meeting (South Africa)
Bojowald, M.	Universe Scenarios from Loop Quantum Cosmology / 5 September 2005 / Pomeranian Workshop on Fundamental Cosmology, Pobierowo (Poland)
Bojowald, M.	Loop Quantum Cosmology / 20 October 2005 / Isaac Newton Institute Workshop on “Global Problems in Mathematical Relativity”, Cambridge (UK)
Bojowald, M.	Quantum Geometry and its Implications for Black Holes / 16 December 2005 / Workshop on Einstein’s Legacy in the New Millenium, Puri (India)

Cutler, C.J.	Gravitational Waves from Rapidly Rotating Neutron Stars / 18 February 2004 / Annual General Meeting of the British Gravitational Physics Group, London (UK)
Dain, S.	Black holes as inner boundaries for the constraint equations / 4 March 2004 / 319th WE-Heraeus-Seminar “Mathematical Relativity: New Ideas and Developments”, Physikzentrum Bad Honnef (Germany)
Dain, S.	A new geometric invariant on initial data for Einstein equations / 19 July 2004 / GR17, the 17th International Conference on General Relativity and Gravitation, Dublin (Ireland)
Dain, S.	Initial data for binary black holes / 3 August 2004 / Penrose inequalities II, workshop, The Erwin Schrödinger Institute for Mathematical Physics, Vienna (Austria)
Dain, S.	A new geometric invariant on initial data for Einstein equations / 21 February 2005 / SFB-Frühjahrstagung im Max-Planck-Institut für Astrophysik, Garching (Germany)
Danzmann, K.	Gravitational Wave Astronomy / 4 January 2004 / Astroparticle European Coordination (APPEC), Gravitational Wave Review, London (UK)
Danzmann, K.	Interferometry on LISA Pathfinder / 11 March 2004 / LISA Pathfinder Kick-Off Meeting, ESTEC Nordwijk (The Netherlands)
Danzmann, K.	Gravitational Wave Astronomy (Plenarvortrag) / 29 April 2004 / ILIAS Meeting, Paris (France)
Danzmann, K.	Network Development / 10 May 2004 / ILIAS Working Group Meeting, Pisa (Italy)
Danzmann, K.	Massive Black Holes and LISA (Plenarvortrag) / 24 June 2004 / Growing Black Holes Conference, Garching (Germany)
Danzmann, K.	The European Gravitational Wave Community / 27 June 2004 / Astroparticle European Coordination Review, Paris (France)
Danzmann, K.	GEO600 and GEO HF / 5 July 2004 / GEO General Meeting, Hannover (Germany)
Danzmann, K.	LISA (Plenarvortrag) / 12 July 2004 / LISA Symposium, ESTEC, Nordwijk (The Netherlands)
Danzmann, K.	Gravitational Wave Astronomy with LISA / 18 July 2004 / 17th Conference on General Relativity and Gravitation, Dublin (Ireland)
Danzmann, K.	The Gravitational Wave Universe / 15 September 2004 / ESA Cosmic Visions Conference, Paris (France)
Danzmann, K.	Advanced Research for Gravitational Wave Detectors / 5 November 2004 / ILIAS Meeting, Orsay (France)
Danzmann, K.	Gravitational Waves / 1 February 2005 / Annual Meeting of the Australian Physical Society, Canberra (Australia)
Danzmann, K.	Gravitational Wave Astronomy / 7 February 2005 / ILIAS General Meeting, Prague (Czechoslovakia)
Danzmann, K.	Gravitational Wave Detection from Space / 13 June 2005 / 13th General Conference of the EPS “Beyond Einstein”, Bern (Switzerland)
Danzmann, K.	LISA and LISA Pathfinder / 21 September 2005 / European Science Foundation Meeting, Perugia (Italy)
Danzmann, K.	The Gravitational Wave Universe / 5 October 2005 / Workshop “Astroteilchenphysik in Deutschland”, DESY Zeuthen (Germany)
de Haro, S.	Knot Invariants, q-Deformed 2d Yang-Mills, and Brownian Motion / 27 October 2005 / 1st Young Researchers Workshop, EU Superstring Network, Crete (Greece)
de Haro, S.	Towards a q-Deformed Structure in Topological Strings / 10 December 2005 / 17th Workshop “Foundations and Constructive Aspects of QFT”, Göttingen (Germany)
Ehlers, J.	Pascual Jordan und die Begründung der Quantentheorie / 3 May 2004 / Universität Ulm (Germany)

Ehlers, J.	Remarks on Exact Solutions to Einstein's Equations / 17 July 2004 / Seminar in the Honor of Prof McCallum; Queen Mary College, London (UK)
Ehlers, J.	Einstein's Principle of Equivalence / 20 October 2004 / International Centre for Relativistic Astrophysics, Pescara (Italy)
Ehlers, J.	Concepts of time in Einstein's relativity theories / 21 January 2005 / Conference "Einstein for the 21st century", Einstein-Forum & Berlin-Brandenburgische Akademie der Wissenschaften, Berlin (Germany)
Ehlers, J.	Axiomatisierung und Wirklichkeitsbezug der Relativitätstheorie / 7 March 2005 / Tagung der Deutschen Physikalischen Gesellschaft "Physik seit Einstein", Berlin (Germany)
Ehlers, J.	The Rise of a Genius: Einstein's Annus Mirabilis / 29 March 2005 / Conference "Spacetime in Action", Pavia (Italy)
Ehlers, J.	Das Verhältnis von Mathematik und Physik in der Entwicklung der Allgemeinen Relativitätstheorie / 14 June 2005 / Festkolloquium der Max-Planck-Gesellschaft zum Einstein-Jahr, Urania Berlin (Germany)
Ehlers, J.	Einsteins Wunderjahr und sein beschwerlicher Weg zur Allgemeinen Relativitätstheorie / 7 July 2005 / Konferenz "Entdeckung, Kreativität und Innovationskultur. Einsteins Annus Mirabilis", Universität Bern (Switzerland)
Ehlers, J.	General Relativity: Einstein's Creation / 6 September 2005 / Conference "100 Years of Relativity", Orviedo (Spain)
Ehlers, J.	Einstein's Path to General Relativity / 21 October 2005 / International Conference on General Relativity, State University of New York, Stony Broke (USA)
Ehlers, J.	Von Newtons Raumzeit zur Speziellen Relativitätstheorie / 27 October 2005 / Philosophisches Seminar der Universität Erlangen (Germany)
Ehlers, J.	Grundlagen der Speziellen Relativitätstheorie Einsteins / 9 December 2005 / Mathematische Gesellschaft in Hamburg (Germany)
Ehlers, J.	Cosmology / 26 December 2005 / International University Centre for Astronomy and Astrophysics, Puna (India)
Friedrich, H.	Smoothness at null infinity and the structure of initial data / 5 March 2004 / Physikzentrum Bad Honnef, 319. WE-Heraeus-Seminar, 1 (Germany)
Friedrich, H.	The initial boundary value problem for Einstein's vacuum field equations / 15 April 2004 / Beijing, Morningside Center of Mathematics, Chinese Academy of Sciences (China)
Friedrich, H.	Concepts of gravitational radiation / 23 April 2004 / SFB TR 7 Frühjahrstagung, Golm, (Germany)
Friedrich, H.	Problems of calculating wave signals which characterize isolated systems / 20 April 2005 / Workshop on numerical relativity, Banff (Canada)
Friedrich, H.	Exploring Einstein's field equations / 29 September 2005 / International Conference on General Relativity, Dornburg (Germany)
Friedrich, H.	Probleme der Mathematischen Relativitätstheorie / 5 November 2005 / Physikzentrum Bad Honnef, DFG Gesprächsrunde zum Status der Gravitationsforschung in Deutschland (Germany)
Friedrich, H.	Null data expansions of asymptotically flat, static, vacuum solutions / 2 December 2005 / Isaac Newton Institute, Programme on `Global Problems in Mathematical Relativity, Cambridge (UK)
Grote, H.	Commissioning of the Dual Recycled GEO600 / 21 June 2005 / 6th Edoardo Amaldi Conference on Gravitational Waves, Okinawa (Japan)
Heinzel, G.	The LTP Interferometer and Phasemeter / 12 July 2004 /5th International LISA Symposium, Nordwijk (The Netherlands)
Heinzel, G.	The LTP Interferometer and Phasemeter / 28 October 2004 / Journées du GREX, Nice (France)

Heinzel, G.	LISA and LISA pathfinder / 28 October 2004 / GREX2004 Observatoire de Cote Azur Nizza (France)
Heinzel, G.	The LTP Interferometer and Phasemeter / 18 February 2005 / TAMA Symposium, Osaka (Japan)
Heinzel, G.	LISA and LISA Pathfinder / 18 February 2005 / TAMA Symposium, Osaka (Japan)
Heinzel, G.	The LISA technology package LPT / 22 June 2005 / 6th Amaldi Conference, Okinawa (Japan)
Heinzel, G.	LISA interferometry / 22 June 2005 / 6th Amaldi Conference, Okinawa (Japan)
Heinzel, G.	The LTP Interferometer / 11 October 2005 / LTP workshop, Trento (Italy)
Heinzle, J.M.	Asymptotic Expansions and Nonlinear Stability of Power-law Inflation Models / 15 September 2005 / Isaac Newton Institute, Cambridge (UK)
Heinzle, J.M.	Equilibrium States in Stellar and Galactic Dynamics - A Dynamical Systems Perspective / 29 November 2005 / Isaac Newton Institute, Cambridge (UK)
Huisken, G.	Mean curvature flow for 2-convex surfaces / 7 January 2004 / Miami Waves, University of Miami (USA)
Huisken, G.	Classifying manifolds and hypersurfaces by geometric evolution equations / 19 February 2004 / Stelson Lecture 2004, Georgia Tech (USA)
Huisken, G.	Geometrical concepts in general relativity / 17 March 2004 / DPG conference in honour of A. Einstein, Ulm (Germany)
Huisken, G.	Mean curvature flow with surgeries of 2-convex hypersurfaces / 25 July 2004 / Conference on Geometric Evolution Equations, Banff (Canada)
Huisken, G.	The surgery construction for the Ricciflow / 2 May 2005 / Workshop on Ricciflow, Oberwolfach (Germany)
Huisken, G.	Surgery for Riccicflow and mean curvature flow / 30 May 2005 / Conference Nonlinear Evolution Equations, Oberwolfach (Germany)
Käppeli, J.	Black hole entropy and topological strings / 20 July 2004 / String theory conference, Ascona (Switzerland)
Kleinschmidt, A.	Kac-Moody Sigma Models / 19 October 2005 / Heraklion Crete, RTN workshop (Greece)
Krishnan, B.	Dynamical horizons and their properties / 23 July 2004 / GR-17, 17th international conference on general relativity and gravitation, Dublin (Ireland)
Lee, H.	The Einstein-Vlasov system with a scalar field / 19 July 2004 / 17th international conference on general relativity and gravitation (GR17), Dublin (Ireland)
Lee, H.	Vlasov equation in gravitational physics / 11 November 2004 / Workshop: Geometric PDEs and gravitation, Golm (Germany)
Lee, H.	Accelerated expanding models with Vlasov matter / 19 September 2005 / Workshop: Dynamical systems, Cambridge (UK)
Metzger, J.	The canonical neighbourhood assumption in Ricci flow / 4 May 2005 / Mini-Workshop: Aspects of Ricci-Flow, Oberwolfach (Germany)
Metzger, J.	Foliations of asymptotically flat 3-manifolds by 2-surfaces of prescribed mean curvature / 11 August 2005 / Workshop Differentialgeometrie im Großen, Oberwolfach (Germany)
Nicolai, H.	Cosmological Billiards / 17 March 2004 / DPG Frühjahrstagung in Ulm (Germany)
Nicolai, H.	Kaluza Klein supergravity on AdS3 x S3 / 5 April 2004 / Deserfest, 3-5 April 2004, University of Michigan, Ann Arbor (USA)
Nicolai, H.	Einsteins unerfüllter Traum / 13 June 2005 / Festkolloquium der Max-Planck-Gesellschaft zum Einstein-Jahr, Urania Berlin (Germany)

Nicolai, H.	Cosmological billiards and the search for a fundamental symmetry / 2 August 2004 / XXV Colloquium on Group Theoretical Methods in Physics, 2-6 August, Cocoyoc (Mexico)
Nicolai, H.	E10 via D9 / 24 August 2004 / 37th International Symposium Ahrenshoop (Germany)
Nicolai, H.	BKL dynamics and cosmological billiards / 17 September 2004 / International Workshop "Quantum Particles and Fields", Baku (Azerbaijan)
Nicolai, H.	Loops vs. strings: the elusive theory of quantum gravity / 20 September 2004 / Modern Problems of Theoretical and Mathematical Physics, Tbilisi, Georgia (USA)
Nicolai, H.	Some thoughts on N=8 supergravity / 28 May 2005 / Bernard-fest, De Bergse Bossen (Netherlands)
Nicolai, H.	Quantum Gravity / 11 July 2005 / EPS Conference, Bern (Switzerland)
Nicolai, H.	The E10 sigma model / 19 August 2005 / IV International Symposium QUANTUM THEORY AND SYMMETRIES, 15-21 August, Varna (Bulgaria)
Nicolai, H.	The E10 sigma model / 16 September 2005 / QG05, Cala Gonone, Sardinia (Italy)
Nicolai, H.	E10 and KE10: Prospects and Challenges / 2 December 2005 / XXIII Solvay Conference "The Quantum Structure of Space and Time", Brussels (Belgium)
Nicolai, H.	KE10 as a generalized holonomy group / 15 December 2005 / "Einsteins Legacy in the New Millenium", 15-22 December 2005, Toshali Sands, Puri (India)
Parameswaran, A.	Network Analysis Using Null-stream / 25 October 2005 / Annual Meeting of the ILIAS-Gravitational Wave Antenna, Universitat de les Illes Balears, Palma de Mallorca (Spain)
Peeters, K.	Black magic symmetries / 28 May 2005 / Bernard-fest
Peeters, K.	Loop Quantum Gravity: an outside view / 1 July 2005 / Third Crete regional meeting in string theory, Crete (Greece)
Plefka, J.	AdS/CFT in a non-BPS sector: Spinning Strings and Stringing Spins / 8 July 2004 / Lecture at the Post-String Meeting, University of Durham (UK)
Plefka, J.	The plane-wave string gauge theory duality / 14 September 2004 / "QCD and Strings" Workshop, Kavli Institute for Theoretical Physics, Santa Barbara (USA)
Rendall, A.D.	Asymptotics of solutions of the Einstein equations with positive cosmological constant / 5 January 2004 / Conference, Miami Waves, University of Miami (USA)
Rendall, A.D.	Mathematical properties of cosmological models with accelerated expansion / 4 March 2004 / Physikzentrum Bad Honnef (Germany)
Rendall, A.D.	Accelerated expansion in cosmology / 8 March 2004 / IHES, Bures sur Yvette (France)
Rendall, A.D.	Introduction to the Einstein equations / 9 July 2004 / HYKE conference, Vienna (Austria)
Rendall, A.D.	Solutions of the Einstein equations with accelerated expansion / 20 July 2005 / Conference, Asymptotic Analysis and Singularity, Senda (Japan)
Rendall, A.D.	Asymptotic expansions for cosmological solutions of the Einstein equations / 26 August 2005 / Isaac Newton Institute, Cambridge, (UK)
Ringström, H.	On the singularity in Gowdy / 5 January 2004 / Miami Waves 2004 (USA)
Ringström, H.	Strong cosmic censorship in T^3 Gowdy spacetimes / 23 July 2004 / 17th international conference on general relativity and gravitation (GR17), Dublin (Ireland)

Rüdiger, A.	Laser-Interferometric GW Detectors - GEO 600 and LISA / 13 February 2004 / Winter College on Interferometry and Applications in Modern Physics, Trieste (Italy)
Rüdiger, A.	AEI Measurements in One-Arm Locking / 19 February 2004 / Aspen Winter Conference on Gravitational Waves and their Detection, Aspen (USA)
Rüdiger, A.	Underground Detector Configurations: Simple, Sufficient, Redundant, Cheap / 17 January 2005 / Aspen Winter Conference on Gravitational Waves and their Detection, Aspen (USA)
Rüdiger, A.	LISA, the space-borne gravitational wave detector, requires the ultimate in Lasers, Clocks, and Drag-Free / 30 May 2005 / Conference on Lasers, Clocks, and Drag-Free, Bremen (Germany)
Schnabel, R.	Squeezed Light at Sideband Frequencies below 100 kHz / 17 February 2004 / The 2004 Aspen Winter Conference on Gravitational Waves and their Detection (USA)
Schnabel, R.	Squeezed Light for Gravitational Wave Interferometers / 3 April 2004 / CVQIP04 workshop on “Continuous variables quantum information processing”, Veilbronn (Germany)
Schnabel, R.	Experimental Characterization of Frequency Dependent Squeezed Light / 18 January 2005 / The 2005 Aspen Winter Conference on Gravitational Waves and their Detection (USA)
Schnabel, R.	Low-loss Grating for Coupling to a High-Finesse Cavity / 21 January 2005 / The 2005 Aspen Winter Conference on Gravitational Waves and their Detection (USA)
Schnabel, R.	Generation and Interferometric Applications of Squeezed Light / 12 April 2005 / ESF Exploratory Workshop on “Long-distance quantum communication networks with atoms and light”, Prag (Czech Republic)
Schnetter, E.	Mesh Refinement / 20 March 2004 / Boca Raton, Florida, Conference “Evolutions in Numerical Relativity” (USA)
Schnetter, E.	Mesh Refinement with Carpet / 30 April 2004 / Cactus Retreat, Baton Rouge (USA)
Schutz, B.F.	Hermes - An Effective Converter from TeX into MathML / 27 April 2004 / University of Minnesota (USA)
Schutz, B.F.	Gravitational wave astronomy facilities / 18 May 2004 / Cosmic Visions, Berlin (Germany)
Schutz, B.F.	The Art and Science of Black Hole Mergers / 24 June 2004 / Growing Black Holes Symposium
Schutz, B.F.	General Relativity Aspects of LISA / 12 July 2004 / LISA Symposium
Schutz, B.F.	Astrophysics and Physics Goals of LISA / 19 July 2004 / 17th international conference on general relativity and gravitation (GR17), Dublin (Ireland)
Schutz, B.F.	The Gravitational Wave Universe / 8 September 2004 / Mexico City (Mexico)
Schutz, B.F.	Potsdam als Wissenschaftsstandort / 30 September 2004 / Altes Rathaus Potsdam (Germany)
Schutz, B.F.	Gravitational Waves / 5 March 2005 / Tagung der Deutschen Physikalischen Gesellschaft, Berlin (Germany)
Schutz, B.F.	General Relativity as physics - evolution of a conceptual framework for relativistic gravity / 12 March 2005 / HGR7 (Seventh International Conference on the History of General Relativity), La Orotava, Tenerife (Spain)
Schutz, B.F.	The inevitability of gravitational waves / 29 March 2005 / Conference “Spacetime in Action”, University of Pavia (Italy)
Schutz, B.F.	LISA and low-frequency gravitational waves / 10 April 2005 / Conference “Physics - a century after Einstein”, University of Warwick (UK)
Schutz, B.F.	Building a Global Gravitational Wave Network: The Next Chapter in Einstein’s Legacy / 1 July 2005 / Yukawa International Seminar, Kyoto University (Japan)

Schutz, B.F.	Gravitational Wave Astronomy / 12 July 2005 / EPS13: Beyond Einstein, Physics for the 21st Century, EPS Einstein Centennial, Bern (Switzerland)
Schutz, B.F.	Einstein´s Unfinished Business / 23 September 2005 / Academia Europaea 2005, Potsdam (Germany)
Schutz, B.F.	Probing Strong Field General Relativity near Black Holes / 7 December 2005/ CERN Colloquium, Geneva (Switzerland)
Staudacher, M.	Integrability in N=4 Gauge Theory, Matrix Models, and Rotating Superstrings / 6 January 2004 / Workshop on large N limits of U(N) gauge theory in physics and mathematics, Far Hills Inn, Quebec (Canada)
Thiemann, T.	The Master Constraint Programme for LQG / 23 January 2004 / UNAM, Mexico City (Mexico)
Thiemann, T.	Workshop on Loop Quantum Gravity / February 2004 /Mexico City (Mexico)
Thiemann, T.	Quantum Dynamics of LQG / 7 May 2004 / CPT Marseille (France)
Thiemann, T.	Quantum Gravity in the Americas / 29 – 31 October 2004 / Workshop at Perimeter Institute, Waterloo (Canada)
Thiemann, T.	Loops 05 / 10 – 14 October 2005 / Potsdam (Germany)
Vanhove, P.j.	Pure Spinors and M-theory / 11 April 2005 / Lebedev Institute, Moscou (Russia)
Willke, B.	Status of GEO600 / 17 February 2004 / Aspen Winter Conference on Gravitational Waves and their Detection, Aspen (USA)
Willke, B.	Lasers for Advanced Interferometers / 18 February 2004 / Aspen Winter Conference on Gravitational Waves and their Detection, Aspen (USA)
Willke, B.	The GEO600 gravitational wave detector / 22 May 2005 / CLEO/QELS, Baltimore (USA)
Willke, B.	The GEO-HF Project / 24 June 2005 / 6th Edoardo Amaldi Conference on Gravitational Waves, Okinawa (Japan)
Willke, B.	Status of GEO / 21 September 2005 / ESF PESC Exploratory Workshop "Toward a 3rd generation European Gravitational Wave Observatory", Perugia (Italy)
Willke, B.	High Power Lasers / 22 September 2005 / ESF PESC Exploratory Workshop "Toward a 3rd generation European Gravitational Wave Observatory", Perugia (Italy)

Lectures and Lecture Series Given by AEI Members

Aufmuth, P.	Gravitationswellen – Theorie, Quellen, Nachweis / 6 March 2004 / Studentische Meteorologen Tagung, Vortreffen, Universität Hannover (Germany)
Aufmuth, P.	GEO600 – das deutsch-britische Gravitationswellen-Observatorium / 6 December 2004 / Physikalisches Kolloquium, Friedrich-Alexander-Universität Erlangen-Nürnberg (Germany)
Aufmuth, P.	Ohren ins All: Gravitationswellendetektoren / 20 January 2005 / Studium Integrale, Universität Kaiserslautern (Germany)
Aufmuth, P.	Laserinterferometer zur Detektion von Gravitationswellen / 26 January 2005 / Laser-Tag, Universität Rostock (Germany)
Aufmuth, P.	Das Universum hören: Gravitationswellendetektoren auf der Erde und im Weltraum / 25 February 2005 / WE-Heraeus Lehrerfortbildung “100 Jahre Einstein: vom Quant zum Kosmos”, Potsdam (Germany)
Aufmuth, P.	Krumme Räume, klingende Sterne – von Gauss zu Einstein / 24 May 2005 / Ringvorlesung, Universität Göttingen (Germany)
Aufmuth, P.	Gravitationswellen - Theorie, Quellen, Detektion / 16 June 2005 / DPG-Lehrerfortbildung “Spezielle und Allgemeine Relativitätstheorie”, Bad Honnef (Germany)
Aufmuth, P.	Detektion von Gravitationswellen / 28 June 2005 / Bildungswerk der Niedersächsischen Wirtschaft, Ruthe (Germany)
Aufmuth, P.	Einführung in den Studiengang Physik / 20 July 2005 / Sommeruniversität, VHS Schaumburg, Rinteln (Germany)
Aufmuth, P.	Angewandte Relativitätstheorie: Gravitationswellenforschung / 20 July 2005 / Sommeruniversität, VHS Schaumburg, Rinteln (Germany)
Aufmuth, P.	Einsteins Traum: Nachweis von Gravitationswellen / 23 November 2005 / “Abenteuer der Erkenntnis - Albert Einstein und die Physik des 20. Jahrhunderts” Akademie Dillingen, Deutsches Museum München (Germany)
Bojowald, M.	Quantum Geometry II / 23 November 2004 / 6th Mexican School on Gravitation and Mathematical Physics: Approaches to Quantum Gravity (Mexico)
Bojowald, M.	Loop Quantum Cosmology I / 22 April 2005 / Mitteldeutsche Physik-Combo, Jena (Germany)
Bojowald, M.	Loop Quantum Cosmology II / 17 June 2005 / Physik-Combo, Leipzig (Germany)
Bojowald, M.	Effective Loop Quantum Cosmology / 28 December 2005 / Raychaudhuri School on Cosmology and the Early Universe, IUCAA, Pune (India)
Cutler, C.	Neutron Stars and Gravitational Waves / 20 September 2004 / Golm (Germany)
Cutler, C.	Introduction to the Post-Newtonian Approximation / 25 September 2004 / Golm, (Germany)
Dain, S.	Elliptic boundary value problems I / 22 September 2004 / School on ``Structure and dynamics of compact objects, SFB/TR7 “Gravitational Wave Astronomy”, Golm (Germany)
Dain, S.	Elliptic boundary value problems II / 22 September 2004 /School on “Structure and dynamics of compact objects”, SFB/TR7 “Gravitational Wave Astronomy”,Golm (Germany)
Danzmann, K.	Physik für Studierende des Maschinenbaus / Wintersemester 2003/04 / Universität Hannover (Germany)
Danzmann, K.	Laserinterferometrie und Gravitationswellendetektoren / Sommersemester 2004 / Universität Hannover (Germany)
Danzmann, K.	Physik I (mit Experimenten) / Wintersemester 2004/05 / Universität Hannover (Germany)
Danzmann, K.	Physik II (mit Experimenten) / Sommersemester 2005 / Universität Hannover (Germany)

Danzmann, K.	Physik I (mit Experimenten) / Wintersemester 2005/06 / Universität Hannover (Germany)
Danzmann, K.	Gravitationswellenastronomie / 5 March 2004 / Perspektivenkommission der MPG, Berlin (Germany)
Danzmann, K.	Laserinterferometrie auf der Erde und im Weltraum (Plenarvortrag) / 16 March 2004 / Jahresversammlung des VDE, Ludwigsburg (Germany)
Danzmann, K.	Vom 3m-Prototyp zu LISA mit 5 Mio. km Armen / 22 April 2004 / Kolloquium zum 90. Geburtstag von Klaus Billing, Garching (Germany)
Danzmann, K.	Astronomie mit Gravitationswellen / 14 May 2004 / Perspektivenkommission der MPG, Berlin (Germany)
Danzmann, K.	Gravitational Wave Detection from Space / 25 May 2004 / Kolloquium im Deutschen Zentrum für Luft- und Raumfahrt (DLR), Köln (Germany)
Danzmann, K.	Einsteins Gravitationswellen / 19 November 2004 / Senatssitzung der MPG, München (Germany)
Danzmann, K.	Gravitationswellenastronomie / 29 November 2004 / Kolloquium der Universität Wuppertal (Germany)
Danzmann, K.	Gravitationswellendetektoren auf der Erde und im Weltraum / 14 March 2005 / Kolloquium der Universität Wien (Austria)
Danzmann, K.	LTP on LISA Pathfinder: AEI Activities / 6 June 2005 / Lisa Pathfinder Science Team Meeting 2, ESTEC Nordwijk (The Netherlands)
Danzmann, K.	An introduction to LISA / 14 June 2005 / LISA Optical Read-out Meeting, Hannover (Germany)
Danzmann, K.	Gravitationswellenastronomie / 27 June 2005 / Physikalisches Kolloquium, Universität Erlangen (Germany)
Danzmann, K.	Forschung am AEI / 5 July 2005 / Sennheiser Kolloquium, Hannover (Germany)
Danzmann, K.	LISA Interferometry Issues / 11 September 2005 / Goddard Space Flight Center, Washington (USA)
Danzmann, K.	Science with LISA and LISA Pathfinder / 11 October 2005 / University of Trento (Italy)
Danzmann, K.	Gravitationswellenforschung in Deutschland / 5 November 2005 / DFG Bonn (Germany)
Danzmann, K.	Gravitational wave astronomy: The large detectors are going into operation! / 7 November 2005 / The London Mathematical Society, Cambridge (UK)
Danzmann, K.	The future of gravitational wave astronomy / 24 November 2005 / Max-Planck-Institut für Physik, München (Germany)
Danzmann, K.	LISA Interferometry / 7 December 2005 / Goddard Space Flight Center, Washington (USA)
Ehlers, J.	Equations of Motion in General Relativity / 20 February 2004 / PennState University (USA)
Ehlers, J.	The Newtonian Limit of General Relativity / 23 February 2004 / PennState University (USA)
Ehlers, J.	Grundbegriffe der Relativitätstheorie / 1 – 5 March 2004 / AEI - Ferienkurs in Gravitationsphysik 2004, Golm (Germany)
Ehlers, J.	Foundations of special relativity / 13 February 2005 / 339th WE Heraeus Seminar: Special Relativity: Will it survive the next 100 years?, Potsdam (Germany)
Ehlers, J.	Grundlagen der Allgemeinen Relativitätstheorie Teil I / 21 February 2005 / WE-Heraeus Lehrerfortbildung “100 Jahre Einstein: vom Quant zum Kosmos”, Potsdam (Germany)
Ehlers, J.	Grundlagen der Allgemeinen Relativitätstheorie Teil II / 22 February 2005 / WE-Heraeus Lehrerfortbildung “100 Jahre Einstein: vom Quant zum Kosmos”, Potsdam (Germany)

Ehlers, J.	Grundbegriffe der Relativitätstheorie / 14 – 18 March 2005 / AEI - Ferienkurs in Gravitationsphysik 2005, Golm (Germany)
Ehlers, J.	Kinetic Theory for Photons and Kosmology / 11 May 2005 / University of Rome (Italy)
Ehlers, J.	Shock Waves in General Relativity / 18 May 2005 / University of Rome (Italy)
Ehlers, J.	The Problem of Motion in General Relativity / 25 May 2005 / University of Rome (Italy)
Ehlers, J.	Kosmologie: Aufbau und Entwicklung der Welt im Großen / 17 June 2005 / DPG-Lehrerfortbildung "Spezielle und Allgemeine Relativitätstheorie", Bad Honnef (Germany)
Ehlers, J.	Einstein und die Allgemeine Relativitätstheorie / 6 July 2005 / Ringvorlesung Universität Essen (Germany)
Ehlers, J.	Einführung in die Allgemeine Relativitätstheorie (3 Vorlesungen) / 6 – 8 October 2005 / Doktorandenschule der Universität Bamberg (Germany)
Fischbacher, T.	Introduction to Linux / 28 May 2004 / CdE Whitsun Convention 2004
Fischbacher, T.	Linux für Fortgeschrittene / 29 May 2004 / CdE-Pfingstakademie 2004
Fischbacher, T.	Introduction to Group Theory / 7 August 2004 / CdE Summer convention 2004
Friedrich, H.	Gravitational radiation and the asymptotic behaviour of space-time / 6 April 2004 / Morningside Center of Mathematics, Chinese Academy of Sciences, Beijing (China)
Friedrich, H.	Die Einsteinschen Feldgleichungen I / 21 April 2004 / Universitaet Potsdam (Germany)
Friedrich, H.	Die Einsteinschen Feldgleichungen II / 20 October 2004 / Universität Potsdam (Germany)
Grote, H.	The status of GEO600 / 25 February 2004 / TAMA Seminar at NAO, Tokyo (Japan)
Grote, H.	GEO600: Where Are We? / 26 October 2004 / LIGO Seminar at Caltech, Pasadena (USA)
Huisken, G.	Variationsprobleme in Geometrie und Physik / 1 – 8 March 2004 / AEI - Ferienkurs in Gravitationsphysik 2004, Golm (Germany)
Kleinschmidt, A.	Introduction to Strings and D-branes / 03 June 2005 / IMPRS Seminar Chorin
Lück, H.	Gravitationswellenmessungen mit GEO600 / 27 April 2005 / Ringvorlesung, Christian Albrechts Universität, Kiel (Germany)
Malec, M.	Simulationen zu fortgeschrittenen Gravitationswellendetektoren / 16 December 2004 / Seminar der theoretischen Astrophysik, Universität Tübingen (Germany)
Nicolai, H.	Kaluza Klein Supergravity on AdS3 x S3 / 9 February 2004 / Institut für Physik, Humboldt Universität zu Berlin (Germany)
Nicolai, H.	Introduction to strings and membranes (6 lectures) / 7 June 2004 / C.M.S. Summer School on Mathematical Physics, Hangzhou (China)
Nicolai, H.	Punkte, Saiten und Membranen - auf dem Wege zur Vereinheitlichung der Physik? / 24 February 2005 / WE-Heraeus Lehrerfortbildung "100 Jahre Einstein: vom Quant zum Kosmos", Potsdam (Germany)
Nicolai, H.	Supermembranen / 19 April 2005 / FU Berlin, FB Mathematik (Germany)
Parameswaran, A.	New class of post-Newtonian approximants to the waveform templates of inspiralling compact binaries / 19 January 2005 / Raman Research Institue, Bangalore (India)
Peeters, K.	The AdS/CFT correspondence: plane waves and beyond / 30 August 2004 / III International Summer School in Modern Mathematical Physics, Zlatibor (Serbia)

Plefka, J.	Introduction to Supersymmetry and Supergravity / 27 September 2004 – 1 October 2004 / Stringsteilkurs I Golm (Germany)
Prix, R.	Einführung in die Physik der Neutronensterne/ 14 March 2005 / AEI - Ferienkurs in Gravitationsphysik 2005, Golm (Germany)
Rendall, A.D.	Mathematische Biologie / 13 April 2004 / TU Berlin (Germany)
Rendall, A.D.	Einführung in die Allgemeine Relativitätstheorie / 12 April 2005 / FU Berlin (Germany)
Ribichini, L.	The seismic isolation chain of the Hannover thermal noise experiment / 13 January 2004 / University of Camerino (Italy)
Runkel, I.	Introduction to Conformal Field Theory / 27 September 2004 – 1 October 2004 / Stringsteilkurs I Golm (Germany)
Schmidt, B.	Grundbegriffe der Relativitätstheorie / 8 – 12 March 2004 / AEI - Ferienkurs in Gravitationsphysik 2004, Golm (Germany)
Schnabel, R.	Non-Classical Light / Wintersemester 2003/04 / Universität Hannover (Germany)
Schnabel, R.	Nonclassical Interferometry / Sommersemester 2004 / Universität Hannover (Germany)
Schnabel, R.	Non-Classical Light / Wintersemester 2004/05 / Universität Hannover (Germany)
Schnabel, R.	Nonclassical Interferometry / Sommersemester 2005 / Universität Hannover (Germany)
Schnabel, R.	Nicht-klassisches Licht / Wintersemester 2004/05 / Universität Hannover (Germany)
Schnetter, E.	An Introduction to Mesh Refinement with Carpet / 28 April 2004 / Cactus Retreat, Baton Rouge (USA)
Schnetter, E.	Cactus from a Physicists Point of View / 29 June 2005 /Tübingen (Germany)
Schutz, B.F.	Gravitational waves: sources and physics / 28 January 2004 / Cardiff University (UK)
Schutz, B.F.	Astrophysical Relativity at the AEI / 12 March 2004 / AEI Ferienkurs 2004 Golm (Germany)
Theisen, S.	Introduction to String Theory / 27 September 2004 – 1 October 2004 / Stringsteilkurs I Golm (Germany)
Theisen, S.	Advanced Topics in String Theory / 26 – 30 September 2005/ Stringsteilkurs II Golm (Germany)
Thiemann, T.	The LQG String: Loop Quantum Gravity Quantization of String Theory / 12 February 2004 / Perimeter Institute for Theoretical Physics Ontario (Canada)
Thiemann, T.	Introduction to Loop Quantum Gravity / November 2004 / McGill University, Montreal (Canada)
Thiemann, T.	Mathematical Physics of Loop Quantum Gravity / April 2005 / Bejing Normal University, Bejing (China)
Thiemann, T.	Physik jenseits des Standardmodells / November 2005 / "Abenteuer der Erkenntnis - Albert Einstein und die Physik des 20. Jahrhunderts" Akademie Dillingen, Deutsches Museum München (Germany)
Winkler, W.	Der Nachweis von Gravitationswellen – eine Herausforderung / 7 September 2004 / Graduiertenkolleg, Universität Aachen (Germany)
Winkler, W.	Experimente zum Nachweis von Gravitationswellen / 17 December 2004 / Graduiertenkolleg Basel/Tübingen (Germany)

Popular Talks Given by AEI Members

Aufmuth, P.	Gravitationswellen: Der Klang des Universums / 25 May 2004 / Schülervorlesung “Einstein und der Kosmos”, Physikalischer Verein, Frankfurt (Germany)
Aufmuth, P.	GEO600 & LISA: Das MPI für Gravitationsphysik auf Einsteins Spuren / 16 June 2004 / Sitzung des Gesamtbetriebsrats der MPG, Lüneburg (Germany)
Aufmuth, P.	Einsteins Traum: Nachweis von Gravitationswellen / 5 November 2004 / Tag der Wissenschaften, Marie-Curie-Gymnasium, Wittenberge (Germany)
Aufmuth, P.	Gravitationswellen: Der Klang des Universums / 5 February 2005 / Physik am Samstagvormittag, Universität Bayreuth (Germany)
Aufmuth, P.	GEO600 - Auf der Suche nach Gravitationswellen / 14 April 2005 / Gymnasium Andreanum, Hildesheim (Germany)
Aufmuth, P.	Gravitationswellen auf der Spur: GEO600 / 21 April 2005 / Tag der Offenen Tür, Universität Magdeburg (Germany)
Aufmuth, P.	Kosmische Klänge - Astronomie mit Gravitationswellen / 22 May 2005 / Planetarium Wien (Austria)
Aufmuth, P.	Die Welt als Formel / 28 May 2005 / Deutscher Evangelischer Kirchentag, Hannover (Germfany)
Aufmuth, P.	Einsteins Enkel in Hannover / 6 and 7 June 2005 / MS Einstein, Hannover (Germany)
Aufmuth, P.	Gespräch über Albert Einstein / 3 September 2005 / Galerie K9 aktuelle Kunst, Hannover (Germany)
Aufmuth, P.	Einsteins Wellen: Der dunklen Seite des Universums auf der Spur / 4 October 2005 / Albert-Einstein-Schule, Laatzen (Germany)
Aufmuth, P.	Auf Einsteins Spuren: Die Suche nach Gravitationswellen / 21 October 2005 / Naturwissenschaftlicher Verein zu Zweibrücken (Germany)
Aufmuth, P.	Das Universum hören: Die großen Gravitationswellendetektoren sind in Betrieb / 25 October 2005 / Deutsches Museum Bonn (Germany)
Aufmuth, P.	Astronomie mit Gravitationswellen / 26 October 2005 / Wilhelm-Foerster-Sternwarte, Berlin (Germany)
Aufmuth, P.	Einsteins Wellen: Klänge aus dem Universum / 26 November 2005 / Volkshochschule Hameln (Germany)
Aufmuth, P.	Gravitationswellen: Der Klang des Universums / 30 November 2005 / DESY Hamburg (Germany)
Aufmuth, P.	Astronomie mit Gravitationswellen / 15 December 2005 / Volkssternwarte Bonn (Germany)
Aufmuth, P.	Experimentelle Gravitationsphysik in Hannover / 20 December 2005 / Begleitveranstaltung zur Weihnachtsvorlesung, Hannover (Germany)
Beyer, F.	Raum, Zeit und der ganze Rest / 26 October 2004 / Schwarzheide, Emil-Fischer-Gymnasium (Germany)
Bojowald, M.	Einsteins Werk und Vorstellungen zum Ursprung des Universums / 28 September 2005 / Astronomische Vereinigung Weikersheim / Volkshochschule Bad Mergentheim (Germany)
Danzmann, K.	Gravitationswellen, Wurmlöcher und Zeitreisen / 19 January 2004 / Geschwister-Scholl-Gymnasium, Garbsen (Germany)
Danzmann, K.	Einstein und die Schwerkraft / 16 September 2004 / Wissenschaft im Rathaus, Dresden (Germany)
Danzmann, K.	Gravitationswellen und der Klang des Universums / 4 November 2004 / Wissenschaftstage Aurich (Germany)
Danzmann, K.	Einstein im täglichen Leben / 4 November 2004 / Öffentlicher Abendvortrag, Aurich (Germany)

Danzmann, K.	Einstein in our daily life / 2 February 2005 / Public Outreach Meeting of the Australien Physical Society, Canberra (Australia)
Danzmann, K.	Auf der Suche nach Einsteins Gravitationswellen / 5 June 2005 / Sennheiser Kolloquium, Hannover (Germany)
Danzmann, K.	Einsteins Relativitätstheorie heute / 11 June 2005 / Physik für Aufgeweckte, Universität Hannover (Germany)
Danzmann, K.	Der Klang des Universums – auf der Suche nach Einsteins Gravitationswellen / 22 June 2005 / Jahresversammlung der Max-Planck-Gesellschaft, Universität Rostock (Germany)
Danzmann, K.	Einstein heute / 24 August 2005 / Berlin-Brandenburgische Akademie der Wissenschaften, Berlin (Germany)
Danzmann, K.	Gravitationswellenastronomie / 6 October 2005 / Deutsches Museum, München (Germany)
Danzmann, K.	Der Klang des Universums / 25 November 2005 / Akademie, Düsseldorf (Germany)
Ehlers, J.	Einstein und der physikalische Zeitbegriff / 22 January 2004 / Stadthaus Ulm (Germany)
Ehlers, J.	Der physikalische Zeitbegriff / 24 April 2004 / Universität Hannover (Germany)
Ehlers, J.	Die Zeit in Physik und Astronomie/ 11 June 2004 / Urania Berlin (Germany)
Ehlers, J.	Der Zeitbegriff in der Physik / 26 June 2004 / Vortrag anlässlich eines Seminars des Cusanus-Werks der katholischen Begabtenförderung, Bautzen (Germany)
Ehlers, J.	Schwerkraft und Weltall / 1 October 2004 / Gymnasium Eichwalde (Germany)
Ehlers, J.	Einstein und der Zeitbegriff / 29 October 2004 / 50jähriges Schuljubiläum des Einstein-Gymnasiums Berlin (Germany)
Ehlers, J.	Allgemeine Relativitätstheorie / 10 November 2004 / Urania Graz (Austria)
Ehlers, J.	$E = mc^2$: Ein wissenschaftlicher Paukenschlag / 24 November 2004 / Universität Wien (Austria)
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Ehlers, J.	Einstein und der Zeitbegriff / 18 April 2005 / Ignaz-Gunther-Gymnasium Rosenheim (Germany)
Ehlers, J.	1905 – Einsteins Wunderjahr – ein Gründungsjahr der modernen Physik / 21 April 2005 / Forum Astronomie Bonn (Germany)
Ehlers, J.	Einstein und die Kosmologie / 27 April 2005 / Wilhelm-Foerster-Sternwarte Berlin (Germany)
Ehlers, J.	Einstein, die Schwerkraft und das Weltall / 2 May 2005 / Gymnasium Bruchsal (Germany)
Ehlers, J.	Einsteins Kosmos: Wie sich Einsteins Ideen auf die moderne Kosmologie auswirken / 19 June 2005 / Sonntagsvorlesung, Telegraphenberg Potsdam (Germany)
Ehlers, J.	Zeit und Raum in Einsteins Relativitätstheorie / 27 June 2005 / Universität Hohenheim (Germany)
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Ehlers, J.	Einsteins Wunderjahr 1905 / 27 September 2005 / Tag der Offenen Türen, Wissenschaftspark Golm (Germany)
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Ehlers, J.	Theorie und Experiment in Einsteins Denken / 9 September 2005 / Urania Berlin (Germany)

Ehlers, J.	Einsteins Wunderjahr 1905 / 12 October 2005 / Fachhochschule Kaiserslautern, Zweibrücken (Germany)
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Ehlers, J.	Der relativistische Kosmos. Was Astrophysiker aus Einsteins Ideen gemacht haben. / 18 November 2005 / Öffentlicher Vortrag im Rahmen der Konferenz “Einstein’s Legacy”, Bayerische Akademie der Wissenschaften, München (Germany)
Ehlers, J.	Allgemeine Relativitätstheorie / 16 November 2005 / Österreichische Urania, Graz (Austria)
Ehlers, J.	Die wissenschaftlichen Errungenschaften Einsteins / 13 December 2005 / Universität Jena (Germany)
Fischbacher, T.	Kosmologie heute / 29 May 2004 / CdE-Pfingstakademie 2004
Heinzle, J.M.	Gravitational Physics Research at the AEI / 24 June 2005 / Nobel Laureates Meeting, University of Potsdam (Germany)
Huisken, G.	Geometry and Gravitation / 23 March 2004 / Urania Berlin (Germany)
Huisken, G.	Optimale Geometrien und die Allgemeine Relativitätstheorie / 21 November 2005 / Albert-Ludwigs-Universität Freiburg / Studium generale (Germany)
Huisken, G.	Deformations of space and time / 18 April 2005 / Public lecture, Urania Berlin (Germany)
Käppeli, J.	Leben und Tod von Schrödingers Katze / 19 June 2004 / Wissenschaftspark Golm (Germany)
Käppeli, J.	Leben und Tod von Schrödingers Katze - Eine Einführung in die Quantentheorie / 24 June 2004 / Königin-Katharina-Stift Gymnasium, Stuttgart (Germany)
Nicolai, H.	Die vereinheitlichte Theorie - heiliger Gral oder Ende der Physik? / 30 January 2004 / URANIA, Berlin (Germany)
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Nicolai, H.	Einsteins Wunderjahr 1905 / 30 March 2005 / Rotary Club Potsdam (Germany)
Nicolai, H.	Einsteins unerfüllter Traum - die vereinheitlichte Theorie / 29 August 2005 / Sitzung des AEI Kuratoriums, Magnushaus, Berlin (Germany)
Nicolai, H.	Einsteins dream - searching for a unified theory / 30 August 2005 / Veranstaltung für Preisträger “Jugend forscht”, BMBF, Berlin (Germany)
Nicolai, H.	Einsteins Universum - vom Urknall bis heute / 19 October 2005 / Heimatverein Werder (Germany)
Nicolai, H.	Raum - Zeit - Materie: was wissen wir von der Enstehung und Geschichte unseres Universums? / 27 October 2005 / Luxemburg Science Festival 2005 (Luxembourg)
Nicolai, H.	La teoria unificada - un sueno no realizado de Einstein / 16 November 2005 / Universidad Simon Bolivar & Universidad Central, Caracas (Venezuela)
Schnabel, R.S.	Auf der Suche nach Einsteins Gravitationswellen / 19 November 2005 / Technische Universität Ilmenau (Germany)
Schneemann, C.	Einstein für Einsteiger / 30 June 2005 / Deutsche Schülerakademie Rostock (Germany)
Schutz, B.F.	Gravitationswellen - Einsteins neues Fenster ins Universum / 10 February 2004 / University of Bremen (Germany)

Schutz, B.F.	What is Gravity? / 28 June 2004 / John F. Kennedy Schule Berlin (Germany)
Schutz, B.F.	Einstein und die Beschleunigung des Universums / 18 February 2005 / Urania Berlin (Germany)
Schutz, B.F.	Gravitationswellen: Einsteins neues Fenster ins Universum / 27 April 2005 / Einstein Lectures, Österreichische Akademie der Wissenschaften, Wien (Austria)
Skorupka, S.	Gravitationswellenastronomie, ein neues Fenster ins All / 1 April 2004 / 25 Jahre Mensa, Hannover (Germany)
Skorupka, S.	Dem Echo des Urknalls lauschen: Neue Astronomie mit Gravitationswellen / 27 September 2004 / Automobilforum Berlin (Germany)
Skorupka, S.	Dem Echo des Urknalls lauschen: Neue Astronomie mit Gravitationswellen / 16 February 2005 / Abendgymnasium Hannover (Germany)
Skorupka, S.	Dem Echo des Urknalls lauschen: Neue Astronomie mit Gravitationswellen / 6 April 2005 / Schillerschule Hannover (Germany)
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Skorupka, S.	Dem Echo des Urknalls lauschen: Neue Astronomie mit Gravitationswellen / 24 June 2005 / Felix-Fechenbach-Berufskolleg, Detmold (Germany)
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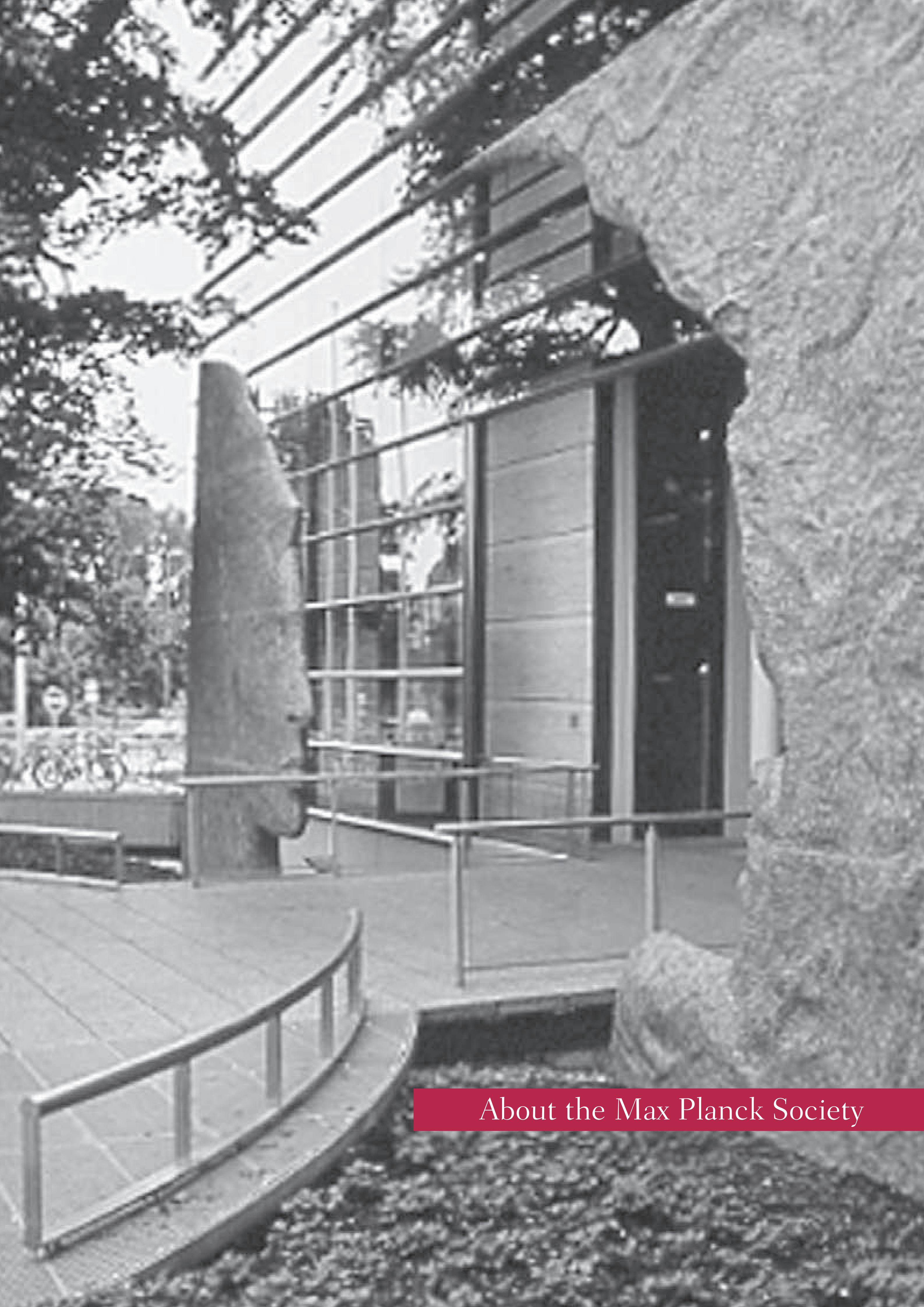
Guided Tours at GEO600

Aufmuth, P., Grote, H., Hild, S., Lück, H., Willke, B.	GEO600. The British-German gravitational wave detector Introductory talk and guided tour 13 January 2004 / 23 January 2004 / 29 January 2004 / 23 February 2004 / 6 March 2004 / 9 March 2004 / 24 March 2004 / 25 March 2004 / 5 May 2004 / 2 June 2004 / 14 June 2004 / 19 June 2004 / 25 June 2004 / 6 July 2004 / 12 August 2004 / 27 August 2004 / 3 September 2004 / 7 September 2004 / 7 October 2004 / 29 October 2004 / 5 November 2004 / 23 November 2004 / 3 December 2004 / 7 December 2004 / 20 December 2004 / 8 January 2005 / 13 January 2005 / 24 January 2005 / 27 January 2005 / 15 February 2005 / 16 February 2005 / 12 April 2005 / 18 April 2005 / 17 May 2005 / 18 May 2005 / 27 May 2005 / 9 June 2005 / 28 June 2005 / 29 June 2005 / 5 July 2005 / 7 July 2005 / 15 July 2005 / 26 July 2005 / 10 August 2005 / 23 August 2005 / 24 August 2005 / 13 October 2005 / 14 October 2005 / 17 October 2005 / 8 December 2005



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Address:
Max-Planck-Gesellschaft zur Förderung der Wissenschaften e.V.
Postbox 10 10 62
80084 Munich, Germany
Phone +49-89-2108-0
Fax +49-89-2108-1111

www.mpg.de

Contacts

AEI Potsdam

Office:
Christine Gottschalkson
phone: (0331) 567-7214
fax: (0331) 567-7297
office@aei.mpg.de

Library:
Elisabeth Schlenk
phone: (0331) 567-7400
fax: (0331) 567-7499
library@aei.mpg.de

Computer Systems:
Christa Hausmann-Jamin
phone: (0331) 567-7204
fax: (0331) 567-7298
christa.hausmann-jamin@aei.mpg.de

Administration:
Christiane Roos
phone: (0331) 567-7600
fax: (0331) 567-7699
christiane.roos@aei.mpg.de

Public Relations:
Dr. Elke Müller
phone: (0331) 567-7303
fax: (0331) 567-7298
elke.mueller@aei.mpg.de

AEI Hannover

Office:
Kirsten Naceur
phone: (0511) 762-2229
fax: (0511) 762-2784

Sabine Rehmert
phone: (0511) 762-17164
fax: (0511) 762-5861
office-hannover@aei.mpg.de

Public Relations:
Dr. Peter Aufmuth
phone: (0511) 762-2386
fax: (0511) 762-2784
peter.aufmuth@aei.mpg.de

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By train:
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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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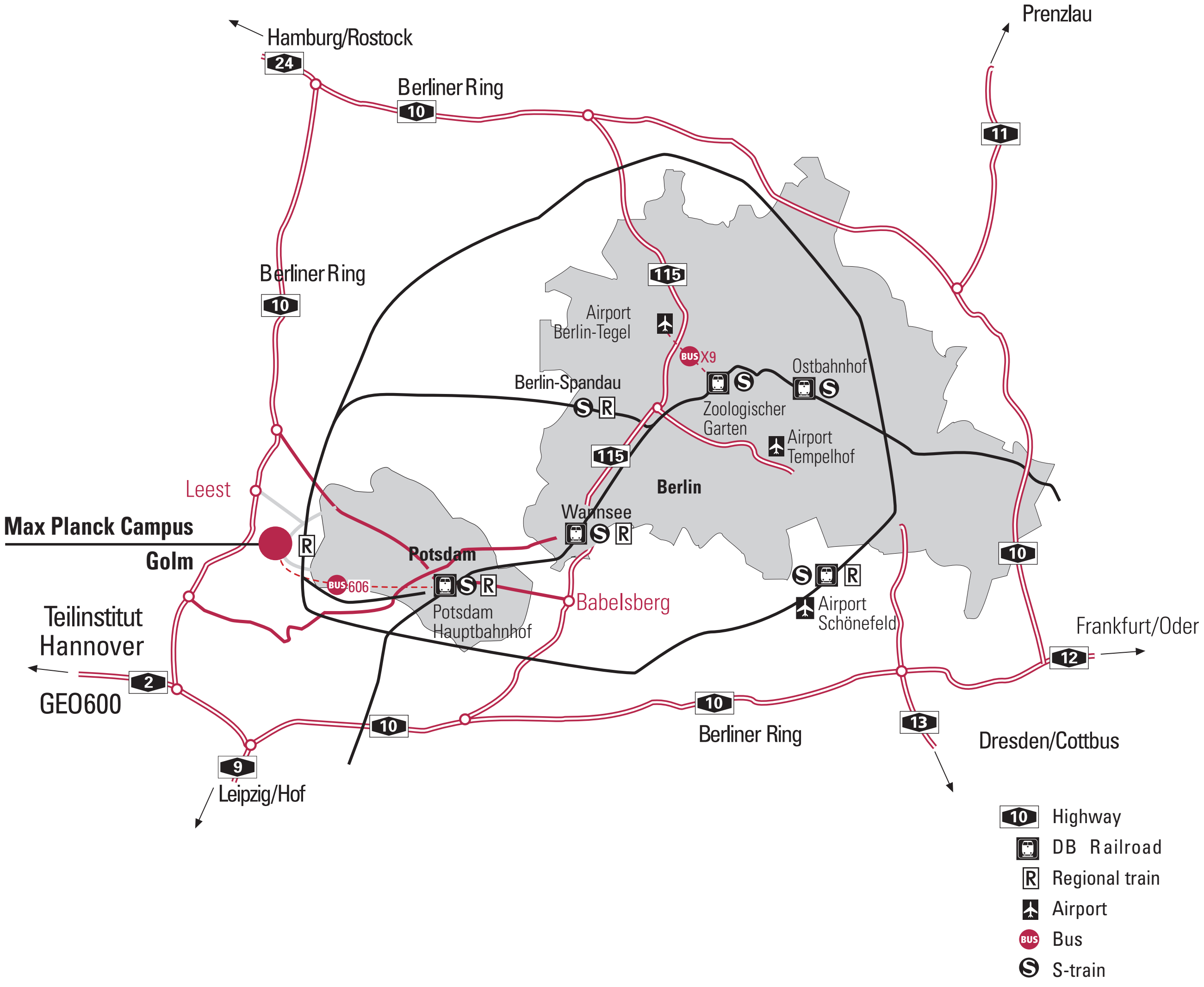

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Tegel: Bus X9 to train station “Zoologischer Garten”
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then take S-Bahn or Regionalbahn to train station “Potsdam Hauptbahnhof” and transfer to Regionalbahn RB 21 (direction Berlin-Spandau) leaving once every hour to Golm (+ 10 minutes walk) or take Bus 606 straight to the Max Planck Campus

By train:
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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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Callinstraße 38
30167 Hannover

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Dr. Elke Müller (AEI)
Susanne Milde, Sascha Rieger (Milde>Marketing Science Communication)

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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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