Max-Planck-Institut

für

Astrophysik

ANNUAL REPORT 2018

Contents

Chapter 1

General Information

1.1 A brief history of the MPA

The Max-Planck-Institut für Astrophysik, usually called MPA for short, was founded in 1958 under the directorship of Ludwig Biermann. It was established as an offshoot of the Max-Planck-Institut für Physik, which at that time had just moved from Göttingen to Munich. In 1979, as part of plans to move the headquarters of the European Southern Observatory from Geneva to Garching, Biermann's successor, Rudolf Kippenhahn, relocated the MPA to its current site. The MPA became fully independent in 1991. Kippenhahn retired shortly thereafter and this led to a period of uncertainty, which ended in 1994 with the appointment of Simon White as director. The subsequent appointments of Rashid Sunyaev (1995) and Wolfgang Hillebrandt (1997) as directors at the institute, together with adoption of new set of statutes in 1997, allowed the MPA to adopt a system of collegial leadership by a Board of Directors. The Managing Directorship rotates every three years, with Simon White in post in 2018.

In 2007 Martin Asplund arrived as a new director but, for personal reasons, decided to return to The Australian National University in 2011. He remains linked to the institute as external Scientific Member, joining the other external Scientific Members: Rolf Kudritzki and Werner Tscharnuter. Eiichiro Komatsu arrived in 2012 from the University of Texas to take up a directorship, bringing new impetus to the institute's research into the early universe and the growth of structure. The generational change in the directorate continued with the internal promotion of Guinevere Kauffmann in 2013 and the return in 2017 of former MPA Group Leader Volker Springel from a professorship at the University of Heidelberg. Their expertise assures the continuation of institute activity in Galaxy Evolution (Kauffmann) and Computational Astrophysics (Springel).

Finally, a search is currently underway for a new director, active in stellar astrophysics, planetary science or high-energy astrophysics. This new director would formally be the successor of Wolfgang Hillebrandt who retired in 2012, and her/his appointment will complete the renewal of the directorate following the retirements of Rashid Sunyaev (2017) and Simon White (2019). The MPA was originally founded as an institute for theoretical astrophysics, aiming to develop the theoretical concepts and numerical algorithms needed to study the structure and evolution of stars (including the Sun), the dynamics and chemistry of the interstellar medium, the interaction of hot, diluted plasmas with magnetic fields and energetic particles, and the calculation of transition probabilities and cross–sections for astrophysical processes in rarefied media. From its inception the institute has had an internationally-recognized numerical astrophysics program that was long unparalleled by any other institution of similar size.

Over the last 25 years, activities at the MPA have diversified considerably, however, and now address a much broader range of topics, including a variety of data analysis and even some observing projects, although there is still a major emphasis on theory and numerics. Resources are channeled into directions where new instrumental or computational capabilities are expected to lead to rapid developments. Active areas of current research include stellar evolution, stellar atmospheres, accretion phenomena, nuclear and particle astrophysics, supernova physics, astrophysical fluid dynamics, high-energy astrophysics, radiative processes, the structure, formation and evolution of galaxies, gravitational lensing, the large-scale structure of the Universe, the cosmic microwave background, and physical and early universe cosmology. Several previous research themes (solar system physics, the quantum chemistry of astrophysical molecules, general relativity and gravitational wave astronomy) have been substantially reduced since 1994.

Since 2001 the MPA has been part of the International Max-Planck Research School in Astrophysics, a joint initiative between the Max Planck Society and the Ludwig-Maximilians University of Munich. About 70 PhD students participate in the school at any given time, most of them at the MPE or the MPA. This has subtantially increased and internationalised the graduate student body at MPA and has resulted in productive social and professional links between MPA students and those at other local institutions. Currently about 25 students at MPA participate in the IMPRS.

MPA policy is effectively set by the Wissenschaftliche Institutsrat (WIR) which has met regularly about 5 times a year since 1995 to discuss all academic, social and administrative issues affecting the institute. This consists of all the permanent scientific staff and the Max-Planck Research Group leaders, as well as elected representatives of the postdocs, doctoral students and support staff. It acts as the main formal conduit for discussion and communication within the institute, advising the directorate on all substantive issues. Ad hoc subcommittees of the WIR carry out the annual postdoc and student hiring exercises, monitor student progress, oversee the running of the computer system, and, in recent years, have carried out the searches for new directions and directorial candidates.

Other aspects of the MPA's structure have historical origins. Its administrative staff have always been shared with the neighboring, but substantially larger MPI für extraterrestrische Physik (MPE) and, more recently, also with the Max Planck Computation and Data Facility (MPCDF). The library in the MPA building also serves the MPA and MPE jointly, while the MPE workshops, security and transportation departments also support the MPA. The MPA played an important role in founding the Max-Planck Society's computer centre in Garching (originally called the Rechenzentrum Garching, RZG, but now known as the MPCDF). MPA scientists have always had free access to the RZG/MPCDF and are among the top users of the high-end computational facilities there. The MPCDF now functions as an independent, cross-institutional competence centre of the Max Planck Society supporting computational and data sciences.

1.2 Current MPA facilities

Computational facilities

Theoretical and computational astrophysicists demand a perfect computing and networking infrastructure. Theoreticians, numerical simulators and data analysts all have different needs. To satisfy these, MPA has its own IT-group, overseen by a senior scientist who ensures efficient communication between the group and the institute's science community. In addition, a representative group of scientists forms the "Computer Executive Committee", which is responsible for long-term strategy and planning, and for balancing the requests of different user groups. The aim is to satisfy in-house needs both by providing extensive in-house computer power and by ensuring effective access to the supercomputers and the mass storage facilities at the Max Planck Computing and Data Facility (MPCDF), as well as at the nearby Leibniz Computer Centre of the state of Bavaria (the LRZ) and at other German supercomputer centres (e.g. in Stuttgart and Juelich).

MPCDF and MPA coordinate their activities and development plans through regular meetings to ensure continuity in the working environment experienced by the users. Scientists at MPA are also very successful obtaining additional supercomputing time, typically of the order of several millions of CPU-hours per project at various Tier-0 supercomputer centres both at national and at international level. The most important resources provided by the MPCDF are parallel supercomputers, PByte mass storage facilities (also for backups), and the gateway to the German high-speed network for science and education. MPA participates actively in discussions of major investments at the MPCDF, and has provided several benchmark codes for the evaluation of the next generation supercomputer options. In 2017 the decision was made by the Max-Planck-Society to replace the present supercomputer by one of the next generation during 2018/19.

MPCDF also hosts mid-range computers owned by MPA. Presently, two such Linux-clusters are located at MPCDF. The largest, Freya, has about 5000 processor cores, - supported by Pascal and Volta GPUs - together with almost 25TB of core memory and Petabyte disk storage capacity. Freya is used for production using moderately parallel codes. In addition, MPA operates a core node of the Virgo (the "Virgo supercomputer consortium") data center at the MPCDF. The node hosts the full results from all important Virgo simulations (e.g. Millennium XXL, Eagle) and provides web access to the world-wide community via the Millenium database. This system consists of 4 PB disk storage and a fat-node server with 48 cores and 1 TB RAM for data access and memory-intensive parallel data analysis.

MPA's computer system guarantees that every user has full access to all facilities needed, and has no need to perform maintenance or system tasks. All desks are equipped with modern PCs, running under one operating system (Linux) and a fully transparent file system, with full data security and integrity guaranteed through multiple backups, firewalls, and the choice of the operating system. With this approach MPA is achieving virtually uninterrupted service. Since desktop PCs are not personalized, hardware failures are quickly repaired by a complete exchange of the computer. In addition to the desktop systems, which amount to more than 150 fully equipped workplaces, users have access to central number crunchers. This cluster comprises about 15 machines (with up to 72 processor cores and 768 GB memory) plus gpfs compute clusters with 1200 cores and about 8 TB of core memory. The total on-line data capacity at MPA is at the Petabyte level; individual users control disk space ranging from a mere GB to several TB, according to scientific need. Energy consumption and cooling have become a crucial aspect of IT-installations. At MPA, we are concentrating on low power-consumption hardware and efficient, environmental-friendly cooling.

All MPA scientists and PhD students may also get a personal laptop for the duration of their presence at the institute. These and private laptops may be connected to the in-house network through a subnet which is separated from crucial system components by a firewall. Apart from the standard wired network (Gb capacity up to floor level, and 100 Mb to the individual machine), access through a protected WLAN is provided. MPA is also a partner in the eduroam-consortium, thus allowing its members unrestricted access to WLAN at all participating institutions.

The basic operating system relies on Open-Source software and developments. The Linux system is a special distribution developed in-house, including the A(ndrew) F(ile) S(ystem), which allows completely transparent access to data and high flexibility for system maintenance. For scientific work, licensed software, e.g. for data reduction and visualization, is in use, too. Special needs requiring Microsoft or Macintosh PCs or software are satisfied by a number of public PCs and through servers and emulations.

The IT-group is made up of four full-time system administrators; users have no administrative privileges nor duties, which allows them to fully concentrate on their scientific work.

Library

The library is a shared facility of the MPA and the MPE and therefore has to serve the needs of two institutes with differing research emphases – predominantly theoretical astrophysics at MPA and predominantly observational/instrumental astrophysics at MPE. At present the library holds a unique print collection of about 54000 books and journals and about 7300 reports and observatory publications, as well as print subscriptions for about 140 journals and online subscriptions for about 500 periodicals, as well as an ebook collection of about 4600 copies. In addition the library maintains an archive of MPA and MPE publications, two slide collections (one for MPA and one for the MPE), a collection of approximately 800 non print media and it stores copies of the Palomar Observatory Sky Survey (on photographic prints) and of the ESO/SERC Sky Survey (on film). The MPA/MPE library catalogue includes books, conference proceedings, periodicals, theses, reports (print and online). Additional technical services such as several PCs and terminals in the library area, copy machines and a colour book-scanner are available to serve the users' needs. The library is run by three people who share the tasks as follows: Mrs. Bartels (full time; head of the library, organisation of business process, administration of books), Mrs. Blank (part time; administration of journals) and Mrs. Balicevic (part time; "Pure", publication management for both institutes).

1.3 2018 at the MPA

The MPA's new director, Volker Springel, started working full-time at the institute on August 1 2018. His new students and postdocs arrived at MPA over the following couple of months, and Ruediger Pakmor also joined the institute over the summer as an associated, permanent member of the scientific staff specialised in the relevant aspects of computational astrophysics. As a result, activity in Volker's subject area ramped up rapidly in the latter half of the year.

Computational Galaxy Formation was also the topic of a week long meeting at Ringberg castle which Thorsten Naab organised in March 2018. This brought together representatives of all the major groups world-wide who are active in this area, and resulted in lively debates on the relative merits of the many different numerical and astrophysical approaches to this complex topic.

The Max Planck Society's other large conference facility, the Harnack House in Berlin, was the venue for a rather different conference on "Stars, Planets and Galaxies" which Guinevere Kauffmann organised in April. The idea here was to bring together 60-70 international experts in the formation and evolution of galaxies, stars and planets, for an intensive programs of talks and discussions about unsolved problems and emerging new observational and theoretical methodologies. Rather than arranging the program by subject area, a number of scientific themes that are of common relevance were identified and discussion was focussed on possible cross-fertilisation between domains. Later in the year, the Harnack House was also used for an MPA-organised summer school on theoretical aspects of Large-Scale structure which was aimed at an international audience of PhD students and young postodcs

A third very different meeting organised by MPA scientists was a workshop to set up a "Strong gravitational lensing data analysis challenge" which was held over three days in Reykjavik, Iceland (to facilitate participation by both european and north american scientists). The meeting brought together all groups carrying out detailed analyses of multiply imaged distant galaxies in order to search for small dark matter structures superposed on one of the images. Its goal was to set up a double-blind challenge which will test whether different groups would detect the same perturbers and assign them similar masses in realistic mock datasets. Such a demonstration will be required to convince the community of the robustness of constraints on dark matter properties that are expected to come from such observations.

The MPA's new lecture hall is ideal for small workshops of 20 to 80 people, and these can easily be organised informally by any MPA scientist who wishes to do so. During 2018 a number of such meetings were held on various topics, for example, a reunion of the LiteBIRD collaboration planning a future CMB mission, and a gathering of all German researchers interested in CMB science. The lecture hall is also often used for the one-week specialist lecture courses offered two or three time a year by the IMPRS on Astrophysics, our Garching/Munich astrophysics graduate school, as well as for regular in-house seminar series, such as the Monday MPA seminar at which scientists introduce their own current research to the rest of the institute. Remarkably there is a complete record of all these seminars since they began in 1991 and 2018 saw the one thousandth in the series. Even more remarkably, Gerhard Boerner who gave the very first such "Hausseminar" was in the audience for number 1000, which was given by Simon White and filled the hall. The hall is also regularly filled for one of MPA's annual highlights, the Biermann Lectures.

Biermann lectures 2018

In 2018, the Biermann Lectures entitled "New probes of distant galaxies and their cosmic environments during the peak epoch of star formation" were given by Professor Alice Shapley of the University of California at Los Angeles (1.3).

Today's galaxies are relatively quiet. In our Milky Way, for example, an average of only three stars is born in any given year. During the peak epoch of cosmic star formation, however, some 10 billion years ago, the rate of star formation in a typical galaxy was more than an order of magnitude higher, and many of the patterns that we observe in the galaxy population today were not yet in place. Based on images and spectra from new ground- and space-based telescopes, astronomers can study these distant galaxies and their environments in more detail than ever before. In her 2018 Biermann lectures, Alice Shapley explained what we know about distant galaxies observed during the peak epoch of star formation, and how these galaxies can teach us about the even earlier cosmic phase transition known as reionization and the evolution of large-scale structure in the universe. Alice's own main research interest is in how galaxies form, evolve, and interact with their intergalactic environments over cosmic time. Recently, she performed a large survey of the rest-frame optical spectra of a statistical sample of distant galaxies using the MOSFIRE near-infrared spectrograph on the Keck telescope. She is currently leading a large program of Hubble Space Telescope observations to constrain the contribution of star-forming galaxies to cosmic reionization.

1.3.1 Prizes and Awards

Gruber cosmology prize

In May 2018, the Gruber Foundation awarded its cosmology prize to the Planck Team, which has included scientists at MPA since the beginning of the project in the 1990's. From 2009 to 2013 the European Space Agency's Planck observatory collected data that has provided a near-perfect image of the entire outer boundary of the visible universe, thus giving a definitive description of the universe when it was just 400,000 years old. These measurements, according to the Gruber Prize citation, have led to the determination of cosmological parameters (matter content, geometry, and evolution of the universe) to unprecedented precision. For example, the age of the Universe and the present densities in baryonic and nonbaryonic matter are all measured to an accuracy of about 1%. Planck also verified at high statistical significance one of the key predictions of the simplest inflationary model for the origin of all cosmic stgructure at the very earliest moments of the Big Bang, namely that the amplitude of gravitational potential fluctuations at early times should be almost, but not exactly independent of scale, varying slightly and in a very specific way with wavelength. The Planck observatory consisted of two instruments, each tuned to its own portion of the electromagnetic spectrum and both invisible to the human eye. The High Frequency Instrument studied the universe in the far-infrared regime; the Low Frequency Instrument observed at longer wavelengths in the microwave regime. Two MPA directors, Simon White and Rashid Sunyaev, were co-Investigators on these instru-

Figure 1.1: Professor Alice Shapley, 2018 Biermann Lecturer *credit: A. Shapley*

ments and secured long-term support from the German Aerospace Center for a team at MPA. Led since 2003 by Torsten Enßlin, this team contributed essential software infrastructure to the project, the mission simulation package, a workflow engine, and a data management system.

Marcel Grossmann Award

Rashid Sunyaev, Director-Emeritus at the MPA, was awarded the individual Marcel Grossmann Award for 2018. The award ceremony took place during the 15th Marcel Grossmann Meeting in Rome in July. The Award is named after the mathematician Marcel Grossmann, a close collaborator of Albert Einstein, who helped develop the mathematical foundations of the Theory of General Relativity. It is presented by the International Center for Relativistic Astrophysics Network (ICRANet) every three years in two nominations - individual and institutional. The citation for Rashid Sunyaev reads: for the development of theoretical tools for scrutinising early structure through the CMB, the first observable electromagnetic appearance of our Universe.

Falling Walls Science Engagement Prize

MPA postdoc Francesca Fragkoudi won the "Falling Walls Science Engagement of the Year" award for 2018 for her project, "Columba-Hypatia: Astronomy for Peace". Falling Walls Engage is an international platform for all forms of science engagement, hosted by Falling Walls in cooperation with the Robert Bosch Stiftung. Its goal is to showcase successful science engagement projects from a wide range of fields. The programme seeks to highlight the scientific communitys responsibility for the common good and spread scientific literacy, with a special focus on "hard-to-reach" target groups. As winner of the "Falling Walls Science Engagement of the Year" Francesca presented her project at the Falling Walls Conference in Berlin to an audience of 750 global leaders, decision-makers, and international media representatives.

Columba-Hypatia is a science outreach project which takes place on the post-conflict island of Cyprus, with the aim of using astronomy as a tool for promoting meaningful communication and a culture of peace and non-violence. Activities include fun and educational astronomy projects in schools all around Cyprus, where children are taught about their place in the cosmos within the modern astronomical context. Children from the two main ethnic communities (the Greek-Cypriot & Turkish-Cypriots) come together in the UN-controlled buffer zone and engage in astronomy activities adapted to promote interaction between the children, to help break down barriers, stereotypes and prejudices. The project is a collaboration between GalileoMobile and the Association for Historical Dialogue and Research, and is supported by the International Astronomical Union's Office of Astronomy for Development and the MPA.

Rudolf-Kippenhahn-Award

The MPA's internal award for graduate students, the Kippenhahn Award, was shared in 2018 by two junior MPA researchers, Aniket Agrawal for his paper on "Large tensor non-Gaussianity from axion-gauge field dynamics" (see picture 1.2) and Jens Stücker for his paper "The median density of the Universe" (see picture 1.3). The Kippenhahn Award is bestowed jointly by MPA and its former director Rudolf Kippenhahn to the best student paper of the year, judged by a committee of several MPA scientists.

It has been widely assumed that the detection of primordial gravitational waves from inflation in, for example, the B-mode polarisation of the cosmic microwave background immediately implies the discovery of the quantum nature of space-time. While this statement is true for the vacuum solution, it does not apply if the gravitational waves originate from matter fields. How can we distinguish between these two origins? The answer is non-Gaussianity. For the first time Aniket Agrawal shows in his paper "Large tensor non-Gaussianity from axion-gauge field dynamics" that gravitational waves from SU(2) gauge fields during inflation are highly non-Gaussian, whereas those from the vacuum are only weakly non-Gaussian. This paper significantly influences the way experimentalists test the physics of inflation using gravitational waves.

Recent studies of fluctuations in the cosmic microwave background radiation have measured the average matter density of today's universe to an accuracy approaching one percent. Surprisingly, however, the matter density at a typical point is unknown, even to the order of magnitude. In his paper "The median density of the Universe", Jens Stücker uses a modified excursion set approach to calculate for the first time the unsmoothed present-day matter density distribution at random points in space for the standard ΛCDM cosmology. He found that the median density is much lower than the mean and depends significantly on the nature of dark matter.

Hochsprung Award honours a start-up based on MPA science

Analysing the data collected by astronomical instruments and interpreting them to gain precise knowledge about the universe is a complex mathematical and statistical problem. Over a number of years, Torsten Enßlin has been developing Information Field Theory at MPA to provide an optimal solution to this problem in a wide variety of contexts. Using this method, more accurate maps of the underlying cosmic mass distribution can be produced from astronomical surveys, and the data collected by different methods and instruments can be combined. His lectures on this topic focus purely on fundamental research, but have nevertheless led to very application-oriented activities. After their studies, two former MPA PhD students, Maksim Greiner and Theo Steininger, together with the engineer Isabell Franck founded a start-up company "IPT – Insight Perspective Technologies GmbH" which applies Bayesian probability calculus, the basis

Figure 1.2: *Simon White congratulated Aniket Agrawal on the Kippenhahn Award (credit: H.-A. Arnolds, MPA)*

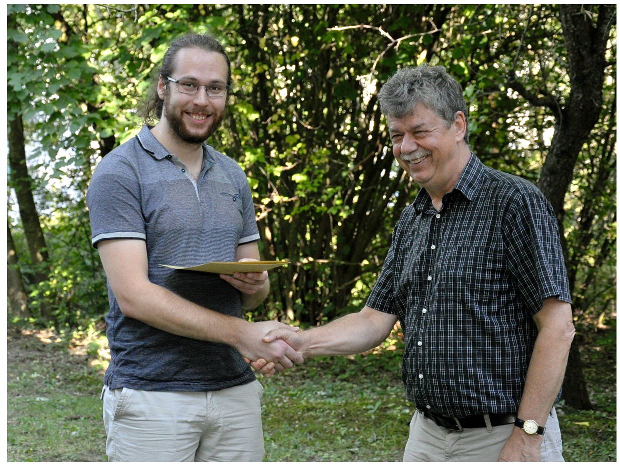

Figure 1.3: *Simon White congratulated Jens Stücker on the Kippenhahn Award (credit: H.-A. Arnolds, MPA)*

of Information Field Theory as developed for astronomical research, to real-world industrial applications. Their start-up offers services based on data analysis, machine learning, and data-based prediction models. In recognition of the effectiveness of this knowledge transfer, both the company founders and their former supervisor were presented with the Hochsprung Award of the Entrepreneurship Network of Bavarian Universities in October 2018.

Universe PhD Award 2018 for Titouan Lazeyras

Dr. Titouan Lazeyras received the 2018 PhD Award of the Garching/Munich Excellence Cluster Universe in the category "Theory" for his outstanding dissertation "Investigations into dark matter halo bias". In this work, Titouan used cosmological numerical simulations to investigate the formation of structures in the Universe. He concentrated on the clustering properties of the so-called dark matter halos (gravitationally bound structures of dark matter), which represent high-density regions and are preferred locations for galaxy formation. In particular, he has measured the so-called halo bias, a key component connecting the distribution of dark matter in the universe with that of visible tracers such as galaxies. "The results of Titouan Lazeyras' dissertation are already recognised as original contributions in this field" emphasises the selection committee.

Public Outreach 2018

Various strategies are employed at MPA to project our science to as wide an audience as possible. More than a dozen groups and school classes visited the institute in 2018 and went on a tour through the Universe in our digital planetarium. These live presentations continue to be very popular and serve not only to tell visitors about astronomy in general but also to showcase

MPA research in a special environment. In July, we also went on a short tour with our digital planetarium to the Werner Heisenberg Gymnasium in Garching. Over the course of two days, we presented our planetarium show to all 5th graders in the course of their geology lessons as well as the physics groups in 11th grade.

The Girls'Day 2018 at the MPA was a little different than in previous years: the 20 girls received not only an insight into the work at a theoretical scientific institute but became young researchers themselves. Tasks ranged from stars and galaxies, the gravitational lensing effect, to the expansion of the universe, and the cosmic microwave background. Autonomous, but with the help of local experts, the girls had to collect further information and data, classify it and perform calculations. Finally, they presented their results to the other groups in a short presentation. On enquiry, some girls stated that they could well imagine a career in astrophysics - even if they found the research tasks pretty difficult and mathematical. Still, their interest in the topic was by no means reduced!

At the end of April, the MPA also hosted another special event: a teacher training programme about gravitational waves including several talks by scientists from MPA and the neighbouring MPE. This event was coorganised with the Bavarian Ministry for Education and attracted about 70 teachers from schools all over Bavaria.

The MPA scientists also went outside the institute to tell people about astronomy research in public talks such as in the framework of Café & Kosmos, an event series organised together with the Excellence Cluster Universe, ESO, MPE and MPP. Further activities included supervising a number of undergraduates, who worked on small research projects during internships.

The public outreach office issued a number of press releases about important scientific results as well as news about awards and prizes for MPA scientists. These were published on the MPA website as well, complementing the popular monthly scientific highlight series. MPA researchers also acted as interview partners for press, TV, and radio journalists.

Chapter 2

Scientific Highlights

2.1 Neutron Stars on the Brink of Collapse

When a very massive star dies, its core collapses in a fraction of a second. In the following supernova explosion, the stars outer layer gets expelled, leaving behind an ultra-compact neutron star. For the first time, the LIGO and Virgo Observatories have recently been able to observe the merger of two neutron stars by detecting the gravitational waves emitted and to measure the mass of the merging stars. Together, the neutron stars had a mass of 2.74 solar masses. Based on these observational data, the international team of scientists from Germany, Greece, and Japan managed to narrow down the size of neutron stars with the aid of computer simulations. The calculations suggest that the neutron star radius must be at least 10.7 km (see Figure 2.1).

In neutron star collisions, two neutron stars orbit around each other, eventually merging to form a star with approximately twice the mass of the individual stars. In this cosmic event, gravitational waves oscillations of spacetime whose signal characteristics are related to the mass of the stars, are emitted. This event resembles what happens when a stone is thrown into water and waves form on the waters surface. The heavier the stone, the higher the waves.

The scientists calculated different merger scenarios for the recently measured masses to determine the radius of the neutron stars. In so doing, they relied on different models and equations of state describing the exact structure of neutron stars. Then, the team of scientists checked whether the calculated merger scenarios are consistent with the observations. The conclusion: All models that lead to the immediate collapse of the merger remnant can be ruled out because a collapse leads to the formation of a black hole, which in turn means that relatively little light is emitted during the collision. However, different telescopes have observed a bright light source at the location of the stars collision, which provides clear evidence against the hypothesis of collapse directly after the neutron-star collision.

The results thereby rule out a number of theories for neutron star matter, namely all model descriptions that predict a neutron star radius smaller than 10.7 kilometers. However, the internal structure of neutron stars is still not entirely understood. The radii and structure of neutron stars are of particular interest not only to astrophysicists, but also to nuclear and particle physicists because the inner structure of these stars reflects the properties of high-density nu-

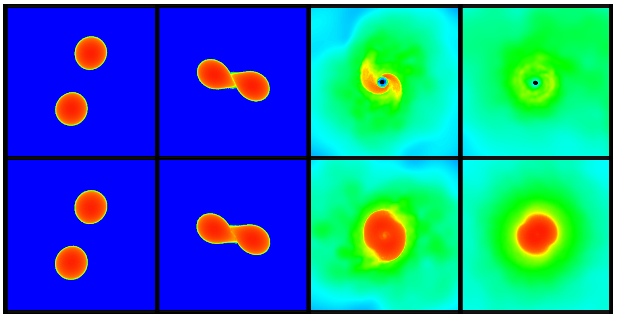

Figure 2.1: The upper and lower series of pictures each show a simulation of a neutron star merger. In the scenario displayed in the upper panels the star collapses after the merger and forms a black hole, whereas the scenario displayed in the lower row leads to an at least temporarily stable star. *Credit* Andreas Bauswein, HITS

clear matter found in every atomic nucleus.

While neutron stars have a slightly larger mass than our Sun, their diameter is only a few 10 km. These stars thus contain a large mass in a very small volume, which leads to extreme conditions in their interior. Researchers have been exploring these internal conditions for several decades already and are particularly interested in better narrowing down the radius of these stars as their size depends on the unknown properties of ultra-dense matter.

The new measurements and new calculations help theoreticians to better understand the properties of high-density matter in our Universe. The recently published study represents a significant scientific progress as it has ruled out some theoretical models. But there is still a large variety of other models with neutron star radii greater than 10.7 km.

However, the scientists have been able to demonstrate that further observations of neutron star mergers will continue to improve these measurements. The LIGO and Virgo Observatories have just begun taking measurements, and the sensitivity of the instruments will continue to increase over the next few years and provide even better observational data. (Andreas Bauswein and Hans-Thomas Janka).

2.2 Tsunamis and Ripples: Effects of Scalar Waves on Screening in the Milky Way

General Relativity has been great at reproducing and predicting phenomena in the Solar System, such as the bending of light by the Sun. However, observational data from supernovae suggest that the expansion of the universe is accelerating and this only be explained in the theory with an additional element. General relativity with a cosmological constant (the so-called ΛCDM-model) is consistent with all current observations - but is plagued by the infamous cosmological constant problem, i.e. nobody can explain the physical nature of this constant.

An alternative is to consider a theory of gravity that reduces to general relativity in the solar system but works differently on cosmological scales, such that it naturally drives the acceleration. In our analysis, we introduce a scalar field that interacts with matter, giving rise to a fifth force that makes matter deviate from their geodesics. Furthermore, the interaction depends on the composition of a massive body, thus allowing for environment-dependent behaviour.

We can use this environment-dependent, specifically local matter density to allow for deviations from general relativity on large scales while hiding troublesome modifications in the solar system. This is called screening. Two exam-

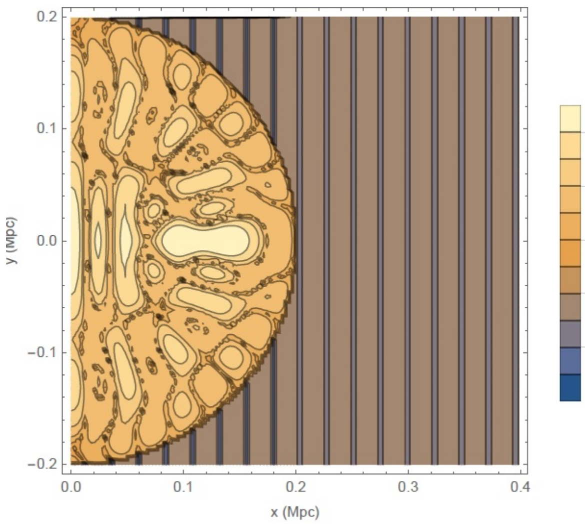

Figure 2.2: The relative effect of an incoming scalar wave on the deviation from general relativity in the Milky Way halo (technically: the parameterized post-Newtonian parameter γ.). The wave effectively travels through a medium with a refractive index different from one, similar to light passing through water. *Credit: MPA*

Figure 2.3: This picture illustrates the refraction of light by a glass of water, which has a refractive index for visible light greater than one. *Credit: CreativeCommons/Pxhere*

ples of screening mechanisms are the symmetron and the chameleon mechanisms. The symmetron mechanism works by suppressing the coupling of the field to matter in high density regions, i.e. suppressing their interaction; while the chameleon field's effective mass increases somewhere dense, resulting in a very short-ranged fifth force, irrelevant to macroscopic dynamics.

Until recently, these screening mechanisms have been studied under the quasi-static approximation. This means that one takes the equation of motion and assumes that the scalar field evolves very slowly. We can then neglect time derivatives and obtain the familiar Poisson-type equation, just like in Newtonian gravity, which does not allow for wave propagation.

In recent cosmological simulations, however, symmetron waves have been found when the quasi-static approximation is relaxed. Such scalar waves appear because the symmetron model allows for two distinct vacuum states in low-density regions. A small region of space can spontaneously flip its vacuum state to conform to its neighbour, this being more energetically favourable. Another source of scalar waves are violent astrophysical events, such as supernovae explosions, where less dense - hence unscreened - massive stars collapse into highly dense neutron stars or black holes, which are screened.

In the specific case of our solar system, the massive halo of the Milky Way should "screen" our neighbourhood, reducing the model to general relativity locally. However, it has been suggested that scalar waves of cosmological and astrophysical sources can observably disrupt this screening, such that a light-ray could experience an observably different amount of bending as it passes by the Sun.

As shown in other studies, an incoming spherical symmetron wave centred on the halo of the Milky Way can significantly disrupt the screening. These effects, however, could potentially violate the current observational bounds, hence ruling out previously viable models. Planar waves on the other hand are expected to be the more physically relevant wave configuration.

For astrophysical events with a source very far away from us, the planar-wave assumption should be very accurate. For waves of cosmological origin, which is only relevant to symmetron models here, the exact form of the incoming wave is less obvious as they are produced throughout the Universe and we are not necessarily in the far-field limit. Nevertheless, it is reasonable to expect that they can be represented as a superposition of plane waves with random wave vectors and phases.

This caveat motivated us to gain a better physical understanding of this scenario. We quantitatively investigated the impact of scalar waves by solving the full field equation linearised in the wave amplitude. We find that inside the halo, the field becomes massive due to screening, which means that its phase velocity is modified. Analogous to light waves being refracted when they pass through water, the wavefronts are then bent.

We then studied the effect of the waves on the deviation from general relativity near the solar system's position within the halo. We find that planar incoming waves are significantly less disruptive than their spherical counterparts. This is of purely geometrical origin. Spherical waves focus a large amount of energy on the inner parts of the halo, where the solar system resides, while the more physical planar waves do not.

So while waves do propagate inside the halo in symmetron models and could potentially have consequences for models that are just marginally screened, the effects are much smaller than previously thought. Still, the effects of other factors, such as the halos density profile, and parameters of the model and incoming wave, are yet to be explored. (Fabian Schmidt)

2.3 Buoyant bubbles in galaxy clusters and heating of the intracluster medium

Galaxy clusters are the most massive gravitational bound structures in the Universe. The temperature of the gas filling the deep potential wells of clusters reaches 10 100 million Kelvin, leading to powerful X-ray emission from these objects. While the gas cooling timescales in the cluster cores are much shorter than the Hubble time, there is no evidence that the gas cools below X-ray temperatures. This implies the existence of a powerful heating source that offsets cooling losses of the gas. Supermassive black holes in cluster cores have been widely accepted as a prime candidate for such a heating source.

Observations of clusters provide us with a unique opportunity to study the impact of supermassive black holes on the ambient gas the process known as active galactic nuclei (AGN) feedback, and in particular its flavour, called radio-mode feedback. In the cluster centre, bubbles of relativistic plasma are inflated by bipolar jets from a supermassive black hole, and subsequently expand until the expansion velocity becomes comparable to their rise velocity driven by the buoyancy force. The bubbles then detach from the jet and buoyantly rise upwards. They finally reach their terminal velocity when the drag force balances the buoyancy force. X-ray and radio observations of nearby clusters show clear signs of the intracluster medium (ICM) interacting with these bubbles (see Fig. 2.4). Estimates of the power needed to inflate the bubbles based on comparing the inflation and buoyancy time scales show that this power is comparable to the gas cooling losses.

For a bubble rising with terminal velocity, energy conservation arguments imply that much of the energy used by the supermassive black hole to inflate it will be transferred to the ICM once the bubble crosses several pressure scale heights. While this argument guarantees a high coupling efficiency of the bubble-heating process, the particular channels responsible for the energy transfer to the ICM have long been debated. In other words, the nature of the drag force that balances the buoyancy of the bubble is largely unknown. Processes contributing to the drag could be the excitation of sound and internal waves, turbulence in the wake of the bubble, the potential energy of the uplifted gas or others (see Fig. 2.5).

Astrophysicists have long attempted to explore bubble dynamics and the relevant heating process through numerical simulations. However, these attempts are hindered by uncertainties in the properties of the ICM and the bubbles, especially in the topology and strength of the magnetic field. For instance, ideal hydrodynamic models often lead to a rapid destruction of rising bubbles. However, observations show that some clusters (e.g. Perseus, M87/Virgo) have X-ray cavities with relatively regular shapes even far from the cluster centre (see Fig. 2.4). As can be seen in this figure, the bubbles are initially almost spherical, but become flattened once they rise buoyantly. Phenomenologically, this can be interpreted as if an effective surface tension acts on the bubble surface and keeps the bubble stable. The flattened bubble shape could result from the combined action of pressure gradients of the flow that squeeze the bubble along the direction of its motion, and surface tension,

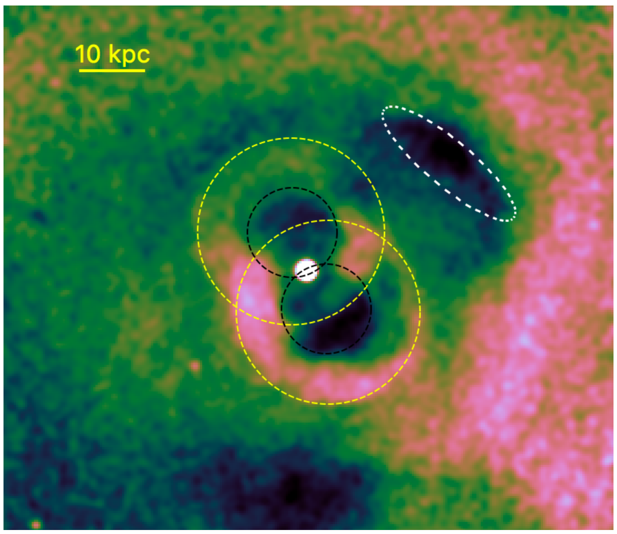

Figure 2.4: Chandra X-ray image of the Perseus cluster. The bubbles appear as dark (X-ray dim) regions in this image. "Active" bubbles (radius $\sim$ 7 kpc) are marked with black dashed circles. They are surrounded by quasi-spherical weak shocks (radius $\sim$ 14 kpc), shown by yellow circles. The outer bubble, to the north-west from the centre, has the "horizontal" and "vertical" (radial) sizes L $\sim$ 25 kpc and h $\sim$ 7 kpc, respectively. *Credit: MPA*

which prevents the bubble surface from shredding. However, the detailed physical description of this effective surface tension, presumably magnetic, is difficult. To circumvent this difficulty, a team of researchers from MPA and Oxford modelled the bubbles as rigid bodies buoyantly rising in the stratified cluster gas and studied the perturbation induced by such bodies in the gas a problem that has many applications in atmospheric sciences and oceanology.

It was found that the degree of flattening has dramatic effects on the nature of the drag force generated by rising bubbles. For spherical bubbles, the turbulence in the wake of the bubble dominates the drag, similarly to the case of a homogeneous fluid, while for strongly flattened bubbles, the stratification leads to pronounced changes in the flow. Flattened bubbles move slower and, in particular, clear signs of internal waves are seen in the simulations. Such waves are conceptually similar to the surface waves excited by ships moving in the water. The movie (below) shows how internal waves are excited and propagate horizontally and downwards from the rising bubble, spreading their energy over large volumes of the ICM. Attractive features of internal waves, as one of the possible bubble-heating channels, are that: (1) internal waves are trapped in the central region of a cluster, because the Brunt-Visl frequency (a.k.a., buoyancy frequency) is a decreasing function of radius, implying that the energy will not leak outside the cluster core; (2) these waves can travel in the tangential direction (azimuthal) and spread energy throughout the cluster core. Another interesting feature is a complex pattern in the wake of the bubble, which reflects the interplay between buoyancy and eddies shed by the flattened bubble.

According to simulations, the expected ter-

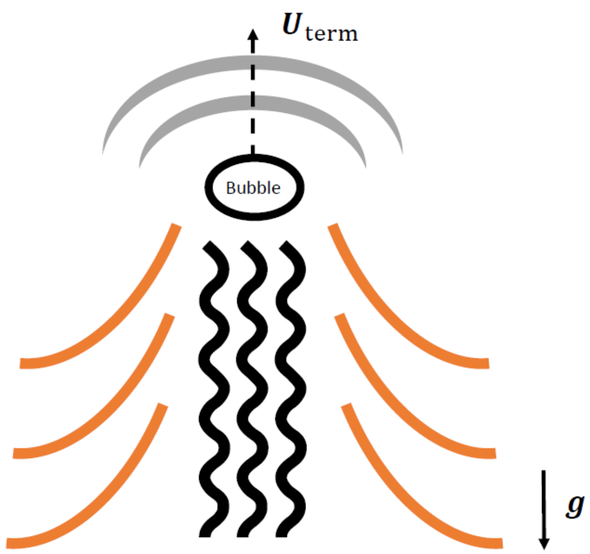

Figure 2.5: Sketch showing a bubble rising in a stratified medium. The bubble rises at the terminal velocity (Uterm) when the buoyancy force is balanced by the drag force. The grey, black and orange lines schematically show sound waves, turbulence, and internal waves excited by the moving bubble, which can all contribute to the total drag. *Credit: MPA*

minal velocity of the north-west bubble in the Perseus cluster (marked with a white ellipse in Fig. 2.4) is ∼200 km/s, which broadly agrees with the sole measurements of the gas velocity by the Hitomi satellite. This estimate also agrees with constraints on the velocity from the analysis of the morphology and size of the cool gas filaments trailing the bubble. These results are very encouraging, but of course they only represent the first step towards a comprehensive modelling of bubbles in galaxy clusters and a complete census of all relevant gas heating channels. (Congyao Zhang and Eugene Churazov)

2.4 The primordial magnetic field in our cosmic backyard

The Big Bang is still shrouded in mystery in many respects. Cosmologists use many different ways to try and get information about the first moments of our universe. One possibility are cosmic magnetic fields, which were created by the Big Bang and should have survived to this day. A number of highly speculative mechanisms have been proposed for this so-called magnetogenesis, but in addition there is a simple plasma-physical effect, the Harrison effect, which should have produced magnetic fields at the birth of the cosmos. This effect describes how vortex movements in the plasma of the early universe produce electric currents due to friction with the very strong radiative field, thus inducing a magnetic field. Knowing the plasma vortices in that early time, one could calculate in detail how these magnetic fields were generated. If one also knew the plasma motions since then, one could calculate what these magnetic fields should look like today.

The necessary information is contained in the

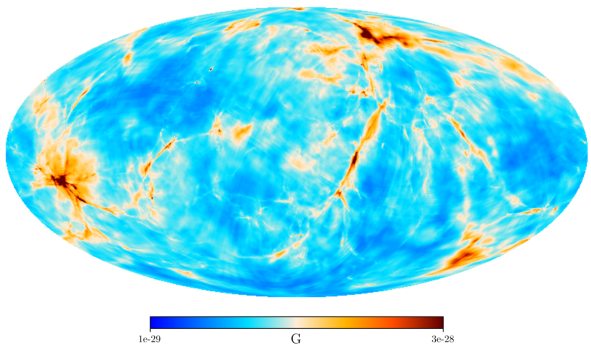

Figure 2.6: Sky view of the Harrison magnetic field strength averaged within a sphere with 300 million light years radius around the Earth. The region with stronger fields on the left side of the image is the Perseus Pisces galaxy cluster, the one in the upper part is the Virgo cluster. *Credit: MPA*

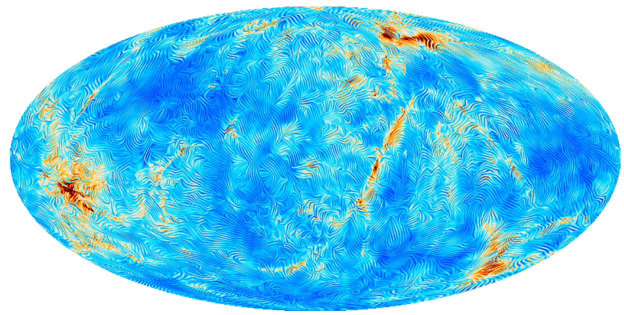

Figure 2.7: Sky view of the magnetic field strength and orientation of the magnet field components perpendicular to the line of sight, again averaged a sphere with 300 million light years radius around the Earth. The texture indicates the direction of the field lines. *Credit: MPA*

distribution of the galaxies around us, as this is the result of the motion of matter since the early universe. As we know the laws leading to the formation of galaxies, from today's galaxy distribution it is possible with some uncertainty to trace the evolution of the matter distribution from the early universe to the present day. This means that the information necessary is available to predict the magnetic fields generated by the Harrison effect in today's universe (Highlight 12/2009: Mapping of the Universe beyond the Known). An international team of scientists led by the MPA used this logic to calculate today's remnants of the primordial magnetic fields in our cosmic neighbourhood, i.e. in the surrounding 300 million light years.

These magnetic fields are extremely weak, twenty-seven orders of magnitude smaller than the Earth's magnetic field (see Figures 2.6, 2.7. In spite of the weakness, the team was able to precisely predict the magnetic field structure as viewed from Earth (Figures 2.6, 2.7) and at known places in the Universe (Figure 2.8) unfortunately these fields are far smaller than the current measuring threshold. Nevertheless, these calculations show that we can understand our cosmos with high precision and calculate subtle effects within. And who knows how precisely we will be able to measure magnetic fields in 100 years Einstein also thought that the gravitational waves he predicted would be too weak to detect. (Sebastian Hutschenreuter and Torsten Enßlin).

2.5 Finding needles in a haystack

Our understanding of the formation paths of supermassive black holes is still very sketchy. In 1982, Andrzej Soltan showed that the summed emission from all observed quasars yields a remarkably accurate estimate of the total mass of

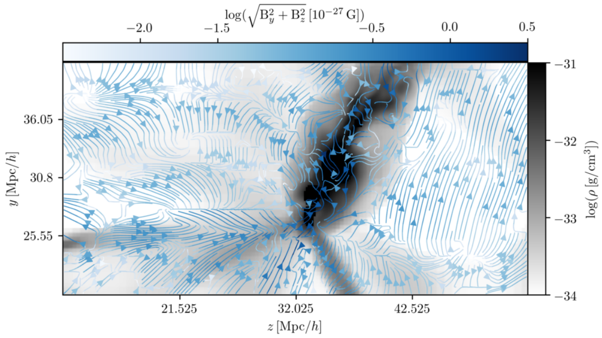

Figure 2.8: A slice through the Perseus Pisces galaxy cluster in the present Universe with the matter distribution depicted in grey and the blue arrows highlighting the Harrison magnetic field. *Credit: MPA*

present-day black holes. His argument was based on the expected conversion efficiency of the rest mass energy of matter in an accretion disk falling into a black hole at the centre of a quasar - these distant objects are thus believed to signpost the main sites of black hole growth across the Universe.

Unfortunately, quasars are not ideal objects to study the mechanisms by which black holes grow. The emission from the central nucleus is more luminous than the underlying host galaxy by many orders of magnitude, making detailed studies of the host system extremely difficult. For this reason, studies to constrain possible triggering mechanisms for black hole growth focus on so called Type II active galactic nuclei (AGN). In these systems, the radiation from the accretion disk is believed to be blocked by a very dense layer of gas and dust (the so-called torus, see Figure 2.9). Large spectroscopic galaxy surveys such as the Sloan Digital Sky Survey have yielded samples of hundreds of thousands of nearby Type II AGN, which are selected according to their optical emission line ratios. At higher redshifts, Type II AGN are commonly selected at X-ray wavelengths.

So far, studies of the host galaxies of these systems appear to rule out theoretical scenarios in which black hole growth occurs when two or more galaxies merge together. Simulations of the gravitational interactions and gas dynamics of two merging galaxies show that tidal torques during the merger cause the gas to shock, lose energy and flow towards the centre of the merger remnant. Energetic processes that act on the gas very close to the black hole are, however, very difficult to simulate in a reliable way.

In recent work at MPA, a new technique combined data from several observing programmes using the Wide-field Infrared Survey Explorer satellite, the Very Large Array (VLA) FIRST Survey (Radio Images of the Sky at Twenty-Centimeters) and the Sloan Digital Sky Survey. This combination of data permits a more reliable selection of a large sample of active galaxies where there is strong hot dust emission from a central torus. The radio data turned out to be a critical element of the selection technique, because there are large number of galaxies where the hot dust extends over a large area and is probably not being heated by the black hole. This had not been accounted for in previous work.

Follow-up work demonstrated that the new selection, which includes only 1.6% of the sources in previous AGN samples, yields galaxies with properties that are very different. More than 80% of the galaxies in the new sample turn out to be merging or interacting systems. For many of them, their stellar spectra show strong bursts of star formation in their central regions. The emission lines indicate that the gas is highly ionized, with the main source of ionization likely

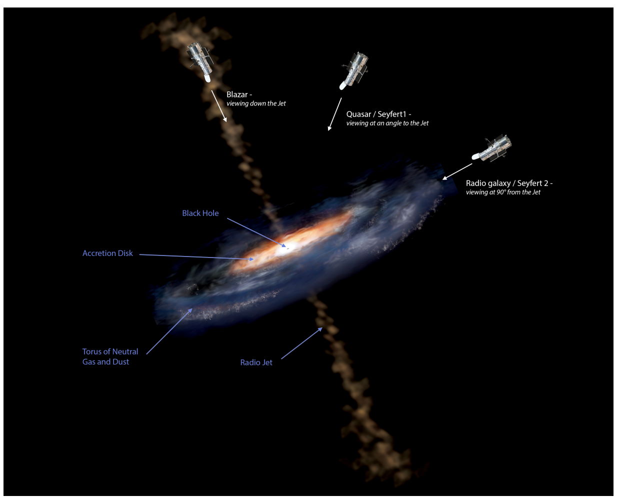

Figure 2.9: This illustration shows the different features of an active galactic nucleus (AGN). The extreme luminosity of an AGN is powered by accretion onto a supermassive black hole. In addition to the accretion disk, models of active galaxies also include a region of cold gas and dust, the torus. Viewed edge-on, the torus blocks out the light from the accretion disk and the system is a Type II AGN. Viewed face-on, the accretion disk dominates the luminosity and the system is a quasar. *Credit: Aurore Simonnet, Sonoma State University*

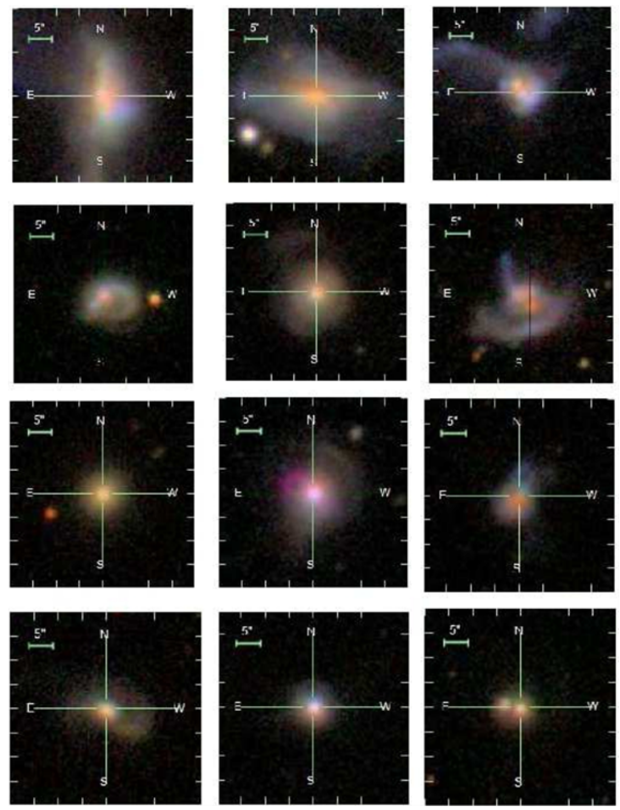

Figure 2.10: SDSS colour images (g,r,i-band) of typical AGN host galaxies in our sample. Many are interacting or have disturbed morphologies. *Credit SDSS*

being an accreting black hole rather than the young stars in the nucleus. The radio emission is usually compact and centrally located and is too luminous to be explained by the observed young stars in the nucleus. With 1300 galaxies the new sample is large enough to show conclusively that these AGN currently signpost the bulk of black hole formation in the most massive galaxies in the local Universe – with the "normal" AGN population dominant in lower mass galaxies.

The challenge now is to go back in time to younger galaxies, i.e. to extend this study to higher redshifts. Pulling similar samples out of surveys of galaxies at higher redshifts, however, will need comparable data sets in different wavelength bands. Then we can investigate how the accreting black holes in these younger systems are influencing the gas in and around their host galaxies. (Guinevere Kauffmann)

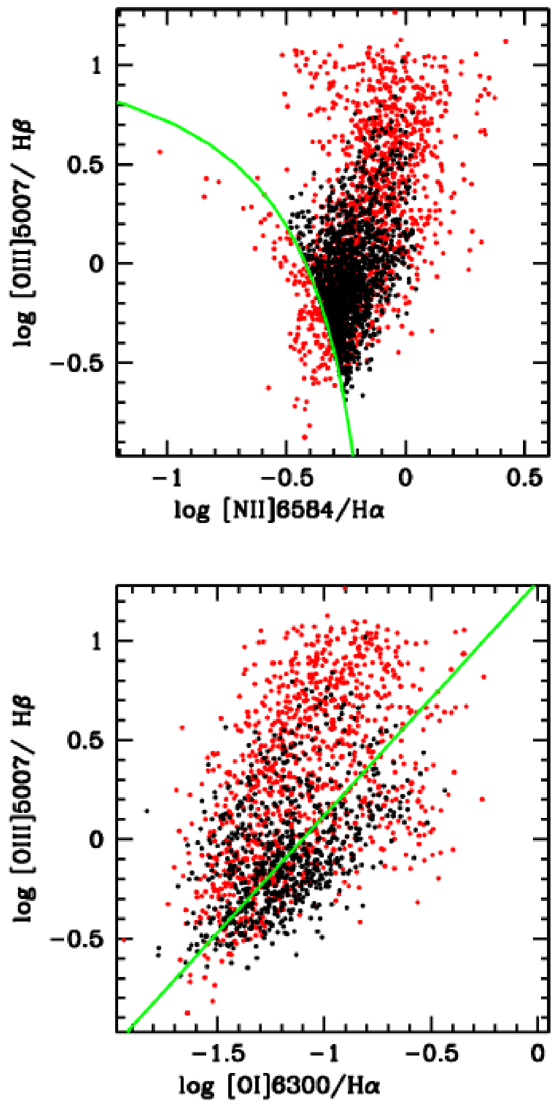

Figure 2.11: Line ratio diagnostic diagrams illustrating that the AGN in our sample (red dots) have gas in a higher ionization state than ordinary AGN (black dots). *Credit MPA*

2.6 Gravitational Wave Messengers from the very early universe

How did the Universe begin? This profound question has fascinated humans for millennia. Precision cosmology has brought us quite close to answering this question, using observations of the cosmic microwave background (CMB) made by NASAs WMAP and ESAs Planck satellites. By making precise measurements of the variation in temperature and polarisation of the CMB over different directions in the sky, cosmologists have zeroed in on a remarkable picture of the origin of cosmic structures such as galaxies, stars, planets, and life: everything around us arose from quantum fluctuations, producing particle-anti particle pairs, in the early Universe. These fluctuations got stretched to very large scales via the accelerated expansion of the Universe, called inflation, in the first fractions of a second. At the end of inflation, the Universe started decelerating and these fluctuations could then seed the present day structures in the Universe.

A key test of the quantum mechanical origin of these fluctuations is their probability distribution, which characterises the probability of the fluctuation having a particular amplitude at a given point in the Universe. For free fields with ground state quantum fluctuations, this distribution is Gaussian (see Fig. 2.12). However, interactions of the fields with other fields or with themselves in the early Universe make this distribution non-Gaussian. This non-Gaussianity is therefore a crucial probe of interactions of fields during inflation, giving us a window into physics at energy scales much beyond the reach of any particle accelerator on Earth.

Photons are strongly coupled to electrons until the temperature is sufficiently low to form neutral atoms, which means that the oldest light that we see was emitted when the Universe was already 380 000 years old. Gravitational waves, on the other hand, travel to us almost unimpeded from the beginning of the Universe and are thus a much cleaner probe of inflationary dynamics. While these gravitational waves are difficult to observe directly, they leave their imprint as a unique pattern of polarisation in the CMB.

More precisely, if gravity is quantized, its vacuum fluctuations would produce gravitational waves and hence, a polarisation in the CMB. The amplitude of this polarisation depends on the energy scale of inflation, allowing us to test the reach of our physical theories. However, there is a catch: other sources of energy, such as gauge fields, can produce gravitational waves as well.

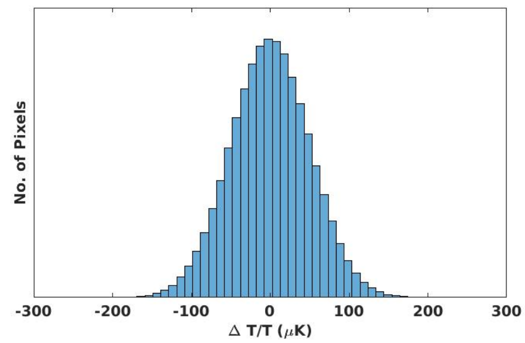

Figure 2.12: Quantum fluctuations produced in the early Universe yield temperature and polarisation fluctuations that obey a Gaussian distribution to high precision. *Credit: MPA*

In this case, the amplitude of the polarisation does not depend simply on the energy scale of inflation, but also on the exact mechanism by which these other fields produce gravitational waves. So, if we observe the imprint of gravitational waves on the CMB polarisation, how can we determine their origin?

Scientists at MPA recently established the Gaussianity of gravitational waves as the discerning test of their origin. Using the skewness of the probability distribution (or more precisely, the so-called three-point function) as a measure of non-Gaussianity, they found that while gravitational waves produced by vacuum fluctuations only have a skewness of few times their variance squared (see Fig. 2.13), those sourced by gauge fields can have a skewness almost a million times their variance squared (see Fig. 2.14).

This can be easily observed in upcoming CMB missions such as Japans LiteBIRD, which greatly improves upon the sensitivities of WMAP and Planck, and in which MPA scientists are also heavily involved. If we find that the observed

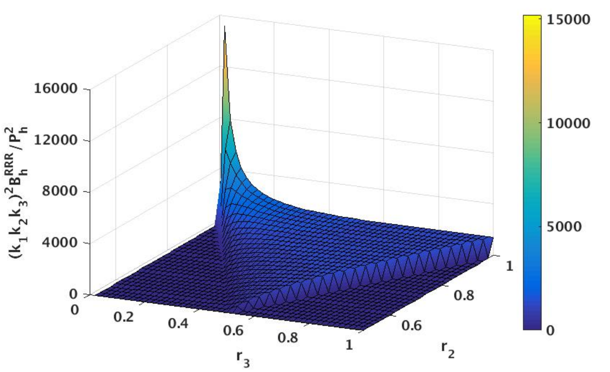

Figure 2.13: The 3-point function of gravitational waves produced by vacuum fluctuations of spacetime, which is the correlation between gravitational waves of three different wavelengths, as a function of the ratios of two longer wavelengths to the shortest one. The value in the limit of equal wavelengths ($r_2 = r_3 = 1$) corresponds to skewness. *Credit: MPA*

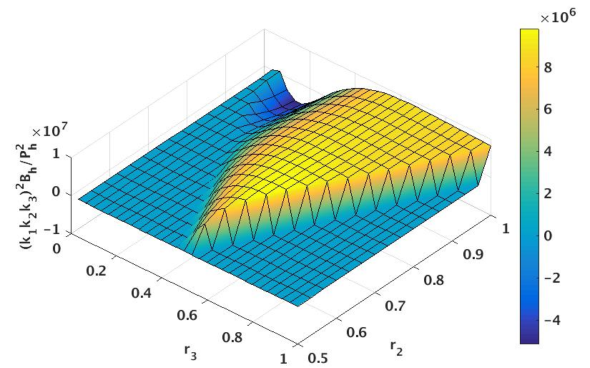

Figure 2.14: Same as Fig. 2.13 but for gravitational waves generated by interactions of gauge fields. The values are much larger than that for vacuum fluctuations (Fig. 2.13). The shape is also visibly different from that of vacuum fluctuations. *Credit: MPA*

primordial gravitational waves are indeed highly non-Gaussian, their skewness can be used to measure the energy density fraction of gauge fields during inflation, allowing us to probe the constituents of our Universe when it was less than a trillionth of a trillionth of a trillionth (10^{-36}) of a second old. (Eiichiro Komatsu)

2.7 Highly ionized oxygen: signatures of galactic feedback

As the dominant "metal" (i.e. element heavier than hydrogen or helium) in the interstellar, circumgalactic, and intergalactic media, oxygen is one of the most important elements in astrophysics. Observations of oxygen in its various forms underpin much of our understanding of galaxy formation and evolution. In its three highest observable ionization states OVI, OVII, and OVIII oxygen traces gas which is either hot, at temperatures above 100,000 Kelvin, or at low densities, with less than 100 atoms per cubic meter. All three ions can arise in the rarefied plasmas which surround galaxies and extend out to large distances, into their hot gaseous halos, which are commonly referred to as the intracluster medium (ICM) or circumgalactic medium (CGM), depending on the mass of the dark matter halo. These highly ionized states of oxygen also emerge in the low gas density structures which make up the topology of the cosmic web of large-scale structure: the intergalactic medium (IGM).

Theoretically, MPA researchers study the relationship between these three states of oxygen using the IllustrisTNG project (first presented here in February), a new set of computer simulations based on the basic laws of physics and modeling the formation and evolution of galaxies across

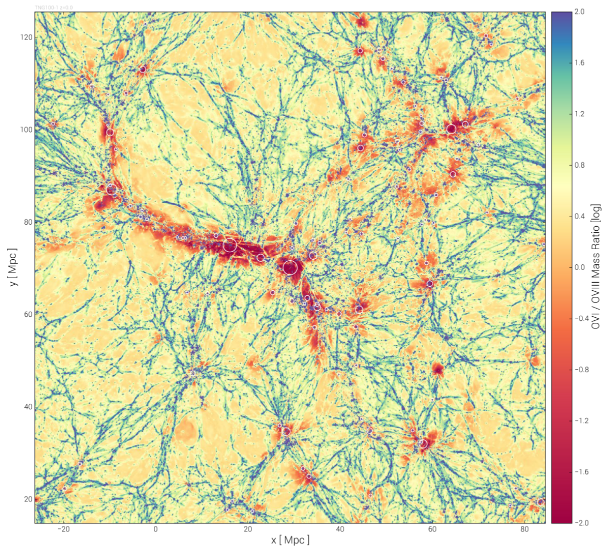

Figure 2.15: This map shows the ratio of two oxygen ions, OVI to OVIII, on hundred-megaparsec scales (roughly 300 million light years). This ratio varies by more than a factor of 10,000, depending on environment. In under-dense cosmic voids, the two ions are roughly in equipartition (orange), whereas in the elongated, dense filaments of the cosmic web OVI dominates by a factor of 100 or more (dark blue). The hot gas halos around massive groups and clusters are dominated by OVIII (dark red). *Credit: MPA.*

cosmic time. In addition to the evolution of dark matter under the influence of gravity, IllustrisTNG simultaneously solves for the hydrodynamical evolution of cosmic gas. As gas collapses to form stars, these stars produce heavy elements including oxygen, which are then released back into the nearby interstellar medium and can even be ejected outside of galaxies entirely. Oxygen is thus an abundant metal throughout cosmic space.

The simulations show that the ratio between different ionization states of oxygen can vary widely, depending on environment, see Figure 2.16. In under-dense cosmic voids, the two ions are roughly in equipartition. The elongated, dense filaments of the cosmic web are dominated by the quintuplely ionized oxygen (that is, an oxygen atom which has lost five of its outermost electrons, commonly labeled as OVI); the gas here is quite "cold", only 10,000 Kelvin. In contrast, the hot gas halos around massive groups and clusters, where gas temperatures can exceed 10 million Kelvin, are dominated by highly ionized oxygen (OVIII). This also holds for the localized IGM around these high mass halos, as well as in the largest cosmic web filaments bridging them.

While detailed observations of the two highest observable states of oxygen (OVII and OVIII) are not yet available they are among the challenging goals for the next generation of space-based X-ray telescope missions, such as Athena and Lynx quintuplely ionized oxygen (OVI), has been the subject of many recent observational campaigns, such as COS-Halos and others using the Cosmic Origins Spectrograph instrument on the Hubble Space Telescope. As this ion can absorb light at a frequency of 103nm, i.e. at ultraviolet wavelengths, space observatories are required to get above the Earths atmosphere.

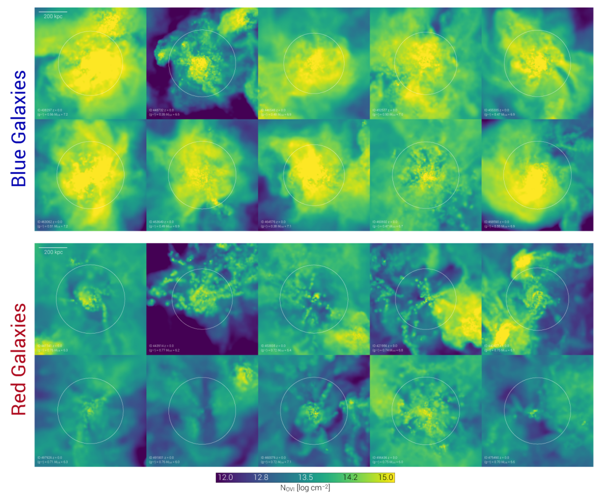

Figure 2.16: This figure shows the distribution of quintuplely ionized oxygen (OVI) around sixteen different galaxies, all with exactly the same mass. Blue to yellow colors denote increasing abundances of OVI. In the top two rows, eight blue galaxies are picked at random, which are still vigorously forming new stars. On the bottom two rows, eight red and dead galaxies are shown, which have already quenched their ongoing star formation. Visible by eye is the difference in the amount of OVI surrounding these two types of galaxies. *Credit: MPA.*

These observations have concluded that OVI is nearly ubiquitous around galaxies which have a similar mass as our own Milky Way it is found essentially 100% of the time, even out to distances as large as the entire dark matter halo, i.e. ten or twenty times larger than the galaxy itself.

Hydrodynamical simulations have long had trouble reproducing this trend, generally finding too little OVI in the circumgalactic media around galaxies of similar mass. Not so IllustrisTNG: Producing mock (or synthetic) surveys of this simulation, the MPA scientists showed that it is fully consistent with the OVI content of the CGM from data in the local universe for the first time, producing as much absorption as observed. This success is primarily because of the updated feedback model used in these simulations, where supernovae as well as energetic winds driven by supermassive blackholes generate strong outflows of metal from galaxies.

In fact, an interesting prediction emerges from IllustrisTNG about the properties of OVI surrounding galaxies. Using the simulation, we find a correlation between the color of a galaxy and the total amount of oxygen in its CGM. The culprit is feedback energy from the central black hole: in the process of quenching, high-velocity outflows from this central engine physically push some oxygen out of the halo and to larger distances, while at the same time increasing the temperature and lowering the density of the remaining halo gas. Both effects combine to systematically lower the amount of OVI found around red galaxies, a theoretical prediction which will require future observations to either confirm or disprove. (Dylan Nelson)

2.8 A novel 3D technique to study the kinematics of lensed galaxies

In the standard model of cosmology, galaxies form as the baryonic gas cools at the centre of dark matter halos. They subsequently grow through accretion and mergers, leading to the hierarchical build-up of galaxy mass. While this general picture is well known, there are numerous physical mechanisms determining the relative contribution of baryons and dark matter within a galaxy and several open questions remain: What are the most important physical mechanisms that lead to the variety of galaxies we observe today? How do these mechanisms influence the matter content within galaxies? The answer to these questions is one of the significant challenges of modern astrophysics.

The study of galaxy kinematics has played a key role in this context. For example, in the local universe, the flatness of observed rotation curves is a well-established fact. The outer parts of the observed rotation curves cannot be explained by the mass predicted from the observed stellar and gas distribution and this discrepancy has been interpreted as evidence for the presence of a "dark matter" halo. Within high redshift galaxies, however, the relative content of baryons and dark matter is poorly known and also its evolution with cosmic time is not well understood. Neither current numerical simulations nor observational studies were able to produce consistent results on the fraction of dark matter within young galaxies.

The diverging results on the kinematics of high-redshift galaxies - and in consequence on their matter content - can be ascribed to the different methods used to overcome the obser-

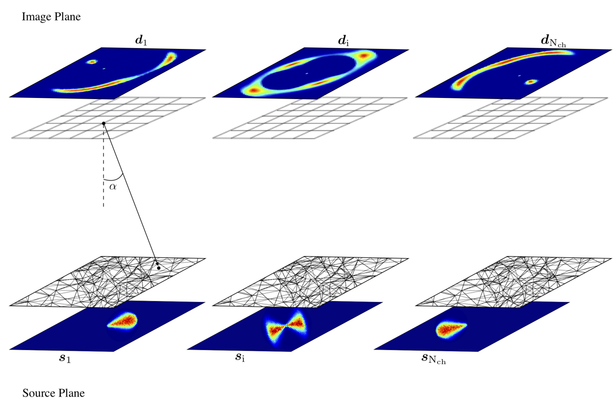

Figure 2.17: This schematic view shows lensed images in the top row and the source plane in the bottom row. Lensed data are shown for three representative velocity channels of the data cube; the respective grid on the image plane is regular. For each velocity channel, the position of a pixel in the image plane corresponds to a position on the source plane (lower panel), determined by the lens equation. The points form the vertices of a triangular adaptive grid on the source plane. The source grid automatically adapts with the lensing magnification, so that there is a high pixel density in the high-magnification regions close to the caustics. *Credit: MPA*

vational limitations. The study of kinematics is mainly hampered by two factors: low spatial resolution and low signal-to-noise ratio.

These observational limitations can be successfully overcome by targeting galaxies for which the line of sight lies very close to a foreground galaxy. The gravitational field of the foreground galaxy then deflects the light from the distant background galaxy, producing distorted, magnified, and even multiple images of the background object. This effect is known as strong gravitational lensing and it offers the opportunity to study the background galaxies at high physical resolution and with good signal-to-noise. Furthermore, the magnifying power of gravitational lensing opens the possibility to study faint galaxies with low stellar masses, which are not easily accessible by surveys targeting unlensed galaxies.

The gravitational lensing group at MPA developed the first three dimensional lens modelling method (see Figure 2.17). This can be applied to 3D (IFU or radio) data, characterized by two spatial dimensions and one spectral dimension (velocity, frequency or wavelength), to simultaneously reconstruct both the mass distribution of the foreground galaxy and the kinematics of the background galaxy (see Figure 2.18).

Our method represents a significant improvement over those used until now, since it does not require the use of high-resolution imaging data for the derivation of the lens parameters, as these are derived from the same 3D data used for the kinematics of the background galaxy. Moreover, the latter is not obtained by fitting on the source plane, but directly the lensed data. This is achieved in a hierarchical Bayesian fashion, where the kinematics on the source plane is essentially a hyper-parameter of the model (i.e. a parameter defining the prior). We are thus able

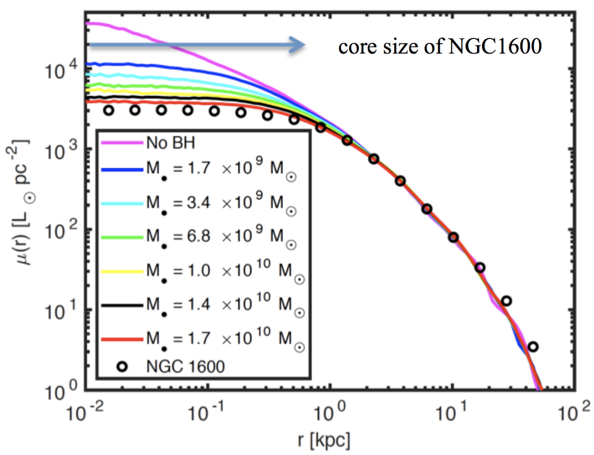

Figure 2.18: Data and modelling for one simulated 3D dataset. The rows show three representative channel maps, corresponding to three velocities. Column 1 shows the input source, a rotating disc with its approaching (first row) and receding side (third row); the middle row shows the component which is at rest relative to the observer. Each row is then lensed forward to obtain the mock lensed data in Column 2. The model obtained with the 3D-lens modelling method is shown in column 3 and the residuals (difference of the data and the model) in column 4. From this model, both the source (column 5) and its kinematics (column 6) can be reconstructed *Credit: MPA*

to study the possible degeneracies between the lens and kinematic parameters and estimate the uncertainties consistently.

With our technique we are able to recover both the lens and the kinematics parameters with great accuracy under different observational conditions. Furthermore, we have successfully tested the capability of this new method in recovering a variety of rotation curves with shapes which are prototypes of different morphological galaxy types, from dwarf to massive spiral galaxies (see Figure 2.19). (Francesca Rizzo and Simona Vegetti)

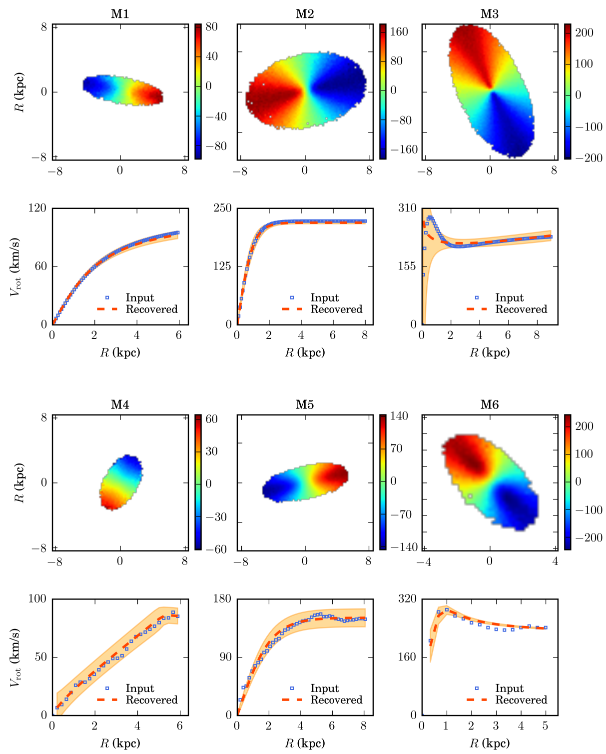

Figure 2.19: For different mock background galaxies, these plots show the velocity fields (upper panels) and rotation curves (bottom panels). The velocity field is colour coded (see bar on the side) with red areas moving away from the observer and blue areas moving towards the observer. The original rotation curves are shown in blue and the best fit kinematic model is shown in red. The orange band shows the possible errors from uncertainties of the parameters that defined the rotation curves. The mock data M1-M3 have input rotation curves described by functional forms, while for M4-M6 the rotation curves were taken from real galaxies. The rotation curves of M1 and M4 are typical of dwarf galaxies, the rotation curves of M2 and M5 are prototypes of spirals, while those of M3 and M6 are typical of massive spirals with a prominent bulge. *Credit: MPA*

2.9 The formation of the most diffuse giant galaxy cores in the Universe

Massive elliptical galaxies are not just the largest with up to 1013 solar masses they also have markedly different properties than their smaller siblings. At their centres they harbour supermassive black holes (SMBHs) with typical masses of 0.1% of the total stellar mass of the galaxy i.e. these SMBHs can easily exceed billions of solar masses. Also the properties of the stars in the centres of these galaxies are very special. The observed surface densities are much lower than for other giant galaxies, and instead of steep central cusps, these galaxies have very flat density cores. In addition, in many cases the stars in the central regions are predominantly moving on circular orbits, with a conspicuous lack of stars on more radial orbits. Furthermore, the central region as a whole is often rotating quite disconnected from the rest of the galaxy a property termed decoupled rotation.

The reason behind these differing properties might be merger events - merging elliptical

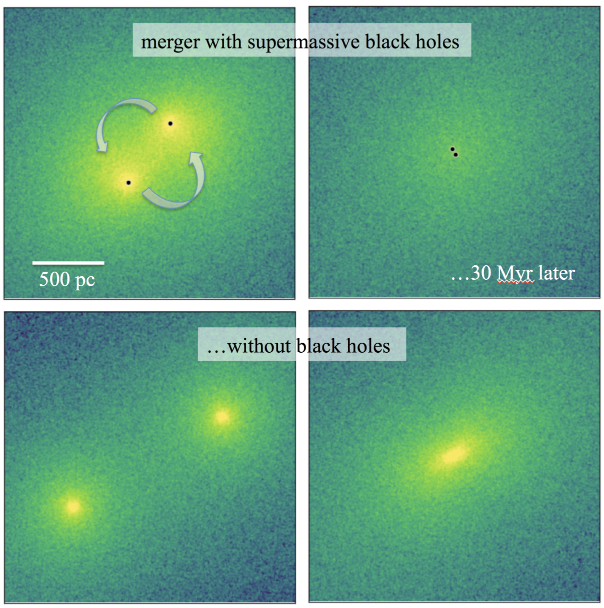

Figure 2.20: These images show the stellar density distribution in the centres of merging elliptical galaxies. About 30 million years before the final coalescence of the galactic nuclei the supermassive black holes (black dots) are still surrounded by a concentration of stars (upper left panel). When the black holes form a tight binary most of these stars have been ejected, leaving behind a low-density core (upper right panel). A core does not form if the galaxies do not have supermassive black holes (bottom panels) *Credit: MPA*

galaxies can be commonly observed in the sky. Already, numerical models have indicated that low-density cores can form when two elliptical galaxies merge. The coalescing nuclei with the SMBHs eject stars from the galaxy centres in a process called SMBH scouring. Reliable models for this process require very accurate simulation codes in order to correctly resolve the small-scale gravitational interaction of the forming binary black holes with the surrounding stars and the final merger of the SMBHs. Earlier studies so far have typically been limited to relatively low particle numbers as well as idealized galaxy models, and often did not simulate the final merger of the two SMBHs.

A team of researchers from the University of Helsinki and MPA/MPE have developed a novel simulation method called KETJU the Finnish word for chain. This simulation technique allows for much larger and more accurate simulations. The KETJU code combines a hierarchical tree method on large-scales with a modern regularization procedure on small-scales. This allows for the accurate computation of the gravitational forces on kilo-parsec scales in the galactic halo down to the milli-parsec scales where the binary SMBHs emit gravitational waves and finally merge. The simulated elliptical galaxy mergers are also more realistic, as they now include the massive and extended dark matter halo component, in addition to the central stellar component.

The study demonstrates that a central low-density core can form rapidly on a timescale of $\sim$ 30 Myr – but only in cases where merging binary SMBHs are found in the centre of the galaxy. Over this timescale, stars with a total mass similar to the combined mass of the two SMBHs are ejected from the galaxy. In the absence of central SMBHs the central region keeps

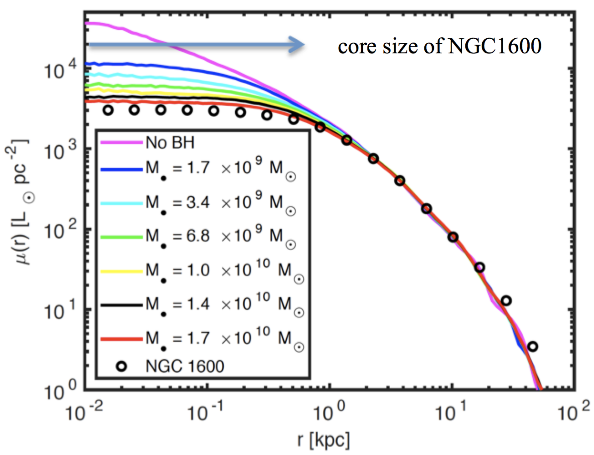

Figure 2.21: Surface brightness distribution of 7 elliptical galaxy merger simulations with increasing masses of the central SMBHs (various colours, from top to bottom). The magenta line shows the simulation without SMBHs. For increasingly more massive black holes, the central surface brightness is systematically reduced and a larger region of the central core is affected. The models can even explain the observed surface brightness distribution of NGC1600 (open circles), a galaxy with an unusually massive SMBH *Credit: MPA*

its high stellar density and no stars are ejected (Fig. 2.20). The ejection process is stronger for more massive black holes, in good agreement with observations. The simulations can even explain the very extended core region of the very massive galaxy NGC1600 (Fig. 2.21). For its stellar mass this galaxy has an unusually massive black hole with an accompanying very large low-density core region.

However, the merging black holes affect not only the stellar density of the cores but also the kinematics of the stars in the central region. After the ejection process, the remaining stars are mostly moving on circular orbits and do not come close to the central SMBH binary. Stars on more radial orbits have already before experienced strong interactions with the central SMBH binary and have been kicked out as a result. Again, this process is found to be stronger for more massive SMBHs and agrees well with observational estimates. Finally, the study also shows that massive SMBH binaries can give rise to rotation of the core region. In the case presented here the core is even counter-rotating (Fig. 2.22). This type of decoupled or misaligned rotation is commonly observed in many massive elliptical galaxies with both SMBHs and low density cores.

The team was able to demonstrate that all major photometric and kinematic properties of the centres of massive elliptical galaxies, such as low density cores, velocity anisotropies, and decoupled rotation, can be explained by a single process: the dynamical evolution and eventual coalescence of SMBHs in a galaxy merger. This process can explain the origin of even the most diffuse galaxy cores in the Universe. In a follow-up study the researchers will investigate the gravitational wave emission signals from the final stages of the SMBH mergers. (Thorsten

Naab)

2.10 The formation of (very) slowly rotating stars

Some stars rotate much faster than the Sun. The star CU Virginis, a single star in the constellation Virgo for example, has a rotation period of only half a day. At the other extreme are stars like Gamma Equulei (the nose of the little horse), which rotates with a period of at least 70 years. That's more than 50 000 times slower. Both stars are members of a special class, the so-called magnetic Ap stars. (Both are just visible with the naked eye.) The rotation period of Ap stars can be measured from changes of the observed strength of the magnetic field on its surface, as the field configuration rotates into and out of view.

But also normal stars more like the Sun show something related: already at a very young age they rotate with periods ranging all the way from a half a day to some 100 days. The rapidly rotating ones are easily explained: small random motions in a star forming cloud are amplified by angular momentum conservation, in parts of the cloud that contract to form protostars. If this were the only effect, however, it would produce only very rapidly rotating stars.

But the contracting gas also has a magnetic field, which gets amplified by the same contraction. At some stage(s) of the star formation process (in particular inside the Herschel filament of Fig. 2.23), this field will be bent (see the sketch in Fig. 2.24). This magnetically dominated form of accretion is sometimes called a pseudodisk, as it differs from the standard view of stars building up their mass through an accretion disk without a strong magnetic field. This view assumes that

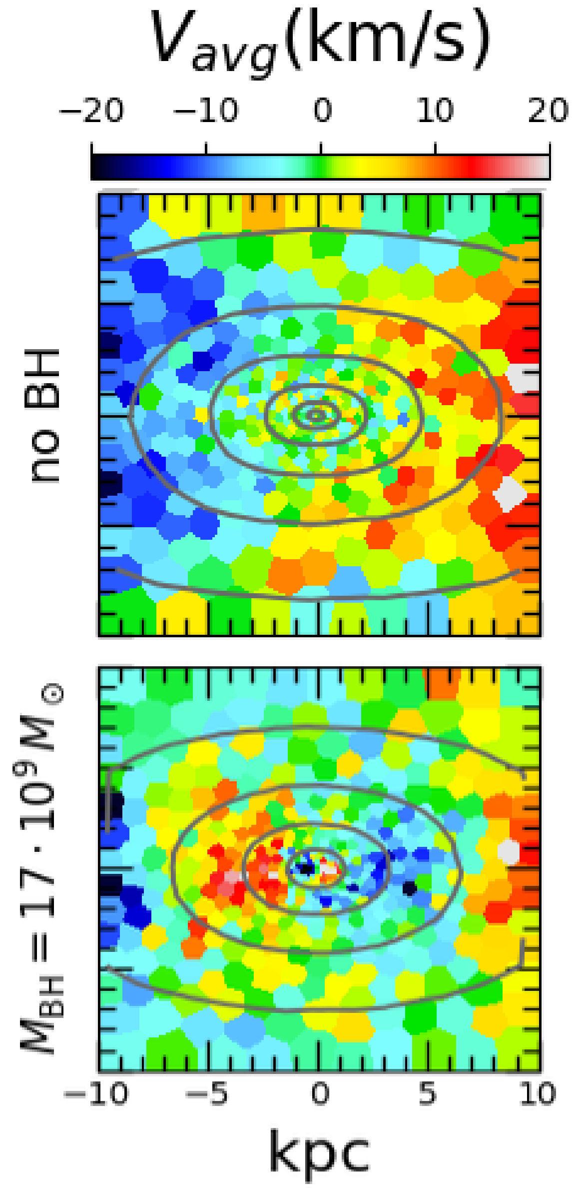

Figure 2.22: Velocity maps for simulations with no black hole (top) and a supermassive black Hole (SMBH with 17 109 solar masses, bottom). Blue coloured regions are moving towards the observer, red coloured regions are moving away from the observer. A counter-rotating region of the size of the diffuse core is forming in the centre if the SMBH is very massive very much like in observed giant elliptical galaxies. The contours indicate constant surface density. *Credit: MPA*

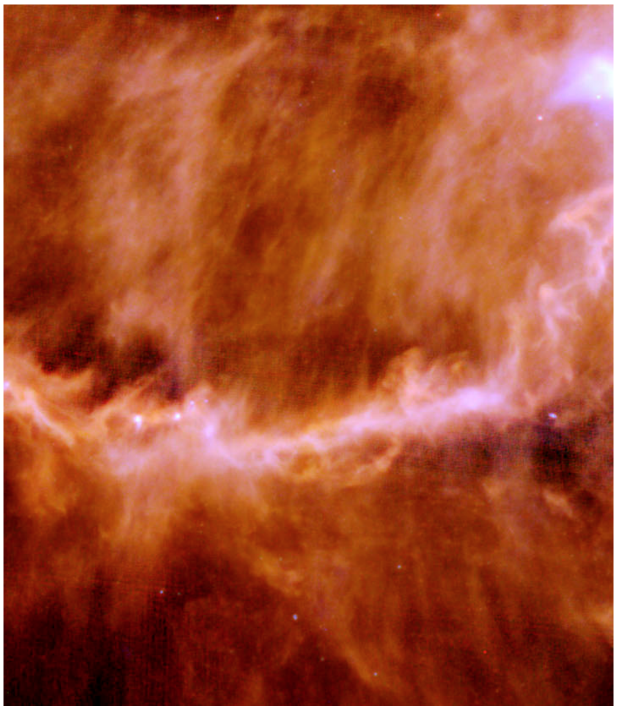

Figure 2.23: The famous star forming filament B211 in the Taurus molecular cloud, as observed with the Herschel satellite. Above and below the filament threads called 'striations' are faintly visible, they trace out the magnetic field of the cloud. Radio telescopes show that gas flows towards the filament along these striations, guided by the magnetic field. In the dense gas accumulating in the filament itself stars are forming, a few are already visible as bright dots. *Credit: ESA/Herschel*

the magnetic field has largely left the gas already at an early stage. In such a disk the host stars gravitational attraction is balanced by orbital rotation of the gas (like planets orbiting their host star).

In a pseudodisk, however, the magnetic tension force between the contracting core and the birth cloud to which it is still connected tries to maintain the very slow rotation of the cloud. The balance between angular momentum conservation and magnetic tension now determines whether the star formed will be a slowly or a rapidly rotating one. Observations appear to show that the balance can tip either way. The work reported here explains how this balance works, and how it can lead even to extremely long rotation periods.

Minor differences in the random velocities in the initial state of the star forming gas cloud can lead to opposite outcomes: either very fast or very slowly rotating stars (see Fig. 2.25). The very slowly rotating ones have accreted mass without accreting angular momentum. Key to the explanation of this result is the observation that it does not take much of a magnetic connection to extract the angular momentum of already slowly rotating gas. The slower the gas rotates, the more effective is the connection to the birth cloud in slowing it to even longer periods. Once this sequence of events is on its way, the gas will end up rotating on typical time scales just like the birth cloud, well before it ends up on the protostar. Its remaining path to the protostar is then determined by gravitational attraction, the opposing magnetic tension, and diffusion of gas across the field lines. A magnetic connection extending to a distance like the orbit of Pluto, for example, would be sufficient to explain final rotation periods of centuries. The calculations show that this unexpected outcome depends critically

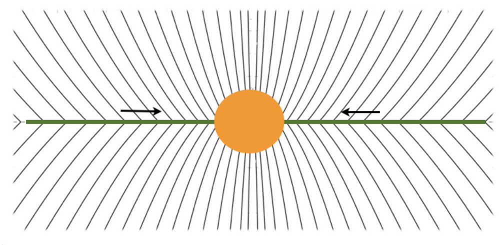

Figure 2.24: Schematic showing the expected shape of the magnetic field lines around a protostar in objects like the B211 filament of Fig. 1. The field lines, still connected at large distances to the star forming cloud, have a kink at the midplane. This distortion is due to the weight of the gas (green) under the force of gravity of the protostar (yellow). The kinks are subject to diffusion of gas across the field lines, allowing the gas to accrete onto the protostar (arrows). *Credit: MPA*

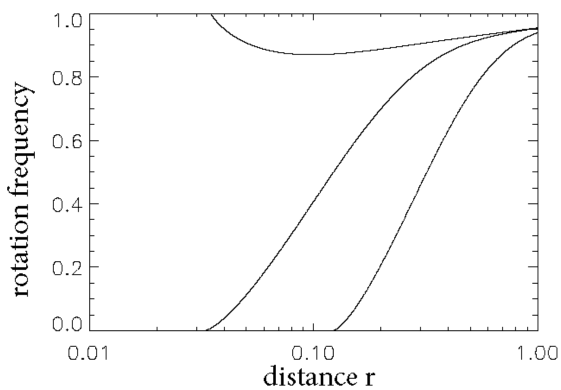

Figure 2.25: Orbital frequency of the gas drifting towards the protostar, in units of the frequency of a local Kepler orbit, as a function of distance r from its centre. Starting at the right boundary (r=1), with a frequency just below that of a Kepler orbit, the calculations show how the rotation of the gas changes as it approaches the protostar (at r=0). With only small differences in the initial rotation, there are two possible outcomes: either the tendency to conserve angular momentum wins and the gas ends up on a Kepler orbit (upper curve), or magnetic torques win and the gas loses its rotation (lower two curves). *Credit: MPA*

on the initial rotation of the gas: it has to be a bit slower than a Kepler orbit.

Observations of protostars indicate that they probably form episodically, in bursts rather than as a continuous process. This may also explain the range of intermediate rotation periods observed in young star clusters, if the balance tips randomly a few times between bursts of accretion with opposite outcomes. This speculation can probably be tested with the large new data sets becoming available from observatories like the Kepler satellite or ALMA. (Henk Spruit)

2.11 Studying Lyman-α-galaxies with strong gravitational lensing

Lyman-α-emitting (LAE) galaxies represent a unique probe of the young Universe, about 1 to 2 billion years after the Big Bang. Typical LAEs are characterised by high-ionisation and strong star formation with low metallicity (i.e. few elements heavier than hydrogen and in general a low mass. The Lyman-α emission is produced when electrons recombine with the ionized hydrogen atoms and the properties cited above, combined with low dust content, allow for the escape of a significant fraction of these photons. While this emission is thought to have had a crucial role in the reionisation of the young Universe, very little is known about the detailed structure of these galaxies and, most importantly, about the mechanism that leads to the production of these high-energy photons.

So far the study of these high-redshift objects has been limited to quantifying the properties of their strong optical lines. Alternatively, many efforts have been spent to identify local analogues, i.e. nearby galaxies presenting similar physical and morphological characteristics. Both these approaches, however, require significant investment in telescope time.

Another resource to study these galaxies lies in high-resolution imaging studies that so far have been very useful to reveal their structure. LAEs are found to be quite compact objects and there is no evidence that they change their size as they evolve. Moreover they are surrounded by a large Lyman-α-emitting halo which is on average 10 times more extended than the UV continuum emitting region. Also this halo does not show an evolution in size with redshift. However, such

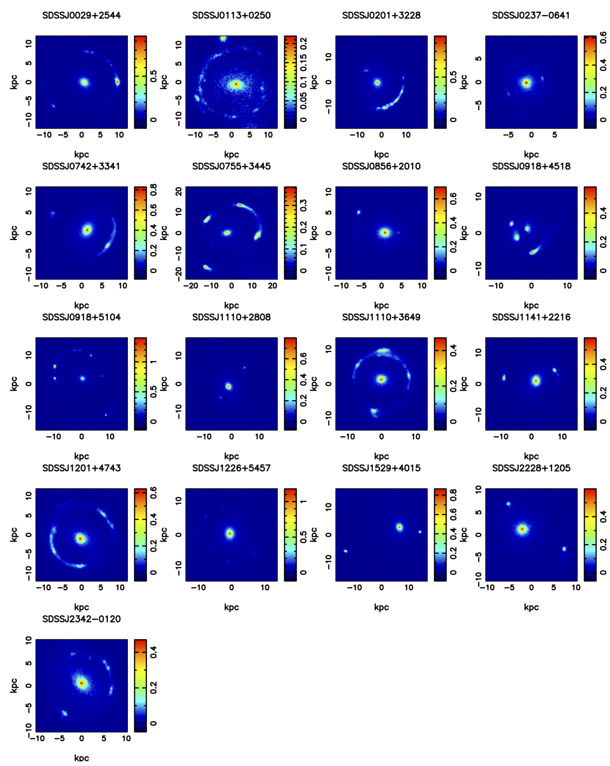

Figure 2.26: Images by the Hubble Space telescope of all gravitational lens systems. The surface brightness scale is in electrons per second. The lensing morphologies are quite varied, from nearly complete Einstein rings to very compact 2-image systems. *Credit: MPA*

studies are currently limited by the angular resolution of the observations and struggle to reveal the detailed structure of these objects.

Strong gravitational lensing can be used to overcome these limits. The first statistically significant sample of LAEs at $z \sim 2.5$, strongly lensed by early type galaxies at $z \sim 0.5$, has recently been revealed by observations with the Hubble Space Telescope. Due to the lensing magnification by a factor of about 20, we can access and probe the detailed structure of these galaxies at scales around 100 pc (some 300 light-years).

We have studied the intrinsic properties of the UV-continuum emission of these LAEs and we found that they have a median star formation rate of 1.4 solar masses per year with peaks of up to 54 solar masses per year. (This is actually a lower limit as we could not correct for dust attenuation.) We have found these galaxies to be quite compact, with a median size of about 500 pc and a range of radii from 200 to 1800 pc our Milky Way with about 60 000 pc is gigantic compared to these LAE. Interestingly, they show quite complex morphologies with several compact and diffuse components, while in some cases they appear to be interacting. In two cases (14 percent of 17?) the galaxies seem to have off-axis components that may be associated with mergers.

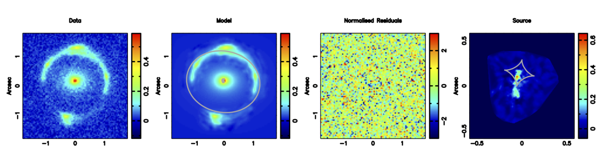

Figure 2.27: These images show the lens model of one of the systems in the sample showing the actual data, the model, normalized residuals, and the reconstruction of the source (from left). Critical curves and caustics are plotted in grey. *Credit: MPA*

Most interestingly, our LAEs are found to be quite elliptical, with a mean axis-ratio of about 0.5. This morphology is consistent with disk-like structures of star-formation for three-quarters of our sample, which would rule out models where the Lyman-α-emission is only seen perpendicular to the disk to favour instead clumpy models. Our results are in agreement with the studies of non-lensed LAEs at similar redshifts, but are more robust given the improved angular resolution of our analysis and given that no stacking techniques are needed.

With 200 pc, our lower limit on the intrinsic size of these objects is a factor of two smaller than what is achieved in non-lensed LAEs studies. In general our analysis further promotes gravitational lensing as a powerful tool to analyse and resolve the detailed structure of high-redshift galaxies, allowing the study of their physical and morphological properties at a resolution otherwise only achievable with nearby targets. (Elisa Ritondale and Simona Vegetti).

2.12 Gamma-rays Reveal the History of Star Formation in the Universe

For their study, the scientists made use of the Fermi Gamma-ray Telescope to track the number of gamma rays, the highest energy form of light, from distant galaxies containing a supermassive black hole. How does this measure extragalactic background light? Because the gamma rays are so energetic, they collide with photons in the EBL and transform into mat-

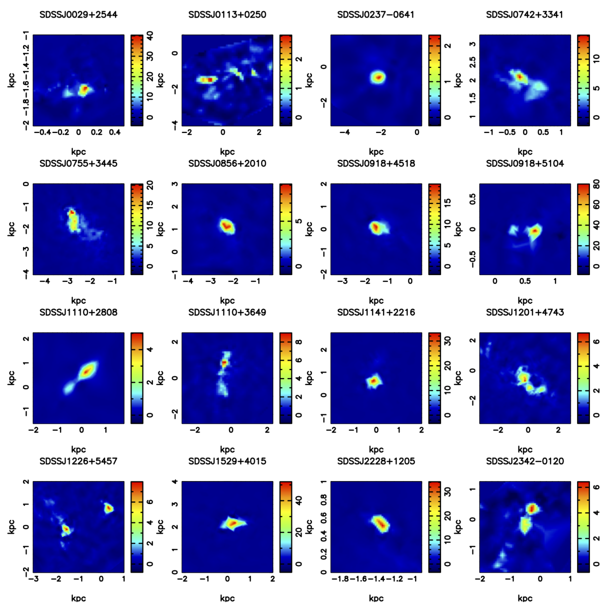

Figure 2.28: The star-formation rate intensity of the objects from Fig. 2.26, based on the source reconstructions from the grid-based gravitational lens modelling. The colour-scale for each object is in units of solar masses per year in a square with 1 kiloparsec on the side. (The reconstruction of the object J0201+3228 was not included as this presented strong residuals.) *Credit: MPA*

ter. According to Einsteins famous equation $E = mc^2$, one electron and one positron are created. The denser the EBL, the more often this interaction takes place. Like a lighthouse beacon shining through a thick fog, the collisions result in many of the gamma-rays being absorbed by the cosmic fog composed of ultraviolet, visible and infrared starlight. As a result, fewer gamma-rays reach Earth than started the long journey. By examining the apparent lack of gamma rays, the team was able to reconstruct the properties of the intervening EBL.

The black holes that produce the gamma rays are millions to billions times more massive than the Sun. Feeding vigorously on gas, they spew out extremely energetic particles in narrow jets shooting outwards from the center. If one of these jets is pointed directly at Earth it is called blazar. The study used 739 blazars detected by Fermi on the entire sky that are distributed over a vast range of distances (see Figure 2.29). The most distant blazar in the sample emitted its gamma rays when the Universe was only 15% its current age. The blazars gave the scientists many sightlines to study the cosmic fog. The team was able, for the first time, to map the gradual buildup of the EBL, the rate at which galaxies add more light into the EBL over cosmic time.

The fact that the night sky appears dark means that the EBL must be exceedingly dim. The study measures it to be equivalent to a single 60-watt light bulb viewed in complete darkness at a four kilometre distance, with the bulbs light spread out over the entire sky. As the universe has expanded to an immense size, the accumulated light from all stars and galaxies has indeed become very diluted. A major obstacle for traditional methods has been to measure the relatively faint EBL in the presence of much brighter contaminants in the foreground, particularly from interplanetary dust in our own solar system (the Zodiacal Light). However, the gamma-ray absorption method is immune to these challenges and offers a clean view of the extragalactic component. The results therefore provide the best measurements of the background light in the ultraviolet, visible and near-infrared parts of the electromagnetic spectrum.

Even after stars burn out, their light continues to travel across the universe. A small part of todays EBL must therefore have originated very early-on in the universes history. Because the sample of blazars extends to distances over half-way across the universe, their gamma-ray absorption signatures can be used to infer the EBL in the early days of galaxy assembly. The study places limits on the amount of light that existed during the epoch of re-ionization, an enigmatic era in the universes early history. During this era, the newly formed galaxies produced enough energetic light such that hydrogen in intergalactic space, the most common element, went from neutral to ionized state. The limits provide clues to be tested by the upcoming James Webb Space Telescope (launch planned in 2021), whose objective is to shed light on this largely unexplored era in the universes history.

Another breakthrough of the study is the ability to accurately reconstruct the history of the star formation in the universe. This has not been attempted using gamma rays before. The amount of ultra-violet light added to the EBL at any given time is closely related to how fast stars are forming in galaxies. This is because massive, newly formed stars shine brightly in the ultra-violet for a short time, contribute light to the EBL, and then quickly burn out. The ultra-violet part of the EBL therefore tells us how many stars of all masses are forming.

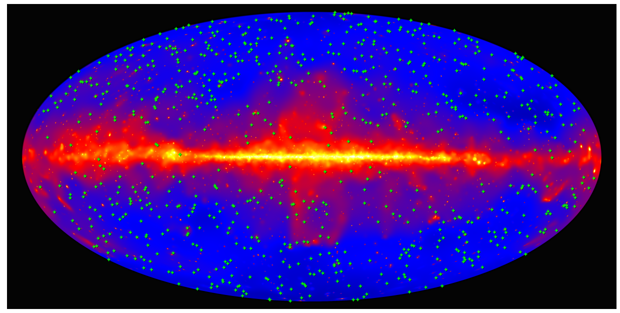

Figure 2.29: The gamma ray sky seen by the Fermi satellite. The band across the middle is the disk of our Milky Way galaxy. The sample of blazars used in this study are marked with green symbols. *Credit: NASA/DOE/Fermi LAT Collaboration*

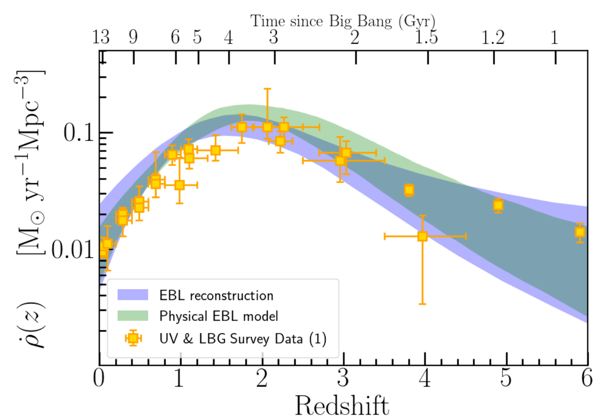

Figure 2.30: This plot shows the star formation history of the universe (number of stars formed per mass and volume) as a function of cosmic time or redshift. The star formation history determined from this study is shown as blue and green areas. The results are in good agreement with independent data from large galaxy surveys (yellow data points). *Credit: AAAS/K. Helgason*

Using large galaxy surveys, astrophysicists have studied the star-formation history of the universe for decades. The consensus is that star formation peaked around 10 billion years ago and has since been on the decline. But one drawback faced by previous research was that some galaxies are just too far away, or too faint, for any telescope to detect. Scientists have therefore had to estimate the amount of star formation missed by these surveys, rather than directly observe it.

The new study circumvents this issue because it is deals with all EBL photons, regardless of whether they originated in bright or faint galaxies. The results, however, show that the star formation history recorded by the EBL over 90% of the age of the universe is in good agreement with that of counting galaxies (see Figure 2.30). This indicates that the majority of star formation has been accounted for in traditional surveys.

In other words, two vastly different methods have given us the same answer. In science, that usually means that we are doing something right. (Kari Helgason)

Chapter 3

Publications and Invited Talks

3.1 Publications in Journals

3.1.1 Publications that appeared in 2018(234)

Abolfathi, B., Aguado, D.S. et al. (incl. A. Jones): The Fourteenth Data Release of the Sloan Digital Sky Survey: First Spectroscopic data from the extended Baryon Oscillation Spectroscopic Survey and from the second phase of the Apache Point Observatory Galactic Evolution Experiment. Astrophys. J. Suppl. **235(2)** 42 (2018).

Agnello, A., Lin, H., et al. (incl. S. Suyu): DES meets Gaia: discovery of strongly lensed quasars from a multiplet search. Mon. Not. R. Astron. Soc. **479(4)**, 4345-4354 (2018).

Agnello, A., Grillo, C., et al. (incl. S. Suyu): Discovery and first models of the quadruply lensed quasar SDSS J1433+6007. Mon. Not. R. Astron. Soc. **474(3)**, 3391-3396 (2018).

Agrawal, A., Fujita, T., and E. Komatsu: Tensor non-Gaussianity from axion-gauge-fields dynamics: parameter search. Journal of Cosmology and Astroparticle Physics, **2018(6)** 027 (2018).

Agrawal, A., Fujita, T., and E. Komatsu: Large tensor non-Gaussianity from axion-gauge field dynamics. Physical Review D, **97(10)** 103526 (2018).

Aihara, H., Arimoto, N., et al. (incl. S. Suyu): The Hyper Suprime-Cam SSP Survey: Overview and survey design. Publications of the Astronomical Society of Japan, **70(SP1)** S4 (2018).

Alp, D., et al. (incl. A. Wongwathanarat and H.-Th. Janka): X-Ray Absorption in Young Core-collapse Supernova Remnants. Astrophys. J. **864** 175 (2018).

Alp, D., et al. (incl. A. Jerkstrand, H.-Th. Janka, M. Gabler): The 30 Year Search for the Compact Object in SN 1987A. Astrophys. J. **864** 174 (2018).

Amati, L., O'Brien, P. et al. (incl. B. Ciardi): The THESEUS space mission concept: science case, design and expected performances. Advances in Space Research, **62(1)**, 191-244 (2018).

Amorisco, N. C. (2018). The virial mass distribution of ultradiffuse galaxies in clusters and groups. Mon. Not. R. Astron. Soc. Lett., **475(1)**, L116-L121 (2018).

Amorisco, N. C., Monachesi, A., Agnello, A., and S.D.M. White: The globular cluster systems of 54 Coma ultra-diffuse galaxies: statistical constraints from HST data. Mon. Not. R. Astron. Soc. **475(3)**, 4235-4251 (2018).

Ando, S., Benoit-Levy, A., and E. Komatsu: Angular power spectrum of galaxies in the 2MASS Redshift Survey. Mon. Not. R. Astron. Soc. **473(4)**, 4318-4325 (2018).

Andreani, P., Retana-Montenegro, E., et al. (incl. S. Vegetti): Extreme conditions in the molecular gas of lensed star-forming galaxies at $z \sim 3$. Astron. Astrophys. **615** A142 (2018).

Arias, M., Vink, J., et al. (incl. B. Ciardi): Low-frequency radio absorption in Cassiopeia A. Astron. Astrophys. **612**, A110 (2018).

Armitage, T. J., Barnes, D. et al. (incl. Y. Bahe): The Cluster-EAGLE project: velocity bias and the velocity dispersion - mass relation of cluster galaxies. Mon. Not. R. Astron. Soc. **474(3)**, 3746-3759 (2018).

Ashall, C., Mazzali, P. A., Stritzinger M., et al.: On the type Ia supernovae 2007on and 2011iv: evidence for Chandrasekhar-mass explosions at the faint end of the luminosity-width relationship. Mon. Not. R. Astron. Soc. **477(1)**, 153-174 (2018).

Banik U., et al. (incl. G. Despali and S. Vegetti): Constraining the Mass Density of Free-Floating Black Holes using Razor-thin Lensing Arcs. Mon. Not. R. Astron. Soc.**483 (2)**, 1558-1573 (2018).

Barreira, A., Krause, E., and F. Schmidt: F. Complete super-sample lensing covariance in the response approach. Journal of Cosmology and Astroparticle Physics, **2018(6)** 015 (2018).

Behrens, C., Byrohl, C., Saito, S., and J. Niemeyer: The impact of Lyman-α radiative transfer on large-scale clustering in the Illustris simulation. Astron. Astrophys. **614** A31 (2018).

Bellini, E., Barreira, A., Frusciante, N., et al.: Comparison of Einstein-Boltzmann solvers for testing general relativity. Physical Review D, **97(2)** 023520 (2018).

Beltran, M. T., Cesaroni, R., et al. (incl. T. Peters): Accelerating infall and rotational spin-up in the hot molecular core G31.41+0.31. Astron. Astrophys. **615** A141 (2018).

Benetti, S., Zampieri, L., et al. (incl. S. Taubenberger): ASASSN-15no: the Supernova that plays hide-and-seek. Mon. Not. R. Astron. Soc. **476(1)**, 261-270 (2018).

Beuther, H., Mottram, J. C., et al. (incl. T. Peters): Fragmentation and disk formation during high-mass star formation - IRAM NOEMA (Northern Extended Millimeter Array) large program CORE. Astron. Astrophys. **617** A100. (2018).

Bolliet, B., Comis, B., E. Komatsu, and J.F. Macias-Perez: Dark energy constraints from the thermal SunyaevZeldovich power spectrum. Mon. Not. R. Astron. Soc. **477(4)**, 4957-4967 (2018).

Boni, C. D., Böhringer, H., Chon, G., and K. Dolag: Evolution of the degree of substructures in simulated galaxy clusters. Mon. Not. R. Astron. Soc. **478(2)**, 2086-2096 (2018).

Bonvin, V., J. Chan et al (incl. S. Suyu): COSMOGRAIL. XVII. Time delays for the quadruply imaged quasar PG 1115+080 Astron. Astrophys. **616** A183 (2018).

Boulanger, F., Enßlin, T., Fletcher, A. et al.: IMAGINE: a comprehensive view of the interstellar medium, Galactic magnetic fields and cosmic rays. JCAP **08** id. 049 (2018).

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3.1.2 Publications accepted in 2018

Di Matteo, P., Fragkoudi, F., Khoperskov, S. et al.: The disc origin of the Milky Way bulge: On the necessity of the thick disc Astron. Astrophys.

Planck Collaboration; Akrami, Y., et al. (incl. S.D.M. White): Planck 2018 results. I. Overview and the cosmological legacy of Planck. Astron. Astrophys.

Planck Collaboration; Aghanim, N. et al. (incl. T. Ensslin and S.D.M. White): Planck 2018 results. VI. Cosmological parameters. Astron. Astrophys.

Planck Collaboration; Aghanim, N., et al. (incl. T. Ensslin and S.D.M. White): Planck 2018 results. VIII. Gravitational lensing. Astron. Astrophys.

Planck Collaboration; Akrami, et al. (incl. T. Ensslin and S.D.M. White): Planck 2018 results. X.Constraints on inflation. Astron. Astrophys.

Schmidt, F., Elsner, F., Jasche, J., et al.: A rigorous EFT-based forward model for large-scale structure, JCAP.

Steininger, T., J. Dixit, P. Frank et al. : NIFTy 3 Numerical Information Field Theory: A Python Framework for Multicomponent Signal Inference on HPC Clusters. Annalen der Physik.

3.2 Publications in proceedings

3.2.1 Publications in proceedings appeared in 2018

Arras, P., Knollmüller, J., Junklewitz, H., and T. Enßlin: Radio imaging with information field theory. In 26th European Signal Processing Conference (EUSIPCO). Los Alamitos, CA, US: IEEE Computer Society, (pp. 2683-2687)

Bauswein, A., Clark, J., Stergioulas, N., and H.-T. Janka: Dynamics and gravitational-wave emission of neutron-star merger remnants. In M. Bianchi, R. T. Jantzen, & R. Ruffini (Eds.), The Fourteenth Marcel Grossmann Meeting: On Recent Developments in Theoretical and Experimental General Relativity, Astrophysics, and Relativistic Field Theories (pp. 4115-4120).

Cucchetti, E., Pointecouteau, E., et al. (incl. K. Dolag):. Simulating x-ray observations of galaxy clusters with the x-ray integral field unit onboard the ATHENA mission. In J.-W.-A. Den Herder, S. Nikzad, & K. Nakazawa (Eds.), Space Telescopes and Instrumentation 2018: Ultraviolet to Gamma Ray (pp. 1-11).

Garaldi, E., Compostella, M., and C. Porciani: Quasars at the Cosmic Dawn: effects onReionization properties in cosmologicalsimulations. In V. Jelic, & T. van der Hulst (Eds.), Peering towards Cosmic Dawn (pp. 56-59).

Jerkstrand A.: Determining nucleosynthesis yields in supernovae with spectral modelling. In M.-K. Cheoun, K. I. Hahn, S. Jeong, S. C. Kim, K. Kwak, Y. S. Lee, et al. (Eds.), 14th International Symposium on Origin of Matter and Evolution of Galaxies (2018).

Mereghetti, S., Savchenko, V., et al. (incl. R. Sunyaev). INTEGRAL results on the electromagnetic counterparts of gravitational waves. Memorie della Societa Astronomica Italiana, 89(2), (pp. 230-235).

Pavlinsky, M., et al. (incl. R. Sunyaev, E. Churazov and M. Gilfanov). ART-XC / SRG overview. In J.-W.-A. Den Herder, S. Nikzad, and K. Nakazawa (Eds.), Space Telescopes and Instrumentation 2018: Ultraviolet to Gamma Ray (pp. 1-10).

Suyu, S. H. (2018). Progress toward an accurate Hubble Constant. In A. Tarchi, M. J. Reid, and P. Castangia (Eds.), Astrophysical Masers: Unlocking the Mysteries of the Universe (IAU Symposium 336) Cambridge, UK: Cambridge University Press (pp. 80-85).

Weiss, A., Aguirre, V. S., and J. Christensen-Dalsgaard: Using low-mass stars as a tool: efforts towards precise models. In C. Chiappini, I. Minchev, E. Starkenburg, and M. Valentini (Eds.), Rediscovering our Galaxy (IAU Symposium 334) Cambridge, UK: Cambridge University Press (pp. 178-181).

3.3 Talks

3.3.1 Invited review talks at international meetings

E. Churazov: Perseus in Sicily: from black hole to cluster outskirts , (Noto, Italy, 14.5-18.5)
– COSPAR General Assembly, (Pasadena, USA, 14.7.-22.7.)
– Frontiers of 21st Century Physics and Ioffe Institute (Sankt Peterburg, Russia, 29.10.-1.11.)

B. Ciardi: IGM2018: Revealing Cosmology and Reionization History with the Intergalactic Medium (Tokyo, Japan, 18.9.-21.9.)
– Rise and shine: galaxies in the epoch of reionization (Strasbourg, France, 18.6.-22.6.)

T.A. Enßlin: University of Amsterdam symposium on Information (Amsterdam, Netherlands)
– 2018 Postgraduate SKA Bursary Conference (Port Elizabeth, South Africa)
– workshop on Radio imaging with compressed sensing (Cape Town, South Africa)
– Web-meeting of darkmachines project (www.darkmachines.org, remotely)
– Barolo Astroparticle Meeting on the Anisotropic Universe (Barolo, Italy)
– workshop on Clustering and Unsupervised Classification for Forensics (European Commission Joint Research Centre, Ispra, Italy)
– 5th IMPRS Student Symposium (MPE Garching, Germany)

M. Gilfanov: IAU GA, IAU Symposium 346 "High Mass X-ray Binaries: illuminating the passage from massive binaries to merging compact objects" (Vienna, Austria, 20.08–31.08.)
– Santander 2018: Stellar Winds in Wind-Fed Systems (Santander, Spain, 08.10–11.10.)

H.-Th. Janka: Supernovae — From Simulations to Observations and Nucleosynthetic Fingerprints (Bad Honnef, Germany, 21.1.–24.1.)
– Conference on "The Transient Universe" (Singapore, 26.2.–1.3.)
– 12th BONN Workshop on Formation and Evolution of Neutron Stars (Bonn, Germany, 14.5.)
– Shocking Supernovae: Surrounding Interactions and Unusual Events (Stockholm, 28.5.–1.6.)
– Neutrino 2018 – XXVIII International Conference on Neutrino Physics and Astrophysics (Heidelberg, Germany, 4.6.–9.6.)
– Gamma-ray Bursts and Supernovae: From the Central Engine(s) to the Observer (Paris, France, 25.6.–20.7.)
– Chemical Evolution and Nucleosynthesis Across the Galaxy (CENAG) (Heidelberg, Germany, 26.11.–29.11.)

A. Jerkstrand: Shocking Supernovae: surrounding interactions and unusual events (Stockholm, Sweden, 28.5.-1.6.)
– Core collapse supernovae and gamma-ray bursts: from the central engine(s) to the observer (Paris, 25.6.-20.7.)

E. Komatsu: "General Relativity - The Next Generation" (Yukawa Institute for Theoretical Physics, Kyoto University, 19.2.-23.2.)
– "Probing Fundamental Physics with Spectral Distortions" (CERN, 12.3.-16.3.)
– "COSMO-18" (Institute for Basic Science, Daejeong, Korea; 27.8.-31.8.)

E. Müller: Core collapse supernovae (Russbach, Austria, 19.3.-23-3.)
– Gamma-ray bursts and supernovae: from the central engines to the observer (Orsay, France, 24.6.-6.7.)

V. Springel: "Ringberg Workshop on Computational Galaxy Formation" (Castle Ringberg, Tegernsee, 19.3.–23.3.)
"Stars, Planets, and Galaxies Conference" (Harnack House Berlin, 13.4.–18.4.)
– "Multi-scale physics of star formation and feedback during galaxy formation" (Heidelberg, 25.6.–27.6.)
– "15th Potsdam Thinkshop: The role of feedback in galaxy formation" (Potsdam, 3.9.-7.9.)
– "Dynamic simulation of systems with large particle numbers" (Heidelberg, 24.9.-26.9.)
– "Intracluster-Medium Physics and Modelling Workshop" (ESO Supernova, 8.10.–10.10.)

H. Spruit: Magnetic fields in stars (Observatoire Midi Pyrenes, Toulouse, 25.6.-29.6.)
– The Gamma Cas phenomenon in Be stars (Observatoire de Strasbourg, 3.9.-5.9.)
– Modern techniques in solar physics (Smadalaroe Gard, Stockholm, 29.8.-30.8.)

R. Sunyaev: CERN, "Probing fundamental physics with CMB spectral distortions" 12.3.-16.3.)
– Marcel Grossmann Meeting, (Rome, Italy, 1.7.-7.7.)
– Ioffe Institute 100th Anniversary, St. Petersburg, (Russia 29.10.-1.11.)

S. H. Suyu: "Observational Cosmology and Hubble Constant" (30th Rencontres de Blois - Particle Physics and Cosmology (Blois, France, 3.6.-8.6.)
– "Strongly lensed AGNs and SNe with LSST" (Conference, Lyon, France, 11.6-15.6.)
– The Hubble Constant: Implications for Cosmology (XIIth International Conference on the Interconnection between Particle Physics and Cosmology, Zurich, Switzerland, 20.8.-24.8.)

S. Taubenberger: European Week of Astron. and Space Science EWASS (Liverpool,3.4.-6.4.)

S. Vegetti: The Small-Scale Structure of Cold Dark Matter Santa Barbara, USA, 26.4.-26.5.)
– Halo Substructure and Dark Matter Searches (Madrid, Spain, 27.7-29.7.)
– Near-Far Workshop: Turnover in the UVLF (Napa, CA, USA, 4.12.-7.12.)

S. White: Lorentz Center, University of Leiden (Leiden, Netherlands, 6.2-9.2.)
– Stars, Planets and Galaxies 2018 Conference (Berlin, 13.4.-18.4.)

S. Zhukovska: IAU Symposium 343: Why Galaxies Care About AGB Stars (Vienna, Austria, 20.7.–23.7)

3.3.2 Invited Colloquia talks

F. Arrigoni Battaia: Osservatorio Astronomico di Roma, (Rome, Italy, 20.11.)

B. Ciardi: Higgs Center for Theorethical Physics (Edinburgh, UK, 23/11)

G. Despali: VI Meeting on Fundamental Cosmology (Granada, Spain, 28.5.)

T.A. Enßlin: Knowledge Exchange Series (European South Observatory, Garching, Germany)
– High Energy Group (MPE, Garching, Germany)

M. Gilfanov: Kazan Federal University (Kazan, Russia, 28.05.)

W. Hillebrandt: Heidelberg Institute for Theoretical Studies (Heidelberg, 23.4.)

H.-Th. Janka: SFB-1258 at ESO (Garching, Germany, 15.1.)
– KIT (Karlsruhe, Germany, 19.1.)
– MPI for Physics (Munich, Germany, 6.2.)
– Erlangen Center for Astroparticle Physics (ECAP (Erlangen, Germany, 16.5.)
– HITS (Heidelberg, Germany, 15.10.)

A. Jerkstrand: ESO (Garching, 18.1.)
– University College London (18.12.)

E. Komatsu: Laboratoire d'Astrophysique de Marseille; 6.4.
– University of Manchester; 2.5.
– Université catholique de Louvain; 17.5.
– Universität zu Köln; 29.5.
– University of Zürich; 7.11.

F. Schmidt: Kavli IPMU (Kashiwa, Japan, 10.4.)
– Yukawa Institute (Kyoto, Japan, 16.4.)
– Nagoya University (Nagoya, Japan, 18.4.)
– LIP (Lisbon, Portugal, 7.5.)

V. Springel: University of Amsterdam, (Amsterdam, Netherlands, 21.2.)
– ITC, Harvard Center for Astrophysics, (Cambridge, USA, 1.3.)
– Instituto de Fisica Teorica, (Madrid, Spain, 18.6.)
– Heidelberg University, (Heidelberg, 6.7.)
– Max-Planck-Institute for Radio Astronomy, (Bonn, 9.11.)
– Ludwig-Maximillians-University Munich, (Munich, 10.12.)
– Universität Wr̈zburg, (Wr̈zburg, 16.12.)

H. Spruit: The formation of (very) slowly rotating stars: Astronomical Institute University of Amsterdam (Amsterdam, 29.6.)

S. H. Suyu: – European Space Astronomy Centre (Madrid, Spain, 8.3.)
– Invited Munich Physics Colloquium, LMU and TUM, (Munich, Germany, 30.4.)
– McGill University (Montreal, Canada, 19.10.)
– Waterloo University (Waterloo, Canada, 28.11.)

W. Trick: Observatoire Astronomique de Strasbourg, (Strasbourg, France, 18.11.)

S. Vegetti: (Vienna, Austria, 22.01) – (Trieste, Italy, 28.02) – (Bologna, Italy, 6.03)
– Pisa, Italy, 7.03) – (Florence, Italy, 8.03)

S. White: Geneva Colloquium (13.2.) – San Sebastian, Spain (13.12.)

S. Zhukovska: – INAF Osservatorio Astronomico di Roma (Rome, Italy, 11.11.)
– Center for Computational Astrophysics (New York, USA, 2.5)

3.3.3 Public talks

G. Börner: Siemensstiftung München, 3.12.
– MPG-CAS Partnergroup Meeting, Shanghai, 8.3.

P. Busch: 'Simulating Universes', Chaos Communication Congress, Leipzig (28.12.)

E. Müller: – Gymnasium Raubling (8.11.)

H.-Th. Janka: – TU München (8.2.)
– Graf-Rasso-Gymnasium Fürstenfeldbruck (9.4.)

E. Komatsu: Sendai Astronomical Observatory (10.2.)
– Japan Club München (28.3.)
– Max Planck Forum (19.4.)
– Embassy of Japan (20.4.)

V. Springel: – Planetarium Mannheim (15.2)
– Wissenschaftlicher Verein Mönchengladbach (10.4.)
– DLR Astroseminar 2018, Konferenzzentrum der Luftwaffe, Köln-Wahn (24.4.)
– Karl-Rahner Akademie, Köln (24.4.)
– HITS Open House Day, Heidelberg (7.7.)

F. Schmidt: – DPG, Garching (26.1.)

3.4 Lectures and lecture courses

3.4.1 Lectures at LMU and TUM

T. A. Enßlin, SS 2018, LMU München

W. Hillebrandt, WS 2017/2018, TUM München

H.-Thomas Janka, WS 2017/2018 and SS 2018, TU München

V. Springel, SS 2018, Heidelberg University

S. H. Suyu, WS 2017/2018 and SS 2018, TU München

A. Weiss, WS 2017/2018 and SS 2018, LMU München

3.4.2 Short and public lectures

T. A. Enßlin: "Information Theory and Signal Reconstruction" (LMU Seminar at MPA, 21.6.–22.6.)

E. Komatsu: "Physics of CMB Anisotropies" (Summer School 2018, ICTP, Trieste, 18.6.–21.6.)
– "Physics of CMB Anisotropies" (Cours d'automne du LAL, Laboratoire de l'Accélérateur Linéaire, Orsay, 15.10.–17.10.)

F. Schmidt: Lecture course on bias, Summer school on large-scale structure (Berlin, 23.-27.7).

H. Spruit: University of Amsterdam (Juni 2018).

A. Weiss: IMPRS Lectures (January 2018)

Chapter 4

Personnel

4.1 Scientific staff members

Directors

E. Komatsu, G. Kauffmann, V. Springel (since 1.8.2018), S.D.M. White (Managing Director).

Research Group Leaders/Permanent Staff

E. Churazov, B. Ciardi, T. Enßlin, M. Gilfanov, H.-T. Janka, T. Naab, R. Pakmor, F. Schmidt, S. Suyu, S. Vegetti, A. Weiss.

External Scientific Members

M. Asplund, R. Giacconi († 9.12.2018), R.-P. Kudritzki, W. Tscharnuter.

Emeriti

W. Hillebrandt, R. Kippenhahn, F. Meyer, R. Sunyaev.

Associated Scientists:

G. Börner, G. Diercksen, W. Krämer, E. Meyer–Hofmeister, E. Müller, H. Ritter, H. Spruit,

Staff/Postdoc

A. Agrawal (1.6.-30.9.), N. Amorisco, M. Anderson (till 30.9.), G. Angelou, R. Ardevol (1.8.-31.12.), F. Arrigoni-Battaia (since 15.11.), A. Barreira, R. Bieri, R. Bollig (since 1.10.), G. Cabass, T. Costa (since 1.10.), R. Bieri, L. Blot (since 1.10.), G. Despali, M. Eisenreich (1.10.-31.12.), F. Elsner (till 30.9.), T. Ertl, E. Ferreira (since 1.10.), F. Fragkoudi (since 8.1.), M. Gabler, E. Garaldi (since 1.11.), R. Grand (since 1.11.), T. Gutcke (since 15.11.), A. Halle (until 16.10.), K. Helgason (until 28.2.), I. Jee (until 30.8.), A. Jerkstrand, R. Kazeroni, S. Kehl, I. Khabibullin, A. Kolodzig (until 30.9.), A. Kozyreva (since 1.10.), T. Lazeyras (1.6.-31.7.), K. Lozanov, A. Maleknejad, T. Melson (until 31.12.), D. Nelson, M. Newrzella, U. Nöbauer (until 30.11.), D. Powell (since 6.8.), M. Reinecke, S. Saito (until 31.12.), A. Schmidt (since 1.12.), X. Shi (until 30.8.), A.-K. Straub, S. Taubenberger (until 30.6. and since 1.10), F. van de Voort (since 1.12.), W. Trick, G. Wagstaff* (1.3.-31.12.), A. Wongwathanarat, N. Yadav, R. Yates, A. Yildirim, C. Zhang.

Ph.D. Students

[1]

F. Ahlborn (since 1.9.), A. Agrawal* (till 31.5.), A. Anand (since 1.9.), R. Ardevol (till 30.7.), P. Arras, M. Ayromlou* E. Batziou (since 1.10.), R. Bollig (until 30.9.), A. Boyle*, P. Busch*, C. Byrohl, C.Y Chao, G. Chirivi, L. Di Mascolo*, W. Enzi, K. Fotopoulou (since 1.9.), P. Frank (since 1.4.), M. Frigo*, I. Galiullin (since 10.9.), R. Glas, M. Glatzle, T. Halbesma*, J. Higl*, J. Hislop (since 1.9.), S. Hutschenreuter, L. Imasheva (since 1.9.), H.Y. Ip* (until 30.6.), M. Jarvis, A. Jörgensen*, J. Knollmüller, D. Kresse (sine 1.12.), J. Kuuttila, T. Lazeyras (until 30.5.), R. Leike, S. May (since 1.8.), L. Mirzagholi, M. Nguyen*, P. Okalidis (since 6.9.), N. Porqueres*, D. Pumpe (until 15.5.), N. Rahman (till 31.12.), T.-E. Rathjen, E. Ritondale, F. Rizzo, F. Rizzuto (since 1.3.), A. Schmidt (until 30.11.), S. Schuldt (since 15.6.), T. Steininger (until 30.5.), G. Stockinger, J. Stücker*, C. Vogl, G. Wagstaff* (until 30.1.).

Master students

T. Aschenbrenner (until 30.6.), J. Corella Puertas (1.2.-31.12.), J. Ehring (until 30.9.), A. Flörs (until 30.9.), P. Frank (until 28.2.), F. Gashi (until 30.9.), D. Gerlicher (until 28.2.), S. Huber (until 30.10.), S. Hutschenreuter (until 28.2.), J. Knollmüller (until 30.9.), M. Kurthen (until 30.9.), J. Oberpiller (until 30.8.), L. Platz (since 1.3.), M. Sag (until 30.9.), S. Schuldt (until 30.3.), M. Wandrowski (since 1.3.), M. Westercamp (until 30.7.)

Technical staff

Computational Support: H.-A. Arnolds (head of the computational support), A. Breitfeld, G. Toth, A. Weiss.

Public relation: H. Hämmerle (MPA and MPE)

Secretaries: M. Depner, S. Gründl, G. Kratschmann, C. Rickl.

Library: C. Bartels (head of the library), E. Blank.

[1] *IMPRS Ph.D. Students

4.1.1 Staff news/Awards

A. Agrawal and J. Stücker received the Kippenhahn Award for the best MPA student publication in 2017.

M. Greiner and T. Steininger received the Hochsprung Award. The two former MPA students founded the start-up “IPT - Insight Perspective Technologies GmbH” on the basis of information field theory.

T. Enßlin was awarded the Hochsprung Award for his lecture on Information Field Theory lecture that lead to a start-up company (Insight Perspective Technologies https://ipt.ai/).

T. Enßlin and F. Elsner received the Gruber Prize for Cosmology as part of the Planck Surveyor Team.

F. Fragkoudi wins Falling Walls Science Engagement Prize of the Year 2018 for her science outreach project “Columba-Hypatia: Astronomy for Peace” in Cyprus.

A. Jerkstrand received the ERC starting Grant.

Titouan Lazeyras received the Universe PhD Award 2018 in the category “Theory”.

Volker Springel: Software Development Award 2018 of the German Astronomical Society.

Rashid Sunyaev received the Marcel Grossmann Award 2018 for the development of theoretical tools in the scrutinising, through the CMB, of the first observable electromagnetic appearance of our Universe.

Sherry Suyu was awarded the Emmy Noether Visiting Fellowship from the Perimeter Institute in Canada.

4.2 PhD Thesis 2018 and Master thesis 2018

4.2.1 Ph.D. theses 2018

Aniket Agrawal: Non gaussianity of primordial gravitational waves and cosmic density and velocity fields. LMU München.

Ricard Ardevol: Development of neutrino treatment for simulations of compact binary mergers. TU München.

Robert Bollig: Muon Creation and Effects in Supernovae. TU München.

Maximilian Eisenreich: Supermassive black holes and multiphase gas in early-type galaxies. LMU München.

Hiu Yan Ip: Gravity in our cosmos: Einstein and beyond. LMU München.

Titouan Lazeyras: Investigations into dark matter halo bias. LMU München.

Daniel Pumpe: Light curves and multidimensional reconstructions of photon observations. LMU München.

Andreas Stefan Schmidt: Measuring the tidal response of structure formation using anisotropic expanding cosmological simulations. LMU München.

Theo Steininger: Rekonstruktion des Magnetfeldes der Milchstraße. LMU München.

Graham Wagstaff: Convective and atmospheric boundaries of asymptotic giant branch stars. LMU München.

4.2.2 Master theses 2018

Philipp Frank: Field dynamics inference via spectral density estimation. LMU München.

Fatos Gashi: Stochastic expectation propagation. LMU München.

Daniel Gerlicher: Well-balanced Finite Volume Methods in Astrophysics. TU München.

Simon Huber: Time Delays in Strongly Lensed Type Ia Supernovae with the Large Synoptic Survey Telescope. TU München.

Daniel Kresse: Stellar collapse diversity and the diffuse supernova neutrino background. TU München.

Maximilian Kurthen: Bayesian causal inference. LMU München.

Christoph Lienhard: Hamiltonian Monte Carlo sampling for fields. LMU München.

Johannes Oberpriller: Bayesian parameter estimation of miss-specified models. LMU München.

Stefan Schuldt: The inner dark matter distribution of the cosmic horseshoe with gravitational lensing and dynamics. TU München.

Margret Westerkamp, Dynamical field inference via ghost fields. LMU München.

4.3 Visiting scientists

Name	home institution	Duration of stay at MPA
Petr Baklanov	Kurchatov Inst. Moscow	11.6.-10.7.
Diego A. Barbosa Trujillo	Univ. Los Andes, Columbia	2.7.- 3.8.
Marvin Baumann	Bachelor Student	8.3. 15.6.
Andrei Beloborodov	Columbia University, USA	1.6.-28.6.
		and 23.12.–14.1.
Andrey Belyaev	Herzen Univ. St. Petersburg	15.4.-4.5.
Kelly Blumenthal	Harvard Univ. Boston	8.10.-24.10.
Sebastian Bustamante	HITS, Heidelberg	12.11.-23.11.
David Casado Moran	Univ. de Madrid	1.3.-30.9.
Marco Celoria	Gran Sasso Institute	13.2.–31.7.
Hailiang Chen	Yunnan Observatory, China	1.11–30.11
Miha Cernetic	MPS Göttingen	5.11.-17.11.
Pavel Denissenkov	Univ. of Victoria, Canada	1.6.-7.7.
Jian Fu	CAS, Shanghai, China	25.11.-7.12.
Ilkham Galiullin	Kazan Federal University, Russia	13.03.–24.03.
Ignacio Garciulio	Univ. La Serena, Chile	1.8.-21.8.
Jasmine Gill	CfA, Cambridge, USA	6.8.-3.9.
Catalina Gomez Caballero	Univ. Los Andes, Columbia	2.7.- 3.8.
Facundo Gomez	Univ. La Serena, Chile	1.8.-21.8.
Chia-Yu Hu	Ctr. Astrophysics, New York	5.8.-17.8.
Svetlana Iakovleva	Herzen Univ. St. Petersburg	22.10.-4.11.
Nail Inogamov	Landau Inst. Moscow	7.8.-18.8.
Takuya Inoue	Doshisha University, Japan	29.4.–8.9.
Rishi Khatri	Tata Inst. Mumbai	14.8.-25.8.
Chiaki Kobayashi	University of Hertfordshire, UK	17.7.–1.8.
Andreas Koch	Bachelor Student	8.3. 15.6.
Titouan Lazeyras	SISSA, Trieste	22.10.-2.11.
Seunghwan Lim	UMass Amherst, USA	1.6.–31.7.
Yen-Ting Lin	ASIAA Taiwan	23.7.-23.8.
Natalia Lyskova	IKI Moscow	18.6.-17.8.
Alexei Maté	Internship	2.1.-31.3.
Paolo Mazzali	John Moores Univ. Liverpool	30.4.-19.5.
		and 3.10.-28.10.
Marcelo Miller-Bertolami	La Plata, Argentinia	29.8.-5.10.
Ben Moews	ROE Edinburgh	14.7.-28.7.
Antonela Monachesi	Univ. La Serena, Chile	1.8.-21.8.
Jakob Mosumgaard	Aarhus Univ. DK	2.2.-1.7.
Marcello Musso	Univ. of Pennsylvania	11.5.-10.8.
Daisuke Nagai	Yale University, USA	25.8.–30.12.
Atsushi Naruko	Kyoto University, Japan	1.8.–23.8.
Igor Ognev	State Univ., Yaroslavl, Russia	15.09.–15.12.

Name	home institution	Duration of stay at MPA
Prakriti Palchoudhury	Indian Inst. Bangalore	since 25.9.
Alice Shapley	UCLA Los Angeles	1.7.-21.7.
Prateek Sharma	Indian Inst. Bangalore	since 8.9.
Kandaswarmy Subramaian	IUCAA Pune, India	15.7.–9.9.
Victor Utrobin	ITEP, Moscow, Russia	15.10.–15.12.
Reiner Weinberger	HITS Heidelberg	9.10.-22.10.
Alexander Wiegand	Cambridge, USA	1.3.-31.3.
Ira Wolfson	Ben-Gurion University, Israel	15.7.–2.8.
Tyrone Woods	University of Birmingham, UK	19.11.–30.11.
Stan Woosley	UCOLICK, Santa Cruz	19.6.-4.7.
Lisiyan Yang	Internship	1.8.-10.9.
Xiaoqi Yu	Gustavus Adolphus College	10.4.-31.7.
Yansong Yun	Peking University, China	29.7.–8.9.
Lev Yungelson	Institute of Astronomy, Moscow	1.11.–30.11.