Max-Planck-Institut
für
Astrophysik

Annual Report 2017

Contents

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 Eiichiro Komatsu in post for the period 2015-2017.

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: Riccardo Giacconi, 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. This generational change continued in 2013 when the MPA's own Guinevere Kauffmann was promoted to a directorship, thereby ensuring that the institute will remain a centre for studies of the formation and evolution of galaxies. In 2017 Volker Springel, a former group leader at MPA, came back from the University of Heidelberg to become a director in the department of Computational Astrophysics.

Finally, another search is currently underway for a new director, active in general areas including, but not limited to, stellar astrophysics, planetary science, and high-energy astrophysics such as accretion disks and compact objects. This new director is formally the successor of Wolfgang Hillebrandt who retired in 2012. 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, dilute 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 MPA has had an internationally-recognized numerical astrophysics program that was long unparalleled by any other institution of similar size.

Over the last 20 years, activities at the MPA have diversified considerably. They 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 over the last decade 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 6 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 is shared with the neighboring, but substantially larger MPI für extraterrestrische Physik (MPE). The library in the MPA building also serves the two institutes jointly. All major astronomical books and periodicals are available. The MPA played an important role in founding the Max-Planck Society's Garching Computer Centre (the RZG; the principal supercomputing centre of the Society as a whole). MPA scientists have free access to the RZG and are among the top users of the facilities there. The Max Planck Computing and Data Facility (MPCDF, formerly known as RZG) is a cross-institutional competence centre of the Max Planck Society to support computational and data sciences. It originated as the computing centre of the Max Planck Institute for Plasma Physics (IPP) which was founded 1960 by Werner Heisenberg and the Max Planck Society (MPS). Since January 2015 the MPCDF became an independent institute of the MPG.

1.2 Current MPA facilities

Computational facilities

Theoretical astrophysicists demand a perfect computing and networking infrastructure. Theoreticians, numerical simulators and data analysts have different needs. To satisfy these needs, MPA has its own, strong and capable IT-group, headed by a scientist to efficiently communicate between scientists and computer specialists. In addition, a group of scientists constitutes the "Computer Executive Committee", responsible for the long-term strategy and planning, and for balancing the requests of the different groups and users. Our aim is to satisfy the needs by providing both 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) and the Leibniz Computer Centre of the state of Bavaria (LRZ).

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 millions of CPU-hours per project at various other supercomputer centres at both national and 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 in 2018.

MPCDF also hosts mid-range computers owned by MPA. Presently, two of such Linux-clusters are located at MPCDF. The larger one with about 5000 processor cores, close to 25TB of core memory and Petabyte disk storage capacity is used for moderately parallel codes. This machine replaced its predecessor in 2017. In addition, MPA is operating 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 2 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 that there is no need for users 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 64 processor cores and 96 GB memory) plus the latest and largest machine with 800 cores and about 5 TB of core memory, which was added in 2015 and upgraded in 2017. 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 has 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 OpenSource software and developments. The Linux system is a special distribution developed in-house, including the A(dvanced) 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 system manager group comprises 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 50000 books and journals and about 7300 reports and observatory publications, as well as print subscriptions for about 160 journals and online subscriptions for about 500 periodicals, as well as an ebook collection of about 4500 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, a colour book-scanner, two laser printers, an d a fax machine are available to serve the users' and the librarians' needs. The library is run by two people who share the tasks as follows: Mrs. Bartels (full time; head of the library, organisation of business process, administration of books and reports) and Mrs. Blank (fu ll time; "Pure", publication management for both institutes and administration of journals)

1.3 2017 at the MPA

New Director

From 1st October 2017, Volker Springel (see Fig. 1.1) is a new director at the Max Planck Institute for Astrophysics and head of the "Computational Astrophysics" department, initially with a partial appointment and from 1st August 2018 full-time. The theoretical astrophysicist, whose main research focus is on structure formation in the Universe and the simulation of galaxies, returns to Garching and the institute where his scientific career began.

For several months, until August 2018, Volker Springel will still devote most of his working time to his current position as group leader at the Heidelberg Institute for Theoretical Studies (HITS) and his professorship in Theoretical Astrophysics at Heidelberg University before he will be based in full at the MPA. He succeeds Simon White, his former PhD supervisor, and will focus mainly on cosmic structure formation, a research area which he significantly shaped with his program code GADGET and the Millennium Simulation. This simu-

Figure 1.1: Professor Volker Springel, new director at MPA

lation in 2005 was the first (and for a long time the only one) to track the development of more than 10 billion particles on a supercomputer over the age of the universe.

It is astonishing, how well the resulting "cosmic web" of galaxies and clusters of galaxies connected by filaments agrees with the actual observed distribution of the large-scale structures in the universe. By publishing the Millennium Data, which many other researchers have then been able to use for their studies, the Millennium Simulation achieved a major impact on cosmology, which has been further enhanced by the follow-up projects Millennium-II and Millennium-XXL.

At the same time, Springel developed an innovative method for the calculation of hydrodynamics on a moving dynamic lattice and implemented it in the cosmological code AREPO. This enabled him to perform the groundbreaking Illustris simulation (and most recently IllustrisTNG), the first major cosmological hydrodynamic simulation of galaxy formation that can actually reproduce the observed mixture of spiral, barred and elliptical galaxies. He also focused on galaxies similar to our Milky Way, which he investigated with the Aquarius project and the Auriga simulations. These simulations have become more and more sophisticated; they now include magnetic fields and can provide an explanation of their origin. Other physical processes, such as the interaction between star formation and the interstellar medium or the growth of black holes are now also included in the simulations.

After completing his doctoral thesis at MPA, Springel initially worked as postdoc at the Harvard-Smithonian Center for Astrophysics in Cambridge, USA, returned to MPA for several years before he became a professor at the University of Heidelberg in 2010 and at the same time accepted a position as head of the research group "Theoretical Astrophysics" at the newly founded HITS. He has won many awards for his groundbreaking work. He has received the Otto Hahn Medal of the Max Planck Society, the Heinz Maier-Leibnitz Prize of the German Research Foundation, the Klung Wilhelmy Weberbank Prize for Physics, was a member of the Young Academy of the Berlin-Brandenburg Academy of Sciences and the Leopoldina, of which he was elected a regular member in 2016, and has been an external scientific member of the MPI for Astronomy in Heidelberg since 2012.

At the MPA, Volker Springel will continue to refine his computer simulations and will focus in particular on taking into account small-scale and previously poorly understood physical processes in large-scale simulations. What regulates star formation in galaxies? How do different theoretical assumptions for Dark Matter and Dark Energy affect the cosmic structures? How do you manage to reach huge masses beyond one billion solar masses shortly after the Big Bang? These are just a few of the questions Volker Springel wants to answer with new calculations on supercomputers.

Biermann lectures 2017

The topic of the 2017 Biermann Lectures by Professor Masaru Shibata from the Kyoto University was *"Neutron-star mergers and gravitational waves"* (see Figure 1.2).

Gravitational waves have become a very hot topic in astrophysics since their detection by LIGO in 2015. This means that also possible precursors are in the focus of research – general relativistic research because these objects are either black holes or neutron stars. The 2017 Biermann Lecturer, Masaru Shibata from the Kyoto University, uses numerical simulations and general relativity (or numerical relativity for short) to study the merger of such extreme objects and the properties of both the electromagnetic radiation and gravitational waves emitted during these events.

The formation of neutron stars and black holes or their mergers in binary systems are very difficult to reconstruct from basic physical laws, because one needs not only to fully solve Einstein's equation but also the equations of motion for the matter involved. Due to the complexity of the mathematics – these are nonlinear, partial differential equations – theoreticians need to use numerical simulations on high-performance computers. Masaru Shibata has been working in this area for many years, developing numerical simulations for a range of astrophysical processes such as the merger of binary neutron stars, black hole-neutron star binaries, or the formation of black holes. In his Biermann lectures at MPA, he gave an introduction into this field and explained how gravitational waves and electromagnetic emission from these events can be predicted.

These were very timely lectures, as the second lecture took place on October 17, just a day after the announcement of the first detection of gravitational waves from a binary of neutron stars by LIGO with the optical counterpart discovered at all the electromagnetic spectrum from radio waves to gamma-rays.

Masaru Shibata received his PhD from Kyoto University in 1994 and worked at assistant professor at Osaka University until 2000. After a brief stay at the University of Illinois at Urbana-Champaign, he returned to Japan and the University of Tokyo and in 2009 became Professor at the Yukawa Institute for Theoretical Physics, Kyoto University. He received the Outstanding Paper Award of the Physical Society of Japan in 2008, the Prize by the Japan Society for the Promotion of Science in 2010, and most recently the "Chushiro Hayashi Prize" of the Astronomical Society of Japan in 2018. Shibata is the 22nd laureate for this prestigious award. He also became a member of the International Society on General Relativity and Gravitation in 2013. In January 2018 he will start his director position in the department of "Computational Relativistic Astrophysics" at the MPI for Gravitational Physics, also known as the Albert Einstein Institute (AEI).

Even though Masaru Shibata is working on similar topics as researchers at MPA, he has never visited the institute before. His stay as Biermann lecturer provided many opportunities for discussions with his colleagues in Garching.

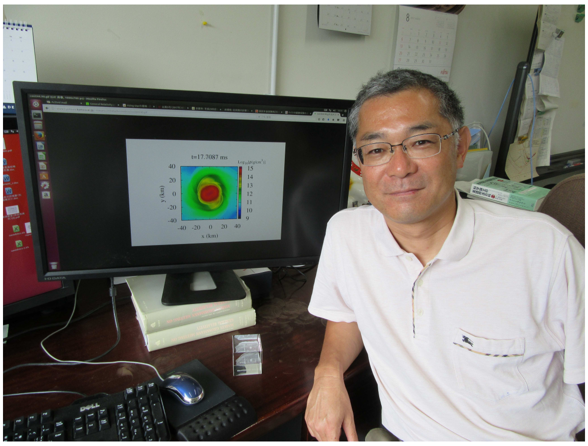

Figure 1.2: Professor Masaru Shibata, 2017 Biermann Lecturer *credit: H.-A. Arnolds, MPA*

ERC Grants

In this year both of our Max Planck Research Group (MPRG) leaders, Sherry Suyu and Simona Vegetti, are awarded the prestigeous and highly competitive European Research Council (ERC) grants. Applications are open to all fields of research and proposals are selected on the basis of excellence as the sole criterion.

In September Simon Vegetti was selected as recipient of an ERC Starting Grant, which will allow her to expand her group and refine her unique modelling technique as well as applying this to new, high-quality data to test the fundamental prediction of the Cold Dark Matter (CDM) paradigm. ERC Starting Grants are designed to support excellent researchers at the beginning of their careers.

Dark matter is believed to make up 85% of the total mass in the Universe - but most of its properties still need to be constrained. Currently, the favoured cosmological model, the CDM paradigm, assumes that dark matter is cold and collision-less. This model has been very successful in describing the Universe on large scales; however, at smaller galactic and sub-galactic scales it remains untested. All dark matter models predict that structures from through gravitational collapse from small, primordial density fluctuations; the (dark) matter distribution therefore should be clumpy and low-mass structures should be scattered around more massive galaxies. The details of this distribution and in particular specific scale where clumps appear depend on the properties of the dark matter particles. The differences between models are largest for low-mass structures, which are inherently difficult to detect and measure in more distant galaxies. This is where gravitational lensing comes in: large mass concentrations not only bend the light of background object, they can also amplify the light coming from the source. If there are low-mass concentrations in a lens galaxy, this will change the gravitational potential locally and lead to a change in the surface brightness distribution of the lensed image, which would otherwise be smooth. Simona Vegetti developed a computer algorithm to analyse the extended arcs observed in strong gravitational lens systems to detect such low-mass dark matter substructures. To place tighter constraints on the amount and distribution of substructures, she needs high-resolution data of many different strong lens systems. The ERC grant, which augments her funding for the next five years, will allow her to hire additional researcher to further refine her technique and obtain additional high-quality radio data for even more lens systems.

End of November, the ERC announced that Sherry Suyu is one of the awardees of the 2017 ERC Consolidator Grants. The ERC Consolidator Grants are awarded to outstanding researchers of any nationality and age in any field of research, with at least seven and up to twelve years of experience after PhD, and a scientific track record showing great promise. With this funding, Sherry Suyu can expand her group to study gravitationally lensed supernovae and find out more about their progenitors. Strongly lensed supernovae also provide an independent way of measuring the Hubble constant, which tells scientists about the rate of expansion of the Universe.

For decades, cosmologists have used a certain type of stellar explosion, Type Ia supernovae (SNe Ia) to measure the distance to far-away galaxies and thus the rate of the expansion of the universe. Only in the past 10 years or so, however, they have started to use an additional cosmic effect to gain even more information: strong gravitational lensing. This occurs if a substantial mass concentration, e.g. a galaxy or galaxy cluster, lies between the source in a far-away galaxy and the observer on Earth. The light rays passing on different sides of the lens will then be bent and lead to multiple images of the same source. Additionally, if the source is intrinsically variable, e.g. lighting up as in the case of a supernova explosion, the multiple images will appear at different times due to the different optical path lengths of their light paths and gravitational delay by the lens. This time delay contains valuable information on the geometry of the Universe. The LENSNOVA project proposed by Sherry Suyu plans to capitalize on her experience in the field of strong lensing time delays. With the aid of lensing, SNe can be observed in their entirety with unprecedented temporal sampling. Observations of the beginning of SN explosions are key to revealing SN progenitors that have been under debate for decades. Strongly lensed SNe Ia also allow an independent measurement of the Hubble constant that sets the cosmic expansion rate. The independent measurement is important to ascertain the possible need of new physics beyond the standard cosmological model, given the tensions in current H0 measurements. Thus, the LENSNOVA project will shed light on the natures of SNe Ia progenitors and dark energy, two of the greatest puzzles in the present era. The advent of new, powerful telescopes such as the Large Synoptic Survey Telescope and the Euclid mission makes LENSNOVA particularly timely for building the first sample of a handful of strongly lensed SNe Ia. The ERC grant now enables Sherry Suyu to recruit further researchers for her team and to acquire the computing resources needed to capitalise on the new data. Thus, the project could potentially revolutionise both the fields of stellar physics and cosmology.

Obituary to Eleonore Trefftz

Dr. Eleonore Trefftz, Emeritus Scientific Member of the Max Planck Institute for Astrophysics, Garching, passed away on 22 October 2017 at the age of 97. With Eleonore Trefftz, the Max Planck Society loses a remarkable researcher and person. Eleonore Trefftz started her scientific career in 1948 - the year in which the Max Planck Society was founded - as a research assistant at the Max Planck Institute for Physics and Astrophysics. In 1971 she was appointed Scientific Member of the institute and focused her work on answering theoretical questions of atomic and molecular physics as well as spectroscopy. In addition, Eleonore Trefftz pioneered the development of mathematical methods and programming techniques, making an important contribution to the introduction of electronic data processing at the institute. Eleonore Trefftz always devoted herself to the Institute as a whole and was available for the Institute and her colleagues. It is to her credit, that several members of her working group have been appointed to teaching positions in Germany and abroad. With deep regrets, the Max Planck Society takes its leave of Eleonore Trefftz and will always hold the memory of her in honour. *Martin Stratmann President of* *the Max Planck Society for the promotion of sciences e. V.*

Obituary to Heinz Billing

A pioneer in the development of electronic computing machines in Germany and one of the founders of gravitational wave astronomy is no more: on 4 January 2017, the astrophysicist Heinz Billing died at the age of 102. Billing was scientific member at the Max Planck Institute for Astrophysics in Garching from 1961 to ’82. Born on 7 April 1914 in Salzwedel, Heinz Billing finished high-school in 1932 and then moved to Göttingen for his studies, which for him was the “stronghold of mathematics”, as he wrote in his autobiography. After his doctoral thesis at the University of Munich in 1938 with a mirror-rotation experiment on the wave-particle dualism of light, he applied at the aerodynamic experimental institute (AVA) in Göttingen. However, he was called to military service and could only return to the AVA in 1941, when he was named “indispensable” for developing microphones to identify enemy aircraft based on their propeller noise. After the end of the Second World War, several institutes of the Kaiser Wilhelm Society (the predecessor of the MPG) moved into the mainly empty buildings of the AVA, the Institute for Physics and the “Institute for Instrumentation”, founded in 1946. Starting in 1948, there Billing developed his first calculation engine with a magnetic drum memory, a technology he was familiar with due to his experiments with noise suppression. The G1 - “Göttingen 1” - was completed in 1950 and operated with a binary code just like today’s computers, i.e. with representations for zero and one. An arithmetic operation took about one second, the memory could store up to 26 numbers - no match for today’s computers, but at the time the G1 was about ten times faster than the more common mechanical computing machines. In particular the astrophysicist Ludwig Biermann (1907-86) showed great interest in the calculation engine and encouraged Billing to develop it further. In 1955 the G2 was finished and in 1960 the G3 (in operation until 1972), which could manage 5000 to 10 000 operations per second. Still, many scientists were quite sceptical about this new technology. An astrophysical working group from Heidelberg asked the Göttingen group to calculate the orbit of a newly discovered asteroid. The results of the G2 differed significantly from those of the computing group, which had worked with mechanical table-top devices, and this was interpreted as a failure of the Göttingen computer. Later observations, however, showed the asteroid appearing at Göttingen’s predicted position - the machine had yielded a better result than the traditional computing group.

In 1961 Billing was appointed Scientific Member of the MPI for Physics and Astrophysics, which had moved from Göttingen to Munich in 1958. In 1968, Billing became chairman of the newly founded “Advisory Committee for Computer Systems in the Max Planck Society” (BAR) due to the increasing importance of computer systems for solving scientific tasks. After stepping down as chairman, Billing was a member of the BAR until 1998. Since 1993, the “Heinz-Billing-Award for the Promotion of Scientific Computing” has been awarded by the Heinz-Billing-Association for the Promotion of Scientific Computing e.V., an association founded within the Max Planck Society. Although Heinz Billing was a computer pioneer, he did not pursue industrial development of his computers. Instead, he returned to physics and tried from 1970 onwards to verify the gravitational wave experiment of Joseph Weber. Therefore, he and his group built heavy aluminium cylinders in Munich and Frascati, Italy, as gravitational wave detectors. These could register relative changes in length of the order of 10^{-15}. The results were negative (as expected); the method was not sensitive enough to detect the theoretically predicted signals. Therefore the group turned to the new technique of laser interferometry; in 1975 the first prototype was built in Garching. These experiments were the starting point for the successful detection of gravitational waves in September 2015, which Billing lived to see with 101 years. Billing received numerous honours and awards. Among others, he was appointed Honorary Professor of the Friedrich Alexander University Erlangen-Nürnberg in July 1967 and was the first to receive the Konrad-Zuse-Medal from the Gesellschaft für Informatik. In 2006 the Bavarian Maximilian Order for Science and Art was bestowed upon him. He became honorary citizen of Salzwedel in 2013 and in 2015 received the Federal Cross of Merit first class of the Federal Republic of Germany as well as the Golden Merit Medal of the city of Garching in 2016, where he lived for more than 40 years.

Prizes and Awards

Breakthrough Prize for WMAP

The WMAP science team has received the 2018 Breakthrough Prize in Fundamental Physics for detailed maps of the early universe that greatly improved our knowledge of the evolution of the cosmos and the fluctuations that seeded the formation of galaxies. The prize will be shared among the entire 27-member WMAP science team including Eiichiro Komatsu, director at the Max Planck Institute for Astrophysics in Garching. The Wilkinson Microwave Anisotropy Probe (WMAP) was a NASA Explorer mission launched in 2001 (and operating until 2010) to measure the Cosmic Microwave Background (CMB), the "echo" of the Big Bang. The properties of this radiation contain a wealth of information about physical conditions in the early universe. WMAP determined, to a high degree of accuracy and precision, not only the age of the universe, but also the density of atoms; the density of the so-called Dark Matter; the epoch when the first stars started to shine; the "lumpiness" of the universe, and how that "lumpiness" depends on scale size. WMAP observations also provided the strongest support ever for the so-called theory of "inflation", in which the Universe underwent an exponential expansion in the first tiny fractions of a second. Eiichiro Komatsu, who is now director at the Max Planck Institute for Astrophysics, performed stringent tests of the key predictions of inflation, analysing the statistical properties of primordial quantum fluctuations that seeded cosmic structure formation. He also led the cosmological interpretation of the five- and seven-year data releases, which (according to Thomson Reuters) were the most highly cited research papers in all sciences published in 2009 and 2011, respectively.

Two distinctions for Rashid Sunyaev

Each year since 2002, analysts at Clarivate Analytics (formerly Thomson Reuters) mine millions of citations in the Web of Science to identify top-tier researchers in physiology, medicine, physics and chemistry as well as economics. MPA director Rashid Sunyaev is one of five 2017 physics laureates for his – profound contributions to our understanding of the Universe, including its origins, galactic formation processes, disk accretion of black holes, and many other cosmological phenomena. Citation Laureates are scientists whose publications have been cited so often by their colleagues and thus who have been so influential that they are forecast as potential recipients of the Nobel Prize in this year or in the future. Clarivate Analytics is an independent company that operates a number of subscription-based databases, providing analytics, curated content and business information to help accelerate the pace of innovation. Its range of well-known brands includes the Web of Science, Cortellis, Derwent, CompuMark, MarkMonitor and Techstreet. As it used to be a part of Thompson Reuters, formerly the Citation Laureates were known as the Thomson Reuters – picks – for the Nobel Prize. In June 2017, Rashid Sunyaev, Director of the Max Planck Institute for Astrophysics, received the State Prize of the Russian Federation in Science and Technology jointly with Nikolay Shakura, professor of astrophysics at Moscow State University, for their groundbreaking work on the theory of accretion. The theory of disk accretion onto black holes developed by them in the early 1970s has now become a classical description of the mass transfer and gravitational energy release in stellar binary systems. Based on the assumption that the radiative efficiency of the disc is high and that turbulent and magnetic viscosity is the key driving mechanism for angular momentum transfer, the self-consistent picture of a geometrically thin accretion disk has been developed. Now it is known as a "standard Shakura-Sunyaev disk" or "Shakura-Sunyaev alpha-disk" since the specific form of the viscosity parametrization suggested by Shakura and Sunyaev turned out to be particularly fruitful and efficient.

The modern theory of accretion continues to evolve with many questions still unanswered, but the "standard Shakura-Sunyaev disk" remains to be one of the cornerstones of the theory. With more than 8020 citations, the seminal paper "Black holes in binary systems. Observational appearance" N. Shakura and R. Sunyaev has become the most frequently cited original paper in theoretical astrophysics, among more than three million scientific publications listed in the NASA ADS Astronomy and Astrophysics database.

Belopolsky Prize in Astrophysics

The Russian Academy of Sciences awarded the 2017 Belopolsky Prize in Astrophysics to Eugene Churazov and Marat Gilfanov for their work on *"X-ray diagnostics of accretion flow in the vicinity of black holes and neutron stars in the Milky Way and external galaxies"*. The A.A.Belopolsky Prize, named after the Russian astronomer and spectroscopist Aristarkh Belopolsky, is awarded by the Russian Academy of sciences once every three years for outstanding contributions to astrophysics. Eugene Churazov and Marat Gilfanov received this award for their studies of the accretion flow around compact objects using the data of MIR-KVANT, GRANAT, INTEGRAL, RXTE and Chandra orbital observatories. Among the results included in the citation are models of the spectral variability of X-ray binaries, diagnostics of the nature of the compact objects in X-ray binaries based on the characteristics of their X-ray emission, mapping the Galactic center region in the 3-200 keV energy band, discovery of new transient and persistent X-ray sources, measuring the brightness of the Cosmic X-ray background, studies of populations of accreting neutron stars and black holes in external galaxies, and X-ray diagnostics of star formation.

Matteo Bugli wins Leibniz Scaling Award During a scaling workshop end of May at the Leibniz-Rechenzentrum, Matteo Bugli from MPA won the Leibniz Scaling Award. He was able to produce the best relative improvement with his ECHO code for three-dimensional simulations of relativistic magnetized accretion disks orbiting around black holes. The Leibniz-Rechenzentrum (LRZ) provides supercomputing facilities for a wide range of scientific applications. Access to the high-performance computer SuperMUC with more than 19000 processors, a total of 155,656 cores, a peak performance of about 3 petaFLOPS, main memory of 340 terabytes and 15 petabytes of hard disk space is highly sought after. Making maximum use of the supercomputer through efficient coding is therefore a high priority for the LRZ. The Extreme Scaling Workshops organised by the LRZ aim to address this challenge. Matteo Bugli from MPA participated with his ECHO code for three-dimensional simulations of relativistic magnetized accretion disks orbiting around black holes. In particular, during his PhD Matteo studied the development of global non-axisymmetric instabilities and the role of magnetic fields in the dynamical evolution of the disk. Over the past two years the code's parallel efficiency was already vastly improved. During the workshop, Matteo and his team achieved the best relative improvement, an eight times increase in scalability on SuperMUC, and won the Leibniz Scaling Award.

Shaw Prize for Simon D.M. White

The 2017 Shaw Prize for Astronomy goes to Simon D.M. White, Director at the MPA, for his contributions to understanding structure formation in the Universe. The Shaw Prize is awarded annually by the Shaw Prize Foundation in Hong Kong in the life sciences, mathematics and astronomy. The universe was born 13.8 billion years ago – in the so-called Big Bang. But how did the cosmos we observe today, with its billions of galaxies of different shapes and sizes, develop from this enormous explosion? Apparently, as Simon White and his collaborator Martin Rees first hypothesised in 1978, gigantic clouds of material separated from expansion and fell back on themselves under the influence of gravity when the universe was just a few hundred million years old, and galaxies then formed as gas cooled and condensed at the centres of immense halos of the mysterious dark matter which are still only detected through their gravitational effects. Over four decades, Simon White, his students and collaborators have simulated this scenario with ever increasing realism on the largest available computers. A well known recent example was the Millennium Simulation, carried out in 2005 on the Max Planck Society's Garching supercomputer in collaboration with Volker Springel and others. This tracked the development of structure and the formation of 20 million galaxies throughout a region of space more than two billion light-years across. In fact, such simulations produce a kind of cosmic net in which matter accumulates in and flows along filaments on the edges of gigantic bubbles. This is precisely the structure that astronomers observe in the real universe on very large scales. The work of White and his colleagues demonstrates how such complex structure develops from the simple, near-uniform conditions initially hypothesised, but now directly observed, to be present in the early Universe.

Rudolf-Kippenhahn-Award

Since 2008, the Kippenhahn Award has been awarded for the best scientific publication written by an MPA student; it was donated by the former director of the institute, Prof. Rudolf Kippenhahn, to motivate students to write a good publication. In 2017 Dijana Vrbanec and Titouan Lazeyras were the recipients for the best scientific publication 2016: Vrbanec for her publication; *"Predictions for the 21 cm-galaxy cross-power spectrum observable with LOFAR adn Subaru"* and Lazeyras for his paper *"Large-scale assembly bias of dark matter halos"*. See Figure 1.3.

Criteria for the award are that the student is the first author and has contributed substantially to the scientific ideas, calculations and analysis, and the writing of the paper. The committee received five applications and was impressed by the quality of the papers. After careful consideration they decided to award the Kippenhahn award to two winners.

Dijana Vrbanec's paper investigated the potential of cross-correlating the 21cm signal with Lyman Alpha Emitters (LAEs), using simulations of reionisation to evaluate the theoretical cross-correlation, and including the characteristics of instruments such as LOFAR and Subaru's Hyper Suprime Cam (HSC) to produce mock observations and assess the feasibility of the experiment. Her main finding is that clear anti-correlation should be seen on scales larger than ~ 60 Mpc/h, allowing an estimate of the typical dimension of ionized regions at various redshifts. While the detection of the 21cm signal from neutral hydrogen during the Epoch of Reionisation remains the best observational probe of the reionisation history and the physical state of the IGM at high redshift ($z > 7$), the weakness of the signal makes its detection extremely challenging. Dijana Vrbanec's cross-correlation technique can not only help in confirming the origin of the signal itself, but also maximizing the success of its extraction with respect to e.g. systematic effects.

Titouan Lazeyras's paper presents clean, high-precision measurements of halo assembly bias. Dark matter halos play a key role in our understanding of the large-scale structure. They host the galaxies that we observe, and their clustering is thus a key stepping stone to understand the clustering of galaxies themselves. It is by now well established that the clustering of halos depends not just on halo mass, but on the halo formation history and other properties as well, such as halo shape, density profile and angular momentum. This is known as assembly bias. For this, he used the novel separate universe simulation technique developed by the MPA cosmology group. His results improve upon previous results in this field in several ways: first, this technique cleanly extracts the truly large-scale clustering. Second, he showed that assembly bias exists in higher-order bias parameters as well. Third, he added several new trends, and, for the first time, was able to show assembly bias with respect to two halo properties at the same time. A key conclusion to take away from his results is that halo assembly bias is a complex phenomenon, which is not simply explained by one additional variable, such as the formation time. There is thus a lot more to explore in the field of assembly bias.

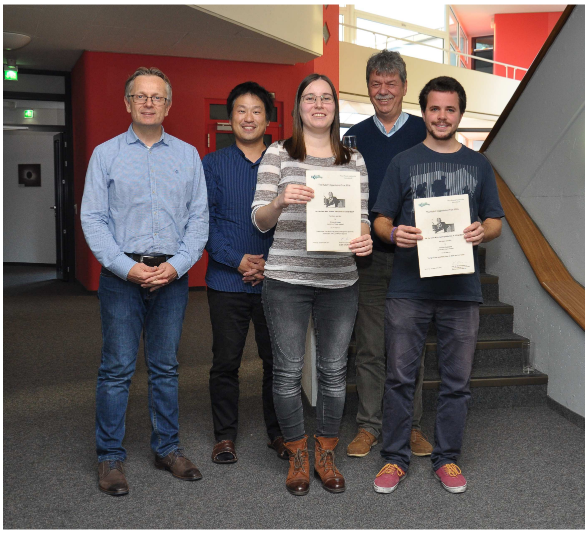

Figure 1.3: Dijana Vrbanec and Titouan Lazeyras received the Kippenhahn award for the best publications written by MPA student in 2016. *credit: H.-A. Arnolds, MPA*

Public Outreach 2017

The research at MPA generated quite some interest also from the general public and many MPA scientists actively engaged with visitors and lay persons. In 2017 more than 10 groups (more than 320 people) visited the institute – one group even all the way from China – and enjoyed a journey through the heavens in our digital planetarium. End of April, MPA invited 30 girls to learn more about astronomy and what it means to pursue a career in science (see Fig. 1.4. This event was part of the annual Girls Day, an initiative throughout Germany to encourage girls to learn more about occupational areas that are still male dominated. Even though the weather did not cooperate, the girls were very active and braved the cold and the rain to visit the roof telescope and launch their "rockets".

The girls showed a lot of interest in astronomical topics and asked many questions, both during the programme and at the end when some female scientists briefly presented their career path and what fascinates them about their chosen topics. During this Q&A session, the girls then asked not only about more details of the objects researched and the research process, but also about the basic conditions in science, such as what they don't like about the work environment or how much freedom an individual researcher has to pursue her own goals.

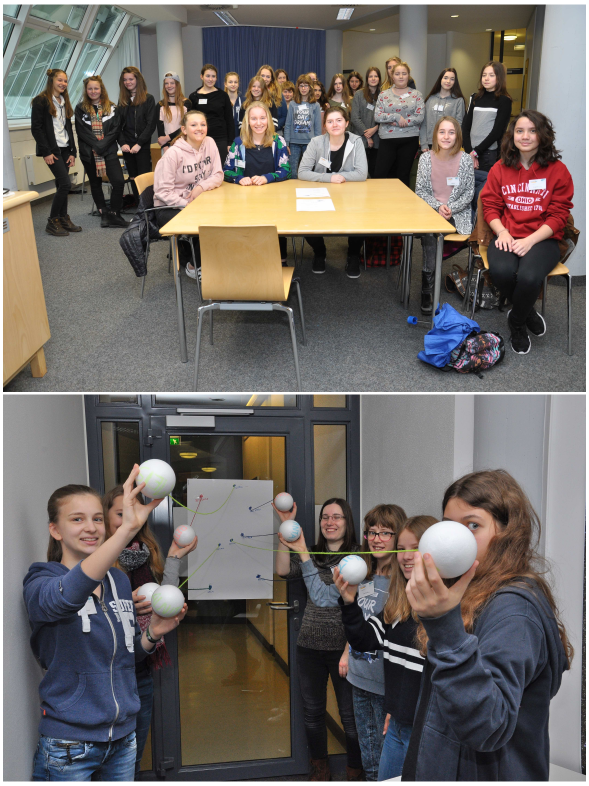

Figure 1.4: The school girls were able to do some research themselves during the Girls'Day.*(credit: H.-A. Arnolds, MPA)*

Figure 1.5: Open Day - October 2017, the biggest outreach activity. *credit: MPA/Vanessa Laspe*

The biggest outreach activity then followed in October with the Open Day, when an estimated 2000 visitors came to MPA (See Fig. 1.5. The programme included hourly talks – for many of which, the lecture hall was completely full – poster presentations and a Q&A with scientists, the Cosmic Cinema, our digital planetarium, guided tours to the telescope on the MPA extension building as well as the "kids lab", which was again hugely popular. Many visitors also profited from the opportunity to take home some further information about the MPA and the MPG in general in the form of brochures and the Max Planck Forschung. 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 and even high school students, 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.

2 Scientific Highlights

2.1 The Hydrangea project: high-resolution hydrodynamic simulations of galaxy clusters

Why do galaxies that live in the enormous structures known as galaxy clusters look different from normal, isolated galaxies, such as our Milky Way? To answer this question, an international research team led by MPA has created the Hydrangea simulations, a suite of 24 high-resolution cosmological hydrodynamic simulations of galaxy clusters. Containing over 20,000 cluster galaxies in unprecedented detail and accuracy, these simulations provide astrophysicists with a powerful tool to understand how galaxies have formed and evolved in one of the most extreme environments of our Universe.

Galaxy clusters are giant associations of up to several thousand galaxies, embedded in diffuse hot gas and invisible dark matter (see Fig. 2.1). Observations have shown that these extreme environments influence the properties of the galaxies within: while isolated galaxies often contain star-forming discs where massive young stars shine in blue, cluster galaxies are mostly yellow or red - indicating that they stopped their star formation several billion years ago. Often, these cluster galaxies present an apparently featureless “elliptical” morphology. Understanding the origin of these differences has been a major unsolved problem in astrophysics for decades.

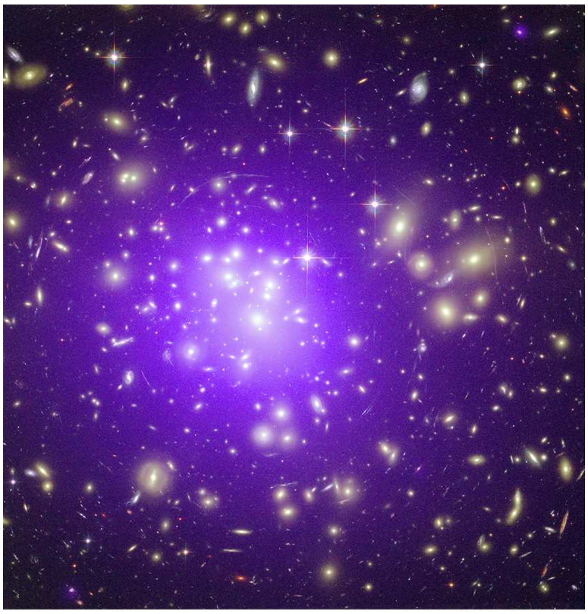

Figure 2.1: The Galaxy cluster “Abell 1689”, located approximately 2 billion light years away, is one of the most massive clusters in the known Universe. This picture is a composite of an optical image, taken with the Hubble Space Telescope, and an X-ray observation with the Chandra Space Telescope. The former shows starlight from more than 1000 galaxies, the latter (in purple) the hundred-million-degree hot gas which permeates the space between galaxies and contributes more mass to the cluster than all its galaxies together. *Credit: X-ray - NASA/CXC/MIT/E.-H Peng et al; Optical - NASA/STScI*

One key reason for this is that galaxies evolve on timescales of millions to billions of years. Astrophysicists therefore cannot directly observe this process through the telescope, they have to rely on computer simulations to “speed up time” and solve this mystery. Starting from the observed tiny density fluctuations in the early Universe (see Planck CMB results), such simulations calculate the growth of structure through the action of gravity, hydrodynamics, and astrophysical processes such as star formation and supernova explosions.

The latest generation of these simulations - for example, those produced by the EAGLE collaboration that also involved participation from MPA - have finally succeeded in producing galaxies that resemble those found in the real Universe in key properties such as their mass, size, and gas content (see here). In principle, such simulations therefore provide an ideal tool to study the physics of galaxy formation. However, galaxy clusters occupy only a tiny fraction of the Universe by volume and are therefore not well represented in the original EAGLE simulations.

The Hydrangea project, led by Yannick Bahé at MPA and involving researchers in Germany, the UK, the Netherlands, and Spain, has filled this gap with a large suite of 24 simulations of massive galaxy clusters. The project name is derived from the flower "Hydrangea", whose petals change their colour between red and blue depending on their environment – an analogy to the aforementioned colour difference between field and cluster galaxies. These simulations employ the so-called "zoom-in" technique, which focuses computing power on a relatively small region (with a diameter approximately 100 million light years). This core region was carefully selected to contain a massive galaxy cluster, within a total volume that is many thousand times larger.

Even with this trick, the Hydrangea simulations constituted a major computational effort. This is due to the vast range of scales involved (see Fig. 2.2): a galaxy cluster exceeds an individual galaxy in mass by more than a factor of 1000. This means that for adequately resolving individual cluster galaxies, the simulations need to follow several billion particles, which interact both gravitationally and hydrodynamically.

The total computational cost of the suite thus exceeded 40 million CPU hours, corresponding to a serial run time of more than 4500 years - as long as the time since the construction of the great pyramids of Giza. Access to large supercomputing facilities, including the "Hazel Hen" system of HLRS (Stuttgart) and "Hydra" at MPCDF (Garching), where the simulations could be run on more than 10,000 CPUs simultaneously, was therefore crucial for completing the project in less than one year. Fig. 2.2 presents a visualization of one of the simulated galaxy clusters. The video below shows its formation from an initially nearly structureless "blob" over the course of 13.5 billion years.

In total, the Hydrangea simulations contain more than 20,000 galaxies. When the researchers compared them to the existing EAGLE simulations, they found a surprising difference: galaxies are, on average, more massive in the vicinity of galaxy clusters than those formed in more typical, lower density regions of the Universe. At least in

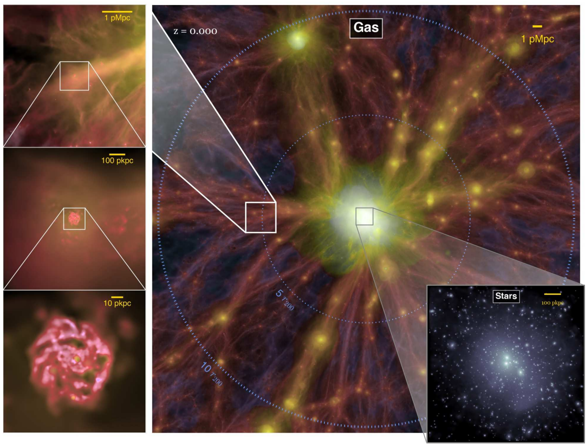

Figure 2.2: Visualization of the most massive galaxy cluster simulated as part of the Hydrangea project. The brightness of the image represents the gas density, while the colour encodes the temperature of the gas (blue: cold, white: hot). The hundred-million-degree hot gas in the central cluster is surrounded by a vast network of filaments stretching out into the surrounding Universe. Over a dozen smaller galaxy groups on the cluster outskirts are visible as yellow knots. The bottom-right inset shows the simulated stars, which are clumped into hundreds of galaxies in the cluster centre; each small point represents a galaxy similar to the Milky Way containing several hundred billion stars each. The three panels on the left-hand side zoom in to one individual galaxy, highlighting the vast dynamic range of the simulation. *Credit: Yannick Bahé/MPA*

part, this difference is likely due to the fact that dark matter haloes (into which all galaxies are embedded) form earlier in the vicinity of clusters. As a consequence, a larger fraction of the gas is concentrated into the star-forming centre, leading to a higher total mass of stars formed. This is an important prediction, not least because astronomers often use stellar mass to compare "similar" galaxies in different environments. Systematic variations in stellar mass fractions with environment could therefore cause biases in such comparisons and must be carefully taken into account.

The full analysis of the simulations is an ongoing effort that will take several years to complete. As well as testing the accuracy of the EAGLE model in the essentially unchartered regime of massive galaxy clusters, this effort will allow astrophysicists to gain ground-breaking new insight into how galaxies interact with their cluster environment. This will significantly improve our understanding of how the structures we see in the Universe formed and evolved over the last 13.7 billion years (Yannick Bahé).

Acknowledgement: The simulations presented in this article were in part performed on the German federal maximum performance computer "HazelHen" at the maximum performance computing centre Stuttgart (HLRS), under project GCS-HYDA / ID 44067 financed through the large scale project "Hydrangea" of the Gauss Center for Supercomputing. Further computing resources were provided by the Max Planck Computing and Data Facility in Garching, and by the DiRAC system "Cosma5" hosted by Durham University (UK).

2.2 Constraining theories of gravity using the large-scale distribution of galaxies

The origin of the current accelerated expansion of the Universe remains one of the major unsolved mysteries in physics today. While this could be a sign of the mysterious "Dark Energy", this puzzling observation might also be evidence for the inadequacy of Einstein's theory of General Relativity (GR) to describe the law of gravity on very large cosmological scales. These considerations would have strong implications on our understanding of fundamental physics, warranting dedicated studies such as the one undertaken recently by researchers at MPA and MPE. In this work, the authors created mock universes with non-GR theories of gravity to test the validity of current observational methods to determine the rate at which structures grow in the Universe. This allowed them to place bounds on how much the current data allows the Universe to depart from Einstein's prediction. Reassuringly, current observational methods do not show evidence for a biased performance when tested on mock universes with modified gravity.

Almost twenty years ago, astronomers observed that the light emitted by distant Type Ia supernovae explosions is even fainter than was expected. This extra dimming provided the first evidence for the accelerated expansion of the Universe. Soon after these observational data were presented to the astronomical community, it became clear that an explanation would require new physics. One way out of the problem consists in adding a new term to Einstein's field equations: some exotic forms of "dark energy" or a cosmological constant, which act as sources that drive the accelerated expansion. Another explanation consists in noting that General Relativity is not nearly as well tested on cosmological scales as it is in our Solar System, and that the acceleration could be simply due to the different nature of gravity on very large scales. This has motivated several recent studies on modified gravity models (as non-GR theories are collectively known) and their cosmological predictions; making this one of the most active areas in cosmology today.

One of the most popular modified gravity scenarios is that of "braneworlds". In these theories, the four-dimensional spacetime we live in (3 space + 1 time dimension) is just a slice, or "brane", of a higher dimensional spacetime. One concrete example is the Dvali-Gabadadze-Porrati (DGP) model, where we live in a four-dimensional brane of a five-dimensional "bulk" spacetime.

Figure 2.3 shows a cartoon that summarizes the idea behind these models: matter and radiation are confined to the brane, but the gravitational interaction can "leak" out of the brane into the higher dimension(s). This leakage modifies how gravity operates in the brane, thereby permitting deviations from General Relativity to occur. A crucial point to bear in mind is that the modifications to General Relativity should only occur on distance scales much larger than the Solar System, otherwise these models would be immediately ruled out by the very precise tests performed in our solar neighbourhood, which confirm the validity of General Relativity extremely well.

Cosmologists have defined the growth rate of

Figure 2.3: Schematic representation of the DGP brane model. Matter and radiation are confined to the four-dimensional brane, but the gravitational interaction is free to propagate out into the additional fifth dimension. *Credit: MPA*

structure as a quantity that measures how fast large lumps of matter merge with one another in the Universe causing structure to gradually grow over cosmic time. The stronger the gravitational interaction, the faster the growth rate will be. Precise and accurate determinations of the growth rate therefore are a very good probe to test gravity.

The growth rate however cannot be directly measured by pointing a telescope at the sky. Instead, it can only be determined through complex and advanced modelling of the observed clustering pattern of galaxies on large scales. A worry then emerges: if the processing of the galaxy clustering data is faulty, the resulting growth rate measurements are shifted away from the true value. Consequently, we would be drawing wrong conclusions about the various theories of gravity. Therefore, to guard against this worry, the modelling techniques for real data are validated against mock observations based on N-body simulations of structure formation in the Universe. In this way, we can test the validity of the observational pipelines in a controlled setup, in which we know the real answer.

A major shortcoming of previous validation tests was that they were only applied to simulations based on General Relativity. The validity of the same techniques with respect to other theories of gravity remained uncertain. Researchers at MPA and MPE have now, for the first time, undertaken a thorough validation of these observational analysis pipelines by testing them on mock observations constructed from N-body simulations of DGP brane models with varying degrees of departure from General Relativity. The mock galaxy catalogues were designed to be fair descriptions of the galaxy samples from the BOSS survey, the largest galaxy survey to date in terms of the number of galaxies and the volume of the Universe covered.

First, the scientists ensured that the modelling steps for determining the growth rate from the data remain valid even in the case of DGP gravity. Then, the authors used the latest data from the BOSS survey to constrain the model. In doing so, it has become standard to focus on a subset of the DGP gravity model to place benchmark constraints on departures from General Relativity. This standard toy model is known as nDGP ("n" for normal) and automatically passes Solar System tests of gravity as well as constraints from geometrical probes sensitive to the expansion rate of the Universe.

The main source of constraining power therefore is the data which probes structure formation on large scales. Figure 2.4 illustrates how the growth rate data can constrain the nDGP model. The growth rate is shown as a function of cosmic time for several values of the so-called “crossover scale”, a parameter that basically determines the distance above which gravity starts to leak out of the brane. Smaller values of the crossover scale lead to stronger gravity, pushing the prediction away from the data, while larger values bring the nDGP model closer to General Relativity – and to a better agreement with the measurements from BOSS.

One of the main conclusions of this work is that, reassuringly, current observational methods do not show evidence for a biased performance when tested on mock universes with nDGP gravity. This constitutes a very much needed test of the validity of current observational analyses, which ensures that current data on the growth rate can be used to test the nDGP model (as well as a plethora of other theories with similar phenomenology) (Alexandre Barreira).

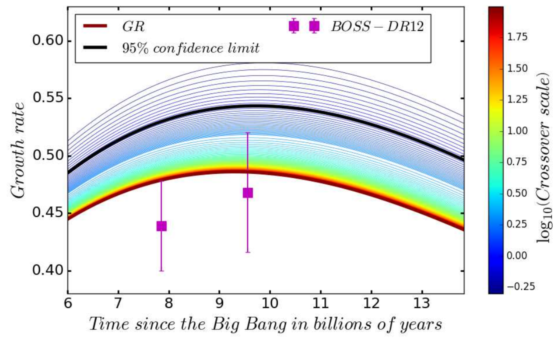

Figure 2.4: Growth rate as a function of cosmic time. The purple squares show the measurements from the final Data Release 12 of the BOSS galaxy survey. The thin lines are colour coded by the crossover scale, please note that the scale is logarithmic. The thick black line shows the result for crossover scale ≈ 1, which marks the so-called 95% confidence limit: given the data, the "true" curve is below the thick black one with 95% probability. This represents the tightest observational constraint on this model to date. The thick red line shows the result from General Relativity. *Credit: MPA*

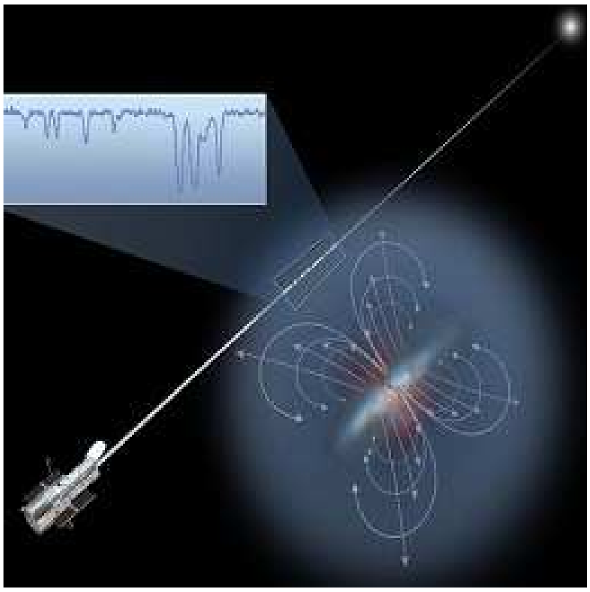

Figure 2.5: Schematics of how the sightline from HST to a quasar goes through the extended gas halo of a foreground galaxy. The inset shows the quasar spectrum including the Lyman α forest. *Credit: COS-HALOS survey*

2.3 The Circum-galactic Medium of Galaxies as Probe of Gas Accretion

In collaboration with researchers from the USA, MPA scientists have mounted a series of ambitious experiments that use a combination of quasar absorption-line spectra, neutral hydrogen line data, and state-of-the-art cosmological hydrodynamical simulations to probe the interface between galaxies and their surrounding gaseous environment. The researchers found that galaxies with gas-rich disks are embedded within gas-rich halos and that the gas in these halos is distributed smoothly and relatively isotropically.

Galaxies need gas to fuel star formation; how galaxies acquire gas is therefore central to our understanding of galaxy evolution. In the standard paradigm, galaxies grow primarily through the accretion of gas that flows from the Inter-Galactic Medium (IGM), through the dark matter halo, and eventually settling onto the disk of the galaxy. Galaxies like or own Milky Way need a continuous supply of gas to fuel star formation, but little is known about the way in which gas cools and condenses into the disk due to difficulties in observationally mapping the disk/halo interface.

Bright quasars at large distances from the observer act as cosmic light beacons. As the light from distant quasars travels through the Universe, it encounters gas clouds containing mainly hydrogen. These clouds absorb and scatter ultraviolet photons, leading to characteristic dips (or absorption lines) in the spectrum of the quasar, the so-called “Lyman α forest”. By choosing quasars that happen to be positioned in such a way that their light will pass within a short distance (a few hundred kiloparsec) of a foreground galaxy, we are able to probe the gas in the so-called “circum-galactic medium” surrounding these systems.

Two large programmes to investigate the circum-galactic medium around nearby galaxies have now received a total allocation of 200 orbits of observation time with the Hubble Space Telescope (HST). The first of these, COS-GASS, used the Cosmic Origins Spectrograph (COS) on board HST to probe neutral hydrogen around nearby galaxies out to the outer radius of their surrounding dark matter halos.

The COS-GASS programme found a highly significant correlation (at 99.5% confidence) between the strength of the Lyman α absorption lines, which are tracing neutral hydrogen in the surrounding halo, with the ratio of gas mass to stellar mass within the disk. This means that galaxies with gas-rich disks are embedded within gas-rich halos.

The Lyman α signature was detected in nearly every quasar spectrum and the average strength of the Lyman α lines decreased gradually as a function of distance from the galaxy. Finally, the

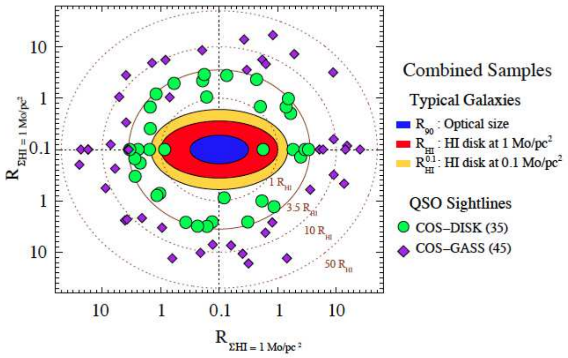

Figure 2.6: Distribution of sight lines as a function of impact parameter and orientation of the target galaxy. The red and blue areas correspond to the HI and the optical disk. The yellow region corresponds to the extended disk region. The quasar sightlines included as part of the COS-GASS programme are shown in purple and the sightlines from the COS-DISK programme in green. *Credit: MPA*

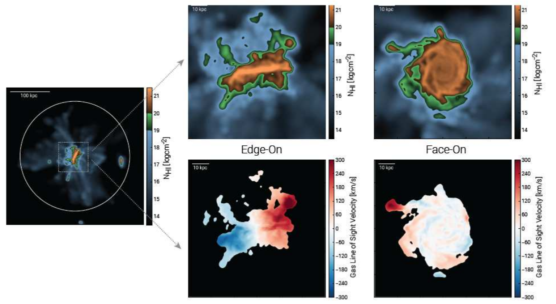

Figure 2.7: An example from the Illustris simulations: the predicted distribution and kinematics of neutral hydrogen surrounding a simulated galaxy (with the same mass as the Milky Way). The image on the left shows the HI column density at the scale of the virial radius (white circle), the middle and right columns show edge on and face on projections of the HI column density (top) and the line of sight velocity (bottom). *Credit: MPA*

strength of the Lyman α lines seems to be independent of the orientation of the disk. This means that the gas in the surrounding gas halos is distributed smoothly and relatively isotropically.

The quasar spectra obtained as part of the COS-GASS programme mainly probed sightlines well outside the disk of the galaxy. In 2015, the follow-on, large programme COS-DISK was approved to probe gas at the interface between disk and circum-galactic medium. While reduction, processing and analysis of the HST data is being carried out at Johns Hopkins University in Baltimore, MPA scientists are closely involved in using state-of-the-art cosmological hydro-dynamical simulations to interpret the observational data.

Most of the work so far has focused on the Illustris simulations. The simulation includes thousands of galaxies with masses in the range of the galaxies in the COS-GASS and COS-DISK samples, making it ideal for studying how the disk, circum-galactic medium and disk/halo interface properties vary as a function of the stellar mass of the galaxy, morphological type, star formation rate, and gas mass fraction (Guinevere Kauffmann and Dylan Nelson).

2.4 Simulating separate universes to study the clustering of dark matter

In the standard cosmological model, dark matter makes up roughly 25 % of the total energy budget of the Universe. However it cannot be observed directly, since it does not emit light. Understanding the way dark matter clusters together and forms structures is of crucial importance since it would help our understanding of the observed spatial distribution of galaxies (which should closely follow the dark matter distribution) and link this with early-Universe physics and the origin of initial perturbations. In this context, researchers at MPA and in other institutions worldwide came up with a new way of simulating the impact of large-scale primordial perturbations on the abundance of structures observed at late times, the so-called separate universe simulations. Using this technique, the MPA researchers recently obtained some of the most precise measurements of the local bias, confirming the known trend that more massive halos are more biased than smaller halos.

Dark matter groups itself in various structures to create what is called the cosmic web (see Figure 2.8). One of the most important components are the so-called halos, which simply represent regions where dark matter has accumulated. The abundance and distribution of these halos is strongly dependent on the distribution of dark matter: one could also say that the halo distribution is biased with respect to the dark matter distribution. Understanding this bias and what physical effects af-

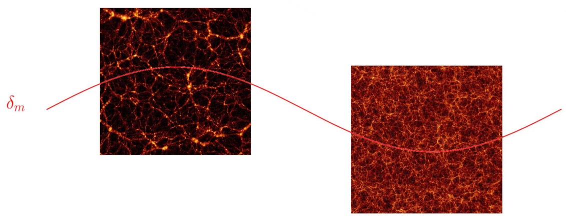

Figure 2.8: Schematic representation of the separate universe idea. The red line represents a long wavelength matter density perturbation. The two panels show results of separate universe simulations in initially overdense (left) and underdense regions (right). The colour indicates the matter density with lighter regions being denser. *Credit: MPA*

fect it is of crucial importance for the statistical description of the halo distribution. This, in turn, is very important as the current paradigm states that cosmological tracers (such as galaxies or galaxy clusters) reside preferentially in dark matter halos.

To study dark matter clustering, physicists traditionally run so-called "N-body" numerical simulations. In their simplest form, these simulations follow a set of particles in a box from an initial distribution to some later time, using Newtonian physics to describe the evolution and our knowledge of dark matter properties. Here the term "particle" is a substitute for "mass element", which are normally on the order of a few million or even billion solar masses, as we are not able to achieve infinite mass resolution. In order to cover a wide range of scales, these simulations must both have a large number of particles (billions) and be of largest possible volume (up to a few Gpc on a side) which means that they quickly become costly computationally.

The main idea behind the separate universe simulations is that a patch of the Universe, which has a different matter density, is treated as a separate universe. Indeed, it can be shown that applying an overall uniform change to the matter density in the simulation (i.e. adding a perturbation with an infinite wavelength) is equivalent to running the simulation with different cosmological parameters (for example going from flat to curved geometry). Hence, it is possible to divide a costly big simulation into smaller ones, where each has a different matter density and correctly adjusted other cosmological parameters. Thus, the dependence of e.g. the density of halos on the matter density can be studied in a clean way.

This technique does not only make the running of simulations easier, it makes it also possible to measure the impact of large-scale perturbations on smaller scales where halo and galaxy formation takes place. Since the overall matter density is now a parameter that can be chosen independently, it is possible to measure the dependence of structure formation on this parameter solely - unlike in traditional N-body simulations where a mixing of scales is unavoidable. Hence it is a fast and easy way to make precise measurements of quantities depending on the matter density.

One of these quantities is the density of dark matter halos found in a simulation. As mentioned above, the bias is the statistical quantity linking the halo density to the matter density. While there are many different bias parameters reflecting the various physical effects entering structure formation, the most well-studied bias parameter on large scales is the so-called local bias. This local bias simply relates the halo density to the matter density at each location in the simulation.

Separate universe simulations provide a perfect framework to obtain precise measurements of this quantity, as one simply needs to run several simulations with various values for the matter density and to measure the final density of dark matter halos in each of them. The obtained relation between matter and halo density then gives the local bias parameter as the proportionality constant between these two quantities, as is shown in Figure 2.9.

Clearly, simulations with higher initial matter density lead to higher halo density at later times, as can also be seen in Figure 2.8. Using this technique, researchers at MPA recently obtained some of the most precise measurements of the local bias, confirming the known trend that more massive halos (which are also less common) are more biased than smaller halos (Titouan Lazeyras and Fabian Schmidt).

2.5 Gravitational noise interferes with determining the coordinates of distant sources

It is widely known that our planet Earth and the Solar System itself are embedded in the Milky Way, and it is through this galaxy that we look out onto the Universe. As it turns out, this has a larger impact on astrophysical studies than previously

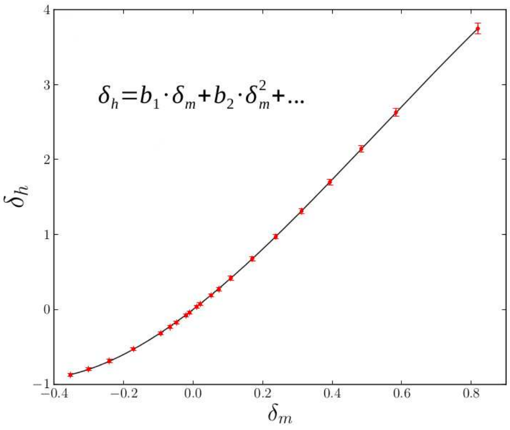

Figure 2.9: The dependence of halo density (δh) on the matter density (δm) in separate universes. Red points show results from simulations and the black line presents the fit of a polynomial to extract the local bias parameters. *Credit: MPA*

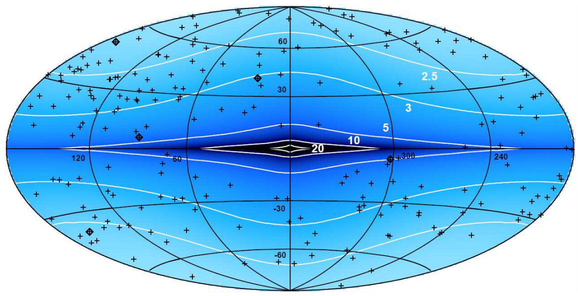

Figure 2.10: A map showing the characteristic values of the "jittering" of source coordinates around their true position caused by the Galaxy's "gravitational noise". The contours give the absolute values in microarcseconds for a ten-year observation period. The crosses represent the positions of ICRF reference sources. *Credit: MPA*

thought. Our Galaxy's gravitational field and its non-uniformity limit the accuracy of astrometric observations of distant – extragalactic – objects. An international group of astrophysicists including a researcher at the Max Planck Institute for Astrophysics tried to find out how strong this effect is.

Proper motions, angular sizes, and trigonometric parallaxes (visible displacements) of astronomical objects such as stars are the basic parameters for many astrophysical studies. These parameters are determined by astrometric techniques, and a coordinate system is needed to calculate, for example, the position or the radial velocity of a star. All coordinate systems which are currently in use, including the International Celestial Reference Frame (ICRF), are based on the coordinates of several hundred "defining" extragalactic sources. Quasars and distant galaxies are ideal reference points for determining the celestial reference frame, as their angular movement is very small, about ten microarcseconds (less than the size of a 1-cent coin on the Moon).

Astrophysical instrumentation is developing rapidly and it is expected that the accuracy of radio interferometric observations will soon reach 1 microarcsecond, and optical observations about 10 microarcseconds. However, with this level of accuracy a new challenge comes into play that interferes with the observations: the general theory of relativity and in particular the deflection of a light beam in a gravitational field.

When a light beam from a distant source passes close to any massive object, it is slightly deflected by its gravity. This deviation is typically very small, but if the beam encounters several objects on its path, the added deviations may become significant. In addition, as the objects are moving, the beam deflection angle changes with time and the source coordinates start to "jitter" around their true value. It is important to note that this "jittering" effect applies to all distant sources, including those that are used as reference points for different coordinate systems. In attempting to improve the accuracy of coordinate reference systems, in the near future we will reach a limit that cannot be exceeded by better detection instruments. In fact, the "gravitational noise" makes it impossible to increase the accuracy of a coordinate system above a certain level.

The group of researchers now tried to estimate the effect of gravitational noise on observations. The study relies on extensive numerical calculations performed by Dr Natalia Lyskova at MPA. She developed a high-performance parallel code and built two-dimensional "deviation maps" of the entire sky based on modern models of the Galactic matter distribution (see Figure 2.10). The calculations show that for a reasonable observation time of about ten years, the shift in the positions of the sources will vary between 3 microarcseconds at high galactic latitudes up to several dozen microarcseconds close to the Galactic centre.

Consequently, when the accuracy in absolute astrometry reaches microarcseconds, the "jittering" effect of the reference source coordinates due to the Galaxy's non-stationary gravitational field, will have to be taken into account. But the scientists also have some good news: when investigating the properties of this gravitational noise they were able to demonstrate that the "jittering" effect of the coordinates can be partially compensated by using mathematical methods (Natalya Lyskova).

Note: The team includes researchers from the Astro Space Center of P.N. Lebedev Physical Institute (Russia), the Space Research Institute of the RAS (Russia), the Moscow Institute of Physics and Technology (MIPT), and MPA .

2.6 Intense radiation and winds emitted by massive stars regulate star formation in galaxies

Only a small fraction of the stars that form in the Milky Way are much more massive than our Sun and explode as supernovae type II at the end of their lifetimes. Still, these high-mass stars influence the surrounding interstellar medium (ISM) much more than their small number might suggest, both by their intense radiation and powerful winds ("pre-supernova feedback") and through their violent supernova explosions ("supernova feedback"). Scientists at the Max Planck Institute for Astrophysics, in the framework of the SILCC collaboration, use complex supercomputer simulations to investigate the detailed impact of the different feedback processes on the ISM with conditions similar to our solar neighborhood. Ionizing radiation from young, massive stars dominates their energy output and can exceed the energy released during supernova explosions by an order of magnitude. Only if the simulation includes this radiative feedback and the momentum input from stellar winds are the results consistent with observations of the ISM and the star formation rate is reduced.

High-mass stars dominate the energy output of newly formed stellar populations. Most of the energy is emitted in the form of radiation, followed by supernova explosions and stellar winds. When the radiation deposits its energy in the ISM, the photoelectric heating of dust and photo-ionization can lead to temperatures of a few thousand degrees and more. The photo-ionizing radiation is also a major source of ionized hydrogen in the ISM and drives the formation of so-called "H II regions", which consist of hot gas with temperatures of ten thousand degrees around young, massive clusters. Supernovae and to some degree stellar winds are energetic enough to shock-heat the ISM to temperatures of a few million degrees.

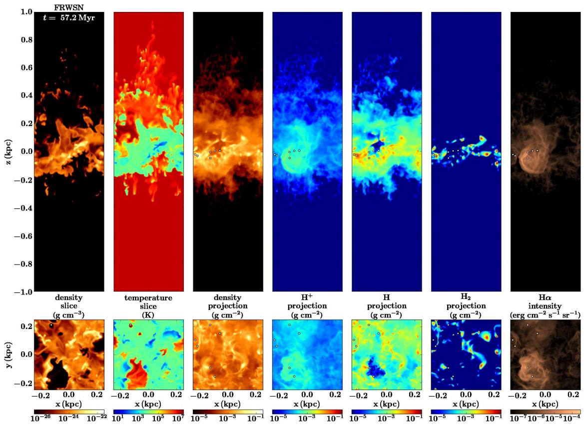

Figure 2.11: Edge-on (top) and face-on (bottom) slices through the center of the simulation box for density and temperature (left two panels), projections of the total gas density (3rd panel) and the density of the different forms of hydrogen, ionized, atomic and molecular, (bluish panels) and an image of the resulting emission in the HÎś line (right). The locations of the star clusters are indicated with white circles. The images are for a simulation with all three feedback processes included, and a giant region of ionized hydrogen created by the ionizing radiation can be seen in the ionized hydrogen (H+) and Hα images. *Credit: MPA*

The emission of radiation, stellar winds and supernova explosions therefore all have different effects in shaping the structure of the ISM and should be considered in concert. Modern attempts to improve the numerical modelling towards a consistent theory of the ISM and star formation need to take all three processes into account. A successful model should then be able to reproduce the ISM as seen in the Milky Way and the observed relation between the amount of dense molecular gas and star formation in galaxies.

Together with a European team of experts, scientists at MPA have used complex supercomputer simulations to investigate the impact of stellar radiation, stellar winds and supernova explosions on the ISM of a galactic disk. For the first time, the simulations include all three dominant forms of stellar feedback and follow the chemical transitions from ionized over neutral atomic to molecular gas. In the simulations, star clusters form dynamically out of parcels of gas collapsing under their own gravity. The team has investigated the effects of the different forms of feedback from the stars in these clusters on the structure of the surrounding ISM and the resulting star formation rate (SFR) in the simulations (see Fig. 2.11).

Photoionization heating is the dominant energy source in the ISM, it exceeds the energy input from supernovae by one and from winds by two orders of magnitude. All the different photochemical processes started by radiation can individually impart more energy into the ISM than supernovae as a whole. This radiation, however, is not a constant source; the star cluster luminosities are highly variable with time because they are dominated by extremely massive stars that shine very brightly but have lifetimes of only a few million years.

The time variability of the cluster luminosities has important consequences for SFR measurements (Fig. 2.12). The observed SFR only matches the true SFR when very massive stars are present in the clusters. Less massive stars do not produce enough ionizing radiation and measurements of the so-called "Hα-line" then underestimate the SFR by up to an order of magnitude; and this result is independent of the calibration used.

Observationally, the amount of star formation within a patch inside a galaxy is closely related to the amount of molecular gas that is present there. The ratio of these two quantities is called the depletion time, and it is universally found to be around 2 billion years. The simulation with radiation naturally exhibits a similar depletion time, while the other simulations fail to do so (Fig. 2.13).

The "pre-supernova feedback" by both radiation and winds also influences the third process by significantly reducing the environmental density of supernova explosion sites. For a simulation with supernova feedback only, 80% of all supernovae go off in gas with mean densities below 100 particles per cubic centimeter. If winds are included in the simulation, this density is reduced by a factor of more than 10, and with radiation by another factor of 100. Exploding at lower environmental densities the supernova can cause more "damage" to the ISM and even drive gas out of the galaxy.

The presence of radiative feedback significantly affects also the mass fractions of the different chemical states of hydrogen. The photoionization by star clusters ionizes the gas in the ISM. This ionized gas then cools radiatively and produces gas in the warm phase, at the same time leading to a substantial reduction of the fraction of gas in the hot phase compared to simulations without radiation. This process is essential to match the observed fractions of the warm and hot phases.

The simulations thus indicate that "pre-supernova feedback" can regulate star formation and the abundance of molecular, neutral and warm ionized gas. "Supernova feedback" determines large-scale turbulent structure of the ISM, its hot gas volume filling fraction and the driving of outflows.

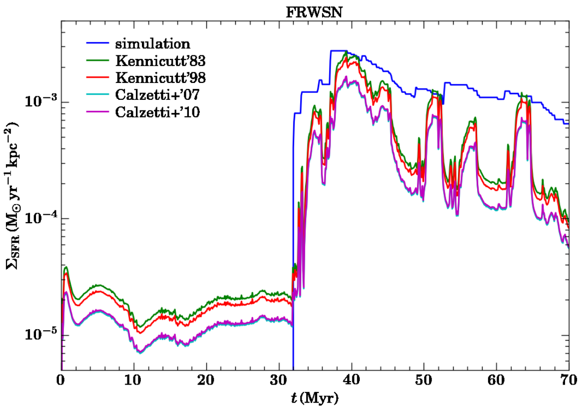

Figure 2.12: The surface density of the Star Formation Rate (SFR) measured in the simulation (blue) and derived via various SFR calibrations of observations (other colours) as a function of time. Please note the logarithmic scale. The offset between the true and the observed SFR can be up to an order of magnitude. *Credit: MPA*

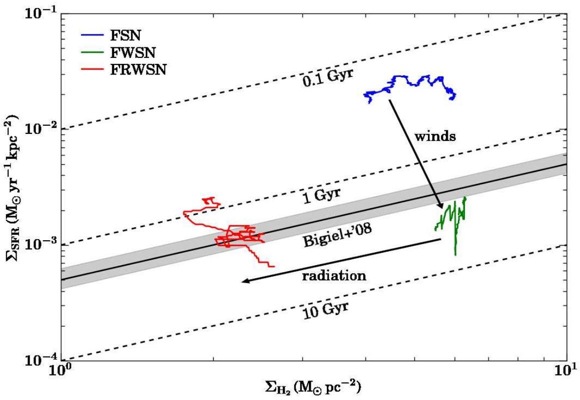

Figure 2.13: The simulations predict the effect of supernova feedback (blue) in the combination with stellar winds (green) and stellar radiation (red) on the star formation rate and the mass in molecular gas. Stellar winds reduce the amount of newly forming stars but do not affect the molecular gas (blue to green). Additional stellar radiation destroys molecular gas but does not change the star formation rate (green to red). Observed galaxies lie in the grey shaded area. The timescales by which all molecular gas would be converted into stars (depletion time - the ratio of star formation rate to molecular gas mass) are indicated by the dotted lines. For galaxies this timescale is around 2 billion years in good agreement with simulations including stellar winds, radiation and supernova explosions. *Credit: MPA*

To understand which physical processes produce the ISM and star formation observed in galaxies, it is crucial to run complex simulations that include all important ingredients, which are at work simultaneously in complex star forming regions. The simulations of the SILCC collaboration are therefore an important step forward in this endeavor. (Thomas Peters and Thorsten Naab for the SILCC collaboration)

2.7 Wanted: the rotating radio emission of the Milky Way

The magnetic fields of the Milky Way cause electrons with nearly the speed of light to rotate and to emit radio waves. As consequence, this radiation should also "rotate" slightly, it is circularly polarized. This very weak circular polarization of the Milky Way, however, has not been observed so far. Researchers at the Max Planck Institute for Astrophysics and colleagues have now predicted some properties of this polarization and created a "wanted poster" to allow targeted searches. A measurement of the circular polarization would provide important insights into the structure of the galactic magnetic fields and confirm that electrons - and not positrons - are the source of this radio emission in the Milky Way.

The vast space in between the Milky Way stars is not empty; it is filled with gas, dust, magnetic fields, and particles with almost the speed of light - the so-called cosmic radiation. This consists of atomic nuclei, electrons and small amounts of antimatter, especially positrons and antiprotons. Part of the cosmic radiation reaches the earth directly, but it can also be detected indirectly. The ultra-fast electrons and positrons emit radiation, which has already been detected and measured (Fig. 2.14). So far, however, it is almost impossible to distinguish whether this radio emission originates from electrons or positrons.

The circularly polarized radiation could tip the scientists off, since electrons and positrons rotate in opposite directions. However, this radiation is less than one thousandth of the galactic radio emission; researchers therefore have been unable to detect it. Moreover, astronomers do not have a clear idea of what patterns to look for in the sky, they do not know what this radiation should look like. This gap has now been filled by Torsten Enßlin and his colleagues. The astrophysicists show that the current information about the magnetic field of the Milky Way is enough to estimate the circular polarization.

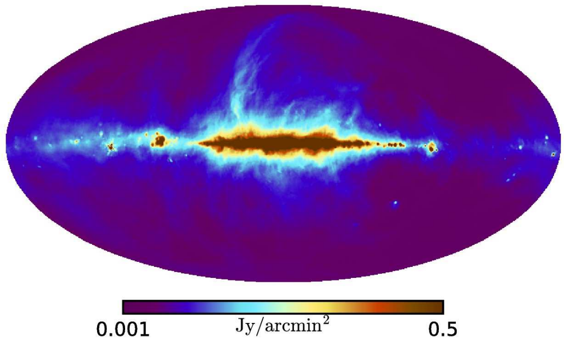

Figure 2.14: Radio map of the Milky Way. This map shows the amount of electrons with nearly the speed of light times combined with the magnitude of the transverse component of the galactic magnetic field, projected along each line of sight through the Milky Way. *Credit: MPA*

Three conditions must be fulfilled for a region in space to radiate circular polarized light. First, there must be an excess of electrons (or positrons) with almost the speed of light, so that the rotation of these particles in the magnetic field will be in a preferred direction. Second, the magnetic field has to be at least partially aligned with the observer so that the direction of rotation is visible in the sky projection. And third, the magnetic field must not be completely in the direction of the line of sight, since the radio waves are mainly emitted transversely to the magnetic field.

Information about both the amount of electrons and positrons with almost the speed of light and the transverse component of the magnetic field is given by the radio map of the Milky Way (Fig. 2.14). In general, it is assumed that this emission is generated mainly by electrons with only a small contribution by positrons.

Information on the line of sight component of the magnetic field comes from measurements of the so-called Faraday effect. Linearly polarized light, radiated from radio-galaxies outside the Milky Way, is being rotated as it traverses the galactic magnetic field. This rotation depends on both the intensity and the orientation of the magnetic field along the line of sight. Radio waves interact with slow thermal electrons in the galactic gas, which perform circular motions in the magnetic fields. The rotation of the linear polarization of the light-waves is in the opposite direction as the rotation of these electrons. Since the magnitude of the Faraday effect varies with the frequency of the radiation, it can be detected and mapped. In this way, a Faraday map of the sky was produced already in 2012 by Niels Oppermann working with Torsten Enßlin (Fig.2.15, MPA Highlight November 2012). This shows the summed up magnetic field component that is aligned with any given line-of-sight.

Thus, all three necessary components are known: the number of electrons at nearly the speed of light, and the strengths of the two magnetic field components involved. The information from observations, however, is always given only as a projection along a line of sight. For an accurate prediction of the circular polarization, further data is needed to describe how these three components are distributed along the lines of sight.

For an estimation of this distribution in the third dimension, Torsten Enßlin used both known and plausible statistical properties of turbulent magnetic fields. Thus, he was able to show that the exact details of the statistics do not have much influence on the results, as long as the magnetic fields do exhibit any improbable structure. The PhD student Sebastian Hutschenreuter then made a prediction of the circular polarization using a coarse model of the distribution of both thermal and highly energetic electrons, as well as the magnetic energy contained in the Milky Way from observed radio and Faraday maps (Figure 2.16).

The details of the prediction will not be accurate in all details as there were uncertain assumptions. However, the map should indicate the preferred direction of rotation of the actual circular polarization more often than not. This statistical prediction therefore is suitable in searches for the extremely weak circular polarization signal.

The next step will be to look for the predicted small circular polarization pattern in the data of both existing and soon-to-come terrestrial radio telescopes. If astronomers were able to actually detect the "rotating radiation", astronomers could draw important conclusions about the galactic magnetic field and confirm that electrons and not positrons are the source of this radiation in the Milky Way (Torsten Enßlin and Sebastian Hutschenreuter).

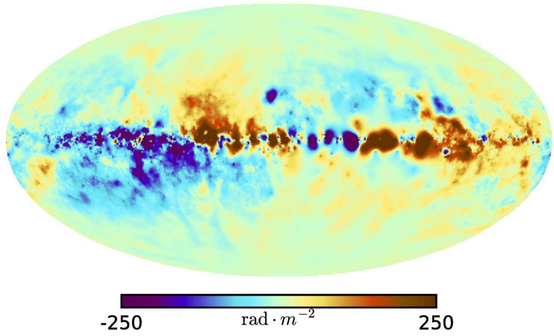

Figure 2.15: Map of the Faraday effect in the Milky Way. This map shows the line-of-sight component of the galactic magnetic field weighted with the amount of thermal electrons, projected along each line of sight through the Milky Way. Regions where the magnetic field is mainly directed at us are red and regions in which it points away from us are blue. *Credit: MPA*

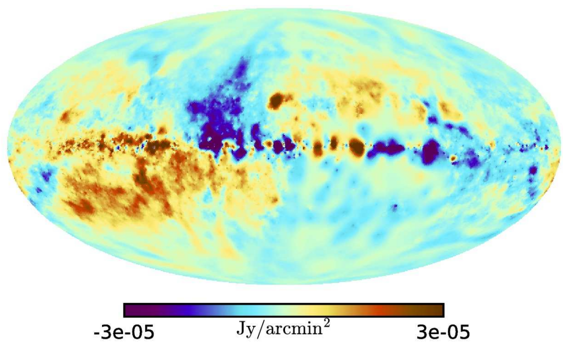

Figure 2.16: Map of the intensity and direction of rotation of the circular polarization of the radio emission. Regions in which the polarization is predominantly clockwise are red, and regions with counterclockwise polarization are blue. This prediction was made by combining the intensity maps of galactic radio emission (Figure 2.14), the Faraday effect (Figure 2.15), and a rough model of the 3D distribution of galactic electrons. The details of the true circular polarization will differ, but the map should show the correct direction of rotation more often than not if our knowledge of particles at near the speed of light in the Milky Way is more or less correct. *Credit: MPA*

2.8 Instabilities in relativistic magnetized accretion disks

Using three-dimensional general relativistic magnetohydrodynamic simulations, scientists at the Max Planck Institute for Astrophysics (MPA) have studied thick accretion disks orbiting around black holes. They find that weak magnetic fields can suppress the development of large-scale over-densities in the accretion flow. The onset of magnetic turbulence reshapes the disk's structure and could even quench the gravitational-wave signal produced by the accreting torus without magnetic fields.

Neutron stars are fairly exotic objects with a density equal to the one found in atomic nuclei. But if two neutron stars merge, an even more exotic object can be the result: a black hole-torus system might form, where a thick disk orbits around the central compact object, emitting highly energetic radiation and feeding mass to the black hole. These thick accretion disks are prone to develop a number of instabilities that shape their structure and determine their properties.

In the absence of magnetic fields, they can experience the so-called "Papaloizou-Pringle instability" (PPI), which leads to the growth of non-axisymmetric perturbations in the disk. From these a characteristic planet-like structure will form that orbits around the central object. Recent numerical hydrodynamic simulations performed in the framework of General Relativity show that such an instability can develop quite generally, possibly leading to a detectable emission of gravitational waves.

The dynamics of the disk can change significantly when magnetic fields are present, because they trigger the so-called "magneto-rotational instability" (MRI). This phenomenon is regarded as one of the main mechanisms driving accretion in a number of astrophysically relevant scenarios, such as active galactic nuclei and X-ray binary systems. There, MRI leads to the growth of linear perturbations on dynamical time scales and magnetic turbulence.

For the first time, astrophysicist at the MPA systematically studied the interplay between these two kinds of instabilities in relativistic disks orbiting around a black hole. Their goal was to better understand how these instabilities interact and whether one dominates over the other. Using three-dimensional general relativistic magnetohydrodynamic (GRMHD) simulations, they investigated how accretion tori evolve, which are threaded by a purely toroidal magnetic field of various strengths. The magnetic field was always sub-thermal, i.e. the magnetic pressure was 1% to 10% of the thermal pressure. All simulations were performed with a highly parallelized version of the "ECHO" code.

In the hydrodynamic case, the PPI develops undisturbed and a characteristic large-scale, non-axisymmetric mode dominates throughout the whole simulation. The inclusion of magnetic fields triggers the growth of a MRI, which develops faster than the PPI. The smooth flow present in the unmagnetized model is replaced by a turbulent plasma, where small scales are excited and there is no clear evidence of a planet-like structure orbiting around the black hole (see Fig. 2.17).

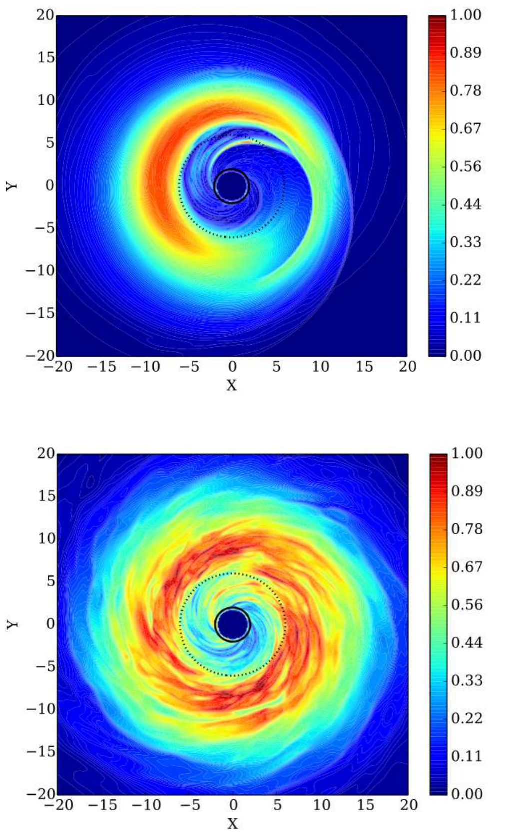

Figure 2.17: Equatorial cuts of the rest mass density for the hydrodynamic (top) and magnetized (bottom) models after 15 orbital periods. The solid black curve represents the black hole event horizon, while the dotted black curve indicates the radius of the last marginally stable orbit. *Credit: MPA*

The time-averaged density spectra (Fig. 2.18) show the difference between the scale-distribution of the resulting turbulence: in hydrodynamic disks a dominant peak is present for the largest scales, which disappears in all magnetized models. The MHD turbulence excites a wider range of scales, leading to shallower spectra, while there are no substantial differences in the shapes of the spectra for different levels of magnetization.

The simulations show that also the time frame changes. When the disk is threaded by a magnetic field, the MRI leads to a faster onset of accretion onto the central black hole. In this case, the transport of angular momentum towards the outer parts of the disk happens on a shorter time scale than in the hydrodynamic case.

In all magnetized models the PPI appears to be severely quenched by the action of the MRI. This is probably due to the fact that the MRI quickly changes the local conditions in the disk, by transporting angular momentum outwards and establishing a turbulent environment where conditions are no longer favourable for the PPI to form.

However, if the MHD turbulence is not well resolved (and hence the magnetic field gets more diffused) the suppression of the PPI appears to be less effective. This behaviour is observed only in lowly magnetized disks, since models with a higher magnetization have a large characteristic wavelength of the MRI and less grid points are required to properly resolve it.

The findings from the simulations suggest that in the presence of dissipative effects - whether they are due to numerical limitations or physical phenomena - the PPI may still give rise to a significant large-scale turbulence. The next step in this study will therefore focus on the possible role that turbulent magnetic diffusivity may play in the disk's evolution.

Future work could also take into account the self-gravity of the disk. Non-linear interactions between the central black hole and the torus can excite additional PPI modes and hence reinforce the growth of non-axisymmetric structures in the disk. These would directly affect the gravitational wave signal emitted by the system. (Matteo Bugli, Jerome Guilet, Ewald Müller).

Note: The parallelization of the "ECHO" code was developed by Matteo Bugli (MPA) in collaboration with Fabio Baruffa (Leibniz-Rechenzentrum) and Markus Rampp (Max Planck Computing and Data Facility).

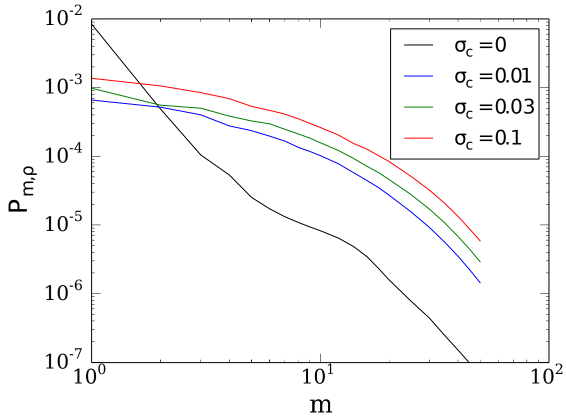

Figure 2.18: Time-averaged rest mass density spectra as a function the mode number m, which indicates the scale of an instability. The black curve represents the hydrodynamic model; here a prominent peak is present for m=1 which is equivalent to a large-scale ordered flow. The coloured solid curves refer to magnetized models, where turbulence is present on a wider range of scales. The parameter c represents the value of magnetization (ratio of magnetic to thermal pressure) at the disk's centre. *Credit: MPA*

2.9 Probing molecular clouds with supermassive black hole X-ray flares

The centre of the Milky Way is a very special place, harboring many exotic objects, such as the supermassive black hole Sagittarius A* and giant molecular clouds. Some of these clouds, despite being cold, are sources of high energy photons. It is believed that the clouds are not producing these photons themselves, but rather scatter the X-ray radiation coming from outside. Even though Sgr A* is currently very faint in X-rays, it is considered as the main culprit of this radiation, in the form of short but intense flares, which happened over the past few hundred years. The time delay caused by light propagation from Sgr A* to the clouds and then to us, allows one to study Sgr A*'s past activity. At the same time, flares serve as an extremely powerful probe of molecular gas properties. In particular, the full 3D structure of molecular clouds and their density distribution on small scales can be reconstructed.

Although our Galaxy's supermassive black hole Sgr A*, which has 4 million times the mass of our Sun, is currently very dim, there are indications that it experienced powerful flares in the not very distant past. In particular, reflection of Sgr A*'s X-ray emission on molecular clouds surrounding it provides evidence for such recent flares.

In reconstructing this history, there are two effects that have to be taken into account. First, the reflected emission is proportional to both the intensity of the illuminating radiation and the density of the gas. Second, the time delay attained during light propagation from the primary source (i.e. Sgr A*) to a reflector (i.e. a molecular cloud), and then from the reflector to an observer amounts to hundreds of years. From this, the history record of Sgr A* activity can be reconstructed, provided that

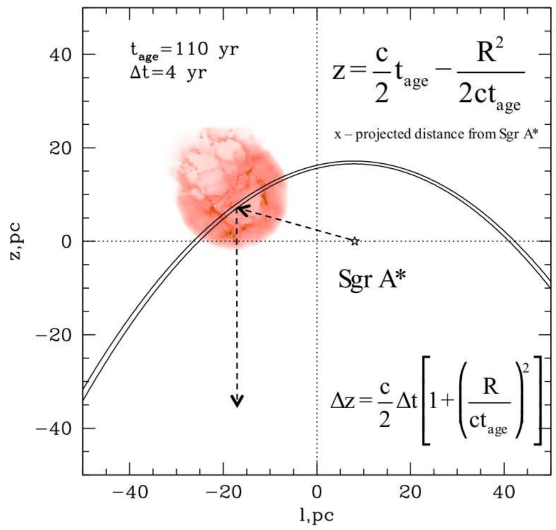

Figure 2.19: Schematic geometry of the problem. The reflected emission from a Sgr A* outburst reaches the observer with a delay caused by the light propagating from the source to the cloud and then to us (dashed arrows). The two thin lines show the locus (?) of illuminated molecular gas 110 years after a 4-year outburst. *Credit: MPA*

the relative positions of the source and the reflector are known with sufficient precision. This is informally known as X-ray archaeology. Unfortunately, the line-of-sight distances are poorly known, so one has to look for some additional ways to break down degeneracies associated with the simple time-delay arguments.

A series of recent papers has shown that exploring spatial and temporal variations of the reflected emission can lift these degeneracies. Indeed, data collected by the space telescopes Chandra and XMM-Newton over more than 15 years show that the reflected X-ray emission is variable on timescales on the order of years and on spatial scales of less than one parsec (see Fig. 2.20).

The observed variability implies that the original flare itself must have been shorter than few years. With this in mind, one may take a more rigorous look at the statistical properties of the variability in time and space, which should be closely related to each other. Indeed, in the short flare scenario, variations in the space domain simply reflect density fluctuations in a thin slice of the reflecting medium projected on the picture plane (Fig. 2.19). On the other hand, variations in the time domain (at a given sky position) arise from similar density fluctuations but sampled along the line-of-sight, i.e. with slightly different time delays. If the statistical properties of the underlying density field are isotropic on small scales, there is a straightforward transformation connecting the two variability patterns. The parameters of this transformation are being determined by the relative 3D positions of the primary source and the reflector.

If one compares the X-ray flux variability in the time and space domains, these variability patterns match each other if one assumes that the light front propagates along the line of sight with a of velocity 0.7 the speed of light. This value immediately gives the position of the cloud with respect to Sgr A* and the age of the flare as about 110 years. Most likely the flare lasted less than one year, and is now reflected by the molecular cloud known as the 'Bridge complex' some 30 pc away from Sgr A*.

Using data on the emission of the same region in various molecular lines, the average density of reflecting the gas can be estimated and from this, the integrated X-ray flux provided by the flare can be inferred. Such an analysis suggests that the flare might have been the result of a tidal disruption of a planet (or the partial disruption of a star) being careless enough to come too close to the supermassive black hole.

Knowing the age of the outburst, it is straightforward to reconstruct the 3D density distribution of the molecular gas (see Fig. 2.21). So far, using the data of 15 years of monitoring, only a thin ~ 3.5 parsec slice can be reconstructed. This is certainly not the end of the story, since the molecular complex, being bright at the moment, will eventually fade away when the illumination front will have completely passed through it. At the same time other molecular clouds in the Central Molecular Zone might come into the spotlight, with 'X-ray echoes' of a single flare being potentially observ-

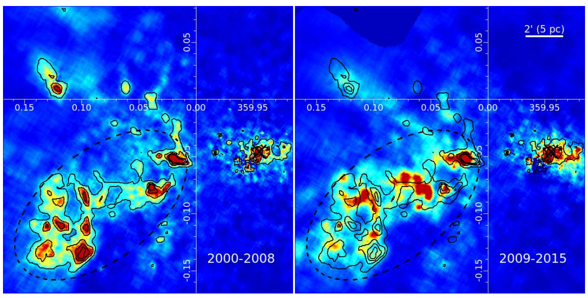

Figure 2.20: Chandra maps of the reflected emission from one of the molecular complexes in the vicinity of Sgr A* taken in 2000-2008 (left) and 2009-2015 (right). The changes in the image morphology reflect propagation of the illuminating front through the cloud. To make comparison easier, the contours of the earlier image (left) are repeated at the same positions in the later image (right) *Credit: MPA*

able over several hundred years, the light-crossing-time of the entire Central Molecular Zone (CMZ). A movie illustrating the possible evolution of the CMZ X-ray map over the next 500 years is shown below.

Interestingly enough, not only studies of Sgr A* activity do benefit from the observations of its 'X-ray echoes'. The properties of the gas density field can be studied in detail, without being hindered by projection effects or by the sensitivity to the chemical abundance of a particular molecular species as is commonly the case for molecular emission lines data.

In the short flare scenario, the illuminated region is just a thin slice of molecular gas and the intensity of the reflected X-ray emission is simply proportional to the number density of the gas (in the optically thin limit). The probability distribution function of the gas density measured in this way appears to be well described by a log-normal shape (see Fig. 2.22), in line with the theoretical and numerical predictions for supersonic turbulence, which is believed to shape the structure of molecular gas on the scales probed.

However, a number of effects could mimic such a shape of the distribution function, namely high opacity even for X-rays for the high end or low count statistics on the low end. These issues can partly be addressed with sufficiently deep Chandra observations complemented by realistic simulations of the molecular clouds. In principle, with the angular resolution provided by Chandra, it is possible to study scales down to 0.05 pc, where self-gravity starts to become dominant and which effectively seed the star formation process.

Thus, X-raying molecular clouds might become useful for solving the long-standing problem of suppressed star-formation efficiency in the Central Molecular Zone. Next generation of X-ray observatories equipped with micro-calorimeters, like ATHENA and Lynx, will be capable of probing also the velocity field in the reflecting gas. The full picture of the turbulent inner life of the Galactic Center molecular clouds could then be reconstructed. Equally important are future X-ray polarimetric observations that will provide solid proof that the source of illuminating photons is indeed Sgr A* by measuring the polarization angle, while the degree of polarization will provide an independent way of measuring the line-of-sight position of the cloud. (Eugene Churazov, Ildar Khabibullin, Rashid Sunyaev).

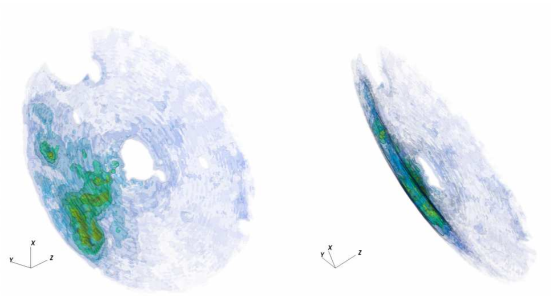

Figure 2.21: Reconstructed 3D map (viewed at two different angles) of the molecular gas density distribution in vicinity of Sgr A*. This map is based on 15 years of XMM-Newton observations, leading to a thickness of the probed region of about 3.5 parsec. The characteristic "saucer" shape of the region is driven by the condition of a constant time delay after the flare. The "holes" in the map correspond to excised regions contaminated by bright compact sources. *Credit: MPA*

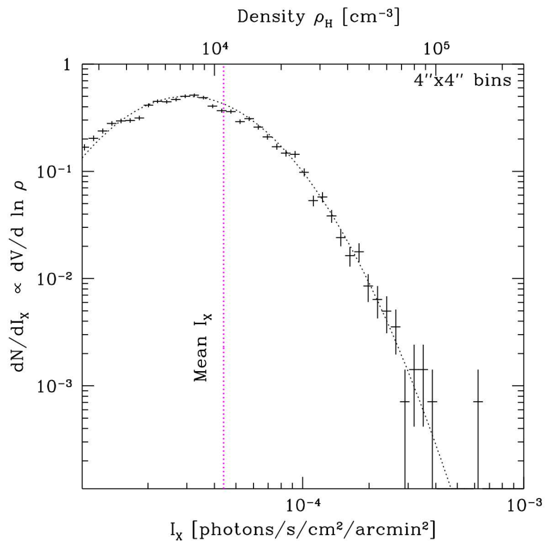

Figure 2.22: Reconstructed probability distribution function of the molecular gas density. It follows a Log-normal distribution, in line with the theoretical models of supersonic turbulence. However, further observations are needed to extend the dynamic range over which the distribution is reliably measured. *Credit: MPA*

2.10 Rise and Shine: Type Ia supernova models at early times

Type Ia supernovae (SNe Ia) are spectacular explosions in white dwarf stars and play an essential role in astrophysics in general and in cosmological studies in particular. However, many puzzles about the nature and the inherent physical mechanisms in SNe Ia are still waiting to be answered. Robotic surveys of the next decade will provide an unprecedented wealth of observed Type Ia supernovae, detected shortly after explosion. Researchers at MPA examine here whether different explosion models are expected to leave clear imprints in such early observations that could be used in future photometric surveys to help shedding light on the progenitors and explosion mechanism of SNe Ia.

Most likely, you are reading this article using a device whose existence relies on the silicon chip, such as a PC, laptop or mobile phone. Together with a number of other chemical elements such as iron, a significant fraction of the silicon in our Universe today has been forged from lighter elements in the thermonuclear fires raging in cataclysmic events known as “Type Ia supernovae” (SNe Ia). These violent explosions mark the brilliant death of a low mass star. During their evolution, SNe Ia can become incredibly bright – to the point at which they outshine their host galaxies (see for example SN 1994D shown in Figure 2.23).

This is one of the properties that make SNe Ia ideal for cosmological studies in which they are frequently used as distance indicators mapping out the recent expansion history of the Universe. Specifically, SNe Ia were instrumental in establishing our current cosmological picture which involves a dark energy component responsible for the accelerated expansion. This discovery was recognized by the Nobel prize committee in 2011. However, despite their astrophysical and cosmological significance, astrophysicists are still in the dark about many aspects concerning SNe Ia.

It is broadly accepted that the supernova marks a thermonuclear explosion in a white dwarf made up of mainly carbon and oxygen that has been part of a binary system. White dwarfs are compact objects which are stabilized by electron degeneracy pressure. They are the evolutionary end state of low mass stars after their nuclear fuel has been exhausted. However, it is still heavily debated what the nature of the companion is, whether it is a sunlike or giant star or another white dwarf.

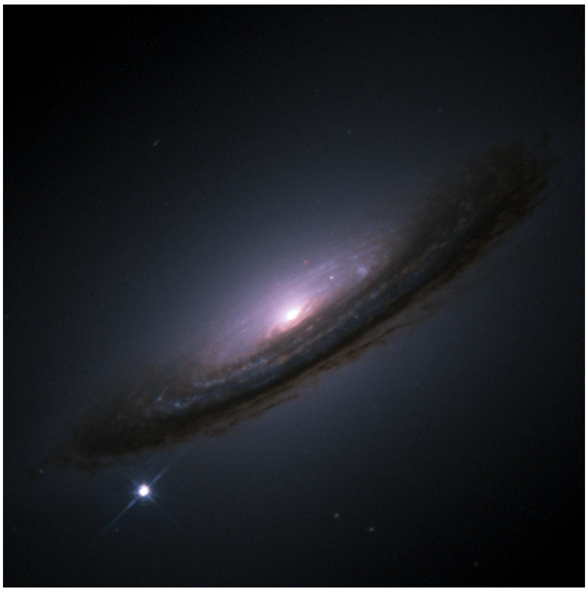

Figure 2.23: An example of the immense brightness SNe Ia can develop: SN 1994D outshines its host galaxy, NGC 4526. The supernova is the bright object in the lower left corner. *Credit: NASA/ESA, The Hubble Key Project Team and The High-Z Supernova Search Team*

Moreover, the details of how the thermonuclear explosion is triggered and how it proceeds are still under active investigation. In particular, it is not clear if the burning front propagates as a supersonic detonation, as a subsonic turbulent deflagration, or whether a mixture of both modes is realized and the burning starts subsonically and then transitions into a detonation (delayed detonation model).

Related to the previous questions, it is still unclear at which mass the white dwarf explodes, in particular whether the supernova sets in at the theoretical mass limit for systems stabilized by electron degeneracy pressure (about 1.4 times the mass of our sun), or below it. This limit is referred to as “Chandrasekhar mass” and consequently one distinguishes Chandrasekhar mass and sub-Chandrasekhar mass models. In the latter case, the explosion can for example be triggered by a merger with another white dwarf.

Finally, it still has to be firmly established whether one scenario is exclusively responsible for SNe Ia or whether a mixture of the different explosion and progenitor possibilities is realised in nature.

Researchers at MPA performed a theoretical study, developing predictions for the early optical appearance for a number of common explosion models for standard SNe Ia. They focussed specifically on identifying clear signatures in the early light curve, i.e. the time evolution of the emission in a particular passband. Such a signature would make it possible to clearly identify specific explosion scenarios from early photometric observations.

The reason for the interest and focus on early observables is two-fold: currently, the tightest constraints on the nature of SN Ia progenitors come from the earliest data points shortly after explosion. Moreover, upcoming high-cadence surveys and upgrades of existing transient search programmes will drastically increase the number of SNe Ia detected shortly after explosion.

For the main part of the study, the scientists selected two Chandrasekhar mass explosion models, namely the well-known carbon deflagration model W7 and the delayed detonation model N100. In addition, they focussed on three sub-Chandrasekhar models, in particular a merger of two white dwarfs, a double detonation in a carbon-oxygen white dwarf with a helium shell and a pure detonation in a white dwarf core. Using the radiation hydrodynamical code Stella, they followed the supernova ejecta evolution in all these models and calculated colour light curves in various pass bands (see Figure 2.24).

While for most scenarios, the light curves of the various models evolve similarly, the double detonation model shows a steep rise and a pronounced first shoulder due to radioactive material located close to the ejecta surface. This material has been synthesized in the first detonation in the Helium shell. Unfortunately, this signature is very similar to the traces left by the interaction between ejecta and a companion star or ejecta and circumstellar material, which have been investigated by other groups, rendering it a challenge to establish a clear link between such a feature in the early observables and the physical properties of the explosion scenario.

Investigating the early light curves in more detail, the researchers found that none of the standard models follow a power-law rise. However, such a behaviour, namely that the emitted luminosity increases proportional to some power of the time since explosion, is often assumed when reconstructing the explosion date from observational data. The scientists demonstrate that this can lead to errors of several days in determining the explosion date without degrading the fidelity of the fits. Potentially, this has severe consequences for estimating the size and nature of the exploding object from early data, which requires a precise determination of the time of explosion.

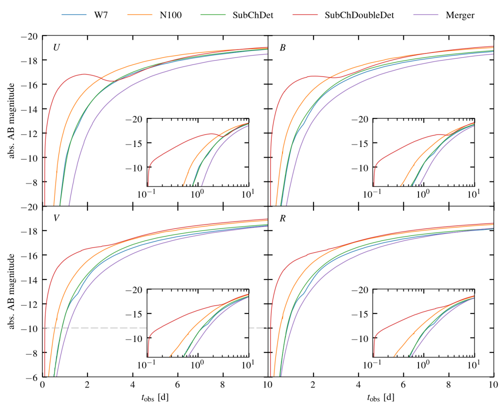

Figure 2.24: Overview of the synthetic light curves for the different models in the Bessell U (upper left), B (upper right), V (lower left) and R (lower right) wavelength bands during the first 10 days after explosion. The inset shows the same curves on a logarithmic timescale, demonstrating that the curves do not follow a power law (which would be a straight line). *Credit: Nöbauer/MPA*

In summary, the researchers demonstrated that it is very challenging to identify specific explosion scenarios based on early photometric data alone. The additional availability of early spectroscopic information may help to break some of the degeneracy. Unlike typically assumed, they predict an early non-power law rise for all of the investigated standard explosion models. This can lead to serious difficulties in dating the explosion and deriving constraints about the nature of the exploding object. (Ulrich Nöbauer, Stefan Taubenberger and Wolfgang Hillebrandt).

2.11 Bridging the Gap: From Massive Stars to Supernovae in 3D

A team of astrophysicists from Queen's University Belfast, the Max Planck Institute for Astrophysics (MPA), and Monash University (Australia) has, for the first time, performed three-dimensional computer simulations that follow the evolution of a massive star from its final phase of nuclear burning, through the collapse of the stellar iron core, into the first seconds of the beginning explosion as a supernova. The simulations show that the large-scale violent convective motions that stir the oxygen burning layer at the onset of collapse can provide crucial support for the explosion of the star.

Massive stars die catastrophic deaths. Once they have exhausted their nuclear fuel at the centre, the innermost part of the star, an iron core about 1.5 times as massive as the sun, succumbs to gravity and collapses to an ultra-dense neutron star within a fraction of a second. In the process, the outer layers of the star are expelled in a gigantic supernova explosion with velocities of thousands of kilometres per second.

Such supernovae are regularly observed in distant galaxies, and within the Milky Way we can still see the debris sits of many such explosions hundreds and thousands of years later. Much of the world around us is, in fact, ultimately debris from massive stars - from the oxygen we breathe to the calcium in our bones. But a puzzle remains: How is the collapse of the star turned into an explosion?

The most promising theory posits that extremely light and weakly interacting elementary particles, called neutrinos, are key in this process. These are emitted copiously from the surface of the young neutron star, which is a few thousand times hotter than the centre of the Sun. Part of these neutrinos are absorbed by matter falling onto the neutron star, heating it up. If the heating is sufficiently strong, the collapse is reversed, and the neutrino-heated matter drives an expanding shock wave through the star.

Theorists have long attempted to show that this idea works with the help of computer simulations. But even though one can now simulate the collapse of massive stars in three dimensions (3D), the computer models often still fail to explode. The international team of researchers including MPA scientists has now worked on a solution to this problem by invoking more realistic initial conditions. The team replaced the spherical stellar models, from which supernova calculations were previously started, by fully three-dimensional initial data.

Taking into account the asymmetries that exist in the progenitor star prior to its collapse enabled a neutrino-driven supernova explosion. The astrophysicists could follow the evolution of the expanding blast wave in a continuous, consistent 3D calculation for the longest period to date. This breakthrough in our understanding of the highly complex processes that lead to the explosion of massive stars has become possible by using supercomputers in Australia, Germany, and the UK.

For a successful explosion in 3D it is crucial that there are already violent overturn motions before collapse driven by nuclear fusion, which need to be stirred even more to trigger an explosion. To explore this possibility, the team simulated the fu-

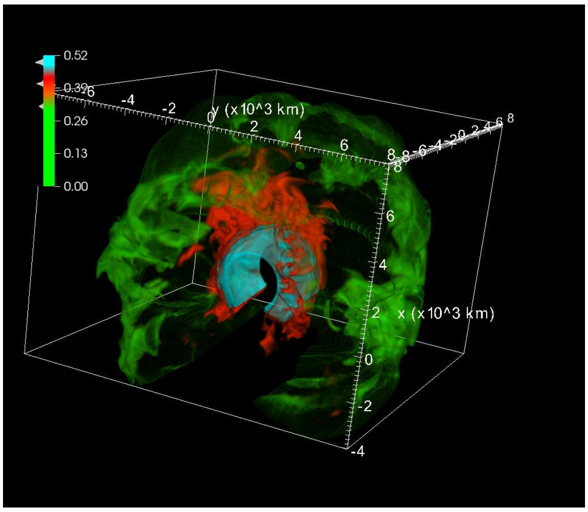

Figure 2.25: Overturn motions in the oxygen burning shell of an 18 solar mass star involving plumes of unburnt oxygen (green) and silicon ashes (red) around the silicon-iron core of the star (cyan). Part of the star is removed for better visibility. *Credit: American Physical Society.*

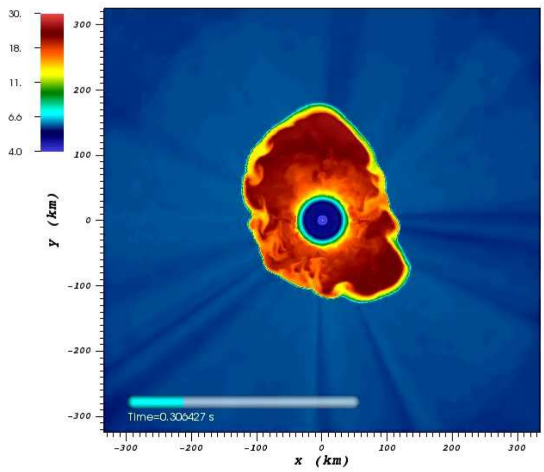

Figure 2.26: Slices through the core of a massive star after collapse. The neutron star is visible as the dark-blue region in the centre, the neutrino-heated matter behind the supernova shock is shown in red. Due to the infall of the asymmetric oxygen-silicon layer, the shock starts to expand at around 0.3 seconds. *Credit: Oxford University Press*

sion of oxygen to silicon in an 18 solar mass star for the last six minutes before the star reached the end of its stable evolution (see Figure 2.25). The researchers found that they could obtain a successful explosion only because the collapsing silicon-oxygen shell was perturbed by vigorous mass flows already. They then followed the beginning supernova for more than two seconds (see Figure 2.26 and 2.27).

It still takes about a day until the shock front reaches the surface of the star and the stellar debris is expelled into the surrounding space; nevertheless the computer model already is able to tell that the explosion and the relic neutron star are starting to look like the ones observed: The explosion produces about 0.06 solar masses of iron-group elements. The neutron star is about 1.7 times as massive as the Sun. It rotates once every 20 milliseconds, and it is kicked away at a speed of 600 kilometres per second because the explosion is strongly asymmetric. This means that the simulations cough up a plausible explosion model – without tweaking.

Now that such successful stellar explosion simulations are feasible, the team will systematically explore how supernovae from different progenitor stars look like. More 3D calculations are needed to clarify which stars blow up by the crucial aid of pre-collapse perturbations in the convective burning shells around the stellar iron core. (Bernhard Müller, H.-Thomas Janka, Tobias Melson, Alexander Heger).

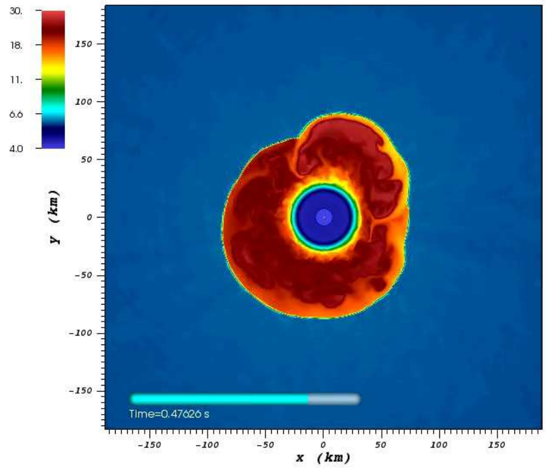

Figure 2.27: (cont. from Fig. 2.26): If the overturn motions in the oxygen burning shell are not taken into account, this does not happen. *Credit: Oxford University Press*

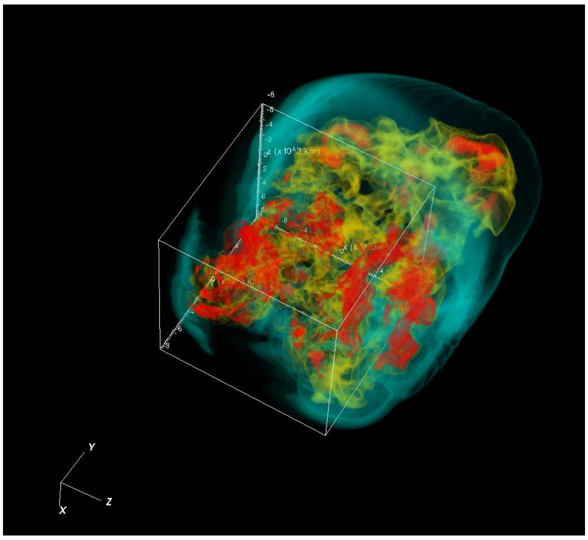

Figure 2.28: Expansion of the neutrino-heated matter (yellow/red) and the supernova shock wave (translucent cyan surface) during the explosion of an 18 solar mass star. *Credit: Oxford University Press*

2.12 LOFAR radio observations document rejuvenation in space

In observations of galaxy clusters, astronomers in collaboration with the MPA discovered a new class of cosmic radio sources. With the digital radio telescope Low Frequency Array (LOFAR) they received the longest radio waves that can be measured on Earth. They identified a remarkable "tail" behind a galaxy in the radio light, which must have been re-energized after it had faded away. In the journal Science Advances, the team describes this discovery, which either confirms a theoretical prediction on the interaction between shock waves and radio plasma or represents a novel phenomenon.

Looking into space with the help of radio telescopes, astronomers often find long, radioluminescent tails behind wandering galaxies. These tails occur when the active black hole in the center of a galaxy produces clouds of energetic electrons with typical velocities close to the speed of light. These clouds then stay behind the galaxy, which is traveling through the gas filling the intergalactic space.

Normally, these luminous trails fade over time until they are not visible anymore, as the electrons radiate their energy away. However, a group of researchers from Germany, Italy, the Netherlands and the United States observed the galaxy cluster Abell 1033 at very low radio frequencies and found that one of the tails was behaving contrary to expectations, starting to glow again in the galaxy gas (See Fig. 2.29). This is surprising as the electron clouds that make up the tail gradually release their energy. They should therefore fade until they finally disappear completely. Instead, in this case, the observed tail still shines after more than a hundred million years - and what is more, it is located in the middle of a cluster in which several galaxies are merging.

For Dr. Torsten Enßlin at the MPA, however, this was not a surprise, but rather the confirmation of his prediction. In 2001, in cooperation with Indian scientist Gopal Krishna (IUCAA), he postulated a connection between gas dynamics in galaxy clusters and a rejuvenation of radio plasma. When radio plasma is compressed via shock waves, electrons gain energy adiabatically, just like molecules in a bicycle pump get heated via compression. If enough energy was transferred, the electrons become visible again in the frequency range of radio telescopes. It is important to note that compression has to happen fast enough so that it outperforms the simultaneous loss of energy via radiation, which makes the electrons invisible again. The recent discovery of a re-illuminated radio tail may therefore confirm the theory of Enßlin and Krishna. Torsten Enßlin was responsible for the theoretical interpretation of the observational data in the current project.

Nevertheless, the structures observed in Abell 1033 and their origin remain mysterious. The tail has gigantic dimensions and should be "dead" in the astrophysical sense, because only then can a radio tail rise from the ashes like a phoenix if a shock wave squeezes the gas over a long distance simultanously. The angle between tail and shock wave needs to be adjusted exactly, otherwise only a small region would light up. Either this special geometry is just a coincidence in this case, which could also explain why this phenomenon occurs so rarely in this size; or a completely different, as yet unknown, mechanism must be responsible for the rejuvenation.

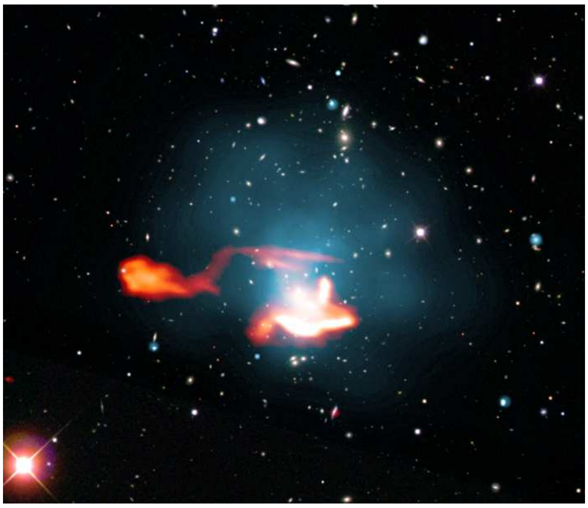

Figure 2.29: False colour image of the galaxy cluster Abell 1033, consisting of a superposition of images in the radio, X-ray and optical frequency range. The radio galaxy with its tail appears as an orange, luminous, outward-directed structure in the left part of the picture. Its tail extends to the right into the upper part of the centre of the cluster of galaxies; as the gas emits X-rays there, it is shown here in blue. This tail was made to shine again by processes in the cluster of galaxies. The bright source in the lower part of the cluster is presumably independent and has also been classified as a re-iluminated radio tail of another galaxy, i. e. another "radio phoenix". *Credit: Lofar/MPA*

The new discovery was made possible by a cooperation between the Indian Giant Meterwave Radio Telescope (GMRT) and the European Low Frequency Array (LOFAR). LOFAR is able to detect radio waves with a length of up to 30 meters. The unique telescope connects thousands of antennas located in eight different countries, their data converge in a supercomputer in Groningen (Netherlands). The computer collects 200 gigabytes of data per second and thus forms a virtual radio telescope, which is just as large as the European continent and can therefore pick up very long-wave and weak radio signals. MPA operates a LOFAR station in Unterweilenbach near Munich.

3 Publications and Invited Talks

3.1 Publications in Journals

3.1.1 Publications that appeared in 2017 (262)

Abbott, B. P., Abbott, et al. (incl. R. Sunyaev): Gravitational waves and gamma-rays from a binary neutron star merger: GW170817 and GRB 170817A. Astrophys. J. Lett. **848** L13 (2017).

Abellán, F.J., et al. (incl. M. Gabler and H.-Th. Janka): Very Deep inside the SN 1987A Core Ejecta: Molecular Structures Seen in 3 D. Astrophys. J. Lett. **842** L24 (2017).

Agnello, A., et al. (incl. J. Chan and S. Suyu): Models of the strongly lensed quasar DES J0408âĹŠ5354. Mon. Not. R. Astron. Soc. **472**, 4038-4050.

Agrawal, A., R. Makiya, et al. (incl. S. Saito and E. Komatsu): Generating log-normal mock catalog of galaxies in redshift space. Journal of Cosmology and Astrop. Phys., **003**, 1-35 (2017).

Alam, S., Ata, M., et al. (incl. S. Saito): The clustering of galaxies in the completed SDSS-III Baryon Oscillation Spectroscopic Survey: cosmological analysis of the DR12 galaxy sample. Mon. Not. R. Astron. Soc. **470**, 2617-2652 (2017).

Albareti, F. D., Allende Prieto, et al. (incl. A. Jones): The 13th Data Release of the Sloan Digital Sky Survey: first spectroscopic data from the SDSS-IV Survey Mapping Nearby Galaxies at Apache Point Observatory. Astrophys. J. Suppl., **233** 25 (2017).

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Bagnulo, S., Cox, N. L. J., et al. (incl. S. Taubenberger): Large Interstellar Polarisation Survey (LIPS) - I. FORS2 spectropolarimetry in the Southern Hemisphere. Astron. Astrophys. **608** A146 (2017).

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Barklem, P. S., Osorio, Y., et al. (incl. A. Jerkstrand): Inelastic e+Mg collision data and its impact on modelling stellar and supernova spectra. Astron. Astrophys. **606** A11 (2017).

Barnes, D. J., Kay, S. T., Bahé et al. (incl. S. White): The Cluster-EAGLE project: global properties of simulated clusters with resolved galaxies. Mon. Not. R. Astron. Soc. **471**, 1088-1106 (2017).

Barreira, A., Bose, S., Li, B and C. Llinares: Weak lensing by galaxy troughs with modified gravity. J. of Cosmology and Astrop. Phys. **031**, 1-35 (2017).

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3.1.3 Publications as electronic file

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3.2.1 Publications in proceedings appeared in 2017

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Savchenko, V., Ferrigno, C., et al. (incl. R. Sunyaev): INTEGRAL follow-up of the gravitational wave events. Proceedings of Science, IFS2017: 058.

Siess, L., and U. Lebreuilly: The binary channels to electron capture Supernovae. Memorie della Societa Astronomica Italiana, 88(3), 294-297.

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Terada, Y., Maeda, K., et al. (incl. A. Summa): Soft gamma-ray observation of SN2014J with Suzaku. In: S. Kubono, T. Kajino, S. Nishimura, et al. (Eds.), JPS Conference Proceedings (pp. 010306-1-010306-4). The Physical Society of Japan.

Wongwathanarat, A.: Linking three-dimensional core-collapse supernova simulations with observations. In: A. Marcowith, M. Renaud, G. Dubner, A. Ray, and A. Bykov (Eds.), Supernova 1987A:30 years later - Cosmic Rays and Nuclei from Supernovae and their aftermaths (IAU Symposium 331) (pp. 101-106). Cambridge, UK: Cambridge University Press.

3.3 Talks

3.3.1 Invited review talks at international meetings

E. Churazov: Ginzburg Centennial Conference on Physics (Moscow, Russia, 29.5-3.6)
– What Matter(s) Around Galaxies (Durham, 19.6.-23.6.)
– Power of X-ray Spectroscopy (Warsaw, 6.9.-8.9.)

B. Ciardi: The many scales of the universe: (Göttingen, 18.9.-22.9.)
– The broad impact of low frequency observing (Bologna, 19.6.-23.6.)

T.A. Enßlin: The Plasma Universe and its Structure Formation (Pune, 30.8.-1.9.)
– 7th Fermi Symposium (Garmisch-Partenkirchen, 15.10.-20.10.)
– Three elephants in the gamma-ray sky: Loop I, the Fermi bubbles, and the Galactic center excess (Garmisch-Partenkirchen, 21.10.-24.10.)

T. Ertl: 11th Bonn Workshop on Formation and Evolution of Neutron Stars (Bonn, 11.12.-12.12.)

W. Hillebrandt: The amazing life of stars (Cefalu, Sicily, 4.9.-8.9.)
– Stellar Evolution, Supernova and Nucleosynthesis Across Cosmic Time
(IPMU Tpkyo, Japan, 18.9.-29.9.)

H.-Th. Janka: Conference on Neutrino and Nuclear Physics (Catania, 15.10.-21.10.)
– Stellar Evolution, Supernova and Nucleosynthesis Across Cosmic Time
(Tokyo, 18.9.-29.9.)
– Theories of Astrophysical Big Bangs (Tokyo, 6.11.-10.11.)
– Phenomena, Physics, and Puzzles Of Massive Stars and their Explosive Outcomes

(Santa Barbara, California, 20.3.-26.3.)
– GW170817: The First Double Neutron Star Merger (Santa Barbara, California, 4.12.-8.12.)
– IAUS 331: "SN 1987A, 30 years later" (Saint-Gilles, La Réunion Island, 20.2.-24.2.)
– NuPhys2017: Prospects in Neutrino Physics (London, 20.12.-22.12.)
– Bridging Nuclear and Gravitational Physics: (Trento, 5.6.-9.6.)

A. Jerkstrand: 7th International Fermi Symposium, Garmisch-Partenkirschen, 15.10.)
Stellar Evolution, Supernova and Nucleosynthesis Across Cosmic Time, (Tokyo, 20.9.)
– Origin of Matter and Evolution of Galaxies (OMEG), Daejong, (South Korea, 29.6.)
– MIAPP 2017: Superluminous supernovae in the next decade, (Garching, 18.5.)

G. Kauffmann: Quantifying and Understanding the Galaxy – Halo Connection, Kavli Institute for Theoretical Physics, University of California, Santa Barbara (15.5.-19.5.)

E. Komatsu: "New Directions in Theoretical Physics 2" Symposium (The Higgs Center for Theoretical Physics, Univ. of Edinburgh, 11.1.-13.1.)
– "Gravity and Black Holes" for Stephen Hawking's 75th birthday (Univ. of Cambridge, 2.7.-5.7.)
– "Inflation and the CMB" (Nordita, Stockholm; 17.7.-21.7.)
– 100th anniversary conference, MPI f. Physik (München 10.10.-12.10.)

E. Müller: IAP Colloquium (Paris, France, 26.6.-30.6.)

T. Naab: Carving through the codes: Challenges in computational astrophysics (Davos, 6.2.-10.2.)
– The 13th Hellenic astronomical conference, (Crete, 2.7.-6.7.)
– The circle of life: Connecting the intergalacrtic, circumgalactic, and interstella media, (Krüger Park, South Africa, 2.8.-5.8.)
– The physics of quenching massive galaxies at high redshift, (Leiden, 6.11.-10.11.)

S. Saito: Cosmology with Neutral Hydrogen (University of California, Berkeley, 11.1.-13.1.)

F. Schmidt: Invited review of modified gravity: TransRegio Workshop on Models of Gravity, (Univ. Hannover 17.3.)
– Invited review of large-scale structure: (Rencontres de Blois, 17.5.)

R. Sunyaev: Symposium on the Future of Physics and Astronomy (Shanghai, 13.9.-17.9.)
– R. Sunyaev: Galaxy Clusters (Santander, 2.7.-9.7.)

S. H. Suyu: Invited Plenary Talk. XI International Conference on Interconnections between Particle Physics and Cosmology (Corpus Christi, Texas, USA, 22.5.-26.5.)
– International Astronomical Union Symposium 336: Astrophysical Masers: Unlocking the Mysteries of the Universe (Cagliari, Italy, 4.9.-8.9)
– Fred K. Y. Lo Memorial Workshop (Taipei, Taiwan, 31.5.)

S. Vegetti: Bright and Dark Universe (Naples, Italy, 10.1.-2.2.)

S. White: Halo Connection, Kavli Institute for Theoretical Physics, University of California, Santa Barbara (15.5.-19.5.)
– IAU Potsdam, International Symposium on meson-nucleon physics and the structure of the nucleon (Potsdam 10.7.-14.7.)
– TDE17: Piercing the sphere of influence (Symposium in honour of Prof. Martin Rees (Cambridge, 13.9.-116.9.)
– Paris (10.12.-12.12.)

S. Zhukovska: Spring Symposium Lifecycle of Metals Throughout Universe, (Baltimore, USA, 24.4.-27.4.)
– Conference The Physics of the ISM, Cologne, Germany (13.2.-17.2.)

3.3.2 Invited Colloquia talks

E. Churazov: MIT (Cambridge, MA, USA, 11.4.)
– Harvard ITC (Cambridge, MA, USA, 13.4.)

T.A. Enßlin: Inter-Univ. Centre for Astronomy and Astrophysics (Pune, 6.9.)
– Tata Institute for Fundamental Research (Mumbai, 7.9.)
– European South Observatory (Garching, 25.9.)
– Technical University Munich (Garching, 29.9.)
– Square Kilometer Array Office (Cape Town, South Africa, 15.11.)
– University Newcastle (Newcastle, 12.8.)

H.-Th. Janka: Technische Universität Darmstadt (Darmstadt, 14.12.)
– Colloquium: ESO (Garching, 2.11.)

A. Jerkstrand: Department of Astronomy, (Uppsala 1.6.)
– Department of Astronomy, Stockholm University, (Stockholm, 19.1.)

G. Kauffmann: University of California, Los Angeles (Los Angeles, USA , 1.6.)
– South African Astronomical Observatory (SAAO, South Africa , 24.8.)

E. Komatsu: Oskar Klein Center, (Univ. Stockholm, 14.2.)
– AlbaNova and Nordita, (Univ. Stockholm, 16.2.)
– ISAS/JAXA, Sagamihara, (Japan, 1.3.)
– Univ. Tübingen, (24.5.)
– Instituto de Fisica Corpuscular, (Valencia, 14.9.)

E. Müller: Physics Colloquium TU Darmstadt (Darmstadt, 01/17)
– Physics Colloquium LMU/TUM (München, 05/17)

T. Naab: Invited colloquium, (Saclay, 16.5)
– Invited colloquium, Tel Aviv University, (Tel Aviv, 24.5.)

S. Saito: The 4th IMPRS Student Symposium (MPE, Garching, 27.10.)

F. Schmidt: University of Manchester, 03/17
– Invited Collloquium: Technion, (Haifa, 03/17)

H. Spruit: Lecture on astrophysical MHD: Astronomical Institute, University of Amsterdam, (Amsterdam, 8.12.)
– Colloqium: Observatoire Midi-Pyrénées, Toulouse (22.8.)

R. Sunyaev: Weizmann Institute of Science Israael (Tel Aviv, 10.1.-13.1.)

S. H. Suyu: – Heidelberg Joint Astronomy Colloquium (Heidelberg, 24.1.)
– Shool of Physics and Astronomy, Univ. of Birmingham (Birmingham, 26. 4.)
– Royal Observatory Edinburgh (Edinburgh, 3.5.)
– NASA Jet Propulsion Laboratory (Pasadena, USA, 1.6)
– Albert Einstein Institute (Golm, 20.10.)
– Perimeter Institute (Waterloo, Canada, 6.11.)
– Queen's University (Kingston, Canada, 8.11.)
– Institute for Advanced Study, Technical University of Munich (München, 29.11.)
– Kavli Institute for Astronomy and Astrophysics (Beijing, 14.12.)

S. White: South African Astronomical Observatory (SAAO, South Africa , 31.7.)

3.3.3 Public talks

V. Böhm: Open Day MPA Garching (21.10.)

T.A. Enßlin: Tage des mathematischen und naturwissenschaftlichen Unterrichts in Erfurt (16.3.)
– 41. Edgar - Lüscher - Seminar am Gymnasium Zwiesel (29.4.)
– Café & Kosmos, München (12.9.)

M. Gabler, Open Day MPA Garching (21.10.)

S. Hilbert: Open Day MPA Garching (21.10.)

H.-Th. Janka: Universität Jena (27.6.)
– TUM – Physik Department (16.10.)
– Open Day MPA Garching (21.10.)
– Institute for Advanced Studies, TUM (21.10.)
– Physik Department, TUM (21.10.)
– UNITAG Physik Department, TUM (24.11.)
– München Café & Kosmos (15.11.)
– München Max Planck Forum (9.3.)
– München Volkssternwarte (7.4.)

A. Jerkstrand, Open Day MPA Garching (21.10.)

G. Kauffmann: – YIN Lecture on Supermassive Black Holes, Karlsruhe Institute for Technology (10.10.)

E. Komatsu: Japanische Internationale Schule München (25.10.)

E. Müller: Lehrerfortbildung Zwiesel (29.4.)
– Volkssternwarte München (29.9.)

S. Saito: The 2nd German Physics Seminar for Japanese Researchers
(MPI für Festkörperforschung, Stuttgart, 3.2.)

F. Schmidt: MPA Open Day Garching, (21.10.)
– MVHS (Münchner Volkshochschule), Abendvortrag (11/17)

S. H. Suyu: Understanding Science (Beijing, 18.12.)
– Beihang University (Beijing, 28.12.)

S. White: The 2017 Shaw Prize Lecture (Hong Kong)
– MPA Open Day Garching, (21.10.)
– Schroedinger Colloquium, University of Zürich (13.11.)

S. Zhukovska: Themenkonzerte Bayerische Staatsoper Series, München (31.1.)

3.4 Lectures and lecture courses

3.4.1 Lectures at LMU and TUM

T. A. Enßlin, SS 2017, LMU München

W. Hillebrandt, WS 2016/2017 and WS 2017/2018, TU München

H.-Th. Janka, WS 2015/2016 and SS 2016, TU München

E. Müller: WS 2016/2017 and SS 2017, TU München

H. Ritter, WS 2016/2017, LMU München, SS 17, LMU München

S. H. Suyu, WS 2016/2017 and SS 2017, TU München

A. Weiss: WS 2016/2017 and SS 2017, TU München

3.4.2 Short and public lectures

T. A. Enßlin: "Information Theory and Signal Reconstruction"
(LMU Seminar at MPA, Garching, 22.6.–23.6.)

H.-Th. Janka: 48th "Arbeitstreffen Kernphysik" (Schleching, 6.3.-8.3.)

A. Jerkstrand, "Stellar Explosions" (TUM München, 10.11. - 8.12.)

G. Kauffmann: Postgraduate lectures at the University of Cape Town
(South Africa 22.8.-4.9.)

E. Komatsu: "Cosmic Microwave Background" (IMPRS on Astrophysics, Garching, 3.4.–7.4.)
– "CMB from A to Z" (Institut d'Etudes Scientifiques de Cargese, Cargese, 12.11.–17.11.)

E. Müller: IMPRS Summer School on "Compact Objects & Gravitational Waves"
(Heidelberg, 11.9.-13.9.)

S. White: Dark Matter Halos, Summer school lectures (Varenna, 3.7.-12.7.)
– Shaw Prize Lectures in Astronomy (Hong Kong, 23.9.-29.9.)

4 Personnel

4.1 Scientific staff members

Directors

E. Komatsu (Managing Director until 31.12.2017), G. Kauffmann, R. Sunyaev, S.D.M. White (Managing Director since 1.1.2018).

Research Group Leaders

E. Churazov, B. Ciardi, T. Enßlin, M. Gilfanov, H.-Th. Janka, T. Naab, E. Müller (until 31.8.)
F. Schmidt (since 1.4.), S. Suyu, S. Vegetti.

External Scientific Members

M. Asplund, R. Giacconi, R.-P. Kudritzki, W. Tscharnuter.

Emeriti

W. Hillebrandt, R. Kippenhahn, F. Meyer, E. Trefftz († 22.10.2017).

Associated Scientists:

U. Anzer, G. Börner, G. Diercksen, W. Kraemer, E. Meyer–Hofmeister, H. Ritter,
H. Spruit, R. Wegmann.

Staff/Postdoc

N. Amorisco, M. Anderson, H. Andresen (since 1.6.), G. Angelou (since 15.10.), Y. Bahe (until 30.8.), A. Barreira, G. Cabass (since 1.11.), S. Campbell (until 30.8.), F. Durier (until), R. Bieri, M. Bugli (1.6.-31.12.), G. Despali, F. Elsner, T. Ertl (since 1.1.), M. Gabler, E. Gatuzz (until 30.10.), F.A. Gomez (until 30.4.), F. Guglielmetti (until 31.1.) J. Guilet (until 30.3.), A. Halle, K. Helgason, I. Jee (since 1.6.), A. Jerkstrand, A. Jones (until 30.9.), O. Just (until 30.3.), R. Kazeroni, S. Kehl (since 15.9.), I. Khabibullin, A. Kolodzig (since 2.10.), K. Lozanov (since 1.10.), N. Lyskova (until 30.5.), Q. Ma (1.8.-31.12.), A. Maleknejad (since 1.11.), T. Melson, Monachesi (until 30.4.), D. Nelson, M. Newrzella (since 1.11.), U. Nöbauer, Th. Peters (until 30.9.), M. Reinecke, F. Schmidt, X. Shi, A.-K. Straub (since 1.11.), A. Summa (until 30.8.), X.P. Tang, S. Taubenberger, W. Trick (since 1.12.), A. Weiss, A. Wongwathanarat (since 1.8.), N. Yadav (since 1.9.), R. Yates (since 15.9.), A. Yildirim, C. Zhang, W. Zhang (until 30.10.).

Ph.D. Students

[1]

A. Agrawal*, H. Andresen* (until 30.5.), Ph. Arras (since 1.7.), M. Ayromlou* (since 1.7.), V. Böhm* (until 31.7.), R. Bollig, A. Boyle*, M. Bugli* (until 30.5.), Ph. Busch*, C. Byrohl (since 1.9.), C.Y Chao, G. Chirivi, A. Chung* (until 28.2.), L. Di Mascolo*, M. Eide*, W. Enzi (since 1.6.), M. Frigo*, R. Glas (since 1.7.), M. Glatzle, M. Greiner, T. Halbesma* (since 1.7.), J. Higl*, S. Hutschenreuter (since 1.5.), H.Y. Ip*, I. Jee (until 30.5.), A. Jörgensen* J. Knollmüller, J. Kuuttila (since 1.9.), T. Lazeyras, R.

[1] *IMPRS Ph.D. Students

Leike, Q. Ma (until 31.7.), L. Mirzagholi (since 1.3.), M. Nguyen*, A. Pardi* (until 30.3.), N. Porqueres*, D. Pumpe, F. Rizzo, B. Röttgers (until 31.7.), M. Rybak* (until 30.4.), A. Schmidt, T. Steininger, G. Stockinger, J. Stücker*, C. Vogl, D. Vrbanec*, G. Wagstaff*.

Master students

T. Aschenbrenner (since 1.7.), C. Bordihn (until 30.10.), R. Dehde (until 30.9.), M. Dupont (until 30.10.), J. Ehring (since 25.10.), A. Flörs (until 30.9.), Ph. Frank (since 15.3.), F. Gashi (since 1.10.), D. Gerlicher (since 1.3.), S. Huber (since 1.11.), S. Hutschenreuter (until 28.2.), J. Knollmüller (until 30.9.), M. Kurthen (since 1.10.)R. Leike (until 30.9.), C. Lienhard (since 1.5.), S. Lietzau (until 30.12.), A. Maté (until 30.9.), J. Oberpiller (since 1.9.), M. Sag (since 15.10.), S. Schuldt (since 1.4.), M. Sraml (until 30.8.), M. Straccia (until 30.11.), M. Westercamp (since 15.8.), F. Wichmann (until 30.8.).

Technical staff

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

Public relation: H. Hämmerle (MPA and MPE)

Secretaries: M. Depner, S. Gründl, G. Kratschmann, C. Rickl, S. Veith (until 30.6.).

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

4.1.1 Staff news

Matteo Bugli won the Leibniz Scaling Award.

Eugene Churazov and Marat Gilfanov received the Belopolsky Prize in astrophysics.

Eiichiro Komatsu: The WMAP science team (incl. E. Komatsu) has received the 2018 Breakthrough Prize in Fundamental Physics.

Alex Kolodzig has been awarded with the "Young excellent science and technology paper award 2017" of the Beijing Astronomical Society

Titouan Lazeyras and Dijana Vrbanec (two junior MPA scientists) received the Kippenhahn Award for the best MPA student publication in 2016.

Ewald Müller retired as Research Group Leader on Aug 31, 2017.

Rashid Sunyaev received the State Prize of Russia of the Russian Federation in Science and Technology.

Rashid Sunyaev became the 2017 Citation Laureate.

Sherry Suyu was awarded an ERC starting Grant.

Simona Vegetti was awarded an ERC starting Grant.

Simon White received the Shaw Prize for Astronomy.

4.2 PhD Thesis 2017 and Master thesis 2017

4.2.1 Ph.D. theses 2017

Haakon Andresen: The study of gravitational waves from three-dimensional simulations of core-collapse supernovae. Technische Universität München.

Vanessa Böhm: Cosmic lensing of galaxies and the cosmic microwave background beyond the linear regime. Ludwig-Maximilians-Universität München.

Matteo Bugli: Non-axisymmetric modes in three-dimensional magnetized tori accreting onto black holes. TechnischeUniversität München.

Thomas Ertl: Modeling neutrino-driven supernova explosions across the stellar mass and metallicity range. Technische Universität München (defence already 2016).

Mahsa Ghampanah: Information Field Theory with INTEGRAL/SPI data. Ludwig-Maximilians-Universität München.

Inh Jee: Time-delay Cosmography with New Angular Diameter Distance Measurements. Ludwig-Maximilians-Universität München.

Qingbo Ma: First star signatures on high-z GRBs and DLAs. Ludwig-Maximilians-Universität München.

Anabele Pardi: The impact of supernova feedback on the evolution of the ISM. Ludwig-Maximilians-Universität München.

Bernhard Röttgers: Simulated absorption lines in the circum-galactic medium. Ludwig-Maximilians-Universität München.

Matus Rybak: Strong lensing with ALMA: resolving the nature of high-redshift galaxies. Ludwig-Maximilians-Universität München.

4.2.2 Master theses 2017

Robin Dehde: Bayesian Component Separation for Tomography. Ludwig-Maximilians-Universität München.

Martin Dupont: On the Practical Application of Information Field Dynamics. Ludwig-Maximilians-Universität München.

Sebastian Hutschenreuter: The primordial magnetic field in our cosmic backyard. Ludwig-Maximilians-Universität München.

Andreas Floers: Nebular Spectra of Type Ia Supernovae. Technische Universität München.

Alexei Mate: Radiation transport in magnetospheres of magnetars. Technische Universität München.

Matevz Sraml: Bayesian Background Modelling for COMPTEL Data. Ludwig-Maximilians-Universität München.

Mattia Straccia: Implicit scheme implementation in FLASH software for simulation of cosmic ray's energy anisotropic diffusion. Polytechik of Turin.

Felix Wichmann: Advanced Aperture Synthesis. Ludwig-Maximilians-Universität München.

4.3 Visiting scientists

Name	home institution	Duration of stay at MPA
Jose Enrice Adsuara	Univ. of Valencia	1.7.-31.8.
Virginia Ajani		10.4.-30.9.
Adnan Akhundov	Informatik, TUM	6.3.-31.8.
Marius Almanstötter	Uni Augsburg	15.3.–15.4.
Raul Angulo	CEFCA, Teruel, Spain	4.8.-26.8.
Patricia Arevalo	Univ. Catolica de Chile	12.1.-3.8.
Petr Baklanov	ITEP Moscow	24.4.-30.5.
Andrei Beloborodov	Columbia University	3.7.-23.7.
Aniket Bhagwat	Internship, Pune, India	8.5.-24.7.
Patricia Blazquez-Sanchez		9.7.-31.7.
Miha Cernetic	Facultate Mathematica, Ljublijana	19.6.-31.7.
James Chan	ASIAA, Taipei, Taiwan	6.6.-31.7.
Hailiang Chen	Yunnan Observ., China	1.11.-30.11.
Prakriti Choudhury	Indian Inst.of Science, Bangalore	until 7.4.
		and 9.7.-23.7.
Jian Fu	SHAO Observ. Shanghai	9.7.-30.7.
Ilkham Galiullin	Kazan Fed. Univ. Rep. Tatarstan	15.1.-15.2.
		and 16.6.-20.12.
Sultan Hassan	Cape Town, South Africa	2.3.-31.7.
Nail Inogamov	IKI Moscow, Russia	5.12.-20.12.
Shi Jia	Yunnan Observ., China	8.7.-21.7.
Xi Kang	Purple Mountain Observ. Nanjing	9.7.-25.7.
Rishi Khatri	Tata Inst. Mumbai, India	24.5.-30.6.
Kei Kotake	Fukuoka Univ., Japan	7.3.-7.9.
Daniel Kresse	student trainee	6.3-31.8.
Nikos Kylafis		10.5.-30.5.
Natalia Lahen	University of Helsinki, Finland	27.11.-22.12.
Chervin Laporte	Columbia Univ., USA	2.10.-17.11.
Stefan Lietzau	student trainee	1.6. -31.8.
Fukugita Masataka	Tokyo University, Japan	27.9.-1.12.
Paolo Mazzali	Liverpool John Moores Univ.	2.5.-30.5.
		and 16.8.-8.10.
Giovanni Mirouh	SISSA, Italy	4.9.-3.11.
Houjun Mo	Tsinghua Univ. China	3.8.-2.9.
Bernhard Müller	Monash University, Australia	since 15.12.
Marcelo Musso	Univ. of Pennsylvania	1.10.-31.12.
Martin Obergaulinger	Univ. of Valencia	1.8.-30.8.
Konstantin Postnov	IKI Moscow, Russia	16.11.-16.12.
Stephan Rabanser	student trainee	1.3.-31.8.
Lukas Ranftl	student trainee	1.5.-30.6.
Antti Rantala	University of Helsinki, Finland	27.11.-22.12.
Nikolai Shakura	Sternberg Astron. Inst., Moscow	15.11.-15.12.
Jia Shi	Yunnan University	9.7.-23.7.
Masaru Shibata	Kyoto University, Japan	8.10.-26.10.
Lionel Siess	Astro, ULB, Bruxelles, Belgium	24.4.-23.7.
Elena Sorokina	Lomonov State Univ. Moscow	29.7.-12.8.
Naonori Sugiyama	University Tokyo, Japan	29.9.-19.11.
Felix Thimm	student trainee	4.9.-30.11.
Victor Utrobin	ITEP, Moscow Russia	16.10.-16.12.
Sebastian Weiß	student trainee	1.3.-31.8.
Alexander Wiegand	CfA, Cambridge, USA	since 1.9.
Lev Yungelson	Inst. of Astron. RAS, Russia	1.11.-30.11.
Shaoming Zhang	student trainee	since 1.10.