Max-Planck-Institut

für

Astrophysik

ANNUAL REPORT 2023

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 the adoption of a 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 being in post throughout 2023.

In 2007, Martin Asplund arrived as a new director but, for personal reasons, decided to return to The Australian National University in 2011. Eiichiro Komatsu arrived in 2012 from the University of Texas to take up a directorship, bringing new impetus to the institute's research into the early universe and the growth of structure. The generational change in the directorate continued with the internal promotion of Guinevere Kauffmann in 2013 and the return in 2018 of former MPA Group Leader Volker Springel from a professorship at Heidelberg University. Their expertise assures the continuation of institute activity in Galaxy Evolution (Kauffmann) and Computational Astrophysics (Springel). Finally, a search for a new director, active in stellar astrophysics, concluded successfully in 2020 with the appointment of Selma de Mink. She is formally the successor of Wolfgang Hillebrandt who retired in 2012, and her appointment completes the renewal of the directorate following the retirements of Rashid Sunyaev (2018) and Simon White (2019).

The MPA was originally founded as an institute for theoretical astrophysics, aiming to develop the theoretical concepts and numerical algorithms needed to study the structure and evolution of stars (including the Sun), the dynamics and chemistry of the interstellar medium, the interaction of hot, diluted plasmas with magnetic fields and energetic particles, and the calculation of transition probabilities and cross-sections for astrophysical processes in rarefied media. From its inception the institute has had an internationally-recognized numerical astrophysics program that was long unparalleled by any other institution of similar size.

Over the last 30 years, activities at the MPA have diversified considerably, however, and now address a much broader range of topics, including a variety of data analysis and even some observational 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 research at the MPA include stellar evolution, stellar atmospheres, binary and multiple systems, accretion phenomena, nuclear and particle astrophysics, supernova physics, gravitational wave progenitors, 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, physical and early universe cosmology, as well as information field theory. 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.

MPA researchers have leading roles in computational astrophysics such as IllustrisTNG and MillenniumTNG simulations, and in providing the theoretical underpinnings for the design, analysis and interpretation of observational projects. Prime examples include the cosmic microwave background data from Planck and WMAP, the galaxy survey data from the Sloan Digital Sky Survey (SDSS), the X-ray data from SRG/eROSITA, and the radio data from the Low Frequency Array (LOFAR) and the Laser Interferometer Space antenna (LISA).

Since 2001 the MPA has been part of the International Max Planck Research School (IMPRS) on 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 MPI für extraterrestrische Physik (MPE) or the MPA. This has substantially increased and internationalised the graduate student body at MPA and has resulted in productive social and professional links between MPA students and those at other local institutions. Currently about 25 students at MPA participate in the IMPRS.

MPA policy is effectively set by the Wissenschaftliche Institutsrat (WIR) which has met regularly about 4 times a year since 1995 to discuss all academic, social and administrative issues affecting the institute. The WIR consists of all the permanent scientific staff and the Max Planck Research Group leaders, as well as elected representatives of the postdocs, doctoral students and support staff. It acts as the main formal conduit for discussion and communication within the institute, advising the directorate on all substantive issues. Ad hoc subcommittees of the WIR carry out the annual postdoc and student hiring exercises, monitor student progress, oversee the running of the computer system, and, in recent years, have carried out the searches for new directions and directorial candidates.

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

1.2 Current MPA facilities

Computational facilities

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

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 at obtaining additional supercomputing time, in 2022/2023 more than 100 million core hours, at various national and international Tier-0 supercomputer centres.

The most important resources provided by the MPCDF are parallel supercomputers, Petabyte (PB) 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.

MPCDF also hosts mid-range computers owned by MPA. Presently, two such Linux-clusters are located at MPCDF. The largest, Freya, has 8160 processor cores on 204 nodes – supported furthermore by 16 Pascal, 8 Volta, and 40 Ampere GPUs – together with almost 40.5 Terrabyte (TB) of core memory and $\sim$4.5 PB disk storage capacity. Freya is used for code development, data analysis, and production simulations using moderately parallel codes. In addition, MPA operates the Virgo (the "Virgo supercomputer consortium") data center at the MPCDF. The node hosts the full results from important simulation projects (e.g. Millennium XXL, Eagle, Illustris-TNG) and provides web access to the world-wide community to a subsect of this data, for example via the Millennium database. This system consists of 4 PB disk storage and a fat-node server with 48 cores and 1 TB RAM for data access and memory-intensive parallel data analysis.

MPA's computer system guarantees that every user has full access to all facilities needed, and has no need to perform maintenance or system tasks. All desks are equipped with modern PCs, running under one operating system (Linux) and a fully transparent file system, with full data security and integrity guaranteed through multiple backups, firewalls, and the choice of the operating system. With this approach MPA is achieving virtually uninterrupted service. Since desktop PCs are not personalized, hardware failures are quickly repaired by a complete exchange of the computer.

In addition to the desktop systems, which amount to more than 150 fully equipped workplaces, users have access to central number crunchers. This cluster comprises about 10 machines (with up to 128 processor cores and 768 GB memory) plus compute servers equipped with the General Parallel File System with 4200 cores and about 24 TB of core memory. The total on-line data capacity at MPA is at the Petabyte level; individual users control disk space ranging from a mere GB to several TB, according to scientific need. Energy consumption and cooling have become a crucial aspect of IT installations. At MPA, we are concentrating on low power-consumption hardware and efficient, environmental-friendly cooling.

All MPA scientists and PhD students may also get a personal laptop for the duration of their presence at the institute. These and private laptops may be connected to the in-house network through a dedicated subnet which is separated from crucial system components. Apart from the standard wired network (10 GB/s capacity up to floor level, and 1 GB/s to the individual machine), access through a protected WLAN is provided. MPA is also a partner in the eduroam consortium, thus allowing its members unrestricted access to WLAN at all participating institutions.

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

The IT-group is made up of five full-time system administrators. Since autumn 2023, the IT group was joined by an expert who takes care of IT security and data protection issues for MPA, MPE and the joint administration of the institutes. Regular users have no administrative privileges nor duties, which allows them to fully concentrate on their scientific work. The technical equipment in the main lecture hall and all seminar rooms have been upgraded for hosting virtual as well as hybrid seminars at high video and sound quality.

Library

The library is a shared facility of MPA and 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. The library currently holds around 50,000 books, conference proceedings and journal, as well as subscriptions to 125 printed and around 500 electronic scientific journals. We use the Pure System of the Max Planck Digital Library to archive electronic publications. In addition the library maintains an archive of MPA and MPE publications, and two slide collections (one for MPA and one for the MPE). The MPA/MPE library catalogue includes books, conference proceedings, periodicals, theses, reports (print and online). Additional technical services such as several PCs and terminals in the library area, copy machines and a colour book-scanner are available to serve the users' needs. The library is run by three people who share the tasks as follows: Mrs. Bartels (head of the library), Mrs. Blank (administration of journals- until 31.10.2023) and Mrs. Balicevic (publication management for both institutes).

1.3 The year 2023 at the MPA

1.3.1 Biermann Lectures

History

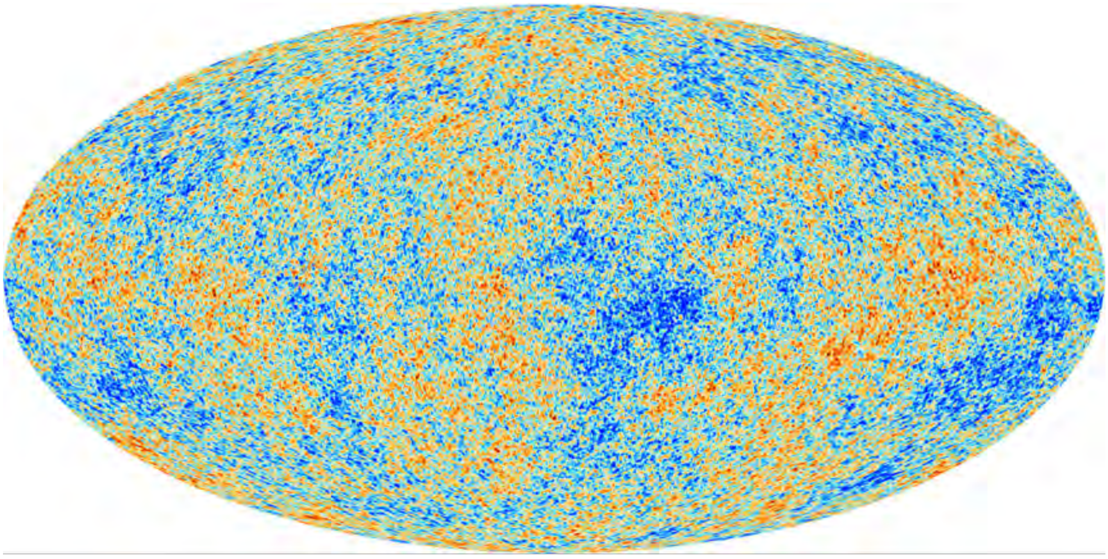
Established in 1997, the Biermann Lecture series is one of the flagship scientific events at the Max Planck Institute for Astrophysics. The lecture series is named after Ludwig Biermann, the founding director of the Institute. The aim is to stimulate scientific activity throughout the Munich-Garching community by bringing a prominent external scientist to Garching for a month. This gives them ample time to interact scientifically with our staff, postdocs and students at coffee, lunch, institute seminars and other events.

Biermann Lectures 2023

"Do we have a standard model of cosmology?"

About 50 years ago, Simon White, Carlos Frenk and Marc Davis teamed up with George Efstathiou to find an explanation for the large-scale structures observed in the galaxy distribution – establishing "Cold Dark Matter" as the standard model of cosmology. Even though inflation and dark energy had to be incorporated in later years, the basic framework still stands. In this year's Biermann lecture, George Efstathiou will explain how ΛCDM cosmology became the standard model for cosmology, its limitations, and how it might evolve in the future.

In the 1970s, large surveys of the three-dimensional galaxy distribution had revealed



The anisotropies of the Cosmic Microwave Background (CMB) as observed by Planck led to the most accurate determination of the cosmological constants. *(Credit:ESA and the Planck Collaboration)*

Prof. George Efstathiou from University of Cambridge, the Biermann lecturer of 2023 *(Credit: University of Cambridge)*

filaments and voids, which was at odds with the uniform matter distribution at the beginning of the universe as seen in the Cosmic Microwave Background. George Efstathiou worked on early computational models of cosmological structure formation, and together with Davis, Frenk and White, he carried out the first cosmological simulations of the cold dark matter model, which to the team's surprise were a close match to the observations. In the late 1980s, the DEFW collaboration produced five papers that established "CDM" as the standard cosmological model.

In 1990, Efstathiou led the study that reported an early indication of a cosmological constant using galaxy survey data from the APM survey. He thus inferred the existence of dark energy years before the discovery of the accelerated expansion of the universe through supernova data. Therefore, dark energy was added to establish the current ΛCDM, for which Efstathiou received the 2011 Gruber Cosmology Prize jointly awarded with Marc Davis, Carlos Frenk and Simon White. He has been involved in many other galaxy surveys such as the "2-degree-field galaxy redshift survey" (2dF-GRS), which first detected "baryon acoustic oscillations".

In addition to his research on large-scale cosmic structure formation, George Efstathiou also made fundamental contributions to investigations of the anisotropies in the cosmic microwave background. With J. Richard Bond, Efstathiou performed the most comprehensive calculation of statistical properties of the CMB, most notably including polarization and the impact of CDM. As a member of the Science Team for the European Space Agency Planck satellite, he made significant contributions to the most detailed analysis to date of the CMB.

George Efstathiou received his B.A. in Physics from Keble College, Oxford University in 1976, and his Ph.D. in Astronomy from Durham University in 1979. Postdoc positions at the Department of Astronomy, University of California, Berkeley, and the Institute for Astronomy at Cambridge led to him becoming Assistant Director of Research. From 1988 to 1994, Efstathiou was the Head of Astrophysics at Oxford University, and returned to Cambridge in 1997, where he has served as Director of the Institute of Astronomy since 2004. He was appointed as the first Director of the Kavli Institute for Cosmology at Cambridge from 2008 – 2013.

Professor Efstathiou has received several prizes for his research including the 1990 Maxwell Medal and Prize of the Institute of Physics, the 2005 American Institute of Physics Heineman Prize for Astronomy (shared with his long-term collaborator Simon White), as mentioned above in 2011 the Gruber Cosmology Prize, and in 2022 the Gold Medal in Astronomy from the Royal Astronomical Society.

1.3.2 Kavli Summer Program In Astrophysics 2023

The lives, deaths and afterlives of interacting stars

MPA hosted the prestigious Kavli Summer Program in Astrophysics (KSPA) from 26th June to 4th August, 2023. This is a high-profile six-week program, substantially supported by the Kavli Foundation, during which outstanding graduate students are each given the opportunity to intensively work on a new project with leading scientists in the field. The Program has been organized from UC Santa Cruz since 2010, supported by the Kavli Foundation since 2016, and broadly alternates between being hosted in Santa Cruz and elsewhere.

The theme of our 2023 Kavli Summer Program was “the lives, deaths and afterlives of interacting stars”, naturally fitting the MPA stellar department, and was directed by Selma de Mink and Stephen Justham. Following a highly competitive selection process, 14 excellent students from outside MPA were admitted as MPA-Kavli Fellows for the duration of the 6-week Program. Over 20 senior external scientists also joined the Program, with a mixture of long- and short-term stays, alongside numerous MPA locals. Such a large influx of energetic people, involved in intense collaborative projects, added to the dynamic feeling within MPA over the summer – the open areas of MPA were even more likely than normal to contain lively scientific discussions.

The student projects covered a variety of stellar topics, including multi-dimensional hydrodynamic simulations of stellar interactions and explosions, novel calculations aiming to explain recently-discovered extraordinary runaway stars, work searching for and aiming to understand asteroseismic signals of prior stellar interactions, and projects aiming to interpret population data from multi-epoch spectroscopic surveys and gravitational-wave detectors. The students took great advantage of their chance to work away from their normal PhD research, broadening their scientific experience, and several manuscripts arising from the Summer Program have already been submitted to journals. We enormously enjoyed this time with such an amazing group of visitors, and we further hope that this young cohort of future leaders in stel-

The participants of the MPA-Kavli Summer Program who were still present on the final day, assembled outside the main entrance. *(Credit: H.-A. Arnolds, MPA)*

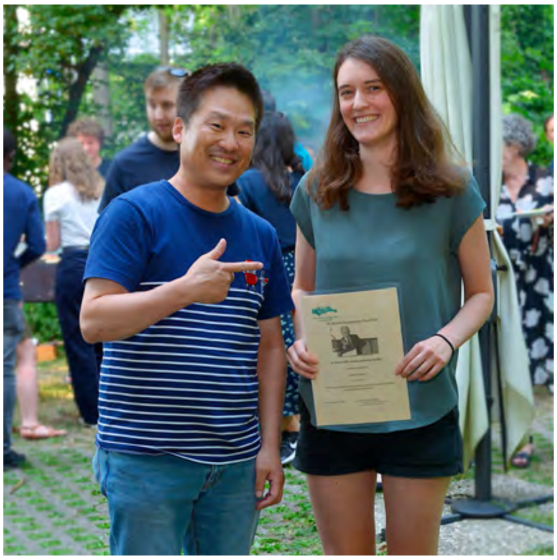
lar astrophysics will benefit long-term from the interactions they experienced in MPA.

1.3.3 Prizes and Awards

Rudolf-Kippenhahn-Award

This year, the award panel decided to bestow the 2023 Rudolf Kippenhahn Award on Dr. Laura Herold for her groundbreaking paper titled "New Constraint on Early Dark Energy from Planck and BOSS data using the Profile Likelihood". Her contributions have already been very impactful in the field.

Early Dark Energy is one of the proposed solutions to the hotly debated problem in cosmology called the "Hubble tension", i.e. a discrepancy between measurements of the current expansion rate of the universe obtained through different methods. However, it was not clear whether the cosmic microwave background and



Laura Herold, this year's recipient of the Kippenhahn Prize with MPA managing director Eiichiro Komatsu. *(Credit: H.-A. Arnolds, MPA)* the large-scale structure data favoured “early dark energy”, as different authors reported very different results.

Collaborating with Dr. Elisa Ferreira during her postdoctoral research at MPA, Laura embarked on an arduous journey to untangle the intricate nature of early dark energy and its potential resolution of the Hubble tension. Laura Herold showed that the difference was caused by a feature of the Markov Chain Monte Carlo technique called the “prior volume effect”.

When a prior-independent method, such as the profile likelihood, is used, the data show a preference for early dark energy. Her work convinced the cosmology community of the importance of the prior volume effect in the Monte Carlo calculations and influenced many other studies. This is a remarkable achievement by a PhD student in a hotly debated area at the frontier of cosmological research.

Winner of the Carl Ramsauer Prize 2023: Dr. Maria Werhahn (now a postdoc at MPA) with her PhD supervisor and the presenter of the award.*(Credit: PGzB)*

Maria Werhahn honoured with the Carl Ramsauer Prize

MPA postdoc Maria Werhahn has been awarded the Carl Ramsauer Prize by the Physikalische Gesellschaft zu Berlin for her doctoral thesis “Simulating Galaxy Evolution with Cosmic Rays: The Multi-Frequency View”. The award ceremony took place on 22 November 2023 at the Technical University of Berlin, where she also presented her work in a short lecture.

Cosmic rays (CR) are an essential component of the interstellar medium of galaxies and play an important role in their evolution. In particular, they can influence the dynamics of a galaxy by driving galactic outflows or heating the interstellar gas, which in turn affects the efficiency of star formation. To understand galaxy formation, it is therefore necessary to model this radiation accurately.

However, we can only directly measure cosmic rays in our local neighbourhood within the Milky Way. In other galaxies, we can only determine their properties indirectly by the radiation they emit. In her PhD thesis at the Leibniz Institute for Astrophysics Potsdam (AIP), Maria Werhahn developed numerical methods to model the spectra of cosmic rays in galaxies and the associated emission processes. “I was particularly fascinated by how the properties of distant galaxies can be investigated using radio and gamma rays that originate from cosmic rays,” says Maria Werhahn.

Using high-resolution magneto-hydrodynamic simulations of galaxies, she compares these results with observations. This gives her an insight into the interplay between the rate of star formation and cosmic rays, the properties of cosmic ray transport and other fundamental physical processes in these galaxies. “I am very pleased that I can continue my work at the MPA in Garching, where I investigate in more detail the role cosmic rays play in galaxies.” she adds.

The Carl Ramsauer Prize is awarded by the Physikalische Gesellschaft zu Berlin in honour of the experimental physicist and first director of the AEG Research Institute Carl Ramsauer (1879-1955). Carl Ramsauer was the first chairman of the Physikalische Gesellschaft zu Berlin, re-established after the war, from

1949 to 1951. The first award ceremony took place in 1989, and since 2002 four outstanding doctoral theses in physics and related fields at Freie Universität Berlin, Humboldt-Universität zu Berlin, Technische Universität Berlin and the University of Potsdam have been honoured each year. Since 2022, the Brandenburg University of Technology Cottbus-Senftenberg has also been eligible to nominate candidates.

Volker Springel becomes Vice President of the Astronomical Society

At its 2023 Annual Meeting, the German Astronomical Society elected Volker Springel, Director at the Max Planck Institute for Astrophysics as Vice President.

MPA director Volker Springel *(Credit: MPA)*

Volker Springel studied physics at the University of Tübingen and UC Berkeley and completed his diploma thesis as well as his PhD at the Max Planck Institute for Astrophysics (MPA). After a postdoctoral period at the Center for Astrophysics in the U.S., he initially returned to MPA as a postdoctoral researcher and received a position there as a group leader in Numerical Cosmology in 2005. In 2010, he moved to the University of Heidelberg and the Heidelberg Institute for Theoretical Studies. Since 2018, he has been director of the Computational Astrophysics Division at MPA and is an honorary professor at Ludwig Maximilian University in Munich. “As vice president, I would like to champion the Astronomical Society, having benefited greatly from it time and again. I believe we are in an excellent position in astronomy in Germany to continue to successfully exploit the opportunities in astronomical research,” said Volker Springel.

In addition to Volker Springel, Prof. Dr. Stefanie Walch-Gassner was elected as president and Prof. Dr. Julia Tjus as a member of the board. Walch-Gassner, who also spent several years doing postdoctoral research at MPA, is the first female president in the 160-year history of the German Astronomical Society. In 2013, she received an appointment to a W3 professorship in theoretical astrophysics at the University of Cologne.

Founded in 1863, the Astronomische Gesellschaft (AG) is the professional association of German astronomy and astrophysics. The AG promotes activities in science and research, strengthens the exchange between its members, communicates science to the public, and promotes education. On the international level, the AG represents the common interests of astronomers in the European Astronomical Society (EAS) and in the International Astronomical Union (IAU). The Council of German Observatories (RDS), as an organ of the Astronomische Gesellschaft, represents the common interests of the German institutes active in astronomical research towards funding agencies, state and federal authorities, international organizations and other bodies in Germany and abroad.

1.3.4 Public Outreach 2023

The public outreach in 2023 was mainly back to normal after the pandemic. Ten groups visited the institute and went on a journey through the

Universe in the MPA digital planetarium. These live presentations continue to be very popular and serve not only to tell visitors about astronomy in general but also to showcase MPA research in a special environment. MPA also took again part in the nationwide Girls' Day, offering a programme for 20 school girls between 14 and 16. In addition to a planetarium show, the girls independently investigated astronomic research questions – with the help of our local experts. They discussed with the scientists at MPA about their work and their career. While the program was mainly in German, the girls also had to deal with the international environment of our Institute and work in English for some of the stations. In addition, MPA scientists gave a number of talks in- and outside the institute to a wider public. Further activities included supervising a number of interns, who worked on small research projects. The monthly highlights as well as press releases about important scientific results – which are also published on our webpages – serve to popularize MPA science to a wide audience. MPA researchers also acted as interview partners for press, TV, and radio journalists.

2 Scientific Highlights

2.1 Gravitational lensing reveals the detailed shape of a galaxy

By Devon Powell (postdoc) and Simona Vegetti (scientific staff)

Einstein's General Theory of Relativity predicts that large concentrations of mass – such as galaxies – will bend light rays passing nearby, a phenomenon known as gravitational lensing. When a distant galaxy (the lens) lies exactly between us and an even more distant object (the source), the source is distorted and magnified into several images around the lens galaxy. A group at MPA and other institutes used very long baseline radio interferometry (VLBI) to study a gravitational lens system in high resolution. This reveals extreme detail in the lensed images, and provides a new window into the physics of lens galaxies.

The precise shape and magnification of the images in a gravitational lens system allows us to learn about the way mass is distributed in the galaxy that is acting as a gravitational lens, which reveals information about the formation and evolution of the galaxy. For instance, gravitational lensing can show whether the center of a lens galaxy is puffy or concentrated, which tells us about the heating and galactic winds blown by supernovae and active galactic nuclei (AGN, supermassive black holes that launch outflows at relativistic speeds). Gravitational lensing can also reveal the presence of low-mass dark matter haloes, which are detectable only through their gravitational effect. This lets us study the nature of dark matter itself.

The success of gravitational lens observations in revealing these physics depends on the smallest level of detail that can be detected, i.e. the angular resolution of the observation. So far, most existing gravitational lens systems have been observed with the Hubble Space Telescope ($\sim$ 120 milli-arcsecond resolution). Some have been followed up using the W.M. Keck adaptive optics system ($\sim$ 70 mas), and still fewer with the Atacama Large Millimeter Array (ALMA; $\sim$ 25 mas). These observations are sufficient to constrain some very simple mass models, or to detect dark matter subhaloes as small as 100 million solar masses. Pushing the field of gravitational lens modeling into the milli-arcsecond regime drastically increases the amount of astrophysical information we can extract from gravitational lens observations; at present, very long baseline interferometry (VLBI) is the only observational tool that can resolve details smaller than 5 milli-arcseconds.

In this work, we present the first analysis of a gravitational lens system observed at $<$5 milli-arcsecond resolution using VLBI, in which both a detailed model for the mass of the lens galaxy and an image of the source are reconstructed. The analysis used an advanced pipeline for VLBI data developed by our group at MPA. This observation of the lensed radio jet MG J0751+2716 exhibits extremely long, thin lensed arcs covering a wide range of positions around the lens galaxy, which are perfect for revealing the underlying gravitational landscape. In the figure, one can clearly see the jet structure of the reconstructed source, with bright knots of radio emission stretching away from the host galaxy.

We needed to include significant complexity in the mass model of the lens galaxy in or-

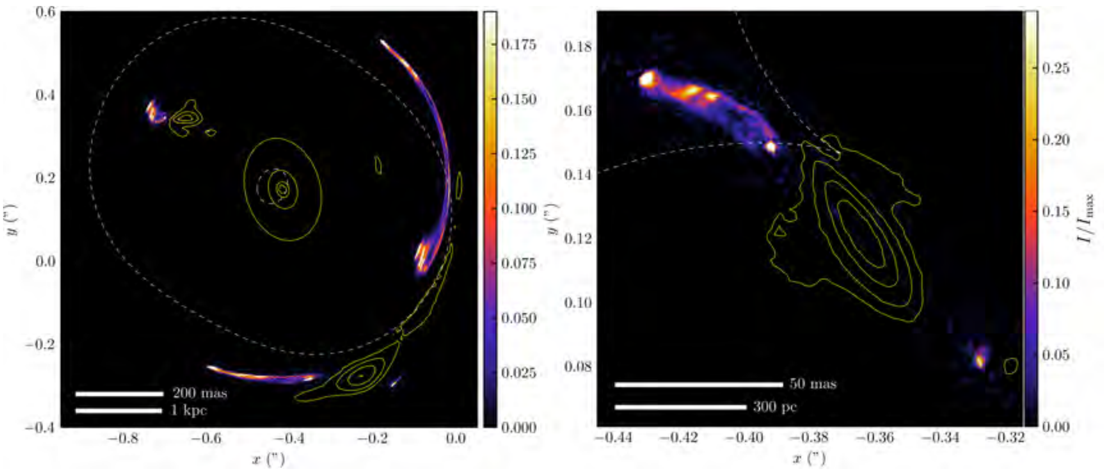


Figure 2.1: Best-fit image-plane (left) and source (right) models of the gravitational lens system MG J0751+2716 from Powell et al. (2022). The color maps show the radio emission, illustrating long, thin gravitational arcs resolved with VLBI. The relatively low-resolution infrared observation from the W.M. Keck adaptive optics system is shown with solid yellow contours; in the center of the lens we see the light from the lens galaxy itself. The critical curves, where the lensing magnification becomes infinite, are shown in dashed white lines. The arcs revealed by the high-resolution radio data are highly sensitive to the mass distribution in the lens galaxy. The details in the structure of the source – a jet stretching away from the host galaxy – can only be reconstructed if enough complexity is included in the lens model. *(Credit: MPA)*

der to clearly reconstruct the source. We found that the mass in this lens is highly concentrated towards the center, indicating that supernova and AGN feedback are relatively weak in this galaxy, a result which has been found in other gravitational lens galaxies as well. We also had to include extra parameters (angular multipole perturbations) in order to account for the fact that the lens galaxy is not perfectly elliptical (as is often assumed in lens modeling), as well as parameters describing tidal forces due to nearby galaxies, which pull on and deform the lens galaxy.

Even though our model captures the mass distribution in the lens galaxy only on scales larger than 1-2 kiloparsecs, we found that it fits the data very well. For a high-resolution observation, which can resolve such fine details in the lensed arcs, this was quite unexpected. This intriguing result motivates our main goal to use gravitational lenses observed with VLBI to search for low-mass dark matter haloes, whose presence or absence will help to constrain dark matter particle models. Our work demonstrates how VLBI observations can play a key role in the science of galaxy-scale strong gravitational lensing, as they can reveal structure in the gravitational landscape that is otherwise inaccessible with current optical telescopes.

2.2 The lingering imprint of the first cosmic structures

By Sten Delos (postdoc) and Simon White (Emeritus Director)

The universe today is host to a vast network of galaxies and an even richer array of invisible dark matter structures. But this was not always the case. The universe was nearly uniform until a time of about 100 million years, when the first cosmic structures gravitationally condensed. These objects were made of dark matter alone and each may have weighed no more than the Earth. Most of these objects do not last long: they rapidly grow and cluster together to form the much larger systems that we know today. Despite this, scientists at MPA have discovered in high-resolution simulations that some unique features of the first structures survive this process. Their lingering imprint could manifest itself in astronomical observations, yielding clues to the identity of dark matter.

About 85% of the matter in the universe is invisible dark matter. While the microscopic nature of dark matter remains elusive, its gravitational influence is well understood. Dark matter drives the formation of all cosmic structure. The galaxies that we observe in the sky lie at the centers of much larger halos of dark matter. In addition, a vast multitude of smaller dark matter halos are believed to exist, too small to hold visible material.

The early universe looked very different. The distribution of matter was smooth and nearly uniform. Over time, gravity amplified the initial, minuscule variations in the density of the universe. Regions of excess density gradually pulled in surrounding material, becoming still denser. This process eventually culminated in gravitational collapse, which created the first dark matter halos (see movie under `https://www.mpa-garching.mpg.de/1069215/hl202302?c=27981`).

Simulations of the gravitational collapse process show that it yields a remarkable feature. Plotting the density inside the resulting halo as a function of the distance from the center of the system, the researchers found a power-law dependence. This kind of mathematical relationship appears as a straight line in the logarithmic plot of density against radius, once the matter has condensed towards the center of the system. Moreover, it is evident from the movie that the density "cusp" forms promptly upon gravitational collapse and remains stable after its formation. Over longer simulated timescales, the researchers continued to find no evidence that these prompt cusps were significantly altered by growth of the dark matter halos around them, even as these halos grew a thousand-fold.

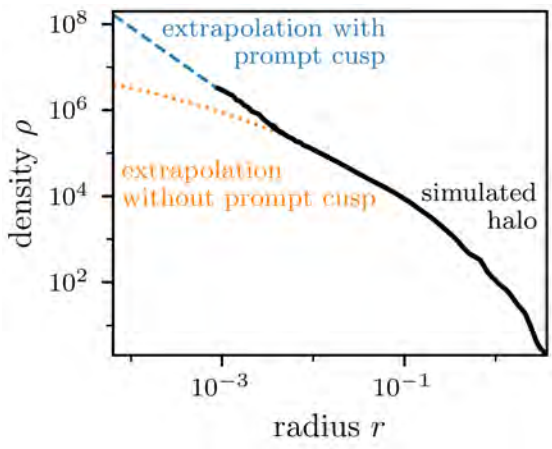


Figure 2.2: The internal structure of the same simulated dark matter halo after growing a thousand times larger. Again, the density inside the system depends on the distance from the system's center. The upturn in the density near the center of the system shows that the prompt initial density cusp persists. The orange dotted curve indicates what the structure would look like without the prompt cusp. The blue dashed line shows an estimate of what the prompt cusp looks like at scales too small for the simulation to resolve. The prompt cusp adds a substantial amount to the halo's centermost regions. *(Credit: MPA)*

The number of halos today is expected to be astronomical. There may be thousands of them for every solar mass of dark matter, with almost all of them being far too small to hold any visible matter. Yet every halo formed from a first-generation object. If prompt cusps survive, every halo should have one at its center. Our own Milky Way galaxy and its dark matter halo may contain over a quadrillion smaller halos. This would mean that prompt cusps of dark matter outnumber stars in the galaxy by a factor of ten thousand! This has significant implications in the search for signs of dark matter's microscopic identity. Dark matter must have formed in the universe somehow, and one of the most widely studied ideas is that it could have been produced in particle-antiparticle pairs in the very hot, very early universe. If the dark matter was produced in this way, then dark matter particle-antiparticle pairs can annihilate today into detectable radiation. A variety of "indirect detection" experiments are searching for this annihilation radiation.

But dark matter annihilates more efficiently inside denser regions. Within prompt cusps, the density is extraordinarily high. MPA scientists estimate that the enormous abundance of these features could raise the predicted dark matter annihilation rate tenfold, a conclusion that significantly alters what our observational data tell us about the nature of dark matter.

2.3 Black hole accretion discs may dance around more slowly than previously thought

By Deepika Bollimpalli (postdoc)

Black holes, resulting from the death of massive stars, are some of the most exotic and powerful objects in the Universe. Since even light cannot escape these objects, the quasi-periodic signals coming from the gas falling into the black hole serve as a probe to infer a great deal of information about the black hole and its surrounding environment. The most-commonly observed quasi-periodic signal is thought to originate from the wobbling of hot gas around the black hole, like a spinning top. One problem, though, is that inferred size of this (isolated) corona seemed to be inconsistent with estimations from other observables. With our recent, state-of-the-art computer simulations, involving a more realistic geometry of the accretion flow, we demonstrated for the first time, that the presence of a disc around the corona significantly slows down its precession, relieving much of the tension between this model and observations. These results thus have important implications for studies of black hole properties and how black hole systems form and evolve.

Accretion onto compact objects like black holes, neutron stars or white dwarfs is an important dynamical process that powers many astrophysical sources in the Universe by generating radiative energy from the gravitational potential energy of the accreting matter. Accretion flows are well studied in X-ray binaries (XRBs): close binary systems which usually have a main sequence or a supergiant star as a donor and a neutron star or black hole as an accretor. Matter transferred from the donor star carries certain angular momentum and due to the central gravity force, it gets confined to the orbital plane, forming disk-like structures around the compact object.

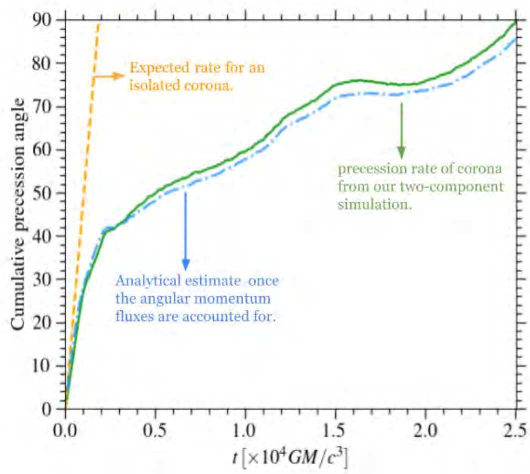


Figure 2.3: Time evolution of the cumulative precession angle of the inner, hot accretion flow around a black hole with spin parameter 0.9. The precession rate is given by the slope of these curves. The precession rate computed from our two-component accretion flow simulations (solid, green curve) is significantly lower than the estimated rate for an isolated torus, i.e., not surrounded by an outer, thin disk (dashed, yellow line). When we include the angular momentum flux terms, in addition to the Lense-Thirring torque term, we find remarkable agreement between the simulation results and the analytical estimate (dash-dotted, blue curve). *(Credit: MPA)*

Long-term observations have shown that black hole X-ray binaries exhibit strong, aperiodic variability over a broad range of timescales: a few milliseconds to seconds. In addition, these systems also exhibit rapid variability in their X-ray light curves, which are termed quasi-periodic oscillations (QPOs); broadly classified into high-frequency (> 60 Hz) and low-frequency QPOs (< 30 Hz). Understanding the nature of these variabilities and the underlying physical processes helps us probe the nature of the compact object and its surroundings. Apart from the broad picture, very few definite properties are known regarding the origin of the observed variability. This is because the physics and geometry of accreting black holes are highly complex with turbulence, radiation, and 3D effects all coming into play.

Using advanced numerical techniques, we performed general relativistic, magneto-hydrodynamic simulations of a truncated disk with an inner, hot flow that is misaligned with the spin axis of the black hole. These simulations are the very first to investigate the effect of the outer, thin disk on the Lense-Thirring precession of the inner, hot accretion flow, and thus add much-needed realism to the usual simulations.

The key finding of our simulations is that the presence of an outer, thin disk decreases the precession rate of the inner torus by nearly 95 per cent. We show that the slowdown in the precession rate is caused by the exchange of the angular momentum between the outer thin and inner thick disks. With this effect, the model now requires a much smaller inner, precessing thick disk to be able to match the typically observed range of type-C QPO frequencies (0.1–10 Hz). Some recent observations have already suggested that the precessing flow needs to be smaller than the estimated size from the Lense-Thirring model for an isolated torus. Thus, our new results help relieve some of the remaining tensions between the model and observations.

2.4 Astronomers witness a monstrous galaxy consuming its neighbour

By Hannah Stacey (postdoc)

Observing a supermassive black hole in the distant Universe, MPA astronomers have discovered that it is in the process of stripping gas from a neighbouring galaxy. The gas is being very quickly turned into stars in the black hole's host galaxy and is allowing the black hole to grow very quickly. This agrees with theoretical predictions that massive galaxies and black holes form with help from mergers with smaller galaxies and bursts of star formation.

A quasar is the extremely luminous nucleus of a galaxy, produced by a supermassive black hole that is rapidly consuming matter. Quasars are thought to play an important role in the formation of massive galaxies in the early universe. But we don't yet know in detail how their supermassive black holes are formed, evolve and activate. Nor do we know how they interact

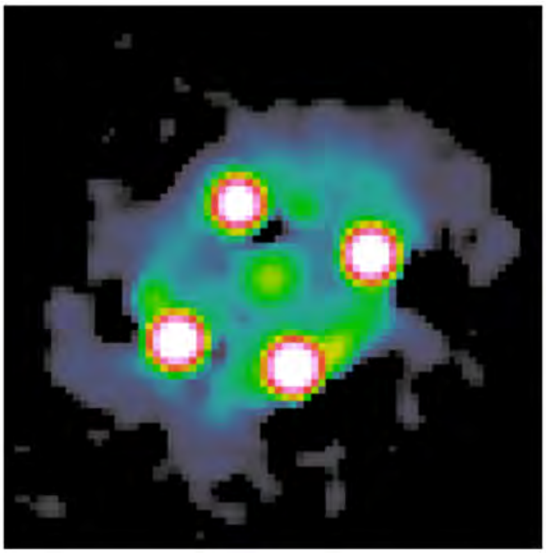


Figure 2.4: An infrared image of the Cloverleaf from the Hubble Space Telescope: this is a gravitational mirage where you can see four images of the point-like quasar. *(Credit: CASTLES / NASA/HST)*

with their host galaxies.

As the host galaxies of quasars are typically very small and much fainter than the quasar, it is a challenge to observe them in detail. The well-known 'Cloverleaf' is an example of a gravitational lens system, whereby a quasar whose light was emitted 11 billion years ago is magnified by the gravitational field of an intervening galaxy. In optical light, we see a mirage of four images (that was dubbed the Cloverleaf) of the accreting supermassive black hole. In microwaves, we see its host galaxy, which is otherwise hidden. This host galaxy is forming an incredible 1000 stars per year. Gravitational lensing magnifies the Cloverleaf galaxy so that we can examine it in detail.

When looking through archive data from the Atacama Large sub-Millimetre Array (ALMA) to catalogue dust and carbon monoxide gas, we found a companion galaxy that was not previously known about. The data showed that the companion is connected to the Cloverleaf by an intergalactic bridge of gas — meaning that the Cloverleaf is in the process of consuming it! For the first time, we have thus directly observed a galaxy stripping its neighbour of star-forming gas in the very distant Universe.

However, we also discovered evidence that a wind is driving gas out of its host galaxy, powered by the quasar or the extreme star formation. This means, that at the same time as consuming its neighbour, some of the gas is being driven out, stripping the galaxy of raw material for star formation. These findings agree with theoretical predictions that massive galaxies form via mergers of smaller galaxies, with black holes playing a role to suppress the formation of new stars.

Over the next hundred million years, we expect the Cloverleaf galaxy to completely consume its companion, then quickly run out of gas. It would then become a very massive, 'dead' galaxy, like the ones we see in the current Universe. It is only because of the very sensitive ALMA data and because the galaxy is magnified by gravitational lensing that we are able to see this happening in the early Universe.

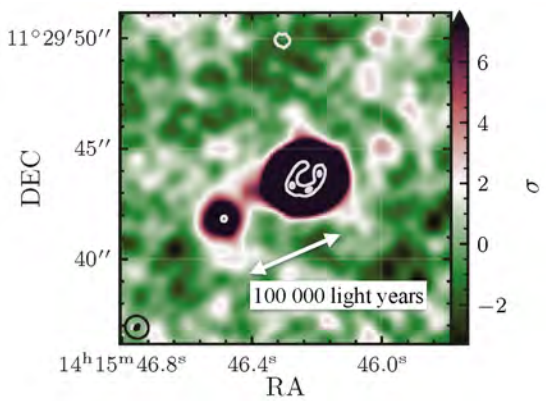


Figure 2.5: This high-resolution ALMA image of the "Cloverleaf" system (indicated by the grey contours) not only shows the host system of the quasar itself (centre) but also a companion galaxy connected by a bridge of material. This is the first time that a galaxy has been observed that is consuming material from a neighbour in the early universe. *(Credit: MPA)*

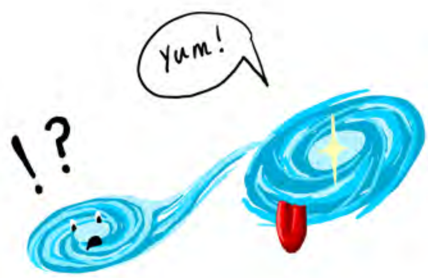


Figure 2.6: This artist's impression shows how the quasar (bright yellow source on the right) and its host galaxy are consuming material from a nearby companion. Over the course of the next hundred million years, the supermassive black hole will not only completely drain the neighbouring galaxy but also driving out gas from its host, ultimately inhibiting star formation and ending up as a typical elliptical galaxy. *(Credit: H. R. Stacey / MPA)*

2.5 Manipulative communication in humans and machines

By Torsten Enßlin (scientific staff)

A universal sign of higher intelligence is communication. However, not all communications are well-intentioned. How can an intelligent system recognise the truthfulness of information and defend against attempts to deceive? How can a egoistic intelligence subvert such defences? What phenomena arise in the interplay of deception and defence? To answer such questions, researchers at the Max Planck Institute for Astrophysics in Garching, the University of Sydney and the Leibniz-Institut für Wissensmedien in Tübingen have studied the social interaction of artificial intelligences and observed very human behaviour.

When our brain receives a message, it can include it in its store of knowledge or ignore it. The latter is appropriate, for example, if there are strong doubts about the truthfulness of the message. In this case, the message may say more about its sender than the sender would like. As a consequence of untrustworthy statements, others may judge the sender to be generally untrustworthy and be more sceptical of him in the future. This would reduce the effectiveness of his communication. Therefore, a message sender should be interested in having a good reputation for credibility.

While honesty can indeed build a good reputation, this is not the only way. Cleverly constructed lies that cannot be easily debunked can also be very successful in this regard. They offer the broadcaster the opportunity to disseminate views that are particularly advantageous to him. Because of such advantages, lies and deception have probably been with mankind since it began to speak.

The use of reputation as well as its manipulation should by no means be limited to humans. Virtually all intelligence, be it human, animal, artificial, or even extra-terrestrial, should be confronted with the dilemma of untruthful, misinforming, or even malicious communication, since there are always advantages to deception. Therefore, it is to be expected that in any societies of intelligent beings, the concept of reputation will arise, as well as communication about the reputation of the individual members of the society. Furthermore, individual members will always seek to manipulate their reputation to their own advantage. At least this seems to be the case with us humans.

Reputation and communication about reputation should therefore be universal phenomena in any intelligent society. Understanding their dynamics is important and urgent, also with regard to problematic developments in social me-

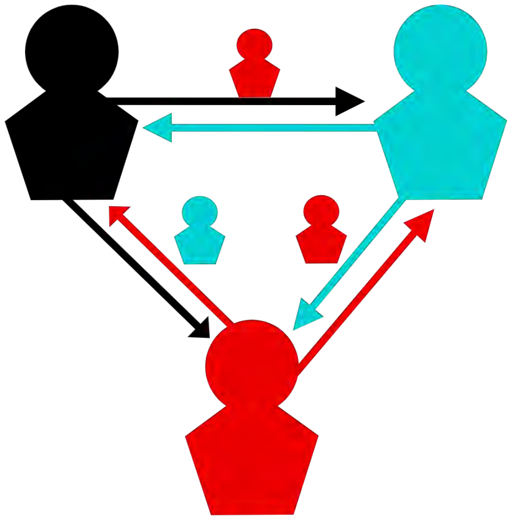


Figure 2.7: Possible communication pattern in the Reputation Game simulation with three agents. The agents Black, Cyan and Red are shown as large figures in the respective colours, their dialogues as pairs of arrows, and the subjects of the dialogues as small, coloured figures. What Agent Black says to Cyan about Red (top) influences what Cyan says to Red about Red (bottom right). The latter influences whether Red perceives Cyan as a friend or foe and thus whether he speaks kindly about Cyan when he exchanges views with Black (bottom left). *(Credit: MPA)*

dia. Here, more people communicate and with greater reach than ever before. Problematic developments such as polarisation and segregation of groups seem to be fuelled by the dynamics of social media.

To investigate such dynamics, Torsten Enßlin and Viktoria Kainz from the Max Planck Institute for Astrophysics, Céline Bœhm from the University of Sydney and Sonja Utz from the Leibniz-Institut für Wissensmedien have created a computer simulation of interacting artificial intelligences, the Reputation Game Simulation. The simulated intelligences, also called "agents", talk to each other, but not necessarily always in an honest way (See Figure 2.7).

The agents try to find out how honest the other agents are, but also how honest they themselves are. At the same time, the agents strive to convince the others of their own credibility. Helpful for this are upgrading lies about themselves or supportive friends, as well as degrading ones about enemies. However, lying always carries the risk of being caught. In addition to tell-tale signs of lying that cannot always be avoided, agents also pay attention to how plausible a claim is in the light of their own knowledge and use this to assess the credibility of the messages received. Depending on the outcome of this assessment, a message is either accepted as more likely to be true and integrated into one's own knowledge, or more likely to be ignored as potentially misleading. In the latter case, the agent receiving the message will register this as an attempt to deceive by the sender. To keep the complexity of the simulation manageable, the scientists allow the agents only one topic of conversation, namely the honesty of the different agents. So, they gossip with each other and about each other.

Such simulations of gossip are nothing new in the social sciences. What is new in the Reputation Game simulation, however, is the more advanced cognitive system of the agents, which follows information-theoretical principles. The agents have opinions that can be either very firm or quite uncertain. They draw logical conclusions taking into account the uncertainty of the information they receive. However, like us humans, the agents are also subject to limitations in the amount and accuracy of information processing. The agents observe themselves and their environment, and adapt to the prevailing social moods. This allows them, on the one hand, to better recognise typical lies and, on the other hand, to possibly design lies themselves in such a way that they spread more successfully.

Using the Reputation Game Simulation, the researchers tested a number of different communication strategies to see how well they were able to help agents achieve a high reputation. They found that while honesty can be a good strategy, less honest approaches may be more successful (see Figure 2.8).

The strategy of flattery turned out to be reliably successful in the simulations (see Figure 2.8, bottom left). This works particularly well when mainly less honest figures are flattered. These will then, in their more frequent lies, give their good buddy, the flatterer, a very good reputation.

Risky, but in many cases extremely successful, is penetrating self-praise, preferably to particularly credible and thus highly respected contemporaries (see Figure 2.8, bottom right). These use their high credibility to convince the other agents of the sincerity of the self-praising agent. In a considerable number of the simulation runs, notorious liars managed this way not only to appear as extremely honest, but also to be ultimately convinced of their own honesty. The latter is an astonishing self-deception, for the liars register very well each of their own lies. But the strong praise from the crowd of their convinced followers gives them a firm belief in their own goodness.

In the reputation game simulations, therefore, a series of phenomena can be observed that can also be found in a very similar way in sociology and psychology. For example, the occurrence of echo chambers, self-deception,

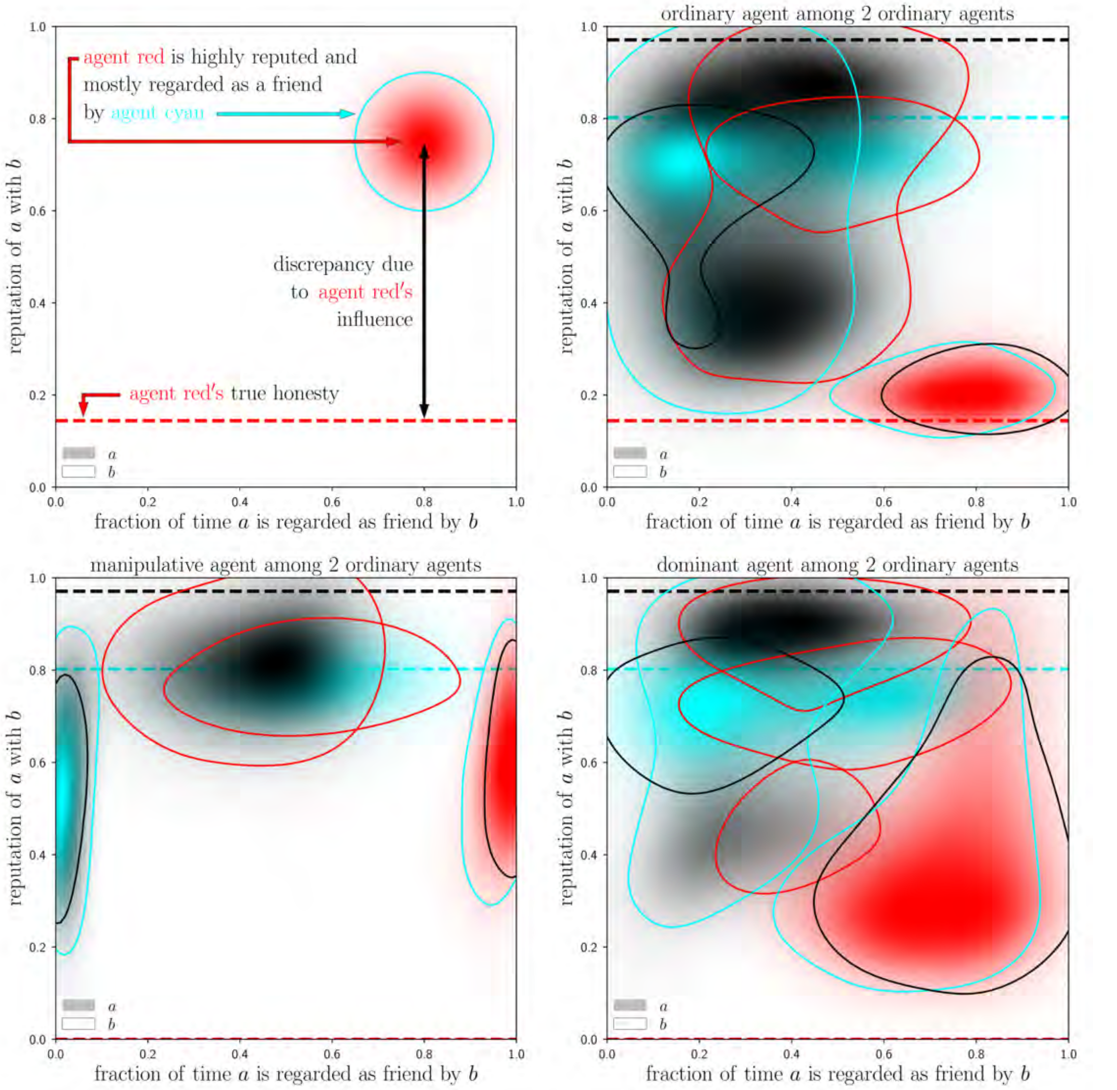


Figure 2.8: Reputation and friendship statistics of agents in Reputation Game simulations. The relationships of three agents are shown. Agent Black is very honest, Agent Cyan is quite honest, and Agent Red is a chronic liar. The diagram at the top left illustrates how to read the other diagrams. In it, the red area with a cyan border shows how Agent Red was seen by Agent Cyan during one hundred simulations. Agent Cyan would see Agent Red as an honest friend according to this diagram. Agent Red's real honesty is lower and indicated by the red dashed line. The upper right diagram shows the mutual assessment of the three agents when they are all ordinary, i.e. not using any special strategy to raise their reputation, but just lie from time to time. The Cassandra syndrome can be observed here: The actually honest Agent Black is perceived as quite dishonest in many simulations. In the lower diagrams, Agent Red always lies and pursues special strategies. Below left shows how efficiently the strategy of flattery allows him to appear as an honest friend of the others. At the bottom right, Agent Red engages in penetrating self-praising and thus often, but not always, achieves a very high reputation. *(Credit: MPA)*

camp formation, toxic as well as frozen social moods, the symbiosis of rogues, and the so-called Cassandra syndrome could be observed. The latter refers to the effect that the most truthful person may be the least believed because their opinion differs too much from the group's belief and is therefore perceived as a lie (see Figure 2.8, top right).

Admittedly, research on lying machines seems far removed from astrophysics, which is still the research focus for Torsten Enßlin and Céline Bœhm. But even in their astrophysical data analyses, these researchers use automated procedures to identify implausible measuring instruments and misleading data sets. It is to be expected that as the complexity of instruments and databases grows, their machine-calculated reputation will play an increasingly important role. Automated communication about such reputation would then be machine gossip.

Torsten Enßlin is an astrophysicist and information theorist. Viktoria Kainz is a theoretical physicist and consultant for artificial intelligence in industrial applications. Céline Bœhm is an astroparticle physicist and cosmologist. Sonja Utz is a psychologist and media sociologist.

2.6 If dark matter is fuzzy, then how fuzzy is it? – A gravitational lens has the answer

By Devon Powell (postdoc)

Dark matter, which makes up over 80% of the mass in the Universe, does not absorb or emit light, interacting with light and normal (baryonic) matter only through its gravitational pull. The nature of dark matter is one of the major open questions in astrophysics and cosmology. One theoretical model for dark matter, known as fuzzy dark matter (FDM), is predicted to leave a very specific imprint on light that is bent around a massive galaxy in a phenomenon called gravitational lensing. By examining the radio light in a gravitational lens system observed at extremely high angular resolution, we have determined just how "fuzzy" the dark matter can be. In the quest to discover the nature of dark matter, many different theoretical models have been proposed. Most of these involve a new type of fundamental particle that interacts with other matter only through gravity. Particles with different masses are predicted to influence the small-scale distribution of the dark matter on galactic scales. For instance, cold dark matter (CDM) with a very massive particle would produce many compact, relatively low-mass clumps of dark matter orbiting every galaxy. In the opposite extreme, an ultra-light dark matter particle (ULDM), commonly called fuzzy dark matter (FDM), is predicted to produce a very blobby, wavy distribution of dark matter in every galaxy.

Gravitational lensing is one of the most promising ways to probe the nature of dark matter. As light from a distant source is bent around a lens galaxy in-between, we see several magnified and distorted copies of the source im-

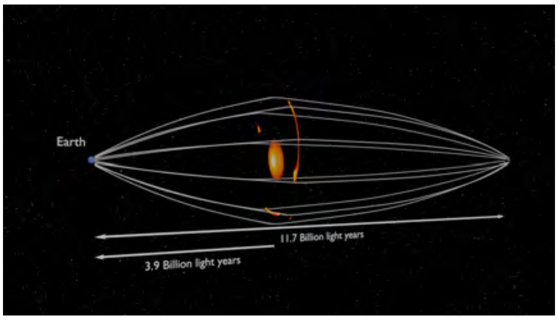


Figure 2.9: Schematic of the gravitational lens system MG J0751+2716. The long, thin gravitational arcs that we observe reveal information on the gravitational landscape of the lens galaxy, and hence properties of the dark matter. *(Credit: Visualization: Robert Schulz (ASTRON, U. Leiden). VLBI data: Spingola et al. 2018. Source reconstruction: Powell et al. 2022.)*

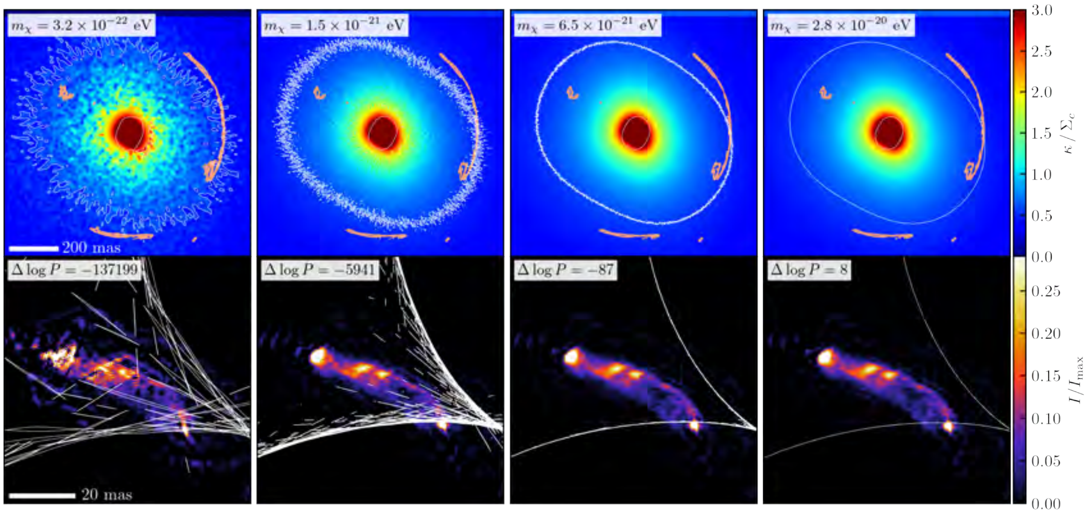


Figure 2.10: Examples of different fuzzy lens models from our analysis. The color maps in the top row show the density of the gravitational lens, with the gravitational arcs of lensed radio light shown in orange. The bottom panels show the corresponding source images inferred for each lens model. The mass of the dark matter particle increases from left to right. A dark matter particle that is too light produces a very fuzzy lens (left column), and the data cannot be explained without a physically unrealistic source. This model is therefore assigned a low likelihood. *(Credit: MPA)*

age (See Figure 2.9). The small-scale distribution of dark matter, which can be thought of as a "texture" in the gravitational lens, imprints a subtle signal on the lensed images that can be observed, if the observation is sensitive enough. In a lens galaxy containing fuzzy dark matter, this effect is similar to a pane of glass with a wavy pattern molded into it – the kind that is used in bathroom windows. It allows light to pass through, but distorts the image so that we cannot clearly see what is on the other side. By looking for the presence (or absence) of such subtle wavy distortions in the light passing through a gravitational lens, we can infer the mass of the dark matter particle. In fuzzy dark matter theories, a lighter particle produces a "fuzzier" lens, so we can use a gravitational lens observation to place a lower bound on the particle mass.

Our ability to see this fuzzy texture in the density of gravitational lens galaxies is limited by the angular resolution of the observation, or equivalently the size of the smallest features we can make out on the sky. Therefore, we get the best sensitivity to the dark matter particle mass by observing a gravitational lens system at the highest angular resolution possible. We achieve this using very long baseline interferometry (VLBI), a radio astronomy technique that combines signals from radio antennas all across the Earth. For this work, we used a VLBI observation of the gravitationally lensed radio jet MG J0751+2716 with an angular resolution of just 5 milli-arcseconds, or roughly one millionth of a degree. In the VLBI images, we can see the long, thin gravitational arcs that are perfect for searching for the small-scale gravitational perturbations that would be imprinted by fuzzy dark matter.

So, if dark matter is fuzzy, then just how fuzzy is it?

We generate many thousands of simulated fuzzy gravitational lenses with different dark matter particle masses (See Figure 2.10). For each of these fuzzy lens models, we compute the likelihood that that such a lens could have produced the observed data. By computing thousands of these likelihoods over a range of proposed particle masses, we infer the probability that the dark matter consists of a particle of a particular mass, given the observed data. If the lens model is too fuzzy, the reconstructed source image becomes physically unrealistic. As the particle mass increases, we reach a point where the data cannot distinguish a fuzzy lens from a perfectly smooth lens model. We find that with 95% certainty, a mass of a fuzzy dark matter particle is not lower than of 4×10^{-21} eV. This work demonstrates the power of high-resolution VLBI observations to probe the nature of dark matter using strong gravitational lenses. Fuzzy dark matter is just one of many different theoretical models for dark matter. In future work we will use VLBI observations of gravitational lenses to constrain other dark matter models, including warm dark matter (WDM) and self-interacting dark matter (SIDM).

2.7 Effects of Neutrino Fast Flavor Conversions on Core-Collapse Supernovae

By Jakob Ehring (PhD student)

Neutrinos are the driving factor for core-collapse supernovae, the violent death of massive stars. According to the neutrino-driven mechanism they are responsible for transferring energy from the hot proto-neutron star (PNS) to the surrounding material. So far, numerical simulations assumed that neutrinos retain their flavor during propagation. Max Planck researchers have now shown that allowing for flavor conversions has a direct influence on the supernova dynamics.

Supernova explosions are the death of massive stars after they have consumed all their raw material and can no longer produced energy through nuclear fusion. Even though the electromagnetic radiation of such supernovae can outshine a whole galaxy, it is faint compared to the energy released in form of neutrinos. These neutrinos only rarely interact with other matter, but interestingly it is just this reluctance to interact that enables neutrinos to play a pivotal role in turning the collapse of the massive stellar core into an explosion.

After a massive star has exhausted its reservoir of material to power nuclear fusion in its core, the missing radiation pressure from the center causes the core to collapse. A dense proto-neutron star forms, which is small (a few tens of kilometers) but massive (more heavy than the sun). Trapped inside is an enormous amount of of heat (a few hundreds of billions of degrees) generated from gravitational energy in the collapse. Neutrinos are the only particles that can escape this monstrous environment as they are interacting very rarely. Therefore they are being produced in vast amounts allowing the proto-neutron star to cool.

Nevertheless, a small fraction of neutrinos will interact with close-by stellar matter and heat-up the region surrounding the core. If the energy transfer is efficient enough (an absorption of about 1% is sufficient), the neutrino heating triggers an expansion strong enough to lead to explode the star, i.e. launching the supernova. If not, the star will finally collapse to a Black Hole.

The neutrino flavor is a quantum mechanical property and influences, how the neutrino interacts with matter. In particular, neutrinos of electron flavor interact more strongly with matter than neutrinos of other flavors (myon and tau). These, in turn, can escape easier making them more energetic on average. Neutrino flavor conversions where individual neutrinos change their flavor are have been known for a few decades already. However, since they are suppressed at very high densities, such as in a collapsing star, so far numerical simulations of supernovae assumed that neutrinos keep their flavor.

Recently scientists discovered that neutrinos can undergo collective self-induced flavor conversions if the neutrino density is sufficiently high, such as in core-collapse supernovae or the early universe. But the conversion length scales are much below the resolution of numerical simulations of supernovae. Also the exact conditions and outcomes of the so-called ‘fast’ neutrino flavor conversions remains incalculable with direct simulations due to the high dimensionality of the problem. Now researchers of the Max Planck Institutes for Astrophysics and for Physics and the Niels Bohr Institute have teamed up to gauge the influence that fast and efficient flavor conversions can have on the dynamics of a core-collapse supernova.

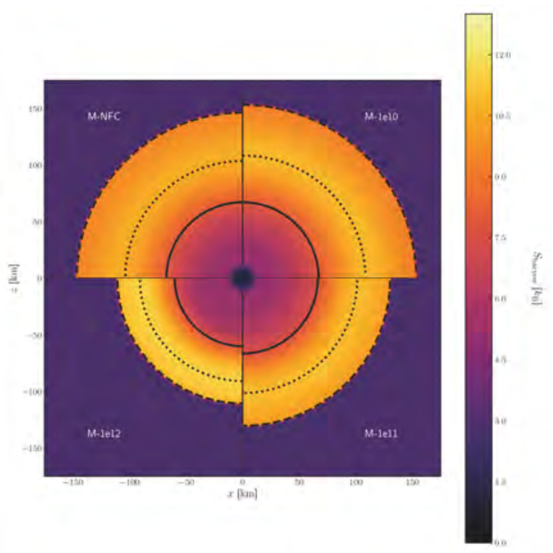


Figure 2.11: These four snapshots show the interior of four different simulations of core-collapse supernovae with the same initial conditions but where neutrino flavor conversions are active in different regions. The solid line shows the size of the proto-neutron star, the dashed line the extent of the shock radius, and the dotted line separates regions where neutrinos cool the stellar matter (inside) from regions where neutrinos heat the stellar matter (outside). The color-coding indicates the specific entropy that increases as the neutrinos heat the matter. All snapshots are taken at the same time, 100 ms after the core-bounce. The labels denote the density, below which flavor conversions are active (in g/cm^3). NFC (top left) means “No Flavor Conversion” and is the reference model. If the flavor conversion is only active in the heating region (top right), the shock expansion is (transiently) stronger. For models with flavor conversion in the cooling region (bottom), the shock expansion is reduced, with flavor conversions happening inside the proto-neutron star (bottom left) leading to an even stronger contraction. *(Credit: MPA)*

Their new, easy-to-calculate scheme integrates an effective treatment of flavor conversions directly into the numerical simulations. It is designed to find out how big the influence of flavor conversions could be. To do so, it maximizes flavor conversions up to the constraints allowed by the Standard Model of Particle Physics. The scientists inspected the collapse and subsequent accretion phase of an evolved stellar model, which is 20 times more heavy than the sun. In multiple simulations, they increased the stellar volume that is under the influence of flavor conversions and investigated how the system reacts to such strong changes in the neutrino field.

In regions where neutrinos are heating the stellar matter, flavor conversions can transiently intensify this heating because some high-energy neutrinos of non-electron flavor are converted to the more reactive electron flavor. However, the effect is not strong enough to trigger an explosion by itself in the particular model. On the other hand, flavor conversions in the proto-neutron star can even accelerate the collapse to a black hole in the model, because in this region the inverse conversions accelerate the cooling.

This study shows that the influence of neutrino flavor conversions should be taken into account for predictive simulations. Flavor conversions will probably not challenge the neutrino-driven mechanism itself but they might add significant modifications to the dynamics. Yet it is too early to draw final conclusions on the details as the implementation of the effects is schematic and not based on detailed calculations. The simulations assume spherical symmetry without multi-dimensional flows that are known to be an important ingredient for successful explosions. Finally, the detailed structure of the progenitor star is also known to strongly influence important aspects of supernovae in a non-linear fashion.

The latter two limitations are already subject to a follow-up investigation still under peer-review. These multi-dimensional core-collapse simulations now also include stars with lower masses, which usually show explosions. The results indicate that flavor conversions could work both ways: For lower mass progenitors the increased heating can trigger the explosions significantly earlier; in higher mass progenitors the flavor conversions could hamper explosions due to cooling effects. Flavor conversions therefore not only influence the explosion dynamics and modify the neutrino signal measured on Earth, they could also be relevant for the distribution of the masses of black holes and neutron stars.

2.8 What happens when you put a star inside a star?

By Rob Farmer (postdoctoral fellow) and Selma de Mink (scientific director)

Throwing one star into another into another star does not bode well for either star. However, given the right conditions and the right types of stars this can lead to the stars merging and forming one single object. If one of the stars is a neutron star (the dense stellar remnant after a supernovae) it can sink to the center of the other star replacing that star's core. Such objects are called Thorne-Żytkow objects (TŻOs) as they where first proposed by Kip Thorne and Anne Żytkow. Now an international team of astrophysicists led by the Max Planck Institute for Astrophysics (MPA) has re-evaluated what these TŻOs look like and whether we can find them.

Irrespective of the original star, the resulting object would expand and become a red supergiant, an object so large that it would consume Jupiter if our Sun became such a supergiant. This gigantic object would then be supported by the neutron star at its center, which is the size of the city of Munich. For the first time, a team at MPA was able to simulate these objects in detail and determined what they would look like.

Inside the TŻO, material continuously falls onto the neutron star providing the energy to keep the star supported. These conditions can produce very exotic nuclear nuclei, so unstable that they would not survive for more than a second. However, some of the exotic elements produced are stable and can migrate to the surface of the TŻO, where they potentially become observable. Unfortunately it is likely harder to find a TŻO in our own Galaxy than previously assumed, so the team was looking for alternative ways to find them.

One avenue could be stellar pulsations. Many stars pulsate as their surface moves inwards and outwards, and TŻOs are no exception. For the first time, the team could show that the TZO's should have both very long ($>$1000 day) pulsation periods and shorter$\sim$500 day peri-

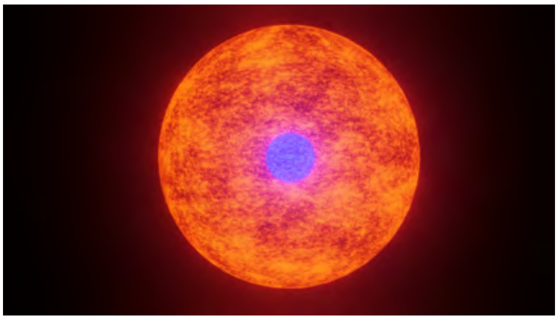


Figure 2.12: In the center of a massive red supergiant may lay a tiny neutron star. Please note that the stellar core is not to scale - a neutron star with a size of just a few kilometres would be too small to see compared to the supergiant extending many millions of kilometers. *(Credit: R Farmer, MPA)*

ods. Combining these different pulsation periods creates an unique fingerprint that can be used to identify a TZO. Based on the pulsation properties of several candidates observed in our galaxy and the nearby Magellanic clouds, the team was able to rule out that these are indeed TŻOs.

TŻOs represent an exotic class of stars that have undergone an extreme form of stellar evolution. The MPA study now provides models for what they should look like, and help astronomers to try to find them. Even though they are probably very rare objects, they do have some distinct features that make them stand out from other stars. Thus, the results presented in this study are only the first step in the - hopefully - eventual detection of these unusual objects.

2.9 Most energetic stellar collisions in the Universe

By Taeho Ryu (postdoc)

In dense stellar environments, stars can collide. If there is a massive black hole nearby – at the centre of galaxies – these collisions can be so energetic that the two stars are completely destroyed upon collision, leaving behind an expanding gas cloud. While the collision itself can generate a very luminous flare for several days, there might be an even brighter flare that can last up to many months, as the gas cloud is captured by the nearby black hole. A research team led by MPA has estimated the observables of such powerful events for the first time using the two state-of-the-art codes AREPO and MESA, developed at MPA.

What are the most energetic collisions between stars in the Universe? Such collisions would happen if the stars move at high relative velocities. In the deep potential well of the massive black hole at the centre of a galaxy, stars can reach a few percent of the speed of light (up to $10000 km/s$). The collision of two such fast-moving stars would be fascinating to observe, because the resulting flare could be at least as luminous as various types of electromagnetic transients, such as tidal disruption events or supernovae.

Because we did not understand their observational signatures, however, not much effort has been spent searching for these high-velocity collisions. A research team led by an MPA fellow has now made quantitative predictions how such black hole-driven destructive collisions between giant stars could be observed. For their analysis, the team used the state-of-the-art simulation codes AREPO and MESA.

In particular, the team analysed two red giant stars, colliding at velocities much greater than the escape velocity of the colliding stars. This means that the two stars are entirely destroyed. Very powerful shocks convert a large fraction of the initial kinetic energy into heat, driving the resulting gas cloud to expand quasi-spherically.

The maximum expansion speed of the cloud is larger than the initial relative velocity of the stars, and the parameters of the gas cloud depend rather strongly on the collision velocity. A collision between larger stars colliding at a higher speed tends to result in greater conversion efficiency. As the heat energy escapes from the cloud, a prompt flare with a peak luminosity comparable to that of a supernova explosion ($10^{41} - 10^{44} erg/s$) can be generated. Because of the rapid expansion of the cloud, the prompt flare becomes very faint in days or a week.

However, the expanding gas cloud interacts with the nearby black hole. The accretion of the gravitationally captured gas creates a second flare that could even be brighter and lasting much longer than the first flare. This heightened luminosity can be sustained for up to ten years.

These unique features of the electromagnetic radiation make such events a promising probe for the existence of dormant black holes. In addition, the growth of black holes through the accretion of the collision products would be another venue for the growth mechanism for seed

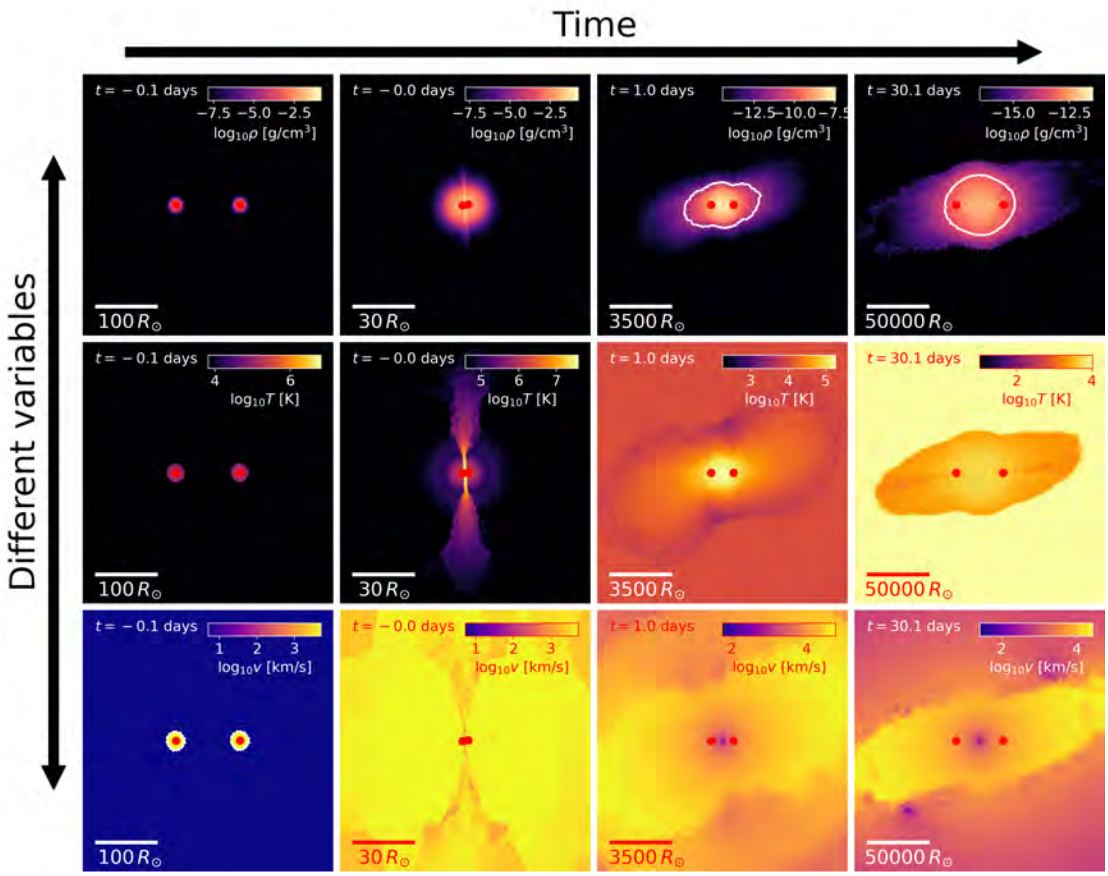


Figure 2.13: These plots show various parameters of the nearly head-on collision between two red giant stars, shortly before collision (left column), at the collision moment (second column), 1 day and 30 days after collision (two right columns). The top row shows the density, the middle row shows the temperature and the bottom row the speed of the gas with the arrows indicating the direction of gas motion. The red dots in each panel indicate the location of the cores. Initially the two stars start to move towards each other with $10000 km/s$. At collision, strong shocks are created when the incoming gas collides with the pressure barrier. The gas bounces off and expands quasi-spherically at supersonic speeds. *(Credit: MPA)*

black holes at high redshifts.

2.10 SPICE connects stellar feedback in the first galaxies and cosmic reionisation

By Aniket Bhagwat (PhD student)

The first billion years saw the transformation of a cold neutral Universe to a hot and ionised one. This Epoch of Reionisation is thought to come about from stellar radiation from the first

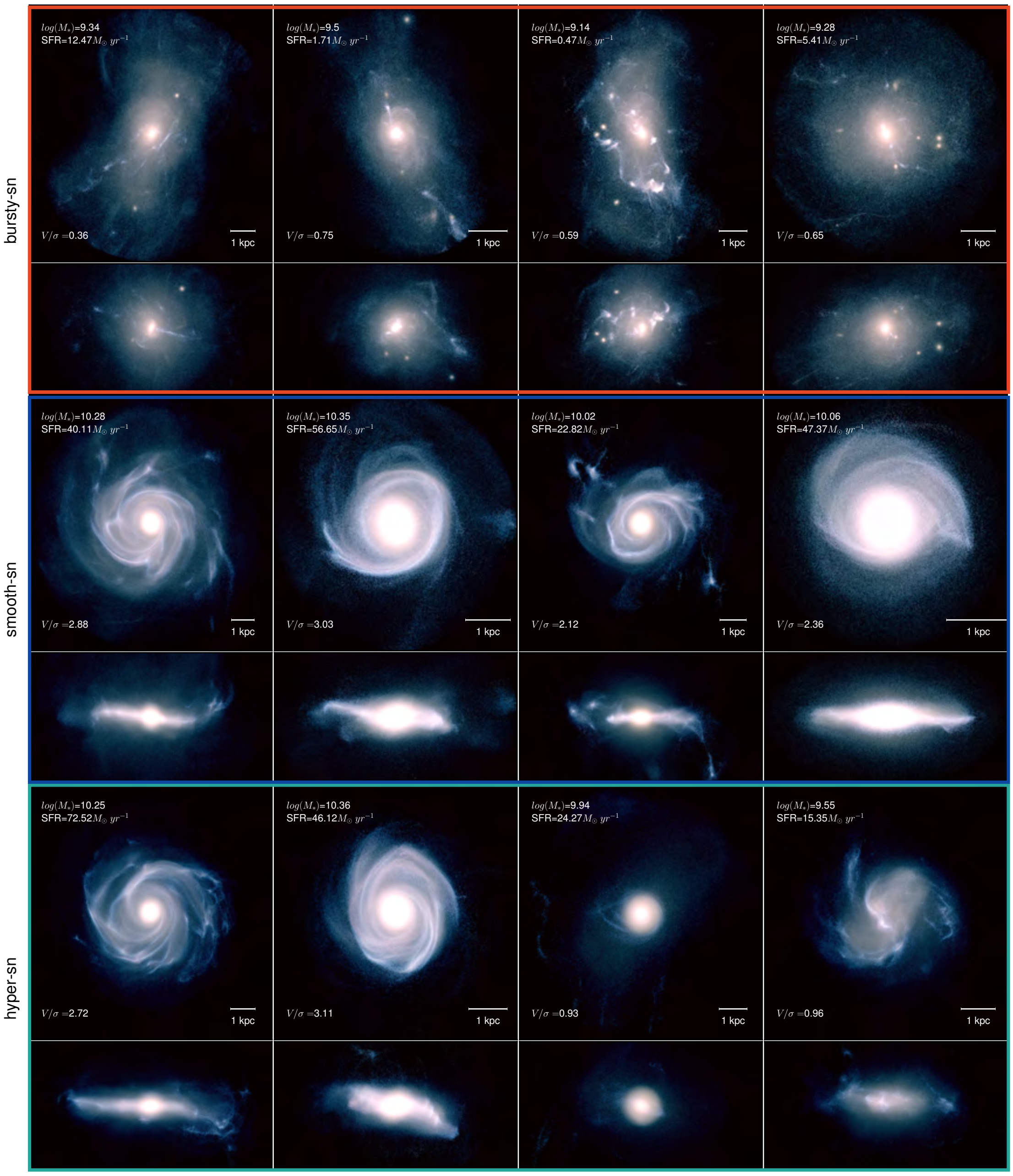


Figure 2.14: These images show the four most massive galaxies from each of the three simulation models. The top two rows show "bursty" feedback, the middle two rows show "smooth" feedback, and the bottom two rows show a mixture of the two, where each galaxy is shown both face-on (top) and edge-on (bottom). The galaxies in each column occupy the exact same environment in every simulation. The effect of different stellar feedback models is evident as the bursty feedback model produces elliptical-like galaxies whereas the smooth and intermediate models predominantly produce spiral-like galaxies. *(Credit: MPA)*

galaxies. Understanding the nature of the galaxies that drove reionisation remains a key question. Scientists at MPA have designed a novel suite of simulations to systematically understand how different modes of energy and mass injection from stars affect the first galaxies. According to these new models, subtle differences in the behaviour of stellar feedback drive profound differences in the morphologies of galaxies and the speed at which they ionise the universe. Combining these findings with the latest observations will help constrain feedback models in the first billion years of the Universe.

Some 300,000 years after the Big Bang, for the first time, protons and free electrons formed hydrogen and helium atoms – the Universe was mostly neutral. In the following billion years, however, the vast majority of hydrogen became ionised. This transition from a neutral to an ionised state is known as the "epoch of reionisation". For this to happen, ionising photons had to escape from galaxies. Massive stars emit ionising radiation and at the end of their lives, they die in supernova explosions, releasing mass and energy into gas around them. These processes are termed "stellar feedback", and change the physical structure of the so-called interstellar medium. How this stellar feedback changes the properties of the first galaxies and in particular the gas within these galaxies is poorly understood, but it is key to interpret the recent flood of observations of the early Universe from the James Webb Space telescope.

In the last decade, advancements in high performance computing and theoretical models have allowed scientists to reproduce observations of the first billion years of the Universe. Even though these sophisticated simulations were able to combine radiation and hydrodynamics, due to the computational costs, they typically explore only one of the many possible models of stellar feedback. A team of researchers at MPA led by Aniket Bhagwat, therefore, developed a new suite of simulations called SPICE to systematically test different models and, in particular, to look at connections between stellar feedback and the properties of galaxies that drive reionisation, which could be tested through observations.

The SPICE simulations follow the hydrodynamical evolution of gas, including key processes like star formation and supernova explosions, while tracking the propagation of radiation emitted by those stars. In particular, they include three different modes of stellar feedback: "bursty", where supernovae explode in clustered bursts; "smooth", where supernova explosions are spread out in time; or a mix of the two. And indeed, the simulations show that differences in the strength and behaviour of feedback can have dramatic effects on the morphology of the galaxies. Bursty feedback preferentially produces red and passive galaxies (elliptical-like), whereas smooth feedback produces mostly galaxies that are blue and star forming (spiral-like).

What implications does this have for the process of reionisation? The researchers connected the morphologies of the galaxies to the fraction of ionising photons that manage to leave the galaxy; this quantity is called the "escape fraction". They find that elliptical-like galaxies show a much higher escape fraction than spiral-like ones (by a factor of 20–50). Why does this happen? The bursts of energy due to the combined supernova explosions are able to substantially disturb the gas and punch low-density holes in the interstellar medium, through which the ionising photons can escape easily. Without bursts, the feedback is unable to disturb the gas enough to allow photons to escape en masse. Therefore, bursty feedback models allow for faster reionisation.

Overall, the new SPICE simulations demonstrate for the first time how sensitive cosmic reionisation and galaxy morphologies are to the mode of stellar feedback, marking a step forward in our understanding of the first billion years of the Universe.

Simulations and data analysis were carried out on the RAVEN and COBRA supercomputers at MPCDF.

2.11 Magnetic fields in multiphase gas: A turbulent tango

By Hitesh Kishore Das (PhD student)

Space is filled with gases of vastly different temperatures and it is important to understand how these interact. A group of scientists at MPA has now looked into the mixing of gases with and without magnetic fields. Surprisingly, they find that the outcome depends on whether turbulence is already present at the beginning. Without turbulence, magnetic fields can suppress the mixing by suppressing turbulence, while if the turbulence is already present, magnetic fields have a marginal effect.

From the Milky Way and Andromeda in our neighbourhood to the farthest observed galaxy JADES-GS-z13-0, galaxies are islands in the vast expanse of space. But, they are not isolated. They accrete gas from their surroundings, churn and compress it to form stars, before throwing it out again when those stars explode as supernovae. This expulsion of gas from the galactic disk creates gigantic galactic outflows. Such outflows can drain the galaxy of the gas that could have fuelled future star formation, leading to a period of low star formation rate, which is also called “quenching” of the galaxy. However, it is believed that the gas that is thrown out as galactic outflows can later be recycled and accreted back into the galactic disk to fuel further star formation. This cyclic expulsion and accretion of the baryonic gas in and out of the galaxy is called the “Baryon cycle” and is a crucial part of the evolution of galaxies.

The gas as the main ingredient of this cycle can exist in different phases: extremely hot gas (with millions of degrees) along with pockets of much colder gas (of only thousands of degrees). Understanding how these gases of different temperatures mingle and mix is important to our knowledge of the Baryon cycle and the many related astrophysical processes.

Turbulent mixing is a well-studied field, as it is important in a lot of applied areas like meteorology, pollutant transport, combustion engines, etc. But in astrophysics there’s a catch: magnetic fields fill interstellar and circumgalactic space, too. Do these invisible fields affect the mixing among the vastly different phases of gas? Scientists have dived into such questions using computer simulations and found that in some cases magnetic fields can suppress mixing. This can pose a problem to the multiphase nature of the gas. Still, this combination of turbulent, magnetised and multiphase gas remains an enigma. In this study, we investigate how the presence of magnetic fields affects the mixing and the interaction between hot and cold gases.

The researchers at MPA, using computer simulations, first mimic a very simple setup called a mixing layer: hot and cold gases are next to each other with a single interface and a relative velocity between them. First, the gases mix without any magnetic field. In this case, turbulence efficiently stirs and mixes the gases. Next, the team introduces magnetic fields and finds that the mixing is suppressed. The magnetic fields stabilize the boundary between the hot and cold gases, preventing turbulence (see first video under `https://www.mpa-garching.mpg.de/1087631/hl202311?c=27981`). However, in a second, more realistic simulation called a turbulent box, turbulence is already present at the beginning. In this case, the magnetic fields do not affect the mixing.

This is a puzzling outcome, as the mixing layer setup was expected to exist within the bigger turbulent box setup. Why should the magnetic fields make a big difference in the first case, where there is only a marginal effect in the second? Until now, mixing layer simulations were thought to be zoomed-in versions of the turbulent box simulations, to situations similar to the mixing-layer-setup at each cold-gas/hot-gas interface. So, a big effect on mixing in these was hypothesised to have an equally big effect on mixing in the turbulent boxes.

To resolve this dilemma, the team had to examine the root cause of mixing, which is turbulence. The mixing depends only on the turbulent motions and not on how this turbulence formed originally. In mixing layers, the presence of magnetic fields hinders the generation of turbulence; in a turbulent box, the turbulence already exists. If the turbulence in a setup is unchanged by magnetic fields, the mixing remains unchanged, which means that there is no effect on the growth and survival of cold gas.

Even though in the more realistic turbulent box simulations, the magnetic fields do not change the overall mixing of the different phases, magnetic fields still leave their fingerprints. Magnetic fields affect the structure of the cold gas, which is very evident from the evolution in simulations: in the presence of magnetic fields, the gas becomes more elongated and filament-like (see second video under `https://www.mpa-garching.mpg.de/1087631/hl202311?c=27981`). The researchers also examined how these changes in the cold gas structure can affect observations. Mock quasar line-of-sight observations were created from the simulations with and without magnetic fields, and in both cases follow the observed relation between number of spectral features and their strengths – but almost no observable difference could be found between the two cases.

In conclusion, these numerical experiments show that magnetic fields can inhibit turbulence and a mixing of gases, if there is a shear between layers of hot and cold gas. However, if turbulence is already present in the gas, the magnetic fields become just bystanders and do not affect the efficiency of the mixing. These findings can help better understand the complex multiphase nature of observed astrophysical gases.

2.12 Our Neighborhood in the Milky Way in 3D

By Gordian Edenhofer (PhD student)

High-resolution three-dimensional maps of the Milky Way have previously been limited to the immediate vicinity of the Sun. In a collaboration led by the Max Planck Institute for Astrophysics with researchers from Harvard, the Space Telescope Science Institute, and the University of Toronto, we were now able to build a high-resolution map of the Milky Way in 3D out to more than 4,000 light-years. The produced 3D map will be highly useful for a wide range of applications from star formation to cosmological foreground correction.

When we think about the Milky Way, we often think about 2D images of the night sky or artist's impressions of how the Milky Way might look from outside our Galaxy. With the advent of Gaia, we are entering a new era of Milky Way science, in which we begin to unfold our previous 2D view of the Milky Way into a rich 3D picture. In recent years, we started to build 3D maps of the distribution of matter in the immediate vicinity of the Sun out to approximately 1,000 light-years. Thanks to these maps, we were able to study the star formation around the Sun in 3D, made numerous discoveries about the shape, mass, and density of nearby molecular clouds, and learned how supernova feedback shaped the space around the Sun.

At the core of maps of the 3D distribution of matter in the Milky Way lies interstellar dust. Interstellar dust closely traces the distribution of matter, cools gas such that stars can form, agglomerates to form planets, and obscures astrophysical observations. Incidentally, this obscuration allows us to quantify the amount of dust between us, on Earth, and the astrophysical object we want to observe in the background, often stars. We can infer the 3D distribution of dust and thus indirectly trace the distribution of matter in the Galaxy using this information. To do so, we combine millions of measurements of the amount of dust to background objects with distance estimates to said objects from Gaia.

Inferring the distribution of dust in the Milky Way from distances and dust measurements is a computationally intensive, statistical inverse problem. The problem is ill posed: from our limited data and prior knowledge about dust, it is not possible to retrieve a definite answer about the true distribution of dust. Still, the language of statistics allows us to translate our noisy data with a physics-informed model of dust into a 3D dust map with rigorously quantified uncertainties. Until now, however, the computational costs of 3D dust models have limited the size of the probed volume.

Recent progress in our physics-informed model of dust enabled us to probe much larger distances. We put forward a new statistical method to model spatially smooth structures in large volumes – a required component of dust maps. At the heart of the new method is an algorithm to iteratively add ever-finer details to a coarse representation of 3D dust. By adding details iteratively instead of modelling everything at once, the modelling problem drastically simplifies and becomes faster by orders of magnitude.

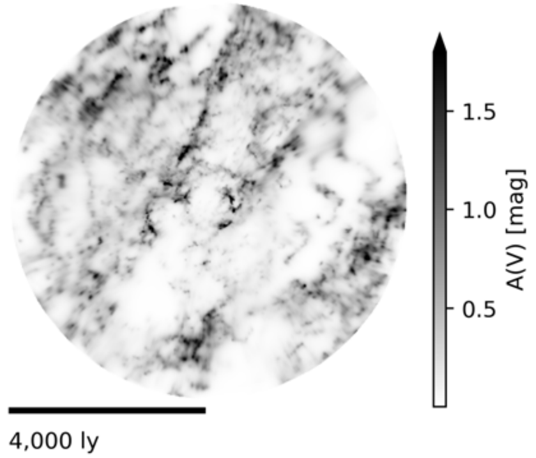


Figure 2.15: Bird's-eye view of the distribution of dust within 4,077 light-years around the Sun. The Sun is at the center and the galactic center is to the right. *(Credit: MPA)*

We combined the new methodological developments with the latest processed Gaia data to create the largest high-resolution map of interstellar dust to date. The new 3D dust map extends 4,077 light-years in all directions from the Sun with a resolution of a few light-years. The produced 3D map will be highly useful for studying the medium between stars in the Milky Way. Understanding the structure of the interstellar medium will help us constrain key relations for star formation. In addition, the 3D dust map will be important for correcting astrophysical observations. For many observations, the interstellar medium in front of the object of interest is a nuisance. The new 3D dust map will allow correcting these measurements for the foreground material in a much larger volume than previous maps.

2.13 Direct Imaging of Gas Recycling around a Massive Galaxy in the Early Universe

By Fabrizio Arrigoni Battaia (scientific staff)

Galaxies are the birthplace of most stars and black holes. However, scientists are still debating, how galaxies accrete the fuel to sustain their growth, and how they in turn pollute their environment with elements heavier than helium. An international team of astrophysicists has now directly observed the neighborhood of a massive galaxy in the early universe. They find that the gas all around the galaxy is enriched with heavy elements, which means it has been polluted by the galaxy itself and by embedded satellite galaxies. Furthermore, this gas is spiraling onto the massive galaxy, fueling further star formation.

According to the first models of galaxy formation, gas fell isotropically onto dark matter halos, was shock-heated to very high temperatures (millions of degrees), and subsequently cooled to form stars in the growing central galaxy. However, it is now clear that this so-called 'hot-mode' accretion accounts for only a small fraction of the fuel powering the violent star formation in massive galaxies in the early universe. Instead, cosmological hydrodynamical simulations indicate that a 'cold-mode' accretion (thousands of degrees) onto galaxies occurs along filaments. This accretion process is more efficient in transporting gas down to the galaxy, providing a natural mechanism to sustain the observed large star-formation rates.

In turn, stars pollute their surrounding environment with elements heavier than helium, globally referred to as "metals". The most energetic phenomena (supernova explosions) are even able to generate galactic outflows, enriching the circumgalactic gas. Recent cosmological simulations indicate that this metal-enriched gas ejected by the galaxy could fall back, resulting in a further supply mechanism to sustain intense star-forming activity. Therefore, a massive galaxy will both recycle its metal-polluted gas and use pristine, inflowing gas. However, direct observational evidence for the presence of such recycled inflows had not been obtained so far.

An international team of astronomers has therefore targeted a massive system in the early universe, to get a first glimpse on how such galaxies accrete their gas. The chosen system, MAMMOTH-1, can be observed at an epoch corresponding to 11 billion years ago. It is a galaxy group embedded in large-scale cold circumgalactic gas, which shines bright in Lyman-alpha emission from hydrogen.

With data from the Keck Cosmic Web Imager (KCWI, Keck II telescope) and narrow-band imaging from the Subaru telescope, the team detected circumgalactic line emission in hydrogen, helium, and carbon extending for 300 000 light years. An analysis of the line ratios allowed the team to obtain the gas properties throughout the halo. The results show that the circumgalactic gas has already been enriched to about solar metallicity, which is quite surprising at this early cosmic epoch.

Further, the KCWI data allowed the team to analyse the kinematics of the emitting gas in the observed region. A detailed comparison of the data with cosmological simulations developed at the Max Planck Institute for Astrophysics and with an analytical model can explain the observed velocity patterns, which are most likely due to recycled inflow gas. The kinematic model indicates that the gas accretion is occurring at a rate of about 700 solar masses per year, much more than the measured star-formation rate of the central galaxy (81 solar masses per year). The metal-enriched inflow could thus fully sustain the intense star formation in the massive galaxy. "Our observations give a first hint that recycled inflows might be an ubiquitous supply mechanism for massive star-forming galaxies in the early universe", remarks Shiwu Zhang of Tsinghua University and first-author of the study.

In addition, the team also found that satellite galaxies in this galaxy group have the same motion as the circumgalactic gas, indicating that they are embedded in the inspiraling streams. Therefore, these satellite galaxies could interact with and pollute the circumgalactic gas. "This makes the galaxy-gas ecosystem even more complex, but also it makes more plausible that gas recycling is an important ingredient," adds Zheng Cai of Tsinghua University and second-author of the study.

"We need a lot more sensitive observations of circumgalactic emission to give us more insights on the intricate ecosystem of galaxies", points out Fabrizio Arrigoni Battaia, co-author and scientist at the Max Planck Institute for Astrophysics. "Our approach together with the upcoming exquisite datasets, such as from the

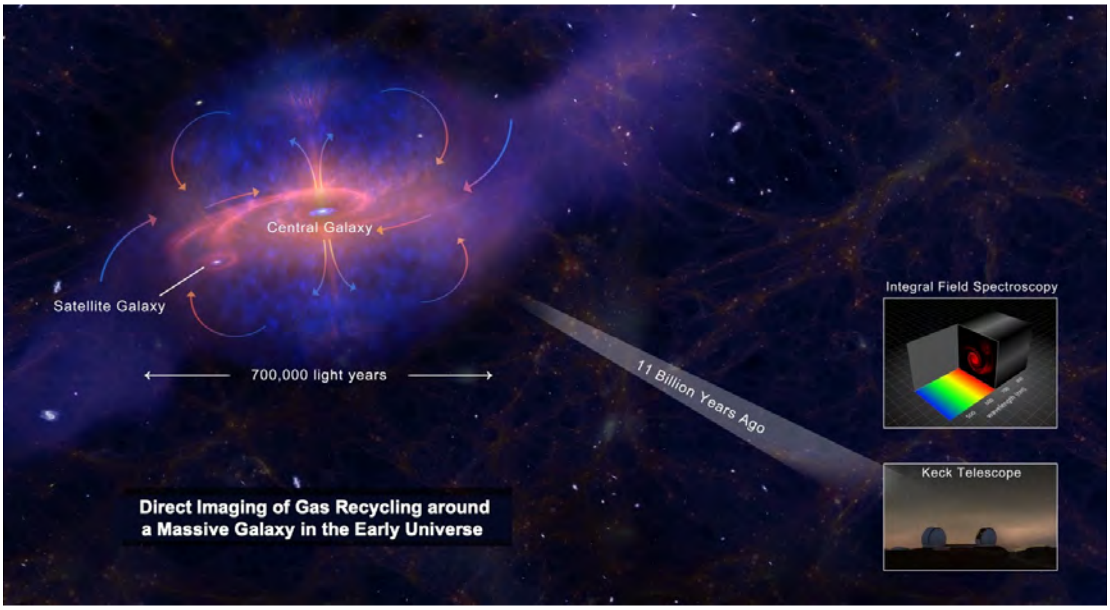


Figure 2.16: Artistic impression of the gas cycle in the circumgalactic medium of a massive galaxy, as well as the setup of the main observations used in this work. The inset figures show the Keck telescope (bottom) used to acquire the data with the KCWI instrument (top), which is an integral field spectrograph and therefore obtains three-dimensional data-cubes (2 spatial dimensions + velocity). Such instruments are key in detecting large-scale diffuse gas, while simultaneously studying its kinematics. *(Credit: Tsinghua University)*

MUSE/VLT, KCWI instruments, and JWST, allows us to directly study the circumgalactic gas in detail and thus better understand the physical processes governing the gas cycle around galaxies."

2.14 Radiation biology, radio astronomy and cosmic rays using information field theory

By Torsten Enßlin (scientific staff)

What do radiation biology, radio astronomy and cosmic ray measurements have in common? For one thing, radiation occurs in all of them. For another, all of these fields are explored using large-scale research facilities and require intelligent algorithms to visualize the quantities that occur in the process. In order to advance this imaging in an interdisciplinary way, the Federal Ministry of Education and Research (BMBF) is now funding the project "Information Field Theory for Experiments at Large-scale Research Facilities". Seven German universities, the Max Planck Institute for Astrophysics (MPA) and Erium GmbH, founded by former MPA students, are involved.

The measured values from large-scale research facilities, such as radio telescopes or particle detectors for cosmic radiation, are not directly accessible to human interpretation or even to the eye alone. Often, these data must first be translated into images using complex computing procedures, which can then be interpreted by humans. So far, these procedures have been developed individually for each instrument. But the underlying question is actually the same, namely "What did the measured quantity originally look like?” The measurement principles of the respective instruments and the properties of the quantities measured with them differ considerably in practice, but from a theoretical point of view these differences are only mathematical details.

To standardize such imaging methods, the research group of PD Dr. Torsten Enßlin at MPA has developed the Information Field Theory (IFT) for spatially varying quantities. The theory describes how an accurate image of these fields can be generated from measurement data and our prior knowledge of physics. Thus, the IFT provides possible images of these quantities and, at the same time, information about the remaining uncertainties of the fields thus reconstructed.

Originally, information field theory was developed for astrophysical measurements. However, it is so general that it can be used for any measurement of field-like quantities. Within the framework program ’Exploration of Universe and Matter’ (ErUM) the project ’Information Field Theory for Experiments at Large Scale Research Facilities’ (ErUM-IFT) is now funded. The aim is to solve exemplary imaging problems for some large-scale research facilities. IFT-based algorithms for radio astronomy and their visualization are being developed at the University of Bielefeld, the University of Hamburg and the Technical University of Munich; at the RWTH Aachen University, the Friedrich-Alexander University Erlangen-Nuremberg and the Karlsruhe Institute of Technology, IFT methods are being used for the detection and analysis of radio pulses caused by cosmic rays. In addition, IFT-based methods for three-dimensional imaging of biological samples are being developed at the Universität der Bundeswehr München. At the Max Planck Institute for Astrophysics in Garching, basic IFT methods are being developed that are needed in the applications.

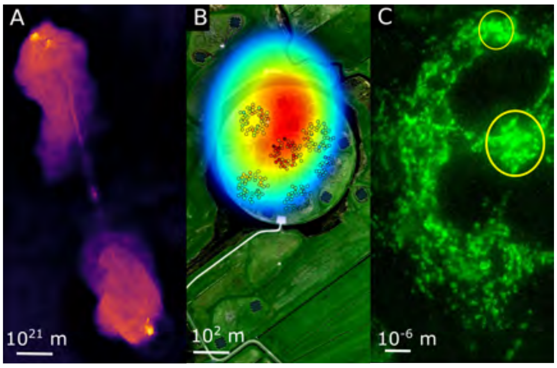


Figure 2.17: Application areas of the information field theory imaging methods developed in ErUM-IFT: (A) radio astronomy, (B) radio detection of air showers triggered by cosmic ray particles of high energy, and (C) cell biological microscopy. Although the typical lengths of the systems involved (see markings) differ by a factor of 10^{27} , information field theory allows their reconstruction using the same methodology. *(Credit: images courtesy of the copyright owners: Philipp Arras and Torsten Enßlin (MPA), Arthur Corstanje (Radbout Universiteit Nijmegen) and Judith Reindel (Universität der Bundeswehr München))*

The phenomena investigated in the ErUM-IFT project have very different length scales (see figure) but can still be analyzed with the same methodology. The individual resulting applications will not only be exchanged between the subprojects and other ErUM projects, but will also be made freely available to the general public as open-source software. At the same time, Erium GmbH will explore their industrial potential.

The spokesperson of the alliance, PD Dr. Torsten Enßlin, explains “The methodologies for information field theoretical imaging developed in this project should also be transferable to other areas. The requirements for methods in medical imaging or geophysics, for example, have many similarities to those in radio interferometry and microscopy. Therefore, the application of information field theory is not limited to large-scale research facilities, but is already feeding into these fields.”

2.15 200 years-old flare of Sagittarius A* confirmed by X-ray polarization measurements

By Eugene Churazov (scientific staff), Ildar Khabibullin (long-term guest) and Rashid Sunyaev (Emeritus Director)

Thirty years ago, astronomers realized that the X-ray emission from giant molecular clouds might in fact be the reflection of a powerful flare from the supermassive black hole Sagittarius A* at the center of our Milky Way that happened a few hundred years ago. Theory predicts several unique features of such X-ray emission, including a hard spectrum with a bright iron fluorescent line, apparent superluminal motions, and polarization of the continuum. All but polarization had been detected over the past 30 years by many X-ray observatories. X-ray polarization was lagging behind for a good reason – there were no X-ray polarimetric missions sensitive enough to address this problem. Until recently...

Molecular clouds are cold. You do not expect to see X-rays from them. Yet, in the 1990s, the GRANAT and ASCA observatories revealed diffuse, hard X-ray emission that was correlated with the distribution of molecular gas in the central region of our Milky Way. The shape of the X-ray spectrum resembled that of reflected emission in Active Galactic Nuclei (AGN) or X-ray binaries. There, a relatively cold accretion disc is illuminated by the bright central source powered by matter falling onto a black hole. This reflected emission typically consists of a very hard continuum due to Compton scattering and a bright iron fluorescent line – exactly what was seen from the clouds.

However, in our galactic center there is no X-ray source bright enough to power the X-ray emission from the molecular clouds – at least today. Therefore, scientists conjectured that there must have been a bright source in the past, a few hundred years ago. The supermassive black hole at the center of our galaxy, Sagittarius A*, is a prime candidate for such a source. While Sgr A* is currently very dim in X-rays, it might produce a million times more X-rays if it is fed with more gas. Such a flare, lasting even just a few hours, could be sufficient to explain all the clouds' emission observed today.

An immediate consequence of the reflection scenario is the possibility of apparent superluminal motions, where an illuminated spot on the surface of a cloud seems to move faster than the speed of light. Very soon, the Chandra and XMM-Newton observatories detected such apparently superluminal motions.

A further direct prediction is the polarization of the reflected continuum emission even if the illuminating radiation is not polarized. The degree of polarization is sensitive to the scattering angle, while the orientation of the polarization plane is perpendicular to the direction towards the primary source. Therefore, if observed, one can not only provide a final proof of the nature of the molecular clouds' X-ray emission but also verify if the primary emission came from the direction of Sgr A* and determine the age of the flare (as illustrated in Figure 2.18).

It took some 20 years before such polarization observations became possible. Until recently, the only secure polarization measurement was that of the Crab Nebula with the OSO 8 graphite crystal polarimeters made some 45 years ago. IXPE is a new type of imaging polarimeter that relies on the photoelectric effect – tracking the trajectory of photoelectrons in a position-sensitive detector. This new technology provides the necessary great boost in sensitivity to detect faint diffuse emission from the galactic center molecular clouds.

The first IXPE observations of the galactic center region were performed in February and March 2022. Almost simultaneously, the Chandra observatory looked at the same region. Both images (Figure 2.19) show the characteristic re-

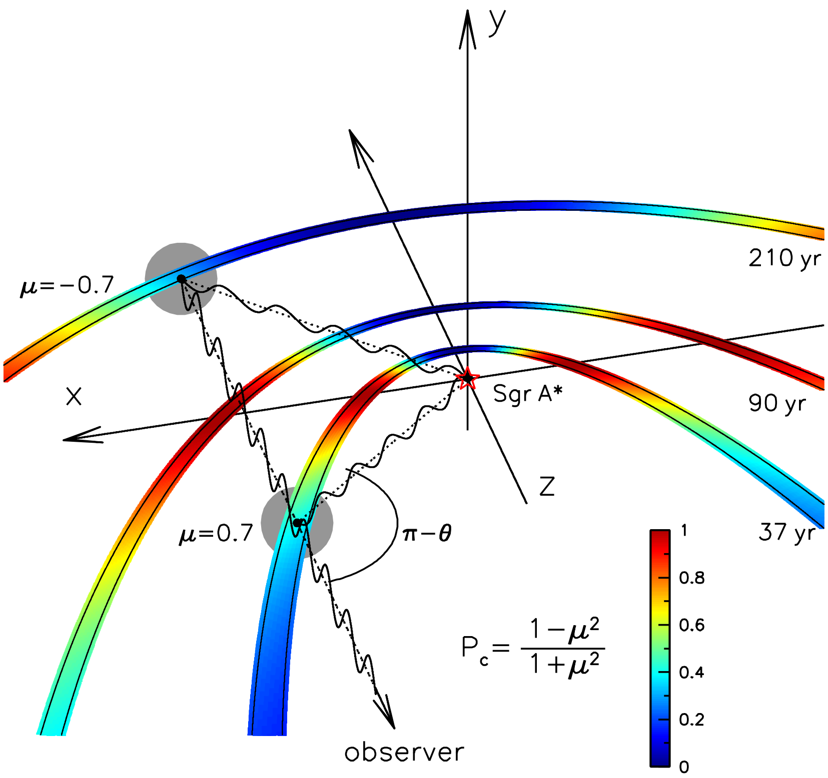


Figure 2.18: Sketch of the geometry, if the polarization signal originates from Sgr A* (centre, marked with a star). X-rays propagate in all directions. At any time after the flare, some of the photons are reflected by a dense gas of individual molecular clouds located near the galactic plane. The reflected emission is polarized according to the value of the scattering angle and the polarization plane is oriented perpendicular to the direction of Sgr A*. The polarization angle indicates the age of the flare, e.g. for the top-most band, we can observe the reflected emission with a delay of 210 years. *(Credit: MPA)*

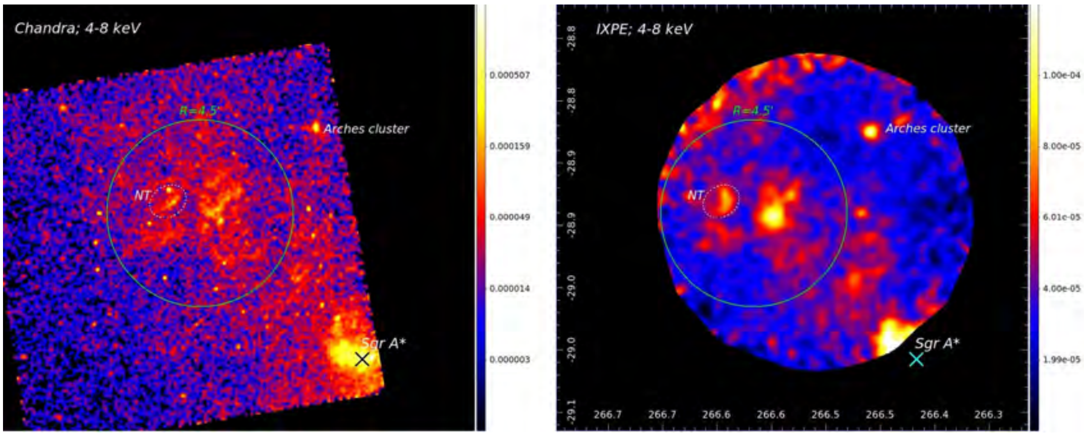


Figure 2.19: Chandra and IXPE X-ray images of the molecular cloud in the vicinity of Sgr A*. The position of Sgr A* is marked with a cross. The big, solid circle highlights the bright diffuse emission, whose spectrum suggests a "reflection" origin. The smaller, dashed ellipse shows the region, which was excluded from the analysis to avoid contamination by a bright non-thermal diffuse source. *(Credit: MPA)*

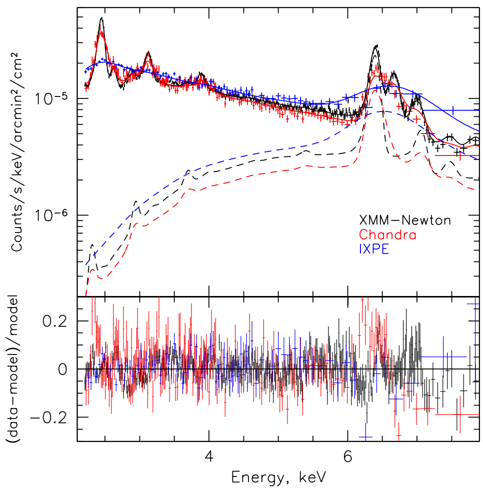


Figure 2.20: Spectrum of the diffuse emission in the galactic center region obtained by IXPE, Chandra, and XMM-Newton. The dashed lines show the contribution of the reflected emission to the total spectrum. *(Credit: MPA)*

flection spectrum. The galactic center environment is complicated and many different components contribute to its X-ray emission. The contribution of the reflected component is relatively modest compared to the total spectrum (see Figure 2.20).

What IXPE adds to previous Chandra and XMM-Newton data? It verifies that this emission is polarized! The analysis of the polarized signal showed that the degree of polarization is $31\pm11\%$. This fixes the scattering angle and therefore the age of the flare: some 200 years ago. At the same time, the polarization direction is consistent with the position of Sgr A* within the uncertainties.

Thus, the IXPE data strengthen the hypothesis that Sgr A* is the primary source powering the reflection from the molecular clouds. This provides a new but long-anticipated "polarized" view on the X-ray-illuminated clouds and a complementary way of studying the energy release of our supermassive black hole in the recent past.

While the current IXPE result is already a remarkable success, many questions remain. Among them: Was it a single flare or multiple flares? Was the primary emission polarized or not? More IXPE observations are already planned that will help finding answers. Moreover, there is the truly exciting possibility that current imaging and future high spectral resolution X-ray missions will reveal the internal structure of the molecular clouds.

About the IXPE mission:

Part of NASA's Small Explorer mission series, IXPE launched on a Falcon 9 rocket from NASA's Kennedy Space Center in Florida in December 2021. The mission is a partnership between NASA and the Italian Space Agency, with partners and science collaborators in 13 countries. Ball Aerospace, headquartered in Broomfield, Colorado, manages spacecraft operations.

2.16 Looking for cracks in the standard cosmological model

By Volker Springel (scientific director)

New computer simulations follow the formation of galaxies and the cosmic large-scale structure with unprecedented statistical precision

An international team of astrophysicists led by researchers from the Max Planck Institute for Astrophysics in Germany, Harvard University in the USA, and Durham University in the UK has presented an ambitious attempt to jointly simulate the formation of galaxies and cosmic large-scale structure throughout staggeringly large swaths of space. Their simulations now also take the ghostly neutrino particles into account and could help to constrain their mass. First results of their "MillenniumTNG" project have just been published in a series of 10 articles in the journal Monthly Notices of the Royal Astronomical Society. The new calculations help to subject the standard cosmological model to precision tests and to unravel the full power of upcoming new cosmological observations.

Over the past decades, cosmologists have gotten used to the perplexing conjecture that the universe's matter content is dominated by enigmatic dark matter and that an even stranger dark energy field acts as some kind of anti-gravity to accelerate the expansion of today's cosmos. Ordinary baryonic matter makes up less than 5% of the cosmic mix, but this source material forms the basis for the stars and planets of galaxies like our own Milky Way. This seemingly strange cosmological model is known under the name LCDM. It provides a stubbornly successful description of a large number of observational data, ranging from the cosmic microwave radiation – the rest-heat left behind by the hot Big Bang – to the "cosmic web", where galaxies are arranged along an intricate network of dark matter filaments. However, the

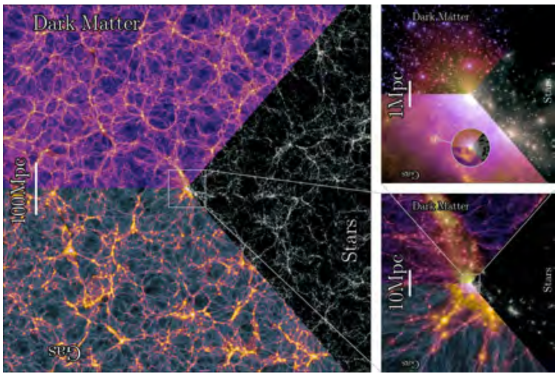


Figure 2.21: Projections of gas (top left), dark matter (top right), and stellar light (bottom center) for a slice in the largest hydrodynamical simulation of MillenniumTNG at the present epoch. The slice is about 35 million light-years thick. The projections show the vast physical scales in the simulation from the full box size, about 2400 million light-years across, to an individual spiral galaxy (final round inset) with a radius of ~150,000 light-years. The underlying calculation is presently the largest high-resolution hydrodynamical simulation of galaxy formation, containing more than 160 billion resolution elements. *(Credit: MPA)*

real physical nature of dark matter and dark energy is still not understood, prompting astrophysicists to search for cracks in the LCDM theory. Identifying tensions with observational data could lead to a better understanding of these fundamental puzzles about our Universe. Sensitive tests are required that need both: powerful new observational data and more detailed predictions for what the LCDM model actually implies.

Scientists at the Max Planck Institute for Astrophysics (MPA), together with an international team of researchers at Harvard University and Durham University, as well as York University in Canada and the Donostia International Physics Center in Spain have now managed to take a decisive step forward on the latter challenge. Building on their previous successes with the "Millennium" and "IllustrisTNG" projects, they developed a new suite of simulation models dubbed "MillenniumTNG", which trace the physics of cosmic structure formation with considerably higher statistical accuracy than was possible with previous calculations.

Large simulations including new physical details

The team utilized the advanced cosmological code GADGET-4, custom-built for this purpose, to compute the largest high-resolution dark matter simulations to date, covering a region nearly 10 billion light-years across. In addition, they employed the moving-mesh hydrodynamical code AREPO to follow the processes of galaxy formation directly throughout volumes still so large that they can be considered representative of the universe as a whole. Comparing the two types of simulations allows a precise assessment of the impact of baryonic processes related to supernova explosions and supermassive black holes on the total matter distribution. An accurate knowledge of this distribution is key for interpreting upcoming observations correctly, such as so-called weak gravitational lensing effects, which respond to matter irrespective of whether it is of dark or baryonic type.

Furthermore, the team included massive neutrinos in their simulations, for the first time in simulations big enough to allow meaningful cosmological mock observations. Previous cosmological simulations had usually omitted them for simplicity, because they make up at most 1-2% of the dark matter mass, and since their nearly relativistic velocities mostly prevent them from clumping together. Now, however, upcoming cosmological surveys (such as those of the recently launched Euclid satellite of the European Space Agency) will reach a precision allowing a detection of the associated percent-level effects. This raises the tantalizing prospect of constraining the neutrino mass itself, a profound open question in particle physics, so the stakes are high.

For the groundbreaking MillenniumTNG simulations, the researchers made efficient use of two extremely powerful supercomputers, the SuperMUC-NG machine at the Leibniz Supercomputing Centre (LRZ) in Garching, and the Cosma8 machine hosted by Durham University on behalf of the UK's DiRAC High-Performance Computing facility. More than 120,000 computer cores toiled away for nearly two months at SuperMUC-NG, using computing time awarded by the German Gauss Centre for Supercomputing (GCS), to produce the most comprehensive hydrodynamical simulation model to date. MillenniumTNG tracks the formation of about one hundred million galaxies in a region of the universe around 2400 million light-years across (see Figure 2.21). This calculation is about 15 times bigger than the previously best is this category, the TNG300 model of the IllustrisTNG project.

Using Cosma8, the team computed an even bigger volume of the universe, filled with more than a trillion dark matter particles and more than 10 billion particles for tracking massive

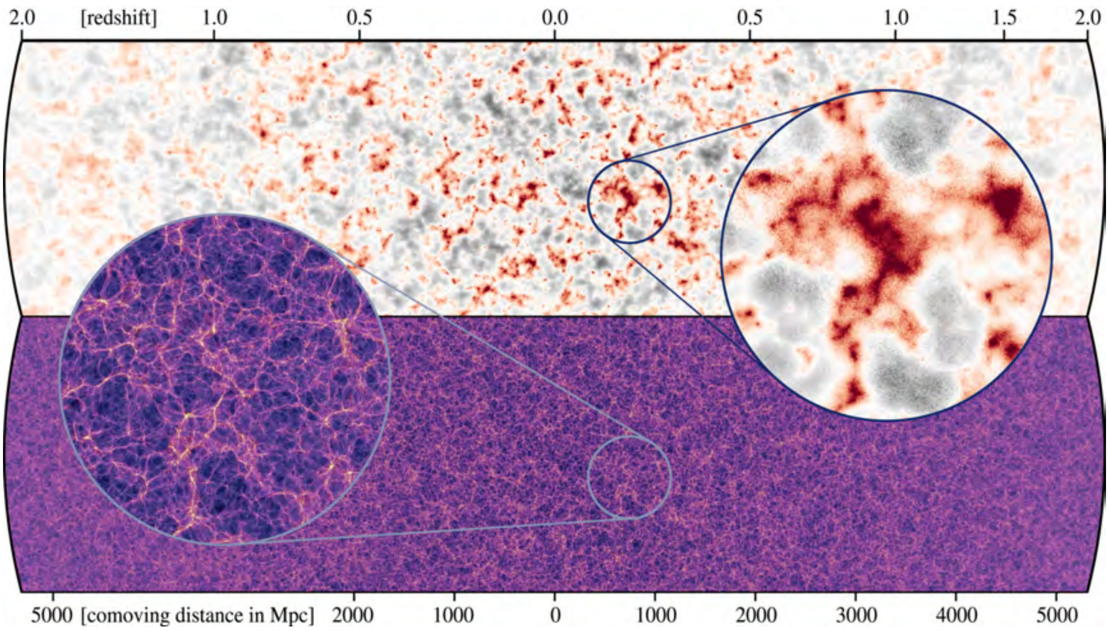


Figure 2.22: Comparison of the neutrino (top) and dark matter (bottom) distributions on the past backwards lightcone of a fiducial observer positioned at the centre of the two horizontal stripes. As cosmic expansion slows down the neutrinos at late times (small redshift/distance), they start to weakly cluster around the biggest concentrations of dark matter as shown by a comparison of the zoomed insets. This slightly increases the mass and further growth rate of these largest structures. *(Credit: MPA)*

neutrinos (See Figure 2.22). Even though this simulation did not follow the baryonic matter directly, its galaxy content can be accurately predicted in MillenniumTNG with a semi-analytic model that is calibrated against the 'full physics' calculation of the project. This procedure leads to a detailed distribution of galaxies and matter in a volume that for the first time is large enough to be representative for the universe as a whole, putting comparisons to upcoming observational surveys on a sound statistical basis.

Theoretical predictions for cosmology

The first results of the MillenniumTNG project show a wealth of new theoretical predictions that reinforce the importance of computer simulations in modern cosmology. The team has written and submitted ten introductory scientific papers for the project. Eight of them have just appeared simultaneously in the journal MNRAS, the remaining two are about to follow shortly. One of the studies had a look at the shapes of galaxies. Nearby galaxies have the subtle tendency to orient their shapes in similar directions instead of pointing randomly, an effect called "intrinsic galaxy alignments". This poorly understood effect distorts inferences based on weak gravitational lensing, which creates its own statistical alignment signal. The MillenniumTNG project could, for the first time, measure intrinsic alignments with very high signal-to-noise directly from the shapes of the simulated galaxies, out to distances of several hundred million light-years. "Perhaps our determination of the intrinsic alignment of galaxy orientations can help to resolve the current discrepancy between the amplitude of matter clustering inferred from weak lensing and from the cosmic microwave background", says PhD-student Ana Maria Delgado,

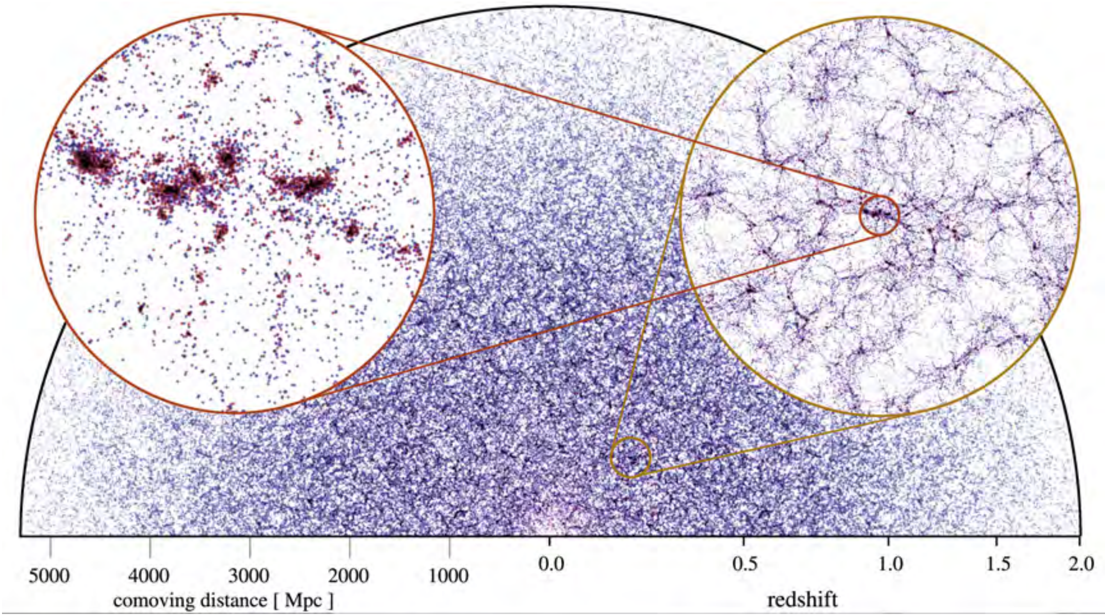


Figure 2.23: Galaxy distribution on the past backwards lightcone in MillenniumTNG, where the galaxies are predicted with a sophisticated semi-analytic model on top of the dark matter backbone. Galaxies are shown down to Johnson apparent magnitude $\mathbf{R} < 23$, in a 180 degrees wide, thin wedge with opening angle 0.24 degrees, out to redshift $z = 2$. The galaxy positions are drawn as circles with comoving coordinates in real space, using red for galaxies with rest frame color index $\mathbf{B} - \mathbf{R} > 0.7$, and blue otherwise. Real observations of the galaxy positions would additionally be perturbed by small shifts along the line of sight due to the Doppler effects from the galaxies' motions, an effect that can also be easily included in the models. The two circular insets show nested zooms with diameters of around 1.25 billion light-years and 125 million light-years, and fainter apparent magnitude limits of $\mathbf{R} < 25$ and $\mathbf{R} < 28$, respectively. *(Credit: MPA)*

first author of this study by the MillenniumTNG team. Using these results, astronomers will be able to correct for this important systematic effect much better.

Another timely result refers to the recent discovery of a population of very massive galaxies in the young universe with the James Webb Space Telescope. The masses of these galaxies are unexpectedly large just a brief time after the Big Bang, seemingly defying theoretical expectations. Dr. Rahul Kannan analyzed the predictions of MillenniumTNG for this early epoch. While the simulations agree with the observations out to redshifts of z=10 (when the universe was less than 500 million years old), he confirmed that, if they hold up, the new results by JWST at even higher redshift will be in conflict with the simulation predictions. "Perhaps star formation is much more efficient shortly after the Big Bang than at later times, or maybe massive stars are formed in higher proportions back then, making these galaxies unusually bright", explains Dr. Kannan.

Other works of the team's initial analysis focus on the clustering signals of galaxies. For example, MPA PhD student Monica Barrera produced extremely large and highly realistic mock catalogues of galaxies on the past backwards "lightcone" of a fiducial observer (see Figure 2.23). In this case, galaxies that are more distant are also automatically younger, reflecting the travel time of the light that is reaching our telescopes. Using these virtual observations, she looked at the so-called baryonic acoustic oscillation (BAO) feature (which provides a cosmologically important standard ruler) in the projected two-point correlation function of galaxies. Her results showed, that measuring these BAOs is a fairly tricky endeavour that can be significantly influenced by so-called cosmic variance effects – even when extremely large volumes are studied in observational surveys. While in simulations one can observe the modelled universe from different vantage points to recover the correct statistical ensemble average, this is unfortunately not readily possible for the real Universe. “The MillenniumTNG simulations are so big and contain so many galaxies, more than 1 billion in the biggest calculation, that it was really hard to study them”, says Monica Barrera. “Analysis scripts that work just fine for smaller simulations tend to take forever for MillenniumTNG.”

Analyzing cosmological data

The flurry of first results from the MillenniumTNG simulations make it clear that they will be of great help to design better strategies for the analysis of upcoming cosmological data. The team’s principal investigator, Prof. Volker Springel from MPA argues that “MillenniumTNG combines recent advances in simulating galaxy formation with the field of cosmic large-scale structure, allowing an improved theoretical modelling of the connection of galaxies to the dark matter backbone of the Universe. This may well prove instrumental for progress on key questions in cosmology, such as how the mass of neutrinos can be best constrained with large-scale structure data.” The MillenniumTNG simulations produced more than 3 Petabytes of simulation data, forming a rich asset for further research that will keep the participating scientists busy for many years to come.

2.17 “Hawking stars” the structure and evolution of stars with a hypothetical primordial black hole inside

By Earl Bellinger (postdoc) and Selma de Mink (scientific director)

In a hypothetical scenario, small, primordial black holes could be captured by newly forming stars. An international team, led by researchers at the Max Planck Institute for Astrophysics, has now modelled the evolution of these so-called “Hawking stars” and found that they can have surprisingly long lifetimes, resembling normal stars in many aspects. Asteroseismology could help to identify such stars, which in turn could test the existence of primordial black holes and their role as a component for dark matter.

Let’s do a scientific exercise: If we assume that a large number of very small black holes where created just after the Big Bang (so-called

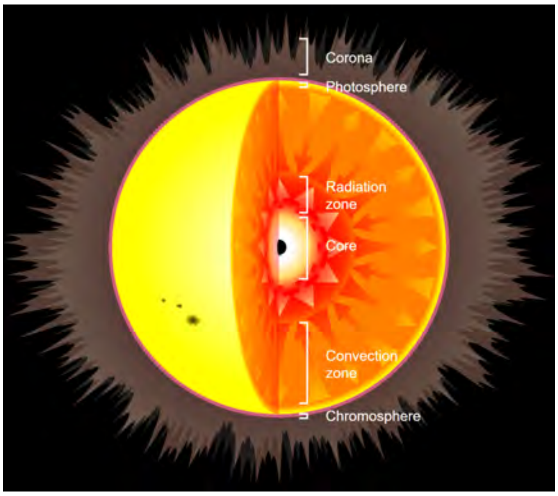


Figure 2.24: Artist’s impression of putting a small black hole at the centre of the Sun in a thought experiment. *(Credit: MPA, background image: Wikimedia/Creative Commons.)*

primordial black holes), some of them might be captured during the formation of new stars. How would this affect the star during its lifetime?

“Scientist sometimes ask crazy questions in order to learn more,” says Selma de Mink, director of the stellar department at the Max Planck Institute for Astrophysics (MPA). “We don’t even know whether such primordial black holes exist, but we can still do an interesting thought experiment.”

Primordial black holes would have formed in the very early Universe with a wide range of masses, from some as small as an asteroid up to thousands of solar masses. They could constitute an important component of dark matter, as well as being the seeds for the supermassive black holes at the centre of present-day galaxies.

With a very small probability, a newly forming star could capture a black hole with the mass of an asteroid or a small moon, which would then occupy the star’s centre. Such a star is called a “Hawking star”, named after Stephen Hawking, who first proposed this idea in a paper in the 1970s. The black hole at the centre of such a Hawking star would grow only slowly, as the infall of gas to feed the black hole is hampered by the outflowing luminosity. An international team of scientists has now modelled the evolution of such a star with various initial masses for the black hole and with different accretions models for the stellar centre. Their astonishing result: when the black hole mass is small, the star is essentially indistinguishable from a normal star.

“Stars harbouring a black hole at their centre can live surprisingly long,” says Earl Patrick Bellinger, MPA Postdoc and now Assistant Professor at Yale University, who led the study. “Our Sun could even have a black hole as massive at the planet Mercury at its centre without us noticing.”

The main difference between such a Hawking star and a normal star would be near the core, which would become convective due to the accretion onto the black hole. It would not alter the properties of the star at its surface and would elude present detection capabilities. However, it could be detectable using the relatively new field of asteroseismology, where astronomers are using acoustic oscillations to probe the interior of a star. Also in their later evolution, in the red giant phase, the black hole might lead to characteristic signatures. With upcoming projects such as PLATO, such objects might be discovered. However, further simulations are needed to determine the implications of putting a black hole into stars of various masses and metallicities.

If primordial black holes were indeed formed soon after the Big Bang, looking for Hawking stars could be one way to find them. “Even though the Sun is used an exercise, there are good reasons to think that Hawking stars would be common in globular clusters and ultra-faint dwarf galaxies,” points out Professor Matt Caplan at Illinois State University, co-author of the study. “This means that Hawking stars could be a tool for testing both the existence of primordial black holes, and their possible role as dark matter.”

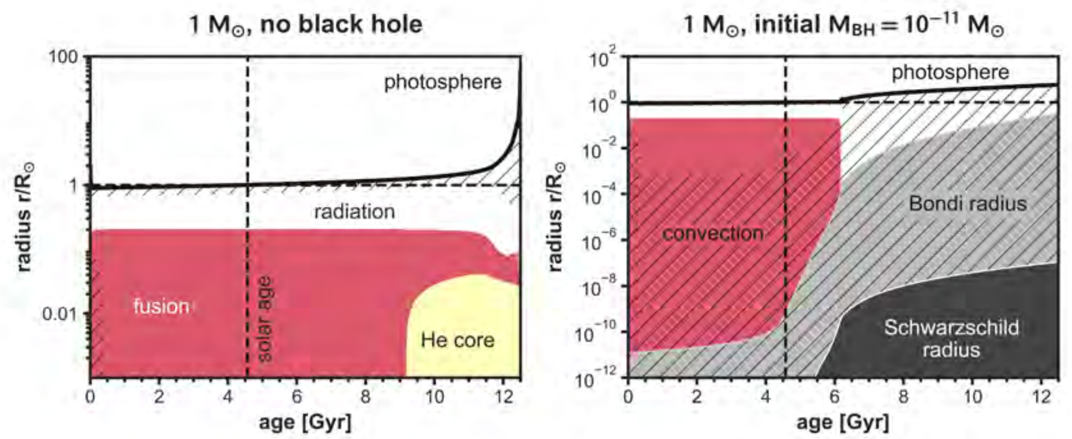


Figure 2.25: These two diagrams show the radial evolution of a star with the mass of the Sun without (left) and with (right) a black hole with an initial mass similar to an asteroid. The black solid line shows the radius of the photosphere, the vertical dashed line the current age of the Sun. The red region shows where hydrogen is converted to helium in nuclear fusion, which provides the bulk of the solar luminosity until the black hole starts to grow noticeably (black region; for lower ages the black hole is too small to be seen in this plot). The black hole drives convection (hatches), which mixes the innermost parts of the star. Note the different scaling of the y-axes. *(Credit: MPA)*

3 Publications, Talks and Committee Work

3.1 Talks and lectures

3.1.1 Invited colloquia and seminar talks

A. Acharya: Nordic Institute for Theoretical Physics (NORDITA), (Stockholm, Sweden, 19.4.)M. Chruslinska: Astrophysics Seminar, Warsaw University Observatory, Warsaw, Poland 05/2023
M. Chruslinska: Gravitation Group Seminar, Labolatoire Astroparticule & Cosmologie, Paris, France (online) 05/2023
M. Chruslinska: Astrophysics Seminar, Geneva Observatory, Switzerland 08/2023
E.Churazov: The University of Alabama in Huntsville (Huntsville, USA, 28.3.)
G. Csoernyei: Astromerique seminar series, University of Montréal (online, Feb 2023)
B. Ciardi: Center for Astroparticle Physics, (Erlangen, Germany, 20.7)
S.E. de Mink, Invited Institute Seminar, Astrophysics department, Hebrew University, Israel, 2023 May 28
S.E. de Mink, Invited Colloquium, Tel Aviv University, Israel, 2023, May 31
S.E. de Mink, Invited Colloquium, Leiden University, The Netherlands, 2023, Nov 9
S.E. de Mink, Rosenblum Lecture (invited), Physics Department of the Hebrew University, Israel
P. Diego-Palazuelos: Copernicus Webinar and Colloquium Series (online, 24.10.2023)
G. Edenhofer: Invited Seminar at Space Telescope Science Institute @ Baltimore, MD, USA
G. Edenhofer: Invited Special Seminar at MIT Haystack @ Westford, MA, USA
T. A. Enßlin: CAS Research Focus "New Foundations for Physics", LMU (Munich, Germany, 5.6.)
T. A. Enßlin: Landessternwarte Tautenburg (Tautenburg, Germany, 17.10.)
T. A. Enßlin: MPI for Radioastronomy (Bonn, Germany, 27.10.)
G. Jin: The European Southern Observatory (Garching, Germany, 02.11.2023)
D. Galárraga-Espinosa: UC Davis (Davis, USA, 20.03.2023)
D. Galárraga-Espinosa: UC Berkeley (Berkeley, USA, 21.03.2023)
A. Genina: Strasbourg Observatory,(Strasbourg, France,08.09.2023)
M. Gilfanov: Institute of High Energy Physics, Beijing, China, 19.07.
M. Gilfanov: Tsinghua University, China, 18.07.
J. González Lobos: The Multiphase Circumgalactic Medium conference,"Characterizing the powering mechanisms of extended Lyman-alpha emission using submm-bright galaxies", Ringberg Castle 28.02.2023 - (contributed talk) M. Gronke: AIP (remote)
M. Gronke: Hamburg Observatory
H.-Thomas Janka: Goethe Universität Frankfurt (Frankfurt, 22.11.)E. Komatsu: Westfälische Wilhelms-Universität Münster (Münster, Germany, 27.1.)
E. Komatsu: Flatiron Institute (New York, USA, 3.2.)
E. Komatsu: Universität Innsbruck (Innsbruck, Austria, 23.5.)

E. Komatsu: Nagoya University (Nagoya, Japan, 16.7.)
E. Komatsu: CERN (Geneva, Switzerland, 13.9.)
Luisa Lucie-Smith: The Oskar Klein Centre, Stockholm, Sweden. Astrophysics Colloquium, invited talk. October 2023.
Luisa Lucie-Smith: Scuola Internazionale Superiore di Studi Avanzati (SISSA), Italy. Astrophysics and Cosmology seminar, invited talk. June 2023.
Luisa Lucie-Smith: University of Vienna. Astrophysics Colloquium, invited talk. March 2023.
Luisa Lucie-Smith: Ludwig Maximilian University of Munich, Germany. Lunch seminar, invited talk. February 2023 T. Naab: Astrophysics colloquium, University of Zurich, December 1st, 2023
R. Pakmor: ”Auriga Superstars”, ICC Durham (8.9.)
R. Pakmor: ”The origin of galactic
magnetic fields”, Cardiff University (18.9.)
R. Pakmor: ”Auriga Superstars”, AIP Potsdam (25.5.)
D. Powell: Cosmology Seminar, Stanford University Stanford, CA, USA
D. Powell: Cosmology and Astronomy Seminar, UC Davis Davis, CA, USA
D. Powell: Seminar, USC Department of Physics and Astronomy Los Angeles, CA, USA
D. Powell: Astronomy Seminar, UC Riverside Riverside, CA, USA
D. Powell: Tuesday Lunch Talk, UCLA Department of Astronomy Los Angeles, CA, USA
D. Powell: Nature of Dark Matter on Small Scales Seminar USA (virtual)
D. Powell: GECO Seminar, Laboratoire d’Astrophysique de Marseille Marseille, France (virtual)
T. Ryu: Department Seminar, the Univeristy of the Balearic Islands, Spain 12/2023
T. Ryu: Astronomy Seminar, the Univeristy of Nova Gorica, Slovenia 11/2023
T. Ryu: Department Colloquium, Kyung Hee University, Korea 11/2023
T. Ryu: Plasma Physics Seminar, Max Planck Institute for Plasma Physics, Germany 11/2023
T. Ryu: Department Colloquium, SNU, Korea 10/2023
T. Ryu: Colloquium, Korea Astronomy & Space Science Institute, Korea 10/2023
T. Ryu: Lagrange Seminar, Lagrange Laboratoire, France 09/2023
T. Ryu: Astronomy Seminar, Max-Planck Institute for Gravitational Physics(AEI), Germany 09/2023
T. Ryu: Special Seminar, New York University, USA 09/2023
T. Ryu: Astronomy Seminar, Columbia, USA 09/2023
T. Ryu: Astronomy Seminar, Stony Brook University, USA 09/2023
T. Ryu: Special Seminar, Northwestern University(CIERA), USA 08/2023
T. Ryu: MPA/Kavli Summer Program Seminar, MPA, Germany 06/2023
T. Ryu: HUJI Astrophysics Seminar, HUJI, Isreal 03/2023
F. Schmidt: Utrecht University (11.10.23)
F. Schmidt: Princeton University (14.11.23)
F. Schmidt: IFAE Barcelona (23.11.23)
S. H. Suyu: Institute of Astronomy, National Central University, (Chungli, Taiwan, 10.3.)
S. Suyu: University of Milan, (Milan, Italy, 11.5.)
S. Suyu: GRAPPA (Gravitation & Astroparticle Physics Amsterdam), University of Amsterdam, (Amsterdam, the Netherlands, 23.10.)
S. Suyu: Munich Physics Colloquium, Ludwig Maximilian University of Munich / Technical University of Munich, (Munich, Germany, 13.11.)
S. Taubenberger: INAF Osservatorio Astronomico di Padova (Padova, Italy, 20.11.)

A. Vigna-Gómez: NBIA Astroparticle Seminar (Copenhagen, Denmark, 04.09)
C. Wang: Department of Physics, Tianjin Normal University, (Tianjin, China, 31.03.2023)
C. Wang: National Astronomical observatories, (Beijing, China, 06.04.2023)
C. Wang: Department of Astronomy, Beijing Normal University, (Beijing, China, 06.04.2023)
C. Wang: Department of Physics, Tsinghua University (Beijing, China, 07.04.2023)
C. Wang: Yunan Astronomical observatories, (Kunming, China, 10.04.2023)
C. Wang: Department of Physics, Anhui Normal University, (Wuhu, China, 04.05.2023)
C. Wang: School of Astronomy and Space Science, Nanjing University (Nanjing, China, 05.05.2023)

3.1.2 Invited Review Talks

A. Basu: GRASCO seminar series, "Decoding Reionization: Unraveling Impacts of Ionizing Sources through Cosmological RT Simulations", (IIT Kharagpur,India, January 2024)
B. Ciardi: HI as a Cosmological Probe across Cosmic Time (Nazareth, Israel, 15.-19.5)
B. Ciardi: Understanding the epoch of cosmic reionization (Sesto, Italy, 6-10.3)
E. Churazov: Science with the Line Emission Mapper: From Planets to Galaxies and Beyond (Cambridge, MA, USA, 28.2-3.3)
E. Churazov: Simons Symposium on Multi-Scale Physics (Schloss Elmau, Germany, 27.8-2.9)
T. A. Enßlin: Debating the Potential of Machine Learing in Astronomical Surveys #2 (Paris/New York, France/USA, 27.11.-1.12.)
T. A. Enßlin: Radio 2023 (Bochum, Germany 14.11.-16.11.)
T. A. Enßlin: "Condensed Complexity" – The Essence of Information Processing and Cognition? (Frankfurt, Germany 8.11.-10.11)
T. A. Enßlin: Sustainability in the Digital Transformation of Basic Research on Universe & Matter (Meinerzhagen, Germany, 30.5.-2.6.)
T. A. Enßlin: EAS 2023 Meeting Special Session 23: Frontier of Interferometric Imaging from Radio to Optical (Krakow, Poland, 14.7.)
T. A. Enßlin: Scientific machine learning for astronomy (Heidelberg, Germany, 14.8.-18.8.)
T. A. Enßlin: 9th International Summer School on AI and Big Data (Dresden, Germany, 3.7.-7.7.)
T. A. Enßlin: VLTI and ALMA Synthesis Imaging (ESO, Garching, Germany, 9.1.-12.1.)
M. Gilfanov: Hot Topics in Modern Cosmology (Cargese, France, 16-22.04)
M. Gilfanov: Detecting Missing Baryons in the Universe (Beijing, China, 20-21.07.)
M. Gilfanov: The Fifth Zeldovich Meeting (Yerevan, Armenia, 12-17.06.)
M. Gilfanov: Cosmology in Miramare (Miramare, Italy, 28.08-2.09.)
H.-Th. Janka: SNvD 2023@LNGS: International Conference on Supernova Neutrino Detection (Gran Sasso, Italy, 29.05.-01.06.)
S. Justham:"Binary effects" invited review, during MIAPbP Program on Interacting Supernovae (delivered 9th February 2023)
E. Komatsu: XXV SIGRAV Conference (Trieste, Italy, 4.-8.9.)
E. Komatsu: The 14th RESCEU International Symposium (Tokyo, Japan, 30.10.-2.11.)
E. Komatsu: 550 years of the Copernican Universe: our place in the Cosmos (Berlin, Germany, 10.11.)
N. Lahén: Two in a million – The interplay between binaries and star clusters, ESO Garching,

Germany (Invited talk) “Star formation and feedback in dwarf galaxies with multiphase ISM and individual stars”
Luisa Lucie-Smith: Excellence Cluster ORIGINS, Garching, Germany. Data Science days, invited overview talk representing research-unit C (cosmology) of Excellence Cluster ORIGINS. January 2023.
Luisa Lucie-Smith: Institut d’Astrophysique de Paris (France)/Flatiron Institute (USA). Invited panelist in a debate at “Debating the potential of machine learning in astronomical surveys” workshop. December 2023.
A. Melo: XVII Latin American Regional IAU Meeting (Montevideo, Uruguay, 27.11.2023-1.12.2023)
T. Naab: New simulations for new problems in galaxy formation, France, December 11-15.2023
T. Naab: Galaxy Formation in Hangzhou, China, October 9-13, 2023
T. Naab: CMG@ND, Ireland, September 4-15.2023
R. Pakmor: “Arepo: Current State and Future Plans”, Arepo ISM Metting (Manchester, UK, 11-15.9)
D. Powell: APEC Seminar at IPMU Kashiwa, Japan
D. Powell: Kashiwa Dark Matter Symposium 2023 Kashiwa, Japan
F. Schmidt: Kosmologietag (Bielefeld, 2.6.23)
F. Schmidt: LSS workshop, FZU Czech Academy of Sciences (Prague, 28.6.23)
F. Schmidt: Novel physics from galaxy clustering, IFP (Trieste, 6.11.23)
S. Suyu: “Cosmology with Strong Lensing”, International Astronomical Union (IAU) Symposium 381: Strong Gravitational Lensing in the Era of Big Data, Otranto, Italy, Jun. 2023
S. Taubenberger: Cosmology on Safari (Hluhluwe, South Africa, 6.3.-10.3.)
S. Vegetti: Origins RU-D science day (Garching, Germany, 19.04)
S. Vegetti: VLBI at 40s (Bologna, Italy, 22.05.-26.05)
S. Vegetti: 17TH international workshop on the dark side of the Universe (Kigali, Rwanda, 10.03-12.03)
S. Vegetti: LeadNet Symposium (Berlin, Germany, 19.09-20.09)
S. Vegetti: Second Workshop on German Science Opportunities for the ngVLA (Leipzig , Germany, 27.10-28.10)
A. Vigna-Gómez: European Astronomical Society (EAS) Annual Meeting (Krakow, Poland, 10.-14.07.)

3.1.3 Invited Conference Talks

M. Chruslinska: Workshop ‘Understanding the massive-star origin of elements’, Heidelberg, Germany 09/2023
S.E. de Mink, Invited plenary talk, Annual Meeting German Astronomical Society (AG), 2023, Sept 15
P. Diego-Palazuelos: Large-scale Parity Violation Workshop “Axion field tomography with the birefringence angles from the epochs of recombination and reionization” (Taipei, Taiwan, 04 - 07.12.2023)
D. Galárraga-Espinosa: Johns Hopkins University (Baltimore, USA, 03.04.2023)
D. Galárraga-Espinosa: Flatiron Institute (New York, USA, 31.03.2023)

D. Galárraga-Espinosa: UCSB (Santa Barbara, USA, 22.02.2023)
M. Guardiani: Bayesian Causal Inference, MIAPP (Differentiable and Probabilistic Programming for Fundamental Physics), 07.23
M. Guardiani: Bayesian Causal Inference, MPA, ErUM Data Workshop on Inverse Problems, (06.12.23))
Luisa Lucie-Smith: Donostia International Physics Center (DIPC), Spain. Invited talk at the Cosmology with the Large Scale Structure of the Universe workshop, May 2023
M. Monelli: Beam Mode workshop, online talk, Stockholm, Sweden, Sep 2023.
M. Monelli: Workshop on Very Light Dark Matter, online talk, Chino, Japan, Mar 2023
M. L. Niemeyer: CGM conference (27. February - 3. March 2023, Ringberg castle): "Lyman-alpha halos around star-forming galaxies in HETDEX"
S. Suyu: "Exploring the Dark Cosmos through Gravitational Lensing and the James Webb Space Telescope", 4th Japanese-American-German Frontiers of Science Symposium, Dresden, Germany, Oct. 2023
S. Suyu: "Timescale of the Universe: The Hubble constant", Timescales in Astrophysics Conference, NYU Abu Dhabi, United Arab Emirates, Jan. 2023
S. Suyu: "Cosmology with Strongly Lensed Supernovae", The 32nd Texas Symposium on Relativistic Astrophysics: Gravitational Lensing, Shanghai, China, Dec. 2023
J. Tan: Global Malaysian Astronomers Convention 2023 (Kuala Lumpur, Malaysia, 15.-18.01.2023)
C. Wang: ESO meeting " Two in a million–The interplay between binaries and star clusters", (Garching, Germany, 11-15.09.2023)
M. Werhahn: The Multiphase Circumgalactic Medium (Ringberg Castle, Germany, February 2023)

3.1.4 Contributed Talks and Posters

A. Acharya: LOFAR Epoch of Reionisation Plenary Meeting, (Ra'anana, Israel, 09.-11.05.2023) - (contributed talk)
A. Acharya:"Reionisation in the Summer", (Heidelberg, Germany, 26.-30.06.2023)- (contributed talk)
A. Acharya: 2023 IAP Colloquium,"New simulations for new problems in galaxy formation", (Paris, France, 11.15.12.2023)- (poster)
S. Almada Monter: Escape of Lyman radiation from galactic labyrinths (Crete, Greece, 18-21 April 2023) - Contributed Talk
S. Almada Monter: Reionisation in the Summer (Heidelberg, Germany, 26-30 June, 2023) - Poster
A. Basu:"ICTS-Big Data Cosmology School", "Constraining Reionization Parameters from 21-cm Observational Data", (Bangalore, India, May 2023) - (contributed talk)
A.Basu:"Reionization in the summer" conference,"Implications of Global Quasar LF Constraints on Helium Reionization", (MPIA, Heidelberg, Germany, June 2023) - (Poster Presentation)
A.Basu:"Shedding new light on the first billion years of the Universe" conference,"Implications of Global Quasar LF Constraints on Helium Reionization", (Marseille, France, July 2023) - (Poster Presentation)
T. Battich: i-process Workshop & School "Exploring i-process inside hot-subdwarf and post-AGB stars", (Limassol, Cyprus, 16.-19.05.2023)- (contributed talk)

T. Battich: MIAPbP Program: Stellar Astrophysics in the era of Gaia, spectroscopic, and asteroseismic surveys“Exploring neutron-capture process inside post-RGB and post-AGB stars”, (Garching, Germany, 7.-25.08.2023)- (contributed talk)
M. Chruslinska: Conference ‘A life devoted to stellar populations’, Tenerife, Spain 10/2023 (contributed talk)
M. Chruslinska: Conference: Gravitational wave populations: what’s next? (GWpopNext’23), Milan, Italy 07/2023 (talk as discussion panel member)
M. Chruslinska: VLT-FLAMES Tarantula Survey (VFTS) collaboration meeting, Garching, Germany 03/2023 (contributed talk)
M. Chruslinska: HERA Workshop ‘Galaxy evolution across cosmic time’, Garching, Germany 02/2023 (contributed talk)
M. Chruslinska: ENGRAVE collaboration Workshop, Garching, Germany 02/2023 (contributed talk)
G. Csoernyei: SuperVirtual 2023, (online, Nov 2023) - (contributed talk)
G. Csoernyei: MIAPP Extragalactic Distance Scale Workshop, (Garching, Jul 2023) - (contributed talk)
G. Csoernyei: IAU Symposium 376 on Period Luminosity Relations, (Budapest, Apr 2023) - (contributed talk + poster)
G. Csoernyei: MIAPP Interacting Supernovae Workshop, (Garching, Feb 2023) (contributed talk)
P. Diego-Palazuelos: International Workshop on Multi-probe approach to wavy dark matters“Measuring isotropic cosmic birefringence with LiteBIRD” (Seoul, Korea, 30.11 - 02.12.2023) - (contributed talk)
G. Edenhofer: KIPAC Tea Talk at Stanford @ remote
G. Edenhofer: Surveying the Milky Way: The Universe in Our Own Backyard @ Pasadena, CA, USA
G. Edenhofer: Annual Meeting of the German Astronomical Society @ Berlin, DE
G. Edenhofer: Interstellar Institute 6 @ Orsay, France
G. Edenhofer: Northeast Star and Planet Formation Meeting @ Cambridge, MA, USA
G. Edenhofer: MIAPbP: Differentiable and probabilistic programming for fundamental physics @ Munich, DE
G. Edenhofer: Enzyme Conference 2023 @ Boulder, CO, USA
F. Ferlito: UniVersum cosmology workshop ”The MillenniumTNG Project: High-resolution weak gravitational lensing convergence maps” (Trento, Italy, 1.-3.02.2023)
F. Ferlito: Large-scale structure and cosmological simulations workshop ”The MillenniumTNG Project: High-resolution weak gravitational lensing convergence maps” (DIPC Donostia, Spain, 15.-18.05.2023)
D. Galárraga-Espinosa: KITP Cosmic Web Workshop (Santa Barbara, USA, 17.02.2023) - (contributed talk)
D. Galárraga-Espinosa: ByoPiC workshop (Porto Vecchio, Corsica, France, 01.05.2023) - (contributed talk)
D. Galárraga-Espinosa: “IX Meeting for Fundamental Cosmology” (Tenerife, Canary Islands, Spain, 22.11.2023) - (contributed talk)
D. Galárraga-Espinosa: “IAP colloquium: New simulations for new problems in galaxy formation” (Paris, France, 13.12.2023) - (contributed talk)
A. Genina: Simons Collaboration on“Learning the Universe” Meeting, (Paris, France, 7.-

10.02.2023)- (contributed talk)
A. Genina: Dynamical Masses of Local Group Galaxies, (Potsdam, Germany, 20.-24.03.2023)- (poster)
M. Gronke: Multiphase solar to ICM (ISSI, Bern)
M. Gronke: ORIGINS Turbulence Day (MPA)
M. Guardiani et al.: ML-IAP 2023,"Towards Automatic Point Source Modeling"- (Paris, France, 27.11.23-1.12.23) - (Poster)
J. Hein: N3AS Summer School,"Multi-dimensional Neutrino Transport", Santa Cruz, USA, July 2023
M. Heinlein: Talk at SFB1258 General Meeting 2023 (2023-07-11, Garching)
G. Jin: LOFAR Family Meeting 2023, (Olsztyn, Poland, 12.-16.06.2023) - (contributed talk)
G. Jin: Resolving Galaxy Ecosystems Across All Scales, (Hong Kong, China, 11.-15.12.2023) - (contributed talk)
G. Jin: The Multiphase Circumgalactic Medium, (Ringberg castle, Germany, 26.02-03.03.2023) - (contributed talk)
N. Lahén: A multiwavelength view on globular clusters near and far: from JWST to the ELT, Sexten, Italy (Contributed talk) "The formation of star clusters in low-metallicity environments"
N. Lahén: 2023 IAP Colloquium: New simulations for new problems in galaxy formation, Paris, France (Contributed talk)"Simulating the formation of globular clusters and their multiple populations in low-metallicity dwarf galaxies" Luisa Lucie-Smith: Instituto de Física Teórica, Madrid, Spain. COSMO'23 conference, talk. September 2023.
Luisa Lucie-Smith: Yukawa Institute for Theoretical Physics, Kyoto University, Japan. Future Science with CMB x LSS conference, talk. April 2023.
J.-Z. Ma: VLT-FLAMES Tarantula Survey Collaboration Meeting, (Garching, Germany, 27.-29.03.2023)- (contributed talk)
J.-Z. Ma: European Astronomical Society (EAS) Annual Meeting, (Krakow, Poland, 10.-14.07.2023)- (contributed talk)
J.-Z. Ma: MIAPbP Workshop"Gaia, Spectroscopy & Asteroseismology", (Garching, Germany, 31.07.-25.08.2023)- (contributed talk)
A. Melo: IAUS 381: STRONG GRAVITATIONAL LENSING IN THE ERA OF BIG DATA (Otranto, Italy, 19 - 23 June 2023) - Poster contribution
A. Melo: MIAPbP 2023, The Extragalactic Distance Scale and Cosmic Expansion in the Era of Large Surveys and the James Webb Telescope (Munchen, Germany, 3 - 28 July 2023) - Talk contribution
I. Millan-Irigoyen:"A life devoted to stellar populations"(Puerto de la Cruz, Spain, 02.10.2023-06.10.2023)(contributed talk)
M. Monelli: Madrid, Spain, COSMO'23 Conference, talk, Sep 2023.
M. Monelli: Workshop on very light Dark Matter, Chino, Japan (online), March 2023
M. Monelli: Beam-mode workshop, Stockholm, Sweden, September 2023
V. Muralidhara:"Time-Ordered Data Simulations for Prime-Cam with TOAST and sotodlib", (Cornell University, Ithaca, USA, 20-23.06.2023) - (Contributed talk) CCAT collaboration Meeting
M. L. Niemeyer: Present and Future of Line Intensity Mapping Workshop (18. - 21. April 2023, MPA):"Lyman-alpha intensity mapping with HETDEX" (contributed talk)
M. L. Niemeyer: Alpine Cosmology Workshop (24.-28. July 2023, Prettau, Italy):"Lyman-alpha intensity mapping with HETDEX" (contributed talk)

R. Pakmor:“Magnetic fields and Cosmic Rays in the CGM”, The Multiphase Circumgalactic Medium (Ringberg 26.2.-3.3.)
D. Powell: Second Workshop on German Science Opportunities for the ngVLA Leipzig, Germany
D. Powell: Strong Gravitational Lensing in the Era of Big Data Otranto, Italy
D. Powell: Dark Matter 2023: From the Smallest to the Largest Scales Santander, Spain
D. Powell: Bologna VLBI: Life begins at 40! Bologna, Italy
D. Powell: UCLA Dark Matter 2023 Los Angeles, CA, USA
A. Rantala: “Two in a million” - The interplay between binaries and star clusters will be held at ESO Garching, Germany, 11-15 September 2023, (contributed poster)
A. Rantala: ”YAGN23”, Istituto di Astrofisica Spaziale e Fisica Cosmica, Palermo, Italy, October 18-20, 2023, (contributed talk)
A. Rantala: ”New Simulations for New Problems in Galaxy Formation”, IAP Paris, December 11-15, (contributed talk)
J. Roth, NRAO Socorro Friday Colloquium, (NRAO, Socorro, New Mexico USA, 25.08.2023)
T. Ryu: Korean Astronomical Society Fall Meeting, KAS, Korea 10/2023
T. Ryu: Two in a Million, ESO, Germany 09/2023
T. Ryu: MODEST23, Northwestern University, USA 08/2023
T. Ryu: European Astronomical Society Annual Meeting, Krakow, Poland 07/2023
T. Ryu: The Black Holes and Gravitational Waves Munich Day, Germany 05/2023
T. Ryu: Aspen Workshop “Extreme Black Holes”, USA 03/2023
T. Ryu: WE Heraeus-EAS Early Career Researchers in Astr. Workshop, Germany 03/2023
J. Stadler: “Imaging the Galactic Center with GRAVITY”, VLTI and ALMA Synthesis Imaging, Workshop, ESO Garching, 11/03/2023
J. Stadler: “Redshift Space Distortions at the Field Level”, MPA Cosmology Seminar, Garching,14/02/2023
J. Stadler: Modeling the Cosmic Large Scale Structure with LEFTfield”, The Road to Differentiable and Probabilistic Programming in Fundamental Physics, Garching, 28/06/2023
J. Stadler: “Field-level cosmology from biased tracers in redshift-space”, New Strategies for extracting cosmology from future surveys, Sexten, Italy, 04/07/2023
J. Stadler: “Field-level cosmology from biased tracers in redshift-space”, Understanding cosmological observations, Benasque, Spain, 31/07/23
S. Suyu: Conference on Probing the Universe at Higher Resolution: A Celebration of the Science and Leadership of Paul T. P. Ho, “Strong Gravitational Lensing: Nature’s Cosmic Telescope to Probe the Universe”, (Academia Sinica Institute of Astronomy & Astrophysics, Taiwan, 30.10-3.11) - (contributed talk)
S. Taubenberger: MIAPbP on“Interacting Supernovae” (Garching, Germany, 6.2.-3.3.), contributed talk
S. Taubenberger: MIAPbP on“The Extragalactic Distance Scale and Cosmic Expansion in the Era of Large Surveys and the James Webb Telescope” (Garching, Germany, 3.7.-28.7.), contributed talk
A. Vani: EAS22: Contributed talk
A. Vigna-Gómez: Kavli Summer Program in Astrophysics 2023, (Garching, Germany, 26.06-04.08) - (contributed talk)
A. Vigna-Gómez: MIAPbP program on “Interacting Supernovae”, (Garching, Germany, 06.02-03.03) - (contributed talk)

A. Vigna-Gómez: 3rd ENGRAVE Collaboration meeting, (Garching, Germany, 06.02-10.02) - (contributed talk)
C. Vogl: Cosmology on Safari 2023, (Hluhluwe, South Africa, 6. – 10.3.2023)- (contributed talk)
C. Vogl: MIAPbP workshop "Interacting Supernovae", (Garching, Deutschland, 6.2. – 3.3.2023)- (contributed talk)
C. Vogl: MIAPbP workshop "The extragalactic distance scale and cosmic expansion in the era of large surveys and the James Webb space telescope" (Garching, Deutschland, 3. – 28.07.2023)- (contributed talk)
M. Werhahn: 2023 IAP Symposium: New simulations for new problems in galaxy formation (Institut d'Astrophysique de Paris (IAP) in Paris, France, December 2023) - contributed talk
M. Werhahn: European astronomical society annual meeting (EAS) 2023 (Krakow, Poland, July 2023) - contributed talk
M. Werhahn: IMAGINE Workshop: Towards a comprehensive model of the galactic magnetic field (Nordita, Stockholm, Sweden, April 2023) - contributed talk

3.1.5 Teaching

T. A. Enßlin, WS 2023, LMU M´unchen
- Information theory (1/3 semester)
- Information field theory (2/3 semester)
T. A. Enßlin: (LMU M´unchen, Garching, 25.9.-29.9.)
- Signal reconstruction with Python, (key qualification course)
T. A. Enßlin: (LMU M´unchen, Garching, 10.10.)
- Artificial Intelligence, Bayes, & Cognition (seminar)
M. Gronke: Astrophysical Gas Dynamics, WS23/24, LMU
J. Grupa with G. Csoernyei, SS 2023, TUM, München, Tutorial for Extragalactic Astrophysics
J. Grupa with S. Huber and I. T. Andika, WS 2023/24, TUM, München, Tutorial for Gravitational Lensing
W. Hillebrandt, WS 2022/2023, TUM, München
- Observational Cosmology
H.-Th. Janka, WS 2022/2023 and SSS 2023, TUM, M´unchen:
- Exploding Stars
- Introduction to Theoretical Astrophysics
H.-Th. Janka: ISAPP 2023: Neutrino physics, astrophysics and cosmology
(Varenna, Italy, 27.06.-06.07.)
H.-Th. Janka: Mainz Physics Academy (Frauenchiemsee, 11.09.-15.09.)
E. Komatsu, MC Specialized Course (1 unit of intensive course, 6.-30.6.), Nagoya University, Nagoya, Japan:- Parity Violation in Cosmology
S. Suyu, WS 2022/2023 and SS2023, TUM, München:
- Experimental Physics 1 in English
- Gravitational Lensing
- Experimental Physics 4 in English
- Extragalactic Astrophysics
- FOPRA Experiment 85: Colour-Magnitude Diagrams of Star Clusters: Determining Their

Relative Ages
Achim Weiss, WS 2022/2023 and SS 2023
- Stellar Structure and Evolution II
- Nucleosynthesis
- Seminar on Stellar Astrophysics

3.1.6 Public Talks

B. Ciardi: Planetario e Museo dell'Astronomia e dello Spazio, Torino, Italy (29.06.2023)
T. A. Enßlin: Pint of Science Talk at Munich Public Observatory (Munich, Germany, 22.5.)
T. A. Enßlin: Talk at Vor und nach dem Urknall (Bad Honnef, Germany, 22.6.-25.6.)
D. Galárraga-Espinosa: IX Escuela Ecuatoriana de Astronomia y Astrofisica, Quito-Ecuador (remote 01.08.2023)
H.-Th. Janka: Olbersgesellschaft, Bremen (24.01.)
H.-Th. Janka: Astronomiefreunde Nordenham (25.01.)
H.-Th. Janka: Deutsches Museum M´unchen (22.02.)
H.-Th. Janka: Volkssternwarte M´unchen (10.03.)
E. Komatsu: Botschaft von Japan in Deutschland (Berlin, Germany, 25.2.)
S. Suyu: Delta Electronics Foundation, Taipei, Taiwan (9.3.)
S. Suyu: Taichung First Senior High School, Taichung, Taiwan (18.3.)
S. Suyu: Gaia STEM Lecture Series, Taiwan [online] (18.11.)

3.2 Community service and outreach

3.2.1 Community service

T. Battich: External postdoc representative at MPA
B. Ciardi: Vice-president of the IAU J2 Organizing Committee
B. Ciardi: Vice-chair of the GLOW Consortium
B. Ciardi: Member of the GLOW Consortium Resource Allocation Committee
B. Ciardi: Member of the GLOW Executive Committee
B. Ciardi: SOC member of the conference LOFAR Family Meeting, Leiden, The Netherlands (2024)
B. Ciardi: SOC member of the conference Cosmic Origins: The First Billion Years, Santa Barbara, USA (2024)
B. Ciardi: SOC member of the GLOW Annual Meeting, Bochum, Germany (2023)
B. Ciardi: SOC member of the conference LOFAR Family Meeting, Olsztyn, Poland (2023)
B. Ciardi: SOC member of the conference Present and Future of Line Intensity Mapping, Garching bei München, Germany (2023)
B. Ciardi: LOC member of the conference Present and Future of Line Intensity Mapping, Garching bei München, Germany (2023)
B. Ciardi: gender equality officer
B. Ciardi: Ombudsperson

B. Ciardi: member of the PhD Thesis Committee panel
B. Ciardi: organizer of the Institute Seminar
B. Ciardi: member of staff and postdoc hiring committees
M. Chruslinska: postdoc representative
M. Chruslinska: local organising committee member, the ENGRAVE Collaboration meeting, Garching, Germany
E. Churazov: Organisation of the MPA Institute Seminar
E. Churazov: IMPRS-related activities
T. A. Enßlin: Editorial Board Member of the Journal for Cosmology and Astroparticle Physics
T. A. Enßlin: Editorial Board Member of the Journal Entropy
T. A. Enßlin: Member of DLR Review Board for "Verbundforschung"
T. A. Enßlin: Member of BMBF Review Board for "Verbundforschung"
T. A. Enßlin: Member of SOC: Debating the Potential of Machine Learing in Astronomical Surveys #2, (Paris/New York, France/USA, 27.11.-1.12.)
T. A. Enßlin: Head of SOC: ErUM-Data Workshop on Inverse Problems (Garching, Germany, 5.12.-6.12.)
T. A. Enßlin: Member of SOC: The Road Differentiable and Probabilistic Programming in Fundamental Physics (Garching, Germany 26.6.-28.6.)
T. A. Enßlin: Member of SOC: Differentiable and Probabilistic Programming for Fundamental Physics (Garching, Germany, 5.6.-30.6.)
T. A. Enßlin: Member of SOC: Towards a Comprehensive Model of the Galactic Magnetic Field (Stockholm, Sweden, 3.4.-28.4.)
T. A. Enßlin: Member of SOC: RESOLVE workshop (Bonn, Germany, 24.10.-27.10.)
F. Ferlito: IMPRS PhD student representative (contributed in the organisation of various events, including Monthly collaboration meetings for IMPRS students, yoga courses, joint IMPRS Munich-Heidelberg workshop, and social dinners)
R. Glas: Offered planetarium shows to a group of approx 25 visitors in April and October 2023
J. González Lobos: IMPRS student representative (November 2020 - 2024)
J. González Lobos: Member of Local Organizing Committee, The Multiphase Circumgalactic Medium conference, 26 February - 3 March, 2023
J. Hein: SESTAS organizing commitee
H.-Th. Janka: Advisory Panel of "Sterne und Weltraum"
H.-Th. Janka: Editorial Board of the "Journal of Cosmology and Astroparticle Physics (JCAP)"
G. Jin: Organisation of the 15th IMPRS Symposium - 05.06.2023
E. Komatsu: Perspektivenkommission of the Max Planck Society
E. Komatsu: Chair of the Munich Joint Astronomy Colloquium
E. Komatsu: PhD Supervisory Panel
E. Komatsu: External Evaluation Committee, National Astronomical Observatory of Japan
E. Komatsu: Selection Committee for the Shaw Prize
E. Komatsu: ArXiv Scientific Advisory Board
D. Kresse: Active member of MPA's planetarium group
T. Naab: Scientific head of the IT department
T. Naab: MPA representative in the library board
T. Naab: MPA contact person for MPCDF
V. Muralidhara: Internal PhD representative

V. Muralidhara: External PhDnet representative
A. Weiss: SOC member of “Unveiling the interiors of stars to grasp stellar populations” (2024)
J. Stadler: New Strategies for Extracting Cosmology from Future Galaxy Surveys”, 07/23 Sesto
J. Stadler: “Black Hole and Gravitational Wave Day”, 12/05/23, Garching
J. Stadler: “Munich Dark Matter Meeting”
S. Suyu: one of the coordinators of the MIAPbP workshop on “The Extragalactic Distance Scale and Cosmic Expansion in the Era of Large Surveys and the James Webb Space Telescope” in July 2023
S. Suyu: co-organised TUM Physics Day of Diversity in November 2023
S. Suyu: serving on various thesis committees
S. Vegetti: MPA fellowship selection
S. Vegetti: Origins RUD coordinator
S. Vegetti: JAC committee
C. Vogl: organiser of the MPA/MPE/ESO supernova meeting
C. Vogl: Google Summer of Code mentor for the TARDIS RT Collaboration

3.2.2 Outreach Activities

A. Acharya: offered a remote lecture to the undergraduate student astronomy club “Taraansh Astronomy Club” of Yeshwantrao Chavan College of Engineering, Nagpur, India on “Machine Learning in Astrophysics” in February 2023.
D. Galárraga-Espinosa: talked to high school students of Lycee La Condamine in Quito-Ecuador to motivate the study of science (09.01.2023)
D. Galárraga-Espinosa: co-organised and spoke at Women in Science Ecuador, an event gathering 1000+ students of age 10-16 from Ecuadorian public schools (15.03.2023)
M. Gronke: Guide the visit of the Swiss consulate (MPA)
J. Hein: 7 Planetarium presentations March, April, November,
J. Hein: Girls’ Day organization and plantarium presentation
V. Muralidhara: Set up an activity for Girls’ Day at MPA in 2023 along with Laura Herold. The activity was related to the Hubble diagram and the expansion of the Universe.
M. L. Niemeyer: Planetarium shows: April 27 (Girls’ day), May 11, November 23
J. Stadler: Girls’ Day organization
T. Ryu: Girls’ day, MPA 04/2023: Preparation and execution of one of the five sessions where a group of high-school female students complete a given scientific task.
T. Ryu: SEDS Celestia, BITS Pilani 01/2023: Invited public lecture about black hole and tidal disruption event
H. Spruit: “Geschichte der Astrophysik 1800-jetzt” Rotary club Hanau-Maintal, 28 November 2023 (by Zoom)
S. Suyu: filmed in BBC Studios documentary on “Science’s Greatest Mysteries”, in the episode on The Age of the Universe (released in 2023)
S. Taubenberger: tour guide for the ESO Supernova exhibition
A. Vani: Talk on recent developments in astronomy for 60 students in 10th grade in India (August 23)
M. Werhahn: offered a station at the Girl’s Day in April 2023

3.3 Publications in 2023

A. V. Meshcheryakov, G. A. Khorunzhev, S. A. Voskresenskaya, ..., M. R. Gilfanov, and R. A. Sunyaev, "SRGz: Classification of eROSITA Point X-ray Sources in the 1%DESI Region and Calibration of Photometric Redshifts,"Astronomy Letters-A Journal of Astronomy and Space Astrophysics 49 (11), 646-661 (2023).

G. S. Uskov, S. Y. Sazonov, M. R. Gilfanov, I. Y. Lapshov, and R. A. Sunyaev, "X-ray Properties of the Luminous Quasar PG 1634+706 at z=1.337 from SRG and XMM-Newton Data,"Astronomy Letters-A Journal of Astronomy and Space Astrophysics 49 (11), 621-638 (2023).

I. Kostyuk, R. Lilow, and M. Bartelmann, "Baryon-photon interactions in Resummed Kinetic Field Theory,"Journal of Cosmology and Astroparticle Physics 2023 (9), 032 (2023).

I. Kostyuk, D. Nelson, B. Ciardi, M. Glatzle, and A. Pillepich, "Ionizing photon production and escape fractions during cosmic reionization in the TNG50 simulation,"Monthly Notices of the Royal Astronomical Society 521 (2), 3077-3097 (2023).

E. Gatuzz, A. G. Javier, E. Churazov, and T. R. Kallman, "Searching for the warm-hot intergalactic medium using XMM–Newton high-resolution X-ray spectra,"Monthly Notices of the Royal Astronomical Society 521 (2), 3098-3107 (2023).

J. R. Eskilt, L. Herold, E. Komatsu, K. Murai, T. Namikawa et al., "Constraints on Early Dark Energy from Isotropic Cosmic Birefringence,"Physical Review Letters 131 (12), 121001 (2023).

P. Arévalo, P. Lira, P. Sánchez-Sáez, P. Patel, ..., E. Churazov et al., "Optical variability in quasars: scalings with black hole mass and Eddington ratio depend on the observed timescales,"Monthly Notices of the Royal Astronomical Society 526 (4), 6078-6087 (2023).

D. Chattopadhyay, J. Stegmann, F. Antonini, J. Barber, and I. M. Romero-Shaw, "Double black hole mergers in nuclear star clusters: eccentricities, spins, masses, and the growth of massive seeds,"Monthly Notices of the Royal Astronomical Society 526 (4), 4908-4928 (2023).

J. Borrow, R. Kannan, ..., A. Smith, R. Pakmor, V. Springel et al., "THESAN-HR: how does reionization impact early galaxy evolution?,"Monthly Notices of the Royal Astronomical Society 525 (4), 5932-5950 (2023).

D. D. Hendriks, L. A. C. van Son, M. Renzo, R. G. Izzard, and R. Farmer, "Pulsational pair-instability supernovae in gravitational-wave and electromagnetic transients,"Monthly Notices of the Royal Astronomical Society 526 (3), 4130-4147 (2023).

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S. Kamann, S. Saracino, N. Bastian, S. Gossage, ..., S. E. de Mink et al., “The effects of stellar rotation along the main sequence of the 100-Myr-old massive cluster NGC 1850,”Monthly Notices of the Royal Astronomical Society 518 (1), 1505-1521 (2023).

M. Valentini, K. Dolag, S. Borgani, G. Murante, U. Maio et al., “Impact of H2-driven star formation and stellar feedback from low-enrichment environments on the formation of spiral galaxies,”Monthly Notices of the Royal Astronomical Society 518 (1), 1128-1147 (2023).

E. K. Lofthouse, M. Fumagalli, M. Fossati, R. Dutta, M. Galbiati et al., “MUSE Analysis of Gas around Galaxies (MAGG) – IV. The gaseous environment of $z \sim 3$-4 Lyα emitting galaxies,”Monthly Notices of the Royal Astronomical Society 518 (1), 305-331 (2023).

N. Sridhar, L. Sironi, and A. M. Beloborodov, “Comptonization by reconnection plasmoids in black hole coronae II: Electron-ion plasma,”Monthly Notices of the Royal Astronomical Society 518 (1), 1301-1315 (2023).

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4 Personnel

4.1 Scientific staff members

Directors

Selma de Mink, Guinevere Kauffmann, Eiichiro Komatsu (Managing Director since 01.01.2023), Volker Springel

Research Group Leaders/W2 Staff

Fabrizio Arrigoni-Battaia, Eugene Churazov, Benedetta Ciardi, Torsten Enßlin, Marat Gilfanov, Max Grönke, Hans-Thomas Janka, Stephen Justham, Thorsten Naab, Rüdiger Pakmor, Fabian Schmidt, Mahdieh Schmidt (Scientific Coordinator), Sherry Suyu (Max Planck Fellow and Associate Professor at Technical University of Munich; TUM), Simona Vegetti, Achim Weiss.

External Scientific Members

Rolf-Peter Kudritzki, Werner Tscharnuter.

Emeriti

Wolfgang Hillebrandt, Friedrich Meyer, Rashid Sunyaev, Simon White.

Associated Scientists:

Gerhard Börner, Geerd Diercksen, Wolfgang Krämer, Emmi Meyer–Hofmeister, Ewald Müller, Hans Ritter, Henk Spruit.

Postdocs

Tiara Battich, Eirini Batziou (since 01.10.2023), Earl Bellinger (until 31.08.2023), Linda Blot (until 30.09.2023), Deepika Bollimpalli (until 30.09.2023), Jan Burger, Paolo Campeti (until 31.10.2023), Raoul Ca*ñ*ameras (until 16.06.2023), Seok-Jun Chang, Martyna Chruslinska, Tiago Costa (until 30.09.2023), Sten Delos (until 14.09.2023), Patricia Diego Palazuelos (since 01.10.2023), Ryan Farber (until 31.10.2023), Robert Farmer (until 31.08.2023), Konstantina Maria Fotopoulou (until (until 30.04.2023), Philipp Frank, Daniela Galarraga-Espinosa, Enrico Garaldi, Anna Genina, Robert Glas, Cesar Hernandez-Aguayo, Andrew Jamieson, Cole johnston (since 01.11.2023), Laura Herold (until 15.10.2023), Simon Huber, Liliya Imasheva (until 31.07.2023), Valeriya Korol, Andrija Kostic (until 31.10.2023), Alexandra Kozyreva (until 28.02.2023), Ivan Kostyuk (since 01.06.2023), Daniel Kresse (until 31.12.2024) Toshiki Kurita (since 01.10.2023), Natalia Lahen, Qi Li, Luisa Lucie-Smith, Alejandra Melo Melo, Iker Millan Irigoyen, Aleksandra Olejak (since 01.10.2023), Conor O'Riordan, Bo Peng (since 01.10.2023), Devon Powell, Holly Preece (until 30.09.2023), Antti Rantala, Martin Reinecke, Taeho Ryu, Adam Schaefer (until 30.09.2023), Matthew Smith (since 01.10.2023), Hannah Stacey (until 31.08.2023), Jakob Stegmann (since 01.09.2023), Rosemary Talbot, Stefan Taubenberger, Alejandro Vigna-Gomez, Christian Vogl, Chen Wang, Maria Werhahn, Oliver Zier (until 30.09.2023)

Ph.D. Students

Anshuman Acharya, Silvia Almada Monter, Shaghaiehj Azyzy (since 01.10.2023), Ivana Babic, Arghyadeep Basu, Monica Barrera, Eirini Batziou (until 31.07.2023), Aniket Bhagwat, Teresa Braun, Vittoria Brugaletta (until 31.12.2023), Sergei Bykov, Benedetta Casavecchia, Safak Celik (since 01.07.2023), Miha Cernetic, Geza Csoernyei, Hitesh Kishore Das, Vincent Eberle, Gordian Edenhofer, Sebastian Ertl, Jakob Ehring, Fulvio Ferlito, Konstantina Maria Fotopoulou (until 31.12.2022), J. Gonzalez Lobos, Alexandra Grudskaia, Jana Grupa, Matteo Guardiani, Johannes Harth-Kitzerow (until 31.12.2023), Jakob Hein, Malte Heinlein, Laura Herold (until 31.05.2023), Eileen Herwig, Gaoxiang Jin, Gaoxiang Jin (since 01.09.2022), Vishal Johnson (since 17.04.2023), Andrija Kostic (until 31.07.2023), Ivan Kostyuk (until 31.05.2024), Daniel Kresse (until 30.06.2023), Jing-Ze Ma, Alexander Mayer, Marta Monelli, Marija Minzburg, Jeongin Moon (since 01.04.2023), Nahir Munoz Elgueta (until 30.09.2023), Vyoma Muralidhara, Simon Ndiritu (until 31.10.2023), Ivana Nikolac (since 04.09.2023), Christian Partmann, Shubham Raghuvanshi (since 05.06.2023), Abinaya Swaruba Rajamuthukumar, Katlego Ramalatswa, Bryce Remple, Johannes Maximilian Ringler, Jakob Roth, Julian Rustig (until 28.02.2023), Maryam Tajalli (since 31.01.2026), Lazaros Souvaitzis, Joanne Tan, Beatriz Tucci-Schiewaldt, Ruggero Valli, Akash Vani (since 01.09.2023), Pavan Vynantheya, Han Wang, Margret Westerkamp, Hanieh Zandinejad

Master students

Anisha Anisha , Mohammadreza Ashari, Nikolis Charalampos, Manik Dawar, Alina Fantauzzi, Sebastian Gil Rodriguez, Sylvia Hofs, Mrinal Jetti, Elias Mamuzic, Tapan Mayukh, Anton Noebauer, Martin Reiss, Jakob Roth, Igor Rzhin, Iason Saganas, Moritz Singhartinger, Philipp Straub, Kristian Tchiorny, Qiang Wang,

Andreas Popp 17.2–31.5, Sebastian Gil Rodriguez (LMU) 1.2–30.6, Manik Dawar (LMU) 1.2.23–31.1.24, Aymeric Galan (TUM) 1.3.23–28.2.25, Satadru Bag (TUM) 1.3.23–28.2.25, Fabian Sigler (LMU) 16.2.23–15.2.24, Benedikt Seidl (LMU) 11.4–31.7, Martin Reiss 17.4.23 - 16.4.24, Mohammadmahdi Movahedi-Najafabadi (LMU) 1.12–29.2,

Technical staff

Computational Support: Heinz-Ado Arnolds (IT management), Andreas Breitfeld, Goran Toth, Andreas Weiss, Gerhardt Werner Grek (since 30.09.2023)
Public relation: Hannelore Hämmerle (MPA and MPE)
Secretaries: Sonja Gründl, Maria Depner (until 30.04.2023), Gabriele Kratschmann, Cornelia Rickl (until 31.01.2023), Isabel Thapa, Marina Pantze (until 31.08.2023) *Library:* Mirna Balicevic, Christiane Bartels (library management), Elisabeth Blank (until 31.10.2023).

4.2 Staff News/Awards

Laura Herold received the 2023 Rudolf Kippenhahn Award for her groundbreaking paper titled "New Constraint on Early Dark Energy from Planck and BOSS data using the Profile Likelihood".

Maria Werhahn has been awarded the Carl Ramsauer Prize by the Physikalische Gesellschaft zu Berlin for her doctoral thesis "Simulating Galaxy Evolution with Cosmic Rays: The Multi-Frequency View".

Volker Springel has been elected the Vice President of the German Astronomical Society.

D. Galárraga-Espinosa has been awarded the Camille Flammarion Prize from the French SF2A and SAF, for the excellence and societal impact of her science outreach projects.

4.3 PhD and Master Theses 2023

4.3.1 Master Theses 2023

Aniruddh Herle: Selection functions of strong lens finding neural networks. Ludwig-Maximilians-Universität München

Alina Fantauzzi: Socio-Physical Simulations of Reputation Dynamics. Ludwig-Maximilians-Universität München

Philipp Straub: Post-Newtonian and Three-Body Effects on the Orbits of Galactic Centre Stars. Ludwig-Maximilians-Universität München

4.3.2 PhD Theses 2023

Daniel Kresse: Towards Energy Saturation in Three-dimensional Simulations of Core-collapse Supernova Explosions. Technische Universität München

Oliver Zier: Taming Rotationally Supported Disks Using State of the Art Numerical Methods. Ludwig-Maximilians-Universität München

Ivan Kostyuk: Investigating Lyman Continuum Escape Fractions of High Redshift Galaxies During the Era of Reionization. Ludwig-Maximilians-Universität München

Laura Herold: Resolving the Hubble Tension with Early Dark Energy, Ludwig-Maximilians-Universität München

Andrija Kostic: Forward Modelling the Large-scale Structure: from the Effective Field Theory to Dark Matter Constraints and Future Survey Optimization. Ludwig-Maximilians-Universität

München

Eirini Batziou: Neutron Star Formation in Accretion-Induced Collapse of White Dwarfs. Technische Universität München

Nahir Muñoz-Elgueta : Multi-Phase Gas Reservoirs in and Around High-z Galaxies. Ludwig-Maximilians-Universitär München

Jakob Ehring: Fast Neutrino Flavor Conversions in Core-Collapse Supernova Simulations. Technische Universität München

Jianhang Chen: Distant, dusty star-forming galaxies. Ludwig-Maximilians-Universitär München

Miha Cernetic: High-Order Discontinuous Galerkin Hydrodynamics for Supersonic Astrophysical Turbulence. Ludwig-Maximilians-Universitär München

4.4 Visiting scientists in 2023

Long-term visitors (longer than 2 weeks)

Marcelo Miller-Bertolami (National University of La Plata, Argentina) 22.04–09.05, Andrea Chiavassa (Observatoire de la Côte d'Azur, France) 17.04–12.05, Silvia Bonoli (Donostia International Physics Center, Spain) [2-month visit, split between May and July, Humboldt], Antonela Monachesi and Facundo Gomez (University of La Serena, Chile) 25.06–15.07, George Efstathiou (University of Cambridge, UK) 03.07–21.07, Saleem Zaroubi (University of Groningen, Netherlands) [6-month visit in September, Humboldt], Isabel Baraffe (University of Exeter, UK) 20.11–15.12, Giles Chabrier (Ecole Normale Supérieure de Lyon, France) 20.11–15.12, Paul Ricker (sabbatical, University of Illinois Urbana-Champaign, USA) 1.09–30.11, Alessandro Greco (Università degli Studi di Padova, Italy) 23.01– 18.06, Beatrice Giudici (University of Valencia, Spain) 1.04–30.06, Claude Cournoyer-Cloutier (McMaster University, Canada) 1.04–31.07, Atal Agrawal (DAAD scholarship from Indian Institute of Technology Roorkee, India) 31.5–31.7, Aura Obreja (Heidelberg University, Germany) 15.11–31.12, Ivan Cabrera Ziri (Heidelberg University, Germany) 22.11–31.12, Natalya Lyskova (Space Research Institute of Russian Academy of Sciences, Russia) 3.11–29.11, Jenny Gonzalez (Pontificia Universidad Católica de Chile, Chile) 30.10.23–30.11, Franklin Bolivar Aldas (Observatorio Astronómico de Quito, Ecuador) 19.6.–20.11, Andrei Beloborodov (Columbia University, USA) 3.10.23–15.1.24, Jiamin Hou (MPE and University of Florida, USA) 24.05–20.07, Patricia Tissera (Pontificia Universidad Católica de Chile, Chile) 10.07–28.07, Ken Osato (Chiba University, Japan) [mid August - end September], Paolo Mazzali (Liverpool John Moores University, UK) 30.7–30.9., Elena Pian (INAF OAS, Bologna, Italy) 30.07–30.9., Paula Lopez (National University of La Plata, Argentina) 9.07–23.09, Marco Marinucci (Technion institute of Haifa, Israel), Analkar Dutta (Indian Institute of Science, India) 8.01–11.02.

External speakers and students of Kavli Summer Program In Astrophysics 2023 at MPA:

Felix Ahlborn (Heidelberg Institute for Theoretical Studies (HITS), Germany) 25.06–05.08, Oliva Andre (Observatory of Geneva, Switzerland) 31.07–05.08, Carles Badenes (University of Pittsburgh, USA) 25.06–28.07, Brandon Barker (Michigan State University, USA) 24.06–05.08, Evan Bauer (Harvard University, USA) 29.06–22.07, Aakash Bhat (University of Potsdam, Germany) 25.06–05.08, Ilaria Caiazzo (California Institute of Technology, USA)25.06–22.07, Diego Calderon (University of Hamburg, Germany) 23.07–05.08, Mami Deka (Cotton University India, India) 25.06–06.08., Marcus DuPont (New York University, USA) 25.06–05.08, James Fuller (California Institute of Technology, USA) 24.06–05.07, Ylva Goetberg (Carnegie Observatories, USA) regular visits from 25.06–05.08, Aldana Grichener (Technion, Israel) 22.06–05.08, Alex Heger (Monash University, Australia) 17.07–28.07, Cole Johnston (Radboud University, Netherlands) two stays during 25.06–03.08, Breivik Katelyn (North Western University, USA) 01.07–06.07, Fragkos Anastasios (University of Geneva, Switzerland) 04.07–07.07, Kerzendorf Wolfgang (Michigan State University, USA) 26.6–30.06, Sills Alison (McMaster University, Canada) 08.07–15.07, Walch-Gassner Steffi (University of Colgne, Germany) 03.07–14.07, Juma Kamulali (Makerere University, Uganda) 02.07–23.07, Camille Landri (Charles University Czech Republic) 25.6–05.08, Norbert Langer (Argelander Institute for Astronomy Bonn, Germany) 22.7–05.08, Linhao Ma (California Institute of Technology, USA) 22.6–25.08, Shazrene Mohamed (University of Miami in Florida (now at University of Virginia), USA) 25.6–17.07, Facundo David Moyano (University of Geneva, Switzerland) 25.06–19.08, Kaila Nathaniel (University of Bonn, Germany) 25.06–05.08, Aleksandra Olejak (Polish Academy of Sciences, Poland) 23.7–10.08, Rachel Patton (Ohio State University, USA) 25.06–05.08, Mathieu Renzo (Center for Computational Astrophysics, Flatiron Institute, USA) five weeks during 25.06–04.08, Paul Ricker (University of Illinois, USA) 25.06–05.08, Jakob Stegmann (Cardiff University, UK) 3 weeks during 27.06–05.08, Jorge Stipetich Cuadra (Pontificia Universidad Católica de Chile, Chile) 01.07–27.07, Christopher Tiede (Niels Bohr Institute, Denmark) 25.06–05.08, Santiago Torres (University of California Los Angeles, USA) 23.06–05.08, Alessandro Alberto Trani (Niels Bohr Institute, Denmark) four weeks during 25.06–29.07, Lieke Van Son (Flatiron Institute, USA) 06.07–07.07, Ashlin Varghese (Newcastle University, UK) 25.06–06.08, Tom Wagg (University of Washington, USA) 25.06–05.08, Xing Zepei (University of Geneva, Switzerland)