Max-Planck-Institut
für
Astrophysik

ANNUAL REPORT 2024

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 2024.

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, and physical and early universe cosmology. 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).

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, Thorsten Naab, 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 inhouse needs both by providing extensive inhouse 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 workingenvironment experienced by the users. Scientists at MPA are also very successful at obtaining additional supercomputing time, in 2023/2024 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, three such Linux-clusters are located at MPCDF. Freya, has 5120 processor cores – supported by 16 Pascal, 8 Volta, and 40 Ampere GPUs – together with almost 29 Terrabyte (TB) of core memory and $\sim$4.5 PB disk storage capacity. The larger Orion cluster has 11872 processor cores and about 52 TB of core memory. Freya and Orion are 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, Millenium TNG) and provides web access for the world-wide community to a subset of this data, for example via the Millennium database. This system consists of 7.1 PB disk storage and a fat-node server with 48 cores and 2 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 3200 cores and about 20$\sim$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, one of whom is 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 Astrobibliothek is the joint library for MPE and MPA. At present it holds a unique collection of about 54000 books and journals, about 7300 reports and observatory publications, as well as print subscriptions to 70 printed and around 500 electronic scientific journals. In addition it maintains an archive of MPA and MPE publications, two slide collections (one for MPA and one for the MPE), a collection of approximately 800 nonprint media, and store copies of the Palomar Observatory Sky Survey (on photographic prints) and of the ESO/SERC Sky Survey (on film). The library catalogue includes books, conference proceedings, periodicals, and theses, in print and online as well. The library is run by two people who share the tasks as follows: Ms. Bartels (head librarian) and Ms. Balicevic (journal and publication management for both institutes).

1.3 The year 2024 at the MPA

1.3.1 Biermann Lectures

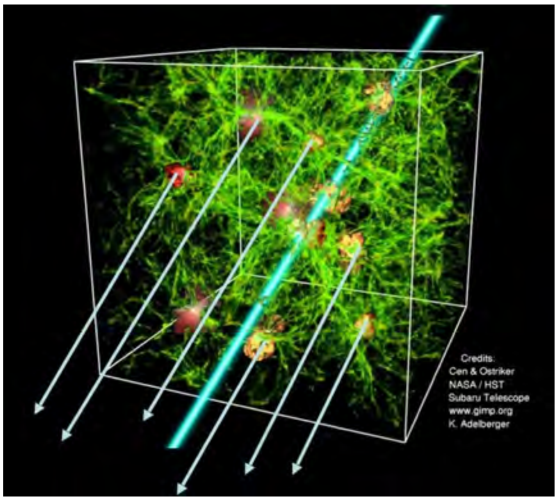
History

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 2024

Galaxies and Intergalactic Matter at Cosmic “Late Morning”

Several hundred million years after the Big Bang, the Universe had cooled sufficiently to allow stars to form within the first galaxies. As the universe continued to expand while galaxy growth proceeded rapidly, eventually the net radiation produced by young stars was sufficient to ionize nearly all of the hydrogen outside of galaxies – a landmark called “reionization”. The subsequent period of time – when the Universe was between 1 and 3 billion years old – witnessed the most intense period of galaxy growth in universal history, culminating in what has come to be called “cosmic noon”, by the end of which many of attributes of a mature universe had developed. Because this period of adolescence happened after reioinization, we have (arguably) the broadest observational access, with the largest dynamic range, to the physical state of both forming galaxies and the dominant reservoir of diffuse gas outside of galaxies that traces the web-like large-scale structure of the universe.



Artist's conception of galaxies forming within the "cosmic web". The sightlines to those galaxies can also probe the diffuse gas between them. *(Credit: Cen & Ostriker; NASA/HST, Subaru Telecope; Gimp/K. Adelberger)*

Biermann lecturer 2024: Charles, "Chuck" Steidel *(Credit: private)*

In this year's Biermann lectures, Chuck Steidel from Caltech discussed what we have learned – and what we still do not understand – about the universe of galaxies and the matter between based on observations of the adolescent universe. He discussed how our "Big Picture" of galaxy formation has evolved over the last few decades, from both a scientific and sociological point of view, and what has driven the changes. He also discussed how the first two years of data from the James Webb Space Telescope (JWST) have altered the developing picture of a still-earlier phase of galaxy formation. Finally, he attempted to synthesize the current picture of the "epoch of galaxy formation", with emphasis on problems that have yet to be resolved.

Steidel's research focuses on observational studies of the formation and evolution of galaxies and the intergalactic and circumgalactic medium surrounding them, and on developing techniques and instrumentation needed to make progress in these areas using large ground-based telescopes. While the large-scale structure of the universe is dictated primarily by dark matter – whose evolution is reasonably well understood thanks to large numerical simulations such as Millennium or Illustris – the behavior of the normal, baryonic matter embedded in this dark matter structure still poses a challenge as the baryonic processes are very complex.

Steidel has made significant contributions to the field of astrophysics. In the early 1990s, Steidel and collaborators developed the "Lyman break" imaging technique for isolating galaxy populations in prescribed redshift intervals at high redshifts; since 1995, his group has used the Keck telescopes in Hawaii to conduct sensitive spectroscopic surveys of distant galaxies and their gaseous environments, focusing on the adolescent universe at redshifts $z = 2 - 4$. Their pioneering work has provided important scientific motivation for semi-analytic models and cosmological hydrodynamical simulations of galaxy formation at MPA for the past 30 years.

1.3.2 Full STEAM ahead for astronomy in Uganda!

End of April, the STEAM (Science, Technology, Engineering, Agriculture, and Mathematics) festival took place at Kyambogo University in Uganda. One of the highlights: the mobile planetarium set up by Benard Nsamba, head of the MPA partner group and Branco Weiss fellow.

How do you inspire young students to consider pursuing a career in STEM (Science, Technology, Engineering, and Mathematics)? With his MPA partner group, Benard Nsamba decided to use astronomy and in particular a mobile planetarium, funded by the Branco Weiss foundation. The planetarium debuted during the STEAM (Science, Technology, Engineering, Agriculture, and Mathematics) festival, held from April 24th to 26th, 2024 at Kyambogo University in Kampala, Uganda.

During a press conference on April 20th, 2024, shortly before the STEAM festival, the first mobile planetarium in Uganda was unveiled and the first planetarium show presented. It will aid in the achievement of the societal goal of the Branco Weiss project led by Nsamba which is to use astronomy as a tool to inspire/motivate high school students to consider pursuing STEM-related careers. The press conference was attended by the Vice Chancellor Prof. Dr. Eli Katunguka Rwakishaya and the Dean of the Faculty of Science Ass. Prof. Edriisa Mugampoza of the Kyambogo University.

Over 1000 people, many from Ugandan schools and universities visited the mobile planetarium during the STEAM festival at Kyambogo University. *(Credit: B. Nsamba (SEISMIC research group))*

In total about 1000 people visited the planetarium during the STEAM festival, primarily from Ugandan high schools and universities, but also some members of the public. The group performed 55 planetarium shows during the three days, with each session lasting about 20 minutes. There were two short shows per session, each about 10 minutes long: The first was a short description of basic concepts in astronomy, such as stars, planets, moons, the solar system, constellations, and galaxies, with an additional brief discussion of the different types of optical telescopes. The second part of the planetarium show was entitled “Journey to the center of the Milky Way Galaxy”. This full dome video was developed by the European Southern Observatory (ESO) and is aimed at enlightening the public and students about what is found at the Center of our Galaxy. It starts with a journey from the driest place on Earth, the Atacama Desert in Chile, through billions of stars to the Center of our Galaxy, where a black hole is consuming anything that strays into its path.

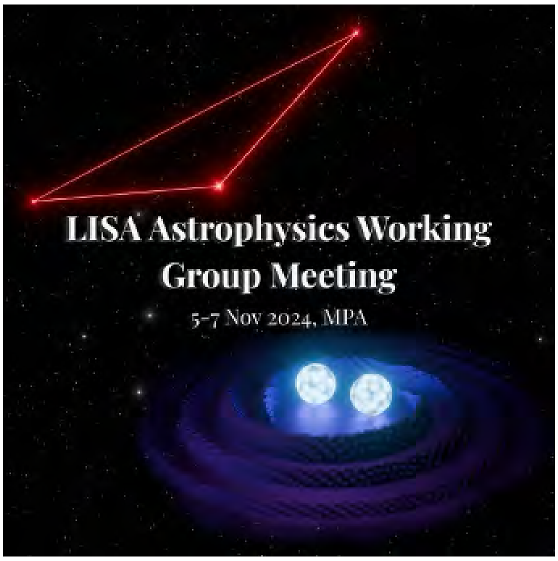
In addition to the planetarium shows, Benard Nsamba was also a keynote speaker of the subtheme “Unveiling the Wonders of Space Science for Community Advancement”, inspired by Uganda’s launch of its first satellite. The discussion did not only serve as a platform to brainstorm how Uganda can leverage its satellite technology to develop home-grown solutions for local challenges but also to acknowledge the historical role of the diverse cultural beliefs regarding celestial bodies in fostering a sense of responsibility, promoting self-reliance and economic growth.

1.3.3 LISA Astrophysics Working Group Meeting at MPA

Astrophysicists are preparing to tune into gravitational waves at new frequencies

In early 2024, the European Space Agency officially adopted the LISA mission (Laser Interferometer Space Antenna) as the world's first space-based gravitational wave observatory, with its launch set for 2035. LISA will provide a revolutionary view into the Universe by capturing gravitational waves in a frequency range inaccessible to ground-based detectors, allowing scientists to study entirely new astrophysical phenomena.

The LISA mission will open a new window into the Universe by detecting gravitational waves in the frequency range of 0.1 mHz to 0.1 Hz that are not accessible with Earth-based detectors due to the inherent seismic noise on the ground. In this regime, LISA will observe a variety of astrophysical phenomena, including binary systems of (super)massive black holes, stellar-mass black holes spiraling into more massive ones, close compact binary stars within our Galaxy, and even exoplanets that orbit around them. LISA's sensitivity will enable the detection of stellar black hole systems years before they merge, offering a unique opportunity to study these extreme environments. The mission also holds the potential to uncover a stochastic gravitational-wave background and discover entirely new unexpected sources.



(Credit: Ruggero Valli(MPA))

As LISA opens a new window onto the Universe, it presents exciting challenges for the astrophysics community: to define the key scientific questions it can answer and develop the tools to do so. In November 2024, over 100 researchers gathered at the Max Planck Institute for Astrophysics (MPA) for the LISA Astrophysics Working Group Meeting. They explored how LISA will deepen our understanding of black holes, stars, galaxies, and other cosmic phenomena.

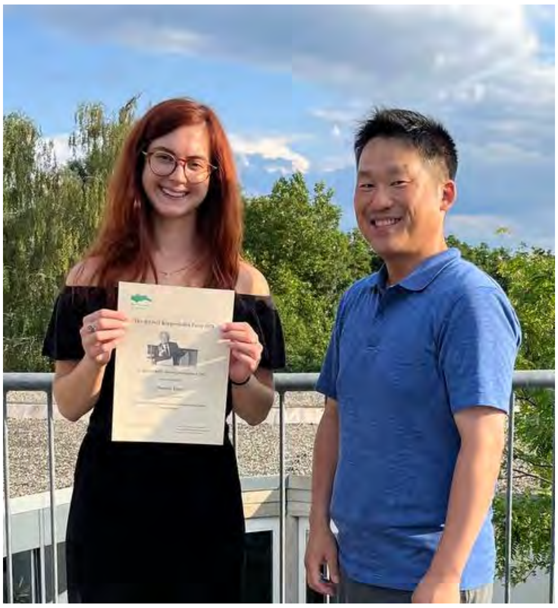
Hosted by MPA, the workshop brought together members of the LISA Astrophysics Working Group—the largest within the LISA Consortium—covering topics from individual gravitational-wave sources to their populations and formation mechanisms. Through talks, discussions, and hands-on projects, participants focused on core astrophysical questions LISA can address. The meeting marked a key step in unlocking LISA's potential to reveal the Universe's most extreme and previously unobservable phenomena.

1.3.4 Prizes and Awards

Rudolf-Kippenhahn-Award

After reviewing the excellent papers nominated for the 2024 Rudolf Kippenhahn Award, the committee decided to split the prize between Beatriz Tucci, for "EFTofLSS meets simulation-based inference: σ_8 from biased tracers," and Jing-Ze Ma, for "Is Betelgeuse Really Rotating? Synthetic ALMA Observations of Large-scale Convection in 3D Simulations of Red Supergiants."

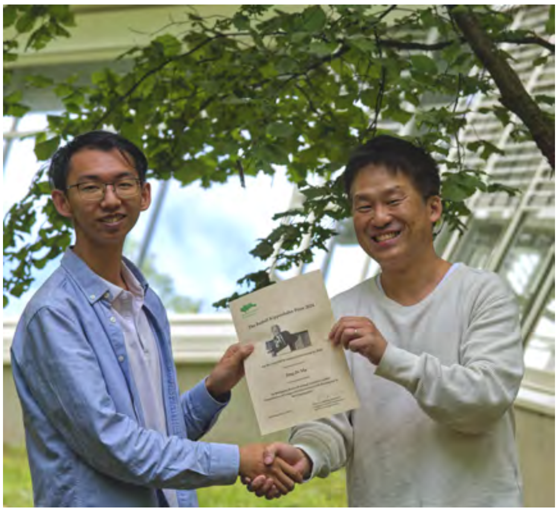
Beatriz' paper represents the first time that state-of-the-art theoretical models for large-scale structure, based on an effective field theory, have been combined with simulation-based inference, a modern deep-learning-based inference technique which avoids the need for explicit likelihoods. This paper demonstrates how this technique can be used to infer cosmological parameters using the galaxy clustering power spectrum and bispectrum. Beatriz' work has enabled a new and powerful pathway of analyzing galaxy clustering for cosmology, as the method is not restricted to those galaxy statistics for which one can derive an explicit likelihood and covariance. Beyond presenting these results, the paper provides an exceptionally clear overview of the different simulation-based inference techniques, as well as the normalizing-flow architecture employed. Indeed, Beatriz' advisor states that he learned most of what he knows about neural simulation-based inference from Beatriz' paper.



Beatriz Tucci, the recipient of the Kippenhahn Prize with MPA managing director Eiichiro Komatsu.) *(Credit: MPA)*

Jing-Ze's paper provides a compelling alternative explanation for the puzzle that the red supergiant star Betelgeuse appears to be rotating about 100 times faster than expected for its supposed evolutionary state. This claim was mainly based on beautiful ALMA data, which suggested that half of the star was moving away and the other half is moving towards us, and led to questions about what we are missing from our understanding of one of the most famous stars. Jing-Ze proposed that the measured velocity dipole could naturally be caused by convective motions, when Betelgeuse is observed with the resolution of that ALMA data, and examined this idea using a combination of clear physical arguments and 3D simulations. Jing-Ze's work for this paper included independently writing his own tailored radiation-transfer code, against the advice of his advisor, as he was not satisfied with existing tools. Presentations of new ALMA data have since given preliminary indications consistent with Jing-Ze's explanation.

The prize is generously funded by a donation from Simon White. The award is not just



Jing-Ze MA, the recipient of the Kippenhahn Prize with MPA managing director Eiichiro Komatsu.) *(Credit: MPA)* a recognition of excellence, but promotes originality, deep results, clarity of presentation, and student creativity in going beyond their advisor's wishes. In particular, the award emphasizes quality over quantity. Happily, the extremely high standard of the nine nominations demonstrated that MPA students continue to produce a great quantity of high-quality work

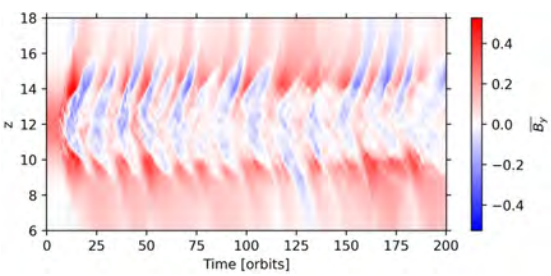
Otto Hahn Medal for Oliver Zier

Former MPA PhD student Oliver Zier received one of the Otto Hahn Medals this year at the Max Planck Society's annual assembly in Berlin. The prize is awarded for the development of novel numerical techniques that allow the accurate simulation of rotationally supported, cold, magnetized astrophysical disks.

Rotationally supported, cold gaseous disks play a central role in astrophysics. They naturally arise from the relentless pull of gravity combined with angular momentum conservation whenever there are dissipative processes in the baryons, leading to protoplanetary disks, accretion disks onto black holes, or large, star-forming galactic disks, to name just the most prominent examples. Numerical simulations are required to study the non-linear physics in such disks, but they are met with substantial technical and physical challenges. In his thesis, Oliver Zier has developed novel numerical techniques that for the first time make it possible to accurately simulate magnetized disk flows with a freely moving, fully unstructured and automatically adaptive mesh. His new methods allow simulations of global disks that can sustain magneto-rotational instability and gravito-turbulence for hundreds of orbits while at the same time can follow local gravitational fragmentation to very high density contrast. This is a significant step forward towards physically more reliable numerical models of astrophysical disks.

After his undergraduate studies of physics and computer science at the University of Bayreuth, Oliver Zier pursued a master of science degree in theoretical and mathematical physics at the Ludwig-Maximilians-University of Munich. He then came to the Max Planck Institute for Astrophysics in 2019 to work on his doctoral research, which he finished at the beginning of 2023 with a thesis on "Taming rotationally supported disks using state of the art numerical methods". Since the fall of 2023 he works as a postdoctoral researcher at the Massachusetts Institute of Technology, USA.

Dr. Oliver Zier and Prof. Dr. Claudia Felser, MPG vize president for Chemistry, Physics and Technology Section *(Credit: David Ausserhofer (Max-Planck-Gesellschaft))*



Time evolution of the magnetic field in a stratified shearing disk, showing a clear signature for the magneto-rotational instability (MRI). The MRI is thought to be of major importance in accretion disks due to its ability to mediate an outward transport of angular momentum. *(Credit: MPA)*

Every year since 1978, the Max Planck Society awards the Otto Hahn Medal and 7,500 euros of prize money to its best junior scientists - mostly for achievements in connection with their doctorates. The prize is intended to motivate especially gifted early career researchers to pursue a future university or research career.

Max Gronke Awarded ERC Starting Grant

The Max Planck Institute for Astrophysics (MPA) is proud to announce that Dr. Max Gronke, leader of the Max Planck Research Group 'Multiphase Gas', has been awarded a highly competitive European Research Council (ERC) Starting Grant. This prestigious grant will fund Dr. Gronke's innovative research project "Resolving the Multiscale, Multiphase Universe" (ReMMU) over the next five years.

Research Focus and ERC Project
Dr. Gronke's research focuses on understanding the complex interactions of multiphase gas in various astrophysical contexts, from galactic winds to the circumgalactic medium. The ReMMU project aims to address a fundamental challenge in our understanding of galaxy formation and evolution: the physics regulating the galactic ecosystem.

"Current cosmological simulations fail to capture the multiphase structure of galactic halos and show a lack of convergence in even basic gas properties," explains Dr. Gronke. "This significantly limits our ability to interpret existing observations and make reliable predictions about the circumgalactic medium."

The ReMMU project will tackle this issue by developing and implementing innovative computational methods to better model multiphase gas in cosmological simulations. This approach will enable more accurate comparisons with observational data, advancing our understanding of galactic ecosystems across cosmic time.

"This work will shed light on the drivers of galactic growth and feedback mechanisms, which are key to understanding the formation and evolution of galaxies," Dr. Gronke adds.

Impact and Future Prospects
The ERC Starting Grant, valued at €1.5 million, comes on top of the approximately €2.3 million funding for Dr. Gronke's Max Planck Research Group. This substantial combined funding will enable Dr. Gronke to expand his research team and pursue this ambitious project.

"The timing of ReMMU is particularly exciting," says Dr. Gronke. "Recent advances in fundamental hydrodynamical theory have constrained the parameter space sufficiently to allow for subgrid models of unresolved gas. Simultaneously, we're seeing a rapidly growing body of observational surveys that are revolutionizing the available data on galactic ecosystems. ReMMU will combine these advances to establish firm predictions for comparison with observations across cosmic time."

We congratulate Dr. Gronke on this outstanding achievement and look forward to the groundbreaking research that will emerge from this project in the coming years. This grant is expected to significantly advance our understanding of the multiphase, multiscale nature of the universe.

About Max Gronke
Dr. Gronke established his Max Planck Research Group at MPA in 2021, following a distinguished early career that included a NASA Hubble fellowship at UC Santa Barbara and Johns Hopkins University. He completed his PhD at the Institute of Theoretical Astrophysics in Oslo, where his thesis on "Lyman-alpha observables of the high-redshift Universe" earned him the His Majesty the King's gold medal for the best PhD thesis at the Faculty of Mathematics and Natural Sciences of the University of Oslo.

Dr. Max Gronke *(Credit: private)*

ERC Synergy Grant for a Three-Dimensional Atlas of the Milky Way

Creating the first three-dimensional, comprehensive atlas of our Milky Way galaxy is the aim of one of the groups at MPA that have been awarded the highly competitive European Research Council Synergy Grant (ERC-SyG). The project called 'mw-atlas' will revolutionize the way we observe and understand the Universe. Led by Torsten Enßlin of the Max Planck Institute for Astrophysics (MPA) in Garching, Germany, Philipp Mertsch of RWTH Aachen University in Aachen, Germany, and Vasiliki Pavlidou of the Institute of Astrophysics of the Foundation for Research and Technology - Hellas (IA-FORTH) in Heraklion, Crete, Greece, the project has a total budget of ten million euros and will be implemented in the three institutes for six years, starting in 2025. The Milky Way galaxy is our home, the cradle of our solar system and of life as we know it. It is also a veil through which we observe the distant universe and therefore needs to be understood in order to sharpen our view into the cosmos," said Enßlin, head of the Information Field Theory Group at MPA, and coordinating PI of mw-atlas.

From left to right: Dr. Torsten Enßlin of MPA, Prof. Vasiliki Pavlidou of IA-FORTH, and Prof. Philipp Mertsch of RWTH-Aachen. Enßlin and Mertsch are holding prototype 3-dimensional reconstructions of the Galactic dust in the neighborhood of our solar system, 3D-printed in transparent material. These prototypes are sample "pages" of the Milky-Way atlas that the team aims to construct. *(Credit: Philipp Mertsch, RWTH)*

"The Milky Way is highly complex," added Mertsch, Professor at the Institute for Theoretical Particle Physics and Cosmology at RWTH Aachen, and PI of the Aachen node. "It contains dark matter, stars, gas, dust, cosmic rays, magnetic fields, turbulent velocities, all interacting through a network of physical processes."

"The three-dimensional structure of these contents is either the protagonist or a major source of noise in all cutting-edge astrophysics research, whether we are talking about the search of the beginnings of our Universe, the nature of dark matter or the origin of stars and of the highest-energy particles in the cosmos," said Pavlidou, Affiliated Faculty Member at IA-FORTH and Professor at the Department of Physics of the University of Crete in Greece, PI of the Crete node.

"Although we have been collecting data on the Milky Way for decades, most information

Close-up of the prototype 3D-printed Galactic dust reconstructions. *(Credit: T. Enßlin, MPA)*

is still two-dimensional: we perceive the 3D Galaxy only as a 2D projection on the celestial sphere," said Enßlin. "Using the framework of Information Field Theory, which my group has pioneered, we can combine the wealth of existing data on the Milky Way to reconstruct the three-dimensional structure of all of its ingredients." "The maps of the Milky Way ingredients will result from physics-informed reconstructions," explained Mertsch. "Although physical interactions between ingredients complicate the reconstruction, they are key to unlocking the third dimension for the atlas. These interactions allow us to use objects at known distances to localize more elusive ones that were observed to interact with the former."

"If we successfully complete the mw-atlas, ten years from now there will hardly be any aspect of astrophysical research that will not be using the atlas. We hope it will enable groundbreaking science in ways we cannot even imagine yet," concluded Pavlidou.

The mw-atlas project will also transfer technologies and algorithms developed by it into other areas, like medical imaging, Earth monitoring, and industrial data analysis. It is funded through the 2024 ERC-SyG program. This program provides grants intended to foster research at intellectual frontiers, by enabling small groups of two to four Principal Investigators and their teams to jointly address ambitious research problems at the interface between established disciplines with unconventional approaches.

In the 2024 competition, 56 research groups across Europe were awarded highly-coveted ERC Synergy Grants. With a total budget of 570 million euros, the grants are part of the EU's research and innovation program, Horizon 2020.

ERC Synergy Grant awarded to obtain a comprehensive view of the Universe in its infancy

Leveraging highly complementary theoretical and observational expertise, the newly funded RECAP project will allow scientists to have a multi-frequency view of the first galaxies and their environment, and to build a coherent picture of galaxy formation and evolution during the Epoch of Reionization.

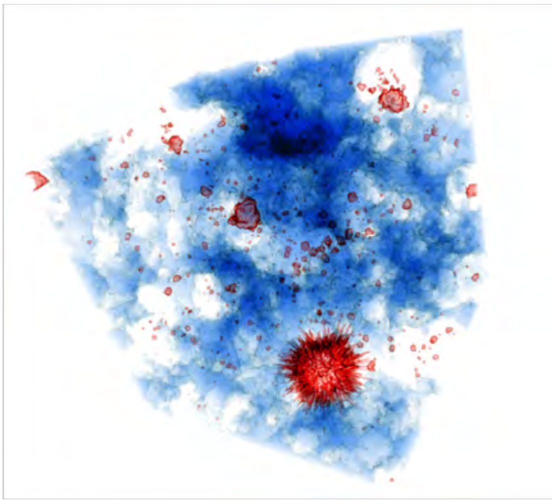
The Epoch of Reionization marks the Universe's last major phase transition, during which the neutral hydrogen in the intergalactic medium became ionized by radiation from the first cosmic sources. Understanding the onset, timeline, and topology of the Reionization process is essential for deciphering what shaped the evolution of the Universe, from an early, uniform matter distribution to the diverse structures observed today.

From left to right: Kirsten Knudsen, Laura Pentericci, Benedetta Ciardi (MPA), and Valentina D'Odorico. *(Credit: private)*

The REionization Complementary Approach Project (RECAP) now being funded by an ERC synergy grant will provide unprecedented insights into this transformative cosmic period through a unique collaborative effort which brings together a team of four internationally recognized scientists with diverse and complementary expertise.

Dr. Benedetta Ciardi's group at MPA will drive the theoretical side of the project, designing and running a state-of-the-art suite of multi-scale hydrodynamical simulations to support the interpretation of the unparalleled datasets available to RECAP. These will be contributed by co-investigators Dr. Laura Pentericci (Osservatorio Astronomico di Roma, Italy), Dr. Valentina D'Odorico (Osservatorio Astronomico di Trieste, Italy), and Dr. Kirsten Knudsen (Chalmers University of Technology, Sweden) thanks to their prominent role in cutting-edge observational facilities, including the James Webb Space Telescope (JWST), the Very Large Telescope (VLT), and the Atacama Large Millimeter Array (ALMA).

"Despite the abundance of simulations of galaxy formation and reionization, none is suited to interpret the vast and varied data on high-redshift objects collected in recent years," said Dr. Ciardi. "RECAP will allow us to design a unique suite of multi-scale simulations to cohesively interpret our superb multi-frequency data, creating a comprehensive framework for this early cosmic epoch."



Volumetric rendering of a large-scale simulation of reionization run within the group of Benedetta Ciardi. *(Credit: Eide et al. 2020.)*

Dr. Ciardi obtained her PhD in 2001 from the University of Florence and has been a research group leader at MPA since 2005. Her academic achievements have been recognized with prestigious awards, including the Marie Curie Excellence Award in 2005 and her appointment as Knight of the Order of Merit of the Italian Republic in 2010.

The highly competitive ERC Synergy Grant is a testament to the PIs' scientific achievements and the potential of RECAP to transform our understanding of cosmic evolution. This funding will enable the team to address longstanding questions about the Universe's formative epochs, illuminating the intricate interplay between ionizing sources and their environments. With a funding of about 10 million Euros for the next six years, the team will enlarge their group with new PhD students and postdocs (some at MPA) as well as computing resources.

Gold for MPA Gender Equality Plan

The MPG Commission "Quality Management of Max Planck Gender Equality Plans (GEP)" awarded the Gold label to MPA's plan, for meeting the Max Planck standards – comprehensiveness, institute-specific and sustainability – to an outstanding degree. The MPA presents an excellent gender equality strategy, which, among other things, impresses with a comprehensive inventory, a stringent, data-based selection of fields of action, goals and measures, and a comprehensive portfolio of measures.

According to the commission, all the components that make the GEP an effective monitoring tool for gender equality objectives and measures (status report, analysis, fields and ob-

The MPA's Gender Equality Plan is awarded Gold. *(Credit: MPG)*

jectives of action, measures, evaluation) are in place. The foreword by the Managing Director explains the institute's gender equality objectives and values in an appealing way and demonstrates commitment at the management level.

The status report contains a comprehensive set of quantitative and qualitative data that includes al-most all the predefined indicators for the gender equality situation at the institute, supplemented by some individually collected data (such as the proportion of women selected for the MPA postdoc fellowship and women from non-European countries). This provides a very good insight into the gender equality situation at the MPI. The effectiveness and take-up of the measures implemented to date is evaluated on an ongoing basis and the results are used as a basis for formulating the new set of measures – an important foundation for making the gender equality strategy more effective in the long term.

The objectives are ambitious and forward-looking when measured against the status quo. The portfolio of measures is comprehensive and very promising. The fact that it includes both cultural measures as well as structural measures promises tangible improvements in the gender equality situation at the institute.

Objectives already achieved, such as the introduction of a transparent and standardized selection procedure for the MPA Postdoctoral Fellowship and the significant increase in the proportion of women at the postdoc and doctoral level and in the science support sector, promise further gender equality successes.

2 Scientific Highlights

2.1 What happens when a star approaches a black hole?

By Pavan Vynatheya (PhD student)

In dense stellar environments, interactions between stars and stellar-mass black holes should occur frequently. Through hydrodynamical simulations, researchers at MPA have explored how stars are disrupted in such encounters, varying key parameters such as stellar and black hole masses, stellar age, and approach distance. The study quantifies the impact of these initial parameters on stellar remnants' masses, spins, and trajectories, offering insights into cluster dynamics and providing best-fit formulae for post-disruption parameters.

The centers of globular and nuclear star clusters are the densest stellar environments in the Universe. Due to this high density, one can expect numerous gravitational encounters between stellar objects, including black holes with masses of about 10-100 solar masses. A particularly close approach of a star towards a stellar-mass black hole can result in the distortion or disruption of the star due to the intense tidal force around the black hole. Such a phenomenon is called a 'micro tidal disruption event' or μTDE. The prefix 'micro' distinguishes it from the more widely studied TDE involving a supermassive black hole (i.e. with a mass greater than a million times the Sun). The TDEs that are due to supermassive black holes have garnered significant interest as transients at optical, UV, and X-ray wavelengths, with more than 100 confirmed observations. Although there have been no confirmed observations of μTDEs as of 2023, future large-scale transient surveys like LSST hold promise.

Detailed studies of μTDEs are crucial for understanding the gravitational dynamics of dense star clusters and the growth of black holes in these clusters. The trajectory of a star undergoing a partial disruption is altered due to mass loss (A full disruption leads to the destruction of the star). Approximately half of the mass lost from the star becomes unbound while the other half stays close to the black hole. This material eventually accretes onto the black hole resulting in the growth of its mass. Therefore, N-body and other simulations need to take these disruptions into account to properly model the long-term dynamics of a star cluster, especially its central dense region. This accuracy can be attained through detailed hydrodynamics simulations of star - black hole encounters.

In this work, we simulated a suite of 58 hydrodynamical partial μTDEs using the 3D moving-mesh code AREPO. Unlike previous studies on μTDEs, we employed realistic stellar models generated through the stellar evolution code MESA. We varied the masses of both the star (0.5 and 1 solar masses) and the black hole (10 and 40 Solar masses), the age of the star (zero-age, middle-age, and terminal-age main sequence), and the distance of closest approach between the two. Our results then ranged from almost no mass loss to full disruption of the star.

Assuming an initially non-rotating star and a parabolic encounter between the star and the black hole, our primary aim was to quantify how the masses, spins, and trajectories of the stellar remnants depend on these initial parameters.

We found that the amount of mass lost from

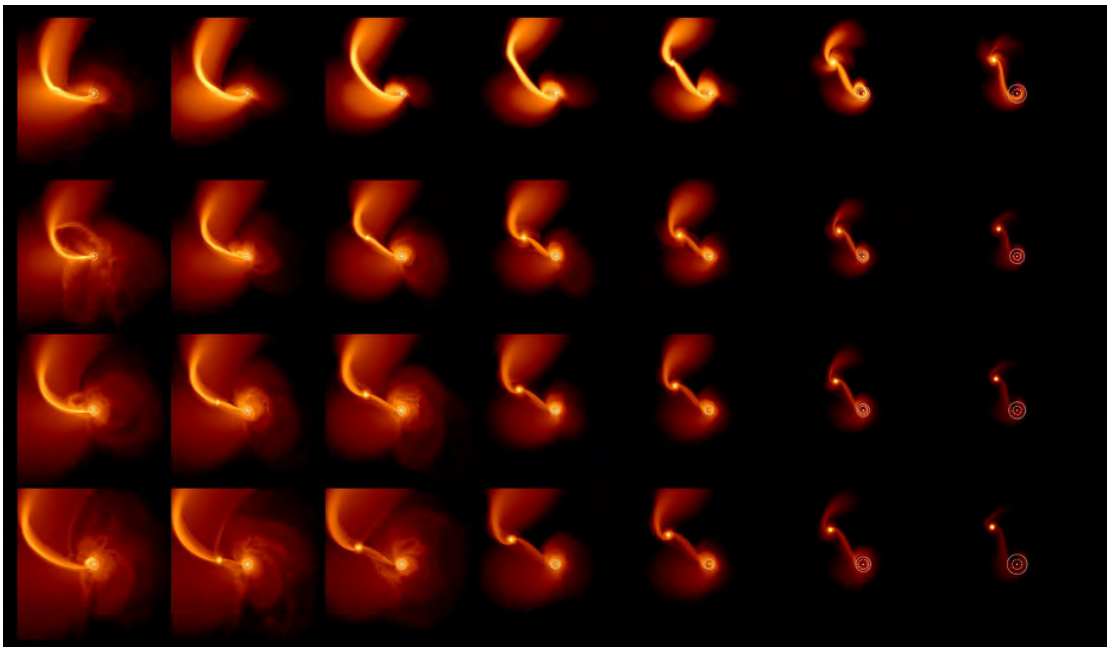


Figure 2.1: Simulations of stars being disrupted by black holes. From left to right the distance of closest approach increases (resulting in full disruption to almost no disruption). The top row shows 0.5 solar mass stars, while the three bottom rows show three ages of 1 solar mass stars. The black holes are of 10 solar masses. *(Credit: MPA)*

a star decreases roughly exponentially with increasing distance of closest approach; i.e. the farther away a star passes the black hole, the less matter it loses. The stellar age also plays a role – main-sequence stars of different ages disrupt differently even when all the other initial parameters are the same. The more evolved a main-sequence star is, the higher its central density as it contains more core helium from hydrogen burning. It is therefore much harder to fully disrupt an older main-sequence star compared to a younger one. In addition, the stellar remnant is spun up due to torque from the black hole. A closer approach results in a higher torque, which translates to a higher angular momentum gained by the stellar remnant.

Finally, the initial parabolic trajectory of the star changes due to the combined effects of stellar tides, asymmetric mass loss, spin-up of the remnant, and ejecta energy. In accordance with previous studies, the remnant can either be bound to the black hole (eccentric orbit) or escape from it (hyperbolic orbit). In the former case, the remnant would then undergo repeated disruptions until it is completely ripped apart. In general, the remnant becomes unbound when the star loses a significant fraction of mass in the disruption and the star-black hole mass ratio is skewed, i.e., the black hole is much heavier than the star. The results from our suite of simulations are available in the form of best-fit formulae for the post-disruption parameters. These can be incorporated into cluster simulation codes to better model elusive star-black hole encounters.

2.2 A new spin on Betelgeuse's boiling surface

By Jing-Ze Ma (PhD student) and Selma de Mink (scientific director)

Betelgeuse is a well-known red supergiant star in the constellation Orion. Recently it has gained a lot of attention, not only because variations in its brightness led to speculations that an explosion might be imminent, but also because observations indicated that it's rotating much faster than expected. This latter interpretation is now put into question by an international team led by astronomers at Max Planck Institute for Astrophysics, who propose that Betelgeuse's boiling surface can be mistaken for rotation even in the most advanced telescopes. Other astronomers are actively analyzing new observational data to test such hypotheses.

As one of the brightest stars in the northern hemisphere, Betelgeuse can be easily found by naked-eye in the constellation of Orion. Betelgeuse is one of the biggest stars known. With a diameter larger than a billion kilometers, it is almost 1000 times larger than the Sun. If it had been in our solar system, it would have engulfed Earth with its atmosphere reaching Jupiter. A star that large is not supposed to rotate fast. In their evolution, most stars expand and spin down to conserve angular momentum. However, recent observations suggested that Betelgeuse is rotating quite fast (at 5 km/s), two orders of magnitude faster than a single evolved star should spin.

The most prominent evidence for Betelgeuse's rotation came from the Atacama Large Millimeter/submillimeter Array (ALMA). The 66 antennas at ALMA work together as though they were a single giant telescope. They use a technique known as interferometry, where two or more antennas pick up a signal from the Universe and join forces to analyze the signal and obtain information on its source of emission. Using this technique, astronomers discovered a dipolar radial velocity map on the outer layer of Betelgeuse: Half of the star appears to be approaching us, and the other half seems to be receding. This observation, along with previous studies, led to the interpretation that Betelgeuse is rapidly rotating.

This interpretation would have been a clear case, if Betelgeuse was a perfectly round sphere. However, the surface of Betelgeuse is a vibrant world, governed by a physical process called convection. We can observe convection in our daily life when we boil water, but in Betelgeuse, this process is much more violent: The boiling bubbles can be as large as Earth's orbit around the Sun, covering a large fraction of Betelgeuse's surface. They rise and fall at a speed of up to 30 km/s, faster than any crewed spacecraft.

Based on this physical picture, an international team led by Jing-Ze Ma, PhD student at the Max Planck Institute for Astrophysics now offers an alternative explanation to Betelgeuse's dipolar velocity map: Betelgeuse's boiling surface mimics rotation. A cluster of boiling bubbles rise on one side of the star, and another group of bubbles sink on the other side. Due to the limited resolution of the ALMA telescope, such convective motions would be blurred in actual observations, which would result in the dipolar velocity map.

The team developed a new post-processing package to produce synthetic ALMA images and submillimeter spectra from their 3D radiation hydrodynamic simulations of nonrotating red supergiant stars. In 90% of the simulations, the star would be interpreted as rotating at several km/s simply because of the large-scale boiling motions on the surface that are not clearly seen in the ALMA telescope.

Further observations are needed to better assess the rapid rotation of Betelgeuse, and the team made predictions for future observations with higher spatial resolution. Fortunately,

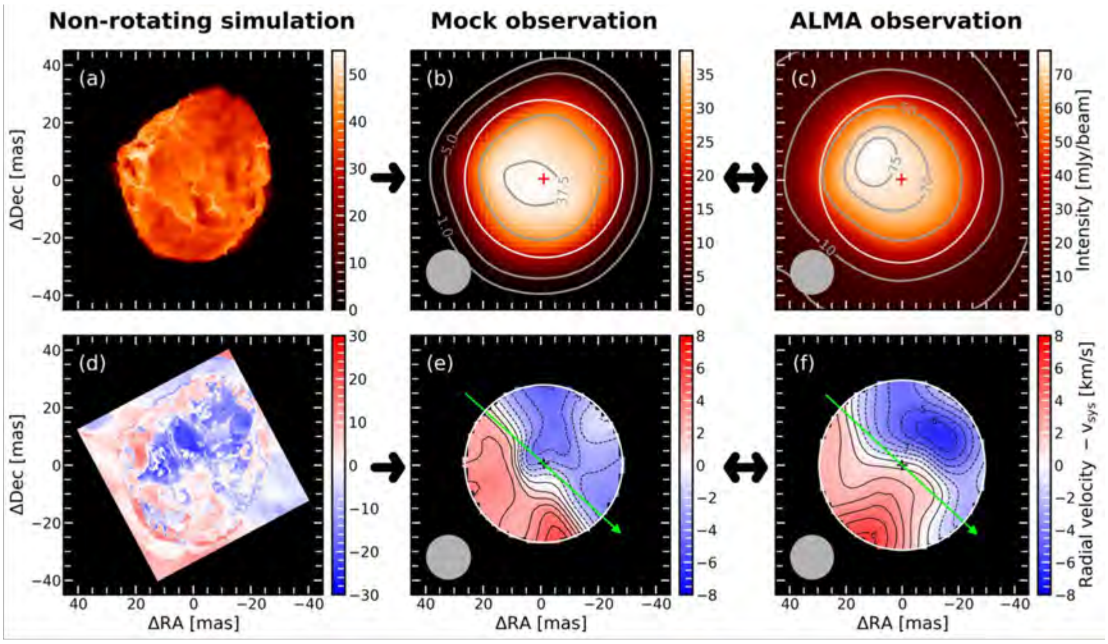


Figure 2.2: A direct comparison of a computer simulation of a nonrotating red supergiant with ALMA observations of Betelgeuse. If not sufficiently resolved in telescopes, the large-scale convection can result in a dipolar velocity map. The top row shows intensity maps, the bottom row shows maps of the radial velocity. The left-hand column shows the simulation of the star in full resolution; the middle column shows mock observations with reduced resolution. The right column shows the actual ALMA observation. *(Credit: MPA)*

other astronomers have already made higher-resolution observations of Betelgeuse in 2022. The new data is being analyzed right now, which will put the predictions to the test and help unveil the mask of Betelgeuse.

"Most stars are just tiny points of light in the night sky. Betelgeuse is so incredibly large and nearby that, with the very best telescopes, it is one of the very few stars where we actually observe and study its boiling surface. It still feels a bit like a Science Fiction movie, as if we have traveled there to see it up close", says coauthor Selma de Mink (director at the Max Planck Institute for astrophysics). "And the results are so exciting. If Betelgeuse is rapidly rotating after all, then we think it must have been spun up after eating a small companion star that was orbiting it."

"There is so much we still don't understand about gigantic boiling stars like Betelgeuse.", says co-author Andrea Chiavassa, astronomer at CNRS. "How do they really work? How do they lose mass? What molecules can form in their outflows? Why did Betelgeuse suddenly get less bright? We are working very hard to make our computer simulations better and better, but we really need the incredible data from telescopes like ALMA."

2.3 Probing Cold Gas with the Resonance Doublet of Singly Ionized Magnesium

By Seok-Jun Chang (postdoc)

Traditional studies of the gas around galaxies rely in particular on absorption and emission features of neutral hydrogen, the simplest and most abundant element in the universe. MPA researchers have now investigated alternative tracers, in particular the resonance doublet of singly ionized magnesium and found that analyzing this emission can lead to significant advances in studying the circum-galactic medium. They showed the potential of the magnesium doublet as an alternative to Lyman-alpha emission through a new radiative transfer code and suggest that the magnesium doublet ratio could even be used as a tracer of the Lyman-continuum escape.

Light, and in particular how it interacts with the atoms of various elements, plays a pivotal role in unveiling the secrets of the universe. At the heart of this interaction lies the resonance line, the transition between the ground state and the first excited state in an atom. This transition is significant and interesting for atoms and ions with just one electron in their outermost shell. Considering the fine structure of these atoms, the resonance line manifests as a doublet, the K and H lines. The most renowned example of such a resonance doublet is the hydrogen Lyman-alpha ($Ly\alpha$) line at 1216 Å. Although the two lines of Lyman-alpha are not distinguishable due to a too small energy gap, other metal doublets are observed as separated doublets.

In astrophysical spectra, the resonance doublets stand out as prominent absorption lines since the abundant electrons in the ground state easily interact with photons near the line center. In addition to absorption features in astrophysical spectra, the doublets also appear as emission lines, acting as one of the main coolants of shock and ionized gas. The atomic physics of the resonance doublet dictates that the scattering cross-section of the K line is always two times higher than that of the H line. This also translates into the ratio of K and H emission from collisional excitation and recombination, which is generally two. Furthermore, due to their resonant nature, photons of the doublet emission suffer scattering with the electrons in the ground state, by which the physical properties of the gas are imprinted on their emission features. The study of resonance doublets, therefore, opens a window into the complexities of astrophysical environments, making it a cornerstone of astrophysical spectroscopy.

Studying CGM with Resonance Doublets

The circumgalactic medium (CGM), the diffuse halo of multiphase gas that envelopes galaxies, is a key to understanding the mysteries of galaxy formation, evolution, and the flow of matter around galaxies. While traditional studies of the CGM have relied on analyzing the absorption features of the resonance lines observed in quasar spectra, this approach offers a view constrained by singular lines of sight. The evolution of observational technology, with instruments like MUSE on the VLT, KCWI on Keck, and HETDEX, has opened new windows into the CGM through the direct observation of spatially extended emissions such as Lyman-alpha and resonance doublets of heavier elements.

The Lyman-alpha emission is central to these advances and a powerful tool for probing the cold CGM (with temperatures up to 10000K) and studying the early universe (at redshift z from 2 to 5). However, observing Lyman-alpha faces significant challenges: it is obscured by Earth's atmosphere at $z < 2$ and becomes difficult to detect beyond $z > 6$ due to the optically thick universe in the epoch of reionization. These limitations highlight the necessity for alternative tracers of cold gas within the CGM across different cosmic epochs.

Resonance Doublet of Singly Ionized Magnesium as a New Tracer of Cold Gas

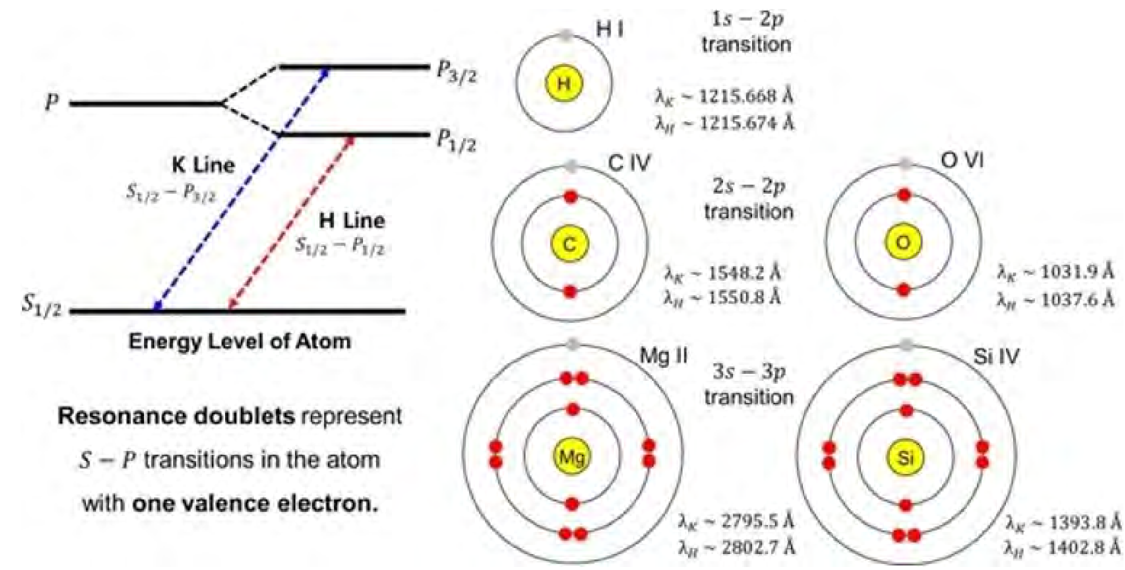


Figure 2.3: Schematic illustration of resonance doublets: the energy levels of resonance doublets are shown on the left, some example atoms and ions with one valence electron on the right. *(Credit: MPA)*

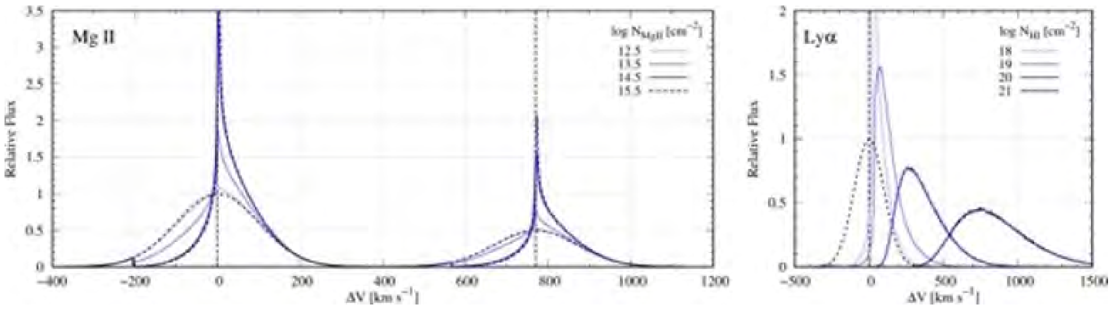


Figure 2.4: These diagrams show the magnesium (left) and Lyman-alpha (right) spectra for various column densities (different color hues). The black dashed line represents the intrinsic Gaussian profile. For magnesium, the doublet is clearly separated, while the energy gap is too small for hydrogen. With larger densities, the asymmetry of the lines becomes more pronounced. *(Credit: MPA)*

The resonance doublet of singly ionized magnesium (Mg II) at 2796 *Å* and 2803 *Å* presents such an alternative. Due to its resonance nature and with a similar ionization energy to atomic hydrogen, the Mg II emission can trace cold gas properties through scattering processes like Lyman-alpha. In this work, we developed a new 3D Monte Carlo radiative transfer code to investigate the escape of both emission lines through homogeneous and clumpy multiphase media. Our new code allows for exploring gas in arbitrary 3D geometries via both Lyman-alpha and metal resonance doublets, significantly enhancing our understanding of the cold gas environment surrounding galaxies.

One of the key findings of this research is the distinct behavior of Mg II emissions compared to Lyman-alpha, despite similarities in atomic physics. Lyman-alpha emission is more spatially extended via scattering than Mg II due to a small fraction of magnesium in the gas. Furthermore, the Mg II escape fraction generally exceeds that of Lyman-alpha, offering a clearer view through the cosmic dust that often

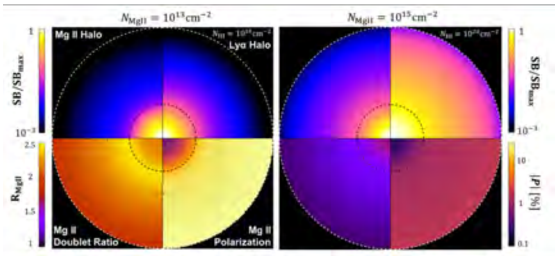


Figure 2.5: The projected images of surface brightness in Mg II (top left) and Lyman-alpha (top right), the Mg II doublet ratio (bottom left), and the degree of polarization of Mg II (bottom right). All quantities are given for optically thin (left) and thick (right) environments in magnesium. *(Credit: MPA)*

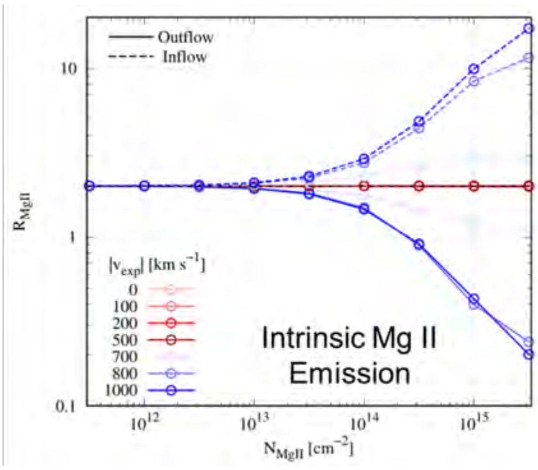


Figure 2.6: The Mg II doublet ratio for various outflow/inflow velocities. While the doublet ratio is insensitive to velocities blow the separation velocity of the two lines (700 km/s), a clear distinction can be sees for larger velocities. *(Credit: MPA)*

obscures Lyman-alpha emissions. This makes Mg II an invaluable alternative for tracing cold gas, particularly in environments where Lyman-alpha emission is weak or unobservable.

Magnesium Doublet Ratio

The escape of the Lyman continuum (LyC) or its leakage is particularly significant for understanding the mechanisms behind galaxy evolution and the reionization of the universe. The Mg II doublet ratio, which is the flux ratio of the two doublet lines, is one of the new promising indicators of the LyC leakage.

Our study investigates the Mg II doublet ratio in various environments. We found that the doublet ratio indicates a strong outflow/inflow. The double ratio of Mg II from stellar continuum becomes ~ 1 for high column densities of Mg II. In addition, we tested the doublet ratio as a leakage indicator of LyC and tracer of the LyC escape fraction.

The Mg II spectrum in the halo is composed of only scattered photons, and the physical properties of cold gas are clearly imprinted on it. We explored this and derived the analytic solution of LyC escape using the halo doublet ratio. These insights not only expand our methodologies in studying the CGM but also pave new pathways for future observation and theory.

Potential of Metal Resonance Doublets

Moreover, our research opens the door to exploring the emission features of other metal resonance doublets as tracers of the CGM. The success of the Mg II doublet in providing new insights into cold gas properties and the escape of ionizing photons suggests the potential for similar analyses for other elements. For example, the C IV doublet can be a good indicator of the galactic wind. Other metal doublets, such as O VI, N V, and Si IV, share similar atomic physics and could trace the CGM at different temperatures. This avenue of research holds promise for broadening our understanding of the multiphase CGM, offering a richer, more nuanced view of the processes that govern galaxy evolution and the cosmic web.

2.4 Unveiling the Universe at the field level

By Julia Stadler (postdoc) and Fabian Schmidt (scientific staff)

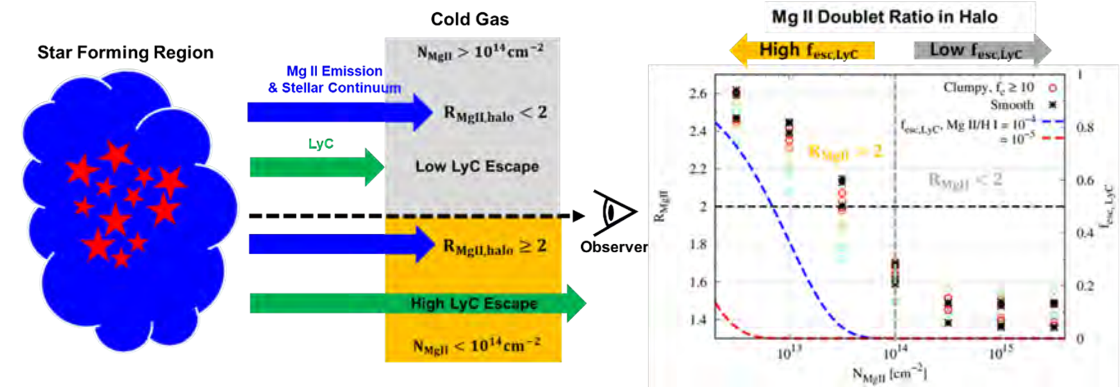


Figure 2.7: Left: Schematic illustration for the relation between the Mg II doublet ratio and the Lyman-continuum (LyC) escape. Right: the Mg II doublet ratio in the halo, which is the flux ratio of Mg II K and H lines, as a function of Mg II column density. Both LyC escape fraction and the doublet ratio decrease with increasing Mg II column density. When the gas is optically thick for LyC, the Mg II doublet ratio in the halo, which is the flux ratio of Mg II K and H lines, is less than 2. On the other hand, the doublet ratio is higher than 2. Hence, the halo doublet ratio can be a tracer of LyC escape. *(Credit: MPA)*

The distribution of galaxies on large, cosmological scales holds important clues on the nature of dark matter, the properties of dark energy and the origin of our Universe. Yet, optimally retrieving this information from observations is challenging. MPA researchers are developing a novel analysis approach, where they follow the evolution of cosmic structures through their entire formation history. Enabling a very detailed comparison between theoretical models and observational data, this approach will allow measuring key parameters of dark matter and dark energy very precisely.

The spatial pattern of galaxies in the Universe exhibits a complex, web-like structure with large galaxy clusters at the nodes that is interspersed by fast voids. Cosmologists have developed a detailed understanding how this cosmic large-scale structure emerged. In a nutshell, an early inflationary period of rapid expansion created very small (of order 1 in 100,000) fluctuations in the cosmic energy density, which subsequently evolved under their self-gravity as the Universe expanded. Yet, in this picture, there remain several open questions:

What is the nature of dark energy that drives the accelerated expansion of the Universe? What is the nature of dark matter, whose presence is required by gravitational dynamics? What is the physical mechanism that drives inflation? Dark matter is about five times more abundant than ordinary, “visible” matter. General Relativity requires visible and dark matter to experience the same gravitational forces, so the evolution of dark matter fluctuations can be predicted very precisely. It depends sensitively on the interplay between gravitational attraction and the cosmological expansion. Therefore, the cosmic large-scale structure holds important clues on the fundamental questions about our Universe. Large cosmological surveys map the distribution of galaxies out to very large distances. Yet, these galaxies comprise only the “tip of the iceberg” while the majority of the cosmic large-scale structure resides in dark matter and remains invisible.

Is there a way to deduce the distribution of dark matter in our Universe from the observed positions of galaxies? Can we understand how the structures we see today have formed? And can this help us to better answer the fundamen-

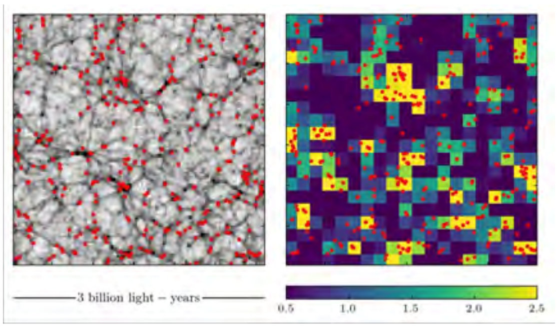


Figure 2.8: Galaxies are only the "tip of the iceberg" of the matter distribution in the universe. On the left, the gray structures represent a slice through the dark matter distribution in a large cosmological simulation with red points indicating the positions of galaxies. The right panel shows the same galaxies, where the colours represent their density on a coarse grid. This large-scale galaxy density is the data considered for the field-level analysis, and is computed directly from the observed galaxy positions. *(Credit: MPA)*

tal questions we have about our cosmos? The answer is yes. However, as we will see, we first need to overcome some challenges.

First, galaxies do not follow the distribution of matter one-to-one, we only observe a limited number of them, and measurement uncertainties affect the observations. Thus, the matter distribution that explains the observations is not unique – there can be multiple possibilities. A statistical Bayesian analysis can capture this uncertainty: we generate several plausible matter distributions, evaluate how consistent they are with the observations, and only keep those that show the highest level of agreement.

The relation between galaxies and the underlying matter density field is modelled with a theoretical framework called the Effective Field Theory (EFT) of Large Scale Structure. This effective theory has a number of free parameters designed to make our results insensitive to the details of galaxy formation on small scales, which we cosmologists do not yet understand completely. Moreover, the theory gives us a "likelihood" that quantifies the level of agreement between a proposed matter distribution and the observed galaxies. Since this comparison is done voxel by voxel (3D pixels), this is also known as a field-level analysis.

The second challenge is how to propose plausible matter distributions in the first place. The matter distribution in the universe today is the result of a complex dynamical evolution. In contrast, the distribution of primordial perturbations, which provide the starting point to this evolution, have simple statistical properties. We can take a guess on the primordial density, forward model their evolution in time, and compare that prediction to the observation. We repeat this over and over to discover the configurations best explaining the data and explore all possible solutions.

Each possible realization of the three-dimensional primordial density is characterized by up to a million parameters. And for each of these realizations we have the full history of structure formation. To explore this huge range of possibilities efficiently, we have developed our own numerical code LEFTfield, which is heavily parallelized, provides gradient information and runs on computing clusters. It can generate plausible matter distributions and forward evolve them through cosmic time in just a few seconds. An animation that can be seen under `https://www.mpa-garching.mpg.de/1095991/hl202405?c=27981` illustrates the result of such an analysis on a simulated dataset, where each frame of the animation shows a separate simulated universe that is compatible with the observation. The observations best constrain the distribution of matter on large scales. Correspondingly, the animation shows little variability in the inferred density for larger structures, but more movement in smaller ones.

How does this help to answer the questions posed above? The properties of dark matter and dark energy are built into our numerical forward model for structure formation. We can now modify these parameters and see how the agreement with the data changes. For example, changing the amount of dark energy or how it evolves leads to a different expansion rate of the universe, which in turn affects the growth of structure. This comparison therefore allows us to measure key parameters of dark matter and dark energy.

The field-level analysis extracts all information available in the large-scale galaxy distribution; our ultimate goal is to achieve a much more precise measurement of dark matter and dark energy than current state-of-the-art analyses. The latter only compare theory and data at the level of highly-compressed summary statistics (such as the RMS fluctuations as a function of scale). A further advantage of forward modeling is that we can incorporate observational and instrumental effects present in cosmological surveys. One example are redshift-space distortions from the peculiar motion of galaxies. In fact, the peculiar motions allow us to extract additional cosmological information, as they directly probe the growth rate of cosmic structures.

We are continuing to advance the technique to apply it to state-of-the-art cosmological observations, where they will hopefully allow us to better understand dark matter and dark energy. A comparative analysis that we performed recently shows that field-level analysis indeed yields tighter measurements than the standard approach, so stay tuned for some exciting highlights we hope to share soon.

2.5 Understanding the cosmic web: Unveiling the evolution of cosmic filaments with the MillenniumTNG simulation

By Daniela Galárraga-Espinosa (postdoc)

A careful analysis of the filaments in the cosmic large-scale structure has revealed interesting new findings about the evolution and complexities of the cosmic web. While some filaments show a significant evolution – depending on their cosmic environment – global filament properties are preserved, which could be used in future cosmological studies. The MPA team also developed a new method to allow for rigorous calibration of the filament catalogues.

What are cosmic filaments?

In the 1980s, observations of galaxies in regions like the Perseus cluster, the Coma/A1367 supercluster, and the Center for Astrophysics galaxy survey unveiled a fascinating discovery: the universe is structured like a complex network, called the cosmic web. This structure is made of nodes, filaments, walls, and vast voids, intricately woven together. Dark matter and gas, influenced by gravity's pull, sculpt this cosmic architecture, with galaxies serving as markers tracing its features. Since its discovery, the cosmic web has been meticulously mapped by numerous galaxy surveys, each providing unique insights into the structure of the cosmos.

While the dense clusters of galaxies, or nodes, have been thoroughly studied, the less dense and more intricate cosmic filaments remain less understood. Their faint signals make them difficult to observe, as research shows that dark matter density in these filaments is significantly lower than in clusters, complicating their detection in galaxy surveys.

Despite these challenges, cosmological simulations suggest that cosmic filaments contain over 50% of the universe's matter. Understanding these structures is therefore essential for a comprehensive view of the universe, and to know how galaxies form and evolve within this large interconnected web.

New insights from the MillenniumTNG simulation

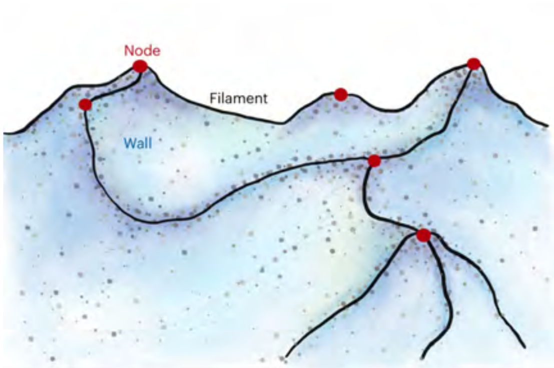


Figure 2.9: Artist's representation of the density field and cosmic web structures, in analogy with a mountain. Gray points illustrate galaxies as tracers of the cosmic web. *(Credit: MPA)*

In this study, MPA researcher Daniela Galárraga-Espinosa, in collaboration with local and international colleagues, has utilized the new state-of-the-art numerical simulation, MillenniumTNG, to delve into the intricate structure of the cosmic web across different epochs of the universe. The hydro-dynamical runs at various redshifts (z = 0, 1, 2, 3, and 4) led to meticulously constructed catalogues of cosmic filaments. This backbone of the cosmic web could then be studied in terms of spatial evolution over cosmic time, as well as lengths, growth rates, and radial density profiles, providing unprecedented insights into the evolution and diversity of these cosmic structures:

1. Unveiling global properties of filament across time: Through careful analysis, the study showed that the filament lengths and density profiles across varying cosmic epochs are remarkably stable. The global population of cosmic filaments shows only minimal evolution over a span of approximately 12.25 billion years.

2. Tracking individual filaments: For the first time, the study has associated a large number of filaments across different redshifts, following the evolution of individual structures across time. While some filaments can significantly contract or elongate with time, the global filament properties are preserved. The team therefore plans to use fundamental filament properties for cosmological analyses in the next study.

3. Understanding cosmic filament diversity: The study also highlights the differences between filament populations at a specific time. At all redshifts, the longest filaments exceed 100 megaparsecs, two orders of magnitude longer than the shortest ones. In addition, these extreme-length filaments have very distinct density profiles. Complementing previous research, the study indicates that environmental factors could drive this diversity: filaments in high-density regions collapse and shorten over time, while those near cosmic voids expand as the cosmic web stretches.

4. Towards more robust filament catalogues: The team developed a method anchored in physical principles to allow for rigorous calibration and testing of the identified cosmic skeletons. This methodology will hopefully inspire future investigations to adopt similar ro-

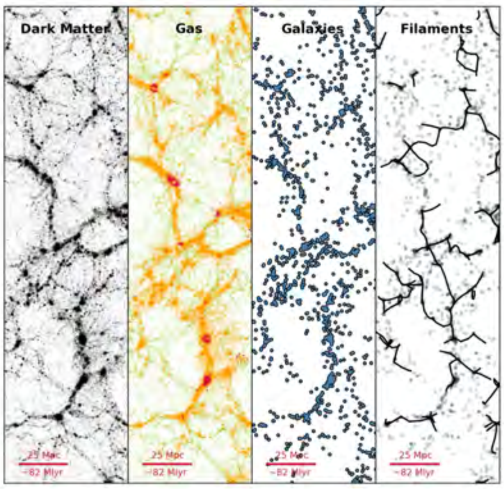


Figure 2.10: Distribution of different matter components revealing the web-like structure of the large-scales of the Universe, the Cosmic Web (simulated image). *(Credit: MPA)*

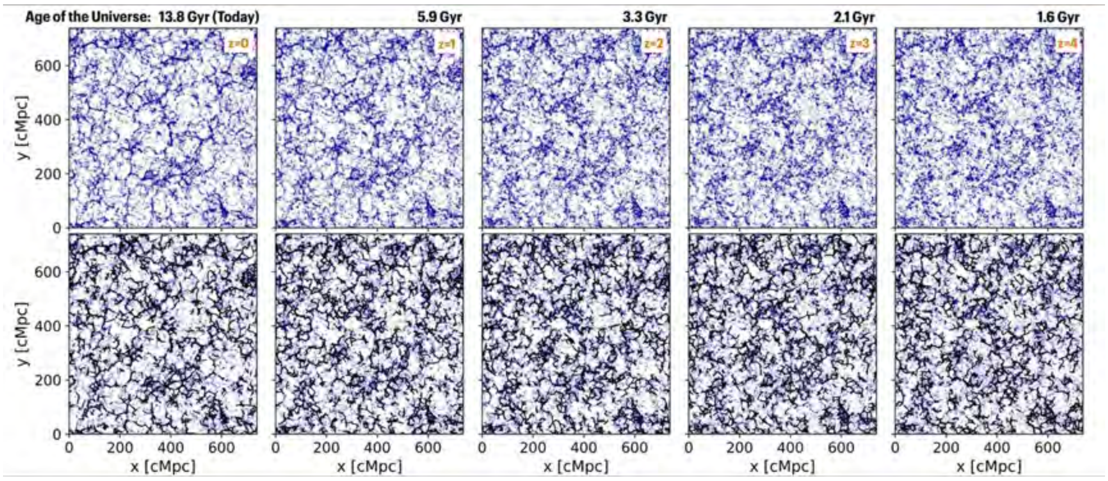


Figure 2.11: Slices of the MilleniumTNG simulation showing the galaxy distribution (top) and the associated filaments (bottom) at different cosmic times. *(Credit: MPA)*

bust approaches, fostering a more unified understanding of cosmic filament detection techniques within the scientific community.

These discoveries represent major advancements in our understanding of the Universe's large-scale structure and open new avenues for exploring the complexities of the cosmic web.

2.6 Explaining the density profiles of dark matter halos with neural networks

By Luisa Lucie-Smith (postdoc)

Can machine learning make new discoveries in astrophysics? An 'explainable' neural network is employed to get insights into the origin of dark matter halo density profiles. The network discovers that the shape of the profile in the halo outskirts is described by a single parameter related to the most recent accretion of mass. This is done without prior knowledge of the halo's evolution history being provided during training.

Artificial intelligence (AI) has rapidly emerged as a powerful tool in astrophysics and cosmology. Typical uses of machine learning in cosmology include emulating the output of computationally expensive cosmological simulations, or accelerating the estimation of cosmological parameters from data. These approaches effectively treat machine learning models as "black boxes": humans cannot understand the inner workings of these complex deep learning algorithms involving often millions of parameters. However, only by understanding how machine learning models reach their predictions can scientists trust AI tools in scientific applications. MPA research fellow Luisa Lucie-Smith's research has focused on developing explainable machine learning frameworks for cosmological structure formation. In these frameworks, the machine learning results can be interpreted and explained in terms of the physics they represent. Luisa Lucie-Smith and her international colleagues designed a neural network, denoted an interpretable variational encoder (IVE), that generates a low-dimensional, compressed 'latent' representation of the input data. This latent representation captures all the relevant information about the final output of

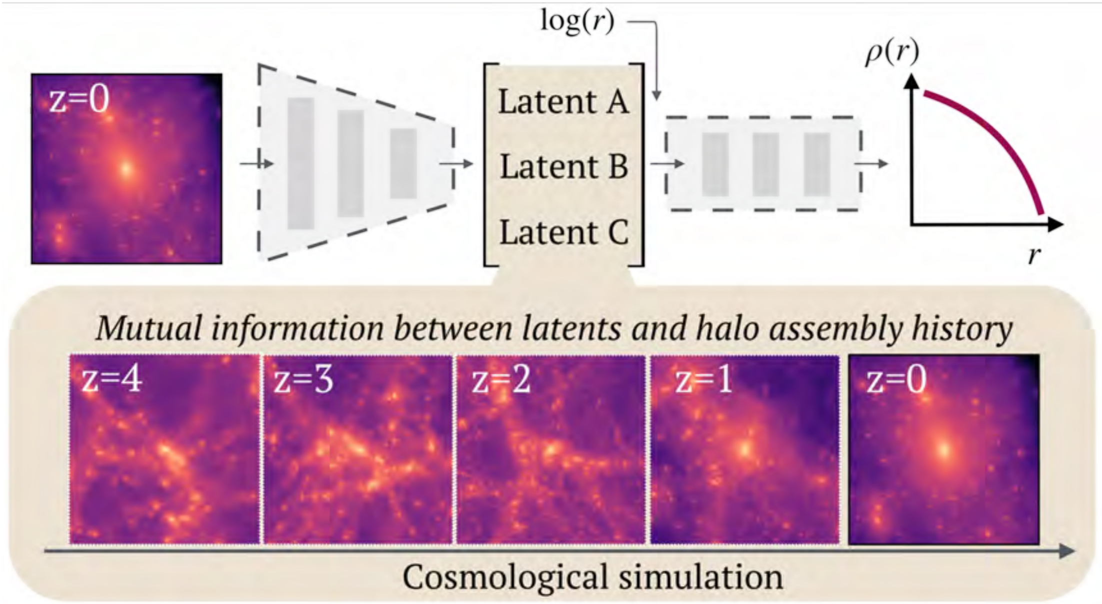


Figure 2.12: A neural network is trained to discover the underlying degrees of freedom in halo density profiles within a low-dimensional latent representation, when presented with the full 3D density structure of a halo at the present-day time (z=0). We physically interpret the discovered representation in terms of the halo's evolution history by measuring the mutual information (MI) between the latent parameters and the assembly history of the halos. *(Credit: MPA)*

interest, and can be physically interpreted using the information-theoretic metric of mutual information (MI).

The team first applied the IVE method to discover the building blocks of the density profiles of dark matter halos. Halo density profiles are not only key ingredients of the galaxy-halo connection in cosmological analyses and of direct and indirect dark matter searches; they are also powerful observational testbeds of fundamental physics. This is because their shape, from the inner core to the outskirts, is sensitive to the nature of dark matter and modifications to gravity. However, on the theoretical side, models of halo density profiles still rely solely on empirically found fitting functions. Observationally, it has recently become possible to measure weak lensing and 3D density profiles through a combination of multi-wavelength data; our ability to make use of these measurements requires a more complete understanding of the physical effects that control the shape of the density profiles and their origin.

Given the 3D density structure of a dark matter halo at the present-day time (z=0), the IVE discovered that a three-dimensional latent space is required and sufficient to describe the density profiles of halos out to their outskirts, beyond the radial range of validity of traditional fitting functions such as Navarro-Frenk-White (NFW) profile (Figure 2.12). The three-dimensional latent space is disentangled, meaning that each latent parameter captures an independent factor of variation in the halo density profile. Two latent parameters consist of a normalization and an inner shape parameter similar to the two parameters of the NFW profile; the third, additional latent describes the shape of the profile in the halo outskirts. The team then exploits the latent space beyond its original training task, to connect the evolutionary history of dark matter halos with their density profiles. Without any

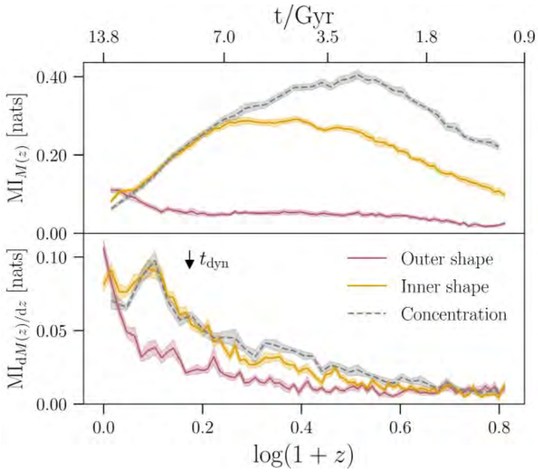


Figure 2.13: The MI between the latent parameters and the halo mass as a function of time (top row), and that between the latent parameters and the rate of change in mass as a function of time (bottom row). The inner shape latent and the NFW concentration carry memory of the early-time mass assembly history, as well as the later-time mass accretion rate. The outer shape latent carries information about the halos' most recent mass accretion rate over the past dynamical time (indicated by the arrow). *(Credit: MPA)*

prior knowledge of the halos' evolution being provided during training, the network recovers the known relation between early formation time and the shape of the inner profile. It additionally discovers that the outer profile, which can be described by a single degree of freedom, is sensitive to the halo's most recent mass accretion rate (Figure 2.13).

The results of this study represent progress towards enabling new machine-assisted scientific discoveries, going beyond artificial rediscovery of known physical laws as presented so far in the literature. The IVE approach towards this goal consists of compressing the information within a dataset into a set of minimal ingredients which disentangles the independent factors of variation in the output (interpretability), and can be explained in terms of the physics it represents through MI (explainability).

2.7 How do Lyman-alpha photons escape from Galactic Labyrinths?

By Silvia Almada Monter (PhD student) and Max Gronke (scientific staff)

With the recent advancements in the Lyman-alpha observations, it becomes more and more important to have theoretical models to help us decode the intricate Lyman-alpha spectral line. Scientists at MPA developed a theoretical approach to describe the escape of Lyman-alpha from scenarios where there is an empty hole to emulate the porous gas around galaxies.

Hydrogen is the most abundant element in the Universe, so it is no surprise that its first transition from an excited state to the ground state is crucial for studying the cosmos. This transition, known as the Lyman-alpha spectral line, lies in the ultraviolet region of the electromagnetic spectrum with a resting wavelength of 1215.67 angstroms. Over 50 years ago, Partridge and Peebles first highlighted the importance of Lyman-alpha for studying the high-redshift Universe, recognizing its brightness as particularly effective for detecting the most distant galaxies and learning about their formation.

Since then, scientists have made significant efforts to observe it through instruments like MUSE on the Very Large Telescope (VLT). The most recent step in this development came through the launch of the James Webb Space Telescope (JWST), which has revolutionized the observation of Lyman-alpha and opened new doors for exploring the high-redshift Universe. Alongside the observational data, there is a growing need for theoretical models to describe and interpret this spectral line fully.

Just like galaxies, the gas around them is highly anisotropic. It is subject to phenomena such as galactic outflows induced by supernova explosions. These outflows often clear out gas, creating low-density channels or holes and making the gas porous, facilitating the escape of radiation from the host galaxy. The study of Lyman alpha emission in this environment is particularly interesting as it provides information about the distribution and state of hydrogen in the Universe. Furthermore, in the Epoch of reionization, these holes and their signature in the Lyman-alpha profile could explain how ionizing photons escaped to reionize the Universe.

With all this in mind, a group of scientists at MPA led by PhD student Silvia Almada Monter performed a theoretical study of the behavior of Lyman-alpha photons in a slab filled with neutral gas in the presence of a simple empty hole. While this setup does not fully represent the complex gas geometry in real galaxies, boiling this problem down to the essentials helped to formulate a theory and understand how Lyman-alpha photons escape even in more complicated setups. This theoretical study was backed by Monte-Carlo radiative transfer simulations, which are known to yield highly accurate numerical results by tracking individual photon "packages" in space (and frequency). Despite the seemingly straightforward setup, these simulations revealed an unexpected and puzzling result.

The puzzle: Walls or windows?

In a high-density medium, Lyman alpha photons diffuse in frequency due to Doppler shifts caused by the thermal motion of hydrogen atoms, resulting in a double-peak line. Conversely, in low-density environments, Lyman alpha behaves as a single-peaked line (like in the video). However, the probability of photons escaping through very dense gas is much smaller than the probability of them finding the hole and escaping through it with no resistance, as the hole is empty. This reasoning naively leads to the thought that the emerging Lyman-alpha from the slab with a pinched hole would be a centered single-peaked line because most of the light we see should have escaped through the hole.

The solution: The Gambler's Ruin and the Fall of a Goat.

We know this phenomenon when we see the light through a window: if the window is clean, the light gets through without any resistance, while a wall blocks the light completely. Similarly, in galaxies, abundant neutral hydrogen should act like a wall, completely stopping light from escaping, while empty channels should behave like clean windows, allowing light to escape effortlessly. In other words, one would expect all Lyman-alpha photons to escape through the low-density channel (window) and not through the wall (high-density gas). Surprisingly, the theoretical and simulation results are out of common sense. They found triple-peaked spectra: the expected two peaks emerge from the high-density gas, while a central peak exits from the empty channel. Lyman alpha photons escape not only from the path of least resistance (the window) but also somehow manage to get through the thick wall! How is this possible?

After examining the interaction of Lyman alpha photons with the gas, specifically their transmission and reflection, the MPA scientists solved the riddle. Due to the high column densities (the wall), most Lyman alpha photons are reflected upon encountering the gas. However, instead of simply bouncing out like ping-pong balls, they penetrate the gas, scatter, and then are reflected. How many times do they scatter? To answer this question, imagine a goat standing one step to the right of a cliff. The goat can either move right and fall or go left and survive. It makes this decision consecutively, performing a random walk until it reaches a safe place or falls to the cliff. The scenario of the goat falling off the cliff after having a random walk is an analogy for a photon scattering in the gas before being reflected. This problem is also known in statistics as 'The Gambler's

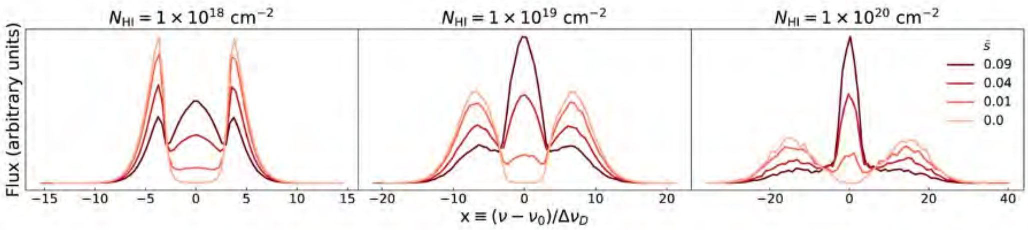


Figure 2.14: Lyman-alpha unexpected triple-peaks emerge from a setup of a slab with a hole. Different colors indicate different hole sizes and the gas is more dense in the panels from left to right. *(Credit: MPA)*

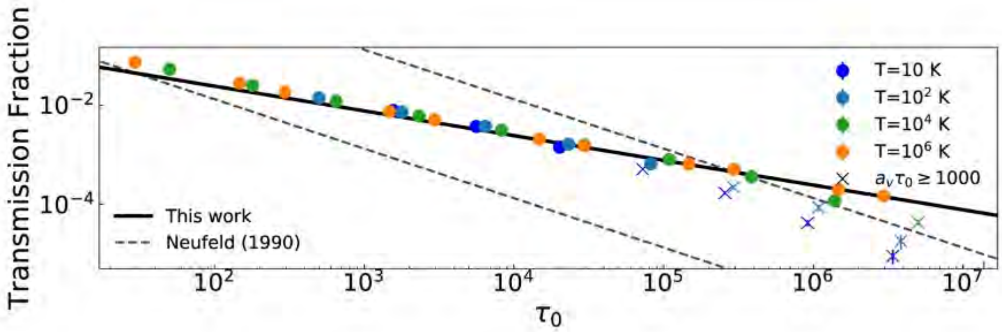


Figure 2.15: The transmission fraction of the simulations (data points) aligns better with the new theoretical approach (solid line) than with the previously expected theoretical one (dashed lines). As the optical depth grows, the data points start approaching the oldt theoretical approach. *(Credit: MPA)*

Ruin Problem,' where, instead of photons (or goats), a gambler bets one euro on each turn, with the possibility of either winning or losing one euro. In this scenario, the probability of losing all the money (or the goat falling off the cliff/the photon being reflected) is 100%. Thus, eventually, all gamblers and goats face an unfortunate destiny. However, the expected time to reach this destiny is infinite! The gambler has no time limit to bet, the goat has no time limit to walk, and the photon has no time limit to scatter. Hence, it scatters many, many times.

This mathematical result directly affects the escaping Lyman-alpha photons and is the key to explaining the puzzling results. A large number of scattering events increases the chances of the photon shifting in frequency and mean free path enough to 'jump' the wall instead of crashing against it. Many more photons manage to pass through the high-density gas. After solving the appropriate diffusion equations, the MPA scientists found that the number of scattering events per reflection closely follows a Lévy distribution and is much greater than expected. This result implies that the transmission probability is orders of magnitude greater than anticipated. In the context of the slab with the hole, the probability of photons finding the hole is not as different than the probability of being transmitted through the gas as expected. As a result, the spectrum's double arise simultaneously with the central peak.

According to the literature, the presence of low-density channels in galaxies implies that the Lyman-alpha emission traces only the gas within them. However, these recent results indicate that due to the increased transmission probability, Lyman-alpha photons could trace the gas simultaneously in both high-density regions and low-density channels. In other words, Lyman-alpha can trace more average quantities of gas. Furthermore, it was previously believed that obtaining triple-peaked spectra was only possible with a tiny channel, an assumption that could be relaxed thanks to these findings. Additionally, these results affect the use of Lyman-alpha as a tracer for Lyman Continuum, as ionized channels are a likely escape route.

2.8 How hyper-accreting black holes shape their environment with anisotropic winds

By Eugene Churazov (scientific staff)

Among many X-ray sources in our Galaxy, the one called SS 433 (as an entry number 433 in the catalog of Halpha emitters by Stephenson & Sanduleak 1977) is especially famous and peculiar. It is likely powered by a black hole in a massive binary system. The accretion rate on this black hole from its companion star is hundreds of times higher than the critical value known as the Eddington limit (when the pressure of produced radiation becomes so great that it can eject matter and form powerful “winds” of the accretion disk). The new model discusses the impact of such winds on the surrounding interstellar medium. In particular, this wind can inflate the giant W50 nebula, encompassing SS 433 and spanning tens of parsecs in size. A similar situation may occur for rapidly growing massive black holes at the dawn of the Universe, galaxies with extreme nucleus activity and star formation rates during the “Cosmic Noon” (when the Universe was about 2-3 billion years old), or in the most extreme ultra-luminous X-ray sources in normal star-forming galaxies today.

By now, millions of X-ray sources are known throughout the sky. The names of several dozen of them are known to almost all astronomers and astrophysicists. Among them is the microquasar SS433 in our Galaxy, a unique object in all parts of the electromagnetic spectrum from radio waves to ultra-high-energy photons. Since the late 1970s, it was known that this microquasar ejects narrow jets of matter, the speed of which is approximately a quarter of the speed of light, and the direction strictly periodically changes in time like a precessing top! Although such a picture was predicted and considered in pioneering works on accretion theory (Shakura & Sunyaev 1973), and since its discovery, several thousand works have been devoted to the study of this source, there are still no generally accepted answers to numerous questions about the structure of the super-Eddington flow of matter onto a black hole and the mechanism for launching the jets.

Similarly impressive and puzzling is the radio nebula W50 surrounding SS433 (Figure 2.16), the origin of which also remains open. Its shape has made another name popular - “Manatee Nebula”. The formation of a close binary system of a massive star + a black hole is preceded by a supernova explosion, which accompanies the formation of a black hole. It is usually believed that the quasi-spherical part of the nebula was created by the expanding shell of the supernova. As for the elongated parts of W50, there is no generally accepted model, but it is often assumed that a certain role is played by those very narrow precessing sub-relativistic jets of matter, although global traces of their deceleration and violent interaction with the environment have not yet been found.

A completely different explanation was recently proposed. Given the gigantic accretion

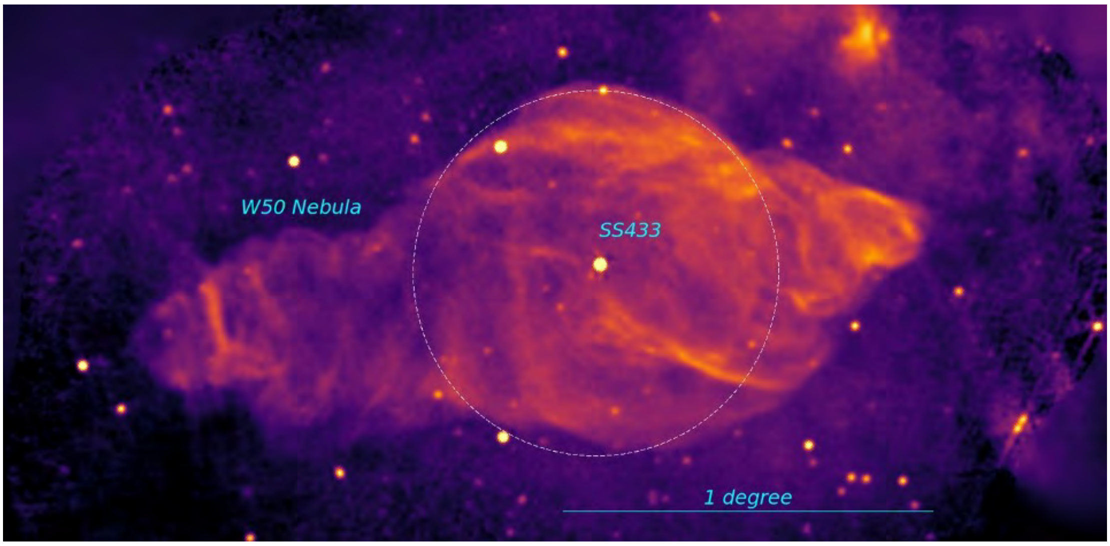


Figure 2.16: ARadio image of W50 nebula. The central bright spot is a hyperaccreting source SS433. The radio nebula (W50), features a quasi-spherical part (indicated by the dashed circle) and two extensions. *(Credit: MPA)*

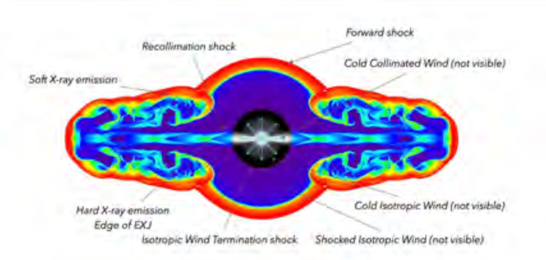


Figure 2.17: Sketch of the W50 model as a combination of isotropic and "polar" winds coming from an accreting black hole. The central region represents a combination of an isotropic wind and a more collimated polar wind aligned with the orbital axis of the binary system. The isotropic wind passes through a termination shock, which converts its kinetic energy into heat, and after that, its increased pressure and density re-collimate in turn the polar wind. The resulting recollimation shocks are capable of accelerating particles to extremely high energies giving rise to the high-energy synchrotron emission from the axial flow. *(Credit: MPA)*

rate onto a black hole, most of the matter should be ejected by radiation pressure, forming a powerful wind with a speed of thousands and even tens of thousands of kilometers per second. The work suggests that this wind is anisotropic, and the entire W50 nebula was created just by the action of such a profiled wind. In this model, the density of the kinetic energy flux in the wind is higher in the direction perpendicular to the plane of the accretion disk and is almost the same in other directions. This explains the shape of the nebula - in the directions where the wind power is higher, the nebula has a more elongated shape (Figure 2.17).

It is remarkable that this assumption also explains the mysterious structures inside the nebula observed at high energies, from keV to TeV. Moreover, the magnetohydrodynamic structure of the anisotropic wind indicates the possibility of efficient acceleration of relativistic cosmic ray protons with petaelectronvolt energies. It is well known how jets of matter behave when interacting with the environment. In astrophysical conditions, such jets arise near supermassive black holes, as well as stellar-mass black holes. When the density of matter in the jets becomes much less than the density of the surrounding gas, shock waves arise that can focus the jets and allow them to propagate over large distances. In the case of SS433, the isotropic part of the wind plays the role of the "environment" for the more collimated part of the wind. It focuses and heats the axial part of the wind, remaining invisible to the observer. As a result, at a large distance from the compact source, a bright structure in the X-ray and TeV range appears "out of nowhere". Depending on the density/velocity contrast between the isotropic and "polar" winds, the morphology of the nebula can change the aspect ratio and its inner structure, but the recollimation shocks are almost always present (Figure 2.18).

If we extrapolate this model to other sources in which the regime of very fast accretion onto a compact object is realized, then we can expect that conditions for effective acceleration of particles in the anisotropic wind can naturally arise in them. As a result, a noticeable share of the released accretion energy is converted into cosmic rays and also stored in a hot multiphase cocoon inside the nebula. The total energy released at this stage of the source's life turns out to be greater than the energy of the explosion of the parent supernova.

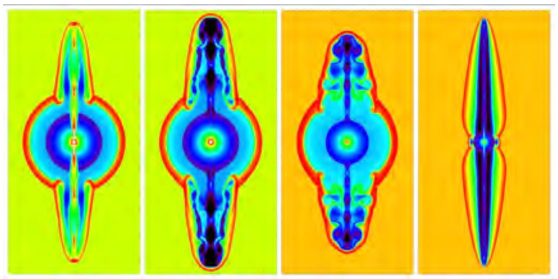


Figure 2.18: Slices of gas density obtained in numerical simulations for different wind configurations. In response to changes in the density contrast between the wind components and/or the wind velocities, the morphology of the nebula changes too. W50 morphology is best reproduced by the two central plots. *(Credit: MPA)*

2.9 How galaxies make black holes collide

By Jakob Stegmann (postdoc)

The groundbreaking detections of gravitational waves from merging pairs of black holes have left us with an intriguing question: how do black holes get close enough to merge? Scientists at MPA show that some of them may have started out as massive stars orbiting one another at extremely large separations — 1,000 to 10,000 times the distance between Earth and Sun. Once these stars end their lives and form black holes, the gravity of the entire galaxy in which they reside could slowly deform the shape of their orbit leading to a close encounter and merger of the black holes. A large fraction of stars are not alone. Observations show that, unlike our Sun, many of them are orbited by a stellar companion and form a so-called binary. The separation at which these binary stars orbit one another closely determines their evolution. On the one hand, stars on very tight orbits are prone to exchange mass leading to a complex interactive stellar evolution. For massive stars, these interactions may leave behind a close binary black hole which could eventually merge due to the energy-loss from gravitational-wave emission. On the other hand, binary stars at wider separations were previously thought to evolve rather unspectacularly, effectively as single stars, leaving behind binary black holes which are too far apart to merge.

In a recent study, published in the The Astrophysical Journal Letters, a group of researchers led by MPA research fellow Jakob Stegmann question this standard lore of binary physics and show that it is only true as long as the binaries are considered to be in isolation. In reality, they are embedded in a galactic environment in which wide binaries separated by more than 1,000 Earth-Sun distances are vulnerable to perturbations from the gravity of the host galaxy

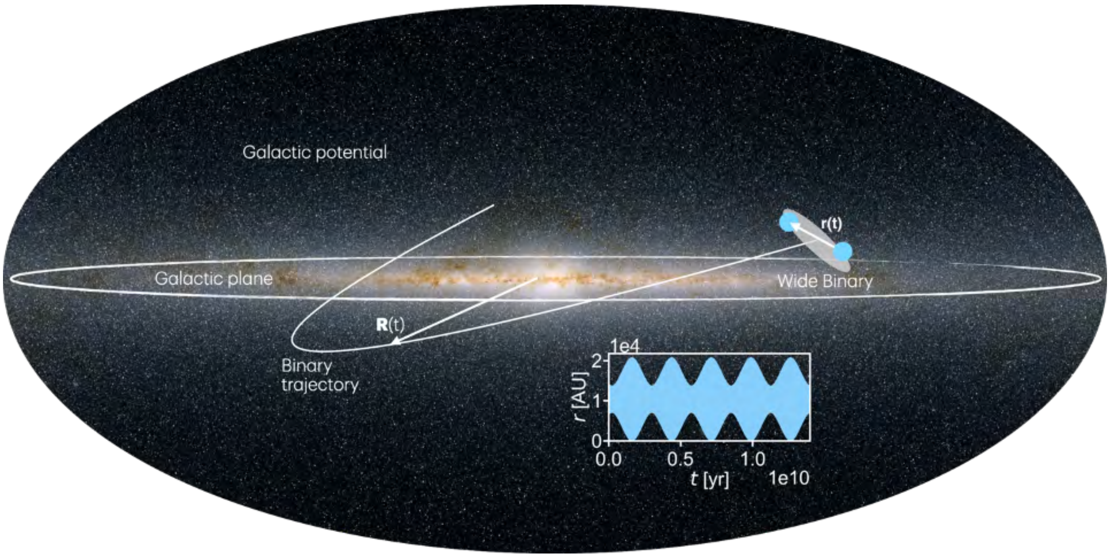


Figure 2.19: Schematic overview of a wide binary orbiting inside the Milky Way. While moving through the Galaxy its ellipticity gets modulated by the gravity of the Galaxy and fly-bys from ambient stars, leading to close encounters (inset). *(Credit: Jakob Stegmann et al 2024 ApJL 972 L19)*

and from fly-bys of ambient stars. Taking into account this galactic influence, the study shows that the dynamics of wide binaries can give rise to extreme interactions between stars and compact remnants.

These interactions are a consequence of the extremely low binding energy that holds very wide binary black holes together. Thus, the gravitational pull of the entire host galaxy can slowly deform the shape of the orbit on which the two black holes move around each other and make it more and more elongated. On these highly elliptical orbits the two black holes remain widely separated for most of the time, but pass close to each other once per orbit (see animation). This leads to a counterintuitive result: In order to bring two black holes closer than a few kilometres so that they can merge, we could nevertheless start with a wide separation of more than 1,000 times the distance between Earth and Sun. The clue lies in the ellipticity of their orbit which slowly grows due to the disturbing effect of the galaxy's gravity.

This mechanism of driving two black holes closer together could also be relevant for the evolution of wide low-mass binary stars. Recently, researchers at MPIA in Heidelberg have searched for wide binaries in the data from the ESA-led mission Gaia. Surprisingly, they found that about ten percent of all low-mass stars possess a distant stellar companion. While systems like those are not massive enough to develop black holes, in this case the MPA study shows that the gravity of the galaxy could drive the stars to a head-on collision. These collisions would not lead to detectable emission of gravitational waves, but could be visible as energetic flares, so-called Luminous Red Novae.

The results of this study represent progress in investigating the plethora of evolutionary pathways of binary stars and their compact remnants. While previous work on wide binaries has mostly focused on ruling out the existence of a distant companion to our Sun (referred to as the "Nemesis hypothesis"), on the one hand, and understanding the upper limit of their separation to remain bound, on the other hand, little attention has been paid to studying the interactions between wide binary stars. With future data releases of Gaia expanding the catalogue of wide binary stars at an unprecedented rate, the MPA study makes an important step towards understanding their co-evolution with the Milky Way. Investigating their dynamics in detail allows us to understand how systems previously thought uneventful could in fact lead to some of the most energetic transients in the Universe.

2.10 Rapidly merging stars and black holes - the birth of supermassive black holes in dense star clusters in the early Universe

By Antti Rantala (postdoc), Natalia Lahén (postdoc) and Thorsten Naab (scientific staff)

New observations by the James Webb Space Telescope (JWST) have revealed that supermassive black holes (SMBHs) of more than one million solar masses were already present only 450 million years after the Big Bang. How did these first SMBHs form? A team of researchers at MPA has used modern supercomputer simulations to show that progenitors of SMBHs (seeds) of a few thousand solar masses can form rapidly in dense and structured star clusters forming in the early Universe. They emerge from collisions of massive stars which form supermassive stars and then collapse directly into black holes, which can further grow by merging with other black holes. This new and more realistic model resembles JWST observations and can explain the formation of SMBH seeds which are massive enough to further grow into the earliest SMBHs observed. For this SMBH seed formation process, the researchers predict a unique gravitational wave fingerprint from black hole merger that can be directly tested with the next-generation gravitational wave observatories.

Supermassive black holes (SMBHs) with masses exceeding one million solar masses are found in all nearby massive galaxies including our own Milky Way. New observations by the James Webb Space Telescope (JWST) have revealed that SMBHs were already present only 450 million years after the Big Bang. The origin of these most massive black holes in the Universe is a major unsolved puzzle in modern astrophysics and an active area of research. The very first stars in the Universe may have left behind black holes with masses up to a few hundred solar masses. However, models with such ‘light’ SMBH seeds struggle to explain the observed high redshift population of accreting SMBHs. The maximum sustainable SMBH gas accretion rate, the so-called Eddington rate, places limits on how fast SMBH seeds may grow after their formation. The light SMBH seeds simply do not have enough time to grow enough only in a few hundred mil-

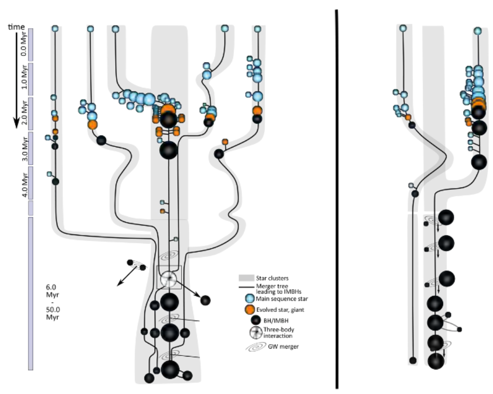


Figure 2.20: The complex formation channel of a supermassive black hole with 2200 solar masses. Six sub-clusters in the collapsing region contribute stars and black holes for the forming massive star cluster. Many stellar collisions (red and blue circles) rapidly form a 2025 solar mass black hole within only a few million years. Thereafter the black hole grows by mergers with other, smaller, black holes and by tidally disrupting stars. Some lower mass black holes are ejected by gravitational recoil kicks. *(Credit: MPA)*

lion years. Therefore, more popular theoretical SMBH formation models assume that the SMBH seeds formed ‘heavy’ with masses exceeding a thousand solar masses. These heavy seeds black holes have a head start against the light seeds in their growth into the observed population of early accreting SMBHs. The major proposed heavy seed formation scenarios include runaway stellar collisions in dense star clusters, directly collapsing metal-free gas clouds in atomic cooling halos, and more exotic ‘new’ physics such as primordial black holes. In dense star clusters, repeated stellar collisions may build up very massive and even supermassive stars. In early Universe which is still little enriched with heavy elements, stellar winds are typically weak and the stellar collision products will retain most of their mass. At the ends of their lives, these collisionally formed supermassive stars collapse and form the seeds for SMBHs.

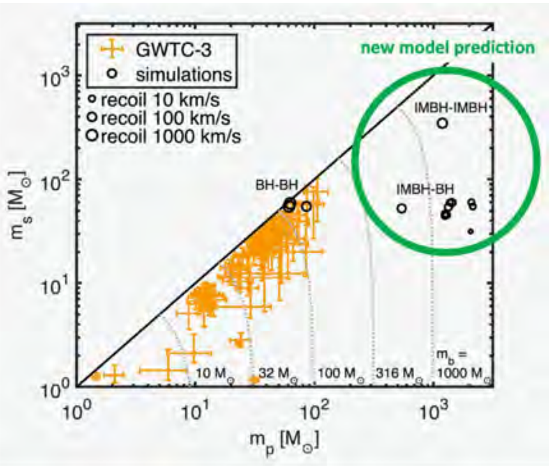


Figure 2.21: Primary and secondary masses of black holes merging in early star clusters by the emission of gravitational waves from the simulation (black circles). Observed gravitational waves from black hole mergers are indicated by yellow crosses (Advanced LIGO and Advanced Virgo). The model predicts mergers of 1000 solar mass black holes with several 10 to 100 solar mass black holes which can be detected with the next generation gravitational wave telescopes like the Einstein Telescope or LISA. *(Credit: MPA)*

Past simulations had focused on studying isolated, spherical star clusters. Both the JWST observations and state-of-the-art hydrodynamical galaxy formation simulations instead support the picture that massive star clusters form through a complex hierarchical assembly. This was the key motivation for the researchers at the MPA to re-explore the runaway collisional SMBH seed formation scenario in the more realistic clustered setup. Such a scenario is very different to the direct collapse gas cloud scenario which relies on avoiding cloud cooling and fragmentation into clusters of stars.

The researchers performed new simulations of massive star clusters with several million individual stars forming from the rapid assembly of several hundred proto-clusters. The newly developed direct N-body simulation code BIFROST used for the simulations runs on energy-efficient GPU hardware can follow stellar evolution, stellar mergers and accurately accounts for general relativistic effects during the interaction of black holes. In particular, the code computes the gravitational wave emission when two black holes merge. At the end of the merger anisotropic gravitational wave emission can kick the newly formed black holes up to speeds of several thousand km/s. These gravitational wave recoil kicks which can eject black hole merger remnants from their birth clusters are also modeled with the code.

The collision pathways massive stars and the formed SMBH seeds are illustrated in (Figure 2.20) Typically, only the most massive star in sub-clusters grows rapidly by collisions with other massive stars. Once the stars exceed the mass of several hundred solar masses, stellar evolution models predict that they directly collapse into black holes at the end of their lives. After their formation, the several SMBH seeds in the assembled massive star cluster experience a rich history of interactions and mergers by which the SMBH seeds can further grow.

Several black holes are ejected from the cluster through strong Newtonian few-body interactions or relativistic gravitational wave recoil kicks. The hierarchical runaway scenario predicts a population of gravitational wave mergers at high redshifts in which the SMBH seeds merge with stellar mass black holes of several 10 to 100 solar masses (Figure 2.21). Current gravitational wave observatories cannot detect black hole mergers above 500 solar masses or high redshifts very well. However, the scenario of the MPA researchers can be tested with the next-generation gravitational wave experiments such as LISA and the Einstein Telescope.

The authors thank Markus Rampp and Klaus Reuter of the Max Planck Computing and Data Facility (MPCDF) for performance optimization of the BIFROST GPU code. The simulations for the study were run using the MPCDF supercomputer Raven in Garching.

2.11 Field-Level Inference: Unlocking the Full Potential of Galaxy Maps to Explore New Physics

By Fabian Schmidt (scientific staff), Beatriz Tucci (PhD students) and Minh Nguyen (KAVLI, IPMU, University of Tokyo)

Galaxies are not islands in the cosmos. While globally the universe expands – driven by the mysterious 'dark energy' – locally, galaxies cluster through gravitational interactions, forming the cosmic web held together by dark matter's gravity. For cosmologists, galaxies are test particles to study gravity, dark matter and dark energy. For the first time, MPA researchers and alumni have now used a novel method that fully exploits all information in galaxy maps and applied it to simulated but realistic datasets. Their study demonstrates that this new method will provide a much more stringent test of the cosmological standard model, and has the potential to shed new light on gravity and the dark universe.

From tiny fluctuations in the primordial Universe, the vast cosmic web emerged: galaxies and galaxy clusters form at the peaks of (over)dense regions, connected by cosmic filaments with empty voids in between. Today, millions of galaxies sit across the cosmic web. Large galaxy surveys map those galaxies to trace the underlying spatial matter distribution and track their growth or temporal evolution.

Observing and analyzing millions of galaxies turns out to be a daunting task. Hence, standard analyses first compress the three-dimensional galaxy distribution into measurements of the spatial correlation between pairs and triplets of galaxies, technically known as the two- and three-point correlation functions (Figure 2.22).

These restricted statistics, however, potentially leave out a lot of information in galaxy maps, especially information encoded on smaller spatial scales. In addition, they do not tell us where in the maps to look further, should some surprising result turn up in these statistics. How much more information can be extracted? A recent study in Physical Review Letters by MPA researchers and alumni, led by Dr. Minh Nguyen, provides compelling evidence for significant information beyond the reach of two- and three-point functions.

For the study, the team have developed and validated a rigorous probabilistic framework, LEFTfield, to model the clustering of galaxies. How the LEFTfield framework leverages the Effective Field Theory of Large-Scale Structure (EFTofLSS) to produce robust and accurate predictions of the observed galaxy field with high efficiency was the topic of another MPA research highlight. LEFTfield fowardmodels the evolution of primordial fluctuations into large-scale structure and galaxy clustering, preserving the entire information in the three-dimensional distribution of galaxies. Further, the LEFTfield forward model is differentiable,

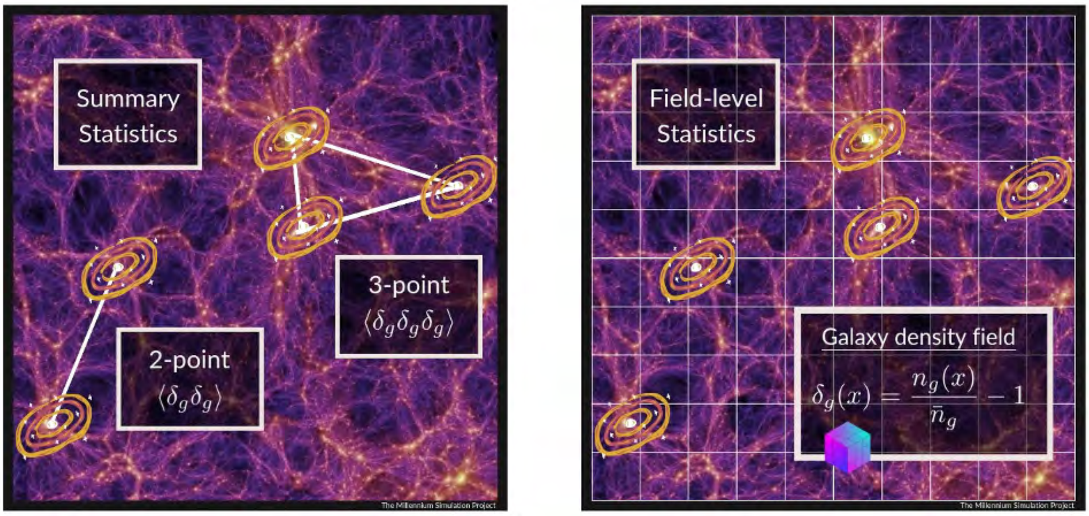


Figure 2.22: Summary statistics like the two- and three-point correlation functions compress the galaxy field into spatial correlations between pairs and triplets of galaxies (left panel). Field-level statistics bypass the compression step to access the entire information in the galaxy field. *(Credit: MPA)*

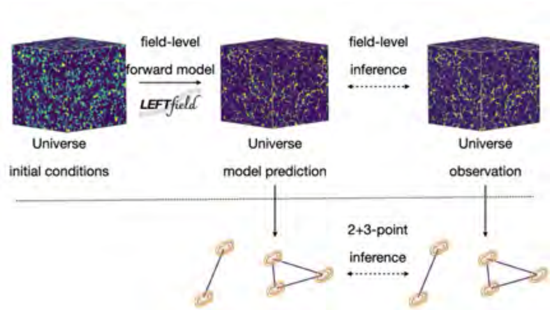


Figure 2.23: The comparison between FLI and 2+3-point inference adopts the same forward model, LEFTfield, for both inference schemes. The key difference is FLI analyzes the entire galaxy field while 2+3-point inference analyzes only the 2+3-point summaries of the (same) galaxy field. *(Credit: MPA)*

allowing for field-level inference (FLI) of both parameters in the cosmological model and the primordial fluctuations from which all structure in the Universe emerged.

In the study, the team set up an apples-to-apples comparison between FLI and the standard two-point plus three-point ('2+3-pt') inference. Both inference pipelines adopt the same LEFTfield forward model, and use the observed maps on strictly the same scales, as illustrated by Figure 2.23

Analyzing the same catalogs of dark-matter halos from the same set of N-body simulations, the team found that FLI improves constraints on the amplitude of structure growth by a factor of 3-5, even with conservative scale cuts in both analyses. The improvement implies that even without agressively pushing down to very small scales – where we expect EFTofLSS or even N-body simulations to fail – much more information can still be extracted from galaxy clustering simply by opening up another dimension: getting rid of the compression of the input data.

Figure 2.24 compares the constraints on the amplitude of structure growth from the FLI and '2+3-pt' analyses. The parameter σ_8 quantifies the typical amplitude of structure in the initial ("linear") density field on a certain scale. Essentially, galaxy clustering constraints on σ_8 probe the growth of structure from the early universe (where we have precise measurements thanks to the cosmic microwave background) to late times. For this reason, this is a parameter

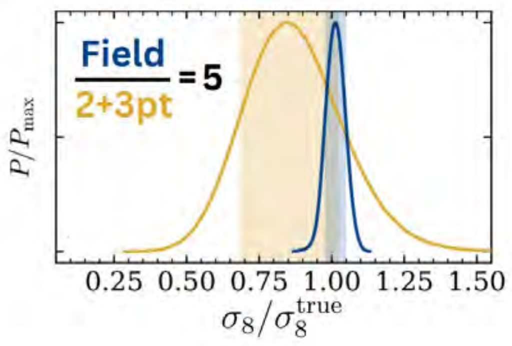


Figure 2.24: Constraints on the amplitude of growth of structure σ_8 are improved by up to a factor of 5 when analyzing the whole galaxy field compared to just the 2- and 3-point correlation functions. *(Credit: MPA)*

that is generally modified in non-standard cosmological models, for example if gravity is not correctly described by General Relativity, or if dark matter is not cold.

A factor of 5 improvement in parameter constraints effectively 'increases' the survey volume by more than an order of magnitude, which is a huge improvement given the time-consuming and expensive process of mapping out the galaxy distribution over a large volume. Moreover, FLI in principle guarantees optimal extraction of cosmological information: there is no data compression, hence no information loss.

While this study used dark matter halos in simulations, the conclusions also hold for significantly more realistic simulated galaxies, which were the subject of a parallel study by the Beyond-2pt Collaboration that includes two researchers from the MPA team, the FLI approach based on the LEFTfield framework again returns unbiased and improved constraint on growth of structure.

Beyond improved parameter constraints, FLI also offers numerous ways to find out where evidence for physics beyond the standard model of cosmology might come from, should such evidence appear. Since we have samples of Universes that are compatible with the data, we can look for those regions most strongly deviant from the standard model, and investigate what is unusual about them. We can also employ independent datasets, for examply by correlating the inferred matter density with gravitational lensing maps, which are an entirely different probe of structure.

The team now set their eyes on applying the novel FLI approach and LEFTfield framework to real data from galaxy surveys. To connect FLI to observations, a better understanding, hence more studies, of how observational systematics impact the model predictions at the field level will be required. A flexible-yet-efficient foward-modelling framework like LEFTfield will be the key for such studies, and for unlocking the full potential of FLI from galaxy maps.

2.12 ESA gives go-ahead for flagship gravitational-wave observatory in space

By Valeriya Korol (postdoc) and Selma de Mink (scientific director)

LISA, the Laser Interferometer Space Antenna, has passed a major review with flying colours: the entire concept – from the definition of the overall mission and operations to the space hardware to be built – stood up to the intense scrutiny of ESA's reviewers. Now the space agency's Science Programme Committee (SPC) has confirmed that LISA is sufficiently mature and that mission development can proceed as planned. LISA should go into orbit in the mid-2030s.

"LISA is such an incredible and unique mission; there is such a variety of sources that can be probed with it," says Valeriya Korol, postdoctoral fellow at the Max Planck Institute for

Astrophysics (MPA) and co-chair of the LISA Astrophysics working group. “We will be able to look at binaries of stellar remnants within our own Galaxy, in-spiralling compact objects onto massive black holes at larger distances and all the way to mergers between nascent massive black holes in the early Universe.”

LISA will detect gravitational radiation in the yet unexplored window between 0.1 mHz and 1 Hz, waves that cannot be detected by ground-based detectors. Waves in this frequency range are created in the collision and merger of two massive black holes, a million or more times heavier than our Sun, lurking at the centres of distant, still forming galaxies. LISA will be sensitive to these mergers across the Universe’s history, directly probing the yet unknown origin and growth of massive black holes. Unique to LISA is the detection of gravitational waves from stellar black holes swirling around massive ones in galactic nuclei, to probe the geometry of space-time and test gravity in its foundations. LISA will also detect a large number of binary and multiple compact objects in our Milky Way galaxy to tell us about stellar binary evolution, and ”see” the Galaxy beyond the Galactic Centre, including many objects invisible to all other astronomical instruments.

Numerous scientists at MPA are already preparing for science with LISA. The primary focus here is on predicting the characteristics of the signals that LISA will detect from galactic binaries, which include white dwarfs, neutron stars, and black holes. Astronomers already know that these objects exist in our Milky Way, and they will probably outnumber other types of sources LISA will encounter. This effort is crucial for developing LISA data analysis methods, interpreting data accurately, and devising strategies for electromagnetic follow-up observations.

“We have already seen gravitational wave signals from ground-based observatories – going into space opens up a whole new window,” emphasizes Selma de Mink, director of the stellar department at MPA. “This will be a totally new way to learn about black holes in our own galaxy and to better understand the stellar sources that are generating gravitational waves.” The LISA instrument is a first of its kind space borne gravitational wave observatory. It will consist of three spacecraft in a triangular configuration with 2.5-million-kilometre arms, moving in an Earth-like orbit around the Sun. Gravitational waves from sources throughout the Universe will produce slight oscillations in the arm lengths (smaller than the diameter of an atom). LISA will capture these motions and thus measure the gravitational waves by using laser links to monitor the displacements of test masses free-falling inside the spacecraft.

“With the Adoption decision, LISA is now firmly established in ESA’s programme of missions. We are looking forward to realising LISA in a close collaboration of ESA, NASA, ESA member states and the wider LISA Con-

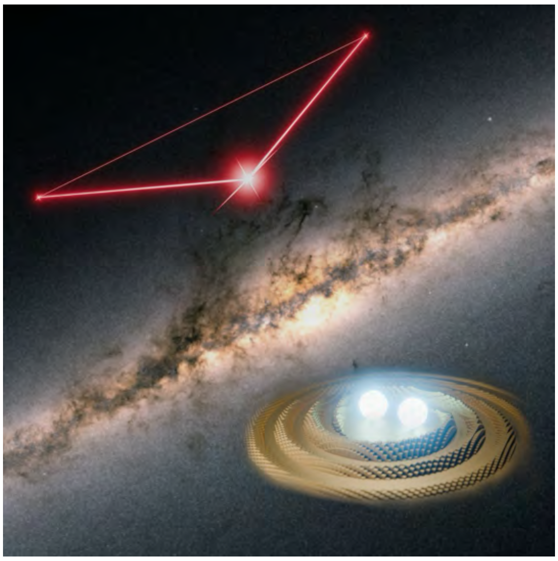


Figure 2.25: Artist’s impression of the LISA triangle arrangement and an illustration of gravitational waves produced by two closely orbiting white dwarf stars superimposed on an optical image of our Milky Way. *(Credit: R.Valli, MPA / background image: ESA/Gaia/DPAC)*

sortium" says Karsten Danzmann, Lead of the LISA Consortium, Max Planck Institute for Gravitational Physics and Leibniz University Hannover. "This trailblazing mission will take us to the next level in a really exciting area of space science and keep European scientists at the forefront of gravitational wave research," adds ESA Director of Science Carole Mundell.

2.13 Black-hole binary tests supernova theory

By Alejandro Vigna-Gómez (postdoc), Daniel Kresse (postdoc), and Hans-Thomas Janka (scientific staff)

Observations of a newly discovered binary star system combined with advanced models of stellar collapse have provided key insights into the formation of stellar mass black holes. A team of international researchers at the Max Planck Institute for Astrophysics and the Niels Bohr Institute (NBI), University of Copenhagen, conclude that massive black holes can form without a bright supernova explosion. The energy from the collapse is carried away mainly by lightweight neutrino particles with only small asymmetry, leading to a small natal kick for the black hole.

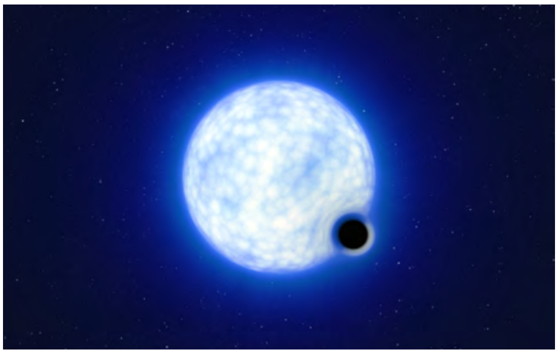


Figure 2.26: This artist's impression shows what the binary system VFTS 243 located in the Tarantula Nebula in the Large Magellanic Cloud might look like if we were observing it up close. The sizes of the two binary components are not to scale: in reality, the blue star is about 200 000 times larger than the black hole. Note that the 'lensing' effect around the black hole is shown for illustration purposes only, to make this dark object more noticeable in the image. *(Credit: ESO/L. Calçada)*

For decades, we have known about the existence of binary star systems in the Milky Way, where one of the stars is a black hole. "The discovery of black-hole binary VFTS 243 in our neighbouring Large Magellanic Cloud was extraordinary, and the system itself is remarkable," says Alejandro Vigna-Gómez, who was a postdoctoral researcher at NBI when the detection of VFTS 243 was announced, and is now based at the Max Planck Institute for Astrophysics (MPA). The binary system consists of a star with 25 times the mass of the Sun and a companion black hole 10 times the mass of the Sun.

Supernova Explosions

Stars that are several times more massive than the Sun end their lives in powerful and luminous explosions known as supernovae. The collapse of the dense metal core of the massive star releases a large amount of energy, mostly in neutrinos, while the outer layers of the star are expelled into outer space. This material can amount to many times the mass of the Sun and is ejected with velocities of hundreds to thousands of kilometres per second, leading to large-scale asymmetries of the ejected matter that we also observe in the remnants of the explosions.

These asymmetries and mass ejecta directly affect the very dense remnant at the core, the newly formed neutron star, which experiences a recoil – a natal kick – that can abruptly change its velocity. There is plenty of evidence of these natal kicks for neutron stars, as we observe them moving at large speeds throughout the Milky Way. However, for the most massive compact objects known, black holes, these natal kicks are not well understood. Such stel-

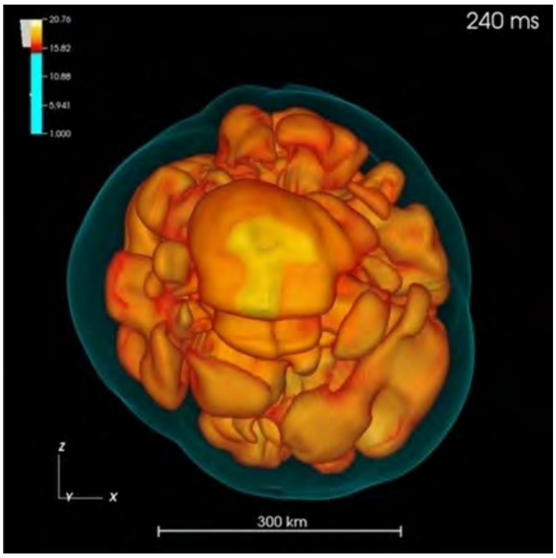


Figure 2.27: Snapshot of a three-dimensional simulation of a supernova based on a stellar model with mass 11.2 times heavier than the Sun. Convective overturns are visible as neutrino-heated matter expands in mushroom-like buoyant plumes. *(Credit: Tamborra et al. 2014)*

lar black holes form in the collapse of massive stars, in particular when the explosion does not succeed and the in-falling matter collapses onto itself.

The recent discovery of "disappearing" stars suggests that a large fraction of collapsing massive stars form black holes without any explosion, which unlike the bright supernovae we cannot observe. However, it is unclear how much mass these stars lose during black hole formation, or how large their natal kicks are. If the massive star directly collapses into a black hole, no baryonic matter is ejected, and energy is predominantly lost via neutrinos. "VFTS 243 has allowed us to test this scenario," says Vigna-Gómez.

Collapse scenario

The team explored the complete collapse scenario for the black hole binary VFTS 243, where a star ten times more massive than the Sun in its final stage had concluded its life-cycle via an implosion. With state-of-the-art models of stellar collapse developed at MPA, they calculated the effects on the orbit of a binary star system during the black hole formation. In the complete collapse scenario, the huge gravitational binding energy released during black hole formation is exclusively carried away by the weakly interacting, neutral, and lightweight particles known as neutrinos.

"Probing the physical processes that take place in the deepest interior of collapsing stars is extremely difficult and only possible under special circumstances," says H.-Thomas Janka, supernova theorist at MPA. "The black hole observed in the binary system VFTS 243 is such a special case," adds Daniel Kresse, postdoctoral researcher in Janka's group. "It allowed us to conclude, for the first time, that neutrinos are emitted nearly equally in all directions when the massive progenitor collapsed to form the black hole."

"Our study is a prime example of the synergy between theory and observations," concludes Vigna Gómez. "Combining advanced numerical models of stellar collapse with the principles of supernovae in binary star systems, allowed us to obtain crucial insights into the complete collapse scenario, in particular proving that massive black holes can form without an explosion."

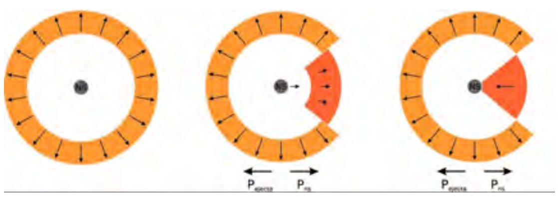


Figure 2.28: Sketch of the asymmetric ejection of matter resulting in a natal kick on the newly born neutron star. *(Credit: Janka 2013)*

2.14 Using small black holes to detect big black holes

By Jakob Stegmann (postdoc) and Selma de Mink (scientific director)

MPA researcher proposes a new idea to detect pairs of the biggest black holes, which occupies the centres of galaxies, by analysing gravitational waves from nearby small black holes, which are the remnants of stars. This approach, now published in Nature Astronomy, which will require a deci-Hz gravitational-wave detector, would enable studying supermassive black hole binaries, which might remain inaccessible otherwise.

The origin of supermassive black holes found at the centers of galaxies, is still one of the biggest mysteries in astronomy. They may have always been massive and formed when the Universe was still very young. Alternatively, they may have grown over time by accreting matter and other black holes. When a supermassive black hole is about to eat another massive black hole, this will emit gravitational waves, which are ripples in spacetime that propagate through the Universe.

Gravitational waves have recently been detected, but only from small black holes which are the remnant of stars. Detecting the signals of individual pairs of big black holes is still impossible, because present-day detectors are not sensitive to the very low gravitational-wave frequencies they emit. Planned future detectors, such as the space-based ESA-led mission LISA, will remedy this, but detecting the most massive black hole pairs will still remain extremely challenging.

“Our idea basically works like listening to a radio channel. We propose to use the signal from pairs of small black holes similar to how radio waves carry the signal. The supermassive black holes are the music that is encoded in the frequency modulation (FM) of the detected signal.” said Jakob Stegmann, lead author of the study and postdoctoral research fellow at MPA. “The novel aspect of this idea is to utilize high frequencies that are easy to detect to probe lower frequencies that we are not sensitive to yet.”

Recent results from pulsar timing arrays already support the existence of merging supermassive black hole binaries. This evidence is, however, indirect and comes from the collective signal of many distant binaries that effectively create background noise.

The proposed method to detect individual su-

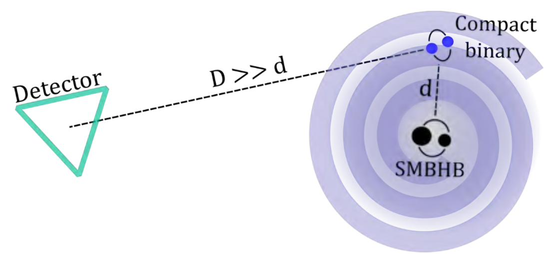


Figure 2.29: Investigated scenario in which a small binary black hole (“Compact binary”) resides in the same galaxy as a supermassive binary black hole (“SMBHB”). Detecting modulations in the gravitational-wave signal from the small binary black hole could indirectly reveal the presence of the supermassive binary black hole. *(Credit: Lorenz Zwick)*

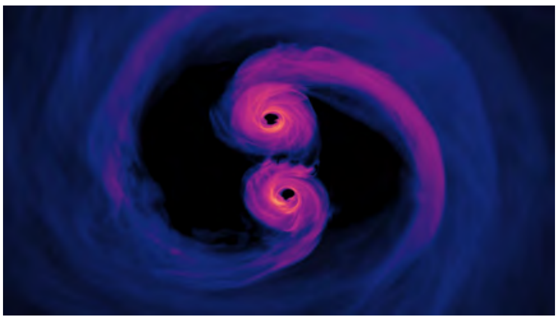


Figure 2.30: Simulation of two colliding supermassive black holes emitting gravitational waves that could be detected with this novel method. *(Credit: NASA’s Goddard Space Flight Center/Scott Noble; simulation data, d’Ascoli et al. 2018)*

permassive black hole binaries leverages the subtle changes they cause in the gravitational waves emitted by a pair of nearby small stellar-mass black holes. The small black hole binary effectively works as a beacon revealing the existence of the bigger black holes. By detecting the tiny modulations in signals from small black hole binaries, scientists could thus identify previously hidden supermassive black hole binaries with masses ranging from 10 million to 100 million times that of our Sun, even at vast distances.

Lucio Mayer, who is a co-author of the study and black hole theorist at the University of Zurich, added, “As the path for the Laser Interferometer Space Antenna (LISA) is now set, after adoption by ESA last January, the community needs to evaluate the best strategy for the following generation of gravitational detectors, above all in which frequency range to focus – studies like this bring a strong motivation to prioritize a deci-Hz detector design.”

“This paper presents a very cool and clever idea, which is still Science Fiction until we have a deci-Hz detector”, says Selma E. de Mink, director at MPA who is not involved in this work, “but we really need creative and out-of-the-box ideas like this if we want a chance to solve the biggest mysteries in the Universe.”

3 Publications, Talks and Committee Work

3.1 Talks and lectures

3.1.1 Contributed Talks and Posters

A. Acharya: LOFAR EoR Plenary Meeting, ”Detecting the Epoch of Reionization 21-cm Signal”, Groningen, the Netherlands, 24-26.04.2024. (contributed talk)
A. Acharya: COSMO21: Statistical Challenges in 21st Century Cosmology ”Detecting the Epoch of Reionization 21-cm Signal”, Chania, Greece, 20-24.05.2024. (contributed talk)
A. Acharya: AstroAI Workshop, ”Detecting the Epoch of Reionization 21-cm Signal”, Cambridge, USA, 17-21.06.2024 (contributed talk)
A. Acharya: Cosmic Dawn at High Latitudes Conference, ”Detecting the Epoch of Reionization 21-cm Signal: new tools and new simulations”, Stockholm, Sweden, 24-28.06.204 (contributed talk)
A. Acharya: Radio 2024 Annual Assembly, ”POLAR: Simulations of the Epoch of Reionization for studying the Intergalactic Medium 21-cm signal”, Erlangen, Germany, 11-15.11.2024 (contributed talk)
A. Acharya: Cosmology and Galaxy Astrophysics simulations and machine learning, ”Machine Learning on simulations and for simulations”, New York City, USA, 9-12.12.2024 (contributed talk)
S. Almada Monter: ”Cosmic Dawn at High Latitudes” (Stockholm, Sweeden, 24–28 Jun 2024)- Contributed Talk.
S. Almada Monter: ”Kochel Cosmic Lyman Alpha Workshop” (Kochel, Germany, 30 Sep. - 4 Oct. 2024)- (contributed talk).
S. Azyzy: Cosmo 24 (Kyoto, Japan, 21. - 25.10.2024) - (poster)
S. Azyzy: IPMU Workshop ”Kashiwa-no-ha Dark Matter and Cosmology Symposium” (Tokyo, Japan, 28.10. - 01.11.2024) - (contributed talk)
S. Azyzy: KEK Workshop ”Evolution of the inhomogeneous universe: From Inflation to structure formation” (Tsukuba, Japan, 06.11.-08.11.2024)
A. Basu : Cosmic Lyman Alpha Conference (Kochel, Germany, 10.2024) – (contributed talk) ”Impacts of Non-stellar Sources on IGM”
A. Basu : ICTP Summer School on Cosmology (Trieste, Italy, October 2024) – (Contributed Talk) ”Impacts of Non-Stellar Sources on the IGM: Interpretation of Lyman-α Forest Observations”
A. Basu : ”Cosmic Dawn at High Latitudes” Workshop (NORDITA, Stockholm, Sweden, 10.2024) – (contributed talk) ”Impacts of Non-stellar Sources on IGM: Interpretation of Lyman-α forest observations”
T. Braun: Nordita: Stellar Convection: Modelling, Theory and Observations, ”Applying the Kuhfuss Turbulent Convection Theory to Convective Envelopes”, (Stockholm, Sweden, 09.09.-20.09.2024), (contributed talk)

B. Casavecchia: ”Beyond the Edge of the Universe: Latest Results from the Deepest Astronomical Surveys” - Deep24 , Sintra (Portugal) , 21-25 October 2024 (contributed talk)
B. Casavecchia: ”AGN feedback and Star Formation Across Cosmic Scales and Time” - Sirolo (Italy), September 2-6, 2024 (contributed talk)// B. Casavecchia: ”Cosmic Dawn at High Latitudes” - Nordita program in Stockholm (Sweden), 24-28 June, 2024 (contributed talk)
S. Chon: Challenges in collisional N-body dynamics, MPA, 22th, March, 2024 - (contributed talk)
S. Chon: Massive Black Holes in the First Billion Years, 29th, April, 2024-(contributed talk)
S. Chon: First Stars and First Galaxies VI, NewYork, 21th, May, 2024-(contributed talk)
S. Chon: Breakthroughs iGalaxy Formation, Ringberg, 23th, October, 2024-(contributed talk)
S. Chon: IAP Symposium 2024 : Unveiling the physics of early galaxy and black hole formation with JWST, Paris, IAP, 5th, December, 2024-(contributed talk)
E. Curazov: “COSPAR General Assembly”, 13-21.07.2024, Busan, Korea
H.K. Das: ”Baryons Beyond Galactic Boundaries” (IUCAA, Pune, India, Dec 2-6, 2024)- (contributed talk)
H.K. Das: ”ORIGINS Turbulence Day” (MPA, Garching, Germany, Oct 16, 2024)- (Contributed talk)
H.K. Das: ”Multiphase Madness: Resolving the CGM in Theory and Observations” (CfA, Harvard, USA, Aug 21-23, 2024)- (Contributed talk)
H.K. Das: ”ISSI Team meeting for ’Observing Local Think Global: What solar obs. can teach us about Multiphase Plasma across Astrophysical scales” (ISSI, Bern, Switzerland, May 13-17, 2024)- (Contributed talk)
H.K. Das: ”Annual meeting of Astronomical Society of India (ASI)” (IISc, Bengaluru, Jan 30-Feb 4, 2024) - (Contributed Poster)
P. Diego-Palazuelos: Cosmo’24, (Kyoto, Japan, 21.-25.10.2024) - (contributed talk)
P. Diego-Palazuelos: LiteBIRD face-to-face collaboration meeting, (Vancouver, Canada, 15.-19.07.2024) - (poster)
P. Diego-Palazuelos: Focus Week Program on ”Parity violation through CMB observations”, (Trieste, Italy, 27.-31.05.2024) - (contributed talk)
A. Dutta: ”Models and simulations of the Circumgalactic medium”, (Aspen Center for Physics, USA 25.08-15.09.24) - (panel discussions)
A. Dutta: ”Demystifying the multiphase CGM using simulations and models” (IUCAA, Pune, India 2.-6.12.24) - (contributed talk)
V. Eberle, ML4ASTRO2, ”Spatially Variant Point Spread Functions for Bayesian Imaging” (Catania, Italy, 8-12 July,2024) - (contributed talk)
V.Eberle, First Results from the SRG/eROSITA All-Sky Survey: From Stars to Cosmology, ”Towards Bayesian Imaging of the eROSITA sky” (Garching, Germany, 15-20 September 2024) - (contributed talk)
V. Eberle, First Results from the SRG/eROSITA All-Sky Survey: From Stars to Cosmology, ”Spatially Variant Point Spread Function Removal with Generative Modeling ” (Garching, Germany, 15-20 September 2024) - (Poster)
T. Enßlin: Multi-Messenger Astrophysics 2024 (Görlitz, 26.3. -27.3. 2024)
T. Enßlin: Emergence of Information in Molecular Systems (MOLINFO, Garching)” (22.7.-2.8.2024)
A. Genina: Building Galaxies from Scratch, ”A calibrated model for dynamical friction acting on supermassive black holes”, (Vienna, Austria),19-23.02.2024-(contributed talk)

A. Genina: Learning the Universe annual meeting, ”A calibrated model for dynamical friction acting on supermassive black holes”, (Tegernsee, Germany), 06-08.03.2024-(contributed talk)
A. Genina: Richard Bower Memorial Meeting, ”A calibrated model for dynamical friction acting on supermassive black holes”, (Durham, United Kingdom), 23-27.09.2024-(contributed talk)
J. Grupa: ESO Workshop ”What Was That? – Planning Eso Follow Up for Transients, Variables, and Solar System Objects in the Era of LSST”, (Garching, Germany, 22.-26.01.2024) - (contributed a poster and a lightning talk)
J. Grupa: Rubin Strong Lensing Meeting 2024 (Oxford, UK, 12.-15.03.2024) - (contributed talk)
M. Guardiani: Machine Learning for Astrophysics 2 ”Introducing LensCharm: A charming Bayesian strong lensing reconstruction framework” (Catania, Italy, 08.07.24-12.07.24) - (contributed talk)
M. Guardiani: First Results from the SRG/eROSITA All-Sky Survey: From Stars to Cosmology, ”Automatic Point Source Detection through Model Stress”, (Garching, Germany, 19.09.24) - (contributed talk)
E. Herwig: Conference ’First Structures in the Universe’ (Paris, France, 24.-28.06.2024) - (contributed talk)
M. Jetti: ”Spectral Bayesian Imaging of Perseus Cluster in X-ray”, Astroparticle School 2024: (Oct 7–15, 2024 Obertrubach-Bärnfels) (Contributed talk) G. Jin: LOFAR Family Meeting 2024, (Leiden, Netherland, 03.-07.06.2024)- (contributed talk)
G. Jin: EAS 2024, (Padova, Italy, 01.-05.07.2024)- (contributed talk)
D. Kresse: ”Transients Down Under” conference, (Melbourne, Australia, 29.01.-02.02.2024) - (poster)
D. Kresse: ANITA workshop, (Melbourne, Australia, 05.02.-09.02.2024) - (contributed talk)
D. Kresse: Supernova Remnants III Conference: “An Odyssey in Space after Stellar Death” (Chania, Greece, 09.06.-15.06.2024), (contributed talk)
D. Kresse: EAS annual meeting, (Padova, Italy, 01.07.-05.07.2024) - (contributed talk)
T. Kurita: COSMO2024 ”Probing the primordial scalar parity violation trispectrum with intrinsic galaxy/halo shapes”, (Kyoto, Japan, 21.-25.10.2024)- (contributed talk)
T. Kurita: The 11th KIAS workshop ”Probing primordial parity-violating trispectrum with intrinsic galaxy/halo shapes”, (Gyeongju, Korea, 28.10.-01.11.2024)- (contributed talk)
N. Lahén: Contributed talk, ”Formation and evolution of star clusters in galactic environments”, MODEST24 - Exploring Dense Stellar Systems Across Cosmic Time, Warsaw, Poland, 19-23 August
N. Lahén: Contributed poster+flash talk, ”Star clusters forming in a low-metallicity starburst – rapid self-enrichment by (very) massive stars”, Building Galaxies from Scratch, Vienna, Austria, 19-23 February
J.-Z. Ma: Conference ”The Progenitors of Supernovae and their Explosions”, (Dali, China, 08.2024)- (contributed talk)
J.-Z. Ma: Lorentz workshop ”Stripped stars”, (Leiden, Netherlands, 07.2024)- (contributed talk)
J.-Z. Ma: KITP workshop ”Tidal disruption events”, (Santa Barbara, USA, 05.2024)- (contributed talk)
J.-Z. Ma: Conference ”Radio Stars in the Era of New Observatories”, (MIT Haystack Observatory, Boston, USA, 04.2024)- (contributed talk)
A. Melo: ”Strong-lens search through deep learning with both high- and multiband low-resolution imaging data”. Strong gravitational Lensing with LSST, Oxford, UK. (contributed talk)

A. Melo: ”Search for strong gravitational lenses combining ground-based and space-based imaging”. Lensing day origin, Garching, Germany. (contributed talk)
A. Melo: ”Search for strong gravitational lenses combining ground-based and space-based imaging”. Euclid strong lensing meeting, Heraklion, Greece.(contributed talk)
I. Millan Irigoyen: ”XIV Workshop of Estallidos collaboration” (contributed talk) 4-7 February
I. Millan Irigoyen: ”XVI scientific meeting of the Spanish Astronomical Society” Granada, 15-19 July (contributed talk)
C. O’Riordan: European AI for Fundamental Physics Conference, Amsterdam Netherlands, May 2024
C. O’Riordan: Strong Beyond the Main Lens Workshop, LUPM, Montpellier, France, May 2024
A. Olejak: Warsaw, Poland; [Talk] Gravitational wave signal from circular, mass transferring star-supermassive black hole systems during conference Galactic and extragalactic X-ray transients, theory and observational perspectives, September 2024
A. Olejak: Liege, Belgium; [Talk] Unequal-mass, highly-spinning binary black hole mergers in stable mass transfer formation channel during 41st Liège International Astrophysical Colloquium: The eventful life of massive star multiples, July 2024
A. Olejak: Garching, Germany; [Talk] Gravitational wave signal from circular, mass transferring star- supermassive black hole systems during conference LISA Astrophysics Working Group Meeting 2024, September 2024
A. Olejak: Cape Town, South Africa; [Talk] Unequal-mass, highly-spinning binary black hole mergers in stable mass transfer formation channel during IAU General Assembly 2024, August 2024
R. Pakmor: Building Galaxies from Scratch (Vienna, Austria, 19.2. - 23.2.)
D. Powell: A VLBI view of strong gravitational lenses”, Radio2024, Erlangen, Germany, November 2024
K. Ramalatswa: School for Astroparticle Physics ”Shell Merger in Core-Collapse Supernova Progenitors”, (07-15.10.2024)-(contributed talk)
A. Rantala: LISA Astrophysics Working Group Meeting, MPA Garching, 5.11-7.11, (contributed talk).
A. Rantala: MODEST24, Warsaw, Poland, 19.8-23.8, contributed online talk
A. Rantala: The Origin and Evolution of Supermassive Black Holes, Sexten, Italy, 15.7-19.7, (contributed talk).
A. Rantala: EAS Annual Meeting, Padua, Italy, 1.7-5.7, (contributed talk) in the session S1: Unveiling Black Hole Growth across Cosmic Time in the JWST and LISA era.
A. Rantala: Alpbach workshop on clouds, star clusters & black holes, Alpbach, 10.6-14.6, Austria, (contributed talk).
A. Rantala: Massive Black Holes in the First Billion Years, Kinsale, Ireland, 29.4-3.5, (contributed talk).
J. Roth: D-MeerKAT Meeting, ”fast-resolve: Fast Bayesian Radio Interferometric Imaging”, Bochum, 29-30.10.2024 J. Roth: Contributed Lectures to ”Principles of Imaging for Radio Astronomy”, African Institute for Mathematical Science, Cape Town, South Africa, February 2024
V. Springel: AG Meeting 2024 ”Star formation across cosmic time” (Cologne, Germany, 9.-13.9.) - (contributed talk)
J. Stadler: Forward modeling the galaxy distribution in 3D for robust and precise cosmological analysis, ORIGINS Science Week, Kloster Seeon

J. Stegmann: LISA Astrophysics Working Group Meeting, Garching, Germany, 2024-11,(contributed talk)
J. Stegmann: Chair of panel discussion on challenges and future perspectives in gravitational-wave astronomy: Lorentz Center, Leiden, Netherlands, 2024-10
J. Stegmann: 15th International LISA Symposium, Dublin, Ireland, 2024-07, (contributed talk)
J. Stegmann: Seminar talk “Teeminar”: University of Heidelberg, Heidelberg, Germany, 2024-06
J. Stegmann: N-body meeting: Max Planck Institute for Astrophysics, Garching, Germany, 2024-03, (contributed talk)
S. H. Suyu: Strong Gravitational Lensing Science with LSST, ”Measuring time delays of strongly lensed Type Ia supernovae with machine learning”, (Oxford, UK, 12.-15.03.2024)
J. Tan: Computational Galaxy Formation Workshop, (Ringberg, DE, 17-22 Oct 2024), (contributed talk)
J. Tan: Resolving the Circumgalactic Medium and its Impact on Galaxy Evolution, (Santa Cruz, Chile, 18-22 Nov 2024), (contributed talk)
R. Valli: EAS 2024 (1-5 July, Padova), (contributed talk)
A. Vani: ’Debugging galaxy evolution across cosmic epochs through galaxy scaling relations’. DIPC, San Sebastian, Spain, Jan 2024, (contributed talk)
A. Vani: ’L-GALAXIES: Debugging galaxy Evolution across $0 \lesssim z \lesssim 10'$, STScI Spring Symposium, Baltimore, April 2024. (contributed poster)
A. Vani: ’Debugging galaxy evolution across cosmic epochs through galaxy scaling relations’, IAU GA 2024, South Africa, August 2024, (contributed talk) (Virtual)
A. Vani: ’L-GALAXIES: Debugging galaxy evolution across $0 \lesssim z \lesssim 10'$, Cosmology and galaxy astrophysics with simulations and machine learning 2024, CCA, New York USA, December 2024 (Virtual), (contributed poster)
A. Vigna-Gomez: New ideas on the Origin of Black Hole Mergers, Niels Bohr Institute
C. Wang: VFTS annual meeting ”Evolved massive stars in young open clusters” (Madrid, Spain, 15.-18.09.2024)- (contributed talk)
C. Wang: Progenitors of Supernovae and their explosions ”Unlocking star formation and evolution mysteries: insights from young open clusters” (Dali, China, 26.-30.08.2024)- (contributed talk)
M. Werhahn: ”Cosmic Ray Feedback in Galaxies and Galaxy Clusters” Workshop at Aspen Center for Physics, Aspen, Colorado, May-June 2024, (contributed talk)
M. Werhahn: ”Building Galaxies from Scratch: Advances and Challenges in Simulating Galaxy Evolution”, Faculty of Mathematics, Vienna, Austria, Feb. 2024, (contributed talk)
H. Zandinejad: A 3D reconstruction of Cosmic Ray Proton Density in the Local Galaxy at 23rd Course of the International School of Cosmic Ray Astrophysics at Erice, Sicily, Italy. July 2024 H. Zandinejad: A 3D reconstruction of Cosmic Ray Proton Density in the Local Galaxy at New Computational Methods in Milky Way Dynamics and Structure workshop at Ringberg Castle, Bavaria, Germany July 2024

3.1.2 Invited Talks or Review Talks

F. Arrigoni Battaia: Co-evolution of galactic eco-systems and their large-scale environments (Hangzhou, China, 8.-12.4.)
F. Arrigoni Battaia: Where the CircumGalactic medium meets the galaxy environment (IFPU Trieste, Italy, 10.-14.06)

F. Arrigoni Battaia: What Matter(s) Around Galaxies 2024 (Varenna, Italy, 17.-21.06)
F. Arrigoni Battaia: Galaxies and diffuse gas in large-scale overdense environments at high redshift (Sexten, Italy, 15.-19.07)
S. Azyzy: Parity Violation from Home 2024 (Online, 19. - 22.11.2024)
E. Churazov: Baryons in the Universe 2024, (Kavli IPMU, Kashiwa, Japan, 8-12.04)
E. Churazov: European Astronomical Society Annual Meeting, (Padova 1-5.07)
B. Ciardi: i2i: back again to linking galaxy physics from Ism to IGM scales (Sexten, Italy, 15.-19.1.)
B. Ciardi: Cosmic Dawn at High Latitudes (Stockholm, Sweden, 24.-28.6.)
B. Ciardi: Cosmic Dawn revealed by JWST: The Physics of the First Stars, Galaxies, and Black Holes (Santa Barbara, USA, 26.-29.8.)
B. Ciardi: Beyond the Edge of the Universe: latest results from the deepest astronomical survey (Sintra, Portugal, 21.-25.10.)
B. Ciardi: Unveiling the physics of early galaxy and black hole formation with JWST (Paris, France, 2.-6.12.)
P. Diego-Palazuelos: CMB-CAL 2024, (Milan, Italy, 04.-08.11.2024)
P. Diego-Palazuelos: Cosmoglobe 2024, Commander4+HFI reanalysis kick-off meeting, (Oslo, Norway, 16.-18.09.2024)
P. Diego-Palazuelos: Focus Week Program on ”Parity violation through CMB observations”, (Trieste, Italy, 27.-31.05.2024)
A. J. Duivenvoorden: Cosmology from the small-scale CMB with the Atacama Cosmology Telescope (COSMO’24, Kyoto, Japan, 25-10-2024)
A. J. Duivenvoorden: Calibration strategy for the Atacama Cosmology Telescope (CMB-CAL, Milan, Italy, 04-11-2024)
T. Enßlin: SIAM Conference on Uncertainty Quantification (Trieste, Italy, 27.2-1.3.2024)
T. Enßlin: European Astronomical Society Annual Meeting (Padua, 1.7.-5.7.2024)
T. Enßlin: 15th International Symposium for Space Simulations (ISSS-15) & 6th International Workshop on the Interrelationship between Plasma Experiments in the Laboratory and in Space (IPELS-16) (Garching, 5-9.8.2024)
T. Enßlin: New Computational Methods in Milky Way Dynamics and Structure” (Ringberg Castle, 14.7.-17.7.2024)
M. Gilfanov: Alpbach workshop on clouds, star clusters & black holes (Alpbach, Austria, 10-14.06.)
M. Gilfanov: Seventeenth Marcel Grossmann Meeting (MG17) (Pescara, Italy, 7-12.07.)
M. Gilfanov: 45th COSPAR Scientific Assembly (Busan, South Korea, 13 – 21.07.)
M. Gilfanov: 45th International School for Young Astronomers (Algeria, 15.09.-5.10.)
M. Gilfanov: High Energy Astrophysics and Cosmology in the era of all-sky surveys (Yerevan, Armenia, 7-11.10.)
M. Gronke: KITP Santa Barbara, Turbulence in the Universe
M.Guardiani: ELT First-light Workshop, ”Universal Bayesian Imaging with J-UBIK”, (Vienna, Austria, 27.11.24)
H.-Th. Janka: Neutrino Frontiers (Florence, Italy, 25.06.-19.07.)
H.-Th. Janka: Multi-Messenger Astrophysics 2024 (Görlitz. Germany, 26.07.-27.07.)
H.-Th. Janka: Towards the Detection of Diffuse Supernova Neutrinos: What will we see? What can we learn? (Mainz, Germany, 16.09.-20.09.)

H.-Th. Janka: Transients Down Under (Melbourne, Australia, 29.01.-02.02.)
H.-Th. Janka: EAS Annual Meeting: Supernovae: now in 3D! (Padova, Italy, 01.07.-05.07.)
H.-Th. Janka: Cosmic Transients in the Era of Large Surveys (Stockholm, Sweden, 13.06.-14.06.)
S. Justham: "Consequences of stellar interactions for the diversity of SN progenitors" in "The Progenitors of Supernovae and their Explosions" (Dali, China, August 25-31, 2024)
E. Komatsu: IFPU Focus Week: Parity Violation through CMB Observations (Trieste, Italy, 27.-31.5.)
D. Kresse: MITP topical workshop "Towards the Detection of Diffuse Supernova Neutrinos: What will we see? What can we learn?", (Mainz, Germany, 16.09.-20.09.2024)
T. Kurita: Parity Violation from Home "Probing the primordial parity violation with intrinsic galaxy/halo shapes", (Online, 19.-22.11.2024)
J.-Z. Ma: Workshop "Horizons for Optical Long Baseline Interferometry", (Paris Observatory, France, 01.2025)
T. Naab: Modelling MeerKats (Stellebosch, South Africa, 26.02.-28.02.2024)
T. Naab: Alpbach workschop on clouds, star clusters & black holes, 10.06. - 14.06.2024, Alpbach, Austria
T. Naab: IoA 50, 22.06.-26.06.2024, Cambridge, UK
C. O'Riordan: International Astronautical Congress, Milan, Italy. Oct 2024.
C. O'Riordan: Euclid UK Annual Meeting, RAS, London, UK, Dec 2024.
A. Olejak: Leiden, Netherlands; [Invited talk] The origin of compact object mergers.Isolated binary formation scenarios. during conference: Challenges and future perspectives in gravitational-wave astronomy: O4 and beyond., October 2024
A. Olejak: Birmingham, UK; [Invited Panelist] Panel Discussion - Binary Formation Channels during Gravitational Wave Physics and Astronomy Workshop GWPAW 2024, May 2024
R. Pakmor: Towards exascale-ready astrophysics, Jülich (virtual), 25.9. - 27.9.
R. Pakmor: Annual meeting of the German Astronomical Society (Köln, 9.9. - 13.9.)
R. Pakmor: Decade of Discovery: Celebrating 10 Years of the Illustris Project in Tuscany (Gorganza, Italy, 27.10. - 1.11.)
D. Powel: "Dark matter constraints from strong gravitational lensing of extended sources", Syncretism, Rethymno, Crete, Greece, June 2024
D. Powell: "Tutorial: Modeling strong gravitational lenses from radio interferometric observations", Workshop on strong gravitational lensing beyond the main lens, Montpellier, France, May 2024
F. Schmidt: BCCP Split Conference (Split, Croatia, July 2024)
F. Schmidt: KIAS Workshop on Large Scale Structure (Gyeongju, Korea, Oct 2024)
F. Schmidt: Separate universe workshop KEK (Tsukuba, Japan, Nov 2024)
F. Schmidt: Yukawa Institute Molecule Workshop (Kyoto, Japan, Nov 2024)
M. Smith: Invited review talk "Modelling Stellar Feedback: Future Challenges and Opportunities" at "Building Galaxies From Scratch" (Vienna, Austria, 19-23.02.24)
M. smith: Invited talk at "The Feedback-Driven Matter Cycle in Galaxies: new perspectives from JWST" (Hengstberger Symposium, Heidelberg, Germany, 2-7.6.24)
M. Smith: Invited talk at "The Alpbach workshop on clouds, star clusters and blackholes 2024" (Alpbach, Austria, 10-14.6.24)
V. Springel: Simulations of Cosmic Structure Formation: Physical and Computational Challenges (Ringberg, Germany, 3.-5.4.)

V. Springel: Large- and small-scale environmental impacts on galaxy formation revealed by hydrodynamical simulations (Hangzhou, China, 9.-11.4.)
V. Springel: High-Performance Computing (Potsdam, Germany, 29.-30.4.)
V. Springel: Exploring cosmic structure formation with hydrodynamical simulations: Past, present, and future (Cambridge, USA, 9.-10.5.)
V. Springel: Next generation galaxy formation simulations: challenges and opportunities (Cambridge, UK, 21.-26.7.)
V. Springel: The promise of next generation hydrodynamic cosmological simulations (New York, USA, 19.-20.9.)
V. Springel: The promise of next generation hydrodynamic cosmological simulations (Jülich, Germany, 25.-27.9.)
V. Springel: The MillenniumTNG Simulations: Interfacing galaxy formation with precision cosmology (Ringberg, Germany, 21.-25.10.)
V. Springel: Towards new science opportunities with new codes: updates on Arepo-2 (Gargonza, Italy, 28.10.-1.11.)
V. Springel: Challenges and opportunities for the next generation galaxy formation simulations (Puerto Varas, Chile, 9.-13.12.)
J. Stadler: Perturbative Forward-Modeling of Large-Scale Structure for Field-Level Analysis and Beyond, Theoretical Modeling of the Large-Scale Structure of the Universe, Workshop at The Higgs Centre for Theoretical Physics, Edinburgh, UK
S. H. Suyu: Cosmology in the Alps 2024, "Strong Lensing as a Probe of Cosmology", (Les Diablerets, Switzerland, 18.-22.03.2024) (invited talk)
S. H. Suyu: 21st Century Cosmology: Tensions, Anomalies & New Physics, "Strongly lensed transients as a probe of cosmology", (Ashoka University, India, 21.-23.08.2024) (invited plenary talk given remotely)
S. H. Suyu: The Role of SN Ia in Current Cosmological Tensions, "Cosmology with Gravitational Lens Time Delays", (Barcelona, Spain, 1.-4.10.2024) (invited talk)
S. Vegetti: EVN symposium (Bonn, Germany,2-6.9.204)
S. Vegetti: Cosmic Magnetism in the Pre-SKA Era (Kagoshima, Japan, 27-31.05.2024)
S. Vegetti: Cosmic Signals of Dark Matter Physics: New Synergies (Santa Barbara, CA, USA, 3-7.06.2024)
S. Vegetti: Radio 2024 Symposium (Erlangen, Germany, 12-15.9.2024)
A. Vigna-Gomez: Black Hole Day, MPE
C. Wang: 2024 Alpbach workshop on clouds, star clusters and black holes "Exploring star formation and evolution: lessons from young open clusters" (Alpbach, Austria 10.-14.06.2024)-(invited talk)
M. Werhahn: "Breakthroughs in Galaxy Formation" Ringberg Castle, Germany, Oct. 2024, invited talk

3.1.3 External Colloquium and Seminar Talks

A. Acharya: University of Cambridge 21-cm Cosmology meeting, "Detecting the Epoch of Reionization 21-cm Signal Power Spectrum", online, 14.11.24.
A. Acharya: SKA India 21-cm CD/EoR Bi-weekly Meeting, "Detecting the Epoch of Reionization

21-cm Signal", online, 4.3.24.
F. Arrigoni Battaia: Academia Sinica, Institute of Astronomy and Astrophysics (Taipei, Taiwan, 15.04)
F. Arrigoni Battaia: Joint Astronomical Colloquium, ESO (Garching, Germany, 11.07)
A. Basu: Lunch Talk (University of Nottingham, UK) – (invited talk) "Impacts of Non-stellar Sources on IGM: Interpretation of Lyman-α forest observations"
A. Basu: Hi-res Meeting (IFPU, Trieste, Italy) – (invited talk) "Galaxies and IGM"
A. Basu: IFPU Lunch Talk (Trieste, Italy) – (invited talk) "Impacts of Non-stellar Sources on IGM: Interpretation of Lyman-α forest observations"
A. Basu: SKA India 21-cm CD/EoR Bi-weekly Meeting (Online) – (invited talk) "Decoding Reionization: Unraveling Impacts of Ionizing Sources through Cosmological RT Simulations"
A. Basu: GRASCO Seminar Series (IIT Kharagpur, India) – (invited talk) "Decoding Reionization: Unraveling Impacts of Ionizing Sources through Cosmological RT Simulations"
S. Chon: CFCA users meeting, Japan, NAOJ, 25th, November, 2024
S. Chon: Cosmic Dawn Revealed by JWST: The Physics of the First Stars, Galaxies, and Black Holes (firstbillion-c24), "Transition of IMF in the Early universe", Kavli Institute for Theoretical Physics, 26th – 28th, August, 2024
S. Chon: 2024 Alpbach workshop on clouds, star clusters & black holes, "Massive seed black hole formation in the early metal-enriched universe", Alpbach, Austria, 10th -14th, June, 2024
S. Chon: Formation, Evolution and Signatures of Supermassive Stars, "Formation of massive seed BHs in the metal-enriched universe", Geneva Observatory, Switzerland, 10th – 12th, January, 2024
E. Churazov: University of Alabama (Huntsville, USA, 28.03)
B. Ciardi: Observatory of Trieste (Trieste, Italy, 27.11.)
H.K. Das: Physics Department, Indian Institute for Science (Bangalore, India, Jan 27)
H.K. Das: Cosmology section meeting, Leibnitz Institute for Astrophysics (Potsdam, Germany, May 8)
H.K. Das: GalRead, Princeton University (Princeton, NJ, USA, Aug 16)
H.K. Das: Computational Structure and Galaxy Formation Group meeting (Kavli Inst. for Astrophysics, MIT, Aug 19)
H.K. Das: Lars Hernquist Group meeting, (Harvard University, CfA, USA, Aug 23)
S.E. de Mink: Main instiute colloquium, CalTech, Pasadena Ca, (15.5)
S.E. de Mink: Seminar, astro department, UCB, Berkeley, California (20,5)
S.E. de Mink: Rosenbaum Lecture, Physics dep. Hebrew University, Israel (26.6.)
S.E. de Mink: Astrophysics Colloquium, Tel Aviv University, Israel (27.6.)
S.E. de Mink: Astrophysics Colloquium, Duisberg University, Germany (5.6.)
P. Diego-Palazuelos: High Energy Accelerator Research Organization (Tsukuba, Japan, 16.10.2024)
P. Diego-Palazuelos: Kavli Institute for the Physics and Mathematics of the Universe (Kashiwanoha, Japan, 08.10.2024)
P. Diego-Palazuelos: Research Center for the Early Universe (Tokyo, Japan, 03.10.2024)
A. J. Duivenvoorden: Measuring galaxy cluster temperatures and delensing for primordial non-Gaussianity (University of Geneva, Switzerland, 28-11-2024)
T. Enßlin: Max-Planck-Institut für Plasmaphysik (Garching, 20.8.2024)
T. Enßlin: Deutsches Zentrum für Luft- und Raumfahrt e.V. (DLR, Bonn, 8.11.2024)
T. Enßlin: Faculty of Astrophysics, University Vienna (Vienna, Austria, 5.11.2024)

T. Enßlin: Faculty of Psychology, University Vienna (Vienna, Austria, 7.11.2024)
A. Genina: Kapteyn Astronomical Institute, (Groningen, Netherlands, 01.10)
M. Gronke: several colloquium talks at various locations, including Caltech, UCSD, CfA, ISTA (Vienna), AIP (Potsdam) and ARI (Heidelberg)
F. Hidalgo Pineda: ARI guest talk
H.-Th. Janka: Standford University (Stanford, California, USA, 08.05.)
G. Jin: Nanjing University, (Nanjing, China, 26.8.)
G. Jin: University of Science and Technology of China, (Hefei, China, 27.8.)
E. Komatsu: Okayama University (Okayama, Japan, 31.1.)
E. Komatsu: University of Cambridge (Cambridge, UK, 11.3.)
E. Komatsu: University of Portsmouth (Portsmouth, UK, 14.3.)
E. Komatsu: Liverpool John Moores University (Liverpool, UK, 10.4.)
E. Komatsu: University of Nottingham (Nottingham, UK, 12.4.)
E. Komatsu: Universität Heidelberg (Heidelberg, Germany, 18.7.)
E. Komatsu: ISAS/JAXA (Sagamihara, Japan, 5.9.)
E. Komatsu: KEK (Tsukuba, Japan, 20.9.)
N. Lahén: Invited talk, ”The life cycle of star clusters in low-metallicity dwarf galaxies” in TOSCA - Topical Overview on Star Cluster Astrophysics, Siena, Italy, 28-31 October
N. Lahén: Invited talk, ”Simulating star cluster formation in low-metallicity dwarf galaxies with feedback from single stars”, Cosmic Threads: Interlinking the Stellar Initial Mass Function from Star-birth to Galaxies, Sexten, Italy, 11-15 March
T.Naab: The formation and evolution of star clusters, 02.10.2024, Trieste, Italy
C. O'Riordan: ORIGINS Strong Lensing Day (organiser)
A. Olejak: Paris, France; [Seminar] The origin of compact object mergers. Seminar for high energy, group of the Institut d'Astrophysique de Paris, December 2024
A. Olejak: Warsaw, Poland; [Seminar] Fingerprints of binary star interactions in the parameters of binary black hole mergers - department seminar at Warsaw Astronomical Observatory, March 2024
R. Pakmor: Leiden University (Leiden, Netherlands, 29.4.)
R. Pakmor: Universität Zürich (Zürich, Switzerland, 24.5.)
A. Rantala: ITA Heidelberg, 16.4
A. Rantala: MPIA Heidelberg, 18.4
A. Rantala: DAMTP Cambridge, 21.5
A. Rantala: KICC Cambridge, 22.5
J. Roth, Max Planck Institute for Radio Astronomy, Special Colloquium, October 2024, Bonn
J. Roth, Ludwig Maximilian University, Garching Maier-Leibnitz-Kolloquium, June 2024, Garching
J. Roth, Max Planck Institute for Physics, Bayes Forum, March 2024, Garching
F. Schmidt: DICP, Donostia, Spain, 31.1.24
F. Schmidt: DAMTP, Cambridge, UK, 12.2.24
F. Schmidt: IFPU, Trieste, Italy, 27.6.24
V. Springel: University of Regensburg (Regensburg, Germany, 17.1.)
V. Springel: Ludwig Maximilian University of Munich (Munich, Germany, 17.1.)
V. Springel: University of Wisconsin (Madison, New York, USA, 13.3.)
V. Springel: Center for Computational Astrophysics (New York, USA, 14.6.)

V. Springel: Heidelberg Institute for Theoretical Studies (Heidelberg, Germany, 24.6.)
V. Springel: University of Bielefeld (Bielefeld, Germany, 18.11.)
J. Stadler: Perturbative Forward Modeling of Galaxy Surveys for Field-Level Analysis and Beyond, Main Colloquium at the MPIfR, Bonn
J. Stadler: Forward modeling the cosmic Large-Scale Structure, Bayesian Inference and Artificial Intelligence Seminar, LMU Seminar
S. H. Suyu: Villanova University, (Villanova, PA, USA, 12.4.2024)
S. H. Suyu: Academia Sinica Institute of Astronomy and Astrophysics, (Taipei, Taiwan, 11.9.2024)
S. H. Suyu: National Sun Yat-sen University, (Kaohsiung, Taiwan, 12.9.2024)
S. H. Suyu: University of Vienna, (Vienna, Austria, 11.11.2024)
S. H. Suyu: Taipei Medical University, (Taipei, Taiwan, 30.12.2024)
R. Valli: Workshop on stable mass transfer, CCA (11-13 March, New York City)
R. Valli: Towards a Physical Understanding of Tidal Disruption Events, KITP (29 April-17 May, Santa Barbara)
S. Vegetti: MIT, Physics Colloquium, (Cambridge, MA, USA, 9.0.5.2024)
A. Vigna-Gomez: Astrophysics Seminar, University of Birmingham
A. Vigna-Gomez: AEI Seminar, AEI Postdam
A. Vigna-Gomez: DTU Seminar, DTU Space
C. Wang: Nanjing University, (Nanjing, China, 30.07.2024)
M. Werhahn: Institute Seminar Hamburger Sternwarte (University of Hamburg), Hamburg, Germany, Jan. 2024

3.1.4 Lectures and Lecture Courses

T. Enßlin, SS 2024 and WS2024/2025, LMU München:
- Information Field Theory (lecture)
- Signal Processing with Python
- Seminar on Information Field Theory

J. Grupa, WS 2023/24 and SS 2024, TUM, München:
- Gravitational Lensing (tutorial)
- Extragalactic Astrophysics (tutorial and substitute for two lectures)

H.-Th. Janka, WS 2023/2024 and SS 2024, TUM, München:
- Measurable Signals from Collapsing and Exploding Stars
- Introduction to Theoretical Astrophysics

A. Melo, FOPRA 86, TUM, München
A. Rantala, "MPA Lecture Series on Computational Astrophysics", 4 lectures in November 2024, topic: latest advanced N-body simulation techniques
J. Stadler: MPA staff lecture, Techniques for sampling and inference
S. H. Suyu, WS 2023/2024 and SS 2024, TUM, München:
- Experimental Physics 1 in English
- Gravitational Lensing
- FOPRA Experiment 85: Colour-Magnitude Diagrams of Star Clusters:
Determining Their Relative Ages

A. Weiss, SS 2024, LMU, Munich: Stars - Theory and Applications

A. Weiss, WS 2023/2024, SS 2024, WS 2024/2025: Seminar on Stellar Astrophysics

3.2 Community work, Outreach and Committee memberships

3.2.1 Community work

A. Acharya: Organised a Hackathon on ”Generative modelling for cosmological simulations” at AstroAI workshop, at the Center for Astrophysics, Harvard University.
S. Almada Monter: Internal PhD representative
F. Arrigoni Battaia: - sustainability officer for MPA - responsible for internship applications at MPA
A. Basu: Member of MPA Mentorship Programme
E. Churazov: Co-organiser of the Institute Seminar
B. Ciardi: Co-organiser of the Institute Seminar
B. Ciardi: Gender Equality Officer
H.K. Das: External PhD representative
T. Enßlin: representing the managing director of MPA in construction matters
M.Gilfanov: Ombusperson
M. Gronke: Member of MPA Mentorship Programme
D. Kresse: administrator of the Garching Core-Collapse Supernova Archive
D. Kresse: co-organization of the Garching Supernova Meeting
I. Millan Irigoyen: External Postdoc Representative
T. Naab: Scientific head of MPA IT group
T. Naab: Liaison to MPCDF
T. Naab: Scientific contact to the library
A. Olejak: Postdoc Representative
R. Pakmor: Chairman of the MPA Work’s Council
R. Pakmor: Co-organiser of the Institute Seminar
R. Pakmor: Co-Organiser of galaxies and cosmology seminar
D. Powell: Co-organizer of the Munich Dark Matter Meeting seminar series (includes TUM, LMU, MPA, MPP, MPE)
F. Schmidt: member of the MPA Work’s Council
F. Schmidt: CPTS representative at the MPG
J. Stadler: member of the MPA Work’s Council
J. Stegmann: Organising journal club in stellar department
S. H. Suyu: Equal Opportunity Officer (Deputy) of the TUM NAT School, where some of the MPA students are enrolled
J. Tan: Internal PhD representative
A. Vani: 18th IMPRS symposium organisation, November 2024
A. Vani: Internal PhD representative
M. Werhahn: Postdoc Representative

3.2.2 Outreach Activities or Public Talks

A. Acharya: volunteer for art and crafts to teach topics in astrophysics to children of a variety of ages at MPA Open Day in October 2024.
A. Acharya: Interviewed for Youtube channel, ”Vidped: Voice of the Young”. (August 2024)
A. Acharya: Outreach talk to ”Singularity” the undergraduate Astronomy Club at IISER Kolkata, India. (24.03.24)
A. Acharya: Live Question and Answer session with SciAstra with high school students from across India about careers in academia and astrophysics in general. (March 2024)
A. Acharya: Delivered an invited lecture on ”Cosmological Simulations & Structure formation” organised by the Astronomy Club of Chandigarh University. (February 2024)
T. Braun: offered planetarium shows at the Day of the Open Campus (03.10.2024)
H.K. Das: Part of Open day, part of activities like Water rocket
S.E. de Mink: Munich Public Observatory (8. 3.)
T. Enßlin: talk for about 30 teachers on at Lehrerfortbildungsakademie Dillingen (Donau, 18.-20.8.2024)
T. Enßlin: Deutsches Museum Munich (18.12.2024)
R. Glas: Planetarium show for approximately 25 visitors, in January x1, April x2 and October (Open Day) x2
J. Hein: Several planetarium shows for visiting students and for the Girls Day
H.-Th. Janka: Physikalischer Verein, Frankfurt (05.06.)
H.-Th. Janka: Haus der Astronomie, Heidelberg, ASTRO & Co, live online talk show, 26.02.
G. Jin: Building tour in MPA Open Day, Munich (03.10.)
D. Kresse: active member of the MPA planetarium group; offered planetarium shows for external visitor groups, school classes, and visitors on MPA's Open Day
J.-Z. Ma: Three invited talks about stellar astrophysics at X-Institute winter/summer school for high school students (Shenzhen, China, 01.2024, 07.2024)
J.-Z. Ma: One-hour podcast with X-Institute mentors about astronomy research (Shenzhen, China, 04.2024)
S. Schnauck: Helped out with the planetarium show on Open Day
V. Springel: Speaker at the Tag der offenen Tür MPA, Garching (3.10.)
J. Stadler: Physics Modern, LMU, Talk
J. Stadler: Girls Day
J. Stadler: MPA Vistors from Dante Gymnasium, Talk
J. Stadler: Cafe & Kosmos
J. Stadler: Bundesweite Lehrerfortbildung Astronomie, Jena, Talk
J. Stadler: Tag der Offenen Tür, Talk
J. Stadler: Tag der Offenen Tür, Kids Program
S. H. Suyu: Invited lecture at a seminar at the Welfare and Equality Group of MPA/MPE/ESO
S. H. Suyu: radio interview on Deutschlandfunk about our Universe” (November 2024)
R. Valli: Outreach presentation to a group of approximately 25 students visiting MPA in March and April 2024
A. Weiss: concept and realization of 2 exhibits for Open House Day (October 2024)
M. Werhahn: organized and presented a station at Girls Day about ”Milky Way and Andromeda”, April 2024

3.2.3 Internal Committees and Boards Membership

F. Arrigoni Battaia: MPA Kippenhahn Prize committee
E. Komatsu: PhD Committee Supervisory Panel
E. Churazov:
- IMPRS Executive Committee
- MPA Kippenhahn Award Committee

B. Ciardi: PhD Committee Supervisory Panel
M. Gilfanov:
- PhD Committee Supervisory Panel
- MPA PhD Advisory Board
- MPA Executive committee

S. Justham: MPA Kippenhahn Award Committee
R. Pakmor: Chair of the MPA Work's council
F. Schmidt: Member of the MPA Work's council
S. Vegetti: PhD Committee Supervisory Panel

3.2.4 External Committees and Boards Membership

F. Arrigoni Battaia:
- External reviewer for ALMA Large Programmes
- Reviewer for FONDECYT (Chile) applications

E. Churazov:
- Member of IAU
- Vice-chair of COSPAR Commission E

B. Ciardi:
- member of the International Astrostatistics Association
- member of the International Astronomical Union (IAU)
- vice-president of the IAU J2 Organizing Committee
- vice-chair of the German LOng Wavelength Consortium (GLOW)
- member of the IAU J2 Organizing Committee
- member of the GLOW Consortium Resource Allocation Committee
- member of the GLOW Executive Committee

S.E. de Mink: ERC Panel
P. Diego-Palazuelos:
- Member of the Speaker Selection Committee of the LiteBIRD Collaboration
- Member of the European Astronomical Society (EAS)
- Member of the Spanish Astronomical Society (SEA)
- Member of the European Consortium for Astroparticle Theory (EuCAPT)

T. A. Enßlin:
- Editorial Board Member of the Journal for Cosmology and Astroparticle Physics
- Editorial Board Member of the Journal Entropy

-Member of DLR Review Board for ”Verbundforschung”
M. Gilfanov:
- member of IAU
- associate of COSPAR (Commission E)
- Member of the Editorial Board of Journal of Cosmology and Astroparticle Physics
- Member of the Editorial Board of Journal of Experimental and Theoretical Physics Letters (JETP Letters)
- Member of the Editorial Board of Astronomy Letters
M. Gronke:
- NASA Hubble Fellowship Committee
- Member of the German Astronomical Society
- Member of the IAU
H.-Th. Janka:
- Member of the Germany Astronomical Society
- Member of Germany Physical Society
- Member of International Astronomical Union
- Member of European Astronomical Society
S. Justham:
- Member of the International Astronomical Union
- Member of the Institute of Physics (UK)
E. Komatsu:
- Astronomische Gesellschaft (AG)
- The American Astronomical Society (AAS)
- The American Physical Society (APS)
- The Astronomical Society of Japan (ASJ)
- The Physical Society of Japan
- RIKEN Committee, Ministry of Education, Culture, Sports, Science and Technology of Japan
- Scientific Advisory Committee of Leung Center for Cosmology and Particle Astrophysics, Taiwan
- Selection Committee for the Shaw Prize
- ArXiv Scientific Advisory Council
N. Lahén:
Junior Member of the International Astronomical Union
Member of the European Astronomical Society
Member of the Finnish Astronomical Society
I. Millan Irigoyen:
- Member of Spanish Astronomical Society
- Member of European Astronomical Society
T. Naab: Editor of Living Reviews in Computational Astrophysics
A. Rantala:
- Member of the European Astronomical Society
- Member of the LISA Astrophysics Working Group
F. Schmidt:
- Coordinator of Origins Connector 4
- Member of Origins Research Board

- NASA Hubble Fellowship Committee
M. Smith:
- Fellow of the Royal Astronomical Society (UK)
- Member of the Institute of Physics (UK)
V. Springel:
- Vice President of the German Astronomical Society
- Member of the International Astronomical Union
- Member of the European Astronomical Society
- Member of the Research Board of the ORIGINS Cluster of Excellence
- Board of Trustees, Welt der Physik
- Member of the Scientific Advisory Board of the Max Planck Computing and Data Facility
- Board of Trustees, MIP.labor, Berlin
- Scientific Advisory Board of the Zentrum für Astronomie (ZAH), Heidelberg University
S. H. Suyu:
- member of telescope time allocation committee
A. Vani: Member of: PhDNet social media work-group

3.3 Publications in 2024

D. Paoletti, ..., P. D. Palazuelos, E. Komatsu, E. Martinez-Gonzalez, M. Monelli, Y. Zhou, ”LiteBIRD science goals and forecasts: primordial magnetic fields,” JOURNAL OF COSMOLOGY AND ASTROPARTICLE PHYSICS (7), 086 (2024).

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M. Remazeilles, ..., C. Hernandez-Monteagudo, P. D. Palazuelos, R. G. Gonzalez, E. Komatsu, E. Martinez-Gonzalez, M. Monelli, Y. Zhou, ”LiteBIRD science goals and forecasts. Mapping the hot gas in the Universe,” JOURNAL OF COSMOLOGY AND ASTROPARTICLE PHYSICS (12), 026 (2024).

D. A. Neufeld, ..., G. Edenhofer, et al., ”The Densities in Diffuse and Translucent Molecular Clouds: Estimates from Observations of C2 and from Three-dimensional Extinction Maps,” ASTROPHYSICAL JOURNAL 973 (2), 143 (2024).

M. Michailidis, ..., A. Bykov, E. Churazov, I. Khabibullin, et al., ”Study of X-ray emission from the S147 nebula with SRG/eROSITA: X-ray imaging, spectral characterization, and a multiwavelength picture,” ASTRONOMY & ASTROPHYSICS 689, A277 (2024).

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D. M. Powell, ”Lensed radio arcs at milli-arcsecond resolution: Methods, science results, and current status”, in IAUS 381: Strong gravitational lensing in the era of Big Data, edited by H. Stacey, A. Sonnenfeld, and C. Grillo (Cambridge University Press, Cambridge, UK, 2024), Vol. 381, pp. 46-51.

C. Partmann, T. Naab, N. Lahén, ..., E. Churazov, and A. Rantala, ”Intermediate mass black hole feedback in dwarf galaxy simulations with a resolved ISM and accurate nuclear stellar dynamics”, in Black Hole Winds at All Scales (IAU Symposium 378), edited by G. Bruni, M. Diaz

Trigo, S. Laha, and K. Fukumura (Cambridge University Press, Cambridge, UK, 2023), pp. 68-71.

A. Maire, ..., J. J. Wang, J. Stadler, et al., ”Direct imaging and dynamical mass of a benchmark T-type brown dwarf companion to HD 167665,” ASTRONOMY & ASTROPHYSICS 691, A263 (2024).

S. Schuldt, ..., G. B. Caminha, S. H. Suyu, et al., ”Improved model of the Supernova Refsdal cluster MACS J1149.5+2223 thanks to VLT/MUSE,” ASTRONOMY & ASTROPHYSICS 689, A42 (2024).

I. Marini, ..., K. Dolag, et al., ”Detecting galaxy groups populating the local Universe in the eROSITA era,” ASTRONOMY & ASTROPHYSICS 689, A7 (2024).

C. T. Davies, ..., B. Li, C. Hernandez-Aguayo, et al., ”Constraining modified gravity with weak-lensing peaks,” MONTHLY NOTICES OF THE ROYAL ASTRONOMICAL SOCIETY 533 (3), 3546-3569 (2024).

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B. Casavecchia, U. Maio, C. Peroux, and B. Ciardi, ”COLDSIM predictions of [C II] emission in primordial galaxies,” ASTRONOMY & ASTROPHYSICS 689, A106 (2024).

C. Fotopoulou, T. Naab, N. Lahen, M. Cernetic, ..., U. P. Steinwandel, et al., ”The masses, structure, and lifetimes of cold clouds in a high-resolution simulation of a low-metallicity starburst,” MONTHLY NOTICES OF THE ROYAL ASTRONOMICAL SOCIETY 534 (1), 215-230 (2024).

P. Vynatheya, T. Ryu, R. Pakmor, S. E. de Mink, and H. B. Perets, ”Simulating the tidal disruption of stars by stellar-mass black holes using moving-mesh hydrodynamics,” ASTRONOMY & ASTROPHYSICS 685, A45 (2024).

A. R. H. Stevens, ..., C. Hernandez-Aguayo, et al., ”DARK SAGE: Next-generation semi-analytic galaxy evolution with multidimensional structure and minimal free parameters,” PUBLICATIONS OF THE ASTRONOMICAL SOCIETY OF AUSTRALIA 41, e053 (2024).

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A. I. Kolbin, ..., M. R. Gilfanov, et al., ”SRGe J194401.8+284452-an X-ray Cataclysmic Variable in the Field of the Gamma-Ray Source 4FGL J1943.9+2841,” ASTRONOMY LETTERS-A JOURNAL OF ASTRONOMY AND SPACE ASTROPHYSICS 50 (6), 351-372 (2024).

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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

Scientific Staff

Fabrizio Arrigoni-Battaia, Eugene Churazov, Benedetta Ciardi, Torsten Enßlin, Marat Gilfanov, Max Grönke, Hans-Thomas Janka, Stephen Justham, Thorsten Naab, Rüdiger Pakmor, Devon Powell, 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

Noemi Anau Montel (since 04.11.2024), Eirini Batziou (until 30.06.2024), Ivana Babic (01.11.24 to 31.01.2025), Tiara Battich (until 30.09.2024), Aniket Bhagwat (since 01.12.2024), Jan David Burger, Sergei Bykov (01.02.2024 to 29.09.2024), Miha Cernetic, Seokjun Chang, Martyna Chruslinska (until 30.09.2024), Geza Attila Csörnyei (01.05.2024 to 31.08.2024), Patricia Diego Palazuelos, Caitlin Christine Doughty (since 01.10.2024), Adriaan Judocus Duivenvoorden (since 09.09.2024), Alankar Dutta (since 19.08.2024), Philipp Frank (until 31.08.2024), Daniela Galarraga-Espinosa, Enrico Garaldi (until 14.01.2024), Anna Genina, Robert Glas, Jayson Gonzalez Lobos (since 01.12.2024), Cesar Hernandez Aguayo, Simon Huber (until 31.05.2024), Andrew Spencer Jamieson, Cole Campbell Johnston (until 15.11.2024), Jakub Andrzej Klencki (since 15.10.2024), Valeriya Korol, Ivan Kostyuk (until 31.03.2024), Daniel Kresse, Toshiki Kurita, Natalia Anne Maarit Lahen, Qi Li, Luisa Lucie Smith (until 17.11.2023), Alejandra Daniela Melo Melo, Iker Millan Irigoyen, Marta Monelli (01.05.2024 to 15.10.2024), Vyoma Muralidhara (06.11.2024 to 31.01.2025), Aleksandra Maria Olejak, Conor O'Riordan, Bo Peng, Devon Powell, Antti Jalmari Rantala, Taeho Ryu, Matthew Smith, Julia Stadler, Jakob Stegmann, Rosemary Yvette Talbot, Stefan Taubenberger (31.05.2024), Alejandro Vigna Gomez, Christian Vogl (until 31.10.2024), Pavan Vynatheya (01.05.2024 to 31.08.2024), Chen Wang, Maria Chiara Werhahn

Ph.D. Students

Anshuman Acharya, Silvia Elizabeth Almada Monter, Shaghaiegh Azyzy, Monica Alejandra Barrera Castillo (until 31.10.2024), Arghyadeep Basu, Teresa Andrea Maria Braun, Benedetta Casavecchia, Safak Celik, Hitesh Kishore Das, Willem de Roo (since 01.09.2024), Vincent Lukas Johannes Eberle, Gordian Victor Arnold Edenhofer (since 30.09.2024), Sebastian Ertl (31.10.2024), Fulvio Ferlito, Aleksandra Grudskaia (until 30.04.2024), Jana Grupa, Matteo Guardiani, Johannes Harth-Kitzerow (until 31.01.2024), Jakob Franz Hein, Malte Laurenz Heinlein, Eileen Herwig, Fernando Hidalgo Pineda (since 01.09.2024), Jonathan Aimé Jäger (since 01.07.2024), Gaoxiang Jin, Vishal Johnson, Thibault Lechien (since 01.10.2024), Maja Vanessa Katherina Lujan Niemeyer, Jingze MA, Elias Mamuzic (since 01.11.2024), Alexander Christian Mayer, Marija Minzburg, Jeongin Moon, Ivana Nikolac, Tilman Oelgeschläger (15.09.2024), Christian Partmann (until 31.10.2024), Silvia Anastasia Popa (since 01.10.2024), Shubham Raghuvanshi, Abinaya Swaruba Rajamuthukumar, Katlego Jafta Ramalatswa, Bryce Alexander Remple, Johannes Maximilian Ringler (until 29.02.2024), Jelena Malwine Constanze Maria Ritter, Julian Adalbert Christian Rüstig, Sophia Christina Schnauck (since 15.09.2024), Lazaros Souvaitzis, Maryam Tajalli, Joanne Tan, Katyayani Trivedi (01.07.2024), Beatriz Tucci Schiewaldt, Ruggero Valli, Akash Darshan Vani, Han Wang, Margret Leonie Westerkamp, Hanieh Zandinejad.

Master students

Alon Aharoni, Anisha Anisha, Mohammadreza Ashari, Jinhao Cai, Eirini Agapi Chaniotaki, Jennifer Faba Moreno, Sylvia Hofst, Mrinal Kedarnath (until 14.06.2024), Kristian Tchiorny (until 30.11.2024), Patrik Kuster, Elias Mamuzic (until 31.10.2024), Anton Darius Nöbauer, Andreas Popp, Jaemin Ryu, Igor Rzhin, Benedikt Seidl, Ananya Shankar, Fabian Sigler, Moritz Singhartinger, Giovanni Stimamiglio, Ethan Tauro Rydell, Qiang Wang (until 03.05.2024).

Technical and support staff

Computational Support: Heinz-Ado Arnolds (until 16.05.2024), Andreas Breitfeld, Goran Toth, Martin Reineke, Andreas Weiss, Gerhardt Werner Grek
Public relation: Hannelore Hämmerle (MPA and MPE)
Secretaries: Sonja Gründl (until 30.05.2024), Gabriele Kratschmann, Ana Lomidze (since 15.10.2024) Isabel Thapa (until 30.09.2024), Solvejg Schröder (since 01.02.2024) *Library:* Mirna Balicevic, Christiane Bartels (library management)

4.2 Staff News/Awards

Benedetta Ciardi has been the a co-recipient of a prestigious ERC Synergy Grant for the project titled ”REionization Complementary Approach” (RECAP).

Torsten Enßlin has been awarded a renowned ERC Synergy Grant together with P. Mertsch (RWTH Aachen) and V. Pavlidou (FORTH Heraklion, Greece) for their mw-atlas project.

Max Gronke has been awarded the highly competitive European Research Council (ERC) Starting Grant. for his research project ”Resolving the Multiscale, Multiphase Universe” (ReMMU).

Beatriz Tucci and Fabian Schmidt’s paper has won Third Prize of the 2024 Buchalter Cosmology Prize for their new approach using powerful computers and algorithms to measure cosmological constraints from galaxy clustering data directly at the field level.

Julia Stadler has been awarded the prestigious Emmy Noether Grant of the Deutsche Forschungsgemeinschaft (DFG).

Matthew Smith has been granted a high performance computing allocation as part of the collaboration ”Learning the Universe: Cosmological inference from numerical models of galaxy formation”.

Benedetta Ciardi has secured a German-Israeli Foundation (GIF) as a co-PI. This project focuses on developing theoretical tools to interpret the high-redshift intergalactic medium.

Sherry Suyu has received the Golden Chalk teaching award for best bachelor physics lectures in 2024, Technical University of Munich, Germany.

Valeriya Korol has been selected to join the LISA Science Team to help ESA shape the scientific potential of its flagship and first-of-its-kind gravitational-wave mission, the Laser Interferometer Space Antenna (LISA). She is the only early career scientist to be selected for this panel.

Benedetta Ciardi has been awarded a grant from the Max Planck Soceity to upgrade the MPA LOFAR station to LOFAR2.0 standards.

Anshuman Acharya was a Co-PI on successful Cycle 32 of Hubble Space Telescope Archival Research proposal.

4.3 PhD and Master Theses 2024

4.3.1 Master Theses 2024

Anton Nöbauer: “Image Reconstruction in 3D Microscopy with Information Field Theory”, LMU München.

Mrinal Jetti: “Spectral Bayesian Imaging of Perseus Cluster in X-ray”, LMU München.

Daniel Muschiol: “Untersuchung der Rekonstruktionsgenauigkeit von Galaxiepositionsdaten aus einem rückwärtsoptimierten digitalen Hologramm”, Hochschule Ruhr West

4.3.2 PhD Theses 2024

Aniket Bhagwat: ”Connecting stellar feedback in the first galaxies and cosmic reionisation”, Ludwig-Maximilians-Universität München.

Bryce A. Remple: ”AGB Evolution and Nucleosynthesis: Understanding the Uncertainties”, Ludwig-Maximilians-Universität München.

Jay Gonzalez Lobos: ”Characterizing the extended Lyman-α emission around high-redshift massive galaxies”, Ludwig-Maximilians-Universität München.

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

Marta Monelli: ”Development of Realistic Simulations for the Polarization of the Cosmic Microwave Background”, Ludwig-Maximilians-Universität München.

Vyoma Muralidhara: ”Spectral distortion and polarization of the cosmic microwave background: Measurement, challenges and perspectives”, Ludwig-Maximilians-Universität München.

Ivana Babić: ”Field level inference of the Baryon Acoustic Oscillations Scale”, Ludwig-Maximilians-Universität München.

Jakob Roth: “Bayesian Imaging with Ground Based Telescopes”, LMU München.

Gordian Edenhofer: “Resolving our Dusty Neighborhood in the Milky Way”, LMU München.

4.4 Visiting scientists in 2024

Long-term visitors (longer than 2 weeks)

Saleem Zaroubi (University of Groningen, Netherlands) 15.01–01.03, Andrea Cabrioul (INAF/Italy) 17.01–15.05, Valentina Vacca (INAF/Italy) 17.01–15.05, Gissel Pardo Montaguth (University of La Serena, Chile) 11.02–08.05, Andrea Chiavassa (Laboratoire Lagrange/France) 19.02–15.03, Changhyun Cho (New York University Abu Dhai) 03.03–31.03, Gen Chiaki (Tohoku University) 18.03–28.03, Brian Tapia (Chile) 05.04–05.05, Leander Thiele, Dr. (Kavli Institute for the Physics and Mathematics of the Universe (IPMU), Kashiwa, Japan) 01.05–31.05, Julio Navarro (Visitor Prof.) (University of Victoria, Canada) 04.05–30.09, Bruno Martín Celiz (IATE, Córdoba, Argentina) 31.05–26.08, Kandaswamy "Kandu" Subramanian (Inter-University Centre for Astronomy and Astrophysics (IUCAA)) 01.06–31.07, Andrei Beloborodov (Columbia University) 02.06–19.01, Nianyi Chen (Carnegie Mellon University) 02.06–26.07, Biwei Dai (University of California, Berkeley) 02.06–26.07, Natalya Lyskova (Space Research Institute of Russian Academy of Sciences) 07.06–08.07, Valentin Skoutnev (Columbia University, USA) 07.06–30.01, Zachary "Zach" Slepian (University of Florida, faculty) 07.06–24.06, Charles "Chuck" Steidel (Caltech, USA) 15.06–06.07, Tomomi Sunayama (University of Arizona (soon ASIAA)) 20.06–07.07, Facundo Ariel Gómez (Universidad de la Serena/Chile) 21.06–20.07, Antonela Monachesi (Universidad de la Serena/Chile) 21.06–20.07, Hanifa Teimourian (Erciyes University) 05.07–15.10, Alexander Heger (Monash Centre for Astrophysics) 08.07–07.08, Giovanni Stimamiglio (LMU) 08.07–30.09, Jing Wang (Peking University) 13.07–28.07, Laura Herold (University John Hopkins, Baltimore USA) 22.07–09.08, Paolo Mazzali (Liverpool John Moores University) 28.07–12.10, Elen Pian (Istituto Nazionale di Astrofisica - INFA, Rom) 28.07–12.10, Luc Dessart (CNRS-Sorbonne Université, France) 31.07–31.08, Evgeni Grishin (Monash University, School of Physics and Astronomy) 24.08–08.09, Juma Kamulali (Kyambogo University, Uganda) 15.09–03.12, Benard Nsamba (Kyambogo University, Uganda) 15.09–03.12, Qiang "Brandon" Wang (MAX!mize Program, Technical Staff) 15.09–28.02.2025, Ritali Ghosh (Indian Institute of Science, Bengaluru, India) 07.10–12.11, Andrea Chiavassa (Observatory of Côte d'Azur, Nice, France / Astrophysicist) 21.10–22.11, Alexey/Aliaksei Bobrick (Technion - Israel Institute of Technology, Doktorand) 28.10–15.11, Norbert Langer (Universität Bonn) 04.11–14.12, Laura Sales (University of California, Riverside / Associate Professor) 19.12–02.03.2025.