Max Planck Institute
for
Astrophysics

ANNUAL REPORT 2025

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 2025.

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 programme 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 the current research include stellar evolution, stellar atmospheres, binary and multiple systems, gravitational wave progenitors, accretion phenomena, nuclear and particle astrophysics, supernova physics, astrophysical fluid dynamics, high-energy astrophysics, radiative processes, the structure, formation and evolution of galaxies and their supermassive black holes, circumgalactic medium, intracluster medium, intergalactic medium, 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, the Ludwig-Maximilians University of Munich, and the European Southern Observatory. Through the IMPRS, the four institutes typically recruit around 26 students per year, with MPA and the MPI für extraterrestrische Physik (MPE) each accounting for approximately 40% of the average total of about 110 students enrolled in the IMPRS programme. 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. It held its 123rd meeting in December 2025. The WIR consists of all the permanent and tenure-track scientists and Max Planck Research Group leaders, together with three elected representatives of scientists on fixed-term positions, three elected representatives of the graduate students, one elected representative of the technical staff, and the scientific coordinator of MPA. 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 in-house needs both by providing extensive in-house computer power and by ensuring effective access to the supercomputers and the mass storage facilities at the MPCDF, as well as the nearby Leibniz Computer Centre of the state of Bavaria (the LRZ) and other German supercomputer centres (e.g. in Stuttgart and Jülich).

MPCDF and MPA coordinate their activities and development plans through regular meetings to ensure continuity in the working environment experienced by the users. Scientists at MPA are also very successful at obtaining additional supercomputing time, in 2024/2025 more than 60 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 centre at the MPCDF. The node hosts the full results from important simulation projects (e.g. Millennium XXL, Eagle, Illustris-TNG, MillenniumTNG) 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 dozens of GB to hundreds of 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 2025 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 2025

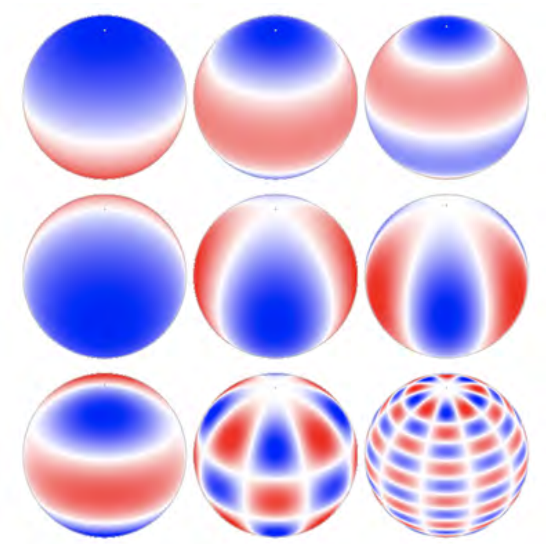
Diving deep into the stars with asteroseismology

Different musical instruments make different characteristic sounds, as a consequence of their different structures. An orchestra has diversity in brass and percussion, woodwind and strings, not for the visual variety but because the different instruments make different musical tones and melodic colours: a cello can make different sounds from a violin, and a tuba different sounds from a piccolo. Now imagine only hearing a new musical instrument, and having to work out the construction of the instrument from details in the sound waves. Seismologists do something similar with the Earth itself, from listening to seismic waves travelling through the Earth with careful instruments to gain information about the internal structure of our home planet. Asteroseismologists use the same principle to infer the internal structures of stars. We cannot hear sound waves from the stars, of course, since they do not reach us through the vacuum of space. Yet carefully observing the light from stars can indicate how they are oscillating, and so allow us to infer how waves travel inside those stars. In turn, combining detailed observations and models teaches about the structures inside stars. This method for investigating the interiors of stars has been used for several decades on the nearest example – our own Sun – but we were unable to adequately measure the oscillations of more distant stars.

In this year's Biermann lectures, Conny Aerts talked about the observational aspects of asteroseismology, the theory behind it, and how to combine both to study the insides of stars – learning more about their interior structures, and the physics which operates during their evolution.

Conny Aerts has been a leading figure in turning asteroseismology into a field which now gives insight into diverse stars beyond the Sun. With a background in mathematics, Conny and her group have developed powerful methods to interpret asteroseismic signals. Conny has further applied these techniques to data from satellite telescopes – notably NASA's planet-hunting missions Kepler and TESS – to reveal new information about the insides of a broad range of stars.

Biermann lecturer 2025: Conny Aerts *(Credit: Rob Stevens)*



Example of different pulsation modes in a star. Red and blue regions represent sections of the star that are alternately moving inwards and heating, or outwards and cooling. *(Credit: C. Aerts)*

Conny is well-known for developing asteroseismology to make discoveries about the internal structures of stars significantly more massive than the Sun. When converting hydrogen to helium in their centres, such massive stars develop convective cores. Understanding the transition from highly-turbulent convection in the core to a stably-layered envelope has defeated even the most sophisticated simulations so far. Conny's group has led in using asteroseismology to probe the deep interior structures of these massive stars, moving us towards resolving this long-standing uncertainty in stellar physics.

Another prominent example of the leadership from Conny's group, based on the methods she has developed, is in making measurements of the internal rotation of stars. This involved moving past a perturbative approach to treating rotational effects, and also beyond using spherical harmonics to represent the oscillation modes. Conny's work has thereby led to insights into angular-momentum transport inside stars, and also to constraining the mixing associated with this rotation.

Conny's fantastic scientific work has won an extraordinary number of prestigious awards. The citation for the 2022 Kavli Prize in Astrophysics, to Conny Aerts and her co-laureates, was: "for their pioneering work and leadership in the development of helioseismology and asteroseismology. Their research has laid the foundations of solar and stellar structure theory, and revolutionized our understanding of the interiors of stars." She also won both the Francqui Prize for Exact Sciences and the 5-year FWO Excellence Award for Exact Sciences (in 2012 and 2020, respectively), and in each case was the first woman to receive them since their creation. In 2023, Conny was made a Grand Officer in the Order of Leopold, the highest Belgian order of merit, and in 2024, she recieved the acclaimed Crafoord Prize in Astronomy.

Conny is the Belgian principal investigator for the European Space Agency's PLATO satellite, due to be launched in 2026, which promises to be even more powerful in enabling asteroseismology of massive stars. She continues to serve on the Editorial Board of the Annual Review of Astronomy and Astrophysics, and was a member of the "High Level Expert Group" on the interim evaluation of the Horizon Europe programme. Conny is one of the rare scientists in Europe who has been awarded two Advanced Grants from the European Research Council, and is currently leading the ambitious ERC Synergy grant "4D-STAR".

1.3.2 Work and Leadership Culture Survey 2024/2025

In the fall of 2024, MPA conducted its regular triannual survey on work and leadership culture. The survey was open from September 25 to October 22, 2024, and all MPA employees across career levels were invited to participate. Broad participation and honest input were essential to gaining a comprehensive understanding of the workplace and identifying areas for improvement. The survey was administered entirely anonymously by an external company, Priotas, to ensure confidentiality, privacy, and data protection.

The survey addressed the following key areas: Satisfaction with the work environment, Leadership culture, Experiences with discrimination and harassment and Work-life balance. All members of the institute, including scientists (students, postdoctoral researchers, and staff), as well as technical and administrative staff, were encouraged to take part.

Participation and Results

A total of 58% of eligible employees participated in the survey. On February 20, 2025, Priotas presented the survey results and their analysis to MPA. The findings highlighted a few important areas requiring further attention in order to improve the institute's work culture. These include: Work-life balance, Policies and practices related to bullying, discrimination, and sexual harassment and Contract length for PhD students. The survey results provided valuable guidance for future measures aimed at strengthening a supportive, inclusive, and sustainable work environment at MPA.

Meet and Greet with MPA Management

Following the great suggestions from both junior and senior employees after Priotas' presentation, the institute management organised a Meet & Greet with Management, including the Managing Director, Deputy, scientific coordinator, and the GEO, to discuss the results. In order to collect discussion topics for the Meet & Greet in a way that ensures everyone's voice is heard, a quick anonymous poll was set up to gather feedback on key areas identified in the survey that could be improved.

On April 10th 2025, a "Meet and Greet" session was held between the MPA management team and the members of the institute from all career levels. The agenda included the presentation of survey results, feedback collection from various groups within the institute, and a discussion on suggested improvements. The session facilitated transparent dialogue between the MPA management and its members, with a focus on institutional development, staff support, and training opportunities. At the conclusion of the session, the PhD and postdoctoral representatives requested the organisation of a mandatory, institute-wide seminar aimed at raising awareness and promoting appropriate conduct within the MPA working environment.

MPA Essential Coaching Seminar

Following the outcomes of the work-culture survey, an internal poll, and a meet-and-greet with MPA management, we requested the Planck Academy to develop and deliver a seminar tailored specifically to the needs identified within the institute. The Planck Academy engaged an expert coach with extensive experience in workplace culture and team development to lead the session.

The seminar was held in person at MPA on October 6, 2025. It was designed as an interactive working session rather than a lecture, with active participation from all attendees considered essential to its success. In recognition of the importance of this event, all employees were asked to make arrangements to attend and to participate fully. To enable institute-wide participation, the schedule for the day was cleared, including the cancellation of the regular institute seminar.

The seminar, entitled "Precarity & Power: The Challenges of Creating Inclusive Research Environments," was attended by nearly all members of MPA and was widely regarded as a success. It addressed key topics such as structural inequalities in research institutions, work-life balance, abuse of power, discrimination and bullying, and microaggressions, as well as practical approaches for addressing these challenges. Key takeaways from the seminar emphasised that anti-bullying and anti-harassment training is not merely a formal requirement, but a moral imperative in modern academia. Such training is essential to protecting individuals, strengthening institutional culture, and ensuring that research and education take place in an environment where all voices are respected and heard.

In addition, the seminar underscored that work-life balance in academia must be addressed as a systemic issue affecting all members of the academic community, including technical and support staff. Promoting healthier boundaries, recognising all forms of labour, and valuing well-being alongside productivity were identified not only as ethical responsibilities, but as critical elements in sustaining a functional, inclusive, and humane academic environment.

Reflections and Actions

Following the seminar, MPA management initiated a feedback poll to gather employees' reflections. The responses were predominantly positive and included suggestions to hold similar awareness-raising seminars on a regular basis. In response, MPA management agreed to organise such seminars on an ongoing basis.

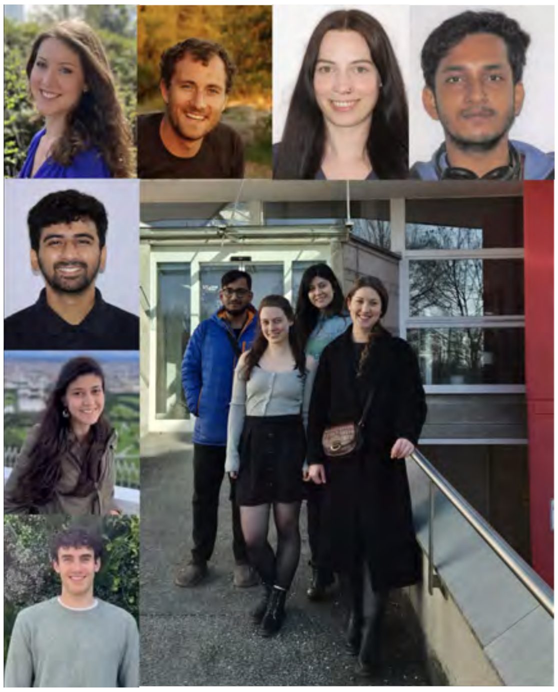
In addition, the MPA Works Council has begun examining options for expanded remote working arrangements across different career levels as a means of supporting improved work-life balance. MPA management has also taken a more proactive approach in encouraging supervisors to support their students and postdoctoral researchers in making full use of their paid leave, as well as mental and physical health-related sick days when needed.

As a direct outcome of the recent survey and continued dialogue with PhD students, MPA management has implemented a considerate increase in the duration of PhD contracts in cases where this supports the residency permit requirements of non-EU students. Furthermore, MPA management has been actively working toward a structural increase in the institute's central budget with the aim of enabling higher PhD student salaries. This initiative addresses the growing financial pressures resulting from inflation in recent years and the high cost of living in the metropolitan area of Munich.

1.3.3 MPA launches Mentorship Programme to support aspiring astronomers

Early-career scientists at the MPA have launched a new Mentorship Programme, designed to connect aspiring astronomers from underrepresented groups with researchers at the institute. This initiative aims to increase diversity and inclusion in theoretical and computational astrophysics, offering participants valuable guidance and insights into the field.

The programme welcomes high school students, undergraduates, and master's students interested in exploring a career in astrophysics. Through informal conversations with MPA researchers—including postdoctoral fellows, senior PhD candidates, and staff scientists—mentees will learn about careers in astronomy, life at a research institute, and the field of theoretical and computational astrophysics.



Mentors of the MPA Mentorship Programme. *(Credit: MPA)*

1.3.4 Prizes and Awards

Rudolf-Kippenhahn-Award

The Rudolf-Kippenhahn Prize, awarded to the author of the best scientific paper written by an MPA student in the past year, was shared by two students: Silvia Almada Monter for "Crossing walls and windows: the curious escape of Lyman-α photons through ionized channels" and Christian Partmann for "The importance of nuclear star clusters for massive black hole growth and nuclear star formation in simulated low-mass galaxies". The prize is awarded to recognize originality, a large impact on science but also the quality of writing for a publication to which students themselves made substantial contributions.

Silvia's remarkable paper on Lyman-alpha radiative transfer through anisotropic media changes completely how we (should) think

Kippenhahn laureate Silvia Almada Monter receives the certificate from MPA managing director Eiichiro Komatsu. *(Credit: MPA)*

Christian Partmann joined virtually to receive the Kippenhahn prize from Eiichiro Komatsu. *(Credit: MPA)*

about Lyman-alpha radiative transfer. Her results challenge long-standing assumptions about how these photons escape from galaxies, pointing instead to an entirely new physical picture — one so counterintuitive that her supervisor Max Gronke spent months convinced it had to be wrong.

Despite Max's doubt, Silvia methodically tested every piece of the old and new theory, combining simulations and analytics with impressive care and clarity. The result is not just a deep and original contribution, but also a beautifully written paper. Go ahead and read it — it is amazing (and it's short!).

In the second paper, Christian investigated the – poorly understood – growth processes of intermediate mass black holes (IMBHs) in the centres of low-mass galaxies. The paper is based an original idea that Christian proposed, and for which he independently developed the more realistic setup necessary to study the idea. His work reveals that nuclear star clusters facilitate the rapid growth of central seed black holes into IMBHs within a few hundred million years. Whereas without nuclear star clusters, the seed black holes show minimal growth.

The accretion cycles of the growing black holes are regulated by nuclear star formation and supernova explosions, which may explain the observed coexistence of nuclear star clusters and IMBHs. Christian's study emphasises the importance of considering these star clusters in future research. This excellent paper represents a significant theoretical advancement, highlighting the power of precise numerical models to uncover important physical processes in black-hole growth through gas accretion.

Marat Gilfanov appointed Distinguished Guest Professor at Nanjing University

The School of Frontier Science at Nanjing University has announced the appointment of Prof. Dr. Marat Gilfanov, Senior Scientist at the Max Planck Institute for Astrophysics (MPA), as a Distinguished Guest Professor. Currently, Gilfanov is working with the Nanjing scientists on a joint project studying intermediate mass black holes (IMBHs).

In particular, the team will search for X-ray emission signatures from IMBHs—objects with masses between 100 and 100,000 times that of the Sun. The collaboration will leverage Nan-

Prof. Marat Gilfanov *(Credit: MPA)*

jing University's advanced data analysis capabilities and MPA's theoretical modeling expertise, combining observational data with cutting-edge simulations. The project is expected to yield new insights into the role of IMBHs in galaxy formation and the broader cosmic structure.

Dr. Gilfanov's internationally recognized career is spanning over four decades. He earned his Ph.D. in Physics from the Moscow Institute of Physics and Technology and started his research career at the Space Research Institute of Russian Academy of Sciences. In 1996 he earned the degree of Doctor of Sciences equivalent to the German Habilitation. Since 1996, he has been working at the Max Planck Institute for Astrophysics, where he has led groundbreaking research on black hole populations, spectral formation in X-ray binaries, nature of progenitors of type Ia supernovae, and a number of other topics. He is one of the creators of the all-sky X-ray map obtained by the eROSITA X-ray telescope aboard SRG orbital observatory on which prominent large scale structures – the eROSITA Bubbles, were identified.

His work has been instrumental in shaping modern understanding of the X-ray binaries, their scaling relations and contribution to X-ray background and the demographics of black holes in the universe. In 1992, he received the COSPAR Zeldovich Medal for Young Scientists, in 1997 the Tsyolkovsky medal of The Russian Federation of Cosmonautics and in 2017 the Belopolsky Prize in astrophysics. He is a full member of the Russian Academy of Sciences and a member of Academia Europaea.

MPA Postdoc Claude Cournoyer-Cloutier awarded Governor General's Academic Gold Medal

For her excellent graduate studies, Claude Cournoyer-Cloutier, who is now a postdoctoral fellow at the Max Planck Institute for Astrophysics, received the Governor General's Academic Gold Medal at the McMaster University in Hamilton, Canada at the end of November.

The prestigious award recognizes students for their outstanding scholastic achievements. In her graduate research, Cournoyer-Cloutier

Claude Cournoyer-Cloutier (center) holding the Governor General's Academic Gold Medal with her PhD supervisors, Dr. Alison Sills and Dr. Bill Harris. *(Credit: C. Cournoyer)* used numerical simulations to study the formation of massive, dense clusters of stars. During her PhD, she gave more than 100 shows for McMaster's on-campus and portable planetariums. She was the graduate student representative on department meetings for several years, and on a faculty hiring committee in 2021-2022. In her role as head teaching assistant for two first-year physics courses, she implemented several new marking practices to make grading more equitable and transparent, and in the final year of her PhD, she started co-supervising student projects and is keen to continue doing so as MPA post-doc.

The Academic Medals were created in 1873 by Lord Dufferin, Canada's third Governor General after Confederation, to encourage academic excellence across the nation. Over the years, they have become the most prestigious award that students in Canadian schools can receive. Today, the Governor General's Academic Medals are awarded at four distinct levels: Bronze at the secondary school level; Collegiate Bronze at the post-secondary, diploma level; Silver at the undergraduate level; and Gold at the graduate level. Medals are presented on behalf of the Governor General by participating educational institutions, along with personalized certificates signed by the Governor General.

2 Scientific Highlights

2.1 Towards direct observation of large samples of intergalactic filaments in the early universe

By Eileen Herwig (PhD student) and Fabrizio Arrigoni Battaia (scientific staff)

The distribution of matter in the universe is predicted by supercomputer simulations to occur in a network of filaments, known as the "cosmic web", where galaxies form and evolve. The vast majority of this intricate structure is in the form of diffuse hydrogen gas, so rarefied that it is extremely challenging to observe it directly. A collaboration led by MPA researchers has targeted the active supermassive black holes of galaxy pairs at close separations to reveal the connecting filamentary structures of the cosmic web in the early universe. The results are promising and unveil evidence for such structures stretching between the observed pairs, ultimately providing excellent targets for future ultra-deep observations.

Galaxies are embedded in large reservoirs of gas bound to them by gravity, the so-called "circumgalactic medium". Like all gas in the universe, it mainly consists of hydrogen and helium with traces of other elements that are produced in stars and ejected from the galaxy disks in bubbles of hot gas or fast winds expanding into the circumgalactic medium. In turn, cool gas is funneled back into the galaxy in streams and can form new stars or feed the supermassive black hole at the galactic center. Galaxies are not hermits though: large filamentary gas structures connect galaxies to their neighbors. This overall skeleton is called "cosmic web", and galaxies can accrete additional material from its filaments to rejuvenate and grow. While simulations have explored this process very well, observational evidence of the filamentary cosmic web is sparse and mainly indirect, e.g. inferred from the observed position of galaxies in the local universe or by how the cosmic web absorbs light from bright background sources.

The areas where multiple filaments of the cosmic web intersect are called "nodes", typically inhabited by the most massive galaxies. In

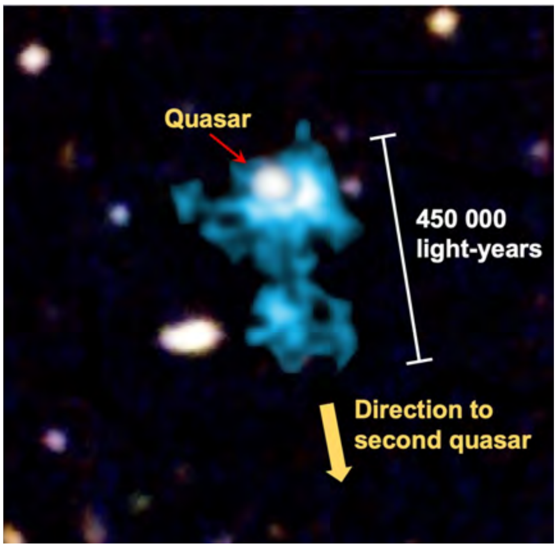


Figure 2.1: One quasar of the sample embedded into extended Lyman alpha emission (cyan), which reaches the edge of the circumgalactic medium of its host galaxy. The uncovered filamentary structure is stretched in the direction of the second quasar of the pair (not shown). Multiple further sources are visible in this field, which are not physically associated with the quasar pair; these lie between Earth and the observed quasar. *(Credit: MPA)*

the early universe, 11.5 billion years ago, these massive galaxies are commonly pinpointed by quasars – a brief phase in these galaxies' life cycle, when matter falling onto their central supermassive black holes powers exceptionally luminous events that easily outshine all stars in their host galaxy. Therefore quasars can act as powerful natural "cosmic flashlights": Their radiation can reach far into the circumgalactic medium and the surrounding cosmic web, lighting up the hydrogen gas at a specific ultraviolet colour, the Lyman alpha wavelength.

Researchers from MPA have now observed a sample of quasar pairs, i.e. two massive active galaxies in direct vicinity to each other, to unveil the Lyman alpha emission in their circumgalactic medium and in-between the galaxies (commonly referred to as "Lyman alpha nebulae"). Extended emission is detected in most targeted systems (see example in Figure 2.1) and the emission is preferentially aligned with the pair direction (see Figure 2.2). These results are in line with expectations, if a cosmic web filament connects the two quasars and cool gas gets funneled directly from the filament through the circumgalactic medium down to the galactic disk.

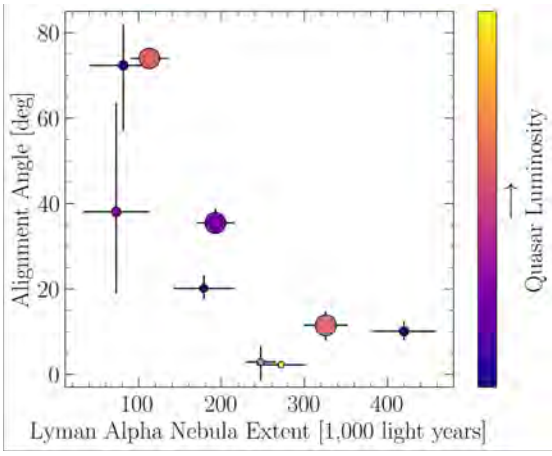


Figure 2.2: This plot shows the alignment of the Lyman alpha nebulae with the quasar pair direction. An angle of zero degrees corresponds to perfect alignment. In the sample studied, all large nebulae (extending into the circumgalactic medium by more than 200,000 light years) trace the quasar pair direction. This trend is not driven by the quasar luminosity (colour of the points) or the distance between the quasar pairs (size of the dots). This shows that the Lyman alpha nebulae indeed trace the cosmic web filaments. *(Credit: MPA)*

Compared to other massive galaxies at this epoch, quasar pairs are embedded in smaller reservoirs of cool gas. Their circumgalactic medium actually resembles that of galaxies at a cosmic time one billion years later. Such an accelerated evolution might be caused by the rich environment inhabited by quasar pairs and/or by highly energetic processes connected to the accreting supermassive black holes, which could heat up the gas surrounding the galaxy and counteract the gas accretion.

This sample of quasar pair observations is the largest to date and represents the best collection of promising targets for directly studying the emission of the cosmic web in the early universe with future ultra-deep observations. More and more observations of the intricate web of cosmic filaments will become available in the near future.

2.2 Debugging Galaxy Evolution with L-GALAXIES

By Akash Vani (PhD student)

The formation and evolution of galaxies are among the most complex challenges in astrophysics. Recent advancements with instruments like JWST and ALMA have shed light on high-redshift galaxies – those that existed billions of years ago. However, most theoretical models are tuned to match galaxies in the local universe. Researchers from the Max Planck Institute for Astrophysics and the University of Bonn now comprehensively evaluated the Munich semi-analytical model L-GALAXIES us-

Figure 2.3: The semi-analytical model L-GALAXIES simulates astrophysical phenomena to predict galaxy properties and scaling relations. *(Credit: MPA)*

ing the latest observations and found that while the model aligns well with the properties of local galaxies, it struggles with key aspects of high-redshift galaxies. Particularly, the study highlights critical issues with the model's predictions of quenched galaxies, those that have ceased star formation. Their results suggest a need to revise the implementation of processes driving star formation quenching, including supermassive black hole feedback and galaxy mergers.

Observations from surveys such as SDSS, CANDELS, and COSMOS provide essential insights into galaxy properties and scaling relations. However, to uncover the underlying processes driving galaxy evolution, astronomers need to simulate the relevant astrophysical phenomena. The Munich semi-analytical model, L-GALAXIES, offers a self-consistent framework for tackling these challenges. Over the past three decades, L-GALAXIES has undergone continuous development, primarily at the Max Planck Institute for Astrophysics (MPA) in collaboration with international teams, establishing itself as a corner-stone tool for studying galaxy evolution. The model strikes a balance between computational efficiency and detailed physical modelling, making it a powerful complement to computationally demanding hydrodynamical simulations.

The L-GALAXIES model builds upon its previous generation with a series of advancements that are motivated both by new observational data and a resulting deeper physical understanding of complex processes such as gas accretion and cooling, star formation, chemical enrichment, and stellar and black hole feedback. The most recent versions incorporate advanced environmental mechanisms like ram-pressure and tidal stripping. The models are calibrated using Monte Carlo Markov Chain (MCMC) techniques and constrained by low-redshift observational data. Together, these updates and calibrations represent the cutting edge of semi-analytical galaxy formation modelling.

Recent observational campaigns, particularly those utilizing advanced ground- and space-based instruments such as the Hubble Space Telescope (HST), the Atacama Large Millimeter/submillimeter Array (ALMA), and the James Webb Space Telescope (JWST), have provided unprecedented insights into the evo-

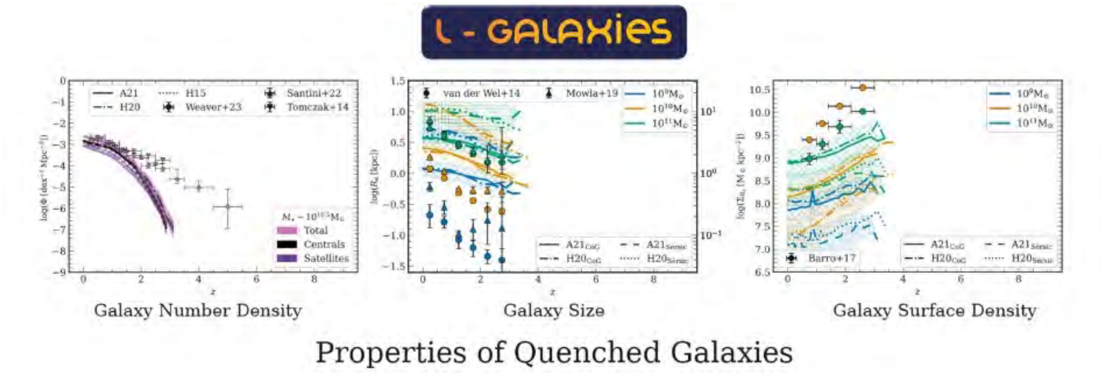


Figure 2.4: The three plots show the L-GALAXIES model predictions (solid lines) for Milky Way-mass galaxies compared to observational data points at the corresponding redshift. The left plot demonstrates that the model fails to produce a sufficient number of quenched galaxies. The middle plot indicates that the model overestimates the sizes of quenched galaxies. The plot on the right shows that quenched galaxies in the model are not sufficiently compact. *(Credit: MPA)*

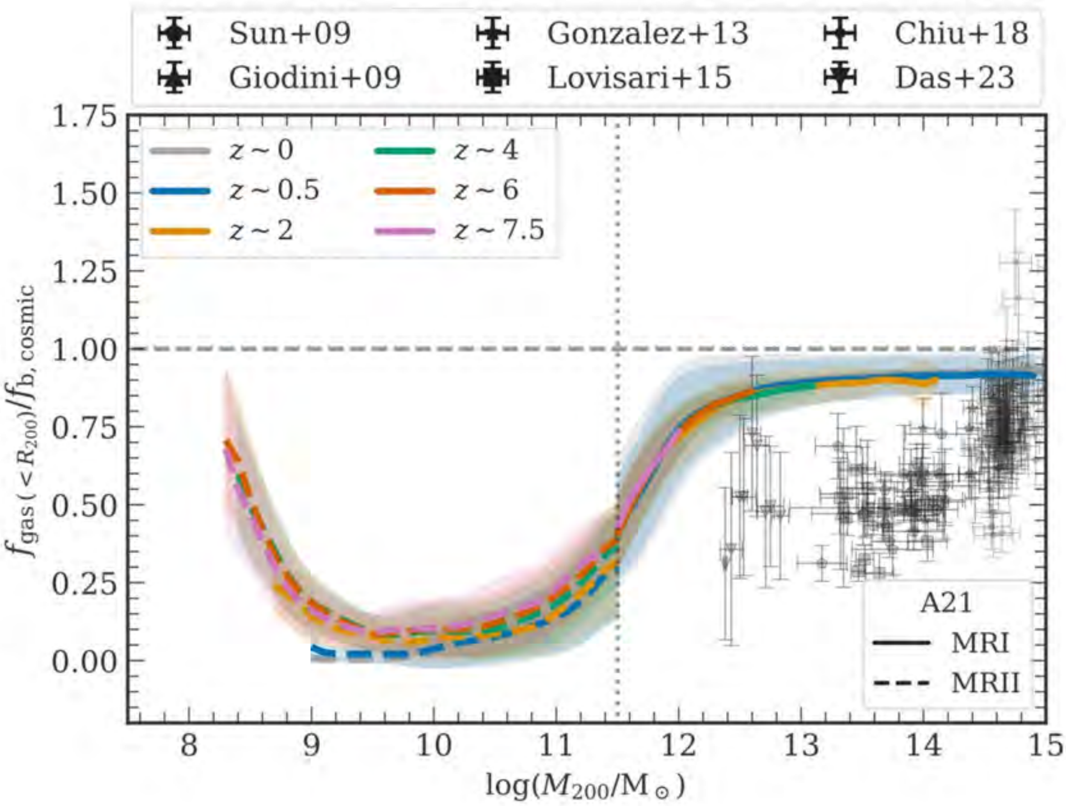


Figure 2.5: The plot illustrates the gas fractions within galaxy halos as a function of halo mass for six redshift intervals (various colors) from two simulations (dashed and solid lines). The lack of redshift evolution suggests that the physical processes governing gas retention within halos in the L-GALAXIES model are largely time-independent. The AGN feedback in L-GALAXIES primarily prevents hot gas cooling without significantly altering its spatial distribution. *(Credit: MPA)*

lution of high-redshift galaxies. These observations reveal the size, compactness, and abundance of quenched galaxies at redshifts around z=2 (when the universe was just 3 billion years old) and beyond, offering a unique opportunity to rigorously test L-GALAXIES predictions well outside its original calibration regime. In particular, they are identifying areas where the model aligns with or deviates from observed trends, providing crucial guidance for improving its treatment of high-redshift galaxy populations.

The current study evaluates the latest version of L-GALAXIES alongside its two preceding iterations, focusing on their ability to reproduce the evolution of galaxy number density, size, and surface density across cosmic time. The analysis spans the history of the universe, from 500 million years after the Big Bang to the present day (13.5 billion years later), with a specific focus on the first few billion years. It marks the first comprehensive comparison of L-GALAXIES predictions to high-redshift observations.

Galaxies were classified as star-forming or quenched based on their near-ultraviolet (NUV) to near-infrared (J-band) color. Sizes and surface densities were determined using methodologies consistent with observational studies. Additionally, X-ray data from instruments such as Chandra and XMM-Newton, along with microwave and longer wavelength data from Planck, were incorporated to examine baryon and gas distributions within host halos, shedding light on the interaction between baryonic matter and galaxy processes.

Although the model shows significant agreement with the properties of star-forming galaxies at both low and high redshifts, the study highlights significant discrepancies in the model's predictions for quenched galaxies, particularly for Milky Way-mass and more massive systems at the times when the Universe was younger than 2 billion years old. The model underestimates the abundance of quenched galaxies by a factor of 60 and over-predicts the fraction of baryonic matter within galaxy clusters by around 15-20%. Moreover, the predicted sizes of galaxies are several times larger than observed, pointing to deficiencies in the modeling of star formation suppression mechanisms such as active galactic nucleus (AGN) feedback and galaxy mergers.

While L-GALAXIES successfully reproduces the stellar mass functions and cosmic star formation rates across a wide range of cosmic times, it fails to capture the size-mass relations and surface density trends of quenched galaxies at high redshifts. These findings suggest that the model's simplified treatment of galaxy mergers and quenching mechanisms limits its ability to accurately predict the abundance and compactness of quenched galaxies.

Addressing these limitations will require recalibration efforts informed by data from JWST and other advanced observations. More critically, the model needs a thorough revision of its implementation of key physical processes relevant to galaxy quenching, such as AGN feedback and galaxy merger events. Additionally, leveraging state-of-the-art machine learning techniques to navigate the extensive parameter space offers a promising avenue for refining the model's physical prescriptions and enhancing its predictive accuracy. These efforts will not only improve our understanding of galaxy evolution but also lay the groundwork for the development of next-generation L-GALAXIES models.

2.3 Simulating the birth, life and dispersal of galactic star clusters

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

Most stars form in clusters, deeply embedded in the densest and coldest cores of giant molecular gas clouds. A few million years into the formation of a cluster the remaining gas is finally expelled by supernova explosions. Thereafter the clusters lose stars in the galactic tidal field and eventually disrupt. This entire life-cycle is very difficult to observe. Star clusters begin their lives deeply embedded in their birth clouds and are invisible to most observatories and the disruption of a single cluster can take tens of millions of years or more. An international team led by researchers at MPA has presented a new high-resolution supercomputer simulation, which can follow entire galactic star cluster life-cycles from birth to disruption and sheds light on the unobservable phases of star cluster evolution.

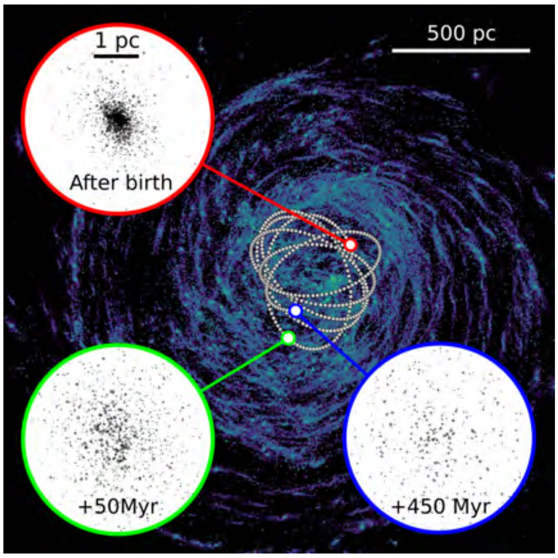


Figure 2.6: This illustration shows the galactic orbit (grey dots) of a star cluster (with 800 solar masses) that formed in a dwarf galaxy. The insets show individual cluster stars at three different times in the life-cycle of the star cluster: when the compact cluster has formed (red); after 50 Myr (half an orbit, green); and after 450 Myr (several orbits, blue), when the cluster is almost entirely disrupted. The background shows stars which have formed in the last 500 Myr. *(Credit: MPA)*

The complex life of star clusters

A typical young star cluster is a home to up to thousands of stars contained in a compact size of a few parsecs. The most massive ones, such as globular clusters, can exceed millions in their stellar count. Some of stars in these clusters are born with masses that exceed the mass of the Sun by tens or hundreds of times. Such massive stars are extremely rare (less than one in every 100 stars) and they live only for a few million years. They are, however, vitally important for creating new chemical elements through nuclear fusion, including those that are requisites for the formation of planets and the development of life.

Once massive stars form, they start releasing energetic photons and fast stellar winds that interact with the surrounding birth-cloud of gas. After a few million years, once the stars have exhausted their nuclear fuel, the most massive ones end their lives as explosive supernovae. These so called “feedback” processes deposit heat, momentum and heavy elements into the birth-cloud, eventually expelling the remaining gas that is left over from star formation.

This marks the transition of a young star cluster into a system that mainly evolves by gravitational interactions among its stars and with the surrounding tidal field. Through dynamical interactions, massive stars can sink to the centre of the cluster and stars can end up in binaries. Further gravitational interactions at the centre of the cluster force low mass stars on increasingly distant orbits. These stars can then become unbound and escape from the gravitational potential of the cluster into the galactic field. While orbiting in the host galaxy, the cluster continuously loses mass and ultimately disrupts entirely Figure 2.6.

More realistic star cluster simulations

Numerical simulations are an invaluable tool to probe the entire cycle of formation and disruption of star clusters on spatial and temporal scales that are inaccessible to observations.

A recent study led by Postdoctoral Fellow Natalia Lahén at MPA presentedthe first star-by-star hydrodynamical galaxy simulations. Detailed modelling of individual stars is crucial for resolving the internal structure of star clusters. The simulation code for this project was first developed at MPA and further improved in international collaboration including researches at the University of Helsinki in Finland and Nicolaus Copernicus University in Poland. For the study presented here the team used a very accurate gravity solver to follow close gravitational interactions between stars. With this method it was possible to simulate, for the first time, the evolution of an entire dwarf galaxy with all its stars, gas and dark matter. At the same time, they could accurately follow the dynamical evolution of hundreds of individual star clusters, each containing at least hundreds or thousands of stars.

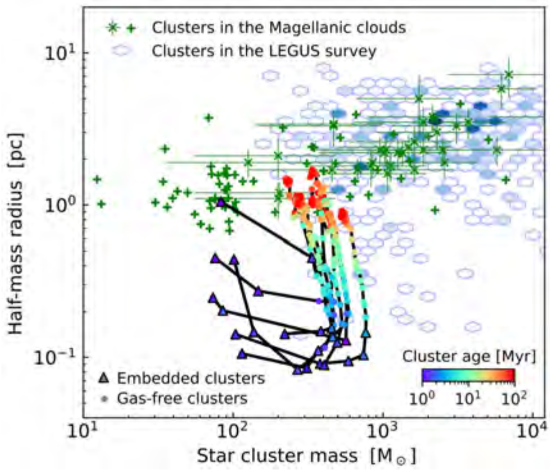


Figure 2.7: This figure shows the time evolution of the size and mass of a number of selected star clusters in the simulation. The color scale indicates the mean stellar age of the clusters and the black lines connecting the data points indicate the evolution of individual clusters. The clusters start embedded (triangles). They first contract and then expand once the star formation is halted and gas is removed (circles). The size evolution is compared to observed clusters in the Large and Small Magellanic clouds (green stars and crosses) and clusters in low-mass galaxies measured in the LEGUS galaxy survey (blue symbols). Even though the simulated clusters form very compact, they evolve to the observed range of sizes over ~ 10 million years. *(Credit: MPA)*

Star cluster evolution in a galactic context

The new high-resolution simulations of a dwarf galaxy similar to Wolf–Lundmark–Melotte (WLM) in the Local Group (see the Movie for an illustration) show how gas and stars interact through cooling, collapse, star formation, and stellar feedback. The orbits as well as the release of energy and chemically enriched material of each star are followed individually along the stellar lifetime. Thanks to the new algorithm for gravitational force computation, in particular encounters with massive stars can be followed down to stellar radii and the dynamical evolution of the clusters embedded in the galactic interstellar medium can be followed at unprecedented accuracy.

The new simulations show that initially, while they are still embedded in the birth-cloud, star clusters can form very compact (see 2.6 and 2.7). During the following ten million years their sizes increase to the observed ~ 1 parsec due to dynamical evolution and stellar mass loss.

The new methodology and its future expansion will play a key role in the next generation of simulations that aim to probe more extreme star forming systems called starbursts. Starbursts can be induced for example by compression of gas in galactic mergers or through gaseous inflows during the early cosmic epochs when galaxies themselves were still forming. The extreme gas densities promote the formation of increasingly massive star clusters.

The next step is to use the new methods to decipher the internal chemical and kinematic structure of the most massive clusters known as globular clusters. Globular clusters are the oldest bound star clusters observed in the Milky

Way, dating back to the Cosmic Dawn. Understanding their birth conditions in synergy with state-of-the art observations of high-redshift star formation (from e.g. HST and JWST) as well as the Milky Way clusters (e.g. from Gaia and the upcoming 4MOST) may thus reveal how our home galaxy first started to form.

This work was supported by Gauss Centre for Supercomputing grants pn49qi and pn72bu at the GCS Supercomputer SUPERMUC-NG at Leibniz Supercomputing Centre and the Max Planck Computing and Data Facility.

2.4 A New Cosmic Ruler: Measuring the Hubble Constant with Type II Supernovae

By Christian Vogl (postdoc), Stefan Taubenberger (postdoc) and Wolfgang Hillebrandt (Emeritus Director)

The expansion rate of the Universe, quantified by the Hubble constant (H_0), remains one of the most debated quantities in cosmology. Measurements based on nearby objects yield a higher value than those inferred from observations of the early Universe—a discrepancy known as the ”Hubble tension”. Researchers at the Max Planck Institute for Astrophysics and their collaborators have now presented a new, independent determination of H_0 using Type II supernovae. By modeling the light from these exploding stars with advanced radiation transport techniques, they were able to directly measure distances without relying on the traditional distance ladder. The resulting H_0 value agrees with other local measurements and adds to the growing body of evidence for the Hubble tension, offering an important cross-check and a promising path toward resolving this cosmic puzzle.

One of the biggest puzzles in modern cosmology is the ongoing discrepancy in measurements of the Hubble constant (H_0) between local and early Universe probes, known as the “Hubble tension”. Since H_0 describes the current expansion rate of the Universe, it is a local quantity and can only be directly measured using nearby objects. In contrast, methods based on the early Universe, such as those using the cosmic microwave background (CMB), do not measure H_0 directly. Instead, they infer its value by assuming a cosmological model to extrapolate from the conditions 13 billion years ago to today. The fact that these two approaches yield conflicting values—with local distance-ladder measurements giving a higher H_0 than early-Universe methods—suggests that our standard cosmological model may be incomplete, potentially pointing to new physics.

Researchers at the Max Planck Institute for Astrophysics (MPA) and their collaborators have explored an independent way of measuring H_0 using Type II supernovae (SNe II). Unlike traditional approaches, this method does not rely on the cosmic distance ladder, making it a powerful cross-check against existing tech-

Figure 2.8: Type II supernova sample used for the Hubble constant measurement. The images show the host galaxies of the ten supernovae, with the explosion sites marked by red star symbols. The images are aligned with a redshift scale reflecting the relative distances of the supernovae from Earth. *(Credit: MPA)*

niques. Their results provide a new, highly precise measurement of H_0 and further contribute to the debate over the expansion rate of the Universe.

Determining the Hubble constant requires accurate measurements of distances to astronomical objects at different redshifts. The most widely used technique, the cosmic distance ladder, relies on several interconnected steps: distances to nearby objects (such as Cepheid variable stars) are used to calibrate further reaching indicators such as Type Ia supernovae (SNe Ia), which then serve as standard candles to measure distances to faraway galaxies.

However, the reliance on multiple steps introduces possible systematic uncertainties, and different teams report slightly different results. A direct measurement based on known physics offers a valuable complementary approach, as it is affected by different systematics and does not depend on empirical calibrations. This is where Type II supernovae provide an exciting alternative.

Type II supernovae occur when massive, hydrogen-rich stars explode at the end of their lives. While their brightness varies depending on factors such as temperature, expansion velocity, and chemical composition, it can be accurately predicted using radiation transport models. This allows researchers to determine their intrinsic luminosity and use them as distance indicators, independent of empirical calibration methods.

A critical step in this process is identifying the best-fitting model for each observed supernova. Key physical properties leave distinct imprints on the supernova spectrum: temperature shapes the overall continuum, expansion velocity sets the width of spectral lines via Doppler broadening, and chemical composition determines the strength of specific absorption and emission features. By systematically comparing observed spectra to simulated spectra from radiative transfer models, researchers can find the model that most accurately describes the supernova's physical conditions. With such a well-matched model the intrinsic brightness—and thus the distance—can be precisely determined.

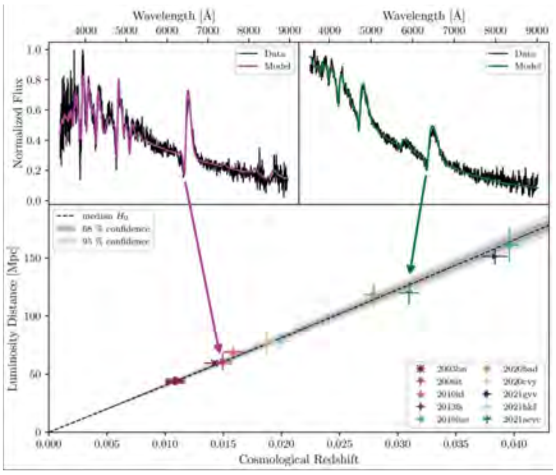


Figure 2.9: Spectral fitting and the Hubble diagram for Type II supernovae. The top panels show two examples of spectral fits used to determine the supernova distances. By comparing observed spectra (black) with model predictions (colour), researchers can extract key physical properties and infer the intrinsic brightness, enabling a direct distance measurement. The bottom panel presents a Hubble diagram, where the measured luminosity distances of the supernovae are plotted against their redshifts. The data points represent individual spectral observations, meaning multiple measurements can exist for each supernova. The dashed black line represents the best-fit relationship between distance and redshift, and its slope is determined by the Hubble constant. The grey-shaded regions indicate the uncertainties for this fit (68% and 95% confidence intervals). The best-fit value for the Hubble constant and its 68% confidence interval are $H_0 = 74.9 \pm 1.9\,\mathrm{km/s/Mpc}$. *(Credit: MPA)*

To make this process efficient, the team used a spectral emulator, an advanced machine-learning tool trained on precomputed simulations. Instead of running time-intensive radiation transport calculations for every supernova, the emulator rapidly interpolates between models, allowing for fast and accurate spectral fitting.

The research team applied their spectral modeling approach to a sample of ten Type II supernovae at redshifts between 0.01 and 0.04, using publicly available data not specifically designed for distance measurements (Figure 2.8). Despite the limitations of the dataset, their method yielded reliable distances. By constructing a Hubble diagram from these measurements (Figure 2.9), they obtained an independent estimate of H_0:

$$H_0 = 74.9 \pm 1.9\,\mathrm{km/s/Mpc}$$

This value is consistent with most other local measurements, such as those from Cepheid-calibrated supernovae and supports the tension with early-Universe probes. The achieved precision is comparable to the most competitive techniques, demonstrating that Type II supernovae are a promising tool for cosmology (Figure 2.10).

This study serves as a proof of concept, showing that Type II supernovae can provide precise and reliable distance measurements in the Hubble flow. Future work will focus on increasing the sample size and improving the accuracy of the technique by using dedicated observations. To this end, the researchers have assembled the adH_0cc dataset (`https://adh0cc.github.io/`), a collection of Type II supernova observations from the ESO Very Large Telescope, specifically designed for precise distance measurements. This dataset will serve as a key resource for refining the method.

By providing an independent check on the local determination of H_0, Type II supernovae help astrophysicists tackle one of the most pressing questions in cosmology today: Is the Hubble tension real, and if so, what does it tell us about the fundamental nature of the Universe?

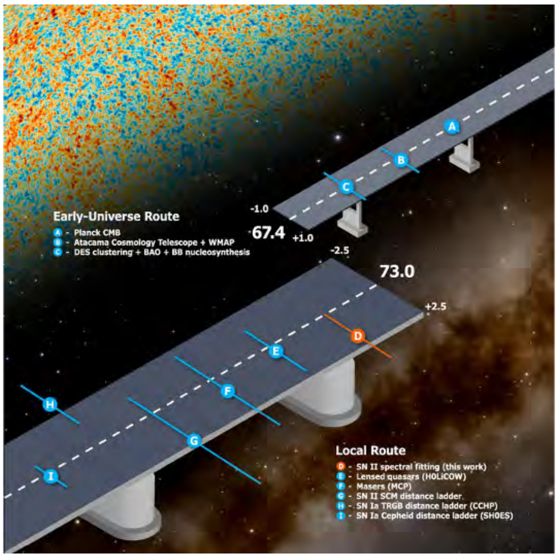


Figure 2.10: Artist's impression of the Hubble tension, showing the two different approaches to measuring the Hubble constant as two bridges that do not quite connect. The depicted early-Universe measurements yield an average value of 67.4 km/s/Mpc, the local measurements an average value of 73.0 km/s/Mpc. The new measurement from this study, based on Type II supernovae (orange), is completely independent of all other measurements and provides compelling support for the Hubble tension. The local route also includes results from various incarnations of the cosmic distance ladder, as well as other direct methods such as gravitational lensing and water masers. *(Credit: Original image by NOIRLab/NSF/AURA/J. da Silva, sourced from NOIRLab (CC BY 4.0), modified by S. Taubenberger.)*

2.5 A Universe made of Black Holes?

By Antti Rantala (postdoc), Fabian Schmidt (scientific staff), Sten Delos (Carnegie Observatories) and Sam Young (University of Sussex)

The nature of dark matter is still very much unknown; viable candidates range from microsopic elementary particles to black holes with masses many times that of the Sun. Researchers at MPA, Carnegie Observatories, and the University of Sussex have recently made concrete and reliable predictions for how the Universe would look if dark matter consists entirely of massive black holes: they performed the first self-consistent study of how structure would form in such a Universe, and how many of these black holes merge and emit observable gravitational waves.

Astronomers and cosmologists have collected a wide range of evidence for the existence of dark matter, a clustering matter component that has so far only been observed via its gravitational effects. Many dark matter candidates have been proposed, from microsopic elementary particles all the way to black holes with masses several times that of the Sun. Black holes comprising the dark matter would have to have formed in the early Universe, and hence are known as primordial black holes (PBH); astrophysically formed black holes (e.g., from stellar collapse) could not explain the evidence for dark matter seen in early-Universe probes, such as the cosmic microwave background, and would not be abundant enough. One possibility is that the PBHs were generated toward the end of the epoch of inflation in the early Universe.

A wide range of observations, including gamma-ray and X-ray backgrounds, gravitational lensing, the large-scale structure of the Universe, and the cosmic microwave background, have placed various constraints on the allowed PBH masses. Nevertheless, at least a fraction of dark matter might still consist of PBHs in several potential “mass windows”.

Researchers at MPA, Carnegie Observatories, and the University of Sussex have recently performed the first self-consistent study of how structure would form in a Universe with primordial-black-hole dark matter (of mass about 16 solar masses), by investigating the evolution of a region in the Universe with slightly above-average density. They carefully treated the evolution throughout the primordial Universe, and then continued the calculation with the state-of-the-art N-body code BIFROST. BIFROST calculates all gravitational forces between each black hole in the simulation without any small-scale resolution limit. It also includes relativistic effects responsible for libration and precession of binary PBH orbits, reminiscent of Einstein’s famous explanation for the periapsis advance of Mercury’s orbit. Most importantly, gravitational-wave radiation reaction effects are also modelled, allowing PBH binaries to merge in the simulations. This pilot study assumed that 100% of dark matter consists of PBHs. Mixed models with various dark matter components including collisional PBHs are numerically far more challenging to simulate, but might become feasible in the next few years.

The right column of Video 1 online shows the evolution of the dark matter density in this scenario. For comparison, the team also performed simulations of the same region within a scenario where dark matter is made of microscopic particles (left column). The distribution of particle dark matter is much more smooth, while the discrete massive bodies are visible in the PBH simulation. The middle column shows the result of an approximate PBH simulation, where small-scale gravitational interactions are neglected; the clearly visible differences with the right column illustrate the importance of an accurate code like BIFROST for this study.

he dynamics of the system of black holes is highly complex. Close encounters between multiple black holes can lead to slingshot effects where one black hole is “kicked” with high velocity (the energy for this kick comes from the deep potential wells of the black holes). This is illustrated in Video 2 online `https://www.mpa-garching.mpg.de/1114849/hl202505?c=1125711`, which shows the motions of individual black holes in the simulation over a short period of time (essentially, a dynamic, zoomed-in version of Video 1 online `https://www.mpa-garching.mpg.de/1114849/hl202505?c=1125711`).

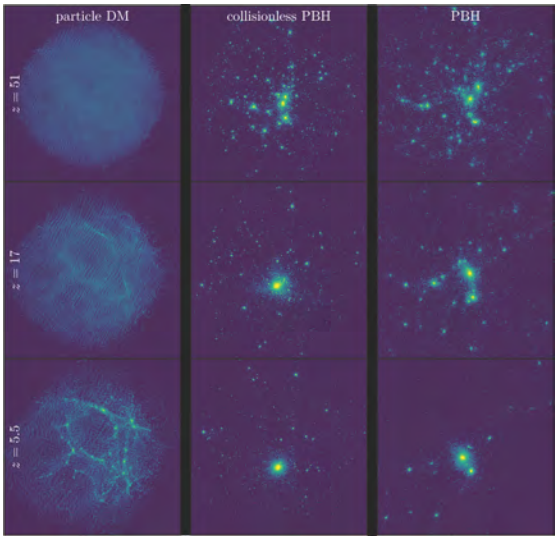


Figure 2.11: The image shows snapshots from a small overdense region in the universe for three scenarios: cold dark matter made of particles (left); cold dark matter made of primordial black holes with $\sim 16 M_{\odot}$ mass, simulated with softened forces (collisionless; middle); and the same primordial black hole initial conditions simulated fully collisionally with Bifrost (right). *(Credit: MPA)*

Capturing these dynamics accurately while also being able to follow the system over the Universe's history (or at least a substantial fraction of it) is very challenging, and this study presents the first such calculation ever performed.

Given the dramatic differences between the primordial-black-hole and particle-dark-matter scenarios in Video 1 online, one would expect that astronomers could easily tell which scenario corresponds to the real Universe. However, we cannot observe either particle dark matter or black holes directly; moreover, the scales shown here are very small and difficult to probe. Thus, a bit of creativity is required to come up with observational routes to probe primordial black holes. For example, the "grainy" mass distribution in the primordial-black-hole case can affect ("heat") the distribution of stars in galaxies. One of the cleanest, and probably the most exciting probe of this scenario however are the gravitational waves emitted by the black hole population, in particular when two black holes merge, which happens when they get sufficiently close to each other. This is the subject of ongoing followup work by the team. A first result was already published in the study reported on here, however: the total intensity of all gravitational waves generated by mergers, as a function of time (Figure 2.12). This signal is already several orders of magnitude larger than that observed in today's Universe by the LIGO/Virgo/Kagra experiments, and is expected to put tough constraints on primordial black holes.

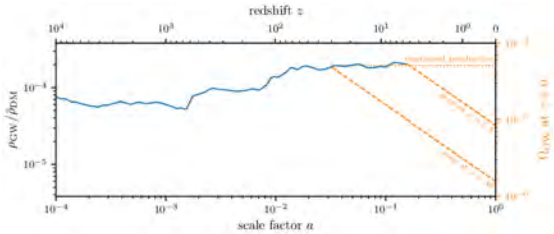


Figure 2.12: Overall intensity of the gravitational-wave background generated by merging primordial black holes in the simulation, plotted as a function of time via the cosmological scale factor. LIGO/Virgo/Kagra limits today (scale factor 1 or redshift 0) are at the level of 10^{-7}, about a factor 30 below the lower limit of the plot. *(Credit: MPA)*

Moreover, the simulations predict that mergers of primordial black holes should already happen in the very young Universe (redshifts $z > 100$), at a time before any stars have formed. Such a merger could not be explained by astrophysical black holes, and it would be a smoking-gun signal of primordial black holes. Future experiments such as the Einstein Telescope will actually be able to detect such mergers, if primordial black holes in the solar-mass range exist.

2.6 Triple Stellar Systems as Gravitational Wave Sources

Abinaya Swaruba Rajamuthukumar (PhD student), Valeriya Korol (postdoc), Jakob Stegmann (postdoc)

Ground-based gravitational wave detectors like LIGO and Virgo have brought significant attention to binary systems composed of black holes and neutron stars as gravitational wave sources. However, two white dwarfs in a binary system are expected to be far more numerous. In particular, the pre-merger phase of double white dwarfs could lead to high-energy astrophysical events that would emit gravitational waves detectable by the European Space Agency's upcoming Laser Interferometer Space Antenna (LISA) mission. Understanding how these double white dwarfs form is essential to interpreting the future LISA data. For the first time, researchers at the Max Planck Institute for Astrophysics (MPA) have now quantitatively assessed the impact of triple evolution on LISA sources. This study underscores the importance of triple interactions in the formation of double white dwarfs, revealing previously unexplored pathways that contribute to the gravitational-wave sources LISA will observe.

Stars often form in hierarchical triples, where a close binary system is orbited by a distant third star. These triple systems undergo complex gravitational interactions, which can dramatically alter the evolution of the stars. Such interactions can induce mass exchange between stars, mergers, or the disruption of one of the stars, all of which influence the final configuration of the system. Thus, triple dynamics can play a pivotal role in driving white dwarf binaries into the gravitational wave frequency range detectable by LISA.

In this research, doctoral student Abinaya Swaruba Rajamuthukumar, along with a group of MPA researchers, studied how triple star systems contribute to the population of double white dwarfs detectable by LISA. They combined simulations of triple star evolution using the Multiple Stellar Evolution (MSE) code with a Milky Way-like galaxy from the cosmological simulation TNG50. The study found that approximately 7.2 million double white dwarfs emitting gravitational waves in the LISA frequency band originate from triple systems, nearly double the number formed in isolated binaries, which account for about 3.8 million. Moreover, about 57% of the LISA double white dwarfs from triples retain a bound third star, though it is typically too distant to leave an observable imprint on the gravitational wave signal.

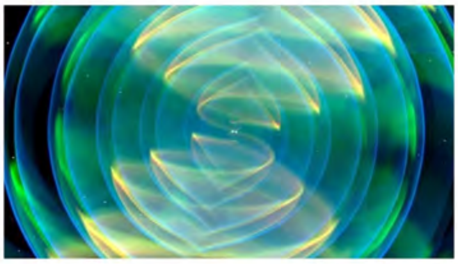


Figure 2.13: Scientific visualization of numerical relativity simulations showing gravitational waves emitted by inspiraling compact objects. *(Credit: T. Dietrich, S. Ossokine, H. Pfeiffer, and A. Buonanno (Max Planck Institute for Gravitational Physics))*

The team identified five key evolutionary pathways through which triple systems can produce LISA-detectable sources. These include induced mass transfer, outer binary mergers, ejected tertiaries, triple common envelope phases, and effectively isolated inner binaries (see graphic). The overall population properties of double white dwarfs from triple systems and those with a binary-origin are largely indistinguishable. Interestingly, the triple channel introduces a rare but intriguing subset of highly

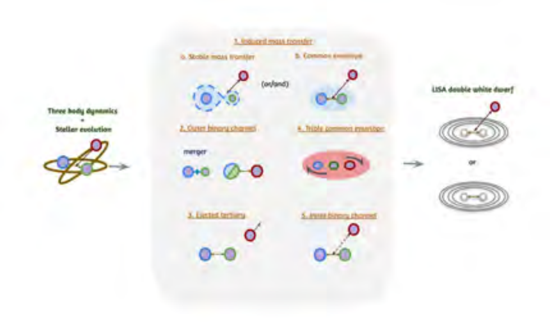


Figure 2.14: A schematic diagram of possible key processes that drive the evolutionary phases of a triple evolution leading to the formation of double white dwarfs in the LISA frequency bandwidth. Depending on the separation of the inner binary and the inclination angle of the two orbital planes, the third star can interact in various ways with the inner binary. Just over half the systems retain the third star, though it is typically too distant to affect the gravitational wave signal significantly. *(Credit: MPA)*

eccentric systems that emit burst-like gravitational wave signals, offering a distinct observational signature for LISA.

This study provides the first detailed exploration of triple-star evolution in the context of gravitational wave astrophysics. As LISA prepares for launch in 2035, these findings will be essential for accurately interpreting the Galactic population of gravitational wave sources and refining data analysis techniques. The results underscore the need to account for triple evolution when modeling LISA sources, paving the way for a more comprehensive understanding of the Milky Way's gravitational wave sources.

2.7 JWST's sharp view unveils intricate details in galaxies' gas halo

By Bo Peng (postdoc) and Fabrizio Arrigoni Battaia (scientific staff)

Galaxies are surrounded by a large reservoir of gas called the circumgalactic medium (CGM), where they refuel and recycle the gas for forming stars and growing in mass. This gas is extremely dim, with current observations being limited to spectral lines that are hard to interpret. It is therefore challenging to understand the mass, distribution, and physical conditions prevalent in the CGM. Recently, a group of researchers at MPA serendipitously discovered bright oxygen emission around a massive galaxy group in the distant universe using the James Webb Space Telescope (JWST). In collaboration with other international scientists and by combining various observations, the study provides a detailed and unprecedented view of the CGM, showing how galaxies influence the gas and their environment.

The well-known galaxy group SMM J02399-

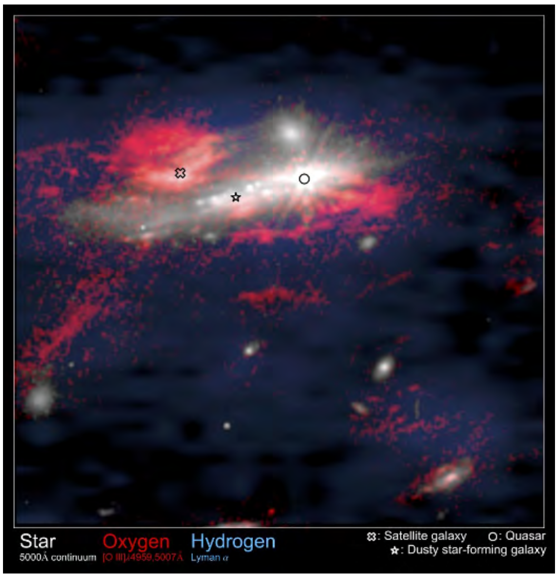


Figure 2.15: Composite JWST image of the galaxy group SMM J02399-0136, which includes a quasar (circle), a dusty galaxy forming stars at very high rates (star sign) and an irregular satellite galaxy ("x" mark). The strong emission lines from doubly ionized oxygen (red) fall in one filter, and it is isolated by subtracting the image of stellar light (white) made from images of neighboring filters. It is compared to the hydrogen (blue) "nebula" obtained from Lyman alpha observations. *(Credit: MPA)*

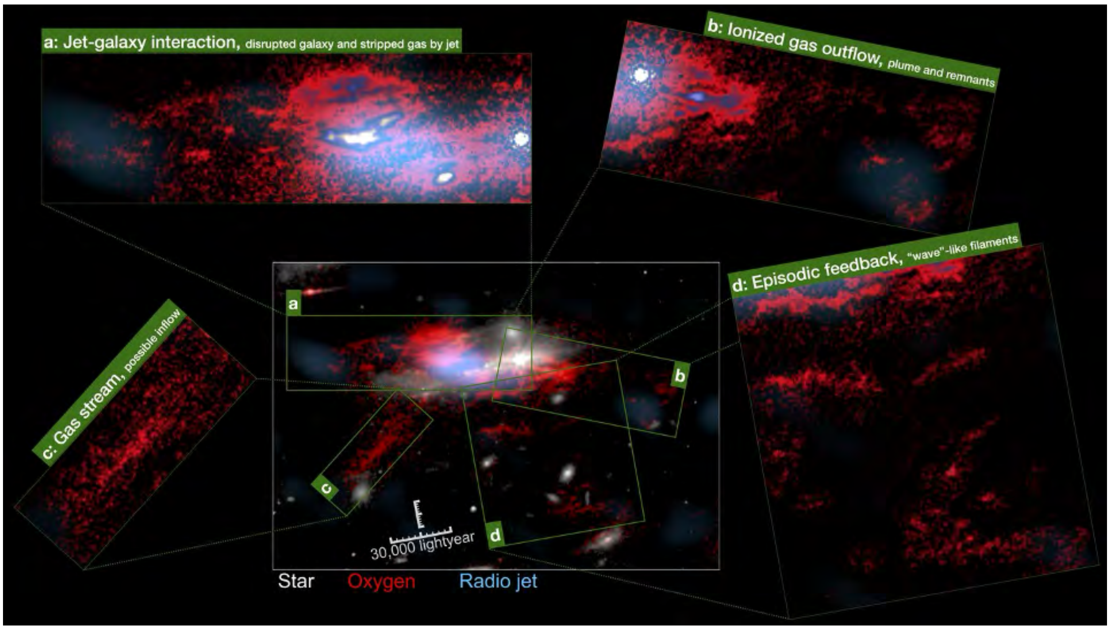


Figure 2.16: Composite image and zoom-in view of the CGM gas. The main figure shows the star (white), oxygen (red), and radio jet (blue) emission around the galaxy group. Two scale bars denote 30,000 light-years, which is the distance between the Sun and the Milky Way center. The difference in the two directions is due to gravitational lensing. Zoomed views are shown of interesting regions, in a color scheme highlighting the oxygen emission. (a) Enlarged image of the disrupted satellite galaxy to the left of the quasar. The relativistic jet from the quasar (in blue) disrupts and strips the gas. The brightened region indicates where the jet interacts with the gas in the galaxy, whereas gas previously blown away from the satellite galaxy is seen as filaments further out. (b) A strong plume-like feature indicates a strong outflow from the quasar, and patchy remnant of previous outflows extends far to the right. (c) A long gas stream with a possible origin of inflow. (d) The "wave"-like structure, consisting of three parallel stripes, suggests episodic black hole activities and their feedback effects in the past. *(Credit: MPA)*

0136 includes a galaxy dominated by an active supermassive black hole, a dusty galaxy forming stars at very high rates, which is colliding with the quasar, and an irregular satellite galaxy (see Figure 2.15). It is located at redshift 2.8 (when the universe was about 2.3 Gyr) and the galaxies appear gravitationally lensed in an east-west direction. Initially discovered due to its high star formation activity, later studies suggested a large reservoir of cool gas in atomic or molecular form in its CGM.

The new JWST observations offer the sharpest and one of the deepest views of the CGM gas. In particular there is strong oxygen emission ([O III]$\lambda\lambda 4959, 5007$ Å), which extends at least 100 kpc (300,000 light-years) across its CGM. The oxygen distribution matches well with the hydrogen distribution revealed by previous Lyman alpha observations. Besides its vast extent, the image also uncovers a detailed filamentary structure of the CGM gas, resolved only by JWST (see zoomed images in Figure 2.16).

The emission line of doubly ionized oxygen provides critical information. The bright emission indicates the presence of denser and warmer gas in the CGM than previously expected. Each of these long and narrow filaments contains a substantial gas mass, about a billion times the mass of the Sun, all in ionized form. Additionally, the large quantities of oxygen—produced only in stars and supernovae—compared to hydrogen in the CGM suggest that the CGM is chemically enriched by gas ejected from galaxies.

The bright filaments significantly contrast the "nebula" picture from previous studies. The high-resolution images show that the gas in the CGM is not distributed more or less uniformly, but rather resides in long and narrow filaments. The morphology, distribution, and oxygen abundance all point to past feedback from galaxy activities, which have fed mass, energy, and heavy elements into the CGM gas. Furthermore, the interaction between the quasar jet and the neighbouring galaxy is a striking example of how massive galaxies can impact their environments. These high-resolution images also challenge numerical simulations, which need to explain and reproduce the exquisitely complex structures revealed in this galaxy group.

The study demonstrates how CGM research can leverage the unprecedented resolution and sensitivity of the JWST, as well as the usefulness of oxygen lines in interpreting the gas's physical conditions. The research group is currently working on additional multi-wavelength data to construct a comprehensive understanding of various forms of gas in the CGM.

2.8 Gravitational Waves from Stars Stripped by Supermassive Black Holes?

By Aleksandra Olejak (postdoc)

Imagine a star not crashing into a supermassive black hole in a fiery explosion, but instead slowly spiraling in, circling closer and closer to its horizon. This is the story of a sub-giant star that is stripped of its hydrogen layer by a black hole companion with a few million solar masses. The left-over helium core is gently drawn in due to strong gravitational wave emission and can be placed so close to the supermassive black hole that it becomes a promising gravitational wave source for the future detector LISA (Laser Interferometer Space Antenna). This scenario has been recently investigated by a team at MPA.

Formation of the System

The story begins with two stars in a binary system that drift too close to a supermassive black hole. The black hole's powerful gravity tears them apart through the so-called Hills mechanism (see Figure 2.17): One star is flung out at incredible speed (a so-called hypervelocity star), while the other star is captured to orbit the black hole on a highly eccentric orbit. If the separation of the captured star is in a certain regime, gravitational waves will lead to gradual circularization and decay of the or-

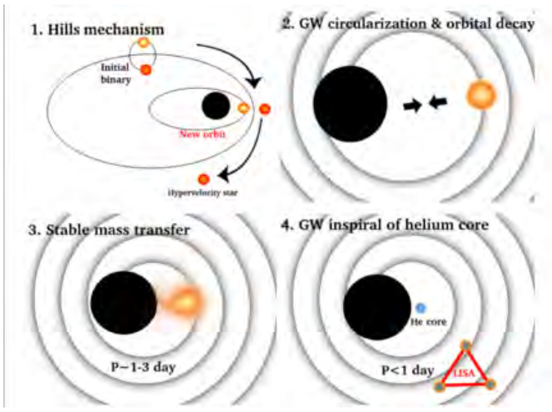


Figure 2.17: Cartoon of the system's key evolutionary stages. Top left: a binary enters the supermassive black hole's Hill sphere and is disrupted. One star is captured on an eccentric orbit, the other ejected as a hyper-velocity star. Top right: the captured star's orbit shrinks and circularizes via gravitational wave emission. Bottom left: the sub-giant star begins stable mass transfer onto the supermassive black hole. Bottom right: after losing its hydrogen envelope, the compact core continues inspiraling via gravitational wave emission, eventually becoming a loud LISA-band source. *(Credit: MPA)*

bit (see Fig.1). As a consequence, the star will finally start to transfer mass onto the supermassive black hole on a relatively circular orbit.

If the captured star is a so called sub-giant, relatively soon after its main sequence phase (i.e. the end of its core hydrogen burning), it has already developed a helium core. Such a star may lose its outer layers to the supermassive black hole companion and be stripped – slowly but steadily – down to its helium-rich core Figure 2.17.

A Slow, Steady Spiral Inward

Unlike in the dramatic tidal disruption events often observed in galactic centers, where a star on a highly eccentric orbit might be ripped apart in one go, the mass transfer process investigated in this study happens over hundreds of thousands or millions of years. The star doesn't disappear right away. Instead, it gradually loses mass, becoming a stripped helium core, and spirals inward.

Such a stripped core is compact enough that it can get very close to the supermassive black hole, at a separation comparable to the size of the black hole's Schwarzschild radius. As the helium-core star slowly spirals in, it sends out a gravitational wave signal with gradually increasing frequency that space-based detectors like LISA are designed to pick up.

Moreover, every now and then, the core might light up again due to hydrogen reignition on the residual hydrogen-rich surface. Accompanying brief bursts of X-rays might be the visible sign of what's happening – and a counterpart to the gravitational wave signal. If the spin of the supermassive black hole is sufficiently high, the final disruption of the helium core will happen near the so-called 'innermost stable orbit'. This could be observable via both electromagnetic and gravitational wave emission, making it a very exciting multi-messenger transient.

These objects could be among the brightest gravitational wave sources in the Milky Way. Due to their loudness, they might also be detectable from large distances in the local Universe (see Figure 2.18). In its several-year mission, LISA could detect dozens of them; hopefully even one right at the center of our own galaxy (with a chance of about 1%).

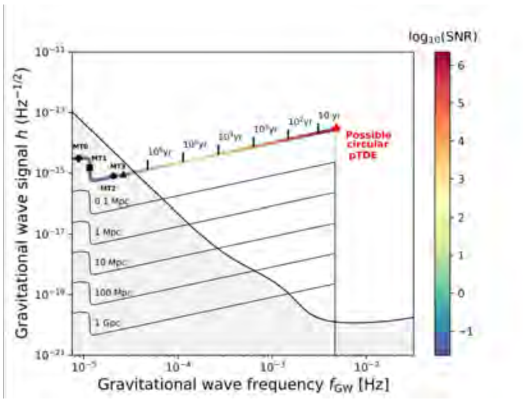


Figure 2.18: Gravitational wave signal from a sub-giant (with initially 2 solar masses) transferring matter to a 4.3 million solar mass supermassive black hole, plotted against the gravitational wave frequency. The coloured curve shows the signal if the system is in the Milky Way, with time counting back from the final tidal disruption of the core (red star symbol). The colour scale indicates the signal-to-noise ratio of the gravitational wave signal, which can reach up to a million for the final disruption. Gray lines show more distant cases (up to 1 Gpc) and the solid black line (red dashed line) indicates the LISA sensitivity curve for a 4-year mission, showing that such a system would be detectable up to $\sim$ 1 Gpc. *(Credit: MPA)*

A New Window into the Heart of Galaxies

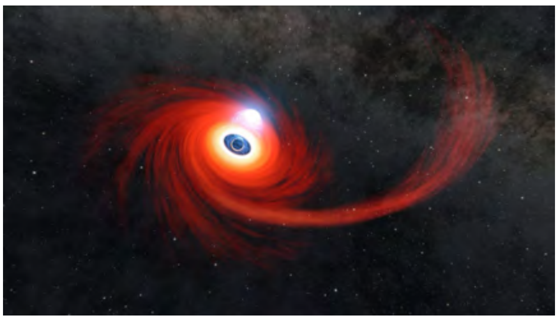


Figure 2.19: Illustration of a black hole stripping a star. *(Credit: NASA/JPL-Caltech)*

The system described here is an example of a so-called 'extreme mass ratio inspiral' (due to the huge mass asymmetry between the star and the supermassive black hole). Such systems offer a unique opportunity to study the surroundings of supermassive black holes. Detecting one would not only shed light on how stars evolve in these exotic environments, but also on how they can feed black holes over extended timescales. Unlike typical interactions involving stellar-mass black holes, these systems may also produce short X-ray bursts from hydrogen flashes and end in a final tidal disruption.

This makes them promising candidates for multi-messenger astronomy, potentially linking gravitational wave signals with electromagnetic observations and offering a richer, more complete view of our universe.

2.9 A large atlas of cosmic structures surrounding high-redshift quasars

By Jay González Lobos (PhD student) and Fabrizio Arrigoni Battaia (scientific staff)

Quasars are active supermassive black holes located at the centres of massive galaxies that emit energy levels that far exceed the binding energy of their host galaxies. This substantial amount of energy has the potential to impact the gas within and around the galaxies, thereby influencing their evolution. While the importance of this process is acknowledged, its details are still the subject of significant debate. An international team of researchers led by MPA scientists has now obtained observations of the most extensive sample of hydrogen structures surrounding quasars in the early universe to better understand this feedback process. The data reveal how the gas responds to the energy released by the supermassive black holes over distances of several hundred thousand light years, providing a new way to study the impact of quasars on galaxy evolution.

Quasar feedback plays a key role in shaping the evolution of the most massive galaxies in the universe. As the supermassive black hole at the centre of a galaxy accretes matter, it powers a quasar — a bright, energetic outburst that can blow powerful winds and emit radiation into the surrounding galaxy. This energy can either heat up or sweep away the gas that would otherwise form new stars, thereby effectively shutting down star formation. This explains why giant galaxies stop growing and become filled with older stars. However, in principle, a quasar is not only able to affect its host galaxy's interstellar medium (its local fuel reservoir), but also the surrounding intergalactic gas. This means that a quasar could have an impact also on the fresh fuel for future star formation in the galaxy, thereby accelerating the galaxy quenching. Despite these ideas have been extensively discussed, the details of this feedback process still need to be fully understood.

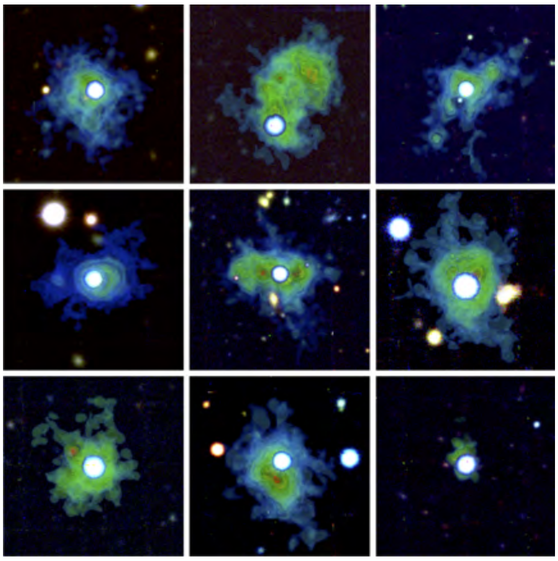


Figure 2.20: Nine of the targeted quasars (white circles) and the uncovered cosmic structures as seen in Lyman-alpha emission (blue-green). Each cutout image is roughly 1 million light years in size. *(Credit: MPA)*

Since the 1980s, it has been proposed that the impact of quasar energy on the surrounding gas could be assessed by targeting one of the most important lines of the hydrogen atom: the Lyman-alpha line. In a hydrogen atom, the electron can occupy different energy levels, like steps on a ladder. This specific ultraviolet line is emitted when an electron drops from the second energy level to the first. Since hydrogen is the most abundant element in the universe, this transition is ubiquitous and results in such bright emission that it can be seen at distances of billions of light years, enabling us to study galaxies and their surrounding gas in the early universe. Novel wide-field spectrographs, in particular, have opened a new window on the Lyman-alpha emission surrounding quasars. They allow the detection of emitting gas at distances of several hundred thousand light years from their host galaxies with short exposure times (about one hour; see, for example, Scientific Highlights on our webpage from November 2019, May 2022 and January 2025 here `https://www.mpa-garching.mpg.de/Current_Research_Highlights`).

Thanks to this new instrumentation — specifically the integral-field spectrograph MUSE on the Very Large Telescope — an international team led by MPA scientists has surveyed the largest sample of quasars to date in order to study their surrounding Lyman-alpha emission. The observations revealed intricate structures enveloping these quasars during cosmic noon, an epoch corresponding to approximately 11.5 billion years ago (examples are shown in Figure 2.20). Importantly, the 120 targeted quasars cover two orders of magnitude in luminosity, enabling the team to explore the effects of different energy inputs.

The scientists discovered that the surface brightness of the Lyman-alpha emission — how bright the emission appears per unit angular area — depends on quasar luminosity. Brighter quasars are associated with brighter extended emission (see Figure 2.21, top panel). Similarly, brighter quasars are associated with more turbulent gas reservoirs within about 30 kpc (approximately 100,000 light years; see Figure 2.21, bottom panel). Both these trends are evidence of the impact of quasar feedback (radiation and winds) on their surroundings.

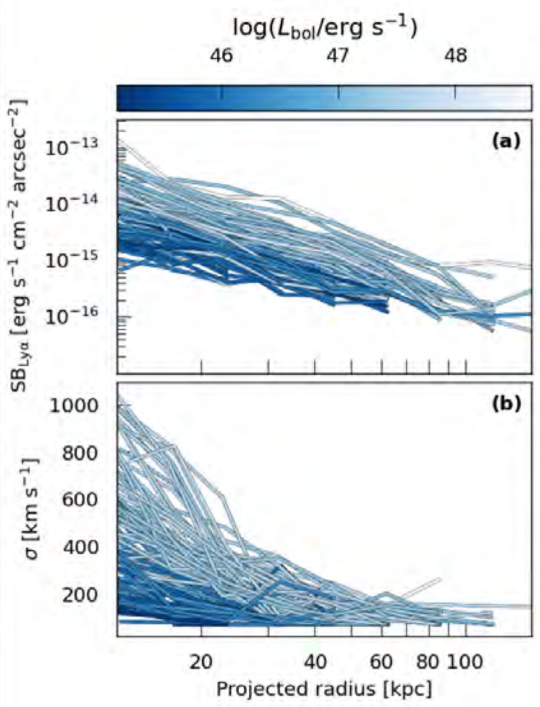


Figure 2.21: Average surface brightness (top panel) and velocity dispersion (bottom panel) of the Lyman-alpha emission as a function of distance from each of the 120 targeted quasars. The curves are colour-coded according to the luminosity of each quasar. *(Credit: MPA)*

The team is now quantifying these trends in detail. For example, they have found that the velocity dispersion on inner scales varies as a function of quasar luminosity, following a well-defined power law. These findings could be used to test quasar feedback models and how they couple with the gas. Future work will focus on targeting additional line emissions besides Lyman-alpha in order to further constrain the impact of quasars on the gas on such large scales, as well as the physical properties of the emitting gas (e.g. Scientific Highlights section 2.7).

2.10 Nuclear star clusters boost the growth of intermediate mass black holes

By Christian Partmann (PhD student) and Thorsten Naab (scientific staff)

Black holes with masses between the stellar and supermassive regime are among the most elusive objects in the Universe. These intermediate-mass black holes are believed to reside in many dwarf galaxies. Using new, high-resolution supercomputer simulations, MPA scientists discovered that nuclear star clusters — compact, massive clusters of stars at the centres of galaxies — may be key to enabling these black holes to grow, thus shedding light on the origins of supermassive black holes.

All massive galaxies, including our own Milky Way, contain supermassive black holes at their centres, with masses ranging from millions to billions of solar masses. However, the formation and growth of these giants remains a mystery. Low-mass galaxies may hold the answer: some of them contain these elusive intermediate-mass black holes (IMBHs), which have masses ranging from hundreds to hundreds of thousands of times that of the Sun. These are more massive than stellar black holes, but have never reached the supermassive stage. IMBHs exert influence only in a tiny region around them. This makes it difficult for them to capture gas and stars, affect their host galaxies, or even be detected in the first place.

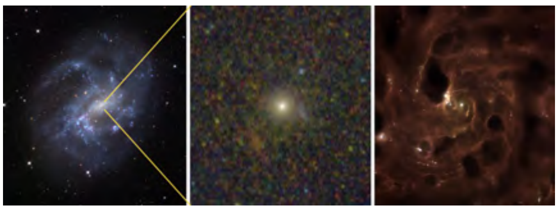


Figure 2.22: The low-mass galaxy NGC 300 (left) hosts a compact nuclear star cluster at its centre that can be resolved using an image from the Hubble Space Telescope (middle). A similar nuclear star cluster is included in the simulations (right). *(Credit: left: Adam Block/Mount Lemmon SkyCenter/University of Arizona; middle: Carson et al. (2015); right: MPA/Partmann et al. (2025))*

Many low-mass galaxies host nuclear star clusters: extremely dense systems of stars spanning only a few light years, yet containing a few percent of the entire galaxy's stellar mass. Nuclear star clusters form an extremely compact and deep potential well at the centre of the galaxy. Recent observations suggest a strong correlation between nuclear star clusters and the existence of IMBHs at their centres. The nuclear star clusters in low-mass galaxies tend to be more massive than their IMBHs, and may play a crucial role in the evolution of galactic centres. The MPA team set out to study how such an environment affects IMBH growth.

Simulating black hole growth is complex as it requires tracking how interstellar gas flows from galactic scales down to the tiny sphere of influence of the black hole. The team of researchers used high-resolution simulations that resolve the black hole's sphere of influence and capture many relevant physical processes in the interstellar gas. The simulations also follow millions of individual stars, including the radiation they emit and the supernovae of the most massive ones. By heating and stirring the gas, these processes strongly influence whether black holes can feed and grow.

The team tested low-mass galaxies with IMBHs of different initial masses. They found that light IMBHs (those below 10,000 solar masses) are barely able to capture gas and grow unless a nuclear star cluster is present. If the IMBH is embedded in a cluster, its additional

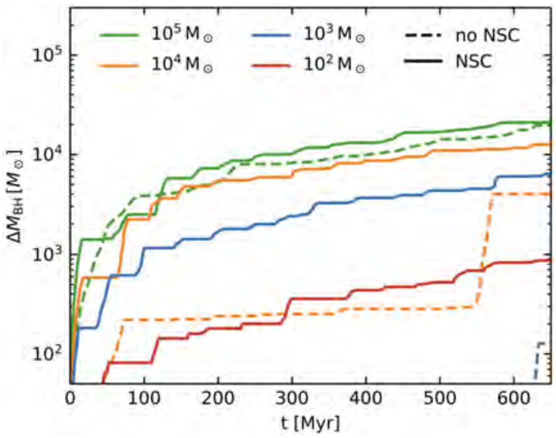


Figure 2.23: Growth of IMBHs of different initial mass in the center of a simulated galaxy. Solid lines show growth without a nuclear star cluster, while dashed lines show growth with one. Low-mass black holes (red, blue and orange lines) only grow when embedded in a nuclear star cluster, whereas more massive black holes, which are comparable in mass to the nuclear star cluster itself, show little additional growth (green line). The nuclear star cluster contains 500,000 solar masses of stars, representing a few percent of the galaxy's total stellar mass. *(Credit: MPA)*

gravitational potential enables rapid gas accretion and swift black hole growth. More massive IMBHs accrete efficiently even without a nuclear star cluster, but the additional growth is small compared to their initial mass. This demonstrates that nuclear star clusters are particularly significant for the smallest black holes, where the cluster's mass far exceeds that of the black hole itself as is typical in low-mass galaxies.

Even with a nuclear star cluster, growth can be easily disrupted by stellar feedback. Some of the gas captured by the nuclear star cluster forms stars, including massive stars. When these massive stars end their lives as supernovae, they can expel gas from the galaxy's centre, temporarily starving the black hole. Consequently, IMBHs undergo cycles of activity and quiet phases. This means that many are likely to be missed in current surveys, which typically detect only actively feeding black holes through the radiation produced by the accretion process.

The study shows that nuclear star clusters are essential for the growth of intermediate-mass black holes in low-mass galaxies, which would otherwise remain stagnant. This is particularly exciting because many theories suggest that the first black hole seeds in the early Universe formed through stellar collisions inside such clusters. Therefore, the new results point not only to nuclear star clusters as the birthplace of intermediate-mass black holes, but also as the sites where they grow most efficiently.

2.11 The Hidden Efficiency of Stellar Interactions

By Thibault Lechien (PhD student) and Selma E. de Mink (scientific director)

When two stars orbit close together, one star can transfer material to its companion, dramatically changing both stars' evolution. However, how much of this transferred material actually stays with the receiving star has remained one of the biggest mysteries in binary star physics. Using a new sample of 16 carefully studied binary systems, MPA scientists have now discovered that binary stars are much more efficient at keeping transferred material than previously thought, with many systems retaining more than half of the mass that was donated. This finding challenges decades of theoretical assumptions and has profound implications for our understanding of stellar evolution, affecting everything from the types of supernovae we observe to the formation of gravitational wave sources, X-ray binaries, and exotic stellar objects like blue stragglers.

Most stars in the Universe are born in binary or multiple star systems, where two or more stars orbit around their common center of mass. When these stars orbit close enough together, over the course of their lifetimes, they can interact gravitationally and exchange material. This can dramatically alter the evolution of both stars, leading to exotic stellar objects, different types of supernovae, and the formation of compact objects like neutron stars and black holes. Therefore, binary interactions play a key role in shaping the stellar populations we observe.

The research team focused on a special type of binary system called Be+sdOB binaries, which consist of a "stripped" star that has lost its outer layers, and a rapidly rotating star that was spun up by accreting these outer layers (see Figure 2.24). These systems are particularly valuable for studying mass transfer because they represent clear examples of past binary interaction. The stripped star reveals how much mass was originally donated, while the other star shows how much was actually retained.

Previous studies have successfully measured the masses of both stars in 16 such systems using a combination of state-of-the-art observational techniques. Namely, high-resolution interferometry from the CHARA Array and VLTI/GRAVITY instruments creates a powerful virtual telescope by combining light from multiple telescopes, allowing them to measure the tiny separations and orbital motions of close binary stars. These interferometric measurements, combined with detailed spectroscopic observations, enabled precise mass determinations. By comparing these present-day masses with stellar evolution models, the team at MPA could determine how much mass must have been transferred and retained during the binary interaction.

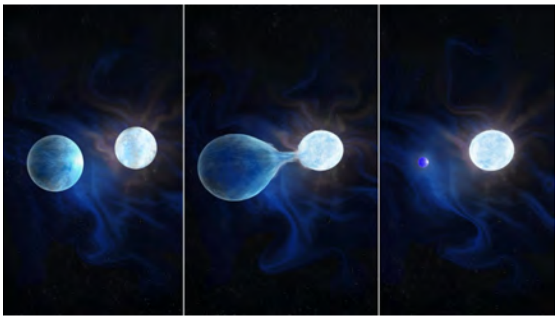


Figure 2.24: Artist's impression of the evolution of a binary system with mass transfer. The left panel represents the initial state, where two regular, main-sequence stars orbit each other. The middle panel shows the mass transfer process, where the more massive star evolves faster and expands, thereby throwing mass onto the other. The right panel shows the present-day configuration consisting of a stripped star and a rapidly rotating star. *(Credit: Navid Marvi, courtesy of the Carnegie Institution for Science)*

The results are striking: half of the systems require that more than 50% of the transferred mass was retained by the receiving star. This is in stark contrast to theoretical models that assume only a few percent of transferred material can be kept, based on the idea that rapidly rotating stars cannot accept much additional mass due to centrifugal forces (see Figure 2.25).

The most likely explanation for this efficient mass transfer is that accretion disks around the receiving star can carry away angular momentum while allowing matter to fall onto the star. This process, well-known in other astrophysical contexts, appears to be much more important in binary star evolution than previously recognized.

These findings will force a major revision of binary evolution models and have wide-ranging implications. Many high-profile theoretical predictions about stellar evolution rely on the assumption that mass transfer is highly non-conservative, which these findings are in strong tension with. The results suggest that mass-gaining stars will be much more massive than currently predicted, leading to different populations of supernovae, white dwarfs, and gravitational wave sources. The orbital properties of post-interaction binaries will also be affected, which provides important constraints for understanding the formation of exotic stellar objects.

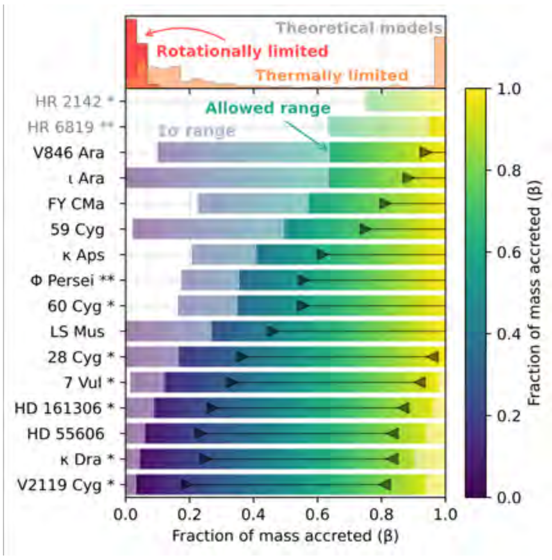


Figure 2.25: The observational constraints on the mass transfer efficiency are in conflict with theoretical models. The main panel shows the available constraints for each of the 16 binary star systems, which shows a preference for stars to accrete 30-90% of the transferred mass. The top panel shows histograms of the predictions of theoretical models. The rotationally limited model (in red) predicts very little mass accretion, namely below 10% of the transferred mass. The thermally limited model (in orange) predicts a bimodal distribution with an accretion efficiency of either below 20% or 100%. Both of these models, which are the main ones used in a large number of theoretical studies and predictions for stellar populations, are therefore in conflict with the observations. *(Credit: MPA)*

2.12 MOGLI: Following the Hidden Life of Astrophysical Gas

By Hitesh Kishore Das (PhD student)

The space around galaxies might not glow brightly in telescopes, but it is, in fact, filled with gases at vastly different temperatures. From plasma at a million degrees Celsius to much colder, tiny, cold clouds at temperatures that can be found on Earth. Understanding how these gases interact is key to explaining how galaxies grow, form stars, and evolve. But the vast temperature difference has proved to be a significant challenge for simulations, as it also results in a big difference in densities. A team of scientists from MPA and AIP (Potsdam) has now developed a new model, MOGLI, that can track these interactions in unprecedented detail. By treating hot and cold gas as two coupled components that exchange material and energy, a multifluid approach, developed in engineering circles for numerous terrestrial applications, allows large cosmological simulations to capture the hidden life of cold gas.

The big bound systems of billions of stars called galaxies, of which our own Milky Way galaxy is one, sit inside an invisible halo of dark matter. The brighter part of the galaxy that is usually seen through a telescope sits close to the centre of this halo. The rest is filled with sparser gas, which is difficult to observe, but plays a very crucial role in shaping the galaxy and moulding its evolution. It acts as a gas reservoir that feeds the galaxy for future star formation, and receives gas when the existing stars explode as supernovae. This reservoir surrounding the galaxy is aptly called the circumgalactic medium.

This surrounding gas is far from uniform. Observations and simulations alike show that it exists in many different forms, hot, thin plasma which fills most of the volume, and small, cold clouds that contain a big chunk of the mass. These cold clouds are essential for feeding star formation, yet they are fragile, constantly buffeted by the hot wind around them. Whether they survive or evaporate determines how galaxies evolve over billions of years.

The cold clouds are so small compared to the galaxy that it is infeasible to simulate the galaxies while resolving the clouds. The key challenge is the vast difference in densities. In the best cases, it is like studying a mixture of air and water; at worst, it is like looking at the mixing of stone in air. Even accounting

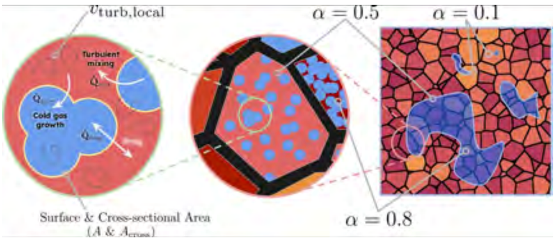


Figure 2.26: A schematic diagram showing the underlying picture of the multifluid method and the MOGLI model. The box on the right shows an example grid showing three different cold gas structures in blue. The volume-filling fractions of cold gas is parametrised as α. The zoomed-in view in the middle shows the model's assumption of the underlying cold gas structure as numerous spheres. Zooming in further, the left panel shows the different interactions in the MOGLI model, in particular drag, mixing and growth, along with other contributing variables, like the local turbulent velocity ($v_{\text{turb,local}}$). *(Credit: MPA)*

for Moore's law of advancing computational technology, a simulation with a sizable number of galaxies which also captures these interactions would take at least a century. So, astrophysicists usually have to compromise on accurately modelling these small-scale effects to simulate whole galaxies in practice. This leads to a limited prediction power with non-trivial dependency on assumptions made for such interactions. One workaround for accounting for small-scale effects that can not be simulated is to rely on "subgrid" recipes. A true subgrid model self-consistently keeps track of processes happening at the small scales without having to resolve those scales, removing the earlier restriction.

To address this, a joint team of researchers from MPA and AIP (Potsdam) developed MOGLI (Model for Multiphase Gas using Multifluid Hydrodynamics), a new framework that represents hot and cold gas as two distinct but interacting fluids. This model borrows the multifluid model implemented in AREPO, an in-house moving-mesh magnetohydrodynamic code at MPA, which is widely used in large-scale simulations. This multifluid method was originally devised to simulate more practical scenarios, similar to studying air bubbles in water. But the same method can also be used to simulate the hot and cold gas interaction, where instead of treating the mixture as a single fluid, the model keeps track of both components and how they exchange momentum, heat, and mass.

In MOGLI, the two components, namely the hot, thin gas and the cold, dense gas, influence each other through three key processes:
Drag, which describes how the hot gas pushes or pulls on cold clouds;
Turbulent mixing, where chaotic motions blend the two phases, and
Growth, where cold gas forms as hot gas cools and condenses.
These interactions depend on the local properties of the astrophysical gas. For example, one important component is the local turbulence, much like how smoke disperses differently in a gentle breeze compared to a storm. By linking the model to measurable flow properties, MOGLI can adapt naturally to a wide range of environments, from the calm outskirts of galaxies to violent galactic winds.

A good model has to pass through a process of verification where it is tested against some benchmark scenarios, to show that a simulation with the subgrid model is indeed equivalent to a simulation that simulates the small-scale effects. In this case, more expensive, high-resolution turbulent box simulations were carried out very similar to the ones in a previous monthly highlight, and were chosen as the benchmarks. Low-resolution simulations with MOGLI were able to mimic the cold gas behaviour with respect to destruction rates, survival criteria and spatial dispersion from the benchmarks across a very wide range of simulation parameters.

This breakthrough means that large-scale simulations can now include a more faithful representation of multiphase gas dynamics,

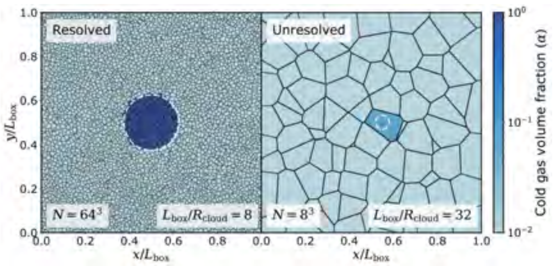


Figure 2.27: Initial cold gas volume fraction slices for MOGLI simulations with resolved and unresolved cold gas clouds with the circles showing the cold gas cloud sizes. The colour bar shows the cold gas fraction α. The left panel shows an example of a resolved cold gas cloud, where the cloud is bigger than the grid cells and grid cells are fully filled with cold gas (dark blue). On the other hand, the right panel shows a simulation with an unresolved cold gas cloud, with much fewer cells. As the cold gas cloud is unresolved, the volume fraction in the cell marked with a circle is less than 1. *(Credit: MPA)*

bridging the gap between what telescopes observe and what computers can model. It opens the door to exploring long-standing questions: how does the cold gas reach so far from galaxies? How do outflows from galaxies recycle their gas? And what determines the mix of hot and cold gas we see in the halos of galaxies like our own Milky Way?

MOGLI is flexible by design. Future extensions could include magnetic fields, denser gas or even colder gas, which are thought to further influence how gas mixes and cools. For now, MOGLI provides a major step toward a more realistic picture of the turbulent, ever-changing environment that surrounds galaxies, giving a peek into the evolution of the tiny, cold gas which can persist and shape the life cycle of galaxies. This will hopefully lead to a new generation of subgrid models and large-scale simulations with stronger predictive capabilities to test our understanding of the Universe.

2.13 Euclid discovers a stunning Einstein ring

By Conor O'Riordan (postdoc)

Press Release from February 2025

In some of the first data from ESA's Euclid space telescope, scientists have found a rare image of a distorted background galaxy, appearing as a so-called 'Einstein Ring' right in our cosmic backyard. Using a state-of-the art computer model at the Max Planck Institute for Astrophysics, the astrophysicists were able to model the gravitational lensing system allowing them to learn more about this rare object.

Euclid blasted off on its six-year mission to explore the dark Universe on 1 July 2023. Before the spacecraft could begin its sky survey, the team of scientists and engineers on Earth had to make sure everything was working properly. During this early testing phase, in September 2023, Euclid sent some images back to Earth. They were deliberately out of focus, but in one fuzzy image Euclid Archive Scientist Bruno Altieri saw a hint of a very special phenomenon and decided to take a closer look.

"I look at the data from Euclid as it comes in," explains Bruno Altieri. "Even from that first observation, I could see it, but after Euclid made more observations of the area, we could see a perfect Einstein ring. For me, with a lifelong interest in gravitational lensing, that was amazing."

The Einstein Ring, an extremely rare phenomenon, turned out to be hiding in plain sight in a galaxy not far away. The galaxy, called NGC 6505, is around 590 million light-years from Earth, a stone's throw away in cosmic terms. But this is the first time that the ring of light surrounding its centre is detected, thanks to Euclid's high-resolution instruments.

The ring around the foreground galaxy is made up of light from a farther-out, bright

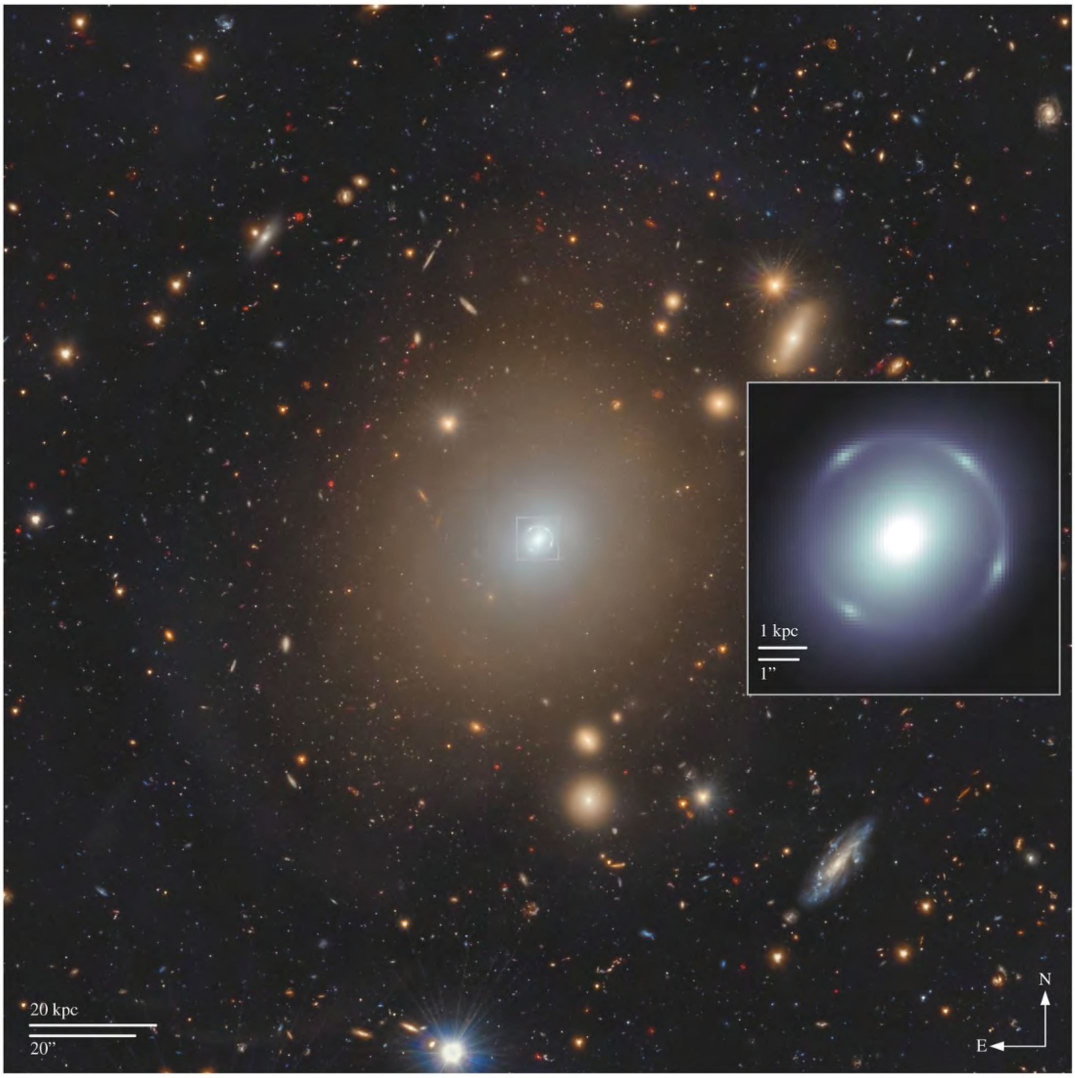


Figure 2.28: The ring of light surrounding the centre of the galaxy NGC 6505, captured by ESA's Euclid telescope, is a stunning example of an Einstein ring. NGC 6505 is acting as a gravitational lens, bending light from a galaxy far behind it. The almost perfect alignment of NGC 6505 and the background galaxy produces a spectacular ring. This rare phenomenon was first theorised to exist by Einstein in his general theory of relativity. This wide field shows the extended stellar halo of NGC 6505 and showcases the Einstein ring (at the centre of the galaxy, shown enlarged to the right), surrounded by colourful foreground stars and background galaxies. *(Credit: ESA/Euclid/Euclid Consortium/NASA, image processing by Tian Li)*

galaxy. This background galaxy is 4.42 billion light-years away, and its light has been distorted by gravity on its way to us. The far-away galaxy hasn't been observed before and doesn't yet have a name.

"An Einstein ring is an example of strong gravitational lensing" explains Conor O'Riordan, of the Max Planck Institute for Astrophysics (MPA), Germany, and lead author of the first scientific paper analysing the ring. "All strong lenses are special, because they're so rare, and they're incredibly useful scientifically. This one is particularly special, because it's so close to Earth and the alignment makes it very beautiful."

Albert Einstein's general theory of relativity predicts that light will bend around objects in space, so that they focus the light like a giant lens. This gravitational lensing effect is bigger for more massive objects – galaxies and clusters of galaxies. It means we can sometimes see the light from distant galaxies that would otherwise be hidden. If the alignment is just right, the light from the distant source galaxy bends to form a spectacular ring around the foreground object.

"With the repeated Euclid observations of the same field, the data for this Einstein ring is so good that it was a challenge to model the system accurately", O'Riordan points out. The team used the state-of-the-art gravitational lensing code 'pronto' developed at MPA to model the light of the ring at an unprecedented level. "We even had to look at some of the raw data to better understand how the detector works."

Modelling the Einstein ring was, however, only the first step. "These types of objects are incredibly useful to study the dark matter substructures in the lensing galaxy, which we'll explore in a subsequent publication," adds O'Riordan. "Euclid is going to revolutionise the field, with all this data we've never had before."

Although this Einstein ring is stunning, Euclid's main job is searching for the more subtle effects of weak gravitational lensing, where background galaxies appear only mildly stretched or displaced. To detect this effect, scientists will need to analyse billions of galaxies. Euclid began its detailed survey of the sky on 14 February 2024 and is gradually creating the most extensive 3D map of the Universe yet. The space telescope will map more than a third of the sky, observing billions of galaxies out to 10 billion light-years. It is expected to find around 100 000 strong lenses, but to find one that's so spectacular – and so close to home – is astonishing. Until now, less than 1000 strong lenses were known, and even fewer were imaged at high resolution. Such an amazing find, so early in its mission, means Euclid is on course to uncover many more hidden secrets.

2.14 How stars stay young and spin slowly

By Taeho Ryu (postdoc)

Press Release from April 2025

Computer simulations suggest that the amplification of magnetic fields in stellar collisions may play an important role in the formation of a particular subset of stars in clusters. Blue straggler stars in clusters appear not only bluer, but also younger than other cluster members. One proposed explanation for their apparently different ages is that they are the result of stellar collisions. However, this would require the resulting star to spin down efficiently without losing too much mass. Scientists at the Max Planck Institute for Astrophysics have now shown, using sophisticated 3D simulations, that the energy of the magnetic field is greatly amplified in the collisions of low-mass stars, providing a potentially efficient spin-down mechanism.

Clusters of stars, containing hundreds of thousands of stars that formed around the same time and from the same molecular cloud, provide astronomers with an excellent laboratory

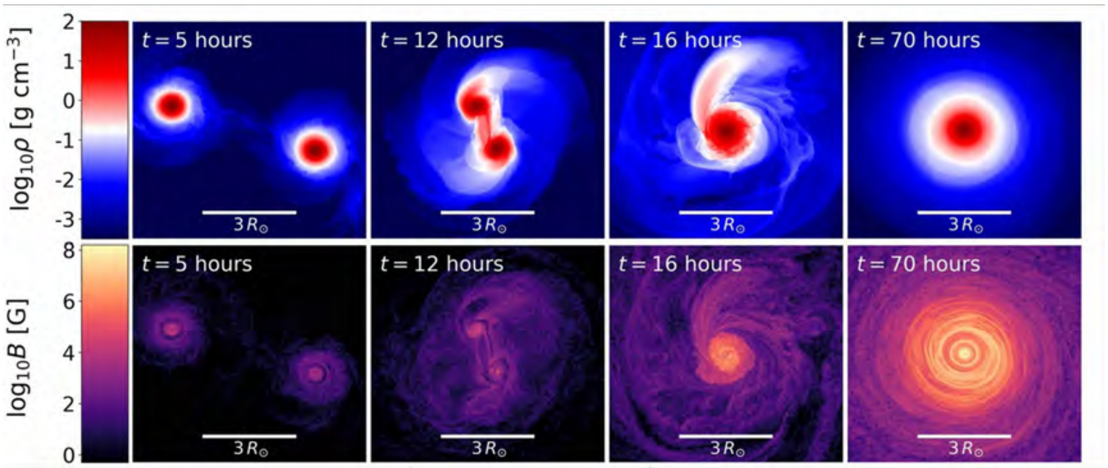


Figure 2.29: Growth of density (top row) and magnetic field strength (bottom row) as a function of time in the collision between two stars of 0.7 and 0.6 solar masses. After the first contact at t = 0 h (not shown), the two stars pass each other (t = 5 h) and get disrupted (t = 12 h). The magnetic fields begin to grow due to instabilities and compression. *(Credit: MPA)*

for studying how stars of similar age, composition and mass evolve over time. However, one particular subset, the "blue stragglers", pose a challenge: they appear bluer and brighter than the other cluster members, and therefore appear to be younger. Why don't they age like typical cluster stars?

The answer could be that they actually formed later than the other stars in stellar collisions and thus gained mass. However, since most collisions between two low-mass stars are off-axis (rather than perfectly head-on), the resulting massive star would rotate rapidly and lose most of its mass during the spin-down to a stable state – unless the spin-down is efficient. While many proposed spin-down mechanisms require magnetic fields, it has remained unclear for more than two decades whether they actually exist and whether they have the strength to play a significant role.

A team at the Max Planck Institute for Astrophysics (MPA) has now presented sophisticated 3D moving-mesh magnetohydrodynamical simulations of collisions between low-mass main-sequence stars, which show that the magnetic field energy is amplified by a factor of up to 10 billion during collisions. At the core of the merged star, the magnetic field can reach 100 million Gauss (for comparison, the magnetic field in sunspots can reach up to 5000 Gauss).

"Our simulations showed that the magnetic field in stellar collisions can be amplified, which is a promising sign for an effective spin-down mechanism," says MPA postdoctoral researcher Taeho Ryu, who led the study. "This amplification is independent of collision parameters, so it could happen every time two stars collide in a cluster."

The simulations also show a flattened, rotating gas structure around the collision, which could indicate the formation of a disk. Magnetic braking and an effect called "disk locking" could further facilitate the spin-down. "Our next step will be to actually follow the long-term evolution after the collision to see how these stars evolve over millions or billions of years and whether they really end up as the blue straggler stars that we observe," adds Ryu.

2.15 Clouds in the Wind: Why Cold Gas Fades in Galactic Outflows

By Alankar Dutta (postdoc) and Max Gronke (research group leader)

Press Release from September 2025

A new study led by Dr. Alankar Dutta at the Max Planck Institute for Astrophysics uncovers why cold gas clouds fail to thrive in powerful winds flowing out of galaxies driven by supernovae. These findings, soon to be published in the Monthly Notices of the Royal Astronomical Society, challenge long standing assumptions about how galaxies exchange matter with their surroundings.

Galactic outflows — giant winds driven by intense star formation — play a key role in shaping the evolution of galaxies. These outflows carry gas, dust, and heavy elements out of the galactic disks and into the surrounding gaseous environment, the circumgalactic medium (CGM). While we know that these winds are multiphase, i.e. containing both hot, ionized plasma and much colder, denser neutral gas, as well as molecular gas. The origin of the hot gas in outflows can be attributed to the highly energetic supernovae explosions that drive them. However, the fate of the cold gas in these outflows and how this survives such a hot and hostile environment has long puzzled astronomers.

In simulations, it has been particularly challenging to resolve and infer the dynamics of the cold component which occur as clumpy parsec/sub-parsec sized clouds in large kiloparsec scale outflows. This has caused astronomers to turn to idealized wind tunnel simulations to study cloud-wind interactions. Many previous studies used idealized setups where cold clouds face a uniform hot wind from the inner regions of galaxies, but real galactic outflows are not uniform. They expand, and that expansion fundamentally alters the game. To capture this realistic behavior, the group ran high-resolution hydrodynamic simulations of cold gas clouds embedded in expanding galactic winds. A well-known model of starburst-driven outflows formed the basis for the wind's structure.

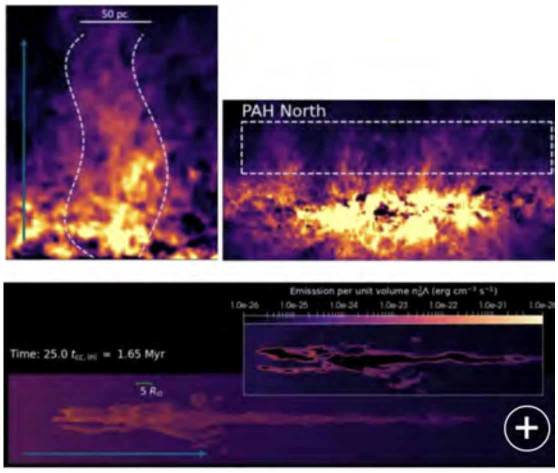


Figure 2.30: The observation (top) of the M82 galaxy shows the emission of a particular molecule (PAH = molecules of poly-aromatic hydrocarbon) in the infrared band of JWST's NIRCam. The leftmost plume is enlarged in the left image. The simulation (bottom) also shows the emission map. The inset shows one projection of the emission field, the larger image shows the total emission (the projection of many such slices along the z-axis). The blue arrows indicate the direction of the head-tail gradient in emission from cold gas along the direction of the wind in both simulations and observations. *(Credit: Observation: Fisher et al 2025; simulation: MPA, A. Dutta)*

The new simulations reveal that as the clouds move outward, they remain in local pressure balance with the background wind. This leads to a steep decline in their density contrast, which means that over time, these clouds become increasingly diffuse and eventually blend into the surrounding hot gas. A marked contrast to earlier simulations with static winds, where the cold gas mass could keep on growing via radiative cooling – whereas in these more realistic simulations, the expanding environment suppresses this growth. Cloud expansion and pressure equilibrium are the key factors that regulate cold gas evolution. Even if initially a cloud would grow, it fades as it travels downstream, losing its ability to stand out from the background.

Moreover, the study finds that cold gas tails – common features seen in both simulations and observations – develop strong head-to-tail gradients in both density and brightness. This offers a natural explanation for recent high-resolution observations from the James Webb Space Telescope of intense star-forming galaxies like M82.

The key new feature to these simulations was a novel 'cloud-tracking' algorithm developed by the researchers, that allowed them to follow the cold gas for a long time/distance in an expanding wind without prohibitively expensive computational requirements. It is the first time, that such spatially expanding backgrounds have been self-consistently incorporated into cloud-crushing simulations – a crucial step towards bridging idealized theory and realistic galactic environments.

Looking ahead, the team plans to expand the simulations to include magnetic fields, thermal conduction, and more complex wind structures, like those relevant to active galactic nuclei (AGN) and cluster environments. This work is not just relevant for idealized simulations but has the potential to serve as the basis for building robust models of multiphase gas and their mixing on various scales, which is typically unresolved in cosmological simulations.

This work lays the foundation for a more complete theory of how galaxies lose – or retain – their fuel for star formation and that's essential for understanding how galaxies live, grow, and die.

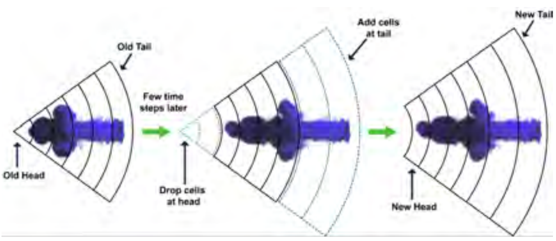


Figure 2.31: A schematic demonstration of our novel cloud tracking scheme that enables the computational box to follow the cloud. This saves a lot of compute time and data processing required for these simulations and allows us to simulate cloud-wind interaction within the capabilities of our computational resources. *(Credit: MPA)*

2.16 Astronomers 'image' a mysterious dark object in the distant Universe

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

Press Release from October 2025

An international team of astronomers has found a low mass dark object in the distant Universe, not by directly observing any emitted light, but by detecting its tiny gravitational distortion of the light from another distant galaxy. This mysterious object has a mass of about one million times that of our Sun, and its discovery seems consistent with the current best theory about how galaxies like our own Milky Way formed.

"Hunting for dark objects that don't seem to emit any light is clearly challenging," said Dr. Devon Powell at the Max Planck Institute for Astrophysics (MPA) and lead author of the study published in Nature Astronomy. "Since we can't see them directly, we instead use very distant galaxies as a backlight to look for their gravitational imprints."

Dark matter is an enigmatic form of matter not expected to emit light, yet it is essential to understanding how the rich tapestry of stars and galaxies we see in the night sky evolved. As a fundamental building block of the universe, a key question for astronomers is whether dark matter is smooth or clumpy, as this could reveal what it is made of. As dark matter cannot be seen, its properties can only be determined by observing the gravitational lensing effect, whereby the light from a more distant object is distorted and deflected by the gravity of the dark object.

The team used a network of telescopes from around the world, including the Green Bank Telescope (GBT), the Very Long Baseline Array (VLBA) and the European Very Long Baseline Interferometric Network (EVN). The data from this international network were correlated at the Joint Institute for VLBI ERIC (JIVE) in the Netherlands, forming an Earth-sized super-telescope that could capture the subtle signals of gravitational lensing by the dark object. They discovered that the object has a mass a million times greater than that of our Sun and is located in a distant region of space, approximately 10 billion light years from Earth, when the universe was only 6.5 billion years old.

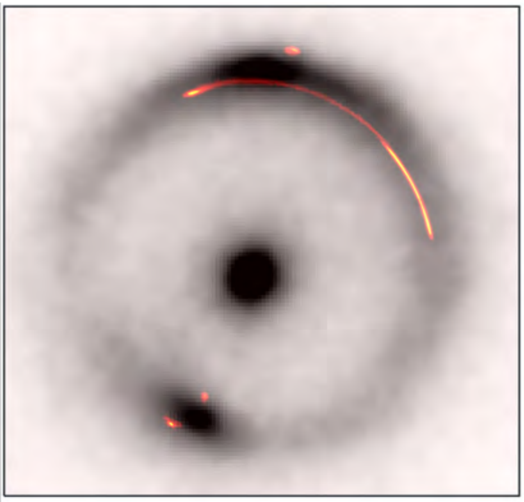


Figure 2.32: Overlay of the infrared emission (black and white) with the radio emission (colour). The dark, low-mass object is located at the gap in the bright part of the arc on the right-hand side. *(Credit: Keck/EVN/GBT/VLBA)*

This is the lowest mass object to be found using this technique, by a factor of about 100. To achieve this level of sensitivity, the team had to create a high-fidelity image of the sky using radio telescopes located around the world. Professor John McKean from the University of Groningen (RuG), the University of Pretoria (UP) and the South African Radio Astronomy Observatory (SARAO), who led the data collection and is the lead author of a companion paper, said: "From the first high-resolution image, we immediately saw a pinch in the gravitational arc, which is the tell-tale sign that we were onto something. Only another small clump of mass between us and the distant radio galaxy could cause this."

To analyse the massive dataset, the team had to develop new modelling algorithms that could only be run on supercomputers. "The data are so large and complex that we had to

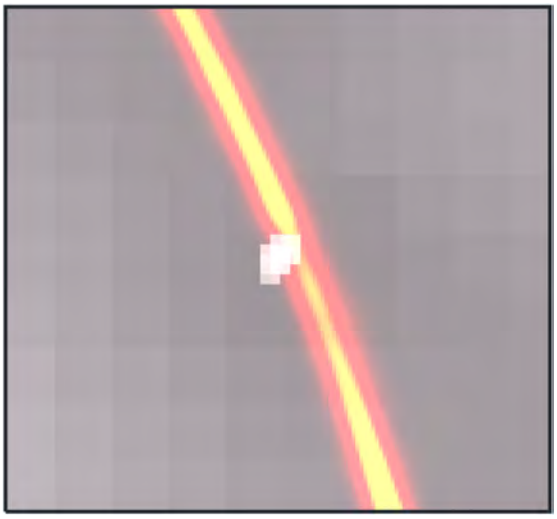


Figure 2.33: The zoom in shows the pinch in the luminous radio arc, where the extra mass from the dark object is gravitationally 'imaged' using the sophisticated modelling algorithms of the team. The dark object is indicated by the white blob at the pinch point of the arc, but no light from it has so far been detected at optical, infrared or radio wavelengths. *(Credit: Keck/EVN/GBT/VLBA)*

develop new numerical approaches to model them. This was not straightforward as it had never been done before," said Dr Simona Vegetti at MPA. "We expect every galaxy, including our own Milky Way, to be filled with dark matter clumps, but finding them and convincing the community that they exist requires a great deal of number crunching," she continued. The team applied a special technique called gravitational imaging, which allowed them to 'see' the invisible dark matter clump by mapping its gravitational lensing effect against the radio-luminous arc.

"Given the sensitivity of our data, we were expecting to find at least one dark object, so our discovery is consistent with the so-called 'cold dark matter theory' on which much of our understanding of how galaxies form is based," said Powell. "Having found one, the question now is whether we can find more and whether their number will still agree with the models."

The team are now analysing the data further to better understand what the mysterious dark object could be, but they are also looking into other parts of the sky to see if they can find more examples of such low-mass dark objects using the same technique. If they continue to find such mysterious objects in other parts of the universe, and if they really turn out to be completely devoid of stars, then some theories of dark matter may be ruled out.

Additional Information:

Gravitational lensing: This is an astrophysical tool used by astronomers to measure the mass properties of structure in the Universe. It is a consequence of Einstein's Theory of General Relativity, where mass in the Universe curves space. If the mass of the foreground lensing object (typically a galaxy or cluster of galaxies) is sufficiently dense, then the light from distant objects is distorted and multiple images are even seen. In the case of this system, called B1938+666, the foreground infrared luminous galaxy (seen at the centre of the ring), results in a beautiful Einstein ring of the distant galaxy. However, the distant galaxy is also bright at radio wavelengths, showing the beautiful multiple images and gravitational arcs (seen in red).

Very Long Baseline Interferometry: The radio observations were taken using a combination of radio telescopes that are combined to form a so-called Very Long Baseline Interferometer. This observational method allows astronomers to improve the imaging sharpness of the data and reveal very small fluctuations in the brightness that otherwise could not be seen. For example, the resolving power of the VLBI data is a factor 13 better than the infrared imaging from the W. M. Keck Telescope adaptive optics system (also shown in the figures in black and white). The telescopes used in the observations were the Green Bank Telescope and the Very Long Baseline Array of the National Radio Astronomy Observatory in the United States, and the telescopes of the European Very Long Baseline Interferometric Network.

Gravitational imaging: This is a novel method astronomers use to 'see' mass in the Universe even though it does not emit any light. This method uses the extended gravitational arcs to look for small aberrations that can only be caused by an additional, invisible component of mass. By combining this method and the exquisite high angular resolution imaging from the VLBI data, the team were able to detect the presence of the lowest mass dark object currently measured.

3 Publications, Talks and Committee Work

3.1 Talks and lectures

3.1.1 Contributed Talks and Posters

A. Acharya: SKAO ”A new era in Astrophysics”, (Görlitz, Germany, 16-20.06.2025) - (contributed talk)
A. Acharya: LOFAR Epoch of Reionisation Plenary meeting, (Bansko, Bulgaria, 29.04 - 01.05.2025) - (contributed talk)
S. Almada Monter: Escape of Lyman radiation from galactic labyrinths ”The Windows and Walls of the Labyrinth: Decoding Lyman-alpha Radiation” (Kolympari, Greece, 8-11 April 2025) - (contributed talk)
S. Almada Monter: EAS meeting ”Tracing Lyman Escape in Early Universe: Insights from Anisotropic Configurations” (Cork, Ireland, 23-27 June 2025) - (contributed talk)
S. Almada Monter: EAS meeting ”The Role of Anisotropic Gas in Shaping Lyman-Alpha Observables” (Cork, Ireland, 23-27 June 2025) - (e-poster with short talk)
S. Almada Monter: HERA2025, The Physics of Galaxies at the Epoch of Reionization ”Escape of Lyman radiation through windows and walls” (Pisa, Italy, 22-26 September 2025)
N. Anau Montel: EuCAIF (European AI for Fundamental Physics) conference 2025, 16 – 20 June, 2025, Cagliari, Italy. Talk title: Tests for model misspecification in simulation-based inference (selected for highlight plenary talk)
F. Arrigoni Battaia: Quo Vadis Galaxy Evolution?” (Heidelberg, Germany, 30.06-04.07) - (contributed talk)
A. Basu: Potsdam Thinkshop, ”Variability in the UVLF : Connecting Stellar Feedback and Bright Galaxies” (Potsdam, Germany, July 2025) (contributed talk)
T. Braun: TASC9/KASC16 Workshop ”Modelling the Sun with a non-local theory of convection” (Vienna, Austria, 7.-11.07.2025) - poster
D. Calderón; X-ray Quasi-Periodic Eruptions & Repeating Nuclear Transients Workshop, ”The effect of relativistic precession on light curves of tidal disruption events (Madrid, Spain, 16.-19.06.2025) - (contributed talk)
D. Calderón; 27th RAGtime workshop (Opava, Czechia, 10.-14.10.2025) - (contributed talk)
S. Celik: DPG Spring Meeting ”Mixed Dark Matter and Galaxy Clustering” (Goettingen Germany, 31.03.25-04.04.2025) Contributed Talk
S. Celik: Invisibles 2025 ”Mixed Dark Matter and Galaxy Clustering” (CERN, 01.09.25-05.09.2025) Poster
S. Celik: New Physics from Galaxy Clustering ”Mixed Dark Matter and Galaxy Clustering” (Florence Italy, 20.09.25-03.10.2025) Contributed Talk
F. Conteddu: Cambridge-LMU Cosmology Meeting: ”Multi-tracer beyond linear theory”
F. Conteddu: Munich Large-Scale Structure Days: ”Multi-tracer beyond linear theory”

W. de Roo: EAS 2025 ”Ordered magnetic field in a lensed spiral galaxy at z=2.6” (Cork, Ireland, 26.06.2025)-(contributed talk)
P. Diego-Palazuelos: ORIGINS annual Science Week ”Cosmic birefringence from the Atacama Cosmology Telescope data release 6”, (Seeon, Germany, 01.-05.12.2025)- (contributed talk)
A. Dutta: Fading in the flow: Fate of cold clouds in expanding galactic outflows, (18th Potsdam Thinkshop, Potsdam, Germany, 14.-18.07.2025)- (poster)
A. Dutta: When Winds Get Messy: Turbulence, Expansion and the Fate of cold clouds, (MMC 2025 conference, Olbia, Italy 06.-10.10.2025)- (contributed talk)
A. Dutta: TBD, (The Baryon Cycle from Reionization to Cosmic Noon, Puerto Varas, Chile 08.-12.12.2025)- (contributed talk)
T. Enßlin: The Universal Bayesian Imaging Kit” at The 35th annual conference on Astronomical Data Analysis Software & Systems 2025 in Görlitz, Germany (8.-12.11.2025)
T. Enßlin: “Polarimetric Imaging Reflecting Strokes Relations at Radio2025 conference in Heidelberg, Germany (26.-28.11.2025)
A. Genina: Virgo Consortium Meeting, ”A calibrated model for dynamical friction acting on supermassive black holes”, (Brighton, UK, 20.-24.01.2025)-(contributed talk)
J. Hein: Stellar Populations and their Explosions: Bridging the Gap, Ringberg, 10.-14.11.2025
E. Herwig: Contributed Talk: ”Searching for cosmic web filaments between quasar pairs at $z \sim 3$” (’ORIGINS RU-D day: Filamentary structures at all scales’, 01/2025)
E. Herwig: Contributed Talk: ”A candidate quadruple AGN merger at $z \sim 3$” (’Dancing in the Dark’, Sesto, Italy, 06/2025)
E. Herwig: Poster ’Gas accretion and AGN feedback imprints on quasar pair Lyalpha nebulae at $z \sim 3'$ (18th Potsdam Thinkshop, Potsdam, Germany, 07/2025)
E. Herwig: Poster+Flashtalk: ”The search for protoclusters around quasar pairs” (’CL2025’, Taipei, Taiwan, 09/2025)
E. Herwig: Contributed Talk (”The multiscale environment of AGN across cosmic time”, Ringberg, Germany, 11/2025)
J. Jäger: EAS Annual Meeting ”Dust formation and destruction in a simulated low metallicity starburst”, (Cork, Ireland, 23.-27.06.2025) - (ePoster)
H.-Th. Janka: Bruno Leibundgut 65Years (Garching, Germany, 7.-11.04.2025)–(contributed talk)
G. Jin: MIAPbP ”Unveiling a Universe of Black Holes: The next Generation of AGN Surveys” (Garching, Germany, 10.03 - 04.04.2025) - (contributed talk)
G. Jin: LOFAR Family Meeting 2025, (Paris, France, 22.-26.2025) - (poster talk)
G. Jin: The multiscale environment of AGN across cosmic time, (Ringberg, Germany, 23.-28.11.2025) - (contributed talk)
S. Justham: at Stellar Populations and their Explosions: Bridging the Gap; ”3D radiation-hydro simulations of red supergiants and their circumstellar material” (Ringberg Castle, Tegernsee, Germany, from 10/11 – 14/11/2025).
D. Kresse: YITP workshop “Stellar black hole formation and detection” (Kyoto University, Japan, 24.-28.03.2025); title: “Three-dimensional Simulations of Black-hole Forming Failed Supernovae” (contributed talk)
D. Kresse: Workshop ”Stellar Populations and their Explosions: Bridging the Gap” (Ringberg Castle, Tegernsee, Germany, 10.-14.11.2025); title: ”Post-explosion Hydrodynamics in 3D Neutrino-driven Supernova Models” (contributed talk)
T. Kurita: Cambridge-LMU Cosmology meeting ”Probing Primordial Parity Violation with Intrin-

sic Galaxy Shapes", (University Observatory Munich, Germany, 15.-18.09.2025) - (contributed talk)
T. Lechien: Talk or Poster: The Lifecycle of Stellar Black Holes, KITP, USA, (November 2025)
T. Lechien: Poster: BLOeM collaboration meeting, Amsterdam, Netherlands (October 2025)
T. Lechien: Poster: Binary Stars in the Space era, Keele University, UK (July 2025). "Evidence for efficient mass transfer from Be+sdOB binaries"
T. Lechien: Talk: 18th Bonn Neutron Star Workshop (May 2025). Germany, "Self-consistent multi-wavelength modeling of neutron stars"
T. Lechien: Talk: AAS 245 Winter Meeting, USA (January 2025). "Multi-Wavelength Light Curve Neutron Star Parameter Inference Using Neural Networks"
M. Lujan Niemeyer: HETDEX Collaboration Meeting, "Lyman-alpha intensity mapping with HETDEX", (remote, Austin, TX, USA, 14.-16.5.2025) - (contributed talk)
M. Lujan Niemeyer: Line Intensity Mapping 2025, "HETDEX - a Lyman-alpha Intensity Mapping Survey", (Annecy, France, 2.-6.6.2025) - (contributed talk)
I. Millan Irigoyen. Munichfest 2025 , 07.04.2026-11.04.2026, Fuencaliente, La Palma, Canary Island, Spain (contributed talk)
B. Peng: Fine-structure line workshop "Comprehensive View of FIR FSLs", (Winona, MN, USA, 10-13.06.2025) - (contributed talk)
B. Peng: ALFALFA legacy workshop, (Ithaca, NY, USA, 1-3.07.2025) - (contributed talk)
B. Peng: MULTISCALE ENVIRONMENT OF AGN, (Ringberg, Germany, 23-28.11.2025) - (contributed talk)
A. Rantala: Getting ready to descend the slippery slope of multi-messenger cosmological black holes data, (Sexten Dolomites, Italy, 10.-14.02.2025)- (contributed talk)
A. Rantala: Unveiling a Universe of Black Holes: The next Generation of AGN Surveys, (MIAPbP, Garching, 10.-14.04.2025)- (contributed talk)
A. Rantala: Numerical recipes in star formation, (Leiden, the Netherlands, 21.-25.07.2025)- (contributed talk)
A. Rantala: Massive Black Holes across Cosmic Time, (Cambridge, UK, 08.-12.09.2025)- (contributed talk)
J. Ritter: EAS meeting 2025, Talk title:"Multiphase gas reservoirs around $z \sim 3$ quasars and the impact of feedback from galaxy to halo scales" (Cork, Ireland, 23-27 June 2025) - (contributed talk)
J. Ritter: MMC 2025, Talk title:"Multiphase gas reservoirs around $z \sim 3$ quasars and the impact of feedback from galaxy to halo scales" (Olbia, Italy, 6-10 October 2025) - (contributed talk)
J. Ritter: Ringberg meeting "The multiscale environment of AGN across cosmic time", (Ringberg, Germany, 23 - 28 November 2025) - (contributed talk)
F. Schmidt: A Universe made of black holes ? AG Tagung, Görlitz September 2025
S. Schnauck: Stellar Populations and their Explosions: Bridging the Gap (Ringberg, Germany, 10.11-15.11.2025)
S.Schnauck: New Frontiers 2025: past, current and future challenges in Numerical Relativity (Palma, Spain, 21.07-25.07.2025) - (Gravitational waves from 3D GRMHD simulations of magnetorotational core-collapse supernovae)
V. Springel: A new divergence-free approach for moving-mesh magnetohydrodynamics (Ringberg Castle, Germany, 2.-7.11.2025) - (contributed talk)
S. H. Suyu: Strong Lensing in the Next Decade workshop, "Cosmology with Strongly Lensed Su-

pernovae", (Center for Astrophysics, Harvard College Observatory and Smithsonian Astrophysical Observatory, USA, 31.3.-4.4.2025) - (contributed talk)
J. Tan: Modeling of Multiphase Astrophysical Media Workshop, "The cosmic evolution of gas and metals in the IllustrisTNG Simulations", (Ringberg, DE, 02.-07.11.2025)-(contributed talk)
J. Tan: Multi-phase, Multi-temperature and Complex, "The cosmic evolution of gas and metals in the IllustrisTNG Simulations", (Olbia, Italy, 06.-10.10.2025)-(contributed poster -¿ contributed talk)
J. Tan: Cosmic turbulence and Magnetic fields: physics of baryonic matter across time and scales, "The cosmic evolution of gas and metals in the IllustrisTNG Simulations", (Corsica, France, 29.09.-03.10.2025)-(remote contributed talk)
J. Tan: 18th Potsdam Thinkshop: The Role of Feedback in Galaxy Formation, "The cosmic evolution of gas and metals in the IllustrisTNG Simulations", (Potsdam, DE, 14.-18.07.2025)-(contributed poster)
J.Tan: EAS 2025, "Cosmic evolution of metals in TNG100: Insights from absorption-line studies", (Cork, Ireland, 23.-27.06.2025)-(contributed poster)
J.Tan: EAS 2025, "Illuminating the kinematics of the simulated CGM via absorption-line analysis", (Cork, Ireland, 23.-27.06.2025)-(contributed poster)
J. Tan: International Workshop on Galaxy Formation and AGORA in Asia 2025, "The cosmic evolution of gas and metals in the IllustrisTNG Simulations", (Osaka, Japan, 26.-30.05.2025)-(contributed talk)
K. Trivedi: 18th Potsdam Thinkshop, (Potsdam, Germany, 14-18.07.2025) - contributed poster
K. Trivedi: HERA2025: "The Physics of Galaxies at the EoR", (Pisa, Italy, 22-26.09.2025) - contributed talk
R. Valli: 18th Bonn Neutron Star Workshop. "Three modes of neutron star formation revealed by Be X-ray binary orbits", (Bonn, Germany 7-9 May 2025)-(contributed talk)
R. Valli: UK-Spins conference, (London, UK 15-17 Sep 2025)-(contributed talk)
R. Valli: Stellar Populations and their Explosions: Bridging the Gap, (Ringberg, Germany 10-14 Nov 2025)-(contributed talk)
R. Valli: Bloem second collaboration meeting, (Amsterdam, The Netherlands 14-16 Oct 2025)-(contributed talk)
A. Vani: Talk: Probing Galaxy evolution from z=0 to $z \sim 10$ through galaxy scaling relations in L-GALAXIES, MIAPbP 2025, Unveiling a Universe of Black Holes: The next Generation of AGN Surveys
A. Vani: Poster: SaasFee advanced course
A. Vani: Talk: Quenching in the early Universe, LGalaxies workshop
A. Vigna-Gomez: Multiplicity in Young Stars, "Formation of Massive Multiple-Star Systems: Early Migration & Mergers", (Copenhagen, Denmark, 26.-29.08.2025)-(contributed talk)
A. Vigna-Gomez: Dynamix, "Prompt Mergers in Tight Triples", (Cambridge, UK, 02.-0.6.06.2025)-(contributed talk)
M. Werhahn: Thinkshop Potsdam on the role of feedback in galaxy formation, "Constraining Cosmic Ray Feedback in Galaxy Evolution", July 14-18, AIP Potsdam, Germany (contributed talk)
M. Werhahn: Annual Meeting of the German Astronomical Society "Constraining Cosmic Ray Feedback in Galaxy Evolution", September 15-19, Görlitz, Germany (contributed talk)

3.1.2 Invited Talks or Review Talks

A. Acharya: New simulations for new observations at the Epoch of Reionization: from SKA to ALMA (ESO Garching, Germany, 06.08.25)
N. Anau Montel: The International Biomedical and Astronomical Signal Processing (BASP) Frontiers Conference 2025, 26 – 31 January, 2025, Villars-sur-Ollon, Switzerland. Talk title: Autoregressive Modelling in Simulation-Based Inference for High-Dimensional.
N. Anau Montel: IAIFI (Institute for Artificial Intelligence and Fundamental Interactions) summer workshop 2025, 11 – 15 August, 2025, Cambridge (MA), USA. Talk title: Bridging Legacy and Modern Inference with SBI in Astrophysics
F. Arrigoni Battaia: Review on AGN imprints on the CGM (MIAPP, Garching, 10.03-4.04)
A. Basu: ESO, Garching, "Sources of EoR and their impact on IGM", April, 2025
E. Churazov: Contents of the Fermi Bubbles and Related Topics: The North Polar Spur and The Sphinx by Edgar Allan Poe (Green Bank, USA, 5-7.05.25)
E. Churazov: Magnetic Fields and Cosmic Rays across Diverse Scales: What's Next?: Non-thermal filaments in clusters. (Boston, USA, 8-12.09.25)
E. Churazov: Merging cluster workshop: Non-thermal filaments in clusters: Dynamical state of the Perseus cluster. eROSITA view. (Seoul, Korea, 27-30.10.25)
B. Ciardi: The Epoch of Helium Reionization (Sesto, Italy, 13.-17.01)
B. Ciardi: Probing the IGM with the Lya Forest and the 21cm Line (Trieste, Italy, 19.-23.05)
B. Ciardi: Helium Reionization (Trieste, Italy, 19.-23.05)
P. Diego-Palazuelos: Cosmology on the steep rise "Cosmic birefringence: searching for parity-violating physics with the CMB polarization", (Sesto, Italy, 03.-07.02.2025)- (invited talk)
P. Diego-Palazuelos: Parity Violation from Home 2025 "Cosmic birefringence from the Atacama Cosmology Telescope data release 6", (online, 18.-21.11.2025)- (invited talk)
T. Enßlin: Interferometric Imaging with Information Field Theory at "Science and Technology with the Wetterstein Millimeter Telescope", Zugspitze, Garmisch-Partenkirchen, Germany (24.06.2025)
T. Enßlin: Information Field Theory: Concepts and Astrophysical Application Applications at IAUS 391, UniversAI: Exploring the Universe with Artificial Intelligence, Athens, Greece (02.06.2025)
T. Enßlin: Achieved information gain as a sustainability measure at Shaping the Digital Future or ErUM Research: Sustainability & Ethics, Aachen, Germany (30.07.2025)
T. Enßlin: Time-Domain Sky Signals with Information Field Theory at the Restless Universe, Görlitz, Germany (14.09.2025)
T. Enßlin: Information Field Theory at NETWORK STUDIO Astrophysics, TU Dresden, Germany (29.09.2025)
T. Enßlin: Milky Way Atlas at IA-FORTH Heraklion, Greece (06.10.2025)
T. Enßlin: Information Field Theory at Politechnika Wrocławska, Poland (23.10.2025)
T. Enßlin: Information Field Theory: Concepts and Astrophysical Applications at Center for Advances Systems Understanding (CASUS) Görlitz, Germany (12.11.2025)
T. Enßlin: Bayesian Basics at sys2025: Systematic Errors across the Sciences – Statistics and Data Science at University of Alabama, Huntsville, Alabama, US (16.11.2025)
A. Genina: EAS 2025, "Dwarfs, tides and the Milky Way", (Cork, Ireland,23.-24.06.2025)-(invited talk)
R. Glas: "Stellar Populations and their Explosions: Bridging the Gap" (at Ringberg Castle in

November 2025) (contributed talk)
M. Gronke: AIP Thinkshop (Potsdam, Germany)
J. Jäger: Dust formation and destruction in a simulated low metallicity starburst (Helsinki, Finland, 28.-30.07.2025)
H.-Th. Janka: Stellar black hole formation and detection (Kyoto, Japan, 24.-28.03.2025)
H.-Th. Janka: An Extraordinary Journey Into The Transient Sky (Padova, Italy, 1.-4.04.2025)
H.-Th. Janka: HEAVYMETAL IV: Neutron star mergers and the origin of the r-process (Ystad, Sweden, 5.-9.05.2025)
H.-Th. Janka: SN2025gw: First IGWN Symposium on Core Collapse Supernova Gravitational Wave Theory and Detection (Warsaw, Poland, 21.-25.07.2025)
H.-Th. Janka: One Hundred Years of Supernova Science: Celebrating the discovery of supernovae by Knut Lundmark in 1925 (Stockholm, Sweden, 18.-22.08.2025)
E. Komatsu: CMB@60 (Turin, Italy, 28.-30.5.)
E. Komatsu: Axions in Stockholm 2025 (Stockholm, Sweden, 30.6.–4.7.)
E. Komatsu: Opening Symposium: Max Planck-IAS-NTU Center (Taipei, Taiwan, 1.–3.9.)
N. Lahén, Invited talk ”Mergers all the way down simulating globular cluster origins in dwarf galaxy starbursts”, Advancing massive black hole modelling across galactic scales, University of Helsinki, Helsinki, Finland, 28–30 July 2025
N. Lahén, Invited talk ”Mergers all the way down: building massive star clusters in dwarf galaxy starbursts”, IAU Symposium 398 & MODEST-25: Compact Objects and Binaries in Dense Stellar Systems, Seoul, South Korea, 16-20 June, 2025
N. Lahén, Invited talk ”Massive star cluster formation in a galactic context”, Star Formation, Stellar Feedback, and the Ecology of Galaxies: Celebrating John Bally’s lifetime in Astronomy, Visegrád, Hungary, 26-30 May, 2025
N. Lahén, Invited review ”Results and Challenges about Cluster Formation, Clumpy Structures and Cluster Early Evolution”, Bridging scales: star clusters and their host galaxies from the local to the high-z Universe, Matera, Italy, 1-5 September, 2025
J.-Z. Ma: Horizons for Optical Long Baseline Interferometry Workshop, Invited review talk ‘Massive Binary Science in the 2040s’ (Paris, France, 27.-30.1.2025)
R. Pakmor: ”Realisations and Superstars. Un update on the Auriga model and Superstars method”, Auriga Superstars Meeting Durham, UK, 15.7.25
R. Pakmor: ”WDWD mergers: an update”, HEAVYMETAL IV, Ystad, Sweden, 7.5.25
R. Pakmor: ”The Diverse Fates of Exploding White Dwarfs”, One hundred years of supernova science, Stockholm, Sweden, 19.8.25
A. Rantala: IAU Symposium 398 / MODEST-2025, (Seoul, South Korea, 16.-20.06.2025)- (invited talk)
A. Rantala: Advancing massive black hole modelling across galactic scales, (Helsinki, Finland, 28.-30.07.2025)- (invited talk)
A. Rantala: Loss cones at Como, (Como, Italy, 15.-17.09.2025)- (invited to lead a 1-hour discussion session)
F. Schmidt: Cosmology from galaxy clustering: field-level vs summaries Conference “Cosmology on the Steep Rise”, Sesto, Italy February 2025
F. Schmidt: Cosmic Rulers: LSS Observables in GR at second order MIAPbP workshop “Big Data, Big Questions” May 2025 F. Schmidt: Large-Scale Structure Observables: an Overview CosmoFondue Conference, Geneva June 2025

F. Schmidt: Cosmology from galaxy clustering: field-level vs summaries CoBALT Workshop Institut Pascal, Saclay June 2025
F. Schmidt: Cosmology from galaxy clustering: field-level vs summaries Understanding cosmological observations August 2025
F. Schmidt: A Universe made of black holes? Alpine cosmology workshop July 2025
F. Schmidt: Non-Gaussianity in Large-Scale Structure Learning the Deep Mysteries of Nature with Cosmology, Fiera di Primiero, Italy September 2025
F. Schmidt: Monodromic Dark Energy and DESI Cambridge-LMU Workshop, USM, Munich September 2025
M. Smith: Invited review ”The Theory of Galactic Winds” at 18th Potsdam Thinkshop ”The role of feedback in galaxy formation” (Potsdam, Germany, 14.-18.07.25)
V. Springel: Supercomputer Simulations of the Universe (EAS Annual Meeting, Cork, Ireland, 23.-27.6)
V. Springel: Cosmological simulations of structure formation: Successes, Challenges and Opportunities (Tokyo, Japan, 10.-12.3.)
V. Springel: L-Galaxies in Gadget-4: Semi-analytic mock galaxy catalogues for new, very large simulations (Berlin, Germany, 15.-17.10.)
S. H. Suyu: VLT, Supernovae, Bruno @65 & H0 @? conference, “Cosmology with strongly lensed supernovae”, (European Southern Observatory, Garching, Germany, 7.-11.4.2025)
S. H. Suyu: Second International Conference on the Physics of the Two Infinities, ”The Hubble Tension”, (Tokyo, Japan, 17.-21.11.2025)
A. Vani: Talk: The multiscale environment of AGN across cosmic time
A. Vigna-Gomez: Open Problems in Astrophysical Dynamics, ”Massive Multiple-Star Systems”, (Copenhagen, Denmark, 10.-13.06.2025)
M. Werhahn: Elucidating the Material Circulation in the Early Universe, ”Constraining Cosmic Ray Feedback in Galaxy Evolution”, March 10-12, 2025, University of Tokyo, Japan (invited talk)

3.1.3 External Colloquium and Seminar Talks

N. Anau Montel: Cambridge-LMU seminar (remote, May 2025)
N. Anau Montel: Modern Numerics for Theoretical Physics seminar @ ITP in Heidelberg (October 2025)
F. Arrigoni Battaia: Université Paris-Saclay (Paris, France, 4.11)
F. Arrigoni Battaia: INAF OAS (Bologna, Italy, 13.11)
D. Calderón: Astronomical Institute, Czech Academy of Sciences (Prague, Czechia, 13.08.2025)
D. Calderón: Departamento de Física, Universidad de Santiago de Chile (Santiago, Chile, 26.03.2025)
D. Calderón: Departamento de Astronomía, Universidad de Concepción (Concepción, Chile, 05.03.2025)
D. Calderón: Departamento de Astronomía, Universidad de Chile (Santiago, Chile, 03.01.2025)
E. Churazov: Harvard-Smithsonian Center for Astrophysics, (Cambridge, USA, 10.09.)
P. Diego-Palazuelos: Lawrence Berkeley National Laboratory (LBNL) CMB lunch seminar ”Cosmic birefringence: searching for parity-violating physics with the CMB polarization” (Berkeley, US, 03.10.2025)

A. Dutta: When Winds Get Messy: Turbulence, Expansion and the Fate of cold clouds, (Monday Lunch Talk, University of Groningen, Netherlands 29.09.2025) - (contributed talk)
T. Enßlin: Towards a Milky Way Atlas with Information Field Theory at Universitätssternwarte München, Germany - USM/LMU (12.05.2025)
T. Enßlin: Information Field Theory: Concepts and Astrophysical Applications at Institut für nachhaltige Wasserstoffwirtschaft (INW), Forschungszentrum Jülich, Germany (28.07.2025)
T. Enßlin: Seminar at ITP, Heidelberg, Germany (25.11.2025)
E. Herwig: ESO Santiago TMT: "The circumgalactic medium and Mpc-scale environment around quasar pairs at $z \sim 3$" (Santiago, Chile, 03/2025)
E. Herwig: ASIAA Lunch Talk: "The multiscale environment of quasar pairs at $z \sim 3$" (Taipei, Taiwan, 09/2025)
E. Herwig: MPIA Galaxy Coffee: "The environment of $z \sim 3$ quasar pairs" (Heidelberg, Germany, 10/2025
H.-Th. Janka: Cardiff University (Cardiff, Wales, 12.3.2025)
H.-Th. Janka: Sauverny Observatory, University of Geneva and Ecole Polytechnique Fédérale de Lausanne (Geneva, Switzerland, 7.10.2025)
E. Komatsu: DESY (Hamburg, Germany, 6.5.)
E. Komatsu: Hamburger Sternwarte (Hamburg, Germany, 7.5.)
E. Komatsu: HEP/Astro Results Forum (online, 6.6.)
E. Komatsu: Asia Pacific Center for Theoretical Physics (Pohang, Korea, 19.9.)
E. Komatsu: Zhejiang University (Hangzhou, China, 30.10.)
N. Lahén, Invited seminar "Mergers all the way down building massive star clusters in dwarf galaxy starbursts", Stockholm University, Stockholm, Sweden, 29 August
N. Lahén, Invited seminar "Unravelling the Formation of Globular Clusters in Low-metallicity Environments", University of Seoul, Seoul, South Korea, 13 June 2025
I. Millan Irigoyen: Institute of Cosmology and Gravitation. University of Portsmouth. 05.03.2026
R. Pakmor: "Connecting the fastest stars in the Galaxy to exploding white dwarfs", AIP Potsdam, 25.6.25
A. Rantala: University of Seoul, (Seoul, South Korea, 13.06.2025)
F. Schmidt: Cosmology from galaxy clustering: field-level vs summaries USM Colloquium, Munich May 2025
V. Springel: Max Planck Institute for Plasma Physics (Garching, Germany, 28.3.)
V. Springel: University of Michigan (Ann Arbor, USA, 10.4.)
V. Springel: Czech Academy of Sciences (Prague, Czechia, 5.6.)
V. Springel: University of Mainz (Mainz, Germany, 8.7.)
V. Springel: Leibniz Institute for Astrophysics Potsdam (Potsdam, Germany, 6.11.)
S. H. Suyu: Monash University, (Melbourne, Australia, 9.1.2025)
S. H. Suyu: CosmoVerse online seminar, (5.2.2025)
S. H. Suyu: Maynooth University, (Maynooth, Ireland, 7.3.2025)
S. H. Suyu: Black Hole Initiative, Harvard University (Cambridge, USA, 24.3.2025)
S. H. Suyu: University of Heidelberg, cosmology seminar, online (22.4.2025)
S. H. Suyu: Max Planck Institute for Gravitational Physics, (Hannover, Germany, 9.7.2025)
S. H. Suyu: California Institute of Technology, (Pasadena, USA, 11.8.2025)
S. H. Suyu: University of Hong Kong, (Hong Kong, SAR, 26.9.2025)
A. Vani: University of Zurich, Astronomy department

A. Vani: Vatican Observatory
A. Vani: Baryon pasting collaboration
A. Vani: Probing galaxy number density, sizes, and surface densities in L-GALAXIES, LGalaxies seminar series
A. Vigna-Gomez: ISTA Seminar, (Vienna, Austria, 29.04.2025)
A. Vigna-Gomez: KU Leuven, (Leuven, Belgium, 16.01.2025)
M. Warkentin: ”The Galactic Conformity Signal” (L-GALAXIES-Workshop, Berlin, Germany, 17.10.2025)

3.1.4 Lectures and Lecture Courses

P. Diego Palazuelos: MPA Postdoc/Staff Lecture Series on Cosmology ”Axion birefringence: probing ultra-light particles with polarized light”, (24.07.2025)
SS 2025, LMU München T. Enßlin: Intelligence & Field Theory lecture (4 SWS, 1 semester) LMU München, 28.4.-22.7.2025
T. Enßlin: Intelligence & Field Theory exercises (2 SWS, 1 semester) LMU München, 28.4.-22.7.2025
T. Enßlin: Signal reconstruction with Python (key qualification course), LMU München, Garching, 22.-26.9.2025
J. Grupa: Blick durch die kosmische Lupe: Wie Gravitationslinsen das Universum enthüllen
J. Grupa: 47. Edgar-Lüscher-Seminar in Zwiesel (Zwiesel, 4.04-6.04.25)
M. Guardiani: Harvard-Smithsonian Center for Astrophysics (Cambridge MA, USA, 5.11.25)
H.-Th. Janka, SS 2025 and WS 2025/2026, TUM, München: - Introduction to Theoretical Astrophysics
- Stellar Explosions
E. Komatsu: LMU, München: - Topics in Theoretical Cosmology
T. Kurita, postdoc/staff lecture series on cosmology 25.03.2025, MPA
E. Mamuzic, SS 2025, TUM: KTA Intro in English Tutorium
E.Müller: WS24/25, TUM, München: - Gravitational Waves

E.Müller (together with H.-T.Janka): SS25 and WS25/26, TUM, München: - Introduction to Theoretical Astrophysics - Exploding Stars
S. H. Suyu, WS2024/2025 and SS2025, TUM, München: - Experimental Physics 1 - Gravitational Lensing - Introduction to Nuclear, Particle and Astrophysics - Extragalactic Astrophysics

3.2 Community work, Outreach and Committee memberships

3.2.1 Community work

S. Almada Monter:
- Internal PhD representative - Member of the mentorship program
Basu: A Basu : Participating mentor for the MPA mentorship programme since 2024
F. Arrigoni Battaia: Contact for MPA internship program

F. Arrigoni Battaia: sustainability officer
D. Calderón: Postdoc representative since 09.2025
E. Churazov: Co-organiser of the MPA Institute Seminar
B. Ciardi: member of the permanent PhD Thesis Committee
B. Ciardi: equal opportunity officer
B. Ciardi: co-organizer of Institute Seminar
B. Ciardi: project manager for the operation of the MPA LOFAR station
W. de Roo: Co-organiser of the IMPRS student symposium (27-28 May 2025)
P. Diego-Palazuelos: Co-organizer of the MPA Cosmology Seminar since September 2025
M. Gronke: MPA mentorship program
E. Herwig: MPA mentorship program, mentored two undergraduate students and one highschool student
D. Kresse: administrator of the Garching Core-Collapse Supernova Archive
D. Kresse: co-organizer of the Garching Supernova Meeting
T. Lechien: Member of the MPA mentorship programme
I. Millan Irigoyen: Postdoc external representative until 01.09.2025
I. Millan Irigoyen: Organizer of the Galaxy Group Meeting until 01.06.2025
B. Peng: external postdoc representative
F. Schmidt: Member, works council (substitute representative of MPA in the general MPG works council)
F. Schmidt: Staff representative in the CPT Section
F. Schmidt: Coordinator, Origins connector CN4 ”Dark Energy”
S. H. Suyu: Equal Opportunity Officer (Deputy) of the TUM NAT School, where some of the MPA students are enrolled
A. Vani: MPA PhD rep Member of the PhDNet social media workgroup Mentor at MPA Mentorship program
M. Werhahn: Internal postdoc representative (July 2024 to July 2025)

3.2.2 Outreach Activities or Public Talks

A. Acharya: Podcast on ”Listening to the Early Universe” organised by ZetaGravit, India (12.07.25)
T. Braun: offered a planetarium show to approx 20 school students in January.
T. Braun: offered a station for the Girls Day in April.
D. Calderón: participated in the activity “Lunch with an Astrophysicist” at Max Planck Institute for Astrophysicist with a group of approx. 20 university students from the USA in May 2025.
T. Enßlin: oha! Abenteuer Wissenschaft in Görlitz (20.9.2025) R. Glas: Planetarium shows for several visitor groups (school classes etc.) with group sizes of ca. 15 to 25 people
J. Hein: Planetarium presentations
E. Herwig: offered a station for the Girls Day in April.
E. Komatsu: Bando Kobe Science Museum (Kobe, Japan, 2.3.)
D. Kresse: active member of MPA’s planetarium group, giving regular shows for national and international visitor groups and school classes (presenter of 4 shows in 2025 so far; help with setting up/down of the dome for other shows)

D. Kresse: help on Girl's Day (answering science questions and on studies/careers in astrophysics)
M. Lujan Niemeyer: will participate in a podcast of the Bayerischer Rundfunk on 25. October 2025.
J.-Z. Ma: Two public talks at X-Institute summer school for first-year bachelor students, China (07.2025)
E. Mamuzic: contribution to science article: "Focus on the universe", June 2025
E. Müller: Gymnasium Königsbrunn (25.11.)
A. Rantala and Schmidt, F.: MPA Research Highlight May 2025: "A Universe made of black holes?"
F. Schmidt: Girl's Day (April 2025)
F. Schmidt: c't Artikel zum Thema Dunkle Energie (Mai 2025)
F. Schmidt: Podcast Radiowissen (August 2025)
F. Schmidt: Interview für Seminarbeit, Schüler an Fachoberschule FOSBOS.
S. Schnauck: MPA Planetarium Shows
V. Springel: Fitting the Universe into a Supercomputer, DLR Optoelectronics Workshop 2025 (Backnang, Germany, 7.10.)
V. Springel: Simulierte Universen: Ursprung und Schicksal unserer Milchstraße, Bad Honnefer Industriegespräche (Bad Honnef, Germany, 6.2.)
V. Springel: Simulated Universes: Origin and Fate of Our Milky Way (University of Michigan, Ann Arbor, USA, 9.4.)
R. valli: gave a colloquium to a group of approx 25 high school students visiting the institute in April 2025

3.2.3 Internal Committees and Boards Membership

E. Churazov: IMPRS Executive Committee
E. Churazov: MPA Kippenhahn Prize Committee
B. Ciardi: member of the permanent PhD Thesis Committee
N. Anau Montel: Munich Dark Matter Meetings co-organizer
T. Enßlin: Managing Director's representative for construction projects
H.-Th. Janka: LRZ Garching (13.10.2025)
S. Justham: Lecture on stars to a group of visiting school students, 25/2/2025.
E. Komatsu: MPA PhD thesis supervisory panel; JAC Chair
T. Lechien: Staffed the NASA Fermi booth at the 245th meeting of the AAS, offering information on the gamma-ray telescope to students and other conference attendees.
R. Pakmor: Works council
R. Pakmor: Cosmology and Galaxies seminar organiser
F. Schmidt: Works council.

3.2.4 External Committees and Boards Membership

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

E. Churazov: Editorial Board of Astronomy Letters
B. Ciardi: member of the International Astrostatistics Associations
B. Ciardi: member of the German LOng Wavelenth (GLOW) Consortium
B. Ciardi: member of the International Astronomical Union
B. Ciardi: vice-chair of the GLOW Consortium
B. Ciardi: member of the GLOW Executive Committee
P. Diego Palazuelos: Speaker Selection Committee of the LiteBIRD Collaboration
P. Diego Palazuelos: European Astronomical Society
P. Diego Palazuelos: European Consortium for Astroparticle Theory
P. Diego Palazuelos: Spanish Astronomical Society
T. Enßlin: Head of Data Science at German Centre for Astrophysics (DZA)
T. Enßlin: Editorial Board Member of the Journal for Cosmology and Astroparticle Physics
T. Enßlin: Editorial Board Member of the Journal Entropy
H.-Th. Janka: Editorial Board of JCAP
H.-Th. Janka: Advisory Board for "Sterne und Weltraum"
E. Komatsu: Member of the German Astronomical Society
E. Komatsu: Member of the American Astronomical Society
E. Komatsu: Member of the American Physical Society
E. Komatsu: Member of the Astronomical Society of Japan
E. Komatsu: Member of the Physical Society of Japan
E. Komatsu: RIKEN Committee, Ministry of Education, Culture, Sports, Science and Technology (MEXT), Japan
E. Komatsu: ArXiv Scientific Advisory Council
E. Komatsu: Scientific Advisory Committee, Leung Center for Cosmology and Particle Astrophysics (LeCosPA), Taipei
E. Komatsu: Selection Committee for the Shaw Prize
T. Kurita: The Astronomical Society of Japan
N. Lahen: Junior Member of the International Astronomical Union
N. Lahen: Member of the European Astronomical Society
N. Lahen: Member of the Finnish Astronomical Society
I. Millan Irigoyen: Member of the Spanish Astronomical Society
I. Millan Irigoyen: Member of the European Astronomical Society
E. Müller: Member of the (German) Astronomical Society
E. Müller: Member of the International Astronomical Union
E. Müller: Member of the German Physical Society
A. Rantala: Member of the International Astronomical Union
A. Rantala: Member of the LISA Astrophysics Working Group
F. Schmidt: DFG member.
V. Springel: Vice President of the German Astronomical Society
V. Springel: Member of the Editorial Board for Living Reviews in Computational Astrophysics
V. Springel: Board of Trustees, Welt der Physik
V. Springel: Board of Trustees, MIP.labor, Berlin
V. Springel: Member of the German Academy of Sciences, Leopoldina
V. Springel: Member of the National Academy of Sciences of the US
V. Springel: Member of the German Astronomical Society

V. Springel: Member of the International Astronomical Union
V. Springel: Member of the European Astronomical Society
V. Springel: Member of the German Physical Society
V. Springel: Member of the Research Board of the ORIGINS Cluster of Excellence
V. Springel: Member of the Scientific Advisory Board of the Max Planck Computing and Data Facility
V. Springel: Scientific Advisory Board of the Zentrum für Astronomie (ZAH), Heidelberg University
V. Springel: Scientific Advisory Board of the Leibniz Institute for Astrophysics Potsdam
S. H. Suyu: member of telescope time allocation committee
S. H. Suyu: reviewer for funding agencies

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X. T. Xu, ..., C. Wang, H. Jin, et al., ”Populations of evolved massive binary stars in the Small Magellanic Cloud I. Predictions from detailed evolution models,” ASTRONOMY & ASTROPHYSICS 704, A218 (2025).

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4 Personnel

4.1 Scientific staff members

Directors

Selma de Mink, Guinevere Kauffmann, Eiichiro Komatsu (Managing Director until 31.12.2025), Volker Springel

Scientific Staff

Fabrizio Arrigoni-Battaia, Eugene Churazov, Benedetta Ciardi, Torsten Enßlin, Marat Gilfanov, Max Grönke (until 30.06.2025), 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

Postdocs in 2025					
Name	**Funding**	**Name**	**Funding**	**Name**	**Funding**
N. Anau Montel	MPA	C. Hernandez Aguayo	DFG Origins Cluster - Springel	B. Peng	MPA
I. Babic	MPA	A. Jamieson	MPA	D. Powell	LME Vegetti
A. Bhagwat	MPA	J. Klencki	MPA	A. Rantala	DFG Leibniz-Preis - Springel
J. Burger	Simons Foundation LtU - Springel	V. Korol	MPA	J. Roth	MPA
S. Chang	FG Gronke	D. Kresse	DFG NDM - Janka	T. Ryu	MPA
P. Diego Palazuelos	MPA	T. Kurita	MPA	M. Smith	MPA
C. Doughty	FG Gronke	N. Lahen	MPA	J. Stadler	MPA
A. Duivenvoorden	MPA	A. Melo Melo	Fellow Suyu	J. Stegmann	MPA
A. Dutta	MPA	I. Millan Irigoyen	MPA	R. Talbot	MPA
D. Galarraga-Espinosa	MPA	V. Muralidhara	MPA	A. Vigna Gomez	MPA
A. Genina	MPA	C. O'Riordan	LME Vegetti	C. Wang	MPA
R. Glas	DFG NDM - Janka	A. Olejak	MPA	M. Werhahn	MPA

Ph.D. Students

PhD students in 2025					
Name	**Funding**	**Name**	**Funding**	**Name**	**Funding**
A. Acharya	MPA	J. Jäger	MPA	K. Ramalatswa	MPA
S. Almada Monter	FG Gronke	M. Jetti	DFG Enßlin	B. Remple	MPA
S. Azyzy	MPA	G. Jin	MPA	J. Ritter	MPA
A. Basu	MPA	V. Johnson	MPA	S. Schnauck	MPA
T. Braun	MPA	T. Lechien	MPA	L. Souvaitzis	MPA
B. Casavecchia	MPA	M. Lujan Niemeyer	MPA	M. Tajalli	LME Vegetti
H. Das	FG Gronke	J. MA	MPA	J. Tan	MPA
W. de Roo	LME Vegetti	E. Mamuyic	Fellow Suyu	K. Trivedi	MPA
V. Eberle	DESY ErUM-IFT - Enßlin	A. Mayer	DFG Origins Cluster - Naab	B. Tucci Schiewaldt	MPA
F. Ferlito	MPA	M. Minzburg	MPA	R. Valli	MPA
J. Grupa	DFG Origins Cluster - Suyu	J. Moon	MPA	J. Tan	MPA
M. Guardiani	MPA	T. Oelgeschläger	MPA	A. Vani	MPA
J. Hein	MPA	S. Popa	MPA	H. Wang	Fellow Suyu
M. Heinlein	MPA	S. Raghuvanshi	MPA	M. Westerkamp	MPA
E. Herwig	MPA	A. Rajamuthukumar	MPA	H. Zandinejad	DFG GGTkS - Enßlin
F. Hidalgo Pineda	FG Gronke				

Master students

Duy Anh Hoang, Ahmet Eren Durmusbas, Leena Iwamoto, Christopher Hecker, Fabian Sigler, Iason Saganas, Andreas Popp, Anisha Anisha, Aditya Kuber Parit, Mohammadreza Ashari, Allan Schweinfurth Pupo, Anton, Darius Nöbauer, Benedikt Seidl, Jinhao Cai, Giovanni Stimamiglio, Patrik Kuster, Jaemin Ryu, Jennifer Faba Moreno, Hannah Röttgen, Ming Kei Chan, Morgane

Krauth, Marion Asasira, Elias-Gabriel Djossou, Francesco Conteddu, Ronald Sembatya, Sangjun Cha, Thomas Stocker, Jeonghun Jeong, Asu Nisa Ünver, Gülsah Zeynep Yigit, Richa Shree, Sreevarsha Srinivasan, Irwin Tay, Marie Erika Diesenberger, Mohammed Farhan Hassan

Technical and support staff

Computational Support: Andreas Breitfeld, Daniel Richter (since 1.7.2025) , Goran Toth, Martin Reineke, Andreas Weiss, Gerhardt Werner Grek
Public relation: Hannelore Hämmerle
Secretaries: Marzia Dallolio (since 1.2.2025), Gabriele Kratschmann, Ana Lomidze , Solvejg Schröder, *Library:* Mirna Balicevic, Christiane Bartels (library management)

4.2 Staff News/Awards

Silvia Almada Monter received the 2025 Rudolf Kippenhahn Award for her groundbreaking paper.

Patricia Diego has received two Extraordinary PhD Award by University of Cantabria and by the Spanish National Research Council (CSIC) (both awarded in 2025 although they refer to the thesis in 2023).

Torsten Enßlin is the Co-PI of two projects bringing information field theory to large German research facilities, ErUM-IFT and ErUM-IFT-2.

Torsten Enßlin is the beneficial of COMMANDER ERC grant.

Eileen Herwig was accepted to the SALTO Exchange Program between MPS and CNRS, including a grant of up to 10,000 EUR.

Natalia Lahen has been awarded the highly competitive European Research Council (ERC) Starting Grant.

Natalia Lahen has been awarded the prestigious Emmy Noether Grant of the Deutsche Forschungsgemeinschaft (DFG).

Thibault Lechien has received the 2025 Giuseppe and Vanna Cocconi Prize as part of the Fermi Collaboration

Antti Rantala has been awarded the prestigious five year Kavli Senior Fellowship at Kavli Institute for Cosmology Cambridge, UK.

Matthew Smith has received two High performance computing time awards for 2025 - 2026 as Co-PI.

Volker Springel has been awarded the Mohler Prize of the Astronomy Department at the University of Michigan

Alejandro Vigna-Gomez has been awarded the Carlsberg Reintegration Fellowship by the Carlsberg Foundation.

Claude Cournoyer-Cloutier was awarded Governor General's Academic Gold Medal for her excellent graduate studies at the McMaster University in Hamilton, Canada.

Marat Gilfanov appointed Distinguished Guest Professor at Nanjing University. Currently, Gilfanov is working with the Nanjing scientists on a joint project studying intermediate mass black holes (IMBHs).

4.3 PhD and Master Theses 2025

4.3.1 Master Theses 2025

Christopher Hecker: "Acceleration of Cosmic Structure Formation Simulations with AREPO using GPUs", Technische Universität München

Giovanni Stimamiglio: " Theoretical Predictions for the Surface Magnetic Fields of Binary-stripped Massive Stars", Ludwig-Maximilians-Universität München

Moritz Singhartinger: "Field-Level Inference of Cosmological Large-Scale Structure: Evaluating Initial Gaussianity and Parameter Convergence in MCMC Sampling", Technische Universität München

Mohammadreza Ashari: "Neutrino Sky Map", Ludwig-Maximilians-Universität München

Karl Heggenberger: "Introduction of the Comptence of Agents in the Reputation Game Simulation", Ludwig-Maximilians-Universität München

Patrik Kuster: "Bivariate Causal Inference with Information Field Theory", Ludwig-Maximilians-Universität München

Andreas Popp: "Calibration and Imaging of the Supernova Remnant SN 1006 with Fast-Resolve", Ludwig-Maximilians-Universität München

Ananya Shankar: "Bayesian Component Separation of the Polarized Microwave Sky", Ludwig-Maximilians-Universität München

Fabian Wolfgang Sigler: "Information Field Theory Based Imaging for Coherent X-Ray Scattering", Ludwig-Maximilians-Universität München

Daniel Muschiol: "Investigation of the Reconstruction Accuracy of Galaxy Position Data from a Backward-Optimized Digital Hologram", Hochschule Ruhr West

Jinhao Cai: "Gravitational Waves from Long-Term Axisymmetric Simulations of Accretion-Induced Collapse of White Dwarfs", Technische Universität München

4.3.2 PhD Theses 2025

Jana Grupa: "Gravitationally lensed supernovae in the era of Rubin Observatory", Technische Universität München

Fulvio Ferlito: “ High-precision weak gravitational lensing predictions with the Millennium TNG simulations”, Ludwig-Maximilians-Universität München

Tirso Marin Gilabert: “ The role of viscosity for mixing and transport processes in galaxy clusters and multiphase gas”, Ludwig-Maximilians-Universität München

Arghyadeep Basu: “ Tracing the start and end of cosmic reionization - exploring the role of ionizing sources as drivers”, Ludwig-Maximilians-Universität München

Anshuman Acharya: “ The intergalactic medium at the epoch of reionization”, Ludwig-Maximilians-Universität München

Beatriz Tucci Schiewaldt: “ Simulation-based inference for galaxy clustering”, Ludwig-Maximilians-Universität München

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

Margret Westerkamp: “ Accelerated Bayesian inference techniques for event based datasets - in nested sampling and X-ray astronomy”, Ludwig-Maximilians-Universität München

4.4 Visiting scientists in 2025

Long-term visitors (longer than 2 weeks)

Name	home institution	Duration of stay at MPA
Conny Aerts	KU Leuven	06.10–24.10
Min Bao	Nanjing Univ.	02.07–30.07
Andrei Beloborodov	Columbia Univ.	01.06–18.01
Ken Chen	Academia Sinica, Taiwan	07.09–20.09
Yanmei Chen	Nanjing Univ.	02.07–30.07
Gen Chiaki	Kochi College	02.09–14.09
Jorge Rodrigo	Univ. Adolfo Ibáñez	13.01–13.02
Dipayan Datta	IIS	13.10–28.02
Paola Dominguez-Fernandez	Harvard–Smithsonian	24.07–03.08
Philipp Frank	Stanford Univ.	04.08–25.08
James Fuller	Caltech	19.06–15.09
Facundo Gómez	Univ. Nac. La Plata	28.06–26.07
Alexander Heger	Monash Univ.	01.07–11.07
Alexander Heger	Monash Univ.	28.07–15.08
Tomasz Kacprzak	ETH Zürich	01.08–31.01
Qingbo Ma	Guizhou Normal Univ.	12.05–12.07
Paolo Mazzali	Liverpool John Moores Univ.	21.07–02.10
Antonela Monachesi	Univ. Nac. de Córdoba	28.06–26.07
Jens Niemeyer	Univ. Göttingen	04.08–22.08
Elena Pian	INAF Bologna	21.07–02.10
Mauro Pieroni	CERN	13.07–27.07
Kandaswamy Subramanian	IUCAA Pune	30.05–29.07
Patricia B. Tissera	Pontif. Univ. Cat. Chile	14.07–25.07
Valentina Vacca	INAF Italy	01.06–02.08
Chen Wang	Nanjing Univ.	17.10–26.10
Yu-Jan Wang	ASIAA, Taipei	01.10–31.10
Saleem Zaroubi	ARCO, Open Univ. Israel	26.09–24.10