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 Volker Springel being in post throughout 2021.

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

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

Over the last 30 years, activities at the MPA have diversified considerably, however, and now address a much broader range of topics, including a variety of data analysis and even some observational projects, although there is still a major emphasis on theory and numerics. Resources are channeled into directions where new instrumental or computational capabilities are expected to lead to rapid developments.

Active areas of current research include stellar evolution, stellar atmospheres, accretion phenomena, nuclear and particle astrophysics, supernova physics, astrophysical fluid dynamics, high-energy astrophysics, radiative processes, the structure, formation and evolution of galaxies, gravitational lensing, the large-scale structure of the Universe, the cosmic microwave background, physical and early universe cosmology, as well as information field theory. Several previous research themes (solar system physics, the quantum chemistry of astrophysical molecules, general relativity and gravitational wave astronomy) have been substantially reduced since 1994.

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

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

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

1.2 Current MPA facilities

Computational facilities

Theoretical and computational astrophysicists demand a modern, stable and powerful computing and networking infrastructure. Theoreticians, numerical simulators and data analysts all have different requirements. To provide optimal support, MPA has its own IT-group, overseen by a senior scientist who ensures efficient communication between the group and the institute's science community. In addition, a representative group of scientists forms the "Computer Executive Committee", which is responsible for long-term strategy and planning, and for balancing the requests of different user groups. The aim is to satisfy in-house needs both by providing extensive in-house computer power and by ensuring effective access to the supercomputers and the mass storage facilities at the Max Planck Computing and Data Facility (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 2020/2021 more than 150 million core hours, at various national and international Tier-0 supercomputer centres.

The most important resources provided by the MPCDF are parallel supercomputers, Petabyte (PB) mass storage facilities (also for backups), and the gateway to the German high-speed network for science and education. MPA participates actively in discussions of major investments at the MPCDF, and has provided several benchmark codes for the evaluation of the next generation supercomputer options.

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

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

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

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

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

The IT-group is made up of four full-time system administrators; users have no administrative privileges nor duties, which allows them to fully concentrate on their scientific work. During the Covid pandemic the IT department has guaranteed full access to all computing facilities at all times. The technical equipment in the main lecture hall and all seminar rooms have been upgraded for hosting virtual as well as hybrid seminars at high video and sound quality.

Library

The library is a shared facility of MPA and MPE and therefore has to serve the needs of two institutes with differing research emphases – predominantly theoretical astrophysics at MPA and predominantly observational/instrumental astrophysics at MPE. At present the library holds a unique print collection of about 54000 books and journals, about 7300 reports and observatory publications, print subscriptions for about 120 journals and online subscriptions for about 500 periodicals, as well as an ebook collection. In addition the library maintains an archive of MPA and MPE publications, and two slide collections (one for MPA and one for the MPE). The MPA/MPE library catalogue includes books, conference proceedings, periodicals, theses, reports (print and online). Additional technical services such as several PCs and terminals in the library area, copy machines and a colour book-scanner are available to serve the users' needs. The library is run by three people who share the tasks as follows: Mrs. Bartels (head of the library), Mrs. Blank (administration of journals) and Mrs. Balicevic (publication management for both institutes).

1.3 The year 2021 at the MPA

1.3.1 Biermann Lectures 2021

Fast Radio Bursts are a newly recognized, mysterious phenomenon consisting of short bursts of radio waves coming from far outside our Milky Way galaxy. Their origin is presently unknown. One of the leading models for Fast Radio Bursts is that they are magnetars: young, active neutron stars having the strongest magnetic fields known in the Universe. In the 2021 Biermann Lectures, Victoria Kaspi from the McGill University in Montreal, Canada, has discussed "The Case For and Against Fast Radio Bursts as Magnetars". Due to the COVID situation, the Biermann lectures were only held online.

As a professor of physics at McGill University, and Director of the McGill Space Institute, Victoria Kaspi's research centres on observational studies of Fast Radio Bursts and neutron stars. She has discovered many new pulsars – rapidly rotating neutron stars – and her research has advanced our understanding of the structure of magnetars, neutron stars with an extremely powerful magnetic field.

Currently her attention has turned to Fast Radio Bursts (FRBs), and she is using the novel CHIME Telescope (The Canadian Hydrogen Intensity Mapping Experiment), newly built in Penticton, British Columbia, to detect hundreds of Fast Radio Bursts. The CHIME/FRB team consists of nearly 100 students, postdocs, faculty and professionals who have developed the instrument, software pipelines and data visu-

Prof. Victoria Kaspi, McGill University, Montreal, Canada *(Credit: Owen Egan for McGill University)* alization tools to take the 13 Terabit/second input CHIME data rate and search in real time for FRBs, providing near real-time FRB alerts to the worldwide community. Among CHIME/FRB's accomplishments is the discovery of dozens of repeating FRBs, the first major FRB catalog consisting of over 500 events, and the detection of a luminous radio burst from a magnetar in our own Galaxy, a demonstration that magnetars are capable of FRB-like emission.

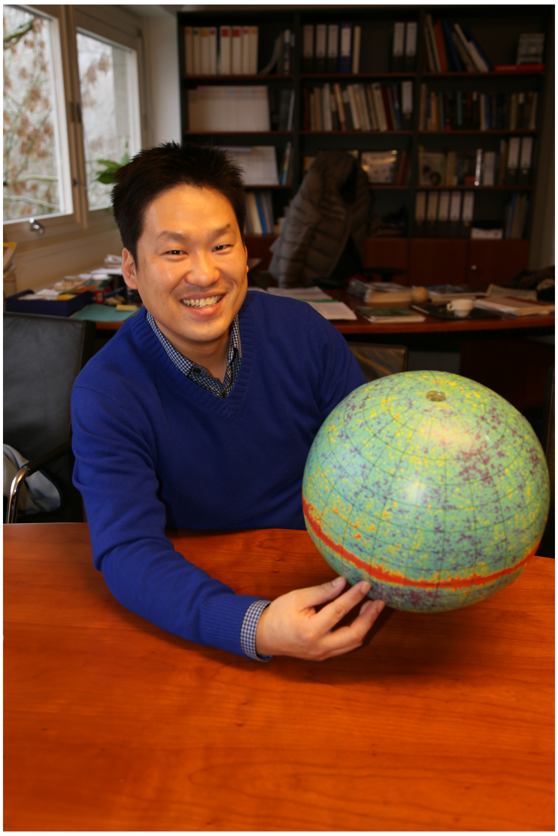
Victoria Kaspi studied physics at McGill and Princeton, where she completed her PhD in 1993 under the supervision of Joseph Taylor (Nobel Prize in Physics 1993 for the discovery of the first binary pulsar). After postdoc positions at the California Institute of Technology, the Jet Propulsion Laboratory, and the Massachusetts Institute of Technology, she took a faculty position at McGill in 1999. Since 2015, she is Director of the McGill Space Institute. Kaspi has won many awards, including the Rutherford Medal in Physics of Royal Society of Canada in 2007, NSERC John C. Polanyi Award in 2010 and the NSERC Gerhard Herzberg Gold Medal for Science and Engineering in 2016, the Queen Elizabeth II Diamond Jubilee Medal in 2013, and in 2021 the Shaw Prize. In 2019, she was named as one of Nature's Top 10 People Who Mattered in Science.

While she introduced the terminology, basics physics, and phenomenology of magnetars and Fast Radio Bursts in her first two lectures, in her final lecture she considered in more depth one possible FRB model, magnetars, and the evidence both for and against the association.

1.3.2 Prizes and Awards

Eiichiro Komatsu awarded the Inoue Prize for Science

Max Planck Institute for Astrophysics Director Eiichiro Komatsu has been selected as one of the recipients of this year's Inoue Prize for Science. He is recognized for his work to study the physics of the early Universe as a researcher with remarkable achievements in the natural and fundamental sciences.



MPA Director Eiichiro Komatsu with a ball depicting the CMB. *(Credit: Hiroto Kawabata)*

The Standard Model of cosmology is known as the ΛCDM model, with Einstein's cosmological constant Λ or Dark Energy, which is responsible for the accelerated expansion of the universe, and Cold Dark Matter, which is the dominating form of matter in the Universe. However, the most extraordinary ingredient of the standard model is not contained in its name – and it's a hard one to grasp: It is the idea that our ultimate origin are the quantum mechanical fluctuations generated in the early Universe.

Using data from the Wilkinson Microwave Anisotropy Probe (WMAP), Eiichiro Komatsu has searched for evidence of these quantum fluctuations. And indeed this idea is not only consistent with all the observational data, but the evidence keeps accumulating. Komatsu has been working as a member of NASA's WMAP team since 2001, using the cosmic microwave background (CMB) observational data to find evidence of inflation, a period of rapid, exponential expansion right after the Universe was born, when the short wavelengths of the quantum fluctuations were stretched exponentially to astronomical lengthscales. The team found that the density fluctuations in the CMB obeyed a certain probability distribution, which depends on physics of the creation of quantum fluctuations. These quantum fluctuations lead to density fluctuations in the CMB, shaping the Universe that we know today.

Rudolf-Kippenhahn-Award

This year's Kippenhahn Prize goes to Francesca Rizzo for her paper on "A dynamically cold disk galaxy in the early Universe". The Prize is awarded annually by the Max Planck Institute for Astrophysics for the best student paper that has been published in an established journal. Rizzo made most of the contributions to all aspects of the paper: code development, data analysis, and the interpretation and writing of the surprising results.

The study of the structural, kinematic and dynamical properties of galaxies at high redshift provides a key route to testing galaxy formation models. Current analytical and numerical models of galaxy evolution predict that high-redshift galaxies should have chaotic interstellar media with much higher turbulence levels than nearby systems.

With the paper "A dynamically cold disk galaxy in the early Universe", Francesca Rizzo challenges these models. By combining the high-angular resolution of ALMA with her powerful three-dimensional lens modelling technique, Francesca studies the emission in the

Francesca Rizzo with managing director Volker Springel. *(Credit: H.-A. Arnolds, MPA)*

[CII] line with a resolution of 60 pc (about 200 light-years) for a dusty star-forming galaxy at redshift 4 (some 1.5 billion years after the Big Bang). This is unprecedented for a galaxy at this redshift. Most interestingly, her analysis reveals a highly starforming but dynamically cold disk with an unexpectedly low turbulence level, in conflict with prior expectations. Francesca's work shows that galaxies at redshift 4 are much more similar to low-redshift disks than previously believed and indicates the need for a significant revision of our understanding of how galaxies form their discs.

Shaking stars to get to their cores

For up to five years, MPA scientist Dr. Benard Nsamba received the prestigious Branco Weiss

Fellowship awarded by the ETH Zürich. In his research, he will combine stellar models with photometric and astroseismology observations of stars to explore the impact of stellar interior physics on the nature and sizes of stellar cores. In addition, he is planning to use astronomy to stimulate the interest of Ugandan students in science.

On 23 August 2021, the "Branco Weiss Fellowship – Society in Science" announced that Dr. Benard Nsamba of the Max-Planck Institute for Astrophysics (MPA) in Garching, Germany, was selected as one of eight new fellows after an extended global recruitment campaign. The fellowship is giving Benard Nsamba up to five years of complete academic freedom to do interdisciplinary research at any institution in the world. As a Branco Weiss Fellow, Benard Nsamba will combine stellar observables such as seismic data from space missions with stellar luminosities and spectroscopic data to tightly constrain stellar models. This technique offers a path towards a robust exploration of stellar interior structure.

Listening to stars allows us to probe their interior structures. Dr. Benard Nsamba *(Credit: Branco Weiss Fellowship)*

Asteroseismology, i.e. the study of stellar oscillations, has emerged as a very promising avenue to gain detailed information on the structure and physics of stellar interiors. Due to the advances in exoplanet research, high-quality photometric data has become available also on their host stars from space missions such as the French-led CoRoT satellite, NASA's Kepler space telescope, and more recently, NASA's TESS. This seismic information can be combined with classical data to constrain stellar models and explore the impact of stellar interior physics.

One particular research focus for Benard Nsamba is the nature and size of stellar cores and how these are affected by convective core overshoot, rotation, metallicity mixtures, and atomic diffusion. Matching stellar observables to stellar evolution models requires skills in photometry/asteroseismic data analysis, spectroscopic analysis, as well as stellar modelling. In addition to contributing to theories of stellar structure, stellar dynamics and evolution, Benard Nsamba's project will also play a significant role in the ongoing preparation activities concerning the precision and accuracy of the exoplanet-host star characterisation for ESA's PLATO (PLAnetary Transits and Oscillations of stars) mission.

In addition to his scientific research into the heart of stars, Benard Nsamba will use astronomy as a tool to stimulate the interest of high school students in STEM (science, technology, engineering, and mathematics) subjects, and encourage and motivate them to consider science related careers. Astronomy is considered to be a stimulating, appealing subject, and an excellent tool for conveying scientific knowledge to young students also in Africa. Benard Nsamba got interested in astronomy in general and stars in particular early on in his studies, with his undergraduate project focussing on designs of refracting telescopes and his master thesis on mass-loss in red giant stars. After studying physics at the Mbarara University of Science and Technology (MUST) in Uganda, Benard Nsamba obtained his PhD at the Institute of Astrophysics and Space Sciences (IA), University of Porto in Portugal in 2019 working on the astroseismology of Sun-like stars. Since 2020, he is working in the Stellar Evolution Group at the MPA as an Alexander von Humboldt Fellow.

1.3.3 New research group led by Max Grönke

There are still many unanswered questions in galaxy formation and evolution, especially on small scales, thinks Max Grönke, who leads the research group "Multiphase gas dynamics" at the Max Planck Institute for Astrophysics since November 1, 2021.

Max Grönke became interested in astronomy at an early age; already as a school-boy he visited Jochen Weller in Cambridge, who happens to be from the same place in the Black Forest. Max Grönke then went on to study physics at the Free University in Berlin, where he wrote his bachelor's thesis at DESY. For his master's and later his doctoral thesis, he moved to the Institute for Theoretical Astrophysics in Oslo. This was followed by postdoctoral positions in the U.S., at the University of California at Santa Barbara and as a Hubble Fellow at Johns Hopkins University in Baltimore. He leads the research group "Multiphase gas dynamics" at the MPA.

Max Grönke /New Max Planck Research Group Leader *(Credit: private)*

Max Grönke's group will explore gas dynamics in and around galaxies, particularly on scales previously too small to resolve in standard galaxy simulations (see Fig. 1.1). Max's previous research has included radiation transport in galaxies and magneto-hydrodynamics; two areas he is now bringing together in his research group.

While galaxy formation and evolution on large scales is mainly dominated by the dark matter distribution, on small scales various baryonic processes determine how gas gets into galaxies, its motion there, how it is partially converted into stars, or is ejected from the galaxies. Max and his group will explore the previously unexplored plasma physics with magneto-hydrodynamic simulations on small scales and then use radiative transfer equations to determine how to observe these processes. This connection to data-driven astronomy is important, though the particular appeal for Max Grönke lies in the focus on the theoretical basics and fundamental questions.

MPA's theoretical focus thus suits Max very well; he enjoys the regular exchanges with colleagues with whom there is much overlap. Max likes to spend his free time with his family and friends, especially enjoying the fresh air outdoors. So despite the pandemic last year, he managed to explore the East Coast of the USA and has also been out and about somewhat in the Bavarian mountains. He is really looking forward to the time after Covid and the opening of the Bavarian "Biergärten".

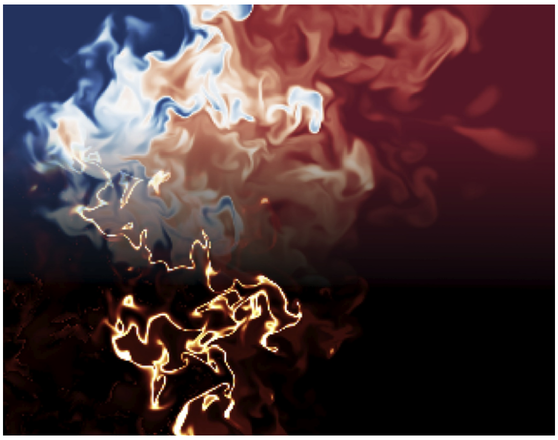


Figure 1.1: The new research group of Max Grönke will study gas in galaxies. *(Credit: MPA)*

1.3.4 The second year of Corona at MPA

As in the rest of Germany, the second calendar year of Corona started with a lockdown, severe travel restrictions, and closed schools. Amid these dreadful circumstances, the start of the vaccination campaign provided a much needed light of hope. For MPA, this meant continuing the hygiene and safety rules adopted in 2020: social distancing, obligatory mask wearing (with FFP2 masks if possible), allowing for general home office, and the single-occupancy office policy, which MPA is fortunate enough to be able to implement (as long as a significant fraction of MPA members work from home). In addition, MPA provided and continues to provide 2 rapid tests to every employee each week. Further, we acquired more air filter devices in order to be able to use different spaces for lunch breaks and small meetings during the cold season. Notably, the daily MPA coffee was continued in the MPA garden, throughout the entire year (albeit with much smaller attendance than in pre-pandemic times).

As it became clear that the pandemic will have a substantial and lasting impact on productivity especially of junior scientists, the MPA directorate in consultation with the WIR and student representatives decided that PhD students who struggled during the lockdowns could receive a contract extension of up to 6 months. All thesis committees are also requested to ask students specifically about how they are dealing with the pandemic situation.

With rising temperatures and an advancing vaccination campaign during Spring, restrictions in Germany were lifted and life at MPA could start back up with limited in-person meetings and lunches. Fortunately, state-wide regulations allowed the MPA works council and secretaries to organize the traditional MPA summer BBQ (outside), which was attended by more than 100 people. It was evident that everyone enjoyed being able to gather again on a nice summer afternoon.

By late summer, everyone at MPA got the chance to get vaccinated, one option being the Max Planck/IPP Campus vaccination drive in August. A completely anonymous survey (which included the option of not revealing the vaccination status) in Fall of 2021 indicated that at least 95% of MPA members were vaccinated at that point.

Given this information, and anticipating federal and state regulations, the MPA directorate in consultation with the works council decided to impose a 3G access rule at MPA, with every MPA member having to certify by signature that they are either vaccinated, recovered, or tested negative (a direct verification of certificates was deemed incompatible with data protection regulations, impractical given the hours when the reception desk is staffed, and finally hardly necessary given the very high vaccination rate). Indeed, the state of Bavaria soon adopted a 3G requirement from most employers.

The year concluded, again unfortunately, with rising incidence rates, and the encouragement to get third (booster) vaccinations. While the circumstances remain challenging, at least interactions among vaccinated persons now carry a greatly reduced risk. Apart from a lessened mental burden in day-to-day interactions, this also allowed MPA to have an afternoon pre-Christmas reception (outside), although this had to be restricted to MPA members only. As in the summer, this was well attended and enjoyed by all.

1.3.5 Public Outreach 2021

Most of the public outreach events had to be cancelled in 2021 due to the Covid pandemic. Nevertheless, a number of press releases were issued and published on the MPA webpage about awards for MPA scientists and project results. In addition, the monthly highlights continued to showcase the broad science research conducted at the institute.

1.3.6 Sustainability at MPA

Since the beginning of 2019 a small sustainability group meets at MPA every first Tuesday of the month, but most of these meetings were suspended in 2020 and 2021 due to the Corona pandemic.

The group evaluates yearly the carbon footprint of MPA. The main part of our CO_2 emission is high performance computing which adds up to 780 tons CO_2 per year. Three quarters of that amount is due to services used by MPA at MPCDF, where we used close to 3000 MWh of electricity, while the other quarter (940 MWh) is used by our own computing center at MPA and all other electrical devices in our institute, including laptops and the indispensable coffee machines. Another 740 MWh are used for heating, of which about $1/3$ is delivered by district heating via natural gas and the other $2/3$ by geothermic heat. Together, this causes about 50t of CO_2 emissions. In 2021, MPA's total energy consumption grew by about 15%, while the CO_2 footprint remained about the same, thanks to the growing fraction of renewable energy in the energy mix of Germany.

Since the research campus Garching can easily be reached by public transport, only about 20% of institute members commute by car. A survey by the sustainability group about commuting habits, the distance to work, time spent on the way to MPA, and the number of home office days in Corona times allowed to estimate that commuting adds another 20t of CO_2 to our budget in 2021. The use of public transport should be growing further due to the introduction of a job ticket at reduced price in 2021, subsidised by the MPA.

The MPA group cooperates with the MPG wide sustainability network that was founded at a workshop in May 2019 at the MPI for Dynamics of Complex Technical Systems in Magdeburg. Meanwhile the Max Planck Society has formed centralized sustainability activities. Each institute is supposed to have a sustainability committee, chaired by the respective directorium. At MPA this committee and the bottom-up sustainability group have merged.

2 Scientific Highlights

2.1 SRG/eROSITA detects large-scale X-ray bubbles encompassing the Fermi bubbles

The first all-sky survey performed by the eROSITA X-ray telescope on-board the SRG observatory has revealed a large hourglass-shaped structure in the Milky Way. These "eROSITA bubbles" show a striking similarity to the Fermi bubbles, detected a decade ago at even higher energies. The most likely explanation for these huge features is a massive energy injection from the Galactic centre region in the past, leading to shocks in the hot gaseous halo around our galaxy.

In the southern part of the sky, a new huge circular structure below the plane of the Milky Way was found in the eROSITA X-ray map. A similar structure in the Northern sky, a "North polar spur", has been known for a long time and had been thought to be the trace of an old supernova explosion. Taken together, the northern and the southern structures instead are reminiscent of a single hourglass-shaped bubble emerging from the Galactic center.

The large-scale X-ray emission observed by eROSITA in its medium energy band (0.6-1.0 keV) reveals the presence of gigantic bubbles at various levels of intensity throughout most of the sky, indicating that their intrinsic size is almost as large as the entire Milky Way ($\sim$10 kiloparsecs or up to 50,000 light-years across). These eROSITA bubbles show striking morphological similarities to the well-known Fermi bubbles detected at much higher energies (gamma-rays) by the Fermi telescope.

The bubbles now seen with eROSITA trace

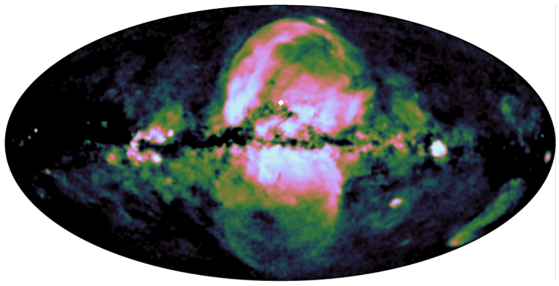


Figure 2.1: The eROSITA bubbles. In this false-colour map the extended emission at energies of 0.6-1.0 keV is highlighted. The contribution of the point sources was removed and the scaling adjusted to enhance large-scale structures in our Galaxy. *(Credit: MPE/IKI)*

disturbances in the hot gas envelope around our Milky Way, caused either by a burst of star formation or by an outburst from the supermassive black hole at the Galactic centre. While dormant now, the black hole could well have been active in the past, linking it to other active galactic nuclei seen in distant galaxies. In either case, the energy needed to power the formation of these huge bubbles must have been enormous (10^{56} ergs, about the energy release of 100.000 supernovae, which is similar to estimates of other AGN outbursts).

"eROSITA is currently performing the second scan of the entire sky, doubling the number of X-ray photons coming from the bubbles it has discovered," points out Rashid Sunyaev, scientific PI of the SRG Observatory. "We have a tremendous amount of work ahead of us because the eROSITA data make it possible to single out many X-ray spectral lines emitted by highly ionized gas. This means that the door is open to study the abundance of chemical elements, the degree of their ionization, the density and temperature of the emitting gas in the bubbles, and to identify the locations of shock waves and estimate characteristic timescales."

The SRG spacecraft was designed by Lavochkin Association, Roskosmos corporation and launched on July 13, 2019 with a Proton launcher from Baikonur cosmodrome. The SRG observatory was built with participation of DLR, Germany in the framework of Russian Federal Space Program by the initiative of the Russian Academy of Sciences represented by its Space Research Institute (IKI). The observatory carries two unique X-ray grazing incidence telescopes: ART-XC (IKI, Russia) and eROSITA (MPE, Germany). The SRG/eROSITA telescope was built under the leadership of the Max-Planck-Institute for Extraterrestrial Physics (MPE) and DLR. The SRG spacecraft is operated by Lavochkin Association and Deep Space Network Antennae in Bear Lakes, Ussurijsk, and Baykonur funded by Roskosmos. (Rashid Sunyaev, Eugene Churazov, Marat Gilfanov)

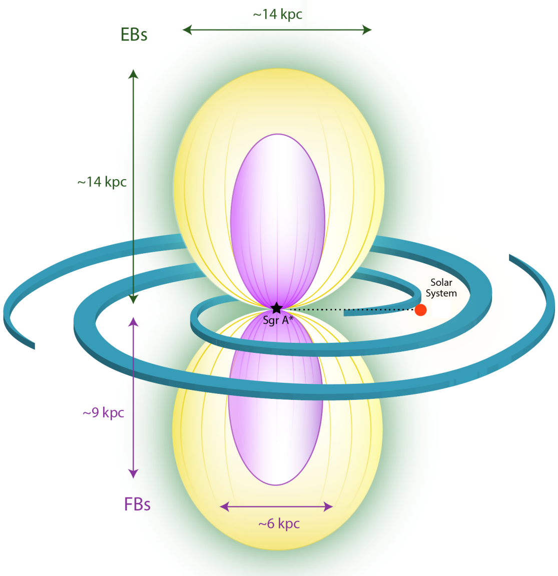


Figure 2.2: Schematic view of the eROSITA (yellow) and Fermi bubbles (purple). The galactic disk is indicated with its spiral arms and the location of the Solar System is marked. The eROSITA bubbles are considerably larger than the Fermi bubbles, indicating that these structures are comparable in size to the whole galaxy. *(Credit: MPE/IKI)*

2.2 Algorithmic improvements for radio interferometry

Radio telescopes observe the sky in a very indirect fashion. Sky images in the radio frequency range therefore have to be computed using sophisticated algorithms. Scientists at the MPI for Astrophysics have developed a series of improvements for these algorithms, which help to improve the telescopes' resolution considerably.

Optical telescopes produce data, which are a direct representation of the observed object's brightness distribution, i.e. an image in the conventional sense, which can be used for further analysis without additional processing. In radio interferometry (i.e. the high-resolution observation of the sky at radio frequencies), the situation is more complicated: here one does not obtain the sky brightness at a specific location, but rather data points indicating the amount, frequency and direction of brightness fluctuations.

If these data points were arranged on a regular two-dimensional grid, converting them to a normal image would be straightforward, but unfortunately no radio telescope design exists which could produce this arrangement. Realistic data point distributions often exhibit complex, inhomogeneous patterns (see Fig. 2.4). Further complications arise if the individual antennae are not placed perfectly on a single plane, and/or if the observed sky region is too large to be approximated by a flat surface. In this case, additional correction terms have to be applied during the image generation, which further increases the computational cost.

Figure 2.3: The 27 antennae of the Very Large Array (VLA) in New Mexico observe the sky simultaneously, forming a single virtual telescope with a gigantic diameter. *(Credit: NRAO/AUI/NSF)*

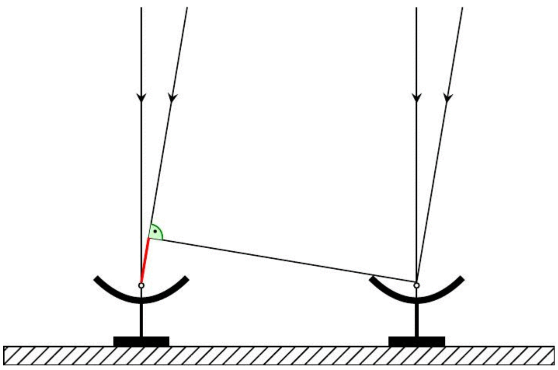


Figure 2.4: Schematic illustration of an interferometer: A larger distance of two sources in the sky leads to an increased difference in travel time (marked red) as does a larger distance between antennae. Antennae placed at larger distances are therefore able to resolve smaller structures, while antennae placed closely together are more sensitive to larger structures *(Credit: MPA)*

The operation described above is called "gridding" and in practice various different implementations exist. Some are not particularly accurate (usually because they date back to the early times of radio astronomy, when computational power was very limited and many approximations and simplifications had to be made). Others provide good accuracy, but often are not fast enough to process the huge amounts of data produced by contemporary radio telescopes in an acceptable amount of time.

Scientists at MPA have now used various approaches – both from radio astronomy itself and from unrelated scientific areas – to implement a new version of the gridding operation. This new implementation produces very accurate results while at the same time consuming considerably less CPU time and computer memory.

Gridding, however, is only one of several components necessary to produce realistic images from interferometric observations. To suppress noise in the data and eliminate the directional changes in antenna sensitivity, sophisticated iterative algorithms are employed. Traditionally, very often a variant of the so-called CLEAN algorithm is used, which is comparatively quick but does not provide an uncertainty estimate for the resulting image. In contrast to CLEAN-based methods, the MPA scientists developed an (admittedly significantly slower) approach, which delivers physically motivated results including error bars, making use of Information Field Theory and Bayesian statistics.

Fig. 2.5 shows a comparison of the two methods. The observed astrophysical source is the radio galaxy Cygnus A with a supermassive black hole (weighing more than a billion solar masses) at its centre. Two jets, observable at radio wavelengths, leave this centre and at some point encounter the intergalactic medium, where they are reflected and start to emit very brightly. The back-flows create large volumes of radio-bright gas, which can be observed with radio interferometers like the VLA.

The image obtained with the new algorithm exhibits significantly better spatial resolution in the bright image regions, since the signal-to-noise ratio in these areas is much higher. At the same time, it does not show the pronounced structures in the darker regions from the CLEAN results; presumably these structures are artefacts of the CLEAN algorithm and do not correspond to real features on the sky.

The methods presented here essentially open up two new possibilities for radio astronomy: they allow re-processing of already existing data sets, in order to gain additional insights from the improved images. For future observations, there may now be an option to reach the desired image quality with shorter observation times, thanks to the improvements in the algorithms, allowing for a higher overall number of observations.

Other scientific disciplines such as medical imaging, especially magneto-resonance tomography (MRT) employ imaging techniques that are closely related to those in radio interferometry. It is therefore possible that the insights gained from these developments will be beneficial in these areas as well. (Philipp Arras, Torsten Enßlin)

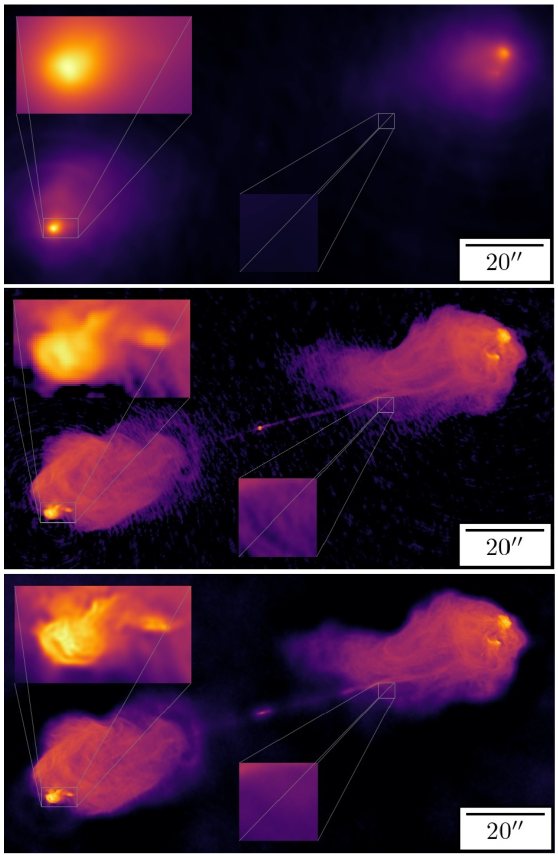


Figure 2.5: Three different image reconstructions of the radio galaxy Cygnus A from VLA interferometry data. Two small regions (a bright and a dark one, respectively), have been enlarged for easier comparison. Top panel: naive Fourier transform without optimization. Middle panel: reconstruction using the CLEAN algorithm. A higher resolution is reached, but some unphysical structures are generated, especially in the darker regions. Bottom panel: reconstruction using Bayesian imaging and Information Field Theory. Resolution in the bright areas is further improved, yet no artefacts are visible in the dark areas. *(Credit: MPA; reconstruction middle image: NRAO, Klasse Richard A. Perley)*

2.3 Tempestuous life of galaxy clusters: X-ray view on the Coma cluster with SRG/eROSITA

Galaxy clusters are dynamic systems that grow by continuously accreting large and small chunks of matter. This accretion process should give rise to a rich substructure in the dark matter distribution within the clusters and to shocks and cold fronts in the hot baryonic gas. Recent SRG/eROSITA observations provided an unprecedented X-ray view of the Coma cluster, revealing intricate signatures of the merger process, which are predicted by numerical simulations.

The Coma cluster (or Abell 1656) is a very special cluster of galaxies. It is very massive (containing thousands of galaxies) and nearby (less than 100 Mpc), and it is the very first object where Fritz Zwicky identified the presence of Dark Matter in 1933. In the radio band, it was the first cluster where a radio halo was found in the 1950s. The proximity of Coma makes it an attractive target for studies in all energy bands, although often the cluster's huge angular size complicates the task. In the X-ray band, the SRG observatory featuring the eROSITA and ART-XC telescopes is specifically designed for wide-field observations, and therefore managed to cover the Coma cluster in its entirety.

The X-ray image (see Fig. 2.6) accumulated during the first two raster scan observations of the whole sky shows a region (extending ~10 Mpc at the distance of the cluster), which is at least twice the virial radius of the cluster. Apart from a multitude of sources (mostly distant Active Galactic Nuclei), two bright diffuse blobs can be readily spotted, which correspond to the main cluster and the NGC4839 group (to the bottom-right from the center). The cluster and the group are in the process of merging. In fact, NGC4839 has already passed through the core of the main cluster once and it is about to start falling back again.

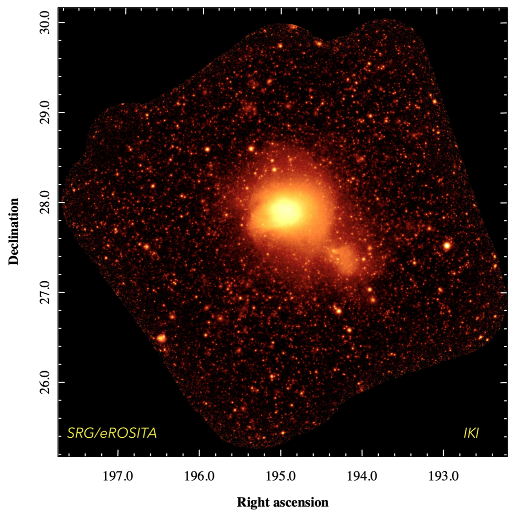


Figure 2.6: X-ray image of the Coma cluster field in the 0.4-2 keV band obtained by eROSITA. The image is ~ 6 degrees on a side, corresponding to 10 Mpc at the distance of the cluster, with the logarithmic color-code spanning 5 orders of magnitude. The main cluster is in the process of merging with the NGC4839 group (a bright blob to the bottom right from the Coma cluster *(Credit:SRG/eROSITA, IKI)*

Numerical simulations predict a number of signatures associated with this particular stage of the merger. The bow shock, produced by the NGC4839 group during its first passage, should now be located in the cluster outskirts, while the gas displaced from the core of the main cluster should be falling back, forming a "secondary" shock. The new data obtained with SRG/eROSITA suggests that this structure on the right (Western) side of the core, which extends to a few Mpc is exactly this "secondary" shock (see also Fig. 2.7).

Complementary information can also be obtained based on the Sunyaev-Zeldovich effect: the ratio of the eROSITA X-ray image and the Planck microwave image of the Coma cluster provides a proxy to the gas temperature map (Fig. 2.8). Such temperature measurements do not require any spectral information in the X-ray band, such as emission lines of heavily ionized ions of iron, nickel, etc. or the shape of the continuum spectrum. In reality, this estimate uses only the "negative" surface brightness of the cluster in the microwave band and the X-ray surface brightness in the 0.4 - 2.3 KeV band, where the eROSITA telescope has the highest sensitivity. As expected in the merger scenario, the core of the main cluster is hot, while the less massive NGC4839 group is able to retain some of its cool gas.

Yet another interesting implication of the merger scenario is that the radio halo, which is encompassed by the secondary shock, has passed in fact through two shocks – the first time through the bow shock driven by

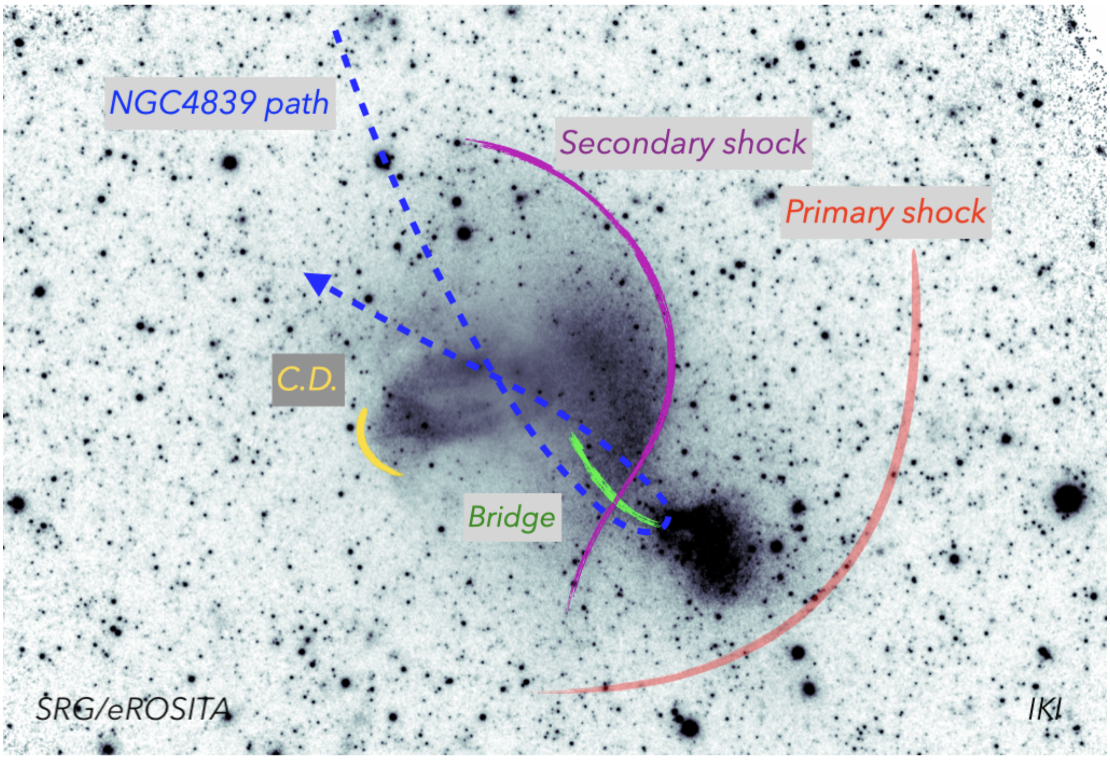


Figure 2.7: Flattened X-ray image of the Coma cluster field with labels schematically marking some of the features presumably associated with the merger with the NGC4839 group. The blue dashed line is the suggested trajectory of the group, which enters the Coma cluster from the North-East direction, and is currently close to apocenter. The presumed positions of two shocks driven by the NGC4839 group are shown with the red and purple curves. The shock closer to the center is driven by the displaced gas that settles back to hydrostatic equilibrium. This is the most salient feature directly seen in the image as the surface brightness edge. The green line shows the faint X-ray "bridge" connecting NGC4839 and the main cluster, which is a possible trace of the group passage through the Coma cluster. The yellow line shows the interface between cold and hot gas patches with the same pressure (the so-called Contact Discontinuity *(Credit: SRG/eROSITA, IKI)*

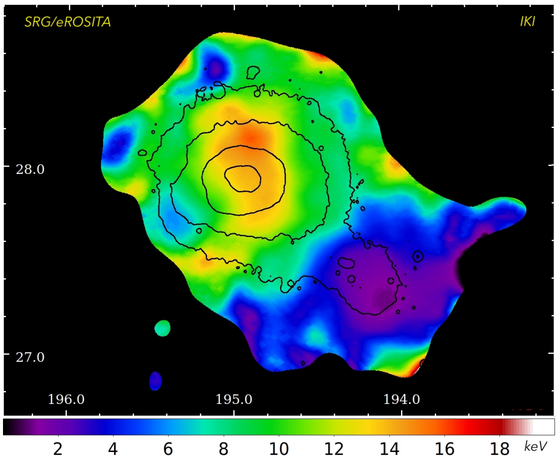


Figure 2.8: Ratio of the microwave and X-ray images of the Coma cluster, converted to the weighted electron temperature. Contours show the X-ray surface brightness. The core of the main cluster is hot, with a temperature of ∼100 degrees. The blue region to the bottom right corresponds to cooler gas of the NGC4389 group with three times lower temperature. *(Credit: SRG/eROSITA, IKI)*

NGC4839 when it was passing through the Coma core, and more recently through the secondary shock. This process might mitigate the rapid "ageing" of relativistic particles in radio halos observed in many other clusters – work on this problem is in progress (Rashid Sunyaev, Eugene Churazov).

2.4 Deep learning provides insights into cosmological structure formation

How can machine learning methods help us understand our tangled cosmic web? A new study presents a 'deep learning' framework to shed light onto the physics of the formation of dark matter halos. The results show that spherical averages over the initial conditions of the Universe carry the most relevant information about the final mass of halos.

All cosmic structures in the Universe were seeded by tiny fluctuations in the density of matter in the early Universe. Due to gravitation, these small perturbations grow over cosmic time into extended halos of dark matter, connected by walls and filaments and surrounded by empty voids. Normal matter follows this dark matter distribution, so that large-scale observations of our Universe show that galaxies and galaxy clusters form a "cosmic web". While the non-linear evolution of matter can be computed using cosmological simulations, a theoretical understanding of this complex process remains elusive.

In our study, we use a deep learning framework to learn more about the non-linear relationship between the initial conditions and the final dark matter halos in cosmological simulations (Fig. 2.9). With this framework, we want to improve our physical understanding of how non-linear, late-time cosmic structures emerge from the linear initial conditions. As it turns out, the major barrier to realising this goal is understanding and explaining how and why complex deep learning algorithms reach particular decisions in most applications, they have effectively acted as "black boxes". In our case, we wish to understand which features of the initial conditions are extracted by the algorithm to make its final predictions.

Our three-dimensional convolutional neural network (CNN) is trained on the non-linear relationship between the initial density field and the final mass of dark matter halos in cosmological simulations. The CNN consists of six layers, where features are extracted across the layers in a hierarchical fashion (from low-level, local features in the initial layers to high-level, more abstract ones in subsequent layers). Two fully-connected layers then combine the features to return the final prediction. By training the network across many examples of mapping initial conditions to halo masses, the model learns to identify those aspects of the initial density field, which impact the final mass of the

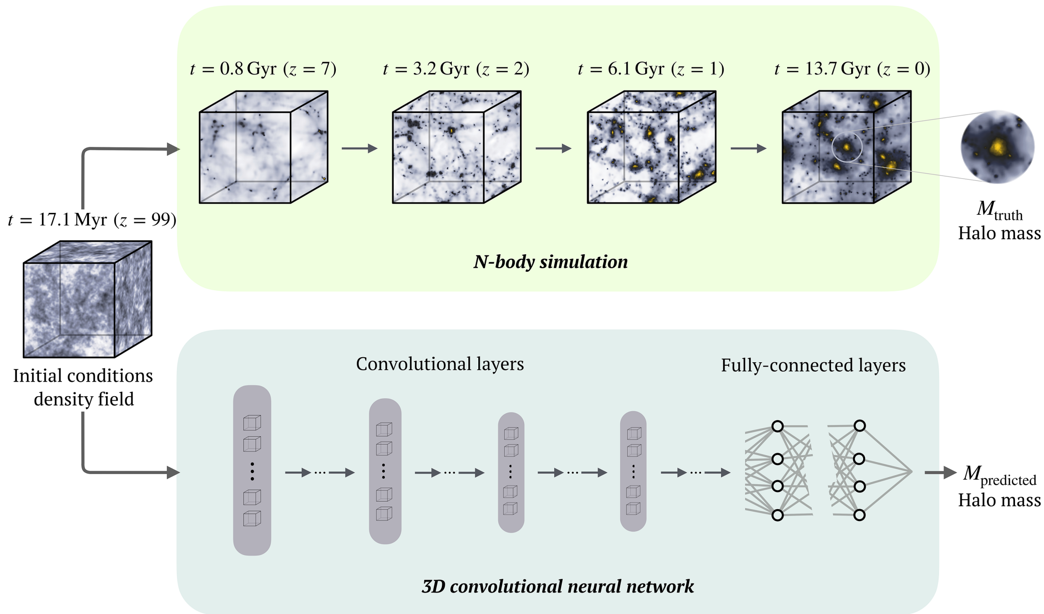


Figure 2.9: *N*-body simulations of cosmological structure formation can accurately compute the gravitational evolution of dark matter over cosmic time, but do not provide a straightforward physical understanding of how cosmic structures arise from the initial conditions. We train a CNN model to learn the relationship between the initial density field and the final dark matter halos, given examples from N-body simulations as training data. The aim is to interpret the mapping learnt by the CNN in order to gain physical insights into dark matter halo formation. *(Credit: MPA)*

resulting halos.

The crucial step now is to generate a physical interpretation of the mapping learnt by the machine learning tool: we remove part of the input information, re-train the model and measure the resulting change in the model's performance. This simple and effective technique reveals, which parts of the input influence the model's output.

We remove anisotropic information about the initial density field and re-train the CNN (Fig. 2.10). The two models, one trained on the raw density inputs and the other on the averaged-density inputs, return consistent predictions; the performance of the CNN does not degrade if we remove anisotropic information about the density. Therefore, the features learnt by the CNN are equivalent to spherical averages over the initial density field. This means that anisotropic properties of the initial density field carry no relevant information for establishing the final mass of dark matter halos.

This fact leads to a re-evaluation of our existing interpretations of gravitational collapse, based on analytic approximations of structure formation. For decades, the interpretation from analytic models has been that accounting for anisotropic properties of the early-Universe, such as external tidal shear effects, yields an improved halo collapse model compared to one

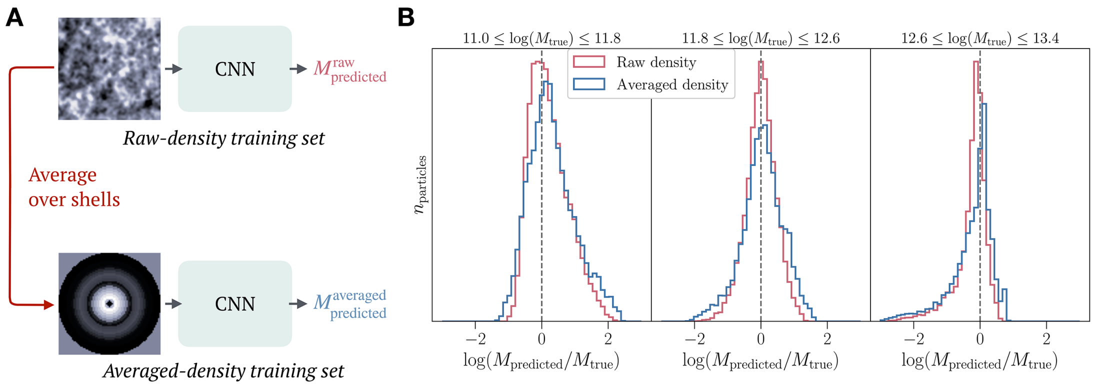


Figure 2.10: (A) We remove anisotropic information from the inputs and re-train the CNN. (B) The plots show the predictions of halo mass for different mass ranges for both the raw and the averaged inputs (red and blue, respectively). Both models return similar predictions, meaning that the CNN identifies features which are equivalent to spherical averages over the initial density field. *(Credit: MPA)*

based on isotropic properties alone. Instead, we show the contrary: anisotropic properties of the initial density field do not play a relevant role in establishing final halo masses. A crucial test of robustness of our framework was to demonstrate that the deep learning model can effectively extract spatially-local features on all scales and yield robust halo mass predictions that match expectations for a simpler test-case scenario.

Our work shows that interpretable deep learning frameworks can provide a powerful tool for extracting insights into cosmological structure formation. Developing toolkits for deep learning interpretability is of great interest also to the broader science community, as only by understanding how machine learning models reach their predictions can scientists trust AI tools in scientific applications. (Luisa Lucie-Smith)

2.5 Optimal measurements of the kinematic Sunyaev-Zel'dovich effect reveal missing matter

Where are the baryons? This question naturally arises as the predicted abundance of baryons in the universe – the basic building blocks of all elements in the periodic table – do not agree with observations of the intergalactic medium. Locating the missing baryons will help us to not only better understand the formation and evolution of galaxies, but also to better constrain possible extensions of the current standard model of cosmology. MPA researchers have turned to a novel approach in modelling the galaxy distribution to optimize measurements of the kinematic Sunyaev-Zel'dovich effect, an emerging tool to probe the distribution of baryons in galaxy clusters.

Before arriving at our satellites and telescopes, the cosmic microwave background (CMB) radiation, the most ancient light of our Universe, often passes through clusters of galaxies, the largest gravitationally bound structures ever observed. These massive objects

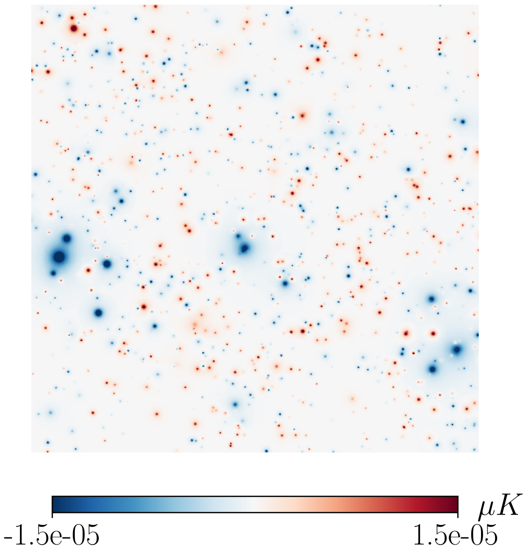


Figure 2.11: A synthetic map of the kSZ effect generated from simulations. Galaxy clusters that are moving away from (towards) us induce blue (red) spots on this secondary CMB temperature anisotropy map. *(Simulation Credit: Websky Simulations.)*

are so hot that their gas is completely ionized. As a first approximation, the CMB photons "feel" the structures through their Thomson scatterings with free electrons residing inside the clusters. These scatterings induce a secondary temperature anisotropy (Fig. 2.11) onto the observed CMB temperature anisotropy map. This effect was, in fact, first predicted by MPA director Rashid Sunyaev together with Yakov Zel'dovich, hence the name kinematic Sunyaev-Zel'dovich (kSZ) effect.

With the advent of CMB experiments that offer unprecedented sensitivities, e.g. Simons Observatory and CMB-S4, the kSZ effect is a raising candidate to hunt down the missing baryons. The key to a precise, unbiased inference of the baryonic abundance through the kSZ signal is information from the bulk flow of matter on very large scales, which is unfortunately not available from CMB data alone.

Until now, measurements of the kSZ effect have assumed a greatly simplified scheme of large-scale bulk-flows using information on the distribution of galaxies, as mapped by spectroscopic (redshift) surveys. Further, this approach often completely ignores uncertainties from reconstructing the velocity information from galaxy measurements when trying to infer the baryonic abundance and distribution.

Recently, researchers at MPA have made a significant step forward: introducing an original inference scheme in which all uncertainties in the reconstructed large-scale motion are accounted for. By doing so, they also unveil that this often-ignored source of systematics can significantly bias the inferred amount of baryons.

The crucial novelty is the use of an innovative framework leveraging modern computational power: Bayesian forward modelling of galaxy clustering. In essence, this approach models the entire three-dimensional matter and velocity fields, constrained by galaxy data. The result is not one, but many possible realizations of matter and velocity fields, all physically plausible given the observational galaxy data. This ensemble of velocity realizations allow MPA researchers to re-formulate the inference problem, accounting for all velocity uncertainties, which are induced by imperfect galaxy observations.

The MPA researchers and their European colleagues have rigorously tested and carefully applied this innovative method onto a CMB temperature map observed by the Planck satellite, a space observatory operated by the European Space Agency. In particular, they looked at locations where massive galaxy clusters have been identified by the Sloan Digital Sky Survey (SDSS) (Fig. 2.12). The secondary anisotropies expected from the kSZ signal is about 100 times smaller than the fluctuations in the original CMB data. Searching for the kSZ signal is thus pretty much like looking for a needle in a haystack.

Nevertheless, the team found evidence for the

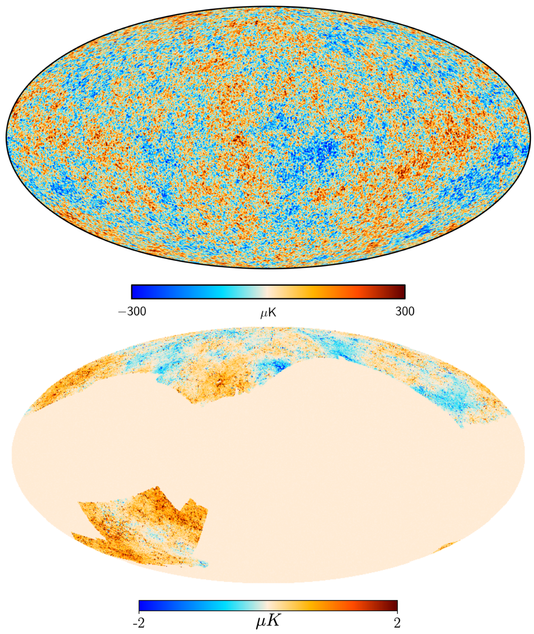


Figure 2.12: CMB temperature anisotropies, as mapped by ESA's Planck satellite. Bottom: Example prediction of the kSZ signal from the large-scale matter and velocity reconstruction using the Bayesian forward modelling approach. Since the reconstruction relies on some input galaxy data, the kSZ signal is only predicted for the sky regions where these galaxies were observed. Note the large difference between the typical amplitude of the observed CMB anisotropies and that of the kSZ signal (scale bars at the bottom of the images). *(Credit: ESA Planck Mission (top); MPA (bottom))*

kinematic Sunyaev-Zel'dovich effect and the missing baryons (Fig.2.13). A kSZ signal was observed at the expected amplitude, although it is not surprising that the evidence is not yet conclusive - only at roughly 2.3 sigma, or with 99 percent confidence level. This measurement has the most rigorous error bar up-to-date, taking into account uncertainties from the velocity reconstruction process.

The algorithm presented by MPA researchers is easily scalable and readily applicable to upcoming datasets. The future goal is clear: to unlock the full potential of kinetic and thermal SZ measurements in probing not only missing baryons but also the nature of inflation and Dark Energy – two long-standing puzzles about the early and late time universe. (Nhat-Minh Nguyen)

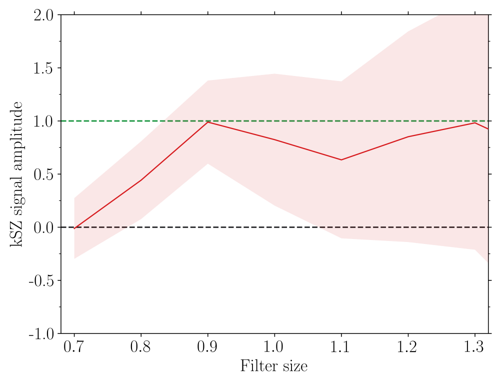


Figure 2.13: The amplitude of the kSZ effect and its 1-sigma uncertainty, shown in red, as a function of filter size, which is measured in units of the apparent size of the clusters. An amplitude of zero (grey dashed line) implies no evidence of the kSZ effect; an amplitude of one (green dashed line) suggests that the baryonic abundance follows the cosmic abundance predicted by the standard cosmological model. *(Credit: MPA)*

2.6 The formation of intermediate mass black holes in young massive star clusters

Intermediate mass black holes (IMBH) should be linking observed stellar black holes and supermassive black holes, but their formation mechanisms are still debated. Young and dense massive star clusters are promising environments for the formation of such black holes through collisions. An international team led by MPA researchers has presented novel realistic simulations of star clusters, where these missing links form by rapid collisions of stars and black holes. The study also predicts an IMBH formation channel by the merging of black holes in a mass regime, which is excluded by stellar evolution models. In this “mass gap” a black hole merger has indeed been observed recently by the LIGO/Virgo gravitational wave collaboration.

Convincing theoretical and observational evidence points to the existence of stellar black holes with masses below about 60 solar masses. These are the end products of massive stars, evolving over several million years. On cosmic scales this is a short life. There is also direct evidence for the existence of supermassive black holes with a million solar masses and more. The most famous one lurks in the center of our Milky Way, whose discovery was honored with the Physics Nobel Prize in 2020. Until recently, however, there was no direct evidence for the existence of intermediate mass black holes (IMBHs) with masses in between those two ranges and several speculations about their formation mechanisms were presented.

Theoretically, young, massive, and dense star clusters are promising environments for the formation of IMBHs. These clusters are gravitationally bound groups of young stars and their early black hole remnants. In the early phase of star cluster evolution, their central stellar densities can reach a million times the average stellar density in our galactic neighborhood. Therefore, direct collisions of massive stars and black holes and even mergers of black holes, which are driven by the emission of gravitational waves, are relatively common. Such collisions can result in the formation of IMBHs.

An international team led by MPA researchers has performed a series of realistic simulations of the early evolutionary phase of compact massive stars clusters to investigate the formation of IMBHs. The high-accuracy simulations have been performed with the GPU accelerated simulation software N-body6++GPU at the Max-Planck-Computing and Data Facility in Garching and the JUWELS system at the Jülich Supercomputing Center. The simulations follow the stellar evolution and motion of each star in the clusters, including accurate orbits of single, binary and multiple systems as well as stellar collisions and mergers of black holes. The study demonstrates that IMBHs can form when a very massive star with up to 400 solar masses – formed by the rapid collision of several main sequence stars – is swallowed in a merger with a stellar mass black hole (Fig. 2.15).

In one of the 80 simulations with 110.000 stars each, a IMBH with 138 solar masses followed a special formation path. It formed in four generations of collisions with several stellar black holes. In the final merger two black holes with 68 and 70 solar masses form a IMBH with over 100 solar masses (Fig. 2.16). Black holes in this mass regime are not predicted by normal stellar evolution models (so called “mass-gap”) and therefore must have formed by other processes such as the collisions in this study.

Less than two weeks after the submission of this theoretical study the LIGO/Virgo gravitational wave collaboration reported the discovery of the merger of two black holes (GW190521) in this “mass-gap” with masses of 66 and 85 solar masses. This was the first direct detection of an IMBH with a mass of 142 solar masses formed in a black hole merger and the theoretical study indeed had predicted a possible formation path for such a gravitational wave event. (Thorsten Naab)

2.7 Magnetogenesis around the first galaxies and its impact on galaxy formation

Magnetic fields are ubiquitous in the Universe today, from stars to clusters of galaxies. Their origin, however, remains a mystery. MPA researchers have now simulated in great detail a variety of proposed mechanisms for magneto-

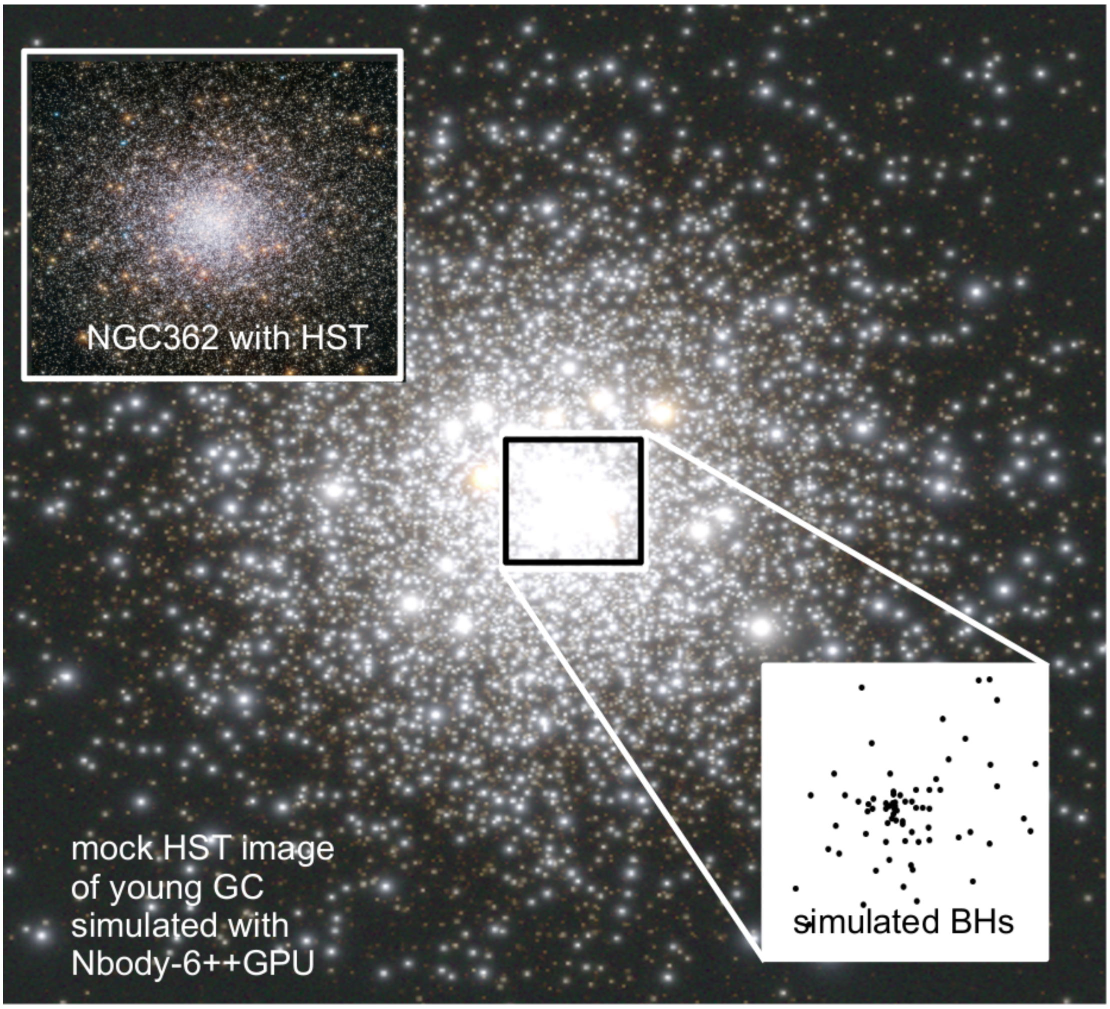


Figure 2.14: Mock HST observation of a simulated young and compact star cluster (large image), which contains a subsystem of stellar mass black holes in its core region (inset on the lower right). This region is dense enough for collisions and mergers between stars and black holes. Such systems could be the progenitors of globular cluster systems like the star cluster NGC 362 shown in the upper left corner. *(Credit: MPA)*

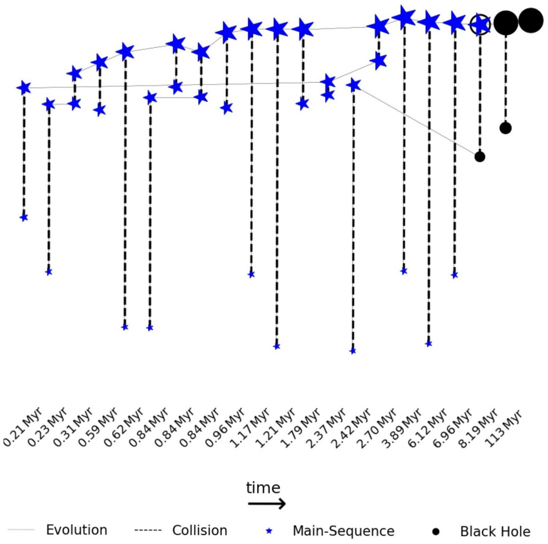


Figure 2.15: Example for the formation of an IMBH in one of the simulations. In the first 8.19 million years (from left to right) after the beginning of the simulation many main sequence stars merge into a very massive star with 315 solar masses which is swallowed by a stellar mass black hole of 12 solar masses forming an IMBH. About 100 million years later, the IMBH merges with another stellar mass black hole of 22 solar masses. *(Credit: MPA)*

genesis – i.e. how magnetic fields might be created – in high-redshift galaxies. They also studied their impact on the formation and evolution of galaxies, providing guidance to both future observations and simulations. Their work demonstrates that high-redshift galaxies may hold the key to understanding the origin of cosmic magnetic fields. It also provides the first-ever investigation on galactic scales of a novel magnetogenesis mechanism.

Magnetic fields have been detected in most cosmic structures in the nearby Universe, from individual stars to entire galaxies and galaxy clusters. These fields are often strong enough to play an important role in the evolution of the material in these structures. At the same time, the Cosmic Microwave Background radiation shows that magnetic fields at the origin of the Universe – if they existed at all – must have been extremely weak.

There are many physical mechanisms that can produce tiny magnetic fields during the evolution of galaxies. The chaotic motion of gas inside galaxies can then amplify these seed fields to the strength observed today. What is the most important source of seed fields for the evolution of the Universe? And are different mechanisms for magnetogenesis affecting the evolution of galaxies in the same way? Can we use galaxies to learn something about the origin of cosmic magnetic fields?

These questions prompted a small team of MPA researchers to perform a series of advanced numerical simulations using different recipes for the generation of initial seed magnetic fields: residual fields left over from the Big Bang, fields produced by supernovae, or different plasma physics processes (including a new type of magnetic battery never studied before on these scales). These simulations are of two kinds. The first type follows the evolution of a representative part of the Universe (2.17), allowing researchers to study the creation and evolution of magnetic fields in and around a large number of cosmic structures. The second type of simulation focuses on a single forming galaxy (2.18), reaching a high level of accuracy and enabling the researchers to study the details of the physical processes inside the zoomed-in galaxy. (Enrico Garaldi, Rüdiger Pakmor, Volker Springel)

2.8 Dust cloud determines distance

Some of the most energetic radiation that reaches Earth comes from an exploded star in our Galaxy. An international team of researchers was now able to measure the distance to this object using an adjacent dust cloud with much higher degree of precision than ever before. This is the first step in better understanding the energetic processes that are going on in

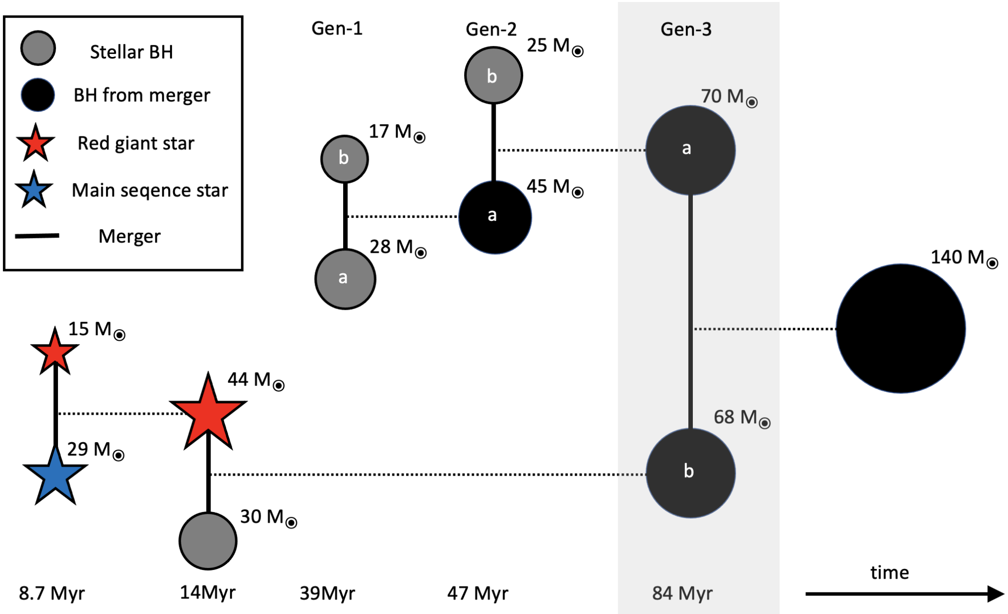


Figure 2.16: Simulated formation path of a mass gap black hole merger of two black holes with 70 and 68 solar masses. The more massive BH (top) grows by two preceding BH mergers. The lower mass BH (bottom) builds up in a stellar collision of a red giant with a main sequence star followed by the merger with a stellar mass BH. The masses of the components (in solar masses) are indicated at the respective times of the merger (black horizontal lines) after the start of the simulation. *(Credit: MPA)*

this supernova remnant.

Normally, what you see in the sky are bright objects, and these are also easy to spot with telescopes. However, sometimes astronomers take a different view and look at objects that are detectable through their shadow. An international team of researchers from Australia, Germany, Italy, Japan, and the USA have now focused on dust in the remains of an exploded star (also called a supernova remnant, SNR in short). This object, with the name RX J1713.7-3946, is one of the brightest emitters of very high-energy radiation and the origin of this has been debated since its discovery.

Rather than investigating the high-energy radiation directly, the scientists investigated the shadows cast by intergalactic dust clouds on stars in the background (2.19). They reconstructed the dust extinction in the region of the SNR using a Gaussian process and more than 260000 stars. While the resulting map indicates the presence of several clouds along the line of sight, only one of the clouds appears to be in the vicinity of the exploded star.

By using distance estimates to the individual stars in the direction of RX J1713.7-3946 provided by the European Space Agency Gaia space mission, the researchers were able to constrain the distance to the dust cloud, and therefore to the supernova remnant, to a 1% accuracy, about 20 times more precisely than previous estimates.

This is an important milestone, as it helps to understand the energetic processes taking place at and around the supernova remnant. Precise distances are among the most challenging measurements in astronomy. Without their knowledge, it is impossible to be sure whether an object is intrinsically brighter and further away, or intrinsically fainter but closer.

A precise distance determination is crucial for this supernova remnant, as it is at the ori-

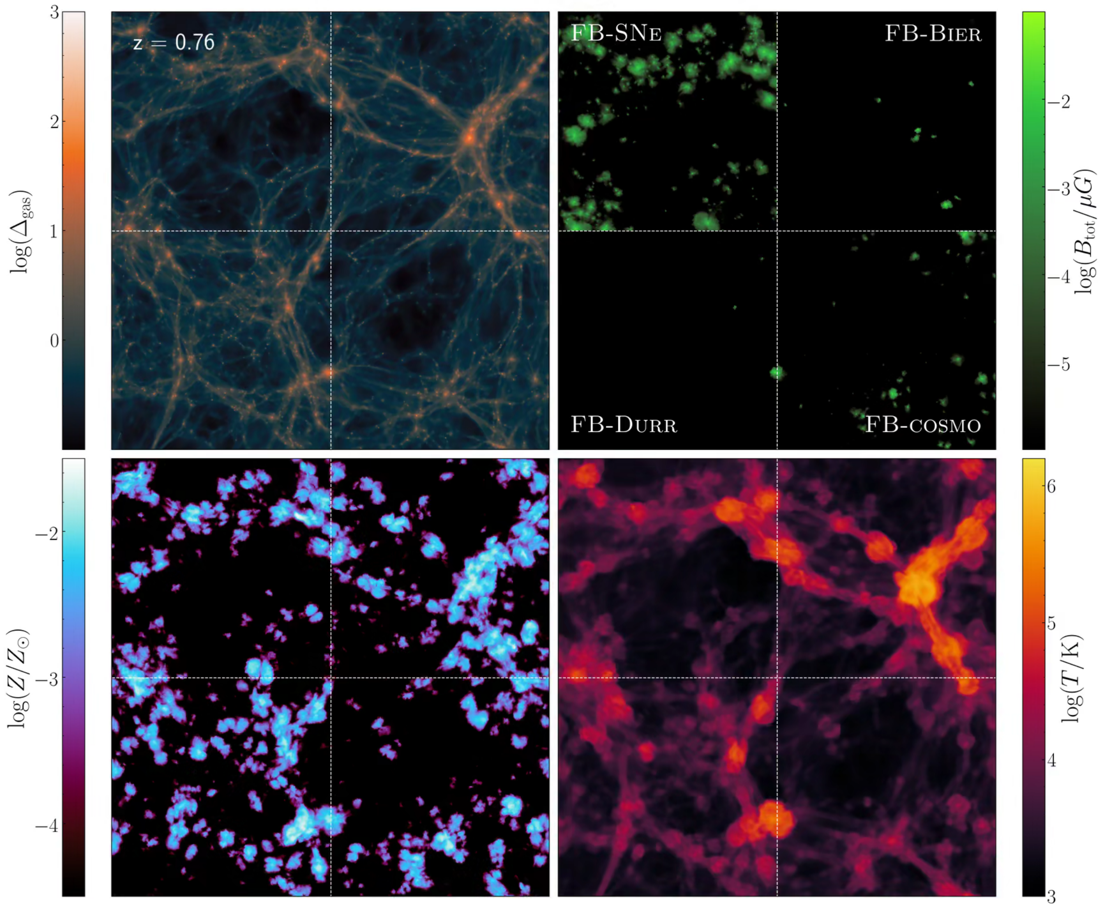


Figure 2.17: Gas overdensity (in arbitrary units, top left), magnetic field strength (top right), metallicity (bottom left) and temperature (bottom right) maps in a slice through the simulation box. Each quadrant of each panel shows results for a different magnetic seed model, as indicated in the top right panel. *Credit: MPA)*

gin of some of the highest energy photons that we see on Earth. Yet, the mechanism by which these photons (or gamma-rays) are generated is still not fully understood. One possible explanation for the high-energy radiation are proton-proton collisions, but previous estimates of the gas content fell short. With an estimated mass of about 7000 times the mass of the Sun, the dust cloud could be big enough to contain the missing protons, but further studies are needed to confirm this. (Reimar Leike)

2.9 The cool circumgalactic medium in SDSS galaxies

The gas in and around galaxies can be probed with absorption line studies using light from background quasars. Scientists at MPA have now used a large sample from the SDSS DR16 to automatically detect absorbers in background quasars and connect them with foreground galaxies. Their analysis shows that cool circumgalactic gas has a different physical origin for star-forming versus quiescent galaxies.

The unseen dark matter halos that surround

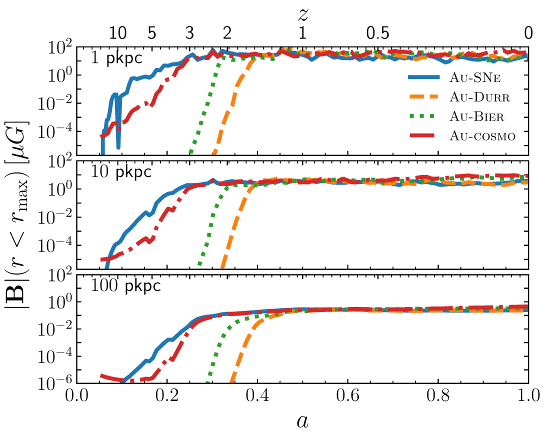


Figure 2.18: Evolution of the mean magnetic field strength inside a certain radius (top: 1 kpc, middle: 10 kpc, bottom: 100 kpc) of a simulated galaxy. Each line shows the results for a different magnetic seed model. Today (right hand side of the plot) the strength is the same for all models, but this value is reached at different times by each model. *(Credit: MPA)*

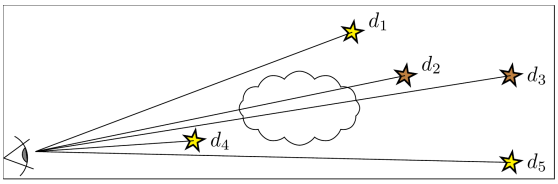


Figure 2.19: This schematic shows how the scientists measured the distance to the supernova remnant. The light of different background stars gets attenuated through the dust cloud, which helps to determine the clouds position. In this figure, one can infer that the dust cloud is between d2 and d4. *(Credit: MPA)*

all galaxies make up most of the mass of galaxies. Only a very small fraction ($<\sim 10\%$) is made of ordinary matter (or baryonic matter) and this can be probed with absorption lines. What is even more exciting: the metals that we see in the spectra of background objects can trace gas flows in action, i.e. gas flowing in and out due to various processes. These gas flows play a pivotal role in the formation and evolution of galaxies, implying that our understanding of galaxy formation is limited by our current understanding of this gas (also called the circumgalactic medium or CGM).

Large sky surveys performed with ground and space-based telescopes such as the Sloan Digital Sky Survey (SDSS), Keck, the Very Large Telescope (VLT), or the Hubble Space Telescope (HST), have significantly deepened our understanding of the CGM over the past two decades. One of the most powerful tools have been so-called transverse absorption line studies, where the CGM is observed in absorption against a bright background source such as a quasar. Different metal absorbers detected at redshifts smaller than the redshift of the background source, i.e. between the source and us, provide direct observational constraints on the gas flows around galaxies at different epochs.

Figure 2.21 shows a schematic diagram describing the quasar absorption lines, where metal species in different ionization states trace different phases of the CGM. For example, ionized Magnesium (Mg II) traces the cool CGM ($\sim$ 10,000 K) and ionized carbon (C IV) traces the warm phase ($\sim$ 100,000 K). However, detecting absorption features in millions of spectra and associating them to galaxies is quite challenging and laborious, and a large ensemble of absorber systems is required to perform any meaningful statistical study.

To study these gas flows, we connect Mg II absorbers in background quasars with foreground galaxies. We use our automated absorber detection pipeline (described below) to identify the Mg II absorbers in about 1 million quasars from the latest SDSS data release (SDSS DR16) and connect them to about 1.3 million galaxies, also from SDSS DR16. These large samples provide us with an unprecedented opportunity to investigate the nature of cold gas absorption for star-forming and passive galaxies.

With a very robust statistical analysis, we could characterize the scale dependence of Mg II with greater accuracy than in previous work.

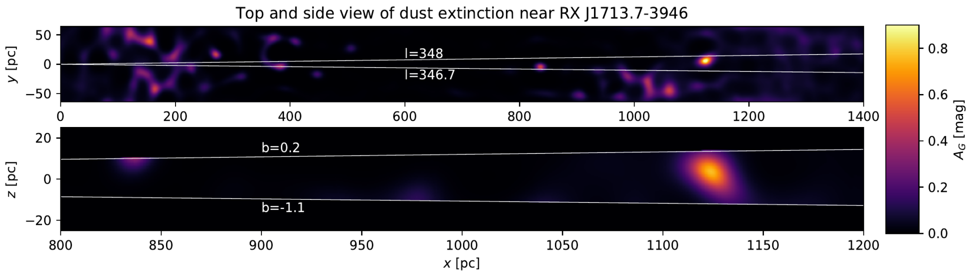


Figure 2.20: The dust clouds found in this study are depicted here as a virtual observer would see them from above the galaxy (top panel) and east of the remnant (bottom panel). The white lines indicate where the supernova remnant is known to be located. The only dust cloud that overlaps with its position is found to be at 1120pc (or 3750 light-years away). *(Credit: MPA)*

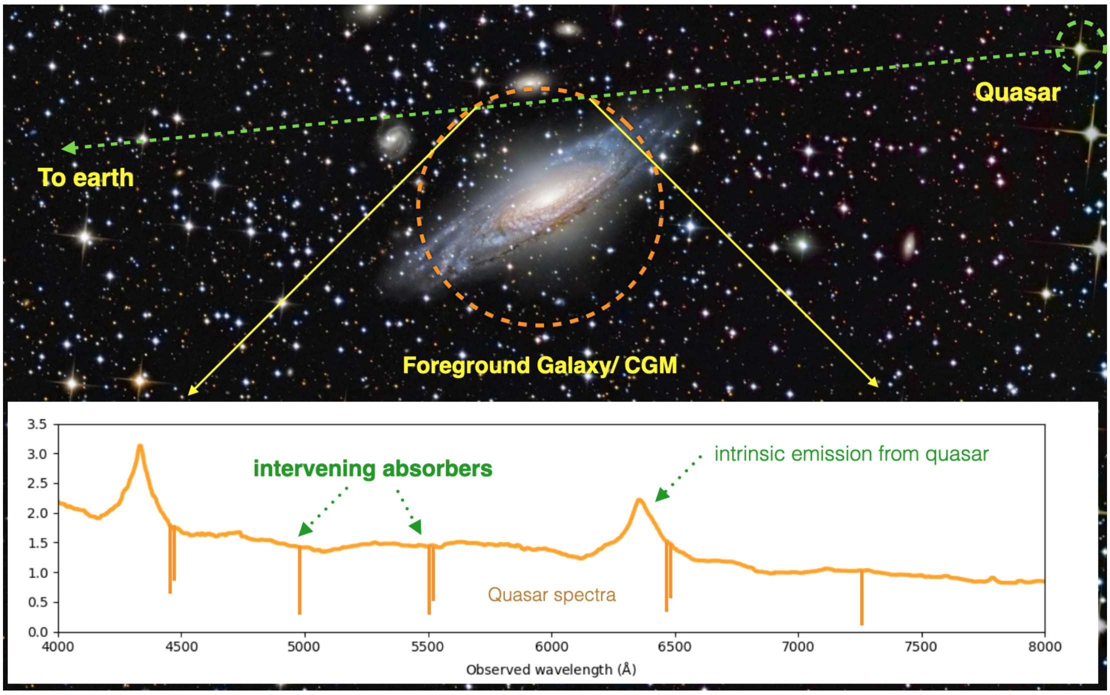


Figure 2.21: Basic setup of an absorber-galaxy cross-correlation study, where the CGM is observed in absorption against a bright background quasar *(Credit: MPA)*

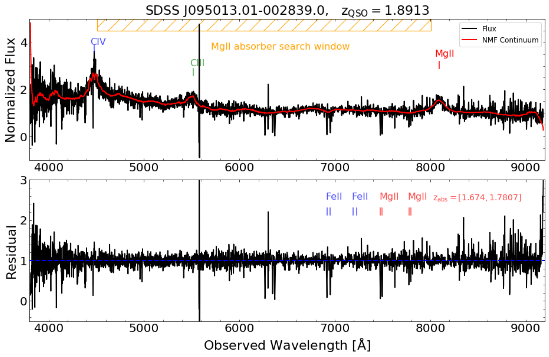


Figure 2.22: Example quasar spectrum, where the Mg II absorbers are detected with our automated pipeline. The two panels show the normalized continuum-fitted quasar flux (top) and residual (bottom) along with two intervening Mg II absorbers (shown in red). *(Credit: MPA)*

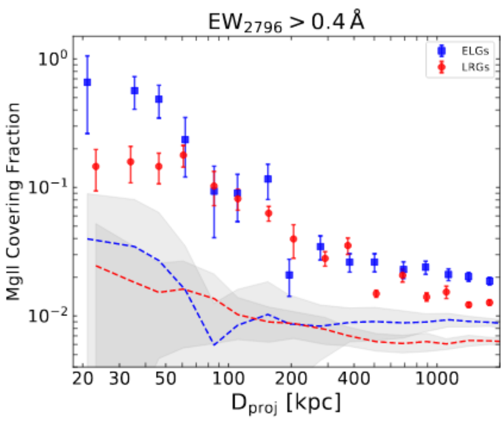


Figure 2.23: The Mg II covering fraction around star-forming (blue) and passive galaxies (red) along with covering fractions expected around the random samples (dashed lines). The star-forming galaxies have a pronounced excess relative to the passive galaxies within about 50 kpc. *(Credit: MPA)*

We find a strong enhancement of Mg II absorption in the central $\sim$ 50 kpc of star-forming galaxies relative to luminous but passive galaxies (Fig. 2.23). Beyond 50 kpc, there is a sharp decline in Mg II for both kinds of galaxies, indicating a transition to the regime where the CGM is tightly linked with the dark matter halo.

Moreover, Mg II correlates strongly with the star formation rate for star-forming galaxies, indicating that stellar activity plays an important role in enriching the metal contents in the CGM. On scales of a few hundred kpc, we find that the average total Mg II equivalent width per absorber dips below the characteristic field value, both for passive and star-forming galaxies. This dip is possibly related to gas inflow processes onto dark matter halos. In summary, our analysis implies that cool circumgalactic gas has a different physical origin for star-forming versus quiescent galaxies.

In our work, we also develop an automated pipeline to estimate the optical continuum of quasars and to detect intervening metal absorber systems in their spectra. Our pipeline is based on a matched kernel convolution technique and adaptive S/N criteria. We run this pipeline on $\sim$ 1 million quasars from SDSS DR16 and have compiled the largest metal absorber catalog to date, consisting of $\sim$ 160,000 Mg II absorbers and $\sim$ 70,000 Fe II systems.

Our automated pipeline is quite general in detecting doublet features in quasar spectra. It is optimized and supports parallelization to run efficiently on millions of quasar spectra. In the future, large imaging surveys such as the Large Synoptic Survey Telescope (2.24) at the Rubin Observatory will provide enormous datasets of galaxies, up to higher redshifts, and with high-quality imaging. Together with upcoming large spectroscopic galaxy surveys such as PFS on the Subaru telescope, statistical analyses of the circumgalactic medium will be a powerful tool to understand the formation and evolution of galaxies across cosmic time. (Abhijeet Anand)

2.10 The SRG X-ray observatory receives the Marcel Grossmann Institutional Award 2021

The Spektrum-Roentgen-Gamma (SRG) orbital X-ray observatory receives the Award “for the

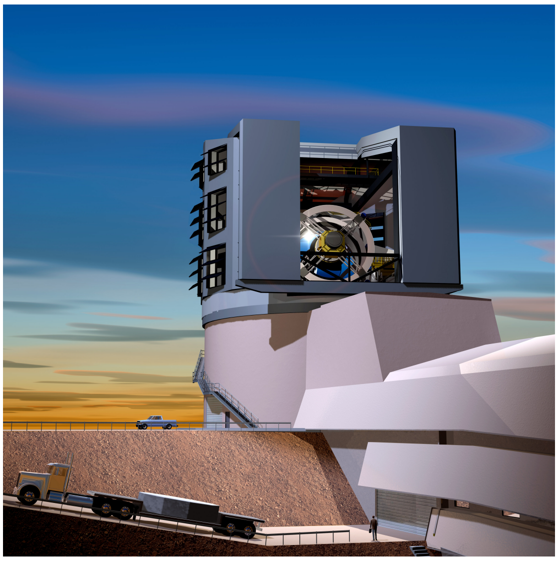


Figure 2.24: Artist rendition of the Vera Rubin Observatory on the Cerro Pachn ridge in north-central Chile, showing the primary mirror of the telescope. This facility is under development and will open up the study of circumgalactic gas tremendously. *(Credit: Todd Mason, Mason Productions Inc. / LSST Corporation)*

creation of the world's best X-ray map of the entire sky, for the discovery of millions of previously unknown accreting supermassive black holes at cosmological redshifts, for the detection of X-rays from tens of thousands of galaxy clusters, filled mainly with dark matter, and for permitting the detailed investigation of the growth of the large- scale structure of the universe during the era of dark energy dominance".

Several MPA scientists are members of the Russian SRG/eROSITA consortium and played a key role in the mission implementation and in obtaining the all-sky map and producing the eROSITA catalog of X-ray sources. By the decision of the Marcel Grossmann Award Committee the Institutional Award goes to S.A. Lavochkin Association, presented to its Designer General Alexander Shirshakov, the Max Planck Institute for Extraterrestrial Physics, presented to Professor Peter Predehl, Principal Investigator of eROSITA until 2020, and the Space Research Institute (IKI) of the Russian Academy of Sciences, presented to Professor Rashid Sunyaev, Principal Investigator of SRG Observatory in Russia.

The S.A. Lavochkin Association created the Navigator space platform carrying the German eROSITA and the Russian ART-XC X-ray telescopes with grazing incidence optics and organized the launch of SRG orbital X-ray observatory to the second Lagrangian point of the Sun-Earth system at a distance of 1.5 million km from the Earth. It now manages the flight of the observatory, sends commands to the spacecraft and telescopes and performs the daily reception of its scientific data on Earth.

The very successful eROSITA soft X-ray telescope on-board the SRG mission was built by a consortium of German institutes led by the Max Planck Institute for Extraterrestrial Physics and supported by DLR. Thirty years after ROSAT, SRG/eROSITA performs an all-sky survey in X-rays with an unprecedented sensitivity, spectral and angular resolution.

The Space Research Institute (IKI) of the Russian Academy of Sciences was responsible for developing the overall concept and scientific program of the SRG orbital observatory and played a leading role in developing the Mikhail Pavlinsky ART-XC telescope and the entire SRG observatory. Rashid Sunyaev, director-emeritus of the Max Planck Institute for Astrophysics and Maureen and John Hendricks distinguished visiting professor of the Institute for Advanced Study, Princeton, is the Principal Investigator of SRG mission in Russia.

The SRG observatory, launched with a Proton-M rocket from Baikonur two years ago on July 13, 2019, started the all-sky survey on December 12, 2019. By the summer of 2021, it scanned the entire sky three times and it is now conducting the 4th survey. In the course of three sky scans, the eROSITA telescope aboard SRG discovered over two million X-ray sources: mainly quasars, stars with hot

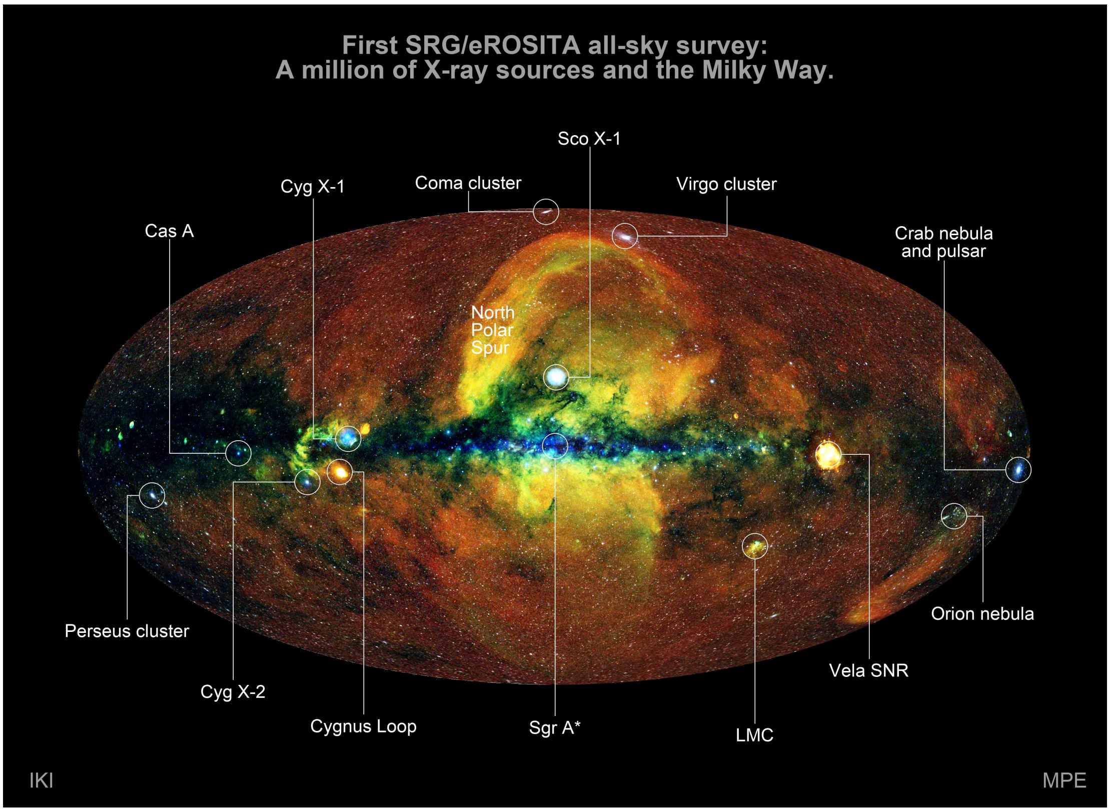


Figure 2.25: The X-ray RGB map of the sky obtained by the SRG/eROSITA telescope. *(Credit: IKI, MPE, MPA, Sunyaev, Churazov, Gilfanov, Merloni, Brunner, Sanders)*

and bright coronae, and more than 30 thousand clusters of galaxies.

In the search for clusters of galaxies, there is a competition and synergy with the ground-based Atacama Cosmology and South Pole Telescopes, which are searching for clusters of galaxies in the microwave spectral band using the Sunyaev-Zeldovich effect. SRG provided the X-ray map of the entire sky in hard and soft bands, the latter now being the best existing one. The huge samples of X-ray selected quasars at redshifts up to z=6.2 and clusters of galaxies will be used for cosmological tests and detailed studies of the growth of supermassive black holes and the large scale structure of the Universe during and after reionization.

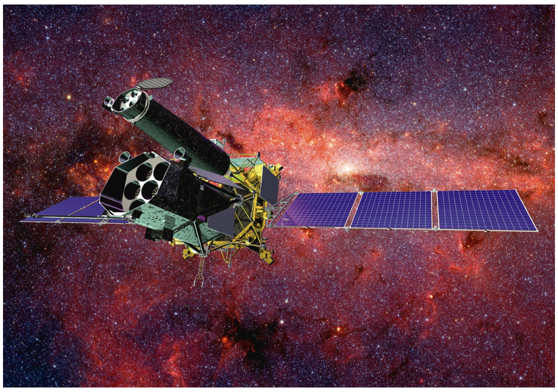


Figure 2.26: An artists view of the SRG orbital X-ray observatory. *(Credit: S.A.Lavochkin Association)*

Every day, SRG is scanning about 1% of the sky and the eROSITA telescope is discovering about half a dozen extragalactic objects, which changed their luminosity by more than an order of magnitude compared to the previous scan half a year ago. Among these highly variable objects are tidal disruption events, connected to the disruption of a star by the enormous tidal forces near a supermassive black hole in the nucleus of the host galaxy. The Mikhail Pavlinsky ART-XC telescope is discovering many bright Galactic and extragalactic transients and absorbed AGN.

The SRG Observatory will continue scanning the sky for another two and a half years and then will start pointed observations of individual targets and deep scans of extended sky regions that are especially interesting for the scientific teams. (MPA team: Rashid Sunyaev, Eugene Churazov, Marat Gilfanov)

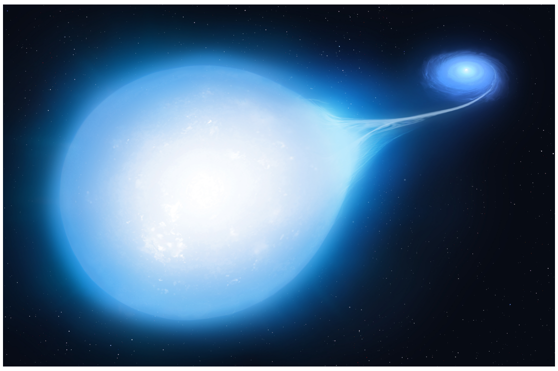


Figure 2.27: Artists impression of the HD265435 system at around 30 million years from now, with the smaller white dwarf distorting the hot subdwarf into a distinct teardrop shape *(Credit: University of Warwick/Mark Garlick)*

2.11 Teardrop shape reveals supernova fate

Astronomers have made the rare sighting of two stars spiralling to their doom by spotting the tell-tale signs of a teardrop-shaped star. The tragic shape is caused by a massive nearby white dwarf distorting the star with its intense gravity, which will also be the catalyst for an eventual supernova that will consume both. Found by an international team of astronomers and astrophysicists led by the University of Warwick, it is one of only a very small number of star systems that have been discovered and that will one day see a white dwarf star reignite its core. Astrophycists at MPA confirmed the ultimate fate of the star with theoretical modelling.

The system called HD265435 is located roughly 1,500 light years away and comprises a hot subdwarf star and a white dwarf star orbiting each other closely at a rate of around 100 minutes. White dwarfs are dead stars that have burnt out all their fuel and collapsed in on themselves, making them small but extremely dense.

A type Ia supernova is generally thought to occur when a white dwarf stars core reignites, leading to a thermonuclear explosion. There are two scenarios where this can happen. In the first, the white dwarf gains enough mass to reach 1.4 times the mass of our Sun, known as the Chandrasekhar limit. HD265435 fits in the second scenario, in which the total mass of a close stellar system of multiple stars is near or above this limit. Only a handful of other star systems have been discovered that will reach this threshold and result in a Type Ia supernova.

Using data from NASA‘s Transiting Exoplanet Survey Satellite (TESS), the team was able to observe the hot subdwarf, which is much brighter than the white dwarf, which was not directly observed. However, that brightness varies over time, which suggested the star was being distorted into a teardrop shape by a nearby massive object. Using radial velocity and rotational velocity measurements from the Palomar Observatory and the W. M. Keck Observatory, and by modelling the massive objects effect on the hot subdwarf, the astronomers could confirm that the hidden white dwarf is as heavy as our Sun, but just slightly smaller than the Earth’s radius.

Theoretical models produced by researchers based at MPA reveal that the subdwarf star is currently about halfway through its expected lifetime, at the end of which it will collapse to

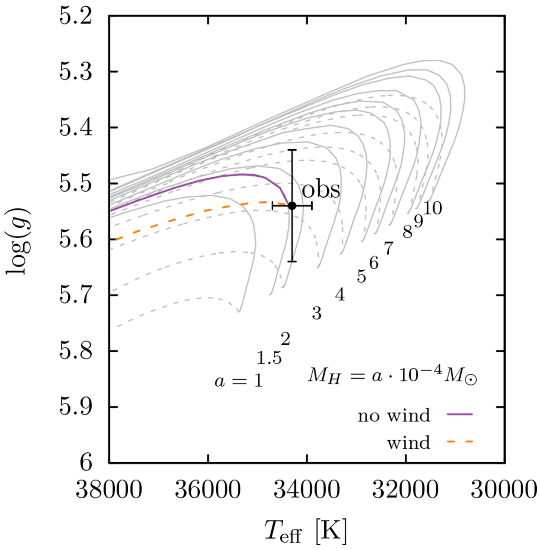


Figure 2.28: Predicted evolutionary tracks for hot subdwarfs with a mass of $0.63 M_\odot$ and different masses of the hydrogen envelope. The purple line represents the favoured model (no wind) starting from the beginning of the binary run. The model including a weak wind is represented by the dashed orange line. The observed position of the hot subdwarf in the diagram is as indicated, with error bars representing the systematic uncertainty of the obtained spectral parameters. *(Credit: MPA)*

become a white dwarf as well. In around 70 million years, this will lead to a supernova when it finally merges with the other white dwarf, as both stars combined have the mass needed to cause a Type Ia supernova. (The total mass of the system is found to be $1.65 \pm 0.25 M_\odot$.) On the way to becoming a white dwarf itself, mass transfer from the subdwarf star will lead to a series of nova outbursts – less energetic cousins of the cataclysmic supernovae – as a precursor to the eventual explosive fate of the binary star.

Type Ia supernovae are important for cosmology as standard candles. Their brightness is constant and of a specific type of light, which means astronomers can compare what luminosity they should be with what we observe on Earth, and from that work out how distant they are with a good degree of accuracy. By observing supernovae in distant galaxies, astronomers combine what they know of how fast this galaxy is moving with our distance from the supernova and calculate the expansion of the universe. As the theoretical predictions show, this system impressively demonstrates that binary systems of a white dwarf with a subdwarf have to be taken into account in the hunt for the still elusive progenitor of Type Ia supernovae. (Patrick Neunteufel)

2.12 Probing the interface between infall and outflows in a high-redshift massive halo

Cosmological simulations show that the growth of galaxies in the early Universe is regulated by the interplay between gas accretion onto dark-matter halos and ejection of matter by stars and active galactic nuclei (AGN). While these processes are routinely described in theoretical works, still little is known from observations on the complex exchanges of mass and energy within the halos of galaxies, where large-scale infall (i.e. accretion) meets outflows (i.e. ejection). Recently, an international team of astronomers was able to probe the halo gas of a massive galaxy system, SMM J02399-0136, using a novel approach. These observations unveiled for the first time the infall towards the galaxies of a large mass of diffuse, highly turbulent multiphase gas, pervaded by powerful outflows and more than 10 times larger than the star-forming galaxies.

Most of the material in the early Universe lies outside galaxies, and is organized in a net of filaments, sheets and knots, where galaxies form and evolve in their dark-matter halos. The material gravitationally bound to each galaxy halo, also known as circumgalactic medium (CGM), encodes key information on the processes (like

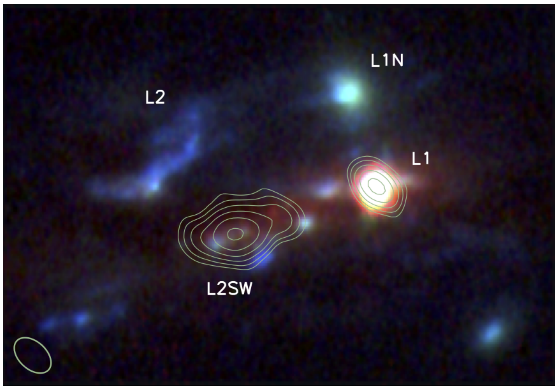


Figure 2.29: False-colour image of the galaxy group SMM J02399-0136, which is known to host a dust-obscured highly star-forming galaxy (L2SW), a bright AGN or quasar (L1), and additional faint emissions (L2 and L1N). Contours indicate the 360micron continuum emission (dust) observed with the ALMA interferometer. The horizontal size of this image corresponds to about 55,000 light years at the epoch of SMM J02399-0136. The field is gravitationally lensed which stretches the image roughly along the L2SW-L1 direction. *(Credit: MNRAS 2021)*

gas infall and outflows) that regulate galaxy evolution. While the importance of unravelling the CGM physics has been clear to astronomers for decades, only recent technical developments in instrumentation at optical and submillimeter wavelengths allow them to directly probe such gas in emission, and in absorption against bright background sources.

In this framework, galaxy systems hosted by the most massive halos in the early Universe, with masses greater than a trillion times the Sun's mass, are the ideal targets for pilot studies of the CGM. These massive halos are observed to host prodigious bursts of star formation and episodes of strong AGN activity, which are predicted to drive powerful outflows that eject matter at high velocities in the CGM. Therefore, these outflows should be able to redistribute material from galaxies to larger scales, and mix it with the infalling material from intergalactic scales.

As the infall and outflow velocities are extremely large, their interface is highly turbulent. To study this, an international team of astronomers envisioned a new set of observations of the galaxy group SMM J02399-0136 (Fig. 2.29). This galaxy group is located in the early Universe, at about 2.3 billion years from the Big Bang, and should sit in a dark-matter halo as massive as ten trillion times the Sun's mass.

As a first step, the astronomers targeted the hydrogen Lyman-alpha (Lyα) emission around the galaxy group to trace the gas reservoir at a temperature of about ten thousand degrees. The observations conducted with the "panoramic" integral field spectrograph Keck Cosmic Web Imager on the Keck telescope unveiled extended, bright (Lyα) emission, with high veloc-

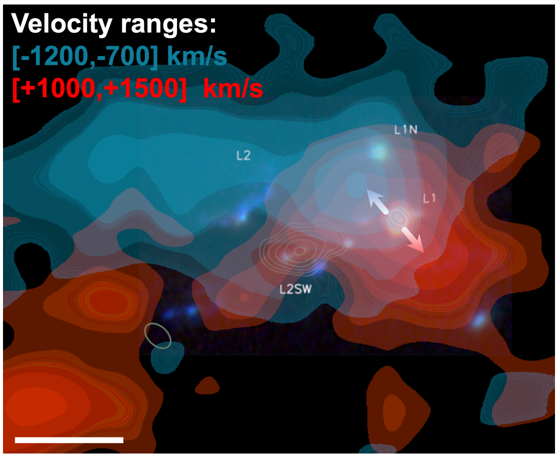


Figure 2.30: The high velocity outflowing gas (red, blue) located in the vicinity of the quasar L1 and the starburst galaxy L2SW as traced by the hydrogen Ly emission in the SMM J02399-0136 galaxy group. The arrows indicate the projected direction of the outflows in the vicinity of the quasar, with the red portion moving away from us and the blue portion approaching us. The velocity ranges used for the figure are shown on the top-left corner, using the quasar L1 as reference. The white scale in the bottom-left corner indicates about 32,000 light years at the epoch of SMM J02399-0136. *(Credit: MPA/LPENS)*

ity outflows located in the vicinity of the quasar L1 and the starburst galaxy L2SW (Fig. 2.30), and a turbulent nebula, which is about twice the size than the region shown in Figure 2.29.

The next step was targeting the galaxy group with the ALMA interferometer to detect the J=1-0 transition of a light hydride (the methylidyne cation CH^+), which requires very dense molecular gas to be excited. CH+ is a very fragile molecule: it needs molecular hydrogen H2 to form, but in low fractions to avoid rapid destruction in collisions with this partner. Moreover, its formation is highly endothermic, requiring a large amount of supra-thermal energy of $\sim$ 0.5 eV. This is why CH^+ is a specific tracer of regions where the kinetic energy of molecular gas is dissipated, e.g. of turbulence or shocks. This fragile molecule can be observed only where it forms, because its lifetime is extremely short (about 1 year).

Remarkably, CH^+ has been detected in both absorption and emission in the SMM J02399-0136 galaxy group. The absorption, occurring in low-density gas in front of the luminous dust continuum of the quasar L1 and the starburst galaxy L2SW, traces a massive turbulent reservoir of cool molecular gas whose extent is comparable to the large Lyα nebula. The CGM of this massive system is therefore multiphase. Importantly, the CH^+ absorption is found at positive velocities with respect to the central galaxies (Fig. 2.31.), similar to those of the large Lyα nebula. As positive velocity means motion away from the observer, the whole multiphase CGM is therefore infalling onto the galaxy group.

CH^+ emission is tentatively detected in structures roughly following the shape of the high-velocity Ly emission (Fig. 2.31). These CH^+ emission lines are extremely broad and trace myriad molecular shocks at the interface of the infalling CGM and the high-velocity outflows.

Thanks to these observations, the astronomers are also able to study the redistribution of energy throughout the CGM. The powerful outflows, driven by bursts of star-formation and AGN activity, inject a considerable amount of kinetic energy into the CGM, sufficient to sustain its turbulence. The substantial mass accretion rate that almost balances the consumption rate of the gas mass due to the ongoing high star formation provides a comparable energy source to the CGM turbulence because accreting matter loses gravitational energy along its infall onto the galaxy group.

Overall, these observations show a promising avenue for the direct study of the interface between infall and outflows in the CGM of massive systems. Future deep targeted observations will be able to unveil the physical properties and energy trails of the turbulent, multiphase large-

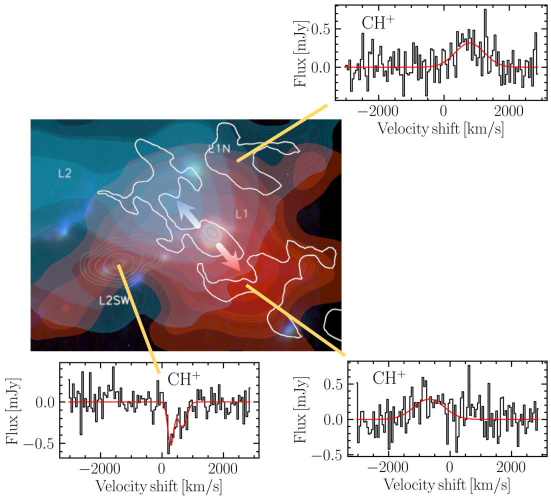


Figure 2.31: Some of the detected CH^+ absorption and emission lines in the SMM J02399-0136 galaxy group. Center: the location of the CH^+ emission regions (white contours) is shown in comparison to the high-velocity Lyα. Sides: the spectra of CH^+integrated over the indicated regions. While the broad CH^+ emission lines are tracing myriad high-velocity shocks at the interface of large-scale infall and outflows, the redshifted absorption lines observed in the direction of the starburst galaxy L2SW trace a more diffuse massive and turbulent molecular reservoir, which is infalling onto the galaxy group. *(Credit: MPA/LPENS)*

scale gas reservoirs surrounding these active environments. (Fabrizio Arrigoni Battaia)

2.13 Binaries boost cosmic carbon footprint

A new study led by the Max Planck Institute for Astrophysics shows that massive stars produce twice as much carbon when they have a binary partner. The scientists base this on new state-of-the-art computer simulations. Their findings are a small but important step towards better understanding the cosmic origin of the elements we are made of.

The cosmic origin of carbon, a fundamental building block of life, is still uncertain. Massive stars play an important role in the synthesis of all heavy elements, from carbon and oxygen to iron and so on. But even though most massive stars are born in multiple systems, the nucleosynthesis models so far have almost exclusively simulated single stars. An international team of astrophysicists led by the Max Planck Institute for Astrophysics (MPA) has now calculated the "carbon footprint" of massive stars that lose their envelope in a binary system.

"Compared to a single star, the average massive star in a binary system produces twice as much carbon," reports Robert Farmer, the lead author of the study at MPA. "Until recently, most astrophysicists ignored that massive stars are often part of a binary system. We investigated, for the first time, how being a binary changes the elements they produce."

Most stars, including our own star the Sun, are powered by fusing hydrogen into helium. In their golden years, after completing about 90% of their life, they start converting helium to carbon and oxygen. Stars like the Sun stop here, but massive stars can continue to fuse carbon into heavier elements up to iron.

The big challenge is not how to produce carbon, but how to get it out of the star, before it is destroyed. In single stars this is very hard. Stars in binary systems can interact and transfer mass to a companion (see illustration). The star that is losing parts of its mass develops a carbon-rich layer close to the surface, which is ejected when the star explodes as a supernova.

"It may not be fair to blame binary stars for greenhouse gases causing global warming", says Selma de Mink jokingly, coauthor of this study and director of the new stellar department at MPA, "but isn't it cool to pinch yourself in the arm and realize that the carbon in your skin was probably made in a binary star?"

Astronomers are also investigating other types of stars that can produce carbon, such as for example, red giant stars or explosions of white dwarf stars. But so far it seems that mas-

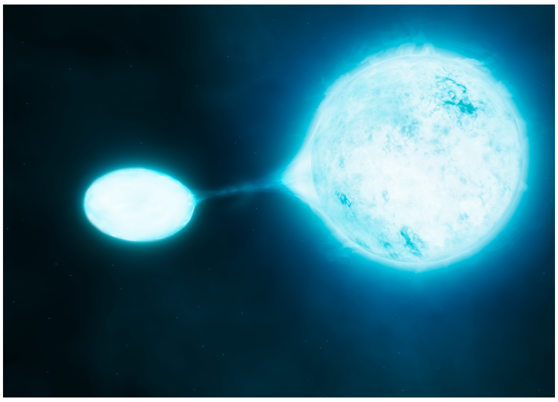


Figure 2.32: Massive stars are often found in close pairs, where one star strips mass from the other star. New research by MPA researchers has now shown that these binary systems produce about twice as much carbon as solitary, massive stars. *(Credit: ESO/M. Kornmesser/S.E. de Mink)*

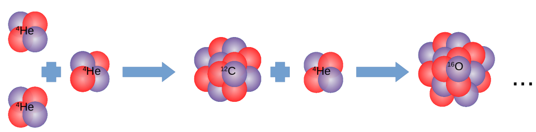


Figure 2.33: Schematic view of the fusion chain in massive stars: After hydrogen burning, helium fuses to carbon, which can then be further processed to oxygen and even heavier elements. *(Credit: MPA*

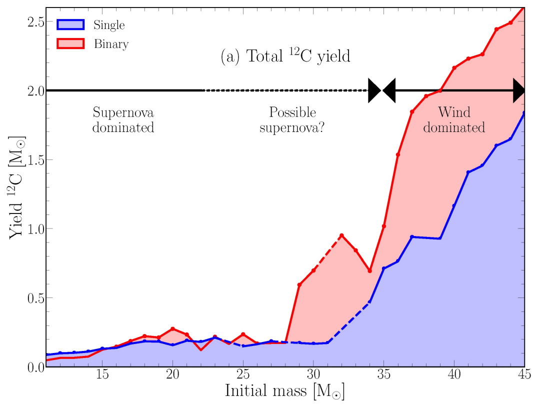


Figure 2.34: The total yield of carbon in massive stars in binary systems (red) is about twice that of single massive stars (blue), as the new study has found. *(Credit: MPA)*

sive stars, and according to this new study binary stars in particular, make the majority of the cosmic carbon.

"Our findings are a small but important step towards better understanding the role of massive stars in producing the elements we ourselves are made of", states Robert Farmer. "So far we have only investigated one type of binary interaction. There are many other possible fates for a star born in the close vicinity of a companion and many other elements to investigate." The results presented in this study are thus only the first in a systematic investigation of the impact of how a close companion will affect the chemical yields of massive stars. (Robert Farmer, Selma de Mink)

2.14 Radio and X-ray observations reveal spectacular fossils in nearby group of galaxies

Combining radio and X-ray images by LOFAR and SRG/eROSITA, respectively, astrophysicists have studied a group of galaxies where an incredibly rich system of radio-bright filaments are embedded in an atmosphere of hot X-ray emitting gas. These filaments were initially produced by outflows from a supermassive black hole a few hundred million years ago – roughly, when dinosaurs appeared on Earth. Despite their impressive age, the filaments still survive and form an intricate maze of threads and geometrical patterns that are reminiscent of structures formed when buoyant plumes rise in the atmosphere. The lack of full mixing between the X-ray and radio-emitting plasma is particularly interesting for physical models of the so-called mechanical AGN feedback.

Massive halos in our Universe, such as giant elliptical galaxies, groups and clusters of galaxies largely consist of Dark Matter, which is responsible for their deep gravitational wells. Part of their mass, though, is normal matter, i.e. baryons, which form a hot gaseous atmosphere filling the halo potential well. At temperatures of 10 or 100 million degrees, this gas can be readily studied in X-rays with modern space observatories, such as Chandra, XMM-Newton, and SRG.

In the central region of each halo, the gas density is high and the gas could cool and condense, providing fuel for the formation of new stars. However, somehow this does not happen – a puzzle that gave rise to the "mechanical AGN feedback" paradigm more than 20 years ago. Here AGN stands for the Active Galactic Nuclei – a supermassive black hole at the center of a halo. The paradigm, also known as "radio-mode AGN feedback", is based on three main conjectures, namely (i) the AGN can supply a sufficient amount of mechanical energy in the form of jets and/or outflows to prevent cooling of the gas; (ii) this energy can be efficiently converted into gas heating; and (iii) the system self-regulates so that approximately the right amount of energy is released by the AGN.

These assumptions can be corroborated by a combination of simple energetic estimates, energy conservation law arguments, and various analytic and numerical models of the feedback

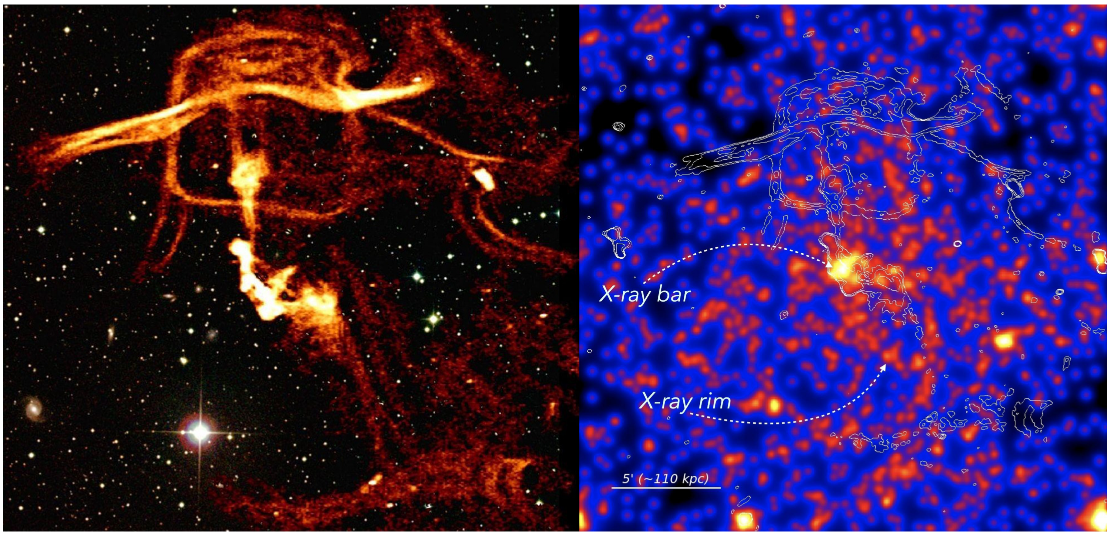


Figure 2.35: NEST200047 galaxy group images in the radio (left) and X-ray (right) bands. These images were obtained by the LOFAR interferometer at frequencies of 144 MHz and by the SRG/eROSITA telescope in the 0.5-2.3 keV band, respectively. In the right image, the structure of the radio emission is indicated by the faint contour lines. The size of the structures seen in the radio band is more than 1.5 million light years. In the center of the group is a supermassive black hole embedded in the hot gaseous atmosphere that emits X-rays. Cooling of the gas drives accretion onto the black hole, which responds by injecting large amounts of energy in radio-emitting bubbles that eventually transfer their energy to the gas and prevent it from further cooling. In the very center, the gas forms an "X-ray bar" perpendicular to the radio-bright regions. On slightly large scales, an "X-ray rim" encompasses the inner radio bubbles. *(Credit: left: LOFAR, right: SRG/eROSITA)*

loop. However, it is difficult to understand from first principles what physical processes are responsible for dissipating the energy released by the supermassive black hole and eventual gas heating. There are simply too many possibilities, including waves, turbulence, mixing, cosmic rays... One has to resort to observations to find clues to this question.

Here comes NEST200047: a nearby group of galaxies, some 75 Mpc (about 250 million light-years) away from us, observed by LOFAR and SRG/eROSITA in their respective radio and X-ray surveys (Fig. 2.35). The characteristic wavelengths of the surveys differ by a factor of about 5 billion, providing a highly complementary view on the galaxy group. These data confirm that a hot X-ray emitting gaseous atmosphere is centered on a giant elliptical galaxy and that its core is bright in the radio band typical ingredients of a group of galaxies where the role of AGN feedback is important.

But NEST200047 turned out to be a very special object. The radio emission comes from a rich and intricate system of filaments covering a region of over 200 kpc. Its structures resemble vortex rings, somewhat similar to those found in the famous nearby galaxy M87, but on much larger spatial scales. The combined radio and X-ray views suggest that the radio-emitting plasma was stretched and deformed by complicated motions over the course of more than hundred million years. At the same time, it does not mix with the thermal plasma on small scales, emphasizing the role of magnetic fields. This also implies that mixing is not required for heating of the X-ray-emitting gas as, in fact, foreseen by the original flavor of radio-mode AGN feedback models.

All in all, NEST200047 represents a unique example of an object, where fossils of AGN activity can be traced over hundreds of millions of years. (Eugene Churazov, Ildar Khabibullin, Rashid Sunyaev)

2.15 Galaxy formation meets Reionization in the THESAN simulations

Approximately 13 billion years ago, the radiation produced by the first galaxies completely transformed the Universe. The vast amount of hydrogen filling the space between galaxies was ionized in a process called cosmic reionization. Despite their intimate connection, the formation of the first galaxies and the reionization process are typically studied separately. An international team led by and including MPA researchers has now produced the first suite of simulations designed to simultaneously investigate these two processes during the infancy of the Universe, unveiling features of their connection. This new numerical effort – soon to be released publicly – provides a unique platform for investigating the young Universe and to fully exploit the forthcoming James Webb Space Telescope. The first results from THESAN have already shown that its unique combination of physical accuracy and simulated scales allows to reproduce most of the available data, including some that escaped previous numerical efforts.

After the Big Bang, the Universe went through its Dark Ages, a period of time when no sources of light were present. This ended when the first stars and shortly after the first galaxies formed. Their intense UV radiation transformed the neutral hydrogen gas in the inter-galactic medium between galaxies into a highly-ionized plasma; a process called Cosmic Reionization that took place 13 billion years ago. Despite this strong relationship, the details of the connection between the first galaxies

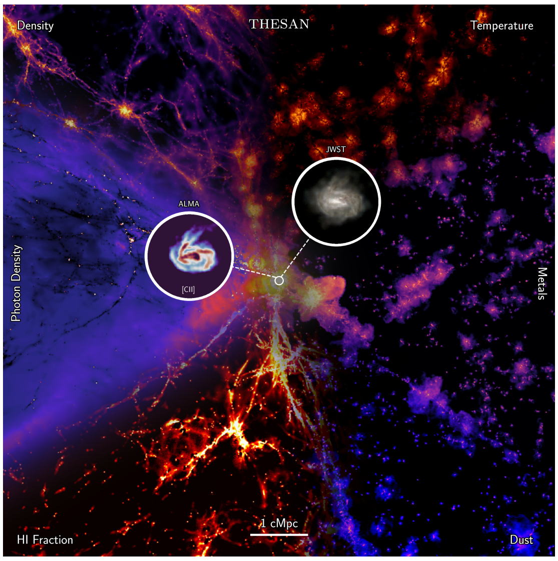


Figure 2.36: Composite image of the main Thesan simulation, showing six different simulated properties of the Universe in a slice through a region of the simulation. The two circular insets show how Thesan is able to predict how large telescopes such as ALMA and JWST will see the first galaxies. *(Credit: MPA)*

and Cosmic Reionization are still poorly understood, as it is extremely difficult to observe this very remote time in the history of the Universe. Thanks to a plethora of forthcoming telescopes, however, this obstacle will soon be overcome. The first one of them, the James Webb Space Telescope, is going to be launched at the end of 2021.

In order to take full advantage of these future observations, an international team led by Dr. Enrico Garaldi at MPA, Dr. Rahul Kannan at Harvard, and Dr. Aaron Smith at MIT, and including other MPA researchers, has developed a new unique suite of simulations named Thesan that pushes beyond the state of the art. Simulations are an essential entry in the astrophysicist's toolbox, since the number and complexity of physical processes relevant in the formation of galaxies renders pen-and-paper studies impossible. Using knowledge about the conditions left behind by the Big Bang and the physics governing the Universe, numerical astrophysicists simulate the formation and evolution of vast regions of space. They can then not only witness and unfold how structures grow but also use the detailed picture obtained from simulations to interpret cryptic observations.

What makes the new Thesan simulation suite unique is the combination of a long list of state-of-the-art numerical techniques that come together to create an exquisite and unprecedented view of the infancy of the Universe. In particular, the Thesan simulations combine an extremely successful galaxy formation model, an accurate and efficient algorithm that simulates the propagation of light, a model for the creation and destruction of cosmic dust, and a novel technique that ensures that the simulated structures are as statistically representative of the Universe as possible. The galaxy formation model is that of Illustris-TNG, which is able to reproduce many properties of galaxies found in the Universe, and includes the effects of energy and matter released from stars and black holes during their life, magnetic fields, and individual elements. Following the propagation of light is required to properly simulate Cosmic Reionization and cosmic dust needs to be included as well, since the molecules produced within the first galaxies give us a lot of information about their properties. Additionally, Thesan also explores different theories for the nature of dark matter and the sources of the photons powering Cosmic Reionization.

It is the first time that all these different techniques are combined in a large cosmological simulation. In order to achieve this one-of-a-kind combination, researchers used one of the biggest supercomputers in the world, the SuperMUC-NG machine at the Leibniz-Rechenzentrum in Garching near Munich. There, the simulation was performed by simultaneously using approximately 60 000 computing cores, for a total of more than 50 million CPU-hours. If the same simulations were run on a normal computer, they would have required more than 5700 years to complete.

Unlike previous studies, the simulations in the Thesan suite were not tuned to match available observations of the reionization epoch. Rather, they build upon knowledge gathered over the years, in which MPA has played a pivotal role. Remarkably, the researchers have now demonstrated that the simulated galaxies and inter-galactic medium are in very good agreement with available data.

The full analysis of the simulations will take many years, but bridging the gap between the formation of galaxies and Cosmic Reionization has already allowed researchers to reproduce for the first time the observed modulation of the radiation intensity around primeval galaxies. In order to allow the entire research community to benefit from this large effort, the researchers will make the simulation data freely available in the coming months. (Enrico Garaldi)

2.16 Galaxy formation with L-GALAXIES: modelling the environmental dependency of galaxy evolution

The colours and star formation rates of galaxies are strongly correlated with each other out to distances as large as 10 Megaparsecs. However, current galaxy formation models fail to reproduce these large-scale correlations accurately. Scientists from MPA, the University of Surrey, and Heidelberg University are in the process of updating the Munich galaxy formation model, L-GALAXIES, with a sophisticated and accurate method to model environmental effects for all galaxies. The most recent updated model is in significantly better agreement with observations than its predecessors and exhibits a stronger environmental dependency of galaxy properties out to several Megaparsecs from the centers of their dark matter haloes.

Modern theories of galaxy formation and evolution operate within the framework of the Lambda Cold Dark Matter (LCDM) cosmological model. One of the critical assumptions of LCDM is that cold dark matter, as the dominant form of matter in the Universe, interacts only gravitationally with itself and with other matter in the Universe. However, the photons that we observe with our telescopes originate from stars and gas in galaxies. This baryonic matter interacts in much more complicated ways than the weakly interacting cold dark matter. Modelling these baryonic components and their interactions as galaxies form and evolve within dark matter haloes is one of the most challenging topics in astrophysics.

According to the standard hierarchical structure formation theory, baryonic matter accretes into the gravitational potential wells of dark matter structures. It then undergoes cooling and contraction, which eventually leads to the formation of stars and galaxies. Furthermore, the evolution of baryonic matter and galaxies is influenced by a set of complex physical processes including the cooling of gas to form molecular clouds, star formation, galaxy mergers, energetic feedback processes from supernovae, and matter accretion onto black holes. This motivates the development of a comprehensive theory of galaxy formation and evolution.

In addition to intrinsic physical processes, the evolution of galaxies will also depend on the environment in which they are located. As a galaxy orbits within a dark matter halo, a drag force caused by its relative bulk motion with respect to the surrounding gaseous medium (commonly referred to as ram-pressure) will cause the more weakly bound gas in the galaxy to be lost (see Fig. 2.37). Gravitationally-induced tidal forces can also act to strip gas and stars out of the low-density outer regions of galaxies. Both processes act to deplete the gas reservoirs of galaxies and reduce the star formation

Figure 2.37: Ram pressure stripping of gas from a galaxy (ESO 137-001). This composite view includes visible light from Hubble and X-ray light from the Chandra X-ray Observatory (in blue). It reveals a tail of hot gas that has been stripped from the galaxy. *(Credit: NASA, ESA, CXC)*

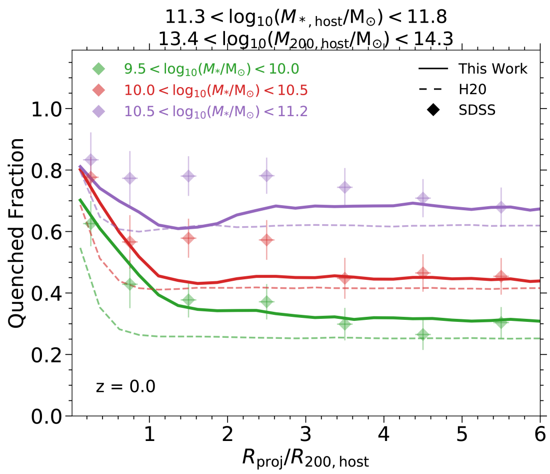


Figure 2.38: Fraction of quenched galaxies as a function of projected distance to the centre of haloes at z=0 for different mass ranges (green, red, purple). The solid lines are our new model and the dashed lines are the previous L-GALAXIES model (Henriques et al. 2020). The overall trends seen in the SDSS observations (data points with error bars) are well reproduced by our new model. *(Credit: MPA)*

in these systems.

The Munich semi-analytic model, L-GALAXIES, implements the key physical processes involved in galaxy formation and evolution on top of halo merger trees extracted from dark-matter-only simulations. As there is no hydrodynamical interaction in the underlying simulations, baryonic environmental processes need to be modelled explicitly using analytical approximations. Traditionally, L-GALAXIES, as well as many other analytic and semi-analytical models, have considered environmental processes only for satellite galaxies within a fixed boundary, typically the virial radius of the host halo. An even simpler approximation is that all galaxy properties can be linked only to the mass of their host dark matter halo. This is the fundamental ansatz of all halo occupation distribution (HOD) models, which are often used as a way of analyzing and interpreting results from large galaxy surveys.

Both assumptions, that environmental processes only depend on halo mass and that they stop at some fixed halo boundary close to the virial radius, are physically incorrect. To demonstrate this in detail, we carried out accurate object-by-object comparisons between L-GALAXIES and the IllustrisTNG hydrodynamical simulations and showed that environmental effects influence galaxies up to much larger halocentric distances (several virial radii) in the hydrodynamical simulation. Furthermore, observational studies have demonstrated that environmental effects extend out to distances well beyond the halo boundary. Therefore, without self-consistent modelling of environmental processes for all galaxies, it is impossible to robustly reproduce the properties of galaxies that reside in different environments. This seriously compromises the accuracy with which key large-scale structure clustering statistics can be predicted.

In our work, we present an updated version of L-GALAXIES with a new gas stripping method. Extending earlier work, we directly measure the local environmental properties of galaxies using the particle data of the simulations. In this way, we are able to treat ram-pressure stripping more accurately for all galaxies. We fully re-calibrate the modified L-GALAXIES model using a Markov Chain Monte Carlo (MCMC) method with the stellar mass function and the quenched fraction of galaxies as a function of stellar mass as constraints. Due to this re-calibration, global galaxy population relations, including the stellar mass function, quenched fractions versus galaxy mass, and HI mass function are all largely unchanged and remain consistent with observations. By comparing to data on galaxy properties in different environments from the Sloan Digital Sky Survey and Hypersuprime-cam Survey, we demonstrate that our modified model improves the agreement with the quenched fractions and star formation rates of galaxies as a function of halocentric distance, stellar mass, and redshift. In the vicinity of intermediate-mass and massive haloes, our new model produces higher quenched fractions and stronger environmental dependencies, better recovering observed trends with halocentric distance up to several virial radii (see Fig. 2.38).

By analysing the actual amount of gas stripped from galaxies in our model, we show that those in the vicinity of massive haloes lose a large fraction of their hot halo gas before they become satellites (see Fig. 2.39 and the video for a schematic view). We demonstrate that this affects galaxy quenching both within and beyond the halo boundary. This is likely to influence the correlations between galaxies up to tens of megaparsecs.

Currently ongoing model improvements, including incorporating results on the large-scale distribution of hot gas in massive halos from hydrodynamical simulations, will hopefully reveal new links between the physics of galaxy evolution and the distribution of gas and dark matter on large scales. These links might be manifested in a variety of statistical measures of the

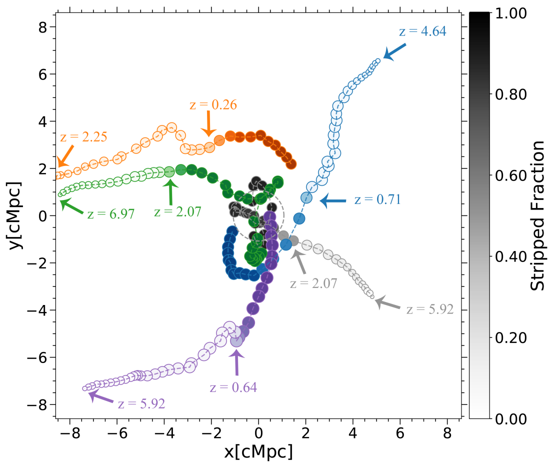


Figure 2.39: llustration of gas stripping in L-GALAXIES with five sample galaxies in the vicinity of a massive cluster. Each colour corresponds to a galaxy, and different circles of the same colour demonstrate the evolution of that galaxy at different redshifts starting with small open circles to larger filled circles. The size of each circle represents, qualitatively, the galaxy's stellar mass. Shown by the colourbar, the transparency of colours denotes the fraction of the gas stripped. The formation redshifts, and the redshifts at which each galaxy starts to be significantly stripped, are indicated by arrows. *(Credit: MPA)*

clustering of the galaxy population as a function of their colours and star formation rates. (Guinevere Kauffmann)

2.17 How do star clusters form in dwarf galaxies?

In the interstellar medium (ISM) of galaxies, stars form in small groups of a few hundred and clusters up to several million stars. A full theoretical model of this process and its impact on galaxy evolution is still in its infancy. MPA researches and their collaborators have developed a highly complex numerical model to simulate the multi-phase ISM and how star clusters emerge in dwarf galaxies. The supercomputer simulations show that the properties of the star clusters depend on how efficiently stars can form from the cold dense gas. Detailed post-processing then allowed the researchers to compare their results to observations. This demonstrates the scientific fidelity of the new model, its current limitations, and observational limitations on how well clusters can be detected in regions of high star formation activity. The studies are a major step towards a comprehensive model for star cluster formation.

Observations show that star formation is clustered, that is, stars form primarily in groups within collapsing cold gas clouds. Studying this with regular galaxy simulations is not possible as their resolution is too low and the stellar population is approximated by artificial star particles representing several thousands of stars at a time. To understand how star clusters form and to probe their intrinsic small-scale features, one needs much higher resolution and numerical tools that capture the important astrophysical processes.

The team has implemented numerical models for intricate heating and cooling processes as well as non-equilibrium chemistry of the ISM in galaxy formation simulations. With their photo-ionizing radiation, as well as supernova (SN) explosions newly formed massive stars can shape their surrounding interstellar medium. These models are essential for the accurate modeling of galactic star cluster formation at sub-parsec resolution. The team has carried out a suite of realistic isolated dwarf galaxy and galaxy merger simulations (see Fig. 2.40 for an example)

The effect of star formation efficiency on star cluster properties

A recent study led by Jessica May Hislop at MPA aims at understanding which physical processes regulate the formation and structural properties, such as masses and sizes, of star clusters in dwarf galaxies. The formation processes of individual stars, i.e. the collapse of

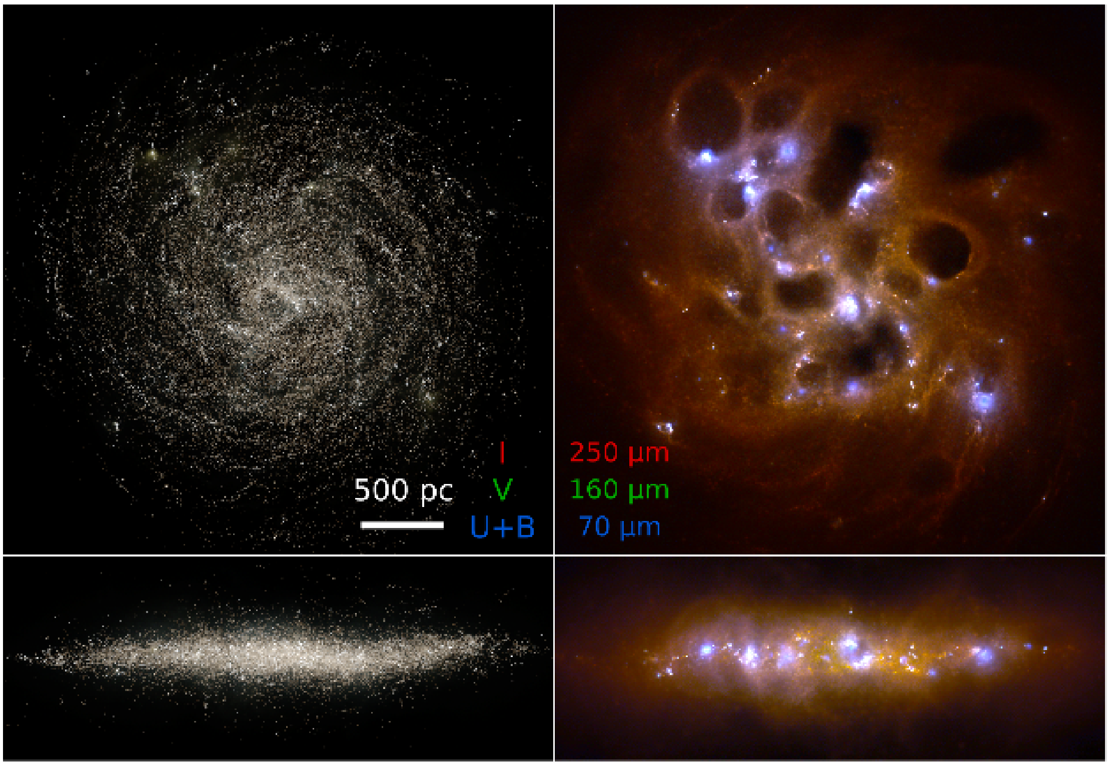


Figure 2.40: Color composite mock images of a simulated gas-rich dwarf galaxy, with face-on (top) and edge-on (bottom) projections. The left images show the galaxy in visual bands (I=red, V=green, U+B=blue), the right images at infrared wavelenths. The visual bands show direct, scattered and attenuated stellar light, while the infrared bands show stellar emission that is absorbed and re-emitted by dust in the ISM. The blue regions are illuminated by young star clusters that can be seen as concentrations of visual light in the left images. *(Credit: MPA)*

gas to real stellar densities, can not be resolved even in such high resolution simulations. However, a model parameter termed star formation efficiency – the fraction of gas in a collapsing cloud converted into stars on the cloud collapse timescale – can be used to capture those smaller scale processes. It controls the typical average ISM density at which the stars form and start dispersing their ambient collapsing birth cloud by radiation and SN explosions. This process is termed “stellar feedback”.

All models for isolated dwarf galaxies form their stars at a similar rate and the cluster mass functions have slopes which are in agreement with observations. The fraction of stars forming in clusters and the cluster properties, however, can differ significantly. In models with low efficiency (e.g. 0.2%) gas clouds can collapse into small regions with high densities before they form stars. It becomes very difficult for stellar feedback processes to destroy the clouds and prevent further star formation. Cloud disruption is much easier for models with high star formation efficiency (e.g. 50%), where stars form at an earlier phase of collapse. This results in less clusters, which are more extended and have lower typical masses. Still, none of the models presented here perfectly reproduces the observed cluster properties (see also Fig. 2.41). This provides motivation for developing more accurate numerical models for star cluster formation in supercomputer simulations.

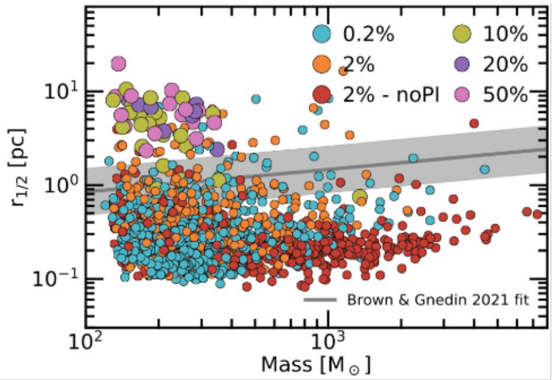


Figure 2.41: The half-mass radius of the star clusters formed in the simulations plotted against the star cluster mass. For lower star formation efficiencies (smaller blue, orange and red circles), the clusters have smaller radii, showing that these clusters are compact and tightly bound. Simulations with higher star formation efficiencies (larger green, purple and pink circles) produce fewer clusters with larger radii for the same mass, meaning that the clusters are more extended, and therefore more likely to be disrupted. The line is a fit of observed cluster properties. *(Credit: MPA)*

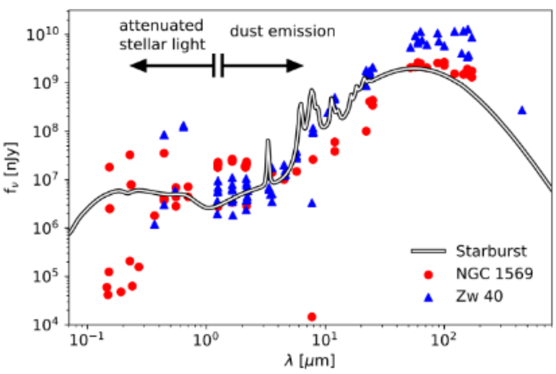


Figure 2.42: The modeled spectral energy distribution (SED) of the simulated dwarf starburst (line) agrees well with observations both of direct starlight and radiation that has been scattered, absorbed and re-emitted by dust. The observed dwarf galaxies NGC 1569 (red circles) and II Zw 40 (blue triangles) are undergoing similar bursts of recent star formation (data from NASA/IPAC Extragalactic Database). *(Credit: MPA)*

Panchromatic observations of simulated star clusters

Mismatches between the simulated and observed star cluster properties may, however, not only be caused by the simulation models alone. The sensitivity, resolution, spectral coverage and noise in observational data can degrade or bias the underlying physical properties. A study led by Natalia Lahén at MPA investigates the effect of observational limitations on determining the mass distribution of forming star clusters. Physical crowding of sources makes it challenging for observers to separate individual star clusters in regions of high star formation activity, especially at distances beyond the Local Group. Using the same model as described above, the researchers generated an observational view of a dwarf starburst galaxy. For this, the simulated system was post-processed with the radiative transfer code SKIRT from UV wavelengths to infrared emission from dust. The good agreement of the spectral energy distribution with observed dwarf galaxy starbursts supports the scientific fidelity of the simulation model (see Fig 2.42).

Many star cluster studies, in particular with the Hubble Space Telescope (HST), rely on photometric studies at visual wavelengths (e.g. the V-band). Here individual star clusters are detected and their properties like mass, size, and age are derived within circular regions (apertures) using automated algorithms. At high star formation activity, the forming clusters might form so close to each other that they cannot be accurately separated; this is called crowding. At larger distances, this problem becomes worse, where even more individual clusters appear as merged and are observed as if they were more massive and larger clusters. Fig. 2.43 shows a V-band image of the simulated galaxy as it would look through the eyes of HST if placed at two different distances. The results of these mock observations indicate that the masses of real, observed young star clusters with masses of a few million solar masses might be overestimated by up to a factor of 2.5 and their observed mass functions could be shallower than the true underlying cluster mass functions .

The two studies demonstrate how modern high-performance simulations can be used to identify and scientifically validate important astrophysical processes that regulate the formation of star clusters. They also highlight the importance of accurate comparison with observations in assessing the power of the underlying theoretical models. This joint approach will pave the way towards a modern comprehensive model for star cluster formation. (Natalia Lahén, Jessica May Hislop, Thorsten Naab, Guinevere Kauffmann)

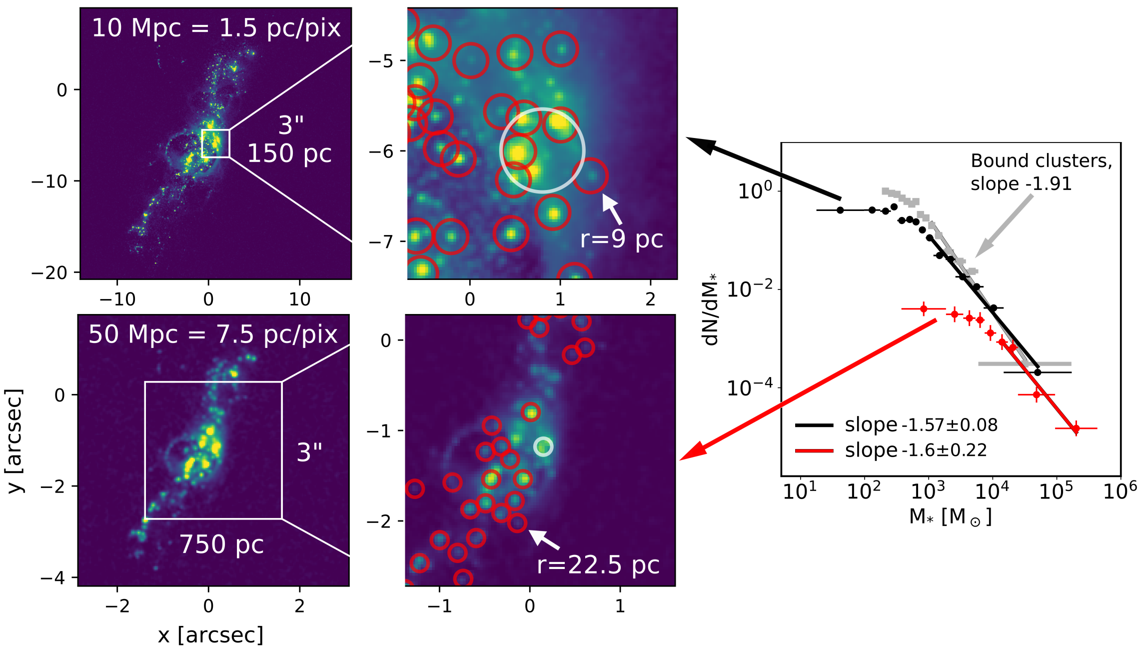


Figure 2.43: Mock HST V-band images of the simulated starburst galaxy at a distance of 10 Mpc (top) and 50 Mpc (bottom). The zoomed-in regions (middle) show the apertures (red circles) placed on the detected clusters. The lower spatial resolution for more distant galaxies (1.5 pc per pixel in the closer galaxy compared to 7.5 pc per pixel in the more distant galaxy) result in an apparent flattening of the cluster mass function and artificially massive super star clusters (right panel). The simulated mass function of bound clusters (grey points) can be used to quantify this effect. The white circle shows the location of the most massive cluster detected in the low-resolution image (bottom middle). It is repeated in the higher resolution image (top middle) and highlights how the region contains a multitude of smaller mass clusters that are blended together at poor resolution. *(Credit: MPA)*

3 Publications and Invited Talks

3.1 Publications in Journals

3.1.1 Publications that appeared in 2021 (352)

Abbar, S., et al. (incl. R. Glas and H.-Th. Janka): On the characteristics of fast neutrino flavor instabilities in three-dimensional core-collapse supernova models. Physical Review D, **103(6)**, 063033 (2021).

Abdul-Masih, M., Sana, H., et al. (incl. S. E. de Mink): Constraining the overcontact phase in massive binary evolution - I. Mixing in V382 Cyg, VFTS 352, and OGLE SMC-SC10 108086. Astron. Astrophys., **651**, A96 (2021).

Agarwal, N., Desjacques, V., Jeong, D. and F. Schmidt: Information content in the redshift-space galaxy power spectrum and bispectrum. J. of Cosmology and Astroparticle Physics, **2021(3)**,

Aghanim et al., (incl. T. Enßlin, M. Reinecke, R. Sunyaev, S.D.M. White): Erratum: Planck 2018 results - VI. Cosmological parameters Astron. Astrophys., **652**, C4 (2021).

Anbajagane, D., H. Aung, et al. (incl. K. Dolag): Galaxy velocity bias in cosmological simulations: towards per cent-level calibration. Mon. Not. R. Astron. Soc. **510(2)**, 2980-2997 (2021).

Anand, A., Nelson, D., and G. Kauffmann: Characterizing the abundance, properties, and kinematics of the cool circumgalactic medium of galaxies in absorption with SDSS DR16. Mon. Not. R. Astron. Soc. **504(1)**, 65-88 (2021).

Anderson, R. I., Suyu, S. H., and A. Merand: Maintaining scientific discourse during a global pandemic: ESOs first e-conference H02020. The Messenger, **184**, 31-36 (2021).

Andrade, U., D. Anbajagane et al. (incl. D. Huterer): A test of the standard cosmological model with geometry and growth. Journal of Cosmology and Astroparticle Physics **2021(11)** 014 (2021).

Andresen, H., Glas, R., and H.-Th. Janka: Gravitational-wave signals from 3D supernova simulations with different neutrino-transport methods. Mon. Not. R. Astron. Soc. **503(3)**, 3552-3567 (2021).

Antoja, T., McMillan, P. J., et al. (incl. F. Fragkoudi): Gaia Early Data Release 3 - The Galactic anticentre. Astron. Astrophys., **649**, A8 (2021).

Anusha, L. S., Shapiro, A. I., et al. (incl. M. Cernetic): Radiative Transfer with Opacity Distribution Functions: Application to Narrowband Filters. Astrophys. J. Suppl. **255(1)**, (2021).

Aoki, M., Primas, F., et al. (incl. A. Weiss): Lithium in NGC 2243 and NGC 104 Astron. Astrophys. **653**, A13 (2021).

Aouad, C. J. Chemissany, W. et al. incl. (P. Mazzali): Beirut explosion: TNT equivalence from the fireball evolution in the first 170 milliseconds. New York, US : Springer (2021).

Arca-Sedda, M., Rizzuto, F. P., Naab, T., et al.: Breaching the limit: formation of GW190521-like and IMBH mergers in young massive clusters. Astrophys. J. **920(2)**, 128 (2021).

Armstrong, P., Tucker, B. E., et al. (incl. Munoz-Elgueta, N.): SN2017jgh: a high-cadence complete shock cooling light curve of a SN IIb with the Kepler telescope. Mon. Not. R. Astron. Soc. **507(3)**, 3125-3138 (2021).

Arnaud, M., Ettori, S., et al. (incl. K. Dolag): The Cluster HEritage project with XMM-Newton: Mass Assembly and Thermodynamics at the Endpoint of structure formation - I. Programme overview. Astron. Astrophys. **650**, A104 (2021).

Arras, P., et al. (incl. R. Leike, T.A. Enßlin): Comparison of classical and Bayesian imaging in radio interferometry - Cygnus A with CLEAN and resolve. Astron. Astrophys. **646**, A84 (2021).

Arras, P., Reinecke, M., Westermann, R., and T.A. Enß,lin: Efficient wide-field radio interferometry response. Astron. Astrophys. **646**, A58 (2021).

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Ayromlou, M., Kauffmann, G., Yates, R. M., Nelson, D., and S. D.M. White: Galaxy formation with L-GALAXIES: modelling the environmental dependency of galaxy evolution and comparing with observations. Mon. Not. R. Astron. Soc. **505(1)**, 492-514 (2021).

Ayromlou, M., Nelson, D. Yates, R. M., Kauffmann, G., Renneby, M. and S. D.M. White: Comparing galaxy formation in the L-GALAXIES semi-analytical model and the IllustrisTNG simulations. Mon. Not. R. Astron. Soc. **502(1)**, 1051-1069 (2021).

Badole, S., Jackson, N. et al. (incl. H. Stacey): Erratum: VLA and ALMA observations of the lensed radio-quiet quasar SDSS J0924+0219: a molecular structure in a 3 Jy radio source. Mon. Not. R. Astron. Soc. **507(1)**, 1513-1513 (2021).

Baker, T., Barreira, A., et al. (incl. F. Schmidt): Novel Probes Project: Tests of gravity on astrophysical scales. Reviews of Modern Physics, **93(1)**, 015003 (2021).

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3.1.2 Publications accepted in 2021

Belvedersky, M., , Meshcheryakov, Gilfanov, M. and P. Medvedev: SRGz: building an optical cross-match model for the X-ray SRG/eROSITA sources using the Lockman Hole data. Astron. Lett.

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Caminha, G.B., S. H. Suyu, C. Grillo, P. Rosati: Galaxy cluster strong lensing cosmography: cosmological constraints from a sample of regular galaxy clusters. Astron. Astrophys.

Farber, R. J., and M. Gronke: The survival of multiphase dusty clouds in hot winds. Mon. Not. R. Astron. Soc.

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Glatzle, M., Graziani L., Ciardi B.: Radiative transfer of ionizing radiation through gas and dust: grain charging in star-forming regions. Mon. Not. R. Astron. Soc.

Gronke, M., Oh, S. P., Ji, S., and C. Norman: Survival and mass growth of cold gas in a turbulent, multiphase medium. Mon. Not. R. Astron. Soc.

Huber, S., Suyu, S. H., et al. (incl. S. Taubenberger): HOLISMOKES – VII. Time-delay measurement of strongly ensed Type Ia supernovae using machine learning. Astron. Astrophys.

Jackson, N., et al. (incl. B. Ciardi): Sub-arcsecond imaging with the International LOFAR Telescope. II. Completion of the LOFAR Long-Baseline Calibrator SurveyAstron. Astrophys.

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Khorunzhev, G., et al. (including M. Gilfanov, R. Sunyaev): Search for distant and luminous X-ray quasars in the SRG/eROSITA all-sky survey. First BTA telescope results. Astron. Lett.

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Morabito, L. K., et al. (incl. B. Ciardi): Sub-arcsecond imaging with the International LOFAR Telescope. I. Foundational calibration strategy and pipeline. Astron. Astrophys.

Naidu, R. P., Matthee, J., et al. (incl. M. Gronke,): The synchrony of production and escape: half the bright Ly α emitters at z $\asymp$ 2 have Lyman continuum escape fractions $\asymp$ 50% Mon. Not. R. Astron. Soc.

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Mereminskiy, I. et al. (including M. Gilfanov): Peculiar X-ray transient SRGA J043520.9+552226/AT2019wey discovered with SRG/ART-XC. Astron. Astrophys.

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3.1.3 Books and Proceedings in 2021

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Forman, W., Jones, C. et al. (incl. E. Churazov): Supermassive Black Hole feedback in early type galaxies. In: 356nd Symposium of the International Astronomical Union: Galaxy Evolution and Feedback Across Different Environments. Cambridge University Press p. 119-125 (2021).

Harrison, C. M., Molyneux, S. J., Sholtz, J., and M.E. Jarvis: Establishing the impact of powerful AGN on their host galaxies. In: 356nd Symposium of the International Astronomical Union: Galaxy Evolution and Feedback Across Different Environments. Cambridge University Press p. 203-211 (2021).

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Pillepich, A., Nelson, D., Springel, V., Pakmor, R. et al.: The TNG50 Simulation: Highly-resolved galaxies in a large cosmological volume to the present day. In: Transactions of the High Performance Computing Center, Stuttgart (HLRS) 2019 Eds. Nagel, W., Kröner, D. and M. Resch. IX, 599 p. 5-22 (2021).

3.2 Talks

3.2.1 Invited review talks at international meetings

Raoul Canameras:
– Workshop on the Hubble Tension at MIAPP (Garching, Germany, 27.9-1.10.)

Selma de Mink:
– Invited talk, Richard Thomas award ceremony, UC Boulder (delivered remotely, 21.5.)
– Invited plenary talk at the Sixteenth Marcel Grossman meeting (delivered remotely, 9.7.)

Torsten Enßlin:
– 2nd Action Plan ErUM-Data Community Meeting (virtual, Germany, 1.7.)
– MaxEnt 2020/2021The 40th International Workshop on Bayesian Inference and Maximum Entropy Methods in Science and Engineering (Graz, Austria, 8.7.)
– From Vision to Instrument: Designing the Next-Generation EHT to Transform Black Hole Science (virtual, 1.11.)

Robert Farmer:
– Standard sirens and the Hubble constant (Garching, Germany, 21.9 - 1.10.)
– Pair instability supernovae and the gap (Hanover, Germany, 14.12 - 17.12.)

Anna Genina:
– Kashiwa Dark Matter Symposium 2021 (Kashiwa, Japan, 29.11.-2.12). (On zoom)

Marat Gilfanov:
– SRG/eROSITA all-sky survey results (Sombreros and lampposts, ISSI, Bern, Switzerland, 29.11.-3.12.)
– Rubin-Athena Synergy Workshop (on-line only, 19.4.-23.4.)
– Physics and Astrophysics - from fundamental constants to cosmology (Saint-Petersburg, Russia, 27.9.-28.9.)

Adrian Hamers:
– TRENDY-3 plenary/review talk (online; 23.3.)

Hans-Thomas Janka:
– SuperMUC Status and Results Workshop (Garching, Germany, 8.-10.6.; Zoom)

Eiichiro Komatsu:
– What is dark matter? Comprehensive study of huge discovery space in dark matter (Kavli IPMU, Tokyo, 6.2.)

Rüdiger Pakmor:
– Simulating galaxies: current status and future challenges (Beirut, virtual, 11.5.-14.5.)
– The efect of magnetic fields in cosmological simulations (RAS, virtual, 9.10.)

Volker Springel:
– National Academy of Sciences, Annual Meeting, Astronomy Section (20.4.)
– Leibniz Supercomputing Centre Results Workshop (Garching, 8.6.-10.6.)
– XXXI IAU General Assembly Business Session (22.8.)

Sherry Suyu:
– Invited plenary talk, "The Hubble tension", Brookhaven Forum 2021: Opening New Windows to the Universe, USA (online, 3.-5.11.)
– Invited plenary talk, "Strong Lensing and Rubin Observatory", Dark Energy Science Collaboration Meeting, Rubin Observatory (online, 19.-23.07.)
– Invited plenary talk, "H0LiCOW! Cosmology with Gravitational Lens Time Delays", American Astronomical Society 237th meeting, USA (online, 11.-15.01.)

Stefan Taubenberger:
– The inverse distance ladder (MIAPP workshop, Garching, Germany, 1.10.)

Simona Vegetti:
– Heridanus, Dark Matter Workshop (London, UK, 3.11.-5.11.)

Achim Weiss:
– SDSS IV Collaboration Council

3.2.2 Invited Colloquia talks

Raoul Canameras:
– Laboratoire J-L Lagrange (Nice, France, 3.2.)
– Seminars of the Pole Machine Learning and Deep Learning, Laboratoire dAstrophysique de Marseille (Marseille, France, 4.5.)

Eugene Churazov:
– JPP Frontiers of plasma physics colloquium, (Zoom; 6.5.)
– INAF: INAF colloguium, (Zoom; 19.5.)

Benedetta Ciardi:
– Sapienza (Rome, Italy, 9.3.)

Torsten Enßlin:
– Radio Camera Initiative Seminar Series (remote, 15.1.)
– Atomphysik-Seminar der Gesellschaft für Schwerionenforschung (Darmstadt)
– Astroinformatics & Astrostatistics Commission of the IAU (remote, 14.12.)
– ORIGINS Data Science Centre Journal Club (Munich, 7.5.)

Marat Gilfanov:
– Harvard-Smithsonian Center for Astrophysics (Cambridge, USA, 14.4.)

– Kazan Federal University (Kazan, Russia, 31.5.)
– Institute of Applied Physics (Nizhnii Novgorod, Russia, 12.11.)

Max Grönke:
– University of Alabama, Huntsville (remote, 16.11.)
– Observatoire Astronomique de Strasbourg (Strasbourg, France, 10.12.)

Hans-Thomas Janka:
– Hebrew University of Jerusalem (Jerusalem, Israel, 21.1.; Zoom)
– National Autonomous University of Mexico (UNAM) (Mexico City, Mexico; 18.3.; Zoom)
– Hebrew University of Jerusalem (Jerusalem, Israel, 22.4.; Zoom)
– CERN (Geneva, Switzerland, 20.5.; Zoom)
– Canadian Institute for Theoretical Astrophysics (CITA) (Toronto, Canada, 15.7.; Zoom)
– University of Melbourne (Melbourne, Australia, 6.8.; Zoom)

Eiichiro Komatsu:
– Copernics Webinar Series (online, 26.1.)
– University of Padova (online, Padova, Italy, 29.4.)
– Agenzia Spaziale Italiana (ASI) (online, Rome, Italy, 17.5.)
– VLLT (online, Vietnam, 23.7.)
– RIKEN (online, Wako, Japan, 27.9.)
– Kings College London (online, 29.9.)
– Ecole Internationale Daniel Chalonge-Hector de Vega (online, Paris, France, 6.10.)

Fabian Schmidt:
– Ben Gurion University of the Negev (Beer Sheva, Israel (virtual, 5.5.)

Volker Springel:
– Invited Colloquium (Institute for Fundamental Physics of the Universe, Trieste, 26.2.)
– Invited Colloquium (Hebrew University of Jerusalem, 16.3.)
– Invited Colloquium (European Space Agency, 6.5.)
– Invited Colloquium (Joint Colloquium University of Geneva and EPFL, 16.11.)
– Invited Colloquium (Universität Münster, 2.12.)

Rashid Sunyaev:
– Dirac Medal 2019 Ceremony (online); (ICTP, Trieste, Italy, 29.1.)
– Princeton Wunsh (talk for astronomy graduate students); (Princeton University, 17.2.)
– Russian Scientific Committee and Working Groups of the SRG/eRosita Telescope (Russian Consortium); Space Research Institute of RAS, (IKI Moscow, 18.2.)
– Joint Munich Colloquium, (ESO Garching, 8.4.)
– Astrophysics Colloquium, University of Alabama and Marshall (Space Flight Center; Huntsville, 8.4.)
– Physics Virtual Colloquium; (Columbia University, New York; 19.4.)
– Scientific Session; General Meeting of RAS (Moscow 21.4.)
– UN Space Committee; (Vienna; 27.4.)
– Astronomy Colloquium at Caltech; (Pasadena, 9.6.)
– Russian Academy of Sciences ”100th Anniversary to Aleksandr Chudakov (16.6.)

– Physical Sciences of the Russian Academy of Sciences, (22.6.)
– The mm Universe conference and NIKA-2; Sapienza University, (Rome, 30.6.)
– Marcel Grossmann conference (M16), (Rome, 5.7.)
– Special Astrophysical Observatory of RAS (23.8.)
– Conference in memory of Dmitry Varshalovich, Ioffe Physical-Technical Institute; (St-Petersburg, 27.9.)
– Conference in Memory of D.A. Varshalovich, Ioffe Institute of Physics and Technology, RAS (St-Petersburg, 28.9.)
– Key results, plans and some news from SRG/eRosita; INTEGRAL-19 (Sardinia, 12.10.)
– talk during SRG/Workshop at Akdeniz University, (Antalya, Turkey; 14.10.)
– Annual High Energy Astrophysics Conference, Space Research Institute of Russian Academy of Sciences (IKI, Moscow, 21.12.)
– Report during the Meeting of the Scientific Council of the Space Research Institute (IKI, Moscow, 29.12.)

Sherry Suyu:
– University of Hull, UK (online, 1.12.)
– Max Planck Institute for Physics (Munich, Germany, 26.10.)
– Durham University, UK (online, 12.5.)
– Physics Department, University of Duisburg-Essen, Germany (online, 28.4.)
– Laboratoire d'Annecy de Physique des Particules, France (online, 5.3.)
– Dunlap Department and Institute for Astronomy at Univ.of Toronto, Canada (online, 3.3.)
– Princeton University / Institute for Advanced Study, USA (online, 16.2.)

Simona Vegetti:
– Donostia International Physics Center (via zoom, 28.5)
– University of Illinois at Urbana-Champaign (via zoom, 27.1)

3.2.3 Public talks

Hans-Thomas Janka:
– LWL-Museum Münster (7.12.)

Eiichiro Komatsu:
– Celebration on the birthday of Stephen Hawking (online, Univ. of Cambridge, UK, 8.1.)
– NHK Culture (online, Yokohama, Japan, 23.1.)
– Physics Discussion (online, Sao Paulo, Brazil, 5.5.)
– Japan Club München (online, Munich, 6.5.)

Volker Springel:
– Deutsches Museum, Munich (27.10.)

3.3 Lectures and lecture courses

3.3.1 Lectures at LMU and TUM

T. A. Enßlin, SS 2021, LMU München
- Information theory (1/3 semester)
- Information field theory (2/3 semester)

W. Hillebrandt, WS 2020/2021 and WS 2021/2022, TUM

H.-Th. Janka & E. Müller, WS 2020/21 and SS2021, TU München

S. Suyu, WS2020/2021, SS2021 and WS2021/2022, TUM

A. Weiss, SS 2021 and WS 2021/2022, LMU München

3.3.2 Short and public lectures

T. Enßlin: (LMU München, Garching, 27.9.-1.10.):
Numerical Information Field Theory (key qualification course)
– LMU München, Garching, 14.10.-15.10.): Artificial Intelligence, Bayes, & Cognition

A. Hamers: IMPRS Advanced Course “Astrophysical Dynamics” (online; 12.4. - 23.4.)

R. Sunyaev: ICNFP 2021 Public lecture, (Crete, Greece, 30.8.)

A. Weiss: Summer School “Stellar Ecosystems”, IMPRS on Astronomy (Heidelberg, 13.9.-17.9.2021)

4 Personnel

4.1 Scientific staff members

Directors

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

Research Group Leaders/Permanent Staff

Eugene Churazov, Benedetta Ciardi, Torsten Enßlin, Marat Gilfanov, Max Grönke (since 1.11.), Adrian Hamers, Hans-Thomas Janka, Thorsten Naab, Rüdiger Pakmor, Fabian Schmidt, Sherry Suyu, 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.

Staff/Postdoc

Fabrizio Arrigoni-Battaia, Tiara Battich, Earl Bellinger (since 1.10), Rebekka Bieri, Robert Bollig, Deepika Bollimpalli, Gabriel Caminha, Paolo Campeti, Raoul Cañameras, Martyna Chruslinska (since 15.10), Tiago Costa, Linda Blot, Sten Delos, Ryan Jeffrey Farber (since 1.11.), Robert James Farmer (since 1.9.), Elisa Ferreira (until 30.10.), Matteo Frigo (until 31.5.) Daniela Galarraga-Espinosa (since 1.10.), Enrico Garaldi, Anna Genina, Robert Glas, Robert Grand (until 14.7.), Thales Gutcke (until 14.11.), Cesar Hernandez-Aguayo, Andrew Spencer Jamieson (since 1.9.), Ildar Khabibullin (until 30.9.), Alexandra Kozyreva, Ann-Kathrin Kummer (until 31.5.), Natalia Lahen, Qi Li (since 15.9.), Luisa Lucie-Smith, Patrick Neunteufel, Max-Niklas Newrzella (until 31.8.), Conor O'Riordan, Devon Powell, Holly Preece, Antti Rantala, Martin Reinecke, Taeho Ryu (since 15.9.), Adam Schäfer, Yiping Shu, Hannah Stacey, Stefan Taubenberger, Wilma Trick, Christian Vogl, Chen Wang (since 1.12.), Naveen Yadav, Akin Yildirim (until 31.12.).

Ph.D. Students

Anshuman Acharya (since 13.9.), Felix Ahlborn, Abhijeet Anand, Mohammadreza Ayromlou (until 30.11.), Arghyadeep Basu (since 22.9.), Monica Barrera, Eirini Batziou, Aniket Bhagwat, Sergei Bykov, Chris Byrohl (until 30.8.) Miha Cernetic, Geza Csoernyei, Hitesh Kishore Das (since 8.9.), Vincent Eberle (since 1.1.), Gordian Edenhofer (since 1.1.), Jakob Ehring, Wolfgang Enzi (until 31.7.), Fulvio Ferlito (since 15.9.), Konstantina Fotopoulou, Philipp Frank (until 31.10.), Ilkham Galiullin, Vale Gonzalez Lobos, Alexandra Grudskaia Johannes Harth-Kitzerow, Laura Herold, Jessica Hislop, Simon Huber, Liliya Imasheva, Andrija Kostic, Ivan Kostyuk, Daniel Kresse, Jere Kuuttila (until 31.7.), Simon May, Marta Monelli, Nahir Munoz Elgueta, Vyoma Muralidhara, Simon Ndiritu, Christian Partmann, Perikles Okalidis, Abinaya Swaruba Rajamuthukumar (since 1.7.), Tim-Eric Rathjen (until 31.10.), Bryce Alexander Remple (since 1.1.), Johannes Maximilian Ringler, Francesco Rizzuto (until 31.12.), Jakob Roth, Julian Rüstig, Stefan Schuldt, Lazaros Souvaitzis (since 15.10.), Beatriz Tucci-Schiewaldt (since 10.10.), Pavan Vynantheya, Oliver Zier.

Master students

Jana Bayer (until 30.8.), Tiberio Ceccarelli (since 1.10.), Gabriela Cudmani (since 1.9.), Nikolaus Deiser (since 1.5.), Simon Ding (until 30.10.), Christoph Eberle (since 1.8.), Richard Fuchs (since 1.10.), Silvia Gasparotto (1.2.-30.9.), David Gorbunov (since 1.10.), Matteo Guardiani (until 30.10.), Jakob Hein (since 15.3.), Malte Heinlein, Alexander Holas (until 30.7.), Vishal Johnson (since 1.8.), Viktoria Kainz (until 30.9.), Jongseo Kim (until 30.8.), Kristina Lautenschütz (until 30.8.), Michael Metz (since 1.5.), David Outland (until 30.9.), Amit Patel (until 30.11), Andres Ramirez (since 1.10.), Ankit Shresta (until 30.5.).

Technical staff

Computational Support: Heinz-Ado Arnolds (IT management), Andreas Breitfeld, Goran Toth, Andreas Weiss
Public relation: Hannelore Hämmerle (MPA and MPE)
Secretaries: Maria Depner, Sonja Gründl, Gabriele Kratschmann, Cornelia Rickl
Library: Mirna Balicevic, Christiane Bartels (library management), Elisabeth Blank.

4.2 Staff news/Awards

Geza Csoernyei received the Pro Scientia Award of the Hungarian Academy of Sciences for the research work carried out during undergraduate years.

Max Grönke started a new research group at MPA, the science topic is ”Multiphase Gas”.

Ildar Khabibullin received the Yakov Zeldovich Medal for his “major contribution to deciphering the historical high energy activity of the supermassive black hole Sgr A* in the center of our Galaxy and insights into the physical processes of galactic collapsed objects”.

Eiichiro Komatsu has been selected as one of the recipients of the 2021 Inoue Prize for Science.

Luisa Lucie-Smith has been awarded the RAS Michael Penston 2020 runner up prize for her thesis "Insights into Cosmological Structure Formation with Machine Learning".

Benard Nsamba received the prestigious Branco Weiss Fellowship awarded by the ETH Zürich in order to study stars and inspire Ugandan students.

Francesca Rizzo awarded with the Kippenhahn Prize for her paper on "A dynamically cold disk galaxy in the early Universe".

Sherry Suyu received the 2021 Lancelot M. Berkeley-New York Community Trust Prize for Meritorious Work in Astronomy from the American Astronomical Society (AAS).

Simona Vegetti has been appointed to head a Lise Meitner Excellence Group.

Christian Vogl received the Otto Hahn Medal 2021 to MPA junior scientist Christian Vogl for his excellent Dissertation.

4.3 PhD and Master Theses 2021

4.3.1 Ph.D. theses 2021

Philipp Adam Arras: Radio interferometry with information field theory. Ludwig Maximilians Universität München.

Mohammadreza Ayromlou: Physical processes that determine the clustering of different types of galaxies on large scales. Ludwig Maximilians Universität München.

Wolfgang Enzi: Astrophysical probes of dark matter: opportunities and challenges from a strong gravitational lensing perspective. Ludwig Maximilians Universität München.

Philipp Florian Frank: Approximate inference in astronomy. Ludwig Maximilians Universität München.

Jere Kuuttila: The observational characteristics of accreting white dwarfs and their connection to type Ia supernovae. Ludwig Maximilians Universität München.

Tim-Eric Rathjen: Simulating the multi-phase interstellar medium and galactic outflows. Ludwig Maximilians Universität München

4.3.2 Master theses 2021

Jana Bayer: Strongly Lensed Type II Supernovae as a Cosmological Probe. Technische Universität München.

Simon Ding: Multi-frequency imaging of HydraA using RESOLVE Ludwig Maximilians Universität München.

Silvia Gasparotto: Cosmic Birefringence from Axion Monodromy Potential. Technische Universität München.

Alexander Holas: Determination of the Expansion Rate of the Universe by Means of Type II-P Supernovae. Technische Universität München.

Jongseo Kim: Filament Generative Model for Bayesian Imaging. Ludwig Maximilians Universität München.

Maja Lujan Niemeyer: Lyman-alpha halos around high-redshift lyman-alpha emitting galaxies. Ludwig Maximilians Universität München.

David Outland: Inferring Deep Sea Bioluminescent Activity from Astrophysical Neutrino Data. Ludwig Maximilians Universität München.

Ankit Shresta: Constraining models of inflation with galaxy clustering.

4.4 Visiting scientists in 2021

Name	home institution	Duration of stay at MPA
Andrei Beloborodov	Columbia University	until 30.1.
James Chan	EPFL, Lausanne	1.11.-30.11.
Janet Ting-Wan Chen	Stockholm University	11.10.-30.11.
Andrea Chiavassa	University of Nice, FR	since 1.9.
Elena De La Hoz Lopez-Collado	Inst. de Fisica de Cantabria, ES	18.10-12.12.
Patricia Diego Palazuelos	Inst. de Fisica de Cantabria, ES	26.9.-26.11.
Dragan Huterer	Univ. of Michigan	until 31.8.
Chervin Laporte	University of Barcelona	since 13.12.
Paolo Mazzali	JMU, Liverpool	1.9.-10.10.
Pavel Medvedev	IKI Moscow	16.6.-31.8.
Marcelo Miller Bertolami	IALP, La Plata, Argentina	until 16.2.
		and 18.10.-10.11.
Marcello Musso	University of Rwanda	since 13.12.
Nicolas Peschken	Nicolaus Copernicus Univ. Torun, PL	15.3.-15.7.
Elena Pian	University of Pisa, IT	1.9.-10.10.
Chitsanupong Somma	Working student	17.8.-18.10.
Icli Tugce	TUBITAK, Turkey	since 15.10.
Mark Lykker Winther	Aarhus University, DK	since 1.9.
Yiheng Wu	University of Shanghai, China	since 1.8.
Zhiyuan Yao	University of Shanghai, China	since 1.5.
Bocheng Zhu	University of Shanghai, China	sine 6.10.