# Max-Planck-Institut

# für

# Astrophysik

ANNUAL REPORT 2020

# 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 2020.

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).

**Figure 1.1:** MPA staff in the inner courtyard of the institute building in Garching 1982. (*Credit: MPA)*

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 25 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 in Astrophysics, a joint initiative between the Max Planck Society and the Ludwig-Maximilians University of Munich. About 70 PhD students participate in the school at any given time, most of them at the MPE or the MPA. This has 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 RZG/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.

## 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 2019/2020 more than 200 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 64 processor cores and 768 GB memory) plus compute servers equipped with the General Parallel File System with 2500 cores and about 15 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 inhouse, 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 one seminar room 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 the MPA and the MPE and therefore has to serve the needs of two institutes with differing research emphases – predominantly theoretical astrophysics at MPA and predominantly observational/instrumental astrophysics at MPE. At present the library holds a unique print collection of about 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, 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 2020 at the MPA

### 1.3.1 New director at MPA

As of 1 January 2021, Selma E. de Mink has started her new directorship at the Max Planck Institute for Astrophysics (MPA). She will head the stellar astrophysics department at the institute and will bolster research into the life, death and after-life of stars. De Mink is a Dutch national and still affiliated with the University of Amsterdam in her home country. She has moved back to Europe from the US, where she held a professorship at Harvard University.

Stars are the main research interest for Selma de Mink. They are the nuclear factories producing all the heavy elements that we are made of, from carbon and oxygen to much heavier elements such as iron. They live an exciting life, interacting with their surroundings not only through radiation but also through winds, and often end their lives in spectacular explosions.

One speciality of Selma E. de Mink: binary stars, i.e. stars that are not alone but rather in a bound system. In the past decade, astrophysicists realised that all massive stars form binary systems, which led to a huge surge of interest. This was further strengthened by the first discoveries of merging black holes through gravitational waves, with massive binary stars as the most likely progenitors.

Depending on their mass, stars end their lives in more or less energetic explosions, leaving behind a compact remnant. While our Sun will end up as a white dwarf, more massive stars

**Figure 1.2:** Prof. Selma de Mink, new MPA director. *(Credit: private image)*

form neutron stars or even black holes - and in the case of massive binary stars also a binary black hole system. While this outcome is very rare, and catching a binary black hole system in the act of merging even more so, astrophysicists are excited about the new window that gravitational wave astronomy has opened into the universe.

While much harder to detect than electromagnetic radiation, gravitational waves are not hampered by dust – they pervade everything. With new gravitational wave detectors being planned and developed, we might be able to "hear" gravitational wave mergers throughout the entire history of the universe. To make accurate predictions for what they will be able to detect, astrophysicists need to understand the physics behind the formation of black hole binaries – and for this, they need to understand also all the other outcomes. And to understand the outcome, one first needs to understand the evolution that led to this end.

Therefore, the evolutionary pathways of stars, in particular the ones leading to the emission of gravitational waves, is a high priority for Selma de Mink in her research at MPA. With her group she will use computer simulations and observational surveys to study the details of stars in the prime of their life. Observations of transients, such as massive amounts of data from robotic surveys, will offer information on the death of stars. From these, her group will then be able to make predictions on the stars afterlife.

Selma de Mink studied physics and mathematics at Utrecht University and finished her PhD there with a thesis on "Stellar evolution at low metallicity" in 2010. Her postdoc positions led her to the University of Bonn, the Space Telescope Science Institute in Baltimore and the California Institute for Technology & Carnegie Observatories, Pasadena, before she became a professor at the University of Amsterdam in 2014 and at Harvard University in 2019.

Her work has been recognised with many prizes and distinctions, among them the Hubble and the Einstein fellowships by NASA in 2010 and 2013, an ERC starting grant in 2016, and the MERAC Prize in Theoretical Astrophysics 2017 by the European Astronomical Society. In 2019, she was elected as Member of the Young Scientific Academy in the Netherlands. She has published more than 100 refereed papers, which have been cited more than 8000 times.

Connecting theory to observations is a central interest for Selma de Mink and one for which Garching is well suited. It is one of the largest astronomy hubs in Europe, with experimentalists next door to theorists and many experts with diverse backgrounds. Stars relate to so many aspects in astronomy and physics that she expects a lot of interaction with the other groups and departments concentrated at the campus. She enjoys creating groups of critical mass and is looking forward to many stimulating discussions about the role of stars throughout cosmic history.

### 1.3.2 Biermann lectures 2020

The Biermann lectures 2020, have been held by Prof. Laurent Gizon from the MPI for Solar System Research in Göttingen.

The department "Solar and Stellar Interiors" was created at the Max Planck Institute for Solar System Research in April 2011 with Prof. Laurent Gizon as director, as a joint initiative of the Max Planck Society, the University of Göttingen, and the state of Niedersachsen. The departments main focus is to understand how the Sun and stars work by looking into their interiors using acoustic oscillations as probes. For the Sun, the space observatories SDO and SOHO, as well as the ground-based network GONG provide the necessary data. An important upcoming mission for the department is Solar Orbiter, launched in February 2020, which will study the dynamics of the polar regions of the Sun for the first time.

After studying astrophysics in Toulouse, Laurent Gizon obtained his Ph.D. in physics at Stanford University in 2003. He was a Max Planck Research Group leader at the Max Planck Institute for Solar System Research from 2005 to 2011, where he developed techniques of local helioseismology to map the interior of the Sun in three dimensions. In 2011 he was jointly appointed a full professor at the University of Göttingen and a Scientific Member and Director at the Max Planck Institute for Solar System Research.

**Figure 1.3:** Prof. Laurent Gizon, Director at the MPI for Solar System Research, Göttingen. *(Credit: MPS)*

### 1.3.3 Rudolf Kippenhahn (24.5.1926 – 15.11.2020)

Rudolf Kippenhahn, former director of the Max Planck Institute for Astrophysics in Garching, passed away in Göttingen on 15 November 2020 at the age of 94. With his passing, we lose someone whose pioneering scientific achievements not only shaped the field of theoretical astrophysics for many years, but who also helped our institute to develop a very special style of research and scientific exchange.

In the mid 20th century, the structure and evolution of stars were a major focus of astronomical research. During this time, Rudolf Kippenhahn was one of the pioneers building numerical models of stars, and he established this field in Germany and elsewhere. This, among other things, led to his appointment as director at the Institute for Astrophysics in 1974, which at that time was still part of the Max Planck Institute for Physics and Astrophysics. Before that, he became Scientific Member and Head of the Department of Theoretical Astrophysics in 1963, but then headed the University Observatory in Göttingen from 1965 until his return to the Max Planck Society, where he succeeded Ludwig Biermann.

Together with Alfred Weigert, Emmi Meyer-Hofmeister and later Hans-Christoph Thomas, Rudolf Kippenhahn developed and established a stellar evolution program which became one of the standard programs in this field and was later used in many countries. With the help of this program numerous aspects of the evolution of stars of different masses and devel-

**Figure 1.4:** Rudolf Kippenhahn († 15.11.2020), former director of the Max Planck Institute for Astrophysics in Garching. *(Credit: MPA)*

opmental phases could be studied and clarified. In addition, Rudolf Kippenhahn developed various methods allowing multidimensional physics effects in stars to be approximated in one-dimensional calculations. These include rotation and thermohaline mixing as well as the evolution of binary stars. These methods are still in use today basically unchanged. His textbook on the subject, written with Weigert, is a standard in the field.

Even though stars were close to his heart, the Institute for Astrophysics did not become a stellar institute under his leadership. Kippenhahn's wide-ranging interest, his unquenchable curiosity for new discoveries and his deep understanding were also reflected in the diversity of research carried out at the institute. The breadth of theoretical work ranged from comets to the theory of relativity and cosmology, and under the leadership of Heinz Billing the institute also housed an experimental department for gravitational wave research.

Under Rudolf Kippenhahn, the institute was established as an internationally recognised centre of numerical-theoretical astrophysics. After his retirement in 1991, he increasingly turned to writing popular science books, for which he was awarded prizes in addition to those for his scientific achievements. Rudolf Kippenhahn was Vice-President of the International Astronomical Union and Chairman of the German Astronomical Society, whose Karl Schwarzschild Medal he received and of which he was appointed honorary member. Among other awards, he received the Eddington Medal of the Royal Astronomical Society and the Order of Merit 1st Class of the Federal Republic of Germany.

Rudolf Kippenhahn managed the institute, which moved to Garching in 1979, with a gentle, liberal hand and with a great deal of humour. It was no coincidence that a room for scientific discussions was called "Forschungsfreiraum". Not only did he value broad theoretical, especially numerically supported research, he also encouraged communication between the individual groups in every respect. The tradition of free theoretical research and scientific dialogue still characterises the institute to this day.

Rudolf Kippenhahn has left his mark not only in theoretical astrophysics. In his institute, he established a unique culture of independent research at the highest level, which still shapes the character of the Max Planck Institute for Astrophysics today. We owe him a great debt, and will honour his memory and this legacy.

### 1.3.4 Prizes and Awards

#### Leibniz Prize 2021

The German Research Foundation DFG awarded Volker Springel the Gottfried Wilhelm Leibniz Prize 2021 for his ground-breaking work in the field of numerical astrophysics (1.5).

Volker Springel developed new numerical methods that have considerably raised the standard of precision in this field of research. This has led to a breakthrough in understanding how the various structures in the cosmos emerged from an early, almost uniform universe. In his research, Springel has investigated many aspects of non-linear structure growth and, in particular, the critical role of feedback processes in the evolution of galaxies and their central black holes. In short, his work has shown that galaxy formation is a self-regulating process. Thus, many of the observed properties of galaxies are a consequence of this feedback within the current standard model on the origin of cosmic structures, the cold dark matter paradigm.

After completing his doctorate in astrophysics at the LMU Munich in 2000, Volker Springel went to Harvard as a postdoctoral researcher and then held various positions at the Max Planck Institute for Astrophysics in Garching from 2001. He declined calls to Cambridge and Harvard in 2009, opting to accept a professorship at Heidelberg University and the Heidelberg Institute for Theoretical Studies (HITS) as one of the founding group leaders. In 2018, he returned to the MPA in Garching as director. Springel has been awarded the Otto Hahn Medal, the Heinz Maier-Leibniz Prize and the Gruber Prize for Cosmology. He has been a member of the Leopoldina since 2016, and since 2020 foreign member of the US National Acacemy of Sciences.

The Gottfried Wilhelm Leibniz Prize is being awarded annually by the DFG since 1986. Per year, up to ten prizes can be awarded, with a maximum of €2.5 million provided per award. Including the ten prizes for 2021, a total of 388 Leibniz Prizes have been awarded up to date.

**Figure 1.5:** Volker Springel received the Leibniz Prize of the German Research Foundation and the Gruber Prize for Cosmology 2020 *(Credit: MPA)*

## Berkeley Prize

Astrophysicist Sherry H. Suyu received the 2021 Lancelot M. Berkeley–New York Community Trust Prize for Meritorious Work in Astronomy (1.6). Bestowed annually since 2011 by the American Astronomical Society (AAS) and supported by a grant from the New York Community Trust, the Berkeley prize includes a monetary award and an invitation to give the closing plenary lecture at the AAS winter meeting, the “Super Bowl of Astronomy.” The 237th AAS meeting was held virtually from 11 to 15 January 2021.

Sherry Suyu (Max Planck Institute for Astrophysics (MPA) & Technical University of Munich (TUM)) is being honoured with the 2021 Berkeley prize for her leadership of the H0LiCOW collaboration, which is measuring the cosmic expansion rate using gravitationally lensed quasars. The group’s work confirms that “local” measurements of the expansion rate do not match up with values obtained by measuring certain properties of the early universe’s cosmic microwave background radiation and extrapolating to the present using the standard cosmological model. There must be something wrong with the measurements, the model, or both, but so far, neither observers nor theorists have been able to figure out exactly what everybody’s overlooking.

Let’s unpack the H0LiCOW acronym, which is actually a nested acronym. It stands for H0 Lenses in COSMOGRAIL’s Wellspring. $H_0$ (properly written as capital H0 with subscript zero, not letter O), is the Hubble constant, the current expansion rate of the universe. Lenses refer to gravitationally lensed quasars, in which the enormous gravity of a galaxy with billions of stars distorts space-time to form multiple images of a background quasar a blazingly

**Figure 1.6:** Sherry H. Suyu received the 2021 Lancelot M. Berkeley–New York Community Trust Prize *(Credit: Astrid Eckert/TUM)*

bright galaxy nucleus powered by a supermassive black hole feeding on surrounding gas, dust, and stars. COSMOGRAIL is the COSmological MOnitoring of GRAvItational Lenses, an international project measuring time delays for most known lensed quasars, producing a wellspring of data. Time delay refers to the fact that quasars vary in brightness; as light from each lensed image follows a slightly different path from the quasar to Earth, fluctuations in brightness appear in different images at different times. From those differences astronomers can determine the geometry of space-time in the lensing galaxy and, by inference, the combined mass of the galaxy's visible and dark matter. Whew!

Each year the three AAS Vice-Presidents, in consultation with the Editor in Chief of the AAS journals, select the Berkeley prize winner for meritorious research published within the preceding 12 months. Reacting to VP Joan Schmelz's email announcing her selection as the 2021 Berkeley prize recipient, Suyu wrote, "Thank you very much for this fantastic news! It is a great honour, not just for me, but for the entire H0LiCOW team! Our results took many years of hard work, and we are excited to establish a completely independent and competitive probe of cosmology. None of this would be possible without my wonderful H0LiCOW collaborators, and I am truly grateful to them."

In addition to serving as Research Group Leader at MPA and an Assistant Professor at TUM, Suyu is a Visiting Scholar at the Academia Sinica Institute of Astronomy and Astrophysics (ASIAA). Her H0LiCOW team includes scientists at institutions in the United States, Europe, Japan, and Taiwan. In 2017, the European Research Council awarded her a grant to launch a new study of gravitationally lensed supernova explosions: HOLISMOKES (Highly Optimised Lensing Investigations of Supernovae, Microlensing Objects, and Kinematics of Ellipticals and Spirals).

Sherry Suyu is also involved in the Excellence Cluster ORIGINS, an interdisciplinary collaboration of German institutions investigating the development of the universe from the Big Bang to the emergence of life. S. Suyu earned her Bachelor of Science degree in astrophysics at Queen's University, Canada, in 2001 and her PhD in physics at Caltech in 2008. Then came postdoctoral stints at the University of Bonn, Germany; the University of California, Santa Barbara; and Stanford University. She became affiliated with Academia Sinica in 2013 and began joint appointments at MPA and TUM in 2016. In 2018, she held an Emmy Noether Visiting Fellowship from the Perimeter Institute in Waterloo, Ontario, Canada. She has published more than 90 research articles in peer-reviewed journals.
(Text was drafted/written by Rick Fienberg at the AAS; https://aas.org/press/holy-cow-sherry-suyu-receive-2021-berkeley-prize).

## Clarivate Citation Laureates for 2020

Simon D.M. White together with Carlos S. Frenk and Julio F. Navarro have been named Clarivate Citation Laureates for 2020 for their fundamental studies of galaxy formation and evolution, cosmic structure, and dark matter halos. The theoretical astrophysicists are among 24 new Citation Laureates with significant contributions in one of the four Nobel Prize areas named this year.

Since 2002, Clarivate has named Citation Laureates in the areas recognized by the Nobel Prize: Physiology or Medicine, Physics, Chemistry and Economics. While Citation Laureates, as the designation implies, exhibit exceptionally high levels of citation among their peers and have produced multiple highly cited papers, this is only a prerequisite for selection. The selection committee also assesses if they have contributed to science in ways that have been transformative, even revolutionary.

In 1996 and 1997, Navarro, Frenk & White have published two papers with citations in the thousands: “A Universal Density Profile from Hierarchical Clustering” has been cited more than 7200 times, “The Structure of Cold Dark Matter Halos” has been cited more than 5600 times. In fact, the NavarroFrenkWhite (NFW) profile for the spatial mass distribution of dark matter halos in N-body simulations, named after the three researchers, has become the standard description of the structure of dark matter halos, the basic building blocks of all cosmic structure.

In his research, Simon D.M. White focuses on the structure, formation, evolution and clustering of galaxies; dark matter and dark energy; gravitational dynamics, the simulation of cosmic structure formation; and cosmology as a whole. In 1994, he was appointed Director of the Max Planck Institute for Astrophysics, Garching, and is emeritus director since 2019. White has received many awards and honours, among them the Gold Medal of the Royal Astronomical Society in 2006, the Gruber Prize in Cosmology in 2011 together with Carlos Frenk, Marc Davis and George Efstathiou, and the Shaw Prize 2017 in Astronomy.

## Rashid Sunyaev as new member of INSA

The Indian National Science Academy (INSA) has announced the election of 39 new Academy members and five foreign fellows. One of the newly elected foreign fellows of INSA is Rashid Sunyaev, director emeritus at the Max Planck Institute for Astrophysics.

INSA’s announcement of the election results states: ”Professor Sunyaev has done pioneering work in the fields of theoretical astrophysics, X-ray astronomy, and cosmology. He, along with Zeldovich, developed the theory of primordial perturbations propagating soon after the Big Bang. Later with Shakura, he developed a model for the accretion of matter onto a black hole. The Shakura-Sunyaev model proved to be very influential and is now widely regarded to be the key theoretical cornerstone for black hole studies.”

Rashid Sunyaev is a member of the Russian Academy of Sciences and of the National Academy of Sciences of Germany ”Leopoldina”, a foreign member of the USA National Academy of Sciences, the Royal Society (London), the Royal Academy of Sciences and Arts of the Netherlands and a number of others Academies. In 2014, the Chinese Academy of Sciences elected R.A. Sunyaev as its Einstein professor.

The National Science Academy of India is the state academy of sciences in India, a country with a rapidly and successfully developing science. India is the second-most populous country in the world and the sixth-largest world economy.

### Otto Hahn Medal for Jens Stücker

During its general meeting, the Max Planck Society announced that former MPA PhD student Jens Stücker receives one of the Otto Hahn Medals for the year 2020. The prize is awarded for numerical investigations of the dark matter phase-space structure in the smallest halos, thereby allowing to better distinguish between Warm and Cold Dark Matter.

The nature of the dark matter, the dominant material component of today's universe, is a mystery. All known particles are excluded, and currently popular speculations for new particles include Cold Dark Matter (for example, an axion) which predicts dark matter haloes to form down to very low mass, and Warm Dark Matter (for example, a sterile neutrino) which predicts no structures less massive than the dark halo of a small dwarf galaxy. In his thesis, Jens Stücker has developed new numerical techniques which, for the first time, make it possible to simulate the formation and internal structure of the lowest mass halos with sufficient accuracy that astronomical observations should be able to distinguish definitively between Warm and Cold Dark Matter.

After his studies of physics at the Technical University of Dortmund and the Ludwig-Maximilians-University of Munich, Jens Stücker came to the Max Planck Institute for Astrophysics (MPA) in 2015 to write his doctoral thesis on "The Complexity of the Dark Matter Sheet". Already during his time as a doctoral student, he was honoured with the Kippenhahn Prize in 2018 for the best scientific student publication (together with his colleague Aniket Agrawal). Since September 2019, he has been doing postdoctoral research at the Donostia International Physics Center in San Sebastian, Spain.

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

### Gruber Cosmology Prize for Volker Springel

Great honour for Volker Springel: the director at the Max Planck Institute for Astronomy has been awarded the 2020 Gruber Cosmology Prize for his defining contributions to cosmological simulations (1.5). Springel shares the $500,000 prize with Lars Hernquist of the Harvard-Smithsonian Center for Astrophysics. The researchers have developed methods to test existing theories about the formation of structures at every scale from stars to galaxies to the universe itself. Springel and Hernquist developed numerical algorithms and community codes which are used by many other researchers today.

Using computational simulations, Volker Springel and Lars Hernquist have also tested theories relating to cold dark matter and dark energy. The former is invisible and comprises roughly four-fifths of the universe's matter; the latter is a mysterious force causing an accelerated late-time expansion of the universe. In addition, the researchers also investigate how the concert of the two unknowns with ordinary baryons give rise to today's visible structures.

Hernquist and Springel have discovered that simulations are necessary to incorporate so-called feedback - the portion of the outflow of material (such as gas) and energy that feeds back into evolutionary processes. In 2005, working with collaborator Tiziana Di Matteo, they demonstrated that black-hole feedback determines the growth relationship between supermassive black holes and their host galaxies.

Feedback is now a standard component of cosmological simulations at virtually every scale, from stellar evolution over dark matter physics that determines the distribution of superclusters of galaxies into web-like tendrils.

The Gruber Prize also recognizes that Springel and Hernquist have written several codes that cosmologists consider indispensable. For example, in 2001 Springel introduced the programme GADGET, together with Naoki Yoshida and Simon White, which he used in creating the Millennium Simulation - the first dark-matter-only simulation to encompass a representative volume of the universe. The resulting series of images provided a vivid and compelling set of images in the form of a "cosmic web."

The Max Planck researcher also led the creation of AREPO, a moving mesh simulation code, which he and Hernquist subsequently used in the creation of Illustris. This largest astrophysical simulation series in the world presents the development of the universe in unparalleled detail. At the same time, it makes it possible to reproduce the properties of the universe from the largest structures to individual galaxies over almost the entire cosmic history.

In 2018, the international Illustris team released an update of the simulation called IllustrisTNG ("Illustris The Next Generation"), the most comprehensive hydrodynamic simulation of galaxy formation in a representative cosmological volume to date. They also took into account physical processes such as the amplification of cosmic magnetic fields, the production of heavy elements in supernova explosions, or the injection of kinetic energy by gas emitted by black holes.

The German Gauss Centre for Supercomputing allowed the realisation of the three main computations TNG50, TNG100, and TNG300, generating a total of well more than 500 terabytes of simulation data. The scientists will continue to work on the evaluation of this data for years to come. With their work, Volker Springel and Lars Hernquist have given cosmology an important impetus and a new, exciting direction.

## Volker Springel elected Foreign Member of the US NAS

On 27 April 2020, the US National Academy of Sciences announced that MPA managing director Volker Springel is among the 26 newly elected international members in recognition of his distinguished and continuing achievements in original research. Membership is a widely accepted mark of excellence in science, especially as the "bar" for electing Foreign Associates is supposed to be quite high, particularly for well-represented countries such as Germany.

The National Academy of Sciences is a private, nonprofit institution that was established under a congressional charter signed by President Abraham Lincoln in 1863. It recognizes achievement in science by election to membership, and – with the National Academy of Engineering and the National Academy of Medicine – provides science, engineering, and health policy advice to the federal government and other organizations. Current NAS membership totals approximately 2,400 members and 500 foreign associates; approximately 500 current and deceased members of the NAS have won Nobel Prizes. The Proceedings of the National Academy of Sciences, founded in 1914, is a well-established international journal publishing the results of original research.

The research interest of newly elected Foreign Member Volker Springel is in computational astrophysics, where he pioneered large-scale cosmological simulations such as the famous Millennium Simulation in 2005. His research focusses on the fields of cosmology and computational astrophysics, with an emphasis on galaxy formation and the large-scale structure of the Universe. He also studies gas dynamics in the intergalactic and interstellar media, the formation of stars and supermassive black holes, the structure and dynamics of dark matter halos, and works on constraining dark energy.

## Rudolf-Kippenhahn-Award

The best student publications at MPA in 2019 are two supernova papers: Andeas Flörs is awarded with the Rudolf-Kippenhahn-Prize for his paper entitled "Sub-Chandrasekhar progenitors favoured for Type Ia supernovae: evidence from late-time spectroscopy" and Simon Huber for his paper on "Strongly lensed SNe Ia in the era of LSST: observing cadence for lens discoveries and time-delay measurements" (see Fig. 1.7).

**Figure 1.7:** The two Kippenhahn laureates Simon Huber (left) and Andreas Flörs (right) with Simon White, director emeritus at MPA. *(Credit: H.-A. Arnolds, MPA)*

The Kippenhahn prize was established in 2009 and is named in honour of Prof. Rudolf Kippenhahn, former director of MPA, to motivate students to write a good publication. The prize is currently funded by a donation from Simon White. Criteria for the prize are that the student is first author and has contributed substantially to the scientific ideas, calculations and analysis, and the writing of the paper. For 2019, the committee decided to award the Kippenhahn prize to two winners for two very different supernova papers.

In his paper, Andreas Flörs uses late-time ("nebular") spectra of type Ia supernovae to constrain their progenitors. In particular, he uses the differences in the abundances of iron-group elements predicted by the different progenitor channels: only near-Chandrasekhar mass white dwarfs reach the high central densities required to synthesize stable iron and nickel by electron capture reactions. Exploding white dwarfs with lower mass and thus lower central density predominantly produce radioactive 56 Ni instead.

A key diagnostic of the central density is the presence of Ni lines in late-time spectra when all radioactive Ni has decayed. Andreas has developed a method by which the fraction of neutron rich (57 Ni and 58 Ni) material synthesized in the explosion can be determined from optical data alone. This allowed him to model archival type Ia supernovae of the past 30 years. His conclusions are striking: He finds that for reasonable progenitor metallicities the fraction of stable Ni is in agreement with the predictions of sub-Chandrasekhar mass models but rules out Chandrasekhar-mass models as the main explosion channel.

Strongly lensed supernovae are emerging as a new probe of cosmology and stellar physics. Even though lensed supernovae are very rare with only 2 events known so far, hundreds of such events are expected in the upcoming Rubin Observatory Legacy Survey of Space and Time, LSST. Different observing strategies of LSST will highly affect the number of lensed supernovae detected. Simon Huber, in his paper, took on the challenge to answer two important questions: (1) what is the optimal LSST observing strategy for lensed supernovae, and (2) how well can the time delays between the multiple images of microlensed supernovae be measured for cosmological studies?

The main conclusions from his thorough analysis are that the current LSST observing strategies are insufficient to provide precise time delays for most of the lensed SN Ia systems. Therefore, he is advocating for using LSST as a discovery machine and obtaining follow-up observations for precise time-delay measurements within 5% uncertainty. This paper is one of the A&A highlighted papers across all areas of astronomy and astrophysics published in 2019.

### 1.3.5 The Corona Crisis at the MPA

The year 2020 will be remembered forever as the beginning of a global pandemic due to the corona virus SARS-CoV-2. Few parts of the world have been spared from this severe health crisis, and of course, MPA has been deeply affected by it as as well.

First news about a new contagious corona virus appeared in January, but initially few people realized the potential danger this represented for the whole world. This began to change when first cases and fatalities were also reported in Europe. The particularly deadly initial outbreak in Italy sent a chilling signal that something dramatic and frightening was happening. Towards the end of February, the spread of the virus dramatically accelerated also in Germany, helped by super-spreader events associated with carnival celebrations and parties in skiing resorts.

On March 1st, the MPA along with all MPG institutes needed to cancel all large institute events and prohibit any business trip to risk areas. By March 12, we asked everyone to work in home office as far as possible, all institute seminars were cancelled, and all domestic business trips were put on hold, too. At the same time, public life came to a near stand-still. This was a situation unlike anything we had experienced before at the institute, and it took until the end of March before we somewhat recovered from the initial shock, and restarted collaborative work and institute seminars via videoconferencing.

In the beginning, there was still the widespread belief that the spell of this virus would soon be over, no later than late Spring. The prospect that even a full year later that would not at all be the case seemed incomprehensible early in 2020, but as we now know this is exactly what happened.

Over the course of 2020, we have introduced and got used to hygiene concepts, social distancing rules, mask wearing duties, single-occupancy office policies, air cleaning devices, quarantine rules, rapid test regimes, virtual coffee meetings, and more. With these measures, MPA could remain open and fully operational throughout the crisis, thanks to the enormous efforts and the dedication of our secretaries, our IT staff, and the general MPA administration. We even managed to welcome new institute members and integrate them into our scientific work during this time of crisis.

Still, doing science in home office without daily personal interactions with colleagues has been a dreadful experience for most, especially for students and postdocs. Instead of experiencing one of the most intense and social periods of their lives, they were relegated to working lonely at home, with videoconferencing being only a poor replacement for the social interactions and candid discussions that are possible in personal meetings.

In addition, countless opportunities to discuss science at conferences, workshops and seminars were just gone completely. And the impact of the corona virus on the institute's social life has been equally devastating. No summer barbecue, no institute hike, no birthday celebrations, no farewell parties, no celebrations of scientific prizes, not even a Christmas party.

It is no surprise that all of this had a negative impact on motivation and scientific productivity, especially among the young scientists, who suffered the most from the reduction in the daily contacts with supervisors and peers that the corona crisis produced. It also caused serious mental health problems for many institute members. It will be a huge challenge for the institute to recover from this blow to the very foundations of how we work and live.

At the moment, the corona crisis still rages on, but there is light at the end of the tunnel through the availability of effective vaccines. We can only sincerely hope that at the end of the crisis it will still be true that only a small number of MPA members has become ill from the corona virus, and that these were all mild cases. It is in any case clear that this cataclysmic event will have a lasting impact on the way we do science.

### 1.3.6 Public Outreach 2020

The pandemic severely affected public outreach efforts at MPA. The first event that had to be cancelled was the annual Girls Day; also the Open Day in autumn could not take place. All public visits and in particular the planetarium shows had to be cancelled from March onwards, so that only one school group with 30 visitors was able to experience a journey "from the skies over Garching to the beginning of the Universe".

Nevertheless, the online activities continued to showcase the ongoing scientific work at the institute. The monthly highlights serve to popularize MPA science to a wide audience and 25 web news and press releases were issued about astonishing scientific results, awards and honours for MPA researchers, as well as project milestones. MPA scientists also acted as interview partners for press, TV, and radio journalists, and gave (online) talks for a wider audience.

### 1.3.7 Sustainability at MPA

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

As much as many of us are tired of virtual meetings per video conference, it had a positive effect on our institute's carbon footprint concerning travel. For the pre-Corona year 2019 we did a rough calculation of MPA's $CO_2$ footprint and identified as main contributions travel by plane and computing. When adding up all flights within Germany, Europe and worldwide


**Figure 1.8:** Beaver in the back garden of MPA transporting a gnawed tree trunk *(Credit: MPA/Andreas Weiss)*

we got the sum of 480t $CO_2$, a number that was reduced in 2020 due to Corona related travel restrictions by 80%.

The main part of our $CO_2$ emissions is high performance computing which adds up to 1000t $CO_2$ per year. Three quarters of that amount is due to services used by MPA at MPCDF where we used 2500 MWh of electricity, while the other quarter is used by our own computing center at MPA and all other electrical devices in our institute including laptops and coffee machines. Another 616 MWh are used for heating of our institute, of which about $1/3$ is delivered by district heating via natural gas and the other $2/3$ by geothermic heat which causes about 50t of $CO_2$ emissions. Due to good public transport to Garching we have less then 10% of people coming by car to the institute and assuming an average of 2.5t $CO_2$ per year per person commuting adds about another 30t of $CO_2$ to our budget. We estimate that the power needed for computing remained the same also in 2020, and that commuting to MPA by car dropped by about 50% in 2020.

Some of the changes during the last 2 years at MPA included a reformed waste management, to collect and separate recyclable waste in central collection bins per floor, an enhancement of biodiversity in the grounds by allowing wild flower meadows to flourish and planting fruit trees for the local colony of bees. We knew for quite a while that a beaver living in our backyard creek cuts down trees and we protected the bigger ones now with wire mesh fence. Recently, we filmed the beaver at night pulling previously cut tree trunks into the creek.

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.

# 2 Scientific Highlights

## 2.1 Our Milky Way not a typical spiral galaxy

In the Milky Way, stars in the central regions move on elongated orbits, which collectively form a structure called a "stellar bar" cutting through the centre of our galaxy (see Figure 2.1). Furthermore, when the disc of the Milky Way is viewed from the side, the bar appears to have a distinctive "X", or peanut-shape, leading to it being called a boxy/peanut bulge. (Bulges get their name from the fact that they "bulge", or stick out of, the plane of the disc.) The MPA scientists looked for signatures of such bars and peanuts in their simulations and found that a fair fraction of the simulated galaxies formed these structures. They then explored in detail the properties of these galaxies as a function of their merger history, i.e. how often other galaxies were swallowed up by the simulated Milky Way.

In order to match the highly ordered rotation of stars in the Milky Way, the simulated galaxies must have had a very "quiescent" merger history in the last 12 billion years. This means that no galaxy with a mass larger than 10% the mass of the Milky Way can have collided with our Galaxy in this time. This is because when a massive galaxy collides with another, the orbits of their stars get "messed up", which leads to less ordered motion, and therefore higher velocity dispersion. As galaxies are built up by small galaxies merging into each other and forming bigger and bigger structures over time this means that the Milky Way has to be a very isolated, and therefore rare, galaxy in the Universe. The scientists found that only 2 out of 40 of their simulated galaxies have properties matching the Milky Way, further pointing to the fact that our home galaxy is probably an "outlier" in the grand scheme of galaxy formation.

This study helps place constraints on a rather cataclysmic event in the life of our Galaxy. From the groundbreaking second Gaia data release (Gaia DR2), it was discovered that the Milky Way likely underwent a merger with another galaxy (dubbed Gaia Enceladus) about 9 billion years ago, which is thought to be the last significant merger in the Milky Ways history. However, the mass of Gaia Enceladus is still being debated. Therefore, with this study, MPA scientists are able to place an upper limit on the mass of Gaia Enceladus, showing that it could have only been up to 10% as massive as the Milky Way, and was likely as small as 3%.

Furthermore, the scientists traced where stars in the inner regions of their best-matching simulated Milky Ways were born and they found that over 99% of these stars were born "in-situ", i.e. in the disc of the Milky Way (see Figure 2.2). This is contrary to what scientists had assumed previously, namely that the stars in the inner regions of the Milky Way, i.e. the so-called bulge, were formed in other galaxies that smashed onto the Milky Way.

The MPA scientists also examined how the bars affect the outer parts of their host galaxies and found that they create ripples and undulations in their host discs. Such ripples have also been discovered in the disc of the Milky Way with Gaia DR2, and the scientific community is still struggling to explain how they were formed. By comparing some specific features in the ripples, which arise at given locations in the disc depending on the bar rotation, the scientists will be able to determine how fast the

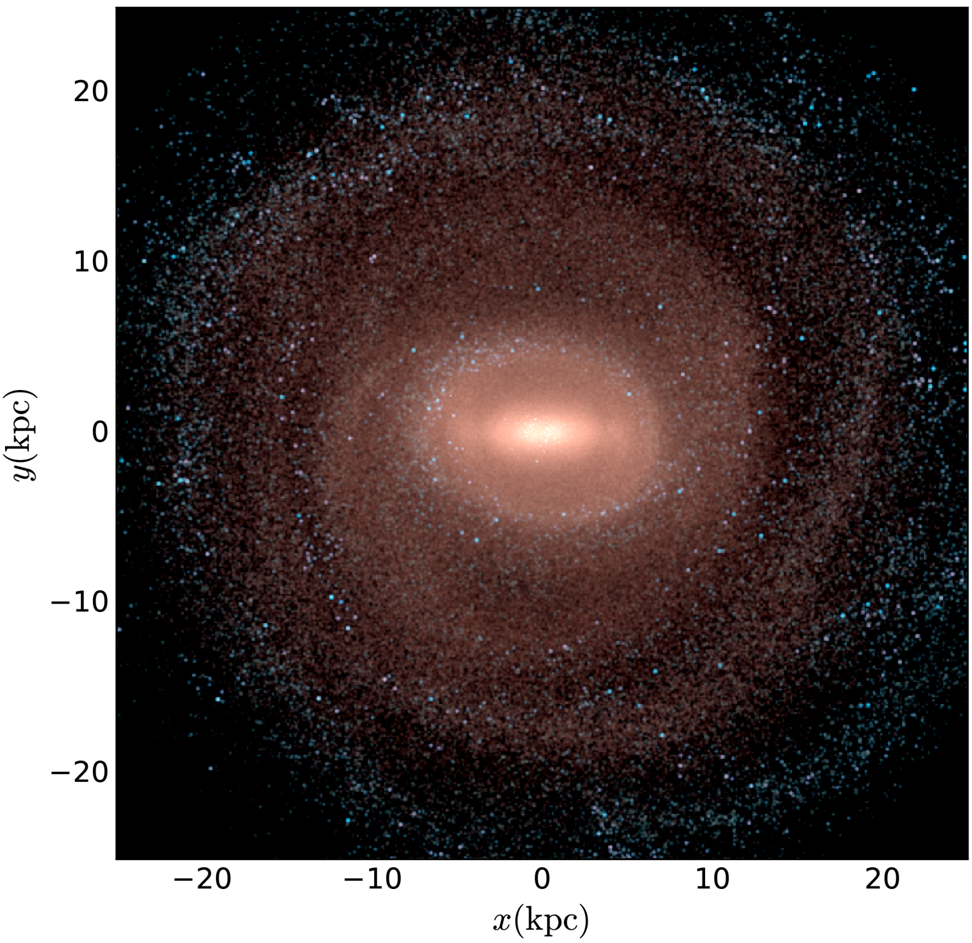


**Figure 2.1:** The simulated galaxy from the Auriga suite in this image is similar to our Milky Way: in shows a clear spiral structure with an elongated stellar bar at the centre. *(Credit: MPA/Auriga)*

bar of our Milky Way rotates. This will help to explain what gave rise to the observed ripples and undulations we see in the Milky Ways disc, thus deciphering the structure of our host Galaxy. (Francesca Fragkoudi)

## 2.2 Artificial intelligence combined

In astrophysics, artificial intelligence (AI) classifies galaxies, stars, and other objects. AI systems help to control telescopes and analyze their data. They process amounts of data no human would even remotely able to handle. In addition, AIs are increasingly used outside of research in almost all areas, from streaming services to provide users with tailor-made suggestions, from autonomous driving to diagnostic systems in medicine.

The training of an AI is complex and expensive. A sufficiently large and pre-classified data set must be assembled. Based on this, a neural network learns to perform a certain task, e.g. estimating the age of a depicted person. AIs can also be trained to generate realistic examples, exhibiting characteristics of the training data, for example high-quality portraits. Dur-

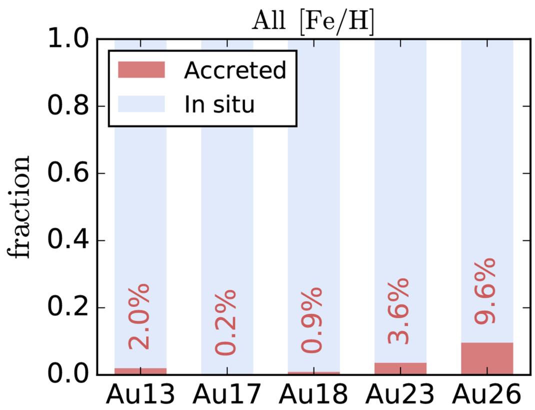


**Figure 2.2:** For five simulated galaxies, this plot shows where the stars in the inner regions were born: either in other galaxies that merged with the galaxy (a small fraction) or in-situ (the vast majority). *(Credit: MPA)*

ing the intensive learning process, networks internalize characteristic features and concepts of the studied faces or other objects. Thus, the networks become representatives of the trained concept. Making the insights of the trained networks available for other tasks is a subject of current AI research.

In the Information Field Theory Group at the Max Planck Institute for Astrophysics, the researchers Jakob Knollmller and Torsten Enlin have now succeeded in combining already trained networks in a way to jointly master tasks, none would have been able to on its own. The manner of combining the networks is completely generic and can be used for many different applications without having to train a new network. A so-called generative network is intelligently combined with one or more classifying networks to generate examples that fulfill the required properties. This way elaborate questions can be asked.

For example, an AI for generating faces can be combined with AIs for determining the age and gender of photographed persons. The combined AI then generates a set of possible images of persons that are consistent with incomplete

**Figure 2.3:** The image on the left shows the original (artificial) person, which is to be reconstructed from the noisy and incomplete data on the right with the additional information of age and gender. *(Credit: MPA)*

**Figure 2.4:** Possible images of the female, 30-year-old person reconstructed using the noisy data in Fig. 2.3 *(Credit: MPA)*

and noisy data of a face (Fig. 2.3 and 2.4 ). Since there is usually no certainty on the correct solution for tasks of this kind, this set of images contains the AI's answer. From them, an average image and its uncertainty can be calculated if required (Fig. 2.5).

To integrate different types of information, the combined AI employs the so-called Bayesian logic, which uses probabilities instead of the binary true or false of mathematical logic. Bayesian probabilities allow to include uncer-

**Figure 2.5:** Left: Averaged image of the possible faces. Right: Remaining uncertainties, where white denotes a higher uncertainty. *(Credit: MPA)*

tain knowledge; in the example here, this would be the information that the person is probably a woman and about 30 years old. Bayesian probabilities optimally support the handling of incomplete and noisy data, such as the rough input image. The various specialized neural networks used to solve a task enter the procedure through probability functions.

The idea of combining AIs with Bayesian logic is not new. However, technical difficulties have until now prevented its realization. The Garching-based researchers were able to overcome this hurdle thanks to a new method originally developed for improved image reconstruction in astronomy. This procedure, called Metric Gaussian Variational Inference (MGVI), allows to perform very large reconstructions, with millions upon millions of unknown quantities, without losing sight of their manifold interdependencies. A first application of MGVI was the three-dimensional reconstruction of the distribution of galactic dust using information field theory.

The researchers have now shown how MGVI can be used to combine individual, highly specialized AIs into logically deductive and thus versatile intelligences. In addition, imaging procedures in astronomy, medicine, and other fields can now directly access expert knowledge stored in AIs without having to re-train these on the characteristics of a new measuring instrument. These expert AIs can contribute their knowledge in various specialized applications, such as tumor detection in medical imaging. (Torsten Enßlin)

## 2.3 L-GALAXIES 2020: Modelling millions of galaxies across billions of years

The key power of L-GALAXIES is it's efficiency. The model runs tens of thousands of times more quickly than the latest hydrodynamical simulations, even though its size is hundreds of times larger. This comes with limitations in the way the dynamics and morphologies of galaxies can be modelled, but allows scientists to precisely pin down the true impact and efficiency of the key astrophysical processes such as gas cooling, star formation, and supernova & black hole feedback, by using sophisticated statistical techniques to constrain their key parameters.

L-GALAXIES 2020 is the first model of its kind to simultaneously incorporate physical prescriptions for molecular hydrogen formation, chemical element production, and the flow of material within radially resolved galaxies. These enhancements have added a completely new dimension to studies that can be carried out. For example, scientists can now use L-GALAXIES 2020 to interpret data on the internal distribution of gas and stars within real galaxies provided by integral field units (IFUs) mounted on powerful ground-based telescopes.

The ability to resolve galaxies spatially is critical for modelling the transition from atomic to molecular gas in galaxies. Molecular gas formation is believed to depend on gas density, occurring predominantly in the densest regions near the centres of galaxies. In order to follow the formation of molecular hydrogen correctly, it is therefore necessary to accurately track the surface density of cold gas.

**Figure 2.6:** A portion of deep space from the L-Galaxies computational model. This image was made using the MRObs virtual observatory, which selects galaxies of known position, mass, age, size, etc., from the model, assigns them random inclinations, and computes their observed colour as it would be seen by the Hubble Space Telescope. *(Credit: R. Overzier & G. Lemson, see Overzier et al. 2012)*

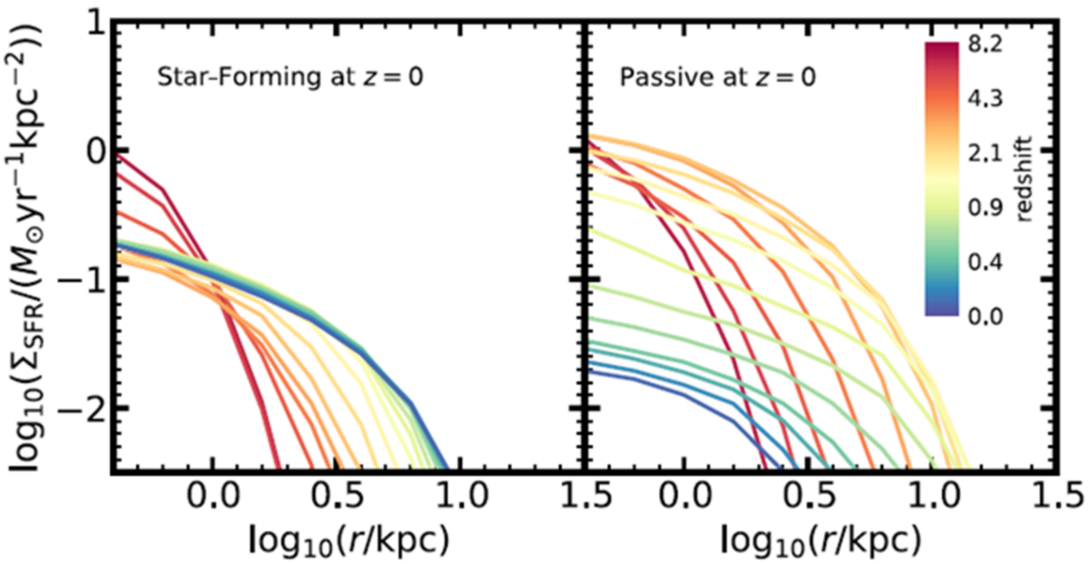


**Figure 2.7:** The two plots show the star-formation-rate density with respect to the distance from a galaxy centre for star-forming galaxies similar to our Milky Way (left panel) and more massive, passive galaxies (right panel). The colour indicates model galaxies in L-GALAXIES 2020, from redshift 8.2 ($\sim$13.2 billion years ago, red lines) down to redshift 0 (the present day, blue lines). Over time, the density of star formation decreases in the centre and increases at edges of the Milky-Way-like galaxies. This is known as 'inside-out growth'. The more massive galaxies exhibit a similar evolution to Milky Ways at first; however, by redshift $\sim$2 their overall star formation starts to decrease greatly, due to the onset of supermassive black hole feedback. *(Credit: Henriques et al. 2020)*

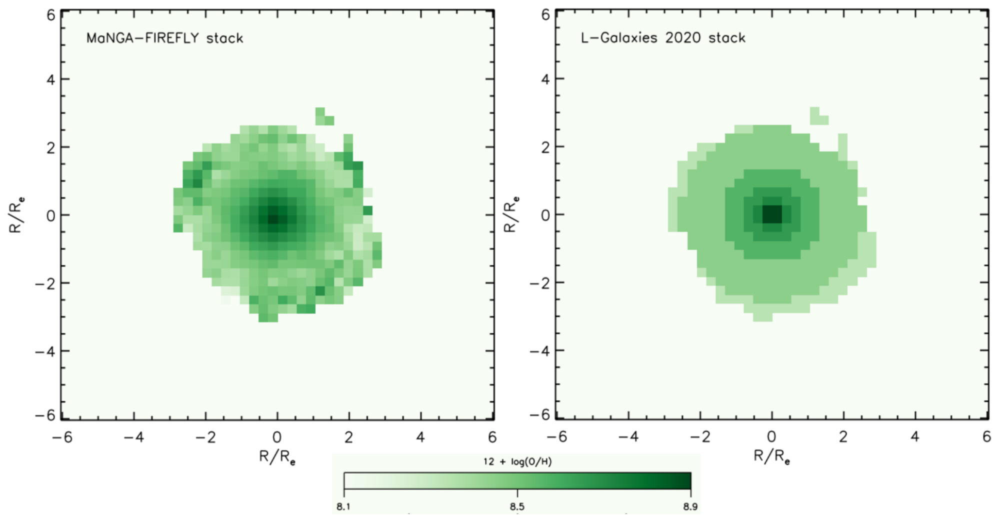


**Figure 2.8:** Stacked maps of the distribution of oxygen atoms in nearby galaxies. Left panel: Real galaxies from the FIREFLY sample (Goddard et al. 2017) observed using the MaNGA IFU. Maps from each galaxy are stacked together to get this composite map showing the typical distribution of oxygen abundance in the sample. Right panel: The same stacking process as for the left panel is used, but for model galaxies from L-GALAXIES 2020. One can distinguish the discreet annuli that are used to model the radial distribution of properties. The amount of oxygen as a function of radius is very similar to that observed by MaNGA. *(Credit: R. Yates/ MPA)*

## So what has L-GALAXIES 2020 revealed?

Well, the model can simultaneously reproduce both the global properties of galaxies and their internal distribution, but only under certain conditions. Firstly, gas must flow rapidly into the centres of galaxies to replenish the fuel required for star formation, reaching speeds of around 200,000 km/h at the edges of galaxy discs. Secondly, the supernova explosions caused by this star formation must be very efficient in blowing out material in large-scale winds reaching nearly 800,000 km/h. Thirdly, nearly all the newly-formed chemical elements forged in the hearts of stars and their supernovae must be blown out in these winds, before raining back down onto galaxies later on.

This last constraint is crucial to match the observed decrease in chemical abundance (often called 'metallicity') with radius seen in nearby galaxies (see Fig. 2.8). If too little material is blown out of the centres of galaxies by supernovae, then the metallicity, gas density, and star-formation rate can become too high.

The total amount of ionised hydrogen (the most common baryonic matter in the Universe) found in galaxies is also well reproduced by this model; and this is true for galaxies ranging from tens of millions of stars to those containing hundreds of billions. This represents a significant success, since it has been particularly challenging for models to match both the stellar and ionised-hydrogen masses in galaxies in the nearby Universe.

## What is the next step for L-GALAXIES 2020?

Scientists at the MPA are already working on further improvements to the model, including the incorporation of gas stripping in galaxies due to ram-pressure effects as they travel through deep space, and improvements to the

**Figure 2.9:** This image shows a distant quasar being lensed due to gravity into five images. The galaxy cluster creating the lens is known as SDSS J1004+4112 and is one of the more distant clusters known (seven billion light-years, redshift z=0.68). Astronomers are using this phenomenon to learn more about the properties of dark matter. *(Credit: ESA, NASA, Keren Sharon, Tel-Aviv University, and Eran Ofek, CalTech)*

modelling of the all-important gas flows within galaxies. The model is now also being used to study the higher-redshift Universe, to decipher how the metallicity gradients formed in the earliest and most distant galaxies evolved over time to become what we see today. So stay tuned for more exciting discoveries soon!

The output data from L-GALAXIES 2020 is now also available online to download via the Millennium Database (log-in required). This online database represents a tremendous resource for other scientists across the world to study model galaxies as they evolve over billions of years of cosmic time, and compare their properties with galaxies in our own Universe. (Robert Yates)

## 2.4 Taking the Temperature of Dark Matter

We have very little idea of what dark matter is, and physicists have yet to detect a dark matter particle. But we do know that the gravity of clumps of dark matter can distort light from distant objects. MPA scientists and their colleagues at UC Davis are using this distortion, called gravitational lensing, to learn more about the properties of dark matter.

The standard model for dark matter is that it is cold, meaning that the particles move slowly compared to the speed of light. This is also tied to the mass of dark matter particles. The lower the mass of the particle, the warmer it is and the faster it will move.

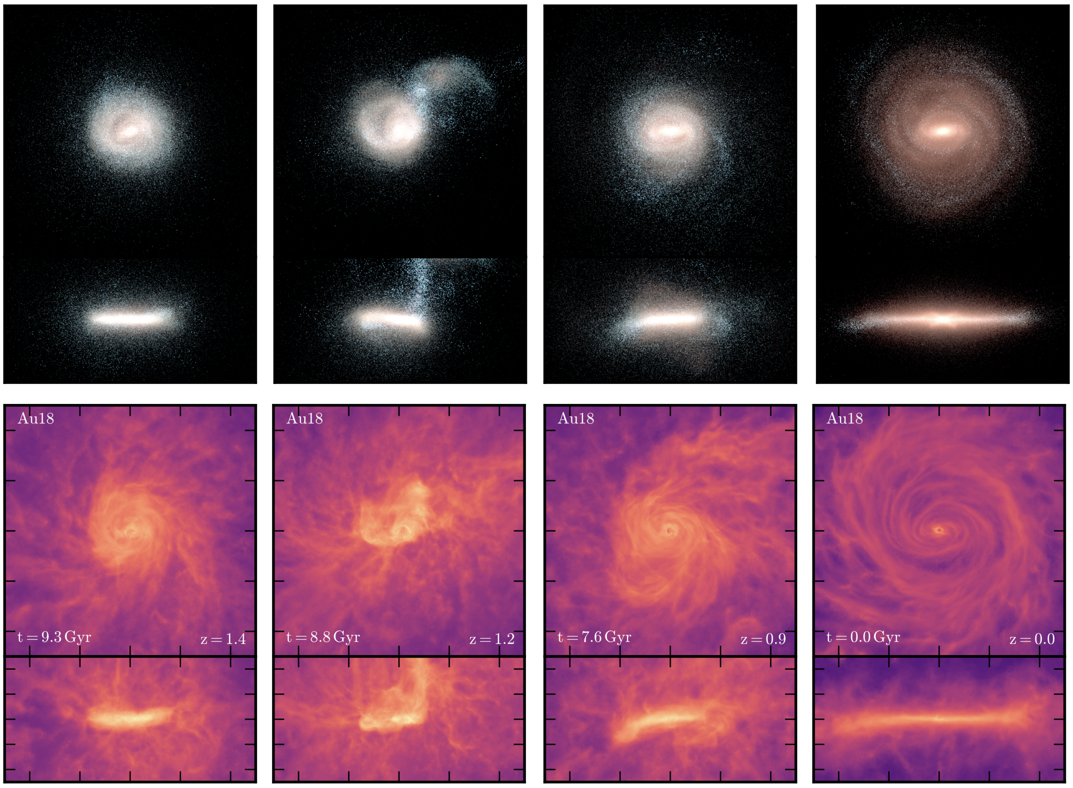


**Figure 2.10:** Thumbnail gallery of the stellar light (top panels) and gas density (bottom panels) of a simulated Milky Way analogue immediately before (first panel), during (second panel), immediately after (third panel) the Gaia-Enceladus merger, and at present day (fourth panel). The merging galaxy brings a lot of gas that fuels a burst in star formation beginning along a bridge of gas connecting it to the Milky Way. *(Credit: MPA)*

The model of cold (more massive) dark matter holds at very large scales but it is unclear if models including warm dark matter are preferred on the scale of individual galaxies. Hot dark matter with particles moving close to the speed of light has been ruled out by observations.

## A limit on the mass of dark matter

The astronomers now used gravitational lensing to put a limit on the warmth and therefore the mass of dark matter. They measured the positions and brightness of seven distant gravitationally lensed quasars to look for changes caused by additional intervening blobs of dark matter. Their lens models included both stellar discs and luminous satellites as well as low-mass dark matter haloes located along the observed lines of sight for the first time. The scientists used these results to measure the size of these lenses and found that about 1% of mass can be found in such dark matter substructures. If dark matter particles are lighter, warmer and more rapidly moving, then they will not form structures below a certain size.

The results put a lower limit on the mass of a potential dark matter particle ($m_{th} > 5.58 keV$, i.e. at least the energy level of nuclear fusion systems) while not ruling out cold dark matter. The teams results represent a major improvement over a previous analysis, from 2002, and are comparable to recent results from a team at UCLA. Adding more lensed objects to the survey will improve the statistical accuracy in the future. (Andi Fell, UC Davies and Simona Vegetti)

## 2.5 Stellar clues reveal properties of significant merger in the young Milky Ways history

The chronicle of the Milky Way is written in starlight: the history of our Galaxy can be deciphered from observing its stars and characterising their properties. For example, stars tend to be born on circular orbits around the Galactic centre, but over time they can begin to orbit on more oval, elongated trajectories, especially under the gravitational strains imposed during a galaxy merger, which may itself provide its own stars on near-radial orbits. In 2018, astronomers analysed the positions and velocities of stars observed by the Gaia satellite and discovered that the Milky Way had experienced a significant merger (Gaia-Enceladus) in its distant past. Stars that belonged to this merger were clearly identified to be on very radial (eccentric) orbits and make up a significant portion of the stellar halo - the faint light surrounding galaxies that constitutes the stellar garbage of debris from previously destroyed galaxies.

### What was the Milky Way like before this cataclysmic event and how did it change?

This question can only be answered with the help of simulations. Researchers at MPA have played a leading role in developing the Auriga simulations - the largest suite of simulations for the formation of the Milky Way in our Universe that model physical processes such as star formation, supernovae, black holes and magnetic fields. These tools provide powerful insights by offering a realtime look at the formation and evolution of galaxies, akin to watching a film that starts just after the Big Bang and ends at present day.

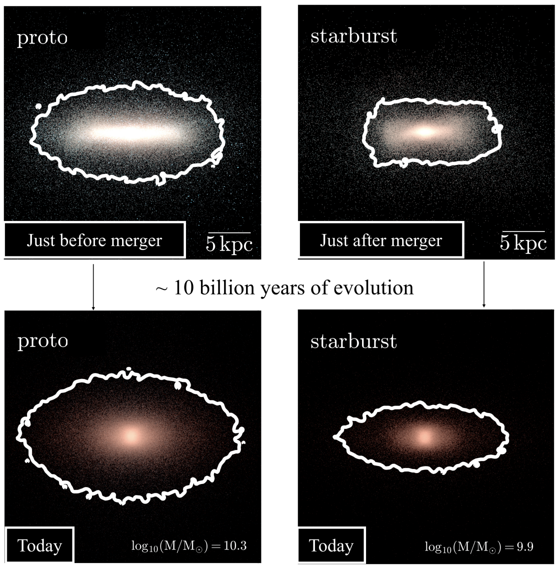


**Figure 2.11:** Left: Edge-on images of the simulated Milky Ways proto-disc stars just before the merger event around 10 billion years ago (top) and at present day (bottom), depicting how disc stars are being scattered into the stellar halo as a result of the merger. Right: Images of stars formed during the merger-induced starburst immediately after the merger (top) and at present day (bottom), illustrating that these stars are flatter and diskier compared to the proto-disc. *(Credit: MPA)*

MPA scientists analysed these sophisticated simulations and found that about a third of the Milky Way analogues produced the Gaia-Enceladus feature in their stellar halo (see also the January Highlight for how MPA researchers revealed how this event shaped the Milky Ways central stellar bar). In each case, this was linked to a significant merger in the Galaxys youth (Fig. 2.10). They found that the mergers had 2 significant effects: i) the merging galaxies were always gas-rich, bringing in a lot of fresh, star-forming material that instigated a powerful burst of star formation; and ii) the Milky

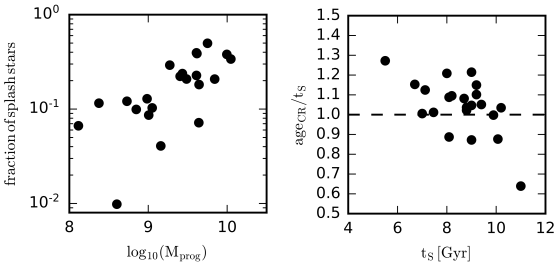


**Figure 2.12:** Left: the fraction of counter-rotating splash stars as a function of stellar mass of the Gaia-Encaladus analogues; a more massive merger leads to a greater fraction of splash stars. Right: the age of splash stars divided by the actual merger time as a function of merger time; most of the data points lie within 10% of the true merger time. This demonstrates that astronomers should be able to date the merger event from careful analysis of these splash stars. *(Credit: MPA)*

Ways proto-disc - the dominant component of its adolescence - suffered serious damage from the impact, losing a hefty fraction of its mass as stellar orbits were splashed out of the disc toward the edges of the visible stellar halo (Fig. 2.11). Nevertheless, some of the proto-disc survived, and, together with the stars formed during the burst of star formation, constitute what astronomers call the thick disc - one of the Galaxys most significant components today.

### Dating and weighing the Gaia-Enceladus merger

Thanks to the large suite of simulations, it was possible for the researchers to measure the impact of many analogue mergers with a range of masses and merger times. A key diagnostic is the fraction of stars orbiting the Galaxy in the direction opposite to the bulk rotation - stars that have been splashed out of the proto-disc because of the strong gravitational perturbation of the merger. Scientists found that more massive mergers lead to a higher fraction of these counter-rotating splash stars and that the ages of these stars are an accurate predictor for the time of the merger (Fig. 2.12).

Importantly, these results highlight that with an accurate census of counter-rotating stars and precise stellar ages in the real Milky Way, astronomers can place tight limits on key properties of this event. Comparing with recent Milky Way observations, these latest results point to a Gaia-Enceladus merger with a mass of about a billion Suns that merged roughly 10 billion years ago. In the future, more expansive observations and simulations will help us understand one of the biggest chapters in our cosmic history in tantalising detail. (Robert Grand)

## 2.6 Toward robust and optimal cosmology from galaxy clustering

Large galaxy surveys are an extremely important tool for cosmologists, as they allow us to construct a map of the galaxy distribution over a significant fraction of the observable universe (Fig. 2.13). Such a map contains information on the expansion of the universe, dark energy, dark matter, as well as the early universe. This is the main motivation behind major efforts such as the recently completed Sloan Digital Sky Survey (SDSS) and the European satellite experiment Euclid that is currently under construction. MPA members are participating in both surveys.

The major challenge in interpreting these maps of the universe is that we need a robust model connecting the galaxies to the underlying matter distribution (mostly dark matter). Both theoretical and numerical calculations allow for a reliable prediction for the matter distribution. Galaxy formation is an extremely complex process that we do not understand in detail - and cannot fully simulate either. So how can we hope to extract reliable information about the underlying matter density field and the history of the universe using these objects?

Recently, researchers at MPA have made significant progress by deriving a prediction for the

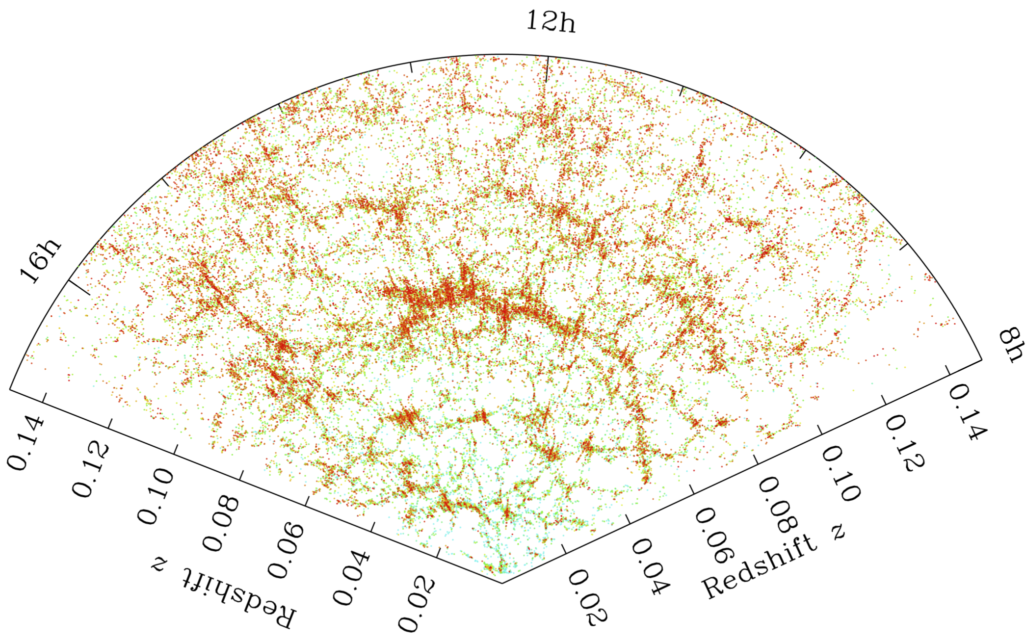


**Figure 2.13:** A slice through the distribution of the main galaxy sample in the northern part of the SDSS survey, with the observer situated at the bottom center (redshift = 0). Each dot depicts the position of a galaxy, with color chosen to represent the actual color of the galaxy (i.e. red dots correspond to redder galaxies). *(Credit: Michael Blanton and the Sloan Digital Sky Survey (SDSS) Collaboration.)*

statistical relation between matter and galaxies within a theoretical framework known as effective field theory. This prediction, technically a conditional likelihood, is based on the fact that gravity (as described by Einstein's General Relativity) is the only relevant force on the extremely large scales on which galaxy clustering is measured. Galaxies are relatively small objects when compared to those scales.

The price paid for this rigorous prediction is that it introduces a set of free parameters that capture the details of galaxy formation, and which we cannot predict. These "nuisance" parameters need to be determined from galaxy data, similar to how we estimate the cosmological parameters of interest, such as those that describe the expansion rate of the universe and the properties of dark energy. Fortunately, there is a well-defined set of these free parameters, and the data are expected to be rich enough to constrain both galaxy and cosmological properties at the same time.

The MPA team, along with European colleagues, are now working on taking this approach closer to data. This work is done in the context of the Aquila consortium. The basic idea is to randomly generate likely matter distributions in the observable universe, which we know how to do based on theory, and compare those with the observed galaxy distribution using the statistical relation derived in the effective field theory. This is done using a statistical approach known as Bayesian inference. There are many, many possible matter distributions that could fit our universe, so this is very challenging. Advanced statistical and numerical techniques, however, allow this full Bayesian inference to be feasible even for data sets as big

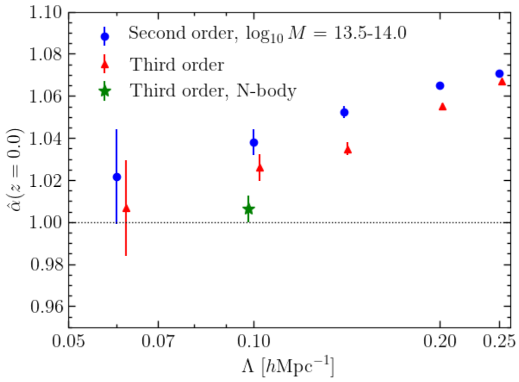


**Figure 2.14:** Ratio of the inferred cosmological parameter (amplitude of matter density fluctuations) to the true value, based on simulated data. A value of 1 corresponds to perfectly accurate inference. The $x$ axis shows the range of scales included in the analysis, with small values corresponding to large scales. The theory is expected to approach the correct answer on large scales (small $x$ value), which is shown to be the case. The blue points show a second-order theoretical prediction, while the red points show the more accurate third-order calculation. The green point uses a more accurate theoretical prediction for the matter density. *(Credit: MPA)*

**Figure 2.15:** Aerial view of the MPA LOFAR station. *(Credit: Rainer Hassfurter/MPA)*

as the SDSS galaxy survey. (Fabian Schmidt)

## 2.7 Towards a LOFAR detection of the 21cm line from the Epoch of Reionization

In the current cosmological framework, the diffuse gas (IGM) in the Universe, was initially very hot and in a highly ionized state. About 450 thousand years after the Big Bang it was cooling down, started to recombine and form neutral atoms. It then remained neutral until the first sources of ionizing radiation, such as stars or black holes formed and started to ionize it once again, about 500 millions years later. This marks a major phase transition in our Universe, which is known as reionization process.

A plethora of observations of distant galaxies, quasars and gamma ray bursts provide estimates of the amount of neutral hydrogen towards the end of reionization, while experiments on the cosmic microwave background radiation give a measure of the abundance of electrons produced by the process. However, observations that map the temporal and spatial evolution of reionization are not yet available.

It has long been known that neutral hydrogen in the IGM may be directly detectable at frequencies that fall in the radio band (in the range $\sim 50 - 200 MHz$) and measurements at different frequencies should allow us to accurately probe the structure and the evolution of the reionizing gas. This experiment is particularly attractive as a new generation of radio telescopes are operational (e.g. LOFAR, MWA, HERA) or under construction (e.g. SKA). The LOFAR core is located in the Netherlands, but several European countries are hosting remote antenna fields. Germany, represented by the GLOW Consortium, has six LOFAR stations. One of these (see Fig. 2.15) has been built and is operated by MPA.

In addition to the LOFAR station, MPA is strongly involved in the scientific exploitation of LOFAR data as MPA scientists are core members of the LOFAR Epoch of Reionization (EoR) Key Science Project. Recently, this

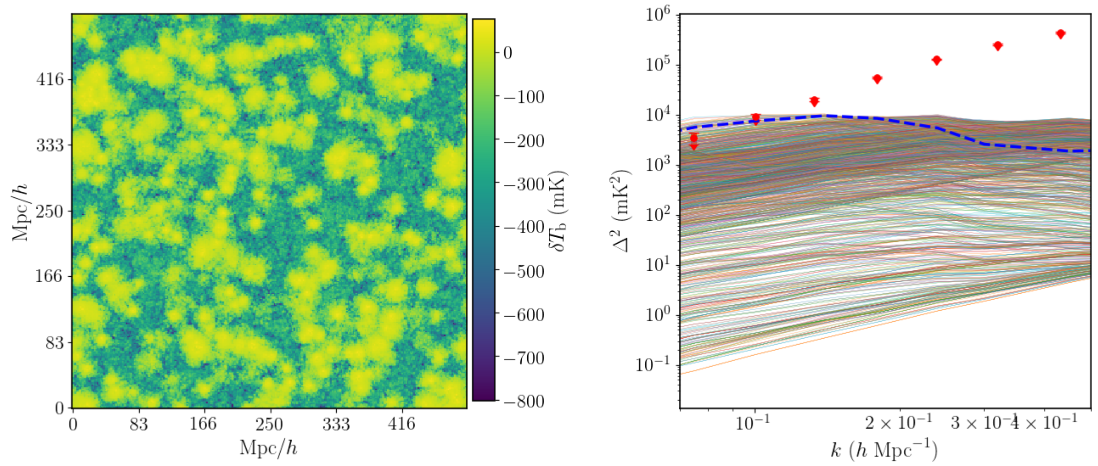


**Figure 2.16:** Left panel: map of 21cm signal at $z = 9.1$ for one of the models studied in Ghara et al. (2020). Right panel: the curves show the power spectra of the 21cm signal at different scales for the 1495 models studied in Ghara et al. (2020). The red points with error-bars show the upper limits from the LOFAR observations by Mertens et al. (2020), while the blue dashed curve represents the model corresponding to the map shown in the left panel. All the models above the observational points are excluded by LOFAR observations. *(Credit: Ghara et al. 2020)*

team has reported an improved upper limit on the 21cm signal from the primordial universe – the characteristic radio signal from neutral hydrogen - as well as its theoretical interpretation.

The analysis is based on 141 hours of data collected with LOFAR in the frequency range 134-146 MHz and gives the best upper limits on the 21cm signal power spectrum of neutral hydrogen at $z = 9.1$, or when the Universe was about 500 million years old. The larger number of hours processed compared to the previously reported upper limit, together with the updated calibration pipeline, show a reduction of a factor of about 8 in the value of the upper limit. This will further improve with the next milestone, which includes future refinements to the signal processing chain and about a 1000 hours of processed data.

Using a combination of state-of-the-art N-body simulations, 1D radiative transfer calculations and a Bayesian inference framework to constrain the parameters, which describe the physical state of the intergalactic medium, the LOFAR EoR team found that the new upper limits are already able to exclude some reionization models (see Fig. 2.16). This exciting result shows that in the near future, once more data will be processed (also at different redshifts), observations with LOFAR of the 21cm line from neutral hydrogen we will be able to constrain the physical properties of the IGM at high redshift and the history of reionization. (Benedetta Ciardi)

## 2.8 How black holes power galactic super-winds

Every massive galaxy is thought to harbour a supermassive black hole in its nucleus. The more massive the galaxy, the greater the mass of the supermassive black hole. Thus, while the Milky Way hosts a black hole with a mass of about four million solar masses, giant galaxies such as M87 contain black holes with masses exceeding a billion times the mass of the Sun.

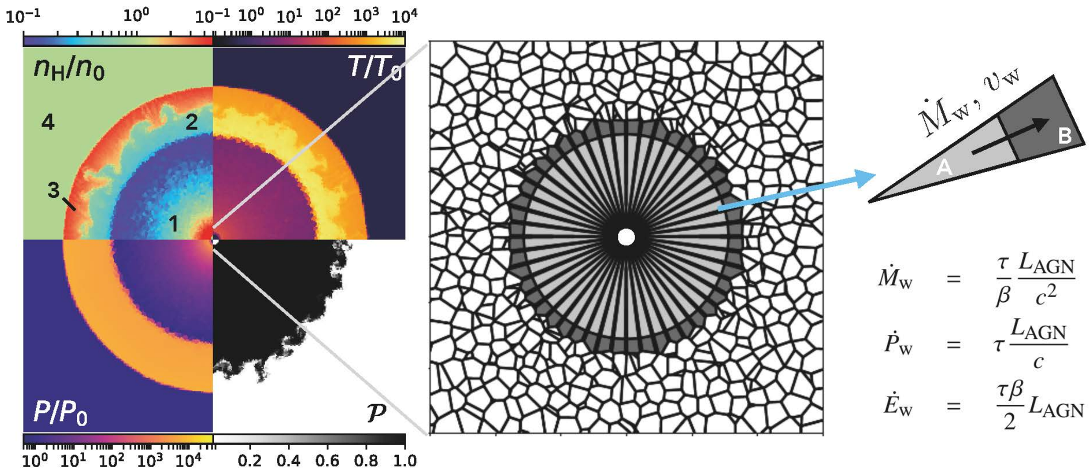


**Figure 2.17:** By arranging AREPO cells in rigid, spherical layers, it is possible to represent accreting black holes as spherical boundaries (central panel). The boundary surfaces are then used to inject a wind with properties in line with those of observed small-scale outflows. When applied to homogeneous media, black hole winds power complex, spherical outflows (left-hand panel). One of the crucial tests to the new model was to verify that the properties of the large-scale, spherical outflows closely agree with theoretical expectations. *(Credit: MPA)*

Supermassive black holes grow by accreting gas from their vicinity. As interstellar gas clouds spiral inwards under the black holes gravitational pull, they accelerate to prodigious speeds. If their kinetic energy is dissipated via friction, it can be liberated in the form of intense radiation or emanate from the galactic nucleus in the form of a wind.

Over the lifetime of a typical supermassive black hole, the total energy liberated via accretion exceeds the binding energy of its host galaxy by a factor of about 100. It takes only 1% of the liberated energy to expel the bulk of the galaxys gaseous reservoir. Without a source of gas, the galaxy is unable either to form stars or to feed its central black hole. Ultimately, supermassive black holes thus may bring about the end of their own growth together with that of their host galaxies.

A small team of scientists based at the Max Planck Institute for Astrophysics (Garching, Germany) led by Tiago Costa has created a new method to accurately model winds launched from the vicinity of accreting supermassive black holes in realistic simulations of galaxy evolution. The new model exploits the irregular geometry of the mesh, on which flows of interstellar gas are represented in the state-of-the-art code AREPO developed by Volker Springel. Unlike in traditional hydrodynamic codes, where fluids are discretised onto Cartesian grids, AREPO solves the hydrodynamic equations on an irregular mesh (Fig. **??**) that is free to move with the gas flow. By arranging AREPO cells in rigid, spherical layers, it is possible to represent accreting black holes as spherical boundaries. The boundary surfaces are then used to inject a wind with properties in line with those of observed small-scale outflows.

After carefully testing the model (see figure **??**), the research team went on to probe the impact of winds driven by supermassive black holes on the evolution of a massive disc galaxy such as the Milky Way. They performed a number of simulations of galactic discs containing, at the centre, a spherical boundary to represent an accreting, supermassive black hole.

While the small-scale winds powered by the

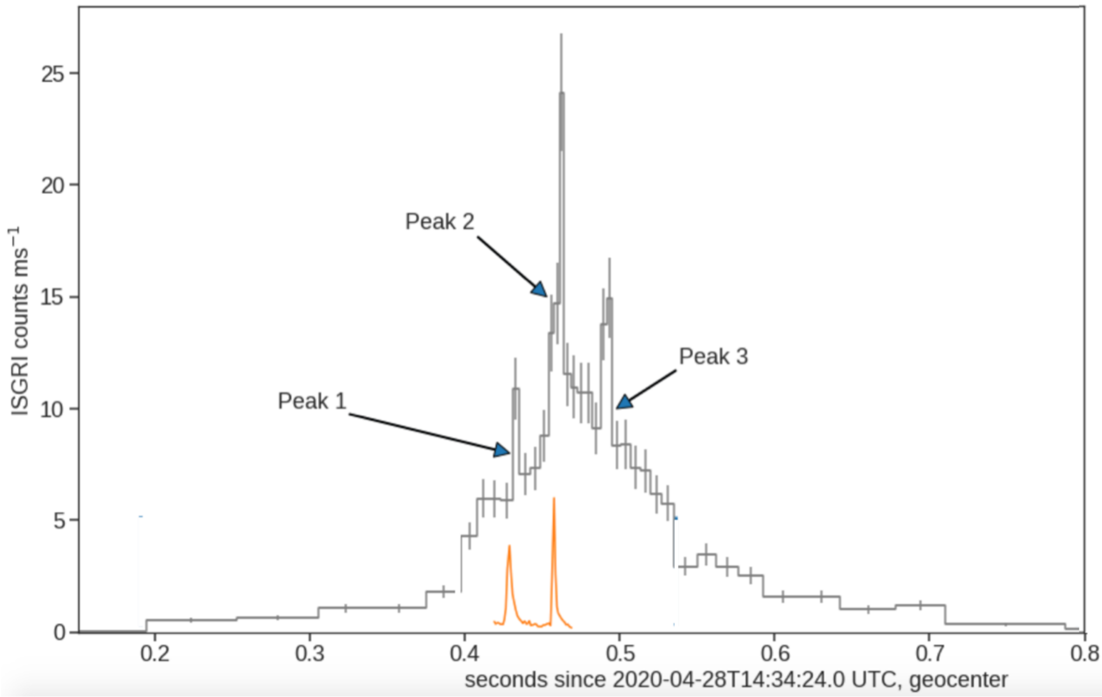


**Figure 2.18:** Two FRBs (orange curve, observed by CHIME) detected during the X-ray burst (black curve, observed by INTEGRAL) from the galactic magnetar SGR 1935+2154 on 28 April 2020. *(Credit: Mereghetti et al. 2020)*

black hole are initially spherical, they are influenced by the geometry of the gaseous environment, having an easier time propagating towards the poles than along the disc. As a result, the winds power large-scale, conical outflows that remove gas from the galactic nucleus as well as from the extended gaseous halo surrounding the disc.

The winds impact the host galaxy through multiple channels. On the one hand, they collide against gas in the galactic nucleus, ejecting it from the galaxy. By clearing out gas in the halo, on the other hand, the winds also prevent new material from replenishing the disc galaxy, slowly starving it off star formation fuel.

The new model for physical, black hole winds makes it possible to shed new light on the multiple mechanisms whereby supermassive black holes impact galaxy evolution. It also permits a completely new treatment for black hole accretion, which can be computed by measuring inflow rates across the boundary, rather than through assumptions about what this rate should look like. Applying the model to large-scale cosmological simulations will prove vital to test whether supermassive black holes can – after all – end star formation in the most massive galaxies. (Tiago Costa)

## 2.9 Fast Radio Bursts from Magnetars

Fast radio burst (FRBs) last only a few milliseconds, but their extreme brightness makes them detectable from cosmological distances. Since 2016, after the first FRB localization, host galaxies have been identified for several FRB sources. Some sources were found to repeat, sometimes producing hundreds of bursts. One such repeater (FRB180916.J0158+65) demon-

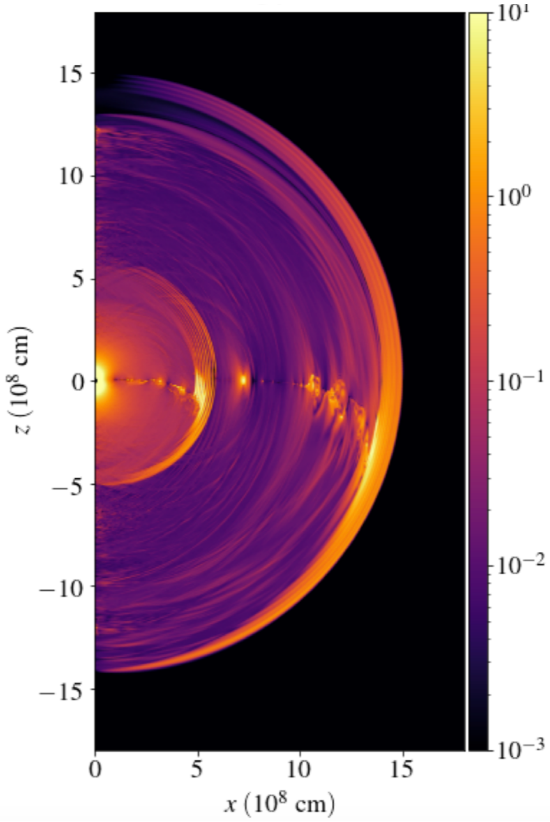


**Figure 2.19:** Numerical simulation of a magnetic explosion. Magnetic energy becomes concentrated in two shells ejected from the magnetar, launching two relativistic blast waves. *(Credit: Yuan et al. 2020)*

strates a 16-day period in its activity.

What could produce these bursts? The short duration of FRBs indicates a compact source, and neutron stars seemed suitable candidates; however, it proved challenging to identify a concrete emission mechanism. One hypothesis was that the bursts come from magnetars. About 30 such objects are known in our Galaxy, with ages of thousands of years. The hallmark of magnetars is their powerful X-ray flares. However, until 2020 none of them was seen to produce a radio burst.

The theory developed at Columbia University and MPA suggested that younger, hyperactive magnetars exist in distant galaxies. They

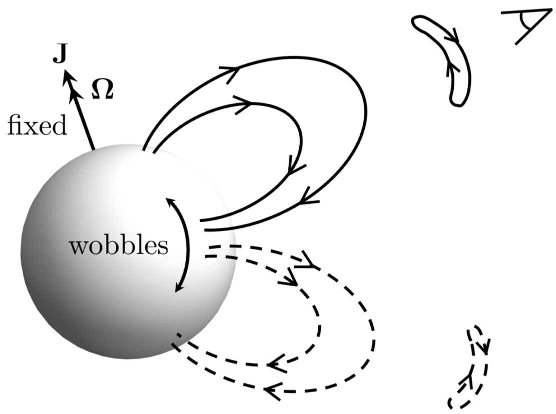


**Figure 2.20:** A precessing magnetar bursts in a direction that oscillates with time. Its observed FRB activity is modulated with the precession period. *(Credit: Levin, Beloborodov, Bransgrove 2020*

flare frequently and launch relativistic blast waves into the persistent wind from the neutron star. These blast waves are capable of producing coherent radio emission by a maser-type instability. The instability develops at the shock front of the explosion and generates GHz radiation when the shock expands beyond 1 AU.

A direct test for the magnetar model is the detection of a radio burst from a known magnetar. This happened on 28 April 2020, when a mega-Jansky radio burst with a duration of a few milliseconds was detected from SGR 1935+2154, a magnetar in the Milky Way. Two radio telescopes, the Canadian CHIME and the STARE2 at Caltech, detected the burst. Data analysis revealed two FRBs, about 30 millisecond apart, which were both emitted during a 0.5-second X-ray burst. The two radio bursts nearly coincided with two narrow, bright spikes in the X-ray emission.

This discovery has established the FRB-magnetar association, and also posed a new question. The FRBs from SGR 1935+2154 are intrinsically weaker than the previously detected cosmological FRBs. Astrophysicists previously thought that such low-energy events were incapable of launching a magnetic explosion. So, are the weak and strong FRBs produced by the same mechanism?

An answer is suggested by a new numerical experiment performed in collaboration with Flatiron Institute in New York. The simulation followed the response of the neutron star magnetosphere to a low-energy perturbation generated by a quake of the magnetar. It shows that the perturbation propagates outward through the magnetosphere, grows in amplitude, and successfully launches a magnetic explosion at about a hundred stellar radii. The result suggests that the same emission mechanism can work across a broad range of FRB luminosities, from the weak bursts of SGR 1935+2154 to the brightest cosmological FRBs.

Hyper-active magnetars the putative cosmological FRB repeaters are rather extreme objects. Their internal temperatures are about one billion degrees, and their cores are likely non-superfluid (in contrast to normal neutron stars). Their shapes are slightly non-spherical, because they are deformed by the ultrastrong magnetic fields. This leads to an interesting observational effect: the hyper-active magnetar can develop free precession with a period of weeks to months. It is consistent with the 16-day period observed in FRB180916.J0158+65. (Andrei Beloborodov)

## 2.10 Planck mission accomplished

Launched on 14 May 2009 in Kourou in French Guyana, the Planck telescope measured the microwave radiation of the cosmos between 3 July 2009 and 3 October 2013. It was placed in a Lissajous orbit around the second Lagrange point of the Sun-Earth system, 1.5 million kilometres – or one percent – further away from the Sun than the Earth. Over the course of more than four years, the telescope scanned the entire sky five times in nine frequency bands between 30 and 857 GHz. By January 2012, the helium-3 coolant ran out and only the detectors between 30 and 70 GHz remained functional. As of October 3, 2013, the satellite was deactivated step by step, sent into a park orbit around the Sun, and finally shut down on October 23, 2013.

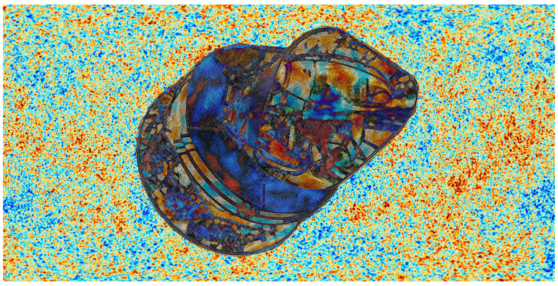

**Figure 2.21:** Artistic final image of the Planck mission: The stylized satellite in front of the temperature variations of the cosmic microwave background. *(Credit: ESA/C. Carreau)*

The Planck data, sent daily to Earth, provided high-resolution images of the sky in the nine different frequency bands as well as seven polarization images of the sky. This data was used to distinguish the various sources of cosmic microwave radiation according to their different origins. The primary goal of the mission was to precisely measure the thermal background radiation of the Big Bang, whose tiny temperature variations provide information about the age, size, composition, and origin of the cosmos. In addition, countless other sources of microwave radiation detected by Planck led to a rich scientific harvest. Planck provided spectacular images of galactic dust clouds, whose polarization indicates the presence of intertwined magnetic fields. More than a thousand clusters of galaxies were measured by Planck using the Sunyaev-Zeldovich effect, some for the first time. Planck was even able to detect planets and smaller objects in the solar system.

The rich scientific yield of the Planck mission is extensive. In 156 publications and on 4627 pages, the Planck Collaboration has described the cosmological, astrophysical and technical results of the mission. To date, these have been cited almost 50,000 times by other research papers. The highest impact, with almost 20,000 citations, was achieved by the publications on the determination of the cosmic parameters – not surprisingly, since this was the mission goal – as well as the publications on investigating the inflationary phase at the beginning of cosmic time, with about 4,500 citations. But also papers on astrophysical objects, statistical tests of the cosmic Standard Model, galactic and primordial magnetic fields, gravitational lensing and many more have left clear marks in science, proven by almost 25,000 citations. As the data from the mission is publicly available, already there are almost 2,000 other publications on Planck written outside the collaboration.

The Planck mission was established in 1996 and has now come to an end a quarter of a century later, in September 2020, with the publication of the final set of publications. The Max Planck Institute for Astrophysics (MPA) in Garching has been involved in the mission since 1999 with the MPA Planck Analysis Centre (MPAC). Originally set up by Matthias Bartelmann, the MPAC developed software for the scientific simulation and data processing of the mission. After Matthias Bartelmann accepted a call to the University of Heidelberg, Torsten Enßlin took over management of the centre in 2003. (Torsten Enßlin)

## 2.11 Revealing the nature of a diffuse Lyman-alpha glow around galaxies

Hydrogen, the most abundant element in the universe, emits ultraviolet radiation through the so-called Lyman-alpha spectral line, when sufficiently excited. In the 1970s it was theorized that this Lyman-alpha line should shine brightly, especially in young galaxies, thus allowing astronomers to observe distant galaxies ten billion light-years away. Since then, the Lyman-alpha line has indeed been verified as a powerful observational tool to study galaxy formation and cosmology.

Just in recent years, the sensitivity and spatial resolution of telescopes and satellites have become powerful enough to observe not just Lyman-alpha within the galaxies but also a faint extended Lyman-alpha glow surrounding them. This allows astronomers a glimpse of the gas that surrounds young galaxies that is of crucial importance for their future evolution. While more and more such observations become available, the source of this Lyman-alpha emission remains unknown.

There have been various hypotheses concerning the source of this glow. Generally speaking, there are two different types of possible mechanisms: On the one hand, the glow could stem from Lyman-alpha photons that are created in the star-forming regions within the galaxies and are subsequently scattered by the neutral hydrogen surrounding the galaxy. On the other hand, the diffuse Lyman-alpha emission could be created in the galaxy's surrounding gas. For example, gravitational cooling or small satellite galaxies could provide a significant energy source for such a diffuse glow.

Theoretical progress has been complicated by two factors: the Lyman-alpha line is resonant and in astrophysical settings, there is a high optical depth. This means that Lyman-alpha photons can scatter thousands or millions of times before a photon reaches us, making it impossible to know where the photon was originally emitted and what was its exact frequency. Given such physical complexity, numerical simulations of galaxy formation coupled to a radiative transfer code to account for photon scatterings are thus an important tool to study Lyman-alpha observations.

In the last years, various simulations have tried to explain the physical origin of Lyman-alpha emission around galaxies, also called Lyman-alpha halos. They performed explicit radiative transfer calculations that properly capture those effects such as scatterings and change

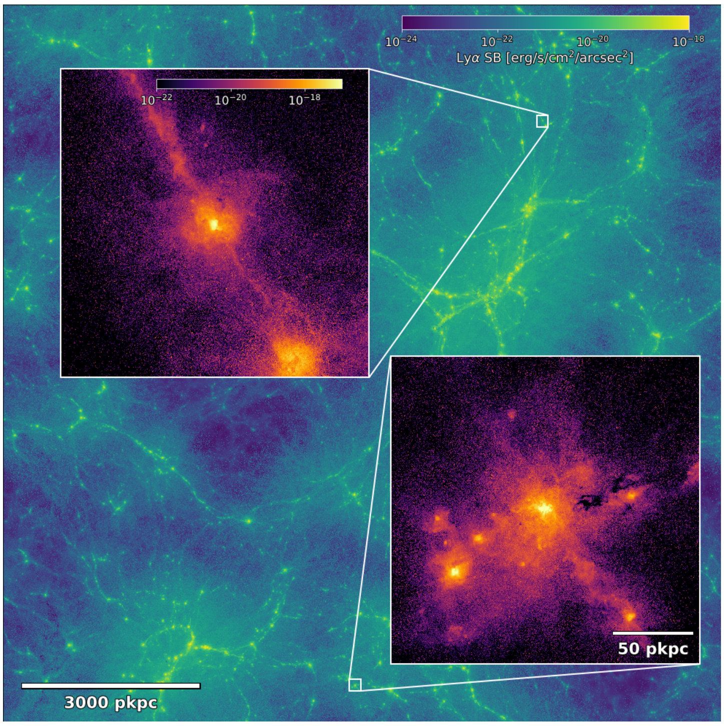


**Figure 2.22:** Lyman-alpha surface brightness map for the entire TNG50 cosmological simulation at redshift $z = 3$, highlighting the structure of the cosmic web as seen in Lyman-alpha emission. The inset panels show two individual Lyman-alpha halos, on the scale of the halo virial radii, for moderate mass objects of 50 and 120 billion solar masses (top and bottom, respectively). Lyman-alpha photons are predominantly emitted in the star-forming regions of the central galaxies, from where they resonantly scatter and illuminate the more extended gaseous halos, including filamentary inflows. The more massive halo (lower right) has a number of star-forming satellite galaxies, which also contribute Lyman-alpha emissivity and boost the local surface brightness. *(Credit: MPA)*

in frequency. Detailed radiative transfer simulations can be run on top of cosmological hydrodynamical simulations, but previous studies could not do so on large scale. A statistically robust sample would require thousands of galaxies that are resolved down to just 100s of light-years, to match up with the manifold of observational data.

In a recent leap, researchers at MPA used the new high-resolution cosmological simulation TNG50 of the IllustrisTNG project and a new radiative transfer code called voroILTIS to determine the origin of the Lyman-alpha glow. The TNG50 simulation provides an unprecedented combination of volume and resolution, while the voroILTIS radiative transfer code includes models for the various Lyman-alpha emission sources mentioned above and explicitly follows virtual photons as they scatter their way towards an observer. This allows to statistically compare the simulation's predictions with existing Lyman-alpha halo observations, while also probing questions regarding the dominant origin and emission mechanism for Lyman-alpha halos.

Comparison of stacked and individual Lyman-alpha radial profiles from those simulations with observational data from the MUSE Ultra Deep Field reveals a promising level of agreement. Those simulated radial profiles

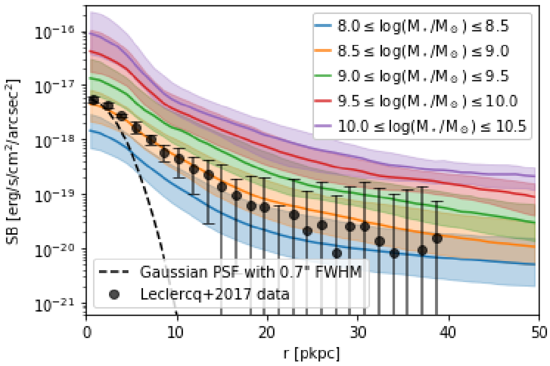


**Figure 2.23:** Stacked radial profiles for simulated galaxies in five different stellar mass ranges from 0.1 billion to 30 billion solar masses at $z = 3$. At fixed cosmic time, the central Lyman-alpha surface brightness increases monotonically with stellar mass. The overplotted dots are measured from 58 observed Lyman-alpha halos from the MUSE Ultra Deep Field (presented in Leclercq et al., 2017) at redshifts between 2.9 and 3.5. Simulations and data show a good qualitative match. *Credit: MPA*

also allow a decomposition into contributions from inside the galaxy, i.e. scattered photons from star-forming regions, and outside, such as recombination from the ultraviolet background and collisional excitations powered by gravitational cooling. This decomposition suggests that the Lyman-alpha glow is dominantly powered by emission from star-forming regions for the majority of galaxies.

Multiple shortcomings in the computational model, such as the lack of a description of clumping hydrogen and dust below the resolution scale and the ionizing flux from local sources, remain to be resolved in upcoming work. Nevertheless, these findings allow multiple exciting opportunities for astronomers in the future: With the nature of the Lyman-alpha glow established, future work can decipher the information contained in the Lyman-alpha glow to deepen our understanding of the underlying gas that surrounds galaxies and shapes their evolution. The recent theoretical findings at MPA also suggest that the large-scale structure, the cosmic web, within which those galaxies reside, can be observed via such Lyman-alpha glow in the near future. (Chris Byrohl)

## 2.12 The light and fuzzy side of dark matter

The nature of dark matter is one of the biggest mysteries in physics. This component is the most abundant matter component in our universe, responsible for all the structures we see in the universe. Evidence for its existence comes from observations on a wide range of scales, from galactic scales to galaxy clusters, going up to the large-scale structure of our universe. Its properties, as measured by the large cosmological observations, are that it needs to clump together, in order to form structures, that it does not interact (or interacts very weakly) with visible matter, and that it dominates the matter content of the universe, accounting for approximately 85% of all matter. In the standard model of cosmology, this is then called “cold dark matter” (CDM).

Until now, dark matter has only been probed through its gravitational interaction with visible matter in the Universe. There has been no direct, indirect or particle collider evidence of a particle that could be the dark matter. The mystery of its nature is therefore one of the most important questions in modern physics. A huge variety of models has been created to explain the nature of dark matter, ranging from new elementary particles to large astrophysical objects like black holes (see Fig. 2.24). In the past few years, a new and appealing class of alternative models of dark matter has emerged as a leading candidate for dark matter, the ultra-light dark matter (ULDM) models. This class consists of the lightest possible particles that could explain the dark matter observations, with masses many orders of magnitude lighter than the mass of the electron.

Such light particles show a very interest-

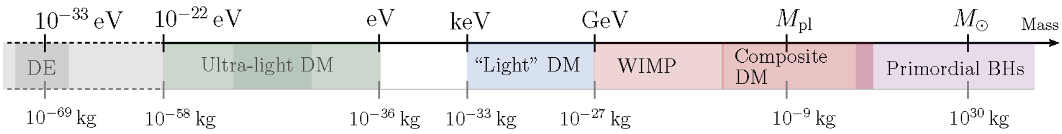


**Figure 2.24:** Sketch (not to scale) of the huge range of possible DM models that have been proposed. They span many orders of magnitude in mass (bottom) or energy (top), with DM being represented by very distinct phenomena. On the far left is shown the scale for Dark Energy, followed by Ultra-Light Dark Matter (ULDM) – the main focus of this work – and Light Dark Matter. Other candidates include also Weakly Interacting Massive Particles (WIMPs), Composite Dark Matter or even Primordial Black Holes from the early universe. *(Credit: MPA)*

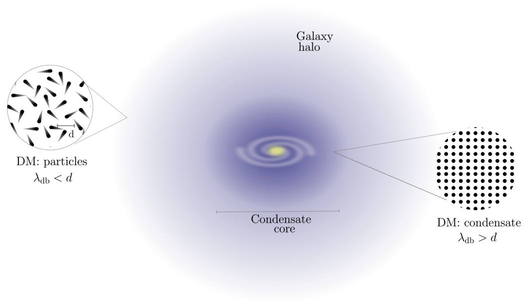


**Figure 2.25:** Illustration of the behaviour of ULDM in galaxies: A condensate core is expected to form in the inner parts of the galaxy, where the wavelength of the ULDM is smaller than the mean separation of the particles, while the Dark Matter behaves more "normal" and as individual particles in the outskirts or outside of galaxies. *(Credit: MPA)*

ing behaviour: They behave as a wave, with its characteristic wavelength inversely proportional to the ULDM mass. This means that in the mass range where ULDM behaves as dark matter, this length is similar to the size of galaxies. Inside galaxies, the wave nature of this DM candidate therefore is manifest and the galaxy is fuzzy, presenting dynamics that depart from standard CDM. On the outskirts and outside of galaxies, on larger distances, the ULDM can effectively be treated as a particle, recovering the observational successes of CDM.

The wave nature of ULDM on small scales might lead to many effects on observables. On Galactic scales, the ULDM waves interfere and superpose, forming a collective macroscopic wave inside the galaxy. In this regime, the pressure exerted by the ULDM avoids clumping of dark matter in the interior of galaxies, instead forming a core (Fig. 2.25). These less dense, cored galaxies are indeed what is preferred by observations. This pressure on small scales has also an impact on the structure formation in our universe, since it counteracts clumping and suppresses the formation of the structures on those scales. This leads to a universe where small DM halos are not present, different from what is expected from CDM.

The wave nature of the ULDM models might also lead to interesting wave-like phenomena like interference. This pattern has already been seen in simulations and would represent a smoking gun signature of ULDM models if actually measured. In the interior of galaxies, where this superposition of ULDM waves takes place, the ULDM forms a Bose-Einstein condensate (BEC) or superfluid. These are some of the most exciting phenomena in quantum mechanics and very well-known and studied in the laboratory. A Bose-Einstein condensate forms, when a gas of light particles is in thermal equilibrium and cools down to temperatures where all particles have the lowest possible energy. In this regime, instead of behaving like individual waves, the waves overlap and create a unique

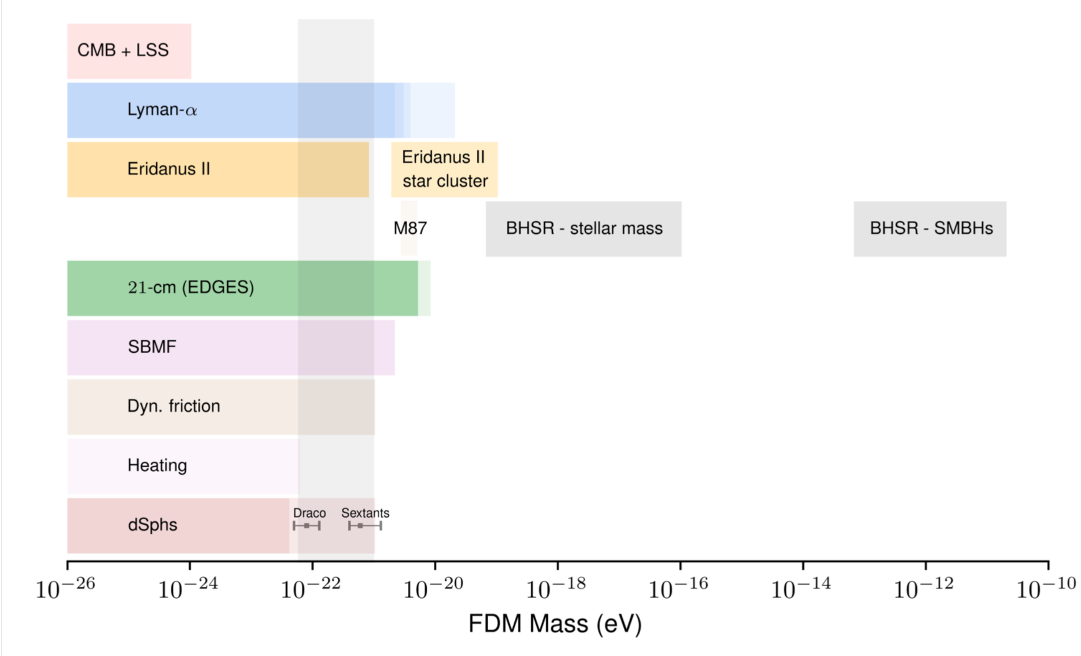


**Figure 2.26:** Summary of the constraints on the mass of the fuzzy dark matter particle to date. The horizontal shaded regions give excluded regions from a range of observations assuming that this form of DM dominates in the universe. The vertical bar shows the masses that originally motivated the creation of the fuzzy dark matter model; this mass range is almost excluded by the present bounds. *(Credit: MPA)*

macroscopic wave that now describes the system – the particles behave as a collective. And this is exactly what happens to ULDM in the interior of galaxies.

The presence of this condensate core formed in galaxies is a prediction of this class of models, and ULDM can be divided into three classes according to the properties of the cores and structures they form inside galaxies, and their resulting observational consequences. The simplest of these models is the fuzzy dark matter (FDM) with a very light ULDM particle, which is only influenced by gravity. This class of models includes the famous axion, a new elementary particle postulated to solve other problems in particle physics, but that can also behave like dark matter. The second class is the self-interacting fuzzy dark matter, with some level of interaction between the ULDM particles. The third class is the superfluid dark matter, a model where the ULDM condenses into a superfluid in the interior of galaxies. This class of models has very different dynamics on small scales, reproducing the empirical behaviour of modified theories of gravity that claim to explain how galaxies rotate more precisely than using the classical Newtonian laws. Each of these models presents different properties and leads to distinct observational effects that can be probed by current and future cosmological and astrophysical measurements.

The most tested and well-known class of models is the fuzzy dark matter model. Using its effects on the dynamics and structures of galaxies and other astrophysical observables, a variety of small- and large-scale observations have put stringent bounds on the mass of this class of dark matter particles in the past few years (Fig. 2.26). While the preferred mass for the fuzzy dark matter is almost excluded by current bounds, this particle can still be heavier than first anticipated, representing a dark matter candidate that behaves more closely to CDM. These bounds still need to be confirmed, but this analysis already gives an indication of the exciting times ahead where effects on such small scales can be probed to answer questions about the nature of dark matter. In addition, the other classes of ULDM models are almost unconstrained, providing us with the opportunity to explore the possibility of these models to describe dark matter. (Elisa Ferreira)

# 3 Publications and Invited Talks

## 3.1 Publications in Journals

### 3.1.1 Publications that appeared in 2020 (310)

Aghanim, N. et al. (incl. F. Elsner, T.A. Enßlin, J. Kim, M. Reinecke, R. Sunyaev, S.D.M. White):Planck 2018 results - I. Overview and the cosmological legacy of Planck. Astron. Astrophys. **641**, A1 (2020).

Aghanim, N. et al. (incl. F. Elsner, T.A. Enßlin, J. Kim, M. Reinecke, R. Sunyaev): Planck 2018 results - III. High Frequency Instrument data processing and frequency maps. Astron. Astrophys. **641**, A3 (2020).

Aghanim, N. et al. (incl. F. Elsner, T.A. Enßlin, J. Kim, M. Reinecke, R. Sunyaev): Planck 2018 results - V. CMB power spectra and likelihoods. Astron. Astrophys. **641**, A5 (2020).

Aghanim, N. et al. (incl. F. Elsner, T.A. Enßlin, J. Kim, M. Reinecke, R. Sunyaev, S.D.M. White): Planck 2018 results - VI. Cosmological parameters. Astron. Astrophys. **641**, A6 (2020).

Aghanim, N. et al. (incl. F. Elsner, T.A. Enßlin, J. Kim, M. Reinecke, R. Sunyaev, S.D.M. White): Planck 2018 results - VIII. Gravitational lensing. Astron. Astrophys. **641**, A8 (2020).

Aghanim, N. et al. (incl. F. Elsner, T.A. Enßlin, J. Kim, M. Reinecke, R. Sunyaev): Planck 2018 results - XII. Galactic astrophysics using polarized dust emission. Astron. Astrophys. **641**, A4 (2020).

Aguirre, V. S., et al. (incl. A. Weiss and G. Angelou): The Aarhus red giants challenge - I. Stellar structures in the red giant branch phase. Astron. Astrophys. **635**, A164 (2020).

Aguirre, V. S. et al. (incl. G. Angelou and A. Weiss): Detection and characterization of oscillating red giants: first results from the TESS satellite. Astrophys. J. **889(2)**, L34 (2020).

Ahlborn, F., E. Bellinger et al. (incl. G. Angelou): Asteroseismic sensitivity to internal rotation along the red-giant branch, Astron. Astrophys. **639**, A98 (2020).

Akhshik, M., Whitaker, K. E. et al. (incl. F. Rizzo): REQUIEM-2D Methodology: Spatially Resolved Stellar Populations of Massive Lensed Quiescent Galaxies from Hubble Space Telescope 2D Grism Spectroscopy. Astrophys. J. **900 (2)**, 184 (2020).

Akrami, Y., et al. (incl. F. Elsner, T.A. Enßlin, J. Kim, M. Reinecke, R. Sunyaev): Planck 2018 results - IX. Constraints on primordial non-Gaussianity. Astron. Astrophys. **641**, A9 (2020).

Akrami, Y., et al. (incl. F. Elsner, T.A. Enßlin, J. Kim, M. Reinecke, R. Sunyaev): VII. Isotropy and statistics of the CMB. Astron. Astrophys. **641**, A7 (2020).

Akrami, Y., et al. (incl. F. Elsner, T.A. Enßlin, J. Kim, M. Reinecke): Planck 2018 results - II. Low Frequency Instrument data processing. Astron. Astrophys. **641**, A2 (2020).

Akrami, Y., et al. (incl. F. Elsner, T.A. Enßlin, J. Kim, M. Reinecke): Planck 2018 results - IV. Diffuse component separation. Astron. Astrophys. **641** A4 (2020).

Akrami, Y., et al. (incl. F. Elsner, T.A. Enßlin, J. Kim, M. Reinecke, R. Sunyaev, S.D.M. White): X. Constraints on inflation. Astron. Astrophys. **641**, A10 (2020).

Akrami, Y., et al. (incl. F. Elsner, T.A. Enßlin, J. Kim, M. Reinecke): XI. Polarized dust foregrounds. Astron. Astrophys. **641**, A11 (2020).

Akrami, Y., et al. (incl. F. Elsner, T.A. Enßlin, J. Kim, M. Reinecke): LV. Reliability and thermal properties of high-frequency sources in the Second Planck Catalogue of Compact Sources. Astron. Astrophys. **644**, A99 (2020).

Akrami, Y., et al. (incl. T.A. Enßlin, J. Kim, M. Reinecke, R. Sunyaev): Planck intermediate results: LVI. Detection of the CMB dipole through modulation of the thermal Sunyaev-Zeldovich effect: Eppur si muove II. Astron. Astrophys. **644**, A100 (2020).

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Zinger, E., et al. (incl. D. Nelson, R. Pakmor and V. Springel): Ejective and preventative: the IllustrisTNG black hole feedback and its effects on the thermodynamics of the gas within and around galaxies. Mon. Not. R. Astron. Soc. **499(1)**, 768-792 (2020).

### 3.1.2 Publications accepted in 2020

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.

Arras, P., M. Reinecke, R. Westermann and Torsten A. Enßin: Efficient wide-field radio interferometry response. Astron. Astrophys.

Belyaev, A. K., S. A. Yakovleva, W. P. Kraemer: Inelastic processes in cupper-hydrogen collisions including fine-structure effects. Mon. Not. R. Astron. So.

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Ding, X.H., T. Treu et al. (incl. S. Suyu): Testing the evolution of correlations between supermassive black holes and their host galaxies using eight strongly lensed quasars. Mon. Not. R. Astron. Soc.

Galiullin I. and M. Gilfanov M., Populations of super-soft X-ray sources in galaxies of different morphological types. Astron. Astrophys.

Gutcke, T. A., R. Pakmor, T. Naab, and V. Springel: LYRA I: Simulating the multi- phase ISM of a dwarf galaxy with variable energy supernovae from individual stars. Mon. Not. R. Astron. Soc.

Harth-Kitzerow, J., R. H. Leike, P. Arras and T.A. Enßlin: Toward Bayesian Data Compression. Annalen der Physik.

Higl, J., E. Müller, E. and A. Weiss: Calibrating Core Overshooting Parameters With Two-dimensional Hydrodynamical Simulations. Astron. Astrophys.

Huber, S., S.H. Suyu, et al. (incl. S. Taubenberger): HOLISMOKES III. Achromatic phase of strongly lensed Type Ia supernovae. Astron. Astrophys.

Khorunzhev, G. et al. (incl. M. Gilfanov and R. Sunyaev): Discovery of the Most X-ray Luminous Quasar SRGE J170245.3+130104 at Redshift $z \approx 5.5$. Astron. Lett.

Kresse, D., Ertl, T., and Janka, H.-T.: Stellar Collapse Diversity and Diffuse Supernova Neutrino Background. Astrophs. J.

Lundman, C. and A. M. Beloborodov: A First-principle Simulation of Blast-Wave Emergence at the Photosphere of a Neutron Star merger. Astrophs. J.

May, S.: minimal-lagrangians: Generating and studying dark matter model Lagrangians with just the particle content. Computer Physics Communications

Powell, D., S. Vegetti et al. (incl. H. Stacey): A novel approach to visibility-space modelling of interferometric gravitational lens observations at high angular resolution. Mon. Not. R. Astron. Soc.

Predehl, P. et al. (incl. E. Churazov, M. Gilfanov, R. Sunyaev): The eROSITA X-ray telescope on SRG. Astron. Astrophys.

Sobacchi, E., Lyubarsky, Y., Beloborodov, A. M. and L. Sironi: Self-modulation of fast radio bursts. Mon. Not. R. Astron. Soc.

Sawatzki, J., Wurm, M., and Kresse, D.: Detecting the Diffuse Supernova Neutrino Background in the future Water-based Liquid Scintillator Detector Theia. Phys. Rev. D.

Schuldt, S., S.H. Suyu, et al. (incl. R. Cañameras, S. Taubenberger): HOLISMOKES – IV. Efficient mass modeling of strong lenses through deep learning. Astron. Astrophys.

Trick, W., F. Fragkoudi et al. (incl. S. White): Identifying resonances of the Galactic bar in Gaia DR2: I. Clues from action space. Mon. Not. R. Astron. Soc.

Zaznobin, I. et al. (incl. M. Gilfanov and R. Sunyaev): Optical Identification of Candidates for Active Galactic Nuclei Detected by the Mikhail Pavlinsky ART-XC Telescope Onboard the SRG Observatory during an All-Sky X-ray Survey. Astron. Lett.

Zaznobin, I. et al. (incl. M. Gilfanov and R. Sunyaev): Spectroscopic Redshift Measurements for Galaxy Clusters from the Lockman Hole Survey with the eROSITA Telescope Onboard the SRG Observatory. Astron. Lett.

### 3.1.3 Books and Proceedings

Hazumi, M. et al. (incl. E. Komatsu and M. Reinecke): LiteBIRD satellite: JAXA's new strategic L-class mission for all-sky surveys of cosmic microwave background polarization. In: Space Telescopes and Instrumentation 2020: Optical, Infrared, and Millimeter Wave. Vol. **11443**, Nr. 114432F (2020).

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Montier, L., Mot, B., et al. (incl. E. Komatsu and M. Reinecke): Overview of the medium and high frequency telescopes of the LiteBIRD space mission. In: Space Telescopes and Instrumentation 2020: Optical, Infrared, and Millimeter Wave. Vol. **11443**, Nr. 114432G (2020).

Ragagnin, A., K. Dolag, M. Wagner et al.: Gadget3 on GPUs with OpenACC. In /Parallel Computing: Technology Trends. Amsterdam: IOS Press, pp. 209-218 (2020).

Roa, J., A. Hamers, M.X. Cai and N.W.C. Leigh: Moving Planets Around: An Introduction to N-Body Simulations Applied to Exoplanetary Systems. September 2020, The MIT Press.
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# 3.2 Talks

## 3.2.1 Invited review talks at international meetings

Andrei Beloborodov:
– Sombreros and lampposts: The geometry of accretion onto black holes (Bern, CH, 13.-17.1)
– The Astrophysics of Fast Radio Bursts (New York, USA, 3.-5.2)
– Fast Radio Bursts and Tidal Disruption Events, ASP (New York, USA, 18.-21.4)

Benedetta Ciardi:
– Next-generation Cosmology with Next-generation Radio Telescopes II (Sesto, 27.-31.1.)

Tiago Costa:
– The Environmentof High-Z Quasars - Black holes and galaxies at the edge of the universe., Schloss Ringberg, Germany (2.3. - 6.3.)
– Radiative Feedback in Galaxy Formation - VIRGO Meeting, Durham, UK (7.1. - 10.1.)

Torsten Enßlin:
– Sampling and Clustering (Munich, Germany, 5.10.)

Marat Gilfanov:
– Dichotomy between X-ray spectra of accreting black holes and neutron stars (Bern, CH, 13.1.-17.1.)
– eRosita aboard SRG: science goals and first results (Bern, CH, 13.1.-17.1.)

Eiichiro Komatsu:
– NCTS Annual Theory Meeting (Nat. Ctr. for Theoretical Sciences, Taiwan, 10.12.)

Volker Springel:
– European Astronomical Society Annual Meeting (Leiden, Netherlands, 29.6.-3.7.)
– ORIGINS Science Afternoons (23.11.-10.12.)

Rashid Sunyaev:
– The sky in X-Rays (invited talk at the Board meeting of the Russian Academy of Sciences, Moscow, 10.3.)
– SRG Orbital Observatory with ART XC and eRosita X-Ray telescopes aboard: Results of the first all-sky survey (Moscow State Univ., Festival of Science, Russia, 10.10.) via zoom.
– SRG Orbital Observatory: a first all-sky survey (4th Zeldovich Meeting, ICRA, Italy, 08.9.) via zoom.
– Recent results of SRG Orbital Observatory (Invited talk for the Scientific Council of the Russian Space Research Institute (IKI, Moscow, 24.12.) via zoom
– Key results of the SRG X-Ray Observatory: the importance of the optical and radio astronomical support (invited talk at the conference on ground-based astronomy in Russia, XXI century, Lower Arkhyz, Caucasus, Russia, 21.9.) via zoom.
– How important were UHURU results for the theory (invited talk on the conference: 50 years of the UHURU spacecraft launch, CfA, Cambridge, Mass, USA, 17.12.) via zoom.

Sherry Suyu:
– Workshop on Astrophysics, Cosmology and Gravitation, Association of Asia Pacific Physics Societies (online, 9.11.-13.11)

### 3.2.2 Invited Colloquia talks

Fabrizio Arrigoni Battaia:
– Colloquium via Zoom Tsinghua University (Beijing, China, 7.5.)

Andrei Beloborodov:
– Princeton University (Princeton, USA, 28.10)

Benedetta Ciardi:
– MIT Kavli Institute for Astrophysics and Space Research (Boston, USA, 01.12.)

Tiago Costa:
– IoA and KICC, Cambridge, UK (15.5.)
– SISSA, Trieste, Italy (9.6.)
– AIP, Potsdam, Germany (17.6.)

Torsten Enßlin:
– Joint Astronomical Colloquium, ESO (Garching, Germany, 13.2.)
– Computational Health Seminar, Helmholtz Zentrum München (remotely, München, 28.9.)
– International Pysics Webinar, Pabna University of Science and Technology (remotely, Pabna, Bangladesh, 3.11.)

Enrico Garaldi:
– University of Bologna (virtual, 6.10.)
– Center for Astrophysics, Harvard (virtual, 16.6.)

Marat Gilfanov:
– SRG/eROSITA all-sky survey and its first results (DAMTP, Cambridge, UK, 16.11.)

Adrian Hamers:
– DAMTP, University of Cambridge (remotely, 19.10)

Hans-Thomas Janka:
– University Manchester (Manchester, UK, 4.3.)

Eiichiro Komatsu:
– Albert Einstein Institute (Potsdam, 7.2.)
– University of Amsterdam (Amsterdam, the Netherlands, 12.3.)
– Indian Institute of Science Education and Research (Pune, India, 8.6.)
– Astrophysical Research Center, University of KwaZulu-Natal (South Africa, 11.9.)
– MPI f. Kernphysik (Heidelberg, 15.10.)
– Central European Institute for Cosmology and Fundamental Physics
(Prague, Czech Republic, 26.11.)

Fabian Schmidt:
– Astronomy Colloquium, The University of Chicago (Chicago, USA, 15.4.)

Volker Springel:
– Munich Joint Astronomy Collquium, (Garching, 14.5.)
– Pontificia Universidad Catolica, Chile, Golden Webinars in Astrophysics, 9.6.)
– Aarhus University, (Aarhus, Denmark, 24.6.)
– Inter-University Centre for Astron. and Astrophys., (Pune, India, 3.9.)
– CERN Theory Colloquium, (Geneva, Switzerland, 21.10.)

Hannah Stacey:
– Lunch talk, INAF (Bologna, 6.7.)
– Kapteyn Astronomical Institute (Groningen, 9.9.)
– Netherlands Institute for Radio Astronomy (ASTRON, Dwingeloo, 10.9.)

Rashid Sunyaev:
– SRG Orbital Observatory: first results (the colloquium of the Nuclear Physics Institute of Moscow State University, Moscow 23.9.) via zoom
– SRG Orbital Observatory: first results (Harvard Smithsonian CfA Colloquium, Cambridge, Mass, USA, 1.10.) via zoom
– Results of the first SRG/eRosita all-sky survey and plans for the future (IAS/PU joint astrophysics colloquium, Princeton, USA, 6.10.) via zoom

Sherry Suyu:
– S. Suyu: Oskar Klein Centre, Stockholm University (Stockholm, Sweden, 21.1)
– CERN, Geneva, Switzerland (online 6.5)
– Physical Society of Berlin, Berlin, Germany (online, 4.6)
– Department of Physics and Astronomy, University of Utah, USA (online, 6.11)
– Department of Physics and Astronomy, York University, Canada (online, 10.11)
– Institute for Nuclear Physics, Johannes Gutenberg Univ. Mainz, Germany (online 8.12)
– Deutsches Elektronen-Synchrotron DESY, Germany (online, 9.12)

### 3.2.3 Public talks

Torsten Enßlin:
– Cafeé & Cosmos, Muffatwerk München (10.3.)

Enrico Garaldi:
– Talk organized by the outreach organization ”Inco. Scienza” (virtual, 17.12.)

Hans-Thomas Janka:
– TUM Astro-Night (17.7.)

Eiichiro Komatsu:
– Summer School on Astronomy and Astrophysics (Tokyo, Japan, 24.8.)
– Summer School on Galaxies and Cosmology (Inst. Teknologi Bandung, Indonesia, 25.9.)

Volker Springel:
– Haus der Astronomie Heidelberg (10.9.)

## 3.3 Lectures and lecture courses

### 3.3.1 Lectures at LMU and TUM

T. A. Enßlin, WS 2019/2020, SS 2020, WS 2020/21 LMU München

W. Hillebrandt WS 2019/2020 and WS 2020/2021 TU München

H.-Th. Janka, WS 2019/2020 and SS 2020, TU München

S. Suyu, WS 2019/2020, SS 2020 and WS 2020/2021, TUM

A. Weiss, SS 2020 LMU München

### 3.3.2 Short and public lectures

T.A. Enßlin: (LMU München, Garching, 5.3.-6.3.) - Information theory and signal reconstruction (seminar)
– (LMU München, Garching, 14.9.-18.9.) - Signal reconstruction with Python, (key qualification course)
– (LMU München, Garching, 1.10.-2.10.) - Information theory and signal reconstruction (seminar)

E. Komatsu: Van der Waals Lecture, the University of Amsterdam (Amsterdam, the Netherlands, 27.2.-19.3.)
– IMPRS Advanced Course (Garching, 3.11.-3.12.)

R. Sunyaev: Key results of SRG X-Ray Observatory all-sky survey (Virtual Special Courses at the Observatorio Nacional - Brazil, 26.11.) via ZOOM.

# 4 Personnel

## 4.1 Scientific staff members

### Directors

Selma de Mink (since 1.1.2021), Guinevere Kauffmann, Eiichiro Komatsu, Volker Springel (Managing Director)

### Research Group Leaders/Permanent Staff

Eugene Churazov, Benedetta Ciardi, Torsten Enßlin, Marat Gilfanov, Adrian Hamers, Hans-Thomas Janka, Thorsten Naab, Rüdiger Pakmor, Fabian Schmidt, Sherry Suyu, Simona Vegetti, Achim Weiss.

### External Scientific Members

Martin Asplund, Rolf-Peter Kudritzki, Werner Tscharnuter.

### Emeriti

Wolfgang Hillebrandt, Rudolf Kippenhahn († 15.11.2020), 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, Alexandre Barreira (until 30.9.), Tiara Battich (since 15.10.), Rebekka Bieri, Robert Bollig, Deepika Bollimpalli (since 1.10.), Giovanni Cabass (until 31.8.) Gabriel Caminha (since 1.10.), Paolo Campeti (since 1.11.), Raoul Cañameras, Tiago Costa, Linda Blot, Sten Delos (since 15.9.), Giulia Despali (until 31.12.), Elisa Ferreira Francesca Fragkoudi, Matteo Frigo, Enrico Garaldi, Anna Genina (since 1.10.), Robert Glas, Robert Grand, Thales Gutcke, Cesar Hernandez-Aguayo (since 1.9.), Anders Jerkstrand (until 17.4.), Ildar Khabibullin, Alexandra Kozyreva, Ann-Kathrin Kummer, Natalia Lahen (since 1.10.), Kaloian Lozanov (until 3.10.), Luisa Lucie-Smith (since 1.11.), Azadeh Maleknejad (until 31.8.), Dylan Nelson (until 31.10.), Patrick Neunteufel (since 1.3.), Max-Niklas Newrzella, Conor O'Riordan (since 15.10.), Devon Powell, Holly Preece (since 8.7.), Antti Rantala, Martin Reinecke, Elisa Ritondale (until 31.3.), Adam

Schäfer (since 1.10.), Yiping Shu (since 1.9.), Hannah Stacey (since 15.1.), Stefan Taubenberger, Freeke van de Voort (until 29.2.),Wilma Trick, Annop Wongwathanarat (until 15.6.), Naveen Yadav, Robert Yates (until 31.8.), Akin Yildirim.

### Ph.D. Students

Felix Ahlborn, Abhijeet Anand, Philipp Arras, Mohammadreza Ayromlou, Monica Barrera (since 1.12.), Eirini Batziou, Aniket Bhagwat (since 15.11.), Sergei Bykov (since 1.9.), Chris Byrohl, Miha Cernetic (since 1.1.), Chun-Yi Chao (until 30.8.), Giulia Chirivi (until 31.7.), Geza Csoernyei (since 1.9.), Luca Di Mascolo (until 31.5.), Jakob Ehring, Wolfgang Enzi, Silvia Fiaschi, Andreas Flörs (until 31.8.), Konstantina Fotopoulou, Philipp Frank, Matteo Frigo (until 30.4.), Ilkham Galiullin, Martin Glatzle (until 30.10.), Valentina Gonzalez Lobos (since 1.9.), Alexandra Grudskaia (since 1.7.), Timo Halbesma (until 30.6./terminated), Johannes Harth-Kitzerow (since 1.1.), Laura Herold, Jessica Hislop, Simon Huber, Sebastian Hutschenreuter (until 15.6.), Liliya Imasheva, Miranda Jarvis (until 30.9.), Jakob Knollmüller (until 30.4.),Andrija Kostic (since 1.10.), Ivan Kostyuk, Daniel Kresse, Jere Kuuttila, Reimar Leike (until 31.7.), Simon May, Nhat Minh Nguyen (until 15.6.), Leila Mirzagholi (until 30.10.), Marta Monelli (since 1.6.), Nahir Munoz Elgueta, Vyoma Muralidhara (since 1.7.), Simon Ndiritu, Christian Partmann (since 1.9.),Perikles Okalidis, Tim-Eric Rathjen, Johannes Ringler, Francesca Rizzo (until 15.10.), Francesco Rizzuto, Jakob Roth (since 15.11.), Julian Rüstig (since 1.3.), Stefan Schuldt, Georg Stockinger (until 14.7.), Christian Vogl (until 31.7.), Pavan Vynantheya (since 1.9.), Oliver Zier.

#### Master students

Jana Bayer (since 1.9.), Simon Ding (since 1.11.), Vincent Eberle (until 30.9.), Gordian Edenkofer (until 30.9.), Sebastian Ertl (until 30.9.), Matteo Guardiani (since 1.11.), Philipp Haim (until 30.3.), Malte Heinlein (since 1.9.), Alexander Holas (since 15.8.), Viktoria Kainz (since 15.10.), Fabian Kapfer (until 15.3.), Jongseo Kim (since 1.9.), Andrija Kostic (until 30.9.), Kristina Lautenschütz (since 1.9.), Rouven Lemmerz (until 30.9.), Sarah Milosevic (until 15.4.), David Outland (since 1.10.), Amit Patel (since 1.12.), Nico Reeb (until 30.9.), Bryce Remple (until 30.9.), Jakob Roth (until 30.9.), Ankit Shresta (since 1.6.), Lewis Walls (until 30.9.), Han Wang (until 30.9.), Brandon Wang (until 30.10.), Philipp Zehetner (until 30.9.).

#### 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

Selma E. de Mink has started her new directorship at MPA (January 1, 2021)

Andreas Flörs and Simon Huber received the Kippenhahn Prize for the best student publication of 2019.

Volker Springel received the Leibniz Prize of the German Research Foundation.

Volker Springel received the Gruber Prize for Cosmology 2020 (together with L. Hernquist).

Volker Springel has been elected as Foreign Member of the US National Academy of Sciences.

Rashid Sunyaev has been elected as one of the new member at the Indian National Science Academy.

Jens Stücker (former MPA PhD student) received the Otto Hahn Medal.

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

Simon White (together with Carlos Frenk and Julio Navarro) have been named Clarivate Citation Laureates for 2020 for their fundamental studies of galaxy formation and evolution, cosmic structure, and dark matter halos.

## 4.3 PhD and Master Theses 2020

### 4.3.1 Ph.D. theses 2020

Chun-Yi Chao: Finding lensed quasars with time variability in imaging surveys. Ludwig-Maximilians-Universität München.

Marius Berge Eide: The epoch of reionization. Ludwig-Maximilians-Universität München.

Luca Di Mascolo: Probing the intracluster medium at high angular resolution via radio-interferometric measurements of the Sunyaev-Zeldovich effect. Ludwig-Maximilians-Universität München.

Andreas Flörs: The Neutron-Rich Ejecta of Type Ia Supernovae and Constraints on the Exploding Mass of Their Progenitors. Technische Universität München.

Martin Glatzle: Transfer of ionizing radiation in dusty,star-forming galaxies. Technische Universität München.

Sebastian Hutschenreuter: Magnetic fields in the local universe. Ludwig-Maximilians-Universität München.

Miranda Jarvis: Multi-wavelength analysis to constrain the role of AGN in galaxy evolution. Ludwig-Maximilians-Universität München.

Jakob Knollmüller: Metric gaussian variational inference. Ludwig-Maximilians-Universität München.

Reimar Leike: Galactic dust and dynamics. Ludwig-Maximilians-Universität München.

Leila Mirzagholi: Chern-Simons Gravity and Fermionsin Axion-SU(2) Gauge Field Modelsof Inflation. Ludwig-Maximilians-Universität München.

Nhat-Minh Nguyen: Bayesian forward modeling of galaxy clustering: cosmology and astrophysics inference. Ludwig-Maximilians-Universität München.

Francesca Rizzo: A strong gravitational lensing view on the dynamical properties of high-redshift star-forming galaxies. Ludwig-Maximilians-Universität München.

Georg Stockinger: Three-dimensional models of core-collapse supernovae from low-mass progenitors. Technische Universität München.

Christian Vogl: Cosmological distances of type II supernovae from radiative transfer modeling. Technische Universität München.

### 4.3.2 Master theses 2020

Vincent Eberle: Efficient Representation of Instrument Responses. Ludwig-Maximilians-Universität München.

Gordian Edenhofer: Spatio-spectral component separation of the cosmic microwave sky. Ludwig-Maximilians-Universität München.

Sebastian Ertl: Automated Modeling of Strong Lensing Systems. Technische Universität München.

Fabian Kapfer: Multi-frequency data analysis with RESOLVE. Ludwig-Maximilians-Universität München.

Andrija Kostic: Bayesian Causal Inference and Quasi Periodic Signal Analysis. Ludwig-Maximilians-Universität München.

Rouven Lemmerz: Separation of plasma waves by means of information field theory. Ludwig-Maximilians-Universität München.

Sara Milosevic: Bayesian decomposition of the galactic multi-frequency sky using probabilistic autoencoders. Ludwig-Maximilians-Universität München.

Nico Reeb: Reconstruction of bioluminescences sources in the Deep Sea with the ANTARES neutrino telescope. Ludwig-Maximilians-Universität München.

Bryce Remple: Age determinations of DLEBs Using Machine Learning. Ludwig-Maximilians-Universität München.

Jakob Roth: Joint bayesian reconstruction of optics and imaged object Ludwig-Maximilians-Universität München.

Philipp Zehetner: Oceanography with the ANTARES neutrino detector: a 3D reconstruction of light sources in the Deep Sea. Ludwig-Maximilians-Universität München.

## 4.4 Visiting scientists

| Name | home institution | Duration of stay at MPA |
|---|---|---|
| Giovanni Arico | Ikerbasque, Bilbao, Spain | 1.10. – 29.11. |
| Andrei Beloborodov | Columbia University | since 7.7. |
| Melanie Bolle | Univ. Paul Sabatier, Toulouse | 24.2. – 24.5. |
| Philipp Busch | Haifa Univ. Israel | 15.1. – 28.2. |
| Jacob Cohen | UC, Davis | 8.1.-12.2. |
| Dragan Huterer | Univ. of Michigan | since 1.9. |
| Anatoli Iyudin | Lomonosov State Univ. Moscow | 26.1. – 9.2. |
| Natalia Lyskova | IKI Moscow | 3.1. – 3.5. |
| Paolo Mazzali | JMU, Liverpool | 7.7. – 15.10. |
| Pavel Medvedev | IKI Moscow | 14.1. – 20.2. |
| | | and 30.7. – 25.10. |
| Marcelo Miller Bertolami | IALP, La Plata, Argentina | since 13.12. |
| Yusuf Özsoy | LMU | 24.2. – 27.3. |
| Nicolas Peschken | Nicolaus Copernicus Univ. Poland | 15.3. – 30.5. |
| Oliver Philcox | Princeton University | 2.8. – 4.9. |
| Elena Pian | Univ. Pisa, Italy | 7.7. – 15.10. |
| Lionel Siess | Univ. Libre de Bruxelles | 4.3. – 18.3. |
| Daniel Walo Martin | Inst. de Astrofisica de Canarias | 26.2. – 5.6. |