Max-Planck-Institut
für
Astrophysik

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Chapter 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 Simon White in post in the first half of 2019, and Volker Springel in the second half.

In 2007, Martin Asplund arrived as a new director but, for personal reasons, decided to return to The Australian National University in 2011. He remains linked to the institute as external Scientific Member, joining the other external Scientific Members: Rolf Kudritzki and Werner Tscharnuter. 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 the University of Heidelberg. Their expertise assures the continuation of institute activity in Galaxy Evolution (Kauffmann) and Computational Astrophysics (Springel). Finally, a search is currently underway for a new director, active in stellar astrophysics, planetary science or high-energy astrophysics. This new director would formally be the successor of Wolfgang Hillebrandt who retired in 2012, and her/his appointment will complete the renewal of the directorate following the retirements of Rashid Sunyaev (2017) and Simon White (2019).

The MPA was originally founded as an institute for theoretical astrophysics, aiming to develop the theoretical concepts and numerical algorithms needed to study the structure and evolution of stars (including the Sun), the dynamics and chemistry of the interstellar medium, the interaction of hot, diluted plasmas with magnetic fields and energetic particles, and the calculation of transition probabil-
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ities 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 observing 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.

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. Theoretical, 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 obtaining additional supercomputing time, in 2019 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, PByte 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 7680 processor cores on 192 nodes - supported by 16 Pascal and 8 Volta GPUs - together with almost 37TB of core memory and 2 Petabyte disk storage capacity. Freya is used for production using moderately parallel codes. In addition, MPA operates a core node of the Virgo (the “Virgo supercomputer consortium”) data center at the MPCDF. The node hosts the full results from all important Virgo simulations (e.g. Millennium XXL, Eagle, Illustris-TNG) and provides web access to the world-wide community via the Millenium 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 15 machines (with up to 72 processor cores and 768 GB memory) plus gpfs compute clusters with 1200 cores and about 8 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 (10Gb/s capacity up to floor level, and 1Gb/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 distribution developed in-house, including the A(ndrew) F(ile) S(ystem), which allows completely transparent access to data and high flexibility for system maintenance. For scientific work, licensed software, e.g. for data reduction and visualization, is in use, too. Special needs requiring Microsoft or Apple PCs/Laptops or 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.

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 and about 7300 reports and observatory publications, as well as print subscriptions for about 140 journals and online subscriptions for about 500 periodicals, as well as an ebook collection of about 4600 copies. In addition the library maintains an archive of MPA and MPE publications, two slide collections (one for MPA and one for the MPE), a collection of approximately 800 non print media and it stores copies of the Palomar Observatory Sky Survey (on photographic prints) and of the ESO/SERC Sky Survey (on film). 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 (full time; head of the library, organisation of business process, administration of books), Mrs. Blank (part time; administration of journals) and Mrs. Balicevic (part time; “Pure”, publication management for both institutes).

1.3 2019 at the MPA

1.3.1 Successful launch of the Spectrum-RG mission

On 13 July 2019 the Russian-German Spectrum-RG satellite mission has been launched from the Baikonur Kosmodrom by a Proton rocket. The space observatory carries two multi-mirror grazing incidence X-ray telescopes: eROSITA, built by the Max-Planck-Institute for Extraterrestrial Physics (Garching, Germany), and ART-XC, built by the Space Research Institute (Moscow, Russia). In September, eROSITA offered a first glimpse of the extragalactic sky and after extensive commissioning and testing, on 18
December, both the ART-XC and eROSITA telescopes began scanning the sky along the big circle on the celestial sphere, thus marking the start of the all-sky survey. For the next four years, the observatory will be mapping the sky in a fashion similar to its predecessor ROSAT as well as the WMAP, Planck and Gaia observatories.

The main scientific goal of the all-sky survey is to study the large-scale structure of the Universe and deduce information on the nature of Dark Matter and Dark Energy. On the other hand, the unprecedented sensitivity and the sheer number of X-ray sources of different types that will be discovered harbour enormous discovery potential, fostering research in all areas of modern high-energy astrophysics. SRG will map the entire X-ray sky in the soft (0.3-8 keV) and hard (4-20 keV) bands with unprecedented sensitivity and discover about 3 million accreting supermassive black holes, 100,000 galaxies clusters, numerous X-ray binary systems, X-ray-active stars and map the diffuse emission of the Galaxy. The success of the mission relies as much on the sensitivity of the telescopes as on the ability of the spacecraft and receiving stations on the ground to perform observations 24 hours per day for 4 years uninterrupted. The SRG observatory will be able to follow up some of the most interesting targets in pointed mode observations for 2.5 years after completion of the all-sky survey.

The SRG spacecraft that holds two complementary X-ray telescopes was built by Lavochkin Association (Russia). The ART-XC telescope was designed and built under the leadership of the Space Research Institute (IKI, Moscow), while the Max-Planck-Institute for Extraterrestrial Physics (Garching, Germany) produced the eROSITA telescope, thereby making a critical contribution to the scientific payload of the satellite. Roscosmos was responsible for the Proton rocket and its BLOCK-DM-3 upper stage, as well as the launch itself. It also controls the spacecraft and provides the downlink of the scientific data during the expected 6.5 years lifetime of the mission.

The Spectrum-RG project was originally conceived in 1987 and experienced a long and eventful history. Several MPA scientists, in particular Director-emeritus Rashid Sunyaev, Eugene Churazov and Marat Gilfanov, have been actively involved in SRG from the very beginning, when it started in 1987 as a collaboration of the Soviet Union with the UK, Italy, Germany, Denmark, USA, and several other countries. After some delays, Sunyaev invited Günther Hasinger (then director of MPE, now ESA Director of Science) to join the project in 2004. Günther Hasinger and Peter Predehl from MPE then came up with the concept of the eROSITA telescope, which was able to satisfy the requirement of detecting 100,000 clusters of galaxies. In 2009, these concepts were formalized by an agreement between the Roscosmos and DLR space agencies, making SRG a Russian-German mission. Two eROSITA scientific consortia, a German and a Russian one were formed, sharing the eROSITA data in equal proportions. Given the history of the project and the long-term contribution of Churazov, Gilfanov and Sunyaev to the SRG mission, MPA scientists became part of the Russian consortium. Together with the German eROSITA team led by MPE, the Max-Planck contribution to the scientific analysis of the data will thus be very substantial.

1.3.2  Biermann lectures 2019

In space, plasma is everywhere: concentrated in stars and star forming regions, diffuse in interstellar and even intergalactic space. Plasma, or ionized matter, interacts in particular with magnetic fields, creating many different and interesting astrophysical phenom-
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The 2019 Biermann lecturer, Prof. Anatoly Spitkovsky from Princeton University, explained various front-line topics of the kinetic modeling of astrophysical plasmas, ranging from astrophysical shocks and pulsar magnetospheres to the creation, amplification, and destruction of magnetic fields.

Figure 1.1: Prof. Anatoly Spitkovsky, 2019 Biermann Lecturer credit: Princeton University

1.3.3 Prizes and Awards
Rudolf-Kippenhahn-Award

In summer 2019, Aoife Boyle received the Kippenhahn Prize for the best student paper at MPA for her publication on “Understanding the neutrino mass constraints achievable by combining CMB lensing and spectroscopic galaxy surveys” (1.2). The selection committee was very impressed by her single author paper, which in today’s publishing culture is quite rare.

Figure 1.2: Aoife Boyle received the Kippenhahn Prize for the best student paper credit: H.-A. Arnolds, MPA

Established in 2009 by former director Prof. Rudolf Kippenhahn, the prize is awarded to the best MPA student paper to motivate students. This year, the committee had to choose between eight papers, which were all very good. Nevertheless, the committee agreed unanimously that one paper stood out, and it was written by a single author: Aoife Boyle, who combined two techniques to constrain the neutrino mass.

Massive neutrinos affect the cosmic structure formation in a number of ways, via the expansion rate of the Universe, the growth rate of density fluctuations, and the scale-dependent modification of the power spectrum due to neutrino free-streaming. The large-scale structure observations have been used to constrain the neutrino mass, but the researchers did not understand where the constraints came from or how the constraints depended on the assumed cosmological models. Boyle’s paper for the first time clarifies how the constraints depend on cosmological models, and shows how to use the neutrino free-streaming signature
1.3. 2019 AT THE MPA

to constrain the neutrino mass in a model-independent manner. Her paper also demonstrates how a popular combination of the data sets, the Baryon Acoustic Oscillation combined with lensing of the cosmic microwave background, wastes a great deal of information, and that the free-streaming signature in the galaxy power spectrum offers promising model-independent constraints on the neutrino mass.

**Dirac Medal 2019 awarded to Rashid Sunyaev**

The Abdus Salam International Centre for Theoretical Physics in Trieste has awarded its 2019 Dirac Medal and Prize to three physicists whose research has made a profound impact on modern cosmology. Rashid Sunyaev (Max Planck Institute for Astrophysics) shares the prize with Viatcheslav Mukhanov (Ludwig Maximilian University of Munich) and Alexei Starobinsky (Landau Institute for Theoretical Physics) for “their outstanding contributions to the physics of the Cosmic Microwave Background (CMB) with experimentally tested implications that have helped to transform cosmology into a precision scientific discipline by combining microscopic physics with the large scale structure of the Universe.” All three winners have made important contributions to the understanding of the early Universe in the context of inflationary cosmology.

Rashid Sunyaev has made groundbreaking contributions to the fields of physical cosmology and high-energy astrophysics. In 1970 he predicted, together with Yakov Zeldovich, the existence of acoustic peaks in the CMB. These can be seen as the elements of a pattern in the CMB sky that show how it is not uniform. They predicted the decrease in brightness of the CMB in the direction of rich clusters of galaxies, which is now known as the Sunyaev-Zeldovich effect. This discovery makes it possible to use clusters of galaxies as a powerful tool of observational cosmology. It is indeed the best tool we have now to measure the abundance and motion of distant clusters of galaxies.

First awarded in 1985, ICTP’s Dirac Medal is given in honor of P.A.M. Dirac, one of the greatest physicists of the 20th century. It is awarded every year on Dirac’s birthday, August 8, to scientists who have made significant contributions to theoretical physics.

**Golden Spike Award for Dylan Nelson**

The High-Performance Computing Center Stuttgart (HLRS), awarded MPA researcher Dylan Nelson and his colleague Annalisa Pillepich at the Max Planck Institute for Astronomy the “Golden Spike Award” for TNG50: a high-resolution simulation of galaxy evolution from the Big Bang to the present day. The Golden Spike award honours the three most excellent projects of that year that have performed computations on the Center’s supercomputer cluster.

When a large simulation is performing a particularly difficult calculation on a high-performance computer cluster, you are likely to see a spike in the usage of computing resources. In 1998, the High-Performance Computing Center Stuttgart established the “Golden Spike Award” to honour particularly ambitious and successful projects running on the Center’s computers. In 2019, one of the three Golden Spikes goes to the two co-leaders (co-PIs) of the TNG50 project: Dylan Nelson and Annalisa Pillepich. Their TNG50 simulation, which traces the evolution of galaxies from the beginning shortly after the hot Big Bang, 13.8 billion years ago, to the present, required 16320 independent processors (computing cores) to run around the clock for more than a year, for a total of more than 130 million processor hours. TNG50 is part of The Next Generation Illustris (IllustrisTNG) set of cos-
mological simulations, and is the first hydrodynamical simulation to combine such a large volume of space (allowing for statistical inferences) with high enough resolution to follow the formation of even small galaxies and their internal structure.

1.3.4 Public Outreach 2019

Sustainability at MPA

Since the beginning of 2019 a small sustainability group meets at MPA every first Tuesday of a month. Some of the changes 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. The group is currently compiling a report of the institutes CO2 footprint, collecting data about business travel (by plane, car or train for varying distances), power consumption (e.g. computer systems inhouse and external), heating, commuting to work and other aspects. 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.

Girls’ Day 2019

Tricky questions, recalcitrant computers, working not in your mother tongue – the girls visiting MPA for the Girls’ Day in 2019 were faced with many challenges (see Fig. 1.3). Fortunately, MPA scientists supported them in their tasks so that at the end of a very busy day, all groups not only finished their tasks but also got an insight into what it means to be working at a scientific institute. Most of the day, the girls spent on actively exploring different astronomical topics. Split into four groups, they could choose between observing stars and galaxies, or rather how to interpret observations correctly, and the composition and evolution of our universe, derived from theoretical considerations and observations. This hands-on activity was complemented by a show in the MPA digital planetarium, moderated live by a junior MPA scientist, as well a talk by a young female scientist about career and her field of research.

Figure 1.3: The school girls were faced with many challenges during the Girls’Day 2019. (credit: H.-A. Arnolds, MPA)

In addition to this special event, 14 school groups visited the institute and went on a journey through the Universe in MPA’s digital planetarium. These live presentations continue to be very popular and serve not only to tell visitors about astronomy in general but
also to showcase MPA research in a special environment. In May, we brought our digital planetarium to the Werner Heisenberg Gymnasium in Garching, where we gave shows to 8 school classes. MPA scientists gave a number of talks in and outside the institute to a wider public, e.g. in the framework of Cafe & Kosmos, an event series organised together with the Excellence Cluster Universe, ESO, MPE and MPP. Further activities included supervising a number of undergraduates, who worked on small research projects during internships. The monthly highlights as well as press releases about important scientific results – which are also published on our webpages – serve to popularize MPA science to a wide audience. MPA researchers also acted as interview partners for press, TV, and radio journalists.
Chapter 2

Scientific Highlights

2.1 Dynamo-amplification and magnetic driven outflows in Milky Way-like galaxies

Magnetic fields can be important for many physical processes in galaxy formation and evolution; yet it is poorly understood how magnetic fields change this picture. In galaxies with halo masses above 10 billion solar masses they can be quickly amplified from a small seed field to a few $\mu$G in the galactic disc. In this scenario there are three main amplification processes for magnetic fields: adiabatic compression, the so called $\alpha - \omega$-dynamo, and the small-scale turbulent dynamo. Once magnetic fields are amplified via one of these three processes they have the ability to launch a galactic wind if the magnetic pressure is in the same order of magnitude (or higher) than the thermal pressure.

Amplification via adiabatic compression is an effect of ideal magneto hydrodynamics (MHD), which is caused when the gas in the centre of a dark matter halo collapses, leading to compressed field lines and therefore an amplification of the magnetic field. In this case the magnetic field strength and the density are correlated by a simple power law relation ($B \sim \rho^{2/3}$). The $\alpha - \omega$-dynamo can amplify magnetic fields in both the linear and the

Figure 2.1: These views show the galaxy in a simulation where the magnetic field is seeded into the ISM with each supernova that occurs. The top and bottom rows show face-on and edge-on views, respectively, with gas density (first and third column) and magnetic field strength (second and fourth column) shown at two different times in the evolution of the galaxy. At 2 billion years (first and second column), thermal pressure is dominating in the galactic disc and outflows due to the magnetic field are not possible. At 3 billion years, the magnetic pressure is dominating in the galactic disc and outflows are possible, which are happening in two cones perpendicular to the disc. Although these cannot be very well identified in the gas-density itself, they can be seen in the magnetic field strength as two lobes above the disc. Credit: MPA
non-linear regime through small-scale buoyant flows (alpha-effect) and large-scale rotation of the disc (omega-effect). The small scale turbulent dynamo can lead to linear and non-linear amplification of the magnetic field due to turbulence in the interstellar medium (ISM). In this case, the turbulence is introduced by supernova-feedback, leading to a similar behaviour as for the $\alpha - \omega$-dynamo (but different physical origin). However, both effects can be clearly distinguished through their respective power spectrum. If both dynamo processes are acting simultaneously the net effect is called $\alpha^2 - \omega$-dynamo.

A team of researchers from the astronomical Max Planck Institutes in Garching, the University Observatory in Munich and the University of Konstanz have carried out high resolution simulations of isolated Milky Way-like galaxies to study the details of these dynamo processes and the consequences of magnetic driven outflows on the general properties of the galaxy. The research team introduced a new galactic model for isolated galaxies including a hot circum galactic medium (CGM) around the central disc, embedded in a dark matter halo. This provides a more realistic framework to model inflows from the hot CGM and effects of magnetic fields can be studied with the Tree-Smooth-Particle-Magneto-Hydrodynamics-(SPMHD)-code Gadget-3. Moreover, the team investigated the impact of different initial conditions for the magnetic field. The fiducial model is the so called supernova-seeding model, in which the magnetic field is given to the ISM in a dipole structure with every exploding supernova. This model assumes that magnetic fields are generated in stars via dynamo action. The alternative model postulates a (small) constant seed field parallel to the disc, assuming that such small seed-fields are generated before inflation and get further amplified during inflation.

The research team finds a magnetic outflow

$$\text{Figure 2.2: Bi-conical outflow in the magnetic field shortly after its onset at 2.4 billion years in the simulation; the outflow appears in both magnetic field models. The outflow is very prominent in the magnetic field strength, reaching values of up to a few 10 \, \mu G, which is comparable with values observed for the Fermi-bubbles reaching far into Milky Ways CGM. In terms of morphology and velocity, the outflow structure is closer to a wind that is driven by an active galactic nuclei (AGN) rather than driven by stellar feedback. Credit: MPA}$$
2.1. DYNAMO-AMPLIFICATION

Median magnetic field strength for the simulation with supernova seeding (red) as well as the $1\sigma$ (dark gray region) and $2\sigma$ (light gray region) errors. The orange line shows a relation known from magnetohydrodynamics theory, indicating amplification by adiabatic compression. The highest magnetic field strengths correlate with the highest gas densities. In the centre the amplification of the magnetic field is driven by both adiabatic compression and small scale turbulence. In the spiral arms the magnetic field is lower and is mainly amplified by adiabatic compression. The magnetic field strength in the inter arm regions, i.e. the less dense areas between the spiral arms, shows a higher magnetic field than could be explained by adiabatic compression. Here the magnetic field is amplified by small scale turbulence. In the outskirts of the galaxy the amplification is not driven by adiabatic compression because the simulation is not following the scaling law known from ideal MHD. Credit: MPA.

For the first time with a particle based method, the research team was able to show that their simulations agreed both with predictions from dynamo theory and with observations of magnetic fields in nearby galaxies. They were able to recover the observed saturation field strengths after a non-linear growth phase of the magnetic field in the simulation. Further, they were able to reproduce the observed morphological appearance of galactic magnetic fields that did not appear in other numerical simulations of the same kind. (Ulrich Steinwandel, Klaus Dolag and Benjamin Moster).
2.2 Next generation imaging

Each day, a large number of astronomical telescopes scan the sky at different wavelengths, from radio to optical to gamma rays. The images generated from these observations are usually the result of a complex series of calculations developed specifically for each telescope. But all these different telescopes observe the same cosmos – possibly just different facets of it. Therefore, it makes sense to standardize the imaging of all these instruments. Not only does this save a lot of work in developing different imaging algorithms, it also makes results from different telescopes easier to compare, allows measurements from different sources to be combined into one common image, and means that advances in software development will directly benefit a larger number of instruments.

The research group on information field theory at the Max Planck Institute for Astrophysics has taken a big step towards achieving this goal of a uniform imaging algorithm by developing and publishing the NIFTy5 software. The research topic of this group, information field theory, is the mathematical theory on which imaging processes are based. Information field theory uses methods from quantum field theory for the optimal reconstruction of images. The latest version, NIFTy5, now automates a large part of the necessary mathematical operations.

To begin with, the users need to program probability models of the image signal (see Fig. 2.4) as well as the measurement. For this, they can rely on a number of prefabricated building blocks, which often simply need to be combined or only slightly modified. These modules include models for typical signals, such as point or diffuse radiation sources, or for typical measurement situations, which may differ in terms of noise statistics or instrument response. From such a ‘forward’ model of the

![Figure 2.4: Probability model of the sky and its observation by a radio telescope. The arrows represent stochastic influences that are ultimately imprinted on the data. When reconstructing the sky signal from the data using NIFTy5, these correlations must be traced backwards in order to deduce causes from the observed effects. Credit: South African Radio Astronomy Observatory; MPA](image)
measurement, NIFTy5 creates an algorithm to 'backwards' calculate the original signal, which results in a computed image. However, since the source signal can never be determined uniquely, the algorithm also provides a quantification of the remaining uncertainties. This is implemented by providing a set of plausible images: the greater the uncertainty in a region, the greater the provided images differ there.

NIFTy5 has already been used for a number of imaging problems, the results of which are published simultaneously. These include the three-dimensional reconstruction of galactic dust clouds in the vicinity of the solar system (see Fig. 2.5, an animation can be found at \url{https://www.mpa-garching.mpg.de/635408/hi201902}), as well as a method to determine the dynamics of fields based only on their observation (see Fig. 2.6). On the strength of past experience, NIFTy5 not only allows new, complex imaging methods to be generated much more conveniently, this software package also includes a number of algorithmic innovations. For example, the "Metric Gaussian Variational Inference" (MGVI) was developed specifically for NIFTy5, but can also be used for other machine learning methods. In contrast to conventional methods of probability theory, the implementation of this algorithm in NIFTy5 does not require the explicit storage of so-called covariance matrices. As a result, the memory requirement increases only linearly, not quadratically with problem size, so that also gigapixel images can be calculated without problems. (Torsten Enßlin).

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{galactic_dust_distribution.png}
\caption{Galactic dust distribution around the Sun reconstructed with NIFTy5 from data of the Gaia satellite. With the highest spatial resolution reached so far, the figure shows (in logarithmic colour scale) the amount of dust in the galactic plane in an square with two thousand light years on a side. The dark region is the local 'super bubble', an area around the Sun cleared of dust by stellar explosions. \textit{Credit: MPA}}
\end{figure}

\footnote{NIFTy - stands for Numerical Information Field Theory. The eponymous information field theory was originally developed for the analysis of cosmological data sets. Thanks to NIFTy5, it can now be used in other scientific and technical fields as well, such as medical imaging.}
2.3 Galaxy physics beyond the halo boundary

Our understanding of the formation and evolution of galaxies has improved significantly during the past few decades. On the theoretical side, numerical simulations have been key to elucidating how large-scale structure in the dark matter component of the Universe emerges in the form of a cosmic web of filaments, sheets, and clusters of galaxies surrounding large under-dense regions, or voids. Galaxies form at the intersections of filaments and sheets, where gas reaches high enough densities so that particle interactions cause it to cool, to lose pressure support, and to collapse to form stars.

Computer simulations that include the hydrodynamics of gas are computationally very expensive. A well-defined, computationally efficient way to apply the theory of galaxy formation to a very large volume of the Universe is to use semi-analytical models. Such a semi-analytical model applies a set of equations describing the main physical processes influencing galaxies to a set of halo merger trees extracted from the simulation. These halo merger trees document, which collapsed structures, or halos, merge with each other as structures in the Universe build up under the influence of gravitational forces. Combining these with the semi-analytic models allows predictions for the observed properties of galaxies as a function of cosmic epoch.

After the gas has cooled and collapsed under gravity to form a centrifugally supported disk galaxy within a dark matter halo similar to our own Milky Way, environmental processes can influence the subsequent evolution of the system. Direct observations have shown that the properties of galaxies depend on the environment in which they reside. The morphology-density relation derives from the
observed fact that galaxies in massive clusters are more likely to be non-star-forming (or quenched). In such dense environments, gravitational tidal effects on galaxies become strong and this strips dark matter and stars from their outer regions. In physics, a body moving through a fluid medium is subject to ram pressure, where the relative bulk motion of the fluid exerts a drag force on the body. In galaxy groups and clusters, ram-pressure forces become strong enough to overcome the gravitational binding energy of the gas, so that the gas is stripped out of the galaxy and star formation ceases.

An important question that has largely been neglected up to now is the radius from the cluster or group centre where these effects start to become important. Most analytic and semi-analytical models of galaxy formation, including our in-house model, L-Galaxies, adopts the virial radius as the boundary beyond which environmental effects are no longer important. However, a number of observational studies have suggested that environmental processes may influence gas and star formation in galaxies well beyond this radius. For example, so-called galactic conformity effects, the observed large-scale correlation between star formation in neighbouring galaxies, extends out to distances of several megaparsec, which is much larger than the virial radius of even the most massive clusters. In addition, hydrodynamical simulations suggest that the shock-heated gas of a dark matter halo can extend beyond its virial radius.

A realistic and accurate model of galaxy formation and evolution needs to contain prescriptions for environmental effects for all galaxies in a simulation. We have developed a new way to measure the properties of the Local Background Environment (LBE), including its density and bulk motion, for every galaxy in the Millennium Simulation. The local background properties are measured in a spheri-
Figure 2.8: Velocity distribution of particles in the background shell of a satellite galaxy in the Millennium Simulation, projected along each of the three spatial dimensions. There are about 50,000 particles in the shell. The colours show the fraction of particles with a certain velocity. Cyan circles denote the velocity of the galaxy; white circles denote the derived mean velocity of the local background after decontamination. The radii of the solid circles are equal to the velocity dispersion of the two modelled Gaussians, while dashed circles show twice that value. The fraction of contaminant particles in the shell is 0.22.  

Credit: MPA

cal shell around each galaxy. Care must be taken to deconvolve simulation particles that are truly part of the background from those which are gravitationally bound to the galaxy. As an example, Figure 2.8 shows the velocity distribution of the particles in the shell of one of the galaxies in the simulation. This is formed by two Gaussians, therefore, the deconvolution of the particles (into background and bound particles) is possible using Gaussian mixture modelling techniques.

In our work, we have analysed the properties of the local background as a function of distance from the group/cluster centre. We show that there is no abrupt change in density or bulk velocity at any radius, indicating that environmental effects vary smoothly across the traditionally adopted halo boundary. Preliminary results indicate that gas stripping may also play an unexpectedly important role in some galaxies in low-density environ-

Figure 2.9: Environmental properties of galaxies in the Millennium Simulation within three times the virial radius of a massive halo. Each circle shows a galaxy, in total 582 galaxies are visible. The colour of each circle corresponds to the local background density (in units of the mean density of the universe, see colour bar at the bottom). The arrows illustrate the velocity of each galaxy (blue) and the bulk velocity of its local background (purple). The dashed black circle corresponds to the virial radius for the main halo. The size of circles is equal to the subhalo size for central galaxies and larger satellites, smaller satellite galaxies are simply shown as dots. While galaxies tend to be smaller in the denser inner region, there is no abrupt change in density or bulk velocity at any radius.  

Credit: MPA
ments, particularly those accelerated by a previous, close encounter with another galaxy, or those falling through parts of the cosmic web. In future work, we will explore the implications of these findings for cosmological studies of galaxy surveys, as well as for models for the formation and evolution of galaxy properties. (Mohammadreza Ayromlou and Guinevere Kauffmann)

2.4 Sloshed and shocked: diagnosing gas motion in galaxy clusters

Galaxy clusters are the largest gravitationally bound objects in the Universe. About 15% of their mass is in the form of hot (100 million Kelvins) ionised gas, whose pressure balances their own enormous gravity. The rest is in the form of dark matter, with only minor contribution from stars in the member galaxies of clusters.

Hot gas in galaxy clusters can be seen in two ways: First, it emits X-rays via thermal bremsstrahlung from scattering of electrons and protons. Second, scattering of electrons off photons of the cosmic microwave background (CMB) transfers the electron’s kinetic energy to photons, distorting the black-body spectrum of the CMB; thus, galaxy clusters are visible over the uniform background of CMB in microwave bands, the effect known as the thermal Sunyaev-Zeldovich (SZ) effect. Now, here is the key: X-ray emission probes gas density because its intensity is proportional to the density squared, whereas the SZ effect probes thermal gas pressure, i.e. the product of density and temperature. Therefore, by combining X-ray and SZ images, we can directly measure the so-called “equation of state” of the gas, i.e., how gas pressure and density are related to each other.

Galaxy clusters do not stand still. They are

Figure 2.10: (Left) X-ray image of RX J1347-1145 at a redshift of z=0.451, taken by the Chandra X-ray Observatory. The cross shows the location of the X-ray peak, while the white lines show the regions used to calculate the smooth distribution of the X-ray emission and SZ signal. (Right) SZ image, taken by ALMA. The cross shows the same location as in the left panel, while the white lines show the contours of the X-ray emission. Adopted from Ueda et al. (2018) Credit: MPA
continuously forming and growing by accreting mass from the surrounding cosmic web. As a result, hot gas in clusters is stirred and disturbed continuously. X-ray images show such disturbances, which are sensitive to irregularities in the density. But how about disturbances in gas pressure? Gentle motion of the gas at velocities much smaller than the sound speed does not alter pressure, whereas motion that is more violent generates shock waves and increases pressure. Thus, the equation of state of perturbed gas measured by a combination of X-ray and SZ data allows us to infer gas motion directly. However, spatial resolution of the SZ data has been limited because of the lack of appropriate telescopes. Now, with ALMA, a team of scientists led by Eiichiro Komatsu at MPA have succeeded in obtaining an image of the SZ effect in the distant galaxy cluster RX J1347-1145 at 5-arcsecond resolution, matching the resolution of X-ray data for the first time (Figure 2.10; see also the MPA press release on March 17, 2017).

Removing the smooth component, this X-ray image shows two disturbances (the left panel of Figure 2.11): a dipolar pattern at the centre, which is characteristic of "sloshing" of gas due to a perturbation from infall of smaller clumps of matter, and an excess X-ray emission in the south-east region. Looking at the corresponding SZ image (the right panel of Figure 2.11), we find nothing at the centre, indicating that the sloshing motion is gentle and does not alter pressure. On the other hand, we find a large excess SZ signal in the south-east region, which is consistent with shock-heated gas, probably due to a major merger with an infalling sub-cluster. This discovery was made possible by the high spatial resolution and high sensitivity of ALMA, both of which are unprecedented in measuring the SZ effect. Another method to characterise the effective equation of state for the gas using the X-ray data alone was proposed by Eugene Churazov and his colleagues. It relies on comparing the amplitudes of gas perturbations seen in different energy bands (Figure 2.12). Given the complementarity of X-ray and SZ observations, adding SZ data enhances this approach in a major way. Recently, scientists at MPA and ESO performed a detailed joint analysis of X-ray data and SZ images as well as interferometric data of this cluster. This study, led by Luca Di Mascolo (PhD student at MPA), broadly agrees with the results of Komatsu’s group. In addition, it discusses a "milder" form of the merger that leads to the perturbations observed in the X-ray and SZ signals. In this scenario, part of the south-east excess observed in the X-ray images may be due to colder gas infalling into the main cluster. More ALMA data on other clusters have been obtained by Komatsu’s team, waiting to be published. These data sets, together with new analysis methodology developed by Komatsu and Churazov’s groups, open up a new window to study gas motion and dynamical states of galaxy clusters. (Eiichiro Komatsu, Eugene Churazov, Luca Di Mascolo)

Figure 2.11: (Left) X-ray image minus the smooth component. (Right) SZ image minus the smooth component. Adopted from Ueda et al. (2018). Credit: MPA
2.5. TOWARDS A COMPLETE MODEL OF THE INTERSTELLAR MEDIUM

The interstellar medium (ISM) is traditionally defined as everything in-between the stars in galaxies. In fact this accounts for most of the observable baryonic matter in galactic disks like the Milky Way, where star formation takes place and galaxies grow in size and mass. The ISM transitions smoothly to the circum galactic medium (CGM) in the more spherical galactic halos, which can contain significant fractions of the total baryonic mass gravitationally bound to galaxies but shows no evidence for star formation. The CGM is supplied with material outflowing from the ISM, similarly the ISM is replenished by material falling in and cooling from the CGM. Part of the ISM is in the form of ionized, neutral and molecular gas as well as dust. Molecular gas is typically found in structured and compact molecular clouds, where all new stars in galaxies are born. Most of the volume in the ISM, however, is occupied by neutral and ionized gas. Interstellar radiation from stars or gas cooling processes is also part of the ISM. In addition, magnetic fields and cosmic rays typically protons at relativistic speeds – are energetically equally important non-thermal components.

There is a plethora of physical processes regulating the structure and composition of the ISM. Molecular clouds form by cooling and gravitational collapse of the magnetized gas in dust shielded regions. O and B star clusters ionize and heat their surroundings by UV radiation and stellar winds partly dispersing their parental clouds. At the end of their lifetime supernovae drive strong shocks into the turbulent ISM by generating hot ionized gas in expanding super-bubbles, which can escape the ISM in an outflow. Cosmic rays generated in these shocks interact with the magnetic field and generate an additional pressure component driving gas out of the ISM.

As part of the SILCC project the team had shown that the interplay of the above processes is so complex that their inclusion or omission in model calculations can qualitatively change the properties of the ISM and lead to scientifically false outcomes. For example not accounting for the hot gas generated in supernova explosions results in an unrealistic ISM phase structure with just two (warm and cold gas) phases instead of the observed three phases (warm, cold and hot gas); omitting stellar radiation and stellar winds results in too much gas cooling and star formation and too little ionized gas; the presence of magnetic fields delays the collapse into dense structures; and cosmic rays diffusing along magnetic fields can suddenly drive smooth stellar winds transporting material out of the stellar disk into the galactic halo. It has become clear that all major processes have to be included in highly complex computer simulations to develop a comprehensive model of the star-forming ISM. Super SILCC, the successor of the SILCC project,
aims at this new frontier in the numerical modeling of a realistic, turbulent, multi-phase ISM.

We have now performed the first self-consistent ISM scale simulations of a small patch of a stratified galactic disk accounting for the evolution of all major thermal and non-thermal components following non-equilibrium chemistry, cooling and heating of the dusty magnetized ISM, clustered star formation, ionizing radiation and winds from massive stars, their supernova explosions and the generation and propagation of cosmic rays. The simulations indicate that radiation wind and supernova feedback from massive stars create a turbulent magnetized multi-phase ISM with realistic star formation rates for solar neighborhood conditions as well as the correct (?) structure and abundance of ionized, neutral and molecular gas. (Fig. 2.13). However, the inclusion of cosmic rays results in the additional generation of a smooth and warm outflow resulting in better agreement with observations of the gas scale heights in the Galactic disk (Fig. 2.14). The difference in outflow properties can be quantified by the mass-loading factor, i.e. the ratio of gas leaving the ISM in an outflow to gas being converted into new stars in the ISM. It is much higher in the presence of cosmic rays due to their additional pressure gradient (Fig. 2.15). As of now, this is the most realistic and also physically most complex simulation of a multi-phase turbulent ISM with solar neighborhood conditions.

To study these effects in more detail the team has been awarded Tier-0 supercomputing time through the Gauss Center for Supercomputing (GCS) project Super SILCC on Super MUC-NG, one of the worlds fastest supercomputers (Top500) at the Leibnitz Supercomputing Center (LRZ). For this project, we will not only investigate the physical origin of the ISM structure on larger scales and in extreme starburst environments at high redshift. We will also simulate the impact of the enigmatic run-
2.6. HEAT CONDUCTION IN THE INTERSTELLAR MEDIUM

Thermal conduction is a fundamental physical process describing heat transport along a temperature gradient. The impact of this effect is measured by the conductivity constant. For every material on Earth the conductivity constant describes how efficiently it transports thermal energy. Iron, for example, has a very...
high conductivity and is very efficient in transporting heat since the electrons can move freely through the whole domain with only minimal losses due to interactions with atoms.

However, the situation in the ISM is very different. It is composed of very cold and dense regions with a lot of mass but covering little volume. The majority of the volume of the ISM is in the warm and hot phases at lower densities. The conductivity depends on the temperature itself and changes significantly over several orders of magnitude within the ISM. In the absence of any other process, however, thermal conduction alone can change the ISM structure, for example by evaporating cold clouds embedded in a hot medium.

A team of researchers from the Max Planck Institute for Astrophysics, the University Observatory in Munich, the University of Cologne and the Center for Computational Astrophysics in New York has investigated how heat conduction can change the properties of the supernova-driven ISM. Supernova explosions...
at the end of the life of massive stars are one of the most important feedback processes in the ISM driving turbulence and restoring the hot phase of the ISM.

The team has performed detailed resolution tests of individual supernovae exploding at various ambient densities, simultaneously following the chemical evolution and non-equilibrium low temperature cooling. Based on these results, the impact of thermal conduction on the structure of the ISM has been simulated in high-resolution, periodic ISM boxes with solar neighborhood conditions and supernova rates. A multi-phase ISM is developing rapidly in all cases. However, the total volume filled by the hot phase changes strongly from 30 to 40 per cent in the absence of thermal conduction to 70 – 80 per cent in the presence of thermal conduction, also resulting in a differently structured morphology (Fig. 2.17).

Why is the impact so strong? Thermal conduction is a physical process, which can redistribute thermal energy within the ISM from hot to colder gas. Due to the conservation of energy this leads to a mass flux from colder to warmer gas, which increases the mass of the hot phase and also its volume.

Heat conduction not only influences the hot phase of the ISM, it also changes the physical properties of the cold phase. The conductivity constant is smaller at lower temperatures and the cooling times in this regime are much shorter (a few hundred to thousand years). There is still energy transport from the warm phase towards the cold regime but due to the short cooling times it is directly cooled away and the mass flux from the cold to the warm phase is suppressed. Therefore, the researchers find less mass in the warm phase of the ISM and more in the cold phase in the runs with thermal conduction (Fig. 2.18). Thermal conduction leads to an extended high-density tail with maximum densities that can be a factor of 10 higher compared to the simulations without

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**Figure 2.18:** Phase Diagram of temperature and density for the turbulent box simulations shown in Fig. 2.17. The colorbar shows the particle count. The top plot shows the run without conduction, the bottom plot with conduction. Thermal conduction results in more gas at high temperatures as well as very low temperatures and high densities. *Credit: MPA*
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thermal conduction. As a result, the fraction of molecular hydrogen, which forms at low temperatures and high densities, can increase by up to a factor of four in the presence of thermal conduction.

The results highlight that thermal conduction has to be taken into account for an accurate model of the multi-phase ISM. (Ulrich Steinwandel, Ben Moster, Thorsten Naab).

2.7 X-ray emission from Warm-Hot Intergalactic Medium

Half of the baryonic budget in the present-day Universe is very well hidden astronomers believe it can be found in the Warm-Hot Intergalactic Medium, which is as abundant and imperceptible as the nitrogen in the air we breathe. Being produced naturally by the ongoing formation of the largest structures in the Universe, this gas has a temperature between 100,000 and 1 million Kelvin and its density exceeds the mean baryonic density by less than a factor of 100. The high temperature of this gas implies that hydrogen and helium should be almost fully ionized and, as a consequence, it cannot be revealed via the Lyman alpha absorption features in the spectra of background quasars (contrary to the high-redshift intergalactic medium, which is readily detected in this way). It is also difficult to observe this gas directly, since its thermal emission is very faint (due to its low density) and also happens to peak in the observationally-challenging extreme UV/soft X-ray energy range.

Fortunately, the Warm-Hot Intergalactic Medium is enriched by heavier elements (such as carbon, nitrogen, oxygen, neon and iron) expelled from the star-forming galaxies by powerful galactic-scale outflows (as hinted e.g. by cosmological hydro-simulations, see Fig. 2.19). Having escaped full ionization, atoms of heavy

Figure 2.19: Distribution of the heavy element oxygen across the density-temperature parameter space in the intergalactic medium, extracted from a snapshot of the Magneticum cosmological hydro-simulation by Klaus Dolag. The color-coding is on a logarithmic scale (arbitrary units) with corresponding white contours spaced by a factor of two. Black solid contours depict the ionization fraction of He-like oxygen taking into account photoionization by the cosmic X-ray background. Credit: MPA
elements produce numerous emission lines and resonant absorption features. For a low density gas, such as the Warm-Hot Intergalactic Medium, the absorption features are particularly important, since their amplitude is proportional to the total number of ions on the line-of-sight, so it scales linearly with the gas number density. While a large amount of observing time has already been invested in searches for the Warm-Hot Intergalactic Medium by this technique (taking advantage of high resolution grating spectrometers on board the Chandra and XMM-Newton X-ray observatories), only marginal detections have been reported so far.

In fact, these absorption features are a result of resonant scattering, which is not a true absorption process by itself. Indeed, the intensity lost in the direction of the bright background sources is compensated by increased intensity in all other directions (see Fig. 2.20). The net effect of course cancels out after integrating over all directions in the case of an isotropic radiation field, such as the Cosmic X-ray Background. Nonetheless, a large portion of this background is contributed by bright individual sources (mainly Active Galactic Nuclei), which can be resolved and excluded from a given aperture. The remaining signal will then contain both the unresolved part of the background radiation (with similar absorption features as in resolved part) plus the spatially-extended resonantly-scattered background radiation. This emission is heavily dominated by the brightest resonance lines and supplements the intrinsic thermal emission from a slab of Warm-Hot Intergalactic Medium, boosting its overall X-ray emissivity and changing important spectral characteristics such as the equivalent widths of the lines and their respective ratios.

Recently, MPA scientists performed calculations of the X-ray emission from a layer of Warm-Hot Intergalactic Medium that take into account resonant scattering and absorption. The results show that the net effect of these processes is to enhance the overall X-ray emissivity and change the spectral characteristics of the emitted radiation. Credit: MPA

Figure 2.20: Three main signatures (middle) of a layer of the Warm-Hot Intergalactic Medium (left) in X-rays: it is seen in intrinsically produced X-ray emission (E, top), resonant absorption in the spectra of bright background sources (A, middle), and resonant scattering of the isotropic cosmic X-ray background emission (S, bottom). The spectrum of the intrinsic emission possesses both significant continuum and line emission, with comparable amplitude of the resonant (r), intercombination (i) and forbidden (f) lines. The absorption spectrum is essentially the spectrum of the background source (black dashed line) with imposed resonant absorption lines. The scattered component is dominated by resonantly scattered emission lines of the most abundant ions, with no contribution from forbidden lines. The right panel illustrates an observing strategy for detecting the scattered component: emission of bright background sources (marked with crossed red circles) should be removed from the aperture. The residual signal will then contain both the unresolved fraction of the cosmic X-ray background and emitted plus scattered radiation from the Warm-Hot Intergalactic Medium. Credit: MPA
Figure 2.21: Calculated energy spectrum of emission in the energy range 0.5-1 keV (smoothed with a 3-eV window) from a typical filament-like structure of the Warm-Hot Intergalactic Medium with a density 30 times higher than the mean density, a temperature of $\sim 1$ million K, a metallicity of $Z=0.3$ (relative to the Solar one) and a Thomson optical depth of $10^{-4}$. Purely collisional emission is shown in green, while emission under influence of photoionization by the cosmic X-ray background (with and without contribution of resonant scattering) is shown in black and red, respectively. The intensity of the cosmic X-ray background (CXB), along with its 10% and 1% fractions are shown with solid, dashed and dash-dotted lines. The brightest emission lines are identified. Credit: MPA

account photoionization by the Cosmic X-ray Background and allow self-consistent inclusion of the resonantly scattered line emission (see Fig. 2.21). The overall boost of emission in the most prominent resonant lines (O VII, O VIII and Ne IX) was found to equal $\sim 30$, and this boost is pretty much uniform across almost the whole region of the density-temperature diagram relevant for the Warm-Hot Intergalactic Medium. Even after averaging over broader spectral bands, the boost factor remains very significant ($\sim 5$) but declines steeply at temperatures above $tT \sim 1T \sim 1$ million K (for all considered densities) and at over-densities $> 100$, as demonstrated in Fig. 2.22 for the 0.5-1 keV band. The predicted total emission in this band is predicted to be dominated by the resonant lines of the helium- and hydrogen-like oxygen, which have comparable intensity for the major part of the explored parameter space.

A significant detection of a layer of Warm-Hot Intergalactic Medium (at a redshift $t \sim 0.1$) in emission might be achieved by an X-ray instrument with an effective area of about $1000 \text{ cm}^2$ (at 0.5-1 keV) with an exposure on the order of 1 million seconds over one square degree of the sky taking into account contamination by the unresolved cosmic X-ray background and the Galactic diffuse soft X-ray foreground. These requirements might already be met with a single observation by the eROSITA telescope onboard of the forthcoming SRG mission.

Future X-ray missions will indeed provide great opportunities to study the Warm-Hot Intergalactic Medium, both with large-area X-ray surveys and with deep small-area observations with X-ray calorimeters. For the former, the signal can be detected by a cross-correlation of the stacked (absorption and emission) X-ray signal with certain tracers of overdensities in the large-scale structure (e.g., 2MASS galaxies), while for the latter detection
2.8. THE HIDDEN SATELLITES

Figure 2.22: Ratio of scattered to intrinsic X-ray emission integrated over 0.5-1 keV energy band as a function of number density and temperature of the Warm-Hot Intergalactic Medium. The black dashed contours indicate the ionization fraction of He-like oxygen weighted with the mass and mean metallicity of the corresponding gas portion extracted from the Magneticum simulation snapshot at $z \sim 0$. The black solid triangle and square connected by a dotted line mark the parameters of typical sheet-like and filament-like structures. Credit: MPA

(and potentially diagnostics) of prominent individual filaments at $z \sim 0.1$ is the primary goal.
(Ildar Khabibullin and Eugene Churazov)

2.8 The hidden satellites of the first massive galaxies and quasars

Quasars are some of the brightest objects in the Universe, powered by supermassive black holes as they swallow prodigious amounts of interstellar gas to grow to masses about a billion times that of the Sun. The luminous output of quasars can be so high that they often outshine entire galaxies, remaining within the reach of telescopes out to extreme distances. The most distant quasars currently known lie close to 13 billion light-years away and their light as observed today was emitted when the Universe was only a few hundred million years old, less than 10% its current age. The properties of the galaxies and cosmic environments in which quasars evolve remain very poorly understood, however.

Sophisticated hydrodynamic simulations performed on large supercomputers are able to model key processes ranging from gas cooling, star formation and the production of hot gas through supernova explosions to black hole growth. These ‘mock or simulated Universes can be used to study the evolution of the first quasars lighting up the early Universe. According to these simulations, quasars form at the centre of massive galaxies with stellar masses on the order of 100 billion Suns. The quasar host galaxy, which is about ten times smaller than the Milky Way, is continuously fed by a network of filaments that bring in large gas masses, ensuring sustained star formation and black hole growth in the galactic nucleus, while the quasar launches powerful galactic outflows (see animation). Another
key prediction of such simulations is that an anomalously large population of massive satellite galaxies should surround the massive galaxies hosting the first quasars.

Most previous simulations have excluded the effect of radiation from young stars on interstellar gas, which can potentially alter the properties of both the quasar host galaxy and its satellites. The importance of stellar radiation for the evolution of these massive systems has therefore remained unknown. An international team of researchers from the Max Planck Institute for Astrophysics, the Centre de Recherche Astrophysique de Lyon (France) and Yonsei University (Seoul, South Korea) therefore set out to explore the effect of ‘switching-on stellar radiation on the evolution of a simulated quasar host galaxy. In order to successfully model stellar radiation, it was necessary to perform fully radiation-hydrodynamic, cosmological simulations, or in other words, to model both the hydrodynamic evolution of interstellar and intergalactic gas as well as to model the propagation of radiation from each individual stellar population in the simulation.

Remarkably, the new simulations show that stellar radiation can have significant consequences for the evolution and the structure of massive galaxies such as those hosting the first bright quasars. Stellar radiation has the counter-intuitive effect of reducing the amount of hot gas at cosmic scales. This is because, as stars form, their radiation heats up interstellar gas in their vicinity preventing it from collapsing and forming stars in turn. But since a reduced star formation implies a smaller number of supernova explosions, stellar radiation indirectly results in lower amounts of hot gas. Stellar radiation not only reduces the total number of stars, but also the number of stellar clumps around the galaxy (see Fig. 2.23). Why is that and what is the nature of the stellar clumps that exist in the simulation without stellar ra-

Figure 2.23: shows the distribution of hot gas in a region hundreds of thousands of light years across around the massive galaxy, in the simulation without stellar radiation (top) and with stellar radiation (bottom). The right-hand panel of Fig. 2.23 zooms-in on the massive galaxy itself, showing the distribution of stars within the central regions. Here again we can see the effects of stellar radiation, which appears to not only result in a larger, more ‘puffed-up’ galaxy (bottom) but also in a smaller number of stellar clumps around the galaxy. Credit: MPA
2.9. VISCOSITY OF HOT GAS IN GALAXY CLUSTERS

Clusters of galaxies are the most massive virialized objects in our Universe. More than 80% of their mass is provided by Dark Matter, while their number density depends on Dark Energy, which affects the expansion of the Universe and the growth of clusters. These links to the Dark Side of the Universe makes clusters an important tool for Cosmology. At the same time, most of the normal (baryonic) matter in clusters is in the form of a hot (100 million degrees) and very tenuous (one particle per 1000 cubic centimeters) plasma permeated with a weak magnetic field. It is hardly possible to produce and study such a plasma in the lab, but clusters offer us this opportunity. In particular, we do not know the thermal conductivity or viscosity of such plasma, and the level of uncertainty can be as high as ten orders of magnitude.

Such uncertainty implies that numerical modeling of clusters properties and evolution may not reach the level of accuracy required for identifying subtle effects related to, e.g., non-trivial properties of the Dark Matter or Dark Energy. In numerical simulations, scientists often assume that both the thermal conduction and the viscosity are small. And indeed, plasma physics theory offers a possibility that particles are scattered by the microscopic fluctuations of the magnetic field so often that the viscosity and conductivity become
very low. However, another extreme possibility is that only particle collisions are important. In this case, particles would be able to move freely over large distances in the hot and low-density plasma of clusters, transporting momentum between adjacent regions and therefore making the plasma very viscous. Which of the two extremes is closer to reality? Answering this question was the primary goal of very long observations of the Coma cluster with NASA’s Chandra observatory. The results of these observations were published in Nature Astronomy in June 2019.

The gas in the Coma cluster is very hot almost a hundred million degrees and has a very low density, especially in regions away from the cluster core that Chandra was observing for more than ten days (Fig. 2.25). These are exactly the conditions where the mean free path of particles is very long (tens of kiloparsecs) and viscosity and conduction are expected to smear out any fluctuations of gas velocity, tem-
2.10. GLOBULAR CLUSTER FORMATION DECIPHERED

perature or density on sufficiently small spatial scales. The higher the viscosity the larger are the affected scales. Therefore, by identifying the scales where fluctuations are suppressed, we can infer the viscosity.

With the superb angular resolution of Chandra, measuring the gas density fluctuations that lead to the brightness variations in X-ray images is a straightforward exercise (see Fig. 2.26). The fluctuations found in the Coma cluster fall exactly in the range of scales, which should be severely affected by viscosity. The presence of fluctuations at these small scales falsifies the assumption that the plasma viscosity is high and that it is set by particle collisions. The opposite assumption of strongly suppressed transport coefficients seems to be consistent with observations. Therefore, numerical simulations that ignore the viscosity maybe not far from reality, even although the exact recipe for modeling weakly collisional cluster plasma is yet to be determined. Importantly, these results demonstrate that observations of turbulence in clusters are giving rise to a new branch of astrophysics that can sharpen theoretical views on such plasmas. (Eugene Churazov)

2.10 Globular cluster formation deciphered

Several hundred globular star clusters orbit the Milky Way galaxy as remnants of an unknown star formation process that had to be common in the early Universe, when these clusters formed, but is rarely observed today. More massive galaxies such as the nearby elliptical M87 have tens of thousands of these clusters, largely resembling those around the Milky Way. These globular clusters all have typical masses of several hundred thousand solar masses and typical radii of several parsecs. It is speculated that the oldest and chemically un-enriched globular clusters formed in the early days of the Universe on timescales of only a few million years in merging small galaxies.

Motivated by this scenario, the team has performed the highest resolution simulation so far of a such a merger spanning seven orders of magnitude in time, density and pressure. In addition to low temperature gas cooling and star formation, the simulation accounts for the mass and energy output from ionization and type II supernovae from individual massive stars, and it includes the non-equilibrium chemical evolution of the dense interstellar medium (ISM) exposed to a space- and time-dependent interstellar radiation field.

The simulation has a maximum spatial resolution of 0.1 pc, a stellar and gas mass resolution of four solar masses and the time evolution is resolved down to 10 years. This is the most realistic and highest resolution simulation of such a system with a baryonic mass of 100 million solar masses. During the galaxy merger the gas is compressed by four orders of magnitudes and the system evolves into a phase of extreme star formation (Fig. 2.27).

In this phase individual star clusters are forming with masses from a few hundred to several ten thousand solar masses following a mass function which is also seen in real dwarf galaxies. In the densest regions of the merger a few star clusters reach almost one million solar masses on very short timescales of only a few million years (Fig 2.27). Their mass distributions are very similar to observed massive star clusters and globular clusters (Fig. 2.28). The velocity dispersions, half-mass radii, and central surface densities of the three most massive forming clusters are indistinguishable from massive stellar clusters and globular clusters in the dwarf galaxies Fornax and the Small and Large Magellanic Clouds (SMC and LMC), as well as in the Milky Way (Fig. 2.29). Their average stellar metallicities are close to the initial value of 0.1 solar, indicating that the clusters
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CHAPTER 2. SCIENTIFIC HIGHLIGHTS

Figure 2.27: Stellar distribution (left), gas (middle), and pressure (right) in a dense region of the dwarf starburst at two different times in the simulation (top: 5 million years, bottom: 3 million years before the final assembly of the cluster). In the highest density and pressure region (white ellipses) stellar protoclusters are forming and rapidly merging into a massive star cluster with globular cluster properties. *Credit: MPA*

Figure 2.28: Left: Density distribution of the three most massive clusters (colored) in comparison to observed local massive star clusters and globular clusters (grey). Right: Density distribution of the most massive simulated globular cluster. *Credit: MPA*

have not been significantly enriched by star formation during their short formation times.

This study provides a general model for the formation of metal-poor globular clusters in chemically unevolved starbursting environments of low-mass galaxies at high redshifts. This formation scenario is also consistent with observations of young massive clusters in the local Universe, which are thought to be the counterparts of old globular clusters. (Thorsten Naab)

2.11 Cool dense hydrogen gas around the first quasars

A prime objective of observational astrophysics is to peer deep into the young Universe and study how the first stars, galaxies, and black holes formed. For decades, astronomers exploited the brightness of quasars to study galaxy formation and evolution at all cosmic times, both as silhouettes against the luminous quasars, and in emission around them. Despite significant progress, we still do not understand the detailed processes whereby super-massive black holes with masses a billion times larger than the Sun assemble their mass in less than one billion years after the Big Bang, a small fraction of the current Universe age (13.7 billion years).

Hydro-dynamical cosmological simulations and analytical arguments suggest that to grow such massive systems in such a short time scale, the host galaxies of the first quasars need a continuous replenishment of fresh fuel. This gas has to be provided by cold filamentary streams from the so-called intergalactic medium down to the quasar’s host galaxy and/or by mergers with other gas rich galaxies. While a merger is a violent short episode, the aforementioned filaments should be present around each quasar.

Emission from this large-scale gas is, how-
2.11. COOL DENSE HYDROGEN GAS AROUND THE FIRST QUASARS

Figure 2.29: Central velocity dispersion (top), stellar half-mass radius (middle), and central stellar surface density (bottom) of the simulated clusters (large red symbols) in comparison to observed massive star clusters (colored) and globular clusters. The simulated cluster properties agree well with observations. Credit: MPA

Figure 2.30: An atlas of the extended Ly-Alpha halos detected at around $z \sim 6$ quasars (i.e., when the Universe is only 1/15th of its current age). The black dot at the center marks the quasar location. See also an animated 3D-version for P308-21 at the end of the page. Credit: MPA

ever, typically too faint to be detected unless it is illuminated by the intense radiation from the quasar. In this case, the hydrogen in the gas reprocesses the incident radiation and shines as an extended "fuzz" of Ly-Alpha emission, now detectable with top-notch facilities. Recently, a team of astronomers from Garching, Heidelberg, and Santa Barbara took advantage of this boosted emission and embarked on a large survey aimed at uncovering the presence of this fuzz around more than 30 luminous quasars in the young Universe.

An investment of more than 50 hours with the panoramic integral-field spectrograph MUSE on the Very Large Telescope revealed that around 40% of first quasars are embedded in Ly-Alpha halos (see Figure 2.30) with a total extent of up to a hundred thousand light years. These halos are directly tracing the presence of cool dense hydrogen gas around the first quasars. In particular, the researchers discovered that this gas is bound within the dark
CHAPTER 2. SCIENTIFIC HIGHLIGHTS

Figure 2.31: In the past years, several studies showed that quasars at the so-called cosmic noon (2-3 billion years after the Big Bang) are embedded in large Ly-Alpha nebulae. This plot illustrates how the average Ly-Alpha emission becomes fainter with increasing distance from the center of the dark matter halo where these quasars reside. The three different colors correspond to studies at different cosmic times. Surprisingly, while the shape of this drop remains similar, the earliest supermassive black holes (this study, red) appears to be surrounded by larger gas masses. Credit: MPA

...matter halo of the quasar host galaxies and that it is abundant enough to maintain both the observed high-rate of gas consumption of the central supermassive black holes and their highly star forming host galaxies.

The presence of these extended nebulae is an important piece of the puzzle that astronomers are building to picture the formation of large cosmic structures more than 12 billion years ago. By providing detailed constraints on the fuel supply, these new observations can be used to test current theories and models for the growth of massive galaxies and black holes from the Big Bang to the present (see Figure 2.31). While additional observations are already planned to fully capture the physical status of the gas, current data already pose new challenges to theoretical models. They indicate that, rather than being smooth, "Lyman-alpha" nebulae take on the consistency of a mist comprising an enormous number of tiny droplets. Reproducing the structure of these clouds may prove to be a key challenge for the next generation of theoretical models of galaxy evolution. (Emanuele Farina, Thales Gutcke, Tiago Costa, Fabrizio Arrigoni-Battaia).

2.12 Galaxy formation in separate universes

Imagine we are travelling across the Universe and want to measure some property such as the number of galaxies around us. This number is not going to be the same everywhere during our journey because various regions of the Universe are not equal. For example, in some regions, there was a slight excess of mass and energy at the beginning of the Universe, the Big Bang, which means there was more material to form galaxies, and so we would count more galaxies there. Astrophysicists need to take this variability into account when analysing observational data. In particular, it could be
the case that the observed part of the Universe is special and not representative of the whole Universe. Such an analysis can be performed with the aid of so-called Response Functions, which tell us how a given statistical measurement of the Universe changes when the properties of the underlying region change.

Researchers at MPA have been interested in studying response functions and their applications for some time now. This can be done with the “Separate Universe Formalism”, which establishes that structures forming in our Universe in a special (e.g. over- or under-dense) region are the same as the structures that would form in a normal region of a different/separate Universe (see Fig. 2.32). Studying responses is easier in this formalism, because numerical simulations can easily be used to study structure formation in other Universes – this is much easier than to simulate structure formation in special regions of our Universe. In the past, numerical studies of response functions were done with simulations that took into account only the effect of gravity. A team of researchers at MPA has recently gone beyond this limitation by running separate universe simulations with the IllustrisTNG galaxy formation model, which, for the first time, allowed them to study response functions including also important baryonic effects such as hydro-dynamical forces, gas cooling, star and black hole formation.

**Galaxy formation with an excess of baryons**

Matter in the Universe can broadly be divided into two types: (i) dark matter, which does not interact with light and comprises the majority of the mass (80 %), and (ii) all the rest. This rest is made up of the particles detected in particle physics experiments, which are called baryons. While dark matter is the dominant source of gravitational energy that drives structure formation, stars and galaxies are made up of baryons. Therefore the number of galaxies should depend on the amount of baryons available inside some observed region. In other words, the number of galaxies responds to the baryonic density.

A few theoretical models of the very early Universe (also known as the period of Inflation) predict that there should be regions in the Universe with an excess of baryons that is exactly compensated by a suppression in the number of dark matter particles; these are called compensated isocurvature perturbations (CIP), see Fig. 2.33. Researchers at MPA have studied how the number of galaxies responds to these perturbations using the separate universe formalism by simulating galaxy formation in Universes with different total amounts of baryons and dark matter.

The results of this study showed that, indeed, the number of galaxies depends strongly on the amount of baryonic matter. More interestingly, however, the sign of this dependency depends also on the quantity used to classify the galaxies. If the number of galaxies is mea-
Figure 2.33: Sketch of a compensated isocurvature perturbation (CIP): the total matter stays the same, but in some regions, more baryons are compensated by less dark matter. Credit: MPA

...sured as a function of total mass (dark matter + baryons), the response to CIP perturbations is negative, i.e., there are fewer galaxies with a given total mass. However, if the number of galaxies is measured as a function of the mass in stars (not the total mass), the response now displays the opposite trend, i.e. there are more galaxies with a given stellar mass. The MPA researchers traced back the origin of this change of sign to the modifications that the CIP perturbations induce on the relation between total mass and stellar mass in the galaxies.

This study provided the first ever prediction of the impact of CIP perturbations on the observed number of galaxies, which can now be incorporated in theoretical models of the distribution of galaxies in the Universe. This in turn will allow astronomers to use the statistics of galaxies to look for important signatures from the early Universe.

Using responses to predict weak gravitational lensing

The separate universe formalism can also be applied to large-scale maps of the total matter distribution. The light emitted by distant galaxies travels towards Earth along trajectories that are perturbed by the gravitational effect of the intervening matter. This effect, known as weak gravitational lensing, distorts the observed images of the distant galaxies and can be used to construct sky maps of the total mass between Earth and the galaxies, see Fig. 2.34. These maps contain information about the physics of our Universe and a popular way to organize this information is in N-point correlation functions: how does the matter density correlate between N points.

For quite some time, cosmologists have considered only the effect of gravity to obtain theoretical predictions for these statistics, but recently the community became aware of the critical importance of baryonic effects. For example, the heating and ejection of gas by black holes at the centre of massive galaxies can significantly alter the total distribution of the mass that weak lensing observations are sensitive to. The impact of baryonic effects on higher-order functions has remained largely unexplored, but researchers at MPA have recently made progress on this front. Specifically, separate universe simulations of galaxy formation were used to measure the impact of baryonic effects on the response of the 2-point function, which was in turn used in theoretical models to predict the impact of baryons on 3- and 4-point functions.

The fractional impact of the baryonic effects on 2-, 3- and 4-point correlation functions is shown in Fig. 2.34. All statistics display a suppression of their amplitude of approximately 5%-20% on the smallest scales (right part). This is as expected from the impact of black hole activity, which makes the density field smoother and the correlation of perturbations weaker. A key aspect revealed by this study was the fact that, quantitatively, the various N-point functions are affected differently by the same black hole activity. This work by the MPA researchers opens up a new window to study important effects on galaxy formation (like black hole activity) using combined analysis of different weak-lensing N-point functions. (Alexandre Barreira).
Figure 2.34: The top image shows a simulated weak-lensing map of the sky, as well as 2-, 3- and 4-point functions drawn on top. The lower panel shows the percentage impact of the baryonic effects on the N-point functions. The quantity on the x-axis is inversely proportional to distance: large scales on the left, smaller scales on the right. The vertical dashed lines correspond to those scales, where the effect of baryons exceed 1%. All N-point functions are affected by baryonic effects on small scales, but they all respond differently. Credit: MPA
Chapter 3

Publications and Invited Talks

3.1 Publications in Journals

3.1.1 Publications that appeared in 2019 (287)


3.1. PUBLICATIONS IN JOURNALS


Bose, S., et al. (incl. D. Nelson, V. Springel): Revealing the galaxy-halo connection in Illus- 

Bostroem, K. A., Valenti, S., et al. (A. Jerkstrand): Signatures of circumstellar interaction in 
the Type II supernova ASASSN-15oz. Mon. Not. R. Astron. Soc. 485 (4), 5120-5141 
(2019).

Boyle, A.: Understanding the neutrino mass constraints achievable by combining CMB lensing 

Bozorgnia, N., et al. (incl. R. Grand, R. Pakmor): On the correlation between the local dark 
matter and stellar velocities. Journal of Cosmology and Astroparticle Physics 045 
(2019).

Bustamante, S., and V. Springel: Spin evolution and feedback of supermassive black holes 

Byrohl, C., Fisher, R., and D. Townsley: The intrinsic stochasticity of the 56Ni distribution of 

Byrohl, C., Saito, S., and C. Behrens: Radiative transfer distortions of Lyman α emitters: a 


Cai, Z., S. Cantalupo, et al. (incl. F. Arrigoni-Battaia): Evolution of the Cool Gas in the 
Circumgalactic Medium of Massive Halos: A Keck Cosmic Web Imager Survey of Ly 

Callingham, T. M., et al. (incl. R. Grand, R. Pakmor): The mass of the Milky Way from 

Cataneo, M., Lombriser, L., et al. (incl. A. Barreira). On the road to percent accuracy: non-
linear reaction of the matter power spectrum to dark energy and modified gravity. Mon. 

Cesaroni, R., Beuther, H., et al. (incl. T. Peters): IRAS 23385+6053: An embedded massive 

Chen, G.-C.-F., Fassnacht, C. D., Suyu, S H., et al.: A SHARP view of H0LiCOW: H0 from 
three time-delay gravitational lens systems with adaptive optics imaging. Mon. Not. R. 


3.1. PUBLICATIONS IN JOURNALS


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3.1. PUBLICATIONS IN JOURNALS


CHAPTER 3. PUBLICATIONS AND INVITED TALKS


3.1. PUBLICATIONS IN JOURNALS


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Minami, Y., Ochi, H., et al. (incl. E. Komatsu): Simultaneous determination of the cosmic birefringence and miscalibrated polarization angles from CMB experiments. Progress of Theoretical and Experimental Physics, 2019(8), 083E02 (2019).


3.1. PUBLICATIONS IN JOURNALS


Planck Collaboration: Akrami, Y. et al. (incl. T. A. Enßlin, R.A. Sunyaev): Planck 2018 results. VII. Isotropy and Statistics of the CMB.


3.1. PUBLICATIONS IN JOURNALS


Rickards Vaught, R., K. Rubin, F. Arrigoni-Battaia et al.: A VLT/FORS2 Narrowband Imaging Search for Mg II Emission around $z\sim0.7$ Galaxies. Astrophys. J. 879(1), 7(2019).


3.1. PUBLICATIONS IN JOURNALS


Übler, H., Genzel, R., et al. (incl. T. Naab): The evolution and origin of ionized gas velocity dispersion from $z \sim 2.6$ to $z \sim 0.6$ with KMOS$^{3D}$. Astrophys. J. Lett. 880(1), 48 (2019).


3.1. PUBLICATIONS IN JOURNALS


CHAPTER 3. PUBLICATIONS AND INVITED TALKS


3.1.2 Publications accepted in 2019


Chluba, J., M. Abithbol et al. (incl. R. A. Sunyaev): New Horizons in Cosmology with Spectral Distortions of the Cosmic Microwave Background. ESA Voyage 2050, Science White Paper.


3.2. PUBLICATIONS IN PROCEEDINGS


Wong, K. C., Suyu, S. H. et al. (incl. E. Komatsu, S. Taubenberger): H0LiCOW XIII. A 2.4% measurement of \(H_0\) from lensed quasars: 5.3\(\sigma\) tension between early and late-Universe probes. Mon. Not. R. Astron. Soc.

Young, S.: The primordial black hole formation criterion re-examined: parameterisation, timing, and the choice of window function. International Journal of Modern Physics D.

3.2 Publications in proceedings

3.2.1 Publications in proceedings appeared in 2019


3.3 Talks

3.3.1 Invited review talks at international meetings

T. A. Enßlin:
- INTEGRAL looks AHEAD to Multimessenger Astronomy (Geneve, Switzerland, 14.2.)
- Big Data Science in Astroparticle Research (Aachen, Germany, 18.2.-19.2.)
- eROSITA Consortium meeting, (Potsdam, Germany, 4.3.-7.3.)
- Accelerating the Search for Dark Matter with Machine Learning (ICTP/IFPU, Trieste, Italy, 8.4.-12.4.)
- German School for Astroparticle Physics (Obertrubach, Germany, 2.10.-10.10.)
- Cosmic turbulence and magnetic fields : physics of baryonic matter across time and scales (Cargese, France, 4.11.-8.11.)

W. Hillebrandt:
- 16th Russbach School on Nuclear Astrophysics (Russbach, Austria, 10.3.-16.3.)

H.-Th. Janka:
- 57. International Winter Meeting on Nuclear Physics (Bormio, Italy, 21.1.–25.1.)
- Solvay Workshop in honour of Michel Godefroid ‘New Frontiers in Atomic, Nuclear, Plasma and Astrophysics’ (Brussels, Belgium, 25.11.–27.11.)
- Supernova Remants II: An Odyssey in Space After Stellar Death (Crete, 3.6.–8.6.)
- Frühjahrstagung der Deutschen Phys. Gesellschaft (München, Germany, 17.3.–22.3.)
- Multi-dimensional Modeling and Multi-Messenger observation from Core-Collapse Supernovae (4M-COCOS) (Fukuoka, Japan, 21.10.–24.10.)
- The Supernova – Supernova Remnant Connection (London, U.K., 11.1.)
- Fifty-One Ergs 2019: An International Conference on the Physics and Observations of Supernovae and Supernova Remnants (Raleigh, North Carolina, USA, 20.5.–24.5.)
- SN Neutrinos at the Crossroads: Astrophys. Oscill., and Detection (Trento, 13.5.–17.5.)
3.3. **TALKS**

**F. Schmidt:**
- CoSyne: Cosmological Synergies in the upcoming decade (Paris, France, 9.-12.12.)

**V. Springel:**
- La Serena Workshop on Galaxy Formation (La Serena, Chile, 11.3.-15.3.)
- First CTA Symposium (Bologna, Italy, 6.5.-9.5.)
- The Impact of Big Data in Astronomy (ISSI, Bern, Switzerland, 4.7.-5.7.)
- KICC 10th Anniversary Symposium (Cambridge, UK, 16.9.-20.9.)
- German Annual Astronomical Society Meeting (Stuttgart, 16.9.-20.9.)

**R. Sunyaev:**
- Synergy and competition of X-Ray and microwave sky surveys of clusters of galaxies: What we can expect from SRG/eRosita and ground based mm telescopes.
  (Uni Tübingen, 16.4.-18.4.)
- TDLI conference (Shanghai, 29.10.-3.11.)

**S. Suyu:**
- CosmoGold conference: The golden age of cosmology from Planck to Euclid, Institut d’Astrophysique (Paris, France, 24.6.-28.6.)
- Understanding cosmological observations conference, (Benasque, Spain, 29.7.-9.8.)
- Non-Standard Cosmology Probes, Aspen Center for Physics, (Aspen, USA 26.8-6.9.)

### 3.3.2 Invited Colloquia talks

**F. Arrigoni Battaia:**
- Instituto de Astrofisica de Canarias, (La Laguna, Spain, 19.3.)

**B. Ciardi:**
- What matter(s) between galaxies: Unraveling the knots in the Cosmic Web
  (Sarteano, Italy, 3.6.-7.6.)
- EWASS 2019: The Universe in the first billion years (Lyon, France, 24.6.-28.6.)

**T. A. Enßlin:**
- Department of Physics, Technical University Munich (Garching, Germany, 10.1.)
- Institute of Experimental Physics, University of Innsbruck (Innsbruck, Austria, 22.1.)
- Applied Mathematics/Statistics seminar, Newcastle University (Newcastle, UK, 5.2.)
- Institute for Computational Cosmology, Durham University (Durham, UK, 7.2.)
- Biomolecular Systems Seminar, Technical University Munich (Garching, Germany, 14.3.)
- Erlangen Centre for Astroparticle Phys., Friedrich-Alexander-Univ. (Erlangen, 2.5.)
- Anton Pannekoek Institute for Astronomy, Univ. of Amsterdam (Netherlands, 8.5.)

**H.-Th. Janka:**
- Ole Roemer Colloquium: Aarhus University (Aarhus, Denmark, 18.9.)
- Charles University (Prague, Czech Republic, 9.4.)
- Seminar Talk: University Heidelberg (Heidelberg, Germany, 4.4.)
CHAPTER 3. PUBLICATIONS AND INVITED TALKS

E. Komatsu:
- University of Portsmouth (Portsmouth, U.K. 31.1.)
- University of Tokyo (Tokyo, Japan 18.4.)
- Univ. Erlangen-Nürnberg (Erlangen, Germany 8.5.)
- MPI für Radioastronomie (Bonn, Germany 24.5.)
- SISSA (Trieste, Italy, 18.6.)
- Univ. of Barcelona (Barcelona, Spain 12.9.)
- CEA Saclay (Paris, France 24.9.)
- Institute for Advanced Study (Princeton, USA 1.10.)
- Uni Bonn (Bonn, Germany, 6.12.)

F. Schmidt:
- Physics Department, Universita di Torino (Turin, Italy, 8.3.)
- Center for Statistics and Inference in Cosmology, Imperial College (London, UK, 23.10.)

V. Springel:
- University of Ulm, (Ulm, Germany 21.1.)
- University of Zürich, (Zürich, Switzerland, 9.5.)
- Leibniz Institute for Astrophysics, (Potsdam, Germany 23.5.)
- Shanghai Astronomical Observatory, (Shanghai, China, 1.11.)
- Center for Computational Astrophysics, (New York, USA, 13.12.)

A. Weiss:
- Kiepenheuer Institut für Sonnenphysik (Freiburg i.Br., Germany, 28.11.)

S. Suyu:
- Colloquium, Perimeter Institute, (Waterloo, Canada, 20.3.)
- Colloquium, Leiden Observatory, (Leiden, The Netherlands, 9.5.)
- Colloquium, Institute of Astronomy, Cambridge University, (UK, 30.5.)
- Seminar, Département d’Astrophysique, CEA Saclay, (Paris, France, 11.7.)
- Colloquium, Academia Sinica Institute of Astron. and Astrophys., (Taipei, Taiwan, 14.8.)
- Colloquium, Observatoire de Sauverny, University of Geneva and Ecole Polytechnique Federale de Lausanne, (Geneva, Switzerland, 29.10.)
- Seminar, Max Planck Institute for Nuclear Physics, (Heidelberg, Germany, 18.11.)
- Astrophysics Coll., Massachusetts Inst. of Technology, (Cambridge, MA, USA, 3.12.)

3.3.3 Public talks

E. Komatsu:
- Japanisches Institut in München e.V. (9.2.)
- Tama Rokuto Science Center (30.3.)
- Japan Institute of Architects (17.4.)
- Tokyo Science Museum (20.4.)
3.4. Lectures and lecture courses

3.4.1 Lectures at LMU and TUM

T. A. Enßlin, SS 2019, LMU München
A. Weiss, SS 2019, LMU München

3.4.2 Short and public lectures

T. Enßlin:
  - “Numerical Information Field Theory” (key qualification course) LMU München, Garching, 9.9.-16.9.

E. Komatsu:
  - “Gravitational waves from the early Universe” (Frontier Research in Astrophysics and Particle Physics, Instituto de Física de Cantabria, Santander, Spain, 4.6.)
  - “Lectures on the cosmic microwave background” (Natur- und Ingenieurwissenschaftliches Kolleg VIII, Studienstiftung des deutschen Volkes, 16.9.-19.9.)

V. Springel:
  - IMPRS Advanced Course (Garching, 25.11.-29.11.)

R. Sunyaev:
  - Chandrasekhar Lecture Series, (Bangalore 10.1.-27.1.)
  - Bragg Lecture, Univ. Manchester (Manchester, 5.3.-7.3.)
  - MPG Public Lecture at Tata Institute for Fundamental Reseach, (Mumbai 13.3.-17.3.)
  - Inaugural Nick Kylafis Lecture (Heraklion, 24.10.-26.10.)
Chapter 4

Personnel

4.1 Scientific staff members

Directors
Guinevere Kauffmann, Eiichiro Komatsu, Volker Springel (Managing Director), Simon White (until 30.9.)

Research Group Leaders/Permanent Staff
Eugene Churazov, Benedetta Ciardi, Torsten Enßlin, Marat Gilfanov, Adrian Hamers (since 1.9.), 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, Friedrich Meyer, Rashid Sunyaev, Simon White (since 1.10.).

Associated Scientists:
Gerhard Börner, Geerd Diercksen, Wolfgang Krämer, Emmi Meyer-Hofmeister, Ewald Müller, Hans Ritter, Henk Spruit,

Staff/Postdoc
Nicola Amorisco (till 30.9.) George Angelou (till 30.11.), Fabrizio Arrigoni-Battaia, Alexandre Barreira, Rebekka Bieri, Robert Bollig, Philipp Busch (1.7.-30.9.), Giovanni Cabass, Raoul Cañameras (since 1.1.), Tiago Costa, Linda Blot, Giulia Despali, Thomas Ertl (until 31.10.), Elisa Ferreira Francesca Fragkoudi, Matteo Frigo (since 1.5.), Michael Gabler,

Ph.D. Students

Felix Ahlborn, Abhijeet Anand, Philipp Arras, Mohammadreza Ayromlou Eirini Batziou, Aoife Boyle (until 30.9.), Philipp Busch (until 30.6.), Chris Byrohl, Dani Chao, Giulia Chirivi, Luca Di Mascolo, Jakob Ehring (since 1.5.), Wolfgang Enzi, Silvia Fiaschi (since 1.9.), Andreas Flörs (since 1.3.), Konstantina Fotopoulou, Philipp Frank, Matteo Frigo (until 30.4.), Ilkham Galiullin, Robert Glas (until 31.12.), Martin Glatzle, Timo Halbesma, Laura Herold (since 14.10.), Johann Higl, Jessica Hislop, Simon Huber (since 1.5.), Sebastian Hutschenreuter, Liliya Imasheva, Miranda Jarvis, Andreas Jörgensen (since 1.10.), Jakob Knollmüller, Ivan Kostyuk (since 1.4.), Daniel Kresse, Jere Kuuttila, Reimar Leike, Simon May, Leila Mirzagholi, Nahir Munuz Elgueta (since 1.9.), Simon Ndiritu (since 1.11.), Nhat Minh Nguyen, Pericles Okalidis, Natalia Porqueres (until 30.9.), Tim-Eric Rathjen, Johannes Ringler (since 1.9.), Elisa Ritondale (since 31.8.), Francesca Rizzo, Francesco Rizzuto, Stefan Schuldt, Georg Stockinger, Jens Stücker (since 30.6.), Christian Vogl, Oliver Zier (since 1.9.)

Master students

J. Bayer (1.5.-31.8.), M. Giese (till 28.2.), V. Eberle (since 1.10.), G. Edenkofer (since 1.10.), S. Ertl (since 1.10.), P. Haim (since 8.4.), B. Holzschuh (1.4.-30.11.), F. Kapfer (since 18.3.), A. Kostic (since 1.10.), R. Lemmerz (since 1.10.), S. Milosevic (since 15.4.), L. Platz (until 28.2.), N. Reeb (since 1.10.), B. Remple (since 1.10.), J. Roth (since 1.10.), M. Wandrowski (since 28.2.), L. Walls (since 20.10.), H. Wang (since 1.10.), B. Wang (since 1.11.), P. Zehetner (since 1.10.).

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 (since 1.1.), Christiane Bartels (library management), Elisabeth Blank.

4.1.1 Staff news/Awards

Fabrizio Arrigoni Battaia has been transferred to a tenure-track position from 1.11.2019.

Aoife Boyle received the Kippenhahn Award for the best MPA student publication.

4.2.1 Ph.D. theses 2019

Philipp Busch: Spatial description of large scale structure and reionisation. Ludwig Maximilians Universität München.


Matteo Frigo: The impact of black holes on the stellar-dynamical properties of early-type galaxies. Ludwig Maximilians Universität München.

Johann Higl: Multi-Dimensional Simulations of Convective Core Hydrogen Burning. Technische Universität München.

Andreas Joergensen: Combining stellar structure and evolution with multi-dimensional hydrodynamic simulations. Ludwig Maximilians Universität München.

Natalia Porqueres i Rosa: Inferring the dynamical growth of structures from high-redshift cosmological data sets. Ludwig Maximilians Universität München.


Malin Renneby: Weak gravitational lensing as a probe of large-scale structure and galaxy formation. Ludwig Maximilians Universität München.


Dijana Vrbanec: Exploring the epoch of reionization with the 21 cm line. Ludwig Maximilians Universität München.
4.2.2 Master theses 2019

Tobias Aschenbrenner: Adaptive reconstruction in information field theory. Ludwig Maximilians Universität München.

Jorge Corella Puertas: Magnification Effects in Galaxy-Galaxy Lensing. Technische Universität München.

Jakob Ehring: Accretion Induced Collapse of White Dwarfs. Ludwig Maximilians Universität München.


Johannes Harth-Kitzerow: Bayesian Data Compression. Ludwig Maximilians Universität München.


Maxim Wandrowski: Building a COMPTEL Response for Bayesian Image Reconstruction. Ludwig Maximilians Universität München.
### Visiting scientists

<table>
<thead>
<tr>
<th>Name</th>
<th>Home institution</th>
<th>Duration of stay at MPA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Irene Abril Cabezas</td>
<td>Univ. Complutense de Madrid</td>
<td>8.9.-22.12.</td>
</tr>
<tr>
<td>Isabelle Baraffe</td>
<td>Exeter Univ.</td>
<td>4.11.-3.12.</td>
</tr>
<tr>
<td>Diego Barbosa Trujillo</td>
<td>Los Andes Univ. Columbia</td>
<td>1.7.-31.7.</td>
</tr>
<tr>
<td>Soumen Basak</td>
<td>IISER, TVM, India</td>
<td>12.5.-2.6.</td>
</tr>
<tr>
<td>Andrei Beloborodov</td>
<td>Columbia Univ.</td>
<td>since 3.6.</td>
</tr>
<tr>
<td>Andrei Belyaev</td>
<td>Herzen Univ. St. Petersburg</td>
<td>20.10.-3.11.</td>
</tr>
<tr>
<td>Silvia Bonoli</td>
<td>DIPC, San Sebastian</td>
<td>1.7.-12.7.</td>
</tr>
<tr>
<td>Sebastian Bustamante</td>
<td>HITS, Heidelberg</td>
<td>several weeks</td>
</tr>
<tr>
<td>Gilles Chabrier</td>
<td>Exeter Univ.</td>
<td>4.11.-3.12.</td>
</tr>
<tr>
<td>James Chan</td>
<td>EPFL, Lausanne</td>
<td>25.4.-9.5.</td>
</tr>
<tr>
<td>Miha Cernetic</td>
<td>MPS Göttingen</td>
<td>24.2.-8.3.</td>
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<tr>
<td>Jessica Doppel</td>
<td>Univ. of California, Riverside</td>
<td>15.9.-14.12.</td>
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<tr>
<td>Mike Fall</td>
<td>STScI, Baltimore</td>
<td>22.7.-14.8.</td>
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<tr>
<td>Emanuele Farina</td>
<td>MPIA, Heidelberg</td>
<td>since 1.1.-30.11.</td>
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<tr>
<td>Andrea Ferrara</td>
<td>SNS Pisa</td>
<td>1.9.-30.10.</td>
</tr>
<tr>
<td>Jaime Forero Romero</td>
<td>Los Andes Univ. Columbia</td>
<td>1.7.-31.7.</td>
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<tr>
<td>Facundo Gomez</td>
<td>Univ. La Serena, Chile</td>
<td>17.11.-30.11.</td>
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<tr>
<td>Jon Grumer</td>
<td>Uppsala Univ. Sweden</td>
<td>1.4.-12.4.</td>
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<tr>
<td>Kim Heinemann</td>
<td>Trainee</td>
<td>13.5.-30.8.</td>
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<tr>
<td>Sofie Liljegren</td>
<td>Uppsala Univ. Sweden</td>
<td>1.4.-12.4.</td>
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<tr>
<td>Yen-Ting Lin</td>
<td>ASIAA Taiwan</td>
<td>5.7.-20.8.</td>
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<tr>
<td>Natalia Lyskova</td>
<td>IKI Moscow</td>
<td>6.8.-30.9.</td>
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<tr>
<td>Umberto Maio</td>
<td>AIP, Potsdam</td>
<td>since 5.11.</td>
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<tr>
<td>Paolo Mazzali</td>
<td>JMU, Liverpool</td>
<td>23.6.-20.7.</td>
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<tr>
<td></td>
<td></td>
<td>and 3.10.-28.10.</td>
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<tr>
<td>Bernhard Müller</td>
<td>Monash University</td>
<td>1.7.-16.7.</td>
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<tr>
<td>Geoff Murphy</td>
<td>Univ. of Cape Town, ZA</td>
<td>17.11.-1.12.</td>
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<tr>
<td>Eva Ntormousi</td>
<td>Univ. of Crete</td>
<td>4.8.-10.9.</td>
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<tr>
<td>Benard Nsamba</td>
<td>Univ. do Porto</td>
<td>1.11.-30.11.</td>
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<tr>
<td>Prakriti Palchoudhury</td>
<td>Indian Inst. Bangalore</td>
<td>till ?</td>
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<tr>
<td>Diego Paller</td>
<td>Univ. La Serena, Chile</td>
<td>17.11.-30.11.</td>
</tr>
<tr>
<td>Name</td>
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<tr>
<td>Laura Sales</td>
<td>Univ. of California, Riverside</td>
<td>3.9.-15.9.</td>
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<tr>
<td>Anatoly Spitkovsky</td>
<td>Princeton Univ.</td>
<td>12.6.-30.6.</td>
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<tr>
<td>John Suarez Perez</td>
<td>Uni Andes, Kolumbien</td>
<td>1.6.-30.6.</td>
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<td>Julia Stadler</td>
<td>Trainee</td>
<td>1.7.-9.8.</td>
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<tr>
<td>Lorenzo Stichler</td>
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<td>1.7.-31.8.</td>
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<td>Hiroaki Tahara</td>
<td>Univ. of Tokyo</td>
<td>1.2.-30.3.</td>
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<td>Patricia Tissera</td>
<td>Univ. Andres Bello, Chile</td>
<td>24.6.-11.7.</td>
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<tr>
<td>Thorold Tronrud</td>
<td>Univ Andres Bello, Chile</td>
<td>1.7.-2.8.</td>
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<tr>
<td>David Villalba</td>
<td>CEFCA, Teruel, Spain</td>
<td>30.6.-28.7.</td>
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<tr>
<td>Theresa Vogl</td>
<td>Student apprentice</td>
<td>19.2.-16.4.</td>
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<tr>
<td>Rodrigo Voivodic</td>
<td>Univ. de Sao Paulo, Brazil</td>
<td>since 17.6.</td>
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<tr>
<td>Yuki Watanabe</td>
<td>Univ. of Sao Paulo, Brazil</td>
<td>since 1.4.</td>
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<tr>
<td>Ira Wolfson</td>
<td>Ben Gurion Univ.</td>
<td>since 1.9.</td>
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<tr>
<td>Svetlana Yakovleva</td>
<td>Herzen Univ. St. Petersburg</td>
<td>20.10.-3.11.</td>
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<tr>
<td>Samuel Young</td>
<td>AvH Fellowship</td>
<td>since 1.2.</td>
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