Max-Planck-Institut
für
Astrophysik

Annual Report 2016

Contents

1 General Information

1.1 A brief history of the MPA

The Max-Planck-Institut für Astrophysik, usually called MPA for short, was founded in 1958 under the directorship of Ludwig Biermann. It was established as an offshoot of the Max-Planck-Institut für Physik, which at that time had just moved from Göttingen to Munich. In 1979, as part of plans to move the headquarters of the European Southern Observatory from Geneva to Garching, Biermann's successor, Rudolf Kippenhahn, relocated the MPA to its current site. The MPA became fully independent in 1991. Kippenhahn retired shortly thereafter and this led to a period of uncertainty, which ended in 1994 with the appointment of Simon White as director. The subsequent appointments of Rashid Sunyaev (1995) and Wolfgang Hillebrandt (1997) as directors at the institute, together with adoption of new set of statutes in 1997, allowed the MPA to adopt a system of collegial leadership by a Board of Directors. The Managing Directorship rotates every three years, with Eiichiro Komatsu in post for the period 2015-2017.

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: Riccardo Giacconi, 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. This generational change continued in 2013 when the MPA's own Guinevere Kauffmann was promoted to a directorship, thereby ensuring that the institute will remain a centre for studies of the formation and evolution of galaxies.

Finally, two searches are currently underway for two new directors, active in general areas of computational astrophysics, and the areas including, but not limited to, stellar astrophysics, planetary science, and high-energy astrophysics such as accretion disks and compact objects. These new directors are formally the successors of Wolfgang Hillebrandt who retired in 2012 and Simon White who will retire in 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, dilute plasmas with magnetic fields and energetic particles, and the calculation of transition probabilities and cross–sections for astrophysical processes in rarefied media. From its inception the MPA has had an internationally-recognized numerical astrophysics program that was long unparalleled by any other institution of similar size.

Over the last 20 years, activities at the MPA have diversified considerably. They 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, and physical and early universe cosmology. 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 subtantially increased and internationalised the graduate student body at MPA over the last decade and has resulted in productive social and professional links between MPA students and those at other local institutions. Currently about 25 students at MPA participate in the

IMPRS.

MPA policy is effectively set by the Wissenschaftliche Institutsrat (WIR) which has met regularly about 6 times a year since 1995 to discuss all academic, social and administrative issues affecting the institute. This consists of all the permanent scientific staff and the Max-Planck Research Group leaders, as well as elected representatives of the postdocs, doctoral students and support staff. It acts as the main formal conduit for discussion and communication within the institute, advising the directorate on all substantive issues. Ad hoc subcommittees of the WIR carry out the annual postdoc and student hiring exercises, monitor student progress, oversee the running of the computer system, and, in recent years, have carried out the searches for new directions and directorial candidates.

Other aspects of the MPA's structure have historical origins. Its administrative staff is shared with the neighboring, but substantially larger MPI für extraterrestrische Physik (MPE). The library in the MPA building also serves the two institutes jointly. All major astronomical books and periodicals are available. The MPA played an important role in founding the Max-Planck Society's Garching Computer Centre (the RZG; the principal supercomputing centre of the Society as a whole). MPA scientists have free access to the RZG and are among the top users of the facilities there. The Max Planck Computing and Data Facility (MPCDF, formerly known as RZG) is a cross-institutional competence centre of the Max Planck Society to support computational and data sciences. It originated as the computing centre of the Max Planck Institute for Plasma Physics (IPP) which was founded 1960 by Werner Heisenberg and the Max Planck Society (MPS). Since January 2015 the MPCDF became an independent institute of the MPG.

1.2 Current MPA facilities

Computational facilities

Theoretical astrophysicists demand a perfect computing and networking infrastructure. Theoreticians, numerical simulators and data analysts have different needs. To satisfy these needs, MPA has its own, strong and capable IT-group, headed by a scientist to efficiently communicate between scientists and computer specialists. In addition, a group of scientists constitutes the “Computer Executive Committee”, responsible for the long-term strategy and planning, and for balancing the requests of the different groups and users. Our aim is to satisfy the needs by providing both 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) and the Leibniz Computer Centre of the state of Bavaria (LRZ).

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, typically of the order of millions of CPU-hours per project at various other supercomputer centres at both national and international level. 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. In 2016, one of such Linux-clusters (with 2600 processor cores, up to 10~TB of core memory and 890~TB disk storage capacity) is located at MPCDF, and is used for moderately parallel codes. This machine is going to be replaced in 2017 by an upgraded, new machine. In addition, MPA is operating 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) and provide web access to the worldwide community via the Millenium database. This system consists of 2~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 that there is no need for users 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 64 processor cores and 96 GB memory) plus the latest and largest machine with 640 cores and about 4 TB of core memory, which was added in 2015. 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 has 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 subnet which is separated from crucial system components by a firewall. Apart from the standard wired network (Gb capacity up to floor level, and 100 Mb 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 OpenSource software and developments. The Linux system is a special distribution developed in-house, including the A(dvanced) 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 Macintosh PCs or software are satisfied by a number of public PCs and through servers and emulations.

The system manager group comprises three full-time and one part-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 53000 books and journals and about 7300 reports and observatory publications, as well as print subscriptions for about 160 journals and online subscriptions for about 500 periodicals, as well as an ebook collection of about 4000 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, doctoral dissertations, and habilitation theses, reports (print and online). Additional technical services such as several PCs and terminals in the library area, copy machines, a colour book-scanner, two laser printers, and a fax machine are available to serve the users' and the librarians' needs. The library is run by two people who share the tasks as follows: Mrs. Bartels (full time; head of the library, administration of books and reports) and Mrs. Blank (full time; "Pure", publication management for both institutes - about 850 publications 2015, and administration of journals)

1.3 2016 at the MPA

New Research group

Sherry Suyu began her independent Max-Planck Research group (MPRG) in January 2016 (see Fig. 1.1). The MPRGs are established as smaller, independent research units, often supplementing departments at Max Planck Institutes, such as at MPA. MPRG's funding comes from the central administration of the Max Planck Society, and is separate from the budget of MPA, assuring financial independence of the groups. The MPRGs are highly competitive positions, selected from the international pool of applicants with the success rate of about 40 to 1. The groups offer young junior scientists who hold a doctorate an exceptional opportunity to further qualify themselves on a very high level. Suyu is appointed for a five-year term (renewable for up to four more years). She has also been appointed as a tenure-track professor (W2) at the Technical University Munich (TUM) as a result of a joint initiative of TUM and the Max Planck Society for MPRGs.

The MPRG of Suyu aims to shed light on three dark components in the cosmos: (1) Dark Energy, which is driving the accelerated expansion of the universe; (2) Dark Matter in galaxies and the effect it has on their formation/evolution; and (3) Supermassive Black Holes at the centres of galaxies, to see how they evolve with their host galaxies. As a tool to study all three topics, the

Figure 1.1: Sherry Suyu, new research group leader since January 2016

MPRG uses strong gravitational lensing, in particular strongly lensed quasars. Strong gravitationally lensed quasars occur when a background quasar and a foreground massive object are aligned along the line of sight such that the background quasar is magnified and split into multiple images around the foreground lens. The quasar is powered by accretion of material onto a supermassive black hole at the center of the background galaxy, and emits radiation that varies over time as the accretion takes place. The same variability pattern appears in each of the quasar images but delayed in time due to the different light paths of the multiple images. This time delay is a direct measure of the distance to the lens system and we can use this measure to study the expansion history of the universe, and how dark energy might influence it. From the multiple images we can also reconstruct the mass distribution of the foreground lens galaxy and probe its dark matter distribution, in order to understand the interplay between dark matter and baryons during galaxy formation/evolution.

Finally, the lensed quasars are powered by supermassive black holes, and strong lensing allows us to get a magnified view of these exotic objects and to study the co-evolution between the black holes and their host galaxies. Suyu is currently leading the H0LiCOW program that uses five of the best lensed quasars for measuring the expansion rate of the Universe and studying galaxies and black holes. Her MPRG is also actively hunting for new gravitational lens systems of all kinds in current wide-field imaging surveys, including the Hyper Suprime-Cam Survey and the Dark Energy Survey, for probing the dark sectors of the Universe.

Biermann lectures 2016

The topic of the 2016 Biermann Lectures by Professor Mitchell Begelman from the University of Colorado was *“Magnetism and Radiation in Motion, in Disks and Jets”* (see Figure 1.2).

Black holes are fascinating – even though or especially because they cannot be seen; nothing, not even light, can escape their gravitational pull. Nevertheless their immediate surroundings are very interesting laboratories to study high-energy and relativistic processes in space. Astrophysical phenomena such as gas dynamics, magneto-hydrodynamics, and radiative transfer in a broad range of astrophysical phenomena were the topic of this year’s Biermann Lectures by Mitchell Begelman from the University of Colorado. After his major in physics at Harvard in 1974, Mitchell Begelman decided to concentrate on theoretical astrophysics for his graduate studies, working with the young professor Martin Rees at Cambridge. Back then, black holes were a purely theoretical thought experiment – many people didn’t believe that such extreme objects actually existed, let alone that sometime astronomers might be able to observe them (or at least their surroundings). Then came the first discovery of cosmic jets: black holes ejecting gas from their surroundings along their rotational axis. In 1984, Begelman co-authored a paper with Roger Blandford and Martin Rees on the physics of jets, which has become one of the standard references of the field.

After his PhD in 1978 Professor Begelman worked at Cambridge and the University of California at Berkeley as a postdoc. He joined the University of Colorado at Boulder as faculty in 1982, and is a full professor there since 1991. He is an author of more than 220 refereed journal articles, many of which had very high impacts in a broad range of research areas in theoretical astrophysics. He received numerous awards and honors for his work, including the Guggenheim Fellowship, the Helen B. Warner Prize of the American Astronomical Society, the Alfred P. Sloan Foundation Research Fellowship, and the Presidential Young Investigator Award.

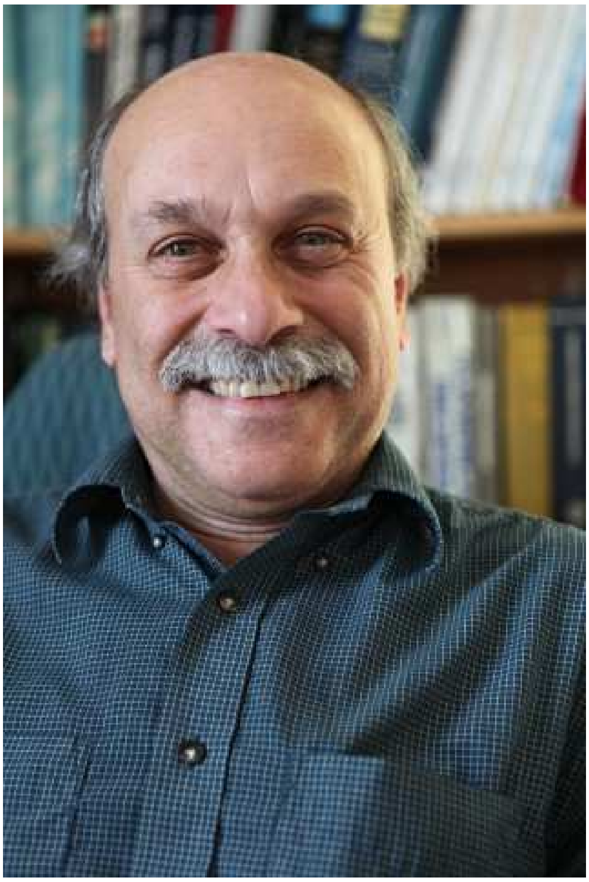

Figure 1.2: The 2016 Biermann Lecturer: Mitchell Begelman *credit: JILA, University of Colorado, Boulder*

In addition to the topic of the Biermann Lectures, Begelman's research includes studies of astrophysical gas dynamics, magnetohydrodynamics, and radiative transfer theory as applied to a broad range of astrophysical phenomena. These include active galaxies and quasars, compact objects, star formation, galaxy formation, and dynamics and evolution of dense stellar systems.

He is also the author of two popular books, "*Gravity's Fatal Attraction*" which was co-authored with Martin Rees, and "*Turn Right at Orion*". The former book has been translated into multiple languages, including German: "*Schwarze Löcher Im Kosmos: Die magische Anziehungskraft der Gravitation*". In 1996 he received the American Institute of Physics Science Writing Award.

Prizes and Awards 2016

MPA director Rashid Sunyaev was awarded the 2015 Oskar Klein medal by the Stockholm University and the Nobel Committee of the Royal Swedish Academy of Sciences. The Memorial lecture on "Unavoidable distortions in the spectrum of CMB and the Blackbody Photosphere of our Universe" took place on 4 February 2016 in the Oskar Klein Auditorium at the Alba Nova University Centre in Stockholm. The Oskar Klein medal is awarded since 1988. Among its 26 recipients are nine Nobel Prize laureates and eight world recognised cosmologists. In their citation the committee highlighted that Professor Sunyaev has made groundbreaking contributions to theoretical astrophysics in the areas of cosmology, high-energy astrophysics and X-ray astronomy through his studies of some of the most extreme physical processes in the universe. His theory of the evolution of density fluctuations in the early universe (developed with Ya.B. Zel'dovich) predicted the acoustic peaks that are observed in the cosmic background radiation. He has also made key contributions to the theoretical description of matter accreting onto black holes, predicting a signature for the resulting X-ray emission.

Fabian Schmidt was among the ten new members appointed to the Junge Akademie (Young Academy) at the Berlin-Brandenburg Academy of Sciences (BBAW) and the German Academy of Sciences Leopoldina. On 11 June 2016, they were introduced in an official ceremony in Berlin, starting a new phase in the interdisciplinary work of the Young Academy with the aim to encourage discourse between science and society, and bring new ideas into the science policy debate. After studying physics at the Humboldt University Berlin, Fabian Schmidt received his Ph.D. from the University of Chicago.

On 28 October 2016 the Russian Academy of Sciences announced that Marat Gilfanov, a research group leader at MPA, was elected to the Academy as a Corresponding Member. The Academy holds elections once every several years and in 2016, three new corresponding members in Astronomy joined the Academy. Marat Gilfanov completed his studies at the Moscow Institute of Physics and Technology and received a PhD in Astrophysics from the Space Research Institute (IKI) in Moscow in 1989. In 1996 he received his Habilitation from IKI and joined MPA the same year. The main focus of Marat Gilfanov's work is high energy astrophysics including X-ray astronomy. He collaborates closely with IKI, in particular in connection with the eROSITA X-ray telescope built by the Max-Planck-Institute for Extraterrestrial Physics and planned for launch aboard Spectrum-X orbital observatory in 2018. Marat Gilfanov is also an extraordinary professor of Amsterdam University.

ERC Grants

Fabian Schmidt is currently head of a research group at the Max Planck Institute for Astrophysics, funded by a Marie Curie fellowship and a Starting Grant by the European Research Council ERC (from September 2016). Fabian Schmidt's research focuses on using the large-scale distribution of galaxies to probe Dark Energy, modified gravity, and the early Universe. In particular, his group studies the relation between galaxies and matter, which is known as bias, and the signatures of the epoch of primordial inflation in the galaxy distribution. Further topics are the effects of modifications of General Relativity on the clustering and motion of galaxies, and novel likelihood approaches to infer robust constraints from large galaxy surveys.

The European Research Council and MPA-postdoc Jérôme Guilet signed the agreement for an ERC Starting Grant in December 2016. The project funded will research exploding stars from first principles, in particular magnetars as engines of hypernovae and gamma-ray bursts. The birth of a neutron star with an extremely strong magnetic field, called a magnetar, has emerged as a promising scenario to power a variety of outstanding explosive events. Simple phenomenological models, where certain properties of the magnetar are adjusted, such as its rotation period and magnetic field, can explain many of the observations of stellar explosions to date. These models, however, lack a sound theoretical basis.

Jérôme Guilet will use the ERC funding to develop an ab initio description of explosions powered by a magnetar in order to delineate the role they play for the production of gamma-ray bursts and super-luminous supernovae. By using state-of-the-art numerical simulations, the project will investigate the origin of the gigantic magnetic field observed in magnetars as well as the various explosion paths that can be explained by the birth of fast-rotating magnetars. Currently based at MPA, Jérôme Guilet will move to CEA-Saclay for this project.

Figure 1.3: MPA Director Eiichiro Komatsu presents Thomas Ertl (right) and Chia-Yu Hu (left) with the Kippenhahn Award certificate. *credit: MPA*

Rudolf-Kippenhahn-Award

Since 2008, the Kippenhahn Award has been awarded for the best scientific publication written by an MPA student; it was donated by the former director of the institute, Prof. Rudolf Kippenhahn, to motivate students to write a good publication. In 2016 Thomas Ertl and Chia-Yu Hu were the recipients: Ertl for his publication "A two-parameter criterion for classifying the explodability of massive stars by the neutrino-driven mechanism"; and Hu for his paper "Star formation and molecular hydrogen in dwarf galaxies: a nonequilibrium view". See Figure 1.3.

Criteria for the award are that the student is the first author and has contributed substantially to the scientific ideas, calculations and analysis, and the writing of the paper. The committee received five applications and was impressed by the quality of the papers. After careful consideration they decided to award the Kippenhahn award to two winners. Thomas Ertl's paper introduces a novel criterion to predict the final fate of massive stars – either collapse to a black hole or neutron star formation accompanied by a supernova explosion. Based on simulations of stellar core collapse and neutrino-driven explosions, which he had performed for a huge set of hundreds of stars of different masses and metallicities, Ertl discovered that two parameters in combination, the enclosed mass and the corresponding gradient at the interface of the silicon layer and oxygen-enriched silicium-shell, can do an excellent job as indicators of the “explodability” of a star. With the paper “Star formation and molecular hydrogen in dwarf galaxies: a nonequilibrium view” Chia-Yu Hu makes a major step forward in understanding star formation in dwarf galaxies. His self-consistent numerical simulations resolve the impact of individual supernova explosions, photoelectric heating, and dust on the non-equilibrium chemo-dynamical structure of the interstellar medium and have reached unprecedented resolution and physical realism. Hu was able to demonstrate that the cold and dense gas reservoir for star formation in dwarf galaxies is dominated by atomic hydrogen instead of H2. Their star formation rates are mainly regulated by feedback from supernovae.

Figure 1.4: The school girls were able to do some research themselves during the Girls’Day. In different experiments they “worked” on several astronomical topics. *(credit: H.-A. Arnolds, MPA)*

Public Outreach 2016

Making the results of its work accessible to a wide audience continues to be an important task for the institute. Many colleagues are actively engaging in public outreach in a broad range of activities, such as talks and live presentations in our planetarium.

In 2016, a dozen school and student groups (about 350 persons in total) visited MPA, not only from Germany, but also from Switzerland, Turkey, Finland and South Korea. In addition, the planetarium was also presented to the colleagues at the headquarters office of the Max Planck Society in Munich, who really appreciated the opportunity to learn about the science at one of the institute first hand and in such a unique environment. Continuing a well-established tradition, the MPA again took part in the annual Girls’Day in April (see Fig. 1.4). After a quiet start – for many girls it was the first time visiting a scientific institute – the girls soon overcame their shyness and asked many questions about the astronomic topics raised in the planetarium presentation. And even if there was the additional hurdle of having to speak English with a number of the helpers, soon this too was no longer a problem and there were many lively discussions. Topics ranged from questions about the sky and astronomical objects to what it means to work in this field - not only as a woman but in terms of the general working conditions. In the end, the programme even took a bit longer than foreseen initially – a clear indication of how much fun it was for both visitors and staff.

MPA scientists were also involved in educational programmes for school teachers and gave public talks outside the institute, e.g. in the framework of Café & Kosmos, an event series organised together with the Excellence Cluster Universe, ESO, MPE and MPP. They supervised undergraduates and high school students on small research projects during internships, served as guides for tour groups through the Cosmology exhibition at the Deutsches Museum, which was curated partly by MPA, wrote articles for popular science media and acted as interview partners for press and TV journalists. The public outreach office issued a number of press releases about important scientific results as well as news about awards and prizes for MPA scientists. These were published on the MPA website as well, complementing the popular monthly scientific highlight series.

2 Scientific Highlights

2.1 The diversity of stellar halos in massive disk galaxies

The stellar halos of galaxies are diffuse and faint components which provide scientists with a window into the assembling history of galaxies. A research team at MPA has investigated the properties of stellar halos in large disk galaxies by using both observations and state-of-the-art simulations of galaxy formation. They find a great diversity in the halo properties for galaxies that are – otherwise – alike in terms of morphology, mass, and luminosity. Observed properties, such as a mean metallicity as a function of galactocentric distance, can be reproduced by the simulations if they are analyzed in the same way as the data.

Stellar halos are diffuse and faint components surrounding most large galaxies. They form largely from the accretion and disruption of smaller satellite galaxies, although their inner regions also contain stars which were formed in the disk of their host galaxy. Stellar halos are highly important to understand galaxy formation and evolution since they preserve a record of the accretion history of galaxies and serve as probes of the total matter distribution of galaxies. However, stellar halos are far less luminous than the main galactic disk. Observing them is therefore an extremely challenging task. Over the past decades, different approaches have been developed to reveal this diffuse component of galaxies. Observations of galaxies with very long exposure times have produced stunning images, an example of which is shown in Figure 2.1. These observations helped characterize the role of accretion and mergers in shaping the outskirts of galaxies as well as unveil their vast extent, reaching distances larger than 100 kpc from their centre.

To study the properties of stellar halos in detail, however, the astronomers need to observe their constituent stars. By doing so, it is possible to estimate the mean age and chemical composition (called metallicity, when all elements but hydrogen and helium are considered) of the halo stellar population as a function of distance from the galactic centre. Until recently, studies of halo stars were confined largely to our own Milky Way and the neighbouring Andromeda galaxy, due to the proximity of their stars. However, during the past years the GHOSTS survey has extended this study to nearby disk galaxies, thanks to the exquisite resolution of the Hubble Space Telescope (Figure 2.2).

Figure 2.1: The observed stellar halo of NGC 474 showing the complex substructure present in the outer regions of this large elliptical galaxy. Shells and tidal stellar streams are formed as a consequence of the interactions with and accretion of smaller galaxies. *Credit: P.-A. Duc (CEA), J.-C. Cuillandre (CFHT) et al. 2013, IAUS, 295, 358.*

In her recent work, MPA scientist Antonela Monachesi has studied individual stars in the halos of nearby galaxies similar to the Milky Way using GHOSTS observations. This study showed that there is a great diversity in the metallicity of the observed stellar halos. In addition, the way this metallicity depends on the distance from the galactic centre also varies from galaxy to galaxy. In half the currently analyzed galactic halos the mean metallicity decreases with galactocentric distance, whereas the other half shows no significant variation with distance.

Moreover, the results from the GHOSTS observations showed that stellar halo properties differ

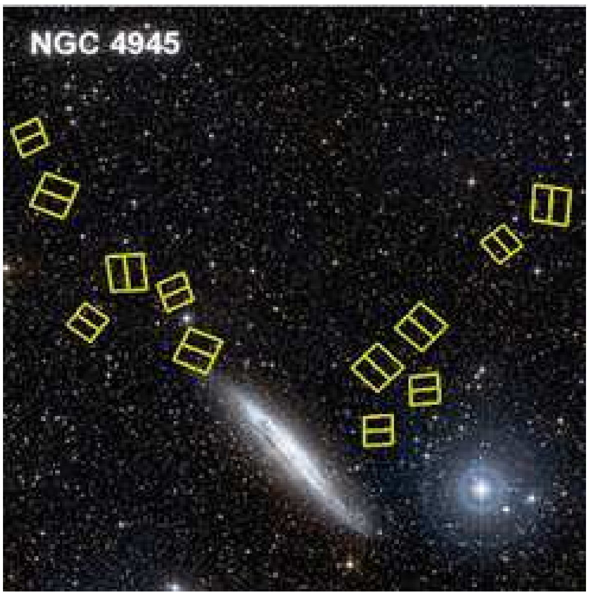

Figure 2.2: Optical image of one of the galaxies in the GHOSTS sample, NGC 4945. Yellow squares indicate Hubble Space Telescope (HST) observations obtained in the stellar halo of this galaxy. *Credit: GHOSTS project.*

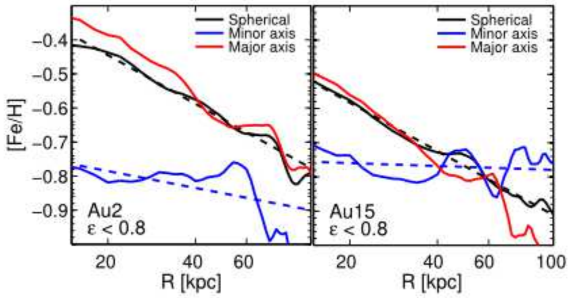

Figure 2.3: Metallicity trends of stellar halos as a function of galactocentric distance for two simulated galaxies using the Auriga simulations. This figure shows how the metallicity behaviour of stellar halos differs as a function of galactocentric distance if the metallicities are measured by averaging the properties of stars in concentric spherical shells (black), by projecting along a direction that is perpendicular to the galactic disk (blue), or on the disk plane (red). Dashed lines are linear fits to the black and blue lines to show trends more clearly. The blue lines are much flatter than the other two, showing that the metallicity variations will be much less, when averaging perpendicular to the disk – the method preferred by observations.*Credit: MPA.*

greatly among galaxies that are otherwise alike in morphology, mass, and luminosity. The process of merger and accretion of satellites is rather stochastic and the properties of the stellar halos reflect the properties of the different accreted satellite galaxies.

The variety in the observed metallicity behaviour of stellar halos, with half galaxies presenting flat metallicity trends with distance, appeared to be at odds with previous results from hydrodynamical simulations, which had predicted large metallicity variations with distance as ubiquitous features. In order to investigate this seeming discrepancy, the research team at MPA used state-of-the art hydrodynamical cosmological simulations called “Auriga”. These simulations include the main physical processes responsible for the formation and evolution of galaxies in the universe and self-consistently follow the evolution of gas, stars and dark matter over time.

The MPA group analyzed the metallicity trends in stellar halos of simulated galaxies with similar mass and morphology as the Milky Way and the GHOSTS galaxies. As the main result, the scientists find from this analysis that the behaviour of the mean stellar halo metallicity with galactocentric distance depends strongly on the way it is measured. If the mean metallicities are derived by spherically averaging the properties of halo stars around the galactic center, as done in previous simulations, large variations in the mean metallicity with distance are obtained. However, if the mean metallicities are derived along a direction that is perpendicular to the galactic disk, the metallicity tends to be much more uniform (Figure 2.3). In observational studies, the latter direction is preferred since it allows the scientists to minimize contamination from galactic disk stars. The MPA group has thus clearly highlighted the crucial importance of preforming careful comparisons between models and observations of halo metallicity distributions. This is the only way to alleviate tension between theory and observations.

In future work, the MPA group will perform a very careful and detailed analysis of the simulations to compare against observations and to interpret the observations. This will allow them to decipher the accretion history of the GHOSTS galaxies. (Antonela Monachesi, Facundo Gomez and Guinevere Kauffmann).

2.2 Where are all of the nebulae ionized by supersoft X-ray sources?

The ultimate fate of low-mass stars, like our own Sun, is to exhaust the nuclear furnace in their cores, expel their extended atmospheres, and leave behind a hot remnant called a white dwarf. Left to their own devices, these objects will simply cool slowly over billions of years. However, if a white dwarf comes to accrete material from some stellar companion, it can become an incredibly luminous source of extreme UV and soft X-ray emission, a "supersoft X-ray source" or SSS. Such radiation is readily absorbed by any surrounding interstellar gas, producing emission line nebulae. Therefore, we would expect such nebulae to be found accompanying all supersoft X-ray sources. However, of all SSSs found in the past three decades, only one has been observed to have such a nebula. Clearly, something is amiss in our understanding of these incredible objects. Now, scientists at MPA and the Monash Centre for Astrophysics have pieced together the puzzle.

Under the right conditions, a white dwarf accreting (2.4) hydrogen-rich matter from a binary companion can process all of this material through nuclear burning at its surface, with luminosities and temperatures of thousands of times that of our Sun (10^{38} erg/s and $10^5 K - 10^6 K$, respectively). First discovered more than 30 years ago by NASA's Einstein observatory, these close binary supersoft X-ray sources soon became favoured candidates for the progenitors of type Ia supernovae: as white dwarfs accrete material, they may grow to reach the Chandrasekhar mass limit and explode. However, testing this hypothesis by trying to find the true number of such objects has been complicated by the great ease with which the emitted extreme UV and soft X-ray photons are completely absorbed by even a modest amount of intervening interstellar matter.

Therefore, an alternative approach is to use this absorption and search for nebular emission lines in interstellar matter that is ionized by these hot, luminous sources. However, narrow-band observations of the vicinity of supersoft X-ray sources in the Magellanic Clouds revealed only one such nebula. This led to a vexing question: is there something very wrong in our understanding of the nature of these sources? Or is there something special about the interstellar environment of CAL 83, where the nebula was found, – and not every other SSS? This dilemma put emission line studies of supersoft X-ray sources largely on hold for the next two decades.

In their recent work, Tyrone Woods (formerly at MPA, now a research fellow at the Monash Centre for Astrophysics) and Marat Gilfanov (MPA) noted that the gaseous nebula surrounding CAL 83 is at least ten-fold overdense relative to the gas

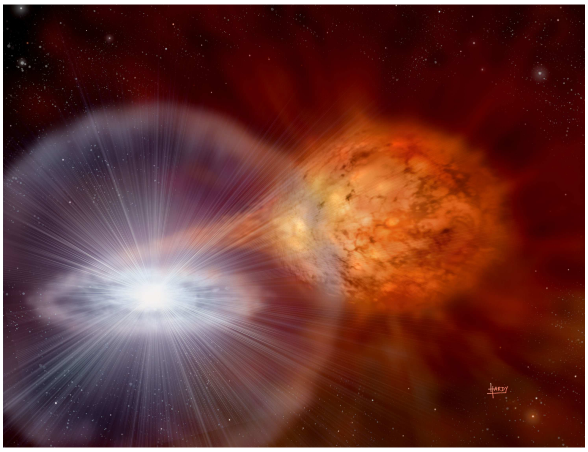

Figure 2.4: Artist's depiction of an accreting white dwarf. *Credit: David A. Hardy/AstroArt.org.*

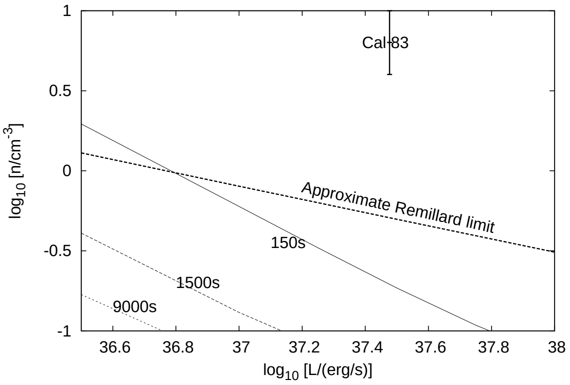

Figure 2.5: ISM density (vertical axis) required to produce a detectable nebula ionized by a accreting white dwarf ($2 \times 10^5 K$, with bolometric luminosity L, horizontal axis). The three lines denote a signal-to-noise ratio of 50, i.e. clear detection, for 150, 1500, and 9000 seconds total integration times using the Magellan Baade telescope. For reference, the inferred density and time-averaged luminosity of CAL 83 is also shown. *Credit: MPA.*

densities found in most of the volume of typical star-forming galaxies. The high surface brightness nebula of CAL 83 thus appears to be the result of a chance encounter of the accreting white dwarf with a region of initially cold, dense interstellar matter. Additional analysis of the size and distribution of cold dense clouds in galaxies (with the aid of mathematics borrowed from the study of concrete porosity) provided further support for this interpretation.

Most supersoft X-ray sources are likely to lie in much lower density media, with correspondingly lower surface brightness nebulae, which extend to larger radii (up to more than 100 parsecs, compared with 10 parsecs for CAL 83). Even though such nebulae are below the detection threshold of past observations, they are detectable given modest integration times with large modern telescopes such as Magellan or the VLT (see Figure 2.5).

This not only re-opens a channel for the study of close binary supersoft X-ray sources; given that the decay time for any SSS nebula will be on the order of ten thousand to a hundred thousand years, one may also search for "fossil" nebulae surrounding the sites of SSSs, which have long since stopped accreting. In particular, this includes those that may have exploded as type Ia supernovae in the recent past and in our cosmic neighbourhood. This means that one should be able to resolve the surrounding nebula and inner supernova remnant separately. A deep narrow-band search using the Magellan Baade telescope is already underway, and we may soon measure (or tightly constrain) the temperatures and luminosities of the progenitors of nearby type Ia supernova remnants. (Tyrone Woods and Marat Gilfanov)

2.3 The DRAGON globular cluster simulations: a million stars, black holes and gravitational waves

An international team of experts from Europe and China has performed the first simulations of globular clusters with a million stars on the high-performance GPU cluster of the Max Planck Computing and Data Facility. These – up to now – largest and most realistic simulations can not only reproduce observed properties of stars in globular clusters at unprecedented detail but also shed light into the dark world of black holes. The computer models produce high quality synthetic data comparable to Hubble Space Telescope observations. They also predict nuclear clusters of single and binary black holes. The recently detected gravitational wave signal might have originated from a binary black hole merger in the center of a globular cluster.

Globular clusters are truly enigmatic objects. They consist of hundreds of thousands luminous stars and their remnants, which are confined to a few tens of parsecs (up to 100 lightyears) – they are the densest and oldest gravitationally bound stellar systems in the Universe. Their central star densities can reach a million times the stellar density near our Sun. About 150 globular clusters orbit the Milky Way but more massive galaxies can have over 10,000 gravitationally bound globular clusters. As their stars have mostly formed at the same time but with different masses, globular clusters are ideal laboratories for studies of stellar dynamics and stellar evolution.

The dynamical evolution of globular clusters, however, is very complex. Unlike in galaxies, the stellar densities are so high that stars can interact in close gravitational encounters or might even physically collide with each other. Because of these interactions there are more tightly bound binary stars than for normal galactic field stars. Moreover, in a process called mass-segregation more massive stars sink to the center of the system.

The evolution of a globular cluster as a whole is further complicated by the life cycle of both individual and binary stars. In the early phases, massive stars (with more than 8 solar masses) suffer significant mass-loss in a stellar wind phase and end their lifetime in core-collapse supernova explosions. The remnants of these long-gone stars are neutron stars or black holes; the latter with masses in the range of ten to fifty solar masses. They are invisible for normal electromagnetic observations and, until recently, could only be detected indirectly.

The light from globular clusters is dominated by just a few hundred very bright red giant stars. Most of the other stars in the systems have a much lower mass than our Sun and very low luminosity. This is why the Hubble Space Telescope has been a preferred instrument to observe the stellar population of globular clusters. Color-magnitude diagrams (CMD) obtained by Hubble have superior quality compared to ground-based instruments due to very low photometric errors (creating sharp structures like the main sequence or giant or white dwarf branches) and very high sensitivity. Hub-

Figure 2.6: Top: The Hydra supercomputer (1.7 PetaFlop/s) operated by the Max Planck Computing and Data Facility is equipped with 676 Kepler K20 GPGPU accelerators (1 PetaFlop/s, bottom left). This supercomputer was used to carry out the DRAGON simulations. Bottom right: The laohu supercomputer of National Astronomical Observatories, Chinese Academy of Sciences in Beijing (96 TeraFlop/s) operated by its Center of Information and Computing is equipped with 64 Kepler K20 GPGPU accelerators. *Credit: MPCDF/NAO.*

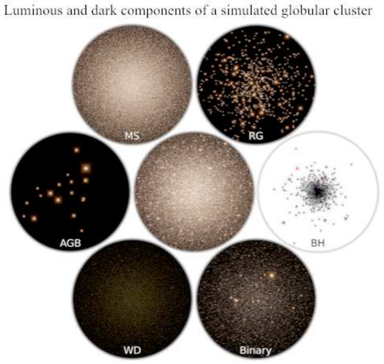

Figure 2.7: Mock color image (BVI) of all stars of a simulated globular cluster (central image covering about 60 pc) after 12 billion years of evolution. The surrounding panels highlight the different stellar types (from top left): main sequence stars (MS), red giants (RG) dominating the light, invisible black holes (BH), binary stars (Binary), white dwarfs (WD) and asymptotic giant branch stars (AGB). The white dwarfs (about 80.000) are unresolved in this mock image and therefore invisible. The black holes (right-most panel) form a dense subsystem in the center (binaries in red). *Credit: MPA*

ble for the first time observed low-luminosity white dwarf features and low mass main sequences in high quality.

It has been a long-standing challenge to follow the evolution of a massive globular cluster with self-consistent numerical simulations. For the first time a team led by international experts at MPA, the Chinese Academy of Sciences and Peking University has carried out the – up to now – most realistic simulations of the evolution of a globular cluster with initially one million stars orbiting in the tidal field of the Milky Way for about 12 billion years. The simulations carried out at the Hydra Supercomputer at the Max Planck Computing and Data Facility (MPCDF) as part of the international DRAGON project set a new standard in globular cluster modeling (see Fig. 2.6).

They have been possible after significant improvements of the simulation software on the laohu supercomputer of the Center of Information and Computing at National Astronomical Observatories, Chinese Academy of Sciences. The code has excellent parallel performance using, simultaneously, multi-node parallelization, OpenMP on the nodes and general-purpose Kepler K20 graphic cards acceleration (GPGPUs) to compute the gravitational forces between the stars. A typical DRAGON star cluster simulation used 8 nodes of Hydra with 160 CPU cores and about 32k GPU threads, for a consecutive computing time of the order of one year (8000 wall-clock hours).

The evolution of the stellar population of a globular cluster can now be followed in great detail through all its dynamical and stellar evolution phases, including the loss of stars in the tidal field of the Milky Way. The evolution of single and binary stars with a large range of masses (0.08 -100 solar masses) are followed through their major evolutionary phases (Fig. 2.7). The DRAGON simulations have also been used to prepare synthetic color magnitude diagrams (CMD) as observed by Hubble (Fig. 2.8).

In the DRAGON simulations the black holes – remnants of massive stars with masses of ten to fifty solar masses – form a dense nuclear cluster in the center of the system (Fig. 2.7, panel with white background). In classical astronomy this black hole cluster can only be observed indirectly by its gravitational influence on the luminous – and observable – stars. A few dozen black holes form binaries and lose energy by gravitational radiation, a process included in our simulations.

Recently the LIGO collaboration has detected gravitational wave emission from a binary black hole coalescence (black hole masses of 36 and 29 solar masses) at a distance of 410 Mpc (see press release of the MPG). Our DRAGON clusters produce such binary black hole mergers with similar pa-

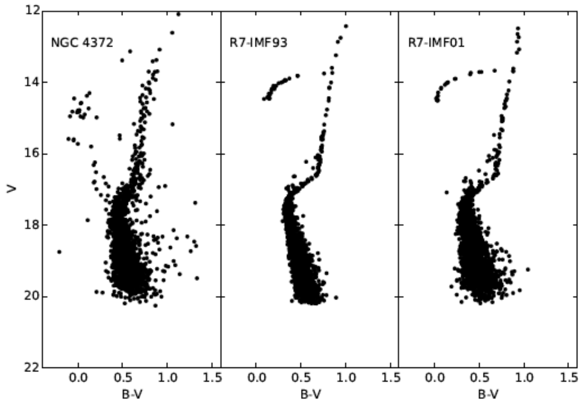

Figure 2.8: Comparison of an HST color-magnitude diagram of the observed globular cluster NGC4372 with those of two simulated clusters. To simulate observations, a typical distance to a Galactic globular cluster has been assumed and the specification of the cameras on board the Hubble space telescope using COCOA. *Credit: MPA.*

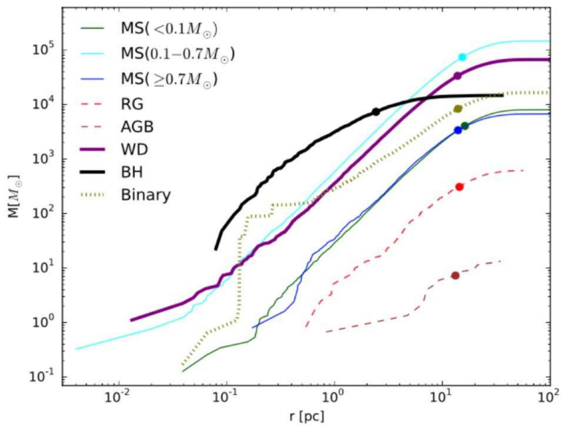

Figure 2.9: Cumulative mass distribution of the stellar components depicted in Fig. 2.7. The center of the system is populated by black holes (black line), whereas the more extended distribution of low mass main sequence stars (cyan line) dominates the total mass. The dots represent the half-mass radius of the respective components. *Credit: MPA.*

rameters; about ten events in each cluster. Therefore we expect that more events will be observed in the coming months or years. A more detailed prediction for gravitational wave events from our models is under way. It depends not only on the internal evolution but also the number and distribution of globular clusters in the Universe. However, we predict that globular clusters – similar to our DRAGON clusters – are a possible origin of the recently observed spectacular gravitational wave event.

The now detected black hole merger event is probably only the tip of the iceberg. The dynamical evolution of the central regions of the simulated clusters is dominated by hundreds (if not thousands) of single and binary stellar mass black holes. Future studies should examine whether such clusters of stellar mass black holes exist in centers of most globular clusters rather than the predicted intermediate mass black holes. (Thorsten Naab, Long Wang, Rainer Spurzem and Riko Schadow for the DRAGON collaboration)

2.4 Is Dark Matter the Source of a Mysterious X-ray Emission Line?

The nature of dark matter is still unknown, but one potential candidate is a theoretical particle known as the “sterile neutrino”. In 2014, two independent groups of astronomers detected an unknown X-ray emission line around an energy of 3.5 keV in stacked X-ray spectra of galaxy clusters and in the centre of the Andromeda galaxy. The properties of this emission line are consistent with many of the expectations for the decay of sterile neutrino dark matter. However, if this hypothesis is correct, all massive objects in the Universe should exhibit this spectral feature. To test this intriguing possibility, scientists at MPA and the University of Michigan examined two large samples of galaxies, finding no evidence for the line in their stacked galaxy spectra. This strongly suggests that the mysterious 3.5 keV emission line does not originate from decaying dark matter. The nature of dark matter, and the origin of this emission line, both remain unknown.

Astronomers have known for decades that about 85% of the matter in the Universe is composed of invisible, non-Baryonic particles known as “dark matter”, which can generally only be studied via gravitational interactions on visible matter. While the nature of this exotic substance is still unclear, a number of potential particles have been proposed. One of the more popular candidates is known as the “sterile neutrino”.

This theoretical particle could have a mass of several keV (around 1/100 of the mass of the electron), which would potentially make these particles numerous enough and heavy enough to account for the dark matter in the Universe. Sterile neutrinos are occasionally supposed to spontaneously decay into ordinary neutrinos, a process which produces an X-ray photon with half the mass of the sterile neutrino. The best hope to find this line is to look

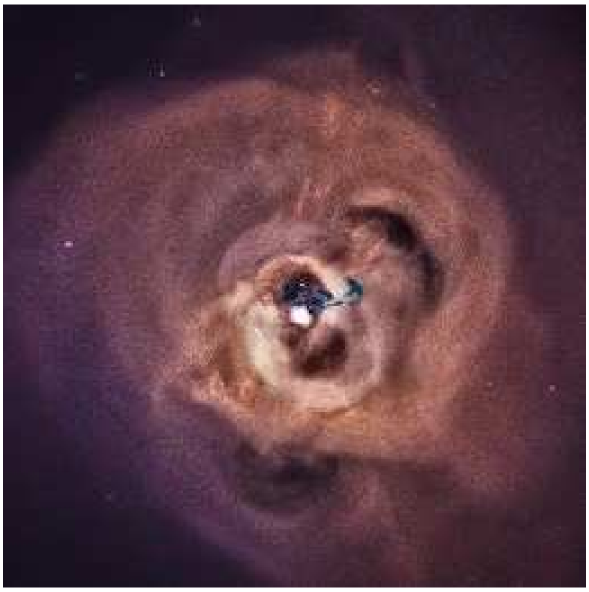

Figure 2.10: A 2014 study of 73 galaxy clusters, including the Perseus cluster (shown in this image), has revealed a mysterious X-ray signal in the data. Using data from NASA's Chandra X-ray Observatory and ESA's XMM-Newton, the stacked spectra of these objects show an excess centered around an energy of 3.57 kiloelectron volts (keV) (see inset). *Credit: X-ray: NASA/CXC/SAO/E.Bulbul, et al.*

towards very massive objects (galaxies or clusters of galaxies), which have the highest amounts of dark matter particles.

In February 2014, two independent groups of astronomers announced within a few days of each other that they had tentatively detected an unidentified X-ray emission line that could be interpreted as the spontaneous decay of sterile neutrinos. The first group (Bulbul et al. 2014) studied a sample of 73 galaxy clusters, while the second group (Boyarsky et al. 2014) studied the Perseus galaxy cluster as well as the central portion of the Andromeda galaxy (see Fig. 2.10). Both groups measured more photons with energies around 3.5 keV than predicted by their models of intracluster gas emission, and the residual emission profiles look similar to what astronomers would expect to see from an emission line.

The immediate question is whether this anomalous line must be due to sterile neutrinos, or whether it may have an astrophysical explanation. If this line indeed comes from decaying dark matter, it should be observed in other, less massive objects as well – and this is what Mike Anderson and Eugene Churazov at MPA, as well as their collaborator Joel Bregman, set out to test.

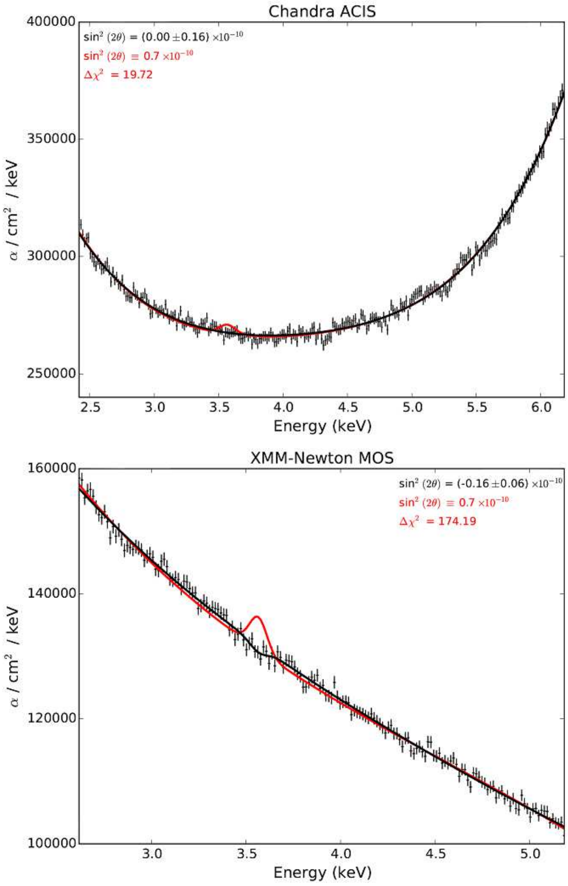

Figure 2.11: These figures show the stacked X-ray spectra of 81 galaxies observed with the Chandra X-ray Observatory (upper plot) and 89 galaxies observed with the XMM-Newton telescope (lower plot) alongside two different spectral models. The red curve is a model for the data, which includes the emission line at 3.57 keV from Figure 1 corresponding to the prediction of sterile neutrino dark matter. The black curve is a model for the data which makes no assumptions about the emission at 3.57 keV. In both cases, the latter model is heavily favoured, showing that the unidentified emission line seen in galaxy cluster spectra does not appear in galaxy spectra. If the line were indeed due to sterile neutrino dark matter, we should see it in both galaxies and galaxy clusters, so this is evidence against that interpretation of the line. *Credit: MPA*

Galaxies are much less massive than galaxy clusters, and so their hot gaseous halos are also correspondingly less massive and cooler than in clusters. While galaxy clusters are able to retain enormous halos of hot gas in their gravitational potential which provides the vast majority of the total X-rays, galaxies have almost no diffuse emission at the $\sim 3.5 keV$ energies corresponding to the location of the new line. The weaker signal from the decaying dark matter in galaxies is therefore balanced by a lower amount of background noise, and galaxies prove to be an excellent complement to galaxy clusters in the study of X-rays from sterile neutrinos.

Anderson and his collaborators assembled very large samples of galaxies for their study: 81 galaxies observed with the Chandra X-ray Observatory and 89 galaxies observed with the XMM-Newton telescope. The total amount of observation time for each sample was about half a year. The team cleaned each image, removed stray X-ray point sources, and added together the X-ray emission from each galaxy, weighting each pixel of every image by the expected dark matter content at that location based on simple models of galactic dark matter halos.

The result is shown in Fig.2.11, for both the XMM-Newton (top) and Chandra (bottom) datasets. As the analysis shows, in both cases the model including an emission line at 3.57 keV from the decay of sterile neutrinos is very strongly disfavoured by the data compared to no emission line; in fact, the XMM-Newton spectrum prefers to have a line with negative flux at that energy.

This study therefore provides very strong statistical evidence against the hypothesis that the unidentified X-ray emission line in the spectra of galaxy clusters originates from sterile neutrino dark matter. Fig. 2.12 illustrates the constraints from this work on the masses and decay probabilities of sterile neutrinos, along with a number of previous constraints from other studies. A large portion of the available parameter space is now ruled out, but there still remains a sizeable region below our constraints where sterile neutrino dark matter might still exist.

If the unidentified X-ray emission line at 3.57 keV is not caused by sterile neutrinos, what is its source? This question is not answered by the current study, and still remains the subject of active debate. One possibility is an atomic interaction such as charge exchange, which may be expected to produce 3.5 keV photons in intracluster plasma but not in the halos of galaxies. There are also several more exotic theories of dark matter, such as axion-like particles which require interactions with magnetic fields to produce X-ray emission and therefore might be likelier to be seen in magnetized intracluster plasma than in the halos of galaxies. New X-ray telescopes such as the Athena observatory will have significantly better spectral resolution, and this will hopefully shed additional light on this question. (Mike Anderson)

2.5 Constraining the reionization history from Lyman alpha emitting galaxies

In cosmology, one of the major challenges in next decades will be probing the epoch of reionization in the early universe. Scientists at MPA, the University of Oslo, and INAF have now used cosmological hydrodynamical, radiative transfer simulations to understand the impact of the complex distribution of neutral gas in the intergalactic medium on distant galaxies. Combining the simulations with observations of so-called Lyman alpha emitting galaxies they find that despite the uncertainty, the current simulation-calibrated measurements favour a late and rapid reionization history. The study also emphasizes that both the large-scale distribution of ionised gas regions and the small-scale structures of the intergalactic gas around galaxies must be understood to derive more robust constraints on the reionization epoch.

The epoch of reionization, when early galaxies or black holes drastically transformed the global state of the universe from neutral to an ionized plasma, is one of the major unsolved mysteries in modern extragalactic astronomy. Big questions remain unanswered: What was the history of reonization? Which sources were responsible for driving it?

One possibility to probe the physical state of the universe at very early times is by observing distant, high-redshift 'Lyman-alpha emitting galaxies'. These galaxies are emitting a strong Lyman alpha line, i.e. radiation from hydrogen gas in their interstellar medium. This strong emission line enables astronomers to observe these objects out to very far distances, at redshifts as high as 10. By now, hundreds of Lyman alpha galaxies have been found beyond redshift 6.

Observations show that the apparent demographics of Lyman alpha emitting galaxies changes over cosmic history. Beyond redshift 6, i.e. when the universe was less than 1 billion years old, the

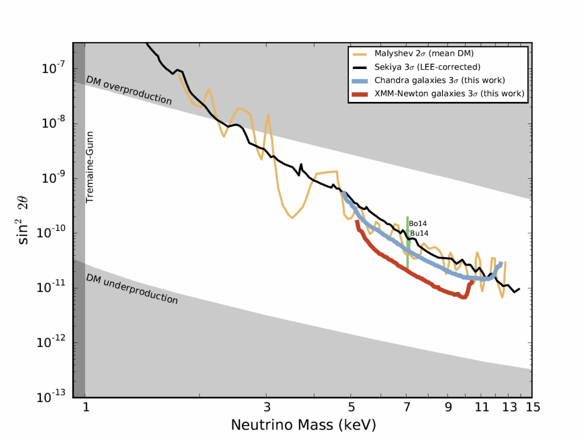

Figure 2.12: Summary of constraints on sterile neutrino dark matter from this work as well as a number of previous studies; the measurements from galaxy clusters are indicated by the green dots (with error bars). The x-axis shows possible neutrino masses, and the y-axis shows possible decay rates for sterile neutrinos (where higher values mean that spontaneous decay is more likely). Sterile neutrino dark matter is only possible in the white region, but the results of this study rule out the portion of the plot above the red and blue curves. It would still be theoretically possible for sterile neutrinos to exist below the red and blue curves (this study did not examine the space to the right or left of these curves), and future X-ray telescopes would be required in order to place constraints on this possibility. *Credit: MPA*

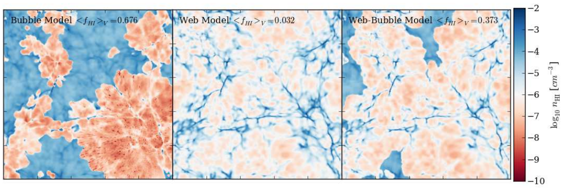

Figure 2.13: The neutral hydrogen number density at a redshift of $z = 7$ in slices of the simulations for different reionization models with large-scale ionized regions (bubble model), small-scale structures (web model), and both combined (web-bubble model) *Credit: MPA.*

observed population of galaxies with Lyman alpha emission suddenly decreases. This is difficult to explain with galaxy formation alone. From medium to high distances (redshift 2 to 6), the fraction of star-forming galaxies that show a strong Lyman alpha emission increases, which is partly caused by less dust in these galaxies. Therefore, the sudden drop at very hight distances, beyond redshift 6, seems to indicate that something is blocking this kind of light. This drop is often interpreted as evidence of the gas in the universe being increasingly neutral at earlier cosmic times – this means the drop marks the time of reionization.

The idea to use Lyman alpha emitting galaxies as a probe of reionization is based on a simple idea. With more neutral gas along the line-of-sight to the galaxies, less Lyman alpha flux reaches the observer. The difference between the expected flux from a galaxy and the observed flux then tells us how much neutral gas exists along the line-of-sight.

Kakiichi and collaborators have used this method to infer the neutral hydrogen content of the universe at redshift 7. They used cosmological hydrodynamical, radiative transfer simulations of reionization (see Figure 2.13) to interpret observations of Lyman-alpha emitting galaxies. The observations are then compared with theoretical models of the apparent population of Lyman-alpha emitting galaxies. In this way, the neutral gas fraction can be inferred from the models that best fit the observations.

The new constraint this provides for the reionization history is shown in Figure 2.14, which shows that the universe is still very neutral at redshift 7. The present analysis therefore seems to suggest that reionization occurred late and rapidly around redshift 6 to 8.

This study also highlights an important uncertainty in this simulation-calibrated measurement of the neutral fraction. Figure 2.15 shows that completely different values of the neutral fraction combined with other ‘topologies’ of reionization work equally well in explaining the observed luminosity function (Figure 2.15). In fact, this leads to a systematic uncertainty in the inferred neutral fraction as high as an order of magnitude. Knowledge about the topology of reionization, namely both the large-scale distribution of ionized bubbles and the properties of small-scale self-shielded gas around galaxies, is crucial to robustly infer the reionization history. Only models containing both large and small-scale structures are able to coherently explain the observations of the Lyman alpha forest and Lyman alpha emitting galaxies from the

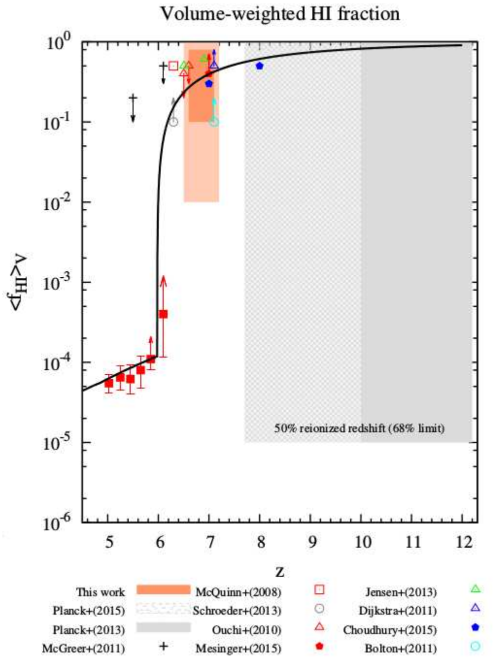

Figure 2.14: This plot shows the cosmological fraction of neutral hydrogen (HI) in the diffuse intergalactic medium at various redshifts z. For earlier cosmic times (higher z), the universe is increasingly neutral. Constraints from previous work are shown with different symbols, the constraints from this work are shown as the orange regions. A late and rapid reionisation is clearly favoured. The solid line indicates the evolution of ionisation according to the models. *Credit: MPA.*

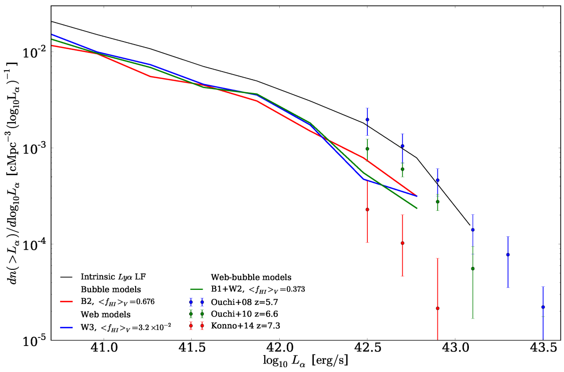

Figure 2.15: The intrinsic (black line) and observed differential Lyman alpha luminosity functions at $z = 7$ as expected for the reionization models of 2.13. Several observed data points are also given. The observed Lyman alpha luminosity can be explained by completely different models. *Credit: MPA.*

reionization epoch to the post-reionized universe.

This difficultly, however, does not limit the scope of using Lyman alpha emitting galaxies as a probe of reionization. The uncertainties can be reduced by simultaneously using multiple statistics such as the luminosity function and the fraction of strong Lyman alpha line in Lyman Break Galaxies in surveys of Lyman alpha galaxies. New survey strategies search for early galaxies in the foreground of quasars at the reionization epoch, which will drastically increase the scope of this method because it allows astronomers to directly study both the state of the intergalactic gas and the properties of Lyman alpha emitting galaxies.

Together with the increasing capability of radiative transfer simulations, Lyman alpha emitting galaxies serve as important beacons to probe the state of the infant universe (Kakiichi Koki and Benedetta Ciardi).

2.6 The deficiency of star formation in dwarf galaxies

Dwarf galaxies form stars very inefficiently compared to spiral galaxies like our Milky-Way. To investigate the origin of this deficiency in star formation, scientists at MPA have used high-resolution numerical simulations to resolve the evolution of the interstellar medium (ISM) in dwarf galaxies. They find that supernova explosions have a significant impact on the structure of the ISM and regulate the star formation rates of the whole galaxy. The reservoir for star formation on scales comparable to molecular clouds in our Milky Way consists mainly of cold atomic hydrogen rather than molecular hydrogen. These findings might also shed light into the birth processes of most other galaxies. Within the current paradigm of hierarchical structure formation, low mass, chemically un-evolved dwarf galaxies are the building blocks of all, more massive galaxies.

In typical spiral galaxies, observations have shown a correlation between the surface density of the local star formation rate and the gas surface density, the so-called Kennicutt-Schmidt relation. The correlation is almost linear, i.e. the gas is converted into stars on a constant timescale of ~ 2 billion years. In the Milky-Way and other spiral galaxies star formation appears to happen exclusively in regions dominated by molecular gas.

However, this linear correlation breaks down in dwarf galaxies, where stars form very inefficiently

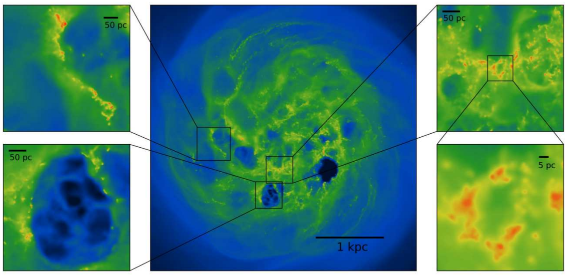

Figure 2.16: Face-on maps of the gas column density in a simulated galaxy at different spatial scales, highlighting the complex structure of the ISM. The central panel shows the entire star-forming region of the dwarf galaxy model. The details shown are a filamentary structure that is about 300 pc long (top left), a 200 pc bubble driven by supernova explosions (bottom left), a group of dense clouds (top right), and a further zoom-in of the dense clouds (bottom right). The effective spatial resolution is about 2 pc, so most of the clouds are well resolved. *Credit: MPA.*

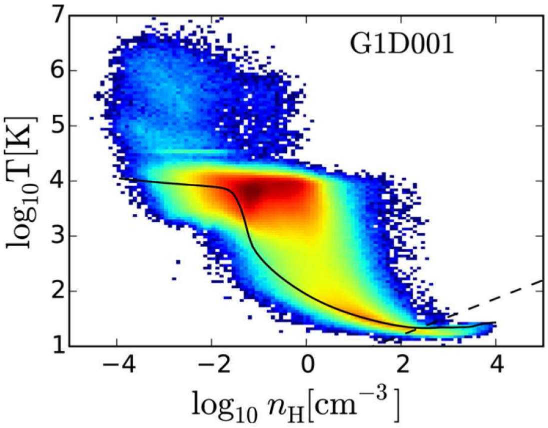

Figure 2.17: This plot shows the gas temperature vs. the gas density in a simulated dwarf galaxy. If the gas was in thermal equilibrium it would follow the solid black curve. The dashed line indicates the resolution limit of the simulations below which the Jeans mass of gas is unresolved. Because the supernova explosions trigger turbulence and shocks, the gas is driven out of thermal equilibrium. *Credit: MPA.*

on timescales that are much longer: 10-100 billion years. It is not yet clear whether the star forming gas in these dwarf galaxies consists mainly of molecules or atoms. Observations have not yet detected molecular gas but it has been speculated that an unseen molecular reservoir could dictate the star formation rate. This would provide an explanation for the longer star formation timescales in dwarf galaxies, which could be regulated by an inefficient transition from the atomic to molecular state.

Recently, scientists at MPA have investigated the star formation in dwarf galaxies using numerical hydro-dynamical simulations, which incorporate a wealth of relevant physical processes. In particular it is assumed that molecular hydrogen forms on dust grains and that interstellar UV starlight can destroy the molecules. The simulations were conducted at an unprecedented high resolution (with a spatial resolution of 2 Parsec and matter particles of 4 solar masses). The impact of individual supernova explosions is numerically resolved. Fig. 2.16 shows a snapshot of the gas surface density in one of the simulations at different spatial scales, demonstrating the complexity of the multi-phase gas structure.

The simulations suggest that the star formation reservoir (the cold and dense gas) is predominately in the atomic phase, contrary to the situation in spiral galaxies. This is because it takes much longer for molecular hydrogen to form in a low-metallicity environment. As the ISM is constantly shaken and stirred by supernova explosions, the molecular hydrogen has no time to reach its (chemical) equilibrium abundance. The supernova explosions inject energy and momentum into the gas, triggering turbulence and shocks, much faster than the gas can cool or heat through radiative processes. As such, the gas is also driven out of thermal equilibrium (Fig. 2.17).

Comparing the Kennicutt-Schmidt relation of these simulations with observations of dwarf galaxies one finds good agreement (Fig. 2.18). The longer timescales compared to spiral galaxies (which is about 2 billion years) is caused by the inability of gas to cool in the outer part of the galaxy. As explained above, this prevents the ISM to form the cold gas needed for effective star formation.

The simulations also demonstrate that, while a change in the dust abundance or the interstellar UV radiation has a dramatic impact on the molecular abundance, it does not affect the thermal gas properties. This suggests that molecular hydrogen plays little role in regulating star formation in dwarf galaxies and is not a good tracer for it – in contrast to spiral galaxies like the Milky Way. (Chia-Yu Hu and Thorsten Naab)

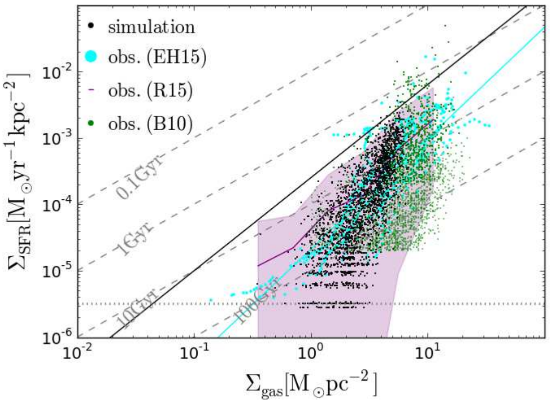

Figure 2.18: The Kennicutt-Schmidt relation in dwarf galaxies, i.e. the surface density of the local star formation rate vs. the gas surface density. The black dots are the simulation results, while the coloured dots are observational results from literature. The dashed gray lines indicate timescales of 1, 10 and 100 Gyr, which agree much better with the results from dwarf galaxies, where the star formation is suppressed. The simulations agree well with observational data as long as supernovae are included, which indicates that the supernova explosions are the key factor that regulates star formation in dwarf galaxies. *Credit: MPA.*

2.7 Predicting the Sunyaev-Zeldovich signal from cosmological, hydro-dynamical simulations

Using recent, extensive cosmological simulations, researchers at the Max Planck Institute for Astrophysics have shown that the expected signal from the Sunyaev-Zeldovich (SZ) effect of galaxy clusters on the Cosmic Microwave Background agrees remarkably well with observations by the Planck satellite. However, only a small fraction of this predicted signal is currently observable. The scientists developed a simple analytical model to understand the SZ probability distribution function, which is also helpful in interpreting the observed distribution of galaxy clusters masses.

Three-dimensional, cosmological, and hydrodynamical simulations of structures in the universe have become precise enough to allow for direct comparison with observations. These simulations close the gap between the gravitationally-driven evolution of dark matter and the formation of visible structures, such as galaxies and galaxy clusters. While dark matter - together with the imprint of dark energy - dominates the large-scale evolution of structures and forms the backbone for visible structure to form, various additional physical processes are at play for shaping the appearance of galaxies and galaxy clusters. State-of-the-art cosmological hydro-dynamical simulations include not only gravity but many other, relevant physical processes as well. Therefore they significantly contribute to making our current models of the universe more precise and predictive.

Observations of the cosmic microwave background (CMB) by satellite missions, such as the WMAP and Planck, as well as by a host of ground-based experiments, like the ACT or SPT, currently deliver the most precise measurements of density fluctuations in the early universe. In addition, they constrain the values of the parameters describing our cosmological model – but they are far more powerful than that. They also encode the imprint of cosmological structures growing over the course of 13.8 billion years, ever since the time of the last-scattering of CMB photons, i.e. when the primordial fog lifted and the Universe became transparent.

Specifically, the black body spectrum of the CMB is distorted due to Compton scattering of CMB photons within the hot gas in galaxy clusters. This intra cluster medium (ICM) can be detected from multi-wavelength data in microwave bands, an effect known as the Sunyaev-Zeldovich (SZ) effect after a seminal paper by MPA director Rashid Sunyaev in 1972.

Multi-wavelength data are necessary for separating the SZ signal from the CMB itself and various other sources of microwaves in the sky. Over the past years, this SZ signal was measured by the Planck satellite and its interpretation attracted the attention of cosmologists world-wide, as it seemed to imply values of the cosmological parameters which were inconsistent with measurements of the CMB at the last-scattering surface. In other words,

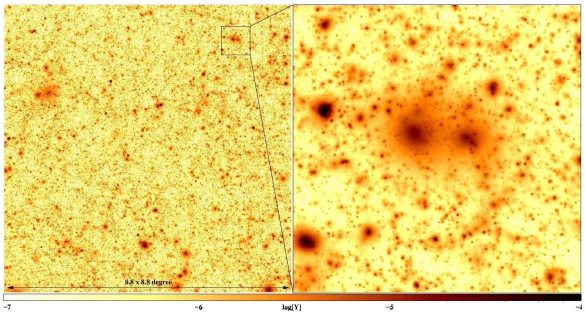

Figure 2.19: Sky map of the SZ signal from the simulation, with darker colours indicating a stronger signal. The zoomed image on the right shows a region containing several rich galaxy clusters. *Credit: MPA.*

the parameters inferred from the early universe (the CMB) were at odds with those inferred from the late universe (the SZ effect). If true, this could be interpreted as hinting at additional processes in our universe, for example neutrino masses slowing down structure formation.

In this study, scientists at MPA and the University Observatory Munich investigated the SZ signal predicted by large, cosmological, hydrodynamical simulations of the growth of structures in the universe, which are a part of the Magneticum Pathfinder (*LINK: www.magneticum.org*) project. For the first time, such simulations sample a volume of the universe large enough to have a good statistical representation of the overall structure and incorporate a variety of physical processes in the calculations to realistically reproduce details of smaller structures. Three of these processes are considered particularly important for the development of the visible universe: the condensation of matter into stars; their further evolution when the surrounding matter is heated by stellar winds and supernova explosions which also enrich the intergalactic medium (IGM) with chemical elements; and the feedback of super-massive black holes that eject enormous amounts of energy into the IGM.

Outputs of this simulation at various time steps – which cover the evolution of structures from the early days of the universe until now – are then stacked to construct a large “sky map”, about 8x8 degrees (almost 20 times larger than the moon) of the predicted SZ imprint onto the CMB. Figure 2.19 shows this map, including a close up revealing the incredible amount of detail resolved by these modern simulations.

The probability distribution function (PDF) of the SZ signal found in this simulated sky map shows a clear power-law tail towards large values caused by galaxy clusters (Figure 2.20). Due to the limited sensitivity and spacial resolution of the Planck satellite, only a small fraction of this predicted signal is currently observable, but in the range accessible by Planck, the predicted and observed signals agree remarkably well.

A simple analytical model can help to qualitatively understand the SZ probability distribution function. To develop such an analytical model, however, the scientists needed the precise number counts of expected galaxy clusters with a given mass. Here as well, the increased precision and large cosmological volume covered by the simulation allows the researchers to precisely obtain this so-called “mass function” for the relevant range of masses and cosmic times.

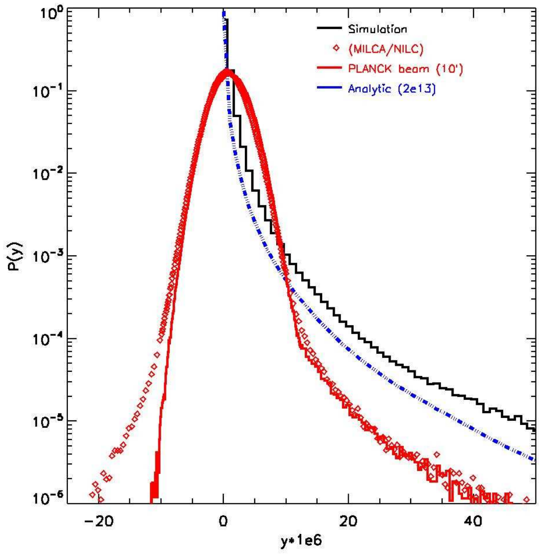

Figure 2.20: Probability distribution function of the predicted SZ signal in the simulated sky map. The horizontal axis shows the Compton y-parameter, which can be understood as the cummulative energy gain of the CMB photons due to repeated scattering in the hot intracluster gas of galaxy clusters. The predicted SZ signal observable with the Planck satellite (incl. resolution observational noise) is shown as red line, which agrees well with the actually observed Planck data (red diamonds). The simple analytical model is shown as the blue line. *Credit: MPA.*

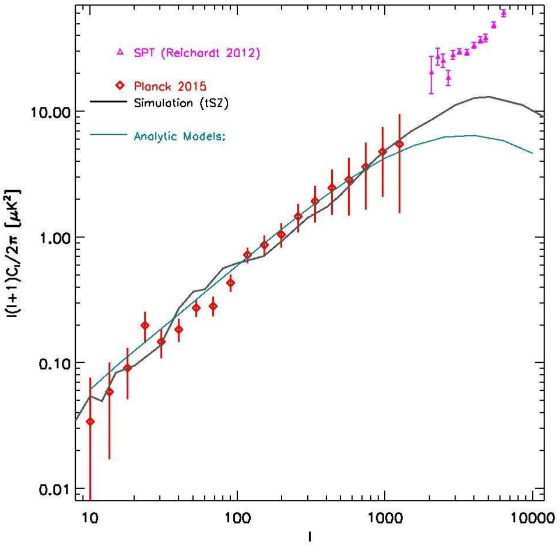

Figure 2.21: Power spectrum of the SZ signal. The parameter l is inversely proportional to the spacial scale, i.e. large l means small structures on the sky. The estimated SZ power spectrum from Planck data is shown as red diamonds, while the red triangles show the power spectrum from SPT data. Note that due to the limited wavelength range covered by the SPT observations these measurements are a sum of the SZ signal and various other sources of microwaves in the sky, i.e. these data points should be seen as a upper limit. The black solid line shows the SZ signal predicted from the simulations; the blue line shows the analytical model. *Credit: MPA.*

It turns out that the analytical model is quite important for interpreting the observed mass function properly. Instead of counting galaxy clusters, one can analyse the fluctuation of the SZ signal across the sky. Namely, instead of just counting peaks in the SZ map, the researchers did a full statistical analysis of the fluctuations. The easiest statistic to obtain and interpret is the so-called power spectrum, which shows how much structure is present at a given scale (Figure 2.21). The Planck data are in excellent agreement with both the simulation and the analytical model, which were both computed for the best-fit cosmological parameters of the Planck CMB data. As there is no discrepancy between the predicted signals and the Planck SZ data, the tension between early and late Universe is resolved.

This work demonstrates that state-of-the-art cosmological hydro-dynamical simulations have reached the precision to yield detailed predictions of the appearance of the visible universe. They significantly contribute to making our current models of the universe more precise, predictive, and helpful to better calibrate analytical models. Moreover, they are also essential for the proper interpretation of observational data being obtained by current and future experiments. (Klaus Dolag, Eiichiro Komatsu and Rashid Sunyaev)

2.8 Thermal conduction in galaxy clusters

From X-ray and SZ observations we know all major characteristics of the hot intracluster medium (ICM) filling the entire volume of galaxy clusters - the largest virialized objects in our Universe. However, several important properties are still poorly known, including thermal conduction in the ICM, mediated by electrons. To explain the sharp temperature gradients in galaxy clusters, it is often proposed that thermal conduction is suppressed both by the topology of magnetic-field lines, which tangle electron trajectories, and by variations of the field strength that can trap electrons. The latter mechanism can be crucially important when the so-called mirror instability generates fluctuations of the magnetic field strength: this kinetic instability is triggered by pressure anisotropies in turbulent plasma. Even if such fluctuations are present on truly microscopic scales, they have the potential to completely shut down heat conduction. Scientists at MPA have investigated such a possibility by analysing the results of recent simulations and found that the suppression of thermal conductivity is in fact rather modest, a factor of ~ 5 compared to unmagnetized plasma. The effect operates in addition to other suppression mechanisms and independently of them, and depends only weakly on the macroscopic parameters of the intracluster medium.

The dominant baryonic component of a galaxy cluster is hot tenuous plasma that has accreted into the deep gravitational well formed by the dominant dark matter component. This makes galaxy clusters unique laboratories for a variety of plasma phenomena on an extremely wide range of scales. Intricate plasma processes on microscales, more than ten orders of magnitude smaller than the size of the cluster, affect the large-scale properties of the cluster; for example modifying particle transport influences the temperature profile. Many puzzling features of galaxy clusters, such as the stability of cool cores, sharp local gradients or the substructure seen in temperature maps, are closely tied to the problem of thermal conduction in the intracluster medium (ICM).

From X-ray observations it is now clear that the ICM demonstrates a variety of violent physical processes, such as cluster mergers, infalling galaxies, shock waves, and active galactic nuclei. These naturally render the plasma turbulent. In addition, radio observations show evidence that the ICM is pervaded by magnetic fields. The field magnitude is sufficient to confine the motion of charged particles to spiralling around field lines with a tiny Larmor radius, much smaller than the mean free paths of the particles. This effectively shuts down particle transport perpendicular to field lines. Moreover, such a plasma turns out to be unstable to pressure anisotropies that are easily generated by turbulent motions. These instabilities then grow rapidly on Larmor scales.

When studying thermal conduction, the mirror instability is of particular interest. In this case, the magnetic field strength is perturbed with a significant amplitude on the order of the local mean magnetic field. The correlation length of mirror perturbations is only two orders of magnitude longer than the electron Larmor radius, but about ten orders of magnitude smaller that the collisional mean free path. This means that such perturbations are capable of magnetically mirroring the electrons: a charged particle spiralling along a field line is reflected from a region with a strong magnetic field. If perturbations of the magnetic field are generated by turbulence on scales above the collisional mean free path, magnetic trapping is ineffective. The mirror fluctuations, in contrast, are at the scales comparable to the ion Larmor radius, where magnetic mirrors can suppress electron transport considerably.

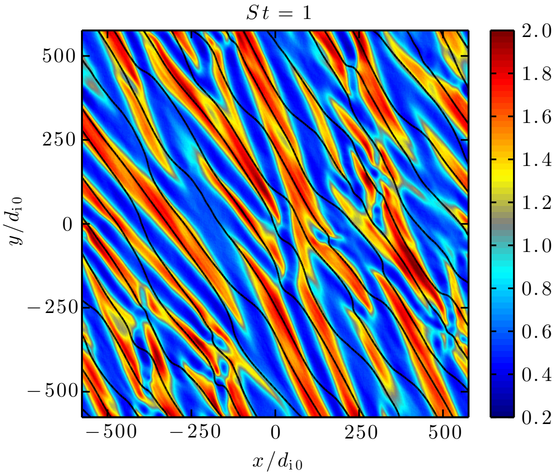

Figure 2.22: Spatial structure of the mirror instability after one shear time in the PIC simulations by Matt Kunz (Princeton). The magnetic-field strength is indicated by colour, where the colour scale is in the units of the initial value of the magnetic field. Field lines are shown by contours. The mirror fluctuations are elongated along the field lines. *Credit: MPA/Princeton.*

The scale of mirror fluctuations is far smaller than the current observational limits. Instead, one has to turn to numerical simulations. Only recently have particle-in-cell codes become capable of studying micro-instabilities driven by pressure anisotropies. In these simulations, a region of plasma (with a linear size of the order of a few hundreds of the ion Larmor radius) is subjected to a shear, stretching the magnetic field lines, producing pressure anisotropy, and triggering the instability.

Scientists at MPA have used the results of these simulations to investigate the motion of electrons in mirror fluctuations (shown in Fig. 2.22). By applying a Monte Carlo approach, the diffusion and thermal conduction coefficients have been estimated for a representative field line extracted from the simulation domain. The probability distribution function of the magnetic field strength along the field line turns out to have a cut-off at a field strength of several times the initial value. This leads to only a moderate amount of particle transport suppression. In the limit where the collisional mean free path is much larger than the correlation length of the mirror fluctuations, diffusion is sup-

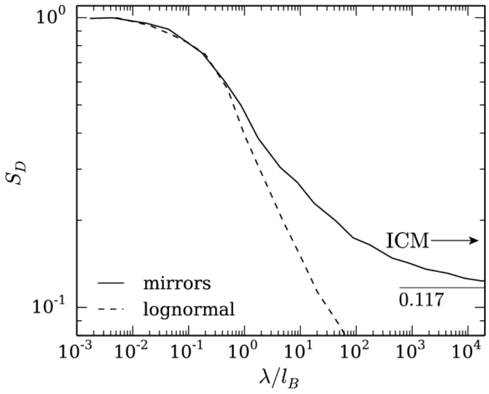

Figure 2.23: Suppression factor of the electron diffusivity in mirror fluctuations (solid line) as a function of the ratio of the mean free path to the correlation length of the fluctuations. At large mean free paths, the suppression stays above a certain lower limit. For comparison, the dashed line shows suppression for a lognormal distribution of magnetic fluctuations with a similar width of the probability density. *Credit: MPA.*

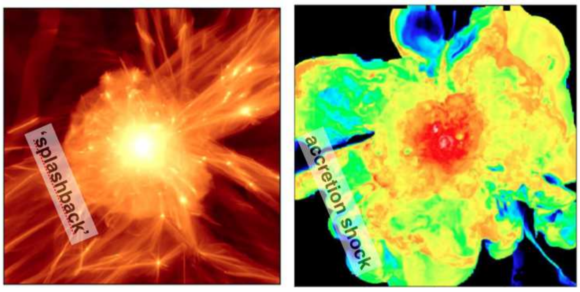

Figure 2.24: Left: dark matter halo of a simulated galaxy cluster. The density steepening at the splashback is highlighted with a special image enhancement technique. Right: gas temperature of a simulated cluster. The accretion shock is clearly visible where the temperature steepens at the outskirts of the cluster. *Credit: More, Diemer & Kravtsov 2015 (left); Vazza et al. 2010 (right).*

pressed by a factor of ~ 10 (see Fig. 2.23). This value then has to be converted into the suppression of thermal conduction.

Due to the additional presence of diffusion in energy space the thermal conductivity is suppressed by approximately a factor of two less effectively than the particle transport. The resulting suppression by a factor of ~ 5 appears to depend only very weakly on macroscopic parameters of the ICM as long as the ion Larmor radius remains much smaller than the correlation scale of the mirror perturbations, which is indeed well satisfied in the ICM. The effect operates on top of other suppression mechanisms and independently of them. (Sergey Komarov).

2.9 At the edge of galaxy clusters: splashback and accretion shock

Observations are beginning to be sensitive enough to see the outskirts of galaxy clusters, where theory predicts interesting features in the dark matter and gas profiles: the so-called splashback and the accretion shock (see Fig. 2.24). Scientists at MPA use an analytical model to compute the locations of these features, and shed new light on the underlying physics.

Providing a simple model for complex cosmic

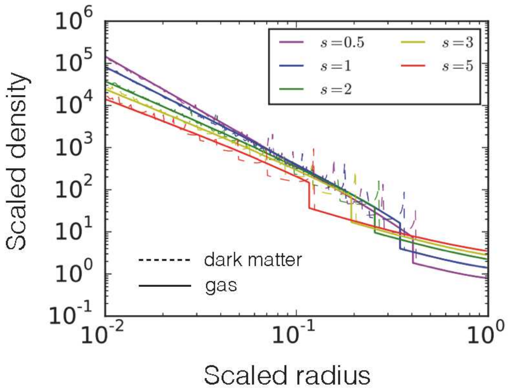

Figure 2.25: The analytical model captures the steepening features in the density profiles of dark matter (dashed line) and gas (solid line) in galaxy clusters, which correspond to the splashback radius and the accretion shock, respectively. The different colours show results for different cluster mass growth rates. In all cases, the locations of the splashback and accretion shock closely track each other. *Credit: MPA.*

phenomena is one of the goals of theoretical astrophysics. When successful, such a model yields a deeper understanding of the underlying physics. Recently scientists at MPA have done just this for better understanding what happens at the outskirts of galaxy clusters.

The observation of galaxy clusters has played an important role in convincing astronomers of the existence of dark matter: Galaxies inside galaxy clusters move with high velocities; hot, X-ray emitting gas fills the galaxy cluster region; often galaxy clusters show a gravitational lensing effect on background galaxies. All these measurements have consistently shown that visible matter is embedded in dark matter halos which make up about 85% of the total gravitating mass of a galaxy cluster.

Unlike a star, which is a 'halo' of gas with a clear boundary and a finite mass, these dark matter halos are fuzzy, extended structures. Their densities typically drop like $\rho \propto r^{-3}$ with radius in the outer regions without a clear cutoff, which has prevented astronomers to assign a definite boundary and mass to them. When you talk to an astronomer about a galaxy cluster with a certain mass, he or she will likely ask 'Within which radius is this mass defined?'

However, scientists recently realized that a particular feature at the outskirts of galaxy clusters can serve as a natural boundary for their dark matter halo. This feature - the so-called 'splashback' - marks the position of a sudden steepening in the density profile. Physically, this 'splashback' is caused by recently accreted dark matter that is piling up near the first apocenter of its orbit through the dark matter halo.

Hydrodynamical numerical simulations have found that the splashback radius closely tracks the position of the accretion shock. The accretion shock is located, where intergalactic plasma gets shock-heated when accreting onto a galaxy cluster. Also the accretion shock associated with a sudden steepening feature – this time in gas density and temperature. Since the physics underlying the splashback and the accretion shock is quite different, it is rather intriguing that they seem to track each other.

While simulations are a powerful tool for studying complex astrophysical systems, analytical models are also needed to simplify the picture and to understand the underlying physics. Using an analytical model called the 'self-similar spherical collapse model', scientists at MPA computed the growth of galaxy clusters in an expanding universe. The profile of a galaxy cluster and the history of its mass growth are treated in a consistent manner.

This model can predict the radial locations of the splashback and the accretion shock as a function of the rate of cluster mass growth. Although both radii depend sensitively on the mass growth rate, they are found to indeed track each other (see Fig. 2.25). For typical mass growth rates for observed galaxy clusters, both quantities shrink at a higher mass growth rates, caused by different physics: For the gas, the inflowing material is associated with higher energy and momentum for a higher mass growth rate. Whereas for the dark matter, a significantly increased mass adds gravitational attraction to the splashback material.

A more intricate finding is that the locations of the splashback and the accretion shock track each other best if the adiabatic index of the gas is close to 5/3. Coincidentally, the intergalactic plasma, which is dominated by single atoms, has approximately this adiabatic index. In this sense, this tracking behaviour is not universal.

Improvements in the quality and quantity of observational data are bringing the outskirts of galaxy clusters into our view. Potential observational evidence for the splashback radius has already been found, and we may expect a direct detection of the accretion shock from X-ray and millimetre observations in the near future. Then, combining analytical predictions with those observations may lead to a deeper understanding and new discoveries of galaxy clusters and the structure assembly in our Universe. (Xun Shi)

2.10 Warps and waves in fully cosmological models of galactic discs

The stellar discs of nearby spiral galaxies are generally not flat and often show waves and warps. Even our own Galactic disc seems to be corrugated. It is still not clear what causes these structures. A research team at MPA, together with external collaborators, have revisited this question by analyzing new simulations of spiral galaxy formation. Their study shows that close encounters with satellite galaxies and more distant flybys of massive companions are the most common drivers. However, in some cases, bending patterns in discs can also be driven by the accretion of cold gas. The vertical motions produced by these patterns can be as large as 60 km/s. Such perturbations should be easily detectable in line-of-sight velocity fields of nearly face-on galaxies. This provides a new way to study the structure of galactic stellar discs, allowing us to understand how and how often such corrugation patterns arise in the nearby universe.

Large observational surveys of spiral galaxies have revealed that their stellar discs are often not flat but rather show a perturbed vertical structure. There is strong evidence that even our own Galactic disc has been significantly perturbed. The most common morphology for these vertical perturbations is what is known as an S-shaped or 'integral sign' warp which is frequently visible in edge-on galaxies. However, although less common, other types of distortion have also been observed. For example, rather than a flat plane, our Galactic disc presents a corrugated structure, resembling the pattern observed on a pond after dropping a rock (see Figure 2.26).

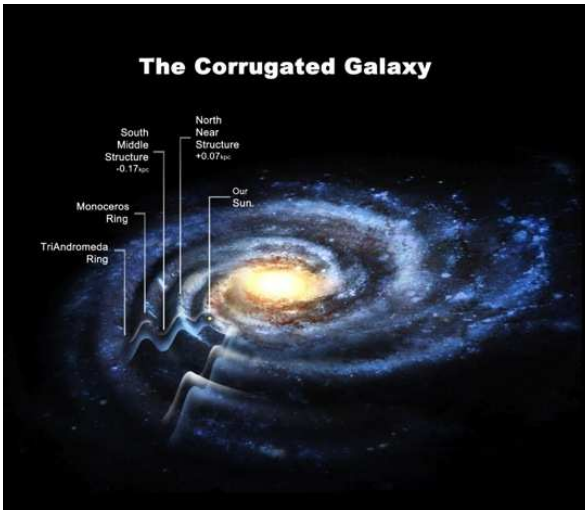

Figure 2.26: An artistic impression of a corrugation pattern in a galactic stellar disc. As the distance from the galactic centre increases, and the surface density of the disc decreases, the amplitude of the vertical oscillation increases. *Credit: Rensselaer Polytechnic Institute/Dana Berry.*

At least two major mechanisms are known to be capable of producing vertical perturbations of the otherwise flat outer discs of spirals. The first mechanism is tidal distortion of a pre-existing disc by an external perturber. The standard paradigm of hierarchical structure formation not only predicts that galaxies are surrounded by a non-spherical distribution of dark matter, but also that they grow in mass and evolve morphologically thanks to mergers with satellite galaxies. Strong tidal torques are exerted on a pre-existing disc as relatively massive satellites pass by and can induce the formation of vertical perturbations such as warps. In addition, a dark matter halo that is misaligned with respect to the embedded disc can also drive the formation of such vertical features. Another mechanism is misaligned accretion of cold gas. Such accretion can result from a close encounter with a gas-rich satellite or from misaligned infall from the cosmic web, or from a cooling hot gas halo.

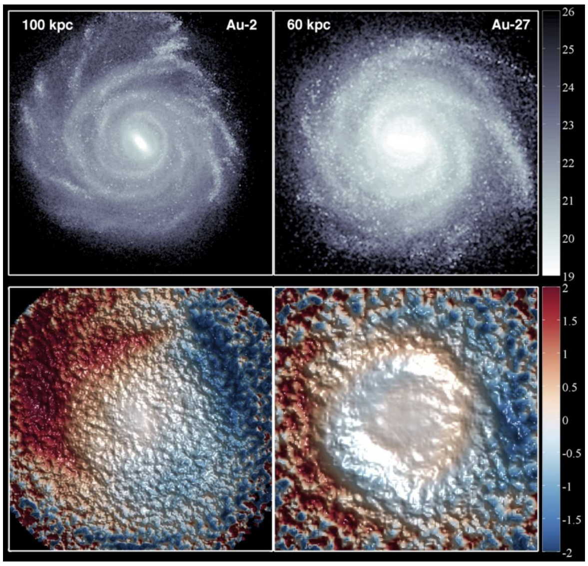

Figure 2.27: Top panels: Two examples of simulated stellar discs obtained from the Auriga Project. The colour bar indicates surface brightness values in the V-band. Bottom panels: Maps of the mean deviation from a flat plane for the same two galaxies shown above. The colour bar indicates the mean deviation. Blue (red) colors indicates that the stellar disc is, on average, below (above) the mid-plane. *Credit: Gómez et al 2016b.*

This strong connection between stellar discs and the outer regions of galaxies indicates that it is possible to study unseen structure in galaxy halos by characterizing their disc's vertical structure. To date, however, it has not been established what is the dominant mechanism driving the observed vertical perturbations. Furthermore, the frequency with which corrugation patterns (such as those observed in the Milky Way disc) arise in a cosmological context has not been quantified. To shed light on this problem a team of scientists at MPA, together with external collaborators, have analyzed a suite of 17 state-of-the art fully-cosmological hydrodynamical simulations of the formation of disc galaxies. These simulations, known as the Auriga

Project, include the main physical processes responsible for the formation and evolution of galaxies and self-consistently follow the evolution of gas, stars and dark matter over time. Overall, they are one of the best currently available simulation sets for studies of the formation of Milky Way sized galaxies.

This work shows that, at the present day, about 70% of the simulated galactic discs show strong vertical distortions, with amplitudes that can exceed 2 kpc – almost seven times the thickness of the disk. Half of these are typical 'integral sign' warps while the rest are corrugation patterns (see Figure 2.27). Such structures are thus predicted to be common.

The vertical perturbations have a variety of causes. The most common is encounters with satellite galaxies which can be effective from surprisingly large distances. In some cases, however, the disc's vertical patterns are clearly driven by the accretion of misaligned cold gas from halo infall or from mergers. Tidally induced vertical patterns can be identified in both young and old disc stellar populations, whereas those originating from cold gas accretion are seen mainly in the younger populations.

The team also characterized the mean vertical motions that arise due to these patterns. They find that satellites can induce vertical velocities as large as 60 km/s, quite substantial when compared to the rotational velocity of Milky Way of 220 km/s (see Figure 2.28). Such perturbations should be easily detectable in nearly face-on galaxies from line-of-sight stellar or gas velocity fields obtained by integral field spectroscopy or radio interferometry. This may be the easiest way to study the vertical structure of galactic discs in nearby galaxies, providing a direct way to assess the frequency with which oscillating vertical patterns arise in the nearby universe. (Facundo Gómez and Simon White)

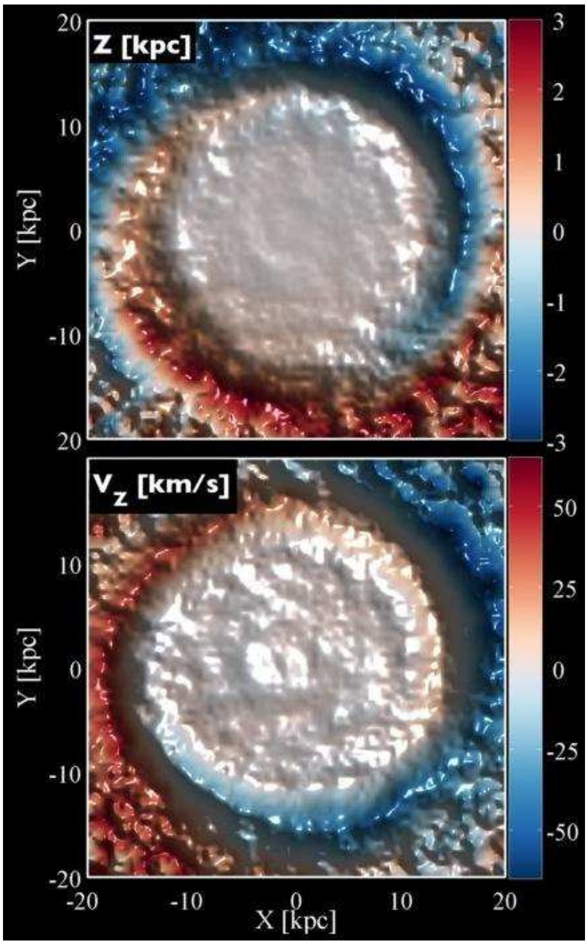

Figure 2.28: Top panel: Map of the mean deviation from a plane in kpc for one of our simulated galaxies. The vertical pattern seen in this stellar disc was excited by a distant fly-by encounter with a relatively massive satellite. Bottom panel: The mean vertical velocity field in km/s for the same galactic disc. The amplitude of the perturbations can be as large as 60 km/s. *Credit: Gómez et al. 2016a.*

2.11 Studying diffuse, warm gas in the outskirts of galaxies

The diffuse gas around galaxies is hard to detect, but shows properties which are quite different to the star-forming gas inside a galaxy. Scientists at MPA have used observations from the recent MaNGA survey to study how the ionized gas changes with distance from the center of the galaxy. They have demonstrated the usefulness of


Image Credit: NASA, ESA, The Hubble Heritage Team, (STScI/AURA)
Acknowledgement: M. Mountain (STScI), P. Puxley (NSF), J. Gallagher (U. Wisconsin)

Figure 2.29: An optical image of galaxy M82 with the ionized gas of hydrogen (HÎś) shown in pink flowing out of the galaxy. *Credit: NASA, ESA, The Hubble Heritage Team, (STScI/AURA).*

adding spectra from multiple galaxies in order to analyze the gas in the outskirts of galaxies. Their study shows that the brightness of the gas decreases, while its temperature increases the further the gas is located from the center of the galaxy. The differences between star-forming and circum-galactic gas also seem to correlate with the star-formation rate and stellar mass of the galaxies.

Understanding gas in and around galaxies is crucial to understanding star formation. The gas within a galaxy is the main ingredient for forming stars, and these stars, in turn, enrich the gas with heavy elements, or "metals". Continuous star formation needs a constant supply of gas, and most likely this comes from a reservoir of gas surrounding the galaxy in its outskirts, or halo, called the circum-galactic medium (CGM). Additionally, enriched gas flows out of the galaxies through supernova explosions, galactic winds, active galactic nuclei, etc. (see Figure 2.29 for an example of gas outflows). By studying the gas in the CGM and near the disk-halo boundary we can better understand these regulatory processes, gas properties and flows.

Gas in the halo is difficult to study because it is very faint and diffuse. Cold neutral gas can be seen by looking for neutral hydrogen (HI), and through HI surveys it is known that most galaxies have large reservoirs of gas surrounding the galaxies. Warm ionized gas with temperatures around 1000 K can be detected with optical emission lines and in the outskirts of galaxies this is called extra-planar, diffuse ionized gas (eDIG). Most previous work has been done with long exposures of individual nearby galaxies, including our own Milky Way.

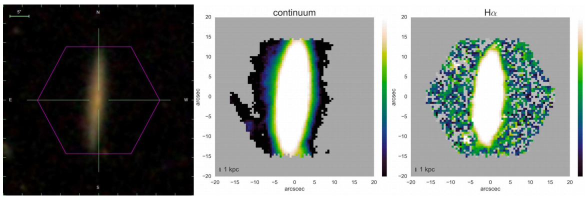

Figure 2.30: An example of one of the MaNGA galaxies. The left panel is an SDSS image with the MaNGA field of view overlaid.The middle panel shows a map of the brightness of the galaxy seen with MaNGA and the right panel shows a map of the ionized gas of hydrogen (HÎś). The color bars are in logarithmic units. For an individual galaxy, the gas can barely be detected in the outskirts. Thus, for scientific analysis, spectra from many galaxies have to be added to increase the signal far enough above the noise level. *Credit: MPA.*

With optical spectroscopy, only a few handfuls of galaxies have been studied, as it is difficult to obtain exposures deep enough to detect and analyze the diffuse gas. These studies find that the eDIG has different properties compared to gas in star-forming regions. Both the eDIG and star-forming gas are ionized mostly by energy from massive OB stars. As these stars are located in the disk of the galaxy, many of the differences arise because the eDIG is farther away from the OB stars than the gas in star-forming regions. Some other differences are not so easy to explain and vary from galaxy to galaxy. In some galaxies an additional source of energy may be needed to explain the properties of the eDIG, such as turbulence or shocks in the gas, or hot evolved stars in the outskirts of galaxies.

With a new dataset from the survey Mapping Nearby Galaxies at APO (MaNGA), which is part of the Sloan Digital Sky Survey (SDSS) IV, a group of MPA scientists addressed these differences and questions about the eDIG. As an Integral Field Unit survey, MaNGA takes spectra at multiple spatial locations. The eDIG is faint and diffuse and in Figure 2.30 we show an example for the MaNGA observations of one particular galaxy. Adding multiple spectra taken at similar locations from similar edge-on, late-type galaxies, we can study the faint diffuse gas.

The first year of MaNGA data includes a sample of 49 galaxies that are suitable for this study. We add the spectra from these 49 galaxies from 7 different locations off the disk of the galaxies to find how the eDIG varies with distance from the center of the galaxy. Our analysis shows that the brightness of the eDIG decreases logarithmically with distance and that most likely the temperature of the gas increases with distance from the center of the galaxies.

For a more detailed analysis, e.g. to figure out which type of galaxies need an additional energy source and what type of source, we to split the sample by different properties of the galaxies, such as stellar mass or star formation. With the first year of data we split the full sample in half and find that in galaxies with a higher star formation rate, the eDIG is more similar to the star-forming gas inside the galaxies compared to low star-forming galaxies where the eDIG is markedly different. Moreover, galaxies with higher stellar mass have a steeper temperature gradient compared to those with lower stellar mass. In the future, with more data, we will be able to split the sample even further to better understand these questions. (Amy Jones)

2.12 The embarrassment of false predictions - How to best communicate probabilities?

Complex predictions such as election forecasts or the weather reports often have to be simplified before communication. But how should one best simplify these predictions without facing embarrassment? In astronomical data analysis, researchers are also confronted with the problem of simplifying probabilities. Two researchers at the Max Planck Institute for Astrophysics now show that there is only one mathematically correct way to measure how embarrassing a simplified prediction can be. According to this, the recipient of a prediction should be deprived of the smallest possible amount of information.

Everybody knows this situation: The weather forecast predicts sunny weather, apparently with one hundred percent probability. You left your umbrella at home, and now you are left standing in the rain. This is not only annoying, but also embarrassing for the weather service. Did the weather people really not know better, or did they just communicate their knowledge imprecisely?

For efficient communication, statements have to be simplified. The weather service, for example, provides rounded probabilities for broad weather categories, even if the values used internally are much more complex. But how much simplification is tolerable before you risk embarrassment? And how do you measure the potential embarrassment of a prediction?

Reimar Leike and Torsten Enßlin at the Max Planck Institute for Astrophysics encountered this question while developing astronomical imaging methods. They show that there are only two requirements necessary to decide how good a simplification of a prediction is. First: if it is possible to communicate the precise probabilities, please do so. The second requirement is a bit more complex: The quality of a prediction depends only on the probability it assigned to the event that ultimately occurred. The simplified probabilities assigned to events which didn't occur are irrelevant.

To determine how to translate a complex probability into a simplified prediction, the researchers introduce a measure, which they call the embarrassment of the prediction (see Figl 2.31). From the requirements above, they deduce mathematically that the embarrassment of a prediction is measured by the negative logarithm of the communicated probability of the event that ultimately occurred. This measure is often called the degree of surprise. A prediction can be called embarrassing if you tend to be surprised when trusting it.

As the event which will ultimately occur is still unknown at the time of the prediction, the expected surprise has to be estimated. All possible events have to be considered, taking into account both the embarrassment of the communicated prediction in case this event occurs, and its probability. The expected embarrassment of the simplified prediction should then be minimised by adapting the communication accordingly.

It thereby turns out that the communication should lack as little information as possible. This may sound obvious, however, it is a precise mathematical instruction for the simplification of probabilities. For example, this instruction implies that small probabilities are better rounded up than off. If the probability for rain is four percent, it is better to communicate this with ten percent rather than zero percent, even if the latter corresponds to the normal rounding rules. This is because the prediction of zero percent rain probability would be infinitely embarrassing in case of rain. According to the scale of the researchers, the occurrence of an impossible event (expressed by zero probability) corresponds to an infinitely great surprise (the negative logarithm of zero is infinite).

The work of Reimar Leike and Torsten Enßlin not only clarifies an academic question - in fact there is confusion about the optimal simplification of probabilities in the corresponding literature - but also has very useful consequences in many diverse areas, such as communication, as-

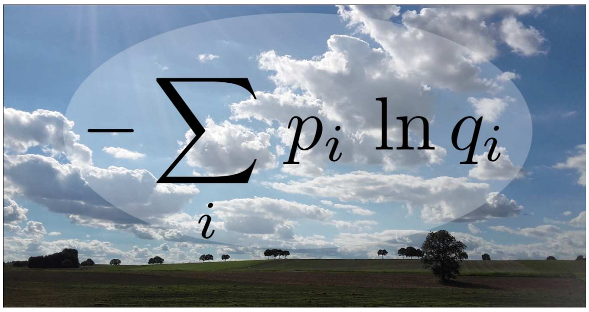

Figure 2.31: The formula for the expected embarrassment of a prediction. The various possible events are labelled by i. For the weather forecast this could represent the possibilities "rain", "sunshine", etc. The original probabilities of these events are pi. The probabilities communicated in the prediction are qi. In case of simplification, these should be chosen in a way that the expected embarrassment is minimised. Ideally, the communicated probabilities are identical to the original probabilities, but often they are simplified or rounded. The concept of the embarrassment expected is closely related to the information concept of information theory, and clarifies how this should be used in the case of probability approximation. *Credit: T. Enßlin, MPA.*

tronomical imaging, and artificial intelligence. All these fields work with probabilities and occasionally have to simplify them - but without embarrassment, please. (Reimer Leike and Torsten Enßlin)

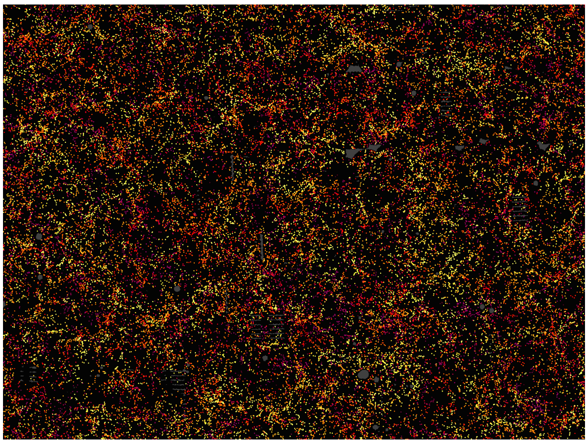

Figure 2.32: This is one slice through the map of the large-scale structure of the Universe from the Sloan Digital Sky Survey and its Baryon Oscillation Spectroscopic Survey. Each dot in this picture indicates the position of a galaxy 6 billion years into the past. The image covers about 1/20th of the sky, a slice of the Universe 6 billion light-years wide, 4.5 billion light-years high, and 500 million light-years thick. Colour indicates distance from Earth, ranging from yellow on the near side of the slice to purple on the far side. Galaxies are highly clustered, revealing superclusters and voids whose presence is seeded in the first fraction of a second after the Big Bang. This image contains 48,741 galaxies, about 3% of the full survey dataset. Grey patches are small regions without survey data. *credit: Daniel Eisenstein and SDSS-III.*

2.13 Million Galaxies in 3D

What are the properties of Dark Energy ? This question is one of the most intriguing ones in astronomy and scientists are one step closer in answering this question with the largest three-dimensional map of the universe so far: This map contains 1.2 million galaxies in a volume spanning 650 cubic billion light years. Hundreds of scientists from the Sloan Digital Sky Survey III (SDSS-III) – including researchers at the Max Planck Institutes for Extraterrestrial Physics and for Astrophyics - used this map to make one of the most precise measurements yet of dark energy. They found excellent agreement with the standard cosmological model and confirmed that dark energy is highly consistent with a cosmological constant.

"We have spent a decade collecting measurements of 1.2 million galaxies over one quarter of the sky to map out the structure of the Universe over a volume of 650 cubic billion light years," says Jeremy Tinker of New York University, a co-leader of the scientific team that led this effort. Hundreds of scientists are part of the Sloan Digital Sky Survey III (SDSS-III) team.

These new measurements were carried out by the Baryon Oscillation Spectroscopic Survey (BOSS) programme of SDSS-III. Shaped by a continuous tug-of-war between dark matter and dark energy, the map revealed by BOSS allows astronomers to measure the expansion rate of the Universe by determining the size of the so-called baryonic acoustic oscillations (BAO) in the three-dimensional distribution of galaxies.

Pressure waves travelled through the young Universe up to when it was only 400,000 years old at which point they became frozen in the matter distribution of the Universe. The end result is that galaxies are preferentially separated by a characteristic distance, which astronomers call the BAO scale. The primordial size of the BAO scale is exquisitely determined from observations of the cosmic microwave background.

Ariel Sanchez of the Max-Planck Institute of Extraterrestrial Physics (MPE) led the effort to estimate the exact amount of dark matter and dark energy based on the BOSS data and explains: "Measuring the acoustic scale across cosmic history gives a direct ruler with which to measure the Universe's expansion rate. With BOSS, we have traced the BAO's subtle imprint on the distribution of galaxies spanning a range of time from 2 to 7 billion years ago."

For the very precise measurements, however, the data had to be painstakingly analysed. Especially the determination of distances to the galaxies posed a big challenge. This is inferred from the galaxy spectra, which show that a galaxy's light is shifted to the red part of the spectrum because it moves away from us. This so-called redshift is correlated with a galaxy's distance: The farther a galaxy is away from us, the faster it moves.

"However, galaxies also have peculiar motions and the peculiar velocity component along the line-of-sight leads to the so-called redshift space distortion," explains Shun Saito from the Max Planck Institute for Astrophysics (MPA), who contributed sophisticated models to the BOSS data analysis. "This makes the galaxy distribution anisotropic because the line-of-sight direction is now special – only along this direction the distance is measured through a redshift, which is contaminated by peculiar velocity. In other words, the characteristic anisotropic pattern allows us to measure the peculiar velocity of galaxies – and because the motion of galaxies is governed by gravity, we can use this measurement to constrain to what level Einstein's general relativity is correct at cosmological scales. In order to properly interpret the data, we have developed a refined model to describe the galaxy distribution." Another approach, used by a junior MPE researcher for his PhD thesis, is to use the angular positions of galaxies on the sky instead of physical 3D positions. "This method uses only observables", explains Salvador Salazar. "We make no prior assumptions about the cosmological model."

Around the world, other groups all used slightly different models and methodologies to analyse the huge BOSS data set. "We now have seven measurements, which are slightly different, but highly correlated," Ariel Sanchez points out. "To extract the most information about the cosmological parameters, we had to find not only the best methods and models for data analysis but also the optimal combination of these measurements." This analysis has now born fruit: the BOSS data show that dark energy, which is driving the cosmological expansion, is consistent with a cosmological constant within an error of only 5%. This constant, called Lambda, was introduced by Albert Einstein to counter the attractive force of matter, i.e. it has a repellent effect. Moreover, all results are fully consistent with the standard cosmological model, giving further strength to this still relatively young theory.

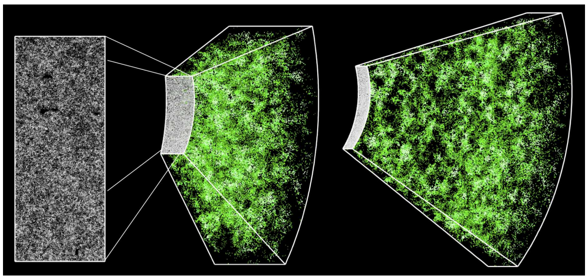

Figure 2.33: This is a section of the three-dimensional map constructed by BOSS. The rectangle on the left shows a cut-out of 1000 sq. degrees in the sky containing nearly 120,000 galaxies, or roughly 10% of the total survey. The spectroscopic measurements of each galaxy - every dot in that cut-out - transform the two-dimensional picture into a three-dimensional map, extending our view out to 7 billion years in the past. The brighter regions in this map correspond to the regions of the Universe with more galaxies and therefore more dark matter. The extra matter in those regions creates an excess gravitational pull, which makes the map a test of Einstein's theory of gravity. *credit: Jeremy Tinker und SDSS-III*

In particular, the map also reveals the distinctive signature of the coherent movement of galaxies toward regions of the Universe with more matter, due to the attractive force of gravity. Crucially, the observed amount of infall matches well to the predictions of general relativity. This supports the idea that the acceleration of the expansion rate is driven by a phenomenon at the largest cosmic scales, such as dark energy, rather than a breakdown of our gravitational theory. (Shun Saito)

2.14 The Sky's Ancient Eye

An international team of researchers have discovered an extremely rare "double source plane" gravitational lensing system, in which two distant galaxies are simultaneously lensed by a foreground galaxy, as part of the on-going Subaru Strategic Survey with Hyper Suprime-Cam. The team dubbed the system 'Eye of Horus' as the system resembles this ancient Egyptian symbol. Such a rare system is a unique probe of the fundamental physics of galaxies as well as cosmology.

Light from a distant galaxy can be strongly bent by the gravitational influence of a foreground galaxy. This effect is called strong gravitational lensing. Normally a single galaxy is lensed at a time. The same foreground galaxy can – in theory – simultaneously lens multiple background galaxies. Although extremely rare, such a lens system offers a unique opportunity to probe the fundamental physics of galaxies and add to our understanding of cosmology. One such lens system has recently been discovered and the discovery was made not in an astronomer's office, but in the classroom. It has been dubbed Eye of Horus, and this ancient eye in the sky will help us understand the history of the universe.

Classroom Research Pays Off

Subaru Telescope organizes a school for undergraduate students each year. One such session was held in September 2015 at the NAOJ headquarters in Mitaka, Tokyo. Subaru is currently undertaking a massive survey to image a large area of the sky at an unprecedented depth with Hyper Suprime-Cam as part of the Subaru Strategic Programme. A group of astronomers and young students were analysing some of that data at the school when they found a unique lens system. It was a classic case of a serendipitous discovery.

"When I was looking at HSC images with the students, we came across a ring-like galaxy and we immediately recognized it as a strong-lensing signature," said Masayuki Tanaka, the lead author of a science paper on the system's discovery. "The discovery would not have been possible without the large survey data to find such a rare object, as well as the deep, high quality images to detect light from distant objects."

Arsha Dezuka, a student who was working on the data, was astonished at the find. "It was my first time to look at the astronomical images taken with Hyper Suprime-Cam and I had no idea what the ring-like galaxy is," she said. "It was a great surprise for me to learn that it is such a rare, unique system!"

What They Saw

A close inspection of the images revealed two distinct arcs/rings of light in different colours. This strongly suggested that two distinct background galaxies are being lensed by the foreground galaxy. The lensing galaxy has a spectroscopic redshift of z = 0.79 (which means it is 6.8 billion light years away) based on data from the Sloan Digital Sky Survey. Follow-up spectroscopic observations of the lensed objects using the infrared-sensitive FIRE spectrometer on the Magellan Telescope confirmed that there are actually two galaxies behind the lens. One lies at z = 1.30 and the other is at z = 1.99 (8.9 and 10.5 billion light years away, respectively).

"Having three galaxies separated by billions of light years but all located on a single sightline from Earth is so rare that it's like hitting jackpot," exults Sherry Suyu, co-author from the Max Planck Institute for Astrophysics, who helped to analyze the lensing system and to weigh the lens galaxies using a software that she developed together with Aleksi Halkola. Upon seeing the beautiful lensing system, Suyu pointed out to her collaborators that it resembles an ancient Egyptian symbol known as Eye of Horus, for the sacred eye of an ancient Egyptian deity.

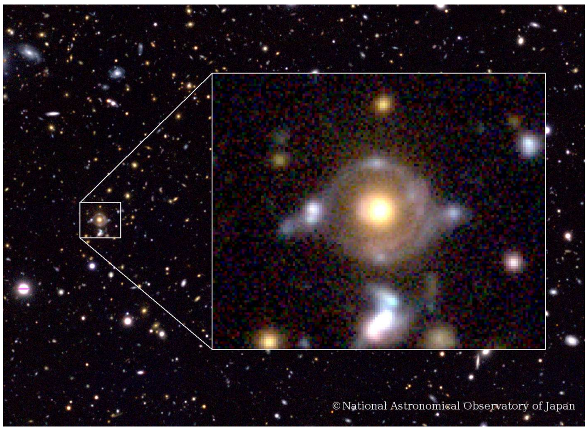

Figure 2.34: Eye of Horus in pseudo colour. There are two arcs/rings with different colours, which are lensed images of two background galaxies. *Credit: NAOJ.*

"The system is showing peculiar features with unexpected image splitting, an exciting sign of the possible presence of an invisible clump of dark matter," Suyu explains. Dark matter does not shine and is extremely difficult to detect - in fact, dark matter has not yet been directly detected. "However, through the gravitational effects of dark matter that imprint on the lensing images, our Eye of Horus is providing a great opportunity for us to "see" it indirectly!

The survey with Hyper Suprime-Cam is only 30% complete and will collect data for several more years to come. Astronomers expect to find roughly 10 more such systems in the survey, which will provide important insights into the fundamental physics of galaxies as well as how the universe expanded over the last several billion years. (Sherry Suyu)

2.15 Fluctuations in extragalactic gamma rays reveal two source classes but no dark matter

Researchers from the Max Planck Institute for Astrophysics and the University of Amsterdam

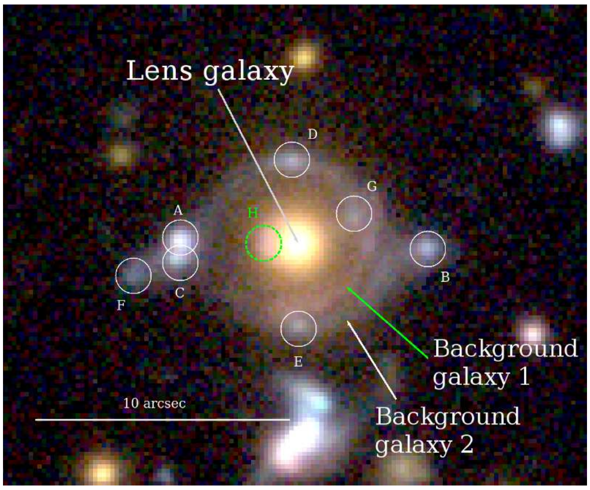

Figure 2.35: Identification of the lensed images: The inner arc has a reddish colour, while the outer arc has a blue colour. The circles show the lensed images of the background galaxies and the green and white circles are multiple images of the same background galaxies as the inner and outer arcs, respectively. The yellow object at the center is a massive galaxy at z=0.79, which bends the light from the two galaxies. *Credit: NAOJ.*

GRAPPA Center of Excellence just published the most precise analysis so far of the fluctuations in the gamma-ray background. They used more than six years of data gathered by the Fermi Large Area Telescope and found two different source classes contributing to the gamma-ray background. No traces of a contribution of dark matter particles were found in the analysis. The study was performed with an international collaboration of researchers and is published in the journal Physical Review D.

Gamma rays are particles of light, or photons, with the highest energy in the universe, invisible to the human eye. The most common emitters of gamma rays are blazars: supermassive black holes at the centres of galaxies. In smaller numbers, gammy rays are also produced by a certain kind of stars called pulsars and in huge stellar explosions such as supernovae.

In 2008 NASA launched the Fermi satellite to map the gamma-ray universe with extreme accuracy. The Large Area Telescope, mounted on the Fermi satellite, has been taking data ever since. It continuously scans the whole sky every three hours. The majority of the detected gamma rays is produced in our own Galaxy (the Milky Way), but the Fermi telescope also managed to detect more than 3000 extragalactic sources (according to the latest count performed in January 2016). However, these individual sources are not enough to explain the total amount of gamma-ray photons coming from outside our Galaxy. In fact, about 75% of them are unaccounted for.

Isotropic gamma-ray background

As far back as the late 1960‘s, orbiting observatories have found a diffuse background of gamma rays streaming from all directions in the universe. If you had gamma-ray vision, and looked at the sky, there would be no place that would be dark.

The source of this so-called isotropic gamma-ray background is hitherto unknown. This radiation could be produced by unresolved blazars, or other astronomical sources too faint to be detected with the Fermi telescope. Parts of the gamma-ray background might also hold the fingerprint of the illustrious dark matter particle, a so-far undetected particle held responsible for the missing 80% of the matter in our universe. If two dark matter particles collide, they can annihilate and produce a signature of gamma-ray photons.

Fluctuations

“The analysis and interpretation of fluctuations of the diffuse gamma-ray background is a new research area in high-energy astrophysics,” explains Eiichiro Komatsu at the Max Planck Institute for Astrophysics, who developed the necessary analysis tools for fluctuations in this radiation. He was also part of the team that for the first time reported fluctuations in the gamma ray background in 2012. For this latest analysis, the researchers used 81 months of data gathered by the Fermi Large Area Telescope – much more data and with a larger energy range than in previous studies.

The scientists were able to distinguish two different contributions to the gamma-ray background. One class of gamma-ray sources is needed to explain the fluctuations at low energies (below 1 GeV), and another type of sources is needed to generate the fluctuations at higher energy – the signatures of these two contributions is markedly different.

The gamma rays in the high-energy ranges – from a few GeV up – are likely originating from unresolved blazars, the researchers suggest in their paper. Further investigation of these potential sources is currently under way. However, it seems much harder to pinpoint a source for the fluctuations with energies below 1 GeV. None of the known gamma-ray emitters have a behaviour that is consistent with the new data.

Constraints on dark matter

So far, the Fermi telescope has not detected any conclusive indication of gamma-ray emission originating from dark-matter particles. Also this lat-

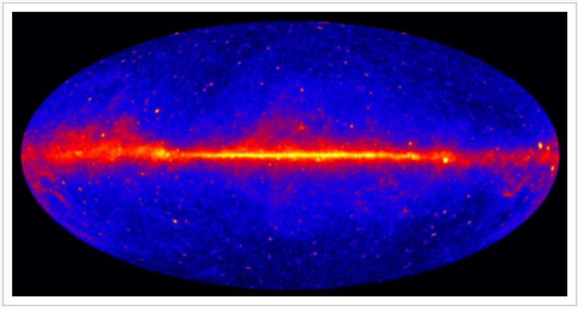

Figure 2.36: This view shows the entire sky in gammy ray radiation, at energies greater than 1 GeV, based on five years of data from the Large Area Telescope instrument on NASA's Fermi Gamma-ray Space Telescope. Brighter colours indicate brighter gamma-ray emission. The large bright band in the middle is the emission from our own Galaxy. *Credit: NASA/DOE/Fermi LAT Collaboration.*

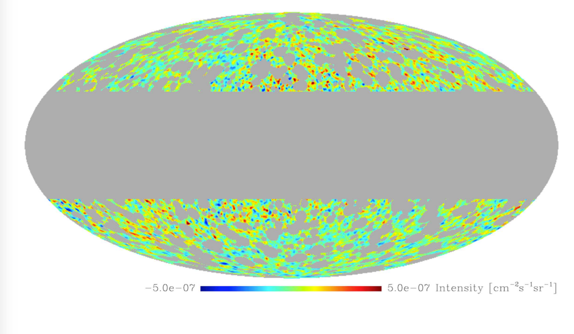

Figure 2.37: Fluctuations in the isotropic gamma-ray background, based on 81 months of data. Emission from our own Galaxy, the Milky Way, is masked in grey. *Credit: Mattia Fornasa, UvA/Grappa.*

est study showed no indication of a signal associated with dark matter. "Our measurement complements other search campaigns that used gamma rays to look for dark matter," says lead author Mattia Fornasa from the University of Amsterdam. "It confirms that there is little room left for dark matter induced gamma-ray emission in the isotropic gamma-ray background."

The precision of the fluctuation measurement has improved markedly since the first result in 2012. "I am glad to see that our measurements provide significant new insights into the origin of the gamma-ray background," says Komatsu.

"My original motivation to do this analysis in 2006 was to find evidence for gamma-rays from dark matter particles. Well, we have not found gamma-rays from dark matter yet," Komatsu concedes, "but I am still excited about our measurements leading to a new understanding of populations of astrophysical gamma-ray sources such as blazars. I have not given up hope on finding gamma-rays from dark matter yet though, and we have some new ideas on how to improve our method." (Eiichiro Komatsu)

3 Publications and Invited Talks

3.1 Publications in Journals

3.1.1 Publications that appeared in 2016(297)

Agnello, A., A. Sonnenfeld, S.H. Suyu, et al. Spectroscopy and high–resolution imaging of the gravitational lens SDSS J1206+4332. Mon. Not. R. Astron. Soc. **458(4)**, 3830–3838 (2016).

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Wuyts, E., E. Wisnioski, et al. (incl. Th. Naab, B. Röttgers): The evolution of metallicity and metallicity gradients from $z = 2.7$ to 0.6 with KMOS3D. Astrophys. J. **827(2)**, 74, 1–18 (2016).

Wuyts, S., N. Förster-Schreiber et al. (inc. Th. Naab): KMOS3D: Dynamical Constraints on the mass budget in early star-forming disks. Astrophys. J. **831**, 149, 1-22 (2016).

Xu, D., Sluse, D., P. Schneider et al. (incl. D. Nelson). Lens galaxies in the Illustris simulation: power–law models and the bias of the Hubble constant from time delays. Mon. Not. R. Astron. Soc. **456(1)**, 739–755 (2016).

Yakovleva, S. A., Y.V. Voronov and A.K. Belyaev: Atomic data on inelastic processes in low-energy beryllium-hydrogen collisions. Astron. Astrophys. **593**, A27, 1-10 (2016).

Yamaguchi, Y., Y. Tamura, et al. (incl. M. Ryu). SXDF–ALMA 2 arcmin2 deep survey: Resolving and characterizing the infrared extragalactic background light down to 0.5mJy. Public. of Astron. Soc. of Japan, **68(5)**, 82 (2016).

Yan, R., et al (incl. R. D'Souza, A. Jones), SDSS-IV MaNGA IFS Galaxy Survey – Survey Design, Execution, and Initial Data Quality. Astrophys. J. **152**, 197 (2016).

Yue, B., A. Ferrara and K. Helgason: Detecting high–z galaxies in the near–infrared background. Mon. Not. R. Astron. Soc. **458(4)**, 4008–4014 (2016).

Zhang, C., H. Xu, et al. (incl. Z. Zhang): A Chandra study of the image power spectra of 41 cool core and non–cool core galaxy clusters. Astrophys. J. **823(2)**, 1–15 (2016).

Zhang, J.–J., X.–F. Wang, et al. (incl. M. Sasdelli, P. Mazzali): A luminous peculiar type Ia Supernova SN 2011hr: more like SN 1991T or SN 2007if? Astrophys. J. **817(2)**, 1–13 (2016).

Zhu, Z., H. Xu, et al. (incl. Z. Zhang): A Chandra study of temperature distributions of the intracluster medium in 50 galaxy clusters. Astrophys. J. **816(2)**, 1–11 (2016).

Zhukovska, S., C. Dobbs, E.B. Jenkins, and R. Klessen: Modeling Dust Evolution in Galaxies with a Multiphase, Inhomogeneous ISM. Astrophys. J. **831 (2)**, 1–15 (2016).

Zhuravleva, I., E. Churazov, E. et al. (incl. R.A. Sunyaev): The nature and energetics of AGN–driven perturbations in the hot gas in the Perseus Cluster. Mon. Not. R. Astron. Soc. **458(3)**, 2902–2915 (2016).

3.1.2 Publications accepted in 2016 (29)

Bahé Y. M., J. Schaye, R.A. Crain et al.: The origin of the enhanced metallicity of satellite galaxies. Mon. Not. R. Astron. Soc.

Beutler, F., H.-J. Seo, et al. (incl. S. Saito): The clustering of galaxies in the completed SDSS-III Baryon Oscillation Spectroscopic Survey: baryon acoustic oscillations in the Fourier space. Mon. Not. R. Astron. Soc.

Braithwaite, J. and H.C. Spruit: Magnetic fields in non-convective regions of stars. Royal Society Open Science.

Carrillo, A., E.F. Bell, et al. (incl. A. Monachesi): dw1335-29, a recently discovered dwarf satellite of M83. Mon. Not. R. Astron. Soc.

Gatto, A. et al. (incl. T. Naab and T. Peters): The SILCC project: III. Regulation of star formation and outflows by stellar winds and supernovae. Mon. Not. R. Astron. Soc.

Gomez, F., S.D.M. White, R. Grand et al: Warps and waves in the stellar discs of the Auriga cosmological simulations. Mon. Not. R. Astron. Soc.

Grand, R., F. Gomez, F. Marinacci et al. (incl. S.D.M. White): The Auriga Project: the properties and formation mechanisms of disc galaxies across cosmic time. accepted by Mon. Not. R. Astron. Soc.

Harmsen, B., A. Monachesi, E.F. Bell, et al.: Diverse Stellar Haloes in Nearby Milky Way-Mass Disc Galaxies. Mon. Not. R. Astron. Soc.

Hsueh, J.-W., C.D. Fassnacht, S. Vegetti, et al.: SHARP - II. Mass structure in strong lenses is not necessarily dark matter substructure: a flux ratio anomaly from an edge-on disc in B1555+375. Mon. Not. R. Astron. Soc.

Huang, X. et al. (incl. W. Hillebrandt, S. Taubenberger): The Extinction Properties of and Distance to the Highly Reddened Type Ia Supernova SN 2012cu. Astrophys. J.

Jia, S. and H.C. Spruit: Instability of mass transfer in a planet-star system, Mon. Not. R. Astron. Soc.

Jerkstrand, A., S. J. Smartt, C. Inserra et al.: Long-duration Superluminous Supernovae at Late Times. Astrophys. J.

Jones, A., G. Kauffmann et al.: SDSS IV MaNGA: Deep observations of extraplanar ionized gas around late-type galaxies from stacked IFU spectra.

Kozyreva A. et al. (incl. U. Nöbauer): Fast evolving pair-instability supernova models: evolution, explosion, light curves. Mon. Not. R. Astron. Soc.

Kreisch, C. D., J. O'Sullivan, R. Arvidson, et al.. Regularization of Mars Reconnaissance Orbiter CRISM along–track oversampled hyperspectral imaging observations of Mars. Icarus.

Larchenkova T.I., A.A. Lutovinov and N.S. Lyskova: Influence of the galactic gravitational field on the positional accuracy of extragalactic sources. Astrophys. J.

Marinacci, F., R. Grand et al. (incl. S.D.M. White): Properties of H I discs in the Auriga cosmological simulations. Mon. Not. R. Astron. Soc.

McKean, J. P., L. E. H. Godfrey, S. Vegetti et al.: LOFAR imaging of Cygnus A - direct detection of a turnover in the hotspot radio spectra. Mon. Not. R. Astron. Soc.

Oldham, L., M.W.A. Auger, et al. (incl. S. Vegetti): Red nuggets grow inside-out: evidence from gravitational lensing. Mon. Not. R. Astron. Soc.

Peters, T., T. Naab, S. Walch, et al.: The SILCC project–IV. Impact of dissociating and ionising radiation on the interstellar medium and Hα emission as a tracer of the star formation rate. Mon. Not. R. Astron. Soc.

Pardi, A., P. Girichidis, T. Naab, et al. (incl. T. Peters): The impact of magnetic fields on the chemical evolution of the supernova-driven ISM, Mon. Not. R. Astron. Soc.

Qu, Y., J. Helly, R. Bower et al. (incl. S.D.M. White): A chronicle of galaxy mass assembly in the EAGLE simulation. Mon. Not. R. Astron. Soc.

Ross, A. J., F. Beutler, (incl. S. Saito): The clustering of galaxies in th e completed SDSS-III Baryon Oscillation Spectroscopic Survey: observational systematics and baryon acoustic oscillations in the correlation function. Mon. Not. R. Astron. Soc.

Sales, L., J. Navarro, K. Oman et al. (incl. S.D.M. White): The low–mass end of the baryonic Tully-Fisher relation. Mon. Not. R. Astron. Soc.

Sasdelli, M., Hillebrandt, W. Kromer, M., et al.: A metric space for type Ia supernova spectra: a new method to assess explosion scenarios. Mon. Not. R. Astron. Soc.

Tang X. and R. A. Chevalier: Shock evolution in non-radiative supernova remnants, Mon. Not. R. Astron. Soc

Zhang, K., et al. (incl. A. Jones): The Impact of Diffuse Ionized Gas on Emission-line Ratios, Interpretation of Diagnostic Diagrams, and Gas Metallicity Measurements.

Zhao, G.-B., Y. Wang, S. Saito, et al.: The clustering of galaxies in the completed SDSS-III Baryon O scillation Spectroscopic Survey: tomographic BAO analysis of DR12 combined sample in Fourier space. Mon. Not. R. Astron. Soc.

Zámečníková, W.P. Kraemer, and P. Soldán: Radiative association of $He(2^3P)$ with lithium cations: $\Pi - \Sigma$ processes. J. Quant. Spectrosc. Radiat. Transf.

3.2 Publications in proceedings

3.2.1 Publications in proceedings appeared in 2016 (18)

Elliott, J., R. de Souza, et al. (incl. E. Ishida): Using gamma regression for photometric redshifts of survey galaxies. In: N. R. Napolitano, G. Longo, M. Marconi, et al. (Eds.), The Universe of Digital Sky Surveys - a meeting to Honour the 70th Birthday of Massimo Capaccioli pp. 91-96 (2016).

Franeck, A., et al. (incl. P. Girichidis, T. Naab, T. Peters): [CII] synthetic emission maps of simulated galactic disks. In: R. Simon, R. Schaaf and J. Stutzki (Eds.), The 6th Zermatt ISM-Symposium Conditions and Impact of Star Formation: From Lab to Space pp. 385-386 (2016).

Goriely, S., A. Bauswein, H.-Th. Janka, et al.: R-process nucleosynthesis during the decompression of neutron star crust material. Journal of Physics: Conference Series, 665: 012052, 1-8. (2016).

Hao, W., R. Spurzem, T. Naab, et al.: Resonant motions of supermassive black hole triples. In: Y. Meiron, S. Li, F. Liu, and R. Spurzem (Eds.), Star Clusters and Black Holes in Galaxies across Cosmic Time (IAU Symposium 312) Cambridge, UK: Cambridge University Press. pp. 101-104 (2016).

Huang, X., T. Enßlin, and M. Selig: GeV excess and phenomenological astrophysics modeling. Journal of Physics: Conference Series, 718: 042029, 1-5 (2016).

Ishino, H., Y. Akiba, et al. (incl. E. Komatsu): LiteBIRD: lite satellite for the study of B-mode polarization and inflation from cosmic microwave background radiation detection. In: H. A. MacEwen, G. G. Fazio, M. Lystrup, et al. (Eds.), Space Telescopes and Instrumentation 2016: Optical, Infrared, and Millimeter Wave pp. 1-8 (2016).

Kruijssen, J. M. D.: Are globular clusters the natural outcome of regular high-redshift star formation? In: Y. Meiron, S. Li, F. Liu and R. Spurzem (Eds.), Star Clusters and Black Holes in Galaxies across Cosmic Time (IAU Symposium 312) Cambridge, UK: Cambridge University Press pp. 147-154 (2016).

Lugaro, M., S.W. Campbell, et al.: Current hot questions on the s process in AGB stars. Journal of Physics: Conference Series, 665: 012021, 1-8 (2016)

Lützgendorf, N., M. Kissler-Patig, (incl. D. Kruijssen, D.): Intermediate-mass black holes in globular clusters: observations and simulations. In: Y. Meiron, S. Li, F. Liu and R. Spurzem (Eds.), Star Clusters and Black Holes in Galaxies across Cosmic Time (IAU Symposium 312) Cambridge, UK: Cambridge University Press. pp. 181-188 (2016).

Mendoza-Temis, J. J., M.R. Wu, et al. (incl. H.-Th. Janka): On the robustness of the r-process in neutron-star mergers against variations of nuclear masses. Journal of Physics: Conference Series, 730: 012018, 1-9 (2016).

Monachesi, A., E.F. Bell, D.J. Radburn-Smith, et al.: Resolving the stellar halos of six massive disk galaxies beyond the Local Group. In: A. Bragaglia, M. Arnaboldi, M. Rejkuba and D. Romano (Eds.), The General Assembly of Galaxy Halos: Structure, Origin and Evolution (IAU Symposium 317) Cambridge, UK: Cambridge University Press. pp. 222-227 (2016).

Predehl, P., et al. (incl. E. Churazov, M. Gilfanov, R. Sunyaev: eROSITA on SRG. In: J.-W.-A. Den Herder, T. Takahashi and M. Bautz (Eds.), Space Telescopes and Instrumentation 2016: Ultraviolet to Gamma Ray pp. 1-8 (2016).

Rembiasz, T., M. Obergaulinger, et al. (incl. E. Müller): Termination of the MRI via parasitic instabilities in core-collapse supernovae: influence of numerical methods. Journal of Physics: Conference Series, 719: 012009, 1-8 (2016).

Schneider, N., Ossenkopf, V., Klessen, R., et al. (incl. Girichidis, P.): What probability distribution functions tell us about the processes of star formation. In: R. Simon, R. Schaaf and J. Stutzki (Eds), The 6th Zermatt ISM-Symposium Conditions and Impact of Star Formation: From Lab to Space pp. 175-176 (2016).

Schwartz, P., Heinzel, P., Jejčič, S. et al. (incl. Anzer U.): Is it possible to use the green coronal line instead of X rays to cancel an effect of the coronal emissivity deficit in estimation of the prominence total mass from decrease of the EUV-corona intensities? In: I. Dorotovic, C. E. Fischer and M. Temmer (Eds.), Coimbra Solar Physics Meeting: Ground-based Solar Observations in the Space Instrumentation Era pp. 89-96 (2016).

Spiniello, C.: The low-mass end of the Initial Mass Function in massive early-type-galaxies. In: N. R. Napolitano, G. Longo, M. Marconi, et al. (Eds.), The Universe of Digital Sky Surveys - a meeting to Honour the 70th Birthday of Massimo Capaccioli pp. 219-223 (2016).

Wang, L., Spurzem, R., Aarseth, S. et al. (incl. Naab T.): Acceleration of hybrid MPI parallel NBODY6++ for large N-body globular cluster simulations. In: Y. Meiron, S. Li, F. Liu and R. Spurzem (Eds.), Star Clusters and Black Holes in Galaxies across Cosmic Time (IAU Symposium 312) Cambridge, UK: Cambridge University Press. pp. 260-261 (2016).

White, S.: Dark matter. In: R. Blandford, D. Gross and A. Sevrin (Eds.), Astrophysics and Cosmology Hackensack, NJ: World Scientific. pp. 216-284 (2016).

3.2.2 Publications as electronic file and books

Leike, R. H. and T. A. Enßlin: Optimal Belief Approximation
https://arxiv.org/abs/1610.09018.

Melson, T., and H.-Th. Janka: Yearbook of the Max Planck Society 2016: Computer simulations confirm supernova mechanism in three dimensions. *https://dx.doi.org/10.17617/1.1N*

Ritter, H. and U. Kolb: Catalogue of cataclysmic binaries, low-mass X-ray binaries and related objects (Edition 7.23). *http://vizier.cfa.harvard.edu/viz-bin/VizieR?-source=B/cb*
http://vizier.u-strasbg.fr/viz-bin/VizieR?-source=B/cb

Spruit, H.: Essential Magnetohydrodynamics for Astrophysics v3
http://www.mpa-garching.mpg.de/~henk/mhd12.zip arXiv:1301.5572v3

Taubenberger, S.: The Extremes of Thermonuclear Supernovae chapter in Alsabti, A. W., Murdin, P., eds., Handbook of Supernovae, Springer, ISBN 978-3-319-21845-8 (2016).

3.3 Talks

3.3.1 Invited review talks at international meetings

B. Ciardi: – Signals from the deep past: unveiling early cosmic structures (Valletta, Malta, 18.7.-22.7.)
– Panorama of the Evolving Cosmos:
6th Subaru International Conference (Hiroshima, Japan, 28.11.-2.12.)
– Computational Galaxy Formation (Tegernsee, Germany, 9.5.-13.5.)
– Physics of Cosmic Dawn and Reionization in the SKA Era (Sexten, Italy, 18.1.-22.1.)

E. Churazov: M87 Workshop: Towards the 100th Anniversary of the Discovery of Cosmic Jets (Taipei, 23.5.-27.5.)
– Frontiers of Nonlinear Physics (Nizhny Novgorod, 17.7.-23.7.)
– XMM-NEWTON: The Next Decade (Madrid, 9.5.-11.5.)

T.A. Enßlin: MERCURE-Winterschool on Plasma-Astroparticle physics (Bad Honnef, 6.3.)
– Ringberg Workshop 2016 on Computational Galaxy Formation (Tegernsee, 12.5.)

M. Gilfanov: Frontiers of Nonlinear Physics (Nizhnii Novgorod, Russia, 17.7.-23.7.)
– Stars: from collapse to collapse (Nizhnii Arkhyz, Russia, 3.10.-7.10.)
– Sino-German Workshop on Galaxy and Cosmology (Guangzhou, China, 5.12.-8.12.)

F. Gomez: – Two talks at the Nordita workshop, Gaia Challenge, (Stockholm, Sweden, 10.10.-4.11.)
– Computational Galaxy Formation Workshop, (Ringberg, Germany, 9.5.-13.5.)

W. Hillebrandt: – The Transient Sky (Harvard University, 16.5.-19.5.)
– The Physics of Supernovae (MIAPP, Garching 22.8.-16.9.)

H.-Th. Janka: – Brainstorming and Fun (Basel, 29.9.–1.10.)
– ISSI Workshop Supernovae (Bern, 3.10.–7.10.)
– Multi-scale Ambient Energy Deposition from Supernovae (Copenhagen, 22.2.–24.2.)
– SuperMUC Status and Results Workshop 2016 (Garching, 26.4.)
– Frühjahrstagung der Deutschen Physikalischen Gesellschaft (Hamburg, 29.2.–4.3.)
– Compact Stars and Gravitational Waves (Kyoto, 31.10.–4.11.)
– Supernovae: The Outliers (Garching, 12.9.–16.9.)
– The Kavli Prize Symposium in Astrophysics (Oslo, 8.9.)
– PRACE Scientific & Industrial Conference (Prague, 10.5.–12.5.)
– INT-16-2: “The Phases of Dense Matter” (Seattle, 8.8.–12.8.)
– INT-16-61W: “Flavor Observations with Supernova Neutrinos” (15.8.–19.8.)

A. Jerkstrand : – Supernovae: The Outliers, (Garching, Germany, 13.9.)
– MIAPP 2016 : The Physics of Supernovae, (Garching, Germany, 25.8.)

G. Kauffmann : Star Formation in Different Environments (Quy Nhon, 25.7.-29.7.)

E. Komatsu: – Annual Meeting of the Physical Society of Japan (Sendai, Japan, 19.3.-22.3.)
– COSMO-16 (Michigan, USA, 8.8.-12.8.)

E. Müller: – The Physics of Supernovae (MIAPP Garching, 23.8.)
– Numerical Relativity in Matter Spacetimes for Gravitational Wave Astronomy
(Valencia, Spain 13.12.)

R. Sunyaev: – B&E workshop, SPEKTR-RENTGEN-GAMMA (eRosita and ART-XC) all sky X-Ray survey (Caltech, 22.7.).
– Towards a next probe for CMB observationsGalaxy clusters + synergy with eRosita (CERN, Geneva, 17.5.)
– International Symposium; Uzbekistan Academy of Sciences, (Tashkent 10.11.)
– MHD Accretion Disk Conference - "Disk accretion onto neutron stars with a weak magnetic field" (Oxford University, 14.7.)
– Conference High Energy Astrophysics: today and tomorrow, Space Research Institute (Moscow, 21.12.)

S. Taubenberger: Late-time observations of Type Ia Supernovae, MIAPP workshop "The Physics of Supernovae" (Garching, 31.8.)

S. Vegetti: From theory to application: a century of gravitational lensing, (Leiden, 11.7. - 15.7.)
– "Sexten 2016 Dark Matter Workshop" (Sexten, 22.2.- 26.2.)

S. White: From Cosmic Strings to CMB Observations: 60th Birthday of Francois R. Bouchet (Paris, 23.3.-25.3.)
– Ringberg Workshop on "Computational Galaxy Formation" (Tegernsee, 8.5. -13.5.)
– "Galaxy clusters: physics laboratories and cosmological probes" (IoA, Cambridge, U.K. 5.12.-9.12.)
– McMaster Univ. (Toronto, Canada 19.6.-22.6.)

S. Zhukovska: Workshop "The Life Cycle of Molecular Clouds" (Cologne, 2.3.- 4.3.)
– Ringberg Workshop on "Computational Galaxy Formation" (Tegernsee, 8.5. -13.5.)

3.3.2 Invited Colloquia talks

B. Ciardi: – Invited Joint Colloquium (Heidelberg, Germany; 31.5.)
– Invited Colloquium, Bologna Observatory and University (Bologna 17.1.)

E. Churazov: Invited Colloquium (Oxford Univ. 5.9.)

T.A. Enßlin: Invited Colloquium (TUM, 20.10.)
– Invited Colloquium (Univ. of Nijmegen, 31.5.)
– Invited Colloquium, Niels Bohr Institute (Copenhagen, 20.9.)
– Invited Colloquium, Albert Einstein Institut (Hannover, 8.12.)
– Invited Colloquium (Univ. Bochum, 12.12.)

M. Gilfanov: Invited Colloquium, Harvard-Smithsonian Center for Astrophysics,(Harvard 18.5.)

F. Gomez: Invited Colloquium: Observatoire Astronomique de Strasbourg, (Strasbourg, France, 09/16)
– Invited Colloquium: MPE), Garching, Germany, 04/16)

H.-Th. Janka: – Bethe Colloquium, Bethe Center for Theoretical Physics, (Bonn, 21.4.)
– Theory Colloquium, DESY (Hamburg, 6.4.)
– Physics Colloquium (Universität Siegen, 9.6.)
– Physics Colloquium, Oskar Klein Centre, (Stockholm, 12.4.)

A. Jerkstrand : Invited presentation, Uni Würzburg Supernova Workshop, (Würzburg 08.12.)

O. Just: – Meeting of Max-Planck-Plasma-Physics Center (MPPC), (Berlin, Germany, 15.1.)
– "Nuclear Astrophysics" Workshop, Ringberg Castle, (Tegernsee 15.3.)
–"Connecting FRIB with the Cosmos" Workshop, Lansing (USA, 15.6.)
– "Nuclei in the Cosmos" Conference, (Niigata Japan, 22.6.)
– "1 Bethe and Beyond" Workshop, (Tokyo Japan, 27.6.)
– RIKEN Group Seminar, (Tokyo Japan, 28.6.)
– RIKEN-RESCEU Joint Seminar, (Tokyo Japan, 27.6.)

G. Kauffmann: Invited Colloquium, Carnegie Observatories (Santa Barbara 23.2.)

E. Komatsu: – Invited Colloquium (Univ. Bielefeld; 12.2.)
  – Invited Colloquium (Univ. of Toronto; 23.9.)
  – Invited Colloquium (Univ. of Milan; 8.11.)

T. Peters: Invited Colloquium (Univ. of Tübingen; 20.6.)

S. Saito: Cosmology Lunch Seminar (Univ. of Cambridge, 21.11.)

R. Sunyaev: – CMB spectral distortions (Univ. of Michigan, Ann Arbor, 6.10.)
  – Invited Colloquium, Ulughbek Astron. Inst. (Tashkent, Uzbekistan, 9.11.)
  – Invited Colloquium, Institut d'Astrophysique (Paris, France 27.5.)
  – ITS seminar – Harvard-Smithsonian Center for Astrophysics, (Cambridge, USA 29.9.)
  – Invited Colloquium, Haverford College, (Philadelphia 23.9.)

S. Vegetti: Invited Colloquium (Univ. of Regensburg; 2.5.)
  – Heidelberg Joint Colloquium (Univ. of Heidelberg; 7.6.)

3.3.3 Public talks

Y. Bahé: Café und Cosmos (München 2.2.)

G. Börner: "Erste Erde Epos" – Podiumsgesprächs mit Raoul Schrott und Petra Schwille
  (Literaturhaus München, 14.11.)

T.A. Enßlin: DLR Astroseminars "Aktuelle und künftige Weltraummissionen" (Cologne 5.4.)
  – Karl-Rahner-Akademie Köln (Cologne 6.4.)
  – Südthüringischen Astr. Tag and 50 year anniversitary of Volkssternwarte Suhl (Suhl, 12.3.)
  – Volkssternwarte München (Munich, 14.10.)
  – Company Explain-It (Munich, 21.10.)
  – Festival "SKOP – Exp. Musik und Kunst im interdisziplinaeren Kontext" (Frankfurt, 14.12.)

H.-Th. Janka: – Schulvortrag am MPI Astrophysik (Garching 3.2.)
  – Schulvortrag am MPI Astrophysik (Garching 21.12.)
  – Max-Planck-Gesellschaft (München 16.2.)

A. Jerkstrand : "Marie Curie Fellowship Workshop", (Munich, Germany, 29.8.)

E. Komatsu: Landeskunde Japan (LMU; 24.1.)
  – Bilingual News (Podcast; 15.9.)

E. Müller: – Gymnasium Vaterstetten (7.3.)
  – Physik Modern, LMU (21.4.)
  – Lehrerfortbildung ESO/ExMuc (23.6.)
  – Gymnasium Beilngries (26.9.)
  – Café and Cosmos (München 10.10.)

F. Schmidt: MVHS (Münchner Volkshochschule), Öffentlicher Abendvortrag, 8.12.

3.4 Lectures and lecture courses

3.4.1 Lectures at LMU and TUM

T. A. Enßlin, SS 2016, LMU München

W. Hillebrandt, WS 2015/2016 and WS 2016/2017, TU München

H.-Th. Janka, WS 2015/2016 and SS 2016, TU München

E. Müller, WS 2015/2016 and SS 2016, TU München

H. Ritter, WS 15/16, LMU München, WS 16/17, LMU München

A. Weiss, WS 2015/2016 and SS 2016, LMU München

3.4.2 Short and public lectures

T. A. Enßlin: "Information Theory and Signal Reconstruction"
LMU Seminar at MPA, (Garching, 23.6.–24.6.)

H.-Th. Janka, "Supernova Theory" (Doctoral Training Programme, ECT* Trento, 20.6.–24.6.)

S. Saito: "Galaxy clustering in redshift space", Postdoc/Staff Lecture Series on
Cosmology at MPA, (Garching, 8.6.)

H. Spruit: "Introduction to MHD" (IKI International school for young astronomers, Tarusa, 7.9.–11.9.)

R. Sunyaev: – Oskar Klein Memorial Lectures (Stockholm, 4.2.)
– Stephen Murray Distinguished Lecture, HEAD Harvard-Smithsonian Center for Astrophysics (Cambridge, USA, 28.9.)
– Distinguished Visitor Lecture, Haverford College (Pennsylvania, 22.9.)
– Mohler Prize Public Lectures (Univ. of Michigan, 7.10.)

S. White: Gold Lecture at Cornell University (Ithaca, New York, 24.4.-29.4.)

4 Personnel

4.1 Scientific staff members

Directors

E. Komatsu (Managing Director), G. Kauffmann, R. Sunyaev, S.D.M. White.

Research Group Leaders

E. Churazov, B. Ciardi, T. Enßlin, M. Gilfanov, H.-Th. Janka, T. Naab, E. Müller, S. Suyu (since 18.1.), S. Vegetti.

External Scientific Members

M. Asplund, R. Giacconi, R.-P. Kudritzki, W. Tscharnuter.

Emeriti

H. Billing († 4.1.2017), W. Hillebrandt, R. Kippenhahn, F. Meyer, E. Trefftz.

Associated Scientists:

U. Anzer, G. Börner, G. Diercksen, W. Kraemer, E. Meyer–Hofmeister, H. Ritter, J. Schäfer († 25.8.2016), H. Spruit, R. Wegmann.

Staff/Postdoc

N. Amorisco, M. Anderson, Y. Bahe, A. Barreira, S. Campbell, R. D'Souza (22.4.-21.5.), G. Di Bernardo (until 30.9.), F. Durier (since 1.8.), R. Bieri (since 17.10.), H.L. Chen (1.9.-31.12.), C.T. Chiang (1.7.-31.8.), M. Compostella (until 30.4.), G. Despali (since 1.1.), F. Elsner (since 1.10.), M. Gabler, A. Gatto (1.2.-29.2.), E. Gatuzz, P. Girichidis (until 31.8.), F.A. Gomez, F. Guglielmetti, J. Guilet, A. Halle (since 17.10.), K. Helgason, C.J. Hu (1.5.-31.8.), A. Jerkstrand (since 11.9.), A. Jones, O. Just, R. Kazeroni (24.11.), I. Khabibullin (since 1.10.), S. Komarov (1.11.-31.12.), N. Lyskova, T. Melson (since 1.11.), M. Molaro (1.6.-31.10.), A. Monachesi, D. Nelson, M. Nielsen (until 29.2.), U. Nöbauer, Th. Peters, M. Reinecke, F. Schmidt, X. Shi, M. Soraisam* (1.6.-31.8), C. Spiniello (until 14.11.), A. Summa, X.P. Tang, S. Taubenberger, M. Viallet (until 30.4.), A. Weiss, A. Yildirim (since 1.10.), C. Zhang (since 27.9.), W. Zhang.

Ph.D. Students

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A. Agrawal*, H. Andresen*, V. Böhm*, R. Bollig, A. Boyle*, M. Bugli*, Ph. Busch*, C.Y Chao (since 9.11.), H.L. Chen (until 30.8.), C.T. Chiang (until 30.6.), G. Chirivi (since 15.11.), A. Chung* (until 28.2.), D. D'Souza* (until 31.3./terminated), R. D'Souza* (until 21.4.), L. Di Mascolo* (since 1.10.), M. Eide*, T. Ertl (until 31.12.), M. Frigo*, A. Gatto* (until 31.1.), R. Glas (since 1.7.), M. Glatzle (since 15.11.), M. Greiner, W. Hao* (until 31.5.), J. Higl* (since1.4.), C.H. Hu* (until 30.4.), H.Y. Ip*, I. Jee, A. Jendreieck (30.6.), S. Jia (until 10.12.), A. Jörgensen* (since 1.9.), K. Kakiichi* (21.11.), J. Knollmüller (since 1.10.), S. Komarov* (until 31.5.), T. Lazeyras, R. Leike (since 15.10.), Q. Ma, T.

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[1] *IMPRS Ph.D. Students

Melson (until 31.10.), M. Molaro* (until 31.5.), M. Nguyen* (since 1.10.), A. Pardi*, N. Porqueres* (since 1.9.), D. Pumpe (since 1.5.), F. Rizzo (since 1.11.), B. Röttgers, M. Rybak*, A. Schmidt, M. Soraisam* (until 31.5.), T. Steininger (since 1.4.), G. Stockinger (since 1.1.), J. Stücker*, C. Vogl (since 1.10.), D. Vrbanec*, G. Wagstaff*, Luo Yu (until 17.4.).

Master students

C. Bordihn (since 16.11.), R. Dehde (since 1.10.), M. Dupont (since 1.11.), A. Flörs (since 1.10), R. Glas (until 30.3.), M. Glatzle (until 30.9.), S. Hutschenreuter (since 22.2.), J. Knollmüller (until 30.9.) R. Leike (until 30.9.), S. Lietzau (since 1.1.), A. Maté (since 1.10.), M. Sraml (since 15.9.), M. Straccia (since 1.1.), C. Vogl (until 30.9.), F. Wichmann (since 1.9.),

Bachelor students

M. Almanstötter (4.4-12.10.), M. Baltac (2.5.31.10.), H. Bauch (22.8.-31.12.), M. Fleischmann (25.4.-31.8.), M. Kurthen (26.4.-26.10.),

Technical staff

Computational Support: H.-A. Arnolds (head of the computational support), A. Breitfeld (since 12.9.), B. Christandl, H.-W. Paulsen (until 31.12.), A. Weiss.

Public relation: H. Hämmerle (MPA and MPE)

Secretaries: M. Depner, S. Gründl, G. Kratschmann, C. Rickl, S. Veith.

Library: C. Bartels (head of the library), E. Blank.

4.1.1 Staff news

Thomas Ertl and Chia-Yu Hu were awarded the Kippenhahn Prize 2015 for the two best scientific papers written by a student.

Marat Gilfanov has been elected as a corresponding member of the Russian Academy of Sciences.

Jérôme Guilet received an ERC starting grant.

Hans-Thomas Janka was appointed as extraordinary Professor at the Technische Universität München.

E. Müller was appointed as extraordinary Professor of Physics faculty of the Technische Universität München.

Fabian Schmidt has been appointed to the Young Academy at the Berlin-Brandenburg Academy of Sciences (BBAW) and the German Academy of Sciences Leopoldina.

Rashid Sunyaev received the Oskar Klein Medal (Royal Swedish Academy of Science and Stockholm University)

Sherry Suyu has started as a new Max Planck Junior Research Group leader at the beginning of 2016.

4.2 PhD Thesis 2016 and Master thesis 2016

4.2.1 Ph.D. theses 2016

Hailiang Chen: Modelling accreting white dwarf populations in galaxies. Ludwig-Maximilians-Universität, München.

Andrew Chung: The long and winding road: Lyman-alpha radiative transfer and galactic outflows. Ludwig-Maximilians-Universität, München.

Richard D'Souza: Stellar haloes of galaxies. Ludwig-Maximilians-Universität, München.

Sebastian Dorn: Bayesian inference of early-universe signals. Ludwig-Maximilians-Universität, München.

Elisabeth Gall: Application of the Expanding Photosphere Method to distant supernovae. Queens University Belfast.

Andrea Gatto: The impact of stellar feedback on the formation and evolution of molecular clouds. Ludwig-Maximilians-Universität München.

Maksim Greiner: Signalrekonstruktion in der Radioastronomie - Signal inference in radio astronomy. Ludwig-Maximilians-Universität, München.

Chia-Yu Hu: Star formation and molecular hydrogen in dwarf galaxies. Ludwig-Maximilians-Universität, München.

Koki Kakiichi: The high redshift universe: galaxies and the intergalactic medium. Ludwig-Maximilians-Universität, München.

Sergey Komarov: Thermal conduction in host gas of galaxy clusters. Ludwig-Maximilians-Universität, München.

Tobias Melson: Modeling neutrino-driven core-collapse supernova explosions in three dimensions. Technische Universität München.

Margherita Molaro: Modelling the interaction of X-rays with the interstellar medium. Ludwig-Maximilians-Universität, München.

Monica Soraisam: Novae - a theoretical and observational study. Ludwig-Maximilians-Universität, München.

4.2.2 Master theses 2016

Robert Glas: Multidimensional Two-Moment Neutrino Transport Scheme for Core-Collapse Supernovae: Implementation and Tests. Technische Universität München.

Martin Glatzle: Implementing dust in CRASH. Technische Universität München.

Jakob Knollmueller: Bayesian Component Separation. Ludwig-Maximilians-Universität, München.

Reimer Leike: Operator formalism for information field theory. Ludwig-Maximilians-Universität, München.

Christian Vogl: Towards Distance Determinations of Type II-P Supernovae by Spectral Fitting. Technische Universität München.

4.3 Visiting scientists

Name	home institution	Duration of stay at MPA
Mitch Begelmann	(Univ. Colorado Boulder, USA)	31.5.–10.7.
Andrey Belyaev	(Herzen Univ., St. Petersburg, Russia)	1.10.–31.10.
Ilfan Bikmaev	(Kazan Federal Univ., Rep. Tatarstan)	2.11.–16.11.
Brian Chaboyer	(Astron. Dept., Dartmouth, Hanover, USA)	20.6.–23.7.
James Hung-Hsu Chan	(ASIAA, Taipei, Taiwan)	since 1.3.
Prakriti Choudhury	(Indian Inst.of Science, Bangalore)	since 1.10
Rafael de Souza	(MTA-ELTE, Budapest)	28.10.–27.11.
Ryan Endsley	(Washington Univ., USA)	until 31.7.
Ilkham Galiullin	(Kazan Fed. Univ. Rep. Tatarstan)	11.7.–11.8.
Angela Gui	(Caltech, Pasadena, USA)	11.6-31.8.
Michal Hanasz	(Nicolaus Copernicus Univ., Torun, Poland)	22.1.–21.2. and 16.6.–16.7.
Ildar Khabibullin	(Space Res. Inst. RAS, Russia)	1.3.–31.2. and 1.6.–31.7.
Rishi Khatri	(Tata Inst. Fund. Res., Mumbai, India)	12.6.–9.7.
Alex Kolodzig	(Kavli Inst. Peking, China)	12.3.–10.4.
Christina Kreisch	(Washington Univ., USA)	until 31.7.
Chervin Laporte	(Columbia Univ., USA)	1.9.–3.10.
Andrei Lazanu	(Univ. of Cambridge, U.K.)	9.5.–20.5.
Paolo Mazzali	(Liverpool John Moores Univ., U.K.)	15.8.–15.10.
Marcello Musso	(Univ. of Pennsylvania, Philadelphia, USA)	1.9.–30.11.
Ken'ichi Nomoto	(IPMU, Tokyo, Japan)	24.7.–16.9.
Martin Obergaulinger	(Valencia Univ., Spain)	14.3.–1.4. and 1.8.–31.8.
Igor Ognev	(State Univ. Yaroslavl, Russia)	15.9.–15.12.
Igor Ovchinnikov	(UCLA, Los Angeles USA)	16.7.–31.7.
Supratik Pal	(ISICAL, Kolkota, India)	6.7.–30.9.
Talytha Pereira Barbosa	(Univ. Sao Paulo, Brazil)	6.1.-25.2. and 15.10.–31.10.
Elena Pian	(Univ. of Pisa, Italy)	15.8.–15.10.
Yuxiang Qin	(Melbourne Univ., Australia)	1.10.-29.10.
Mika Rafieferantsoa	(Astron. Observ., South Africa)	unitl 20.11.
Sergey Sazonov	(Space Research Inst., Moscow, Russia)	21.6.–12.7.
Aldo Serenelli	(ICE, Carer de Can Magrans, Spain)	1.3.–31.3.
Nikolai Shakura	(Sternberg Astron. Inst., Moscow)	2.11.–2.12.
Nassim Tanha	(Univ. Cologne, Germany)	23.10.–5.11.
Nicole Thomas	(Univ. of Cape Town, South Africa)	16.10.–29.10.
Todd Thompson	(The Ohio State Univ. USA)	7.6.–6.7.
Grigori Uskov	(Kazan Fed. Univ. Rep. Tatarstan)	11.7.–11.8.
Victor Utrobin	(ITEP Moscow, Russia)	17.10.–17.12.
Annop Wongwathanarat	(RIKEN Inst., Japan)	2.5.–24.6.
Lev Yungelson	(Inst. of Astron. RAS, Russia)	12.9.–8.10.
Yuxiang Qin	(Univ. of Melbourne, Australia)	1.10.–31.10.