MAX PLANCK INSTITUTE FOR EXTRATERRESTRIAL PHYSICS

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Space Technology and Basic Research

A brief glimpse into the Max Planck Institute for Extraterrestrial Physics

Over the course of the past few decades astronomy has developed into a central pillar of contemporary physics. In no other research area has our horizon broadened as quickly, and in no other branch of physics is the interest of the public as great as in astronomy. Black holes, dark energy, dark matter, extrasolar planets – the recent big discoveries have given us a new picture of the Universe. At the front line of contemporary astronomical research is the Max Planck Institute for Extraterrestrial Physics (MPE) in Garching near Munich, Germany. Founded in 1963, today it occupies a key international position in experimental astrophysics.

The institute is part of one of the largest conglomerations of outstanding astrophysical research centres in Europe. Situated next to MPE, and working in close collaboration with it, are the European Southern Observatory (ESO), the Max Planck Institute for Astrophysics (MPA), and the Excellence Cluster "Origin and Structure of the Universe". Together with the Technical University of Munich, the Max Planck Institute for Plasmaphysics (IPP), and the Max Planck Institute for Quantum Optics (MPQ), the Garching campus represents one of the largest science centres worldwide.

THE INSTITUTE

Research topics at MPE range from the physics and chemistry of stars and interstellar matter, exotic objects such as neutron stars and Black Holes, to nearby and far away galaxies. These are pursued mainly using experimental and observational methods that span over twelve decades of the electromagnetic spectrum. Scientific work is carried out within four major groups, each overlooked by one director: Infrared and Sub-millimetre/Millimetre Astronomy, Optical and Interpretative Astronomy, High-Energy Astrophysics, and the Centre for Astrochemical Studies.

MPE's name originates from both its areas of research and the instrumentation used, which once were both exclusively extraterrestrial. Today, parts of the work are done on Earth, either in laboratories or with ground-based telescopes, but many experiments still have to be carried out without the distortions from the Earth's dense atmosphere using aircraft, rockets, and space probes. The excellent reputation of the institute is mainly due to the innovative high-tech instrumentation often developed and built in-house in our own workshops. In order to perform extensive tests, the institute maintains not only its own test laboratory, an integration hall and a cleanroom, but also the PANTER X-ray test facility with a 130m long vacuum tube. Experimental development is complex and takes time, and as a result many of the engineers and project scientists of the institute are employed long-term or hold permanent positions at MPE. With about 400 employees, MPE is the largest of all astronomical institutes of the Max Planck Society.

THE INSTITUTE

Already within the first few years of its foundation by Reimar Lüst in 1963, the institute began to establish its reputation as an outstanding manufacturer of instruments. For example, in the 1960s MPE built an instrument for AZUR, the first German spacecraft, launched in 1969. Over the following decades it developed into a widely respected global player of innovative technology development for scientific instruments. The highlight of the 1990s was the launch of the X-ray satellite ROSAT, which brought MPE world-fame and had a lasting impact on a wide range of astronomical fields. With its plasma experiment PKE-Nefedov, MPE opened the era of scientific experiments on the International Space Station (ISS) in 2001. The PACS project – MPE's contribution to ESA's Herschel Space Observatory – was of similar importance to ROSAT from 2009 - 2013.

MPE research is performed using instruments that the institute develops either independently or together with other institutions, often taking on a leading role. Theoreticians, observers, experimenters, engineers, and technicians at MPE work closely together. This close internal cooperation is very efficient, and forms the basis for the success of the institute's research projects. Close collaboration with other top research facilities is also a very important aspect of MPE's success, both on a national and an international level.

THE INSTITUTE

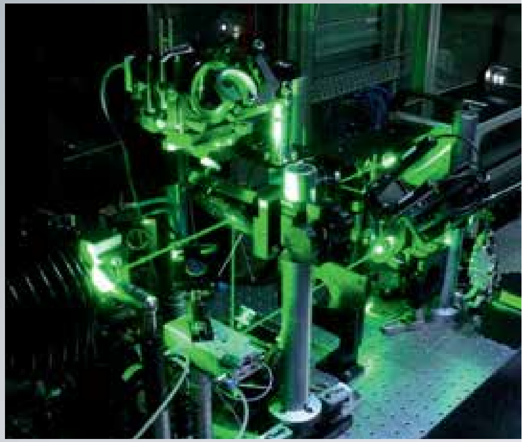
Indeed, especially for space projects, the size and complexity of instruments often requires different institutes to work together. Both in science and in technology the institute has an excellent reputation: according to citations, MPE ranks among the leading institutes in space science worldwide; some of the most cited space scientists in Europe work at MPE.

The scientific excellence of the institute is due to its outstanding scientific and technical staff, and its highly gifted young students and postdocs. In the year 2000, the "International Max Planck Research School" (IMPRS) on Astrophysics at the Ludwig Maximilian University Munich was founded by MPE, together with the MPI for Astrophysics, the Observatory of the Ludwig Maximilian University, and the European Southern Observatory. Open to students from all countries, the school attracts highly qualified and motivated young people who are aiming for a graduate degree in Physics and Astronomy. About 75 PhD students follow a joint set of courses and carry out research projects within the four institutes. The students conduct their graduate studies in a very stimulating environment and have the opportunity to develop a broad background in astrophysics beyond their own dedicated research projects. Many former MPE students have become respected members of the scientific community or occupy leading positions in industry today.

THE INSTITUTE

The training of young people is vital for maintaining the excellence of research at the institute. To attract young researchers, university and high-school students are incorporated into research projects through internships; additionally MPE supports vocational training of young people in its technical departments. The institute also actively encourages more women to consider a career as a scientist, engineer or technician. In particular, since 2008, MPE participates in the national initiative "Girls' Day" and offers a special "children's programme" on the bi-annual Open House. This has been so popular that it has led to other institutes starting similar initiatives.

Besides these major events, the institute carries out a broad range of public relations activities: guided tours for school classes and groups, regular news and press releases on the website, internal and external talks, as well as taking part in exhibitions. With these activities the institute aims to engage, in particular, young people and to arouse their enthusiasm for astrophysics. Another large outreach project is the cosmology exhibition at the Deutsches Museum in Munich, which MPE has developed together with MPA, MPP, ESO and the Excellence Cluster Universe. It takes visitors on a journey through time, from the Big Bang to the present and even the future, forecasting what may happen to our Universe eventually.



Future developments at the institute will continue to be influenced by constant changes in research areas and facilities. Observational astronomy from high energies to optical and millimetre wavelengths will remain the focus of the institute. More emphasis will be placed on tackling astronomical themes with observations from across the complete electromagnetic spectrum and combining them with observation-based theory.

MPE has a bright future: The X-ray satellite eROSITA – currently under construction – will soon be launched to perform the first imaging all-sky survey at medium X-ray energies. This will shed light on the origin of the mysterious Dark Energy. Meanwhile, the next generation X-ray observatory ATHENA is already in its design phase. At visible and near-infrared wavelengths, MPE and other European scientists have proposed the EUCLID mission to study the "Dark Universe" from space. These projects are complemented by ground-based observatories such as the Large Binocular Telescope, where our first instruments are in use. Instruments designed for the world's largest optical telescope, the ESO VLT, are well underway, especially GRAVITY, which will enable us to use the four telescopes simultaneously as an interferometer. For the next generation telescope, the European Extremely Large Telescope (E-ELT), MPE leads the development of the camera MICADO, which will record and analyse the "first light" of the E-ELT.

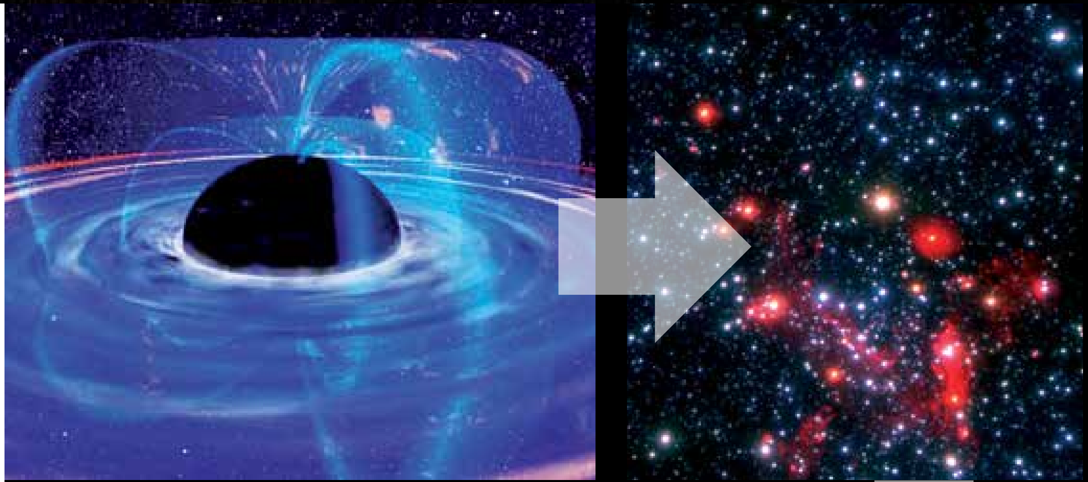
Science at MPE

Even though the past decades have seen big advances in astronomy, important questions remain unanswered: Do we understand the extremes of the Universe? How do galaxies form and evolve? What are Dark Matter and Dark Energy and how do they influence the evolution of the Universe?

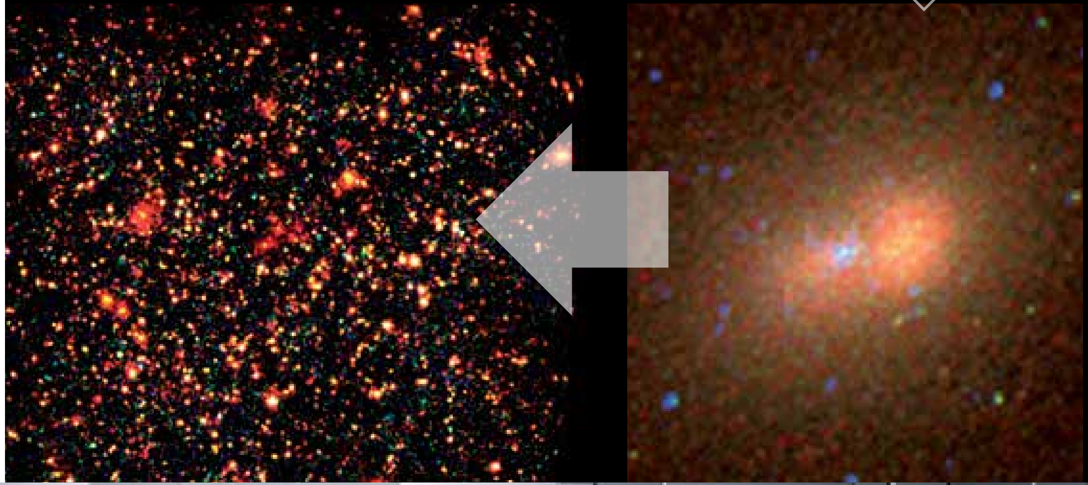
At MPE we tackle these and other open questions by focussing on two key scientific themes: Black Holes and galaxies. Black Holes are extreme objects in space which can be found both as remnants of burnt-out stars and as huge mass concentrations at the centres of galaxies. The galaxies as a whole and their evolution can tell us about the history of the Universe and thus help to address cosmological problems.

Three out of four groups at MPE do research on these topics across the entire electromagnetic spectrum, in combination with observation-based theory. Results obtained in one wavelength band can be crosschecked with findings from other bands and thus confirm our assumptions about the physical processes in the Universe.

Objects are studied both individually and in detail within our nearby environment and also as a general class of objects deep in space, often studied statistically. Since in astronomy distance means looking back in time (due to the finite speed of light) we can trace the history and evolution of these objects and – at least in some respects – the history of the Universe as a whole.



Black Holes are one of the main research themes at MPE. These extreme objects are the burnt-out remnants of exploded stars, and are studied locally in the centre of our own Milky Way, in nearby galaxies, and in far away galaxies that formed when the Universe was in its infancy.



Scientists at MPE observe astronomical objects in many different wavelength bands and use instruments that are mounted on Earth as well as on satellites, and which are often built in-house. In addition, physics experiments are conducted in the laboratory for a better understanding of our astrophysical findings.

From our detailed studies of Black Holes in our Milky Way and nearby galaxies, we can, for instance, predict the observational signatures of these objects from the distant Universe. While "local" observations are mainly carried out in infrared and optical wavebands, the globally summed signal of Black Holes reaches us as a diffuse X-ray background. The fact that our local estimates from rather soft radiation agree surprisingly well with measurements of hard radiation from far-away objects gives us confidence in the reliability of our current knowledge about the Universe.

Since 2014 the astrophysical research at MPE has been supplemented by astrochemistry, which combines observations with telescopes, laboratory work, theory and simulations within a single group. Researchers study the birth of stars and planets, i.e. young planetary systems, in our Milky Way, especially on a molecular level. This enables us to understand more clearly, not only the formation of our solar system, but also the origin of complex organic molecules – the building blocks of life – in comets and asteroids.

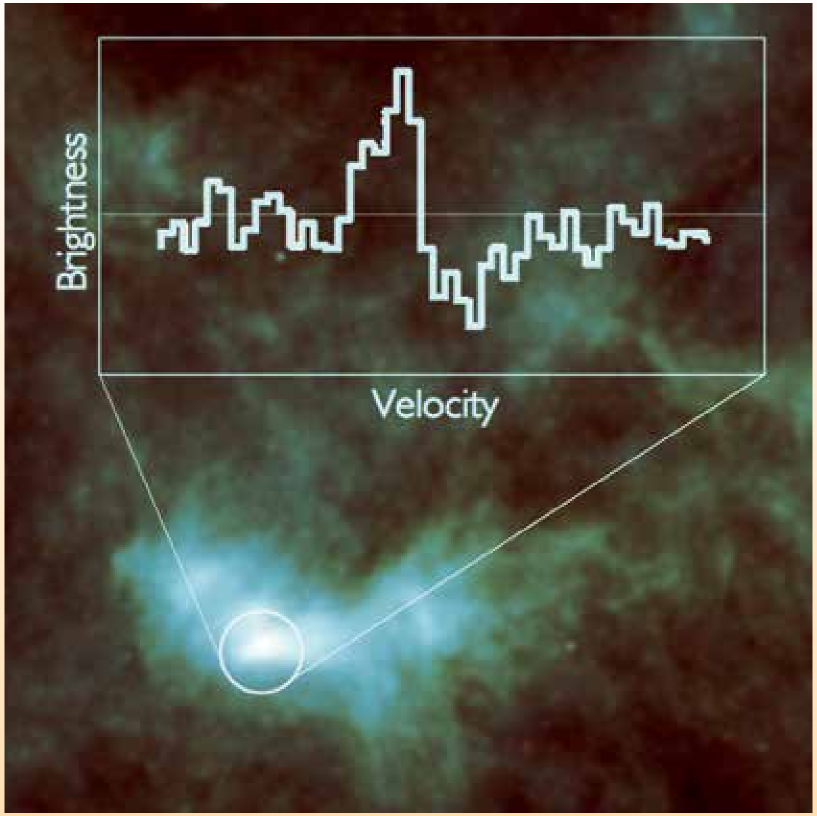
MPE´s astronomical groups work hand in hand, taking advantage of the specific and unique information reaching us at different wavelengths, to jointly explore the Universe as a whole.

Astrochemistry – a Jigsaw Puzzle

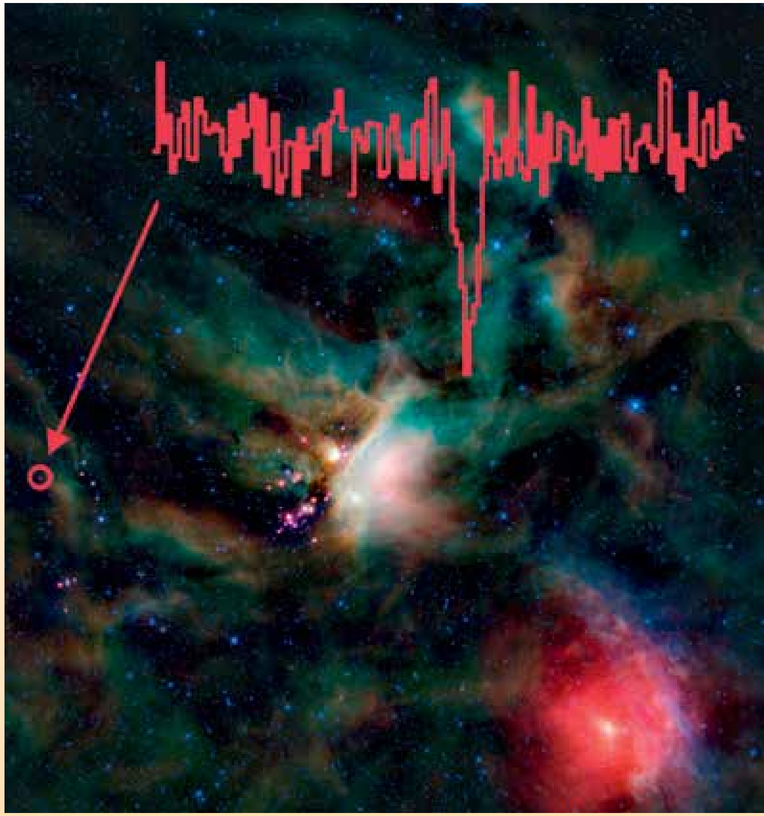
Dense clouds of gas and dust are a prerequisite for the formation of new stars and planets. These clouds have to be dense and massive, but also very cold – otherwise the pressure of the (warm) gas would be too high for gravitational collapse. These giant molecular clouds have a temperature of only about 10 Kelvin (or about –260°C), while the interstellar gas is comparatively "warm", with a temperature of about 100 Kelvin (or some –170°C).

The clouds' ingredients are mainly molecular hydrogen, with some atomic hydrogen, other simple molecules such as carbon monoxide, water ice, and traces of more complex organic compounds (such as methanol) mixed in. In addition, these clouds contain about 1% interstellar dust, which plays a special role.

This dust blocks the high-energy radiation from nearby stars and thus allows complex organic molecules to form. In part, the molecules can even form onto and/or attach themselves to the dust grains, leading to a very complex composition and structure of the cloud. Sensitive instrumentation is needed to observe this.



For the first time, the "fingerprint" of water was detected in this pre-stellar core L1544 located in the constellation Taurus. In addition, more complex molecules may be formed by the combined effects of dust grains and energetic radiation from nearby stars.



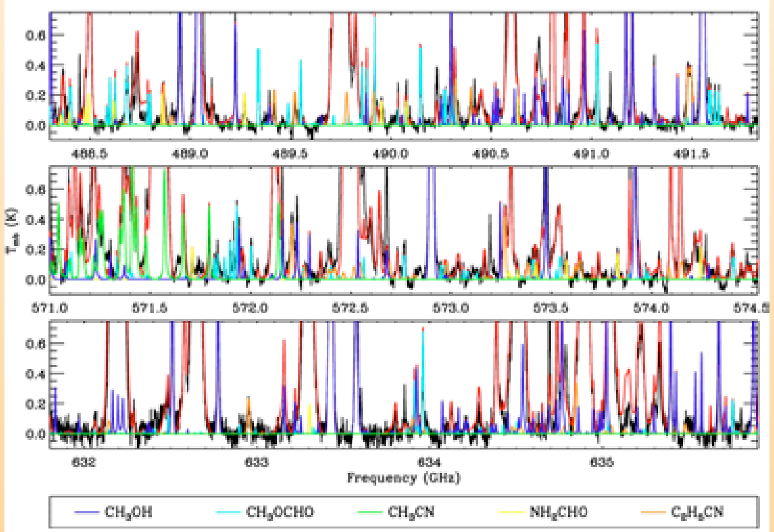
This false-colour infrared image shows the Rho Ophiuchus star-forming complex at a distance of some 400 light years from Earth. The signal from a particular hydrogen molecule in the cold cloud of molecular gas and dust around a young triple proto-star system allowed the scientists to determine its age: dense cloud cores, where stars form, are at least one million years old.

STELLAR BIRTH

To observe stars and planetary systems in their early stages, astronomers at MPE use special telescopes for radio, submillimetre and infrared wavelengths as these clouds are too cold and dense to be observable with optical telescopes. It is a challenge for the researchers to find exactly the right wavelengths for optimal observations of the clouds' radiation.

What's more, only certain (complex) molecules have observable emission lines so that a basic knowledge of chemistry is needed to understand the results. The radiation from various molecules overlaps and these signatures have to be disentangled to learn more about the complex chemistry, the effects of magnetic fields and turbulence, and the detailed conditions for star and planet formation. Such astrochemical studies – in theory, in the laboratory, and with observations – are carried out by the CAS group at MPE.

Many molecules in star forming regions emit radiation at radio wavelengths. Once completed, NOEMA will consist of twelve 15-metre radio antennae dishes (as shown in this montage). MPE astronomers use this facility together with other observatories, such as ALMA, to observe the cold gas in galaxies.



In the spectrum of a star forming region, the "fingerprints" of many molecules overlap, simulated here for a cold, dense molecular cloud in our Milky Way.

"Here, we bring together expertise from theory, laboratory and observations which will enable us to bridge the gaps in our knowledge of the various stages in the formation of stars like our Sun and planets like our Earth. At the same time, we follow the evolution of chemical complexity through time."

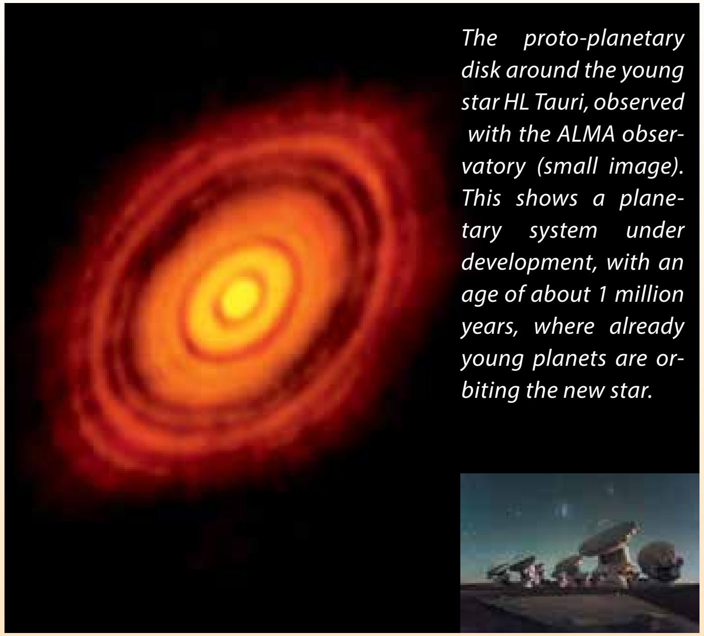
Paola Caselli, MPE director and head of the group 'Centre for Astrochemical Studies'

STELLAR BIRTH

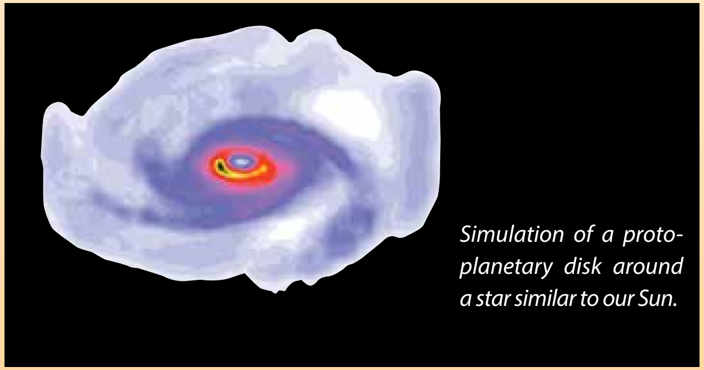
Cosmic Recycling

In principle, the steps leading to the formation of a new star are well understood: interstellar clouds of gas and dust are not distributed homogenously in space but reside predominantly in the spiral arms of galaxies, where the gas has been enriched with heavy elements by previous generations of stars. These clouds are "clumpy", i.e. they contain regions with slightly higher density. Due to their own gravity, such a clump condenses and initially forms a "pre-stellar core", which condenses even further. Eventually a proto-star is born at its centre. At the same time, an accretion disk forms because the angular momentum of the interstellar material does not allow it to fall into the proto-star directly. Proto-planetary disks are therefore a natural by-product of star formation in this scenario. After a few million years, the proto-star has reached a critical density and temperature to ignite stellar fusion – a new star is born.

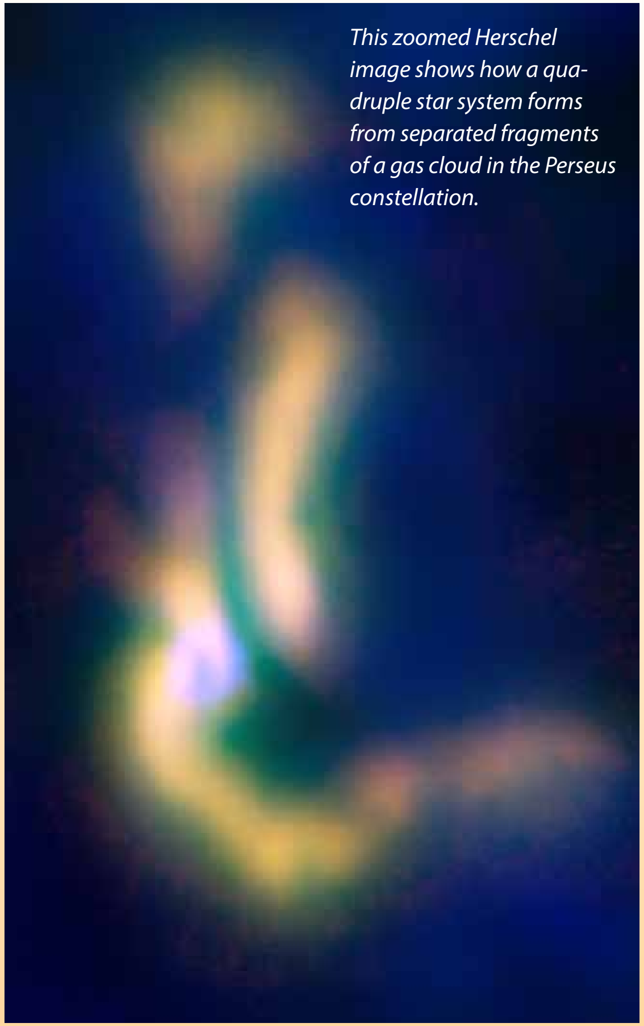
But how and when does a new star form in an interstellar cloud? What are the conditions, exactly? How does star and planet formation progress in detail? And how is it possible to observe these star forming regions? MPE researchers are finding and employing the best observing strategies to peer through the dense clouds of gas and dust.



The proto-planetary disk around the young star HL Tauri, observed with the ALMA observatory (small image). This shows a planetary system under development, with an age of about 1 million years, where already young planets are orbiting the new star.

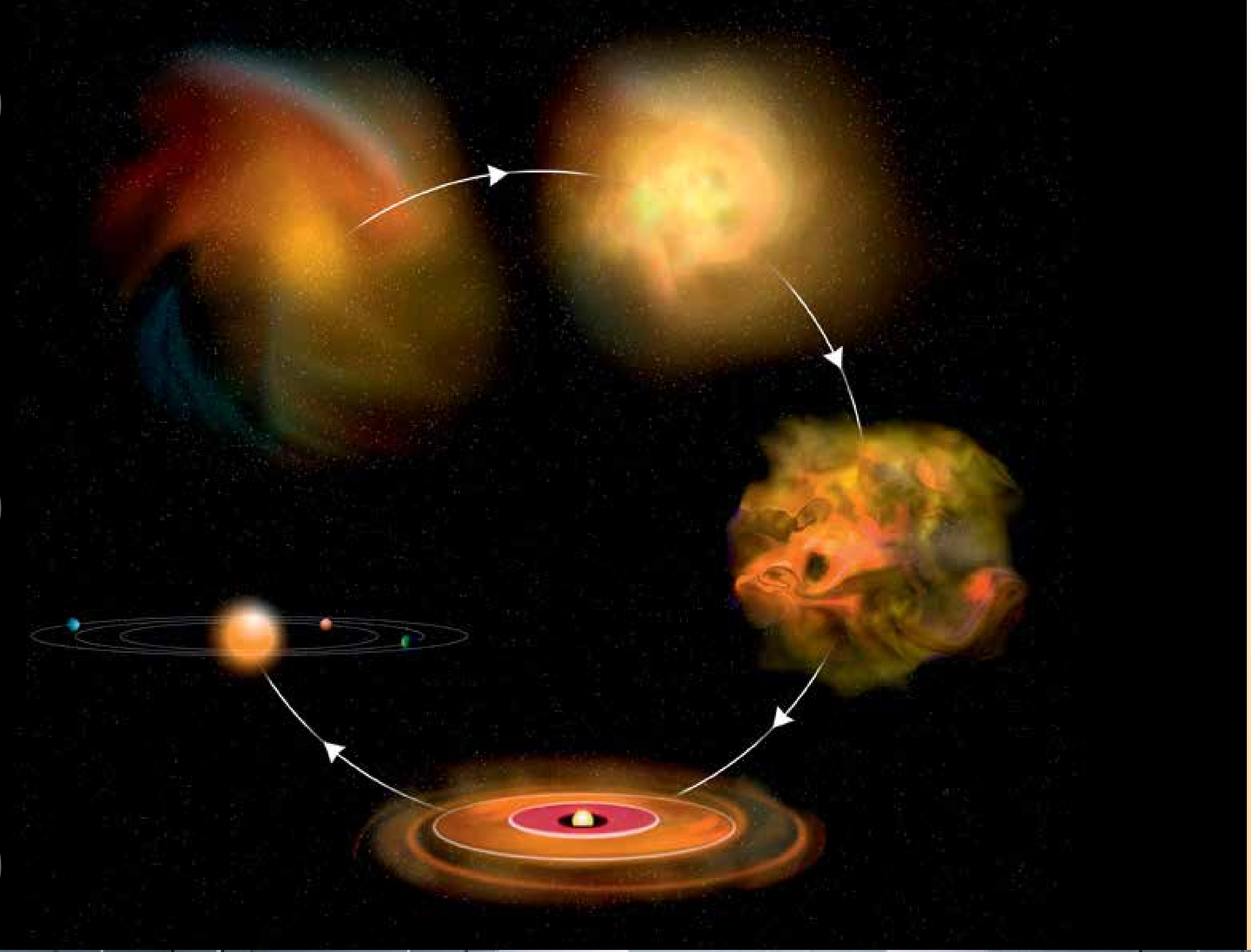


Simulation of a proto-planetary disk around a star similar to our Sun.



This zoomed Herschel image shows how a quadruple star system forms from separated fragments of a gas cloud in the Perseus constellation.

STAR FORMATION



Stars and planets form in diffuse gas clouds (top left), which condense (top right) to form a proto-star (middle) a proto-planetary disk (bottom) and finally a new planetary system. During their lifetime they fuse heavy elements and return these to their cosmic environment at the explosive end of their lives – for the next generation of stars.

Young Stars – Looking into the Nursery

Star formation usually takes place in dense clouds of gas and dust and is therefore hidden from observations at optical wavelengths. With infrared detectors, however, we can take a look inside these nurseries and observe the infant stars directly. With infrared imaging and spectroscopy, for example with Herschel/PACS, MPE scientists measure the physical and chemical structure and evolution of young stars, which gives us a better understanding of how they form.

Inside our Milky Way, we study the formation of individual stars. In other galaxies, we study star formation on a global, i.e. statistical, scale by looking for specific signatures in the galaxy images and spectra. These studies tell us about the star formation history of the Universe and the evolution of galaxies.

Two images of the same molecular cloud in the constellation Orion, a gigantic star forming region, which includes the "horse head nebula" to the right of the image. In optical light (top) the nebula is mainly dark, just a few new-born stars are visible. Infrared light, however, reveals the impressive inner structure of the cloud that has a shape moulded by stellar winds.

STELLAR BIRTH

↗ When dense gas clumps within interstellar clouds contract, nuclear burning ignites: a new star is born.

This infrared image taken by the Herschel Space Observatory shows the young star Fomalhaut and its surrounding dust disc.

The young Sun-like star Herbig Haro 46, observed with the Spitzer Space Telescope, gains matter by accretion but also ejects mass in a gas jet, showing the typical behaviour of "baby" stars.

Chaotic networks of dust and gas in the Cygnus-X star-formation region. The reddish-pink objects in this image are infant stars, uncovered by the infrared eyes of Herschel.

From Birth to Death – Stellar Evolution and the Interstellar Medium

The evolution and fate of stars, individually, as groups, and as entire populations, is intimately related to their interactions with the surrounding interstellar medium.

Stars are born in interstellar gas clouds. Dense clumps collapse under their own gravity, densities and temperatures rise until a critical point is reached to ignite nuclear burning, fusing hydrogen to helium: a new star starts to shine. For the majority of its lifetime the star then radiates with a roughly constant rate until its nuclear fuel is exhausted.

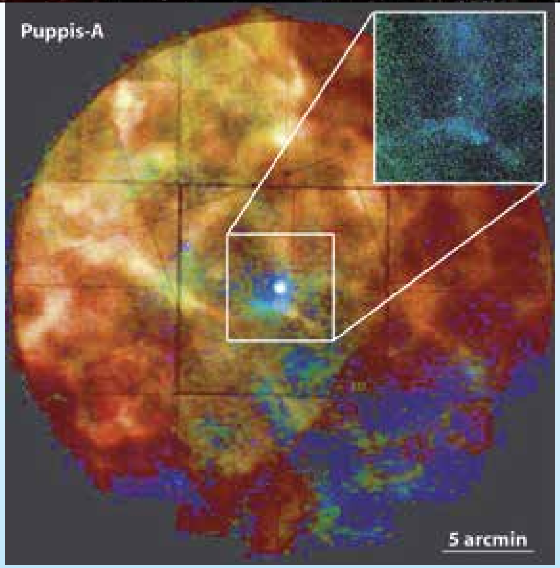
For low-mass stars, stellar evolution ends in a relatively quiet and peaceful manner as so-called white dwarf stars. High-mass stars end their lives in violent explosions – supernovae – resulting in neutron stars or Black Holes. In both cases, a large fraction of the stellar matter is ejected and recycled in the interstellar medium, forming the next generation of stars and smaller objects such as planets. Since heavier elements are only generated in stars, all the material that is important for the emergence of life, in particular carbon and oxygen, originates from dead stars.

The gas and dust of the interstellar medium play a key role in the formation of stars, but also in later phases of stellar evolution. How newly-produced elements from stellar winds and explosions are mixed with ambient gas and incorporated into the next generation of stars is still poorly understood.

This Hubble Space Telescope image of the Sagittarius star cloud, a rich star cluster in our Milky Way, shows many stars of different colours, representing different temperatures.

STARS

The supernova remnant Puppis-A as seen by the X-ray satellites XMM-Newton and Chandra (inset). About 5000 years ago a massive star collapsed and exploded in a supernova, leaving behind a gas cloud and a neutron star in the centre.



The planetary nebula M27 as seen with the Wendelstein observatory. An old star has blown its atmosphere into the interstellar medium, thereby enriching our Milky Way with freshly generated elements.

STARS

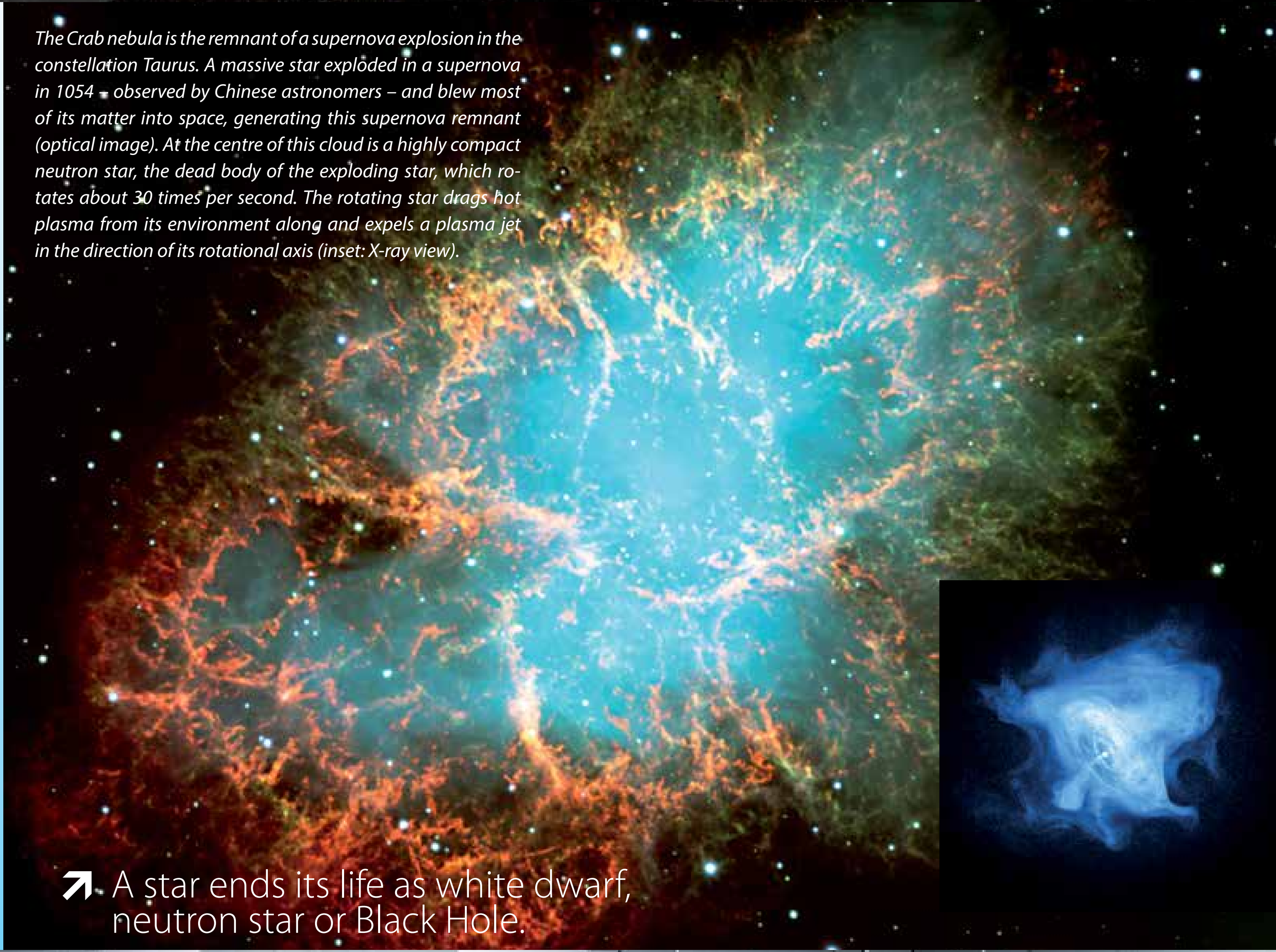
MPE's LUCI on the Large Binocular Telescope looks with its infrared instrument eyes through the dust curtain into the young star forming region Sh-2 255.

This Herschel image shows a sequence of star-forming regions in the molecular cloud W48. Here, star formation was probably triggered by an external event: dozens of supernovae that exploded over 10 million years ago.

Stellar Death – The Extreme Objects left behind

White dwarfs, neutron stars, and Black Holes are very dense stellar bodies that are the end products of the evolutionary stages of most stars. Due to the enormous gravitational and magnetic power near their surface, unusual physical processes become important around such objects. As these compact stellar remnants accrete matter, for example from a binary companion, the conversion of gravitational energy into radiation allows us to study them, primarily through high-energy emission in X- and gamma-rays. The accretion heats up the impact region and its surroundings, and may even lead to the acceleration of plasma in a jet outflow.

Analysing the high-energy emission of compact stellar objects allows us to determine their physical properties, such as type or mass, as well as the chemical composition, temperature, velocity, and density of the surrounding material. These results improve our understanding of the peculiar physics around these powerful objects governing accretion and particle acceleration.



The Crab nebula is the remnant of a supernova explosion in the constellation Taurus. A massive star exploded in a supernova in 1054 – observed by Chinese astronomers – and blew most of its matter into space, generating this supernova remnant (optical image). At the centre of this cloud is a highly compact neutron star, the dead body of the exploding star, which rotates about 30 times per second. The rotating star drags hot plasma from its environment along and expels a plasma jet in the direction of its rotational axis (inset: X-ray view).

↗ A star ends its life as white dwarf, neutron star or Black Hole.

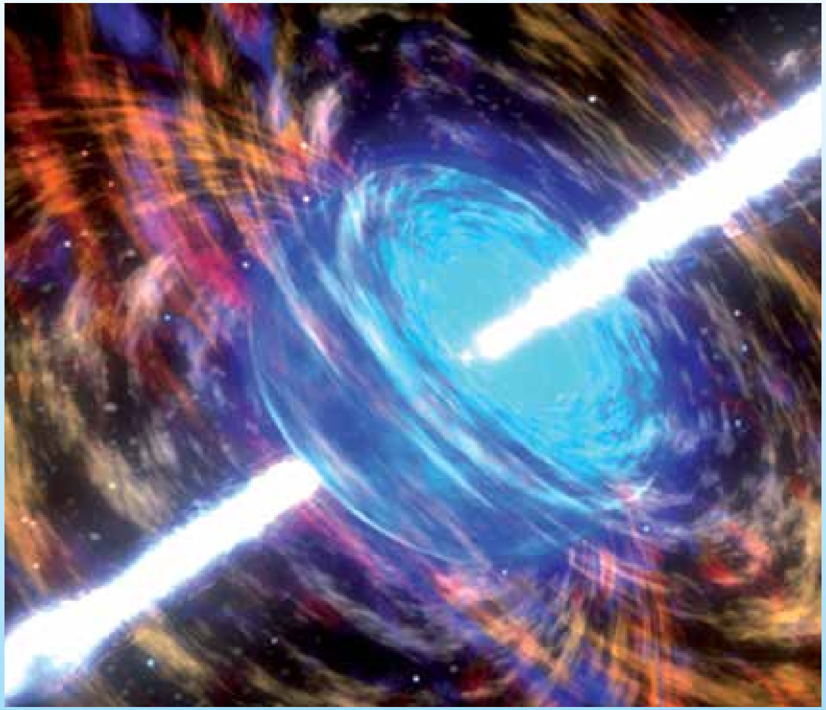
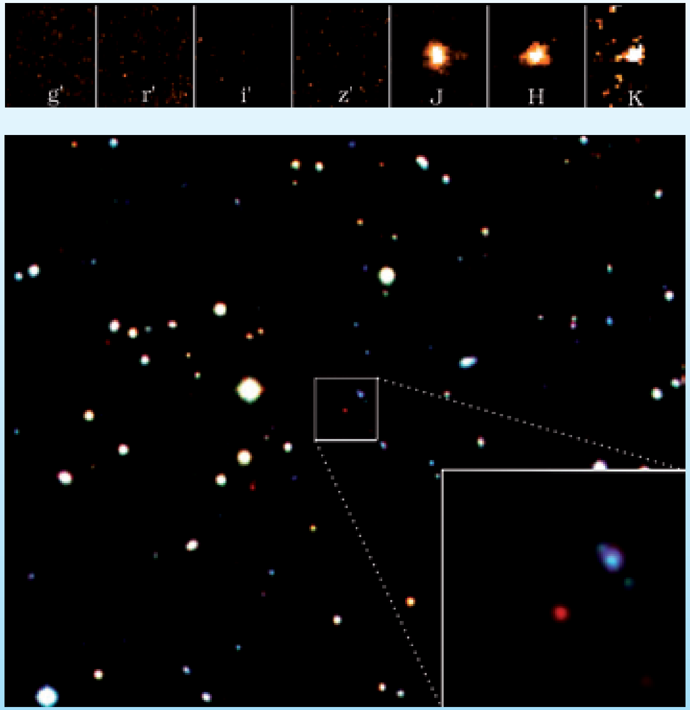


Illustration of a GRB scenario: a young and massive star ends its life by the implosion of its nuclear region into a Black Hole. A huge explosion and a fast plasma jet are generated, which provide the observable properties of the Gamma-Ray Burst.



The red object in this GROND image is the GRB of 23 April 2009, one of the most distant objects observed. By its appearance or absence in certain spectral bands (row of images above), its distance and thus its age can be estimated. The explosion occurred about 13.1 billion years ago, when the Universe was only about 5% of its current age.

Almost every day astronomers witness huge explosions occurring somewhere in the Universe. These explosions last only for a few seconds and are particularly visible at gamma-ray energies. These flashes – called Gamma-Ray Bursts or GRBs for short – are dramatic events: They are the brightest beacons in the Universe, visible from very large distances. Due to their enormous luminosities, GRBs regularly set new distance records.

Often these GRBs produce afterglow emission, which can be observed at X-ray, optical or near-infrared wavelengths. The most probable scenarios leading to a GRB are that a massive star explodes or two neutron stars merge in an explosion, in both cases producing a Black Hole.

↗ Gamma-ray bursts are the most gigantic explosions known in the entire Universe.

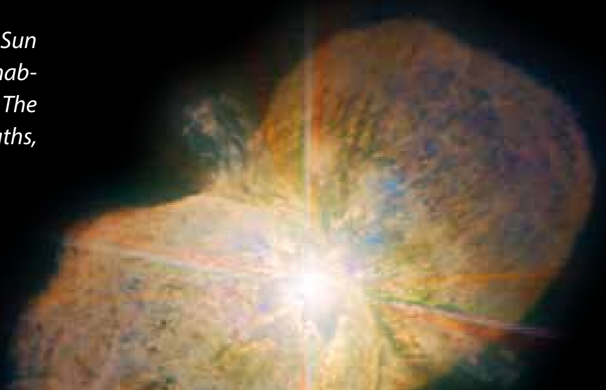
BLACK HOLES

Black Holes – light and heavy

Black Holes are mysterious objects in space that are composed of extremely compact matter. The gravitational force on their surface (respectively their "event horizon") becomes so strong, that nothing – not even light – can leave. The event horizon is a kind of "one-way street", where you can drive in only one direction: light and matter can enter, but they cannot get away.

Nonetheless, Black Holes often shine very bright; they generate lots of energy in a very small volume located just outside the event horizon. Matter falls onto the Black Hole, emitting its kinetic energy. Thereby the matter around the Black Holes is strongly heated up and radiates brightly into space.

Astronomers assume that Black Holes form, amongst other ways, when a very massive star collapses at the end of its life. The gravitational forces increase incredibly, so that no pressure prevents the collapse and the matter condenses almost infinitely. This is the scenario for the formation of "light" stellar Black Holes, with a mass of 5 to 20 times the mass of the Sun. Presumably quantum effects on very small scales prevent the collapse to a "zero-volume" inside the Black Hole.



The star Eta Carinae has about 100 times the mass of our Sun and is one of the most massive stars in our Milky Way. Presumably, it will explode in a hypernova and thus create a Black Hole. The picture shows the unstable star at near-infrared wavelengths, imaged by the ESO VLT.

An artist's impression of a close binary star system with a normal star and a Black Hole. The Black Hole collects matter from the normal star in an accretion disk. Due to heating, this matter shines brightly before it is swallowed by the Black Hole.

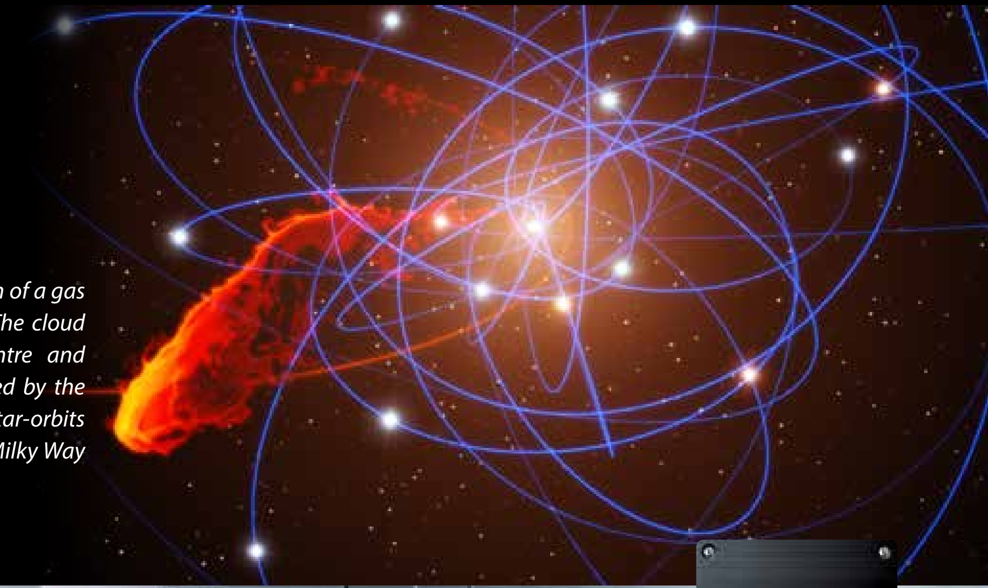
BLACK HOLES

The centres of galaxies harbour super-massive Black Holes, reaching a million to even several billion times the mass of our Sun. At present, their evolutionary history is not yet clear. Presumably the first stars in the Universe were frequently very massive, developed quickly, and created the first Black Holes. By accumulating surrounding matter, such as entire stars or gas and dust, they grew to their current size during the course of cosmic time.

At MPE, investigating Black Holes is an important topic. We are working on proving the existence of Black Holes in general as well as measuring the characteristics of both stellar and massive Black Holes.

An artist's impression of the centre of an active galaxy, a quasar. A massive Black Hole, possibly with a mass a billion times the mass of the Sun, attracts and swallows matter in the centre of the galaxy. This creates the typical properties observed in quasars.

Simulation of the Black Hole in the centre of our Milky Way, Sgr A, and the accumulated gas around it. The (invisible) Black Hole distorts space-time and causes light emitted by the gas behind the Black Hole to be deflected. In combination with the Doppler effect caused by the motion of the gas towards the observer, a characteristic arc forms, which is visible in this picture.*



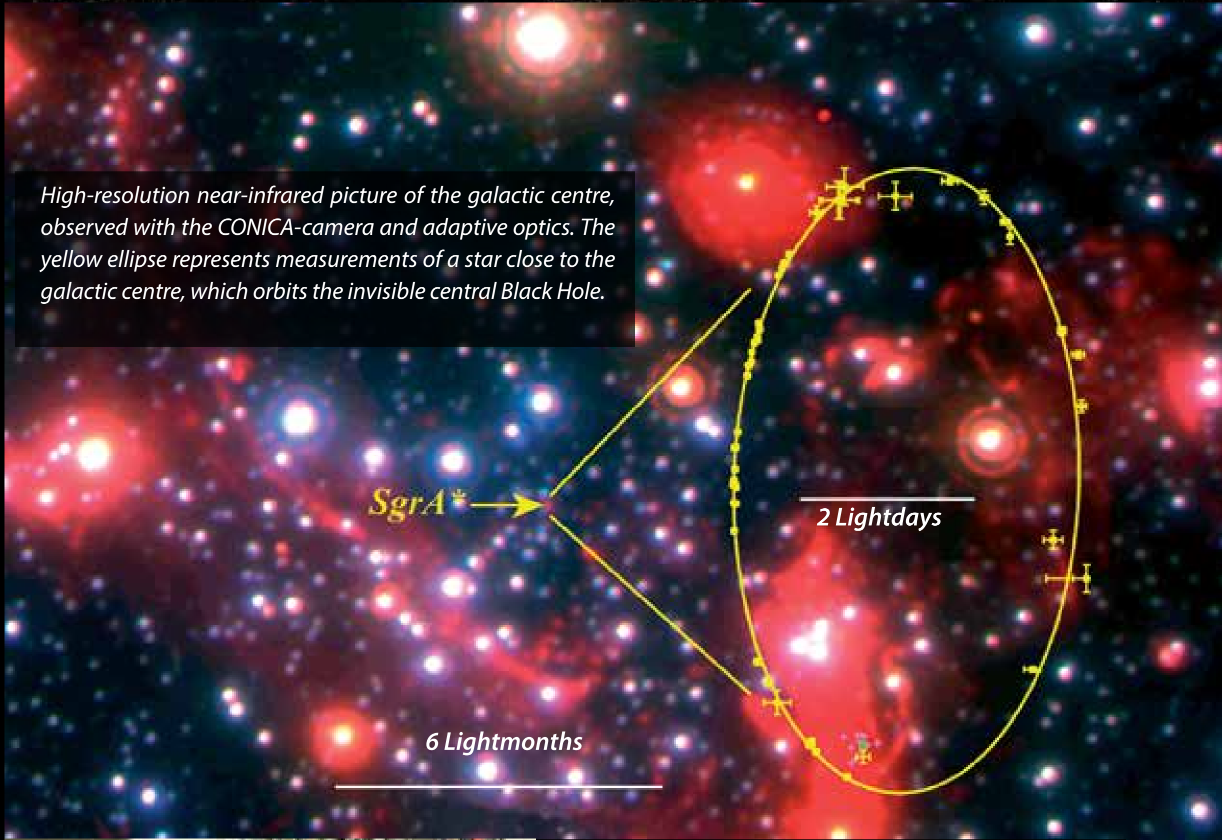
This simulation shows the path of a gas cloud in the galactic centre. The cloud approaches the galactic centre and a part of its mass is swallowed by the Black Hole. The measured star-orbits around the Black Hole in our Milky Way are illustrated in blue.

The Galactic Centre – a unique Laboratory

The closest galactic nucleus is the one in the galactic centre, the centre of our Milky Way, at a distance of "only" 25000 light years. Its relative proximity gives us the opportunity to study the detailed physical processes at play in the environs of a supermassive Black Hole. Research at MPE has centred on proving the existence of the Black Hole, and then deriving some of its properties. Since 1992, we have regularly observed the galactic centre in the near-infrared with high spatial resolution instruments that were designed and built for ESO telescopes with substantial contribution from MPE.

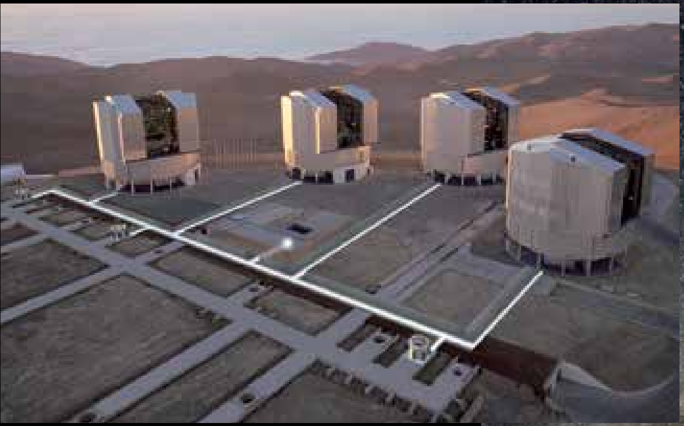
By measuring the positions of stars close to the galactic centre with extremely high accuracy, we showed that they move along Keplerian orbits around a central mass of about four million times the mass of our Sun. The innermost star comes as close as 18 light hours – about four times the orbital radius of the planet Neptune around the Sun – to this central mass. A Black Hole is the only viable explanation for such a high but invisible mass density, thus proving the existence of Black Holes in general. For this scientific result Prof. Reinhard Genzel was awarded the Crafoord-Prize in Astronomy by the Royal Swedish Academy of Science in 2012.

In order to measure the galactic centre with even higher precision, MPE is currently developing the instrument GRAVITY. It will combine the light of the four VLT telescopes as an interferometer leading to a significantly improved angular resolution. GRAVITY will allow us to peer all the way to the event horizon of the Black Hole, so that we can explore gravity near a singularity. In particular, we will be able to measure the quasi-periodic near-infrared flares in detail and thus test the limits of general relativity theory.

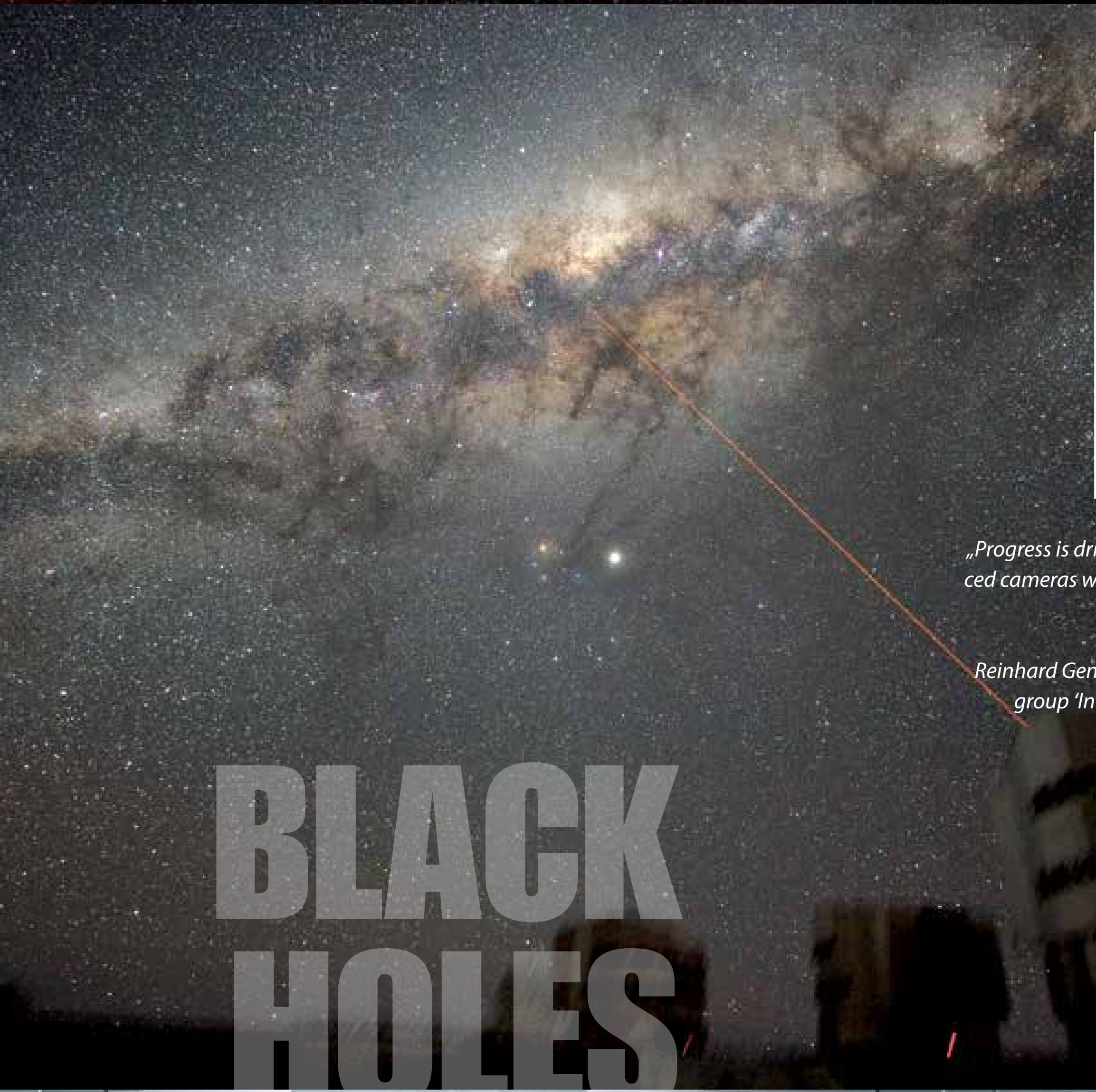


High-resolution near-infrared picture of the galactic centre, observed with the CONICA-camera and adaptive optics. The yellow ellipse represents measurements of a star close to the galactic centre, which orbits the invisible central Black Hole.

The MPE GRAVITY team in the laboratory. GRAVITY, encased in the cylindrical vacuum tank, is near completion and will soon be handed over to the ESO VLT. It will exceed the angular resolution of its predecessors by orders of magnitude.



The GRAVITY instrument will use the four ESO VLT telescopes shown here for interferometric imaging with unprecedented angular resolution.



„Progress is driven by experiments. With advanced cameras we can lift the curtain covering the galactic centre.“

Reinhard Genzel, MPE director and head of the group ‘Infrared/Submillimetre Astronomy’

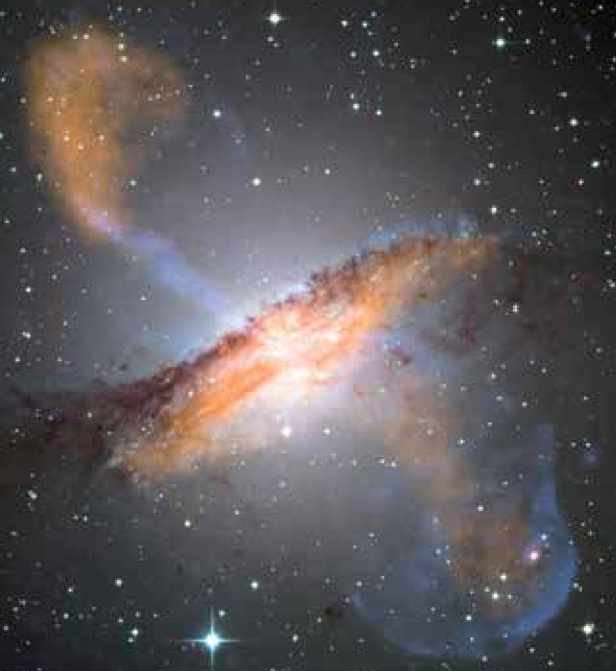
Active Galactic Nuclei – Monsters in Space

When massive Black Holes at the cores of galaxies become active, they can be very luminous and constantly vary their brightness. Some even become a trillion times more luminous than our Sun! The force powering this activity is the supermassive Black Hole, attracting the surrounding matter by its gigantic gravitational pull, accumulating it in an accretion disk and finally "swallowing" it. Once this happens, these objects radiate a measurable amount of energy across the entire electromagnetic spectrum, from radio up to gamma-ray energies.

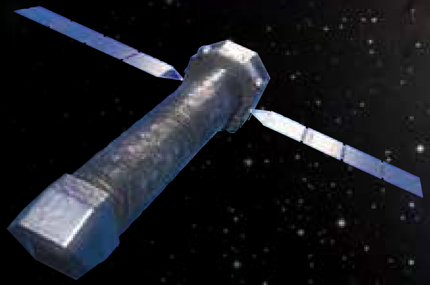
Many phenomena, such as the plasma jets expelled at nearly the speed of light, or the heating of the accretion disks, are still a mystery. The scientists at MPE try to understand these phenomena by using the currently active high-energy satellite missions, Chandra, XMM-Newton, and Fermi.

The future X-ray observatory ATHENA, a more sensitive successor to current X-ray telescopes, is in the design phase and will be able to observe active galaxies even in the early Universe. ATHENA will not only observe the first Black Holes, but also study their evolution and how they influence the evolution of the Universe.

A multi-wavelength (radio, optical, X-ray), composite image of the active galaxy Centaurus A. The jets, expelled by the central Black Hole and reaching far beyond the galaxy, are clearly visible.

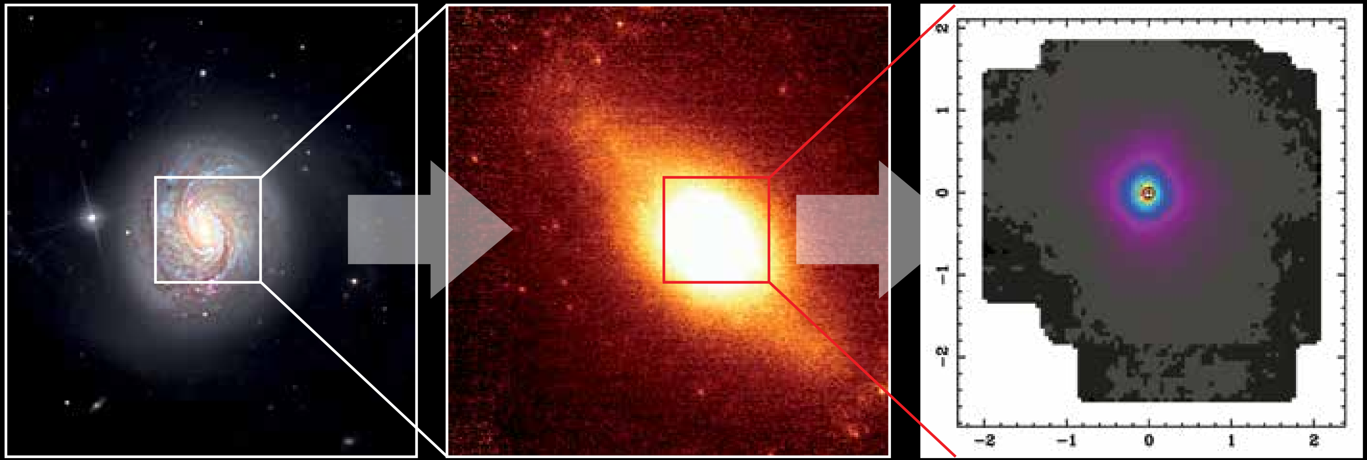


↗ The activity of galaxies is influenced by the activity of their central Black Holes.



Artist's impression of ATHENA. By measuring X-ray emission, the properties of the central Black Holes in galaxies can be deduced.

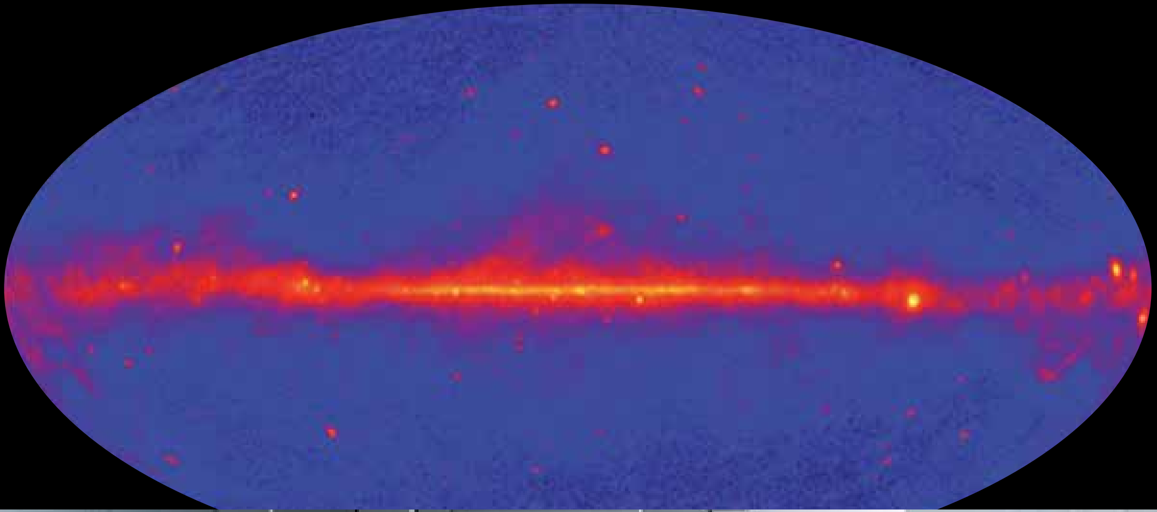
BLACK HOLES



Zooming into the very centre of the active galaxy NGC 1068, optical (left), and near-infrared (middle, right). To observe the active nucleus the very high resolution provided by MPE's SINFONI camera on the VLT telescopes is necessary.

The centres of galaxies are often hidden behind thick swathes of dust that block our view. Infrared wavelengths, however, can penetrate this dust. Peering into the heart of the active nucleus, we can discern the role that different processes play in producing the radiation close to the centre.

Ground based observatories equipped with adaptive optics systems, such as SINFONI at the VLT telescopes and in the future also GRAVITY, reveal the nuclei and also the accretion flow in exquisite detail. Using these observations, we can study the interplay between gas and stars, and understand how these influence the rate at which the Black Hole is fuelled. By measuring the motions of the stars we are able to "weigh" the Black Holes, an important step in understanding how Black Holes and host galaxies grow and evolve together.



Active Galactic Nuclei, sending us gamma-radiation from the deep Universe, are visible as point sources below and above the diffuse glow of gamma-rays along the galactic plane in the all-sky map as observed by the Fermi Gamma-ray Space Telescope. The sources on or near the galactic plane are mostly sources in our Milky Way; basically all of them are rotating neutron stars, so-called pulsars.

GALAXIES

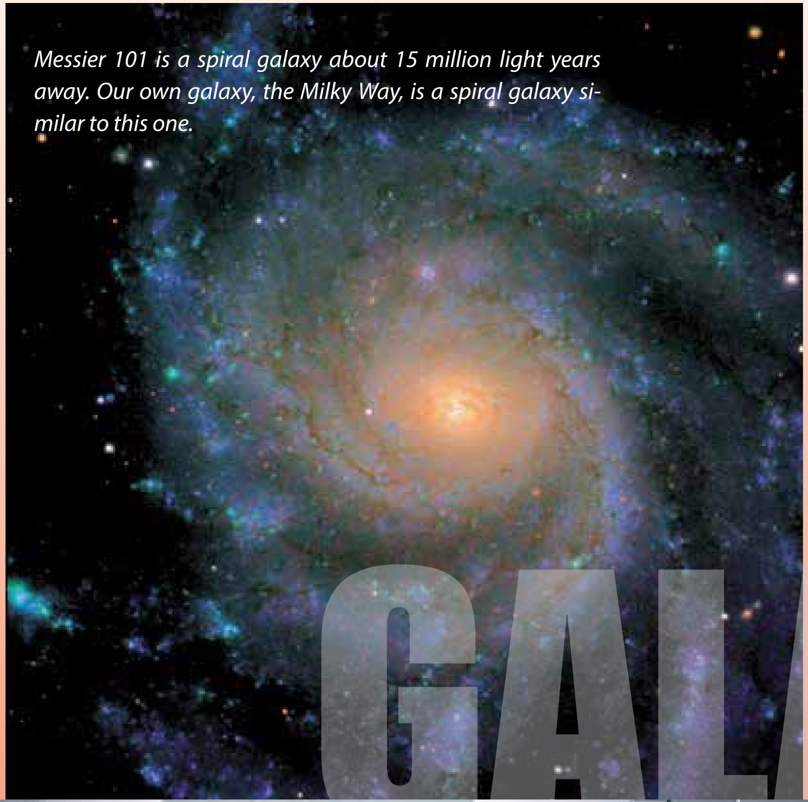
Galaxies – Cosmic Islands of Stars, Dust, and Gas

Looking up at the heavens in a clear night, we can see not only stars and planets, but also a faint band across the whole sky: the Milky Way. This is our home in the Universe, a spiral galaxy with about 200 billion stars. Our Sun is one of its fairly ordinary stars, orbiting the centre of our Milky Way at a distance of 25000 light years, once in about 200 million years.

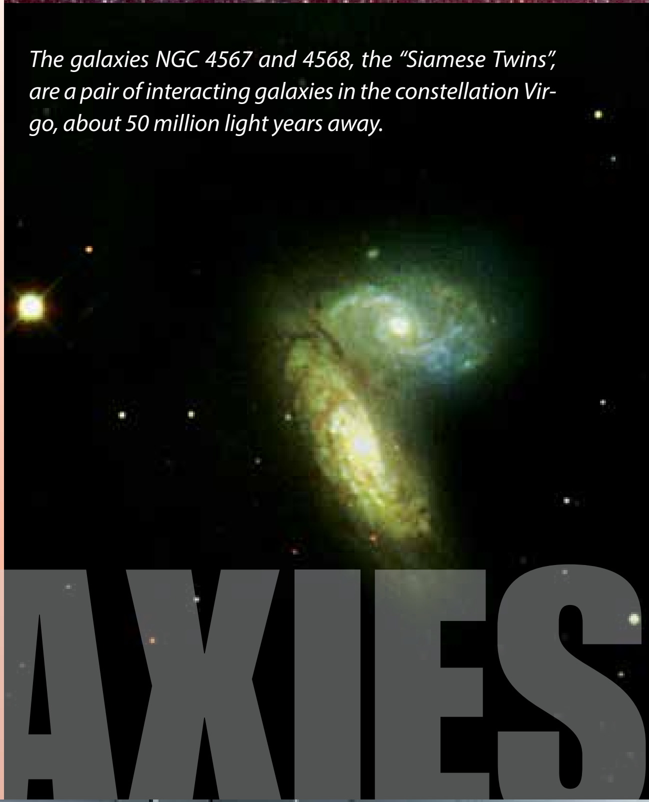
Galaxies are beautiful and spectacular islands of stars, dust and gas, mostly embedded in halos of Dark Matter. Galaxies come in all kinds of shapes and sizes, ranging from dwarf galaxies with some thousand stars, to gigantic elliptic galaxies with 100 trillion stars. Each galaxy is unique, and its morphology, size and mass give us clues on how it developed and evolved from a time when the Universe was in its infancy, to the present day.

MPE scientists study galaxies across the entire electromagnetic spectrum, both in the local and in the distant Universe, which offers the opportunity of looking into the past. They are searching for answers to fundamental questions: How and when did galaxies form and how do they evolve? Why are disk galaxies exclusively star factories, whereas massive, elliptical galaxies produce hardly no stars?

A particularly interesting research area for the scientists at MPE are the massive Black Holes in the centres of galaxies. When such Black Holes accrete new material, their host galaxies become active: they constantly vary in luminosity.

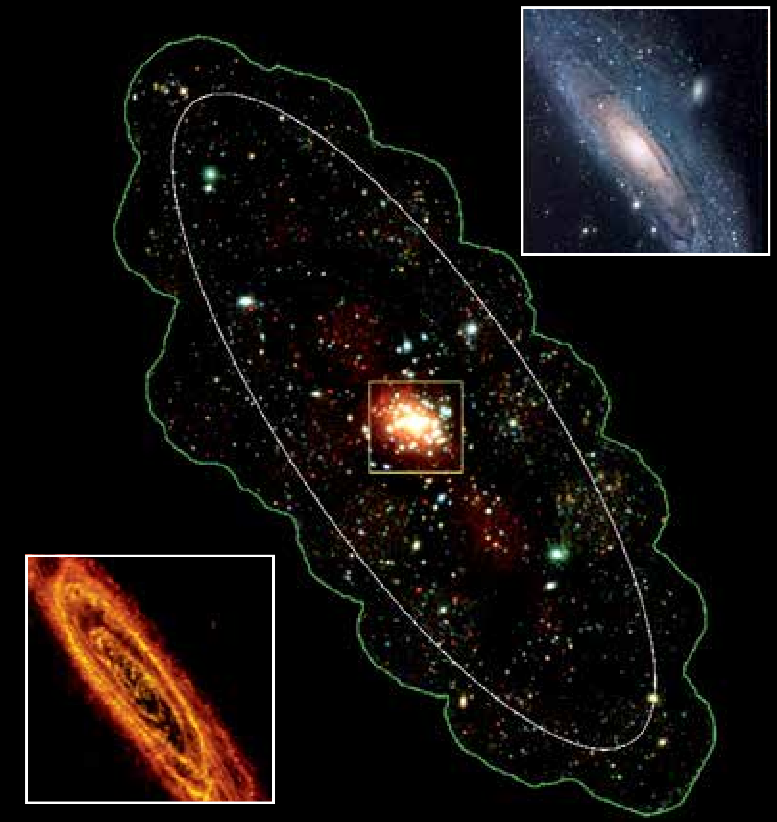


Messier 101 is a spiral galaxy about 15 million light years away. Our own galaxy, the Milky Way, is a spiral galaxy similar to this one.

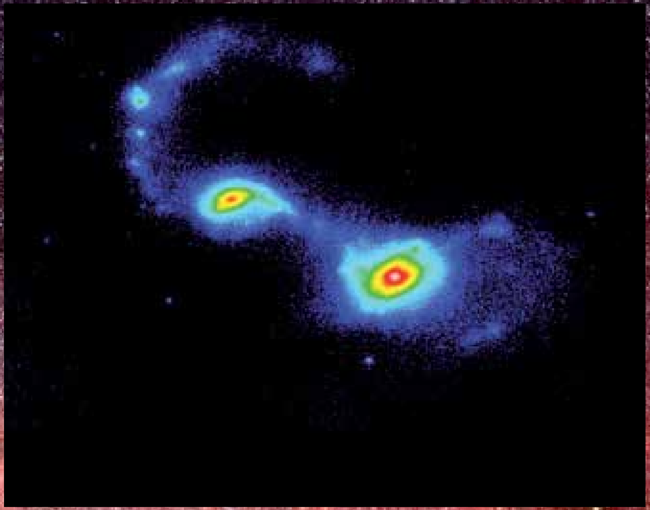


The galaxies NGC 4567 and 4568, the "Siamese Twins", are a pair of interacting galaxies in the constellation Virgo, about 50 million light years away.

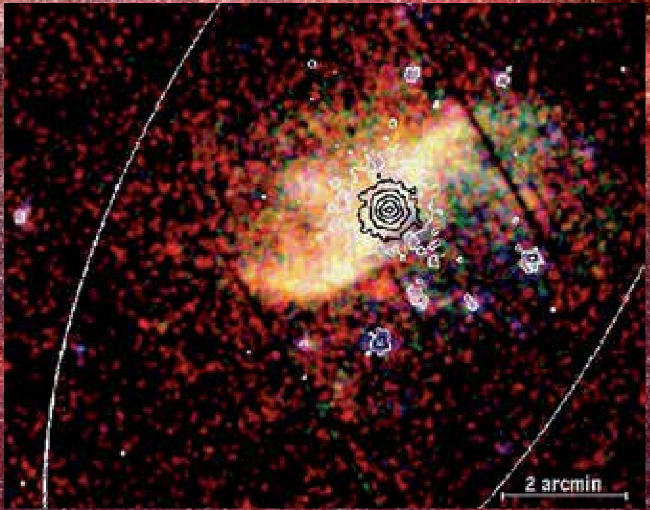
GALAXIES



Raster observations by XMM-Newton yield a mosaic image of the Andromeda galaxy, which reveals the hot, X-ray radiation emitting objects. Two small images show Andromeda's stars in optical (top) and its gas in infrared light (bottom) for comparison.



The galaxy merger IRAS 06035-7101, which is ultra-luminous at infrared wavelengths. This image was observed in very high resolution by the ESO NACO-camera and PARSEC, the laser guide star facility of MPE. Galaxy mergers trigger very intense bursts of star formation, resulting in bright objects.



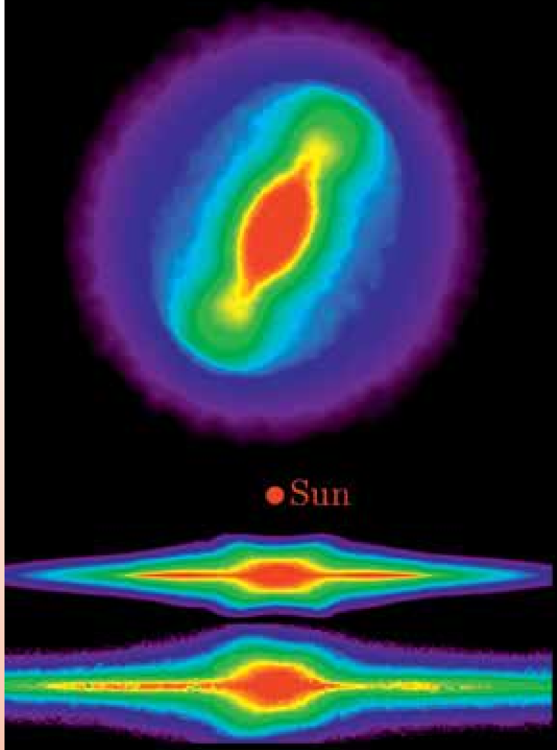
The active galaxy NGC 4258 as seen in X-rays by XMM-Newton. The false colour image shows the soft X-rays, in particular the central region. The contour lines indicate the hard X-ray emission, mainly emitted by the AGN at the very centre. The white line indicates the optical size of the galaxy.

Nearby Galaxies – a Case Study for Galaxy Physics

In nearby galaxies we are able to see many details, which are invisible – not resolvable – for our telescopes in faraway galaxies. In order to study the structure of galaxies in detail, we regularly observe our neighbouring galaxies, as well as the nearest of them, our own galaxy, the Milky Way.

Even though the centre of our Milky Way is "only" 25000 light years away, we do not have a complete picture of its inner structure. Dense clouds of gas and dust shroud the centre from our view. Several surveys of our Milky Way at near infrared wavelengths, where the galactic dust clouds are more transparent, enabled us to determine the positions and distances of millions of red giant stars. With this data we were able to map the inner regions of our Milky Way in three dimensions, especially both its central "bulge" and the lengthy bar crossing its central region.

Contrary to the previous opinion that bar and bulge are two different components of our galaxy, the new results imply that they are the inner and outer parts of the same structure, which has the shape of a peanut when looking from the side. The Milky Way's bar is exactly in the middle plane of our galaxy and is longer and thinner than previously thought. This indicates that our Milky Way was once a pure stellar disk, which formed a thin bar billions of years ago. This new map can now be used to study the dynamics and evolution of our Milky Way, for example the influence of the bar on the orbits of stars close to the Sun.

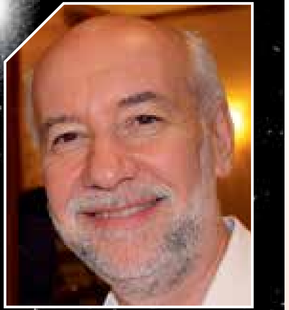


The upper image shows the new model of the Milky Way seen from above. The central bulge and the long bar are visible as a peanut-shaped connected structure. The middle image shows the model in a side view, the lower image as seen from the Sun.

The Milky Way above an ESO-telescope in Chile. Its stellar band reaches across the entire picture. The galactic plane and the thicker central region, the so-called bulge, are clearly visible. Darker regions are caused by dust-absorption of starlight.

A model of our Milky Way with the spiral arms in the disk and the bright galactic bulge with billions of stars in the central region.

GALAXIES

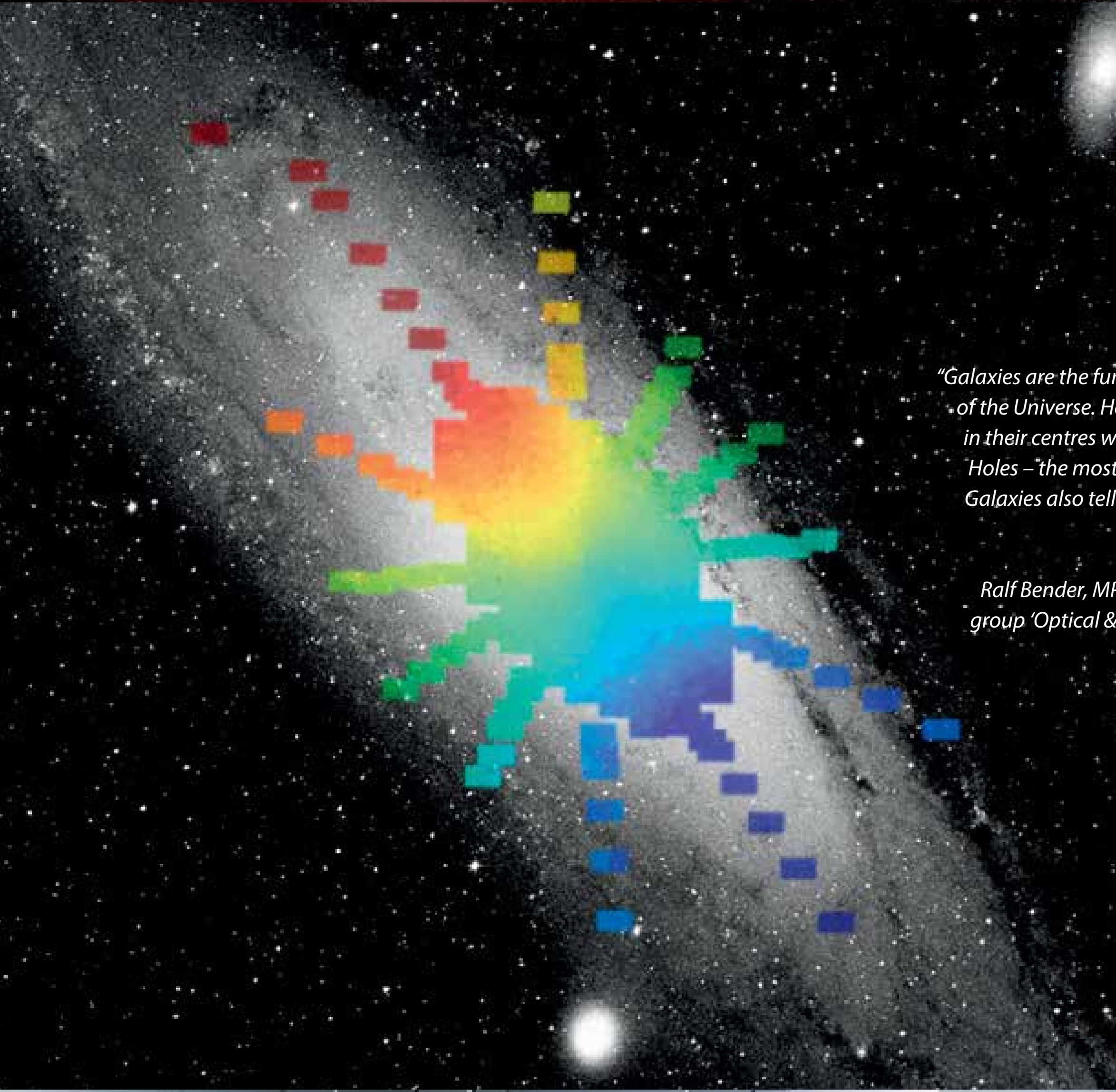


"Galaxies are the fundamental building blocks of the Universe. Here stars and planets form, in their centres we find super-massive Black Holes – the most extreme objects we know. Galaxies also tell us about Dark Matter and Dark Energy."

Ralf Bender, MPE director and head of the group 'Optical & Interpretative Astronomy'

Another important object under study is our sister galaxy in the local galaxy group, the Andromeda galaxy. Spectroscopic measurements tell us about the dynamics of its stars and dust. We have learned, for example, that the rotational velocity of Andromeda is some two hundred kilometres per second and that Andromeda and the Milky Way move towards each other – in about 4 billion years they will "collide".

The average speed of the inner stars, which have velocities of more than 1000 kilometres per second, indicate the mass in the centre: a Black Hole with about 140 million solar masses. During the past years, similar measurements of other galaxies led to an important discovery of the 20th century: probably all luminous galaxies with a bulge host a central massive Black Hole, which is more massive the more massive the galaxy's central bulge. This simple relation suggests that there is a link between the evolution of the galaxy and its central Black Hole. Understanding the processes involved is currently a hot topic in MPE´s research on galaxy evolution.

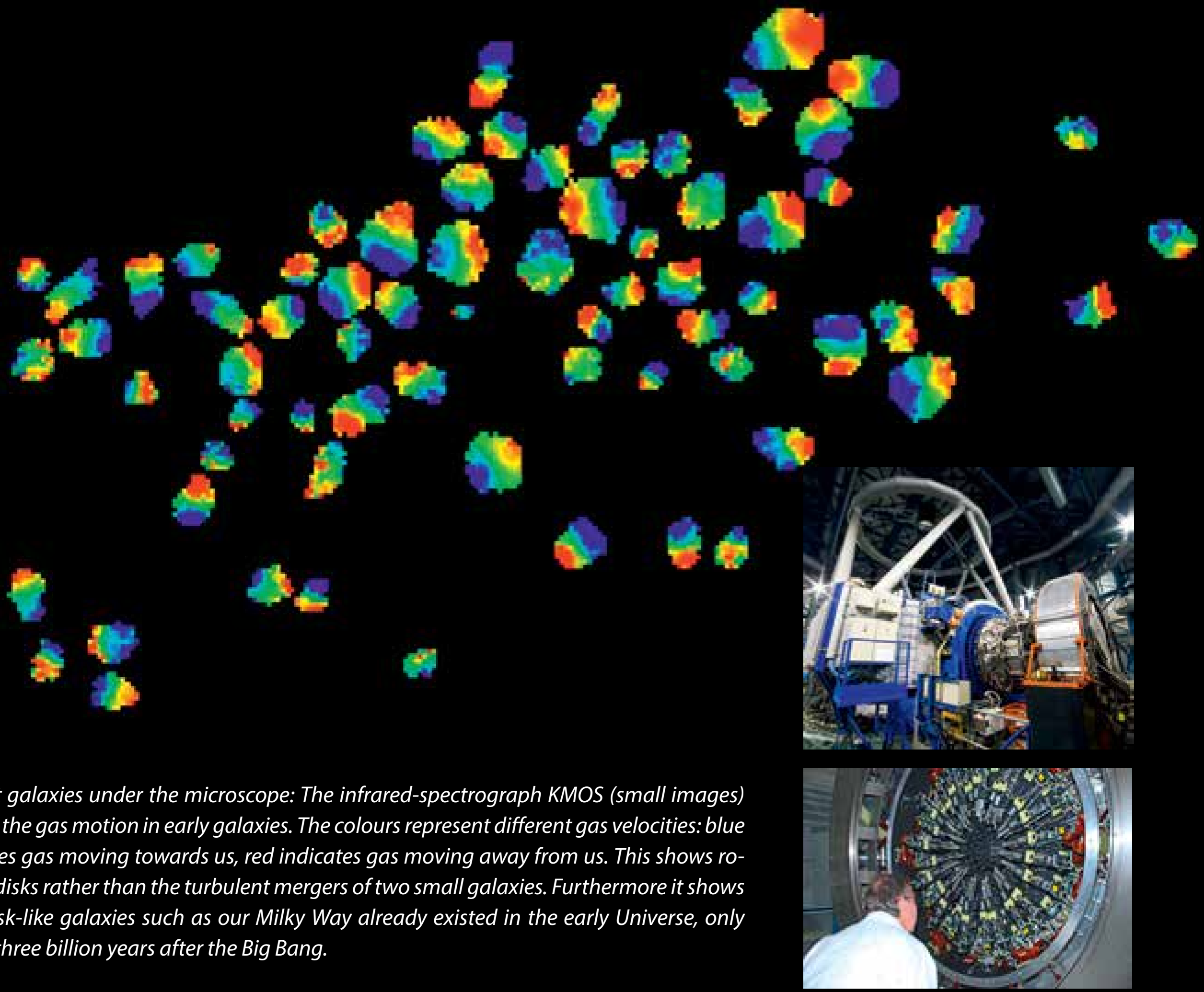


To understand galaxy physics, MPE studies not only our own Milky Way, but also near-by galaxies such as the Andromeda galaxy shown here. The spectroscopic analysis of individual observed fields across Andromeda provides its velocity field. The colours represent rotational velocities of up to 180 kilometres per second. Blue indicates that Andromeda rotates towards us, whereas its stars move away from us in the red coloured region.

The Highest Resolution – a Sharp Look at Early Galaxies and their Evolution

Astronomers approach the evolutionary history of galaxies through observations and simulations. Today there are large elliptic galaxies, disk-shaped galaxies and irregular galaxies. With precise measurements in infrared, optical and X-ray, MPE-scientists contributed to decode the basic steps in the evolution of galaxies. We know that galaxies formed when baryonic gas accumulated in the centre of massive halos of Dark Matter due to their gravitational force, where it cooled down. Because this gas had an angular momentum, proto-galaxies with discs formed already 500 to 800 million years after the Big Bang.

Today we can observe up to 24 galaxies in parallel with the KMOS spectrograph and ESO's VLT telescopes, which allows us to measure even more galaxies at the smallest scales and in the deep past. This leads to a better understanding of the formation and early evolution of galaxies. The MPE KMOS survey measures about a thousand distant galaxies spectroscopically in a "journey through time", whose light has been travelling for 6 to 11 billion years. The result was kind of a "census": the typical appearance of young galaxies, what physical processes are active and how they evolve. More than two thirds of young proto-galaxies already contain a rotating disk. The existence and the characteristics of these early rotating disk-shaped galaxies provide new basic conditions for evolutionary models of galaxies.

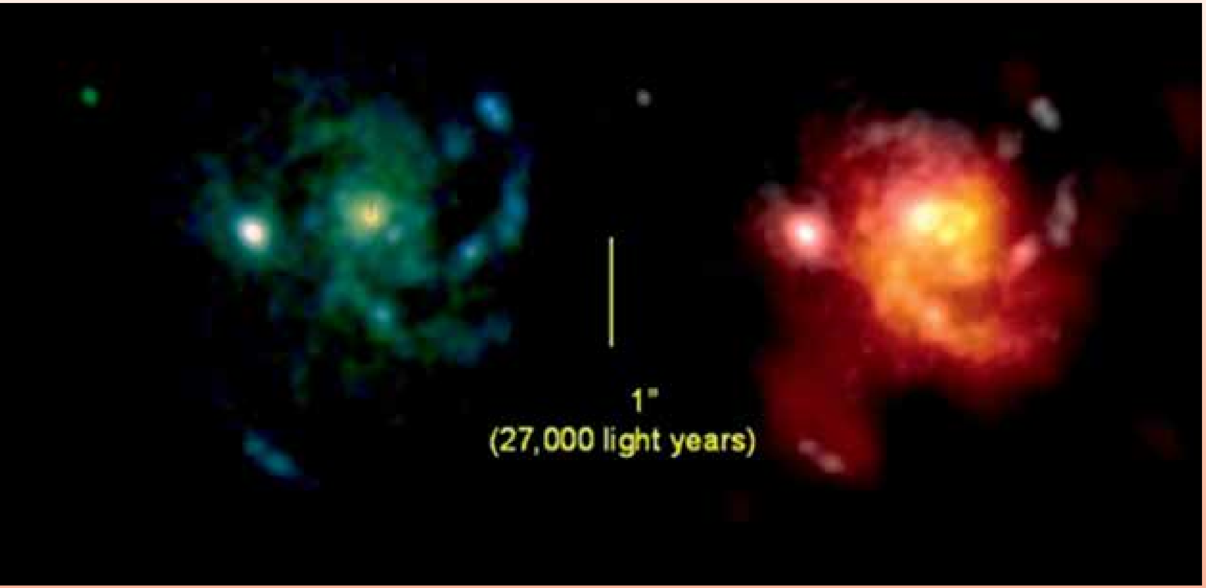


Distant galaxies under the microscope: The infrared-spectrograph KMOS (small images) reveals the gas motion in early galaxies. The colours represent different gas velocities: blue indicates gas moving towards us, red indicates gas moving away from us. This shows rotating disks rather than the turbulent mergers of two small galaxies. Furthermore it shows that disk-like galaxies such as our Milky Way already existed in the early Universe, only about three billion years after the Big Bang.

GALAXIES

Young Galaxies are the star factories of the early Universe – they were a lot more productive than today.

Using different observations, for example with the IRAM telescopes in the French Alps, scientists at MPE found that early galaxies contained way more molecular gas than today's galaxies. This result explains the increased star formation rate in the early Universe. While about 2 to 3 stars per year form in our Milky Way today, the rate was about 20 times higher approximately 10 billion years ago.



Two views of a typical galaxy, about 5,5 billion years after the Big Bang, when the Universe was only about 40% its current age. The molecular gas, detected by the IRAM-interferometer (right image), follows the distribution of the recently formed stars imaged by the Hubble Space Telescope (left picture). The mass of the cold gas in this galaxy is about 10 times larger than in today's galaxies.

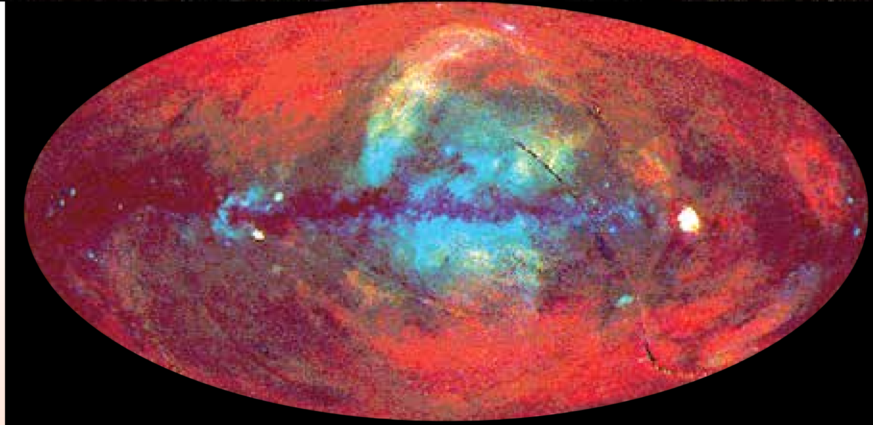
The interferometer of the Institut de Radioastronomie Millimétrique (IRAM) on the Plateau de Bure. It is located in the southern French Alps at a height of 2600 meters.

The Galaxy Background

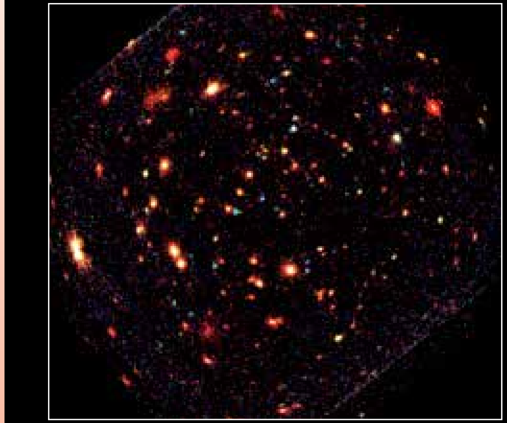
In June 1962, American astronomers made two pioneering discoveries with an X-ray detector on a high-altitude research rocket, marking the birth of X-ray astronomy: a strong X-ray source was found in the constellation Scorpius, and unexpectedly and surprisingly, the whole sky appeared to glow in X-rays. A mysterious radiation reaches us from every direction: the X-ray background. Determining its origin became a prime goal of X-ray astronomy, in which MPE participated at the front line.

The MPE X-ray satellite ROSAT was launched into orbit in 1990 and carried the most sensitive imaging telescope for soft X-rays (0.1 – 2 keV) at that time. It unravelled the mystery: 80 percent of this background radiation originates from individual celestial sources. The discovery however, in turn raised the question of what kind of astronomical objects are responsible for this radiation. Follow-up observations with large optical telescopes found so-called "active galactic nuclei" (AGN) in almost all cases. AGN are galaxies with a growing supermassive Black Hole at their centre, which feeds on matter from its environment and emits X-ray radiation in the process.

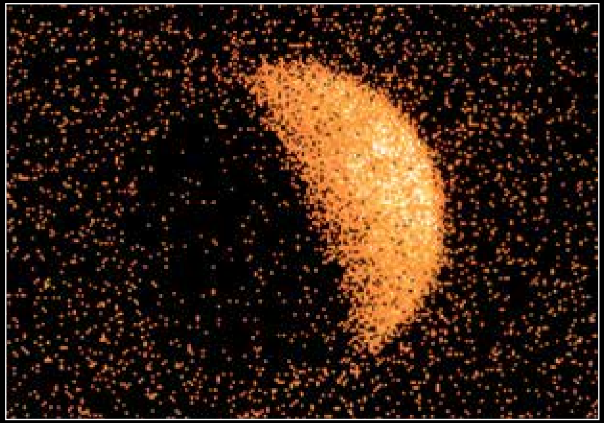
The current generation of X-ray satellites, Chandra and XMM-Newton, could resolve nearly 100 percent of the X-ray background in soft X-ray bands (up to 2 keV) into single sources. But at higher energies, up to 10 keV, the situation is still unclear. Therefore, future instruments such as the MPE eROSITA satellite and the ESA X-ray observatory ATHENA, built with a major MPE contribution, will play a leading role in studying the X-ray background.



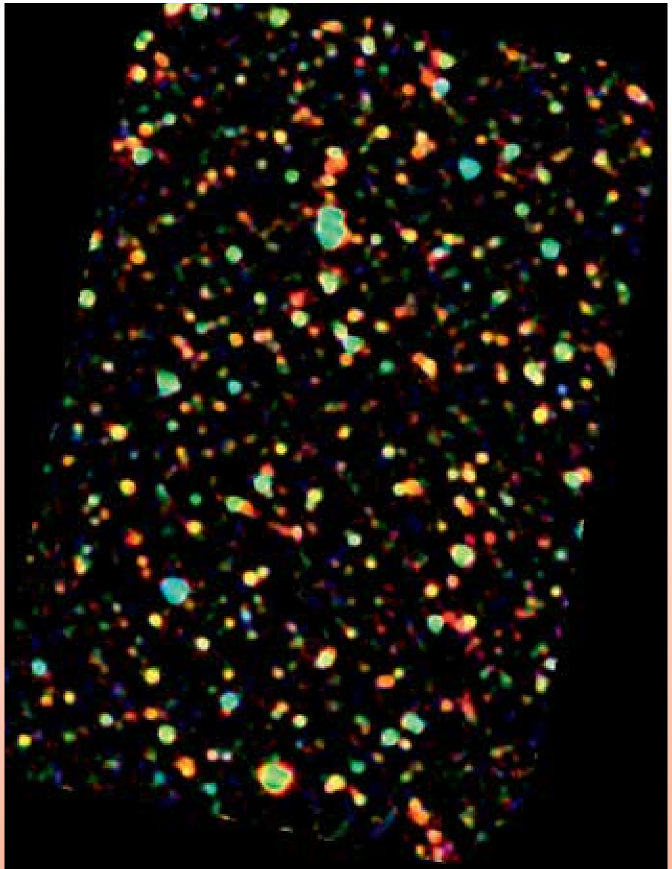
The diffuse X-ray background measured by ROSAT across the whole sky. The colours refer to different X-ray energies. The universal red glow, the extragalactic X-ray background, has been resolved into a huge number of individual X-ray sources in some small sky regions such as the "Lockman Hole".



XMM-Newton deep observations of the Lockman Hole. Many X-ray sources of different colours, i.e. different temperature, are visible in the image, and together produce the X-ray background radiation. The sources are active galactic nuclei, galaxies with an active ('feeding') supermassive Black Hole at their centre.



X-ray image of the Moon as measured by ROSAT. The sunlit crescent of the Moon reflects – just as in optical light – the X -ray emission of the Sun. The dark side of the Moon's disk shadows the X-ray background radiation coming from deep space.



This impressive deep view of the GOODS-S field with the Herschel PACS instrument shows that the weak cosmic infrared radiation field is mainly caused by single galaxies.

The Herschel satellite studied the sky at infrared wavelengths with its three instruments, in particular with "PACS" (Photodetector Array Camera and Spectrometer) from MPE. PACS (small image) analysed the incoming infrared radiation at the focal point of the mirror.

↗ The cosmic background radiation consists of many individual sources.

The whole sky glows in a diffuse light not only in X-rays but also in infrared. From the beginning scientists thought that this radiation – just as in X-rays – originates from many single sources not resolvable at that time.

With various infrared space observatories MPE scientists embarked on the mission to explain the nature of this diffuse radiation. Like in X-rays, selected regions of the sky have been observed at infrared wavelengths for long exposures in order to detect weak and far-off objects. We achieved the latest and best results with MPE's PACS instrument, operating on board of ESA's Herschel satellite. PACS finally provided confirmation: it was able to resolve around 75% of the diffuse IR background into single galaxies. Now the known luminosities and distances – also in time – of these galaxies allow us to retrace the history of star formation in the Universe.

Back to the Beginning – Large Scale Structure and Cosmology

Over the past two decades an increasingly detailed model has emerged about how our Universe, including the Milky Way and the Sun, formed and evolved: it all started with the Big Bang about 13.8 billion years ago. The infant Universe expanded very quickly – with a velocity higher than the speed of light – in a so-called "inflationary phase" at the very beginning. After 10^{-30} seconds the Universe was as big as an orange and after a thousandth of a second as big as our solar system. About 3 minutes after the Big Bang the first elements formed, which assembled into the first stars about 400 million years later. Small galaxies and Black Holes developed in clumps of Dark Matter around half a billion to one billion years after the Big Bang, larger galaxies and galaxy clusters grew on cosmic time scales. But Dark Matter is not the only mysterious component – there is also Dark Energy, a kind of anti-gravitation, which accelerates the expansion of the Universe.

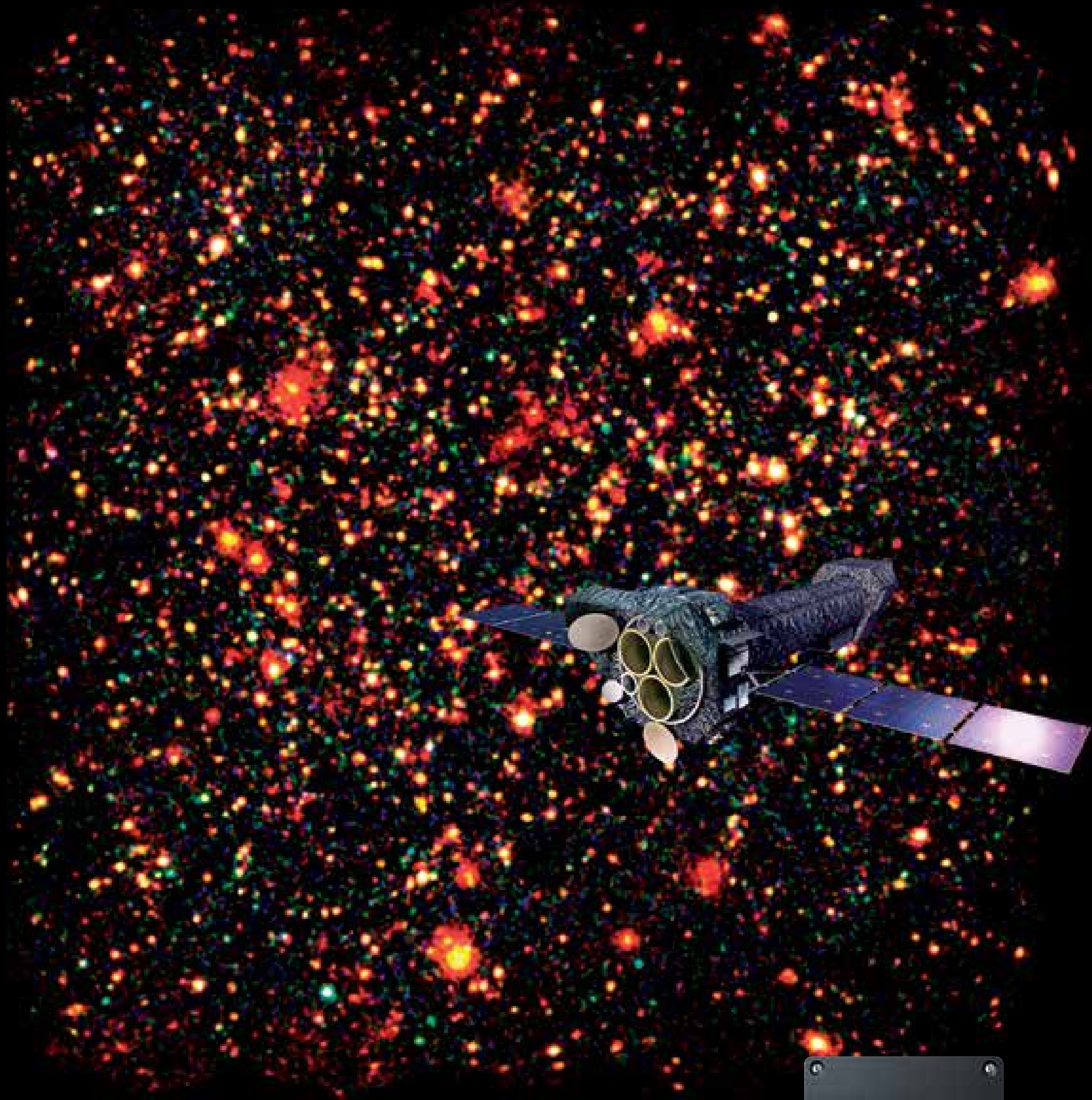
At MPE we are combining expertise from different science groups in a concerted effort to pursue some of the key questions in modern astrophysical cosmology: How did the Universe attain its present structure and appearance? How and when were the first stars born? How and when did galaxies and large structures form? What are Dark Matter and Dark Energy?

↗ Deep Sky Surveys allow a look in the past.

A look outside our galaxy deep into the Universe reveals its appearance today: billions of galaxies with a wide range of morphologies and sizes. This optical image taken by the Hubble Space Telescope is well known, but now we observe these distant galaxies also in other wavelength bands…

COSMOLOGY

The two square-degree Cosmic Evolution Survey (COSMOS) field covers a sky region about ten times the size of the full moon. It is located in the constellation Leo and provides a window for looking deep into the Universe. The field is observed by all modern observatories from radio to X-ray wavelengths, and MPE participates in this international effort in the far-infrared with Herschel/PACS (left) and in X-rays with XMM-Newton (right). The infrared image shows galaxies in different (false) colours: red objects are far away or dusty galaxies, while blue objects are nearby galaxies. The X-ray image shows active galaxies and diffuse galaxy clusters. Multi-wavelength analyses of deep survey fields such as COSMOS provide clues on the evolution history of the Universe.

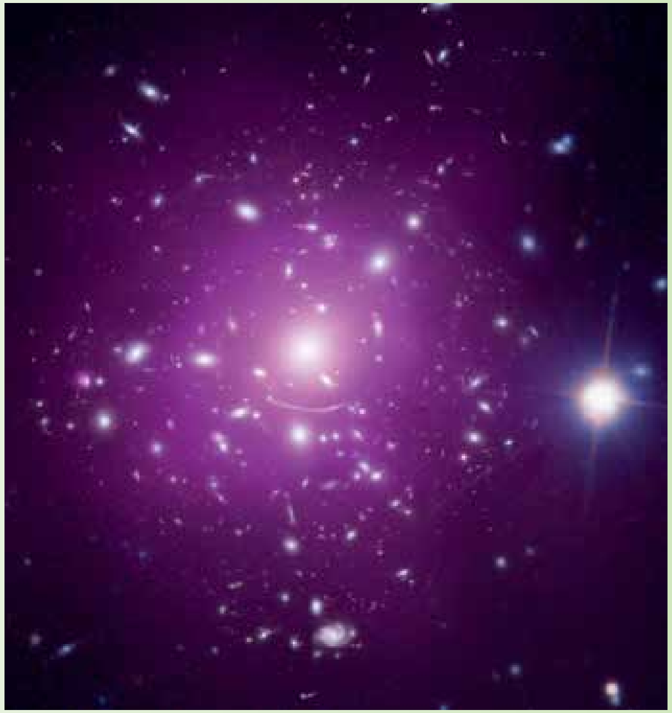


Clusters of Galaxies – Superlatives in Space

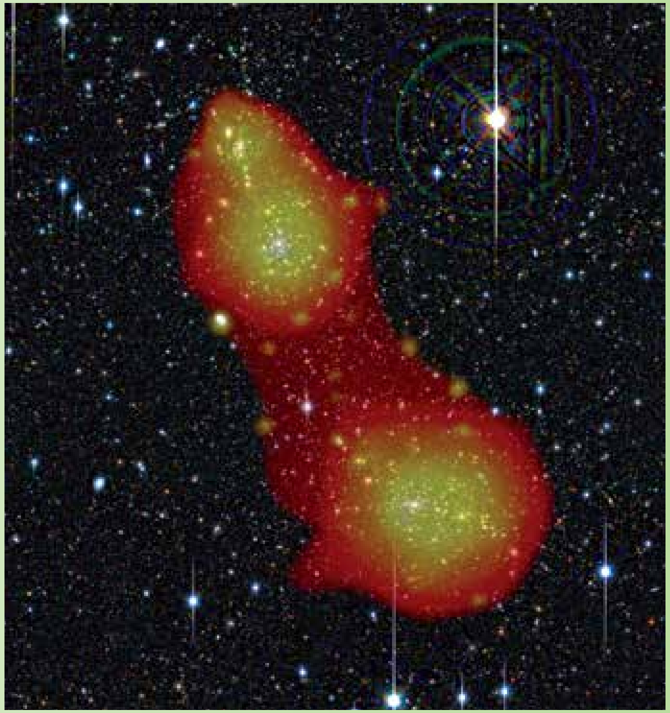
Clusters of galaxies are the largest well defined and fully developed objects in the Universe with up to several thousands of individual galaxies. In optical images they appear merely as a collection of galaxies, but X-ray observations reveal the glow of a hot intra-cluster medium that fills the entire cluster volume proving that they are indeed connected entities.

As the largest building blocks of the Universe they are extreme in every way: the X-ray emitting plasma has temperatures of tens of millions of degrees, and because of their huge mass they cause a bending of light rays leading to strongly distorted images of background galaxies. Mergers of galaxy clusters, a common mode in which they grow in size, are the most energetic events in the Universe, equivalent to a trillion supernova explosions.

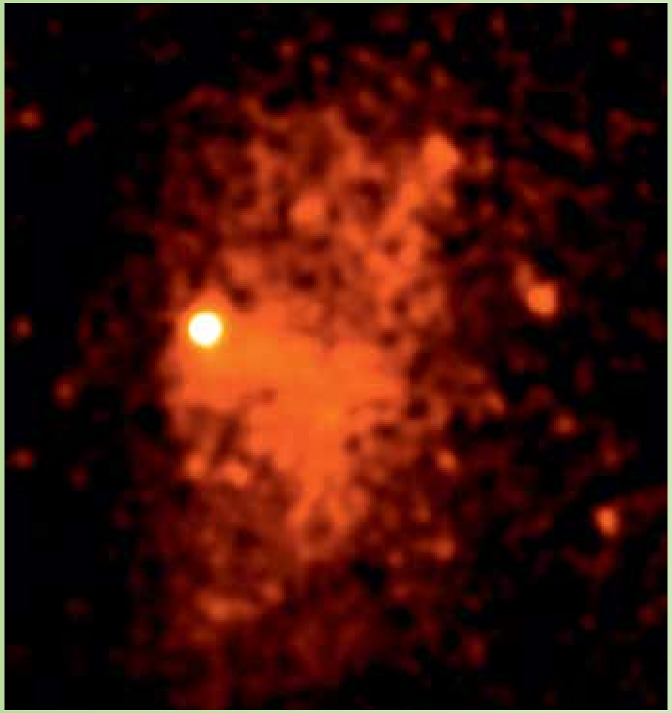
MPE scientists study galaxy clusters to learn about the matter distribution and the hierarchical build-up of structure, which we observe in the Universe today. By using the gravitational lensing effect, we determine the mass of a cluster and – by detailed analyses – even the mass distribution within a cluster. The gravitational lensing effect shows great promise for determining how much Dark Matter the galaxy clusters contain, and for calculating the ratio between Dark Matter and common, luminous matter.



Optical (single galaxies) and X-ray (diffuse violet emission) composite image of the galaxy cluster Abell 383. The X-ray emission proves that these galaxies are gravitationally bound and thus form a cluster. The galaxy image directly underneath the centre has the shape of an arc, which is a typical sign of strong gravitational lensing.



A bridge of hot matter, 'shining' in X-rays, connects the galaxy clusters Abell 222 and Abell 223. This was seen for the first time with the XMM-Newton X-ray telescope and reveals part of the missing baryonic matter in the Universe. The filamentary connection between those two clusters also supports the theory that visible matter is distributed along universal filaments of Dark Matter.



X-ray image of a galaxy cluster. This system shows a small and compact cluster merging with the main cluster. The small and compact cluster with its bright core penetrates the less dense cluster like a bullet.

The eROSITA-instrument was specifically designed at MPE to scan the entire sky with its seven X-ray telescopes. Each contains 54 nested special mirrors. Its large field-of-view together with its high sensitivity for X-ray radiation promises the most accurate all-sky map of the X-ray background.

"eROSITA will peer through dust and gas into the deep Universe. By discovering some 100000 galaxy clusters, it will be able to map the large-scale structure of the Universe and may uncover some secrets of Dark Energy. Also, it will watch millions of growing Black Holes."

Kirpal Nandra,
MPE director and head of
the group 'High-Energy Astrophysics'

The Fate of the Universe – Dark Matter and Dark Energy

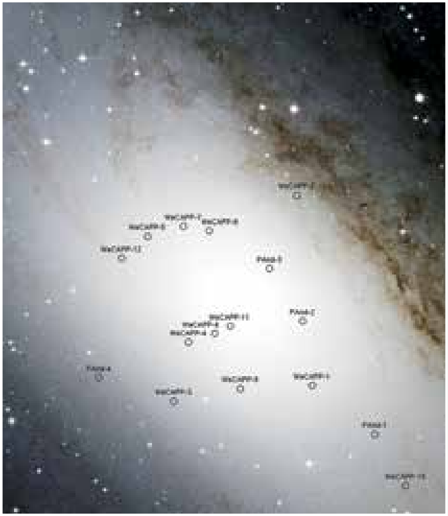
Astronomers know that stars in galaxies and individual galaxies in clusters are moving much too fast for their visible mass to hold them together. Since celestial motions are governed by gravity, and gravity is caused by matter, there must be a large amount of additional, invisible matter – the so-called "Dark Matter". There are two types: non-baryonic matter in the form of exotic particles and baryonic matter as dark heavenly bodies. We estimate that there is about five times more non-baryonic than baryonic matter, of which only a small fraction is visible, e.g. as luminous stars.

MPE is actively searching for Dark Matter, mainly using the most common method, the so-called "gravitational lensing effect": a light ray is deflected by a massive object such as a galaxy or galaxy cluster. The distorted image of a background object allows us to calculate the total mass of the lensing object, and so to determine its Dark Matter content by comparing it to visible matter.

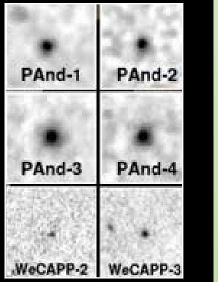
In nearby galaxies we trace the motion of stars and conclude that galaxies are embedded in halos of Dark Matter. The remaining fundamental question is whether Dark Matter consists of non-baryonic particles or compact dark baryonic objects. We regularly observe our neighbouring galaxy Andromeda to detect the effect of gravitational lensing, which temporarily enhances the brightness of a star when an invisible object passes in front of it. The galaxy's countless stars increase the probability to observe such a rare event and thus to find non-luminous objects and to estimate their mass contribution to Dark Matter as a whole.

The massive galaxy cluster Abell 2218 acts like a gravitational telescope and bends the light of objects located behind it. The arc-like structures are the typical signs of gravitational lensing.

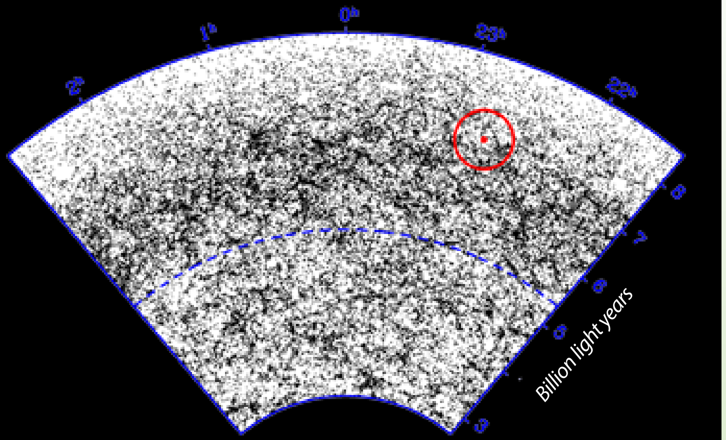
↗ Dark Matter is postulated to originate from mass in galaxies and galaxy clusters that is unaccounted for.



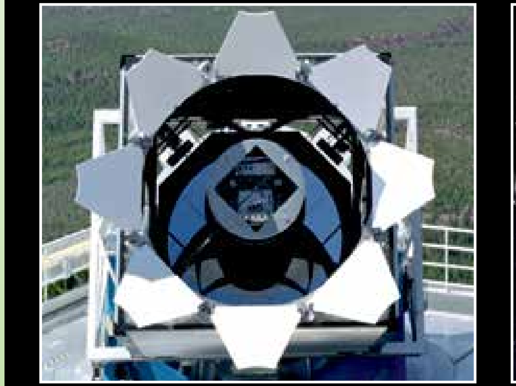
A zoom into the central region of the Andromeda galaxy, imaged with the Pan-STARRS telescope on Hawaii. It shows a region 15000 x 16500 light-years. The 16 gravitational lensing events discovered are marked and shown at their maximum on the right (selection). The objects responsible are presumably faint "white dwarfs" or "brown dwarfs".



↗ The expansion of the Universe is accelerated by the force of Dark Energy.



A map of the galaxy distribution of a thin slice through the BOSS catalogue. Each point corresponds to a galaxy. The red circle shows the length of baryonic acoustic oscillations, the astronomer's standard yardstick. The probability to find two galaxies within this distance is a bit higher than for smaller or larger distances.



The 2.5-meter telescope in New Mexico (USA), which surveys the northern sky for galaxies in the so-called "Sloan Digital Sky Survey".

In the 2020s the ESA-mission EUCLID will investigate the "dark" Universe, Dark Matter and Dark Energy.

About 20 years ago, detailed measurements were carried out of far-away supernova explosions to observe and quantify how the expansion of our Universe changes. Surprisingly, however, the astronomers discovered that the expansion does not slow down, on the contrary: the Universe now expands with an increasing velocity. An unknown phenomenon, now called Dark Energy, is counteracting gravity and so accelerates the expansion of our Universe.

MPE scientists aim to determine the equation of state, i.e. the relation between pressure and density, of Dark Energy as a function of time. For this, astronomers have to understand how the Universe has expanded since the Big Bang. Acoustic waves, stimulated by quantum fluctuations, imprinted a wave pattern in the density of the primordial plasma. Since slightly more galaxies formed in (over-dense) wave crests than in (under-dense) wave troughs, measurements of the spatial distribution of galaxies as a function of distance reveal the expansion history of the Universe and so the influence of Dark Energy.

To measure this spatial distribution, MPE actively participates in several galaxy surveys conducted on large telescopes. For example, the BOSS survey (Baryon Oscillation Spectroscopic Survey) has determined the exact positions and red-shifts of 1.2 million galaxies so far. Using these measurements the wave pattern of the early Universe (up to 6 billion years ago) and the distances to galaxies as well as their velocities can be calculated with high accuracy. A comparison with values of nearby galaxies, which represent the present-day Universe, allows the MPE-scientists to "see" the evolution of the Universe and so to constrain the characteristics of Dark Energy and to explore its secret.

In the future, the ESA mission EUCLID – with the participation of MPE – will have a similar task. EUCLID will measure the three-dimensional distribution of galaxies at optical and near-infrared wavelengths and thus determine the evolution of cosmic structures at even earlier times, 10 billion years into the past. In this way EUCLID will cover the entire period, in which Dark Energy significantly accelerated the expansion of the Universe.

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