The Universe as a physics lab
(Curator Michael Kramer)

1. At a glance

- MPG researchers explore the universe, study its beginning and its possible end, and reveal its contents and the fundamental laws and processes that govern it.
- MPG researches address the oldest, deepest and biggest questions of mankind including the origin of life and the formation of everything that surrounds us.
- By designing new instruments, by operating sophisticated telescopes and detectors, and by undertaking enormous calculations using massive super-computers, MPG researches make discoveries of new, often mysterious phenomena, objects and forces, and conduct research to explain them, now and in the future.

2. Definition of research

Scientists at the Max-Planck-Institutes study the universe. They learn about its contents (including us!) and about the fundamental laws and processes that govern it. They study the complete solar system, including the Sun, the planets, their moons, comets and asteroids; they study extra-solar planets, stars, stellar remnants, stellar and super-massive black holes, galaxies and the diffuse gas between them; and they study the beginning of the universe and its current state and structure, and its possible end.

Astronomy research thus is a highly interdisciplinary endeavor, combining the knowledge and progress in a number of fields, including fundamental and applied physics, material science, electronics and computing, chemistry (and perhaps soon biology), as well as engineering at the state of the art. This allows MPG researchers to address the biggest questions. What is the origin of life? Can current physics describe the most extreme objects and events? What is the mysterious dark energy and matter that surrounds us? And what new forces and physics do these imply?

Answering these questions requires advances in technology and the development of new experiments, instruments and methods. Experiments are conducted in the laboratory, under micro-gravity conditions on the International Space Station and by observing the universe using the long-range forces: electromagnetism and gravity. MPG scientists are working on new ground and space-based telescopes covering the 18 orders of magnitude in the electromagnetic spectrum, from radio waves, infrared, visible, UV and X-ray to gamma ray frequencies. Infrared, visible and radiation up to X-rays allows us to study objects in the Universe which emit because they are “hot”, ranging from interstellar dust glowing in the infrared through the stars studied in the optical up to extreme objects hot enough the emit X-rays. Radiation also probes high-energy particles, which permeate the universe, accelerated near black holes, in exploding stars or in the giant magnetic fields of pulsars; these particles are traced by their emission of radio waves, of X-rays and of gamma rays. Similar efforts are underway to build and operate detectors over an even broader range of gravitational wave frequencies. The gravitational wave detectors will “see” objects like binary black holes that are electromagnetically invisible, resulting in unique tests of Einstein’s general theory of relativity that complement studies in the electromagnetic spectrum.

The understanding and interpretation of these data require theoretical input and numerical modeling to compare them with what is predicted by the current laws of physics. Solving complex equations, combing through massive data sets, or simulating the formation of galaxies or structure formation in the Universe as a whole, require some of the world's fastest computers, and new numerical methods and algorithms.

Collectively, this research addresses some of the oldest and deepest questions of mankind. It helps us to understand our universe, and our place in the universe, in the broadest possible way.

3. Status of the field

In all areas of astronomy and astrophysics, recent discoveries have not only uncovered new knowledge but have also revealed fascinating new puzzles. In the past two decades, detailed information about the structure of perturbations in the cosmic background radiation, and detailed studies of the evolution of these perturbations to form cosmological-scale structures like galaxies, have led to one of the greatest and most puzzling discoveries of the last century. It has been the demonstrated that our Universe is not primarily made of atoms, but rather of “Dark Matter” and “Dark Energy”. Both are unexpected and seem to require major extensions of our current ideas of fundamental physics. The former is apparently a new kind of elementary particle yet to be detected in an Earth-bound laboratory, while the latter is a near-uniform energy field that is currently accelerating the expansion of the Universe. Major observational and experimental programmes at several MPG institutes are designed to clarify the nature of these dark components, and simulations of cosmic structure formation are required to understand how their properties affect, and thus can be constrained by, the things that we can observe [4, 9].

Precision experimental tests over the past few decades, including many by MPG researchers [3], have shown striking agreement with Einstein’s general relativity. But one of the most important predictions of the theory, the existence of gravitational waves, has never been directly verified. MPG scientists, in collaboration with researchers in the USA, UK, France and Italy have developed and now operate detectors of gravitational waves, GEO-600 (in Germany) LIGO (in the USA) and VIRGO (in Italy) which have become now so sensitive that first direct gravitational wave detection is increasingly likely. These detectors will provide a new window on the universe, allowing us to observe systems that do not emit electromagnetic waves. Possible sources include “chirp” signals from the inspiral and merger of two compact stars, continuous emission from rapidly-rotating deformed neutron stars, a stochastic background of gravitational wave noise produced during the big bang, and short bursts from Galactic supernovae or the mergers of massive black holes [6].

Studying the super-massive black hole in our own galaxy, Keplerian orbits of individual stars around the central mass where determined over eighteen years. With orbits coming very close (about 130 AU) to the central object it is clear that the a supermassive black resides in the centre of the Milky Way, which mass and distance could be determined very precisely [5]. More and even more massive black holes are found in the centre of other galaxies where they appear to play also an important role in the evolution of their host galaxies. In order to understand this interplay, such galactic nuclei need to be studied with exceptional resolution and detail from high radio to X-ray frequencies. In the early Universe, entire galaxies merged during their evolution so that their central black holes formed a binary system. While this should have produced a background signal of low-frequency gravitational waves that should be detected over the next decade with a special type of neutron stars called radio pulsars, it is only one aspect of the formation and early and recent evolution of galaxies.

Understanding galaxy formation is one of the key challenges in contemporary astrophysics, which is tackled both from large samples of galaxies at different redshifts or time as well as detailed studies of our own Milky Way Galaxy and its neighbors. The Galactic structure and evolution is probed through high-precision astrometry to study the dynamics and through the nucleosynthetic imprints in the chemical compositions of stars of different environments and ages. In the hierarchical merging prescription of galaxy formation in a Universe dominated by dark energy and dark matter, galaxies are continuously built up from smaller building blocks, a process that is still ongoing today and can be unraveled through large surveys.

Observations across the whole electromagnetic spectrum have revealed the dynamic nature of the sky and its rich variety of extreme events and emitting objects. New types of radio sources have been detected while previously unidentified gamma-ray sources have been identified as neutron stars. At even higher photon energies, new telescopes detect the optical Cherenkov radiation generated by charged particles in the particle cascades that high-energy gamma rays initiate in the Earth’s atmosphere. A key result of recent years was that sources of very high-energy particles are ubiquitous in our Galaxy and beyond, confirming the conjecture that such high-energy phenomena play a significant role in the cosmic matter cycle.

Understanding the cycle of matter from the interstellar medium to the formation of stars and back to interstellar space during the explosions of massive stars reveals the formation of the first elements and metals in the early universe and those that we find on Earth and everywhere else. The beginning of this cycle, the initial formation of stars, is a key process in the Universe, driving the chemical and physical evolution of entire galaxies. The formation of a first generation of very massive stars at high redshifts is expected to have led to re-ionization of the hydrogen gas and marked the end of the “dark ages” – the time before the first stars and galaxies lit up [10]. In our and other galaxies, massive stars drive the dynamical evolution trough their powerful winds and explode at the end of their lifetime as energetic supernovae. MPG astronomers simulate such explosive events with supercomputers and investigate the resulting chemical enrichment of the interstellar medium from which subsequent generations of stars are born; essentially all elements are forged in the fiery interiors of stars [1].

The high-speeds outflows driven by massive stars in the final stages of evolution serve as cosmic particle accelerators; particles are accelerated even more efficiently in the giant shock waves generated when stars explode or collapse to neutron stars or black holes. Energies reached by such cosmic particle accelerators dwarf by orders of magnitude all man-built accelerators, even the new LHC particle collider. At the same time, cosmic accelerators are much more efficient in converting input energy – such as the kinetic energy of a shock wave plowing through the interstellar medium – into particle energy. Throughout much of the Universe, there are roughly equal amounts of energy in thermal radiation, in interstellar magnetic fields and in high-energy particles; whether this is a coincidence or reflecting deeper principles is not fully understood. While the particles accelerated in distance regions of the Universe never reach the Earth, they can be traced and imaged through the electromagnetic radiation which they emit, all the way from radio waves to highest-energy gamma rays [2].

Despite their importance for cosmic evolution, the formation process of massive stars is poorly understood. Scientists in the MPG combine large-scale numerical simulations with dedicated infrared and (sub-) millimetre observations to reveal their formation mechanisms. The successfully launched Herschel Space Observatory, carrying instruments built at Max-Planck Institutes, (sub)millimetre facilities such as APEX, ALMA and the IRAM 30 meter telescope and the Plateau de Bure interferometer, and the active participation in building mid-infrared instrumention for the upcoming James Webb Space Telescope (JWST) will provide unique capabilities to characterize the earliest stages of massive star formation and to search for the first light sources in the Universe.

Our nearest star, the Sun, is of crucial importance for life on Earth as the basic source of energy, but also through the impact of solar irradiance variations on the climate and of solar eruptions on technical systems. The Sun also serves as the reference for many other astronomical objects throughout the universe, in particular other stars. Observations in the last decade revealed the Sun to be unexpectedly dynamic, but the processes responsible for this are in many cases not well understood [8].

Comparison between the planets in our Solar system helps to improve the understanding of our home planet. Space missions in the last decades found surprising results. Liquid water may have existed on other planets in earlier times, and microbiological life may have been or may be possible. They revealed dynamic processes in planetary atmospheres and partly unexplained planetary magnetic structures. Just like the Sun for other stars, the planets in the solar system serve as reference to which the properties of extra-solar planets are compared. Combined with the direct imaging of proto-planetary disks, we can put the origin of our own solar system in context and open the view on the structure of other worlds [7]. A variety of techniques have already led to the detection of more than 400 exo-planets, including the first planets in the Earth mass regime. MPG researchers are developing new techniques to search for planets and to image these with high-contrast observations. Transit spectroscopy from the ground and with the SPITZER satellite now, and in the future with the JWST, enables the characterization of exoplanet properties.

4. International activities

Research in astronomy and astrophysics is often done within international collaborations, in particular if the development of new, complex instrumentation is involved. This is also true for the research conducted at Max-Planck Institutes where powerful new telescopes and instruments are constructed and exploited that equip us with "eyes" to receive cosmic information from radio waves, infrared radiation, and very energetic photons like X- and gamma-rays with satellites and large ground-based telescopes.

At radio frequencies, the Low Frequency Array (LOFAR) is an international telescope that involves in addition to Max-Planck Institutes, colleagues in the Netherlands, France, Sweden and the UK. The European and Global VLBI Network literally connect radio telescopes in Europe and around the world. The European Pulsar Timing Array uses the 100-m Effelsberg radio-telescope in collaboration with colleagues in France, Italy, the Netherlands and the UK in an experiment to detect low-frequency gravitational waves. The APEX radio telescope is a collaboration between the MPG, ESO and Sweden and serves as a pathfinder experiment for ALMA and provides longer wavelength complementarity to the Herschel Space Observatory. ALMA brings together the European countries of ESO with the USA and Japan. At shorter wavelengths, the MPG is a major partner in the operation of and provides important instruments for the Large Binocular Telescope (LBT) on Mount Graham, USA, which is a joint project of three countries (USA, Italy and Germany) and nineteen institutes. MPG scientists also provide and develop infrared instrumentation for ESO telescopes such as the VLT in Chile with the Matisse and Gravity instruments and at (sub)millimeter wavelengths to the IRAM 30 meter and the APEX telescopes. At the same time, MPG scientists also work towards the construction of an European Extremely Large Telescope. The Cherenkov telescope HESS was constructed in Namibia by MPG researchers in collaborations with European partners in order to investigate cosmic gamma rays in the 100 GeV to 100 TeV energy range across the Southern sky; sources of high-energy gamma rays in the Northern sky are target of the MAGIC telescopes on the Canary Islands, an installation also driven my MPG scientists.

MPG researchers also participate in international satellite missions such as the PLANCK mission to study the evolution of the Universe and the origin of cosmic structure with precision measurements of the Cosmic Microwave Background. Similarly, the largest infrared space observatory launched to date, ESA's Herschel, carries instrumentation built by a number of MPG institutes. In order to solve the mystery of dark energy, MPG researchers also contribute to the development of EUCLID and plan to use THESIS to discover extrasolar planets. Involvement in international space missions continues to higher frequencies, such as with the X-ray observatories XMM-Newton of ESA and NASA's Chandra or with gamma-ray observatories such as FERMI or ESA's INTEGRAL

These activities extend to the gravitational wave spectrum, as scientists in the MPG play a major role in the construction, operation and exploitation of gravitational wave detectors including GEO600, LIGO, VIRGO and, in the future, the European Einstein Telescope and the space-born LISA detector. The MPG is a full member of the international collaboration sharing data and providing key subsystems. The joint Advanced LIGO project may be the first gravitational wave detector sensitive enough to 'guarantee' observations. In addition to developing and contributing technology, MPG scientists also play an active leadership role in the analysis and interpretation of the data, carried out by collaborations of hundreds of people.

The international collaborations are obviously not restricted to the development of instrumentation but in fact also include large joint projects in observational astronomy such as surveys, ambitious theoretical or numerical studies such as the Millennium Simulation led by MPG scientists or imposing data analysis tasks as the search for weak gravitational wave sources in the data streams from multiple instruments. Joint international centres like the UCB-MPG Center for International Exchange in Astrophysics and Space Science, established in collaboration with the University of California, Berkeley and seven Max-Planck institutes are aimed to foster direct interaction between international scientists.

5. Research opportunities and needs

The open questions in our understanding of the Universe will be at the focus of activities at Max-Planck Institutes involved in astronomical/astrophysical research. The eventual detection of gravitational wave signals, unprecedented computer power and all its implications for modeling and data analysis, together with a phalanx of powerful new telescopes and instruments does not only promise to answer these but will also make this a hugely important in the history of astronomy.

With the next generation of infrared instruments at the European Extremely Large Telescope (ELT), we expect to be able to detect young exo-planets in their formation stage and to obtain the first observation of the inner regions of a proto-planetary disk with high-resolution near-infrared spectroscopy, revealing Keplerian rotation and an inner gap, probably formed by a planetary system. A similar huge increase in sensitivity is also expected at radio frequencies with the Square Kilometre Array (SKA) which will not only survey one billion galaxies to solve the Dark Energy mystery, but will also be used to detect the first stars and black hole in the Universe, determining the time when the Universe lit up, as well as answering the question about the origin of cosmic magnetism. The revolution in radio-astronomical techniques will also allow us to monitor the dynamic sky and to detect the signals of extreme events on cosmic scales.

For gravitational wave detection, the MPG is currently playing a major role in a European design study for a third-generation ground-based instrument, the Einstein Telescope (ET), to follow the operations of Advanced Virgo and Advanced LIGO. ET holds the promise to detect most of the binary star mergers within our universe, at the rate of a few mergers per hour, providing a complete catalog of all compact binary stars and revolutionizing the understanding of stellar evolution. Simultaneous observations at high-energies during the final moments of inspiral and merger should paint a detailed picture of this process, and resolve long-standing mysteries about the origins of gamma-ray bursts from cosmological distances.

Similarly, in space, the MPG plays a lead role in the design of the space-based LISA detector planned to launch after 2018 as a NASA/ESA partnership project. Complementary to ground-based detectors, LISA will be sensitive to low frequencies in the 1mHz-0.1Hz range, observing solar-mass compact binary star systems several years before they merge violently together, as well as massive and super-massive black holes undergoing inspiral and merger.

The success of the HESS telescope promises even greater results for the Cherenkov Telescope Array (CTA) which will explore our universe in very high energy (VHE) gamma-rays and investigate cosmic non-thermal processes with an order of magnitude increased sensitivity, broader energy coverage, larger detection area, improved angular resolution, and enhanced all sky survey capability. In space, future missions like e-ROSITA mission will add to MPG's scientists' capability to study the universe.

The activity and variability of the Sun and other solar-type stars is strongest in their outer atmosphere, but has its origin at the surface and in the interior. For improved insight an integral approach covering the different layers and their interaction is required, with the solar/stellar magnetic field as the main driver being in the focus of research. To understand the generation of the magnetic field in the interior together with its transport towards the surface requires knowledge of the convection, rotation and magnetic field. These topics will be addressed by helio-seismology missions like the Solar Dynamic Observatory (2010+), and Solar Orbiter (2017+) and the recently launched Kepler satellite for other stars. Developing sophisticated models for these physical processes in the stellar interior will be a key factor for the interpretation.

Small bodies in the solar system carry primordial material and thus provide information about the formation of the planetary system. New insight is expected from the missions ROSETTA and DAWN, which will investigate and analyze a cometary nucleus composition and the structure of two asteroids, respectively. Questions of exobiology will be addressed by an instrument analyzing organic compounds onboard the EXOMARS mission to Mars (launch 2018), but also by Rosetta. The interior and the magnetic field of Mercury will be analyzed by a laser altimeter within the BepiColombo mission (arriving 2019). Together with such data from Jupiter and Ganymede and a strong theoretical effort, new insights into planetary magnetism are expected. Planetary surfaces and atmospheres will also be explored by instruments aboard MARCO POLO (targeting a near-Earth asteroid) and the EJSM mission to Jupiter (2020+).

6. Expected outcome and benefits

Over the next decade, in order to answer the big questions about our – and the Universe's – origin and future, scientists working at the Max-Planck institutes will study objects and phenomena in front of our door step to the far reaches of space and time. Using new techniques to peer inside the opaque Sun to study the physical processes responsible for the Sun's active and energetic phenomena, we will learn how these affect the Earth, our (technical) environment and our global climate. Comparing the properties of planets and the search for water in the solar system and beyond, as the basis for extraterrestrial life is important for understanding what makes the Earth special. Combined with the direct imaging of proto-planetary disks, we can put our own origin in context and open the view on the structure of other worlds. In the coming years, MPG scientists will develop new techniques to search for extrasolar planets and to characterize their properties. An improved understanding of stars and their explosive deaths at different cosmic epochs will explain how, when and where the chemical elements that we are all made up of were produced.

On farther scales, we can expect to study the sky using gravitational waves and should expect to probe theories of gravity in very strong fields to an unprecedented level. This will go in hand with unique measurements of black hole properties across the whole electromagnetic spectrum and other observations of extreme objects. Ultimately we should be able to identify the nature of dark matter and dark energy by establishing or refuting the reality of dark energy - does dark energy (if it is real) interacts with dark matter and is new physics required to explain them?

It is clear that with new capabilities and new insight, new mysteries and new questions will arise. We will discover new types of sources, new phenomena and with it a new and better understanding of the cosmos that we will live in. We can expect those new questions tomorrow to be even more exciting and fascinating than those we try to answer today.

7. Future perspectives

It's been 400 years since humans started to explore the Universe with the help of more than just the naked eye. At the beginning it was Galileo Galilei with his telescopes, but since then astronomers continuously constructed bigger, far more powerful instruments. The reward was a wealth of knowledge about our place in the Universe, about the birth of stars and planets and the evolution of galaxies and the Universe as a whole. However, more knowledge has lead to even more, even bigger questions from the origin of life, over the understanding of extreme objects and events in the Universe, to the presence of previously unknown forms of matter and mysterious forces. In truly exciting times to come, MPG's researchers promise to unlock some of the greatest mysteries of this exciting laboratory that we call Universe. Over the next decade, scientists working at the Max-Planck institutes will study objects and phenomena in front of our door step to the far reaches of space and time. The universe will be studied in ever greater detail enabled by technological progress: bigger and faster CCD cameras, lighter hence bigger and faster mirrors, arrays of new types of radio telescopes and new satellites allow fast and prompt observations of signals which can not only be seen in electromagnetic light but also in the signals received by particle or gravitational wave detectors. In fact, for the continued exploration of energetic phenomena in stars, stellar remnants and galaxy clusters, the whole sky will be monitored with unprecedented regularity and time resolution, revealing a truly dynamic and eventful Universe. Many of the expected advances in our understanding of our Universe are directly coupled to the development and availability of new technological capabilities. This does not only apply to the construction of new telescopes or instruments but also includes the continued development of algorithms and continued access to top-end computing resources. In most cases, harnessing the world's best supercomputers will be critical to support the acquisition, reduction, archiving and publication of data from new experiments, but it is also vital for the theoretical modeling and numerical simulation needed to understand their physical meaning. Overall, we can expect the largest progress from the interplay between different aspects of "traditional" astronomy using new upcoming facilities in the electromagnetic spectrum with neutrino detectors and the emerging field of gravitational wave astronomy. The next decade will see the operation of advanced gravitational wave detectors, and important progress in even more sensitive ground-based and space-based detectors will be made. Combined with unprecedented computer power and all its implications for modeling and data analysis, together with a phalanx of powerful new telescopes and instruments does not only promise to answer Big Questions in our understanding of the Universe but will also make this a big decade in the history of astronomy.

<u>References (those to certainly include are in bold)</u>

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Images

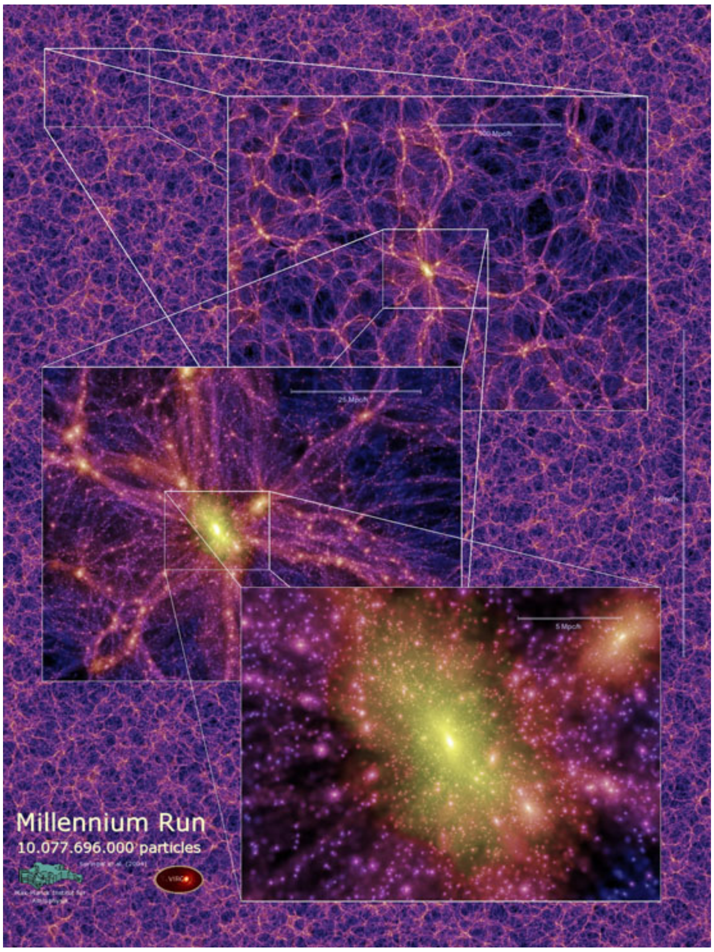

Fig 1: Result of the Millennium simulation addressing the formation of structure in the Universe. A projected density field for a 15 Mpc/h thick slice of the redshift z=0 output. The overlaid panels zoom in by factors of 4 in each case, enlarging the regions indicated by the white squares. Yardsticks are included as well.

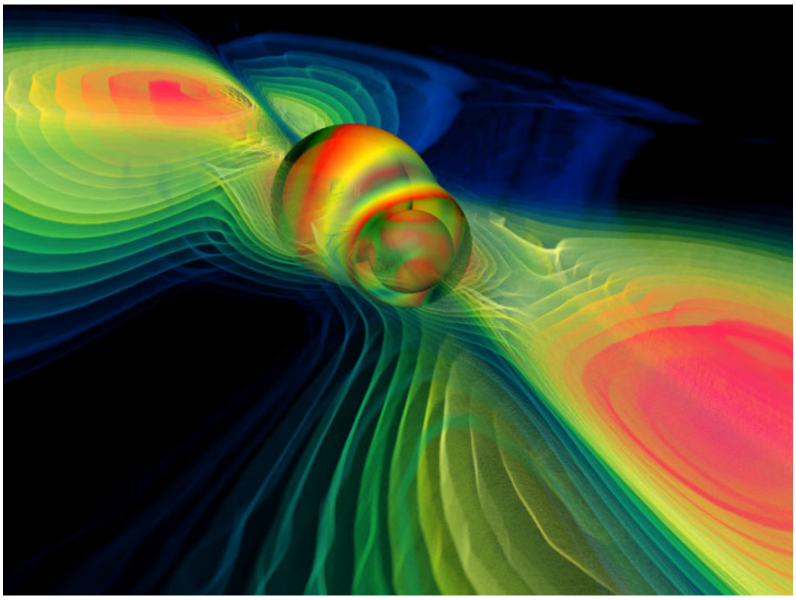

Fig 2: Numerical simulation showing the gravitational radiation emitted by the violent merger of two black holes.

Fig 3: The Large Binocular Telescope (LBT)

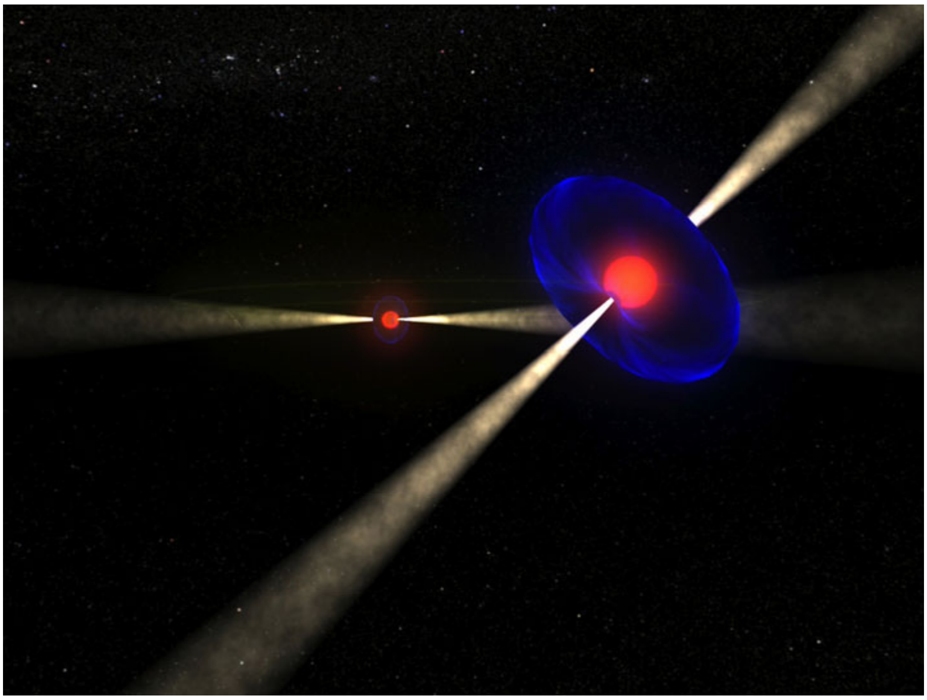

Fig 4: Artistic impression of the Double Pulsar system that is exploited as a unique laboratory for gravitational and neutron star physics

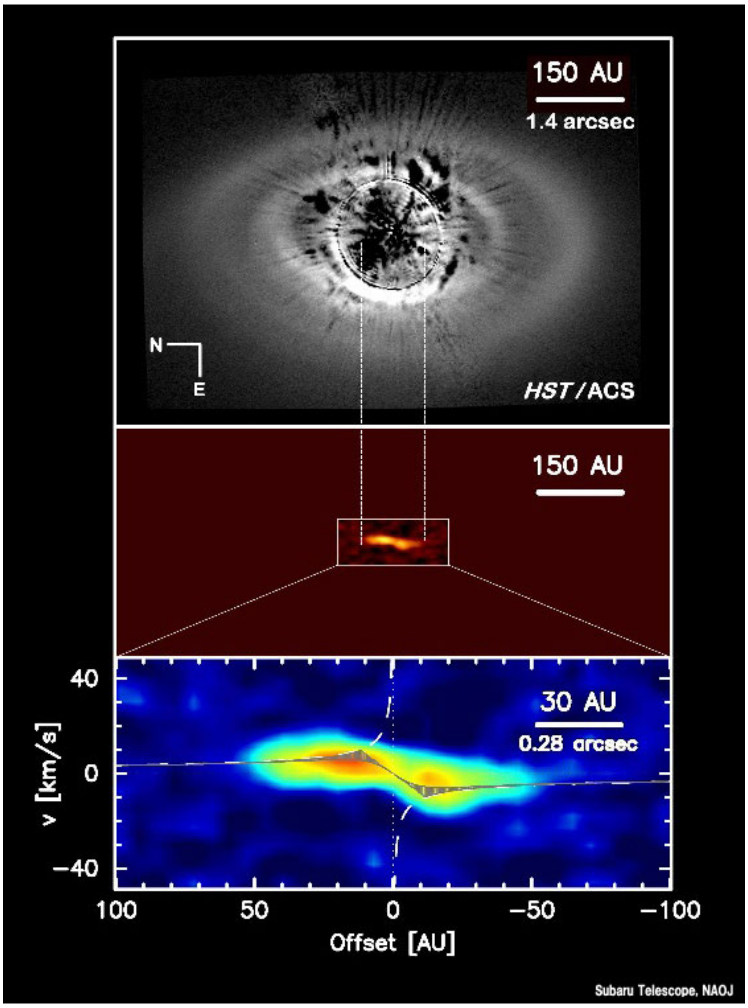

Fig 5: The upper part of the figure shows the *HST/ACS* image of the disk around HD 141569A (Clampin et al. 2003). The lower part shows the CO emission and reveals an inner cavity with 11 AU radius and a Keplerian velocity curve (MPIA - Goto et al. 2006).

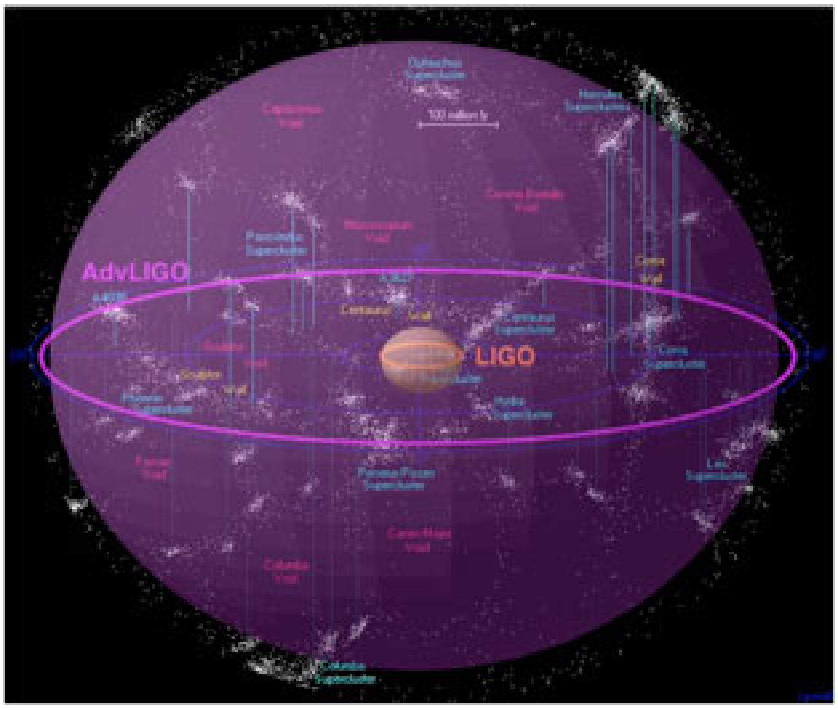

Fig 6: Illustration showing the increased observational range of the Advanced LIGO and Advanced VIRGO detectors in comparison with the current (2009) state-of-the art.

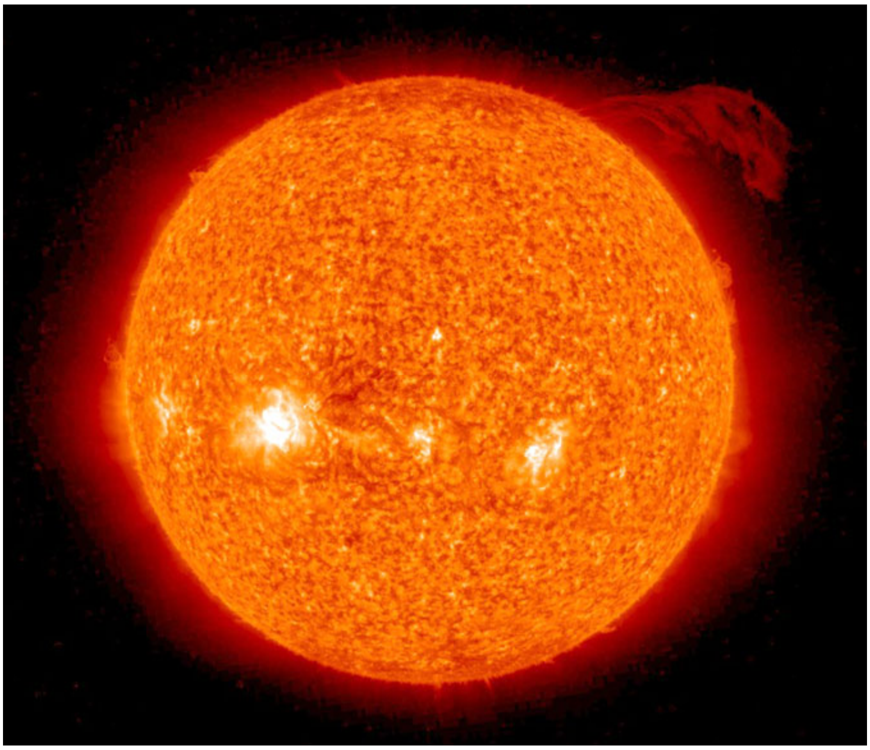

Fig 7: The Sun imaged in the extreme ultraviolet by the STEREO spacecraft while an eruptive prominence broke away from the Sun on June 6, 2007.

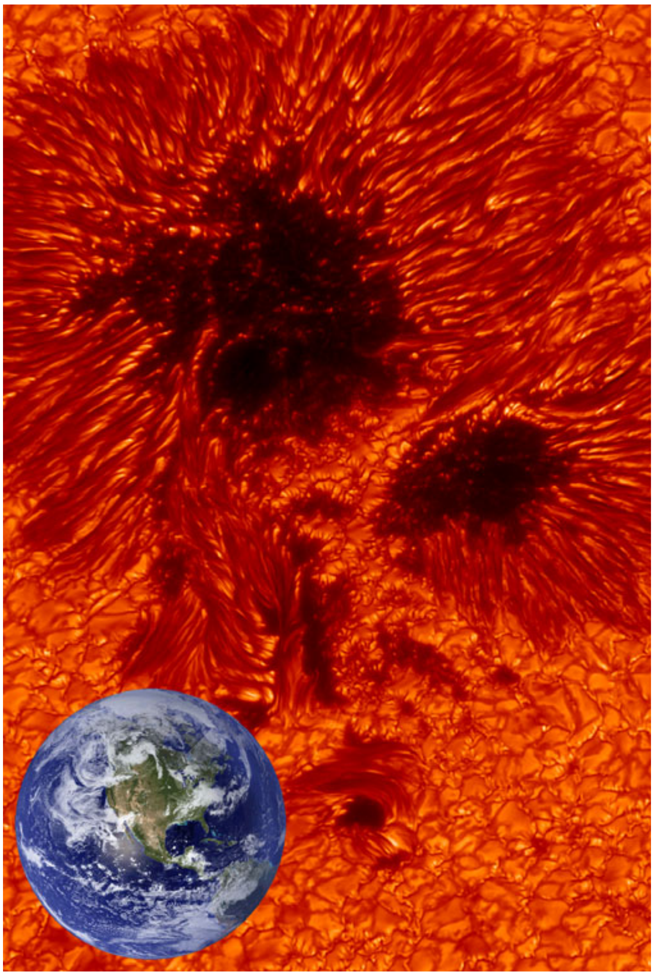

Fig 8: A sunspot as seen by the SST on La Palma on Aug 13, 2006 at 436nm. The terrestrial globe was added for comparison of size

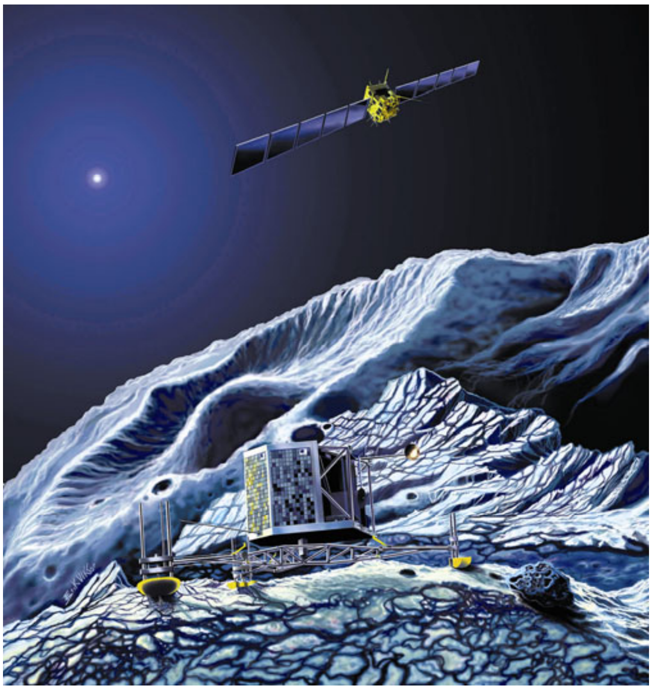

Fig 9: Rosetta mission to comet "67P/Churyumov-Gerasimenko". Visualization of the landing unit on the cometary nucleus.

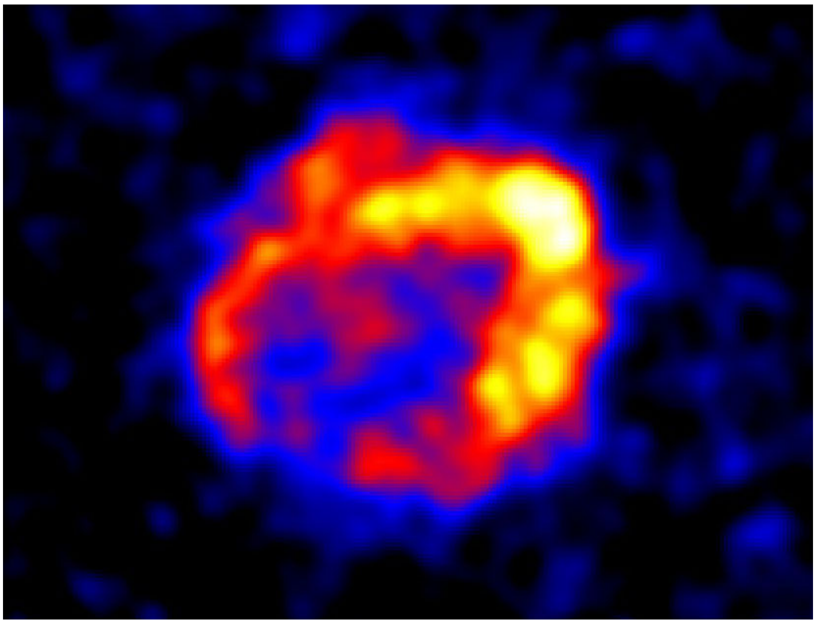

Fig 10: A supernova remnant glowing in high-energy gamma rays. The roughly circular shell tracing the shock wave of the explosion extends over tens of light years, covering roughly twice the angular diameter of the moon. This observation confirms that shock waves act as cosmic particle accelerators.

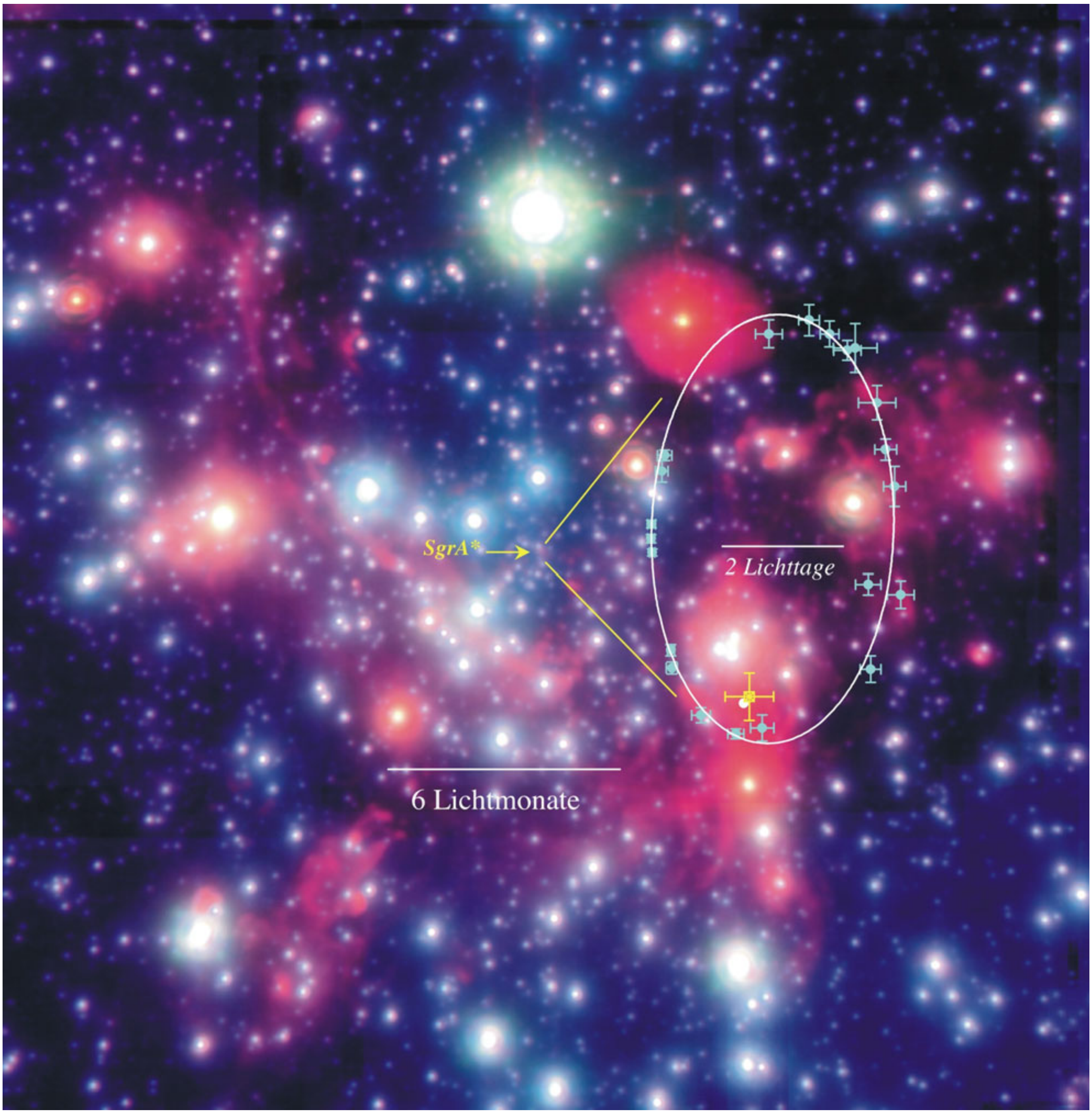

Fig 11: The Galactic Centre and the measured orbit of a star moving around the central black hole.

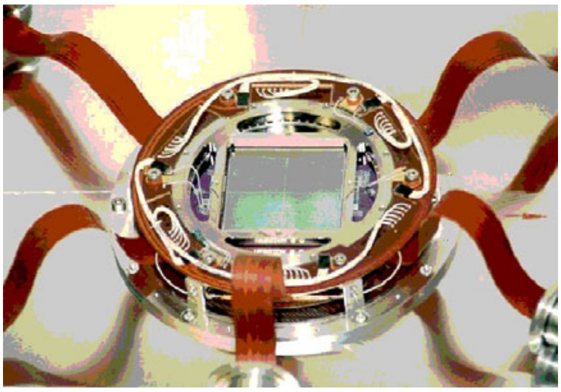
Fig 12: Detector chip developed by MPG researchers

Fig 13: VLT Laser

Fig 14: HERSCHEL observatory