EXCELLENCE CLUSTER UNIVERSE

ORIGIN AND STRUCTURE OF THE UNIVERSE

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Technische Universität München

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Excellence Cluster
Universe

Max-Planck-Institut für Astrophysik

Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

IPP Max-Planck-Institut für Plasmaphysik

FOREWORD

Photo: Andreas Heddergott

PROF. STEPHAN PAUL

Photo: Astrid Eckert

PROF. ANDREAS BURKERT

How did the universe come into being? Why do stars and galaxies exist? Where does the oxygen we breathe come from – and the iron in our blood? What are black holes made of? What does the future hold for our universe? These are questions that many people ask themselves when they turn their gaze heavenward or think about the universe's future and past.

To get closer to the answers, the Excellence Cluster Universe was founded in 2006. Because the questions are related to many different disciplines of physics, the collaboration of experts is needed: of cosmologists, who deal with the origin and the evolution of the universe, of particle physicists, who explore the elementary particles and fundamental forces, and of astronomers and astrophysicists, who investigate the celestial objects and phenomena. Therefore, scientists from various institutes are members of the Excellence Cluster Universe, coming from the Technische Universität München (TUM), the Ludwig-Maximilians-Universität München (LMU), the Max Planck Institutes for Physics (MPP), Astrophysics (MPA), Extraterrestrial Physics (MPE) and Plasma Physics (IPP), the European Southern Observatory (ESO) and the Leibniz Supercomputing Centre of the Bavarian Academy of Sciences. Overall, more than 250 researchers work together.

The major scientific questions are assigned to seven Research Areas within the Excellence Cluster Universe. Since 2012, two new important pillars have been established: the computing centre C^2PAP and the international visiting research centre MIAPP. With this brochure, we would like to introduce you to many of the people working at the Excellence Cluster Universe – and especially to the questions, experiments and tasks they deal with. For those of you who want to learn more about our universe, we would like to recommend our exhibition 'Evolution of the Universe' at the Deutsches Museum that was realized by the Excellence Cluster Universe together with its partner institutions. More about our exhibition can be found at the end of this brochure.

We wish you an informative reading.

Prof. Stephan Paul
Coordinator of the Excellence Cluster Universe

Prof. Andreas Burkert
Co-Coordinator of the Excellence Cluster Universe

UNRAVELLING THE BEGINNING OF OUR UNIVERSE

Most physicists assume that our universe emerged with a 'Big Bang'. This means, our universe originated from a moment of maximum energy in the smallest space. This beginning marks not only the origin of matter, but also the initiation of space and time. But which physical laws prevailed at that extreme moment?

The two most important physical theories of the 20th century, quantum physics and general relativity, deliver a description of our world for very small and very large dimensions.

Max Planck claimed that the basic physical values energy, length and time cannot be randomly small, but must have smallest units instead. Planck's constant h is the measurement for the smallest energy portion. The smallest unit of length is 10^{-35} meters, the shortest unit of time 10^{-43} seconds, which corresponds to the time a beam of light takes to pass this length. This smallest unit of time is therefore the earliest moment our universe can be described by using physical laws.

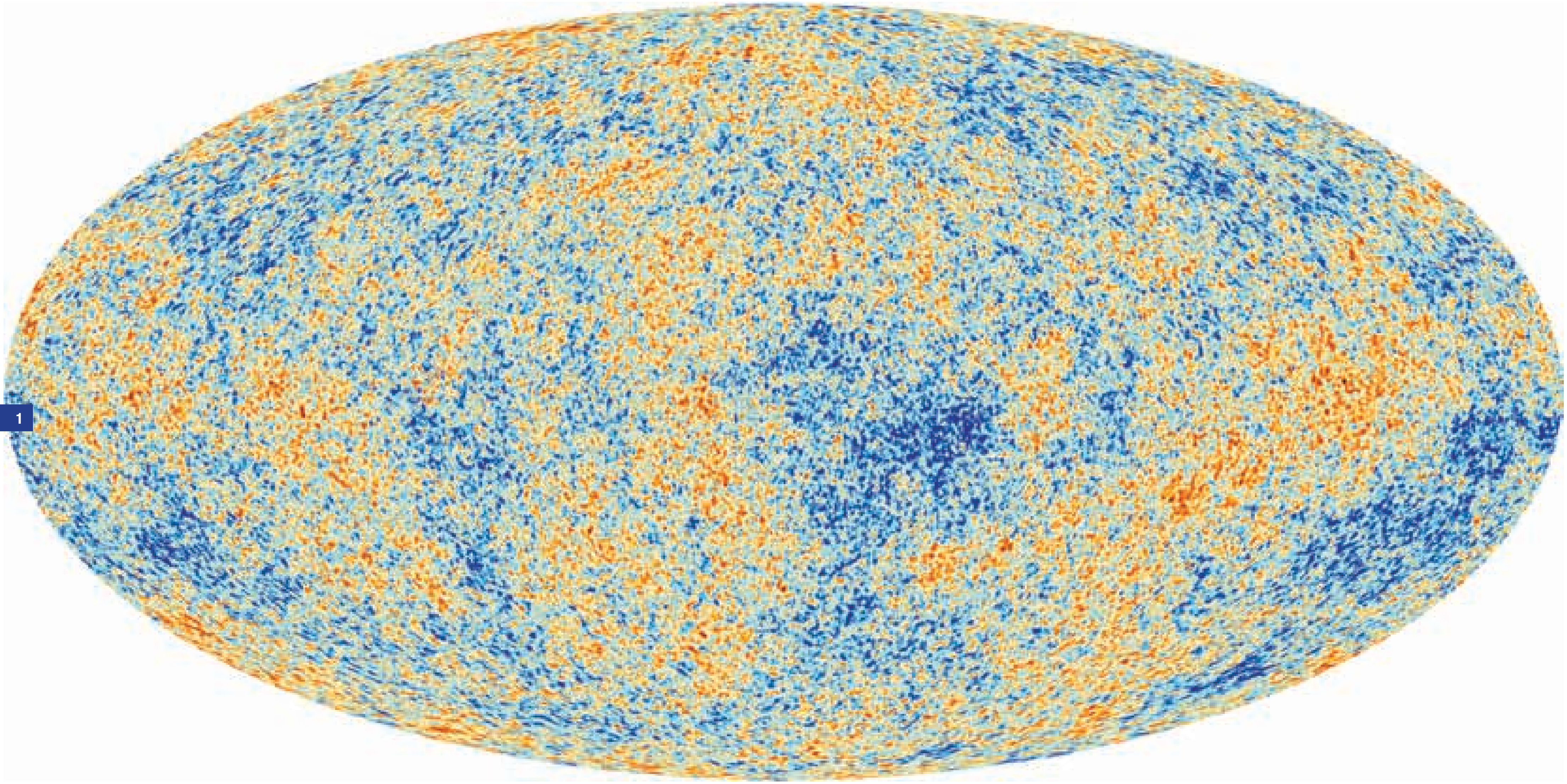
With his general theory of relativity Albert Einstein, too, has revolutionized our understanding of time, space and energy. Space and time are not the universe's stage on which the matter performs its play. The space-time continuum itself is part of the performance, which is affected by matter and in turn influences the motion of matter.

Both theories have been perfectly confirmed with experiments. However, for the moment of the Big Bang they deliver contradictory results. Therefore, the physicists are looking for a new theory that connects both. Such a theory should also answer the question of the origin of the forces. Two of the four fundamental forces of physics are familiar to us: gravity and the electromagnetic force. The other two, the strong and the weak nuclear force, provide the firm cohesion of the constituents of atomic nuclei, but play no perceivable role in our daily life. But how could the four fundamental forces have emerged from the primordial force at the beginning of the universe?

In **Research Area A**, the Excellence Cluster Universe scientists are working to resolve these theoretical questions of the origin of our universe.

From left: Daniel Jaud – *PhD student (LMU)* | Patrick Vaudrevange – *Research Fellow (TUM)* | Ilka Brunner – *Professor (LMU)*
Photo: Astrid Eckert


What happened
at the beginning of our
universe?



1 | Traces of the Big Bang: From everywhere in the universe we are reached by light that was emitted about 400,000 years after the Big Bang and since then has moved almost unhindered through the universe. At that time, the cosmos was very hot with several thousand degrees Celsius. The expansion of the universe led to the fact that this light has lost some of its energy and can now be received as cosmic microwave background with a temperature of minus 270 degrees Celsius (or precisely 2.7 Kelvin). Recently, the Planck space telescope has measured this microwave background with the highest precision across the entire sky. The colours represent tiny differences in temperature in the dimension of 0.000001 degrees Celsius (blue: colder, red: warmer). They were created by small irregularities in the distribution of matter in the early universe. The irregularities are the source of the large-scale cosmic structure of today's universe, from galaxies and galaxy groups to clusters and to the extensive network of galaxy filaments. *Photo: ESA and the Planck Collaboration*

RESEARCH PRIORITIES

Testable predictions of the string theory

The string theorists assume that the elementary particles known to us are harmonics of a string-like object with a length of 10^{-34} meters. However, these strings exist mathematically only in ten or eleven dimensions. Four of them are known to us as the time and space dimensions, supplemented by six or seven ‘extra dimensions’ which, so the theory, are wrapped up so tightly that they are hardly noticeable. These extra dimensions are considered to be the strength as well as the weakness of the string theory: Their length units are relevant for the origin of the universe, but difficult to verify experimentally. However, the string theory is supported by the fact that it is uniquely able to unite quantum physics and general relativity as well as the four fundamental forces. The scientists of the Excellence Cluster Universe are working on hypotheses of the string theory that are verifiable with today’s particle accelerators like the Large Hadron Collider (LHC) at CERN.

String cosmology

According to the speculative, but very popular theory of inflation, our universe has expanded about 10^{-34} seconds after the Big Bang by a factor of 10^{26}. A phase of cosmic inflation could explain some of the amazing characteristics of our universe, like for example that our universe has no measurable space curvature and, at large dimensions, looks the same in all directions. However, the theorists have no idea what could have caused such a sudden expansion. They therefore try to derive inflation models from string theory and compare these models with the experimental results about the early universe found in the cosmic microwave background by the Planck satellite. In addition, the physicists want to study how dark matter and dark energy can be incorporated into string theory.

Quantum gravity

There is no theory for quantum gravity which has been experimentally proven. The electromagnetic force is described in Quantum Electrodynamics (QED), the strong nuclear force in Quantum Chromodynamics (QCD) and the weak nuclear force together with Quantum Electrodynamics in the theory of Electroweak Interaction (EWI). A ‘theory of quantum gravity’ is still lacking. The theorists are working to investigate a new methodological approach to further extend it to quantum field theories to get closer to quantum gravity.


Do
we
know
all
elementary
buil-
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blocks
of the
universe
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SEARCHING FOR NEW PARTICLES

With the discovery of the Higgs particle, all elementary particles of the Standard Model of particle physics have been confirmed. During the last 100 years, 18 fundamental building blocks of the universe were predicted by physicists, and have subsequently been confirmed in experiments.

These include twelve matter particles, the quarks and leptons, and five force particles, which mediate the fundamental forces between the matter particles: the photon for the electromagnetic force, the gluon for the strong and the two W bosons and the Z boson for the weak nuclear force. The Higgs particle was the last to be discovered in 2012, the existence of this particle that imparts mass to the elementary particles was predicted 50 years ago.

But are these all of the fundamental building blocks? Physicists suspect that the universe hides more elementary particles. And indeed, there are some indications: Gravity is missing within the Standard Model, due to the absence of a force particle of gravity. Furthermore, we know about another substance in the universe, which is evident only through its gravity. There is some indication that this dark matter is composed of a yet unknown kind of particle.

Additionally, the Standard Model lacks the answer to the question why there is so much matter in the universe, but virtually no antimatter. From the energy of the Big Bang, particles and their antiparticles must have emerged in pairs only to be immediately annihilated and converted into energy again. Some particles have apparently remained – the matter from which the visible universe is built – otherwise there would only be light in the universe. On the basis of the amount of light, physicists can estimate the excess matter: After the annihilation of one billion pairs of particles and antiparticles, one matter particle remained. Why this is the case is still unknown.

There are several theories that attempt to address the problems of the Standard Model. The most elegant one is Supersymmetry. Within this theory, the distinction between matter and force particles disappears. As a result, the number of particles is doubled and each known elementary particle is assigned a supersymmetric partner. Supersymmetry also provides ideal candidates for dark matter. Is Supersymmetry the new model, in which the old Standard Model of particle physics will converge? Or is there another substructure with still unknown fundamental building blocks? The physicists don't know yet, because so far they haven't found any particles beyond the Standard Model.

Therefore, the particle physicists from **Research Area B** of the Excellence Cluster Universe are looking in all directions for further fundamental building blocks of the universe.

back row, left to right: Ralf Hertenberger – *Senior Scientist (LMU)* | Christopher Unverdorben – *PostDoc (LMU)* | Frank Simon – *Senior Scientist (MPP)* | Otmar Biebel – *Professor (LMU)*
front row, left to right: Wolfgang Hollik – *Director (MPP)* | Jeanette Lorenz – *PostDoc (LMU)* | Dorothee Schaile – *Professor (LMU)* | Alexander Mann – *PostDoc (LMU)*
Hubert Kroha – *Senior Scientist (MPP)*
in front: Frank Steffen – *Staff Scientist (MPP)* *Photo: Astrid Eckert*

RESEARCH PRIORITIES

Beyond the Standard Model

There are strong indications that the Standard Model of particle physics is only an incomplete description of the physical reality. Physicists expect that looking at even higher collision energies at the Large Hadron Collider (LHC) at CERN, new, yet unknown fundamental particles will be revealed. For this, after the first run in the years 2009 to 2013, the LHC was upgraded so that in the second run, which started in 2015, particles collide with twice the energy of the first run. Whether this energy is high enough and one of the proposed new theories will prove to be correct, is to be seen. To delve into theory and experiment for new physics beyond the Standard Model is a main focus of the Excellence Cluster Universe.

Future particle accelerator experiments

The confirmation of the Standard Model of particle physics is the result of many generations of particle accelerator experiments and the successful interplay between verifiable theories and experiments. Higher and higher collision energies have made the discovery of new particles possible. There are many reasons why today's collision energies should give evidence of new particles. In order to look further beyond the Standard Model, even higher energies will be required. Therefore, physicists of the Excellence Cluster Universe are developing concepts and technologies for future particle accelerators and detectors.

1 The 18 elementary particles of the Standard Model of particle physics: All particles of this model – twelve matter, five force and the Higgs particle – were detected in experiments and are currently regarded as the fundamental building blocks of the universe. *Photo: wikipedia/MissMJ*

2 Looking into the tunnel of the particle accelerator LHC at the European Organization for Nuclear Research CERN in Geneva: In a ring with a circumference of 27 kilometres, 100 metres below the ground, particles are accelerated to nearly the speed of light. *Photo: Claudia Marcelloni di Oliveira/CERN*

3 Preparation for the second run of the LHC: View of the calorimeters of the ATLAS detector just prior to the closure in December 2014; the detector is 46 meters long and 25 meters high and is dedicated to the search for new fundamental particles. *Photo: Jaques Fichet/CERN*

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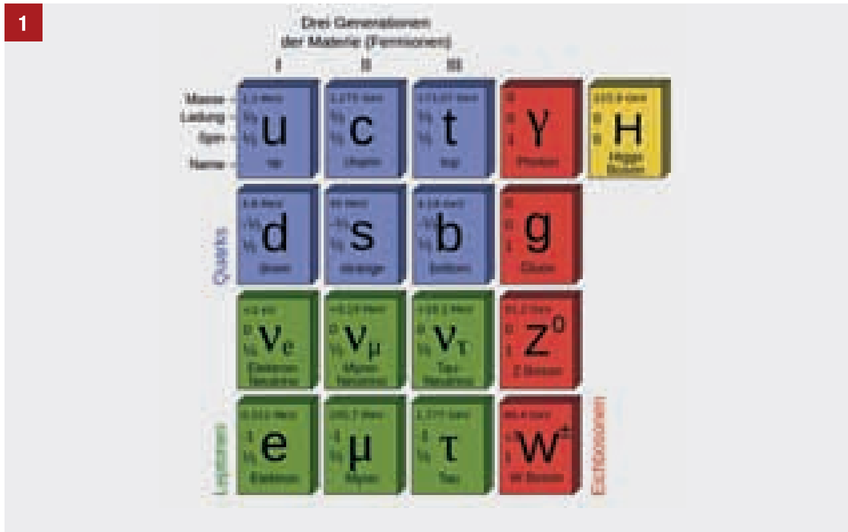

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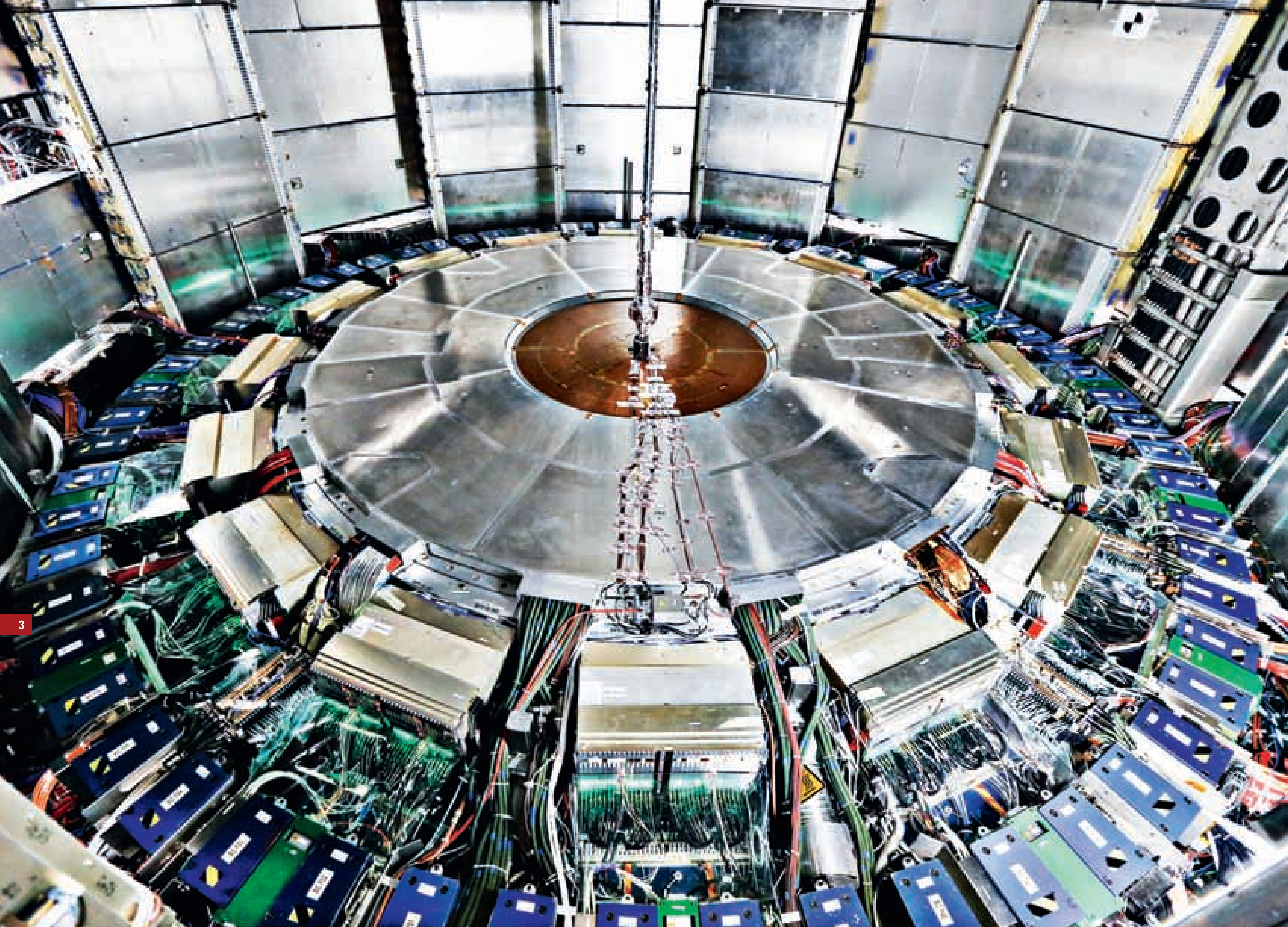

3


Are there
any
particles
with
yet
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?

TRACING NEW PARTICLE CHARACTERISTICS

Physicists have divided the elementary matter particles into two groups with six members each, according to their characteristics: the quarks (up, down, charm, strange, bottom, top) and the leptons (electrons, muons, tauons and their associated neutrinos). Not all of them are found in equal measure in the universe: In our cosmos there is, above all, light, hence photons, and the lightest of the matter particles, the up- and down-quarks and the electrons that make up the atoms, and, finally, the neutrinos.

The Standard Model of particle physics describes exactly how all these particles behave: Quarks are never found alone, but in groups of two or three. The protons and neutrons in the atomic nuclei, for example, are made up of three quarks each. Furthermore, there are unstable particles that consist of quark-antiquark pairs which emerge in the process of cosmic radiation.

The fundamental building blocks identified so far are called ‘elementary’. However, according to the Standard Model, they can be created and destroyed and even transformed into one another. In our everyday understanding forces can not change the character of a body, only accelerate it or slow it down. The weak nuclear force, though, can change the nature of a matter particle and transform a quark into another quark of different mass and charge, the same applies to a lepton.

The physicists are confident that the Standard Model of particle physics is only an approximation to the laws of nature, only a part of the truth. As regards neutrinos, there are a number of indicators for new physics: Neutrinos should have no mass, but experiments reveal the opposite. Additionally, it remains a mystery how these particles transform into one another. Finally, there is the hypothesis that neutrinos are their own antiparticles. Neither of these phenomena fit into the Standard Model.

In the **Research Area C**, physicists are investigating the fundamental constituents of matter, searching for new characteristics that are not predicted by the Standard Model and that could be evidence for new elementary particles.

back row, left to right: Kai Krings – *PhD Student (TUM)* | Joost Veenkamp – *Student (TUM)* | Peter Stangl – *PhD Student (TUM)* | Björn Garbrecht – *Professor (TUM)*
front row, left to right: Anna Bernhard – *PhD Student (TUM)* | Laura Vanhoefer – *PhD Student (MPP)* | Elisa Resconi – *Professor (TUM)*
Andrzej Buras – *Professor (TUM)* | Martin Jung – *Research Fellow (TUM)*
in front: Christoph Niehoff – *PhD Student (TUM)* *Photo: Astrid Eckert*

RESEARCH PRIORITIES

Physics with neutrinos

Electron neutrinos are produced in great numbers in nuclear fusion processes inside the sun. First investigations of the neutrino flux from the sun in the 1960s showed that only about one third of the expected electron neutrinos arrive on Earth. Today, the reason for this solar neutrino deficit is known: The electron, muon and tauon neutrinos are able to transform into one another. As this transformation occurs within certain periods, physicists refer to it as neutrino oscillations. However, the physical laws of the neutrino oscillations are not yet fully understood. Scientists at the Excellence Cluster Universe are involved in a variety of neutrino experiments dedicated to the exploration of the neutrino's fundamental characteristics, including Borexino at the Gran Sasso underground laboratory in Italy, Double Chooz at the nuclear power station Chooz in France, IceCube at the Amundsen-Scott South Pole Station in the Antarctica and Juno, an experiment that is currently being set up at the Jiangmen underground laboratory in China. Moreover, neutrinos are also crucial as messengers of high energy cosmic events such as stellar explosions.

The double nature of neutrinos

Contrary to the Standard Model, it has been experimentally attested that neutrinos have vanishingly small masses (but they have not been measured exactly so far). An explanation for these non-zero masses could be that neutrinos are their own antiparticles, called Majorana particles. Theoretical expansions of the Standard Model of particle physics also suggest the Majorana nature of neutrinos. If this hypothesis proves to be true, scientists could get a better understanding of the origin of our universe and could better understand the origin of the matter-antimatter asymmetry. Physicists of the Excellence Cluster Universe are significantly involved in two independent experiments to test the double nature of neutrinos: Gerda in the Gran Sasso underground laboratory in Italy and EXO-200, located in the US state of New Mexico. Both teams of researchers have published the world's most precise measurements, but they could neither confirm nor refute the hypothesis. The experiments are being continued.

B physics

A certain group of quark-antiquark-pairs are particularly well suited for testing the Standard Model of particle physics: the B mesons. They are produced by the collision of electrons with their antiparticles, the positrons, in large particle accelerators and contain at least one bottom quark. Their lifespan is only one trillionth of a second and then they decay – there are hundreds of ways on how they do this. The Standard Model of particle physics precisely predicts the details of these decays. Deviations may therefore give indications of new particle characteristics or new particles. Among other scientists at the Excellence Cluster Universe, a junior research group systematically explores B decays in search for conspicuous features.

1

Physics with neutrons

A research group at the Excellence Cluster Universe has set up an experiment to measure the charge distribution within neutrons – a phenomenon that physicists refer to as electric dipole moment. Neutrons are composed of three quarks, with their charges cancelling each other outwardly. According to the Standard Model of particle physics, only an extremely small charge displacement of the quarks should result. Theoretical expansions of the Standard Model predict however much higher electric dipole moments of the neutron. The measurement setup developed at the Excellence Cluster Universe is so sensitive that it will be possible to test these hypotheses for the first time.

1 | Lots of unsolved mysteries: Professor Stefan Schönert (left) and Professor Lothar Oberauer (both TUM) are working on the optimization of detectors for neutrino experiments in the clean room of the underground laboratory located at the research campus Garching. *Photo: Astrid Eckert*

2 | Research work in the smallest magnetic field of the solar system: Professor Peter Fierlinger (left) and the PhD student Michael Sturm (both TUM) are preparing a highly sensitive experiment which will make it possible to measure the charge distribution of the three quarks in neutrons for the very first time. *Photo: Astrid Eckert*

2

RECONSTRUCTING THE EVENTS AT THE BEGINNING

The answers to questions how and why our universe began to exist, are only speculations. However, experiments allow scientists to quite accurately reconstruct what happened in the first three minutes of our universe. This reconstruction starts a split second after the Big Bang, more precisely at about 10^{-30} seconds. With 10^{25} Kelvin, the universe was incredibly hot and expanding with great force. Particles could not fuse at these temperatures. Instead, the quarks and their force particles, the gluons, could move almost independently from each other. Among physicists, this 'primordial soup' of the universe is called the quark-gluon plasma.

After about 10^{-6} seconds, the temperature was at 10^{13} Kelvin and the gluons succeeded in merging the first quarks. The first protons and neutrons were formed. The universe further cooled down and diverged; for one second, the conditions were just right so that protons and neutrons could constantly convert into each other. These conversions released neutrinos in large numbers.

After about ten seconds, the temperature was suitable to start a first phase of nuclear fusion and protons and neutrons formed the first hydrogen atomic nuclei. This phase ground to a halt after three minutes. The remaining neutrons decayed shortly afterwards to protons, electrons and neutrinos. At the end of these first three minutes, the matter existed as protons (75 percent), the later hydrogen atomic nuclei, as well as helium (25 percent) and traces of lithium and beryllium nuclei. For a few hundred million years, they were the only chemical elements that populated our universe - until the first stars formed and a new phase of nuclear fusion set in.

The sequence of these three minutes is an integral part of the Standard Model of particle physics. However, many details are not yet understood and it was not possible to explain them theoretically and/or confirm them experimentally: What are the characteristics of the quark-gluon plasma? Are the predictions of Quantum Chromodynamics, the theory that describes the strong nuclear force, correct? Why can quarks and gluons join in almost any combination?

These issues relating to the first three minutes of the universe are the focus of the research activities of the Excellence Cluster in the **Research Area C.**

from left to right: Joachim Hartmann – *Senior Scientist (TUM)* | Torsten Dahms – *Junior Research Group Leader (TUM)*
Siegfried Bethke – *Director (MPP)* | Hubert Kroha – *Senior Scientist (MPP)* | Frank Simon – *Senior Scientist (MPP)* | Stephan Paul – *Professor (TUM)*
in front, from left to right: Martin Berger – *PhD Student (TUM)* | Jia-Chii Berger-Chen – *PostDoc (TUM)* | Rafal Lalik – *PhD Student (TUM)* *Photo: Astrid Eckert*


What
happened
within the first
three minutes
after
the
Big Bang
?

RESEARCH PRIORITIES

The quark-gluon plasma

Shortly after the Big Bang, the quarks could move as almost free particles in a quark-gluon plasma for a split second. This 'primordial soup' is no longer observed in nature, but must be produced by collisions of heavy nuclei in particle acclerators. How the first heavier particles and the components of our elements developed from that plasma, is of great importance for the understanding of the origin of our universe. At the Excellence Cluster Universe, a junior research group investigates the quark-gluon plasma by exploring the data from the experiment ALICE at the Large Hadron Collider (LHC) at CERN.

Understanding the quark confinement

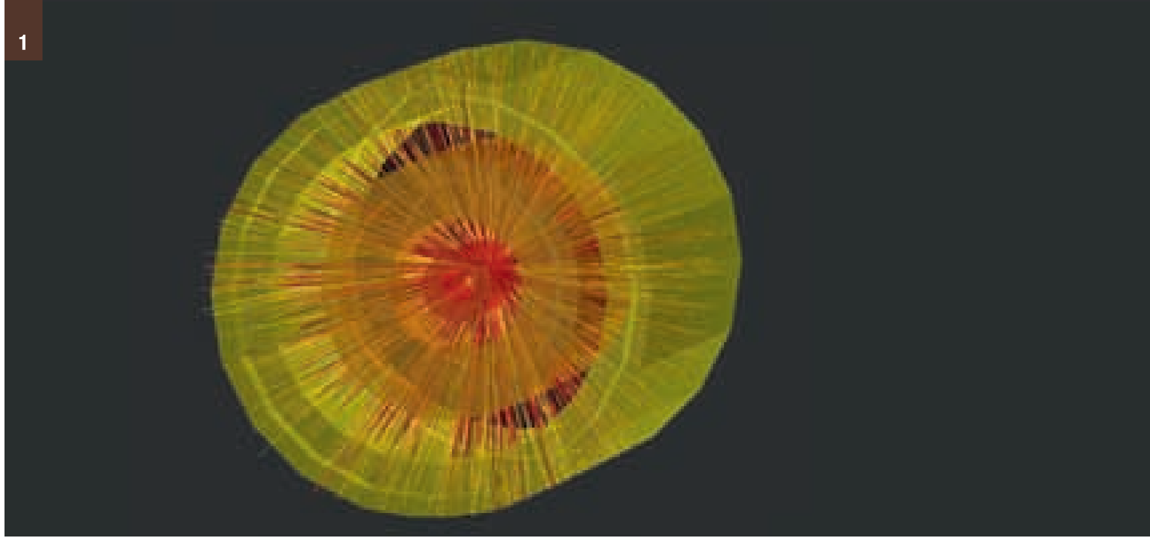
The force particles of the strong nuclear force, the gluons, seem to act like springs between the quarks: The farther away the quarks are moved from each other, the stronger the spring force tightens them. The energy that is required for removing the quarks from one another is accumulated as spring tension. The spring breaks only when the accumulated energy is sufficient to form a new quark-antiquark pair. In this way, quarks and gluons never occur as individual particles, but are 'confined' in quark compounds. The reasons are not fully understood within Quantum Chromodynamics and are further investigated by the physicists of the Excellence Cluster Universe.

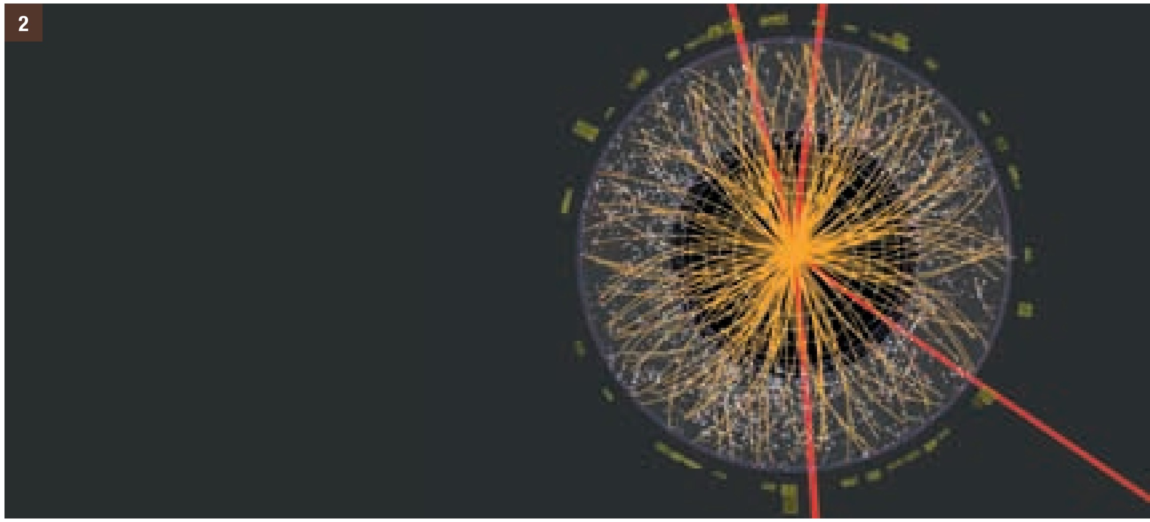
Compounds of the strong nuclear force

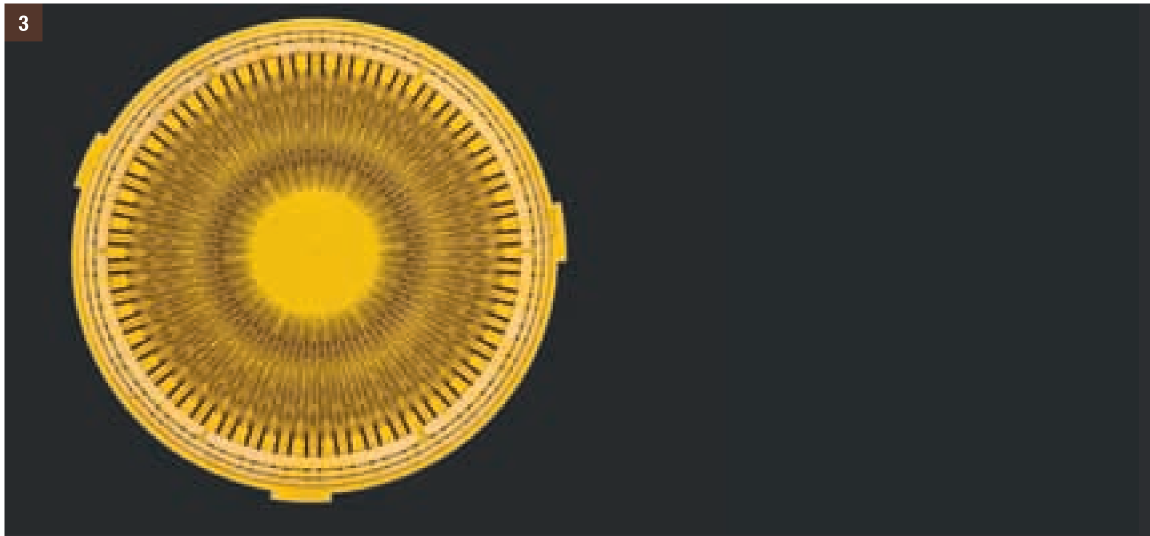
The six quarks and their antiparticles can combine in almost any way, especially forming groups of two or three quarks. But only the quark trios of the protons and neutrons are stable, and for neutrons this is only true as long as they are bound in atomic nuclei. All other quark combinations are very short-lived and must be produced in particle accelerators to investigate them. While physicists very well understand the formation of molecules from atoms with the laws of atomic physics, they are still puzzled by the forming of quark compounds. The improvement of the theoretical and experimental understanding of the strong nuclear force is an important research focus of the Excellence Cluster Universe. Research is conducted at numerous experiments: At the ATLAS and ALICE experiments at the LHC at CERN, at the COMPASS experiment at the Super Proton Synchrotron at CERN, at HADES and PANDA at the GSI Helmholtzzentrum für Schwerionenforschung in Darmstadt – and in future also at the experiment BELLE II at the KEK high energy accelerator in Japan.

Measuring the Higgs particle

When the Higgs particle was discovered in 2012 at the LHC, scientists knew very little about this new particle that imparted mass to the elementary particles. By now, after analysing lots of collision data, physicists are convinced that the new particle has exactly the characteristics that have been predicted by Peter Higgs and other scientists 50 years ago. Physicists now have measured the mass, the life-time and the spin of the Higgs particle with great accuracy. However, there are other characteristics that have not yet been sufficiently investigated. These will be explored in the next few years at the LHC at CERN. At the experiment ATLAS a number of particle physicists from the Excellence Cluster Universe contribute to a better understanding of the Higgs particle.







1 First collisions of lead nuclei: reconstruction of particle tracks, recorded at the beginning of the first run of the LHC as part of the ALICE experiment.
Photo: ALICE team/CERN

2 Last missing particle of the Standard Model: Tracks of a Higgs decay, observed at the detector ATLAS at LHC in 2012.
Photo: ATLAS collaboration/CERN

3 Research and development for the experiment ALICE: The read-out device of a detector chamber newly developed at TUM; the new detector technique will be used at the LHC in future.
Photo: Wenzel Schürmann/TUM


What
is
the
nature
of
dark
matter
and
dark
energy
?

BRINGING LIGHT INTO THE DARK UNIVERSE

Modern physicists are completely mystified by the fact that 95 percent of the universe is completely unknown. It seems that we have only discovered 5 percent of the existing matter, which is the material we and our surrounding universe consist of.

From the observations of galaxies, galaxy clusters and their large-scale distribution in the universe as well as from the observations of the cosmic microwave background, we know about a new and invisible substance in the universe, detectable only by its gravity. This substance called dark matter is supposed to amount to approximately 25 percent of the cosmic matter and apparently does not consist of a single compact celestial body, like, for example, brown dwarfs or old, extinct and cooled down stars, but of particles yet unknown. Based on its observed characteristics, some physicists suggest that dark matter consists of WIMPS (Weakly Interacting Massive Particles), massive elementary particles that barely interact with ordinary matter.

What is even more confusing is that our universe keeps expanding faster and faster, an amazing fact discovered about 15 years ago. Physicists suppose that this expansion is being caused by a mysterious dark energy, which represents 70 percent of the total energy in the universe. But they don't have a clue where this dark energy comes from. Speculations go in different directions: Is the dark energy simply a fundamental characteristic of our universe that can be described by a 'cosmological constant'? Or is it just an effect of a 'quintessence', a yet unknown fifth fundamental force in the universe? Or is it that Einstein's theory of relativity has to be modified because it might not work for extremely large distances?

Solving this puzzle is the aim of the Excellence Cluster Universe scientists in **Research Area E**.

from left to right: Stella Seitz – *Staff Scientist (LMU)* | Jörg Dietrich – *Staff Scientist (LMU)* | Hans Böhringer – *Senior Scientist (MPE)* | Korbinian Huber – *PhD Stundent (TUM)*
Roberto Saglia – *Senior Scientist (MPE)* | Marion Cadolle Bel – *PostDoc (LMU)* | Malin Renneby – *PhD Student (TUM)* | Xavier Defay – *Research Fellow (TUM)*
in front, from left to right: Jens Jasche – *Research Fellow (TUM)* | Margarita Petkova – *PostDoc (LMU)* *Photo: Astrid Eckert*

RESEARCH PRIORITIES

Direct search for dark matter

Physicists are following two separate approaches to search for dark matter particles: For one, they are looking for WIMPs in the products of particle collisions at the Large Hadron Collider at CERN. For another, they are also trying to observe possible WIMPs directly. For that reason, Excellence Cluster scientists are participating in the experiment CRESST (Cryogenic Rare Event Search with Superconducting Thermometers), which is located at the Gran Sasso underground laboratory in Italy. Incoming WIMPs can be detected and identified by the light and heat when colliding with atomic nuclei of an extra-pure superconducting crystal. So far, in spite of the CRESST intense research and other experiments, no WIMPS have been detected. The search continues.

Dark matter observation

Astronomical observations show that galaxies and galaxy clusters are embedded in huge dark matter environments. To quantify the amount of dark matter, physicists are using the effect of gravitational lensing, described for the first time by Albert Einstein: The bigger the mass and the closer light gets to it, the more the light is bent. Through exact measurements, the scientists of the Excellence Cluster Universe wish to determine the amount of dark matter in our galaxy and the galaxy near us, called Andromeda. Excellence Cluster physicists are also involved in a big observational campaign with one of the most powerful existing digital cameras in the world, specially designed for observing the dark energy: To get more information about the distribution of dark matter in the universe, the gravitational lenses of more than 200 million galaxies are currently being measured by the Dark Energy Survey (DES).

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Observation of the cosmic expansion

Astronomers use supernovae to measure cosmic distances. The larger the distance (and, as a consequence, the older the supernovae), the weaker the light that reaches us. As the universe expands, the supernova light is deferred towards red wavelengths with lower energy – physicists refer to it as the cosmological 'redshift'. In 1998, two teams of astronomers discovered for the first time that our universe doesn't expand with constant speed, as had been assumed previously, but, in fact, the expansion is accelerating. By observing supernova events which occurred in the past, astronomers are able to measure how the expansion speed of the universe has changed over a long period of time. Excellence Cluster Universe physicists are involved in big observational campaigns to study this phenomenon, especially with the Very Large Telescope (VLT) of the European Southern Observatory (ESO) and with the Dark Energy Camera (DES) at the Cerro Inter-American Observatory, both located in Chile. These observations lead physicists to conclude that the percentage of dark energy in the universe has to be constant for billions of years. These are important conclusions for theoretical explanations of the nature of dark energy and the cosmological expansion.

The universe's large structures

There are about 100 billion galaxies in our universe, they have typical diameters of 100,000 light years and the distance from one galaxy to another is of the order of a few million light years. But galaxies are not randomly distributed – on the contrary: One galaxy is seldom found alone. Usually, there are so many galaxies in one place that astronomers refer to them as galaxy groups or clusters (our galaxy, too, belongs to a small group of galaxies, the Local Group, in which the Milky Way and the Andromeda Galaxy are the largest). Then, there are large, almost empty regions in the universe. Apparently, over billions of years, the galaxy groups and clusters have arranged into an intricate web which spreads through our universe. Cosmologists assume that the origin of this structure lies in quantum fluctuations at the beginning of our universe which then, so the theory, swelled due to an inflationary expansion of the universe by least a factor of 10^{26}. The astrophysicists of the Excellence Cluster Universe aim at a better understanding of the underlying physics.

1 Galaxies 1.4 billion kilometres away: the large galaxy cluster Abell 3827 as seen from the Hubble space telescope. *Photo: NASA/ESA/ESO*

2 Crystal growing for the direct dark matter search: a calcium tungstate single crystal is slowly extracted from a 1,600 degrees Celsius hot melt; experts at the TUM process the crystal into a highly sensitive detector to be used in the CRESST experiment. *Photo: Andreas Heddergott*

3 A superconducting thermometer: Jean-Côme Lanfranchi, group leader (TUM) of the experiment CRESST, is preparing a detector crystal with a cylinder cut for testing; on the left there is the cryostat that cools down the crystal to one ten thousandths of a degree Celsius above absolute zero. *Photo: Andreas Heddergott*

UNDERSTANDING THE EVOLUTION OF THE CELESTIAL OBJECTS

Our universe includes billions of galaxies, very different in appearance, size, structure and age. What they all have in common is that they have supermassive black holes located in their centres – and that fascinating things are going on: Within a galaxy, cold, very dense gas clouds collapse and give birth to new stars. Through nuclear fusion, new heavy chemical elements are created inside the new stars which are ejected into the outer space during the star's lifetime.

This matter forms clouds, out of which in turn new chemical enriched stars emerge. In the dust disks around the new stars also planets can form themselves.

These processes are driven by gravity. Above all, from the dark matter's gravity since galaxies are embedded in enormous areas of dark matter.

From observations, models and simulations astrophysicists know that the wide variety of different galaxies can be explained by their evolution history: Normally, a galaxy grows very slowly by absorbing the gas from its cosmic surroundings. Occasionally, though, two big galaxies pull towards each other and merge into one, and, as a consequence, change shape and mass dramatically – an event which can take up to a million years.

Galaxies are the result of complex physics. There remains a lot to be discovered: Why does every galaxy host a supermassive black hole? Where did it originate from? Is there a connection between the mass of a supermassive black hole and the characteristics of its home galaxy? How do stars and planets form?

Excellence Cluster Universe scientists of **Research Area F** are working on a better understanding of the evolution of these diverse cosmic objects.

from left to right: Ghazaleh Erfanianfar – *PostDoc (TUM)* | Andrea Merloni – *Staff Scientist (MPE)* | Andreas Burkert – *Professor (LMU)*
Mara Salvato – *Staff Scientist (MPE)* | Paola Popesso – *Junior Research Group Leader (TUM)* | Paola Mucciarelli – *PostDoc (TUM)*
in front, from left to right: Laura Morselli – *PhD Student (TUM)* | Michael Opitsch – *PhD Student (LMU)* *Photo: Astrid Eckert*


How
galaxies,
black holes,
planets develop
stars
and
do
?

RESEARCH PRIORITIES

Planet formation

It is not completely understood yet how planets are formed out of a star formation chaos. A lot of different conditions have to be met, so that during thousands of years huge chunks can be formed in the dust disk around a newly born star, that, in the following millions of years, can further merge to form gas, ice or rock planets. Excellence Cluster Universe astrophysicists are working on a theoretical understanding of these complex physical processes. To test their models about the formation of planets, they also use data from space telescopes like Kepler.

Galaxies and their black holes

Physicists are convinced of the existence of a strong connection between the masses of supermassive black holes and the characteristics of their home galaxies. It seems that the formation of a galactic centre is very closely linked to the growth of its black hole and to the evolutionary history of the whole galaxy. But how? What is particularly difficult to understand is that supermassive, matter absorbing black holes already existed in a very early state of the universe, whereas smaller, less mass-greedy ones seem to appear later. This is contradictory to the idea that small objects are formed first and then merged into bigger ones.

1 | Blue marble: View of the Earth as seen by the crew of the Apollo 17 lunar mission in 1972 from around 45,000 kilometres altitude. *Photo: Harrison Schmitt/NASA*

2 | Milky Way look-alike: This spiral galaxy in the constellation Virgo is about 50 million light years away and in shape and size similar to our home galaxy. *Photo: ESO*

3 | Enormous energy: The galaxy Centaurus A emanates energetic jets from the active galaxy's central black hole. *Photo: ESO/WFI (Optical), MPIfR/ESO/APEX/A.Weiss et al. (Submillimetre), NASA/CXC/CfA/R. Kraft et al. (X-ray)*

4 | Stellar splendour: The dwarf galaxy Barnard's in the constellation Sagittarius; the reddish nebulae reveal numerous regions of active star formation. *Photo: ESO*

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Active galactic nuclei

The enormous gravity of a supermassive black hole in a galaxy centre causes all matter within its radius of influence to be attracted to it. Due to the physical law of conservation of angular momentum, the approaching matter doesn't fall directly into the centre, but instead forms a rotating disk around the black hole. This rotating matter is heated by friction. As a result, its matter loses energy emitting bright light before it finally falls into the black hole. Such active galactic nuclei and their manifestation as quasars or blazars are an important investigation focus for Excellence Cluster Universe physicists. The scientists are involved in two important observational campaigns: the radio interferometer LOFAR and the space telescope eROSITA, which will be launched in the autumn of 2016. Both were designed to observe more than 100,000 very distant galaxies, in order to select the most interesting objects for future studies.

Star formation history

The first stars could only form some hundred Million years after the Big Bang, when the primordial matter has cooled down enough. More and more stars came into existence during the first two billion years after the Big Bang. Then the rate of star formation slowed down and stayed constant during a long period of time. Approximately eight billion years ago however, the rate of star formation in all galaxies dropped precipitously. This reduction is still continuing. An Excellence Cluster Universe junior research group is trying to find explanations for this complex phenomenon. To test their hypotheses, the astronomers need very deep all-sky surveys in the X-ray and infrared region. Within the next years, the space telescope eROSITA will deliver an X-ray survey with an unprecedented high resolution which will be an excellent basis for future investigation.

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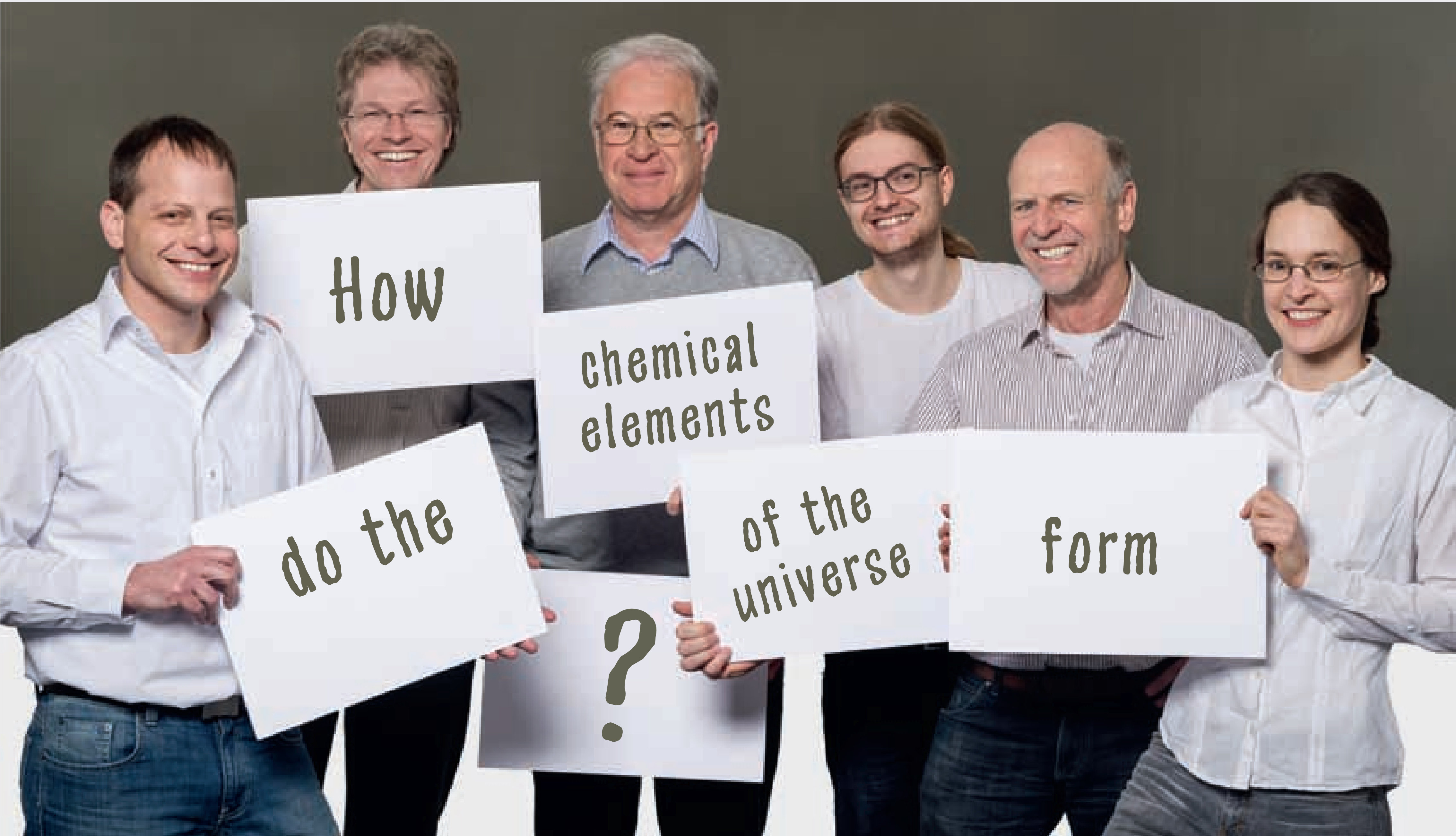

How
chemical elements
do the
?
of the universe
form

COMPREHENDING THE ABUNDANCE OF CHEMICAL ELEMENTS

All chemical elements such as hydrogen, oxygen, iron and gold, which we find on Earth, are 'Made in Universe'. The building blocks of the atomic nuclei, the neutrons and protons, were formed within the first three minutes after the Big Bang. In fusion reactions they were arranged to the elements that make up our universe. However, the universe expanded so quickly that at first only few of the light atomic nuclei could fuse: hydrogen and helium and traces of lithium and beryllium.

The second phase of the element formation began not until a few hundred million years later when the birth of the first stars took place – and it continues to date: In the hot stellar core nuclear reactions are ignited that generate new atomic nuclei. These reactions also produce the energy that saves the star from collapsing under its own gravity and let it shine afar.

The fusion of hydrogen into helium creates the biggest amount of energy. Therefore, a star can exist billions of years before it runs short of hydrogen. The fusion of helium and the heavier atomic nuclei generates less and less energy, so that the fuel supply is depleted faster and faster.

Finally, in iron nuclei the protons and neutrons are bound so strongly that the fusion comes to a standstill. Without an internal energy source the star with its iron core collapses under its own gravity. For very massive stars this ends with the formation of a black hole. For lighter stars, however, the implosion is slowed down: In the shock front near the star's very dense centre, heavy atomic nuclei disassemble and reassemble in a new way.

Meanwhile, many protons convert into neutrons by emitting neutrinos in large quantities. The nuclei are now heavily bombarded by neutrons. Heavier atomic nuclei can emerge by way of neutron capture. Usually, such a slowed down collapse results in a supernova starburst. As a remnant there remains a compact neutron star and the repelled supernova shell. This shell also contains the newly generated nuclei.

The stars have given our universe its abundance of different elements and provided for the basics of life on our planet. In detail, however, it is still unclear how especially the heaviest elements are formed.

Scientists at the **Research Area G** deal with the formation of the atomic nuclei and the astrophysical principles that are necessary for their understanding.

from left to right: Assaf Sternberg – *Research Fellow (TUM)* | Bruno Leibundgut – *Senior Scientist (ESO)* | Wolfgang Hillebrandt – *Director (ret.) (MPA)*
Thomas Siegert – *PhD Student (MPE)* | Roland Diehl – *Senior Scientist (MPE)* | Katharina Fierlinger – *PostDoc (TUM)* *Photo: Astrid Eckert*

RESEARCH PRIORITIES

Element formation

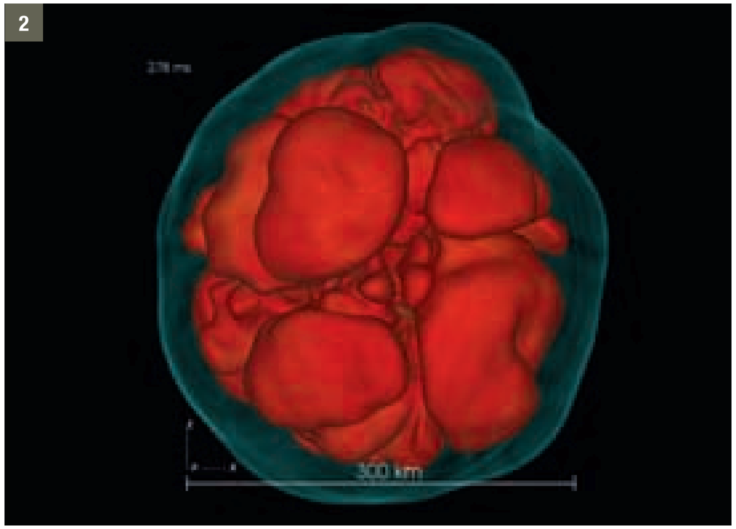
The universe is populated with stars of different sizes and ages. Small stars are usually very old and are often still fusing their hydrogen fuel into helium. At the same time very massive and therefore short-lived stars exist, which have formed from gas clouds with chemically enriched material from earlier generations of stars. The rapidly developing massive stars are mostly responsible for the abundance of chemical elements that we find in the universe. In order to model these processes, physicists need deep knowledge and many kinds of data: They need to know, for example, the likelihoods of neutron captures for particular atomic nuclei and the half-lives of unstable nuclei. They need to understand how a star collapse can be reversed into a stellar explosion and the role of neutrinos and nuclear reactions within this process. To explore the cosmic chemical evolution, the physicists of the Excellence Cluster Universe are working with simulations and laboratory experiments, such as being conducted at the Maier-Leibnitz Laboratory in Garching, and they analyse observations with the ground-based telescopes of the European Southern Observatory (ESO) and the space telescopes of the European Space Agency (ESA).

Neutrons and atomic nuclei

Heavier atomic nuclei than iron can only be formed by the addition of electrically neutral neutrons because protons are immediately repelled from the nucleus due to their positive charges. The decay of a captured neutron into a proton increases the atomic number, and a new nucleus is formed. There are two processes known: The slower one, the s-process, primarily takes place in the outer regions of giant stars. Here, neutrons are emitted in nuclear reactions, but the temperature is so low and the number of neutrons so small that an atomic nucleus only very rarely manages to capture a neutron. But bit by bit, atomic nuclei are gradually built up to lead and bismuth in this way. In the fast neutron capture, the r-process (r for rapid), the nuclei are flooded by lots of neutrons so that the nuclei accumulate several neutrons in quick succession. These eventually decay into stable nuclei. In this way, radioactive isotopes of uranium and plutonium emerge as well as rare elements such as gold. While physicists have a very good understanding of the s-process, which can easily be studied in experiments, the r-process remains a major challenge.

Cosmic gas

The material from which stars are formed is called interstellar medium. This gas may be a million degrees hot plasma or an ultra-cold molecular cloud with temperatures close to absolute zero; but it can also take any conditions in between. The interstellar medium moves between the star systems of galaxies and is thereby enriched by the material that stars dispense during their lifetime from the star's surface as wind or that is ejected in the last phase of a starburst. The dynamics of interstellar gas are very complex. Physicists of the Excellence Cluster Universe are investigating it by using simulations and models and comparing them with astronomical observations of hot and cold gas phases, which are illuminated in part from the depths of the universe by gamma-ray bursts and quasars.



1 Star remnants: This gas bubble in the Large Magellanic Clouds shows the traces of a supernova that occurred about 400 years ago.
Photo: NASA/ESA and the Hubbel Heritage Team

2 Simulation of a supernova: Inside the collapsing star the matter implodes and the neutrinos, which are emitted in masses, heat the gas (red). Just like in boiling water, bubbles form with hot, rising material.
Simulation: Hans-Thomas Janka/MPA

3 The Helix Nebula as seen from the Spitzer space telescope: This celestial object, about 650 light years away from Earth, is one of the Earth's nearest planetary nebulae; the gas shell and the dust was repelled by the star at the end of its evolution.
Photo: NASA/JPL_Caltech/Univ. of Arizona

THE COMPUTING CLUSTER C²PAP

In physics just like in many other disciplines, research is not really possible without high-performance computers or advanced programming methods. Both, theoretical models as well as experimental observations are so complex that without the help of computer methods, calculations or analysis is hardly possible.

One of the biggest challenges in theoretical physics are for example the equations of Quantum Chromodynamics which cannot be solved using mathematical methods alone. These equations require intricate computer simulations, which need enormous amounts of computing time.

In astrophysics, too, physicists have to cope with larger and larger amounts of data. Systematic all-sky surveys in the different wavelength ranges conducted by modern Earth- and space-bound telescopes produce large data archives that contain new insights into our universe – treasures that can only be retrieved by means of computer technology. Particularly in the field of astrophysics, simulations are important to ascertain whether the beginning of the universe as well as the important physical processes are well understood; processes that, over billions of years, have driven the evolution of the stars, planets, galaxies and black holes that we observe today.

In all research areas of the Excellence Cluster Universe the demand for high-performance programming methods, computing power and storage capacity has increased enormously in the more recent past. Therefore, the Excellence Cluster Universe has founded the Computational Centre for Particle and Astrophysics (C²PAP), which is run by five physicists. They support the Excellence Cluster scientists in developing code, simultaneously using multiple computer processors, integrating new algorithms, running simulations and storing data. The C²PAP is located at the Leibniz Supercomputing Centre (LRZ) operated by the Bavarian Academy of Sciences, posses two percent of the computing capacity of the LRZ supercomputer SuperMUC and has a direct link to SuperMUC's data storage.

The scientists of the data centre **C²PAP** support the theoretical and experimental physicist of the Excellence Cluster Universe to use the latest computer technology efficiently and to achieve further scientific progress.

from left to right: Frederik Beaujean – *PostDoc (LMU)* | Margarita Petkova – *PostDoc (LMU)*
Aliaksei Krukau – *PostDoc (LRZ)* | Jovan Mitrevski – *PostDoc (LMU)* *Photo: Astrid Eckert*


Computational
Centre
for
Particle
C2PAP
and
Astrophysics

PROJECT HIGHLIGHTS

A data centre for cosmological simulations

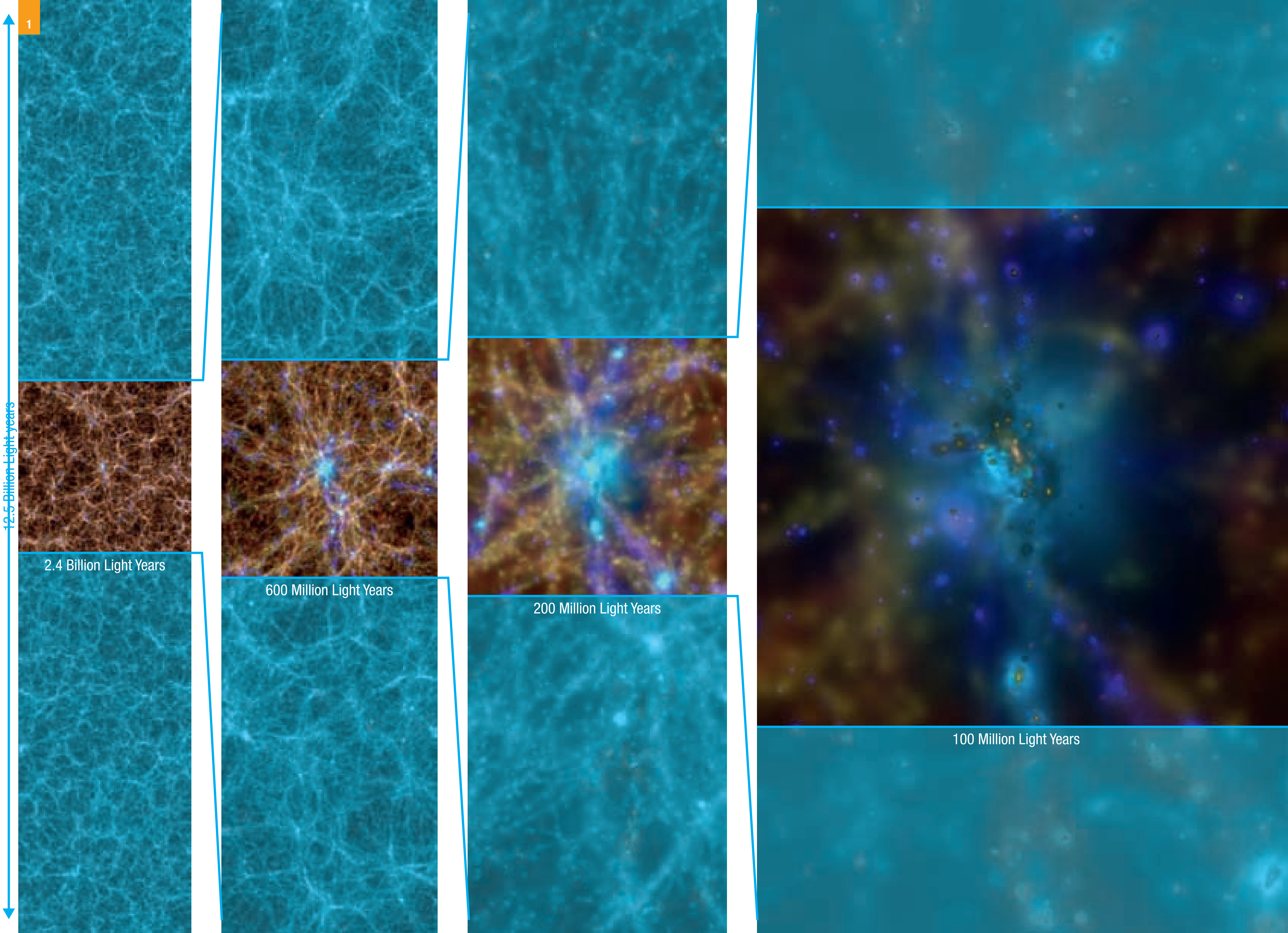
The aim of the project is to build a data centre for cosmological simulations at the C^{2}PAP and make it available to Excellence Cluster Universe scientists and interested researchers worldwide. Within the Magneticum Pathfinder project, the C^{2}PAP physicists together with experts from the Excellence Cluster Universe and the Leibniz Supercomputing Centre have realized new, extensive simulations. As a result, the world's largest, hydrodynamic cosmological simulations have been accomplished. They are taking into account the most recent results regarding the three most important cosmic ingredients – the dark energy, the dark matter and the visible matter. Moreover, the scientists incorporated a variety of physical processes in the calculations that are considered particularly important for the development of the visible universe. The largest simulation within the Magneticum Pathfinder project pursues the development of a record number of 180 billion tiny spatial elements in a previously unreached spatial area of 12.5 billion light years. For the first time, a hydrodynamic cosmological simulation is large enough to be directly compared with large-scale astronomical surveys.

Rare decay analysis

Within this project, rare decays of B mesons are investigated to ascertain whether experimentally observed tiny anomalies give evidence of new physics beyond the Standard Model of particle physics. B mesons are pairs of quark-antiquarks, which are composed of at least one bottom quark. They are produced in large particle accelerators and decay after a very short lifetime. Because bottom quarks are more than four times heavier than protons, there are hundreds of different ways of disintegrating into lighter particles. This makes B mesons the ideal objects to systematically test the Standard Model as the Standard Model predicts even the rarest decay. Within this project, the C^{2}PAP experts together with particle physicists of the Excellence Cluster Universe investigate the most recent measurement data from the experiments LHCb, CMS and ATLAS at the Large Hadron Collider (LHC) at CERN, some of which show deviations from the theoretical predictions. These analyses are the most extensive of their kind because they aim to consider all the relevant theoretical uncertainties. The task requires challenging algorithms and powerful computing resources, as are available at the C^{2}PAP data centre.

1 The Magneticum Pathfinder project: The world's most elaborate cosmological simulation of the evolution of the universe shows the large-scale distribution of matter with its galaxy groups and clusters and the extensive network of galaxy filaments.

Simulations: Klaus Dolag/LMU, www.magneticum.org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12.5 Billion Light years
2.4 Billion Light Years
600 Million Light Years
200 Million Light Years
100 Million Light Years

Munich
Institute
for
Astro-
and
Particle
Physics
MIAPP

THE INTERNATIONAL VISITING RESEARCH CENTRE MIAPP

Exchange with other researchers is one of the most important key elements of scientific work. From the very beginning, the Excellence Cluster Universe has supported the scientific exchange with an extensive guest and co-operation programme that involves major scientific institutions worldwide.

In order to even further promote international networking and to further establish Munich/Garching as international top-level research address, the Excellence Cluster Universe founded the international visiting research centre Munich Institute for Astrophysics and Particle Physics (MIAPP) in 2014.

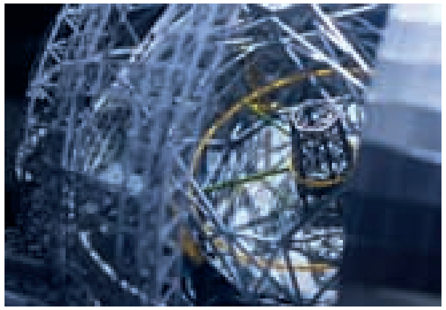
MIAPP organizes six four-week programmes per year on the main subjects of nuclear and particle physics, astrophysics and cosmology. The programme themes may be proposed by scientists from around the world. The annual programme is selected by an international committee.

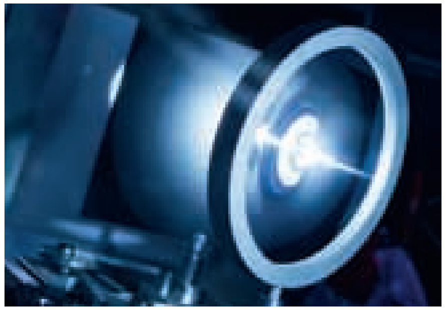
The visiting research centre on the Research Campus Garching gives international and local top researchers the room for discussion away from their daily duties and the opportunity to develop new ideas and to establish new collaborations. Also, talented young scientists have the unique chance to meet outstanding researchers at an early stage in their academic career. An average of 60 scientists participate in each programme. The excellent academic environment, including the physics departments of the two Munich universities, four Max Planck Institutes and the European Southern Observatory (ESO), guarantees for a lively exchange between international guests and local scientists.

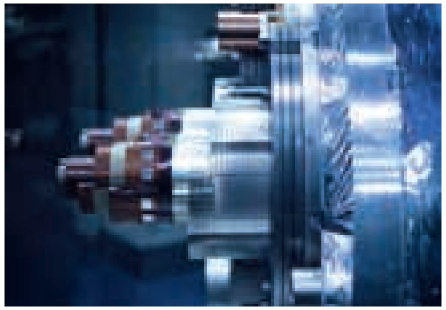
The team of the international visiting research centre **MIAPP** coordinates and organizes the programmes, takes care of the guests, manages all finance and accounting matters and provides IT support.

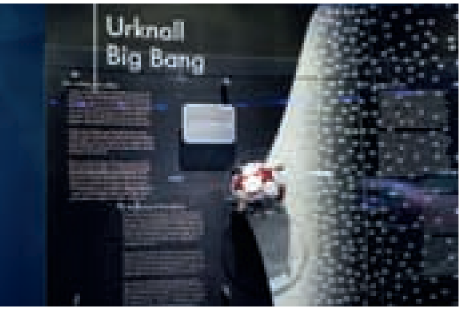
back row, from left to right: Rolf-Peter Kudritzki – *Professor (Institute for Astronomy, Hawaii/LMU)* | Martin Beneke – *Professor (TUM)*
Thomas Würstl – *Accountant (LMU)* | Mario Neßler – *System Administrator (TUM)*
front row, from left to right: Sonja Lutz-Lampertseder – *Assistant (TUM)* | Tina Jacobs – *Assistant (TUM)*
Gabriele Hartmann – *Accountant (TUM)* | Ina Haneburger – *Programme Manager (TUM)* *Photo: Astrid Eckert*

EVOLUTION OF THE UNIVERSE









EXHIBITION AT THE DEUTSCHES MUSEUM

How did the universe begin? Why did the universe develop that way? Will it ever end? The exhibition 'Evolution of the Universe' at the Deutsches Museum intends to give an impression of the origin and evolution of our universe.

According to our current knowledge, matter, space and time were created 13.8 billion years ago. Only minutes after the Big Bang, the particle and forces mix existed out of which millions and billions of years later stars and galaxies were able to form, processes that are still on-going. Astrophysicists know that the universe is expanding: The galaxies are drifting apart faster and faster. The distances to the farthest and oldest objects in the universe physicists measure in billions of light years.

'Evolution of the Universe' highlights the great prevailing conclusions about our universe. The current state of research is vividly illustrated with exhibits, video and image material. Interactive displays illustrate the significance of the cosmic microwave background and the dark matter and make clear why oxygen, iron and gold can be found on Earth.

The exhibition is located in the circular room of the astronomy section on the 5th floor of the Deutsches Museum and can be visited during the opening hours of the museum. 'Evolution of the Universe' was planned, financed and realized by the Excellence Cluster Universe and its partner institutions, the European Southern Observatory (ESO) and the Max Planck Institutes for Physics (MPP), Astrophysics (MPA) and Extraterrestrial Physics (MPE).

Photos: Joshua Burkert

PUBLISHER
Excellence Cluster Universe
Technische Universität München
Boltzmannstraße 2
D-85748 Garching
Tel.: + 49 89 35831 - 7100
Fax: + 49 89 3299 - 4002
info@universe-cluster.de
www.universe-cluster.de

COORDINATORS
Prof. Stephan Paul (TUM)
Prof. Andreas Burkert (LMU)

AUTHOR
Petra Riedel · petra.riedel@universe-cluster.de

TRANSLATIONS
Petra Riedel, Sabine Kaps, Jenny Wiedemann Delgado

FINAL PROOFREADING
Tina Jacobs, Theresa Kämper, Petra Riedel

PRINTING
flyeralarm.com

DESIGN
Sabine Kwauka · s.kwauka@muenchen-mail.de

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Astrid Eckert

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