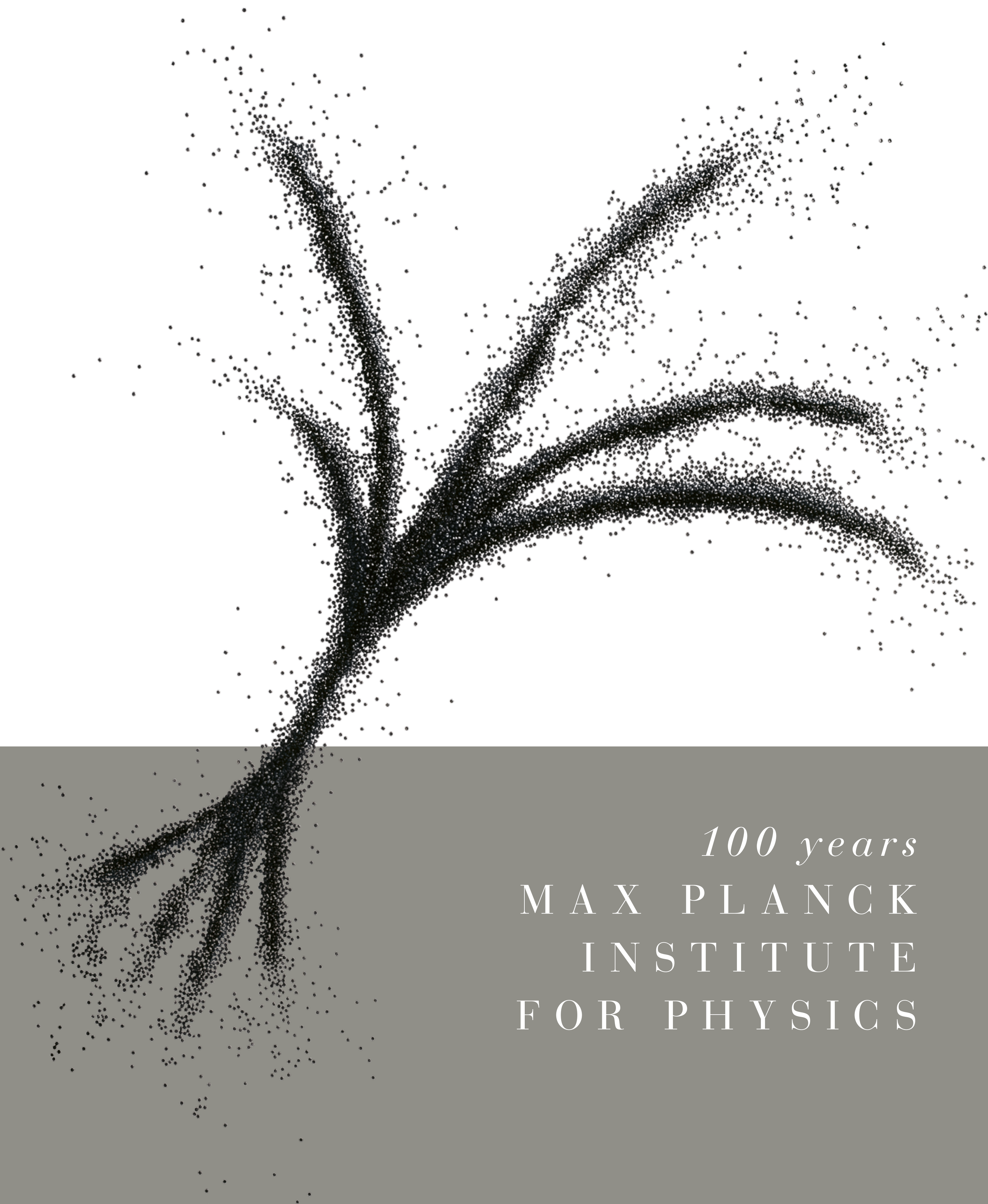
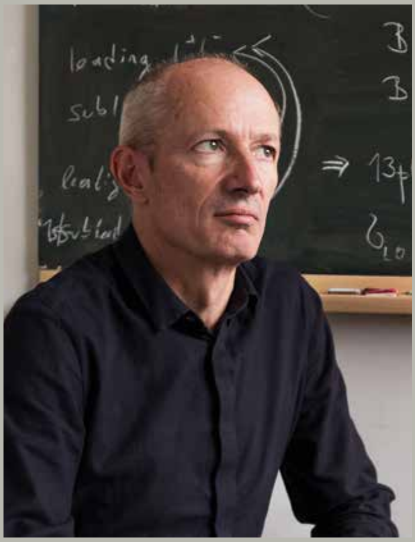


100 years

MAX PLANCK INSTITUTE FOR PHYSICS



Prof. Dr. Allen Caldwell

Managing Director at the Max Planck Institute for Physics

POISED *for new* DISCOVERIES

Our Institute is celebrating its 100th birthday – and with this magazine we want to give you a brief and entertaining glimpse into our history, our research past and present, and some of the people who worked here at various times.
Max Planck, Albert Einstein, Werner Heisenberg – scientists who are very closely intertwined with our history and are still revered by physicists and non-physicists alike.

Without a doubt, the largest part of our universe still lies hidden. The matter we are familiar with covers only about five percent. What does »dark matter« consist of? And even the constituents we know about still puzzle us: Why is there more matter than antimatter? Is there a unified theory of all the natural forces – gravitation, electromagnetism, and the weak and strong interactions?

We are prepared for new discoveries, in both theoretical and experimental physics, and look ahead to the future with high expectations.

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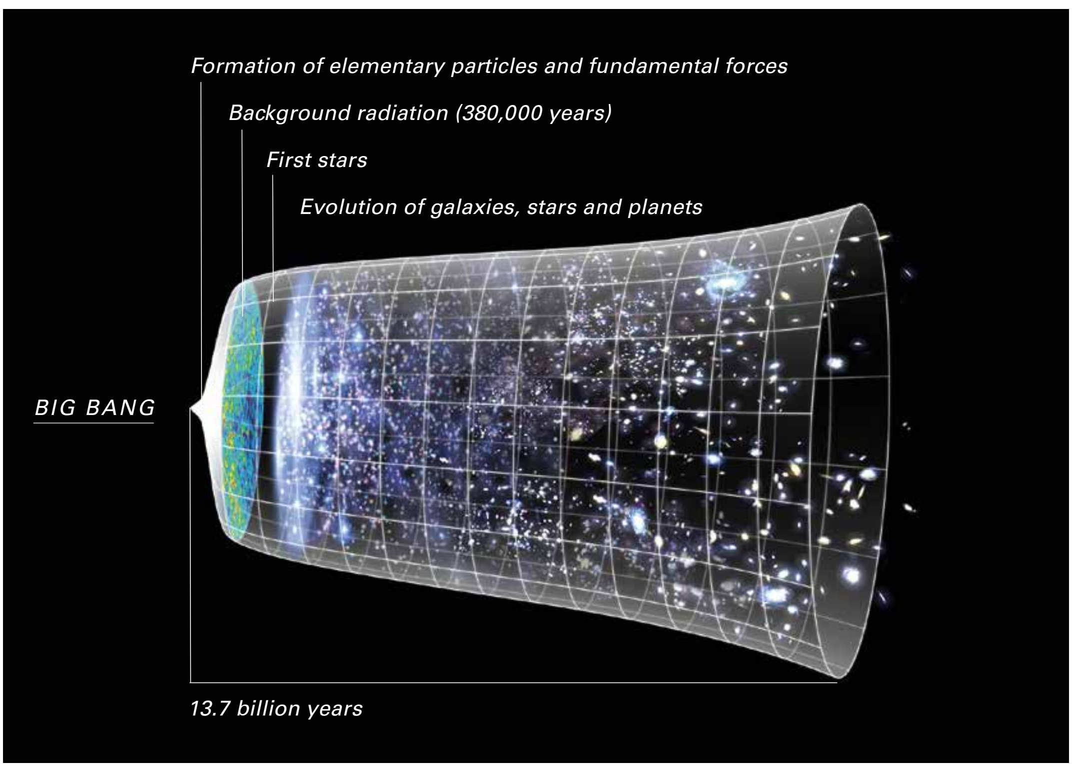


The evolution of the universe

When and how did elementary particles form? What are the properties of matter? How can we explain physical phenomena which are not yet understood? The Max Planck Institute for Physics is pursuing these questions – with the aim of solving the mysteries of the universe.

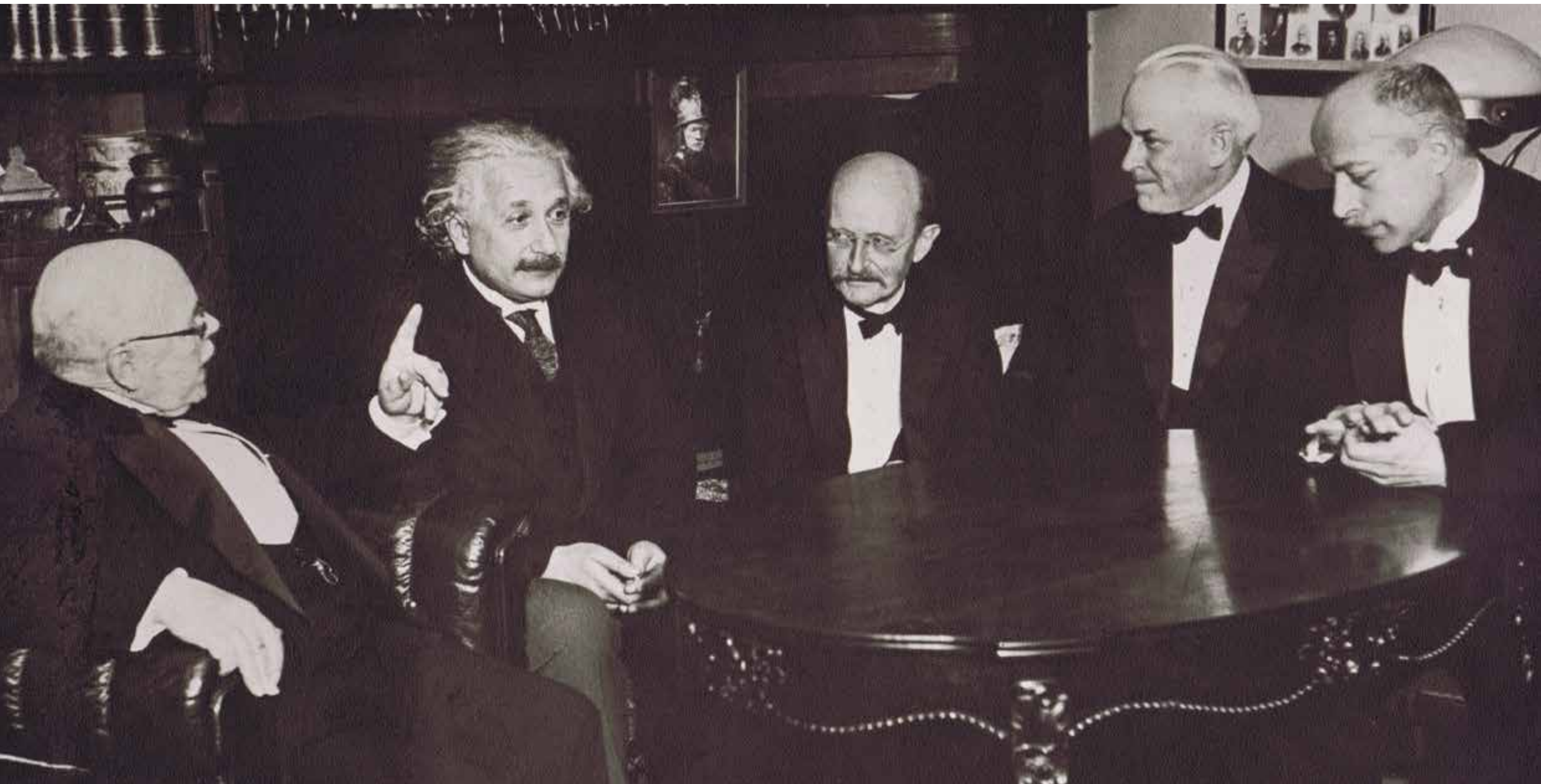
»RESEARCH ON THE *smallest scale* TO UNDERSTAND THE *grand scale*«

Guiding principle of the research at the Max Planck Institute for Physics

MAX PLANCK INSTITUTE FOR PHYSICS
1917
2017
100 YEARS

100 years MAX PLANCK INSTITUTE FOR PHYSICS

THE INSTITUTE WAS FOUNDED under the name of the »Kaiser Wilhelm Institute for Physics« before the end of the First World War. It was initially housed in Albert Einstein's living room, before it moved into its own building in Berlin-Dahlem in 1937. The research covered a broad spectrum encompassing relativity theory, quantum, nuclear, low temperature and high-voltage physics. In 2017, the Max Planck Institute for Physics concentrates on particle and astroparticle physics.



1 The Kaiser Wilhelm Institute in Berlin

2 Werner Heisenberg as a young man

3 The Swedish king presents the Nobel Prize to Heisenberg

October 1, 1917

Foundation of the Kaiser Wilhelm Institute for Physics, Berlin. (1)
Director: Albert Einstein (until 1933).

November 9, 1922

Albert Einstein *awarded the Nobel Prize in Physics for his services to theoretical physics.*

1932 (awarded 1933)

Werner Heisenberg (2)*, then professor at the University of Leipzig, awarded the Nobel Prize in Physics.* (3)

1936/37

New Institute *built in Berlin-Dahlem.*
Director: Peter Debye.

1939

Placed under the command *of the German military ordnance office (uranium research with the aim of investigating possible fields of application for nuclear fission).*

Albert Einstein

*Left:
And colleagues on November 11, 1931 in Berlin (from left to right: Walther Nernst, Albert Einstein, Max Planck, Robert Millikan, Max von Laue)*

1917

Existing fundamental theories:

Electrodynamics, Theory of Relativity

Known particles:

Protons, Electrons

World view of cosmology:

Planets, Stars, Galaxies, Universe assumed to be static

1920 – 1940

Existing fundamental theories:

- *Quantum mechanics (Heisenberg 1923)*
- *Existence of the neutrino (Pauli 1930)*
- *Theory of radioactive beta decay caused by weak interaction (Fermi 1934)*

Known particles:

Neutrons (Chadwick 1932), Muons, Positrons, Pions (Anderson 1932/36)

World view of cosmology:

Expanding universe (Friedmann 1922, Lemaitre 1927, Hubble 1929)

4 *After the German surrender, allied forces search the Haigerloch research site*

5 *Workshop at the Max Planck Institute for Physics in Göttingen*

5 *A staff member evaluates particle collisions*

1942

Attempts to enrich uranium 235 as fission material for an atomic bomb *are dropped. Institute returned to the Kaiser Wilhelm Society (see box).* Werner Heisenberg becomes Director.

1943 – 1945

Parts of the Institute moved to *Hechingen and Haigerloch in the southwest of Germany.*

April/May 1945

Occupation *by American and Soviet troops.* 4

Loss of equipment and library; internment of Directors and several Institute members.

1946

New building and reopened as Max Planck Institute for Physics *in Göttingen* 5 *, Werner Heisenberg again Director.*

For the first time, two departments: *for theoretical physics (head: Carl Friedrich von Weizsäcker) and experimental physics (head: Karl Wirtz).*

Niels Bohr and Werner Heisenberg 1924

1933 – 1945

What was Werner Heisenberg's role in the uranium program of the Third Reich?

Together with other scientists, including Otto Hahn and Carl Friedrich von Weizsäcker, he was called up to work on the German army weapons program. In the uranium project initiated there, the researchers were to investigate possible applications for nuclear fission – whereby the focus was certainly on developing an atomic bomb.

Attempts to enrich uranium 235 and thus to make it »critical« were abandoned in 1942. There are different interpretations as to how this came about, however: Some science historians are convinced that Heisenberg deliberately delayed the uranium project so as not to provide the Nazi government with atomic weapons. According to other authors, the group working with Heisenberg failed purely and simply because the task was too difficult.

In 1941, Heisenberg had several discussions with his Danish friend and mentor Niels Bohr on the issue of »nuclear weapons«. In addition, between 1950 and 1960 Bohr wrote several letters to Heisenberg, but never sent them. Studying these sources does not allow a final assessment of Heisenberg's role in the uranium project either.

Klaus Gottstein, Emeritus Scientific Member of the Max Planck Institute for Physics and a scientific companion of Heisenberg for many years, discusses the most important questions and answers in his article »Werner Heisenberg and the German Uranium Project (1939 – 1945). Myths and Facts«. The text is published at www.heisenberg-gesellschaft.de. There are also further references to biographical publications.

6 The new building of the Max Planck Institute for Physics

7 Centaur-type rockets transported scientific instruments into space

8 Clockwise from top left: Hans-Peter Dürr, Norbert Schmitz, Léon Van Hove, Klaus Gottstein, Ulrich Stierlin

September 1, 1958

Relocation to Munich as the Max Planck Institute for Physics and Astrophysics. (6) *Director: Werner Heisenberg (retired 1970).*

June 28, 1960

Independent Institute for Plasma Physics *becomes a spin-off in the form of a GmbH.*

1963

Founding of the Institute for Extraterrestrial Physics: Research on the physics of space with the aid of balloons, probes and satellites. (7)

October 1, 1971

For the first time, a Board of Directors *made up of several Scientific Members manages the Max Planck Institute for Physics and Astrophysics.* (8)

October 1979

The Institute for Astrophysics *relocates to Garching.*

1990

Julius Wess*, father of supersymmetry, appointed as Director at the Max Planck Institute for Physics.*

1940 – 1960

Existing fundamental theories:

- *Parity violation in weak interaction (Lee, Wang, Wu 1956/57)*
- *Dark matter (Zwicky)*
- *Nucleosynthesis (formation of nuclei, e. g. helium, lithium) in the universe*

Known particles:

Kaons, lambda particles – the term »particle zoo« is coined

World view of cosmology:

Big Bang theories for the creation of the universe (Gamow, Bethe)

1960 – 1980

Existing fundamental theories:

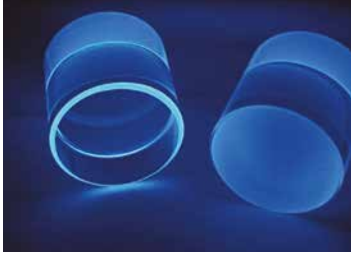
- *Development of the Standard Model of particle physics (Glashow, Salam, Weinberg) – order is brought to the particle zoo!*
- *Quark model*
- *Quantum chromodynamics*

Known particles:

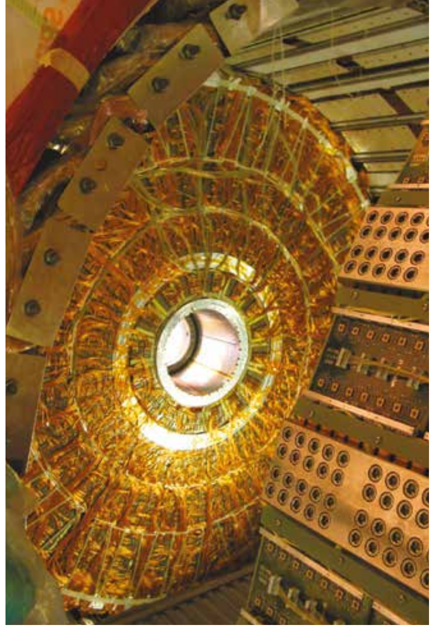
Quarks (up, down, strange, charm, bottom), Leptons, Vector bosons (W, Z), Gluon as exchange particle of the strong interaction

World view of cosmology:

Discovery of cosmic background radiation (»echo of the Big Bang«, Penzias, Wilson 1964)



9 CRESST uses crystals of calcium tungstate to detect dark matter particles



10 The ATLAS detector at CERN

11 Cleanroom laboratory at the MPI for Physics: Installing a component for the GERDA experiment

April 1991

Split up into 3 autonomous Institutes: *»Max Planck Institute for Physics« (Werner Heisenberg Institute, Munich), »Max Planck Institute for Astrophysics« and »Max Planck Institute for Extraterrestrial Physics« (Garching).*

1996

The CRESST experiment 9 *to search for dark matter begins. Current head: Director Masahiro Teshima.*

1999

The MPI for Physics joins the ATLAS experiment 10 *at CERN. Head: Director Siegfried Bethke.*

2002

Research Group for phenomenology *is established. Head: Director Wolfgang Hollik.*

2003

With Dieter Lüst as Director, the string theory research field *is firmly established at the MPI for Physics. The first of two* MAGIC telescopes *inaugurated – the second follows in 2009. Head: Director Masahiro Teshima.*

1980 to today

Existing fundamental theories:

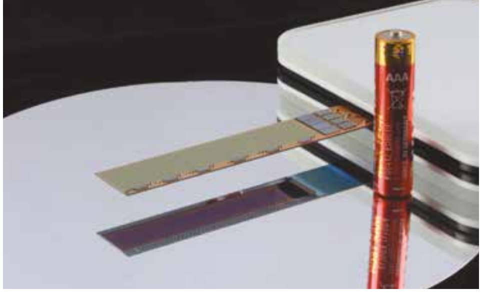
- *Precise computation of the particles of the Standard Model*
- *Development of string theory*
- *Development of supersymmetry*

Known particles:

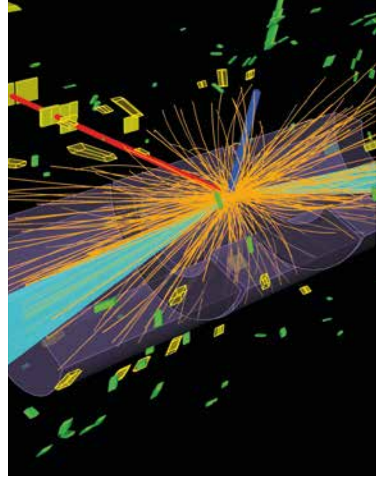
Top quark as the hitherto last member of the quark family, Higgs boson

World view of cosmology:

- *Detection of the accelerated expansion of the universe*
- *Constituents of the cosmos: 5% known matter, 25% dark matter, 70% dark energy*
- *Universe acquires a structure*
- *Inflation after the Big Bang*
- *Detection of gravitational waves postulated by Einstein*



12 Silicon chip for the pixel detector the Institute is developing for Belle II



13 Higgs boson decay in the ATLAS detector

14 Key component of the AWAKE experiment: The 10-meter-long plasma cell

2004

Start of the GERDA experiment (11) *to detect neutrinoless double-beta decay.*

2006

The MPI for Physics takes up the development of high-purity germanium detectors (GeDet). *Head: Director Allen Caldwell.*

2008 and 2009

The Institute becomes a member of the Belle II research collaboration, *whose aim is to investigate the imbalance between matter and antimatter.* (12) *Head: Director Allen Caldwell.*

Giorgi Dvali becomes Director at the MPI for Physics and establishes the particle Physics and Cosmology *research field.*

2012

Discovery of the Higgs particle, *in which the MPI for Physics plays a crucial role with the ATLAS experiment* (13). *With* AWAKE (14), *the MPI for Physics initiates a cooperation to develop a new acceleration technology. Head: Director Allen Caldwell.*

2016

The MPI for Physics commences the MADMAX *project to investigate axions and sets up a new research group for neutrino physics. Project leader: Director Allen Caldwell.*

Future

No one would venture a guess as to when and in which field the next breakthrough in particle physics will occur. There is no lack of unsolved issues: the nature of dark matter, the mysteries of neutrino physics, and the unified theory for all natural forces, to name just a few.

Many experiments have yet to exhaust their potential: From 2025 onwards, an upgrade of the Large Hadron Collider, for example, will provide much more data than today, and these may contain the particles of supersymmetry, which have hitherto been sought in vain.

And if not? Physicists will nevertheless make many discoveries that can be used to continually refine theories and adapt them to new findings. There are more than enough ideas for new experimental projects – more about this on p. 42.

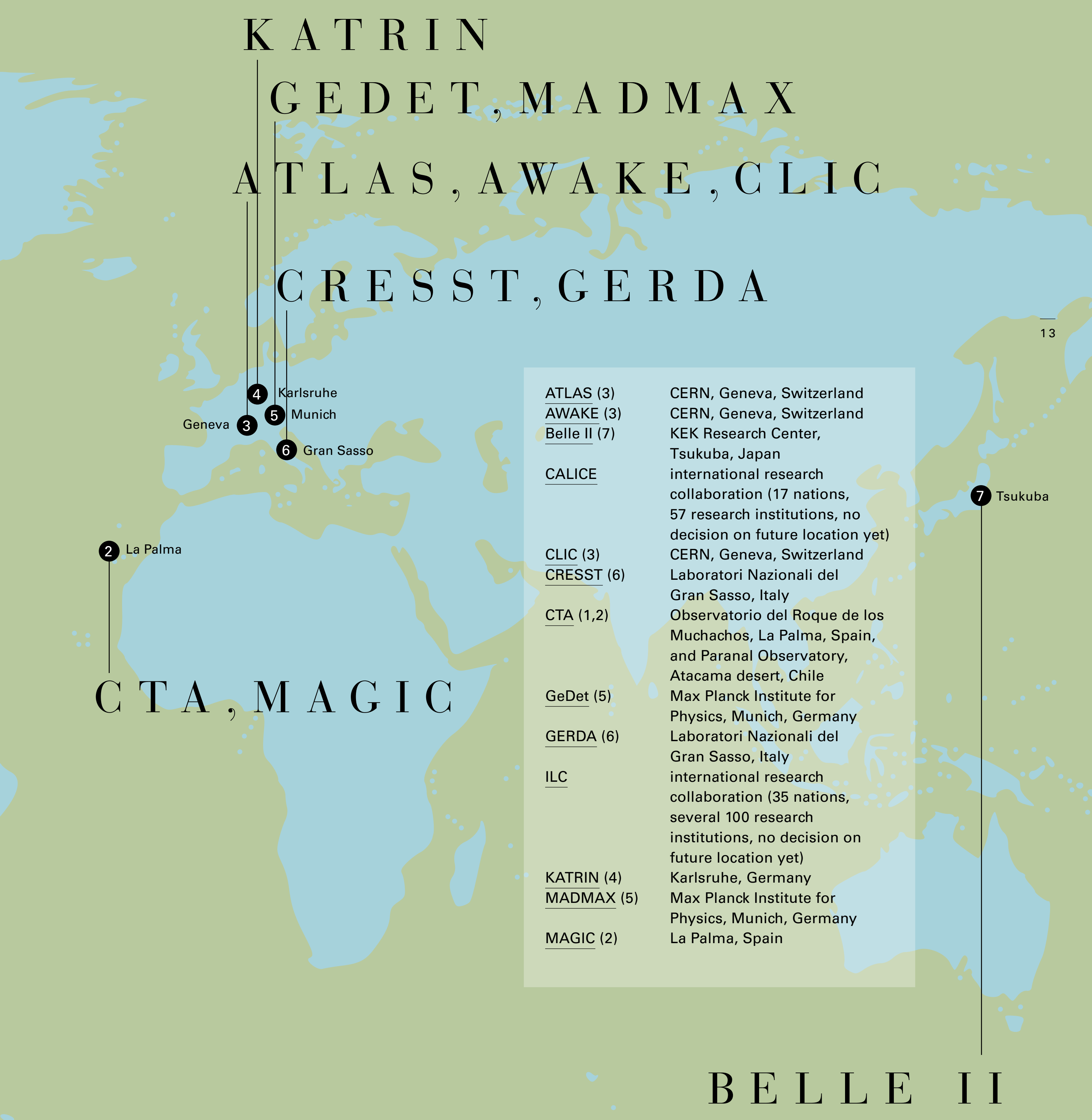
RESEARCH *spans the* GLOBE

Marie Curie, Ernest Rutherford, Albert Einstein and Werner Heisenberg rank among the pioneers of modern physics. They did their research in different fields, but had one thing in common: They made their discoveries alone or in small working groups at most.

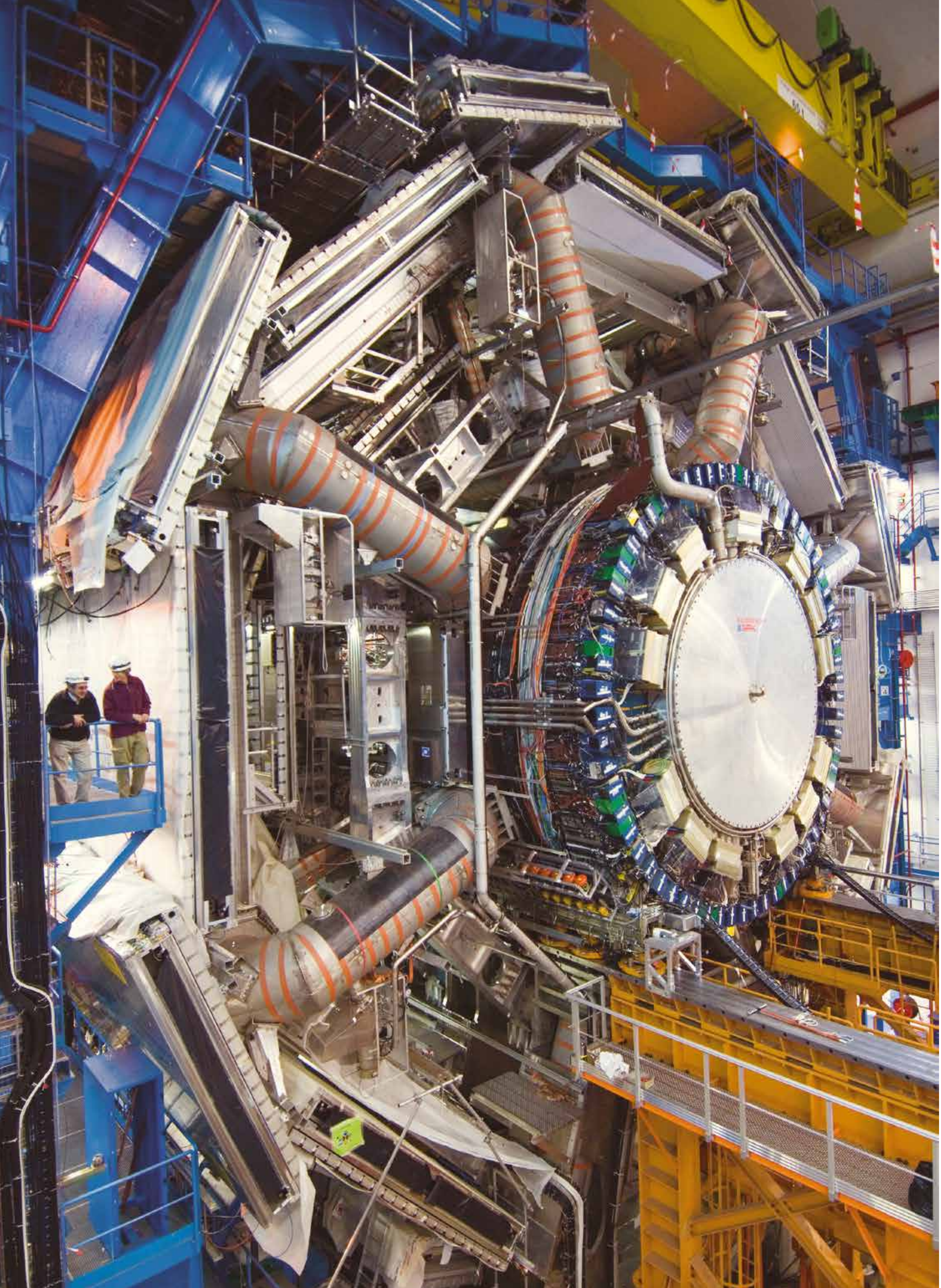
The idea of the lone researcher is a thing of the past, especially in experimental particle physics. Research goals in this field can only be realized with elaborate, sometimes huge pieces of equipment: for particle accelerators, telescopes or instruments to detect extremely rare decays, for example.

Such projects require enormous intellectual and financial resources. Physicists therefore join forces with partners, often in LARGE INTERNATIONAL RESEARCH COLLABORATIONS. The Max Planck Institute for Physics is playing its part in 13 of these cooperations, which are located across the globe.

The example of ATLAS shows that teamwork brings success: 3,200 scientists from 38 countries collaborated on the construction of this huge detector.



ATLAS (3)	CERN, Geneva, Switzerland
AWAKE (3)	CERN, Geneva, Switzerland
Belle II (7)	KEK Research Center, Tsukuba, Japan
CALICE	international research collaboration (17 nations, 57 research institutions, no decision on future location yet)
CLIC (3)	CERN, Geneva, Switzerland
CRESST (6)	Laboratori Nazionali del Gran Sasso, Italy
CTA (1,2)	Observatorio del Roque de los Muchachos, La Palma, Spain, and Paranal Observatory, Atacama desert, Chile
GeDet (5)	Max Planck Institute for Physics, Munich, Germany
GERDA (6)	Laboratori Nazionali del Gran Sasso, Italy
ILC	international research collaboration (35 nations, several 100 research institutions, no decision on future location yet)
KATRIN (4)	Karlsruhe, Germany
MADMAX (5)	Max Planck Institute for Physics, Munich, Germany
MAGIC (2)	La Palma, Spain



PARTICLES *on* TOUR

Why do galaxies, stars, planets – and we ourselves – exist? Physicists see an ingenious interplay between the laws of nature here, which, however, are not yet fully understood. They use PARTICLE ACCELERATORS in their attempt to coax some of the mysteries out of the universe.

ATLAS detector: Physics at extreme energies

Left: The biggest machine ever built by humans is searching for indications of a »new physics« in particle decays, for example for supersymmetric particles.

Precise track readout with the Belle II detector

Right: Belle II investigates the particle decays which occur after electrons and positrons have collided. The goal is to find the cause for the matter/antimatter imbalance.

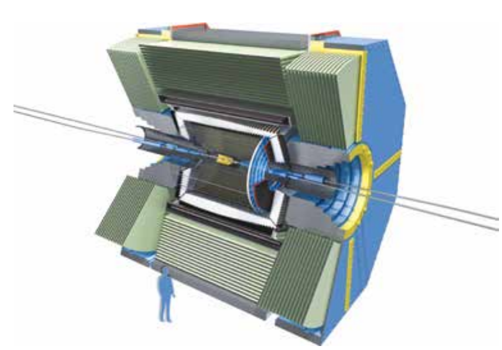
Almost 14 billion years ago, the universe came into existence in a Big Bang. For a long time, physicists have left no stone unturned in their attempts to turn back the clock and repeat the Big Bang on a miniature scale. The biggest time machine is the LHC accelerator at CERN in Geneva. It fires protons at each other and generates for fractions of a second a state that existed immediately after the Big Bang. In 2012, the physicists at the CMS detector and at the 7,000-tonne ATLAS detector reported a great success: the discovery of the Higgs particle, which completes the Standard Model of particle physics.

Researchers from the Institute have played a leading role in ATLAS since the initial planning around 25 years ago. The concept and crucial parts for some key components come from Munich: The high-precision inner detector, which tracks the path of the »fragments« from the collision, the calorimeters, which determine the energies of the particles, and the muon spectrometer, which searches for special decay products.

Almost as impressive as ATLAS are the computers that sit in a climate-controlled hall, sifting through the signals for interesting traces. Now that the Higgs particle has been found, the search in the future will concentrate mainly on supersymmetry. This involves elementary particles that are much heavier than those already known. After step-by-step technical upgrades, in 2025 at the latest it is expected that the LHC will bring so many protons to collide that such particles would be produced in sufficient numbers.

But this is by no means certain: It could turn out that the supersymmetric particles are so heavy that even the LHC will not be able to produce them, and the ATLAS detector thus be unable to find them.
It would then be up to the theoreticians to again come up with new ideas for experiments. After all, a definite physical motivation is required to build an even bigger particle accelerator.

A further mystery from the very beginnings of the universe: Why does the universe contain only matter, but no antimatter? After all, both should have been created in precisely equal amounts at the time of the Big Bang and have rapidly annihilated each other. But this would mean we would not exist. One loophole could be so-called CP violation, which states that particles and antiparticles are not as symmetric as initially thought. This asymmetry could explain why more matter than antimatter was left over after the Big Bang. The fact that CP violation exists has been known for some time. It can be detected ›



with precision in accelerator experiments in which electrons and their antiparticles, the positrons, collide with each other, for example. This process creates pairs of B mesons and their antiparticles, a particle species which provides a good means of detecting this effect. With the Belle I experiment at the KEKB accelerator in Japan, the physicists have collected a huge amount of data that supports this theory.

Unfortunately, the CP violation observed so far is not sufficient to explain the existence of our matter-dominated universe. »There are peculiarities in the old Belle I data and it is inescapable that there is new physics beyond the Standard Model,« says Prof. Dr. Christian Kiesling, spokesperson for the Belle team. The Max Planck Institute for Physics is therefore participating in the successor experiment Belle II, which is to become operational in 2018. The accelerator is currently being upgraded to become the Super-KEKB and is being equipped with the new detector. At the heart of Belle II, an extremely sensitive, high-precision camera is on the lookout for the B mesons; around 1,000 of them are formed here per second and immediately decay again. This »Pixel Vertex Detector«, which was developed in Munich, records the tracks taken by the collision fragments with an accuracy of ten thousandths of a millimeter. High-speed computer programs then compute the exact position at which the B mesons and their antiparticles decayed.

ATLAS and Belle II have the potential to push back the boundaries of our knowledge. The teams are not in competition with each other, says Christian Kiesling: »We are crossing our fingers for our ATLAS colleagues, because we can be sure of our interpretation only if several independent experiments are successful.« *

Magic MONSTERS

Gamma rays are the most energetic electromagnetic waves. In the universe, they are produced everywhere where high energies are involved: during stellar explosions or in the vicinity of active black holes at the center of galaxies, for example. The MAGIC telescopes PICK UP GAMMA RAYS – and thus enable us to look deep into the universe.

MAGIC: Taking a look into the unknown universe

One of two MAGIC telescopes on La Palma which set their sights on celestial objects emitting high-energy gamma radiation.

The sky is blue, leaves are green and bananas are yellow: The perception of colors is one of the most fascinating sensory achievements. Our eyes can only see anything at all in a tiny spectral region; they are blind to all other regions. This also applies to gamma rays, which have several billion times more energy than visible light. But it is precisely these »colors« that are of interest to astrophysicists, as this radiation originates in the universe, where enormous amounts of matter and energy are in motion. It can only be picked up with sensitive telescopes – by the two MAGIC telescopes (Major Atmospheric Gamma Imaging Cherenkov Telescopes), for example, which have been built on La Palma in the Canary Islands under the supervision of the Max Planck Institute for Physics.

If gamma rays from space enter Earth's atmosphere, they collide with atoms, thereby producing lighter elementary particles in only a few billionths of a second at altitudes of ten to fifteen kilometers; these particles then race down to Earth faster than the light, emitting a kind of photonic boom as they do so – the so-called Cherenkov radiation. This light cone in the sky illuminates a circle roughly 500 meters in diameter on Earth's surface. The two MAGIC telescopes catch a ›

Roque de los Muchachos – mount of the observatories

Ideal observation conditions prevail on the highest mountain of this Canary island. The MAGIC telescope is only one of more than a dozen observatories in total on the 2,426-meter-high mountain.

portion of this light with their 17-meter-diameter collector mirrors and measure it with sensitive cameras, which take images of a few nanoseconds duration. The astrophysicists use the brightness and the spread of the light to reconstruct where the gamma radiation came from, its energy and what its source was.

Gamma ray astronomy is a young discipline that picked up steam only in 1989 with the observation of the Crab Nebula in the Taurus constellation, but which has been booming since the start of the millennium, primarily thanks to the construction of the first MAGIC telescope in 2003 and comparable telescopes such as H.E.S.S. in Namibia (2002) and VERITAS in the USA (2007). Whereas only six sources of gamma rays in the universe were known in the 1990s, their number increased rapidly with the new telescopes. Today, astrophysicists know of 200 or so sources and new ones are continually being added.

MAGIC plays a leading role among the gamma ray telescopes – it is currently the world's largest Cherenkov stereo telescope. The larger the mirror used to collect the Cherenkov light, the greater the sensitivity for low-energy light. The design with two telescopes 85 meters apart is also advantageous, as interfering background signals can be separated out from the real signals, and the direction of the incoming radiation can be determined more accurately. MAGIC is therefore the only Cherenkov telescope to have recorded spectra with energies below 50 gigaelectronvolts (GeV). This is important for the study of objects like pulsars or very distant blazars, which emit gamma rays with a maximum of a few tens of GeV. Blazars are supermassive black holes that guzzle up magnetized matter and produce gamma radiation in the process. But high-energy gamma rays tend to fall by the wayside on their journey so that distant blazars can only be observed with telescopes which are very sensitive to lower energy radiation. MAGIC has already discovered two blazars that are seven billion light years away. The gamma rays they emitted therefore originate from a time when the universe was half its present age. »MAGIC allows us to do some archaeology and see what the gamma ray universe used to look like,« says Dr. David Paneque, physics coordinator of the MAGIC collaboration.

The current Cherenkov telescopes have led to astronomy with high-energy gamma rays successfully establishing itself during the past 15 years. The scientists now want to take the next step and build the CTA (Cherenkov Telescope Array) together. It will be ten times more sensitive than the current observatories. In addition, it is to cover low energies of 20 GeV as well as high energies above 300 TeV. This enormous progress will increase the number of known ultra-high-energy gamma sources from hundreds to thousands, allowing detailed studies of these sources.

CTA will comprise two observatories. It can thereby observe larger regions of the sky and provide a more detailed image of the extreme gamma ray sources in the universe. The northern observatory is being built at the MAGIC site on La Palma; the southern telescope will be built in the Chilean Atacama desert over the next few years. The construction of the first large telescope with a 23-meter mirror has already started on La Palma. When this telescope becomes operational in 2018, further telescopes will follow. *

The MATHEMATICS *of the* UNIVERSE

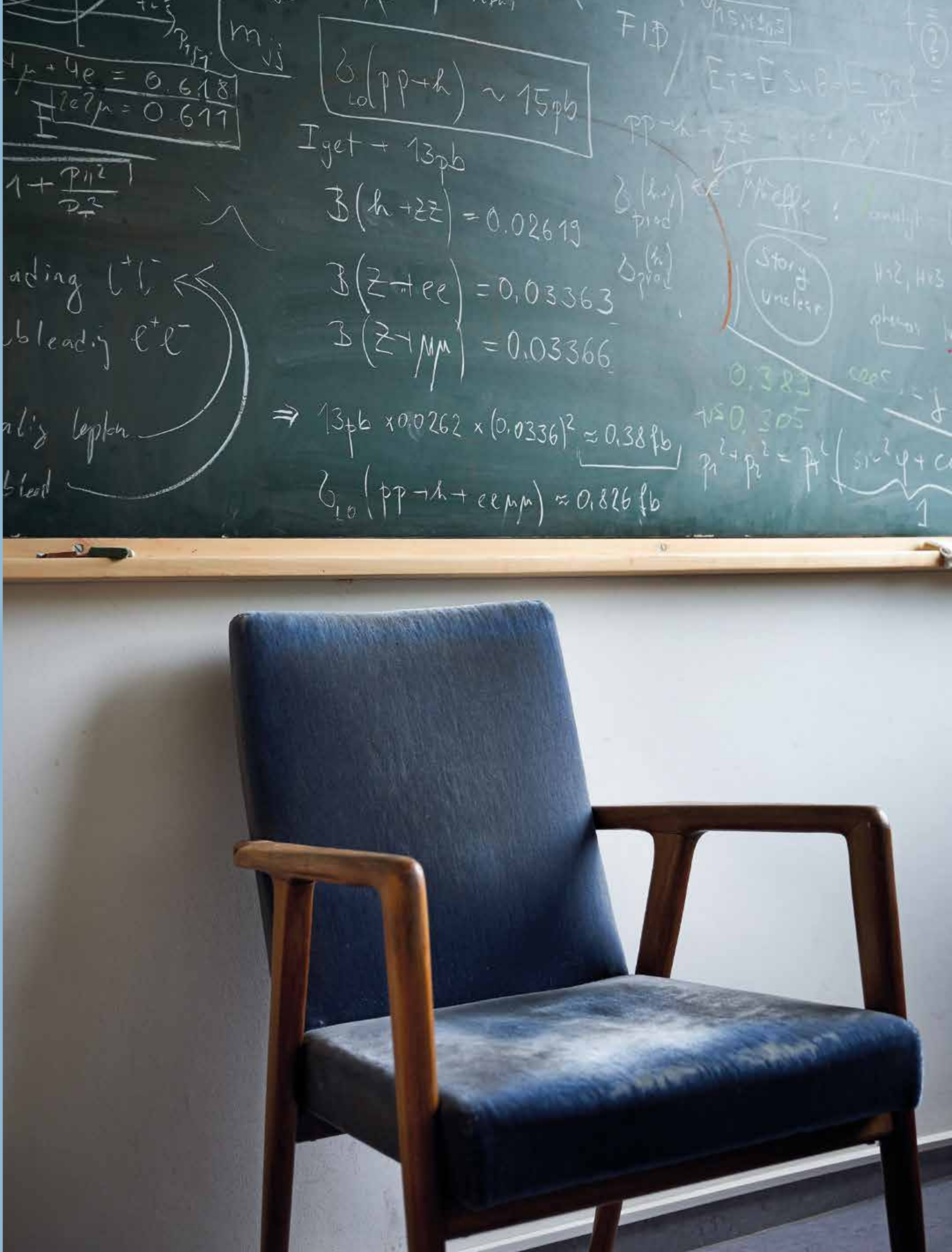
NO EXPERIMENT, NO THEORY – NO THEORY, NO EXPERIMENT.
Theoretical physicists develop models to understand facts known from experiments in terms of mathematically formulated principles and to predict new relationships. If this is successful, the next step can follow: The attempt to prove the predictions found mathematically by experiment.

The common room

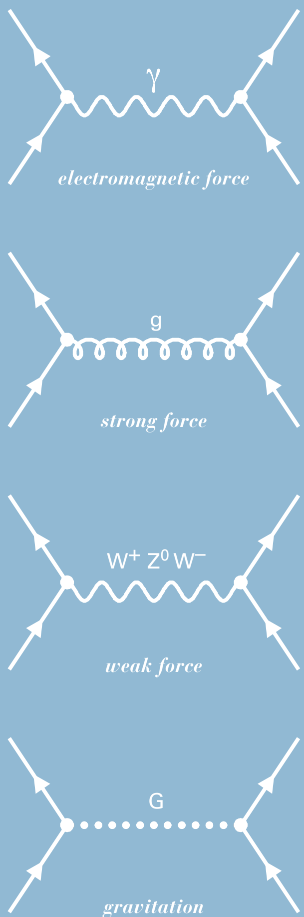
Without a (good!) cup of coffee, nothing would happen in theoretical physics. The common room is therefore an important and very popular place at the Institute – with a huge blackboard where the scientists can develop and discuss their ideas.

On April 10, 2014, many physicists saw their world collapse. In episode 155 of »The Big Bang Theory« TV series, the physics genius and pain in the neck Dr. Sheldon Cooper announced that he no longer wanted to work on string theory. He wrestled with the prospect that this theory may perhaps never be proven. Cooper's doubts are understandable – but unjustified nevertheless. After all, the very task of a theoretical physicist is to explain the world with equations, even though an experimental proof may be a long way off.

Theoretical physicists see it as nothing short of a gift that mathematics can bring us so close to the laws of nature. Around 50 of them work at the Max Planck Institute for Physics, where they collaborate closely with their colleagues from experimental physics. The theoreticians produce the »statics calculations« and specify limits for a new theoretical model. Only when



»The *theory of everything* is not the sole objective, the route physicists are taking to get there is worthwhile in itself.«



Feynman diagrams:
Shorthand for theoreticians

The diagrams developed by the physicist Richard Feynman allow complex interactions to be represented in a simple and clear way. They are therefore a simple tool to illustrate forces between particles.
The Feynman diagrams above show the four fundamental forces of the universe: the electromagnetic, the strong and the weak interaction, and gravitation.

Left:
Heisenberg's office isn't merely a museum within the Institute – it is still used today by scientists.

this model is sound in itself and has convinced the experts, do the experimental physicists consider how they can put this theory to the acid test. Some projects, such as CRESST or MADMAX, have even come about at the suggestion of the theoreticians. Both are searching for dark matter – in completely different ways. The results of experiments will be introduced back into the theory again in a few years, the partners playing a kind of ping-pong with their ideas.

This is how the Standard Model developed, with its aim to describe the fundamental structures of matter and forces in accordance with the principles of quantum theory. Three of the fundamental interactions – electromagnetic, strong and weak forces – are mediated by the quanta of the respective force fields, i. e. the »force particles«, which act as exchange particles between the building blocks of matter. For gravity, the fourth fundamental interaction, such a microscopic description is still purely hypothetical and not satisfactory from a theoretical point of view, however.

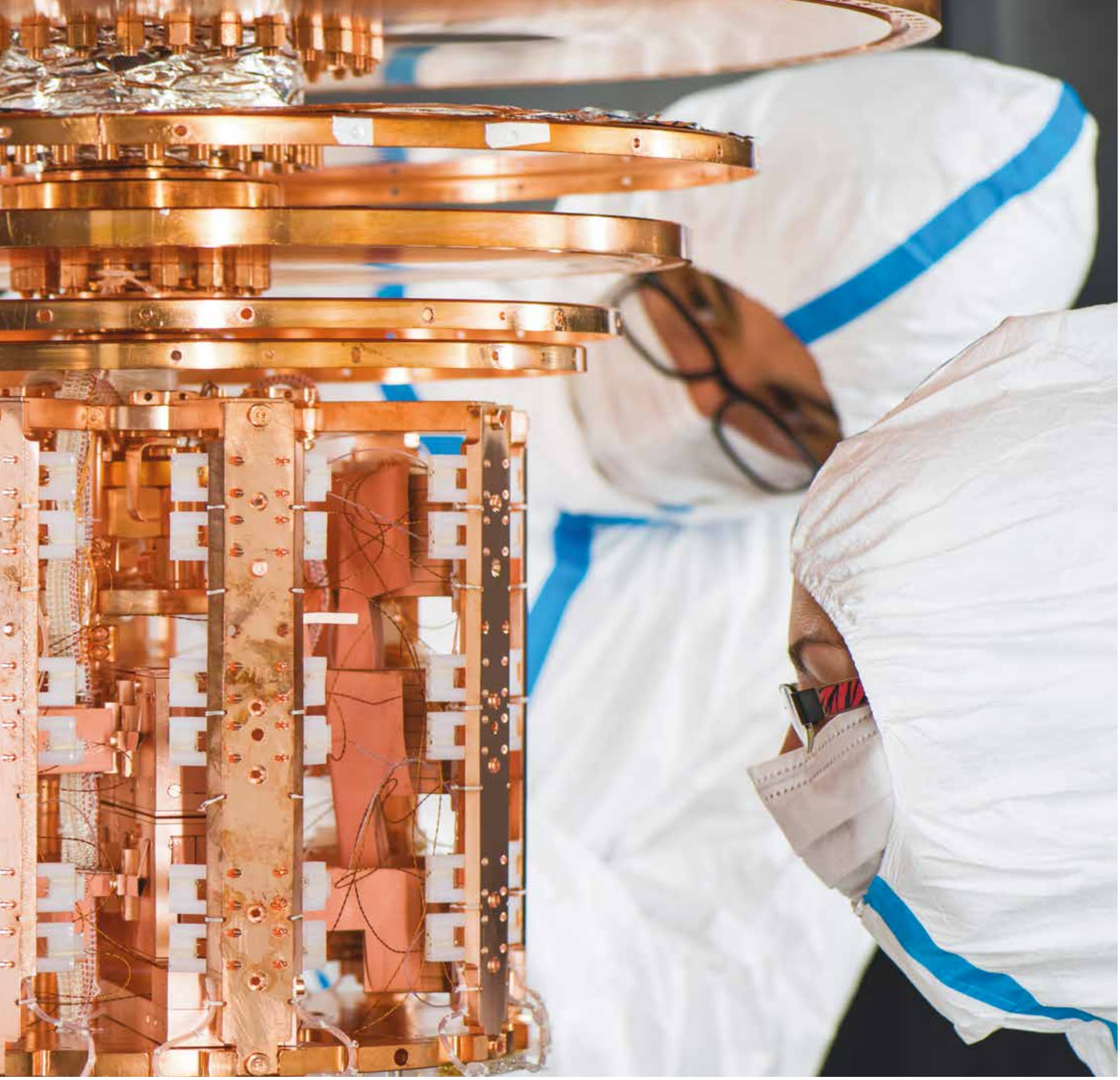
One of the research fields at the Institute is theoretical astroparticle physics. It is the link between elementary particle physics and cosmology, and systematically investigates the microcosmos. A key issue is to investigate what effect neutrinos have on supernova explosions, and what this tells us about neutrino properties.

A further field is particle cosmology, where one objective pursued by the scientists is to complete the Standard Model of particle physics and overcome known weaknesses. This includes questions about how the number of quark and lepton families, the origin of dark matter and energy, and the microscopic origin of inflation can be explained. The physicists also investigate the quantum structure of black holes and of cosmological space-times.

The third member of the trio is experiment-oriented phenomenology. The phenomenologists work out specific model predictions, deliberately insert variations, and thus compute how different types of matter interact with each other and which tracks they leave behind in the detector, for example. This helps their colleagues working on accelerator experiments to find the needle in the haystack. The problem is that the particle tracks churned out by the ATLAS detector at the world's most powerful particle accelerator in Geneva consist largely of garbage. Only very rarely does an interesting track appear on the screens, for example the Higgs particle, which had been predicted back in 1964, but was not finally detected in ATLAS until 2012. To cope with the enormous computing effort, the phenomenologists develop ingenious mathematical methods and complex computer programs and today obtain predictions which are much more precise than they were ten years ago. Not only because the computers have become faster, but also because the physicists now have a better understanding of the physical interactions and the mathematical structures.

And string theory? It is the fourth and most mathematical pillar in the theoretical construct. It is searching for a »theory of everything«, which unifies the theory of the very tiny things – quantum theory – with the theory of the universe – gravitation – under one roof. Even though there is still a long way to go until this objective is achieved, string theory is already bearing fruit. In recent years, significant progress has been made in understanding gravitation and black holes. Furthermore, the new mathematical methods that have been developed in this extremely ramified research field are now being used in other disciplines, for example in phenomenology, in cosmology and also in traditional disciplines such as solid state physics.

It is becoming increasingly apparent that: The »theory of everything« is not the sole objective of theoretical physicists, it is more the route they are taking to get there which is worthwhile in itself. No matter where this route may lead, the finishing line for physics – an ultimate theoretical construct – is a very long way off. *



SEARCH *for the* INVISIBLE

Hardly any other research topic in particle physics harbors as much fascination as the search for DARK MATTER. While there are numerous indications for the existence of this invisible matter, it is not at all clear what it consists of.

Searching for dark matter with CRESST——
Left: Scientists have made the experiment even more sensitive by installing new crystal detectors. CRESST can now detect particles with very low mass as well.

The axion: One particle for two questions——
Right: Test setup for a newly planned experiment: The existence of axions could solve two unsolved problems in particle physics – one of them is the nature of dark matter.

What is essential is invisible to the eye.« This famous quotation from the »The Little Prince« by Saint-Exupéry could also apply to physicists – after all, the universe seems to contain things that cannot be observed even with the best telescopes. If the total mass of the visible galaxies and stars, the atoms and the molecules, were added together, we would arrive at only five percent of the total energy density in the universe. The fact that there should be five times as much matter can be deduced indirectly: from the rotational speed of galaxies or the cosmic background radiation. Invisible masses seem to pull at the visible ones and affect their motion. Physicists call them »dark matter«. But this still leaves the biggest part – 70 percent. The scientists suspect that so-called dark energy is behind it.

How can we bring this mysterious dark matter to light? Not only with the heart, that's for sure, as the fox recommends to the Little Prince in Saint-Exupéry's book. But with highly sensitive experiments. One of them is CRESST (Cryogenic Rare Event Search with Superconducting Thermometers), which has been searching for dark matter in the underground laboratory below the Gran Sasso Massif in Italy since 1996, and which set off on its third measurement campaign in 2016 after undergoing technical upgrades. To set the record straight right at the outset: CRESST has not yet found dark matter; measured values that seemed promising have all turned out to be vagabond natural radioactivity. But conceding defeat is not an option. Sensitivity has increased with CRESST III; it could now see dark matter down to masses of 300 megaelectronvolts. Are scientists ever going to find anything? »This depends on what nature has decided,« says Dr. Federica Petricca, spokesperson for the CRESST team.

The team has done its homework and developed a high-sensitivity crystal detector. If one of these dark-matter particles collides with the atomic nuclei in the crystal, these are pushed away slightly, thus increasing the temperature of the crystal by a marginal amount. To measure this heating, the detector is cooled to minus 273 degrees Celsius, about as cold as it gets.

And if CRESST III also finds nothing? This will not mean that the theory of dark matter must be abandoned completely, says Petricca. Maybe it's simply that the »net« of the experiment is too coarse and the particles too light. This could be the time for MADMAX (Magnetized Disc and Mirror Axion Experiment) to step up. The concept for the experiment standing behind the grim-sounding name was developed at the Max Planck Institute for Physics and is being planned with international partners. Location and starting date have yet to be fixed. MADMAX could be sensitive to axions, hypothetical particles that could explain a phenomenon which has to do with symmetries between matter and antimatter. If axions exist, they would also be a candidate for dark matter. They would be very light, however: between a nanoelectronvolt and a thousand microelectronenvolts – apparently much lighter than neutrinos, the hitherto lightest particles. MADMAX could »weigh« axions upwards of a few ten microelectronvolts.

The physicists want to use a special property of axions for the measurement. In a magnetic field, an axion exhibits an electric field – and thus resembles a light particle, also known as a photon. The electric field is refracted at interfaces between non-conductive media – between air and plastic, for example – thereby generating microwave radiation. Its power is so weak, however, that no sensor can measure it. The physicists use a trick: They construct many of these transitions one after the other – the plan is to have 80 – and amplify the microwaves through interference. The signal builds up to a hundred thousand times its original intensity. MADMAX is surprisingly small for particle experiments: The discs will only be one meter in diameter, but they have to be positioned with a precision of a few thousandths of a millimeter.

And if it turns out that there is no such thing as an axion? Dr. Béla Majorovits, project head of the planned experiment, is relaxed: »I have every confidence in our theoreticians.« *

Double IDENTITY

NEUTRINOS were predicted in 1930 by Wolfgang Pauli and detected in 1956. Numerous experiments since then have been trying to clarify fundamental questions, for example: What is the mass of the neutrino? And: Are they their own antiparticles?

Germanium detectors for GERDA

1 Germanium detectors are used in the search for neutrinoless double-beta decay. They have a sensitive surface and are stored in specially cleaned vacuum vessels (converted pressure cookers).

The GERDA experiment

2 Looking downwards into the GERDA experiment: Germanium detectors are lowered into the tank filled with liquid argon.

KATRIN – measuring scales for neutrinos

3 Working on the KATRIN experiment, which is being set up at the Karlsruhe Institute of Technology. Its aim is to provide a precise determination of the mass of the neutrino.

One of these experiments is GERDA. The »Germanium Detector Array« is attempting to track down neutrinoless double-beta decay. This is a process whereby two neutrons in an atomic nucleus decay into two protons, emitting two electrons as they do so – but no neutrinos. This process can take place only if the neutrino and its antiparticle are identical. And it would help physicists to overcome a predicament. If neutrinos were their own antiparticles, this could help to explain why more matter than antimatter survived in the universe after the Big Bang, and thus the fact that the universe – and we – exist at all.

An awful lot of optimism is required if you want to detect neutrinoless double-beta decay in an experiment. Even normal double-beta decay, where two neutrinos are produced in addition, is extremely rare: It takes around a hundred billion billion years until half of a material has decayed in this way. Neutrinoless double-beta decay is at least 10,000 times less frequent. In the underground laboratory underneath the Gran Sasso Massif in Italy, GERDA has been waiting for these incredibly rare events – in vain up to now. The experiment is a success nevertheless, as it has actually succeeded in shielding the 35 kilograms of germanium crystals in which the decay is to occur and which are to measure the event as well, against natural radioactivity. This is the purpose of a tank of liquid argon which in turn stands in a ten-meter tank of water. »We have not observed any natural radioactivity in the relevant range,« says Dr. Béla Majorovits, GERDA project manager at the Institute.

Should GERDA not find anything, the successor project LEGEND will offer a new opportunity. It is to start work in a few years' time, then in several steps with up to 1,000 kilograms of germanium. To this end, the properties of new types of germanium detectors and new possibilities for actively shielding them are being investigated in great detail. LEGEND will make it possible to detect neutrinoless double-beta decay if the mass of the neutrino is in a range that theoretical considerations have assessed as being of interest. »With ultrapure germanium detectors we can also look for signals from dark matter, the invisible mass in the universe,« says Dr. Iris Abt, who heads the LEGEND team.

GERDA and LEGEND are not the only neutrino experiments the Institute is involved with. In 2017, the »Karlsruhe Tritium Neutrino Experiment« – or KATRIN – will go into operation at the Karlsruhe Institute of Technology with the aim of weighing the neutrino. When neutrinos were first discovered, scientists initially thought they had no mass. We now know that neutrinos do have a mass after all, albeit a very small one. The neutrino 'scales' actually determine the energy of the electron that is produced in the decay of radioactive tritium. The neutrino which is also released in the tritium decay robs the electron of at least as much energy as corresponds to its mass, however. The neutrino mass can therefore be deduced from the energy that the electron is lacking.

The physicists at the Institute are concentrating on analyzing the data from KATRIN, on the one hand, but they are also developing a new detector for KATRIN, called TRISTAN (Tritium Beta Decay to Search for Sterile Neutrinos), which is to look for new types of neutrinos – so-called sterile neutrinos. The name has nothing to do with disinfection, but refers to the as yet unobserved right-handed partner of the known (always left-handed) neutrino. Dr. Susanne Mertens, head of the TRISTAN project: »If sterile neutrinos exist – and this is what theoreticians assume – they could explain a large portion of the dark matter in the universe.« *

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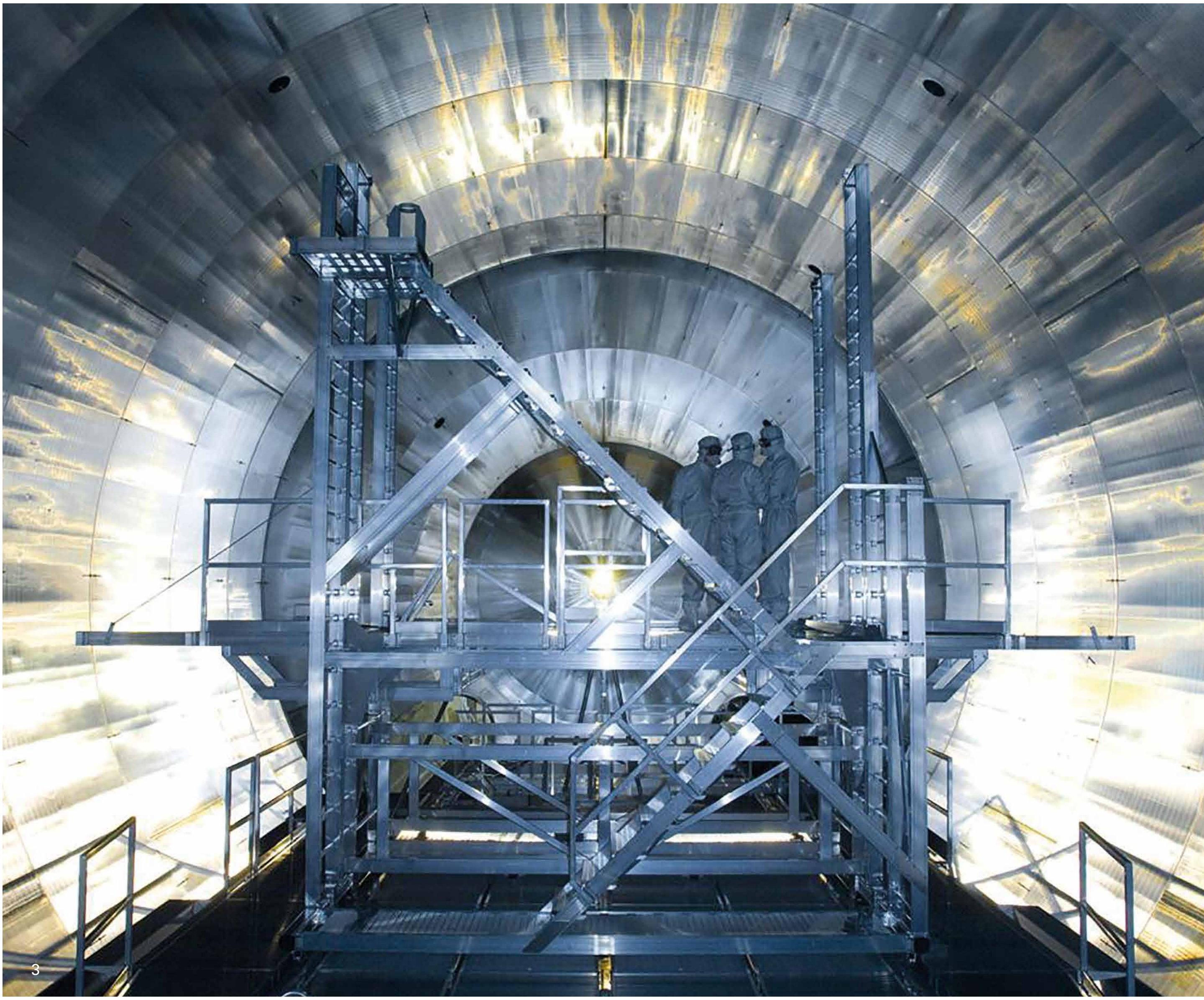

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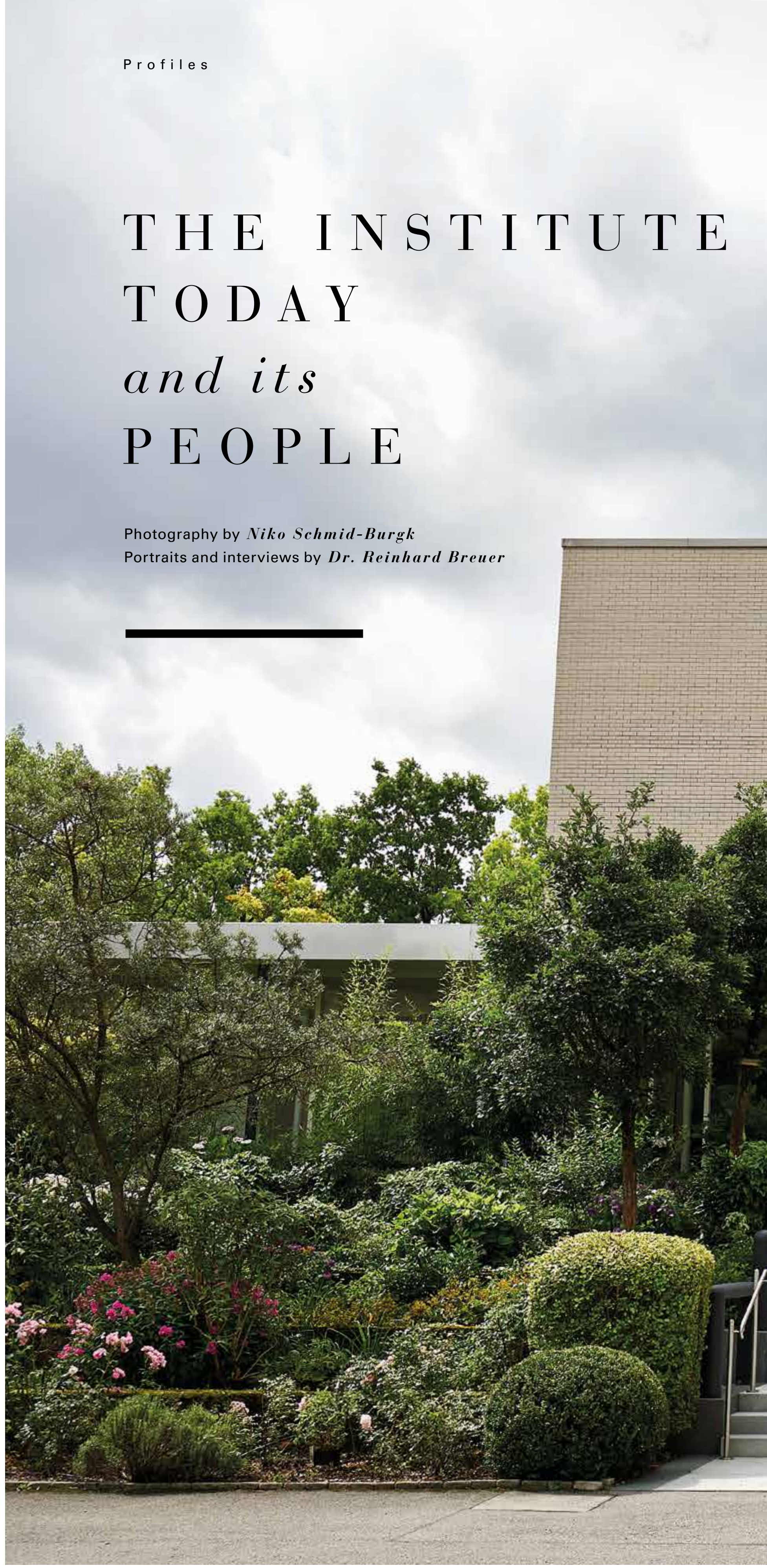
THE INSTITUTE TODAY *and its* PEOPLE

Photography by ***Niko Schmid-Burgk***
Portraits and interviews by ***Dr. Reinhard Breuer***



The people at the Max Planck Institute for Physics

Three research departments work on theory, three dedicate themselves to experiments. The MPI for Physics has a total staff of 330: Around 100 scientists and 75 doctoral students from a variety of countries conduct research at the Institute. In addition, there are 110 employees in technical services and administration, as well as 15 trainees in the electronics and engineering departments.

SCIENCE IS DONE BY PEOPLE – not by computers, satellites, telescopes or particle accelerators. Researchers at the Max Planck Institute for Physics study the fundamental questions of particle and astroparticle physics, assisted by the staff in the technical departments and the administration. It would be impossible to manage the diverse research tasks without them. *Five members of the Institute offer insight into their work.*

How to EXPLAIN NATURE

RALPH BLUMENHAGEN heads a theory group at the Max Planck Institute for Physics and is also a senior lecturer at the Ludwig Maximilian University of Munich. The mathematical physicist dedicates his time to string theory, the ambitious project that seeks to *mathematically unify all the forces of nature.*

The holy grail of theoretical physics can be found on a mountain top. And the path that leads there is paved with craggy mathematics. Dr. Ralph Blumenhagen is one of these mountain climbers – and whoever talks to him must expect to be showered with specialist terminology which sometimes sounds more like science fiction than ordinary explanations for the physical wonders of the world. »I admit,« says the leader of a Max Planck Institute for Physics working group with a smile, »that it's advisable to have taken some courses in higher mathematics before you can talk to me directly about my work.«

The Holy Grail: nothing less than the unification of all the forces of nature within a theoretical framework. Ideally, it should be possible to derive essential properties of our world and the universe from such a »Grand Unified Theory«: laws of nature, dimensions of space and time (a total of four), strength and number of fundamental forces (four in number), the masses of the elementary particles.

The researchers have thus spent four decades now exploring the approach of so-called string theory. »By fundamental we don't mean point-like elementary particles such as quarks or electrons, but tiny strings.« And there are two sorts of strings: open and ring-like closed strings. It is only when they oscillate that the one-dimensional entities form the familiar elementary particles. To design a complete theory from these fundamental strings, they are embedded in mathematical spaces with ten or eleven dimensions. »I know,« admits the mathematical physicist, »that this is difficult for a lot of people to digest.« And it is also unclear how our four-dimensional physics can be embedded into an eleven-dimensional theory.

How did it come about that Blumenhagen turned his attentions to such an abstract topic? »Even at an early age,« explains the 51-year-old physicist, »I was impressed that things in nature could be explained with the power of mathematical expressions, as happens in the theory of relativity or quantum mechanics.« First he studied at the TU Clausthal »where there were only 22 other students in my discipline in the first semester, an idyllic situation!« Afterwards, in Bonn, things became serious, so to speak. His Diplom and doctoral theses with Werner Nahm already involved special field theories that were playing an important role in string theory even then.

As a postdoc, initially at the University of North Carolina in Chapel Hill, he subsequently came in contact with the guru of string research at the prestigious Institute for Advanced Study in Princeton. Edward Witten had achieved a great breakthrough in string theory in 1995. He had succeeded in unifying the five different string models in eleven dimensions which were making the rounds at that time. »The whole field was given a huge boost by this 'string revolution', as some soon began to call it.«

Afterwards, his career took him back to Berlin to Humboldt University, where he obtained his German postdoctoral lecturing qualification. Here he had a more or less fateful encounter with Dieter Lüst, also one of the string theory pioneers and a professor there at the time. When Lüst was later appointed Director at the MPI for Physics, Blumenhagen followed him to Munich – via a detour to Cambridge, England – in 2004. »This is where I really feel at home now,« confesses the string researcher. »At the Institute, I have an enormous amount of freedom to push on with the theoretical problems that will perhaps one day allow us to talk about a unified theory of all the forces of nature.« *

Ms. Geib, why did you become a physicist?

At school in Korntal, I had already had an incredible teacher who encouraged me and the other female students in his higher-level physics course and my interest in physics in particular. This made a lasting impression on me and motivated me to study this discipline.

What happened next and how do you come to be at the Max Planck Institute for Physics?

I then studied physics at the Technical University of Munich (TUM). The TUM offers a master program in nuclear and particle physics and astrophysics. I specialized in theoretical particle physics and also wrote my master's thesis on this topic. One of my fellow students was already at the Max Planck Institute for Physics at the time and told me how much he liked the supervision and the work atmosphere at the Institute. So I applied for the doctoral program and was accepted, which made me really happy.

Surrounded by nature

View of the Institute's lecture hall – designed by Sep Ruf, the building dates back to 1958 and is characterized by slender tubular elements that are repeated both inside and outside.

What does the MPI for Physics offer you?

On the one hand, excellent supervision of my research work, and on the other there are frequent exchanges among the scientists, be it during a coffee break or in the colloquium. The staff at the Institute is open and friendly, so I quickly made contact with a number of colleagues. In addition, it's evident that the administration considers supporting us to be an important task – when we go on trips, for example, with contracts, or with events like Career Day (see below). The financial situation in the Max Planck Society also differs to that at the universities. All doctoral students here have three-year contracts from the start, plus an option for a fourth year.

What does that mean for your work in particular?

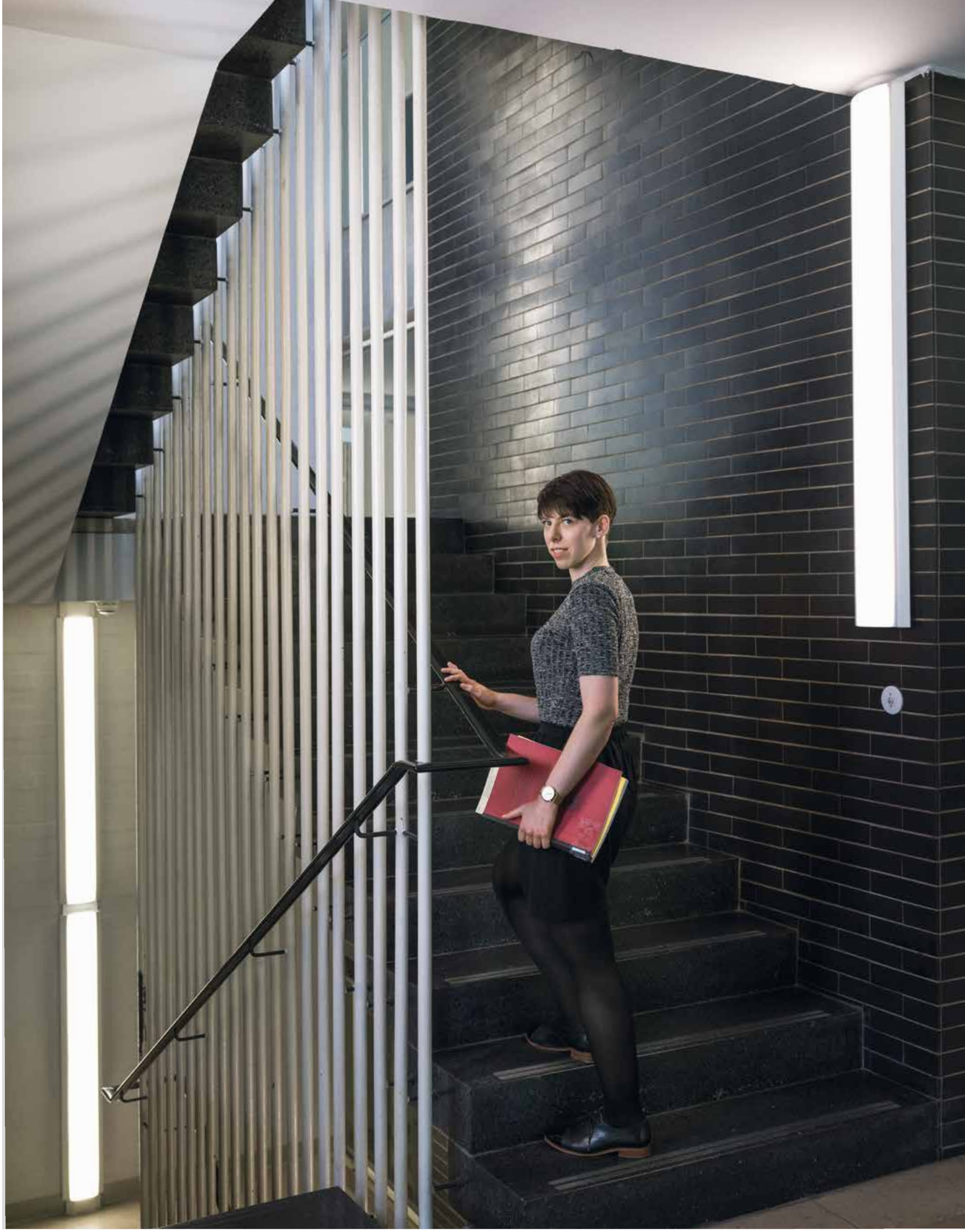
My work is supported from all sides. As part of our doctoral work, we can introduce our own ideas and have a say in which projects we do. We are allowed to present our results at international conferences and attend advanced training programs to enhance our specialist knowledge. This brings us into contact with the international research scene and establishes a network. In this way we can set up project cooperations directly – a huge plus for doctoral students.

What is the subject of your doctoral thesis?

Basically, all particle physicists are searching for new physics that goes beyond the Standard Model. We know from experimental observations, for example, that neutrinos have mass that cannot be explained with the Standard Model. We therefore must expand the Standard Model. There are many different ways of doing this. What we cannot yet say is which of them is actually realized in nature. My doctoral thesis deals with the computation of processes that could help us to check the models proposed experimentally.

To change the topic: You are very committed to the professional orientation of doctoral students, and have even helped to organize a so-called Career Day. What does this involve?

We actually all know that only a few percent of all doctoral students will remain in research. But a lot of people only start to consider their professional future towards the end of their doctoral work. Our Career Day aims to make doctoral students aware of how sought after their skills are, even outside of science. We therefore invited companies which could be of interest to physicists. Many representatives of companies were originally in research themselves and were able to pass on their own experiences. We've thus gained a lot of insight into career paths and prospects in business and industry. There are exciting jobs in companies as well! *



TANJA GEIB is a doctoral student at the Max Planck Institute for Physics. The physicist from Korntal near Stuttgart is engaged in research in the field of theoretical neutrino physics. She is also giving some thought to life after her doctorate – and is involved in career planning. *»Our skills are sought after.«*

KARLHEINZ ACKERMANN is a member of the core team in the design department at the Max Planck Institute for Physics. The 62-year-old mechanical engineering technician has already been actively involved in a great many experiments in particle physics. Why does he still enjoy his work? *»There are new challenges all the time!«*

Mr. Ackermann, how did you come to be at the Max Planck Institute for Physics?

This was a while back. You could say I've spent almost all of my professional life here, in various functions with different tasks. An exciting time. I started in 1977 as a technical draftsman. Later, I qualified as a mechanical engineering technician. I was then able to take on technically very demanding tasks in our department.

Who works there and what do they do?

We have four German and two Russian engineers, plus six technicians. The scientists tell us what they would like and we then implement their ideas in instruments. This entails the design, the working drawings, and the selection and control of the companies that supply us with components or which we commission to manufacture parts. In the end, everything is assembled and tested.

So you act as a link between science and industry?

Yes, absolutely. First, we talk to the researchers about what they want and what they need. Then, we select the companies and discuss whether they can manufacture the things we need. Then we place the order and follow it through.

How much do you manufacture yourselves and how much do you outsource?

Our principle is: Whatever we can purchase from outside companies and providers we should do so. Individual or special parts we manufacture ourselves, also when it's urgent.

Do you also cooperate with other institutes?

This has changed a lot over the course of time. In the past, small experiments were predominant. The Institute could handle these itself to a large extent, together with maybe one or two external partners. Today, the experiments are so large that they can only be undertaken in complex, international collaborations – Europe-wide or even across the globe.

What kind of specialists do you need in the design department?

We don't have any actual specialists, nor do we need them. We need jacks-of-all-trades. Each experiment is different and brings new challenges. Specialists would have to continually relearn their trade, because technology changes radically every ten years. But unfortunately it's difficult to recruit all-rounders, as industry can always pay more than we can.

Which projects are you involved in?

I spent several years working on the ALEPH detector of the LEP accelerator at CERN near Geneva. Then I worked on ATLAS, one of two gigantic detectors at the LHC (Large Hadron Collider), the successor to the LEP. In recent years, I've been working on BELLE II in Tsukuba in Japan. We are designing a so-called pixel detector for this project. A test instrument will be installed at the collision point of the KEK accelerator there at the end of 2017.
The measurements are scheduled to start in 2018, and then our real pixel detector should be in place. The scientists have great expectations. As always, they are searching for new physics.

What is the interaction like between you and the researchers?

We work with scientists who are specialized in experiments, of course. So we speak the same language. But we then often have to determine which of their ambitious ideas can really be put into practice. Reality can definitely differ from theory. We frequently reach the limits of what is feasible in our projects.

What are the greatest challenges facing you?

Things frequently heat up in the final phase of a nearly finished installation (laughs). The real challenge for me has always been to realize the task set by the scientist with the best technology available at the time. This sometimes requires a bit of convincing when dealing with the manufacturer. *

Modern and traditional

In addition to the most up-to-date, computer-controlled milling machines and lathes, »good old technology« is also still in use at the MPI for Physics.

Dr. Mertens, what led you to take up physics?

I really liked the subject at school, and I enjoyed the advanced course that focused on physics. But after taking my Abitur I still considered my other interests as well: art, philosophy and psychology. But then, physics just happened – and I have never regretted it.

How did you get to the Max Planck Institute for Physics?

Not so fast. First, I studied physics in Karlsruhe and thought initially it would have to be theoretical physics. I then wrote my degree thesis on supersymmetry, a theory to expand the Standard Model of particle physics.

But you weren't satisfied with this.

No. I soon had the distinct feeling that I could contribute more to research in experimental physics. It so happened that the neutrino experiment KATRIN (Karlsruhe Tritium Neutrino Experiment) was just being set up in Karlsruhe. I applied to do my doctoral studies there – and was immediately accepted!

Was that a simple step?

I did have some difficulties initially. While conducting experiments, you always have to take technical details into consideration as well: electrodes, high-voltage technology and other things. But I was quickly able to get a feel for this. And I realized: I can also understand this in detail and even find solutions.

Exterior views

The building designed by Sep Ruf has clear architectural lines and is a listed building.

What fascinates you about neutrino physics?

Emotionally, I have always found neutrinos somehow agreeable, very mysterious entities! Plus, they help us to understand the major questions: What is the universe made up of? Why do we exist at all? For instance, the big mystery of dark matter is closely related to neutrinos. It's all about the fundamental observation that the visible matter in the cosmos amounts to only five percent of the total mass-energy. The remainder is completely unknown to us.

And what does that have to do with neutrinos?

The three known neutrino species can actually make only a small contribution to dark matter. Their masses are too small to do otherwise. We want to search for a new, still hypothetical neutrino species that could be much heavier. We call them »sterile neutrinos«, because they are even more elusive than the neutrinos we already know, so to speak. If they do exist and possess the appropriate mass as well, they could in principle even explain the whole problem of dark matter. We'll be searching for this dark matter candidate with an upgrade to the KATRIN experiment which bears the nice name of TRISTAN.

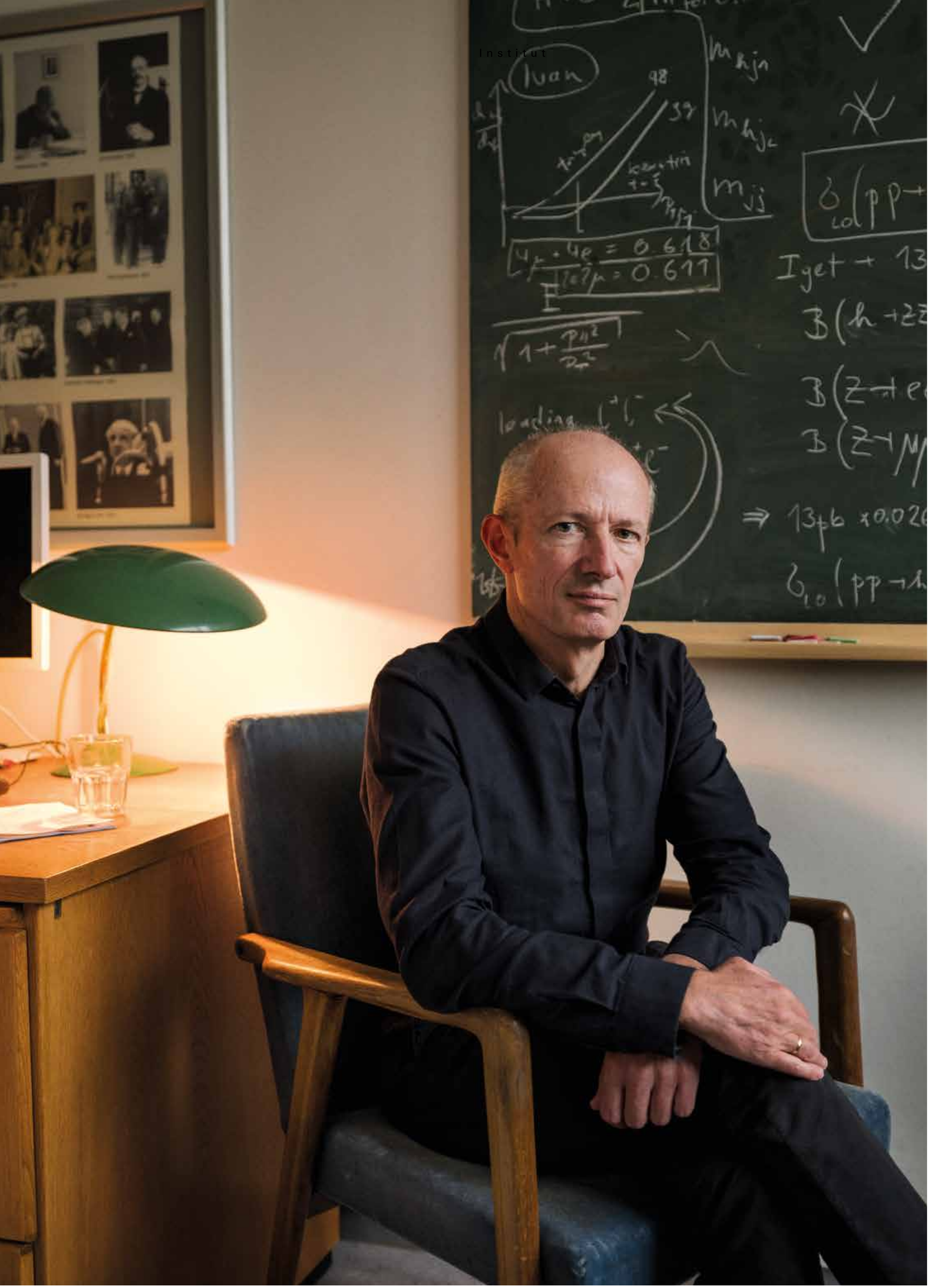
What would be the relationship between neutrinos and our existence?

We consist of matter, but the corresponding antimatter is nowhere to be found. Both should have been created in equal parts during the Big Bang and have annihilated each other. The reason why this didn't happen can actually only be owed to an asymmetry in particle processes in which neutrinos play a crucial role. Expressed in physical terms, the issue is whether neutrinos are their own antiparticles. This is what we want to find out – with the so-called LEGEND experiment. This will be bigger and more sensitive than all previous experiments – very exciting!

You not only lead a Research Group at the MPI for Physics, you also hold a tenure-track professorship at the Technical University of Munich, a position which can lead to a full professorship. How did this come about?

Yes, it is a relatively new program for the cooperation between Max Planck Institutes and the TUM. It has the advantage that I can teach students and supervise doctoral students. I enjoy teaching very much. And it is of great benefit for our research, as well as for the teaching at the TUM. I am delighted to have this opportunity. *

SUSANNE MERTENS is the Leader of a Max Planck Institute for Physics Research Group that devotes itself to experimental neutrino physics. In addition, she holds a tenure-track professorship at the Technical University of Munich. What motivates her? »*I want to know why the universe exists!*«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Attempt the IMPOSSIBLE

ALLEN CALDWELL
is an American physicist and Managing Director at the Max Planck Institute for Physics, where he heads the »Experimental Particle Physics« department.
His motto:
»Always look for new paths to pursue.«

Meeting Prof. Dr. Allen Caldwell and talking about his research is a particular pleasure. The American researcher has taken experimental particle physics at the Max Planck Institute for Physics under his wing. In his case, this includes several ambitious projects that are intended to tackle a number of fundamental problems in physics: alternative accelerators, dark matter, neutrinos, antimatter.

Anyone interested in physics knows that these are the crown jewels of the discipline. And whatever they do, the researchers come up against limits where it is unclear whether it will ever be possible to overcome them. »Yes, we often have to attempt the impossible and this involves continually going down new paths,« says the Max Planck physicist. »And we don't know whether we will ever be successful here.«

But one thing at a time. The academic career of the 58-year-old physicist can be understood as an American-European joint venture, so to speak. Born in France, father American, mother French, he studied in Houston/Texas, and obtained his doctorate at the University of Wisconsin. Later, the physicist alternated between positions in New York at the famous Columbia University and at the DESY research center in Hamburg, where he met his future wife, who is German. »As the parents of two children in Manhattan,« the American remembers, »we decided we would prefer to move back to Germany.« The offer in 2002 to become Director at the MPI for Physics came at the perfect time. »Life in Munich is very pleasant for a family,« Caldwell says. He can also make frequent use of his racing bike here. »I regularly ride parts of the Tour de France route with friends. We have already conquered the infamous Mont Ventoux.«

Researchers have known for some time that particle accelerators have now reached a critical phase. Planned successors are coming up against technological and financial limits. The planned Future Circular Collider will have a circumference of 100 kilometers and correspondingly high costs.

Caldwell is looking for new paths to tread here, for novel compact accelerators, for example. The experiment at CERN is called AWAKE, and he is its spokesperson. In its ten-meter-long plasma tube, electrons can be accelerated with a hundred times the efficiency of normal installations. This would have dramatic consequences: »These plasma accelerators can be much more compact and thus more cost-efficient than conventional systems.«

He is also involved in the hunt for dark matter. The mystery that around 80% of all matter in the universe is comprised of a substance which nobody has ever seen has been irritating researchers for some time. »We're looking in particular for a hypothetical candidate particle, the so-called axion,« explains Allen Caldwell. »Finding axions is tricky. But our experiment has discovery potential. This means: If these particles do in fact exist, we should observe a clear measurement signal at some stage.«

He doesn't see his job as Managing Director as a boring administrative task – on the contrary: »The Institute is on the brink of significant changes,« says the Max Planck researcher. »We are in the process of planning a new building in Garching, a very interesting phase for us. In addition, the Institute is currently experiencing a change of generation. A few of the other Directors are retiring. The appointment of the successors will have a crucial impact on our future research. In both cases, we are dealing with the future of the Max Planck Institute for Physics.« *

ON THE VALUE *of* RESEARCH

Text *Dr. Patrick Illinger*
Illustration *Marco Melgrati*

100 years Max Planck Institute for Physics – 100 years basic research in physics: Why do scientists dedicate themselves to TOPICS WHICH HAVE NO IMMEDIATE PRACTICAL APPLICATION? Which do not, for instance, produce clean engines or new drugs? We at the MPI for Physics are also frequently faced with this question. So we decided to ask science journalist *Dr. Patrick Illinger* to explain what it is that drives basic research and makes it valuable.

The Earth rises over the lunar horizon

Basic research opens up new ways of looking at things, as this view of our planet shows. The picture was taken as Apollo 8 orbited the Moon in 1968.

Basic research can hurt. A lot. If the data obtained simply refuses to confirm a theory that the researchers have grown fond of. If the measured values refute what was so elegantly expressed on paper. Even worse: If the self-image of all mankind as such is dented. It hurt people's feelings to discover that we humans are not at the center of the solar system, not even, as was still assumed to be the case at the beginning of the 20th century, at the center of all the galaxies, at least. And it hurts when evolutionary biologists come to the conclusion that Homo sapiens is not the »summit of creation«, but simply a primate (albeit with more complex cognitive skills than a lemur). But investigating precisely these things about ourselves, the universe, and our place within it, is the greatest thing a thinking biological species that is capable of self-reflection and thus unique after all, can do. And the interplay of empirical knowledge and theory, which is performed so painstakingly, does ultimately stir up a feeling of awe and grandeur. For example, when the exploration of exoplanets leads us to increasingly suspect that although Earth is not located at the geometric center of the universe, it does represent an extremely precious and rare habitat in the vast expanse of the cosmos. Or when physicists find an elementary building block of the universe whose existence theoreticians had already predicted half a century ago, such as the Higgs boson. Basic research is much more than the fulfillment of immediate physical needs and artistic desires. It is the tool whereby a transitory biological species gains access to eternity. Science is often unjustly equated with the pure search for knowledge, as if the issue were simply to prospect for facts like ore from a mine. The idea of amassing irrefutable knowledge is an absolute contradiction of the principles of good science. As Karl Popper explained, the latter must always allow itself to be subjected to the coup de grace of a possible falsification. More important than new knowledge, which is replaced at some stage by even better knowledge when science is done correctly – take Newton and Einstein – is the constant wanting to know more.

These philosophical principles encounter all sorts of obstacles during day-to-day research work, of course, financial, organizational – and human. Even in the Middle Ages, it was by no means only the representatives of the church who insisted on the geocentric view of the world. The astronomers of the time also meticulously honed the long-forgotten theory of »epicycles« to interpret the strange capers the planets performed in the night sky, instead of accepting the simplest explanation: The Earth orbits the Sun, and not the other way round. The literally superhuman might of the scientific principle prevails over these and other obstacles in the long run. Science is a corrective for vanity, false desires and, yes, even dishonest researchers.

Given today's complex questions, natural scientists must engage in collaborative teamwork that goes beyond the boundaries of individual institutes, disciplines and countries much more frequently. And expensive machines are required. The need to find common ground with governments and society is increasing. How much money should we spend on a few speeding protons? Do the means justify the anticipated benefit? What benefit is actually meant here?

The pragmatic response can be: Good science always yields what economists call spin-off. The construction of a particle accelerator or neutrino detector requires a lot of new, avant-garde technology, which often has first to be invented, and later finds its way into profitable products. In response to the question about what the first electric generators could be used for, the British physicist Michael Faraday is said to have replied that he didn't know either, but he was certain there would come a day when they would be taxed.

The danger with this argument is that researchers get into a situation where they are obliged to advance an economic justification for their work. The important issue here is to make clear beyond any doubt that spin-offs, patents, new products, exploitable findings are welcome by-products of good research, but are never its actual purpose. The essence of basic research includes the fact that its added value cannot be measured with the tools of economics. A lot of things have to be tried out, even if only some of them turn out to be beneficial in the economic sense. The knowledge about the origin of one's own species or the discovery of dark matter in the universe – there are no price tags for these findings.

Basic research is not a pretty rose garden in the backyard of Germany Inc. Science is the foundation of any sustainable society. Cultural, economic and social progress fatefully depends on new knowledge continuously being gained. Naturally, the issue cannot be to aimlessly shower scientists with money and then leave them to it. In times of global challenges, governments and society must be allowed to make suggestions to science about urgent topics, for example ocean acidification, resistances against antibiotics, and demographic change.

The possibilities for doing this exist. The global expenditure on Research and Development has doubled during the past ten years. And the number of academic publications has reached one million. There is also a danger here, however. The danger that the expanding science system, increasingly fixated on itself, becomes a victim of its own success. Too much importance is nowadays placed on generating as much throughput as possible, too much data, and too many publications. The length of the publication list is more crucial today for careers than the quality of the individual publications, or the ingenuity of the individual researcher. The thickness of doctoral theses, the number of doctoral students in the research group, one's own h-index, all these all too numerical indicators which are common in the academic world have taken on an absurd importance. Some universities maintain departments whose sole job is to keep their own institution at the top of the international rankings. Some research organizations and institutes conduct aggressive marketing, instead of balanced PR. Researchers should demonstrate the value of their work not only in publication lists, rankings and glossy brochures, but above all by their activities themselves. What is important is to create values, not only in the sense of measured values.

»More important than new knowledge, which is replaced at some stage by even better knowledge, is the constant wanting to know more.«

Despite all adversity, science and education still prove to be the driving force behind success. All those who today question democracy, deny climate change, and doubt the medical benefit of vaccinations, will also perceive this to be the case. Wanting to know more is always the solution, and never a mistake.

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What does the FUTURE HOLD?

One thing is certain: The Max Planck Institute for Physics is set to relocate

In a few years' time, the particle physicists will leave their site in Munich and relocate to the Garching research campus. This is also the home of the Max Planck Institutes for Plasma Physics, Extraterrestrial Physics, Astrophysics and Quantum Optics. What is less certain is how particle physics itself will move forward. The suspense continues.

The mid-20th century can truly be called the 'gold rush' of particle physics: Every couple of years, scientists discovered new connections and new particles, for example the tau leptons or bottom quarks. The Standard Model established itself – everything was exciting and dynamic. The era of rapid research successes now seems to be at an end. Today, physicists are wrestling with the major fundamental questions: Why does matter exist, but hardly any antimatter? What is dark matter made up of? What is dark energy?

The next giant step on the journey of discovery in particle physics can be neither planned nor predicted, nor is it possible to say whether it will manifest itself in supersymmetry or neutrino physics, as a theoretical model or in an experiment.

What is certain is that the foundations for the future are being laid now – and that the Max Planck Institute is involved in many of these projects.

A linear accelerator is to complete the research at the Large Hadron Collider and replace it at some stage. Two different concepts are currently still in the running – CLIC and ILC. Although it is not clear which of them will ultimately be realized – and when – physicists are already working on the matching detectors for it. In addition to familiar accelerator technologies, completely new approaches will probably also come into play: AWAKE is experimenting with the plasma acceleration of electrons, a promising and low-cost method, as very high energies can be achieved over a very short distance.

The hard-to-get neutrinos also offer a lot more scope for new discoveries: Is the neutrino its own antiparticle? What is its mass? Does a new, hitherto purely hypothetical »sterile« neutrino species exist? The LEGEND, KATRIN and TRISTAN projects could provide the answers here in a few years' time.

Like sterile neutrinos, axions are the result of theoretical, mathematically-stated considerations. A further common feature is that both particles could be the »substance« for dark matter; axions could additionally explain a not yet understood property of the strong interaction, one of the four fundamental forces. An axion experiment called MADMAX is currently being set up.

Still undecided are the developments and trends in theoretical physics. Whether astroparticle physicists, phenomenologists, or cosmologists: All are working on the detailed questions of the »new physics«, which must exist beyond the Standard Model, but about which we still have little knowledge. In the field of string theory, the researchers are motivated by two fundamental problems. Firstly: What does this theory look like exactly, with its mathematical eleven dimensions? And secondly: How can the four-dimensional world in which we live then be sifted out from the large number of solutions provided by the theory?

If and when we will obtain answers to all these questions is written in the stars, as the saying goes. But the successes of the past 100 years should motivate us to continue thinking and searching. *

ABBREVIATIONS

ALEPH detector — Apparatus for LEP Physics

ATLAS — A Toroidal LHC Apparatus (particle detector at the Large Hadron Collider)

AWAKE — Proton Driven Plasma Wakefield Acceleration Experiment (experiment for a new accelerator technology at CERN)

Belle I, II — particle detector at the KEKB accelerator in Japan

CALICE — Calorimeter for Linear Collider Experiment

CERN — European Organization for Nuclear Research

CLIC — Compact Linear Collider

CRESST — Cryogenic Rare Event Search with Superconducting Thermometers (experiment for the detection of dark matter particles)

CTA — Cherenkov Telescope Array (gamma ray observatory on La Palma, Spain, and in Chile)

GeDet — Germanium detectors

GERDA — Germanium Detector Array (experiment to search for neutrinoless double-beta decay)

H.E.S.S. — High Energy Stereoscopic System (gamma ray observatory in Namibia)

ILC — International Linear Collider

KATRIN — Karlsruhe Tritium Neutrino Experiment (measurement of the neutrino mass)

KEK — High Energy Accelerator Research Organization in Tsukuba, Japan

KEKB — particle accelerator at KEK

LEGEND — Large Enriched Germanium Experiment for Neutrinoless ββ Decay (experiment to search for neutrinoless double-beta decay)

LEP — Large Electron-Positron Collider (particle accelerator at CERN)

LHC — Large Hadron Collider (particle accelerator at CERN)

MADMAX — Magnetized Disc and Mirror Axion Experiment (experiment for the detection of axions)

MAGIC (telescopes) — Major Atmospheric Gamma Ray Imaging Cherenkov (gamma ray telescopes on La Palma, Spain)

TRISTAN — Tritium Beta Decay to Search for Sterile Neutrinos

VERITAS — Very Energetic Radiation Imaging Telescope Array System (gamma ray observatory in the USA)

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Föhringer Ring 6, 80805 Munich, Germany
info@mpp.mpg.de, mpp.mpg.de

CONCEPT AND EDITING

Barbara Wankerl
(legal responsibility for content)

CREATION, DESIGN, REALIZATION

Lively Brand Ideas GmbH,
Robert Wohlgemuth

Anne Bauer, Munich

AUTHORS

Prof. Dr. Allen Caldwell
Dr. Reinhard Breuer
Dr. Patrick Illinger
Bernd Müller
Barbara Wankerl

TRANSLATION AND FINAL EDITING

Valerie Scholes / Baker & Harrison

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Logo of the Max Planck Institute for Physics with Heisenberg's expression for the uncertainty relation named for him