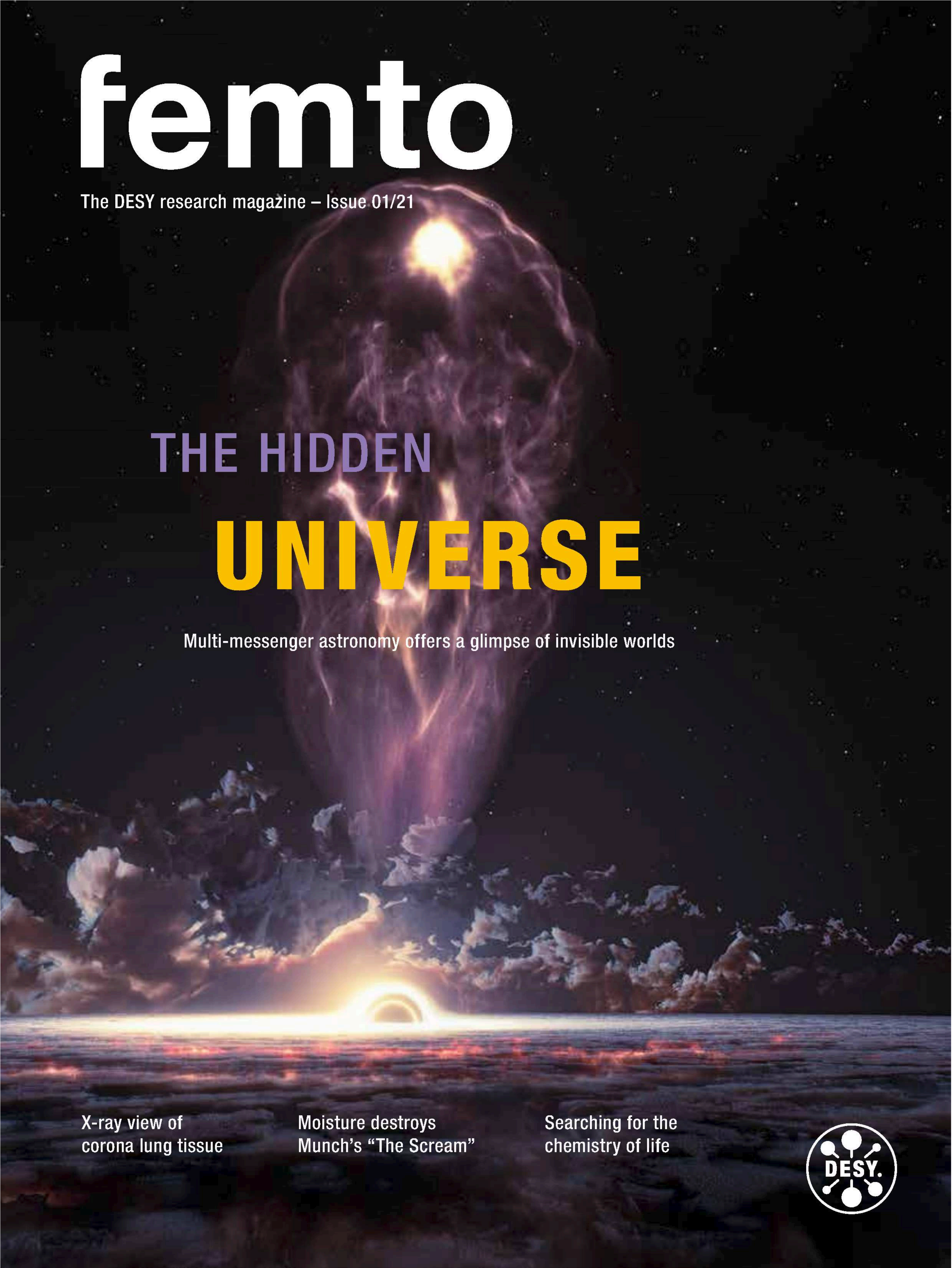

femto

The DESY research magazine – Issue 01/21

THE HIDDEN UNIVERSE

Multi-messenger astronomy offers a glimpse of invisible worlds

X-ray view of corona lung tissue

Moisture destroys Munch's "The Scream"

Searching for the chemistry of life

Interstellar road trip

The universe is full of natural particle accelerators: Black holes, the remnants of exploded stars and other exotic objects hurl fast subatomic particles into space, whose energy exceeds anything that can be achieved with terrestrial particle accelerators. The cosmic particle accelerators reveal themselves through X-rays and gamma rays produced by the fast particles. Using the gamma-ray observatory H.E.S.S. (High Energy Stereoscopic System) in Namibia, a team of researchers has studied a special cosmic accelerator: The binary star Eta Carinae in the constellation Carina in the southern sky, 7500 light years away, produces gamma rays with energies all the way up to 400 gigaelectronvolts, as measured by the team led by Stefan Ohm, Eva Leser and Matthias Füßling from DESY. That is around 100 billion times more than the energy of visible light.

Here, too, the gamma rays originate from fast particles. These are accelerated in a shock region where violent stellar winds from the two suns of the binary star system collide. The dynamics are complex. To illustrate the phenomenon, DESY astrophysicists have produced an animation together with specialists from the award-

Picture: DESY, Science Communication Lab

winning Science Communication Lab. The computer-generated images are close to reality because the measured orbital, stellar and wind parameters were used for this purpose.

The multimedia artist Alva Noto created the sound for the animation. The appeal for him lay in the artistic communication of research results, says Noto: “I particularly like the fact that it is not a film soundtrack, but has a genuine reference to reality.”

Astronomy & Astrophysics, DOI: 10.1051/0004-6361/201936761

www.desy.de/youtube

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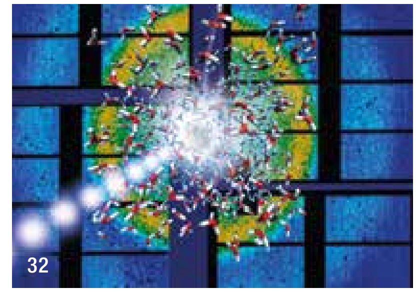
THE HIDDEN UNIVERSE

Multi-messenger astronomy offers a glimpse of invisible worlds

Away from the shining stars lies a universe that is usually hidden from our eyes: Black holes set the cosmos vibrating with gravitational waves, subatomic particles like neutrinos race through space with hellish energies. Today, for the first time in human history, these fundamentally different messengers from outer space can be observed and analysed for astronomical purposes. What does a supernova stellar explosion look like inside? What happens when two neutron stars collide? Neutrinos and gravitational waves reveal celestial objects in entirely new ways, augmenting the observations made using light and other electromagnetic radiation from outer space. Science finds itself at the dawn of a new form of stargazing: multi-messenger astronomy.

Picture: DESY, Science Communication Lab

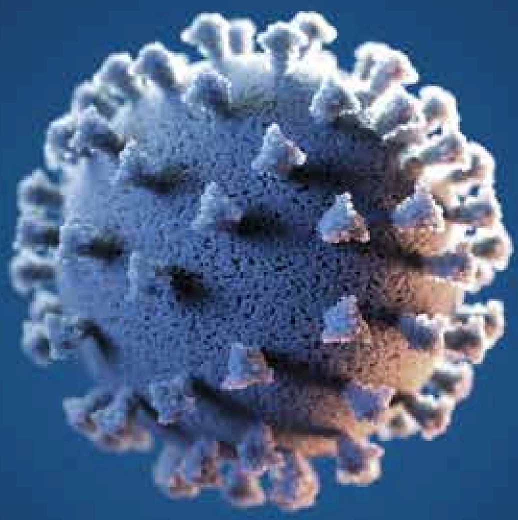


CAMPUS

ZOOM

SPECTRUM

SECTIONS



High-precision X-ray view of lung tissue

New imaging technique shows Covid-19 damage in detail

The coronavirus pandemic not only disrupted our daily lives, but also parts of the research programme at DESY: The lockdown put laboratory operations on hold for a short time, measurements were delayed and conferences had to be cancelled. Nevertheless, the centre quickly got involved in the current challenges and was able to make important contributions to research on the coronavirus. Among other things, a team led by Göttingen X-ray physicist Tim Salditt quickly redesigned a new imaging technique at DESY's X-ray source PETRA III so that it can show the lung tissue of Covid-19 patients in extreme detail. The results help medical experts to better understand the disease and treat it more specifically.

"Originally, we developed phase contrast tomography to be able to examine especially brain tissue in detail," explains Salditt. "This allows conclusions to be drawn about the causes of Alzheimer's disease, for example." But when the corona pandemic swept across the country in spring 2020, Salditt immediately offered help to the pathologists and lung specialists led by Danny Jonigk at the Medical University Hannover and the German Centre for Lung Research – in the hope that his fledgling method could provide high-resolution 3D images of Covid-19-damaged lung tissue and yield new insights about the still little-known disease.

3000 images in one and a half minutes

To obtain sharp, high-resolution images with phase contrast tomography, extremely bright X-rays are needed. This is why the scientists use one of the world's most powerful X-ray sources for their experiments, the PETRA III particle accelerator at DESY in Hamburg. Here, the focused X-ray beam hits the sample, a slice of lung tissue a few millimetres in size, embedded in paraffin. A precision turntable rotates the sample through 360 degrees – in one and a half minutes, the apparatus takes 3000 images from all directions. A detector captures the X-rays and converts them into visible light. The special properties of the focused beam from PETRA III make it possible to record holograms of the sample. A sophisticated algorithm can then calculate high-resolution 3D images from this measurement data.

> *"Where I only see a few grey shadows on the CT, on our images I can see how the smallest vessels are branching"*

Over the past ten years, Tim Salditt and his team have been able to steadily refine phase contrast tomography. In order to screen Covid-19-damaged lung tissue, however, they had to adapt the method in a few ways. “First and foremost, it was important for us to be able to look at a relatively large section of the image first in order to orient ourselves and locate the relevant spots,” Salditt explains. “We then had to really zoom into these places to analyse them in the finest detail.”

High-contrast images

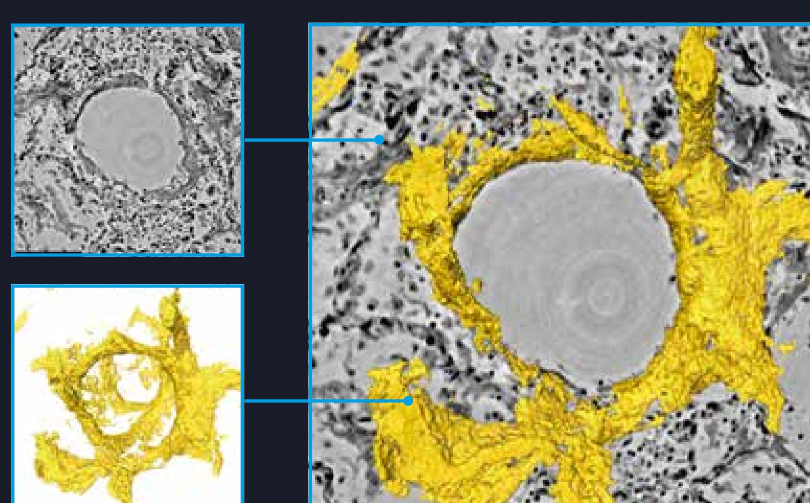
The result is high-contrast images of the lung tissue that are significantly more detailed than images from a standard clinical CT scanner. “Where I only see a few grey shadows on the CT, on our images I can see how the smallest vessels are branching and how the thin tissue walls of the alveoli are changing,” Salditt explains. Among other things, the images were able to confirm the assumption that SARS-CoV-2 stimulates the formation of new blood vessels in the lungs. However, this rescue response of the body, which is usually helpful, is undone by countless tiny thrombi that massively limit lung function in severe cases of the disease.

After that, the team set their sights on another organ also attacked by the coronavirus – the heart. The question was: Does the virus cause the same adverse formation of new vessels there as in the lungs? “Our measurements so far suggest that this is indeed happening,” Tim Salditt reports. However, it is unclear what the medical consequences are and to what extent the heart can recover from this damage.

> *“In the long term, we hope to bring the method to university hospitals”*

One thing, however, seems certain: With phase contrast tomography, experts now have a new, powerful tool at hand that can image the finest tissue structures in great detail. “In the long term, we hope to bring the method to university hospitals,” says Salditt. “There, pathologists could use it to classify tumours, for example. This information could then also flow back into treatment.” Conversely, it would also be conceivable to bring pathology to the accelerator. The vision is that specialists from all over Germany would send their samples to Hamburg, where they would automatically be screened by sample robots – an idea that could be particularly interesting for medical research projects.

eLife, DOI: 10.7554/eLife.60408

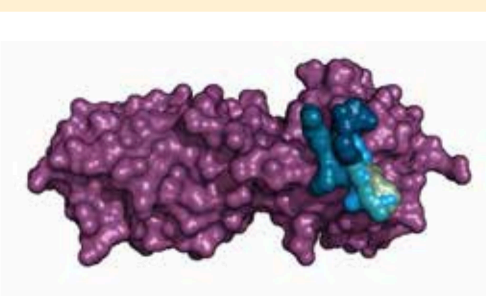


Detailed view into the lungs
Sections through the three-dimensional reconstruction volume (upper left, grey) around a pulmonary alveolus with hyaline membrane (lower left, yellow). On the right, the images are superimposed. The air sac (alveolus) is in the centre. The electron density is represented by different shades of grey. On the inside of the alveolus is a layer of proteins and dead cell residues, the hyaline membrane. This deposit, which can be represented in its three-dimensional structure for the first time by the new method, reduces the gas exchange and leads to respiratory distress.

RESEARCH AGAINST THE PANDEMIC

The corona crisis poses enormous challenges for science: New findings and concrete solutions regarding SARS-CoV-2 are required within a very short time. Experts on the DESY campus are involved in corona research in multiple ways:

- At the X-ray source PETRA III, a research team screened several thousand active substances for their basic suitability as drugs against Covid-19. After testing around 7000 samples with almost 6000 active substances, 37 were identified that bind to an important viral protein, the main protease. It is of central importance for the multiplication of the virus in the cell. In cell cultures, seven of these substances significantly slowed down viral replication. Two of them were so promising that they entered preclinical studies. One of the two active substances docks onto a previously unknown binding site on the main protease.



New binding site on the main protease

- A European research group at PETRA III identified a synthetic antibody among hundreds of candidates that could prevent the virus from infecting human cells. The so-called Sybody 23 occupies the receptor binding domains on the characteristic spike protein with which the coronavirus couples to the ACE2 protein on human cells. In test tube studies, the antibody, originally from camels and llamas, successfully deactivated a genetically modified lentivirus with spike protein. Further tests must show whether it is suitable as a drug.
-
- DESY's computer centre makes parts of its computer power available for data analyses and complex computer simulations. These are used, among other things, to calculate how certain virus proteins behave. In the first six months up to 30 September 2020 alone, this amounted to 13 997 439 hours of computing time, corresponding to the power of around 800 laptops in continuous operation.

- With the help of PETRA III, experts are looking for innovative ways of administering corona drugs. To this end, the researchers are testing methods to apply active substances as evenly as possible to different carrier materials so that they can be dosed much more precisely and individually tailored to each patient. The aim is to alleviate possible side effects, which can be considerable with various potential corona drugs.

- A DESY theorist and his team are modelling the spread of SARS-CoV-2 with big-data models from particle physics. One of the results is the smartphone app CoVis, which creates an individual risk analysis with the help of artificial intelligence and information about one's own behaviour. The algorithm not only tracks the development of immunity and has the potential to reduce the burden on clinics, it can also be customised: With a bespoke user interface, for example, a company could determine the infection risk of its employees and take appropriate countermeasures. In addition, the app could be modified for other infectious diseases such as influenza, perhaps also for allergies or even pollen counts. **www.covishealth.com**

- At PETRA III, the Mainz-based vaccine developer BioNTech is looking for ways to improve the still young class of RNA vaccines. At the measuring stations of the European Molecular Biology Laboratory (EMBL), BioNTech has investigated how messenger RNA (mRNA) can be better packaged in nanoparticles so that it can have a greater effect in the organism. mRNA vaccines induce the cell's own machinery to produce characteristic proteins of a pathogen, which are harmless on their own, but train the immune system for the pathogen in question. The hope is to produce not only corona vaccines in this way, but also vaccines against other infectious diseases or even against cancer.

Further information:
www.desy.de/news/corona_research

Silicon with muscles

Perspectives for chip-based technologies of tomorrow

Smartphones, laptops, smart watches: The chemical element silicon is found in almost every electronic component and computer chip, no matter how small. A research team from Hamburg has now succeeded in giving silicon muscle power. This new property enables the hybrid material to convert electrical signals into mechanical movements, offering completely new perspectives for the chip-based technologies of tomorrow. The team led by Patrick Huber from the Hamburg University of Technology (TU Hamburg) monitored the movement of the silicon atoms live using X-rays.

In order for the loudspeaker in a smartphone to work, for instance, so-called actuator materials are required. These perform small movements in the micrometre and nanometre ranges electrically and very precisely, causing air, for example, to vibrate. Until now, silicon could not perform such functions.

Nature as a model

"To change this, we artificially imitated what nature has already achieved in biomaterials such as bones or teeth through a clever combination of soft and hard matter," explains Huber. For this purpose, his team equipped the small nanocanals in hard silicon, which can form spontaneously in huge numbers, with the artificial, environmentally friendly and soft muscle polymer polypyrrole. "We have succeeded in causing these muscle molecules and thus the entire silicon skeleton of the hybrid material to expand under electrical voltage and then contract again," explains the physicist.

What is particularly exciting about the new material is that, in an aqueous environment, only very small electrical voltages are required for the actuator function. These voltages are similar in magnitude to those used in many living systems to conduct stimuli and control movement. This makes the hybrid material particularly promising for applications in biological or biomedical systems, the team emphasises – especially as only biocompatible substances that are available in large quantities are used.

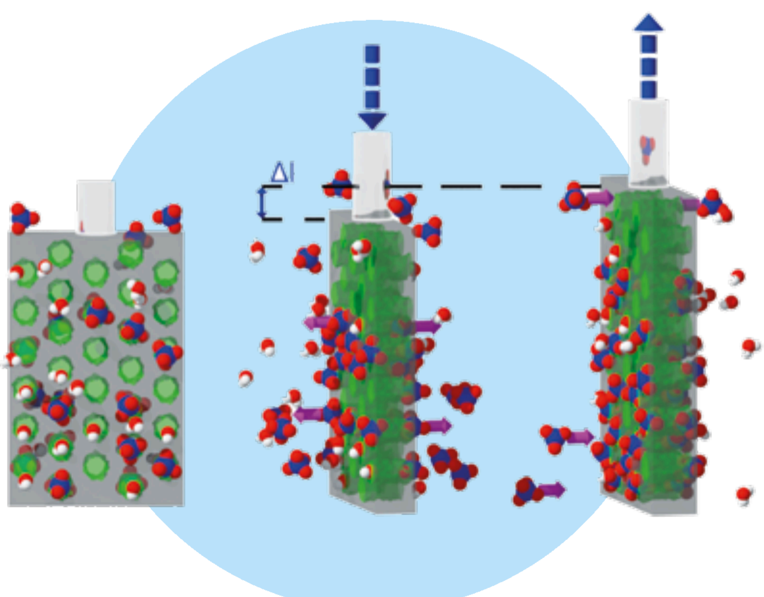
In time with the voltage

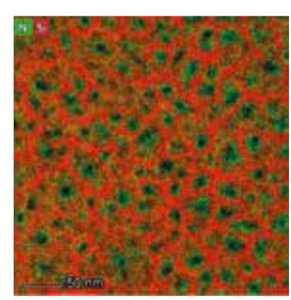
In order to understand the functioning of the new nanoporous hybrid material, researchers from the Helmholtz Centre Hereon carried out computer simulations. On this basis, the properties of the material can now be precisely predicted and thus strategies can be proposed to optimise it for applications. Using DESY's PETRA III X-ray microscope, the authors have even been able to observe live how, driven by the muscle molecules, the silicon atoms move back and forth in time with the small electrical voltages and how in detail this concerted movement on the nanoscale makes the deformation on the macroscale possible in the first place.

The new material design is an example of how the physics peculiar to the nanoscale can be combined with self-organisation principles to give a classic base material of enormous technological importance a completely new functionality – muscle power in this case. By applying design principles modelled on nature, a new type of hybrid base material with actuator properties has been developed that can be used to design tomorrow's technology in a more bio-inspired and thus more sustainable way, concludes lead researcher Patrick Huber.

Science Advances,
DOI: 10.1126/sciadv.aba1483

Hybrid material
Silicon (grey) with muscle polymers embedded in nanopores (green) shows reversible expansion and contraction as a function of small electrical voltages in an aqueous environment.





The distribution of artificial muscles (green) in silicon (red) under the electron microscope

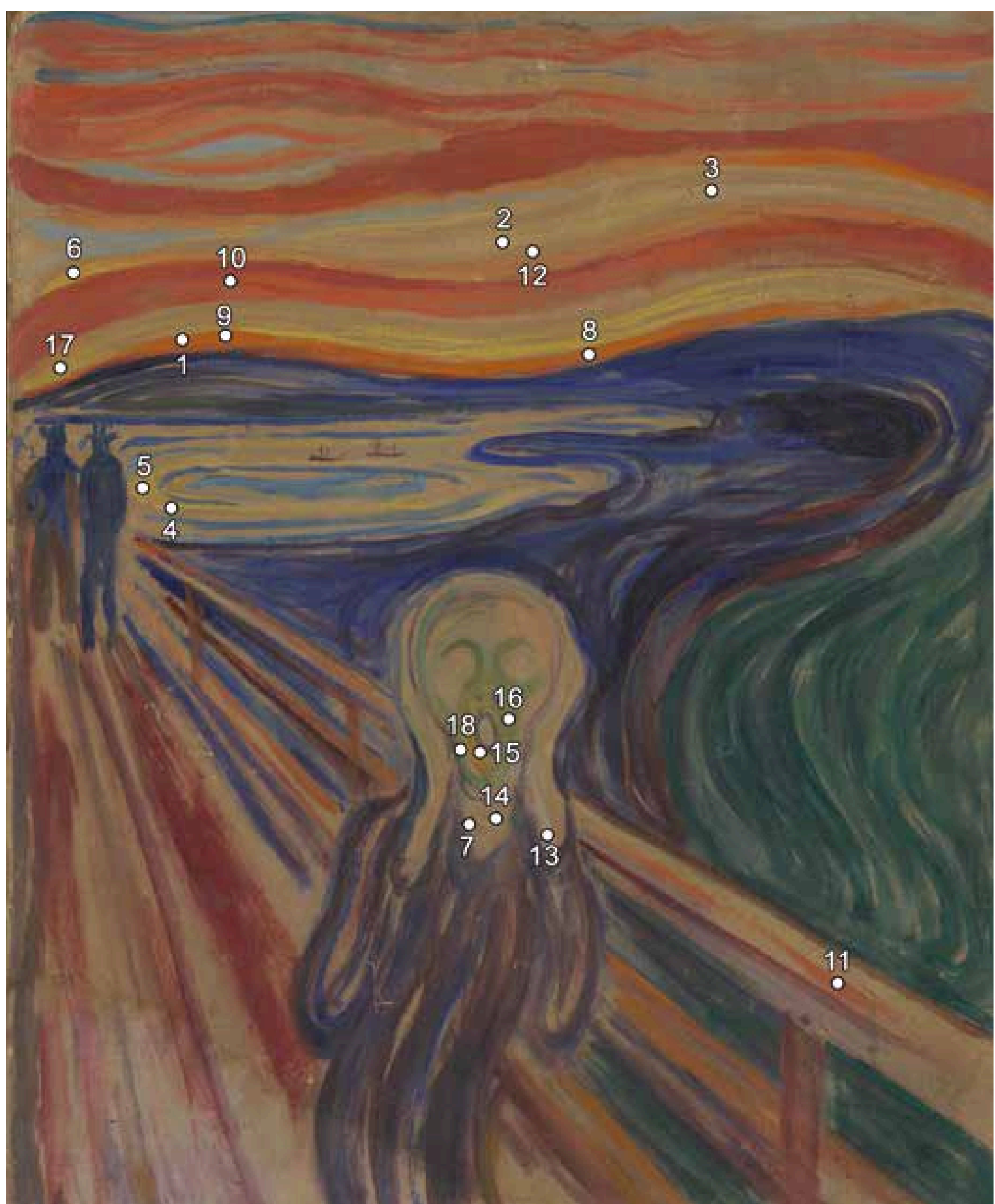
Moisture destroys Munch's "The Scream"

X-ray examination provides key to better conservation of the painting

Few works of art show existential anguish as impressively as „The Scream“ by the Norwegian painter Edvard Munch. There are several versions of the painting, created by Munch over many years using different techniques – each version is unique in itself. Probably the most famous version of the painting, belonging to the Munch Museum in Oslo, was stolen in 2004 and was only recovered two years later, in a poor condition. Since then, the work has not been exhibited, but has instead been stored in an air-conditioned room in the museum. A new investigation now shows that moisture – and not light – is the main factor causing the deterioration of the valuable work of art.

"The Scream" (Norwegian "Skrik") consists of a series of four paintings and a lithograph. In 1893, Munch (1863–1944) created a pastel and a tempera version, followed by another pastel in 1895 and another tempera painting in 1910. Munch also produced a lithograph to make black and white prints of the motif, which was already popular at the time. The Munch Museum's version clearly shows traces of water damage in the lower left corner, but there is more: Some of the yellow paint is fading and crumbling away, particularly in the areas of the sunset, the lake and the neck of the main figure.

The team of scientists led by Letizia Monico from the Italian Research Council CNR in Rome and Koen Janssens from the University of Antwerp in Belgium examined



The Inspiration for the motif "The Scream" came to the Norwegian Edvard Munch (1863–1944), in his own words, on an evening walk in 1895: "I was walking down the street with two friends. The sun was setting – the sky turned blood-red, and I felt a touch of melancholy. I stood still, dead tired – blood and tongues of fire lay over the blue-black fjord and the city. My friends went on – I stayed behind – trembling with fear – I felt the infinite scream in nature... I painted this picture – painted the clouds like real blood – the colours screamed," Munch explained. So the scream does not come from the person depicted, but it is "The Scream of Nature", as Munch had originally called the painting. The numbered circles on the photo mark the points of investigation of the current study.

the painting to find out more about the causes of this deterioration. They first illuminated the painting with X-rays at the museum in Oslo. Using so-called macroscopic X-ray fluorescence, the scientists were able to show how chemical elements such as cadmium, mercury and chlorine are distributed across the entire surface of the painting. They discovered that some of the cadmium yellow paint is rich in chlorine compounds and that it is precisely in these areas that the paint has suffered damage.

Tiny fragments of paint

The researchers went on to examine some tiny fragments of yellow paint that had come loose, using high-intensity, narrowly focused X-ray radiation at DESY and at the European Synchrotron Radiation Facility (ESRF) in France. In addition, they analysed artificially aged samples that they had made from original cadmium yellow pigment and a tube of cadmium yellow oil paint that had belonged to Munch.

spontaneous transformation has already been observed in paintings by other famous artists from the same period, such as Vincent Van Gogh, James Ensor and Henri Matisse.

Artificial ageing

Such bleaching is usually attributed to the effects of light shining on the painting. In the case of "The Scream", however, the deterioration occurred mainly in areas where chlorine-rich cadmium yellow was present, but not in other parts of the painting, although all of them have been exposed to approximately the same amount of light. A different or an additional factor must therefore be responsible for the chemical reaction of the yellow paint.

Using artificial ageing experiments on cadmium yellow paint, which they had made themselves and which contained either high or low levels of chlorine compounds, and by comparing light-induced ageing with ageing induced by heating the paint under humid

> *"With the X-ray microscope, the distribution of cadmium compounds can be imaged at sub-micrometre resolution"*
>
> **Gerald Falkenberg, DESY**

Their aim was to compare the data from the various pigments to determine what might be causing the chemical changes. "With the X-ray microscope at the PETRA III beamline P06, powder diffraction can be used to image the distribution of cadmium compounds at sub-micrometre resolution," says DESY scientist Gerald Falkenberg, who is in charge of the beamline and who was also involved in the project.

The scientists discovered that bright yellow cadmium sulphide oxidises to become the colourless cadmium sulphate, which explains why the colour fades. This

conditions, the scientists were able to show that it is mainly the high humidity and not the incident light that is causing the yellow paint in "The Scream" to crumble away and fade.

Based on the results of this study, the museum's curators now want to ensure that, in future, "The Scream" will be stored under conditions of comparatively low relative humidity (45%) but normal light intensity so as to slow down or stop further ageing as much as possible.

Science Advances,
DOI: 10.1126/sciadv.aay3514

Pictures from top to bottom:
1 Examination of the original painting with a spectral scanner at the Munch Museum in Oslo
2 DESY scientist Gerald Falkenberg at the beamline P06 of DESY's X-ray source PETRA III
3 Series of artificially aged oil paints produced with different types of cadmium sulphide-based pigments

Pictures: Munch Museum, Irina Crina Anca Sandu and Eva Storevik Tveit (painting); MOLAB Italy; DESY, Heiner Müller-Elsner; CNR-SCITEC, Letizia Monico (right from top to bottom)

From DESY to CERN: Joachim Mnich at a model of the ATLAS detector

"The Standard Model leaves **essential questions** open"

Upgrading the world's largest accelerator LHC could pave the way for new physics

For 12 years, Joachim Mnich was the Director in charge of Particle Physics at DESY. In January 2021, he started a new job – as the Director for Research and Computing at the world's most renowned particle physics research centre, CERN in Geneva. Among other things, he is now in charge of the experiments conducted at the giant accelerator LHC, which is to be significantly upgraded over the coming years. Researchers hope to find answers to important unresolved issues in the Standard Model of particle physics.

femto: Mr Mnich, how does one become research director at CERN? Did you simply send an application to Geneva?

Joachim Mnich: No, I was sitting in my office one day when I got a call from Fabiola Gianotti, CERN's Director General. She said: I'd like you to be my new research director! I almost fell off my chair; I never expected that. It took me a while to get used to the idea; but it's an offer you can hardly refuse. So two weeks later I picked up the phone and said yes. And the CERN Council then approved my nomination.

femto: You know CERN quite well; you'd already spent a few years there, hadn't you?

Joachim Mnich: That's right. I did research there for 12 years in the 1980s and 1990s. That's over 20 years ago, but I've always been in close contact with CERN ever since, for example through my involvement in CMS, one of the large detectors at the LHC. Of course, CERN has evolved significantly since the late 1990s, and I'm still unfamiliar with many of the details. That's something I have to learn now, in the course of numerous conversations with the people who work there.

femto: Looking briefly into the past: What were the most important developments during your time as particle physics director at DESY?

Joachim Mnich: When I started, in 2009, HERA, the largest accelerator Germany had ever built, had been shut down just two years earlier. There was no successor, so we embarked on a new course and joined in the LHC experiments in Geneva. This was a great success – today, the DESY groups are among

Picture: DESY, Martha Mayer

the most important partners at the LHC. We also got involved in another accelerator project, the Belle II experiment in Japan. And in Hamburg, we have initiated a new programme: experiments looking for a hitherto undiscovered particle, the axion, which could be behind the mysterious dark matter. An experiment called ALPS II is going to be installed in the old HERA tunnel and should collect its first data in 2021. Other axion experiments, such as the IAXO solar telescope, are to follow. DESY was assessed by the Helmholtz Association at the beginning of 2020. And its particle physics division has received top marks from an international panel of experts. This is a strong indication that DESY is well positioned for the future.

femto: What is the current situation in particle physics? What big topics are being discussed?

Joachim Mnich: We have an extraordinarily successful theory that has evolved over half a century, in the form of the Standard Model. But this model leaves essential questions unanswered: What is behind dark matter, and why does the universe seem to contain significantly more matter than antimatter? We hope that new accelerator experiments will provide answers. On the one hand, we are going to upgrade the LHC over the coming years, making it significantly more powerful. On the other hand, the particle physics community is already forging plans for new accelerators.

femto: What kind of accelerator do the scientists have in mind?

Joachim Mnich: To complement the LHC, the particle physics community would like to build a “Higgs factory”, i.e. an accelerator that produces a vast number of Higgs particles in its collisions. Experiments at such a facility could make precise measurements of this particle, which was discovered at the LHC in 2012, and thus reveal gaps in the Standard Model. Japan is currently considering building such a facility by the name of ILC, but the final decision has not yet been made. At CERN, we have long-term plans for a ring accelerator, which, with a circumference of 100 kilometres, would be about four times larger than the LHC. During a first stage, it could fire electrons at their antiparticles, called positrons, and thus serve as a Higgs factory. Later, it could be upgraded to become a proton accelerator, which would achieve new record energies and thus be able to produce previously unknown particles.

femto: You took up your position as CERN’s research director at the beginning of 2021. What are the big topics of your five-year term in office going to be?

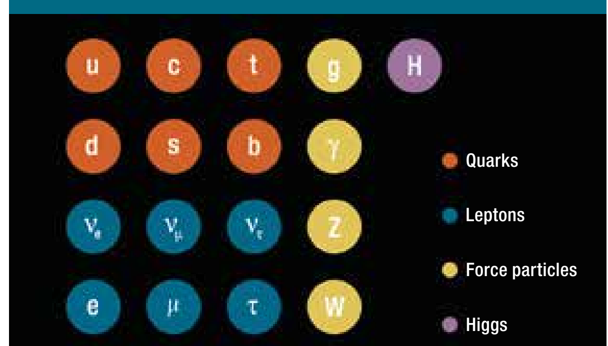
Joachim Mnich: The next few years will be dominated by the upgrade of the LHC. We want to improve it so that we can produce five to ten times as many particle collisions from 2027 onwards. This will allow us to observe very rare processes that have so far eluded us. Perhaps we’ll find evidence for the existence of new particles. To achieve this, we need to improve not only the accelerator, but also the detectors.

femto: CERN is not just the LHC; the centre also conducts other research programmes. What is on the agenda there?

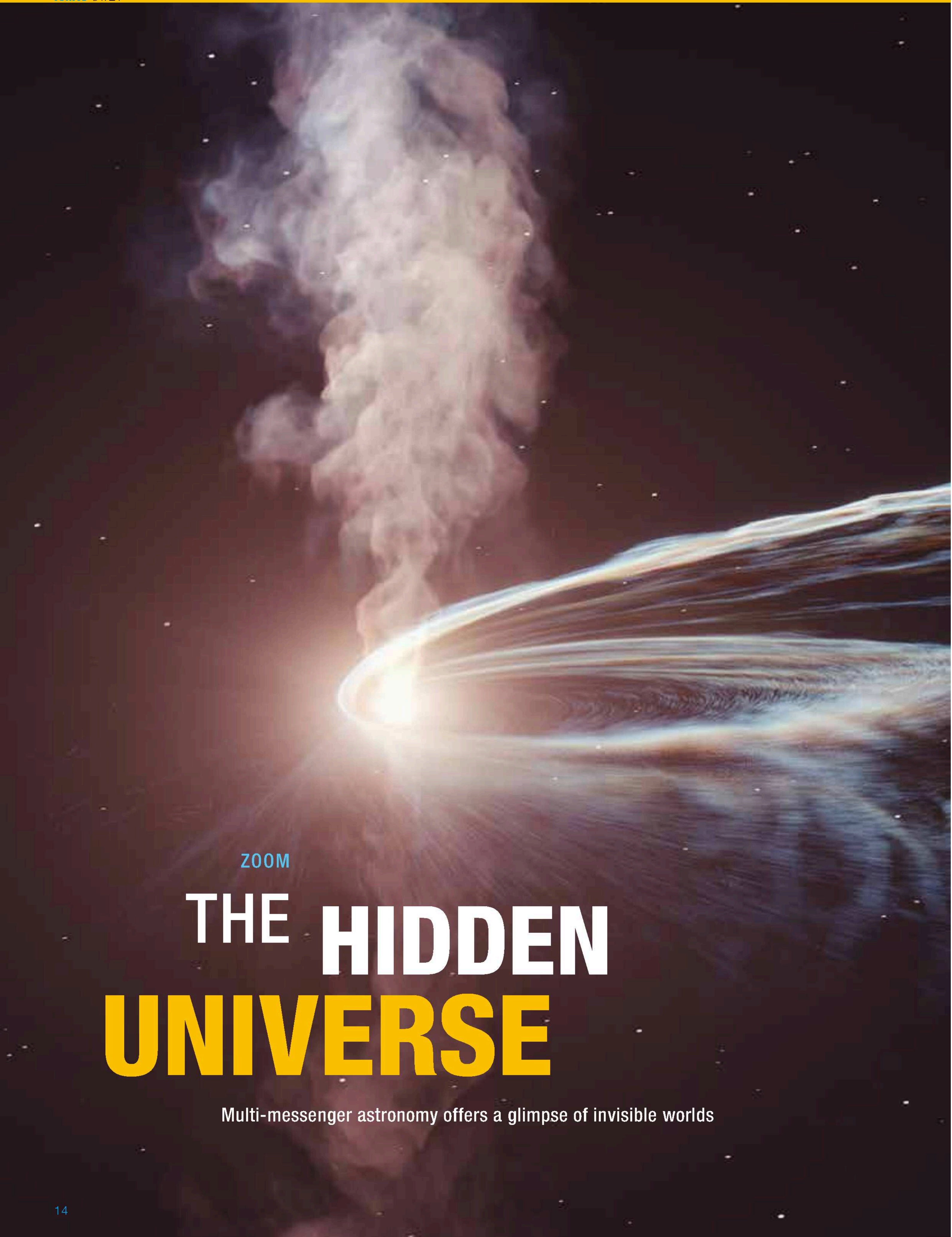
Joachim Mnich: There is neutrino research, for example. The neutrino is a common but extremely elusive particle and could be important for the question why there was more matter than antimatter after the Big Bang. The USA is currently setting up a large-scale experiment called DUNE, and CERN is providing a platform for the European groups involved. Other programmes, such as research into antihydrogen and the creation of rare isotopes for nuclear physics, will also continue. However, the upgrade of the LHC will be the top priority during my tenure.

FORCES AND PARTICLES

The Standard Model of particle physics summarises our current understanding of the microcosm. It describes the basic building blocks of the world around us: Protons and neutrons, the components of atomic nuclei, are made up of up and down quarks. Electrons, which are also elementary particles, form shells around these atomic nuclei. Both electrons and quarks have heavy, unstable sister particles. These are created, among other things, when cosmic rays hit the Earth’s atmosphere, and they decay rapidly into stable particles. In addition, there are neutrinos – extremely light, elusive particles that are created, for example, during nuclear fusion in stars, and that dash through space in huge numbers, hardly interacting with matter at all. The Standard Model also describes force carriers: These particles transmit the natural forces that act between the particles of matter. The Higgs boson, discovered in 2012, completes the model. It gives other elementary particles their mass.



Quarks and leptons form matter, bosons transmit forces.



ZOOM

THE HIDDEN UNIVERSE

Multi-messenger astronomy offers a glimpse of invisible worlds

Cosmic particle accelerator: the remnants of a shattered star surrounding a black hole hurl fast neutrinos in our direction.

For thousands of years, people have been fascinated by the starry skies. Over the centuries, observers have learned to glean an extraordinary wealth of facts from the visible light of the stars. In recent decades, astronomers have finally opened up the entire electromagnetic spectrum to observing the cosmos, from radio waves to gamma rays, thus enormously broadening our view of an astonishingly diverse universe. But that is only part of the picture: In addition to electromagnetic radiation, celestial objects and phenomena also emit particles and gravitational waves. Today, for the first time in human history, these fundamentally different messengers from outer space can be observed and analysed for astronomical purposes. Neutrinos and gravitational waves reveal celestial objects in entirely new ways, augmenting the observations made using electromagnetic radiation. Science finds itself at the dawn of a new form of stargazing: multi-messenger astronomy.

Picture: DESY, Science Communication Lab

On 1 October 2019 , the IceCube observatory in Antarctica captured a very special particle arriving from outer space: a cosmic neutrino hurtled into the perpetual ice around the South Pole, carrying at least ten times the energy produced by Earth's most powerful particle accelerator, the Large Hadron Collider (LHC) at the European research centre CERN in Geneva. "Tidal disruption events are so far poorly understood. Finding this neutrino points to the existence of a powerful machinery that ejects high-speed particles." Together with observations made in the range of radio waves as well as visible and ultraviolet light, the discovery demonstrates that such tidal disruption events can function as natural particle accelerators. This marks an important milestone, gravitational waves and so-called cosmic rays, i.e. the stream of high-energy atomic nuclei that strike Earth uniformly from all directions.

The bulk of our current astronomical understanding comes from observing electromagnetic radiation. Over the decades, astrophysicists have learned to extract an amazing abundance of information from the light arriving from stars and other celestial

"Tidal disruption events are so far poorly understood"

Robert Stein, DESY

What was really spectacular about the neutrino, though, was its origin: This fast, ultralight elementary particle was evidently a messenger from a rare cosmic catastrophe. The gigantic gravitational and tidal forces generated by an extremely massive black hole had torn apart an entire star, parts of which were then swallowed up by the black hole.

This was the first time that scientists had managed to capture a particle from such a "tidal disruption event". "It provides valuable clues," says DESY researcher Robert Stein, lead author of a scientific paper that reported the discovery made by the large international team. because until now researchers have only suspected this to be the case.

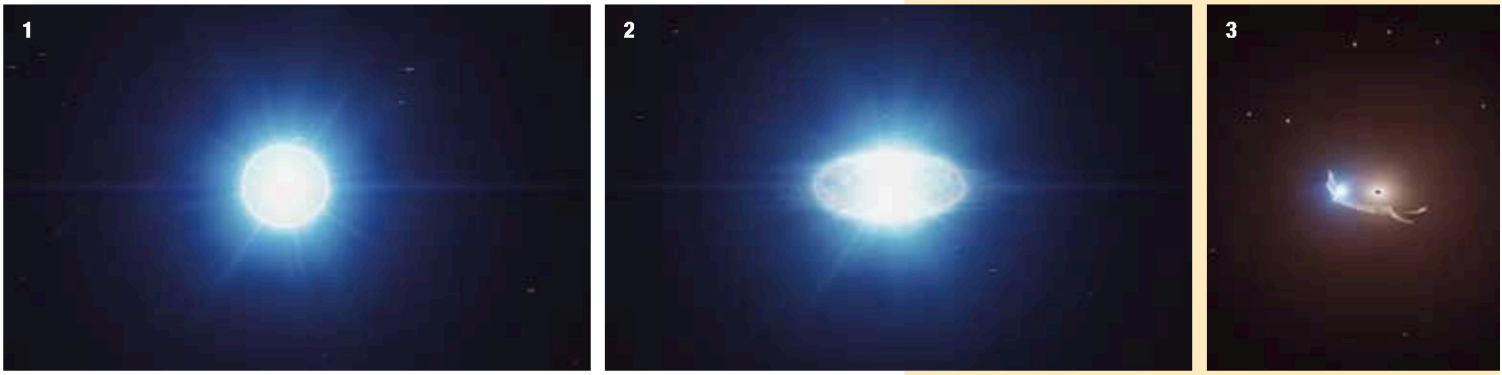
Detection in the perpetual ice

The detection of the neutrino in the Antarctic ice is an example of a new type of celestial observation: multi-messenger astronomy (MMA). It combines the signals from different messengers arriving from outer space. "Basically, there are four different cosmic messengers," explains Walter Winter, head of astroparticle theory at DESY. "First, there is electromagnetic radiation, ranging from radio waves through visible light to gamma radiation." The other messengers are neutrinos,

End of a star

In a tidal disruption event, a star **(1)** is torn apart by the enormous gravitational forces exerted by a supermassive black hole. The gravitational pull becomes stronger and stronger the closer the star gets to the black hole. This also means that the black hole tugs harder on the side of the star that is slightly closer than it does on the far side. This difference can become so large that the star is stretched more and more lengthwise **(2)**, until it is eventually torn apart **(3)**. About half the matter that made up the star was ejected directly into space, the rest accreted to form a swirling disk around the black hole **(4 and 5)**. This so-called tidal force, i.e. the difference between the forces acting on the near and far side, is also how the Moon causes the tides of the seas on Earth. The tidal force acts on the entire planet. Since the water in the oceans is not rigidly connected to the rest of the Earth, it is able to follow the tidal force, sloshing back and forth to produce rising and falling sea levels. In the case of a tidal disruption event, however, the gravitational force of the black hole is far greater than that of our Moon – scientists estimate the mass of the gigantic black hole is equivalent to some 30 million suns.

An animation shows how a tidal disruption event unfolds: https://youtu.be/jgKjZL9EJZ8



The observations made at the IceCube neutrino observatory are analysed live in the laboratory building at the Amundsen–Scott South Pole Station.

objects. Cosmic rays, on the other hand, are the hardest to interpret. Their misleading name comes from the fact that, when they were discovered more than a century ago, they were initially thought to be a hitherto unknown type of radiation.

It only turned out later that they are in fact extremely high-energy atomic nuclei, which are constantly beating down on the Earth's atmosphere from outer space, especially hydrogen nuclei, some of which can carry more energy than a sharply hit ping-pong ball. "To this day, the origin of these high-speed particles has not been conclusively established," notes Winter. "This is because the electrically charged atomic nuclei are deflected by countless magnetic fields inside and outside galaxies as they travel through space, until their origin is completely obscured."

New windows into space

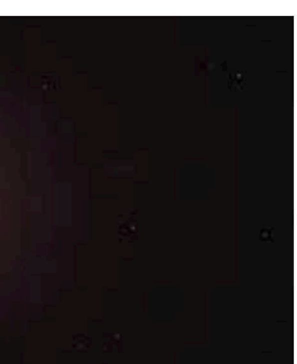
In recent years, astrophysicists have developed new observational techniques, opening new windows into space that enable neutrinos and gravitational waves to be exploited for astronomic observations for the first time. These messengers are fundamentally different from the messenger particle of electromagnetic radiation, the photon.

According to Albert Einstein's general theory of relativity, gravitational waves occur whenever a mass is accelerated. If the mass is large enough and accelerated sufficiently rapidly, as when two black holes merge, this vibration in space-time may still be detectable at cosmic distances (see page 26).

Neutrinos are often a by-product of cosmic particle accelerators. "The phenomena we are training our sights on in multi-messenger astronomy always belong to the so-called non-thermal universe," explains Marek Kowalski, head of neutrino astronomy at DESY and one of the pioneers of MMA. Most of the light in the universe comes from "thermal" processes: Stars derive their energy from nuclear fusion, whereby light atomic nuclei merge to form heavier ones. "This is a comparatively inefficient process," notes Kowalski. "Throwing something into a black hole or onto some other very dense object is far more efficient. Doing so releases up to ten percent of the rest mass in the form of energy, that is about ten times as much as is released during nuclear fusion."

Until now, the non-thermal universe too has primarily been examined using electromagnetic radiation, such as radio waves or gamma rays, which often reveal cosmic particle accelerators indirectly. Neutrino astronomy and gravitational wave astronomy are still in their infancy, but they have already led to some spectacular discoveries and promise a completely new approach, especially to high-energy processes in the universe – and thus possibly also to the origin of cosmic rays. »

Pictures: Felipe Pedreros, IceCube/NSF; DESY, Science Communication Lab, DESY (portrait)



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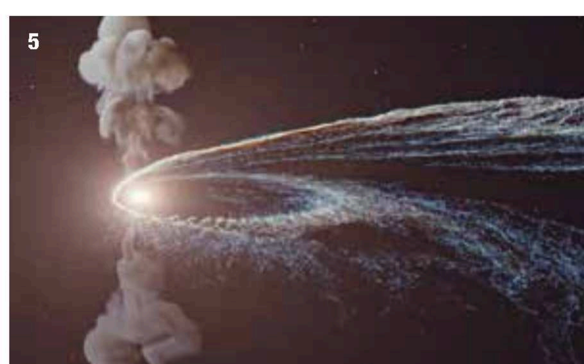
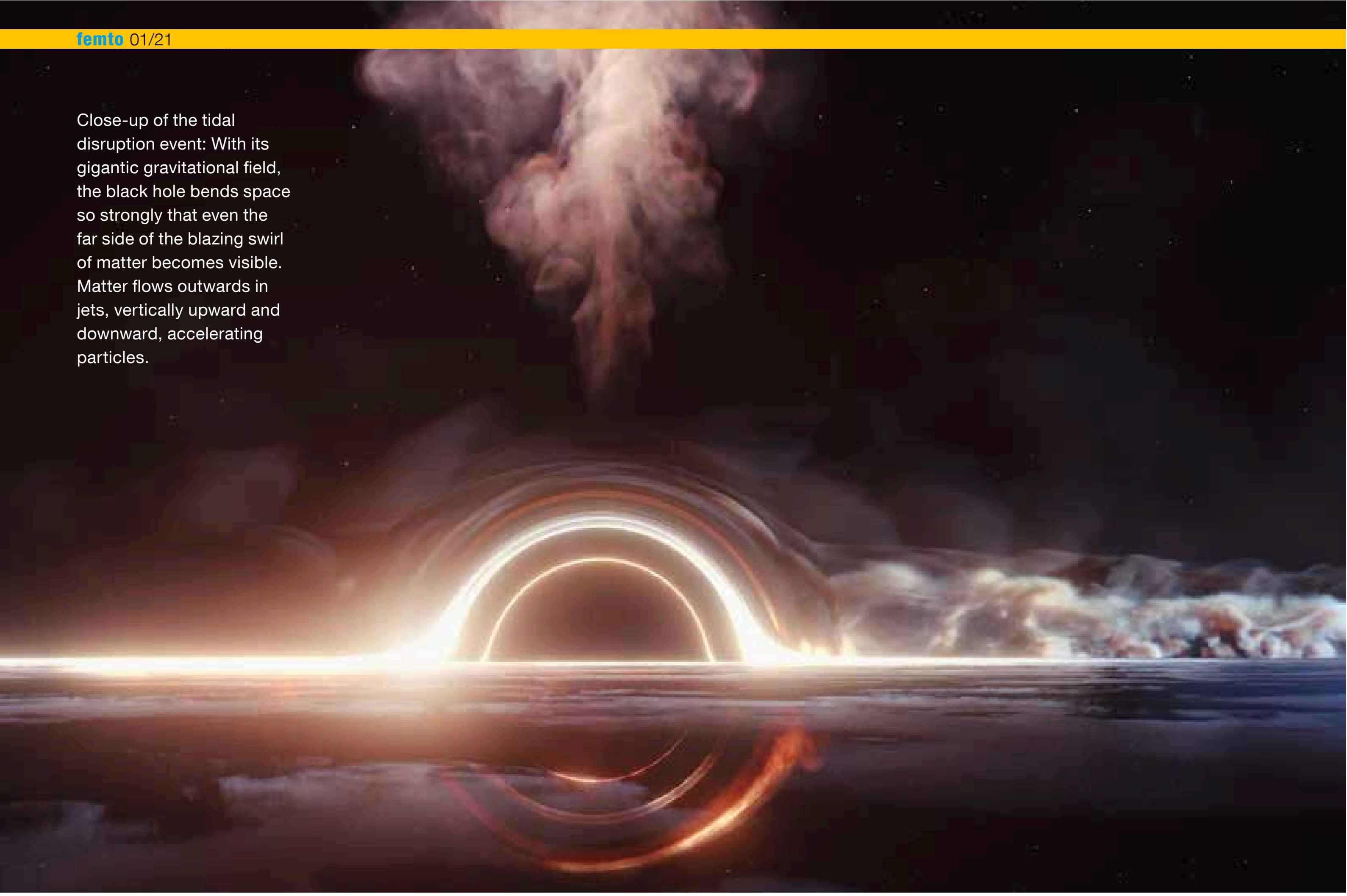




Close-up of the tidal disruption event: With its gigantic gravitational field, the black hole bends space so strongly that even the far side of the blazing swirl of matter becomes visible. Matter flows outwards in jets, vertically upward and downward, accelerating particles.

Combining different messengers

Ideally, the observations made using different messengers augment each other, as in the case of the tidal disruption event. It was first discovered by the Zwicky Transient Facility (ZTF), an optical telescope that regularly scans the sky for variable phenomena. The neutrino arrived six months later.

Its discovery triggered further observations in different wavelength ranges of the electromagnetic spectrum. “The combined observations demonstrate the power of multi-messenger astronomy,” says Kowalski. “Without the evidence of the tidal disruption event, the neutrino would just be one of many; and without the neutrino, the observation of the tidal disruption event would just be one of many. Only by combining the two were we able to track down the cosmic particle accelerator and learn about the processes taking place inside it.”

The neutrinos also reveal something about the nature of the accelerated particles. “Neutrinos are effectively the smoking gun of a proton accelerator,” explains theoretical physicist Winter – an electron accelerator, by contrast, would not be expected to produce neutrinos. This means that the tidal disruption event is probably also accelerating protons, the atomic nuclei of hydrogen. Hence, this phenomenon also contributes to the overall barrage of cosmic rays, though only to a small extent.

The neutrino has two properties that are of special interest in astronomy: first, the absence of electric charge. Being electrically neutral, it is not deflected by the numerous magnetic fields in space as is the case with the particles that make up cosmic rays. Its path of travel therefore points directly back to its source. Second, hardly anything can stop this ultralight elementary particle, which effortlessly penetrates walls, entire planets and galaxies. “Neutrinos allow us to see further than any

“Neutrinos are effectively the smoking gun of a proton accelerator”

Walter Winter, DESY

Pictures: DESY, Science Communication Lab (2); ESO, L. Calçada; DESY (portrait) other messenger," Winter asserts. For the same reason, they can be used to look inside an exploding star, for example, a region from which particles of light (photons) cannot escape.

The spark that ignited multi-messenger astronomy

"Electromagnetic radiation only allows you to look at the surface of an object," Kowalski explains. "If you want to know what is going on inside the Sun or an exploding star or, say, merging neutron stars, you have to observe other messengers." The first multi-messenger signal of this type was picked up by accident on 24 February 1987, when a shower of neutrinos struck various detectors on Earth that had been built for other studies. Three hours later, optical telescopes detected the supernova explosion of a star in the Large Magellanic Cloud, a satellite galaxy of our Milky Way.

The neutrinos had been created during the collapse of the stellar core and were able to escape unobstructed from the centre of the dying star. The actual explosion, on the other hand, did not reach the surface of the star until about three hours later, when it became visible to terrestrial telescopes. This chance observation confirmed the notion that a supernova caused by a collapsing stellar core produces large numbers of neutrinos and that a significant part of the energy released in the explosion is emitted in the form of these ultralight elementary particles.

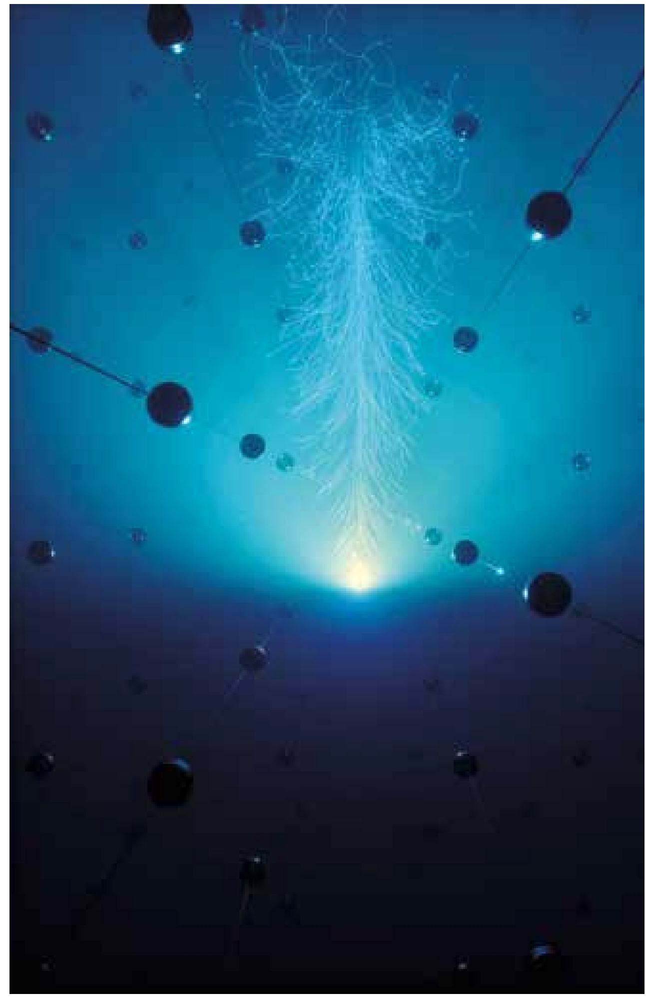
With this event too, combining different messengers was a prerequisite – if the supernova had not been located with the help of optical telescopes, no one would have known where the sudden stream of neutrinos had come from. "Supernova 1987A was something like the spark that ignited multi-messenger astronomy," says Kowalski.

At the time, however, it was not yet possible to specifically observe neutrinos arriving from outer space. "It had long been known that neutrinos might be interesting particles from the point of view of astronomy," explains Anna Franckowiak, who leads a research group on multi-messenger astronomy at the University of Bochum in Germany and coordinates the data analyses at IceCube. "But neutrinos are difficult to detect." This is because their ghostlike ability to pass unhindered through walls and entire stars also makes these particles very elusive – virtually all the neutrinos passing through a detector go undetected.

Superluminal flash

This is why an international collaboration built the IceCube observatory, sinking 86 steel cables into the perpetual ice of Antarctica. A total of 5160 sensitive detectors, so-called photomultipliers, are suspended from these, reaching to a depth of up to 2.5 kilometres beneath the surface. In total, the array is spread out across one cubic kilometre of underground ice, hence the name IceCube. The thousands of photomultipliers peer into the gloom, waiting for the faint bluish glow that is emitted by a neutrino when it happens to collide with an ice molecule. This then leads to a cascade of further particles, which race through the ice faster than the speed of light.

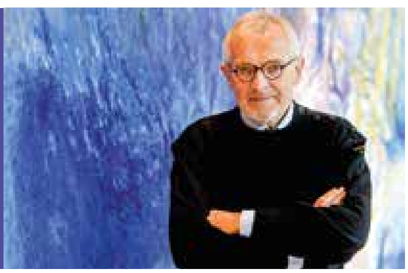
"Of course, the underground avalanche of particles must obey Einstein's absolute speed limit, the speed of light in a vacuum," explains Franckowiak. "However, the speed of light is slightly lower in ice, ››



Deep within the Antarctic ice, cosmic neutrinos can trigger an avalanche of particles, whose bluish glow is recorded by the sensitive IceCube detectors.

The supernova 1987A in the Large Magellanic Cloud was heralded a few hours earlier by a neutrino shower. The exploding star left behind two outer rings, an inner ring and a central remnant (artist's impression).

just as it is in glass or plastic, which is why light is refracted, making it possible to produce spectacles or magnifying glasses, for example." Because of this, the high-energy particles can travel through the ice slightly faster than light itself, which is slowed down a little, and this leads to the optical equivalent of a sonic boom, known as Cherenkov radiation. By analysing these light signals in the extremely clear subsurface ice, IceCube is able to determine the energy of the original



"We may only be seeing the tip of the iceberg here"

Francis Halzen, University of Wisconsin-Madison

cosmic neutrino and the direction from which it came.

The scientists have used this technique not only to trace the October 2019 neutrino to the tidal disruption event that occurred 700 million light years away in the constellation Delphinus; they also traced a cosmic neutrino that had already been recorded in 2017 back to an active galaxy almost four billion light years away in the constellation Orion. A supermassive black hole at the centre of this distant galaxy has gathered large amounts of matter into a vortex. Though it devours most of the matter, it flings some of it vertically up and down into space, forming sharply focused beams known as jets. Here on Earth, we are looking straight along one of these jets. "We're looking down the barrel of a gun, so to speak," says Franckowiak.

Colossal particle accelerator

In this so-called blazar, too, a colossal cosmic particle accelerator is at work. This is confirmed by the IceCube discovery and backed up by further neutrinos found to be arriving from the direction of the blazar. Thanks to the combination with a large-scale observational campaign extending to almost all wavelengths of the electromagnetic spectrum, the scientists had thus for the first time directly located a specific source of cosmic rays outside our own galaxy. "And if you can find one example of such a phenomenon, it will be going on elsewhere too," explains Franckowiak. "Nothing is unique in the universe. So what

A narrowly focused jet of matter shoots outwards from the centre of a blazar, its strong magnetic fields accelerating particles to extreme energies.

When giant galaxies merge (artist's impression), three types of cosmic messengers might be dispatched: light, neutrinos and gravitational waves.

"Two galaxies merging could be a fantastic multi-messenger event"

Marek Kowalski, DESY

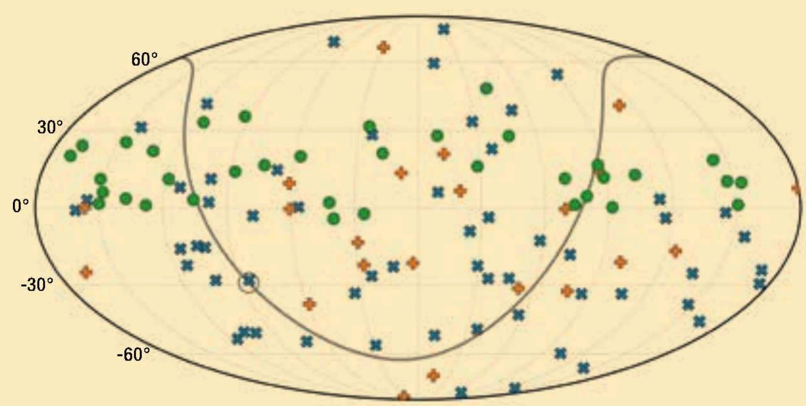
we are learning is that blazars can accelerate protons to very high energies." This is an important confirmation in the search for cosmic particle accelerators as a source of cosmic rays – the scientists had been suspecting active galaxies for a long time.

"IceCube currently records about ten highly energetic cosmic neutrinos per year," Franckowiak reports. "In most cases, we have no idea where they're coming from. All we know is that they come from outer space, far beyond our own galaxy." Only in two cases has it been possible to locate their source, thanks to combining different types of observation. So multi-messenger astronomy is still in its infancy, but it promises an exciting new era. "We may only be seeing the tip of the iceberg here," IceCube's chief scientist Francis Halzen from the University of Wisconsin-Madison in the USA believes. "We are expecting many more such connections between high-energy neutrinos and their sources in the future." The major expansion of the Antarctic neutrino telescope to become IceCube-Gen2, possibly increasing the number of observed cosmic neutrinos by a factor of ten, will also be helpful (see page 24).

Neutrino astronomers hope that they will then be able to detect signals in common with gravitational wave detectors. Until now, the latter have mainly been observing black holes merging, i.e. events that take place literally in the dark and that emit no light. In one case, however, the gravitational wave antennas registered a signal from two colliding neutron stars, a cosmic collision that could also be observed in the electromagnetic spectrum, all the way up to gamma rays. "Such collisions should also produce extremely energetic neutrinos, however, and IceCube-Gen2 may be able to detect these particles," says Kowalski. Observing them could shed light on what goes on inside neutron stars when they collide, for example.

New class of event

Astronomy is still waiting for a celestial event of this kind, i.e. one observed using all three messengers: electromagnetic radiation, neutrinos and gravitational waves. "Two galaxies merging could also be a fantastic multi-messenger event," says Kowalski. "So much energy is released in the process. And the elements needed to produce gravitational waves and neutrinos are all available. When two galaxies merge with each other with all their paraphernalia, huge amounts of matter collide on an enormous scale, and shock regions are created in which particles are accelerated »



Neutrino sky

Whereas we are able to draw a detailed map of the sky observed using visible light, up until now IceCube's neutrino sky only consists of individual events. The diagram shows the directions from which cosmic neutrinos originate on a map of the complete celestial sphere. Green indicates neutrinos that have been accurately determined, red those whose energy is not very well known, and blue those whose direction of origin is uncertain.

Pictures: DESY, Science Communication Lab; DESY, Jakob van Santen; El Pais/Bernardo Pérez (www.elpais.com); NASA, ESA, and J. Olmsted (STScI) to a massive degree. That would constitute a whole new class of event." And it would not only be an interesting observation in itself; it could also provide new insights into the evolution of the universe. Because to this day, the formation and evolution of galaxies is not fully understood.

The astronomy community is only just beginning to understand the tools of multi-messenger astronomy and to optimise them based on their first insights. In addition to the expansion of IceCube, further neutrino observatories are also being planned – as well as new gravitational wave detectors, such as the Einstein Telescope and the space-based project LISA (Laser Interferometer Space Antenna). And the gamma-ray observatory CTA (Cherenkov Telescope Array) will take observations of the high-energy cosmos using highest-energy electromagnetic radiation to a whole new level.

"As yet, we're really in the early stages. Right now, we have one event here and one there," explains Kowalski. "But by increasing the sensitivity of all three methods simultaneously – that is, the observation of electromagnetic radiation, gravitational waves and neutrinos – the combined yield will increase enormously, because any advance in one method also affects the other two methods. We don't yet know what it will help us to discover. But one thing is certain: It will surprise us."

THE CHERENKOV TELESCOPE ARRAY

Next-generation gamma-ray observatory

Cosmic gamma rays play a special role when observing the non-thermal universe, and hence also for multi-messenger astronomy. Gamma rays are always the product of high-energy processes, such as cosmic particle accelerators or catastrophic collisions between neutron stars, for example. This means that cosmic gamma rays may also point to objects that are worth observing using other messengers, such as neutrinos or gravitational waves. However, they too are not easy to detect.

The Cherenkov Telescope Array (CTA) is set to become the world's largest observatory for cosmic gamma rays. It is being constructed at two separate locations, one in the southern hemisphere and one in the northern hemisphere, which will allow it to observe the entire sky. The southern site is in the extremely dry Atacama Desert in the Chilean Andes. Over the coming years, a total of 99 gamma-ray telescopes will be set up near the Paranal Observatory of the European Southern Observatory (ESO), coming in three different sizes. The northern site, on the Canary Island of La Palma, will be equipped with 19 telescopes. Thanks to its enormous collection surface and broad coverage of the skies, CTA will achieve ten times the sensitivity of existing gamma-ray observatories. More than 1400 scientists and engineers from 31 countries are participating in this global project.

Cherenkov telescopes detect a bluish glow triggered by cosmic gamma rays when they enter the Earth's atmosphere. The original gamma rays are not visible to telescopes, as they are absorbed by the Earth's atmosphere. In the process, however, the high-energy gamma photons trigger an avalanche of follow-up particles, which swells in size as a result of repeated collisions. These particles race through the air slightly faster than light (though not faster than light in vacuum, the absolute speed limit). In a process similar to the sonic boom of aeroplanes, this produces shimmering bluish Cherenkov radiation, which carries information about the direction of origin and the energy of the original cosmic gamma photon.

www.cta-observatory.org

CTA will be the largest and most sensitive gamma-ray observatory in the world, with 99 telescopes at its southern site and 19 telescopes at its northern site.

Picture: Gabriel Pérez Diaz, IAC / Marc-André Besel, CTAO femtopolis

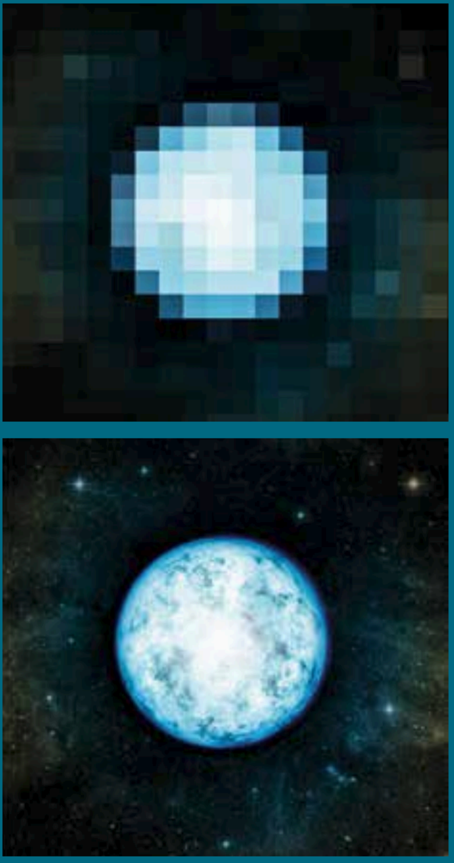
Measuring the stars

A German lullaby asks how many stars there are, twinkling in the night-time skies… and nowadays it is possible to give quite a good answer to that question: Looking up at the sky on a clear night, as far as possible from civilisation, you could count up to 6000 twinkling dots in the firmament. Large state-of-the-art telescopes are capable of peering much deeper into space. Nowadays, they are able to detect well over ten billion individual stars. But that's next to nothing compared with the total number of stars in the universe. **The universe is estimated to contain two trillion galaxies,** and with galaxies often containing many billions of stars, the final count is on the order of 100 sextillion – beyond all imagination.

But astronomers are not satisfied with simply counting: They want to know all about the many distant stars in as much detail as possible – including how big they are. Their sizes can vary considerably. The smallest are neutron stars: These compact remnants of once fiery suns are just 20 kilometres across, no bigger than a large city. The largest known star, by contrast, is a red supergiant that is more than 2000 times the size of our Sun.

But how can the diameter of a star be determined in the first place? That's a tricky question; after all, when viewed from Earth, almost all stars appear to be the same size – twinkling specks that can essentially only be distinguished by their brightness. A relatively simple angle measurement, which can be used to estimate the size of the Sun or the Moon, is generally no good. Instead, scientists have had to come up with other, indirect methods: One way is to analyse the spectra and certain interference patterns of the celestial bodies. Now, they have added two new tools to this toolbox, both with the assistance of DESY.

The trick behind these two innovative techniques is a cunning re-allocation of resources. Because the teams are using an observatory that was actually designed for a completely different purpose than stellar surveying: The four VERITAS telescopes in the US state of Arizona normally search for the faint bluish glow that occurs when high-energy gamma rays from distant regions of space strike the Earth's atmosphere. **However, this glow can only be observed on dark, moonless nights.** So the scientists were looking for a sensible way of using the equipment during the remaining time – and hit upon measuring the size of distant stars. The conditions are ideal: The four VERITAS telescopes can detect even the tiniest variations in the intensity of light, including starlight.

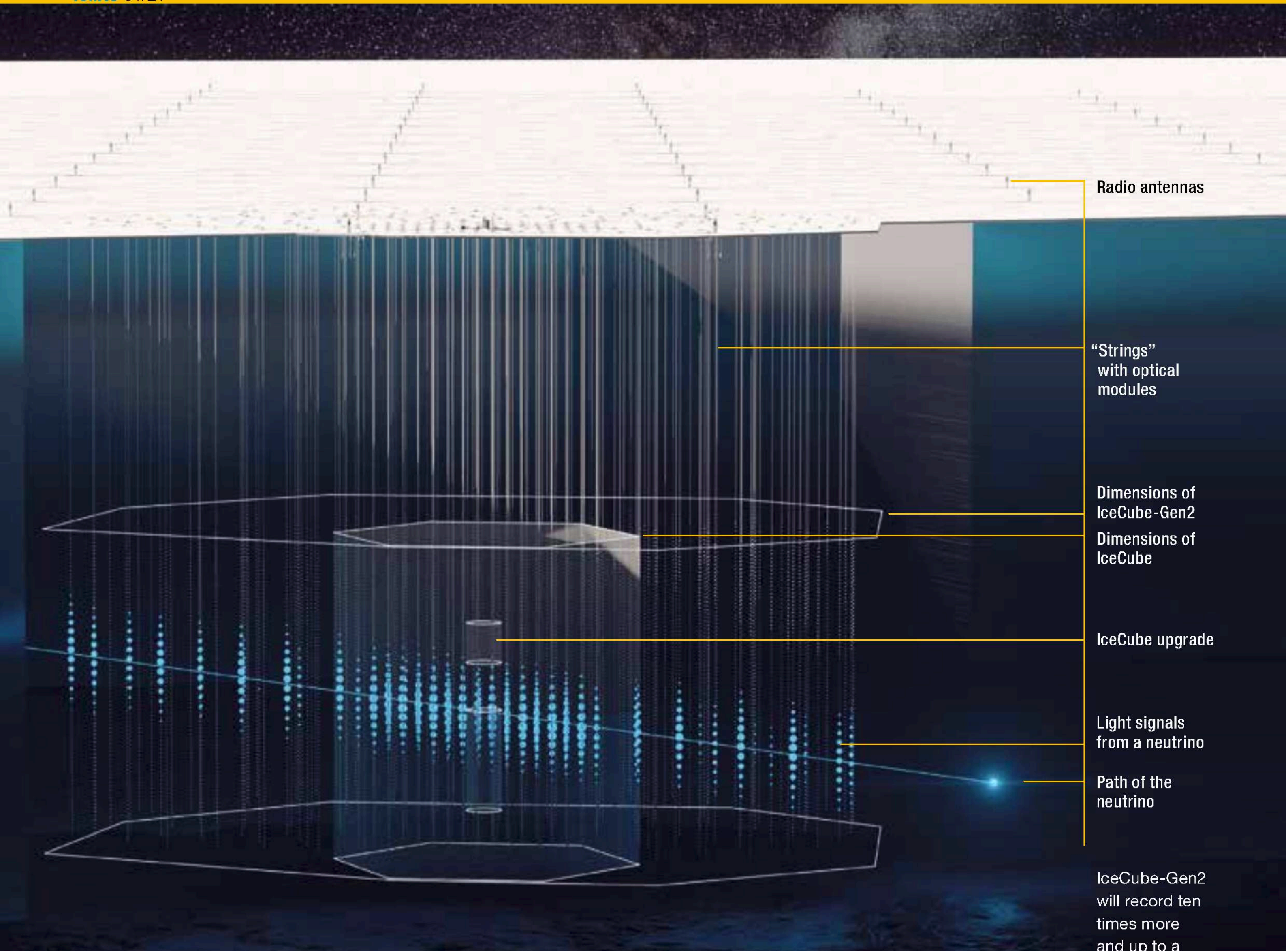


By connecting together several telescopes located far apart from each other, it might even be possible to see details on the surface of stars (artist's impression).

One of the two new methods uses the wanderings of celestial vagabonds within the solar system. **If an asteroid happens to pass in front of a star, it creates a certain brief light effect: a diffraction pattern.** The shape and size of the pattern allow the size of the light source, i.e. the star, to be deduced. On 22 February 2018, VERITAS managed to pick up the diffraction pattern of a star that was briefly occluded by the asteroid Imprinetta. The results indicated that the star is 11 times bigger than our Sun – meaning it belongs to the class of red giants. Three months later, the asteroid Penelope passed in front of another star. This one turned out to be about twice the size of the Sun. In principle, it ought to be possible to observe at least one asteroid star occultation per week – this would make the new technique a valuable means of measuring star sizes.

For the other method, the experts revived an old technique – intensity interferometry. **Ultrahigh-speed electronics were used to combine the light signals from the four different telescopes.** A sophisticated algorithm was then able to precisely determine the diameter of two stars and confirm previous measurements: The blue giant Beta Canis Majoris is ten times, the supergiant Epsilon Orionis as much as 30 times bigger than the Sun. The new technique will also be transferable to future gamma-ray telescopes. Thus, the more than 100 individual telescopes that form the Cherenkov Telescope Array (CTA) should allow stars to be measured with far greater precision than has been feasible before.

Nature Astronomy, DOI: 10.1038/s41550-020-1143-y
Nature Astronomy, DOI: 10.1038/s41550-019-0741-z



IceCube-Gen2 will record ten times more and up to a thousand times more energetic neutrinos than the existing setup.

A NEW DIMENSION OF NEUTRINO ASTRONOMY

Expansion of the IceCube observatory at the South Pole promises new insights into cosmic phenomena

The IceCube neutrino observatory in the perpetual ice of Antarctica has already achieved several milestones for the fledgling discipline of neutrino astronomy. Now the IceCube comunity plans to upgrade and substantially expand the huge detector at the South Pole: IceCube-Gen2, as the project is called, could explore cosmic phenomena that have until now remained hidden – as Marek Kowalski, lead scientist at DESY and a professor at Humboldt University in Berlin, explains. DESY is the largest European partner in the international IceCube collaboration.

femto: Ever since its completion in 2010, IceCube has been successfully searching for neutrinos from the depths of space. Now there are plans to significantly expand the facility. What will the second-generation IceCube detector look like?

Marek Kowalski: At the moment, IceCube encloses a volume of one cubic kilometre of Antarctic ice. In the future, we want to increase this volume about tenfold – so IceCube-Gen2 will be around ten times larger than the current detector. Today's setup consists of just over 5000 spherical sensors embedded kilometres deep beneath the ice, which measure specific light pulses originating from high-energy neutrinos. For the new detector, we are planning to deploy a further 12 000 sensors within the ice, but they will be much more sensitive than the first-generation sensors. We also plan to install an additional measuring technology based on radio antennas. This is because the neutrinos not only generate pulses of visible light in the ice, but also short radio pulses that can be used to detect the particles as well. The technology could allow neutrinos having extremely high energies to be measured – something the current detector cannot do. That's because radio waves can travel several kilometres in ice, so we can significantly increase the dimensions of the new detector in this energy range.

femto: What do you stand to gain from this? What will IceCube-Gen2 be able to do that the existing setup cannot?

Marek Kowalski: The new detector will be ten times larger than the previous one, meaning it will be able to intercept ten times as many cosmic neutrinos. So whereas until now we have had to wait many years to make a particularly exciting observation, with IceCube-Gen2, this should happen every few months. At the same time, we will improve our sensitivity to point sources. This should allow us to better identify those objects in space from which a strikingly large number of neutrinos is arriving. And by using the new radio technology, the detector will be able to record extremely high-energy events – neutrinos with energies up to 1000 times higher than those detected by IceCube so far. This should open up completely new possibilities for us.

femto: What scientific questions is the new detector meant to find answers to, especially in terms of multi-messenger astronomy?

Marek Kowalski: The question what exactly happens when two neutron stars merge, for example. This type of collision was first observed with the help of gravitational waves in 2017 – an amazing discovery that taught the scientific community a great deal about this violent cosmic event. However, such collisions should also produce extremely high-energy neutrinos, and IceCube-Gen2 ought to be able to detect these particles. This would give us valuable additional information, for example, about what goes on inside neutron stars. Another highlight would be if we were able to observe a supernova, i.e. an exploding star, in our galactic neighbourhood – by means of neutrinos, gravitational waves and other telescopes too, all at the same time. But IceCube-Gen2 will also be able to measure the properties of the neutrino with higher precision. That should give us a better understanding of this strange elementary particle.

"The new detector will be ten times larger, meaning it will be able to capture ten times as many cosmic neutrinos"

Marek Kowalski, DESY

femto: How expensive is IceCube-Gen2 likely to be and when might construction work begin – funding provided?

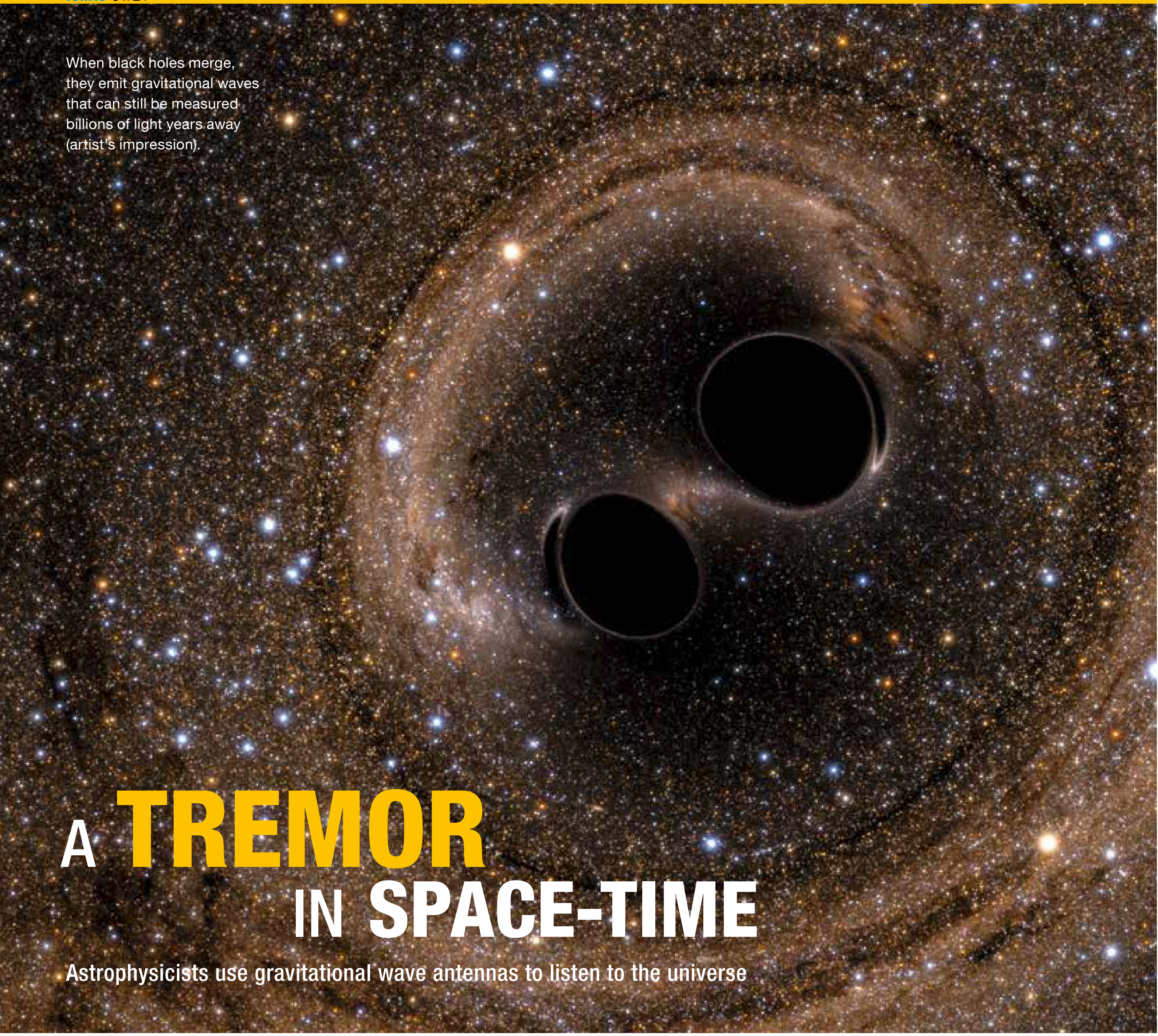
Marek Kowalski: We have gained a lot of experience in how to build such a detector effectively. So despite being so much larger than the previous setup, IceCube-Gen2 is not expected to cost much more than that, around 400 million US dollar. Quite soon, we will be able to test the new, improved spherical sensors as part of an IceCube upgrade, in which an additional 750 sensors will be sunk into the ice. Construction of IceCube-Gen2 could then begin in 2024 and would take about eight years to complete. The new detector could be ready by 2032.

femto: Other neutrino telescopes are under construction around the world: KM3NeT in the Mediterranean and Baikal-GVD in Russia. There are also plans for a further facility in the Pacific, P-ONE. Do you see these projects more as rivals or as complementing your own?

Marek Kowalski: These telescopes are essentially complementary because they will be observing different regions of the sky than IceCube. So they will complement ours. That's why I would like to see these facilities go into operation as soon as possible and produce results – that would enrich our field enormously. And even if these telescopes end up snatching the occasional insight away from us, that would be a positive thing in terms of the science, and it would advance research. That's why I hope all the projects get up and running. After all, competition is good for business.

www.icecube-gen2.de

Pictures: DESY, Gesine Borns



When black holes merge, they emit gravitational waves that can still be measured billions of light years away (artist's impression).

A TREMOR IN SPACE-TIME

Astrophysicists use gravitational wave antennas to listen to the universe

Gravitational waves were not even discovered until 2015, yet already they appear to be indispensable to astrophysics. In some cases, they complement other observational techniques perfectly, making them a key element of multi-messenger astronomy.

When Albert Einstein presented his general theory of relativity in 1915, he astounded experts and laypersons alike: The highly abstract equations painted a completely new picture of gravity, one in which gravity is the result of a mass bending the surrounding space and time. It soon became clear that Einstein's theory had spectacular consequences: When a violent cosmic event takes place in outer space, such as two stars colliding, gravity ought to change so rapidly in its vicinity as to produce veritable dents in space-time. These dents would then propagate through the universe at the speed of light – in the form of gravitational waves. Throughout his life, Einstein was convinced that such waves could never be detected – believing they would simply be too weak for earthbound detectors. But in 2015, a hundred years after the advent of general relativity, two kilometre-long detectors in the USA proved otherwise. On 14 September, the LIGO observatory registered a tiny fluctuation in its laser signals. After careful analysis, only one explanation remained: 1.3 billion light years away, two black holes that had been circling each other warily had finally merged with an almighty crash and emitted gravitational waves as a result. More than a billion years later, these reached Earth in the form of a faint but distinct tremor in space-time.

When the LIGO team announced its results to the public in February 2016, the world celebrated a scientific sensation for which the Nobel Prize in Physics was awarded the following year: By discovering gravitational waves, LIGO had furnished impressive proof of general relativity – a cornerstone of physics. Something else was even more important to the experts, though: "We have opened the window to a completely new observational method," said LIGO's Director David Reitze enthusiastically on the very day of the release, "astronomy using gravitational waves".

Global network

The reason for this euphoria was that the vast majority of telescopes capture all kinds of different electromagnetic waves, including visible light, X-rays and thermal radiation. However, some objects in space make their presence known also or exclusively through other signals: They are ejecting very high-speed particles, such as ghostly neutrinos – or emitting gravitational waves. "Some of their frequencies lie in the sonic range," says Rafael Porto, a lead scientist at DESY, **"so this means we can not only look at the universe, we can also listen to it."**

Detector technology has advanced significantly since gravitational waves were first detected in 2015. The sensitivity of the two LIGO detectors has been increased step by step, and two further facilities have been added: Virgo in Italy and now KAGRA in Japan. Together, they form a global network of gravitational wave antennas. The scientific results are certainly impressive: By the end of 2020, the detectors had captured several dozen events, all caused by unimaginably powerful collisions between incredibly massive celestial bodies.

Most of them come from colliding black holes. The gravitational field of these monsters is so abnormal that they swallow up light itself. "The only thing these objects emit are gravitational waves," ››

The two arms of the Virgo observatory in Italy each stretch three kilometres across the Tuscan countryside.

"We have opened the window to a completely new observational method"

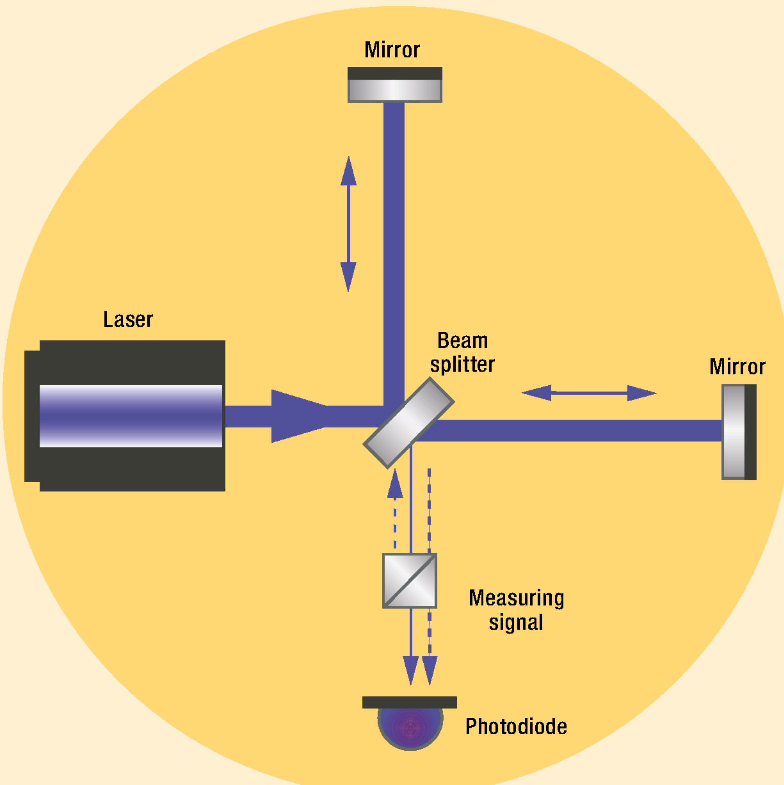
David Reitze, LIGO

Before two black holes merge, they orbit each other in ever tighter spirals (artist's impression).

Pictures: SXS, the Simulating eXtreme Spacetimes (SXS) project (http://www.black-holes.org) (black holes); The Virgo Collaboration, The LIGO Collaboration (2)

HOW A GRAVITATIONAL WAVE DETECTOR WORKS

Lasers measure differences in length amounting to less than the diameter of an atomic nucleus



A gravitational wave detector is basically an oversized yardstick: It measures a distance, albeit with ultrahigh precision. It is based on laser beams that travel to and fro down two kilometre-long evacuated tubes, reflected by special, vibration-damped mirrors.

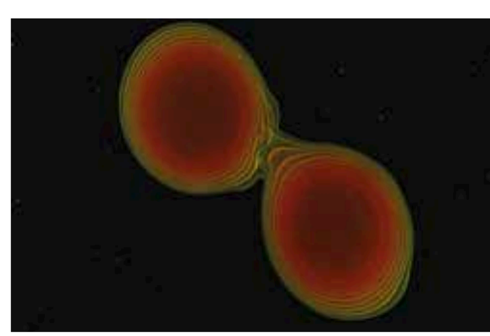
The two tubes are perpendicular to each other. When a gravitational wave passes by, it stretches and compresses the kilometre-long laser arms by a tiny bit, a fraction of the diameter of an atomic nucleus. The crucial point is that because they are pointing in different directions, the two arms undergo different deformations – one a little more, the other a little less.

This tiny difference can be measured by bringing the two laser beams together at a sensitive light sensor. Where the light from the laser beams meets, a pattern of light and dark fringes is formed. If the length of one or both tubes changes, the waves of the laser beams shift very slightly with respect to each other, and the fringe pattern also shifts. So ultimately, a gravitational wave causes a faint flicker in a pattern of light and dark fringes.

explains Porto. "And those waves allow us to explore the nature of black holes." However, deducing the underlying event from the signals measured by the detectors is not an easy task. The experts first have to work out, based on Einstein's general theory of relativity, what the signals resulting from the collisions ought to look like. Porto and his team are developing precise mathematical calculations to determine how two celestial bodies orbit each other increasingly rapidly shortly before they merge, and what gravitational waves they should emit in the process, which could then be measured by the detectors – an essential element of the analyses. Porto is supported by the European Research Council (ERC) and is involved in the Cluster of Excellence "Quantum Universe" at Universität Hamburg.

Catalogue of cosmic catastrophes

Many thousands of calculations and simulations like these have been carried out by different research teams – generating an extensive catalogue of possible cosmic catastrophes. When the detectors pick up an actual signal from deep space, this can be matched against the catalogue. Only then can the scientists accurately determine what exactly happened in outer space, for example whether a light black hole collided with a much heavier one. So far, the detectors have recorded almost 50 collisions of black holes.



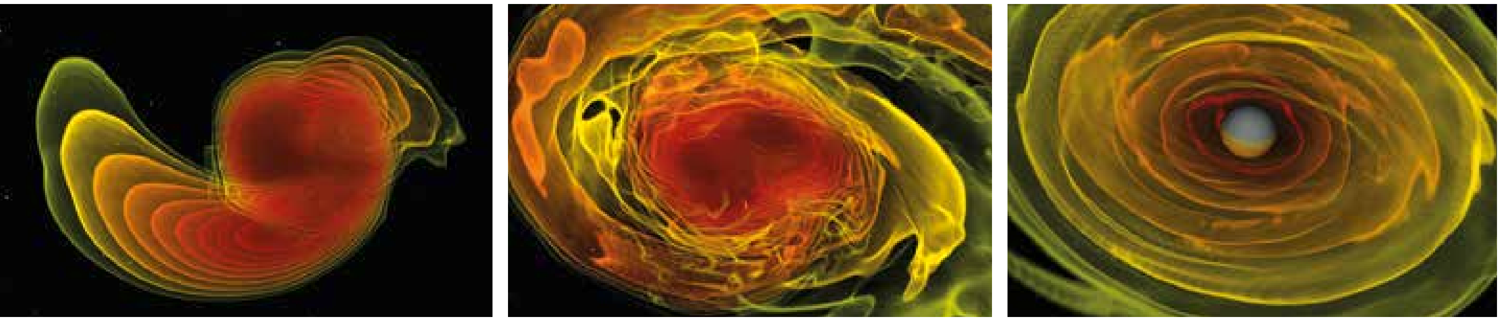
The collision of two neutron stars in August 2017 was a spectacular multi-messenger event (artist's impression).

Pictures: NASA/Swift/Dana Berry, T. Dietrich, S. Ossokine, H. Pfeiffer, A. Buonanno (Max Planck Institute for Gravitational Physics); BAM Collaboration; DESY (portrait)

To the surprise of the experts, these events have turned out to be extremely varied. **"Some people suspected that all the black holes would have roughly the same mass,"** says Frank Ohme, a physicist at the Max Planck Institute for Gravitational Physics in Hannover, Germany. "Instead, we have observed very different specimens – some quite light, others comparatively heavy." In actual numbers: The smallest black hole detected was only about five solar masses, while the largest was 91. The most spectacular observation so far, however, was made in August 2017. At the time, LIGO and Virgo detected a gravitational wave that had been produced by the collision of two neutron stars. Neutron stars are the extinct remains of once-radiant suns that have ended their lives collapsing into an immensely compact something – equivalent to squeezing our Sun down to a radius of ten kilometres, the size of a city. Unlike ordinary celestial bodies, these oddballs are for the most part not made of atoms at all; instead, they are compressed clumps of neutrons, i.e. nuclear particles. ››

"Gravitational waves allow us to explore the nature of black holes"

Rafael Porto, DESY



In order to recognise the signal of a gravitational wave within the data at all, researchers carry out detailed simulations of how an expected event would unfold. These images show the numerical relativistic simulation of two neutron stars orbiting each other and fusing. Higher densities are depicted in red, lower densities in yellow.

Prime example of multi-messenger astronomy

What makes the event so special: “During the collision of the two neutron stars, we observed not only gravitational waves, but also visible light, radio waves, flashes of gamma radiation and X-rays – the entire spectrum,” says Alessandra Buonanno, Director at the Max Planck Institute for Gravitational Physics in Potsdam, Germany. “That was a huge breakthrough.” Because of this, the event is considered a prime example of multi-messenger astronomy: The combination of different types of signals provided a cornucopia of new scientific findings.

Among other signals, the Fermi space telescope had detected a flash of gamma rays 1.7 seconds after the gravitational wave signal ended – impressive confirmation of the long-held conjecture that neutron stars crashing into each other are indeed a cause of the hitherto mysterious gamma-ray bursts. **A further insight was that vast amounts of gold, platinum and similar elements were created during the violent fusion.** The scientists had thus discovered a mechanism capable of producing such heavy metals.

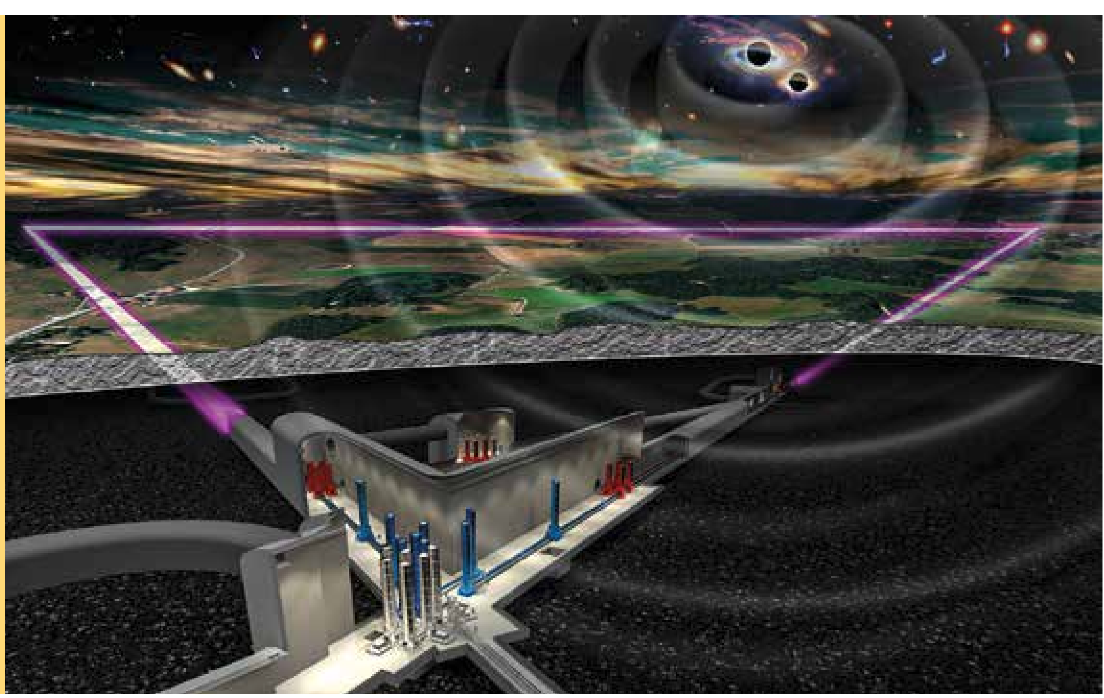
In future, gravitational waves promise to reveal further spectacular findings: A supernova, for example, i.e. a massive stellar explosion, should not only release a cocktail of light, radio and X-ray waves as well as a flood of neutrinos; it should also generate clearly detectable gravitational waves. Combining all these different signals should help to unravel exactly how these celestial spectacles unfold.

On the trail of dark matter

The physics community is hoping for a special boost from future detectors, which will be much more sensitive; among other things, there are plans to build the Einstein Telescope, possibly in the region of Lusatia in Germany and Poland. Its ten-kilometre-long laser arms will make it significantly larger, and hence more sensitive, than LIGO or Virgo. And in 2034, the LISA space telescope is due to be launched – an ensemble of three satellites, each a million kilometres apart. “Among other things, we are hoping this will allow us to observe collisions between supermassive compact objects at the centre of galaxies,” says DESY physicist Rafael Porto. “This could allow us to determine whether there are supermassive black holes at the centre of galaxies, as suspected, or perhaps entirely different, new objects.”

“During the collision of the two neutron stars, we observed not only gravitational waves, but also visible light, radio waves, flashes of gamma radiation and X-rays”

Alessandra Buonanno, Max Planck Institute for Gravitational Physics in Potsdam



The Einstein Telescope is to be fitted with three laser arms instead of two, which will be situated 200 to 300 metres below ground. The ten-kilometre-long arms will be used in pairs, meaning that there will be a total of six detectors. Three will be optimised for low frequencies and three for higher frequencies.

And the future detectors could solve another mystery of the universe: What is the ominous dark matter made of that appears to hold together galaxies like an invisible glue? Some experts believe that a new, hitherto undiscovered class of elementary particles is behind this – so-called axions or axion-like particles. "We have worked out how we can use gravitational waves to look for them," explains Porto. "We believe it is possible that axion-like particles form a kind of condensate around a black hole. This condensate could reveal itself in the form of a faint imprint in future gravitational wave signals."

If the undertaking succeeds, it would not only solve an astrophysical mystery; it would also revolutionise particle physics. All of a sudden, there would be a new fundamental building block of matter – the first elementary particle outside the established Standard Model.

The LISA (Laser Interferometer Space Antenna) space telescope will consist of three interconnected satellites and will peek inside massive galaxies, among other things.

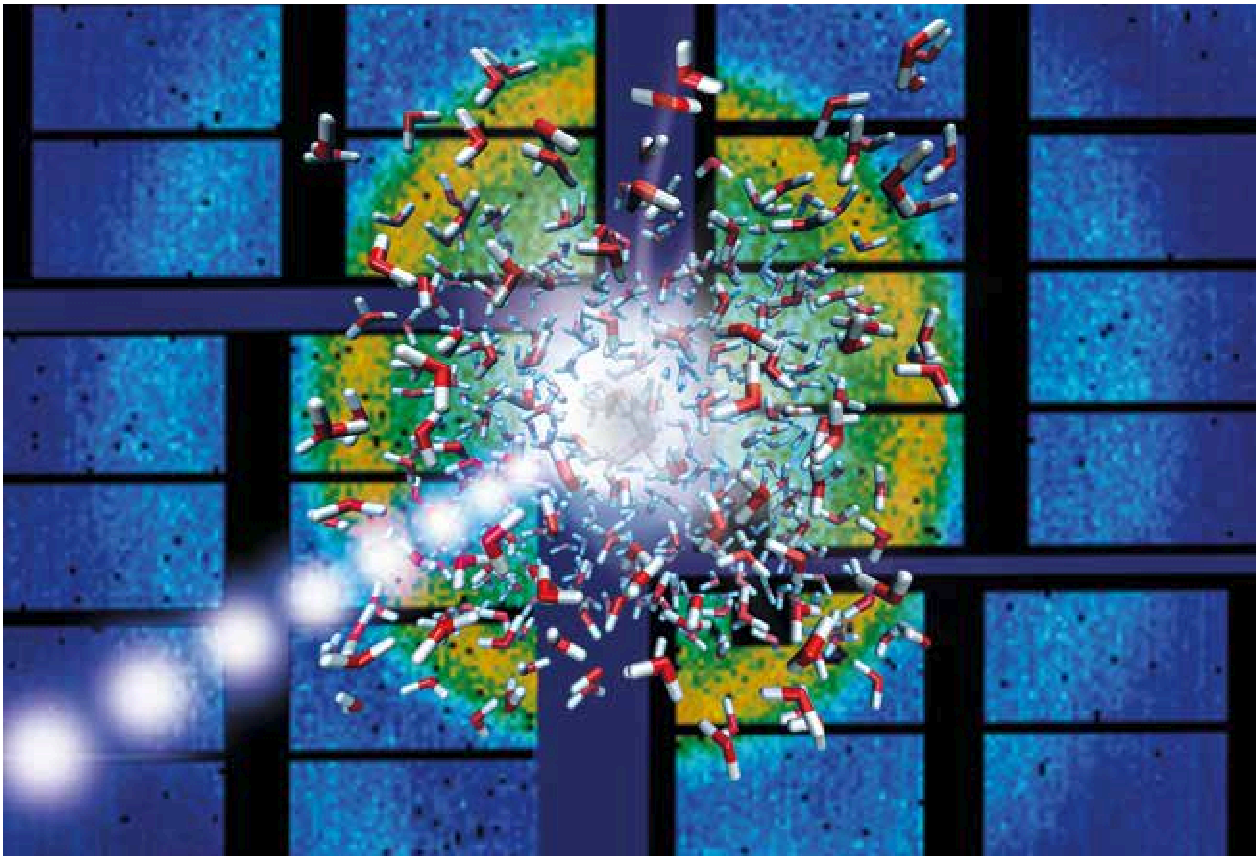
Pictures: MPG/AEI, A. Klaer, Max Planck Institute for Gravitational Physics, Milde Marketing Wissenschaftskommunikation, exozet, NIKHEF

THE EINSTEIN TELESCOPE – 500 TIMES MORE SENSITIVE

The dimensions of today's gravitational wave detectors are already impressive, with laser arms measuring up to four kilometres. The next generation will surpass them, though. In Europe, for example, the planned Einstein Telescope will form an equilateral triangle with each side ten kilometres long, fitted with six laser interferometers. It is to be constructed underground to substantially reduce the vibrations of the highly sensitive mirrors. In addition, they will be cooled to minus 260 degrees Celsius to minimise the thermal noise within the apparatus. Taken together, these precautions will make the Einstein Telescope far more sensitive than current detectors: Instead of registering one event per week, it should record around 500 – a huge increase. The billion-euro project has not yet been given the go-ahead, but already the experts are on the starting blocks. Various possible sites are being considered, including Sardinia, the three-border region between Germany, Belgium and the Netherlands, and Lusatia, where a scientists' initiative would like to set up a German Centre for Astrophysics. The USA is also thinking of building a new detector: If current plans go ahead, the Cosmic Explorer will reach a length of no less than 40 kilometres.

www.einsteintelescope.nl/de, www.deutscheszentrumastrophysik.de

Science in brief



The X-ray flashes of the European XFEL (violet) do not only heat the water (red and white molecules), but also produce a diffraction pattern of the sample (background) from which the state of the water can be determined after each flash. This gives a detailed time history of the process.

Liquid water at 170 degrees Celsius

Using the European XFEL X-ray laser, a team of researchers has heated water so quickly that it remained liquid even at temperatures of more than 170 degrees Celsius. The investigation served to explore water under extreme conditions and revealed an **anomalous dynamic behaviour.** The results are also of fundamental importance for the planning and analysis of investigations of sensitive samples using X-ray lasers.

For their experiments, the researchers used series of 120 X-ray flashes from the European XFEL. The scientists sent these pulse trains into a thin, water-filled quartz glass tube and observed the reaction of the water. "With the X-ray flashes, we were able to heat the water up to 172 degrees Celsius within a ten-thousandth of a second without it evaporating," reports lead author Felix Lehmkühler from DESY.

Such a boiling delay can normally be observed only up to temperatures of about 110 degrees Celsius. "But that is not the only anomalous feature," the physicist emphasises. The scientists investigated the movement of silicon dioxide nanospheres floating in the water as markers for the dynamics in the sample. In the extremely overheated water, the movement of the nano-spheres deviated significantly from the expected random thermal motion, the so-called Brownian molecular motion. "This indicates an uneven heating of the sample," says Lehmkühler. Existing theoretical models cannot yet satisfactorily explain this behaviour because they are not designed for water under these extreme conditions.

The experiments not only aim to explore the behaviour of water. A detailed understanding of superheated water is also essential for a large number of investigations on heat-sensitive samples, such as polymers, biomolecules or biological tissues. In addition, the studies intend to clarify very practical questions about superheated water. "For example, does it still function as a coolant at high temperatures?," asks Lehmkühler.

Proceedings of the National Academy of Sciences, DOI: 10.1073/pnas.2003337117

Picture: DESY, Britta Liebaug

Earth's mantle recreated in the lab

A team of researchers has recreated the conditions of Earth's deep mantle in the laboratory at DESY, deforming real rock for the first time under conditions comparable to those that prevail more than 1000 kilometres below the surface. At the Extreme Conditions Beamline of DESY's X-ray source PETRA III, the scientists exposed the mineral olivine to almost 400 000 times atmospheric pressure and a temperature of more than 700 degrees Celsius, thereby creating a **high-pressure mixture of the two most common minerals on Earth,** bridgmanite and ferropericlase.

Most simulation experiments exploring the Earth's lower mantle have examined samples of a single mineral at a time. "However, due to grain-to-grain interactions, the deformation behaviour of a mixture of several minerals is potentially different from that of a single mineral," explains lead author Samantha Couper from the University of Utah in the USA. Indeed, the study revealed an unexpected behaviour of the mineral mixture, which is typical of the Earth's lower mantle.

Unlike in experiments with pure samples, ferropericlase did not form any significant texture in the mixture. This probably means that, surprisingly, ferropericlase does not contribute to the observed directional differences in the propagation of earthquake waves (seismic anisotropies) within the lower mantle.

Frontiers in Earth Science, DOI: 10.3389/feart.2020.540449

The inner structure of the Earth. The investigations simulated condition like those in the lower mantle.

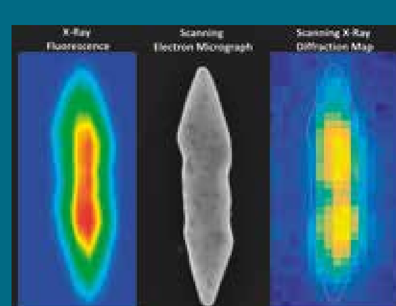
Unconventional gold nanocrystals are better chemical catalysts

Gold nanoparticles can be better catalysts if their atoms are packed differently from the conventional arrangement. At DESY's X-ray source PETRA III, an Indian–German team of scientists has elucidated the inner composition of so-called multiphase gold nanoparticles, which comprise mixed crystal structures. The results help to better understand the catalytic properties of these nanocrystals and to develop even more effective catalysts.

Gold nanoparticles have a wide range of applications because of their special properties, which differ in many respects from gold in bulk form. For example, while gold is normally hardly active as a catalyst, gold nanoparticles have outstanding catalytic properties.

Recent studies indicate that gold is an even significantly better catalyst when its atoms are not arranged in the usual face-centred cubic (fcc) crystal lattice. At PETRA III, the team investigated nanoparticles consisting of different crystal lattices. The results showed that the usual fcc lattice is mainly found in the tips of the nanoparticles, while their bodies are made up of other crystal lattices. Thanks to the study, the growth of the individual crystal structures can be better understood and the proportion of favourable structures possibly increased even further.

ACS Nano, DOI: 10.1021/acsnano.0c02031



A gold nanoparticle in the light of X-ray fluorescence (left), under the electron microscope (centre) and as a scanning X-ray diffraction microscopy image (right). The latter reveals the arrangement of the atoms inside the particle. It is 0.0016 millimetres long.

Pictures: DESY, Abhisakh Sarma (nanocrystals); Istockphoto (Earth layers)

Luminosity world record

With the SuperKEKB accelerator, researchers aim to unravel the mysteries of antimatter.

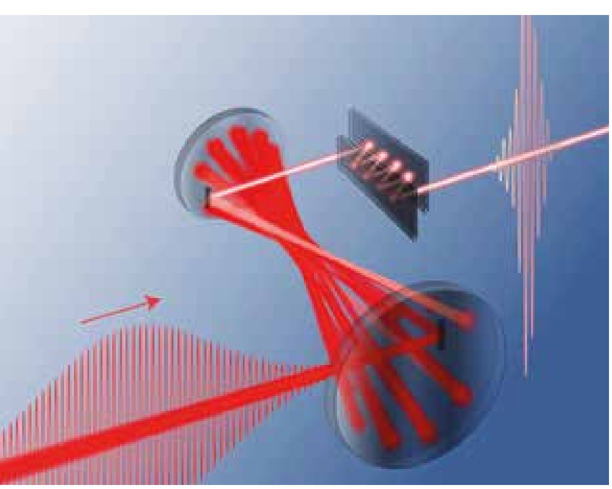
Tailwind for the search for rare particle decays in the Belle II detector in Japan: The SuperKEKB accelerator ring has achieved the highest luminosity ever measured. The electron–positron accelerator beats not only its predecessor KEKB, but also the world's biggest particle accelerator, the Large Hadron Collider (LHC) at the CERN research centre near Geneva.

The luminosity indicates how many particles are gathered per second and square centimetre. It is thus an important measure of the number of collisions that can be generated in Belle II – the more measurement data, the higher the probability of finding even very rare processes. SuperKEKB reached the enormous number of **2.22×10^{34} particles per square centimetre** per second, or 22.2 billion septillions.

With the help of Belle II, scientists from all over the world want to find out more about what causes the different behaviour of matter and antimatter in the universe. To do this, electrons and their antiparticles, positrons, are first brought to high energies in the SuperKEKB accelerator and then collided inside the detector.

The luminosity record is just the beginning: In the next few years, the luminosity is expected to increase up to 40 times.

Record compression yields ultrashort laser pulses



The originally monochromatic infrared laser pulse (left) passes through the krypton gas several times, expanding its colour spectrum, and is then compressed with special mirrors.

With the help of a special "light compressor", a team of researchers has produced ultrashort laser pulses at DESY. In collaboration with colleagues from Sweden and France, scientists led by Christoph Heyl from DESY and the Helmholtz Institute Jena succeeded in compressing high-energy laser pulses of about one third of a millimetre in length to about **a hundredth of a millimetre** in just one step. In a further step, the researchers compressed the pulses to only about four thousandths of a millimetre (micrometre), which is about one tenth of the thickness of a human hair.

Ultrashort laser pulses are needed in many areas of research, including the study of ultrafast dynamics of matter and in plasma acceleration. The researchers started with infrared laser pulses of 1.2 trillionths of a second (picoseconds) duration. That is inconceivably short already, but not short enough for the desired applications. Therefore, they sent the pulses through two light compressors, each consisting of a mirror tube filled with krypton gas and additional special mirrors. In the first step, the pulses shrank to 32 quadrillionths of a second (femtoseconds) at 80 percent of the original pulse energy, and in the second to 13 femtoseconds, with the pulse energy halved. This corresponds to a record total compression factor of about 90.

Optics Letters, DOI: 10.1364/OL.388665

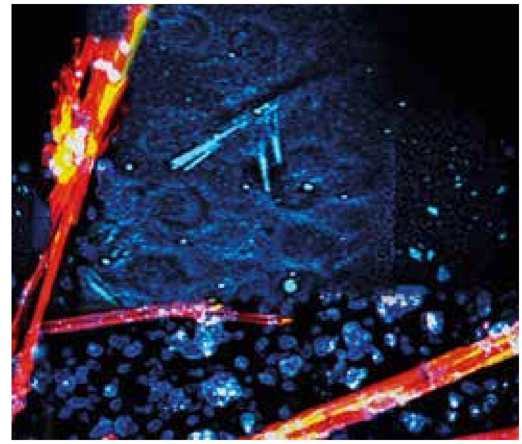
Super microscope for protein crystals

A novel kind of microscope is able to detect tiny protein crystals that are beyond the imaging power of even modern light microscopes. The so-called multiphoton microscope relies on **various non-linear optical effects** to image even nanocrystals, which are increasingly being used for protein structure analyses nowadays. The device is driven by an infrared fibre laser whose pulses are converted into two colours. From these, the protein crystals generate radiation at wavelengths of a half and a third of the incoming wavelength, the so-called second and third harmonics, which in this case are in the blue and ultraviolet (UV) range.

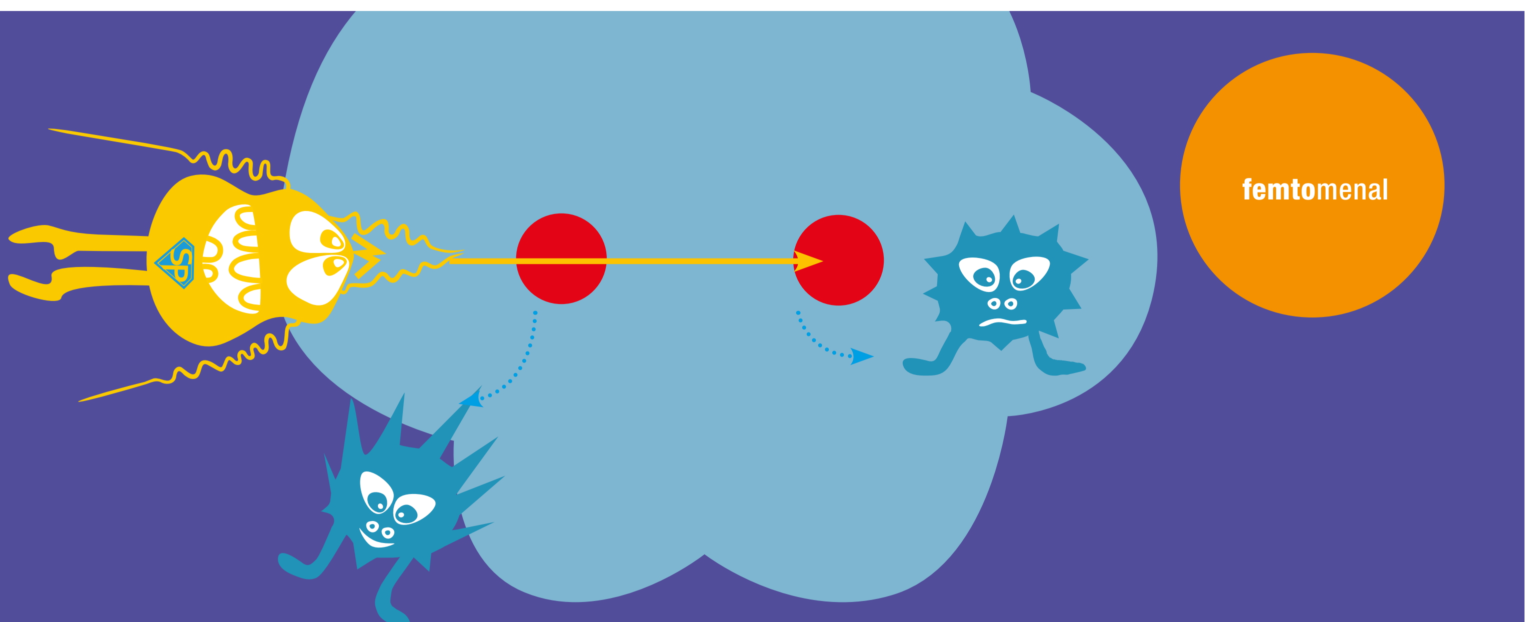
One of the two colours of the incoming laser pulse is chosen in such a way that it can trigger fluorescence in the amino acid tryptophane, which occurs in proteins. The emitted fluorescence light is again in the UV range, so that the glow of the proteins from the various processes can be clearly separated from the incoming infrared laser light.

In the laboratory, the team of developers led by Franz Kärtner from DESY, Christian Betzel from Universität Hamburg and Guoqing Chang from the Chinese Academy of Sciences was able to reliably detect tiny crystals of the proteins lysozyme, thaumatin, thermolysin and PAK4 using their multimodal multiphoton microscope.

Communications Biology, DOI: 10.1038/s42003-020-01275-8



Among other things, the multimodal multiphoton microscope can reliably distinguish salt crystals (red) from protein crystals (blue).



247 zeptoseconds

is the time it takes for a light particle (photon) to pass through a hydrogen molecule (H_2). That is 247 trillionths of a billionth of a second (0.000 000 000 000 000 247 seconds) and the shortest time span ever measured. To achieve this record, a team led by Reinhard Dörner from Goethe University Frankfurt am Main used a special reaction microscope at DESY's X-ray source PETRA III. Electrons behave like particles and waves at the same time, and so when the two electrons were knocked out of the hydrogen molecule, two electron waves were created in quick succession, the superposition of which could be measured with the reaction microscope. In these experiments, the team was also able to observe for the first time that the electron shell in a molecule does not react to light everywhere at the same time. The time delay occurs because information within the molecule only spreads at the speed of light.

Science, DOI: 10.1126/science.abb9318

Mysterious **gamma-ray “heartbeat”** from outer space

Cosmic gas cloud blinks in sync with wobbling black hole

The microquasar SS 433 (background) sways with a period of 162 days. The inconspicuous gas cloud Fermi J1913+0515 (foreground), about 100 light years away, pulsates with the same rhythm, suggesting a direct connection.

In the constellation Aquila lies an inconspicuous cloud of cosmic gas. The otherwise unspectacular object, however, amazes astronomers with a puzzling gamma-ray “heartbeat”: The cloud is beating with the rhythm of a precessing black hole in the cosmic neighbourhood, indicating a connection of unknown nature between the two objects. Exactly how the black hole drives the gamma-ray “heartbeat” of the gas cloud over a distance of about 100 light years is unclear.

A team led by DESY Humboldt Fellow Jian Li and Diego F. Torres from the Institute of Space Sciences (IEEC-CSIC) in Barcelona has rigorously analysed more than ten years of data from the US space administration NASA’s Fermi gamma-ray space telescope, looking at a so-called microquasar. The system catalogued as SS 433 is located some 15 000 light years away in the Milky Way and consists of a giant star with about 30 times the mass of our Sun and a black hole with about 10 to 20 solar masses. The two objects are orbiting each other with a period of 13 days, while the black hole sucks matter from the giant star.

“This material accumulates in an accretion disc before falling into the black hole, like water in the whirl above the drain of a bath tub,” explains Li. “However, a part of that matter does not fall down the drain, but shoots out at high speed in two narrow jets in opposite directions above and below the rotating accretion disk.” This setting is known to astronomers from active galaxies called quasars with monstrous black holes with millions of solar masses at their centres that shoot jets of matter tens of thousands of light years into intergalactic space. As SS 433 looks like a scaled-down version of these quasars, it has been dubbed a microquasar.

Wobbling top

The high-speed particles and the ultrastrong magnetic fields in the jets produce X-rays and gamma rays. “The accretion disc does not lie exactly in the plane of the orbit of the two objects. It precesses, or sways, like a spinning top that has been set up slanted on a table,” explains Torres. “As a consequence, the two jets spiral into the surrounding space, rather than just forming a straight line.”

The precession of the black hole’s jets has a period of about 162 days. Meticulous analysis of the measurement data revealed another gamma-ray signal with the same period from a position relatively far from the microquasar’s jets. It was given the catalogue number Fermi J1913+0515 and comes from the site of an unremarkable accumulation of interstellar gas. The coinciding periods indicate that the regular gamma-ray “heartbeat” of the cloud must be driven by the microquasar.

> *“The microquasar continues to amaze observers at all frequencies and theoreticians alike”*
>
> **Jian Li, DESY**

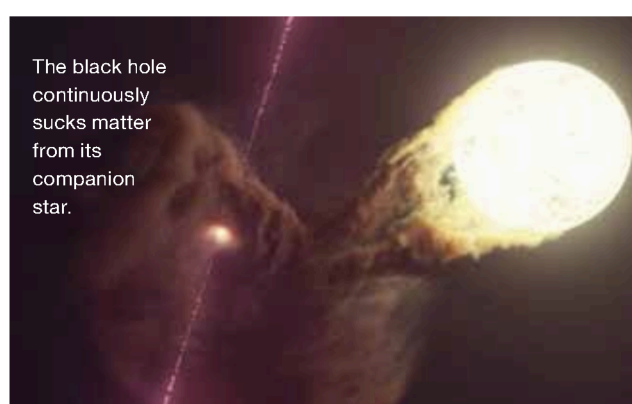
“Finding such an unambiguous connection via timing, about 100 light years away from the microquasar and not even along the direction of the jets, is as unexpected as it is amazing,” emphasises Li. “But how the black hole can power the gas cloud’s heartbeat is unclear to us.” The scientists certainly have a few ideas. A direct periodic illumination of the clouds by one of the jets seems unlikely in any case.

Cosmic test bed

As an alternative model, the team has explored the idea that fast protons (the nuclei of hydrogen atoms) are produced in the jets or near the black hole and generate gamma rays when they hit the molecules of the gas cloud. Such protons could also be part of an outflow of fast particles from the outer edge of the accretion disk. Whenever this outflow strikes the gas cloud, this lights up in gamma rays, which would explain its strange “heartbeat”. “Energetically, the outflow from the disc could be as powerful as that of the jets, and it is believed to precess in synchrony with the rest of the system,” explains Torres.

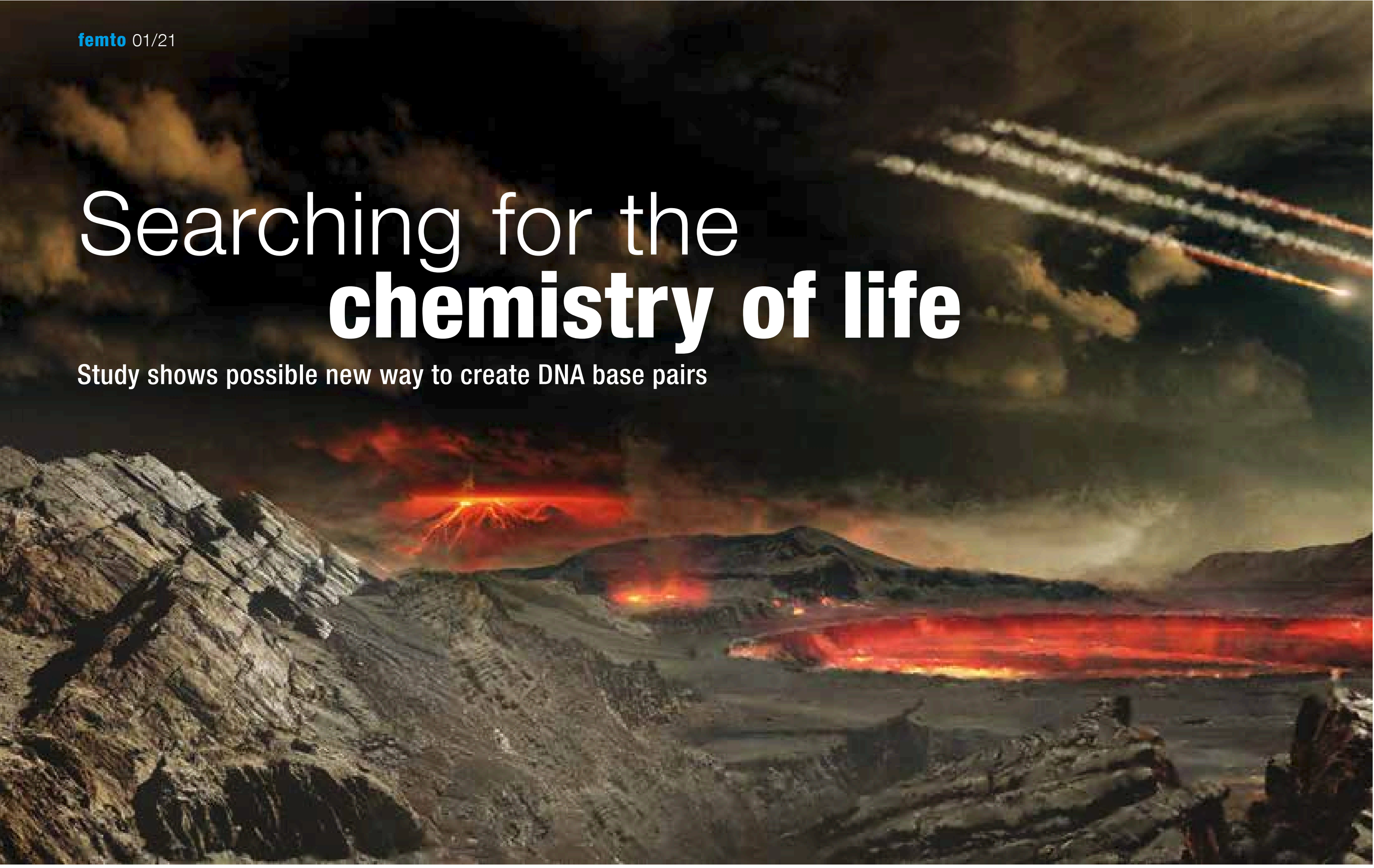
However, in order to understand the enigmatic gamma-ray “heartbeat” of this unique system in detail, further observations and theoretical analyses are necessary, the scientists emphasise. “SS 433 continues to amaze observers at all frequencies and theoreticians alike,” says Li. “And it is certain to provide a test bed for our ideas on cosmic-ray production and propagation near microquasars for years to come.”

Nature Astronomy,
DOI: 10.1038/s41550-020-1164-6



The black hole continuously sucks matter from its companion star.

Picture: DESY, Science Communication Lab



Searching for the **chemistry of life**

Study shows possible new way to create DNA base pairs

In the search for the chemical origins of life, researchers using DESY's X-ray source PETRA III have revealed a possible alternative pathway for the emergence of the characteristic pattern of DNA: According to the team led by Ivan Halasz from the Ruđer Bošković Institute in Zagreb, Croatia, and Ernest Meštrović from the pharmaceutical company Xellia, the characteristic DNA base pairs can form by dry heating, without water or other solvents.

"One of the most intriguing questions in the search for the origin of life is how the chemical selection occurred and how the first biomolecules formed," says lead author Tomislav Stolar from the Ruđer Bošković Institute. While living cells control the production of biomolecules with their sophisticated machinery, the first molecular and supramolecular building blocks of life were likely created by pure chemistry and without enzyme catalysis. For their study, the scientists investigated the formation of nucleobase pairs in deoxyribonucleic acid (DNA).

Our genetic code is stored in the DNA as a specific sequence spelled by the nucleobases adenine (A), cytosine (C), guanine (G) and thymine (T). The code is arranged in two long, complementary strands wound in the familiar double-helix structure. In the strands, each nucleobase pairs with a complementary partner in the other strand: adenine with thymine and cytosine with guanine.

> *"Our results open up many new paths in the search for the chemical origins of life"*
>
> **Tomislav Stolar, Ruđer Boškovic Institute**

"Only specific pairing combinations occur in the DNA, but when nucleobases are isolated they do not like to bind to each other at all. So why did nature choose these base pairs?," asks Stolar. Investigations of pairing of nucleobases surged after the discovery of the DNA double-helix structure by James Watson and Francis Crick in 1953 – with surprisingly little success in achieving specific nucleobase pairing despite conditions that could be considered prebiotically plausible.

Alternative reaction pathway

"We have explored a different path," reports co-author Martin Etter from DESY. "We have tried to find out whether the base pairs can be generated by mechanical energy or simply by heating." To this end, the team studied so-called methylated forms of the nucleobases. Having a methyl group (-CH_3) attached to the respective nucleobases in principle allows them to form hydrogen

Under the environmental conditions on the young Earth with volcanoes, earthquakes and meteorite impacts, nucleobase pairs could have formed even without water or other solvents.

bonds at the Watson–Crick side of the molecule. Methylated nucleobases also occur naturally in many living organisms where they fulfil a variety of biological functions.

In the lab, the scientists first tried to produce nucleobase pairs in purely mechanically driven reactions by grinding. Powders of two nucleobases were loaded into a milling jar along with steel balls, which served as the grinding media, while the jars were shaken in a controlled manner. The experiment produced adenine–thymine pairs, which had also been observed by other scientists before. Grinding, however, could not achieve the formation of cytosine–guanine pairs.

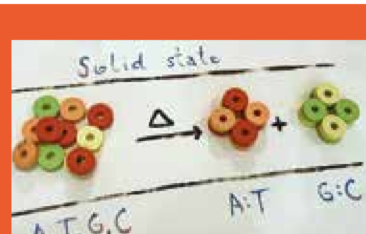
Conditions of the young Earth

In a second step, the researchers heated the ground cytosine and guanine powders. “At about 200 degrees Celsius, we could indeed observe the formation of cytosine–guanine pairs,” reports Stolar. To test whether the bases only bind to each other under thermal conditions in the way that is known from DNA, the scientists repeated the experiments with mixtures of three and four nucleobases at PETRA III, where they could monitor the detailed molecular structure of the mixtures. In this way, they were able to follow whether and which new compounds formed during heating.

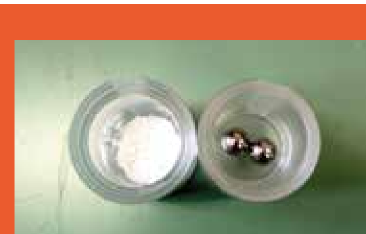
“At about 100 degrees Celsius, we were able to observe the formation of adenine–thymine pairs, and at about 200 degrees Celsius the formation of pairs of guanine and cytosine,” says Etter. “No other base pairs formed, even with further heating until melting.” This proves that the thermal reaction of nucleobase pairing has the same selectivity as in the DNA.

“Our results show a possible alternative route as to how the molecular recognition patterns that we observe in the DNA could have been formed,” adds Stolar. “The conditions of the experiment are plausible for the young Earth, which was a hot, seething cauldron with volcanoes, earthquakes, meteorite impacts and all sorts of other events. Our results open up many new paths in the search for the chemical origins of life.”

Chemical Communications,
DOI: 10.1039/D0CC03491F



From the mixture of the four nucleobases adenine (A), cytosine (C), guanine (G) and thymine (T), A:T pairs were formed by purely mechanical means at about 100 degrees Celsius and G:C pairs at 200 degrees Celsius.



Purely mechanical grinding of mixtures of nucleobase powders with steel balls did not lead to the formation of the desired guanine–cytosine pairs.

Pictures: NASA's Goddard Space Flight Center Conceptual Image Lab; Ruđer Bošković Institute, Ivan Halasz; Ruđer Bošković Institute, Tomislav Stolar

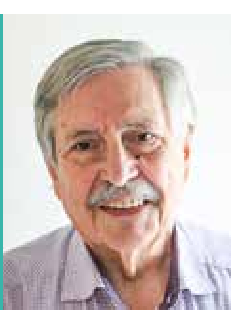
Signs of new physics?

An experiment on the magnetic moment of the muon is keeping scientists in suspense

In physics, there is a theory that describes all subatomic particles and all the forces acting between them with very great precision. This theory, known as the Standard Model of particle physics, remains rock solid, despite the fact that physicists are constantly shaking it to see whether cracks might after all appear somewhere in its foundations. All over the world, many small and large experiments are being conducted, trying to find such a crack or an error in the Standard Model. This is because it is unable to explain certain phenomena, such as dark matter and dark energy. The principle behind most such experiments is to compare experimental data with the theoretical predictions of the Standard Model. Until now, the Standard Model has always turned out to be right.

Always? No! A small experiment by the name of Muon g-2 carried out at Fermilab in the USA has observed a clear difference between the predicted and experimental value. The Muon g-2 experiment studies muons, the heavier relatives of the better-known electron, and their properties. One of these, the magnetic moment, deviates from the theoretical prediction. Fermilab's results thus confirm measurements made at the Brookhaven National Laboratory in New York, which had already led to considerable surprise. The magnetic moment describes, among other things, how a particle reacts in a magnetic field. The difference between the value now measured and the one predicted by theory lies in the ninth significant figure, but it still has particle physicists on tenterhooks. Could this be the first sign of new particles, such as those associated with the long postulated but never observed phenomenon of supersymmetry? Could they be dark photons, which might also explain the mysterious dark matter? Or is it still too early for such conjectures, and should more data be collected first?

Having worked on the magnetic moment of the muon for decades, though not actively involved in this latest measurement, DESY's theoretical physicists Fred Jegerlehner and Peter Marquard remain curious.



"We'll only get excited once other experiments confirm the measurements"

Fred Jegerlehner, DESY

femto: What does this result mean? Will physics textbooks have to be rewritten?

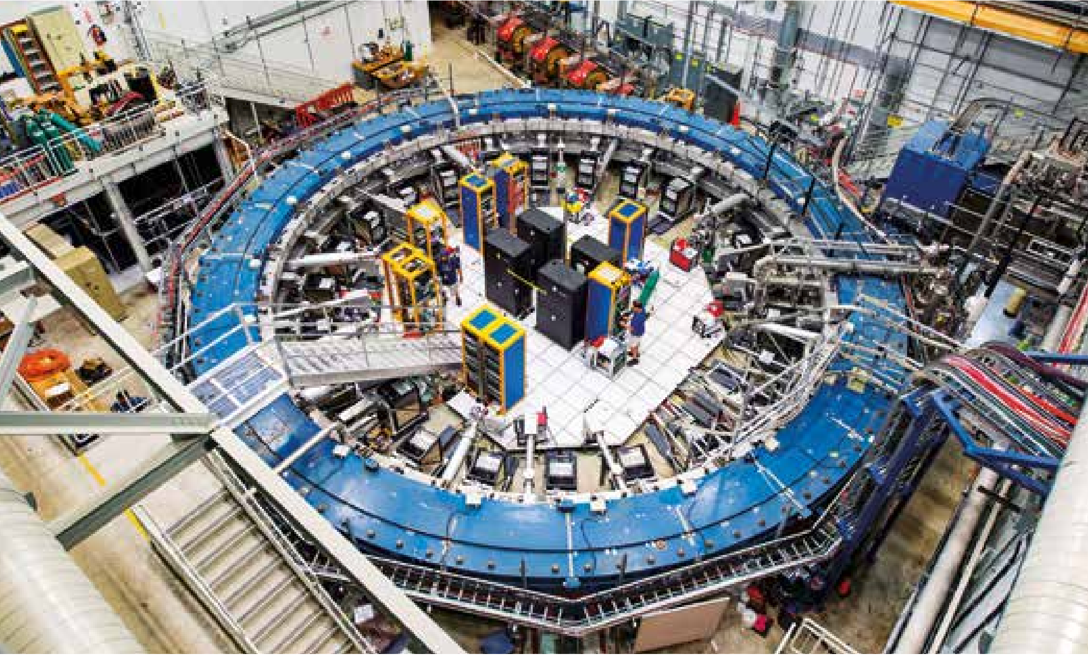
Fred Jegerlehner: The fact that we have been able to get to grips with a phenomenon like this with such high precision is a tremendous achievement, both for the theory and for the experiments. However, when it comes to potential consequences, I tend to be rather conservative. The results are exciting, and they also confirm the previous measurements made at Brookhaven. But the problem is that both experiments – at Brookhaven and at Fermilab – use the same approach. We'll only get excited once other experiments confirm the measurements. For example, an experiment that is currently in preparation in Japan will make the same measurement but work completely differently. Using different approaches to the same question should give us more certainty. But I am very optimistic that a few years from now the fog will have cleared.

Peter Marquard: As fantastic as the results are, they have not changed anything for the time being. We are in a very precise domain in which every single detail is important. That is why an alternative measurement would be very desirable. Only once the statistical error of the measurement becomes even smaller will it become interesting, and then we can start trying to explain it. Of course, some of our colleagues are already publishing possible explanations, but we have often had observations with similar probabilities in the past that turned out in the end to be statistical fluctuations.

femto: So you don't yet see the measurement as an indication of dark matter or supersymmetry, a physics beyond the Standard Model?

Peter Marquard: We'd all like to find something new; that would be very exciting, of course. But the data

Pictures: Fermilab, Reidar Hahn (accelerator ring); portraits private



The Muon g-2 experiment operates at freezing temperatures of minus 267 degrees Celsius and observes how strongly muons oscillate in an external magnetic field.

doesn't permit that yet. However, we do indeed lack a grand new theory in physics – at the moment, we are patching individual particles onto the Standard Model; but this is also because the Standard Model is so successful. Many proposals have been made to extend the Standard Model so as to explain new phenomena, but few of them could actually be an embedding in a more comprehensive, consistent theory.

Fred Jegerlehner: Of course, we have to think in all directions. But I am a supporter of the Standard Model. This desire to kill off the Standard Model is odd. It may be a complicated and strangely constructed theory, but until now it has always been confirmed, even though we know that it is incomplete.

femto: So what is the next step in terms of the magnetic moment of the muon?

Fred Jegerlehner: I hope that theoreticians will make a concerted effort and sort things out!

femto: You mean that they will correct the theory in the light of the Muon g-2 results?

Peter Marquard: No, we need to take another, closer look and see what we have missed. By now, both the theoretical predictions and the experimental measurements are so precise that they agree to the first eight digits. This is an outstanding achievement on both sides. The fact that it was possible to make this measurement and that everything fits as well as it does is fantastic. But as we have said – an alternative measurement would be very desirable.

Fred Jegerlehner: I for one am currently calling my own findings into question, in order to understand the discrepancy between theory and experiment. A genuine discrepancy will be corroborated by further measurements, and the theory will keep us in suspense for a long time. I have been working on the magnetic moment of the muon for more than 30 years now, and have even written a book about it, and my colleagues and I have been working on the Muon g-2 experiment since 1995. Recently, the prediction of the magnetic moment of the muon has revealed a significant difference between two different approaches to the calculation. On the one hand, there is the most accurate one so far, which is based on the use of experimental data; and on the other hand, there is the purely theoretical prediction, which leads to a larger value and would halve the discrepancy between theory and experiment. Who is closer to the truth? I see a tendency for the discrepancy to become smaller. What remains to be emphasised: The new Muon g-2 experiment sets new standards in precision physics and is driving the theory along before it; the latter has already made great progress, but will have to continue to do so.

"The fact that it was possible to make this measurement is fantastic"

Peter Marquard, DESY

An electron bunch with varying energy (dark blue to orange) drives a plasma wave (white) with strong electric fields (red and blue). Removing thin slices from the tail of the electron bunch in a controlled manner allows the precise measurement of the electric fields.

Measuring the wave

Innovative method offers unrivalled insight into plasma accelerators

It promises to deliver a new generation of powerful and compact particle accelerators: the technology of plasma-based acceleration, in which bunches of electrons are brought up to speed by plasma waves instead of radio waves. Prior to applying this new technology, however, various obstacles must be overcome. In particular, precise control of the acceleration process itself must be achieved.

Using an innovative technique, a team of researchers led by DESY scientist Jens Osterhoff has succeeded in measuring the accelerating plasma wake with previously unattained precision. Their method allows the shape of the effective accelerating field to be determined with a resolution on the order of femtoseconds (quadrillionths of a second) so that the acceleration process can be studied in great detail, thereby paving the way for the controlled and optimised operation of future plasma accelerators.

A plasma is a gas but with its molecules stripped of their electrons. A high-energy laser or particle beam can force these freely moving plasma electrons to oscillate, which results in strong electric fields. These can then be used to accelerate charged particles. To achieve this, DESY's FLASHForward facility fires bunches of electrons into a plasma at close to the speed of light.

"Our method is an important step on the path to a detailed understanding of the plasma wake"

Jens Osterhoff, DESY

The acceleration produced by the plasma wake can be up to a thousand times greater than that of the strongest conventional facilities currently in operation. "To achieve optimal acceleration, the electron bunches and the wake need to be precisely tuned to each other," explains Sarah Schröder, the lead author of the publication, who works at DESY and Universität Hamburg. "To do that, you have to be able to measure the shape of the wake precisely, and this is

View of the FLASHForward accelerator module. The plasma is generated in the narrow channel in the centre by a high voltage.

very challenging due to its small dimensions, being just a few thousandths of a millimetre long.”

Rotated electron bunch

The team therefore developed a method in which the accelerated electrons themselves are used to reveal the shape of the plasma wake’s accelerating field. To achieve this, the electron bunch is first rotated perpendicularly to the direction of flight in an arrangement of magnets. Thin slices can then be removed from the bunch tail by transversely inserting a piece of metal. Finally, the electron bunch is rotated back again.

The resulting energy spectrum of the outgoing electron bunch is altered due to the missing electrons, allowing the strength of the accelerating field at the location where part of the bunch was removed to be deduced. If the bunch is sliced thinly enough, the profile of the effective accelerating field in the plasma wake can be determined with a temporal resolution of femtoseconds. In the experiment, the scientists were able to achieve a resolution of 15 femtoseconds – corresponding to a spatial resolution of around 5 thousandths of a millimetre in the wake. The researchers believe that even higher resolutions are possible.

“For the first time, we have precisely measured the effective electric field responsible for the acceleration,” says Schröder. “Using this technique, the interaction between the individual experimental components and the process of acceleration can now be studied in detail.” Other experimental facilities for plasma acceleration also stand to benefit from the new technology, emphasises team leader Osterhoff. “Our method is an important step on the path to a detailed understanding of the plasma wake and to optimising it.”

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RECORD-BREAKING RUN

It is an important milestone: For the first time in the world, a laser plasma accelerator has run for more than a day while continuously producing electron beams. The LUX beamline, jointly developed and operated by DESY and Universität Hamburg, achieved a run time of 30 hours. “This brings us a big step closer to the steady operation of this innovative particle accelerator technology,” says team leader Andreas R. Maier from DESY.

LUX is driven by powerful laser pulses shot into a fine capillary containing hydrogen gas. “The laser pulses plough their way through the gas in the form of narrow discs, stripping the electrons from the hydrogen molecules and sweeping them aside like a snow plough,” explains Maier. “Electrons in the wake of the pulse are accelerated by the positively charged plasma wave in front of them – much like a wakeboarder rides the wave behind the stern of a boat.”

100 000 electron bunches

During the record-breaking non-stop operation, the physicists accelerated more than 100 000 electron bunches, one every second. Thanks to this large data set, the properties of the accelerator, the laser and the bunches can be correlated and analysed much more precisely. “Unwanted variations in the electron beam can be traced back to specific points in the laser pulse, for example, so that we now know exactly where we need to start in order to produce an even better particle beam,” says Maier.

“This approach lays the foundations for an active stabilisation of the beams, such as is deployed on every high-performance accelerator in the world,” explains Wim Leemans, Director of the Accelerator Division at DESY. “This work demonstrates that laser plasma accelerators can generate a reproducible and controllable output. This provides a concrete basis for developing this technology further, in order to build future accelerator-based light sources.”

A number of technical challenges still need to be overcome, however, before these devices can be put to practical use. “Now that we are able to operate our beamline for extended periods of time, we will be in a better position to tackle these challenges,” explains Maier.

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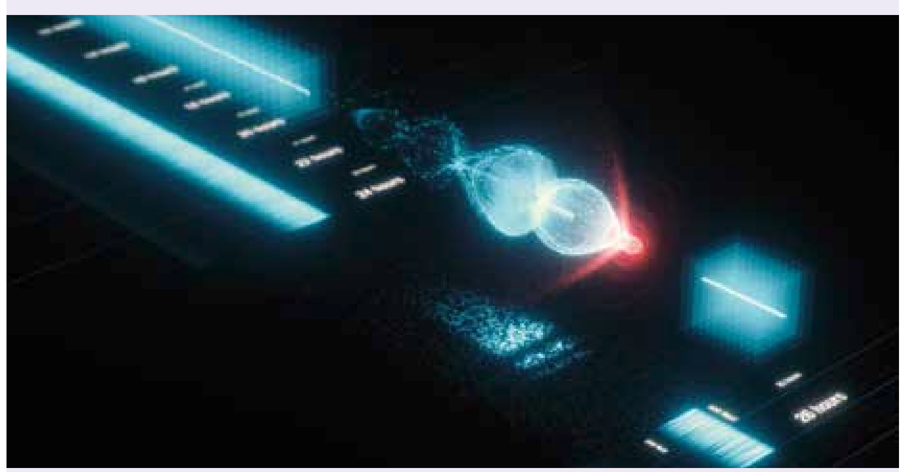
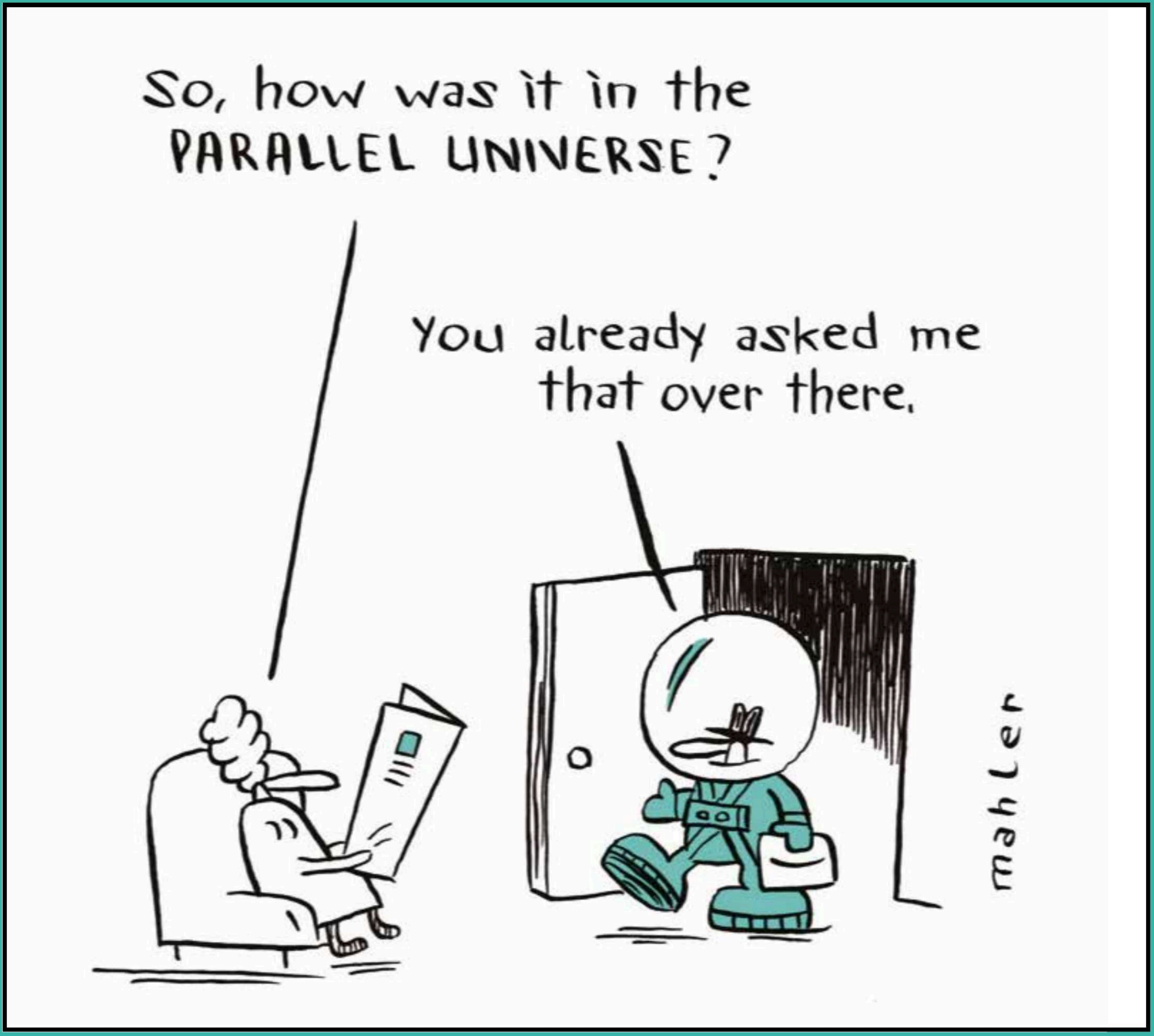


In laser plasma acceleration, a strong laser pulse (red) generates a plasma wave (blue) in hydrogen gas by stripping electrons from gas molecules. The electrons ride the wave like a surfer in the wake of a boat. This pushes them to high energies extremely quick.

Pictures: DESY, Ángel Ferran Pousa; DESY, Alexander Knetsch; DESY, Science Communication Lab femtofinale



Cartoon: Nicolas Mahler

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The DESY research centre

DESY is one of the world's leading particle accelerator centres and investigates the structure and function of matter – from the interaction of tiny elementary particles and the behaviour of novel nanomaterials and vital biomolecules to the great mysteries of the universe. The particle accelerators and detectors that DESY develops and builds at its locations in Hamburg and Zeuthen are unique research tools. They generate the most intense X-ray radiation in the world, accelerate particles to record energies and open up new windows onto the universe.

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