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The DESY research magazine – Issue 02/19

The next big scoop

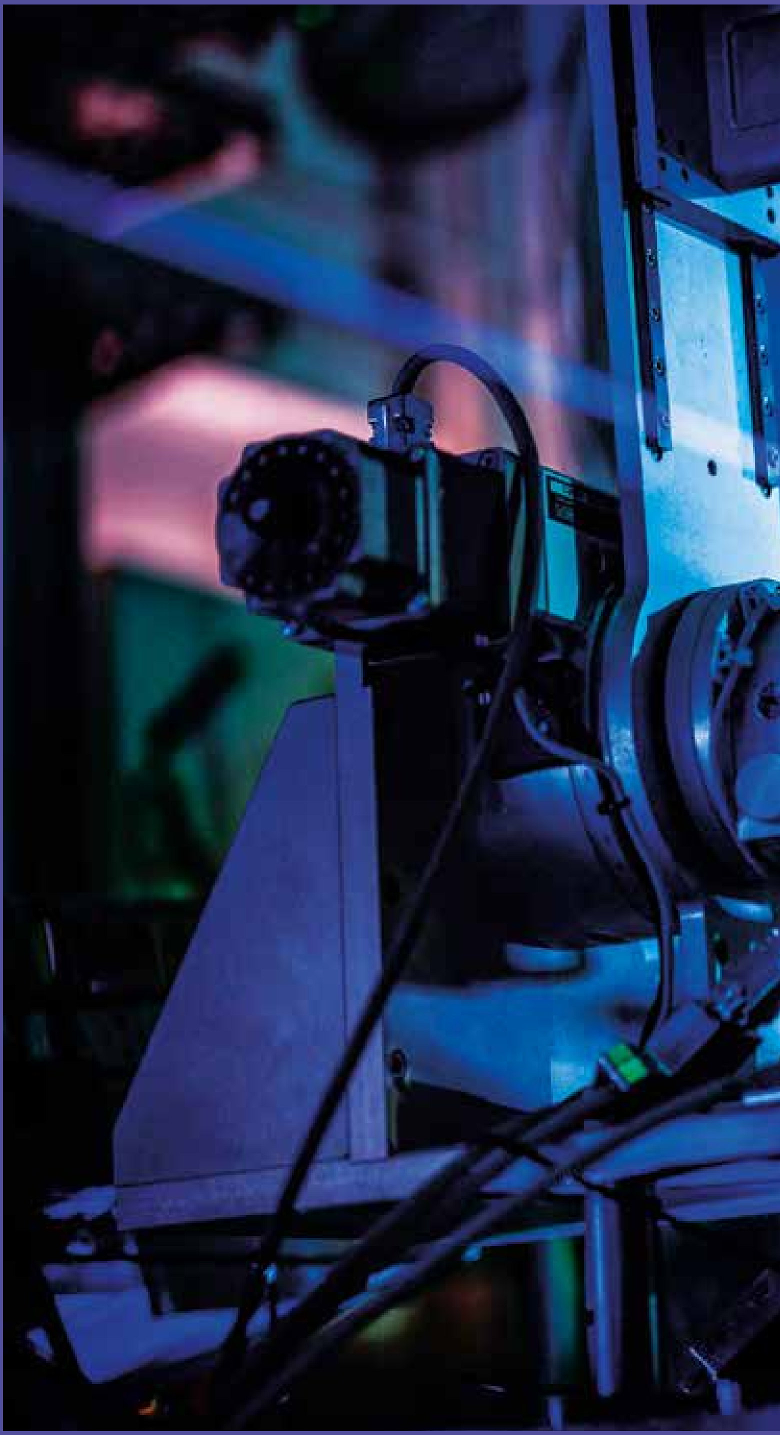
DARK MATTER

Hunting for new particles

Asteroids reveal size
of distant stars

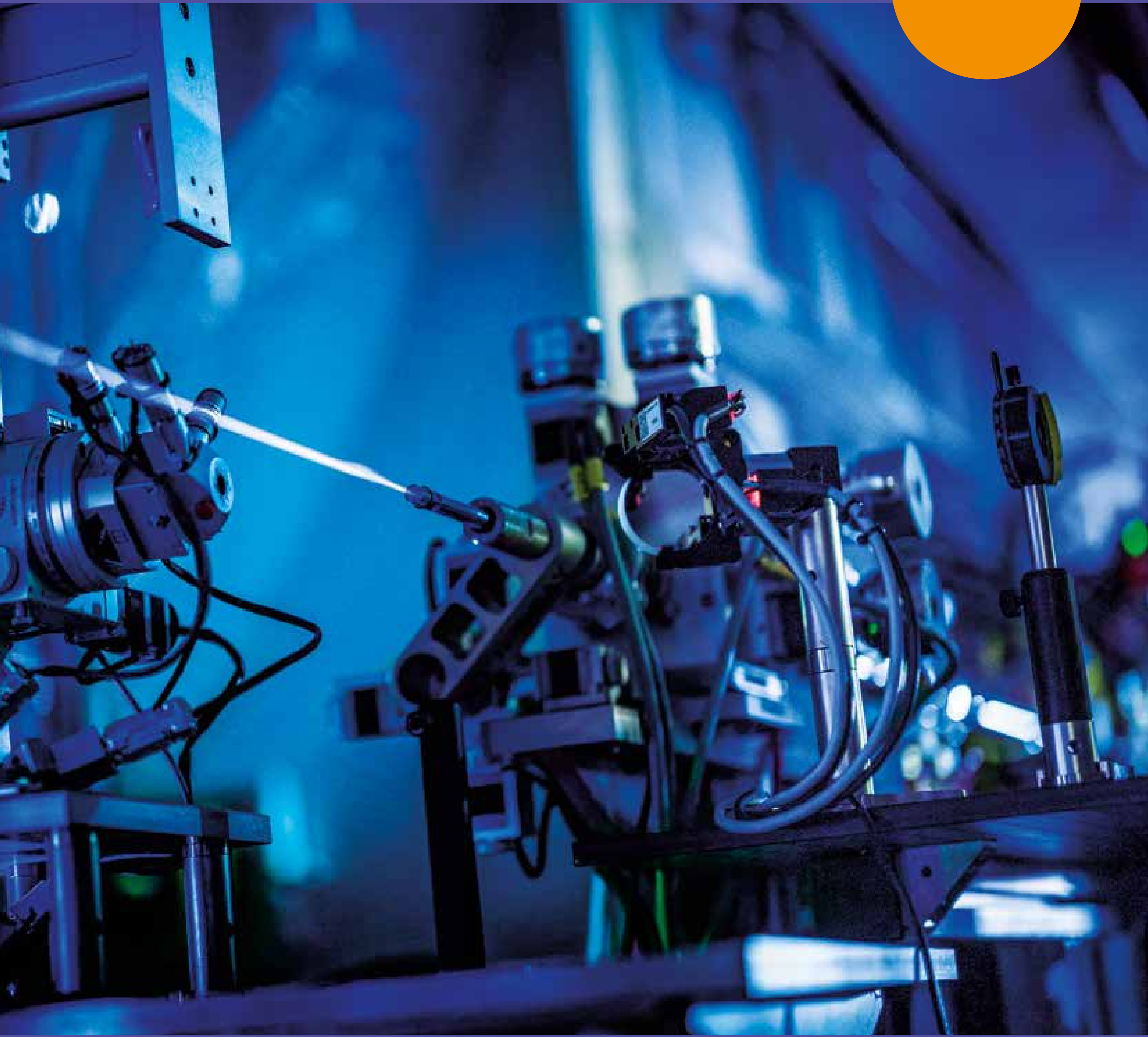
3D-printed
water sensors

Using gold to track
down diseases



The world's strongest X-ray laser beam

As the largest X-ray laser in the world, the European XFEL produces extremely strong X-ray light with which scientists can take pictures of molecules, for example. It is billions of times brighter than that of conventional X-ray sources, but as X-ray light is invisible to the naked eye, the beam cannot usually be seen. Working together with a professional photographer, scientists have now managed to capture an image of the intense X-ray laser beam, which is



Picture: European XFEL, Jan Hosan

generated in a 3.4-kilometre-long underground tunnel between DESY and the experimental hall in Schenefeld near Hamburg. This is possible because the X-ray beam causes the nitrogen in the air to glow when the molecules cross its path.

The principle is similar to that of a fluorescent tube, in which the high voltage applied causes the gas inside the tube to glow. Despite the extremely high intensity of the beam, the glow of the nitrogen is comparatively weak and would not be so easy to see with the naked eye. The beam only becomes as clearly visible as in the photograph in complete darkness and with an exposure time of 90 seconds. The picture was taken of a beam with a diameter of one millimetre, consisting of 800 X-ray flashes per second. Since nobody is allowed inside the experimental station during the experiments, the photographer operated the camera remotely from the adjacent control room.

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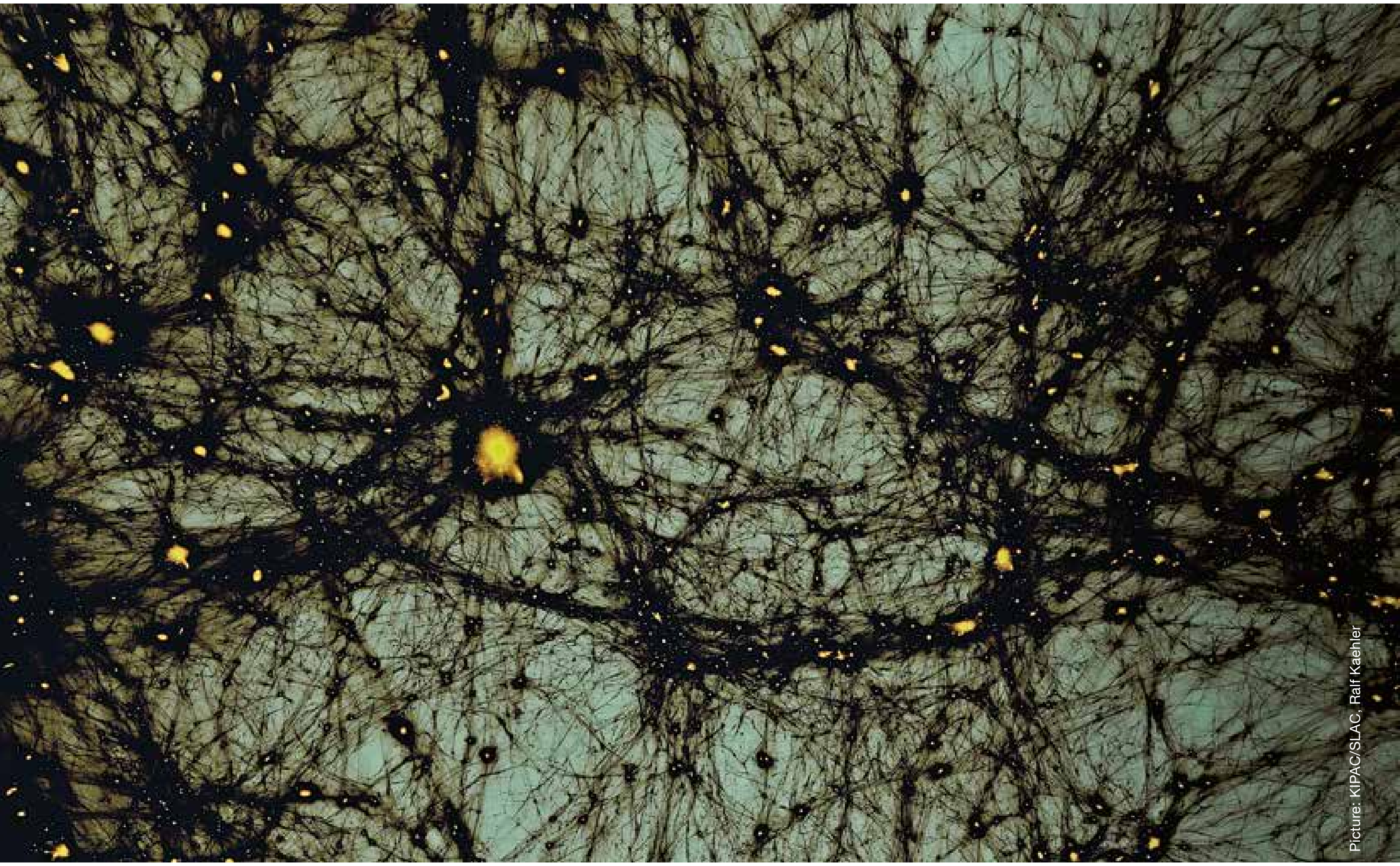
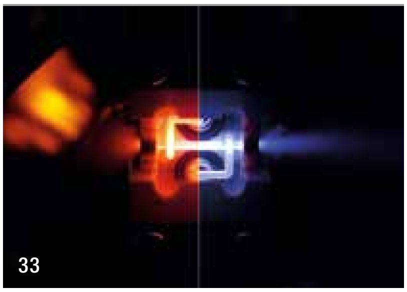

Picture: KIPAC/SLAC, Ralf Kaehler

ZOOM

DARK MATTER

Hunting for new particles

Physicists have been searching for the mysterious dark matter for many decades. As early as the 1930s, astronomers had been puzzled by a strange finding: Galaxy clusters held together even though they should actually fly apart. In addition to the visible celestial objects – stars, planets and clouds of dust – there must therefore be some kind of invisible matter whose gravity keeps the galaxies in check. But what is this ominous dark matter, without which it's almost impossible to explain how galaxies and galaxy clusters formed as the universe developed? Could it consist of still undetected, ultralight or extremely heavy elementary particles? And are black holes related to this phenomenon? Around the world, the search is on, and a new generation of experiments might soon be able to finally solve the mystery of dark matter.



CAMPUS

ZOOM

SPECTRUM

SECTIONS

Asteroids reveal the size of distant stars

Gamma telescope technique doubles resolution of astronomical angular size measurements

When an asteroid passes in front of a star, the resulting diffraction pattern (here greatly exaggerated) can reveal the star's angular size.

Picture: DESY, Lucid Berlin

Using the unique capabilities of gamma-ray telescopes, scientists have determined the diameter of distant stars. The measurements with the Very Energetic Radiation Imaging Telescope Array System (VERITAS) reveal the size of a giant star 2674 light years away and of a sun-like star at a distance of 700 light years. The study of the team led by Tarek Hassan from DESY and Michael Daniel from the Smithsonian Astrophysical Observatory (SAO) establishes a new method for astronomers to determine the diameter of stars and provides the smallest angular diameters of stars in the sky to date.

Almost any star in the night sky is too far away even for the best telescopes to determine its size directly. To overcome this limitation, the scientists used an optical phenomenon called diffraction to determine the stars' diameter. This effect, which illustrates the wave nature of light, occurs for example when an object such as an asteroid from our own solar system happens to pass in front of a distant star. "The incredibly faint shadows of asteroids pass over us every day," explains Hassan. "But the rim of their shadow isn't perfectly sharp. Instead, wrinkles of light surround the central shadow, like water ripples." This is a general optical phenomenon called a diffraction pattern and can be reproduced in any school lab with a laser hitting a sharp edge.

The shape of the diffraction pattern can reveal the angular size of the light source. However, unlike in the school lab, the diffraction pattern of a star occulted by an asteroid is very hard to measure. “These asteroid occultations are hard to predict,” says Daniel. “And the only chance to catch the diffraction pattern is to make very fast snapshots when the shadow sweeps across the telescope.” This way, astronomers have already measured the angular size of stars that were occulted by the moon. This method works right down to angular diameters of about one milliarcsecond, which is about the apparent size of a two-cent coin atop the Eiffel Tower in Paris as seen from New York.

Eyes for starlight

However, not many stars in the sky are that “big”. To resolve even smaller angular diameters, the team employed Cherenkov telescopes. These instruments normally watch out for the extremely short and faint bluish glow that high-energy particles and gamma rays from the cosmos produce when they encounter and race through Earth’s atmosphere. Cherenkov telescopes do not produce the best images. But thanks to their huge mirror surface, which is usually segmented in hexagons like a fly’s eye, and their powerful cameras, they are extremely sensitive to fast variations of light, including starlight.

> “This is the smallest angular size of a star ever measured directly”
>
> **Michael Daniel, SAO**

Using the four large VERITAS Cherenkov telescopes at the Fred Lawrence Whipple Observatory in Arizona, the team could clearly detect the diffraction pattern of the star TYC 5517-227-1 as it was occulted by the 60-kilometre asteroid Imprinetta on 22 February 2018. The VERITAS telescopes enabled the scientists to take 300 snapshots every second. From these data, the brightness profile of the diffraction pattern could be reconstructed with high accuracy, resulting in an apparent size, or angular diameter, of the star of 0.125 milliarcseconds. When combined with its distance of 2674 light years, this means that the star’s true diameter is eleven times that of our sun. This result categorises the star – whose class was ambiguous before – as a red giant star.

The researchers repeated the feat three months later on 22 May 2018, when asteroid Penelope with a diameter of 88 kilometres occulted the star TYC 278-748-1. The analysis revealed an angular size of 0.094 milliarcseconds, which at a distance of 700 light years corresponds to a true diameter of 2.17 times that of our sun. The result coincides perfectly with an earlier estimate, based on indirect methods, which had placed its diameter at 2.173 times the solar diameter.

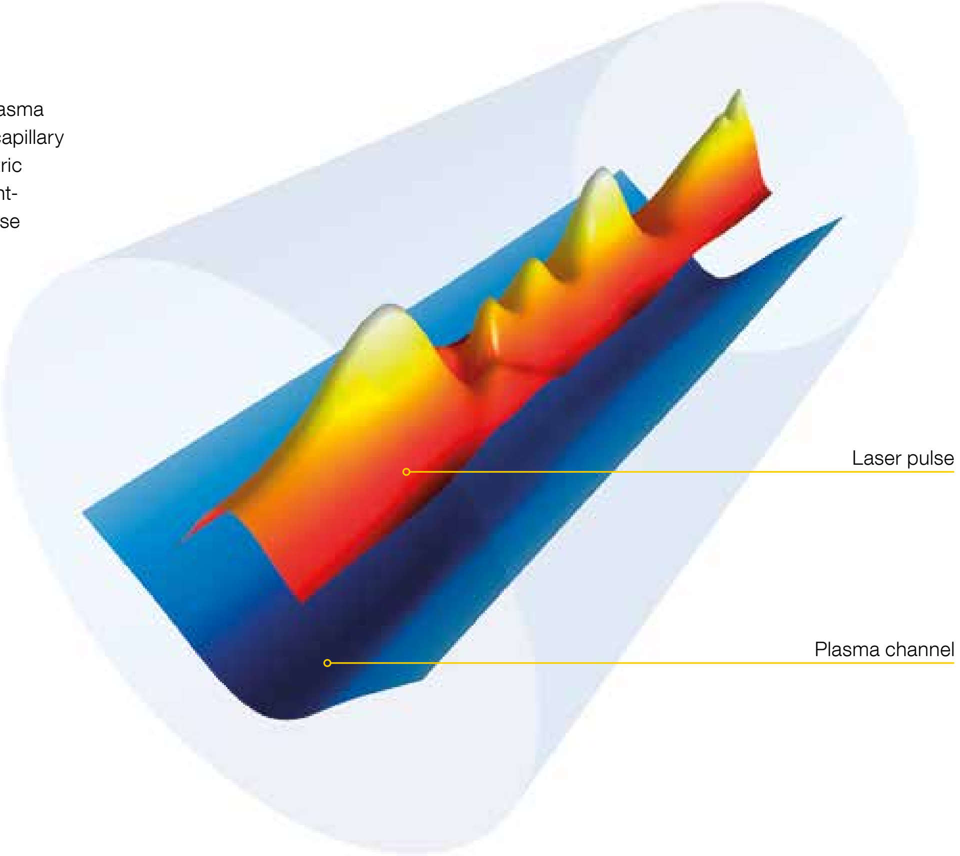
> “Our pilot study establishes a new method to determine the true diameter of stars”
>
> **Tarek Hassan, DESY**

“This is the smallest angular size of a star ever measured directly,” emphasises Daniel. “Profiling asteroid occultations of stars with Cherenkov telescopes delivers a ten times better resolution than the standard lunar occultation method. Also, it is at least twice as sharp as available interferometric size measurements.” According to the authors, the measurement uncertainty of the new method is currently about ten percent. “We expect this can be notably improved by optimising the setup, for example by narrowing the wavelength range of the colours recorded,” says Daniel. Since different wavelengths are diffracted differently, the measured pattern is smeared out if wavelengths from a too big range are recorded at the same time.

“Our pilot study establishes a new method to determine the true diameter of stars,” summarises Hassan. The scientists estimate that suitable telescopes could view more than one asteroid occultation per week. “Since the same star looks smaller the farther away it is, moving to smaller angular diameters also means extending the observation range,” explains Hassan. “We estimate that our method can analyse stars up to ten times as far away as the standard lunar occultation method allows.” The technique could deliver enough data to investigate a larger number of stars in so-called population studies.

Nature Astronomy, 2019;
DOI: 10.1038/s41550-019-0741-z

Artist's impression:
Visualisation of the plasma channel (blue) in the capillary generated by an electric discharge and an eight-nanosecond laser pulse (red/yellow)



Picture: Keldysh Institute of Applied Mathematics, Gennadiy Bagdasarov, and Berkeley Lab, Anthony Gonsalves/Jean-Luc Vay

A boost for plasma acceleration

Laser drill enables new world record

Wim Leemans, DESY's new director of the accelerator division, is an internationally renowned top scientist and a pioneer in the development of groundbreaking laser plasma accelerators. Prior to joining DESY in February 2019, he headed the accelerator technology and applied physics division at Berkeley Lab (California, USA) and the Berkeley Lab Laser Accelerator (BELLA) Center. Together with his team at Berkeley, he established important milestones for a novel generation of compact particle accelerators.

At the beginning of the year, the BELLA scientists set a new world record for plasma accelerators using a laser to "drill" through a plasma. In a plasma capillary only 20 centimetres long, they accelerated electrons to an energy of 7.8 billion electron volts (gigaelectronvolts, GeV), a value for which today's most advanced conventional particle accelerators require several hundreds of metres.

> *"This new technology opens up completely new possibilities, also for our work at DESY."*
>
> **Ralph Aßmann, DESY**

A plasma is a gas in which the molecules have been stripped of their electrons, creating a mix of positively charged gas molecules and negatively charged electrons. "The development of stable plasma acceleration with energies near 10 GeV is a milestone on the route from the lab to first applications," says Leemans, who plans to improve the method further at DESY. "We have developed a new concept in the toolbox, and together with other concepts for acceleration, beam stability and beam control existing at DESY, this will allow for compact electron sources."

Particle accelerators are indispensable tools in many areas, from science to industry and medicine. Conventional accelerators use radio waves to push bunches of electrically charged particles such as electrons forward faster and faster. The technique is very advanced and produces high-quality particle beams with almost any desired property. However, ever higher particle energies require ever larger and more expensive facilities.

Surfing on the plasma wave

Laser plasma acceleration – which is currently still experimental – is based on a completely different concept. It uses a short, extremely bright laser pulse that ploughs through a plasma. Like a speedboat on a lake, the laser pulse creates strong waves in its wake. The electrons can ride these plasma waves like a wakeboard surfer rides the waves in the wake of the speedboat. Plasma waves can accelerate particles hundreds of times more strongly than conventional accelerators. Although numerous challenges remain to be solved, the novel technique promises cheaper, drastically smaller particle accelerators and new applications.

The more powerful the laser pulse is, the stronger the acceleration in the plasma. The team at BELLA shot incredibly intense and short infrared laser pulses, each with a peak power of about 850 trillion watts (850 terawatts) and lasting just 35 quadrillionths of a second (35 femtoseconds), into a 0.8-millimetre-wide sapphire tube filled with hydrogen gas. The peak power of the laser is equivalent to lighting up about 8.5 trillion 100-watt light bulbs simultaneously, though only for tens of femtoseconds.

The clou of the technique was that a preceding laser pulse had first drilled a channel through the plasma for the actual accelerator pulse. This allowed the plasma acceleration to be maintained over the entire length of the capillary.

"This Berkeley Lab result, published in *Physical Review Letters*, is a milestone for laser plasma accelerators," comments Ralph Aßmann, leading scientist for accelerator research and development at DESY, who was not involved in the study. "This does not only establish a new energy record, but describes an innovative method that allows an average accelerating gradient of 40 billion volts per metre to be established in a robust setup over a distance of 20 centimetres. This new technology opens up completely new possibilities, also for our work at DESY."

While plasma accelerators cannot accelerate as many particles at once as conventional accelerators, they can enable new applications that were previously impossible, such as table-top X-ray lasers. "Our method is a major step forward towards future compact light sources," emphasises Leemans. "The time is here to bring laser plasma acceleration from the lab to application."

Physical Review Letters, 2019;
DOI: 10.1103/PhysRevLett.122.084801

Pictures: Berkeley Lab, Marilyn Chung; DESY, Werner Bartsch (portrait)

Wim Leemans, who was born in Belgium, moved to California early on in his career. He wrote his doctoral thesis in electrical engineering at the University of California Los Angeles, after which he worked at Berkeley Lab for 27 years. During this time, he established the laser accelerator programme at the lab and led it to international acclaim.

> *"The time is here to bring laser plasma acceleration from the lab to application"*
>
> **Wim Leemans, DESY**

A 20-centimetre plasma cell as used for the world record acceleration

Printable water sensors

X-ray investigation reveals functioning of highly versatile copper-based compound

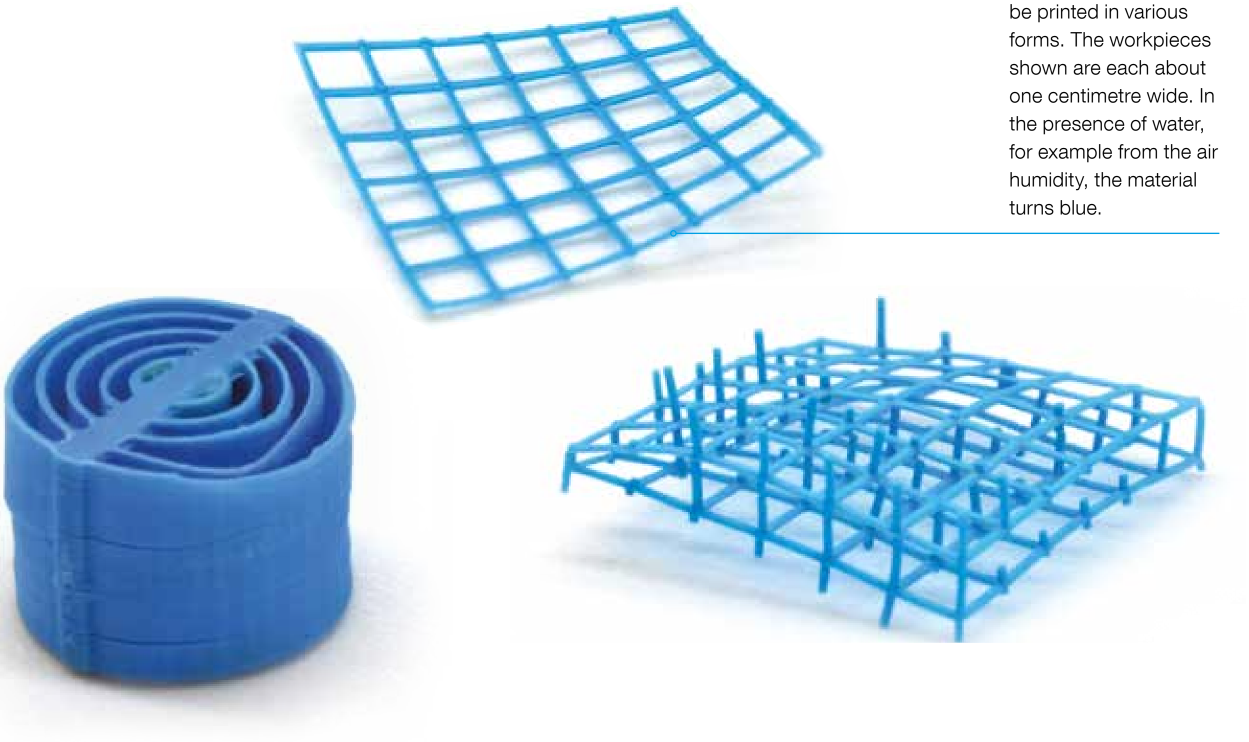
A new, versatile plastic-composite sensor can detect tiny amounts of water. The 3D-printable material, developed by a Spanish–Israeli team of scientists, is cheap, flexible and non-toxic and changes its colour from purple to blue in wet conditions. The researchers led by Pilar Amo-Ochoa from the Autonomous University of Madrid (UAM) used DESY's X-ray light source PETRA III to understand the structural changes triggered by water within the material, which lead to the observed colour change. The development opens the door to the creation of a new family of 3D-printable functional materials.

In many fields, from health to food quality control and environmental monitoring, there is a rapidly growing demand for sensors that show fast and simple changes in the presence of specific molecules. Water is among the most common chemicals to be monitored. "Understanding how much water is present in a certain environment or material is important," explains DESY scientist Michael Wharmby. "For example, if there is too much water in oils they may not lubricate machines well, whilst with too much water in fuel, it may not burn properly."

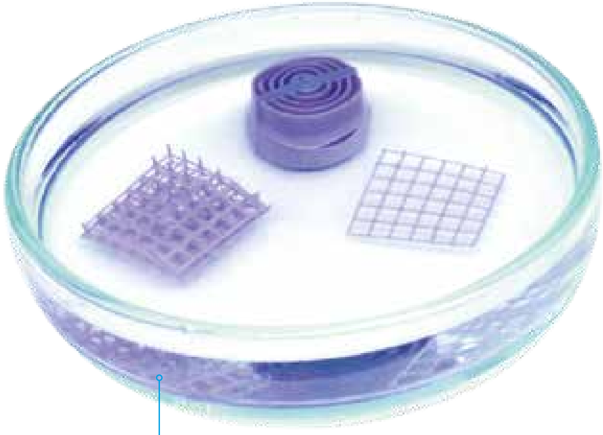
Colour change in the sensor

The functional part of the new sensor material is a so-called copper-based coordination polymer, an organic compound with a water

> *"The highly versatile nature of modern 3D printing means that these devices could be used in a huge range of different places"*
>
> **Shlomo Magdassi, The Hebrew University of Jerusalem**



The sensor material can be printed in various forms. The workpieces shown are each about one centimetre wide. In the presence of water, for example from the air humidity, the material turns blue.



When dried, for example in a water-free solvent, the sensor material turns purple.

DESY researcher Michael Wharmby is in charge of the experimental station at which the investigations took place.

molecule bound to a central copper atom. “On heating the compound to 60 degrees Celsius, it changes colour from blue to purple,” reports Pilar Amo-Ochoa. “This change can be reversed by leaving the material in air, immersing it in water, or putting it in a solvent with trace amounts of water in it.” Using high-energy X-rays from DESY’s research light source PETRA III, the scientists were able to see that in the sample heated to 60 degrees Celsius, the water molecules bound to the copper atoms were missing. This leads to a reversible structural reorganisation of the material, which is the cause of the colour change.

“Having understood this, we were able to model the physics of this change,” explains José Ignacio Martínez from the Institute for Materials Science in Madrid (ICMM-CSIC). The scientists were then able to mix the copper compound into a 3D printing ink and print sensors in several different shapes. They tested the printed sensors in air and with solvents containing different amounts of water.

These tests showed that the printed sensors are even more sensitive to the presence of water than the copper-based compound by itself, thanks to their porous nature. In solvents, the printed sensors were able to detect 0.3 to 4 percent of water in less than two minutes. In air, they could detect a relative humidity of only 7 percent.

If the material is dried, either in a water-free solvent or by heating, it turns back to purple. A detailed investigation showed that the material is stable even over many heating cycles and that the copper compounds are evenly distributed throughout the printed sensors. In addition, the material is stable in air over at least one year and also at biologically relevant pH ranges from 5 to 7.

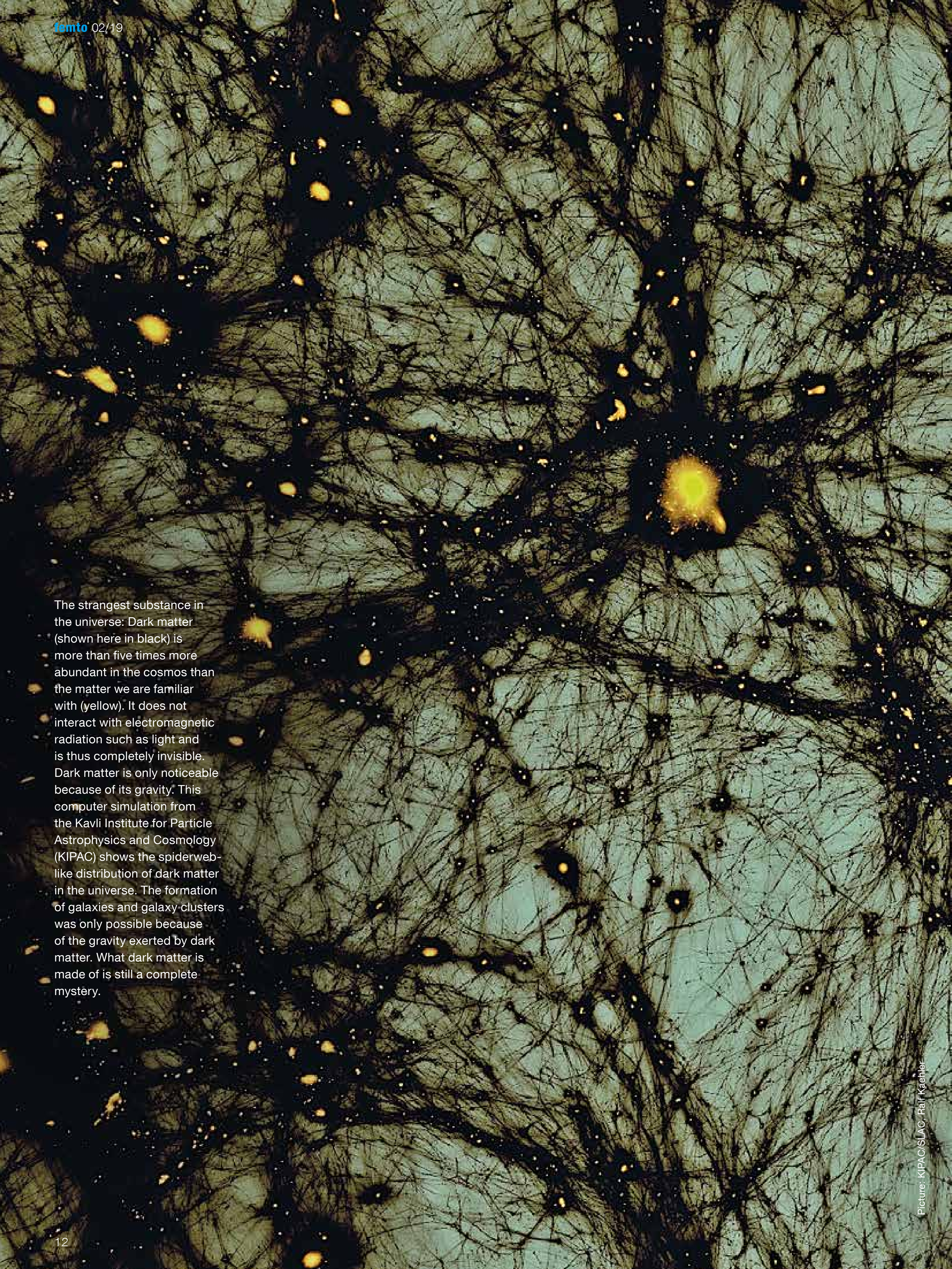
> *“Understanding how much water is present in a certain environment or material is important. For example, if there is too much water in oils they may not lubricate machines well”*
>
> **Michael Wharmby, DESY**

“Furthermore, the highly versatile nature of modern 3D printing means that these devices could be used in a huge range of different places,” emphasises Shlomo Magdassi from The Hebrew University of Jerusalem. He adds that the concept could be used to develop other such functional materials as well.

“This work shows the first 3D-printed composite objects created from a non-porous coordination polymer,” says Félix Zamora from the Autonomous University of Madrid. “It opens the door to the use of this large family of compounds that are easy to synthesise and exhibit interesting magnetic, conductive and optical properties, in the field of functional 3D printing.”

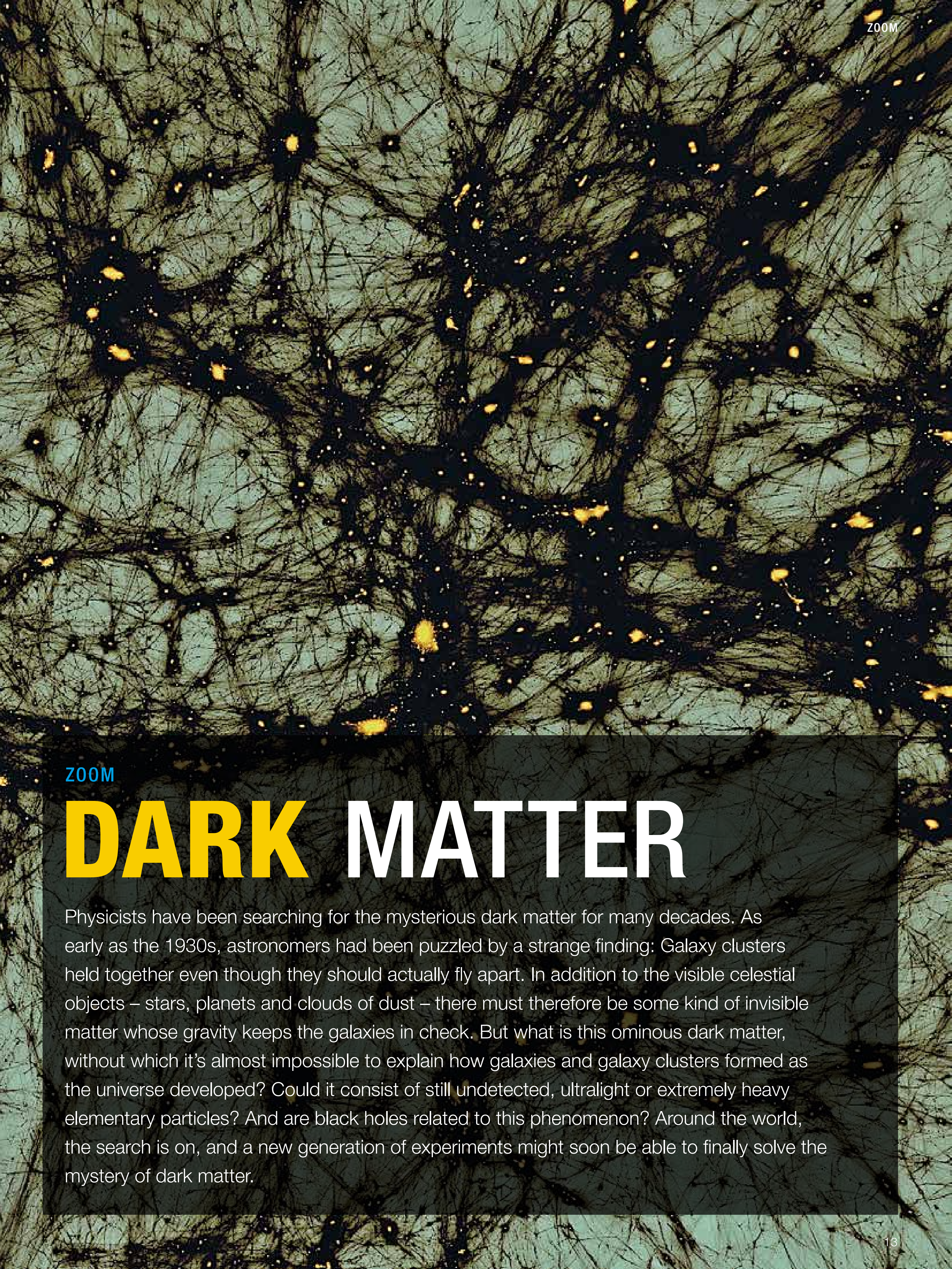
Advanced Functional Materials, 2019;
DOI: 10.1002/adfm.201808424

Pictures: TUAM, Verónica García Vegas



The strangest substance in the universe: Dark matter (shown here in black) is more than five times more abundant in the cosmos than the matter we are familiar with (yellow). It does not interact with electromagnetic radiation such as light and is thus completely invisible. Dark matter is only noticeable because of its gravity. This computer simulation from the Kavli Institute for Particle Astrophysics and Cosmology (KIPAC) shows the spiderweb-like distribution of dark matter in the universe. The formation of galaxies and galaxy clusters was only possible because of the gravity exerted by dark matter. What dark matter is made of is still a complete mystery.

Picture: KIPAC/SLAC, Ralf Kaehler



ZOOM

DARK MATTER

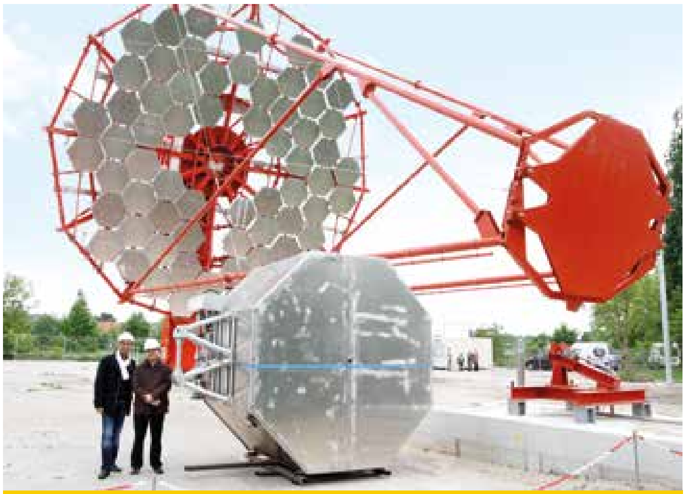
Physicists have been searching for the mysterious dark matter for many decades. As early as the 1930s, astronomers had been puzzled by a strange finding: Galaxy clusters held together even though they should actually fly apart. In addition to the visible celestial objects – stars, planets and clouds of dust – there must therefore be some kind of invisible matter whose gravity keeps the galaxies in check. But what is this ominous dark matter, without which it's almost impossible to explain how galaxies and galaxy clusters formed as the universe developed? Could it consist of still undetected, ultralight or extremely heavy elementary particles? And are black holes related to this phenomenon? Around the world, the search is on, and a new generation of experiments might soon be able to finally solve the mystery of dark matter.

BIRTH OF THE UNIVERSE

10^{-32} seconds	1 second	100 seconds	380 000 years	300–500 million years	Billion years	13.8 billion years
Inflation: The very young universe expands very rapidly in a short span of time.	Light and matter first appear.	Light and matter are coupled. Dark matter develops independently: It begins to clump together and to form a web-like structure.	Light and matter decouple: Protons and electrons create atoms, and light can propagate freely. The ubiquitous cosmic microwave background radiation arises at this time (see picture on the right).	After the decoupling of light and matter, there are no stars yet. However, the atoms of the matter we are familiar with begin to feel the effects of the web of dark matter. After 300 to 500 million years, the first stars and galaxies begin to shine at the densest knots of this web.	Galaxies continue to develop.	Today’s universe

Picture: European Space Agency (ESA)

“We’re in luck. It’s cloudy.” After a brief look up at the sky, Markus Garczarczyk opens a metal door that leads into a small tower. Inside, the researcher taps on a touchscreen, and the tower resounds with the buzzing of powerful electric motors. The motors are raising what is mounted on the tower – a 60-tonne reflecting telescope with a diameter of 12 metres. “If the sky had been clear, we’d have had to leave the telescope in its parking position,” says Garczarczyk. “On clear days, the reflector would focus the sunlight so strongly that it would damage the device.”



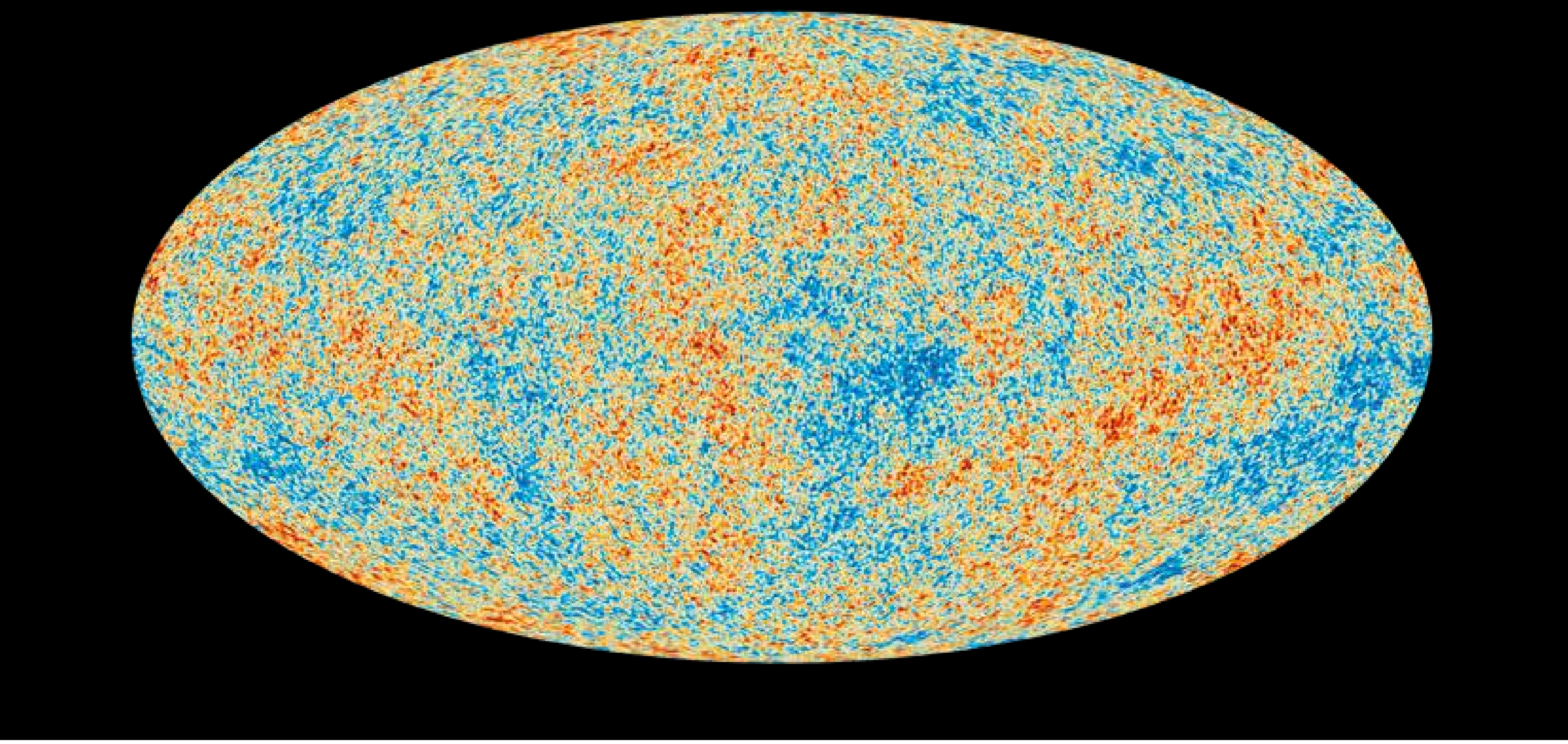
The prototype of the mid-sized-telescopes of the Cherenkov Telescope Array (CTA) has been in operation at the Adlershof Science Park in Berlin since 2013.

Picture: DESY

The heavy telescope is located on the edge of the Adlershof Science Park in Berlin. It’s a prototype for a new major international astronomy project: the Cherenkov Telescope Array (CTA). “It will consist of about 100 individual telescopes and search for gamma rays from space,” says Garczarczyk, a physicist at DESY in Zeuthen, which is one of the main operators of CTA. Gamma rays are the electromagnetic waves with the highest energies. Their sources include violent cosmic processes such as supernova explosions and stellar collisions. Gamma rays might also help us to solve one of the biggest riddles of physics: What is the composition of the ominous dark matter that seems to hold galaxies together like some kind of invisible glue?

As early as the 1930s, astronomers had been puzzled by a strange finding: Galaxy clusters held together even though they should actually fly apart. Later, in the 1970s, a team from the USA found out that stars orbiting the centre of a galaxy are moving so rapidly that they should actually be catapulted out. Their conclusion was that in addition to the visible celestial objects – stars, planets and clouds of dust – there must also be some kind of invisible or “dark” matter. The gravity of this matter keeps the stars in a galaxy in check and has prevented our Milky Way, for example, from drifting apart long ago.

There is also other evidence for the existence of this enigmatic substance. For



The cosmic microwave background radiation arose 380 000 years after the big bang and is still billowing through the universe. Small temperature fluctuations such as those measured by the European satellite "Planck" served as the seeds of future structures such as galaxy clusters.

example, it seems as though dark matter deflects the light of distant galaxies slightly in what the experts call the gravitational lensing effect. Cosmic microwave background radiation – the "echo" of the big bang – also contains clues to its existence. What's more, without dark matter, it would be almost impossible to explain how galaxies and galaxy clusters formed as the universe developed.

Helping to give birth to galaxies

Today, cosmologists assume that the universe was born in a great explosion – the big bang – out of a tiny point around 13.8 billion years ago. "There were probably tiny quantum fluctuations right after the big bang, when the cosmos was still extremely small," explains Kai Schmidt-Hoberg, a theoretician at DESY. "Driven by these fluctuations, gravity may have caused dark matter to contract and form the first structures in the universe: filament-like concentrations that, in computer simulations, look like the web of nerve cells in the brain." The gravitational force of this web subsequently attracted normal matter, which clumped together and formed celestial bodies – dark matter has helped to give birth to galaxies.

The striking aspect of this theory is that it only works if we assume that there is about five times as much dark matter as visible matter. And there's yet another mystery. In the 1990s, astronomers discovered that the universe is expanding much faster than expected. A mysterious force seems to be literally driving it apart. The experts have since then postulated a "dark energy" that seems to constitute about 68 percent of the universe. Dark matter accounts for another 27 percent, and only a minuscule five percent of the universe consists of the familiar visible matter that we and our surroundings are made of.

The problem is that in spite of decades of searching, nobody knows what dark matter consists of. Theoreticians have proposed a variety of new elementary particles, some of which are ultralight, while others are extremely heavy. Other scientists think that black holes are the cause. Still others assume that something is wrong with one of the basic equations of physics: Isaac Newton's law of gravitation. "There are many candidates at the moment – almost too many," says Schmidt-Hoberg. "That's one of the reasons why it's so hard to find out what dark matter actually is."

> *"There are many candidates at the moment – almost too many"*
>
> **Kai Schmidt-Hoberg, DESY**

All over the world, the search is being conducted on a broad front. Particle accelerators are specifically trying to create dark matter. Highly sensitive detectors installed deep inside

››

Pictures: European Space Agency (ESA) and the Planck Collaboration; DESY (portrait)

The Large Underground Xenon Experiment (LUX) was located at a depth of 1500 metres in an old mine in South Dakota. It tried to directly capture particles called WIMPs (see right). Its successor, the LUX-Zeplin experiment, will be the most sensitive WIMP detector in the world.

By contrast, physicists at the world's largest particle accelerator, the Large Hadron Collider (LHC) at the European particle physics centre CERN near Geneva, are trying to directly create WIMPs in high-energy collisions.

The XENON1T detector, located around 1400 metres beneath Italy's Gran Sasso mountain massif, has been searching for WIMPs since 2016. It hasn't seen anything yet, but its exclusion limits are more precise than those previously set by LUX.

mountains are on the lookout for the mysterious particles. Various kinds of telescopes are directed at the sky in search of clues. Another offensive will be launched in the years ahead, when scientists will make the next attempt with a new generation of instruments.

> “WIMPs fit in very well with our current cosmological view”

Joachim Mnich, director of particle physics at DESY

Searching for clues with the LHC

Many experts favour a special class of elementary particles called WIMPs (weakly interacting massive particles). These are relatively heavy compared to many other particles. WIMPs could weigh as much as a carbon atom, a uranium nucleus or even a small protein. Largely ignored by the rest of the universe, they would travel in vast numbers through space. They would only sporadically interact with normal matter, but would become noticeable on a large scale because of their gravitational force

“WIMPs fit in very well with our current cosmological view,” says Joachim Mnich, director of particle physics at DESY. “Furthermore, some theories predict that particles with precisely such properties should exist.” The most widespread of these theories is probably supersymmetry, or SUSY for short. If it is correct, it would solve certain theoretical problems of particle physics and explain why the gravitational force is so weak, for example. As a byproduct, it would also supply promising candidates for dark matter, such as the neutralino, which could be produced by the world's largest particle accelerator, the LHC at CERN near Geneva, Switzerland. The strategy is to make particles of normal matter (in this case protons) collide with one another as forcefully as possible in the hope that some dark matter will be produced as a result.

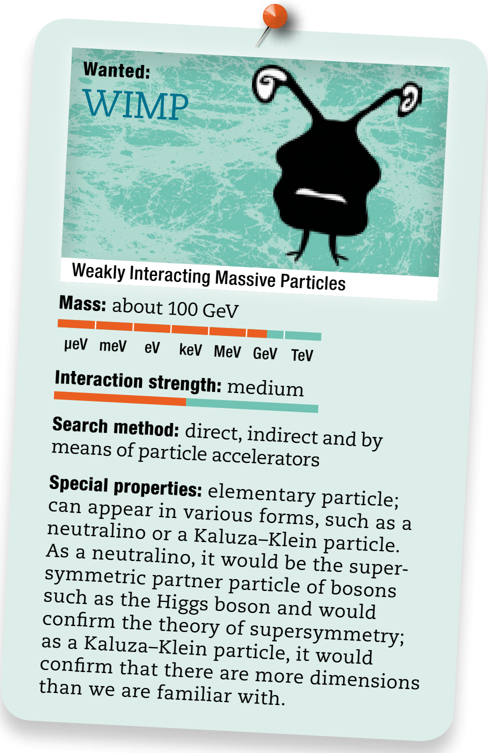
The LHC has been recording such collisions since 2010, but it has not found any traces of SUSY particles to date. Does this mean the theory can be written off? “By no means,” says Mnich. “We are continuing to pursue it.” To the scientists' chagrin, the theory of supersymmetry doesn't say anything about how heavy such SUSY particles could be, thus forcing physicists to conduct their search largely in the dark. “That's why it's worthwhile to continue the search for these particles,” Mnich says. “In order to maximise the chances of finding anything, however, we have to observe as many collisions as possible.”

This should be possible beginning in 2026, when an upgrade of the LHC will enable five times as many protons to collide in the 27-kilometre ring than was previously the case. That would greatly increase the likelihood of a discovery.

But even if the Geneva accelerator produces enough dark matter particles, it would be difficult to detect them. “These particles are practically invisible,” says DESY physicist Sarah Heim, who heads a Helmholtz young investigator group. “They interact so weakly with matter that the LHC detectors, such as our ATLAS detector, are unable to catch them.”

The scientists are therefore resorting to a trick: They analyse the momentum of the particles that the detectors have measured.

Pictures: Lawrence Berkeley National Laboratory; CERN; XENON1T Collaboration; DESY (portrait)



Wanted:
WIMP

Weakly Interacting Massive Particles

Mass: about 100 GeV

Interaction strength: medium

Search method: direct, indirect and by means of particle accelerators

Special properties: elementary particle; can appear in various forms, such as a neutralino or a Kaluza–Klein particle. As a neutralino, it would be the supersymmetric partner particle of bosons such as the Higgs boson and would confirm the theory of supersymmetry; as a Kaluza–Klein particle, it would confirm that there are more dimensions than we are familiar with.

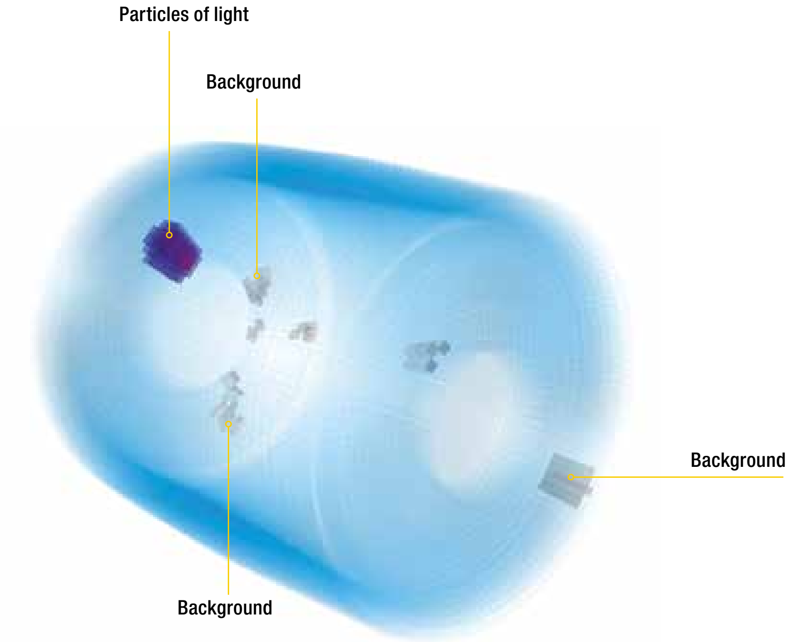
Their sum has to be exactly as large as the momentums of the original collision partners. In effect, it's a zero-sum game. "If we should measure a significant deviation, it would mean that the missing momentum was carried off by an invisible particle – perhaps one made of dark matter," says Heim.

> *"These particles are practically invisible"*
>
> **Sarah Heim, DESY**

So far, the scientists have been unable to find any dark matter. "However, we can now exclude some ranges within certain models," says Heim. As a result, the researchers know where they no longer have to look. But what if even the upgraded LHC is unable to find any dark matter after 2026? The research community would then pin its hopes on an even bigger accelerator, for which CERN is currently drawing up plans. "A larger ring with a circumference of perhaps 100 kilometres could generate substantially heavier particles," says Heim. "It would increase the likelihood that we could finally find SUSY particles or other dark matter candidates." ››

ATLAS is the biggest detector that has ever been built at a particle accelerator. Together with the CMS detector, also at the LHC, it discovered the Higgs boson. The universal detector is also searching for particles of dark matter.

Pictures: CERN; DESY (portrait)



A simulated dark matter event in the Belle II detector. The red and blue cluster was created by a particle of light. The simulated dark matter particle itself is invisible and has exited the detector on the opposite side.

> *“That would at least provide indirect evidence for the existence of dark matter”*
>
> **Torben Ferber, DESY**

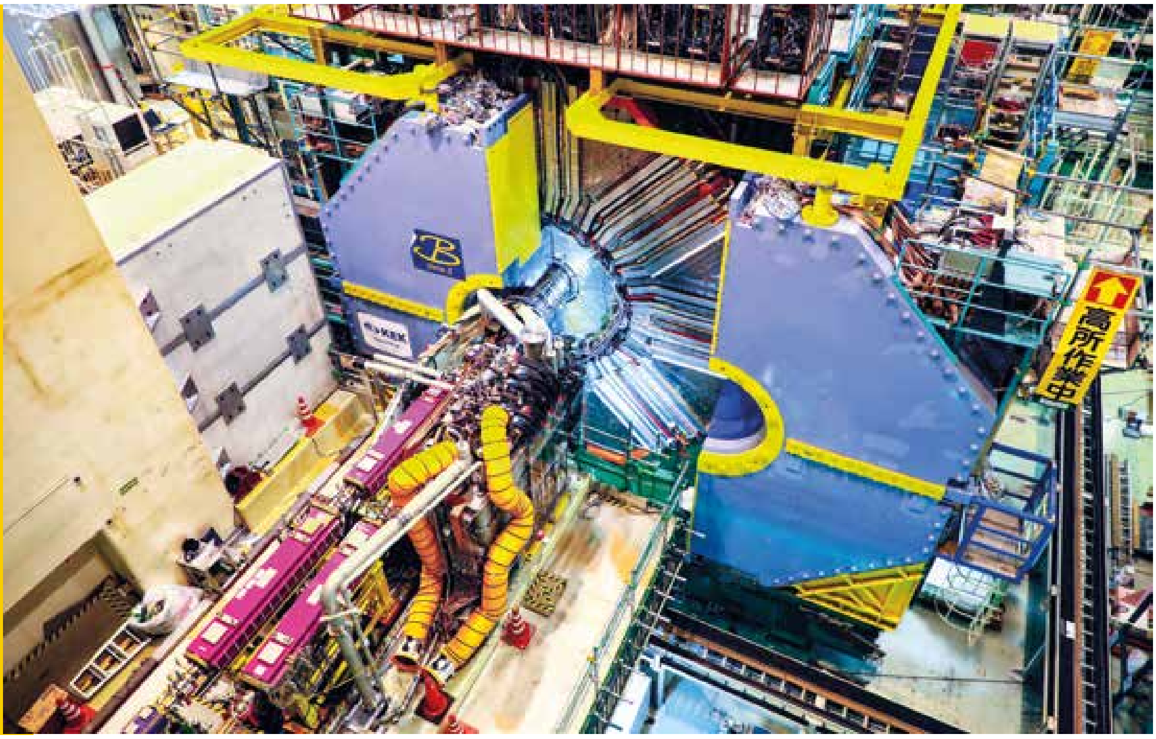
Hunting for dark matter in Japan

Torben Ferber, the head of another Helmholtz young investigator group at DESY, is also using an accelerator to look for the exotic particles. Instead of the LHC, however, he’s trying his luck with a new, smaller facility, called SuperKEKB, which was recently put into operation in Japan. This accelerator has a circumference of three kilometres and, unlike the Geneva giant, it fires electrons and their antiparticles, positrons, at one another rather than protons. The collision energy is chosen in such a way that a ϒ particle is created. This particle immediately decays after it has been created, forming two B mesons.

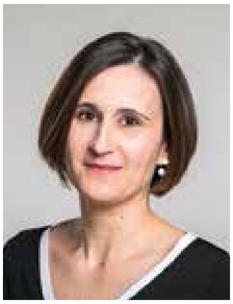
“That’s why we also refer to the facility as a B factory,” says Ferber. “Collisions here are much cleaner than at the LHC, enabling us to make very precise measurements.” Another advantage is that the Japanese accelerator shoots extremely large numbers of particles at one another. As a result, it produces huge amounts of measurement data, thus further increasing precision. “We record 30 000 events per second,” says Ferber. “At the scheduled end of the project, we’ll have 50 times more data than we gained from the predecessor experiment.”

The official experimentation programme began in April. Part of it is devoted to the search for dark matter. “We’re trying to create it directly,” says Ferber. “We’re looking for relatively light particles that are about as heavy as a proton.” In order to track down these exotic particles, the scientists are watching for a certain signal in

During its operation from 1999 to 2010, the Belle detector registered almost 800 million pairs of B mesons. Its successor, Belle II (right), is expected to record around 40 billion pairs. The detector at the Japanese particle accelerator SuperKEKB is around 7 metres tall and 7.5 metres long.



Pictures: KEK; Belle II Collaboration (graphic)



Federica Petricca heads the CRESST group at the Max Planck Institute for Physics in Munich.

their Belle II detector. This signal would consist of a brief flash of light – and nothing more. However, dark matter might also act behind the scenes, as it were, by affecting the decay of the ϒ particles, thus causing tiny deviations in the measurement data. “That would at least provide indirect evidence for the existence of dark matter,” says Ferber.

The cave detectors

Another class of experiments doesn’t need any accelerators. Instead, it uses detectors that can directly catch the roaming dark matter particles. These detectors are located in special places: labs that have been dug deep into mountains. “That way the detectors are protected against the ubiquitous cosmic rays, which otherwise would interfere with the sensitive measurements,” says Federica Petricca from the Max Planck Institute for Physics in Munich. Petricca is the spokesperson of an experiment called CRESST, which is buried 1400 metres underground in the Gran Sasso Laboratory in Italy.

> *“Because we’re looking for very rare and weak events, we have to understand our experiment down to the last detail”*
>
> **Federica Petricca , Max Planck Institute for Physics**

The principle behind it is as follows: If a dark matter particle hits the detector, it could collide with one of the atomic nuclei. The resulting recoil would reveal itself in the detector as a tiny input of heat. “To measure it, we have to operate CRESST at extremely low temperatures – ten millikelvin, or ten thousandths of a degree above absolute zero,” Petricca explains.

The detector material consists of ten crystals of calcium tungstate. Each crystal weighs 25 grams and is a little bigger than a sugar cube. In order to protect them from the natural radioactivity of the surrounding rock, the intensely cooled crystals are located behind thick protective layers of polyethylene, lead and copper. “Because we’re looking for very rare and weak events, we have to understand our experiment down to the last detail,” emphasises Petricca.

The Cryogenic Rare Event Search with Superconducting Thermometers (CRESST) experiment is located 1400 metres beneath Italy’s Gran Sasso mountain massif, where it searches for tiny temperature fluctuations that can be triggered by the rare collision of a dark matter particle. Work on the central detector part must be conducted under cleanroom conditions.

CRESST has been waiting to catch dark matter for years. “We haven’t found anything yet,” says Petricca. “However, we’ve managed to exclude a certain mass range.” The CRESST team is now planning to expand its detector from ten to as many as 100 modules next year. This should significantly increase its measurement sensitivity, similar to other planned detectors of this kind, such as XENON1T, LUX-Zeplin and SuperCDMS.

››

Wanted:

FIMP

Feebly Interacting Massive Particles

Mass: in the GeV range

Interaction strength: extremely weak

Search method: very hard or even impossible to detect because of its weak interaction with the rest of the universe. The XENON1T experiment in Italy would have a small chance of directly discovering it.

Special properties: extremely shy particle

Pictures: MPI for Physics, A. Eckert

Cherenkov telescopes such as the planned CTA look for the faint blue flashes of “air showers” in the Earth’s atmosphere. These are cascades of particles triggered by high-energy atomic nuclei and gamma quanta from space as they collide with molecules in the atmosphere. The observation of this Cherenkov radiation enables scientists to reconstruct the direction a gamma quantum came from.

Picture: DESY, Science Communication Lab

Our home galaxy, the Milky Way, is probably surrounded by a halo of dark matter, shown in blue in this artistic rendition. However, measurements indicate that there might not be any significant amounts of dark matter around our sun.

Signals from the night sky

Scientists at DESY in Zeuthen are pursuing a different strategy. They will use a network of reflecting telescopes called CTA, which is scheduled to begin looking for gamma rays from outer space in a few years. The principle behind it is as follows: If a high-energy flash of gamma rays strikes the atmosphere of the Earth, it triggers a cascade of particles. These particles, in turn, cause flashes of blue light known as Cherenkov radiation, which are captured by several telescopes distributed over a large area. The measurement data can then be used to reconstruct where the gamma-ray flash came from and how much energy it contained.

> *“Dark matter particles could also produce gamma rays”*
>
> **Gernot Maier, DESY**

“Dark matter particles could also produce gamma rays when they decay or annihilate one another in a collision,” says DESY physicist Gernot Maier. “If this is the case, we should see especially large numbers of gamma-ray flashes in areas of the sky where there is a concentration of dark matter.” This could be the case in the centre of our galaxy, for example. Unfortunately, this area is anyway very active in the gamma range, and that could make signals due to dark matter hard to detect.

That’s why the scientists also want to look at dwarf spheroidal galaxies, which are small companions of the Milky Way. They produce almost no new stars, making them a kind of galactic retirement home. “From an astrophysics standpoint, they’re very boring,” says Maier. “But that’s precisely why they are promising contenders for detecting dark matter.” That’s because there’s very little interference going on in such dwarf galaxies. If gamma-ray flashes were discovered there, they would probably be caused by dark matter.

Gamma-ray telescopes could also find evidence for other dark matter candidates, including the traces of primordial black holes. These black holes must have originated during the time right after the big bang and are much smaller than the black holes caused by the collapse of dying stars. “Stephen Hawking found out that black holes could evaporate and become smaller and smaller over time,” explains Maier. “Just before the end of their lives, they could become so hot that they emit gamma rays. We’re watching for these signals.”

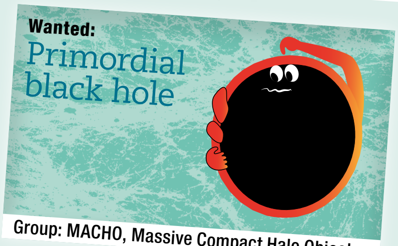
CTA could also be receptive to another class of candidates known as WISPs (see “Smart upcycling”, page 26). Scientists hope that these extremely light particles could reveal themselves through certain properties in the energy spectrum. “We can’t see this with our current telescopes,” says Maier’s colleague Elisa Pueschel. “However, CTA might enable us to do just that.”

There are already three gamma-ray observatories on Earth: VERITAS in Arizona, MAGIC on the Canary Islands and H.E.S.S. in Namibia. But whereas these observatories consist ››

Gernot Maier heads the CTA group at DESY.

Wanted:

Primordial black hole



Group: MACHO, Massive Compact Halo Objects

Mass: extremely massive; ranging from the mass of Mount Everest to that of the sun

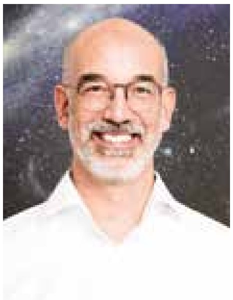
µeV meV eV keV MeV GeV TeV

Interaction strength: gravitational, i.e. only by means of gravity – very weak

Search method: with telescopes using the gravitational lensing effect; with gravitational-wave detectors upon black hole merger; with gamma-ray telescopes upon black hole annihilation.

Special properties: must have been created very early in the history of the universe. The only candidate that is not an elementary particle.

Pictures: ESO, L. Calçada, CC BY 4.0; DESY



Christian Stegmann is director of astroparticle physics at DESY.

of no more than five individual telescopes, CTA will encompass around 100. The biggest of them will have mirror diameters of 23 metres. They will be supplemented by small- and mid-sized telescopes specialising in different energy ranges. To ensure that the entire sky is covered, CTA will be set up at two locations: a smaller one on the Canary Island of La Palma and a larger one in the southern hemisphere, on an area the size of 100 football pitches in Chile.

"I expect to see a revolution in our worldview, because CTA will enable us to see everything ten times better than with our current telescopes," says Christian Stegmann, the director of DESY's new astroparticle physics division, which was established in early 2019. DESY is closely involved in the CTA project, of which it owns 25 percent. "Among other things, we are responsible for developing the cameras for the small telescopes and the control software," says Stegmann. "In addition, DESY in Zeuthen will become the home of the Science Data Management Centre. Plans are already being drawn up for the new building." DESY is also playing the leading role in the construction of the 40 mid-sized telescopes.

> *"I expect to see*
> *a revolution*
> *in our worldview"*
>
> **Christian Stegmann, DESY**

As a precautionary measure, Markus Garczarczyk has put the Adlershof prototype back into its secure parking position, because the sun is becoming visible through the clouds. He points to the 12-metre reflector, which looks a bit like an oversized shaving mirror. However, the reflector isn't made of just one piece. Instead, it consists of dozens of individual mirrors, which cost 2500 euros each, arranged in a honeycomb structure that focuses the light on a special camera 16 metres away. "We're going to make more than 4000 of these mirrors in total," says Garczarczyk. "They have to be mass-produced, because that's the only way it can be done in an acceptable amount of time."

The prototype went into operation in 2013. Since then, the researchers have cooperated with international partners to prepare the telescope for series production, reduce costs and eliminate faults. "We've conducted countless tests with the mirrors and tried out various versions," says Garczarczyk. He points to a storage area in the corner: "Over there are old mirrors, some of which were broken during the tests." The first telescopes will soon be built on La Palma, followed later on by those in Chile. The majority of the telescopes are scheduled to be completed in 2025, when they will, among other things, begin to search for the gamma-ray traces of dark matter.

The search at the South Pole

Another kind of telescope is located at a very exotic place: the South Pole. This instrument, called IceCube, lies in wait for neutrinos – very volatile "ghost" particles from space that can provide information about distant violent processes. Very occasionally, a neutrino will collide with an atomic nucleus in the three-kilometre-thick ice cap. Such collisions create

Wanted:

Axion

Group: WISP, Weakly Interacting Slim Particles

Mass: between 0.1 and 1 meV

μeV meV eV keV MeV GeV TeV

Interaction strength: extremely weak

Search method: e.g. using ALPS II at DESY

Special properties: can go through a wall and turn into light in a magnetic field. Originally not conceived as a dark matter particle, would thus kill two physics problems with one stone.

Wanted:

Gravitino

Group: SUSY, Supersymmetric Particles

Mass: in the GeV to TeV range

μeV meV eV keV MeV GeV TeV

Interactions strength: extremely weak

Search method: very hard to detect because of its weak interaction with the rest of the universe. However, it might very slowly decay into particles of light and neutrinos. This decay could be detected by gamma-ray telescopes.

Special properties: supersymmetric partner particle of the graviton

Picture: DESY

Markus Ackermann
is a neutrino astronomer
at DESY.

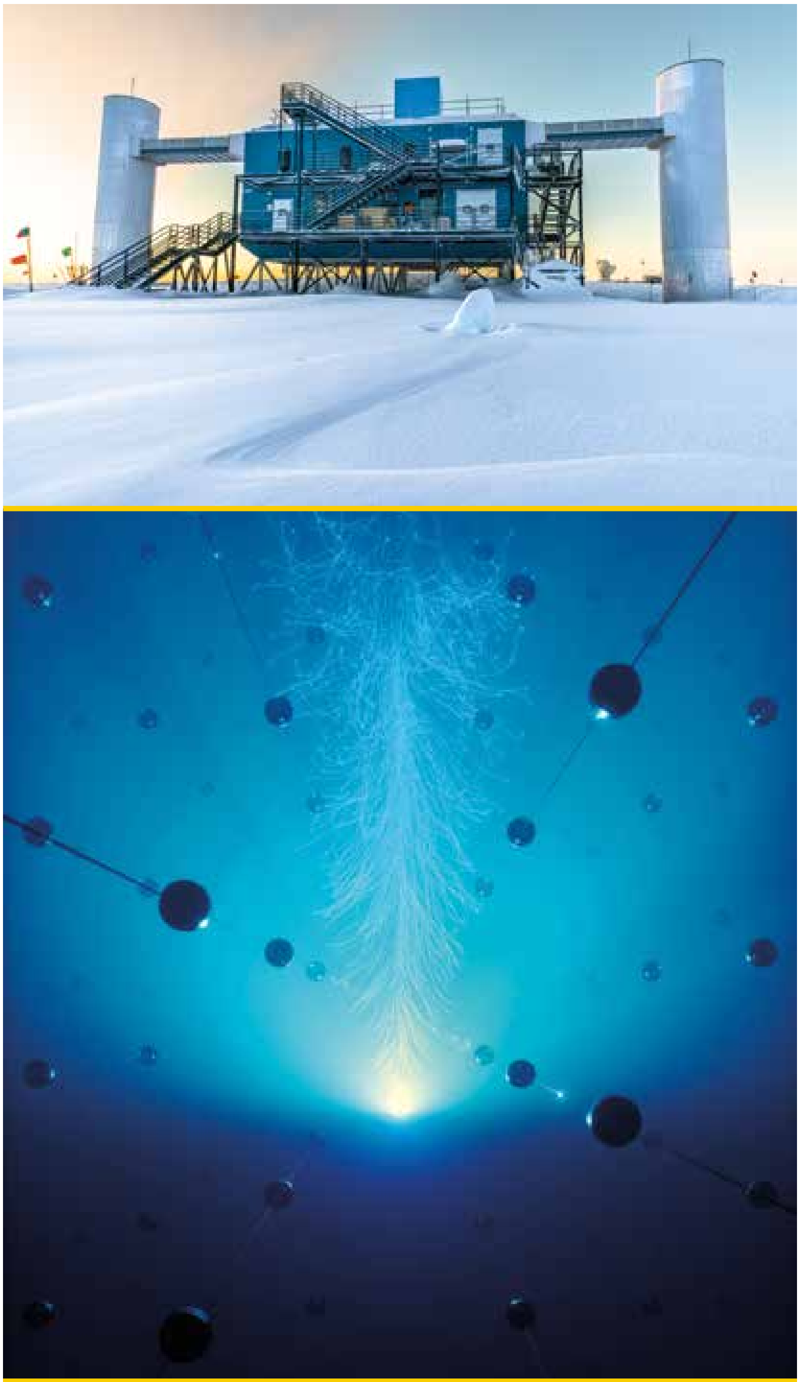
a faint blue light that propagates unimpeded through the ice. The ice contains 5000 basketball-sized special sensors, which are distributed over a volume of one cubic kilometre in order to catch the light signals.

Under certain circumstances, IceCube might be able to capture evidence of dark matter. Theoreticians think it's possible that dark matter accumulates in the interior of the sun. "The dark matter particles could decay there," says DESY physicist Markus Ackermann. "And the only particles created in this process that could emerge from the sun would be neutrinos." Although the scientists haven't found anything yet, they have already been able to narrow down certain properties of dark matter candidates. "Such measurements can only be made with a neutrino telescope," says Ackermann.

Another possibility is that somewhere in the universe, extremely heavy dark matter particles are decaying into neutrinos, which could be detected in the clear ice of Antarctica. "At the moment it doesn't look as though such particles exist," says Ackermann. "However, they might reveal themselves in the long term through a special spectrum." Last but not least, the IceCube team is searching for indications of a new type of neutrino, the "sterile neutrinos". They would interact with matter even more weakly than normal neutrinos and would actually only be perceptible as a result of their gravitational force.

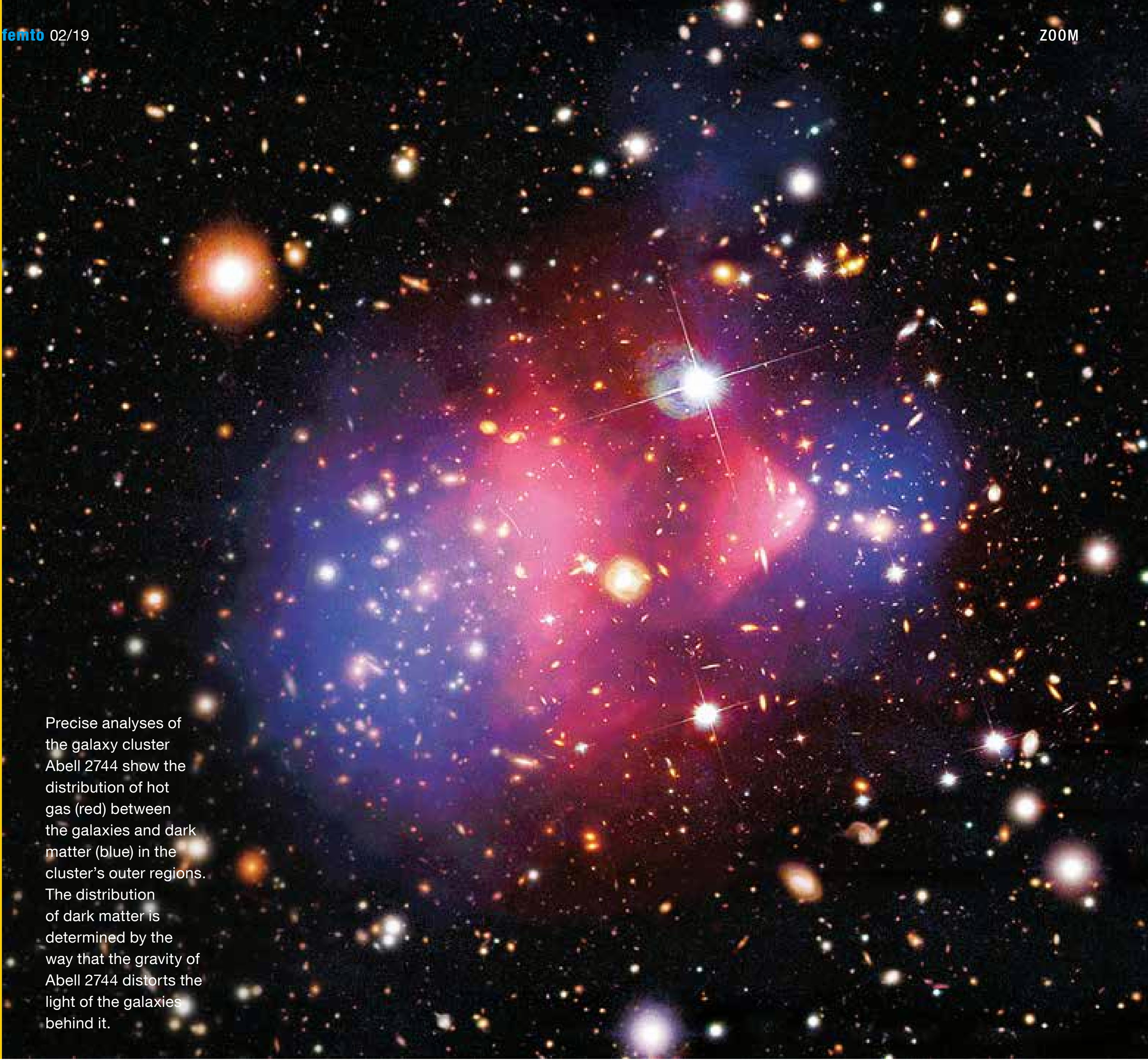
> *"Such measurements can only be made with a neutrino telescope"*
>
> **Markus Ackermann, DESY**

The existence of such particles has been postulated for reasons of symmetry. There would in fact be several types of these particles, and some of them could in principle be heavy enough to constitute dark matter. Scientists think that normal neutrinos could turn into sterile ones as they travel along. "IceCube could detect evidence for such oscillations into light sterile neutrinos," says Ackermann. "It would be a possible indication that heavier sterile neutrinos might exist as well, which could in turn be behind dark matter." IceCube hasn't found anything yet, but the scientists are planning to upgrade the South Pole detector in order to increase its sensitivity. ››



IceCube searching for neutrinos at the South Pole: The rare neutrino collisions trigger particle showers in the ice that show up as blue flashes. This light is registered by sensitive detectors (photomultipliers), long strings of which are embedded up to 2500 metres deep in the Antarctic ice.

Pictures: IceCube, Martin Wolf (top); DESY, Science Communication Lab (bottom)



Precise analyses of the galaxy cluster Abell 2744 show the distribution of hot gas (red) between the galaxies and dark matter (blue) in the cluster's outer regions. The distribution of dark matter is determined by the way that the gravity of Abell 2744 distorts the light of the galaxies behind it.

A dark mirror world

However, some theoreticians don't really believe that dark matter consists of hypothetical new elementary particles. Instead, they think that Newton's law of gravitation is not valid at large scales, such as the diameter of galaxies. At these distances, a theory such as MOND (Modified Newtonian Dynamics) might apply.

But even though it would explain why galaxies are stable and don't fly apart, the MOND hypothesis seems to have lost adherents in recent years. "There are still a few stalwarts who continue to fight for it," says Kai Schmidt-Hoberg. "But 99 percent of the scientific community doesn't believe it's true." That's because the theory can explain the rotation speed within the galaxies, but not other phenomena caused by dark matter, such as the creation of structures in the early universe.

Schmidt-Hoberg is pursuing a different approach and investigating the possibility of self-interacting dark matter. Most theories assume that dark matter particles generally ignore one another when they meet. "As a rule, not much happens when two of these particles encounter each other," explains Schmidt-Hoberg. "However, things could also be very different: The particles could interact with each other as strongly as colliding billiard balls."

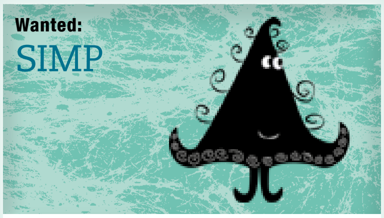
If this is the case, it would have serious consequences for the nature of dark matter.

Pictures: NASA/ESA/ESO/CXC, D. Coe (STScI)/J. Merten (Heidelberg/Bologna)

"You could then exclude many of the candidates – especially the WIMPs, but also the axions, because they don't have any strong self-interaction," he adds. This would result in a real paradigm shift, because dark matter would be much more complex than scientists had previously thought. It could even mean that there is a kind of dark mirror world – a shadow universe made up of completely new particles and forces. "There could be things like dark protons or dark electrons," Schmidt-Hoberg speculates. "There might even be dark light."

However, this shadow world would practically never interact with our matter. Direct evidence would be almost impossible to come by. That's why this hypothesis can probably be proven only indirectly – by taking a close look at distant galaxies. "There are indications that the concentration of dark matter is lower than expected in the centres of galaxies," says Schmidt-Hoberg. This could be explained if we assume that dark matter interacts with itself more strongly than is generally assumed. Figuratively speaking, the particles would push each other away and therefore accumulate less densely in the centres of galaxies. That, at least, is the theory.

One thing is clear, however: The situation is complicated. At the moment, there is a virtual flood of theories about dark matter. While some of them sound plausible, others are rather exotic. As a result, when new measurement data excludes one of the theories, new ones appear to take its place. "We won't be able to study the entire range of parameters anytime soon," says Markus Ackermann. Consequently, even if the upcoming experiments can't solve the mystery of the origin of dark matter, that wouldn't mean that dark matter doesn't exist.



Wanted:

SIMP

Strongly Interacting Massive Particles

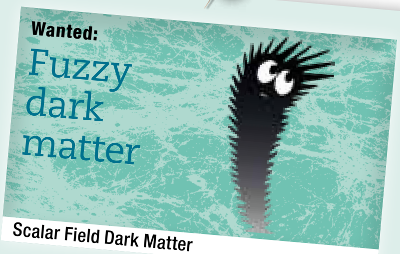
Mass: in the GeV range

µeV meV eV keV MeV GeV TeV

Interaction strength: strong (in the dark sector)

Search method: Because it reacts very strongly with itself, this type of dark matter might reveal itself in astrophysical systems, such as in the vicinity of stars. When star systems collide, the SIMPs would be shifted relative to the associated stars.

Special properties: typically a part of a more complex dark sector



Wanted:

Fuzzy dark matter

Scalar Field Dark Matter

Mass: extremely light (in the 10^{-22} eV range)

µeV meV eV keV MeV GeV TeV

Interaction strength: extremely weak

Search method: astrophysical observation via the wave–particle dualism. The wave would be as big as an entire galaxy! It could only be detected indirectly with the help of telescopes.

Special properties: Its properties are more wave-like than particle-like.

> *"There could be things like dark protons or dark electrons. There might even be dark light"*
>
> **Kai Schmidt-Hoberg, DESY**

This detail from the Illustris simulation – one of the world's largest astrophysical simulation series on the formation and evolution of galaxies – shows how a big galaxy cluster is woven into a web of dark matter in today's universe. The region shown here is about 300 million light years wide.

Picture: Illustris Collaboration, www.illustris-project.org

SMART UPCYCLING

How the high-tech experiment ALPS II is searching for dark matter with the help of used magnets

In its search for axions, ALPS II is relying on the same high-precision laser technology that is used in gravitational-wave detectors.

Dieter Trines steers his old BMW into a blind alley that ends at the edge of the Volkspark in Hamburg. Here, hidden behind trees, is Hall H1 – a relic of a past era of research. “It was part of the HERA storage ring,” Trines, a former director of the accelerator division at DESY, recalls. “The ring’s circumference of more than six kilometres made it the biggest particle accelerator in Germany.” In 2007, HERA was switched off and mothballed – and Hall H1, 20 metres underground, was closed down along with it. But today, when Trines takes the elevator down to the hall, he arrives in the midst of hustle and bustle. Technicians are dismantling parts of the accelerator in order to make room for a new experiment, ALPS II, which will search for a hypothetical new type of particle called an axion. If axions exist, it’s possible that they fill the universe in vast quantities and form the enigmatic dark matter.

The concept of the axion was actually developed at the end of the 1970s in order to resolve certain difficulties with the strong interaction, one of the four fundamental forces of nature. “Later on, theoreticians came up with the idea that axions could also be behind dark matter,” says ALPS project leader Axel Lindner. Because these elusive particles could be extremely light by comparison to the WIMPs, scientists refer to them as WISPs (weakly interacting slim particles). In 2005, the research community found indications that axions might actually exist. Thereupon, Andreas Ringwald, a theoretician at DESY, initiated an experiment called ALPS (Any Light Particle Search). In 2010, the team led by Lindner presented its results: During this initial phase, it had discovered nothing.

In order to take a closer look, the physicists launched a follow-up experiment, ALPS II, in cooperation with the Albert Einstein Institute in Hanover, Johannes Gutenberg University Mainz, the University of Cardiff in the UK and the University of Florida in Gainesville, USA. ALPS II is much bigger and more sensitive than its predecessor. The principle behind it is as follows: Laser light is guided into a magnetic field, where it could transform into an axion. “This axion would then fly through a lightproof wall and there enter another magnetic field,” Lindner explains. “And there the axion could transform back into light, which we want to detect using highly sensitive measuring technology.”

However, the approximately three-million-euro budget for this experiment, which was partly financed by the Heising-Simons Foundation in the USA, was tight. As a result, the team could not afford to construct new magnets and instead had to rely on used ones. The crucial idea came from Dieter Trines. “I suggested that the old curved HERA magnets could be straightened so that we could use them for our experiment,” he recalls. “Axel Lindner was so enthusiastic about my idea that he said to me, ‘Why don’t you join us?’”

The procedure takes place on an old HERA test bench. Each of the magnets is a tube 12 metres long and 70 centimetres thick, with a highly complex interior. In order to straighten out the central part, the beam pipe, the tube is fastened down at both ends, and then the middle part is pressed into shape by a screw jig with a force of four tonnes. “It’s basically very simple and inexpensive,” says Trines. In the near future, 24 of these straightened magnets will be installed in the HERA tunnel along a stretch of approximately 300 metres.

Picture: ALPS, Marian Dürbeck

In contrast to the magnets from the 1980s, the laser-optical measuring technology is state-of-the-art. “Most of the technology we’re using is the same as that employed in gravitational-wave detectors,” explains DESY physicist Aaron Spector. “For example, our laser is basically the same as those used in the two LIGO detectors in the USA.” Gravitational waves are tiny disturbances in space–time that are generated by violent cosmic events and propagate at the speed of light. To detect them, the researchers need extremely sensitive measuring technology: lasers that maintain their frequencies with extreme stability and sensors that register even the weakest shimmers of light. By applying this principle, in 2015 LIGO registered the first-ever evidence of a gravitational wave, caused by the collision of two black holes – a discovery that was honoured with the Nobel Prize in Physics in 2017.

> *“Later on, theoreticians came up with the idea that axions could also be behind dark matter”*
>
> **Axel Lindner, DESY**

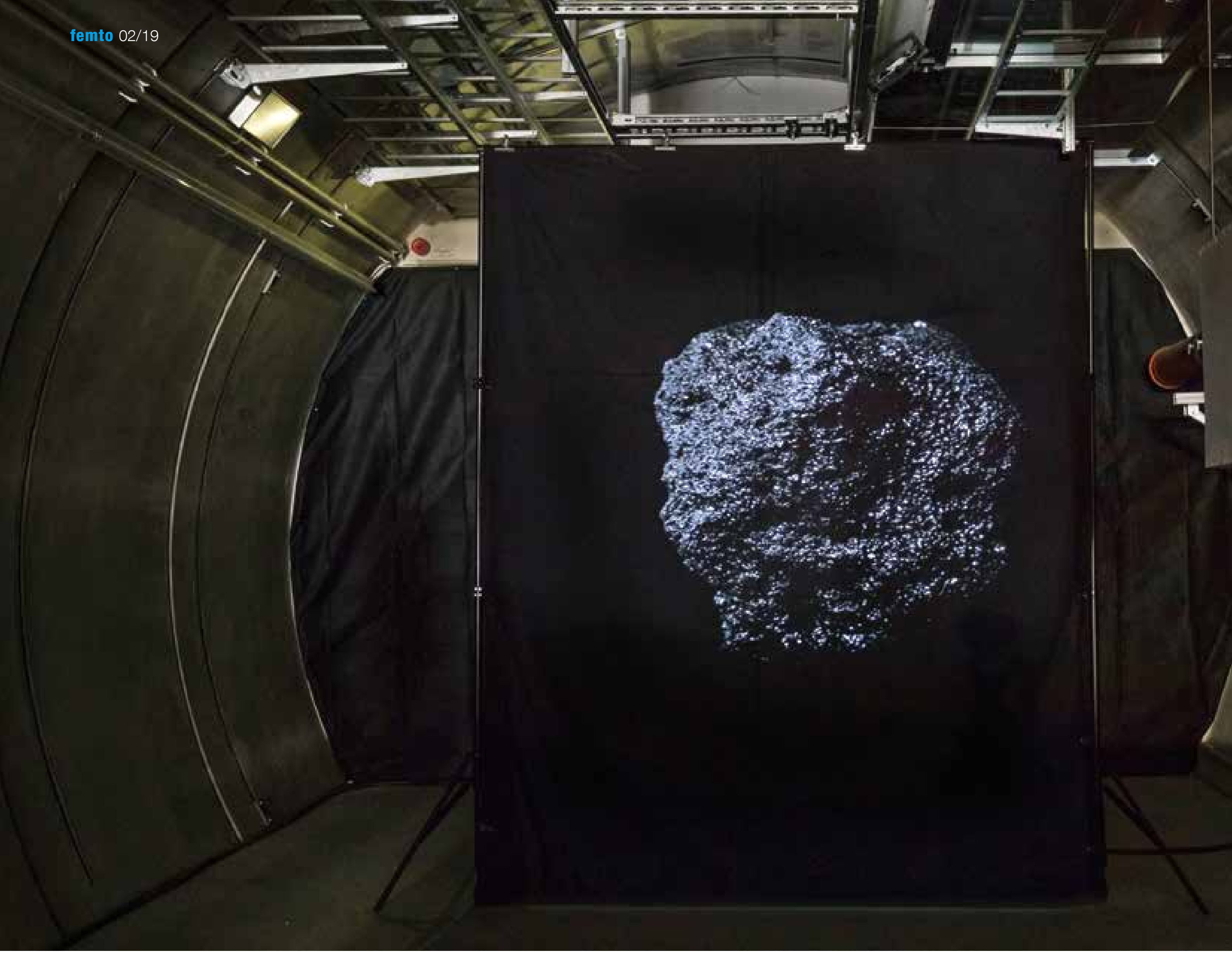
The researchers working on ALPS direct their highly precise laser beam through the field of 12 magnets and cause it to bounce back and forth using mirrors. If an axion were to be created in this process, it would pass through a lightproof wall to the area where the remaining 12 magnets are located. If the axion transformed back into light within this magnetic field, various detectors are waiting to register this light. “These detectors are able to spot individual photons – individual particles of light,” Spector explains. In addition, a special system makes it possible to position the components extremely quickly and precisely. “That way we can minimise the influence of the ever-present vibrations that would otherwise greatly interfere with our experiment,” Spector says. Data acquisition is scheduled to begin in 2021 at the latest. If ALPS actually does discover axions, it would be a sensation. The axion would be the first elementary particle to be discovered beyond the standard model of particle physics – and an extremely promising dark matter candidate.

The researchers are already tinkering with two follow-up experiments. “Some theories assume that axions are generated inside the sun,” says Lindner. “We want to detect these particles with a special telescope called the International Axion Observatory.” IAXO would be located on the DESY campus and follow the daily course of the sun. Its basic feature would be a lightproof magnet within which a solar axion could transform into X-ray light. If everything goes according to plan, the first prototype, named babyIAXO, could start up as early as 2023. Subsequently, a further experiment would clarify whether axions are really responsible for dark matter. Starting in 2028, MADMAX (Magnetized Disk and Mirror Axion) could help researchers find out whether our environs are teeming with large numbers of axions.

Axel Lindner heads the ALPS group at DESY.

Pictures: DESY; DESY, Gesine Born

Light through the wall: For ALPS II, 12 of these straightened HERA magnets are being installed in front of a lightproof wall and 12 more behind it. An intense laser beam will be directed at the wall from one side. If the detectors on the other side of the wall register a flash of light, this might indicate the presence of an axion that has been created from a particle of light in the magnetic field in front of the wall and transformed back into light on the other side of the wall.



THE ART OF DARK MATTER

For four weeks in autumn 2017, DESY was the venue of an unusual event. At a show called “Dark Matter”, 15 artists from all over Germany exhibited their works on the DESY research campus in Hamburg. The project was a huge success, and it will be continued in 2020, as DESY physicist Christian Schwanenberger explains.

femto: How did the idea of staging an art exhibition at DESY come about?

Christian Schwanenberger: It was pure coincidence. At a birthday party in St. Pauli, I got into a conversation with the artist Tanja Hehmann. We quickly came to the conclusion that there are countless parallels between art and science – for example, the fact that an incredible amount of experimentation goes on in both disciplines. That’s why we had the feeling that it could be worthwhile to open up a channel of communication between the two disciplines.

femto: Why did you choose dark matter as the theme?

Christian Schwanenberger: We physicists know that dark matter has to exist. However, we have no idea what it consists of or what exactly we’re searching for. There’s a similar situation in art. Artists also sometimes address questions without being really sure what they’re actually looking for. That’s why it seemed to us that dark matter would be very suitable as a thematic

Pictures: DESY, Helge Mundt (3)

“time – image (dark matter)” is a video sculpture by Sybille Neumeyer in which a chunk of rock revolves around its own axis at the same speed as the Earth’s rotation.

framework for an art exhibition. However, not all of the artists slavishly adhered to this theme, and of course we wanted to leave them a certain amount of leeway.

femto: What was your collaboration with the artists like? Was it a collision of two different cultures?

Christian Schwanenberger: It certainly was. When all of us met up for the first time, I initially had the feeling that we were absolutely talking at cross purposes. It took each group some time to understand what the other one was actually saying. Physicists tend to think in a logical and linear way, while artists think in terms of a surface or a space. The process of developing a shared language was really exciting. It was also fascinating to see how the artists drew inspiration from specific locations on the DESY campus.

> *“The process of developing a shared language was really exciting”*
>
> **Christian Schwanenberger, DESY**

I’ll give you two examples. The artist duo “wearevisual” built a kind of walk-in fort out of huge blocks of concrete that are normally used to shield areas from radiation. If you pressed a button inside this fort, a black plastic film would be blown up like a balloon, quasi as a symbol of dark matter. And in the underground tunnel of the former HERA accelerator, the audio artist Chris Pfeil built a loudspeaker installation that gave you the feeling that you could hear the rapid particles flying past.

femto: How was the exhibition received by the public?

Christian Schwanenberger: A total of 2500 visitors came to the six events we organised as part of the project. Three quarters of the visitors had never come to DESY before – so we obviously succeeded in getting a whole new audience interested in our research. The exhibition was also well received by the 20 000 visitors who came to DESY’s open day. After the exhibition was over, many artists got in touch with us to ask whether they could participate the next time around. In short, the project was so successful that we plan to continue it.

Science meets art: Physicist Christian Schwanenberger leads visitors through the exhibition (top); Daniel Engelberg presented his experimental modules in a test hall for particle accelerators.

femto: When will be the next date for art and science to meet at DESY?

Christian Schwanenberger: We already organised an event in Berlin in summer 2018: a light and sound installation by the artist Tim Otto Roth that dealt with the IceCube neutrino telescope. We’re preparing to stage another big exhibition in Hamburg at the end of 2020. In this one, we want to try to intensify the interaction between art and science. We’re planning to pair up artists and scientists in two-person teams so that they can develop shared ideas. We also want to offer the artists the opportunity to spend a few weeks at DESY so that they can have a close-up experience of the themes we are dealing with.

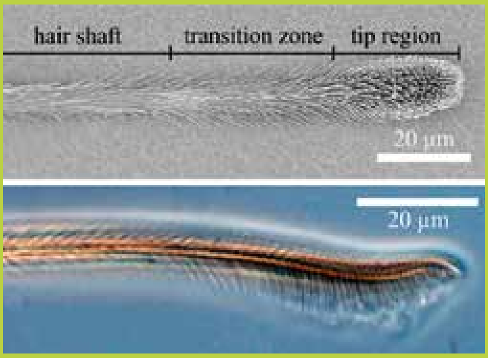
SPECTRUM

Science in brief

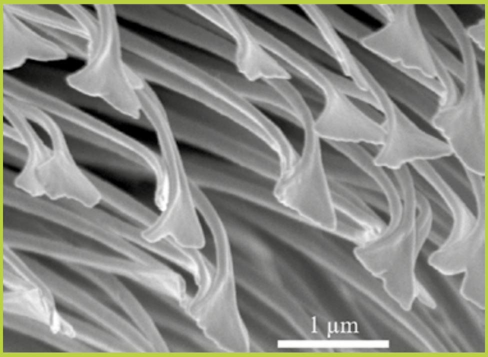
What keeps spiders on the ceiling?

In order to find out why the hunting spider *Cupiennius salei* adheres so well to vertical surfaces, the interdisciplinary research team investigates the tiny adhesive hairs on the spider's legs.

Different areas of the adhesive hair are visible under the microscope.



The scanning electron microscope reveals the tiny contact plates at the tip of the adhesive hair. They are just 20 nanometres (millionths of a millimetre) thick.



Hunting spiders easily climb vertical surfaces or move upside down on the ceiling. Tiny hairs at the ends of their legs make sure that they do not fall off. These bristle-like hairs are called setae, and spiders have about one thousand of them.

Like the spider's exoskeleton, these hairs mainly consist of proteins and chitin, a polysaccharide. To find out more about their fine structure, an interdisciplinary research team from the biology and physics departments at the University of Kiel (CAU) and the Helmholtz-Zentrum Geesthacht (HZG) examined the molecular structure of these hairs in closer detail, among others at DESY's X-ray light source PETRA III.

Thanks to the high-energy X-rays, the researchers discovered that the chitin molecules of the setae are specifically arranged to withstand the stresses of constant attachment and detachment.

"Their arrangement in a parallel fibre structure strengthens the legs," says Martin Müller from the institute of experimental and applied physics, head of the materials physics department at the HZG. "In addition, the chitin molecules can be found up to the tips of the tiny hairs on the spider legs." Similar adhesive hairs can be found for example on the legs of geckos. The researchers therefore hypothesise that this could be a key biological principle that allows animals to adhere to different surfaces. Their findings could be helpful to develop new materials with high resilience.

Journal of the Royal Society Interface, 2019;
DOI: 10.1098/rsif.2018.0692

Pictures: © Siekmann, Univ. Kiel, © Schaber et al. (2019) J. R. Soc. Interface (2), http://creativecommons.org/licenses/by/4.0/

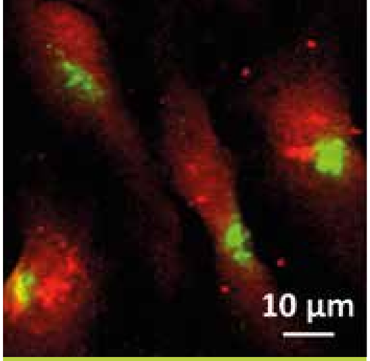
Parkinson's symptoms due to manganese poisoning

A new X-ray study has revealed one of the key mechanisms behind certain familial parkinsonian disorders. Poisoning with the metal manganese, which is vital in low concentrations, is considered a possible cause of certain forms of the nervous disease.

The study, carried out at DESY and at the European Synchrotron Radiation Source (ESRF) in Grenoble, France, demonstrates in detail how poisoning with manganese, which leads to parkinsonian symptoms, occurs inside a cell. It found that a specific genetic defect results in manganese accumulating in the cell's Golgi apparatus, the dispatch centre for proteins in the cell.

The team headed by Richard Ortega from the University of Bordeaux had been studying a mutation in the *SLC30A10* gene previously identified in a series of cases of familial parkinsonism, which appears to lead to genetically inherited disorders. "In the mutated form, this transport is disrupted so that toxic concentrations of the metal accumulate in the cell," says Ortega. "An exact understanding of this manganese poisoning is a crucial step towards designing possible therapies."

Parkinsonism is a syndrome that includes a group of disorders affecting the nervous system, which lead among other things to a characteristic tremor known as shaking palsy.



Where the manganese is located: An X-ray fluorescence image shows the distribution of manganese (green) within the cells under study (red).

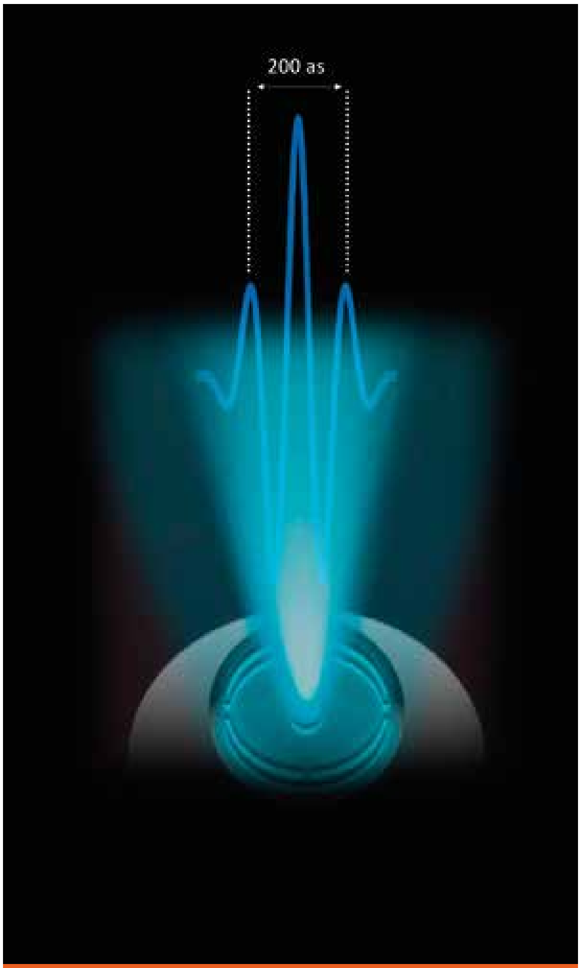
ACS Chemical Neuroscience, 2018; DOI: 10.1021/acschemneuro.8b00451

Holographic technique measures ultrashort pulses

A novel optical technique can analyse ultrashort X-ray flashes in the attosecond range. An attosecond is a billionth of a billionth of a second, or 0.000 000 000 000 000 001 seconds (10^{-18} s). Attosecond light pulses are short enough to capture the extremely fast motion of electrons in matter in real time. A prerequisite for such measurements, however, is that the properties of the short flashes are known.

Optical methods normally used for such purposes cannot easily be extended to the X-ray domain, however. Holography offers a way out. Using this method, an international team including DESY researcher Francesca Calegari analysed the spectral intensity of two unknown attosecond pulses together with their coherent interference. The team demonstrated that the sum of these contributions behaves as a hologram, from which the temporal characteristics of the two unknown pulses can be reconstructed.

"The technique is a promising tool for the characterisation of other ultrafast light sources," says Calegari. It could for example be extended to free-electron lasers and open up new possibilities for holographic diagnostics of ultrashort ultraviolet and X-ray laser pulses.

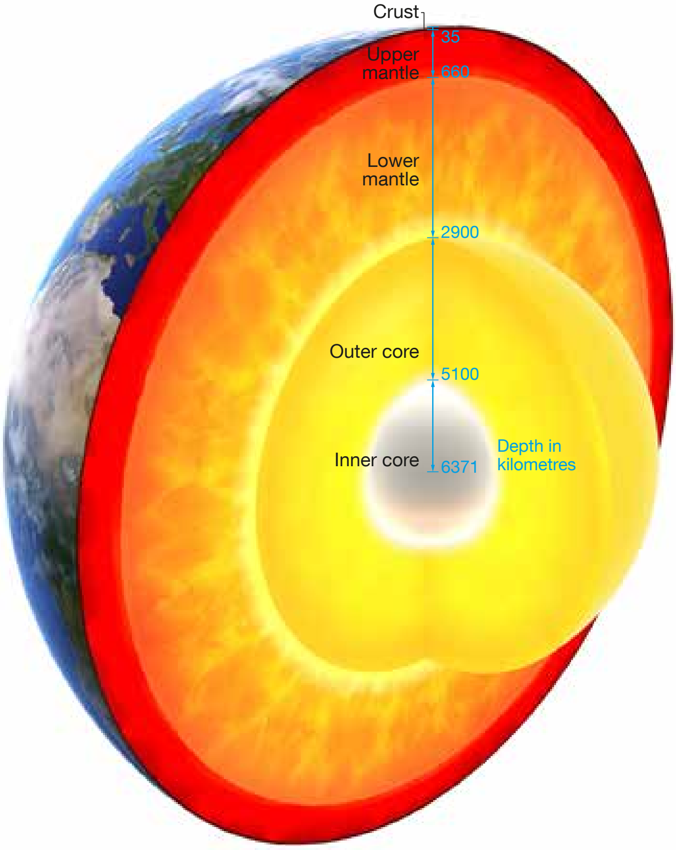


The holographic method can characterise light pulses in the attosecond regime.

Nature Photonics, 2019; DOI: 10.1038/s41566-018-0308-z

Pictures: CNRS, Richard Ortega (manganese); DESY, Andrea Trabattoni (holographic technique)

New view into the Earth's interior



The Earth in cross section: the inner structure of the Earth

An innovative X-ray method enables new high-pressure investigations of samples under conditions like those found in the deep mantle of the Earth. For their experiments, the team led by Georg Spiekermann from DESY, the German Research Centre for Geosciences (GFZ) and the University of Potsdam exposed samples of germanium dioxide to a pressure of up to 100 gigapascals, about one million times as much as the atmospheric pressure at sea level. This pressure corresponds to a depth of 2200 kilometres in the lower mantle of the Earth.

The X-ray study shows that the coordination number of germanium dioxide does not rise higher than six even under this extreme pressure. This means that, even in the high-pressure phase, the germanium atoms each still have six neighbouring atoms, as they did at 15 gigapascals. The result is of great interest for the exploration of Earth's interior, because germanium dioxide has the same structure and behaves like silicon dioxide, which is thought to be the main component of magma in the lower mantle.

Since melts such as magma generally have a lower density than the solid form of the same material, it has long been a mystery why magmas at great depth do not rise towards the surface over geological periods. The new study supports the idea that heavy elements must accumulate in the magma of the deep mantle in order for it to be stable.

Physical Review X, 2019; DOI: 10.1103/PhysRevX.9.011025

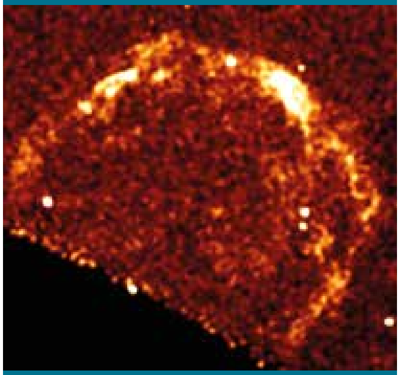
Gamma rays from the superbubble

An international research team has revealed how very-high-energy (VHE) cosmic gamma rays are produced by a so-called superbubble in the southern sky. Using the "Chandra" X-ray observatory of the US space agency NASA, the scientists led by Patrick Kavanagh from the Dublin Institute for Advanced Studies showed that these gamma rays are chiefly produced by the interaction of fast electrons with ambient light.

The superbubble 30 Doradus C is an astronomical object in the Large Magellanic Cloud, a dwarf satellite galaxy of the Milky Way at a distance of about 170 000 light years. The Large Magellanic Cloud produces new stars at a high rate. Most of them are large giant stars, dozens of times more massive than our sun. These fast-paced giant suns generate strong stellar winds, which stream into their cosmic environment, and end their relatively short existence in massive supernova explosions. Both phenomena together create a gigantic bubble in the gas of the satellite galaxy.

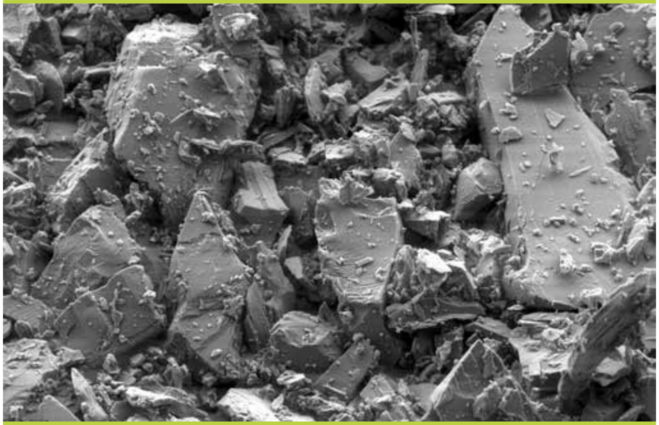
"While VHE gamma rays have been detected from 30 Doradus C before, it was not clear which mechanism dominates the gamma-ray production," explains DESY physicist Stefan Ohm.

Astronomy & Astrophysics, 2018; DOI: 10.1051/0004-6361/201833659



The superbubble 30 Doradus C, captured by the "Chandra" satellite

Pictures: DESY, Franziska Lorenz & Jochen Stuhrmann/illustrato (Earth core); NASA (superbubble)



Scanning electron microscopy image of the microstructure of the feldspar mineral under study. The image spans about 0.036 millimetres.

Simulating meteorite impacts in the lab

A US–German research team has simulated meteorite impacts in the lab and followed the resulting structural changes in two common feldspar minerals with X-rays in real time. The results of the experiments at DESY and at the Argonne National Laboratory in the USA show that these changes of the atomic structure can occur at very different pressures, depending on the compression rate.

The findings will aid scientists to reconstruct meteorite impacts using impact craters on Earth and other Earth-like planets. Meteorite impacts play an important role in the formation and evolution of Earth and other planetary bodies in our solar system. Even after hundreds to millions of years, impact craters can still allow conclusions to be drawn about the size and speed of the meteorite in question as well as about the pressure and temperature during its impact. To this end, the researchers use X-ray crystallography to investigate changes in the inner structure of the crater material and compare the observations with the results of high-pressure experiments with the same material in the lab.

To be able to follow the changes in the crystal structure in real time, the team used DESY's highly brilliant X-ray light source PETRA III, among others, together with a sensitive and fast special detector.

Earth and Planetary Science Letters, 2019;
DOI: 10.1016/j.epsl.2018.11.038

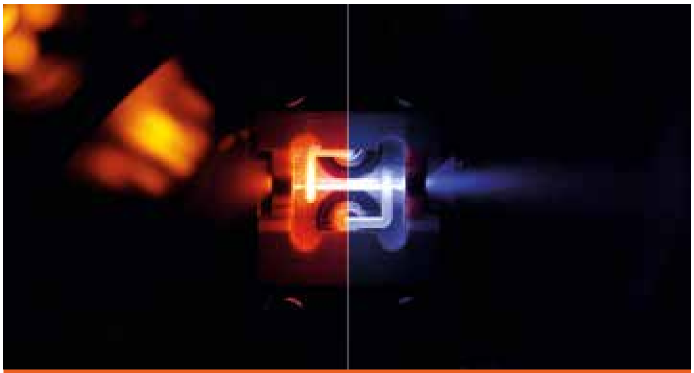
New gas for plasma lenses

Particle beams can be focused in accelerators using a kind of lens made of plasma, an ionised gas. An international team has now removed a major obstacle that previously prevented the technical use of such plasma lenses in practice.

In an active plasma lens, a strong electric current creates a magnetic field vortex that can simultaneously focus the height and width of a particle beam. This property makes plasma lenses very attractive for use in particle accelerators. However, one of the main problems of the lenses was an optical flaw that destroyed the quality of the focused particle beam as it passed through the plasma cell.

The team of researchers from Oslo, Oxford, DESY and CERN switched the type of gas used to produce the plasma from the usual helium, a light gas, to the heavier argon. This slows down the heat conduction within the gas for long enough to allow a bunch of particles to be focused immediately after the plasma has been formed and the magnet current has been switched on, without the quality of the beam suffering as a result. The findings are an important step towards making active plasma lenses a standard component of future accelerators.

Physical Review Letters, 2019; DOI: 10.1103/PhysRevLett.121.194801



Montage of two photos during the operation of the plasma lens: with helium (red) and with argon (blue)

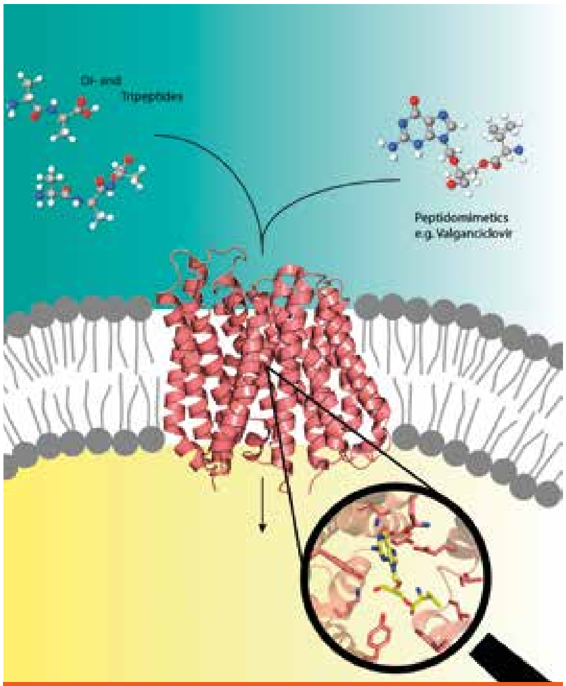
Pictures: Stony Brook University, Lars Ehm (meteorites); C.A. Lindstrom, Univ. Oslo (plasma lens)

X-rays reveal layout of loaded drug transporter

Experiments at DESY's X-ray source PETRA III have revealed the first structure of a biological transporter protein loaded with a pro-drug. Pro-drugs are inactive medications that are metabolised into an active, functional form within the body. They can hijack certain human nutrient transporter proteins that are located in the cell membrane and usually channel peptides derived from digested food into cells. This way, pro-drugs can hitch a ride directly into the cell, accelerating the drug's absorption. While the pro-drug concept is very effective, little is known at the molecular level about the peptide transporters' structure and how they recognise, bind and transport pro-drugs.

A group of researchers led by Christian Löw and Jan Kosinski from the European Molecular Biology Laboratory (EMBL) and working at the Centre for Structural Systems Biology (CSSB) – a cooperation of ten research institutions including DESY – are now a step closer to understanding this phenomenon. The scientists determined the first high-resolution crystal structure of a peptide transporter in complex with the pharmacologically relevant pro-drug valganciclovir, a medication that combats certain viral infections. Their results may facilitate the development of medications and pro-drugs with improved absorption rates in order to reduce the administered dose.

Journal of the American Chemical Society, 2019; DOI: 10.1021/jacs.8b11343

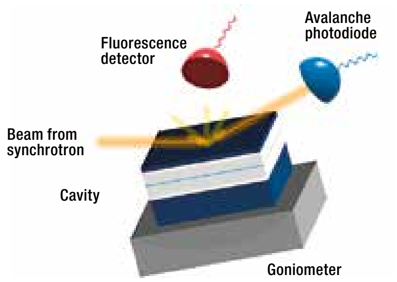


Drug transport in detail:
Nutrients (top left) and pro-drugs (top right) enter the cell using the peptide transporter (centre) in the cell membrane.

Control out of the vacuum, virtually

Certain optical properties of metal atoms can be controlled with the help of virtual photons, as measurements at DESY's X-ray source PETRA III have shown. Virtual photons, which do not exist at all in the classical sense, can be created in the vacuum out of nothing, only to disappear again after an extremely short time. If these photons interact during their short existence with the electrons of an atom, the binding energies of the electrons shift ever so slightly.

This fundamental effect was first measured on hydrogen atoms in 1947 by Willis Lamb. The eponymous Lamb shift changes fundamentally, however, if many similar atoms are involved. If these atoms are very close to each other, the virtual photons can cause an interaction between the atoms. This collective Lamb shift, predicted in 1973, was only demonstrated in 2010 by the DESY group of Ralf Röhlsberger.



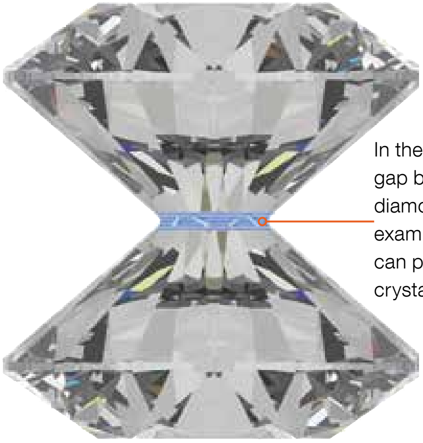
Experimental setup to measure the collective Lamb shift using the metal tantalum

A team led by Röhlsberger has now succeeded for the first time in detecting the collective Lamb shift of inner-shell atomic excited states, or resonances, using the metal tantalum. This results in comparatively large Lamb shifts, corresponding to a significant change in the optical properties. These properties can be controlled with the help of the virtual photons, which opens up new applications, for example in X-ray quantum optics.

*Physical Review Letters 2019;
DOI: 10.1103/PhysRevLett.122.123608*

Pictures: DESY, Haber et al. EMBL (Lamb); Yonca Ural-Blimke (drug transporter)

Liquids crystallise in nanometre gaps



In the nanometre gap between two diamonds, for example, liquids can partially crystallise.

Very narrow gaps make liquids partially crystallise. X-ray investigations at DESY show that in gaps just a few molecule diameters wide, both liquid and crystal properties of a material can exist at the same time. The observation is important among other things for the study of friction (tribology). It was already known that liquids form atomically thin layers at an interface, such as the bottom or wall of a vessel. What happens when two walls are so close that their layers overlap, however, was unclear. A team led by DESY researchers Milena Lippmann and Oliver Seeck has now investigated this phenomenon. The scientists filled a gap only a few millionths of a millimetre (nanometres) wide with carbon tetrachloride as a model liquid. The X-ray analysis showed a coexistence of liquid layers and crystals.

"Our observation has direct consequences for all types of liquids in very small cavities," says Seeck. "This can be important for catalysis or other chemical reactions in nanometre gaps, for example, but also for investigating friction and for correct lubrication."

The Journal of Physical Chemistry Letters, 2019; DOI: 10.1021/acs.jpclett.9b00331

Picture: Yonca Ural-Blimke (crystal)

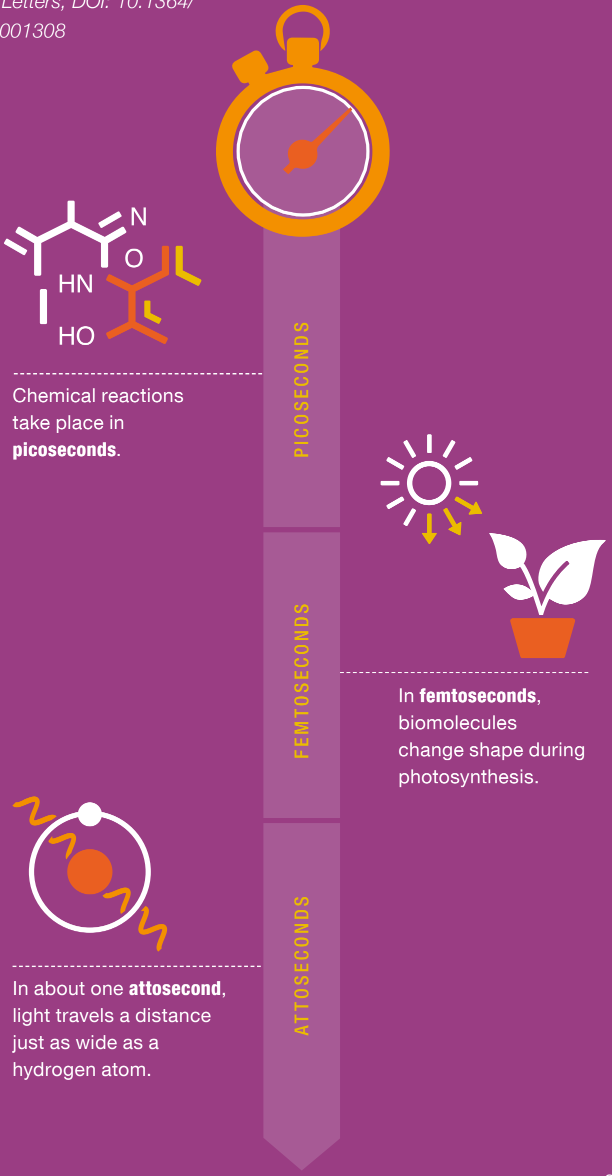
femtomenal

0.000 000 000 000 0019 seconds…

or 1.9 quadrillionths of a second (femtoseconds) – this is the duration of the world's shortest ultraviolet (UV) laser pulse. A team led by DESY researcher Francesca Calegari has thus significantly outscored the record of 2.8 femtoseconds set in 2010. Each flash is only about 600 nanometres long, i.e. 0.0006 millimetres, which is about twice as long as a wave train of the UV light used.

The ultrashort flashlight lies in the biologically very relevant wavelength range of UVB and UVC radiation. It opens up new perspectives for ultrafast molecular spectroscopy – for example to investigate in real time the first moments of biochemical processes triggered by UV light, such as damage to DNA molecules.

Optics Letters, DOI: 10.1364/OL.44.001308



Chemical reactions take place in **picoseconds**.

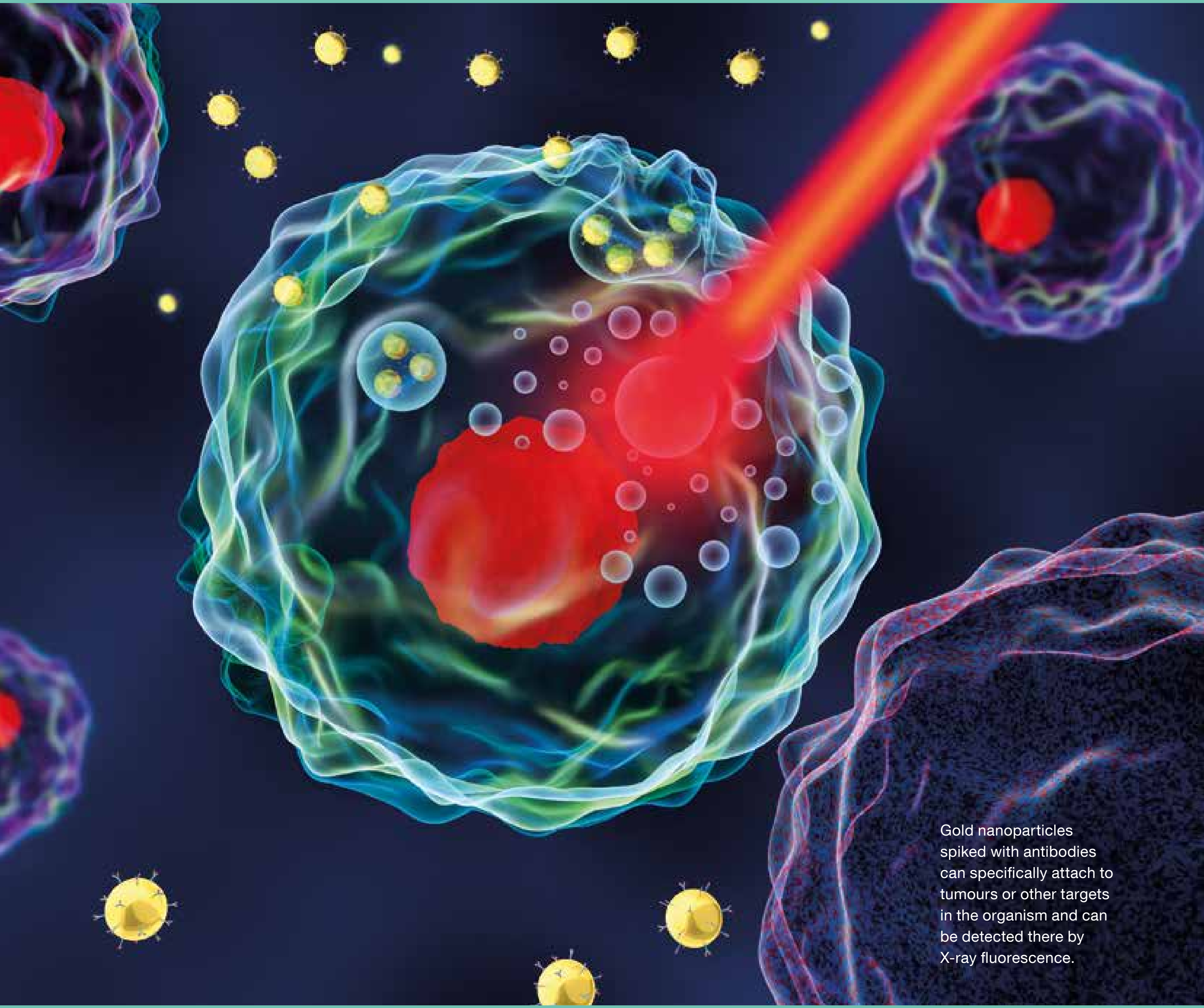
In **femtoseconds**, biomolecules change shape during photosynthesis.

In about one **attosecond**, light travels a distance just as wide as a hydrogen atom.

Using gold to track down diseases

X-ray method opens up new diagnostic possibilities in medicine

A high-precision X-ray technique could catch cancer at an earlier stage than is possible today and facilitate the development and control of pharmaceutical drugs. At DESY's research light source PETRA III, a team led by Florian Grüner from the University of Hamburg tested the X-ray fluorescence method for this purpose. The technique offers the prospect of carrying out such X-ray studies not only with higher precision than existing methods, but also with less of a dose impact. However, before the method can be used in a clinical setting, it still has to undergo numerous stages of development.



Gold nanoparticles spiked with antibodies can specifically attach to tumours or other targets in the organism and can be detected there by X-ray fluorescence.

The idea behind the procedure is simple: Tiny gold nanoparticles with a diameter of 12 nanometres (millionths of a millimetre) are functionalised with antibodies using biochemical methods. “A solution containing such nanoparticles is injected into the patient,” explains Grüner, who works at the Center for Free-Electron Laser Science (CFEL), a cooperative venture between DESY, the University of Hamburg and the Max Planck Society. “The particles migrate through the body, where the antibodies can latch onto a tumour that may be present.” When the corresponding parts of the patient’s body are scanned using a hair-thin X-ray beam, the gold particles emit characteristic X-ray fluorescence signals, which are recorded by a special detector. The hope is that this will permit the detection of tiny tumours that cannot be found using current methods.

> *“The particles migrate through the body, where the antibodies can latch onto a tumour that may be present”*
>
> **Florian Grüner, CFEL**

“In breast cancer, tumours often remain undetected until they are more than a centimetre across,” explains Grüner, who collaborated among others with the group of Christoph Hoeschen from the University of Magdeburg for this study. “Our method has the potential to detect tumours or metastases that are just a millimetre across, which would greatly improve the prognosis.” Another area in which the method could be applied is the development of new medical drugs. In this case, new potential active ingredients could be attached to the nanoparticles and then traced using X-ray fluorescence imaging to see how the drug spreads through the body and whether it actually reaches the intended site with sufficient concentration. The hope is that promising active ingredient candidates could thus be distinguished from ineffective ones at an earlier stage than is currently the case.

Methodical breakthrough

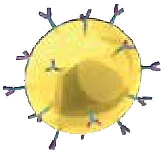
Although the idea of X-ray fluorescence imaging has been around for over 30 years, it has not been possible until now to implement it in human beings. This is because X-rays are repeatedly scattered inside the body. The result is a vast background from which it is very difficult to extract the actual signal. “My team delved into this issue, and we have now become the first group in the world to show experimentally how this problem can be solved,” says Grüner. They accomplished this feat using a computer algorithm that determines precisely those detector elements within the full solid angle of the measured X-ray spectra whose signals contain particularly little background noise.

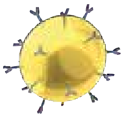
For a first experimental test, the scientists sent the beam from PETRA III through a 30-centimetre-thick cylinder made of polymethyl methacrylate (PMMA), which can be used to simulate the conditions in human tissue. These measurements of the background signal provided good confirmation of the preceding simulations. They also showed that X-ray fluorescence imaging promises to require significantly lower levels of radiation exposure than computer tomography (CT): Whereas radiation levels are four to seven millisieverts in a CT, Grüner calculates that X-ray fluorescence imaging could get by with around one millisievert. Furthermore, to locate the same number of gold nanoparticles using a normal CT scan, the dose would have to be increased to unacceptable levels.

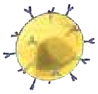
However, before the method can be used in medical diagnostics, it will need to be developed a lot further. Among other things, the effect of gold nanoparticles on the human body still calls for closer examination. Another obstacle is the availability of appropriate X-ray sources. Large particle accelerators such as DESY’s PETRA III, with a circumference of more than two kilometres, are not suitable for a hospital, let alone a doctor’s surgery. In future, however, innovative accelerator technologies that are currently being developed could make it possible to build X-ray sources that can provide the necessary quality for such experiments while still fitting inside a laboratory.

Scientific Reports, 2018; DOI: 10.1038/s41598-018-34925-3

Florian Grüner is head of accelerator physics at the University of Hamburg.



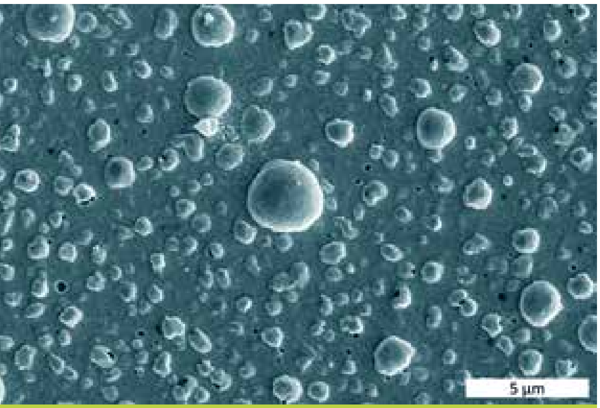




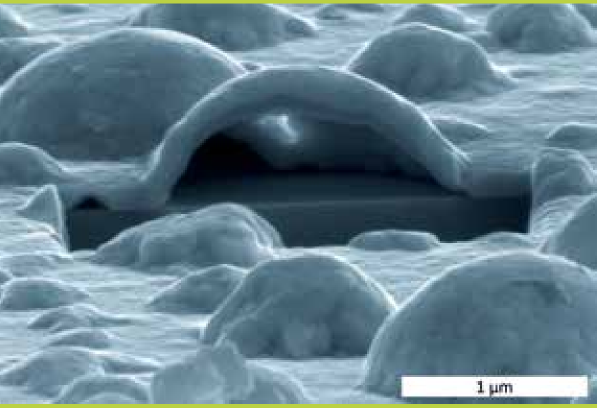
Pictures: www.istockphoto.com, Meletios Verras, DESY; Heiner Müller-Elsner (portrait)

Platinum forms nanobubbles

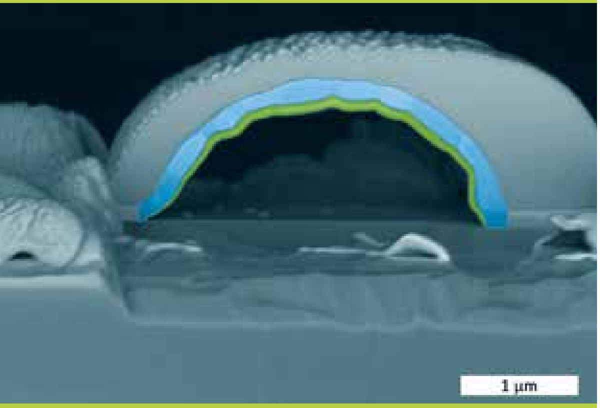
Technologically important noble metal oxidises more readily than expected



Under the scanning electron microscope, the platinum film shows many bubbles after the electrochemical experiment.



Electron microscope view into the interior of a platinum bubble. The cross section was exposed with a focused ion beam. The angular YSZ crystal can be seen below the hollow platinum bubble.



The chemical element analysis of the platinum bubble, which is coated with a protective layer, shows an outer metallic shell made of platinum (coloured in blue) and an inner shell made of platinum oxide (green).

Platinum, a noble metal, can oxidise more quickly than expected under technologically relevant conditions. As a result of this reaction, devices that contain platinum, such as the catalytic converters used to reduce exhaust emissions in cars, can suffer a loss in efficacy. “Platinum is an extremely important material in technological terms,” says the main author of the study, Thomas Keller from DESY and the University of Hamburg. “The conditions under which platinum undergoes oxidation have not yet been fully established. Examining those conditions is important for a large number of applications.”

The scientists studied a thin layer of platinum that had been applied to an yttria-stabilised zirconia crystal (YSZ crystal), the same combination that is used in the lambda sensor of automotive exhaust emission systems. The YSZ crystal is a so-called ion conductor, meaning that it conducts electrically charged atoms (ions), in this case oxygen ions. The vapour-deposited layer of platinum serves as an electrode. The lambda sensor measures the oxygen content of the car’s exhaust fumes and converts it into an electrical signal, which in turn controls the combustion process electronically to minimise toxic exhausts.

In the DESY NanoLab, the scientists applied a voltage of about 0.1 volts to the platinum-coated YSZ crystal and heated it to around 450 degrees Celsius – conditions similar to those found in many technical devices. As a result, oxygen collected beneath the impermeable platinum film, reaching pressures of up to 10 bars, which corresponds to that in the tyres of a lorry. The pressure exerted by the oxygen, along with the raised temperature, caused small bubbles to form inside the platinum film, typically with a diameter of about 1000 nanometres (one micrometre or 0.001 millimetres). “Platinum blistering is a widespread phenomenon, and we would like to develop a better understanding of it,” explains Keller. “Our investigation can also be considered representative of this type of electrochemical phenomenon at a range of other boundary layers.”

The scientists used a focused ion beam (FIB) as a sort of ultrasharp scalpel to slice open the platinum bubbles and examine their inside more closely. They found that the inner surface of the bubbles was lined with a layer of platinum oxide that could be up to 85 nanometres thick, much thicker than expected.

“This massive oxidation took place in conditions under which it is not normally observed,” reports Sergey Volkov, who has written his doctoral thesis at the University of Hamburg on the topic. “As a rule, platinum is a highly stable material, which is precisely why it is chosen for many applications, such as catalytic converters in cars, because it is not easily altered. Our observations are therefore important for such applications.”

The scientists suspect that the high pressure of the oxygen within the bubbles speeds up the oxidation of the metal. This needs to be taken into account in the operation of electrochemical sensors.

Solid State Ionics, 2019;
DOI: 10.1016/j.ssi.2018.11.009

Pictures: DESY, Satishkumar Kulkarni (2); DESY, Satishkumar Kulkarni/Thomas F. Keller (bottom)

Why lightning often strikes twice

Lightning flashes over LOFAR (montage)

Thunderstorms come along not only with hail, storm, lightning and thunder, but also with all sorts of myths, which usually do not stand up to scientific scrutiny. Why should one, as a German saying would have you do, “avoid oaks and look for beeches” when a thunderstorm is brewing? Because it rhymes (at least in German)? A lightning bolt likes to strike tall, isolated objects and doesn’t care about botanical subtleties. The fact that lightning never strikes twice in the same place also belongs to the realm of myths. The best protection is not where the lightning bolt has already been, but in the car (a Faraday cage) or in the house.

An international research team has now discovered in an unusual way why lightning can strike several times. They made use of the LOFAR radio telescope, which consists of thousands of simple antennas set up decentrally in various European countries, connected to one another via fibre-optic networks and linked to high-performance computers. This interconnection allows the use of the antennas as a single, giant virtual telescope. LOFAR is primarily used for astronomical observations. The system is very flexible, however, and surprisingly also suitable for looking inside thunderclouds. Thanks to the radio waves, the researchers were able to observe the lightning propagation so precisely that individual physical processes became visible.

The observations revealed hitherto unknown needle-shaped structures. When lightning spreads, it discharges the thundercloud only in a few places. The needles now discovered allow electrical charges to be stored, thus enabling a thundercloud to be discharged several times at the same location. This is why repeated lightning strikes to the ground can occur from one cloud, and why thunderstorms produce not only one lightning bolt, but many spectacular yet also dangerous discharges.

LOFAR allows the radio waves emitted by a flash of lightning to be stored unprocessed in their original form. This in turn makes it possible to develop new imaging techniques that can draw a three-dimensional image of a lightning bolt from the raw data – ten times better than previous measurements, with an accuracy of up to one metre and, owing to the radio waves, inside a cloud that can be up to 20 kilometres away from the telescope.

“The measurements originally came from our research group dealing with cosmic rays,” reports DESY scientist Anna Nelles. “At the interface between particle physics and astronomy, this area was already quite exotic for a radio telescope. LOFAR was built mainly for astronomy. The fact that we are now the best lightning interferometer in the world came as a surprise to everyone and shows the exciting possibilities that can result from basic research with an outstanding infrastructure.”

Nature, 2019; DOI: 10.1038/s41586-019-1086-6

Picture: University of Groningen, Olaf Scholten

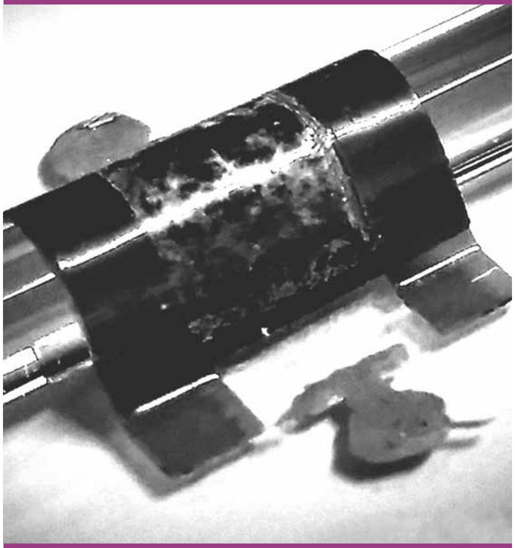
Flexible circuits for 3D printing

New process for flexible and transparent electronics

A research cooperation between the University of Hamburg and DESY has developed a process suitable for 3D printing that can be used to produce transparent and mechanically flexible electronic circuits. The electronics consists of a mesh of silver nanowires that can be printed in suspension and embedded in various flexible and transparent plastics (polymers). The technology can enable many new applications, such as printable light-emitting diodes, solar cells or tools with integrated circuits. The research team led by Tomke Glier from the University of Hamburg demonstrated the potential of their process with a flexible capacitor, among other things.

> *“With our novel approach, we want to integrate electronics into existing structural units and improve components in terms of space and weight.”*
>
> **Michael Rübhausen, CFEL**

Example of a flexible and transparent electronic component: a flexible capacitor



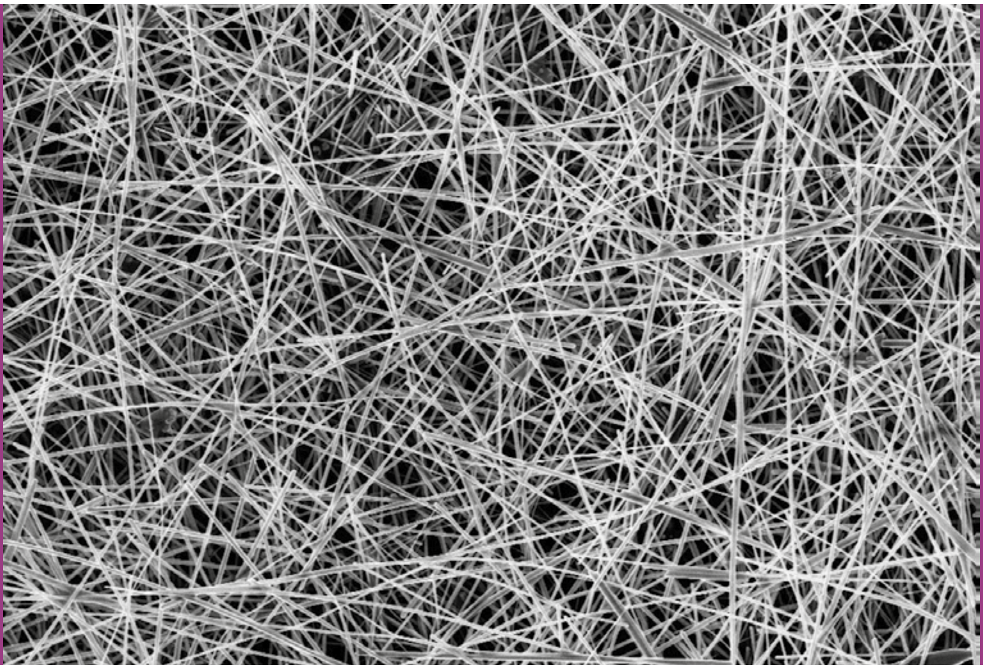
Picture: University of Hamburg, Tomke Glier

“The aim of this study was to functionalise 3D-printable polymers for different applications,” reports Michael Rübhausen from the Center for Free-Electron Laser Science (CFEL), a cooperation of DESY, the University of Hamburg and the Max Planck Society. “With our novel approach, we want to integrate electronics into existing structural units and improve components in terms of space and weight.” Rübhausen led the project together with DESY researcher Stephan Roth. Using the bright X-rays from DESY’s research light source PETRA III as well as other measuring methods, the team precisely analysed the properties of the nanowires in the polymer.

“At the heart of the technology are silver nanowires that form a conductive mesh,” explains Glier. The silver wires are typically several tens of nanometres (millionths of a millimetre) thick and 10 to 20 micrometres (thousandths of a millimetre) long. The detailed X-ray analysis shows that the structure of the nanowires in the polymer is not changed, but that the conductivity of the mesh even improves thanks to compression by the polymer, as the polymer contracts during the curing process.

Silver nanowires

The silver nanowires are applied to a substrate in suspension and dried. “For cost reasons, the aim is to achieve the highest possible conductivity with as few nanowires as possible. This also increases



A mesh of silver nanowires forms the flexible electronics. The wires are typically 0.01 to 0.02 millimetres long and a few dozen nanometres (millionths of a millimetre) thick.

the transparency of the material," explains Roth. "In this way, layer by layer, a conductive path or surface can be produced." A flexible polymer is then applied to the conductive paths, which can in turn be covered with conductive paths and contacts. Depending on the geometry and material used, various electronic components can be printed in this way.

In this study, the researchers produced a flexible capacitor. "In the laboratory, we carried out the individual work steps in a layering process, but in practice they can later be completely transferred to a 3D printer," explains Glier. "However, the further development of conventional 3D printing technology, which is usually optimised for individual printing inks, is also essential for this. In inkjet-based processes, the print nozzles could be clogged by the nanostructures," notes Rübhausen.

In the next step, the researchers now want to test how the structure of the conductive paths made of nanowires changes under mechanical stress. "How well does the wire mesh hold together during bending? How stable does the polymer remain?," says Roth, referring to typical questions. "X-ray investigation is very suitable for this because it is the only way we can look into the material and analyse the conductive paths and surfaces of the nanowires."

Scientific Reports, 2019; DOI: 10.1038/s41598-019-42841-3

> *"X-ray investigation is the only way we can look into the material and analyse the conductive paths and surfaces of the nanowires."*
>
> **Stephan Roth, DESY**

Picture: University of Hamburg, Ferdinand Otto; DESY (portrait)

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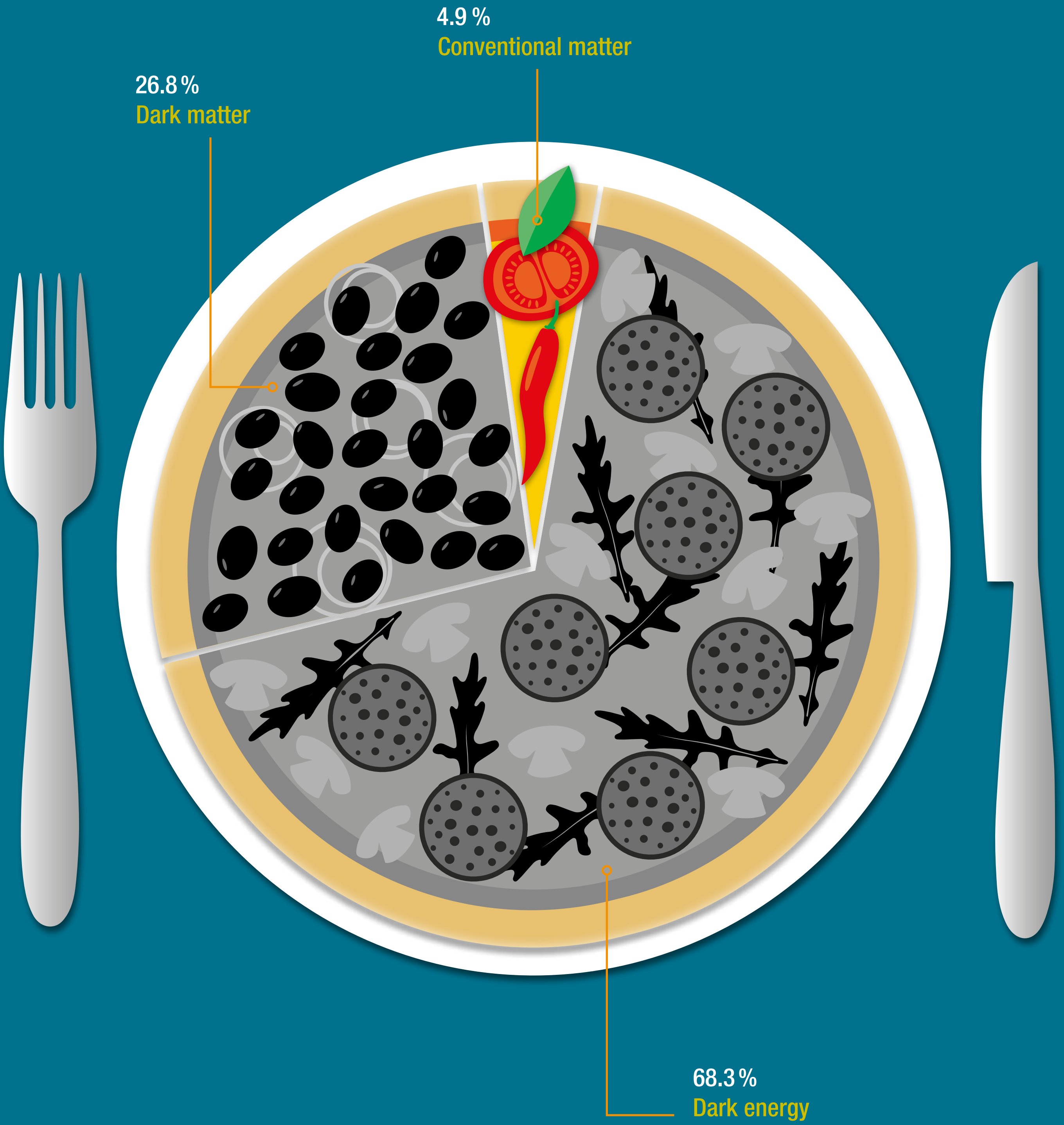
Recipe for a universe

Around 0.000 000 000 000 000 000 000 000 000 000 000 01 seconds after the big bang, inflate the universe quickly and boldly at least 100 000 000 000 000 000 000 000 000-fold. Attention, hot! Then let it rest for 13 800 000 000 years. After 300 000 000 to 500 000 000 years, the first stars should form. Important: Do not disturb, otherwise the matter will not spread properly. Lump formation is normal and desired. The recipe is sufficient for at least 100 000 000 000 galaxies with around 100 000 000 000 stars each.



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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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