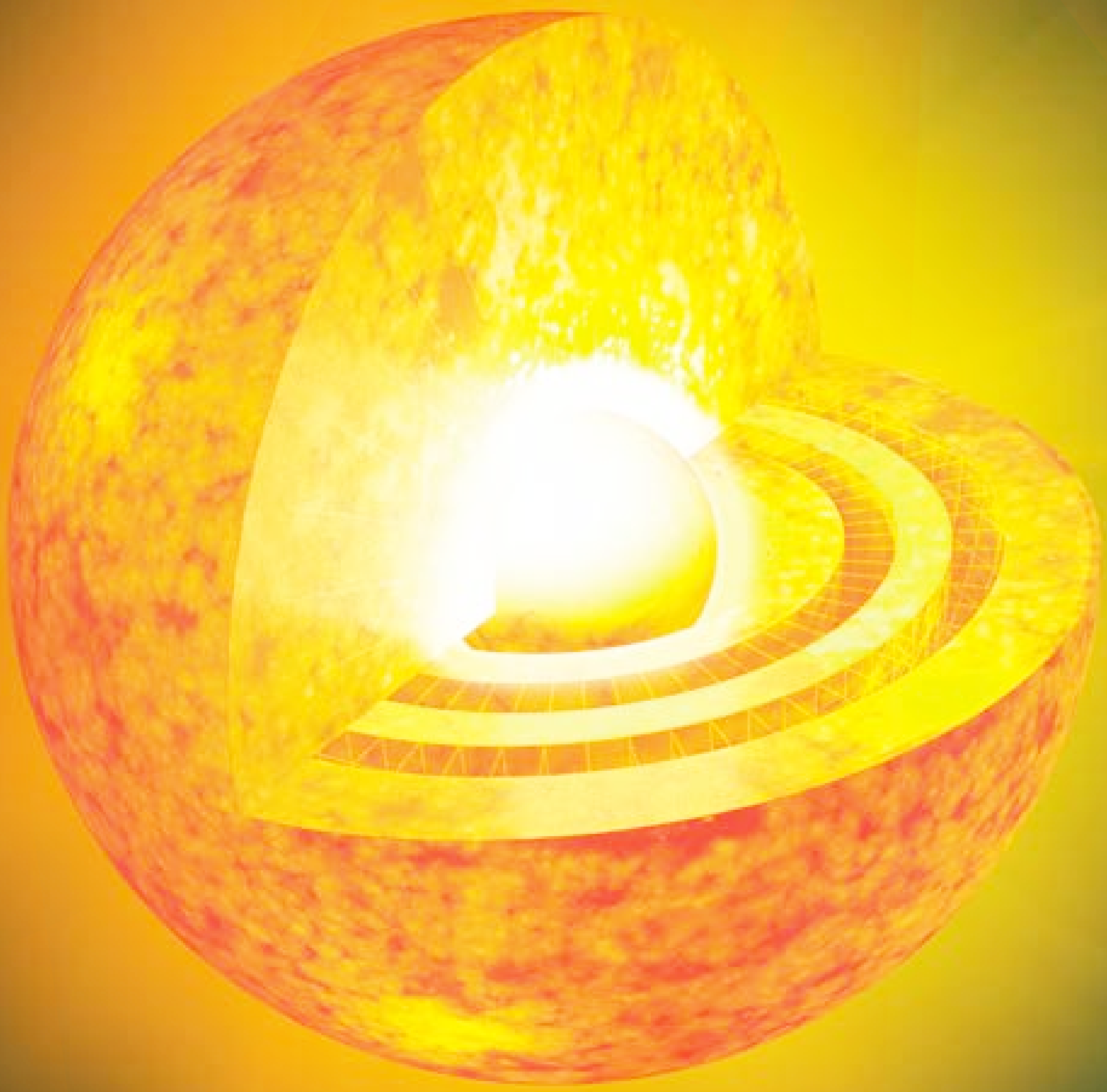


Sun

Graphics: ediundsepp

Links

www.e15.ph.tum.de
borex.lngs.infn.it

Neutrinos II

Signals from Deep inside the Sun

With the Borexino experiment, physicists at TUM have been able to gain direct insight into the core of the Sun for the first time and explore how it generates energy. This success was enabled by a custom-built experimental set-up with the lowest levels of radioactivity on Earth.

Signale aus dem Innersten der Sonne

Im Gran-Sasso-Untergrundlabor ist es Forschern der TUM mit dem Experiment Borexino im Rahmen einer internationalen Kollaboration gelungen, Neutrinos nachzuweisen, die direkt bei der Verschmelzung von Protonen im Inneren der Sonne zu Helium entstanden sind. „Damit konnten wir zum ersten Mal wirklich zusehen, wie die Sonne ihre Energie gewinnt. Das ist die fundamentalste Reaktion, die Ursprungsreaktion, alles andere baut darauf auf, auch das Leben auf der Erde“, sagt Prof. Lothar Oberauer, der zusammen mit Prof. Stefan Schönert und Prof. Franz von Feilitzsch das Borexino-Experiment von deutscher Seite initiiert hat.

Bisherige Analysen der Sonnenenergie beruhten auf Messungen der Sonnenstrahlung. Im Durchschnitt braucht diese jedoch über 100.000 Jahre, um aus dem dichten Sonneninneren an die Oberfläche zu gelangen. Das bedeutet, dass die errechneten Werte der Energie entsprechen, die über 100.000 Jahre zuvor im Inneren der Sonne freigesetzt wurde. Ganz anders verhalten sich Neutrinos: Weil diese als elektrisch neutrale Elementarteilchen mit anderer Materie kaum in Wechselwirkung treten und sich deshalb frei bewegen können, verlassen sie auch das Sonneninnere wenige Sekunden nach ihrer Erzeugung und erreichen bereits nach gut acht Minuten, also quasi mit Lichtgeschwindigkeit, die Erde.

Mit diesem Erfolg, der 2014 in „Nature“ veröffentlicht wurde, vervollständigten die Wissenschaftler am Borexino-Experiment eine ganze Reihe von Messungen, bei denen schon in den vergangenen Jahren Neutrinos aus unterschiedlichen Fusionsschritten in der Sonne nachgewiesen wurden. Da die Neutrinos aus der Proton-Proton-Reaktion zwar am häufigsten sind, aber gleichzeitig eine besonders niedrige Energie aufweisen, war es vorher nirgendwo auf der Welt gelungen, sie direkt in Echtzeit nachzuweisen. Borexino konnte aufgrund seines einzigartigen Aufbaus, der von radioaktiven Einflüssen fast vollständig frei gehalten wurde, den störenden Untergrund bei den Messungen unterdrücken und eine fünfprozentige Messgenauigkeit erzielen. *Brigitte Röthlein*

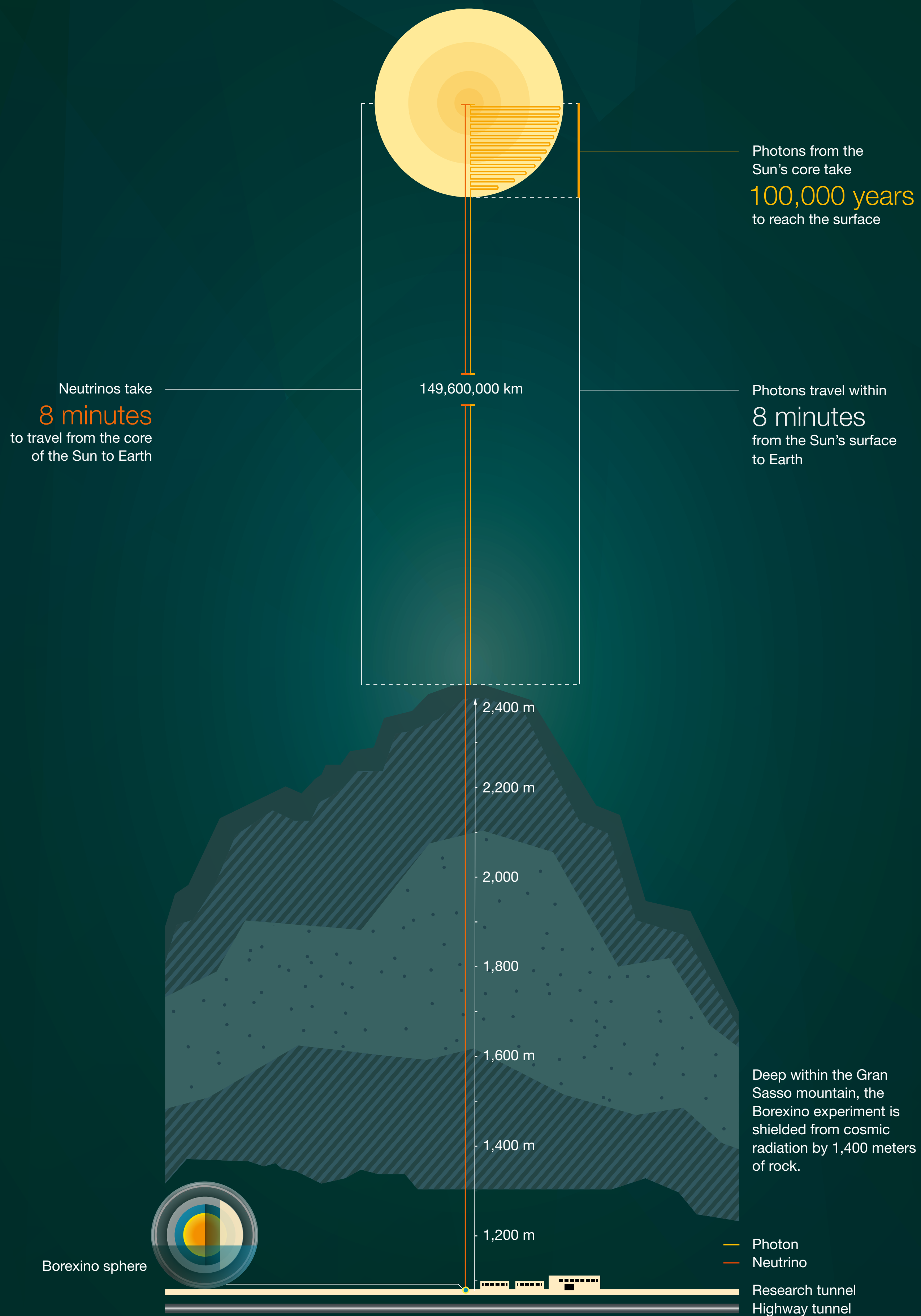
One does not have to look billions of light-years into space to find exciting astrophysical events – sometimes a glance in the immediate vicinity is sufficient. Although the Sun is just eight light-minutes removed from us, it only recently became possible to observe fundamental processes within its core in real time. The reason for this is that the Sun – a gas ball with a temperature of 15 million degrees Celsius – is so dense that photons can escape from the center to the outside only with great difficulty. It takes about 100,000 years on average for a light particle to reach us from the Sun. A photon experiences so much in this time that is does not provide information on how it was formed.

Neutrinos: messengers from the Sun

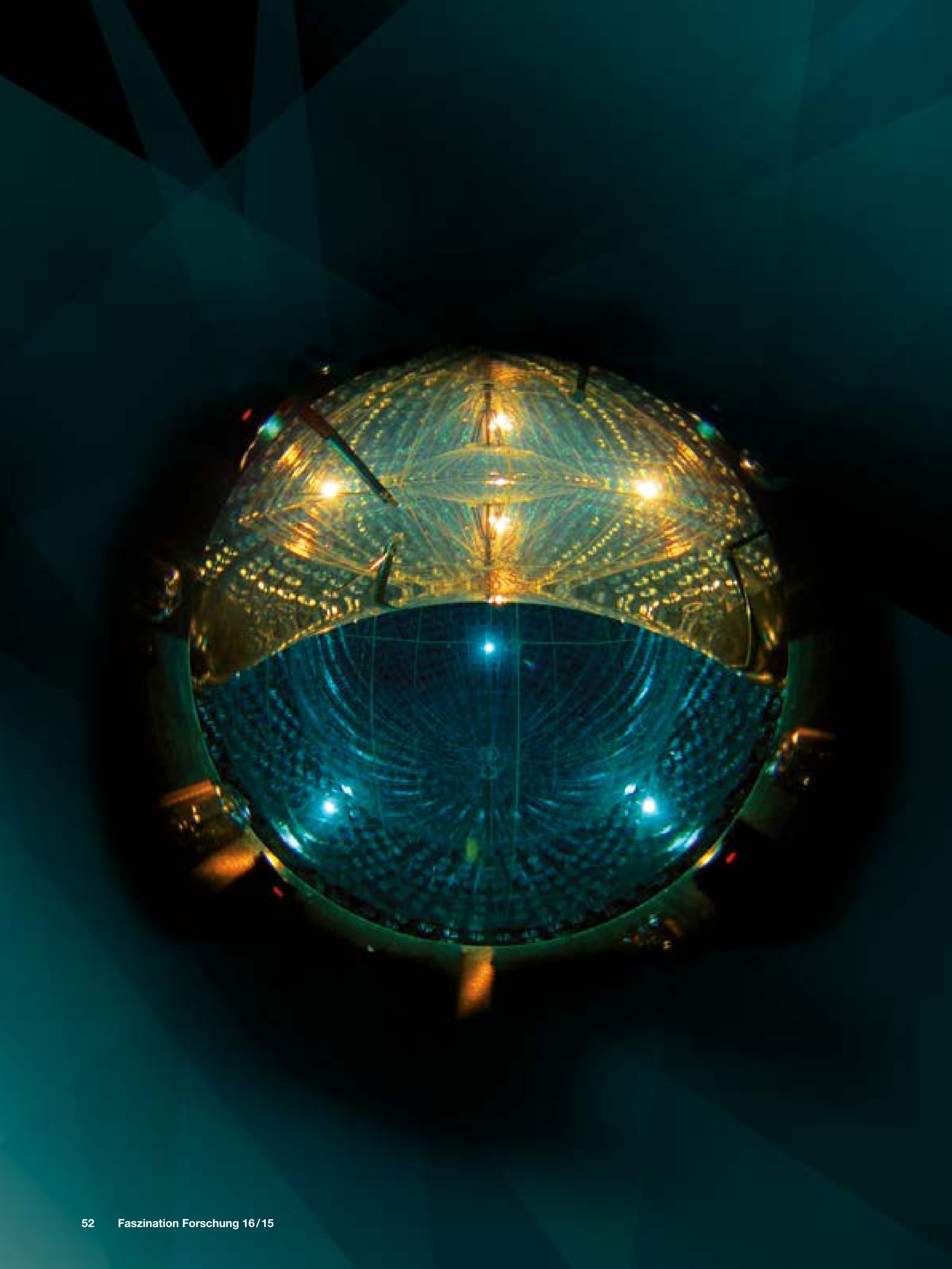
However, there are other elementary particles that pass through the Sun relatively unimpeded. As a result, they can provide us with information from the heart of the Sun. Neutrinos have no electric charge and are therefore subject to only the forces of gravity and weak interaction. The latter is what now gives researchers the opportunity to prove their existence in an experiment.

Rutherford, Walton and Cockcroft were the first to observe the nuclear reactions of light elements as early as 1932. They showed that a lithium nucleus, after capturing a ▷

The Gran Sasso laboratory lies deep underground in a tunnel in the Abruzzo region, around 120 kilometers northeast of Rome. It is shielded from unwanted radioactivity by 1,400 meters of rock. Solar neutrinos not only pass through all the layers of the Sun, but also through the rock more or less unhindered. Photons, on the other hand, need to travel for 100,000 years or so until they reach the edge of the Sun.



Graphics: ediundsepp



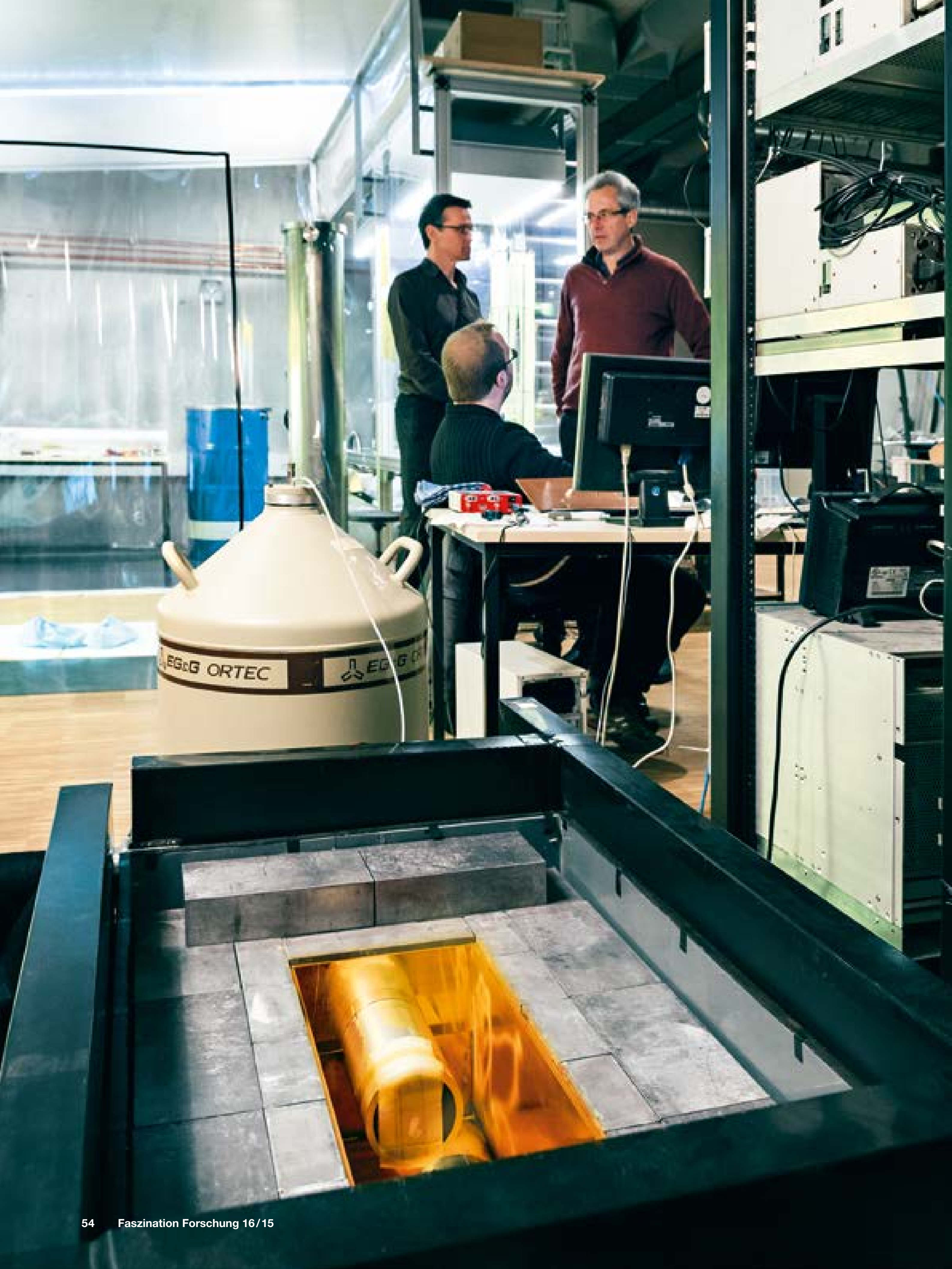
300

tons of organic liquid scintillator

Picture credit: Borexino Collaboration

"We were able to really see for the first time where the Sun get its energy from. This is the most fundamental reaction – the first ever reaction – everything else derives from it, including life on Earth."

Lothar Oberauer


EG&G ORTEC
EG&G OR

The scientists commute between their institutes and the Gran Sasso facility. A lot of detailed work and preliminary investigations, as well as data analysis and theoretical discussion, also happen outside of the Borexino lab. At TUM's underground laboratory in Garching, the scientists test the radioactive purity of their detector materials for Borexino using a germanium detector.

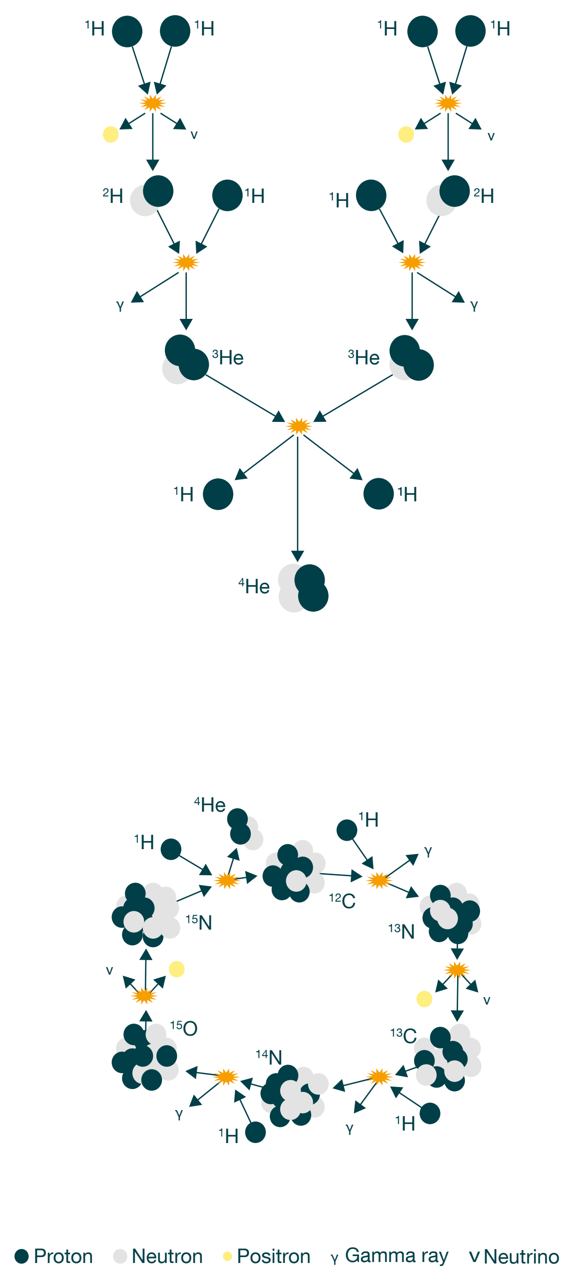
proton, splits into two helium nuclei and releases energy in the process. The knowledge gained from this event and from later experiments prompted theoretical physicists to examine fusion processes more closely to see where the Sun gets its energy. Today we know in what processes neutrinos are created inside the Sun: first, in the fusion of two hydrogen nuclei (or protons, p) to form heavy hydrogen (deuterium, D); then in lateral lines during radioactive decays of the beryllium isotope with an atomic weight of 7 (^{7}Be) and of the boron isotope ^{8}B. At the same time, there is the Bethe-Weizsäcker cycle – another cascade of fusion reactions named after its discoverers – in which neutrinos are also created. All neutrinos have very different but in some cases characteristic energy distributions; these allow us to identify the process that created the corresponding neutrinos. They fly out of the interior of the Sun in all directions. Even on Earth, 150 million kilometers from the Sun, almost 70 billion solar neutrinos pass through each square centimeter every second.

Solar research in a tunnel

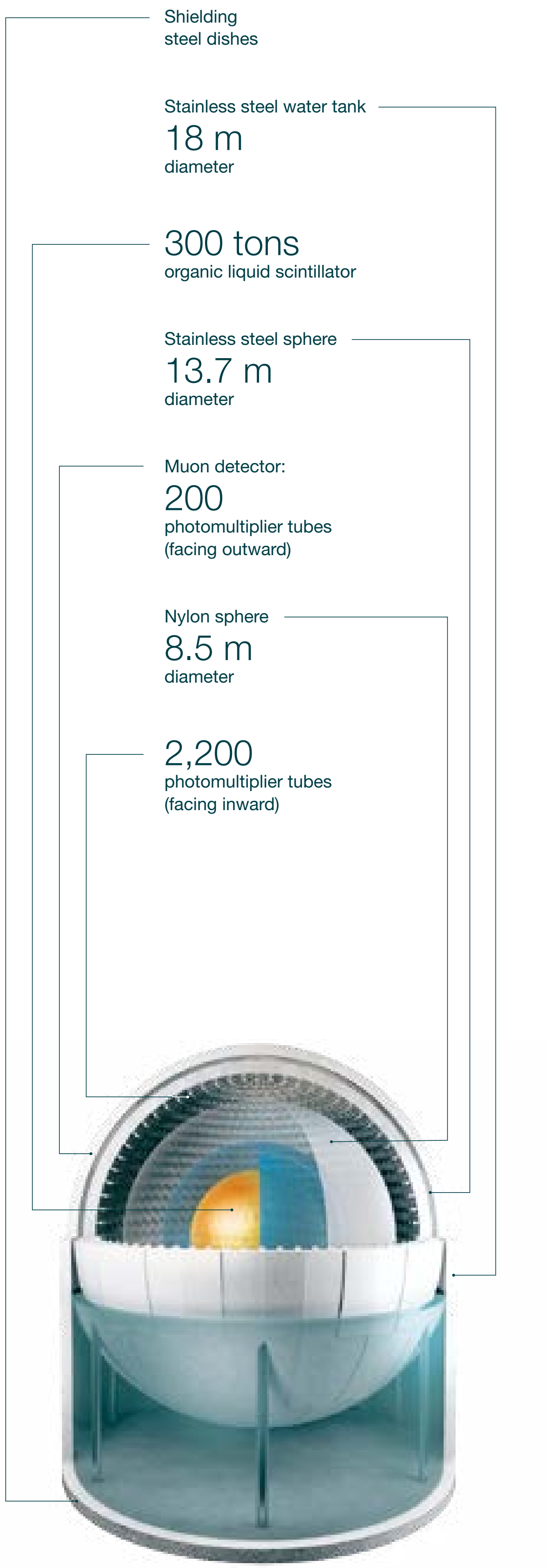
What is paradoxical here is that these particles are being measured at a location where there is absolutely no evidence of the Sun – in a tunnel deep underneath the Gran Sasso mountain in Italy. The tunnel houses Borexino, which contains an 8.5 m large, transparent sphere made of nylon foil and filled with 300 tons of exotic liquid scintillator. Using this sphere, researchers collaborate across borders to unravel the solar fusion processes by measuring solar neutrinos. The experiment began in 2007 and a large number of exciting results have been published since. For example, scientists there were able to detect and measure a wide range of neutrinos derived from different fusion steps: ^{7}Be neutrinos in 2007, ^{8}B neutrinos in 2009, and so-called pep neutrinos in 2012. "These neutrinos occur during very rare three-body processes in the Sun, in which two protons and an electron come together at the same time and fuse with each other," explains Prof. Lothar Oberauer, who initiated Borexino together with ▷

Fusion reactions inside the Sun

In principle, the Sun gets its energy from the fusion of hydrogen nuclei into helium. This involves a number of stages that produce heavy hydrogen (deuterium, D) and an isotope of helium with one neutron (helium-3) (top diagram) as intermediate products. At the same time, there is the Bethe-Weizsäcker cycle or CNO (carbon-nitrogen-oxygen) cycle, in which the elements act as a catalyst (bottom diagram). With all of these fusion processes, energy is released and a range of elementary particles are formed, including the neutrinos.



Picture credit: Eckert; graphics: ediundsepp



The actual Borexino detector is the innermost sphere (yellow), where incoming neutrinos create tiny flashes of light. This core is surrounded by a number of layers of shielding intended to intercept all disturbances from external radioactivity or decay processes. Photomultiplier tubes around the sphere amplify and record the strength and direction of the light flashes.

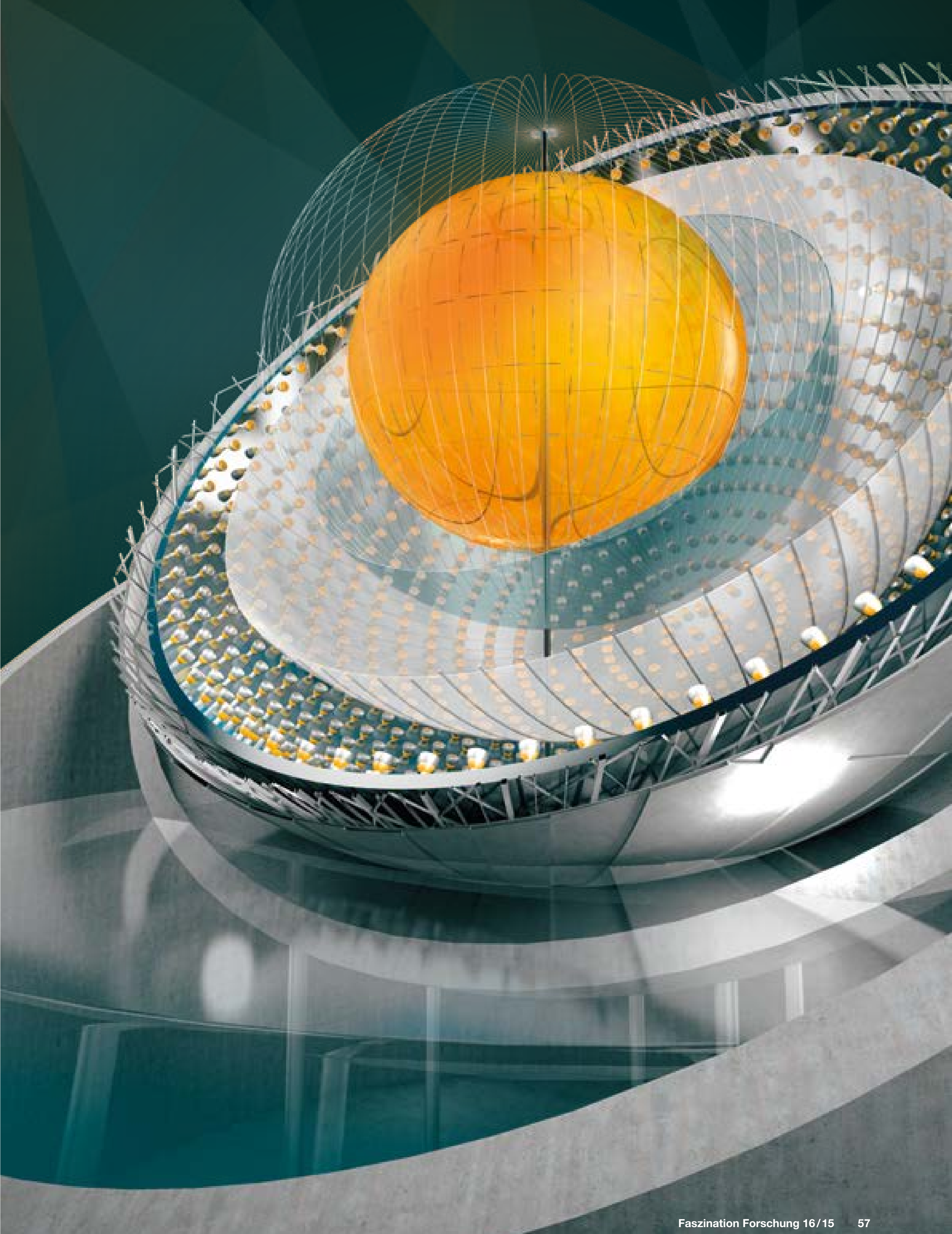
Graphics: ediundsepp

his colleagues Prof. Stefan Schönert and Prof. Franz von Feilitzsch. “In doing so, heavy hydrogen – a deuteron – and an electron neutrino are formed. These events are so rare that the radioactive background in the experiment plays a major role. At Borexino, we were the first in the world to prove the existence of these neutrinos.”

A dream come true for the physics community

2014 marked a new highlight: at long last, the researchers in the underground laboratory were able to prove the existence of neutrinos from the core of the Sun that were the result of the very fundamental fusion of proton with proton. In this way, they could practically directly observe how hydrogen nuclei fuse together inside the Sun to produce energy – the fulfillment of an ancient physics dream. The generated pp neutrinos have very little energy and can therefore be detected only in extremely sensitive systems, since the lower the energy, the more difficult it is to distinguish the flash of light from the background for absolute proof. “We were very pleased that we were able to verify their existence with the required level of certainty after such a long time, because we have come to know our detector very well,” says Oberauer. “We were able to really see for the first time where the Sun gets its energy from. This is the most fundamental reaction – the first ever reaction – everything else derives from it, including life on Earth.”

The measurements taken benefited from the fact that the researchers constructed Borexino with particular care and attention. “We were able to measure in real time neutrinos with particularly low energies and thus provide quantitative information on the processes taking place within the core of the Sun. This was impossible with previous experiments,” Stefan Schönert emphasizes. “The measurements were successful only because Borexino is the most sensitive detector on Earth and because we were able to massively reduce disturbances due to radioactivity and other cosmic particles.” This was attributable to the care that was taken when setting up the experiment to ensure ▷



that all sources of radioactivity were diminished as much as technically possible. No normal materials were used, as these always contain some natural radioactivity. Instead, each component had to be composed of extremely pure material; the further into the system, the purer the material.

Incredible standards of cleanliness

The reason for these precautionary measures is that the Borexino detectors cannot, in principle, distinguish a natural decaying process from a neutrino event. "This means, however, that we have to be very careful and develop an incredible level of cleanliness. Materials cannot be purchased and transported as pure as we need them. Instead, we have to develop ways of purifying them," explains Oberauer. And that is what was done, using chemical and physical methods. For example, the liquid scintillator inside Borexino – in which some neutrinos generate their revelatory light flashes – contains trace elements of uranium and thorium with a concentration of less than 10^{-19} g/g. This means that, in reference to uranium and thorium, the liquid scintillator is 10 trillion times purer than any natural building material. "Borexino is now the purest spot in the world when it comes to radioactivity," claims Lothar Oberauer.

Nevertheless, a certain trace of radioactivity can never be fully avoided. In recent years, however, researchers have continually increased the precision of their measurements over a number of test series using artificial sources of radioactivity. They have identified an inner core of the liquid volume of around 100 tons, into which external interference can practically no longer penetrate. If only the measurements performed in this "fiducial volume" are accepted as valid, overall uncertainty concerning the measurements of ^{7}Be neutrinos can be reduced to about 5 percent. "It is interesting that theoretical predictions in astrophysics have an error margin of 8 percent," notes Oberauer. "That means that we measure more precisely than theory can predict." To get an idea of what kind of precision this means, consider that, of the 1.5 x 10^{21} (1.5 trillion billion) neutrinos that fly through the fiducial volume every day, only 48 are detected on average. And most of these are emitted due to the proton-proton fusion reaction in the Sun.

The new results, published in "Nature", present the first experimental proof that the release of energy inside the Sun has remained unchanged for a very long time. To prove this, researchers compared the values of current solar energy – which can now be measured using the new method – with values of the solar energy from more than one hundred thousand years ago – which can be calculated from solar radiation. The results of the comparison ▷

2,200 sealed, custom-made photomultipliers are arranged around the innermost sphere. These were subject to intensive prior testing to ensure that the material they are made of releases practically zero radioactivity. In addition, all electrical wires fed through the outer water-filled tank had to be completely sealed, which made assembly much more difficult.

Picture credits: Eckert;
Top right: Paolo Lombardi Infn Mi/LNGS

“We were able to measure in real time neutrinos with particularly low energies. This was impossible with previous experiments.”

Stefan Schönert

tally with current theoretical solar models. In this way, the picture we have of the fusion processes inside the Sun is gradually coming together, although many of the measurements have yet to be more closely verified.

Do sterile neutrinos exist?

Nonetheless, fundamental questions remain unanswered, and these will command the attention of particle physicists in particular. Neutrinos have a characteristic that makes them very enigmatic: they exist in three different forms and change from one to the other – what physicists call neutrino oscillations. Previous measurements as well as Borexino have confirmed this theory, even if they do not seem to match the theoretical constructs of the standard model. In Borexino analysis, the solar matter effects on these oscillations were observed with unprecedented accuracy. There are now signs that there are “sterile” neutrinos, which are not subject to weak interaction. The existence of such exceptional particles is an as yet unproven hypothesis. “Many people are skeptical and their existence is the subject of a lively debate in the scientific community,” says Oberauer. Stefan Schönert adds: “It must be examined experimentally in any case, since the consequences would be immense for particle physics. The proof of existence of sterile neutrinos would represent a revolution of sorts.” Schönert and Oberauer therefore co-initiated the setting up of a new experiment in Italy whose purpose is the search for sterile neutrinos.

Both physicists are also involved in preparing and developing other future neutrino experiments in China and Italy – these will build on the insights gained thus far and will be able to measure with even greater precision. Yet another objective at Borexino is to measure the neutrinos from the Bethe-Weizsäcker cycle more precisely, thus eliminating all remaining uncertainties regarding the generation of energy in the Sun. The topic is one that has taken a firm hold of Oberauer: “I think neutrinos are the most interesting objects any physicist can study. We have only just celebrated the discovery of the Higgs boson – a fantastic achievement, as it represents the final cornerstone in the standard model. Nevertheless, I am certain that the neutrino masses are not created due to the Higgs mechanism. These particles are, so to speak, our link to a new, unknown world.”

Brigitte Röthlein

Physics professors Lothar Oberauer (above left) and Stefan Schönert (above right) jokingly refer to themselves as part of the “bedrock” of the Borexino research facility. They have been there from the beginning and will lend a hand in the conception and planning of future experiments. They are pictured here working on a detector for a new neutrino experiment.

Picture credits: Eckert