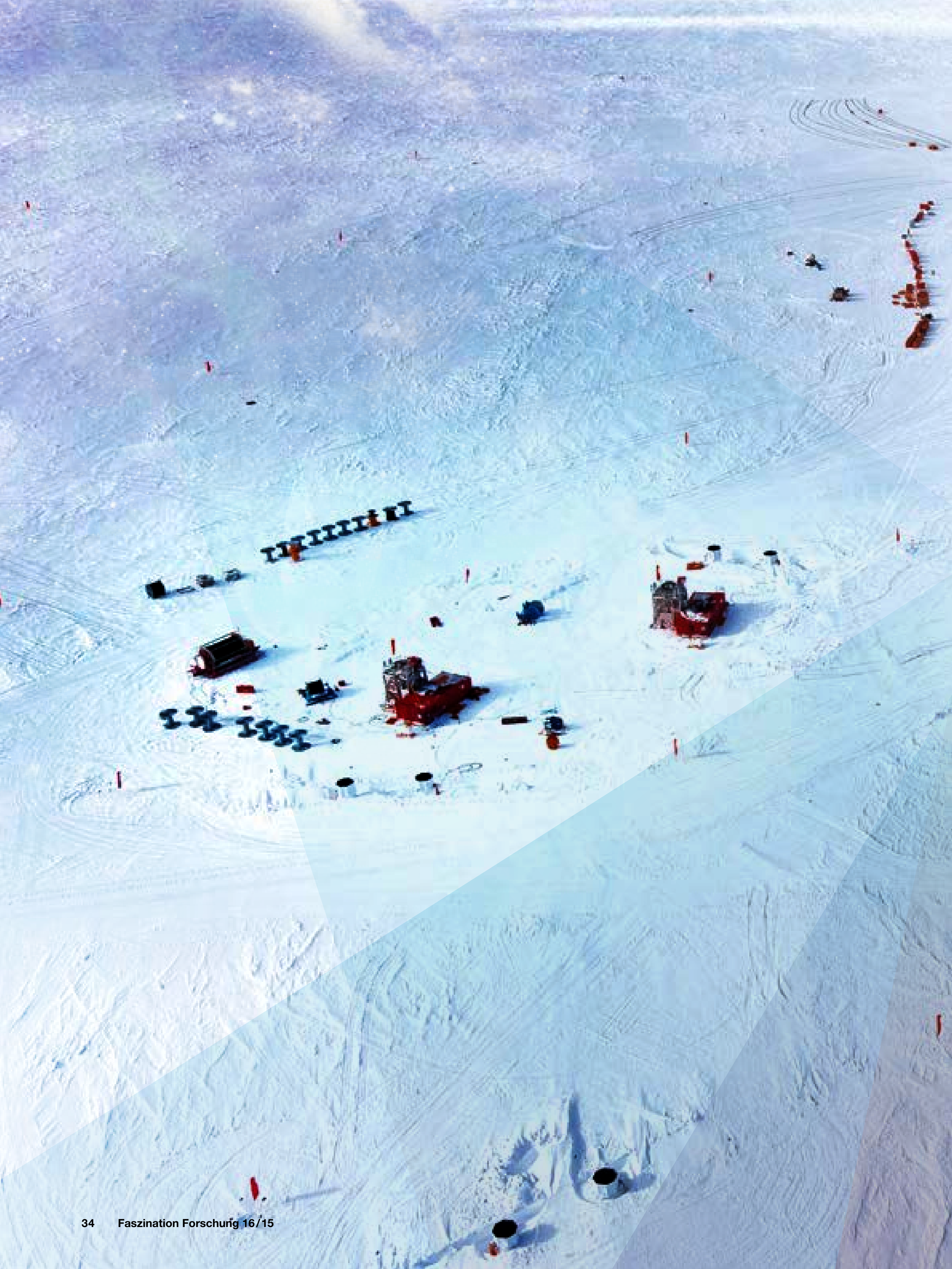
Neutrinos I

A New Window **on the Universe**

Energy-laden neutrinos making their way to us from outer space must have originated in cosmic catastrophes that were more powerful than anything we could ever imagine here on Earth. As part of the IceCube project, TUM physicists are investigating various phenomena including the sources of such cataclysmic events in the heavens.

Links
www.cosmic-particles.ph.tum.de www.icecube.wisc.edu

Picture credit: IceCube Collaboration; graphics: ediundsepp



An aerial view of the IceCube Lab. To the left of the lab are drilling hoses, towers and equipment, to the back right is the seasonal equipment site. The lab covers a surface of 1 square kilometer.

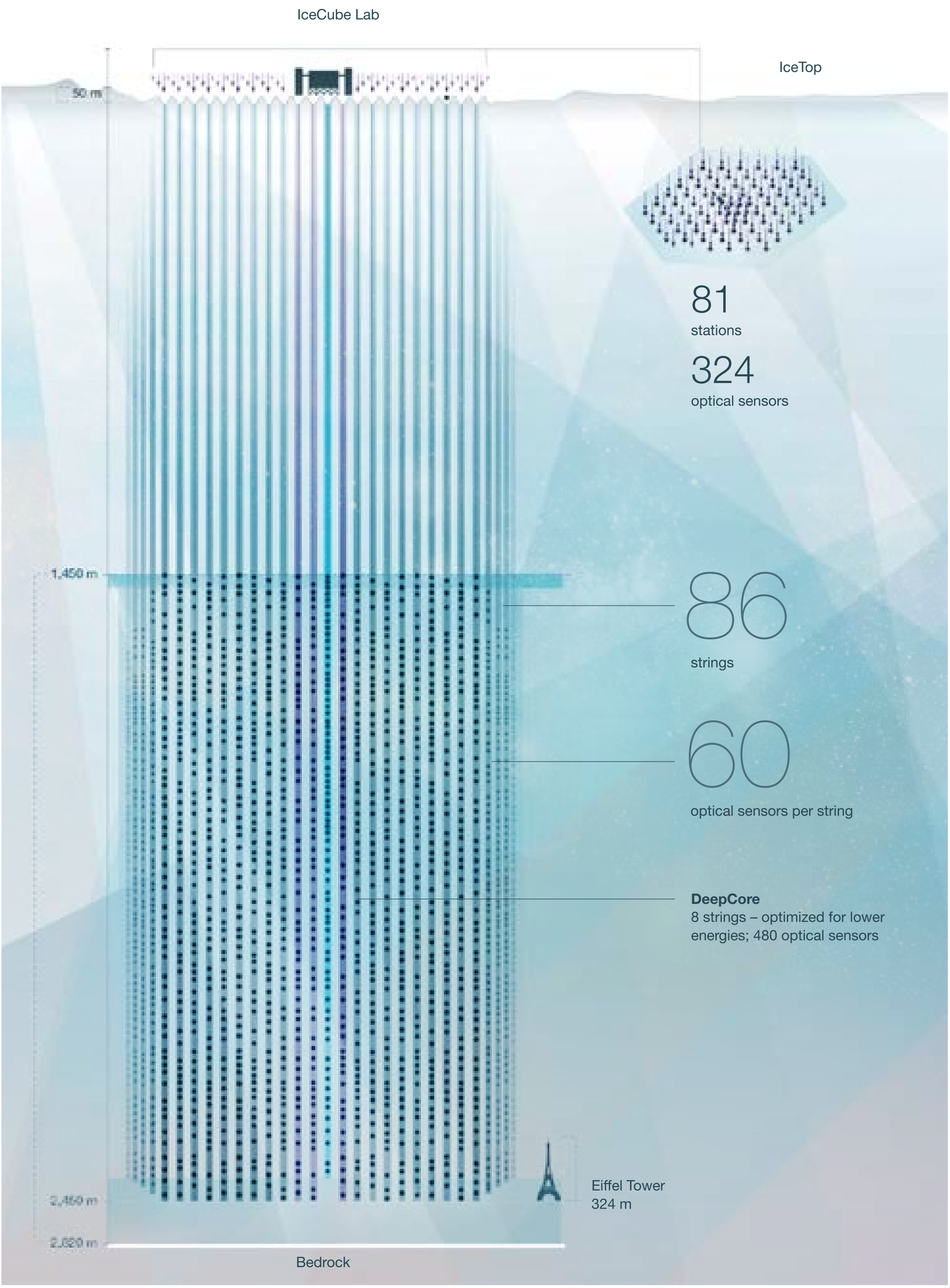
Picture credit: Ben Tibbets, IceCube/NSF, © 2012

Ein neues Fenster zum All

Am Südpol befindet sich das außergewöhnlichste Teleskop der Welt: Es heißt IceCube und soll die kleinsten Teilchen des Universums, sogenannte Neutrinos, aufspüren. 44 Organisationen aus zwölf Ländern beteiligen sich an der Kooperation, darunter auch ein zwölfköpfiges Team der TUM unter der Leitung von Prof. Elisa Resconi.

Die Anlage, die aus 5.160 optischen Sensoren besteht, wurde 2.000 Meter tief ins antarktische Eis versenkt und umfasst ein Volumen von rund einem Kubikkilometer. IceCube registriert Zusammenstöße von Neutrinos mit Eismolekülen, die Teilchenschauer auslösen und letztlich zu einem blau-ultravioletten Tscherenkow-Blitz führen. Durch die große Ausdehnung des Experiments lassen sich sowohl die Energie als auch die Einfallsrichtung der Teilchen messen. Eines der Hauptziele von IceCube ist es, hochenergetische Neutrinos aufzuspüren, die aus katastrophalen Ereignissen im Weltall stammen. Sie sollen sowohl helfen, die Prozesse bei ihrer Entstehung zu verstehen, als auch die Quellen derartiger kosmischer Ereignisse zu finden. Bis Anfang 2015 konnten die IceCube Forscher bereits 53 derartige Neutrinos aufspüren. Je nachdem, welches Bild sich in den kommenden Jahren aus der Durchmusterung des Himmels ergibt, könnten sie alternativ auch Hinweise auf dunkle Materie im All sein. Ein weiterer wichtiger Forschungszweig, an dem die TUM Wissenschaftler beteiligt sind, ist die Erforschung der Natur des Neutrinos. Durch die Untersuchung von atmosphärischen Neutrinos, von denen weit über 100 täglich in IceCube registriert werden, möchte man Näheres über die Oszillation dieser Teilchen erfahren. Bisher weiß man nur, dass sie aus drei verschiedenen Zuständen bestehen, die ineinander übergehen können. Welche Masse diese Zustände jeweils haben und wie sie physikalisch erklärt werden können, ist heute noch nicht bekannt. Zur Klärung der Lage soll ein neuer Detektor namens PINGU beitragen, der im Zentrum von IceCube geplant ist. Die Forscher hoffen, dafür finanzielle Mittel zu bekommen.

Brigitte Röthlein



Picture credit: ediundsepp (source: IceCube Collaboration)

The IceCube Neutrino Observatory is the world's largest neutrino detector. Located at the South Pole, IceCube is buried inside the ice masses of Antarctica, reaching a depth of about 2,500 meters. In total, it encompasses a cubic kilometer of ice. IceCube is made up of 5,160 light sensors attached to 86 vertical strings spaced at intervals of 125 meters. The sensors collect light emitted by particles that are produced during interactions between neutrinos and ice molecules.

"Trillions of neutrinos are passing through your body alone while you are reading this sentence, but probably only once in your life does one remain inside you."

Elisa Resconi

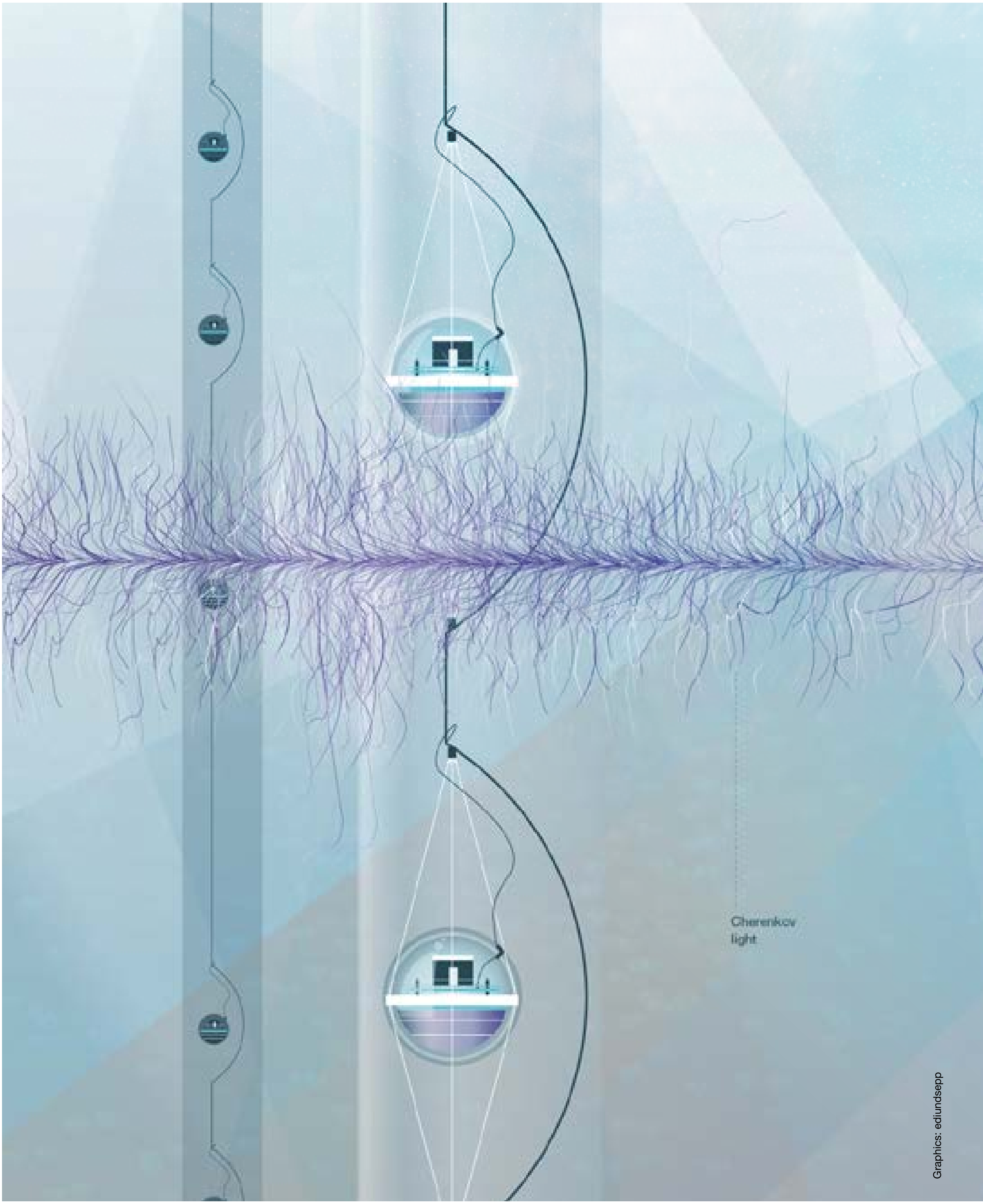
The Sun never sets – it circles the horizon, always at the same height, and night is just as bright as day. Dr. Martin Jurkovic from TUM experienced this spectacle when he spent a month at the South Pole in December to work on the yearly inspection of the IceCube neutrino telescope. "It was a fantastic experience," says the physicist, "and a completely foreign world to me. While there, I worked on the IT system and I spent a lot of time outside digging snow, as we need to measure the snow accumulation on the surface detectors."

IceCube is a large-scale international project intended to detect neutrinos – particles that have the special property that they can pass through matter without difficulty. They fly straight through stars as well as the Earth without impact.

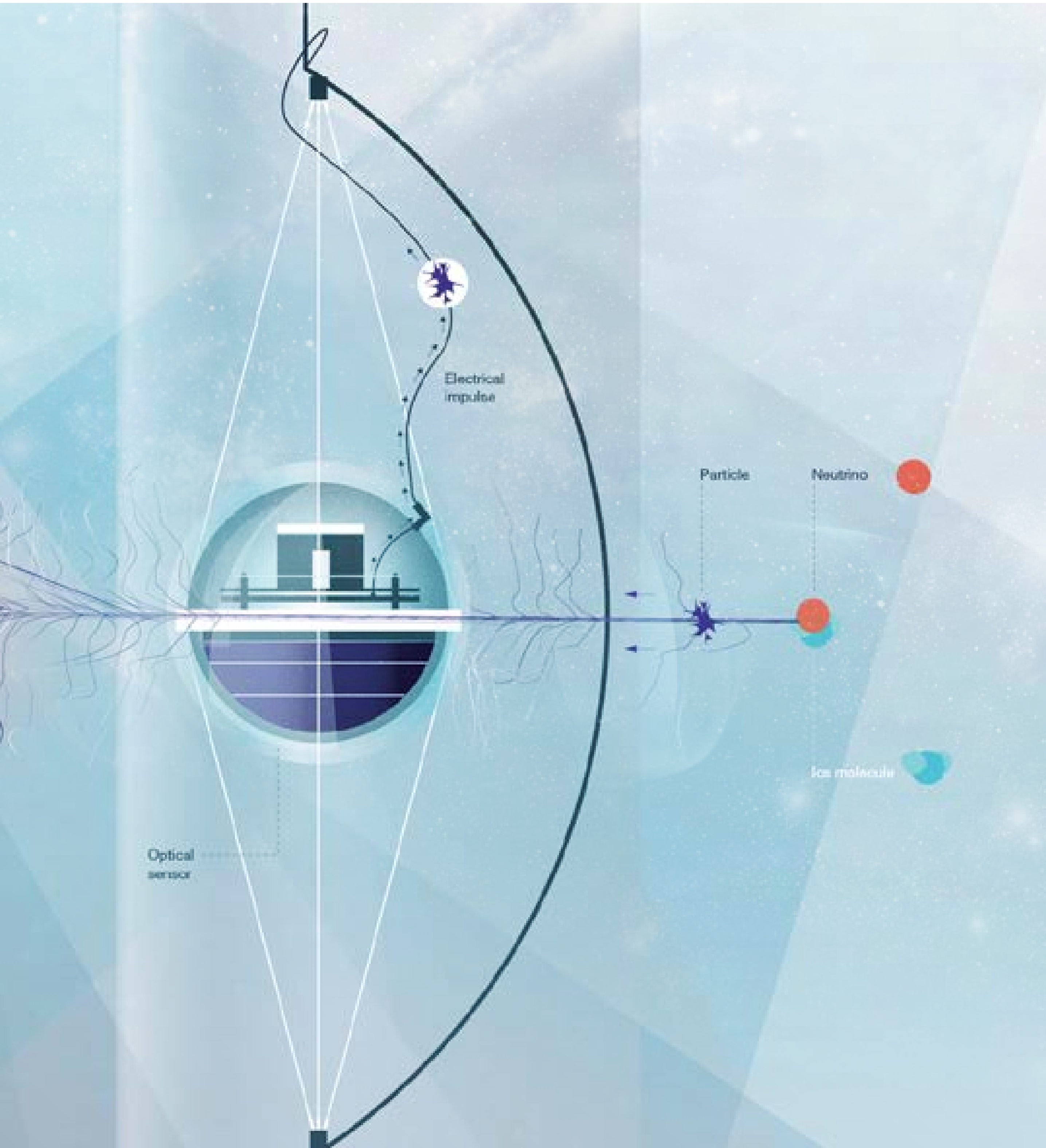
As a result, neutrinos are difficult to detect, although countless numbers of them are continuously racing through the galaxy and the solar system. "Trillions of neutrinos are passing through your body alone while you are reading this sentence," claims Prof. Elisa Resconi, Head of TUM's research team at IceCube, "but probably only once in your life does one remain inside you." One of the objectives of the experiment is to detect extremely energetic neutrinos arriving from outer space. In November 2013, the IceCube Collaboration announced the first detection of such neutrinos. These may have arisen during the birth of a supernova, or they could have been ejected from the vicinity of a black hole. Neutrinos could offer a means of receiving signals directly from these objects that until now have been regarded as mysterious. This is not possible with light, radio or X-ray radiation because their photons are hindered by intergalactic clouds or other obstructions. IceCube is continuously searching the skies for such neutrinos, thus opening up a completely new window on the universe.

A three-kilometer-thick layer of high-quality ice

The neutrino detector was sunk deep into the Antarctic ice, where it occupies a volume of about one cubic kilometer. It has 5,160 optical sensors, each the size of a basketball, which were deployed into the ice in vertical lines (strings) in groups of 60 to depths between 1,450 and 2,450 meters. Power supply and signal cables are integrated in the strings. The reason to choose such a harsh environment – the South Pole – for the high-tech observatory is due to the huge volume and the quality of the ice there. It is three kilometers thick, highly transparent, and the adjacent US Amundsen-Scott Station provides the necessary infrastructure. It is located at an altitude of 2,835 meters on the inland ice, only a few hundred meters from the geographic South Pole. ▷



Graphics: ediundsepp



IceCube registers neutrinos from their collisions with ice molecules. This produces charged particles that emit blue to ultraviolet Cherenkov light as they travel through the ice. The IceCube optical sensors collect this light and convert the signal into an electrical impulse. The amplified and digitized electrical signal is sent to the IceCube Lab on the surface. Each sensor module also measures the arrival time of the light with very high accuracy. The combined data of all sensor modules yields the direction and the energy of the neutrons.

There are 44 universities and organizations from 12 countries, the so-called IceCube Collaboration, participating in this mammoth project. The experiment is led by the University of Wisconsin-Madison in the USA. About half of the participating institutions are European, nine of them located in Germany. The 12-person TUM team is primarily involved in software development for analyzing data searching for signatures of energy-rich, so-called cosmic neutrinos. This is an extremely demanding task, as the required results have to be filtered out of the terabytes of data recorded every day by the experiment. The group is also involved in the design and sensor development of the next-generation IceCube detector, an even larger neutrino telescope.

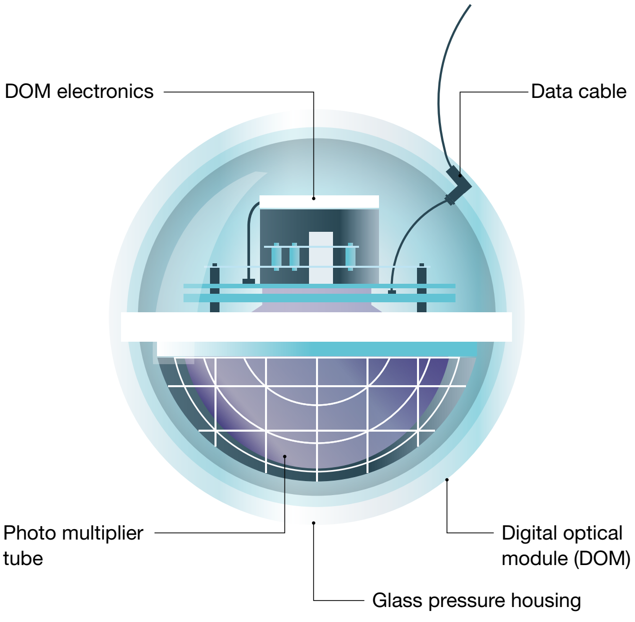
"More data and a larger detector will provide a clue about the origin of these incredible neutrinos in the coming years."

Elisa Resconi

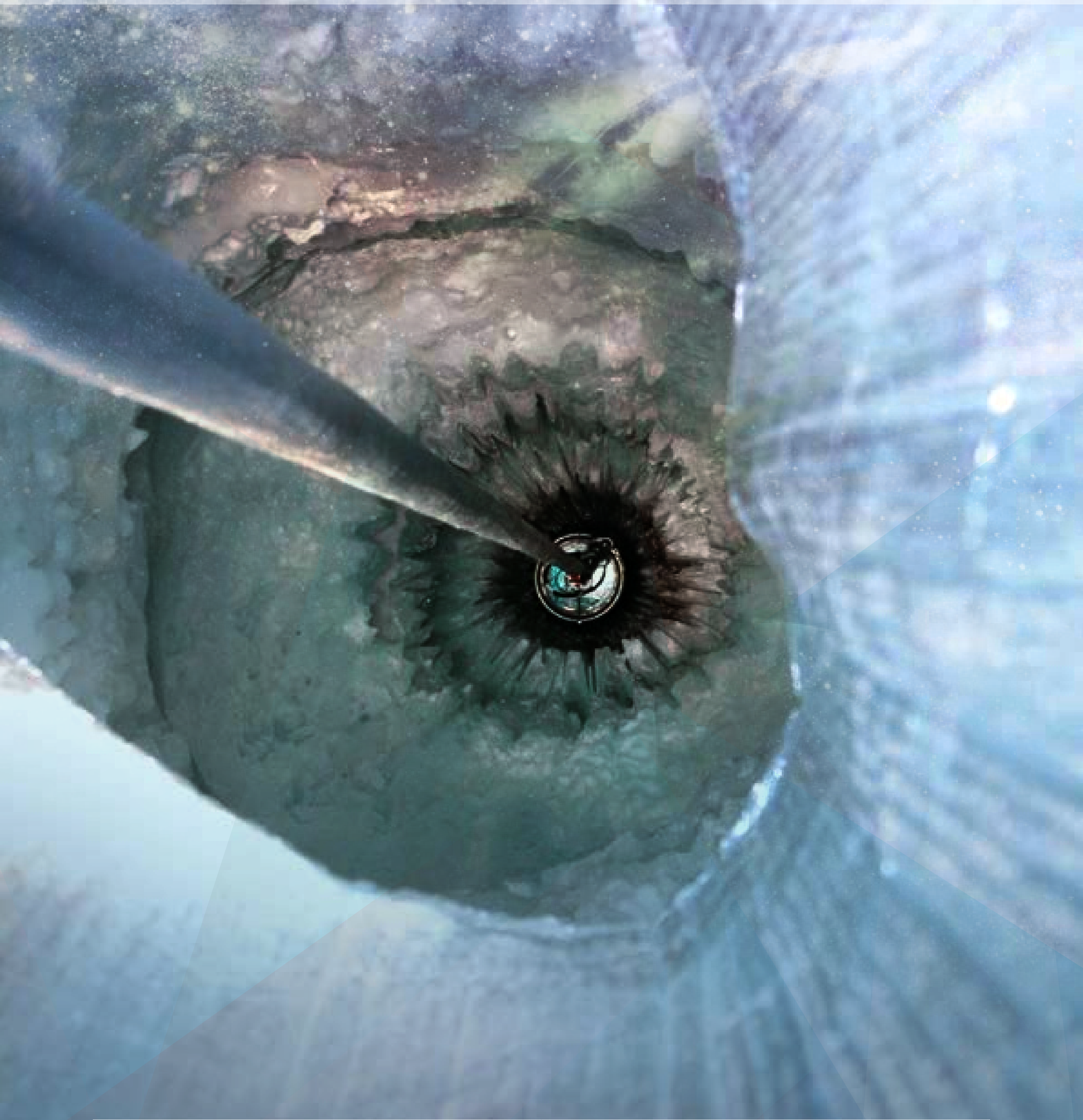
Collisions between neutrinos and ice molecules

IceCube registers collisions between neutrinos and ice molecules. This results in charged particles that radiate a shock wave of blue to ultraviolet Cherenkov radiation in the ice. The optical sensors of the IceCube detector are so sensitive that they react to a single photon. Each light signal is amplified, converted to an electrical pulse and then to a digital signal while still in the detector. Each module has its own mini-computer and a high-precision clock to accurately measure the arrival time of photons to within 5 nanoseconds. The digitized signals then run through kilometers of cables to the data center near the South Pole Station, from where they are finally transmitted to researchers in different centers throughout the world for further analysis. Despite the shielding afforded by the kilometer-thick ice layer, many other particles can still interfere with the measurements. Using a host of clever tricks, the researchers are able to distinguish these particles from the neutrinos. Moreover, it is vital to separate particularly energetic neutrinos from the depths of outer space from neutrinos that occur due to the effects of cosmic radioactivity in the Earth's atmosphere – i.e., directly on our doorstep. These are admittedly also objects of interest for research, but for completely different purposes, as we will explain later in this article. Scientists involved in IceCube discovered, in 2012, two of the sought-after neutrinos with an incredibly high energy level of more than one peta electron volt (PeV), which they named Ernie and Bert. "One PeV corresponds to roughly the energy of a tennis ball moving at hundreds of kilometers per hour," estimates Resconi. This is an unfathomably high value for a particle that is even smaller than an electron. "The neutrinos we detect at IceCube come from all directions and therefore ▷

IceCube comprises 5,160 light sensors called digital optical modules. Each sensor is made up of a glass sphere containg a photomultiplier tube and electronics for time measurement and signal processing. The sensors are so sensitive that they react to a single photon.



Graphics: ediundsepp; picture credit left: Jooss; right: IceCube/NSF

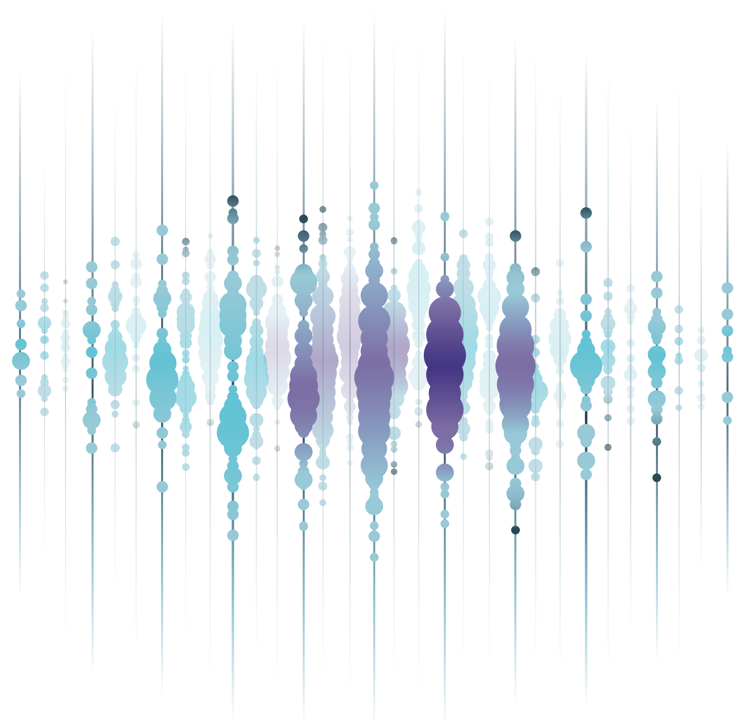


Hot-water drilling

It was no easy task to position the optical detectors precisely in their designated locations at depths of between 1,450 and 2,450 meters. Although ice can be easily melted with a hot-water drill, the technical challenge lies in transporting the hot water to such great depths. The tube made of reinforced aramid rubber specially developed for the task was 2.5 kilometers long and weighed more than 11 tons when empty. “This is a really high-tech device,” explains system engineer Jeff Cherwinka. “It was the critical part of the project and we could find only one manufacturer to produce it.”

The first hole was drilled and the observatory tested in January 2005. Another eight holes were drilled the following year. The holes around the sensors freeze over immediately.

A further 14 holes were bored in each of the subsequent years until the system was completed in 2010. John Wiley, former Chancellor of the University of Wisconsin-Madison, even compared the gigantic project, in terms of its scale and difficulty, to the construction of the Egyptian pyramids.



A neutrino observed in IceCube: The colored spheres indicate optical sensors that detected light. The color corresponds to the arrival time of the light signal. Red marks the beginning, light blue the end of the event, which typically lasts a few microseconds. The size of the colored spheres corresponds to the amount of detected light.

Powers of ten and their syntax		
kilo-	k or K	10^3
mega-	M	10^6
giga-	G	10^9
tera-	T	10^{12}
peta-	P	10^{15}

most of them have passed through Earth. Hence we are using our planet to filter out particles that are not neutrinos. We did so for our first searches, but in 2013 we showed that we can significantly increase measurement accuracy if we consider only the interior volume of our experiment. This relatively simple observation was a major step in the search for the cosmic neutrinos," says the physicist. "Think of it as an onion. Most particles get caught in the outer layer, while we look only at the inner parts." When using the method to again search through the data that had already been collected up to that point for slightly lower energy levels, another 26 high-energy candidates of between 30 and 2,000 TeV were found. By the beginning of 2015 the count had already reached 54 particles.

Where do the neutrinos come from?
The direction of entry of the neutrinos measured by IceCube can be used to trace them back to their origin. With a thousand times more energy than can be generated with a terrestrial particle accelerator, astrophysicists conclude that these neutrinos can only derive from cataclysmic events in outer space, and that they could supply information regarding the genesis of these events. So far, arrival directions of the observed high-energy neutrinos are distributed regularly across the entire globe. However, the greater the number of particles, the more complete the picture. It could be the case that there are particular sources that transmit significantly large numbers of these neutrinos. Resconi illustrates this with an image: "It is like the situation on a cloudy day: We can't see the Sun as the light is diffuse in all directions. We cannot say that the light is emitted by the Sun until we have taken more measurements over time. In analogy, we think that individual objects emit these high-energy neutrinos. Currently we cannot yet resolve these objects, but more data and a larger detector will provide a clue about the origin of these incredible neutrinos in the coming years." The researchers could then draw their conclusions about the properties of these sources. Should ▷

Graphics: ediundsepp (source: IceCube); Picture credit: Jooss

Physicist Elisa Resconi is a Heisenberg Professor at TUM and leader of the research field “Experimental Physics with Cosmic Particles.” She heads the 12-person IceCube research group at TUM’s Excellence Cluster Universe.

“Our goal is to significantly progress in the understanding of the nature of neutrinos, and in doing that, provide a clue about the still many unknowns in particle physics.” *Elisa Resconi*

the neutrinos remain not associated to point sources, then they could only come from dark matter. “We shall attempt in the coming years to associate the detected neutrinos with the universe as we know it from explorations with high-energy photons and gamma rays,” says Resconi. “If we are unsuccessful, it could be that the neutrinos provide us with a completely different insight into the dark universe. This would then suddenly no longer be so dark anymore.”

The nature of the neutrinos themselves

An even more ambitious undertaking for the future is that Resconi and her team want to investigate the nature of the neutrinos themselves, which remains a mystery to this day. We know that they have to have mass, even if extremely low, and that they comprise three different states that can change from one to another in a phenomenon called oscillation. However, different theories have different predictions for which of these states is heavier or lighter, and whether perhaps completely different types of neutrinos exist. Resconi and her team want to make a substantial contribution in this regard. “The atmospheric neutrinos are particularly suitable for analyses of this kind. Hundreds of these are registered every day,” explains the professor. “For this reason, we are working on a new detector for IceCube – we call it PINGU, an acronym for Precision IceCube Next Generation Upgrade, which we could use to carry out precision measurements. It would be located at the center of the current IceCube. At the moment, we are looking for national and international funding. Just five years ago, nobody believed that we would be able to observe the oscillation of atmospheric neutrinos in IceCube. But now, after the first results, we are being taken very seriously. Our goal is to significantly progress in the understanding of the nature of neutrinos, and in doing that, provide a clue about the still many unknowns in particle physics.” *Brigitte Röthlein*

The IceCube research team at TUM is one of nine German members of the IceCube Collaboration. The scientists develop software for analyzing the extreme amounts of data collected by the IceCube detector. The TUM team is also involved in the design and sensor development for a next-generation IceCube detector, an even larger neutrino telescope.

Picture credit: Jooss

Picture credit: Freija Descamps, IceCube/NSF

Pulling cables to connect the deployed sensors to the IceCube Lab in the detector's center. The 86 strings holding the sensors are distributed over an area of about one square kilometer. The lab houses data processing and storage and sends about 100 gigabytes of data by satellite every day.