



An optical sensor begins its 2,500-metre journey down a borehole to become part of the IceCube neutrino detector in Antarctica.

Invest in neutrino astronomy

Spencer Klein calls for bigger telescope arrays to catch particles from the most energetic places in the Universe.

Neutrino astronomy is poised for breakthroughs. Since 2010, the IceCube experiment in Antarctica — 5,160 basketball-sized optical sensors spread through a cubic kilometre of ice — has detected a few score energetic neutrinos from deep space. Although these are exciting finds that raise many questions, this paltry number of extraterrestrial particles is too few to tell their origins or to test fundamental physics. To learn more will require a new generation of neutrino observatories.

Neutrinos are subatomic particles that

interact only weakly, so they can travel far through space and even penetrate Earth. IceCube detects highly energetic neutrinos, with energies above about 100 gigaelectronvolts (1 GeV is 10^9 electronvolts, roughly the rest mass of a proton). These are produced when cosmic rays — high-energy protons or heavier nuclei from space — interact with matter or light. This might happen either at the sites where the cosmic rays are produced, or later when the rays enter Earth's atmosphere and collide with gas molecules, releasing a cascade of elementary particles.

Neutrinos produced in the atmosphere are hundreds of times more numerous than the astrophysical ones.

Many physics puzzles stand to be solved by neutrino astronomy¹. One is the origin of the ultra-high-energy cosmic rays. In 1962, the Volcano Ranch array in New Mexico detected an enormous shower of particles coming from one cosmic ray smashing into the upper atmosphere with a kinetic energy of above 10^{11} GeV — equivalent to the energy of a tennis serve packed into a single atomic nucleus. Tens more such events have been

BLAINE GUDBJARTSSON, ICECUBE/NSF

detected since. But 50 years on, physicists still have no idea how nature accelerates elementary particles to such high energies. The energies far exceed the range of Earth-bound accelerators such as the Large Hadron Collider (LHC) near Geneva, Switzerland; mimicking them would require a ring the size of Earth's orbit around the Sun.

There is also much we need to find out about neutrinos themselves — their accurate masses, how they transform from one type (flavour) into another, and whether other predicted forms (such as 'sterile' neutrinos) exist. Neutrinos could also help to find dark matter, invisible material that has a part in controlling the motions of stars, gas and galaxies. Decaying or annihilating dark matter could produce energetic neutrinos that would be visible to neutrino telescopes.

The downside of neutrinos' weak interactions is that an enormous detector is required to catch enough particles to distinguish the few space-borne ones from the many more originating from Earth's atmosphere. IceCube is the largest neutrino-detection array in operation but it is too small, and further data collection is probably too slow to yield major breakthroughs in the next decade.

Bigger neutrino observatories, with volumes that are 10–100 times greater than that of IceCube, are essential to explore the most energetic processes in the Universe. Determining the masses of different types of neutrino and studying how neutrinos interact with matter within Earth could distinguish or rule out some models of extra spatial dimensions and address key concerns for high-energy nuclear physics such as the density of gluons (which mediate forces between quarks) in heavy nuclei.

Designs for neutrino telescopes are on the drawing board and could be up and running in five to ten years — if the astro-, particle- and nuclear-physics communities can come together and coordinate funding. A complementary set of several neutrino observatories would test physics at energies beyond the LHC's at a fraction of the cost — tens to hundreds of millions, rather than tens of billions, of dollars.

MORE QUESTIONS THAN ANSWERS

IceCube, which became fully operational in Antarctica in 2010 (and with which I have been involved since 2004), detects blue light: Cherenkov radiation that is emitted by the charged particles produced when energetic neutrinos interact with atomic nuclei in water or ice. Computers comb through the data to look for interactions — long tracks or radial cascades of particles emanating from a point (see 'Neutrino observatory'). IceCube sees more than 50,000 neutrino candidates per year. Fewer than 1% are from space.

There are several ways to distinguish cosmic from atmospheric neutrinos. The

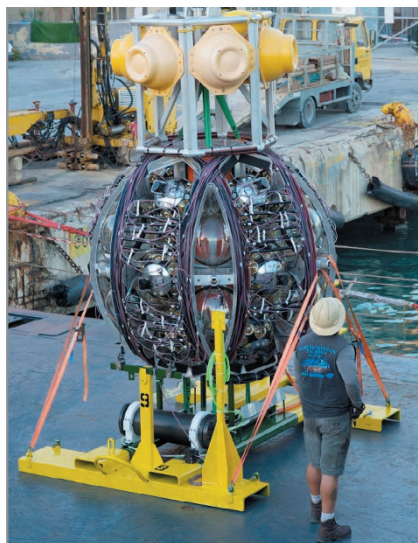
NEXT-GENERATION NEUTRINO TELESCOPES

Bigger neutrino arrays have been proposed that would catch enough cosmic neutrinos to probe extreme energies and test basic physics and astronomy.

Experiment	Detects	Where	Volume	Estimated cost (US\$)
IceCube-Gen2	Optical	South Pole, Antarctica	10 km ³	\$400 million
Cubic Kilometre Neutrino Telescope (KM3NeT)	Optical	Mediterranean Sea (two sites being considered)	5 km ³	\$250 million
Gigaton Volume Detector	Optical	Lake Baikal, Russia	1 km ³	Unknown
Askaryan Radio Array	Radio	South Pole, Antarctica	>100 km ³	\$5 million to \$30 million
ARIANNA	Radio	Ross Ice Shelf, Antarctica	>100 km ³	\$5 million to \$30 million

highest-energy events are more likely to be astrophysical. Atmospheric neutrinos are accompanied by particle showers, which can be seen with detectors on the ice surface. Muons, short-lived subatomic particles produced in these showers, are 500,000 times more numerous than neutrinos, and can also penetrate the ice; so signals accompanied by muons travelling downwards from the sky are probably atmospheric in origin. That leaves extremely energetic events with light trails that are travelling upwards (through Earth) or that originate from a point within the array volume as potentially astrophysical in origin.

Since 2010, IceCube has seen about 60 astrophysical neutrino candidates^{2,3}. Other experiments are too small to detect any such neutrinos; these include ANTARES, an array of strands of detectors anchored to the floor of the Mediterranean Sea off Marseilles, France, and another similar array in Lake Baikal, Russia. Their detection rate of astrophysical neutrinos is as high as could be expected — if there were more neutrinos, they would drain the cosmic rays of most of their energy⁴. So finding the astrophysical sources of the neutrinos should be easy. The fact that we have not is a growing puzzle.



A string of optical modules of the KM3NeT array.

So far, neutrinos do not seem to be coming from particular sites on the sky⁵, although several groups have suggested a weak link to the plane of the Milky Way. And analyses disfavour the many sites once thought likely to have accelerated energetic cosmic rays and neutrinos, including γ -ray bursts (GRBs) and active galactic nuclei (AGNs).

GRBs are short bursts of powerful γ -rays that are picked up by satellites. They are

“Finding the astrophysical sources of the neutrinos should be easy.”

thought to emanate either from a black hole coalescing with a neutron star or another black hole (producing a rapid burst lasting less than 2 seconds); or from the slower collapse of supermassive stars (bursts lasting seconds or minutes). Particles are accelerated by the implosion or explosion. Of more than 800 GRBs examined by IceCube scientists, none was accompanied by a burst of neutrinos, implying that GRBs can produce at most 1% of the astrophysical neutrinos seen by IceCube⁶.

AGNs are galaxies that at their centres have supermassive black holes accreting gas. Particles may be accelerated to relativistic speeds in jets of material that are blasted out from the black hole. But IceCube sees no associations between energetic neutrinos and active galaxies with jets that point towards Earth, suggesting that active galaxies explain at most 30% of the neutrinos⁷.

Other unlikely sources include starburst galaxies, which contain dusty regions of intense star formation that are riddled by supernova explosions⁸; magnetars, which are neutron stars surrounded by strong magnetic fields that expel powerful bursts of neutrinos for a few days (these should have been seen by IceCube); and supernova remnants, whose magnetic fields are too weak to explain the most energetic neutrinos⁹, even though they are believed to be responsible for most lower-energy (up to about 10^{16} eV) cosmic rays seen in the Galaxy.

More exotic possibilities remain untested: as-yet-unseen supermassive dark-matter

particles that annihilate and produce energetic neutrinos; or the decay of cosmic 'strings', discontinuities in space-time left over from the Big Bang.

IceCube has also tested alternative physics theories. It has constrained how neutrinos 'oscillate' from one flavour to another and set limits on the properties of dark matter and on the constituents of high-energy air showers.

NEXT GENERATION

There are two ways forward: enlarge the current optical arrays to collect more neutrinos, or find other strategies for isolating the highest energy neutrinos that must be cosmic in origin. These approaches cover different energy ranges and thus complementary physics. Both merit support.

First, larger optical Cherenkov telescopes could be deployed in ice or a lake, sea or ocean — similar to IceCube or ANTARES but with more efficient optical sensors and cheaper technology. Several groups have developed advanced designs for these concepts but lack funding. The detectors could be constructed and operational by the early 2020s. For IceCube, technical improvements would include more efficient drilling technology and sensors that fit in narrower bore holes, which are cheaper to drill.

Different sites offer different benefits. Antarctica offers a large expanse of clear, compacted ice and infrastructure. But arrays in the Northern Hemisphere, for example, in the Mediterranean, can more directly observe astrophysical neutrinos from the centre of the Galaxy that have passed through Earth, without having to reject down-going atmospheric neutrinos, as a southern site would have to. The absence of potassium-40 and the lower bioluminescence in fresh water (which contribute to background light and can confuse the reconstruction of particle tracks), and the presence of a frozen surface during the winter, simplifying construction, make Lake Baikal an attractive site.

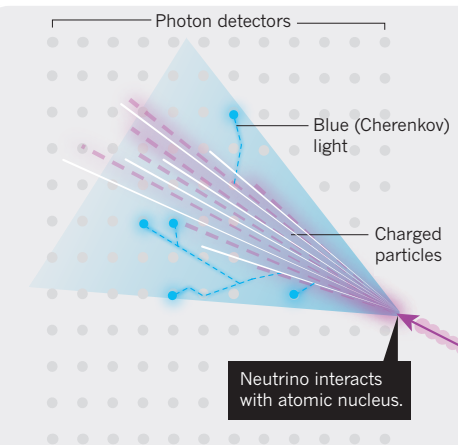
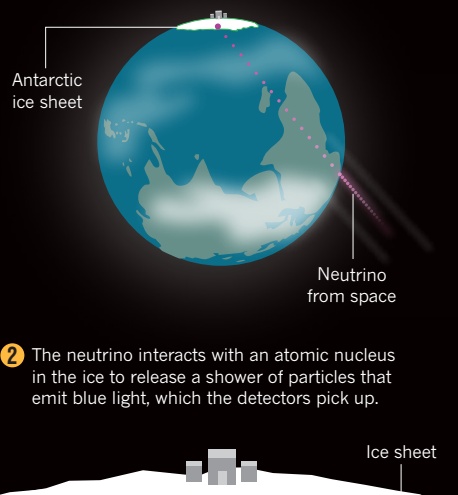
The second approach requires catching neutrinos with energies above 10^8 GeV. Neutrinos this energetic are rare — IceCube has seen none — and an array of at least 100 km^3 would be needed to capture enough events. Because optical Cherenkov light travels only tens of metres in ice or water, covering such a volume would require millions of sensors and would be expensive.

A more practical way is to search for radio emissions from neutrino interactions with the Antarctic ice sheet. When the neutrinos hit an atomic nucleus in the ice, they create a shower of charged particles that give off radio waves in the 50 megahertz to 1 gigahertz frequency range, as well as visible light. Radio waves can propagate for kilometres through ice. So an radio-sensing array over 100 km^3 could be more sparsely populated with instruments, with roughly one station per cubic

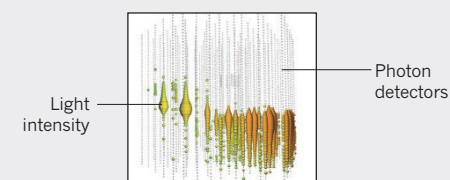
NEUTRINO OBSERVATORY

As a neutrino from space (1) interacts with atomic nuclei in water or ice, the shower of particles given off emit blue light (2). The light can be tracked with detectors to reveal the neutrino's energy and the direction the particle came from (3).

1 Cosmic neutrino passes through Earth.



3 Strings of buried optical sensors track blue light from the particles as they move through the array.



kilometre. The radio pulses from neutrinos with energies above 10^8 GeV should be strong enough for antennas in the ice to pick up. Two international groups are building prototypes and have sought funding to expand (I am involved with one, ARIANNA).

GREEN LIGHT

With a range of affordable, next-generation designs shovel-ready, decisions about design priorities need to be made and

grants deployed. The main obstacles are limited national science budgets and funding-agency silos. Neutrino astronomy falls between the particle-, nuclear- and astrophysics communities, which need to pool resources to realize the promise of these techniques.

First, one or both of the successors to IceCube and ANTARES should be funded and built. An upgraded IceCube experiment (IceCub-Gen2) and the Cubic Kilometre Neutrino Telescope (KM3NeT), a proposed European project, are both strong candidates (see 'Next-generation neutrino telescopes'). If necessary, the teams coordinating IceCube, KM3NeT and the Gigaton Volume Detector¹⁰, a proposed Russian array, should explore merging these collaborations to focus on a single large detector at the most cost-effective site. Funding should be sought from a wider range of agencies, including those focused on particle and nuclear physics.

Second, at least one 100-km^3 radio-detection array needs to get the go ahead. Because such a project can be done only in Antarctica, the onus is on the US National Science Foundation, which is the largest supporter of Antarctic research and realistically the only group that has adequate logistical resources to pull off such a project. Many non-US groups are interested, and collaborations should be set up and costs shared internationally. Once proven, such an array could be expanded to cover $1,000 \text{ km}^3$ by around 2030 to monitor the ultra-high-energy Universe.

By finding the astrophysical sources of ultra-energetic neutrinos and cosmic rays — or ruling out remaining models — the next generation of neutrino observatories is guaranteed to make discoveries. ■

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