IceCube neutrino search sets first constraints on proton fraction of ultrahigh-energy cosmic rays

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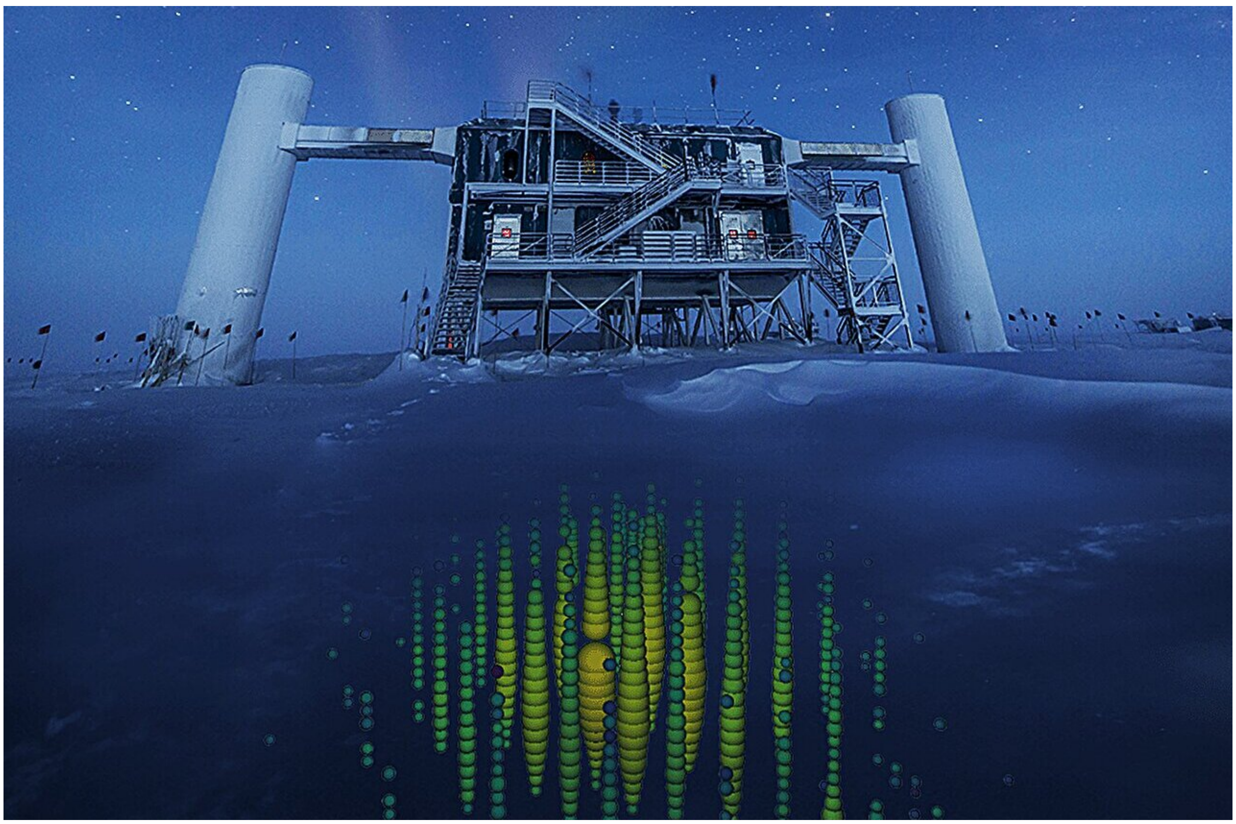

In this artistic rendering, based on a real image of the IceCube Lab, a high-energy starting event is shown in the ice below Antarctica's surface. This is one of the three events found in this study, which is also the highest energy neutrino event recorded by IceCube. Credit: Alexa Nelson, IceCube. Original photo taken by Felipe Pedreros, IceCube/NSF

Neutrinos are subatomic particles with no charge and very little mass that are known to weakly interact with other matter in the universe. Due to their weak interactions with other particles, these particles are notoriously difficult to detect.

A class of neutrinos that has so far proved particularly elusive to detection methods are extremely-high-energy neutrinos, which have energies above 10^{16} electronvolts (eV). Physical theories suggest that these neutrinos would be produced from very energy-intensive astrophysical phenomena, such as interactions of ultrahigh-energy cosmic rays.

The IceCube Collaboration, a large group of researchers based at various research institutes worldwide, has been searching for extremely-high-energy neutrinos for over a decade. Their most recent findings, published in *Physical Review Letters*, set constraints on the proportion of protons in ultrahigh-energy cosmic rays, for the first time relying on data collected at the IceCube observatory, while also placing limits on the diffuse flux of extremely-high-energy neutrinos.

"IceCube is, first and foremost, a gigantic neutrino detector," Maximilian Meier, co-author of the paper, told Phys.org. "So, for me, searching for the highest energy neutrinos produced by the universe (cosmogenic neutrinos) is naturally very exciting, and IceCube has been performing this kind of search already for more than a decade. If we don't see any of these cosmogenic neutrinos, we can place a strong limit on how many of them exist in the universe."

To look for neutrinos, the IceCube experiment relies on the largest neutrino detector in the world, which is located at the South Pole, deep within the Antarctic ice. This detector, known as the IceCube Neutrino Observatory, detects Cherenkov radiation (i.e., blue light) emitted when particles travel through ice. Searching for extremely-high-energy neutrinos using this detector should, in principle, be quite straightforward, as it essentially identifies the brightest events within collected data.

"When looking up, however, we see a lot of background from cosmic ray air showers," said Meier. "We can deal with this by reconstructing the direction the particles are coming from, and by how their energy depositions differ from those expected by our neutrino signal. We looked at 12.6 years of data, which contains approximately a trillion events, and filtered that down to the three most promising candidates."

After analyzing more than a decade of data collected by the IceCube detector, the researchers found no events that appeared to be "energetic" enough to be associated with cosmogenic neutrinos, the particles they were looking for. Cosmogenic neutrinos are extremely-high-energy neutrinos produced when ultrahigh-energy cosmic rays interact with other cosmic photon fields (i.e., the so-called cosmic microwave background).

Although the IceCube Collaboration did not detect the events of interest, over the past decade it placed increasingly stringent limits on the flux of these neutrinos. Their most recent findings represent a further advancement toward their detection, as it could improve the selection of extremely high-energy neutrino events and thus increase the chances that they will be observed.

"In the end, we did not find any neutrinos with extreme energies," explained Meier. "These neutrinos we expect are closely linked to ultrahigh-energy cosmic rays (UHECR), as they are created in the interactions of protons with background light in the universe.

"This means, by not seeing neutrinos, we can limit the amount of protons making up UHECRs, which we have done—with IceCube—for the first time. We can limit the proton fraction to be less than ~70% if the sources of cosmic rays are distributed similar to how new stars are formed throughout the universe."

The recent efforts by the IceCube Collaboration will inform future searches for extremely-high-energy neutrinos, particularly those produced as a result of ultrahigh-energy cosmic-ray interactions with the cosmic microwave background. The ultimate goal of the experiment will be to successfully detect these neutrinos and better understand their properties.

"We can work toward this goal by improving IceCube's efficiency to cosmogenic neutrinos even more, which can be done, e.g., through the use of machine learning," added Brian Clark. "The big thing on the wish list here is IceCube-Gen2 though.

"This is a planned extension of IceCube that will increase the sensitivity to cosmogenic neutrinos by about a factor of 30 (assuming a similar data-taking period). This will allow us to find cosmogenic neutrinos even if the UHECR proton fraction is on the percent level."

More information: R. Abbasi et al, Search for Extremely-High-Energy Neutrinos and First Constraints on the Ultrahigh-Energy Cosmic-Ray Proton Fraction with IceCube, *Physical Review Letters* (2025). DOI: 10.1103/PhysRevLett.135.031001. On *arXiv*: DOI: 10.48550/arxiv.2502.01963