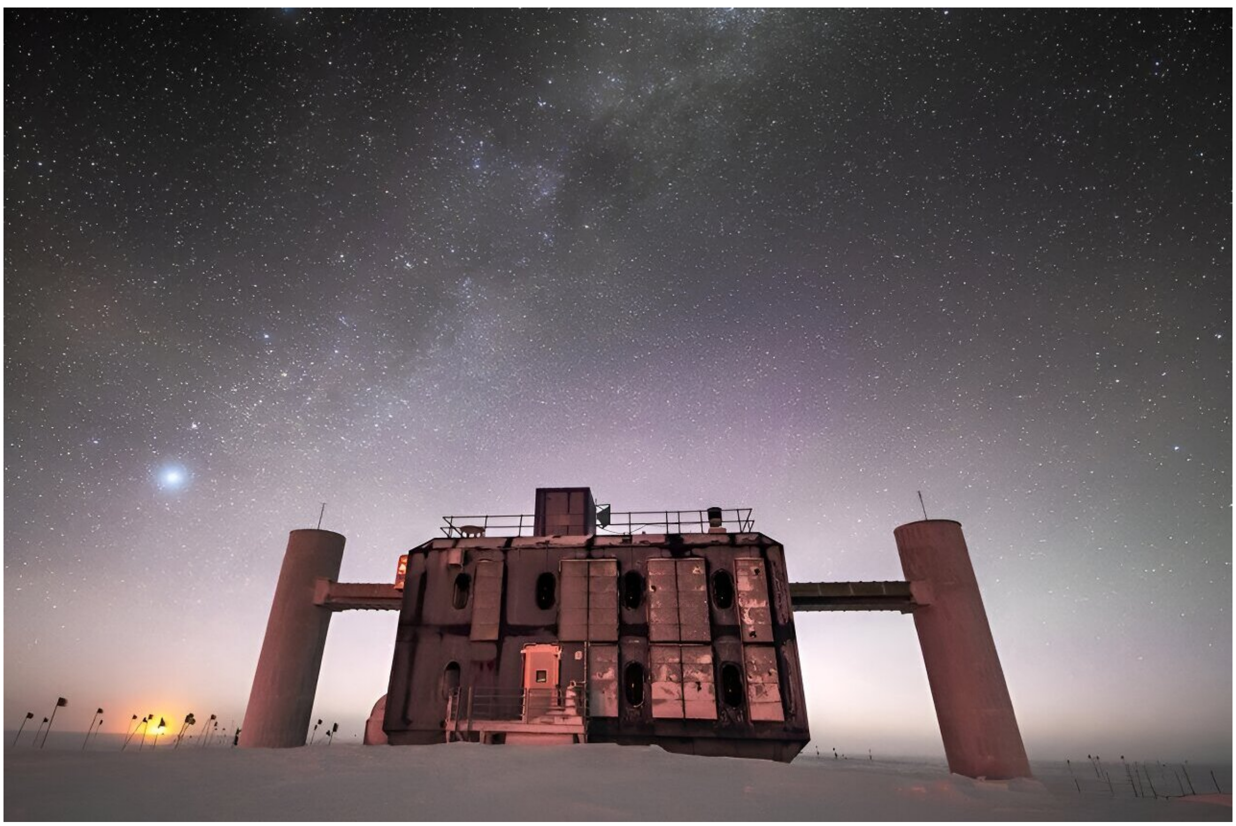
IceCube identifies seven astrophysical tau neutrino candidates

March 13 2024



Front view of the IceCube Lab at twilight, with a starry sky showing a glimpse of the Milky Way overhead and sunlight lingering on the horizon. Credit: Martin Wolf, IceCube/NSF

The IceCube Neutrino Observatory, a cubic-kilometer-sized neutrino telescope at the South Pole, has observed a new kind of astrophysical messenger. In a new study recently accepted for publication as an Editors' Suggestion by the journal *Physical Review Letters* and available on the *arXiv* preprint server, the IceCube collaboration, including Penn State researchers, presented the discovery of seven of the once-elusive astrophysical tau neutrinos.

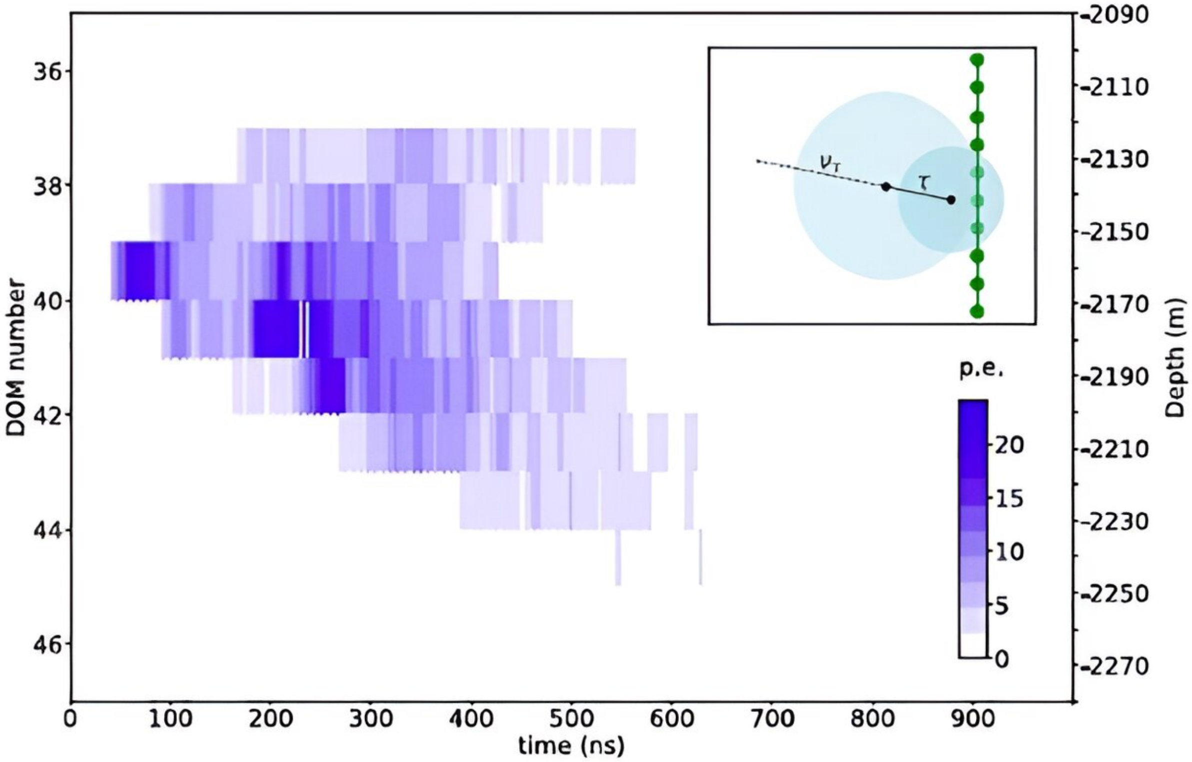
Neutrinos are tiny, weakly interacting subatomic particles that can travel astronomical distances undisturbed. As such, they can be traced back to their sources, revealing the mysteries of their cosmic origins. High-energy neutrinos that originate from the farthest reaches beyond our galaxy are called astrophysical neutrinos. These cosmic messengers come in three different flavors: electron, muon and tau, with astrophysical tau neutrinos being exceptionally difficult to pin down.

"In 2013, IceCube presented its first evidence of high-energy astrophysical neutrinos originating from cosmic accelerators, beginning a new era in astronomy," said Doug Cowen, professor of physics and of astronomy and astrophysics in the Eberly College of Science at Penn State and one of the study leads. "This exciting new discovery comes with the intriguing possibility of leveraging tau neutrinos to uncover new physics."

IceCube detects neutrinos using strings of digital optical modules (DOMs), with a total of 5,160 DOMs embedded deep within the Antarctic ice. When neutrinos interact with nuclei in the ice, charged particles are produced that emit blue light—which is registered and digitized by the individual DOMs—while traveling through the ice. The light produces distinctive patterns. One of these patterns, called double cascade events, is indicative of high-energy tau neutrino interactions within the detector.

Prior IceCube analyses saw hints of these subtle signatures produced by astrophysical tau neutrinos, so the researchers remained motivated to pinpoint these elusive particles. The researchers rendered the data from each potential tau neutrino event into images and then trained convolutional neural networks (CNNs), a type of machine learning algorithm optimized for image classification, on the images.

This allowed the researchers to distinguish images produced by tau neutrinos from images produced by various backgrounds. After running simulations that confirmed its sensitivity to tau neutrinos, the technique was then applied to 10 years of IceCube data acquired between 2011 and 2020. The result was seven strong candidate tau neutrino events.



The IceCube Neutrino Observatory has detected seven astrophysical tau neutrinos. The once-elusive particles are weakly interacting, can travel astronomical distances unscathed, and can be traced back to their sources, potentially revealing the mysteries of their cosmic origins. Image shows the light signal of one of the energetic astrophysical tau neutrinos detected by multiple photosensors in the IceCube Neutrino Observatory at the South Pole. Credit: IceCube Collaboration

"The detection of seven candidate tau neutrino events in the data, combined with the very low amount of expected background, allows us to claim that it is highly unlikely that backgrounds are conspiring to produce seven tau neutrino imposters," Cowen said. "Since tau neutrinos at the observed energies can only be produced by astrophysical sources, their detection also provides a strong confirmation of IceCube's earlier discovery of the astrophysical neutrino flux."

Cowen added that the probability of the background mimicking the signal was estimated to be less than 1 in 3.5 million, corresponding to greater than a five-sigma significance, considered the statistical gold-standard for new discoveries in physics.

Future analyses will incorporate more of IceCube's strings, since this study used just the three most-illuminated ones. Such a new analysis would increase the sample of tau neutrinos that can then be used to perform the first three-flavor study of the phenomenon where neutrinos change flavors—called neutrino oscillations—over cosmological distances. This type of study could address questions such as the mechanism of neutrino production from astrophysical sources and the properties of space itself through which neutrinos travel, researchers said.

Currently, there is no tool specifically designed to determine the energy and direction of tau neutrinos that produce the signatures seen in this analysis. Such an algorithm could be used in real time to better differentiate a potential tau neutrino signal from background and to help identify candidate tau neutrinos at the South Pole. Similar to current IceCube real-time alerts issued for other neutrino types, alerts for tau neutrinos could be issued to the astronomical community for follow-up studies.

Approximately 300 physicists from 59 institutions in 14 countries make up the IceCube collaboration. In addition to Cowen, the Penn State authors of the study include Derek Fox, associate professor of astronomy and astrophysics; postdoctoral researchers Aaron T. Fienberg, Kayla Leonard DeHolton, and Jan Weldert; and graduate student Daria

V. Pankova.

More information: Observation of Seven Astrophysical Tau Neutrino Candidates with IceCube, *arXiv* (2024). DOI: 10.48550/arXiv.2403.02516

Provided by Pennsylvania State University