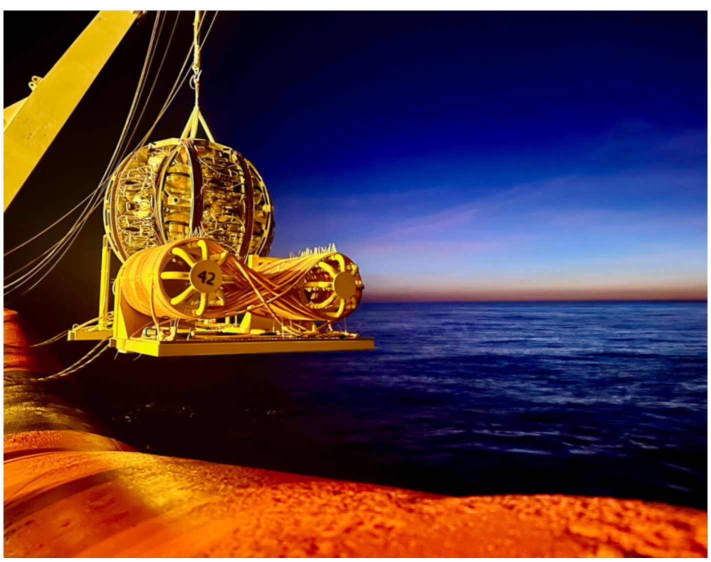
An Ultrahigh Neutrino Detection Makes Waves

A new underwater neutrino experiment—for now, only partially installed—has detected what appears to be the highest-energy cosmic neutrino observed to date.

By **Michael Schirber**

Sometimes what you're looking for arrives when you least expect it. That appears to be the case for the Cubic Kilometer Neutrino Telescope (KM3NeT), an array of photodetectors on the floor of the Mediterranean Sea. Today the team behind KM3NeT reports the measurement of a signal coming from a neutrino with an energy of 220 peta-electron-volts (PeV), an energy 30 times more than the previous record for the highest measured neutrino energy [1]. This rare event was captured while the experiment had only 10% of its detectors in place. The measurement could have major implications for our understanding of particle acceleration in the Universe.



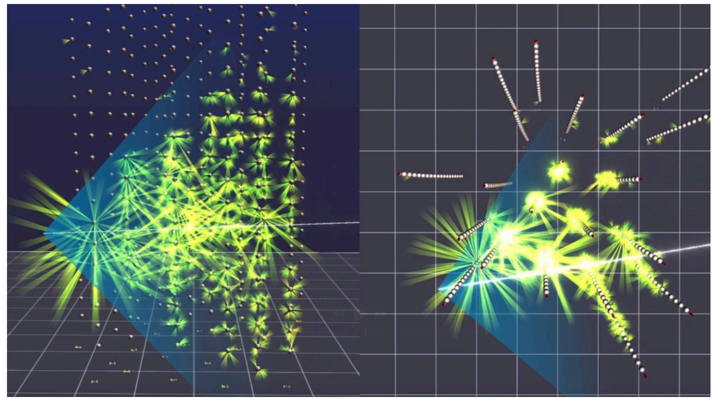
The KM3NeT experiment uses an array of optical-sensor modules fixed to the floor of the Mediterranean Sea. This photo shows the deployment of one set of modules.
Credit: INFN/A. Simonelli

"We've detected by far the most energetic neutrino ever recorded up until now," said KM3NeT spokesperson Paschal Coyle from the Center of Particle Physics of Marseille, France. "This neutrino is very likely of cosmic origin." He and other members of the KM3NeT Collaboration presented their results in an online press briefing.

The neutrino detection will undoubtedly make a splash in the field of astrophysics. High-energy neutrinos are likely created alongside high-energy cosmic rays, whose sources remain a mystery. The advantage of observing neutrinos is that they are not diverted on their cosmic journey to Earth, so measuring their arrival direction should reveal their origin. In describing KM3NeT's motivation, Aart Heijboer from the Dutch National Institute for Subatomic Physics said: "This is part of trying to understand the highest-energy processes in the Universe."

The KM3NeT experiment comprises two detector arrays—ARCA, which lies off the coast of Italy at a depth of 3450 m, and ORCA, which lies off the coast of France at a depth of 2450 m. Each array consists of a collection of vertical detection lines that are anchored to the seafloor and spaced out in a grid pattern. Currently, about 50 of the planned 345 detection lines have been installed. Along each detection line lie 18 spherical optical-sensor modules that record light flashes produced by high-energy particles shooting through the pitch-black seawater. Neutrinos themselves do not produce flashes—rather

One of the optical-sensor modules being calibrated in the lab.
Credit: CNRS/N. Busser



A reconstruction of the KM3-230213A event, seen from the side and the top.
Credit: KM3NeT

they collide with atoms, creating secondary particles that produce light that the sensors can detect.

The ultra-high-energy event, named KM3-230213A, occurred at the Italian ARCA site during a preliminary measurement campaign in which 21 detection lines were in operation. In the early hours of February 13, 2023, the detector array picked up the signal of a high-energy particle—identified as a muon—shooting through the array in a matter of a few microseconds. What stuck out about this event was how bright it was. Roughly a third of the ARCA sensors recorded photons. From that fireworks display, the KM3NeT Collaboration calculated the energy of the muon to be around 120 PeV, or 1.2×10^{17} eV, by far the most energetic event that KM3NeT has seen.

Another unique aspect was the particle's direction. KM3NeT constantly detects muons—most of which rain down from the upper atmosphere when cosmic rays strike Earth. However, the KM3-230213A muon did not fit the bill of a cosmic-ray muon. It came from the west, at an angle very close to that of the horizon. Such a horizontal direction implies that this muon was created by a neutrino colliding with an atom in the deep sea surrounding the detector. "When you look at the direction and you look at the energy, the only real explanation is that a neutrino made the event," Coyle said.

The energy of this neutrino cannot be directly measured, but it must have been greater than that of the muon that it produced. From their models, the researchers estimate the neutrino energy was 220 PeV, which is 30,000 times the energy that physicists can obtain in their most powerful particle accelerators. Heijboer remarked that this single neutrino carried the energy equivalent of a ping-pong ball falling from a meter height.

"This is clearly an interesting event. It is also very unusual," said Ignacio Taboada, a physicist from the Georgia Institute of Technology and spokesperson for the IceCube experiment in Antarctica. IceCube, which has a similar detector-array design as KM3NeT but is encased in ice rather than water, has detected neutrinos with energies as high as 10 PeV, but nothing in 100 PeV range. "IceCube has worked for 14 years, so it's weird that we don't see the same thing," Taboada said. Taboada is not involved in the KM3Net experiment.

The KM3NeT team is aware of this weirdness. They compared the KM3-230213A event to upper limits on the neutrino flux given by IceCube and the Pierre Auger cosmic-ray experiment in Argentina. Taking those limits as given, they found that there was a 1% chance of detecting a 220-PeV neutrino during KM3NeT's preliminary (287-day) measurement campaign. "It's not crazy," Heijboer said. "One percent effects do happen."

That assessment was echoed by David Saltzberg, a neutrino expert from UCLA who is not involved with KM3NeT. “It happens from time to time that one sees such a remarkable event early in the lifetime of an experiment, and the flux initially seems anomalous,” he said. If future observations don’t see similar high-energy events, then it might be that the KM3-230213A event was a statistical fluke, Saltzberg explained. But it’s possible that this event is the first indication of a higher-than-expected flux. “Time will tell,” he said.

If more ultra-high-energy neutrinos are detected, it could offer new insights into high-powered accelerators in our Universe. High-energy neutrinos are expected to be made in the accelerating process for cosmic rays. In this scenario, the KM3-230213A neutrino may be a long-distance messenger from a cosmic-ray source, such as a supernova explosion or a gamma-ray burst. The KM3NeT researchers searched the sky around the arrival direction of the KM3-230213A neutrino and did not find any signs of supernovae in our Galaxy. But they did find possible extragalactic sources: Twelve blazars (bright cores of active galaxies) were found in the vicinity of the neutrino’s direction. Further analysis might be able to pinpoint the most likely candidate, explained KM3NeT team member Rosa Coniglione from the National Institute of Nuclear Physics in Italy.

There could be another explanation, however. High-energy cosmic rays traversing the Universe should occasionally interact with photons from the cosmic microwave background. Such interactions are predicted to produce a population of high-energy neutrinos called cosmogenic neutrinos, which should have energies that extend from the peta-eV range (10^{15} eV) into the exa-eV range (10^{18} eV and above). Saltzberg said that cosmogenic neutrinos are “guaranteed” to be out there, but their abundance is unknown because of uncertainties about cosmic rays. “This guaranteed flux has been a Holy Grail of neutrino astronomy for a long time,” he said. If KM3-230213A is a cosmogenic neutrino and others like it are observed, such events could reveal when the highest-energy cosmic-ray sources turned on, Saltzberg said.

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REFERENCES

1. The KM3NeT Collaboration, “Observation of an ultra-high-energy cosmic neutrino with KM3NeT,” **Nature 638, 376 (2025).**