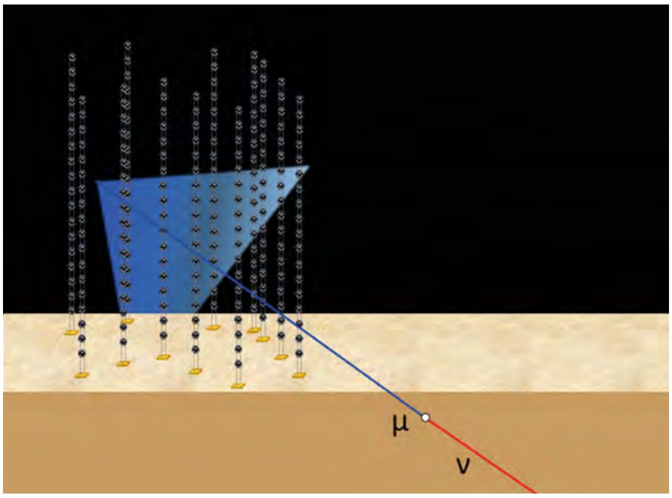

PEERING INTO THE COSMIC DEPTHS WITH HIGH-ENERGY NEUTRINOS

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Neutrinos, elusive particles that can be detected with extraordinary apparatus located in the hostile environments of deep water or deep polar ice, offer a unique opportunity to explore the most violent phenomena in our universe. The observation of the first high-energy astrophysical neutrinos has ushered in a new era of neutrino astronomy.

For centuries astronomy has been a field of incessant expansion. Beginning with observations of visible light and subsequently encompassing the entire electromagnetic spectrum, the technological progress of recent decades in particle, gravitational wave and neutrino detection has further enriched our understanding of the universe. The existence of cosmic accelerators, single sources or galaxies, has been proven by the detection of ultra-high-energy cosmic rays and high-energy gamma-rays. In these accelerators, high-energy neutrinos can be produced through the interactions of protons with gamma-rays or dense matter. While cosmic rays are deflected by intergalactic magnetic fields and high-energy gamma-rays are absorbed by the intergalactic photon background, neutrinos, being electrically neutral and weakly interacting with ordinary matter, can escape from dense cosmic environments and propagate through the universe without significant absorption or deflection. This allows to point back to their origin, providing a glimpse into hidden processes and the far universe. Moreover, neutrinos are the only direct evidence of hadronic acceleration in the universe. However, their weak interaction with matter makes detection a significant challenge. This article focuses on recent discoveries in neutrino astronomy and the innovative detectors used to explore the high-energy universe.

Current neutrino detector landscape

M. A. Markov first proposed the concept of using underwater detectors to search for cosmic neutrinos in the late 1960s. He envisioned "to install detectors deep in a lake or in the sea to determine the direction of charged particles with the help of Cherenkov radiation" [1]. In the decades since then, it became evident that high-energy neutrino astronomy demands detectors on a cubic kilometer scale or even larger, which can only be implemented in open environments (see Fig. 1). After over two decades of research and development, neutrino telescopes capable of monitoring massive targets (around 10 million tons) in deep ice or seawater have been successfully built. This achievement overcame the significant technical challenges posed by these harsh environments.

Deep-ice and underwater neutrino detectors capture the Cherenkov radiation emitted by high-speed particles created when neutrinos collide near or within the detector (see the conceptual illustration in Fig. 1). Deep ice or water act both as target material and Cherenkov radiator, while also shielding against downward-moving atmospheric muons. The Cherenkov light is detected by a 3D grid of photomultiplier tubes, housed in glass spheres (Fig. 2) that can withstand the water/ice pressure, and distributed on vertical strings. The current network of neutrino telescopes includes underwater and under-ice detectors (Fig. 3). Leading these detectors are the IceCube Neutrino Observatory at the South Pole[1], the largest (about 1 km^3) of its kind with thousands of sensors embedded in the Antarctic ice; ANTARES[2], the Mediterranean Sea's pioneering underwater telescope; KM3NeT[3] the second-generation Mediterranean telescope; and Baikal-GVD[4] which is in construction with a volume already reaching about 0.6 km^3. These underwater/under-ice detectors are designed to capture the elusive neutrinos from cosmic sources. By studying these particles, scientists hope to gain insights into the most extreme astrophysical phenomena, such as supernovae explosions, gamma-ray bursts and acceleration of cosmic rays.

Observations and current understanding

After more than 50 years from Markov's idea, the existence of the postulated high-energy cosmic neutrino was confirmed by IceCube [2] in 2013 with the detection of a significant excess above the background of events at energies beyond 100 TeV (1 Teraelectronvolt = 10^{12} electronvolt) detected looking at the full sky. This detection opened the era of neutrino astronomy.

Four years later, a high-energy neutrino coming from the blazar TXS 0506+056 was detected by IceCube [3]. An excess in the flux was simultaneously observed

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◂ **FIG. 1:** Clockwise: Concept of a Cherenkov neutrino detector; construction of IceCube in the ice of Antarctica; construction of Baikal-GVD in Lake Baikal, Russia; construction of KM3NeT in the Mediterranean Sea.

▾ **FIG. 2:** The KM3NeT multi-PMT optical module (DOI 10.1088/1748-0221/17/07/P07038).

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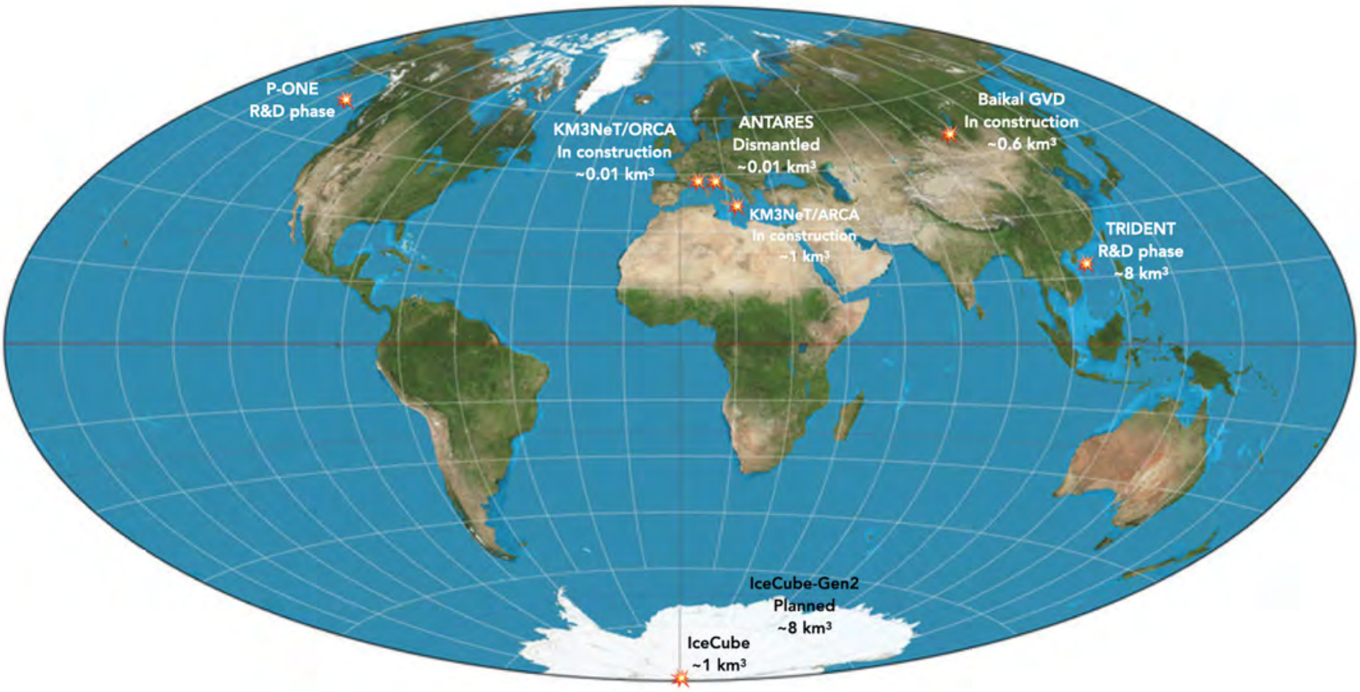
[1] IceCube homepage at https://www.icecube.wisc.edu/

[2] ANTARES homepage at: https://antares.in2p3.fr

[3] KM3NeT homepage at https://www.km3net.org/

[4] Baikal-GVD homepage at https://baikalgvd.jinr.ru/



▲ FIG. 3: The global network of massive underwater and under-ice neutrino detectors.

● ● ● from the same direction in gamma-rays and lower energy photons confirming this blazar as the first detected source of high-energy neutrinos [4]. This observation marked the birth of the multi-messenger observations with neutrinos. In the last few years other sources have been identified as probable neutrino sources: the Seyfert galaxies NGC 1068 [5] and NGC 4151 [6] and the blazar BL Lac PKS 1424+240 [7].

Active Galactic Nuclei (AGN) are cosmic objects powered by a supermassive black holes at their centers. These black holes rapidly accrete matter, creating a swirling accretion disk and powerful jets of energy that shoot out perpendicularly from the galaxy's plane (Fig. 4). Blazars are a class of AGN in which one jet is pointing towards the Earth making them extremely bright objects. Seyfert galaxies are another type of active galaxies, known for their extremely bright cores which make distinct from the other types of active galaxies.

As some of the most powerful sources known in the universe, AGN and Seyfert galaxies emit across the whole spectrum of electromagnetic radiation, from radio waves to high-energy gamma-rays. In the case of the Seyfert galaxy NGC1068, it has been shown that the emitted neutrino flux in the TeV energy range is higher than the gamma-ray flux at the same energy. This can be explained in the hypothesis that neutrinos originated in the interaction of protons in the vicinity of the black hole where gamma-rays are produced. The gamma-rays are however not able to leave the source because they are absorbed by the dense core matter while neutrinos, being weakly interacting particles, can escape and reach the Earth undisturbed.

A recent significant observation was neutrino emission from the Galactic plane, reported by IceCube using data collected over 10 years [8]. The neutrino excess above the background was identified by comparing diffuse emission models to a background-only hypothesis. The detected neutrinos originate from extended regions, not only around the galactic center where a massive black hole is known to exist, but also from other areas. Due to the limited number of neutrinos and the poor angular resolution, specific Galactic sources have not been clearly identified. However, the identification of Galactic neutrino sources, due to their proximity, will offer a unique opportunity to study neutrino production mechanisms in detail.

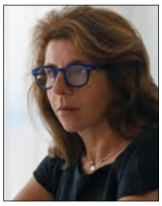
The observations of cosmic neutrino from the full sky, from AGNs and Seyfert galaxies, from the galactic plane and the very recent KM3NeT's groundbreaking detection of a cosmic neutrino with unprecedented energy [9], confirm the key role played by Cherenkov neutrino telescopes in the fields of high energy astrophysics and multi-messenger astronomy. These observations have shed some light on the longstanding questions such as the region of the acceleration mechanisms of ultra-high-energy particles (cosmic rays) and gamma-rays. However, many questions remain still unanswered.

A key question is the origin of the observed diffuse neutrino flux. The evidence for proton acceleration in the vicinity of the black hole in NGC 1068 is not conclusive and the question of the production region is still open. To definitively determine the acceleration mechanism and constraint models of high-energy neutrino production, identifying the acceleration region and characterising the produced flux is necessary. The combined neutrino flux from extragalactic sources, such as AGN and Seyfert galaxies is insufficient to explain the all-sky neutrino flux. To further understand this, the analysis of the energy spectrum is crucial. It remains unclear whether one or more components exist in the energy spectrum, and even assuming a single power-law spectrum, the value of the slope is uncertain.

A general consensus is that a high-energy neutrino catalog, a high-resolution neutrino sky map, and multi-messenger observations are essential for providing clear answers. Substantially improved sensitivity and resolution in next-generation neutrino telescopes are crucial. The challenging projects currently underway, P-ONE[5], TRIDENT[6] and IceCube-Gen2[7], aim to discover multiple high-energy astrophysical neutrino sources, significantly enhancing flux measurement of cosmic neutrinos of all flavors. ■

About the Authors

Giovanna Ferrara holds a temporary academic position at the University of Catania's Department of Physics and Astronomy, while contributing to research at the INFN-LNS laboratory in Catania. She is an active member of the international collaborations ANTARES and KM3NeT.



Rosa Coniglione is a senior researcher at the Istituto Nazionale di Fisica Nucleare - Laboratori Nazionali del Sud. She has been actively involved in the KM3NeT project since its inception and she is currently the deputy spokesperson of the collaboration. She has also contributed to the ANTARES project.

References

[1] M.A. Markov, Proc. 10th ICHEP, Rochester, p. 578 (1960)

[2] M. G. Aartsen *et al.*, *Science* **342**, 6161 (2013) DOI: 10.1126/science124285

[3] M. Aartsen *et al.*, *Science* **361**, 6398 (2018) DOI: 10.1126/science.aat2890

[4] M. Aartsen *et al.*, *Science* **361**, 6398 (2018). DOI: 10.1126/science.aat1378

[5] R. Abbasi *et al.*, *Science* **378**, 6619 (2022) DOI: 10.1126/science.abg3395

[6] R. Abbasi *et al.*, https://arxiv.org/abs/2406.06684

[7] M. Aartsen *et al.*, *Phys. Rev. Lett.* **124**, 5 (2020) https://arxiv.org/abs/1910.08488

[8] R. Abbasi *et al.*, *Science* **380**, 6652 (2023) DOI: 10.1126/science.adc9818

[9] KM3NeT Coll., talks presented at Neutrino2024 (https://agenda.infn.it/event/37867/contributions/233917/attachments/121916/178248/JCoelho_202406_Neutrino_KM3NeT.pdf) and at CRIS-MAC2024 conferences (https://agenda.infn.it/event/36661/contributions/231872/attachments/122006/178349/Talk_KM3NeT_CRIS-MAC_Trapani_Coniglione_v4.pdf). Submitted to Nature.

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[5] P-ONE homepage at https://www.pacific-neutrino.org/

[6] TRIDENT homepage at https://trident.sjtu.edu.cn/en

[7] IceCube-Gen2 homepage at https://www.icecube-gen2.de/index_eng.html

▾ **FIG. 4:** A blazar emitting neutrinos and gamma-rays. Credit: IceCube/NASA