



Neutrino sources: from meV to EeV

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Abstract Neutrinos are among the most abundant fundamental particles in the Universe, produced across a wide variety of natural sources. Their energies span an immense range, from meV to ultra-high energies (UHE) in the EeV range. Natural sources include the Sun, Earth's core, the atmosphere, and other astrophysical objects. Neutrinos are also generated artificially in nuclear reactors and particle accelerators. This article provides an overview of these diverse neutrino sources, focusing on the current state of research and recent advancements in each sector.

1 Introduction

Neutrinos, which are among the most abundant yet elusive particles in the Universe, are produced by a multitude of natural and human-made sources. An extensive study of each of these sources has contributed to our understanding of the fundamental properties of these particles. Neutrinos are produced through various processes across the Universe, with a diverse range of energy and flux, and each source brings unique insights into their nature. Figure 1 summarizes the natural and artificial sources of neutrinos at Earth integrated over directions and summed over flavors.

Neutrinos were present in the early Universe, produced within the first second after the Big Bang [3]. Their remnants, known as relic neutrinos or the cosmic neutrino background (CNB), still exist in the Universe today. They have energies ranging from μeV to meV, these neutrinos interact with other matter via the weak force, which is characterized by extremely small interaction cross sections at these low energies. This renders their direct detection exceptionally challenging.

Neutrinos are also produced inside our Earth, known as geoneutrinos, which originate from radioactive decay within Earth's crust and mantle. These neutrinos have energies in the MeV range. Detection of geoneutrinos helps quantify our planet's radiogenic heat production, providing insights into geological processes and Earth's internal structure. The Sun is also a major source of neutrinos passing through the Earth. Studies of solar neutrinos have provided insights into fusion processes within the Sun's core, validating models of stellar evolution and neutrino oscillation. Solar neutrinos have energies in the keV to MeV range. The interaction of cosmic rays with atomic nuclei in the atmosphere also leads to the production of neutrinos, known as atmospheric neutrinos. These neutrinos span a wide range of energies from GeV to PeV. The study of atmospheric neutrinos has provided critical evidence for neutrino mass through oscillation studies. Apart from the Earth and the Sun, neutrinos are also produced inside various celestial bodies or during diverse astrophysical phenomena; a few examples are active galactic nuclei (AGN), neutron stars, supernova explosions, and gamma-ray bursts (GRBs). During the supernova explosion, protons and electrons combine through the neutronization process to form neutrons, releasing a vast number of neutrinos. These neutrinos carry away about 99% of the supernova's energy. They have energies in the MeV to GeV range. Neutrinos from other astrophysical sources usually have very high energy, reaching PeV and beyond, known as astrophysical neutrinos, which offer a new realm of multi-messenger astronomy. Furthermore, cosmogenic neutrinos, produced by the interactions of ultra-high-energy cosmic rays with the cosmic microwave background (CMB), are expected

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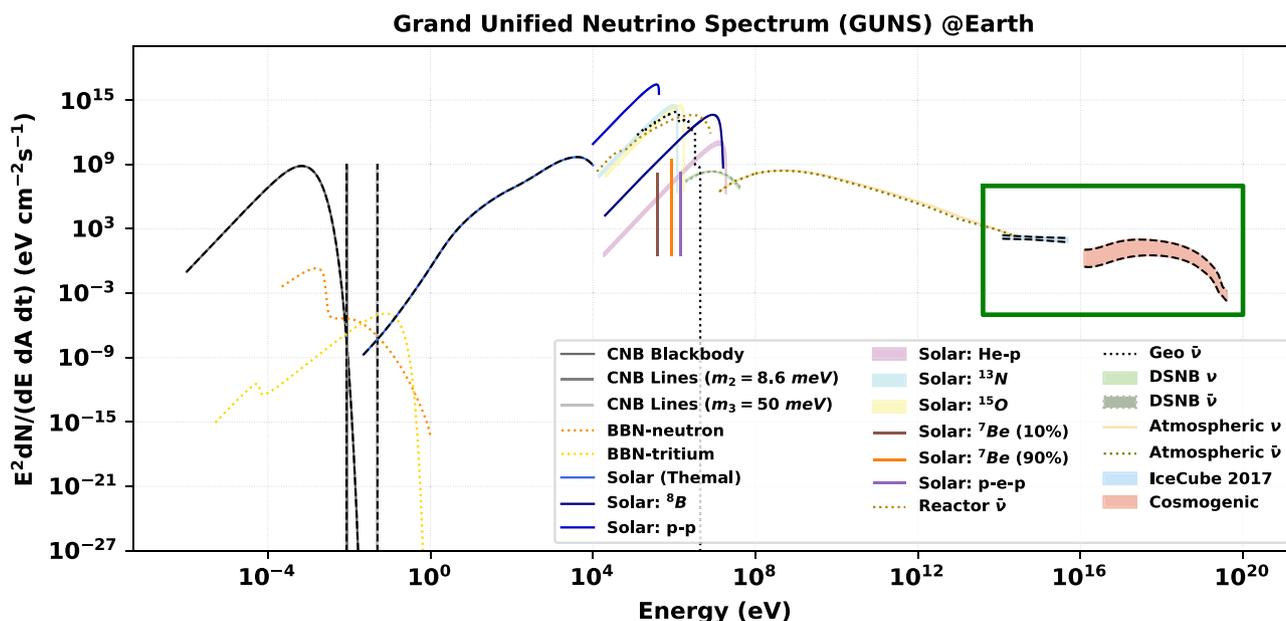


Fig. 1 A representation of the Grand Unified Neutrino Spectrum (GUNS) at Earth, integrated across all directions and summed over all neutrino flavors. The flavor conversion between the source and the detector does not impact this depiction. Solid lines denote the neutrino flux, while dashed or dotted lines correspond to the antineutrino flux. Superimposed dashed and solid lines depict sources of both neutrino and antineutrino. This figure is taken from Ref. [1], which was originally adapted from Ref. [2]

to appear at even higher energies (extending into the EeV regime). Their detection promises to provide unique insights into the propagation and composition of ultra-high-energy cosmic rays and the extreme environments that accelerate them.

Neutrinos are also generated artificially in nuclear reactors and particle accelerators. Reactor neutrinos, emerging from nuclear fission in power plants, have been proven instrumental in measuring the mixing angle θ_{13} [4–6] and refining our understanding of neutrino oscillation. These neutrinos typically have energies in the MeV range. Accelerator-generated neutrinos are produced by high-energy proton beams impacting fixed targets composed of nuclei (containing both protons and neutrons). In these proton–nucleus collisions, pions are generated via interactions with the target nucleons, and their subsequent decays yield neutrinos. An additional neutrino flux arises from the decay of muons produced in the pion decay process. (see Eq. 1). The well-controlled neutrino beam from the accelerator is observed at the detector placed at a fixed baseline, providing insight into the neutrino oscillation phenomena with precise measurements of oscillation parameters, including mass-squared differences and mixing angles.

Each of these diverse neutrino sources probes different aspects of neutrino physics, from the study of neutrino flavor oscillations to investigating various astrophysical events where neutrinos play a crucial role. Also, the study of neutrino sources offers excellent opportunities to test various fundamental theories in physics. By leveraging the complementarity among solar, reactor, atmospheric, accelerator, geoneutrino, astrophysical, and cosmogenic neutrinos, the scientific community can achieve unparalleled sensitivity in probing the remaining unknowns of the three-neutrino oscillation paradigm. In this review, we will explore the status of neutrino research across these varied sources, highlighting the latest experimental results, challenges, and future directions.

2 Relic neutrinos

In the early Universe (temperature, $T \geq 1$ MeV), all the fundamental particles, including photons, electrons, neutrinos, and nucleons, were in thermal equilibrium, forming a dense plasma of particles. With the expansion of the Universe, as its temperature dropped below 1 MeV, neutrinos decoupled from the other particles in thermal equilibrium, once the weak interaction rate fell below the Hubble expansion rate. Following decoupling, neutrinos propagated unimpeded throughout the cosmos, establishing the relic neutrino background. Contemporary cosmological models predict an average density of approximately 114 relic neutrinos per flavor per cubic centimeter across the Universe [7]. However, for neutrino masses in the sub-eV range, these particles exhibit kinetic energies

on the order of 10^{-4} eV. This extremely low energy severely limits their interactions with matter, rendering direct detection exceptionally challenging.

Direct detection of the relic neutrinos has not been possible yet. However, proposed experiments like PTOLEMY (Princeton Tritium Observatory for Light, Early-Universe, Massive-Neutrino Yield) [8] may observe relic neutrinos through their capture in the beta-decaying nucleus. Also, ongoing experiments like KATRIN are expected to play an important role in this direction and have put a constraint on the local relic neutrino background overdensity [9].

3 Geoneutrinos

Geoneutrinos are antineutrinos produced by the radioactive decay of long-lived isotopes within Earth's interior, particularly uranium-238 (^{238}U), thorium-232 (^{232}Th), and potassium-40 (^{40}K). These isotopes, with half-lives on the order of Earth's age (4.543 billion years), contribute both to geoneutrino production and to the planet's radiogenic heat output. Because both the antineutrino flux and heat generation arise from the same decay processes, measurements of the geoneutrino flux provide valuable constraints on the radiogenic heat output of otherwise inaccessible regions within the Earth [10].

The first successful geoneutrino measurements were made by the KamLAND [11] and Borexino [12] experiments. Both detectors utilize inverse beta decay (IBD) reactions on free protons to capture antineutrinos. In 2005, KamLAND, situated in Japan, made the pioneering geoneutrino measurement, recording 25 events over approximately 749 days of detector live-time [11]. However, reactor antineutrinos, whose energy spectrum partially overlaps with geoneutrinos, pose a significant background. The reactor antineutrino flux varies with power plant output, while geoneutrino contributions remain constant. By jointly analyzing both sources, KamLAND has refined estimates of the geoneutrino flux and advanced understanding of neutrino oscillation parameters.

In 2010, Borexino, an Italy-based detector initially designed for low-energy solar neutrino detection, made its first geoneutrino measurement [13]. Approximately 25 to 85% of Borexino's geoneutrino signal comes from Earth's crustal lithosphere, with contributions from the mantle requiring accurate modeling of the lithospheric signal. Ongoing and future experiments, including SNO+ [14] and JUNO [15], aim to further enhance geoneutrino research. SNO+, a 780 t liquid scintillator detector at Canada's SNOLAB, will provide the first measurement of uranium/thorium geoneutrino flux from the North American Plate and the Western Hemisphere [16]. Although current SNO+ data does not yet allow precise geoneutrino measurements, future measurements are expected to play a crucial role in global Earth model studies.

JUNO, located in South China, is a 20 kt liquid scintillator detector with unprecedented sensitivity and scale. JUNO's capabilities could yield 300–500 geoneutrino interactions annually [17], rapidly surpassing the current global sample of recorded events, which remains under 220. This will significantly improve statistical analyses of Earth's radiogenic heat sources.

Another major development in geoneutrino research is the proposed Jinping Neutrino Experiment in China's Sichuan province [18], located on the Himalayas' slopes – the region with the Earth's thickest continental crust. Jinping is expected to observe a geoneutrino signal predominantly from the lithosphere, with only 15% coming from the mantle. Although it may not directly clarify mantle heat production, data from Jinping will complement multi-site studies across other detectors.

To isolate mantle signals, researchers have proposed deploying detectors in oceanic regions, where the thinner, uranium and thorium-poor oceanic crust minimizes lithospheric contributions. Originally conceptualized as the "Hanohano" experiment, this idea has been revitalized by the Ocean Bottom Detector (OBD) project, a joint effort by Tohoku University (KamLAND team) and JAMSTEC. A kt-scale OBD on the seafloor would enhance interdisciplinary studies in particle physics, geoscience, and ocean engineering [19].

In terms of advancing detection technology, current methods primarily detect geoneutrinos from uranium and thorium decay chains. Recently, researchers proposed using charged-current IBD reactions with various isotope targets to detect potassium geoneutrinos [20]. This method, relying on the LiquidO detection technique enables positron identification from antineutrino interactions, expanding the detection scope to potassium decay. Further, directional measurements, initially tested by the Chooz experiment, are being explored as a future means to map geoneutrino sources, although their application in large detectors presents technical challenges.

These multi-faceted approaches in geoneutrino science, spanning detection sites, technology, and collaborative projects, hold promise for revealing fundamental insights into Earth's heat production, mantle dynamics, and compositional structure [21, 22].

4 Solar neutrinos

Solar neutrinos have provided valuable insights into both particle physics and solar dynamics. Initially, observations of solar neutrinos aimed to explore solar fusion, which powers the Sun. The first significant experiment, conducted in 1967 at the Homestake mine, revealed a puzzling result: the observed neutrino flux was about one-third of what was expected. The puzzle led to decades of experimental work, ultimately solving the Solar Neutrino Problem and confirming neutrino oscillations. These high-precision flux and spectral measurements have not only shed light on the fusion processes inside the Sun but have also provided evidence for neutrino mass and mixing. Today, most solar neutrino fluxes have been measured with exceptional accuracy, even surpassing theoretical predictions in some cases. These measurements help to refine our understanding of processes like chemical mixing in stars and improve stellar models, which rely on inputs such as radiative opacities. Additionally, the fluxes of specific neutrinos, like those from the Boron-8 (^8B) and Beryllium-7 (^7Be) reactions, provide key insights into the temperature and environment of the solar core. Borexino's final results achieved a more precise measurement of the carbon–nitrogen–oxygen (CNO) solar neutrino signal by integrating standard multivariate analysis with the charge identification (CID) technique, which effectively distinguishes solar neutrino events from background noise. By constraining the proton–electron–proton (pep) neutrino flux to its expected value, the analysis was able to reject the hypothesis of no CNO contribution at the 5.3σ confidence level [23, 24]. The CNO Cycle provides direct information on the metallicity of the Sun's core, i.e., its abundance of elements heavier than helium. Borexino disfavors at 3.1σ the “low metallicity” Standard Solar Model (SSM) as compared to the “high metallicity” SSM.

Despite these achievements, several challenges remain in the study of solar neutrinos. One of the unresolved tasks is detecting the helium-proton (*hep*) neutrino flux, which has the highest energy but the lowest flux in the Sun's output. A conclusive observation of this flux may require large-scale detectors like Hyper-Kamiokande [25] or the Deep Underground Neutrino Experiment (DUNE) [26]. Another major goal is the detection of the electron content of CNO (ecCNO) neutrinos, which would offer new information about the metal content of the solar core and probe the electron neutrino survival probability in the transition region between vacuum and matter-enhanced oscillations. These measurements could test the large-mixing-angle (LMA) MSW oscillation theory [24]. Additionally, investigating phenomena such as the day/night effect, where neutrinos regenerate as they pass through the Earth, is ongoing but currently limited by statistics. Future experiments may also resolve mild tensions between the mass splitting parameter values obtained from solar neutrino and terrestrial experiments. Further, recent results have hinted at a Gallium anomaly, confirmed by the BEST experiment, which could point to new physics, though a sterile neutrino explanation is disfavored. Thus, while much progress has been made, future experiments will continue to push the boundaries of our understanding of both neutrinos and solar physics.

5 Atmospheric neutrinos

Atmospheric neutrinos are produced by cosmic ray interactions with nuclei in the Earth's atmosphere. These interactions generate secondary particles—primarily pions and kaons—that decay into muons and neutrinos, resulting in a significant flux of neutrinos that continuously traverse the Earth.

$$\begin{aligned}\pi^\pm/K^\pm &\rightarrow \mu^\pm + \nu_\mu(\bar{\nu}_\mu), \\ \mu^\pm &\rightarrow e^\pm + \bar{\nu}_\mu(\nu_\mu) + \nu_e(\bar{\nu}_e).\end{aligned}\quad (1)$$

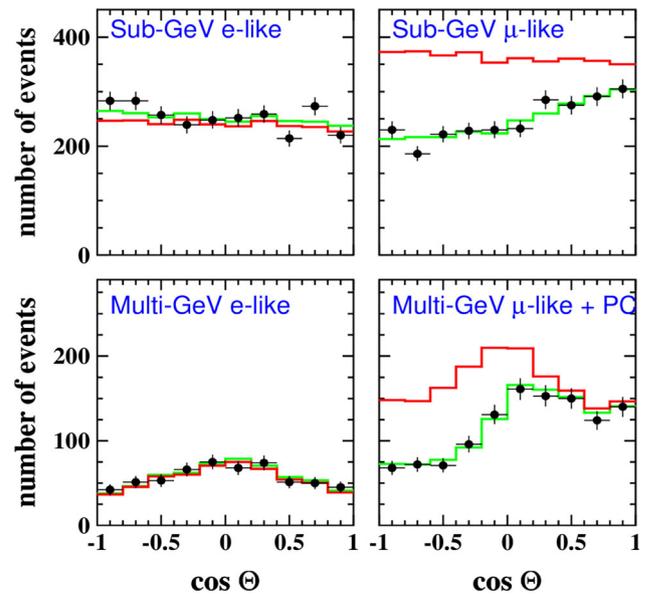
So, the atmospheric neutrinos are dominated by muon-type neutrinos. Note that other semi-leptonic decay modes of kaons contribute to a small but relevant fraction of atmospheric neutrinos, shown as follows,

$$\begin{aligned}K^+/K^0 &\rightarrow \pi^0/\pi^- + \mu^+ + \nu_\mu, \\ K^+/K^0 &\rightarrow \pi^0/\pi^- + e^+ + \nu_e.\end{aligned}\quad (2)$$

A simulation-based prediction of the atmospheric neutrino flux can be found in Ref. [27, 28], commonly referred to as the Honda flux. Recently, the authors in Ref. [29] have presented a refined calculation of the atmospheric neutrino flux ranging from GeV to PeV energies. Their method, Daemonflux, utilizes data-driven inputs and incorporates adjustable parameters to account for uncertainties. By optimizing these parameters with a combination of muon data and constraints from fixed-target experiments, they achieved uncertainties in the calculated neutrino fluxes of less than 10% up to 1 TeV, while keeping neutrino ratios constrained below 10%.

Atmospheric neutrinos played an important role in the discovery of the neutrino oscillation phenomenon. During the 1990s, the Japan-based neutrino observatory Super-Kamiokande (Super-K) observed a deficit in upward-going muon neutrino events from the standard expectation, as shown in Fig. 2.

Fig. 2 Electron (left panels) and muon (Right panels) neutrino events at Super-Kamiokande with 1144 live days of data (shown by the dots). Red solid lines in each panel show the simulated result with the no-oscillation scenario, whereas green curves depict the oscillation between muon and tau neutrinos with the benchmark value of the oscillation parameters, $\Delta m^2 = 3.2 \times 10^{-3} \text{ eV}^2$ and $\theta_{23} = 45^\circ$. For details, see Ref. [30]



This provided compelling evidence for neutrino oscillations, demonstrating transitions between muon and tau neutrinos and confirming that neutrinos have mass. This discovery marked a pivotal breakthrough in particle physics. Over the subsequent years, atmospheric neutrino experiments such as Super-Kamiokande [31] and Ice-Cube (particularly its DeepCore region) [32] have progressively refined the measurements of oscillation parameters, including the mass-squared differences and mixing angles. By exploiting the extensive baselines afforded by naturally occurring atmospheric neutrinos, these experiments have enabled highly precise tests of oscillation parameters. Atmospheric neutrinos are particularly effective for discovering beyond the Standard Model (BSM) physics due to their coverage of ten orders of magnitude in the baseline-to-energy ratio (L/E_ν). This vast L/E_ν range, combined with their passage through significant amounts of matter, has enabled precise measurements of oscillation parameters and stringent tests for new neutrino states, non-standard interactions (NSI), and physics beyond the Standard Model. The atmospheric mixing angle remains the least precisely measured parameter among the mixing angles, showing indications of being close to maximal ($\sin^2 \theta_{23} = 0.5$) but with data suggesting potential deviations without resolving the octant. It is projected that combining measurements from Super-K [31], the IceCube Upgrade [33], KM3NeT-ORCA [34], and Hyper-Kamiokande [25] will achieve half-percent precision on Δm_{31}^2 and approximately 2% on the precision measurements of $\sin^2 \theta_{23}$ [35]. Also, it is predicted that by 2030, atmospheric neutrino measurements are expected to exclude the incorrect octant solutions with over 3σ confidence, assuming current best-fit values. Another initiative is P-ONE [36], a planned deep-sea neutrino observatory located in the Pacific Ocean. P-ONE aims to probe high-energy neutrinos across a wide spectrum, thereby complementing existing detectors and enhancing our understanding of both cosmic and atmospheric neutrino phenomena. Recently, in Ref. [37], authors explore how atmospheric neutrinos, interacting via weak interactions while traversing Earth's interior, can complement gravitational and seismic measurements in probing Earth's structure, using a five-layer Earth model and the proposed INO-ICAL detector [38] to constrain density distributions and the core-mantle boundary of the Earth. Also, previously in Ref. [39], for the first time, the authors exhibit a novel method to explore the neutral-current NSI in atmospheric neutrino experiments using oscillation dips and valleys in reconstructed muon observables at INO-ICAL.

6 Reactor antineutrinos

Nuclear reactors are artificial sources of neutrinos. The first-ever experimental evidence of the neutrino came from the nuclear reactor experiment, 26 years after the particle was postulated by Wolfgang Pauli in his famous letter. In January 1956, two physicists, Clyde Cowan and Frederick Reines from the Los Alamos Laboratory, New Mexico, wrote a telegram to Prof. Pauli stating – “We have definitely detected neutrinos from fission fragments by observing inverse beta decay”. These two physicists performed the pioneering experiment using the liquid scintillation detector to detect the electron antineutrinos emitted from Hanford and Savannah River nuclear reactors. Frederick Reines received the Nobel Prize in 1995 for this pathbreaking discovery.

Nuclear reactors are a pure source of electron antineutrinos. Inside the reactor core, radioactive materials, mostly uranium and thorium, undergo nuclear fission reactions, which produce a dense flux of electron antineutrinos. These

neutrinos generally have energy up to a few tens of MeV. The detailed understanding of the nuclear fission process allows for an accurate estimation of the neutrino energy. The IBD process in the reactors follows

$$\bar{\nu}_e + p \rightarrow e^+ + n. \quad (3)$$

Since 2002, out of eight proposed reactor experiments [40], three were constructed to study reactor antineutrinos: Daya Bay, Double Chooz, and RENO. The purpose of these experiments was to measure the parameters related to neutrino oscillation, with a particular focus on the angle θ_{13} . In 2012, a non-zero θ_{13} was discovered by Daya Bay [4] and RENO [5], following earlier upper limits from T2K [41], MINOS [42], and Double Chooz [43]. This discovery paved the way for investigating leptonic CP violation in the neutrino sector [44–46].

The Reactor Antineutrino Anomaly emerged in 2011 following a re-evaluation of reactor antineutrino flux calculations by Mueller and Huber, and it has since been recognized as one of the most intriguing unresolved discrepancies in reactor antineutrino research over the past decade. Over 25 reactor antineutrino flux measurements from 15 independent experiments conducted over four decades consistently show that the measured integrated flux is about 6% smaller than the Huber–Mueller model prediction, with an experimental uncertainty under 0.5% [47]. These experiments used various detector technologies and nuclear reactors. In addition to discrepancies in the overall flux, significant disagreements also exist in the energy spectrum, most notably the “5-MeV bump,” which has been observed in roughly ten experiments (including RENO, Daya Bay, Double Chooz, NEOS, preliminary results from DANSS, Neutrino-4, STEREO, PROSPECT, Gösgen, and ROVNO). These spectral deviations challenge the predictions of the Huber–Muller model. Recent findings suggest a potential bias in the ^{235}U measurement, and new summation models better match experimental data, though the shape anomaly above 4.5 MeV remains unresolved. New experiments designed to measure these factors affecting the spectrum are currently being established, as presented during the second IAEA meeting in 2023 [48]. Upcoming high-resolution experiments like JUNO-TAO could further clarify these issues [49].

7 Accelerator neutrinos

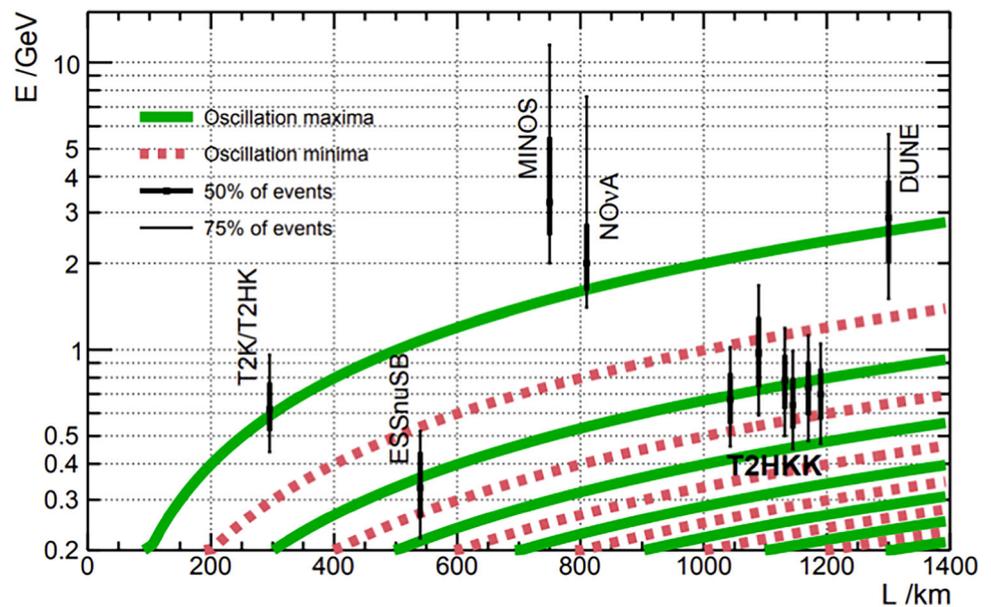
Accelerator neutrinos constitute another source of artificial neutrinos produced in particle accelerators. In a typical setup, high-energy proton beams are directed onto a fixed target composed of nuclei—commonly from materials such as graphite or beryllium. In these proton–nucleus collisions, secondary particles like pions and kaons are generated. Charged pions, in particular, are focused by magnetic fields into a decay tunnel where they predominantly decay into muons, muon neutrinos, and antineutrinos. The resulting muon neutrinos and antineutrinos continue forward, while charged particles are absorbed or deflected by shielding materials, ultimately yielding a high-energy neutrino or antineutrino beam.

In long-baseline neutrino experiments, the beam produced by the accelerator is observed at a far detector located at distances ranging from several hundred to over a thousand kilometers from the source. The neutrino flux measured at the distant detector is compared with that observed near the accelerator, where oscillations are negligible, to infer neutrino oscillation phenomena. Figure 3 illustrates the baselines and energy ranges for both operational and forthcoming long-baseline experiments, highlighting the energy regions in which the maximum neutrino event rates are anticipated.

Early experiments, such as MINOS [51] and K2K [52], provided the first evidence for neutrino oscillations, thereby confirming that neutrinos possess mass and undergo flavor transformations during propagation. The MINOS/MINOS+ collaboration utilized the NuMI beam to measure 2–3 oscillation parameters by measuring both ν_μ disappearance and ν_e appearance, while also probing BSM physics through searches for sterile neutrinos, Lorentz invariance violations, and non-standard interactions. Similarly, NO ν A [53] enhanced these findings by employing an off-axis design that improves sensitivity to oscillation phenomena and facilitates tests of the three-neutrino framework, including further probes of sterile neutrino scenarios. The T2K experiment [54] in Japan, using a narrow-band beam from J-PARC tuned to the energies corresponding to maximal mixing, has also contributed significantly by investigating both oscillation parameters and potential BSM effects, such as light sterile neutrinos and CPT violation. Furthermore, improvements in neutrino cross-section measurements achieved, for example, through the NA61/SHINE collaboration, have helped reduce systematic uncertainties and thereby refine the oscillation parameter estimates. The different energy regimes and baselines of T2K and NO ν A provide complementary perspectives on neutrino oscillation physics, and a recent joint analysis [55] by these collaborations has highlighted the synergies and challenges inherent in combining their data sets. In Ref. [56], the authors addressed for the first time the possible degeneracies between the octant of θ_{23} and leptonic CP phase in muon-neutrino to electron-neutrino appearance channel considering large θ_{13} and observed that equal statistics in neutrino and antineutrino modes are mandatory to resolve this degeneracy.

Despite these successes, several outstanding questions remain, such as neutrino mass ordering, CP violation, and the octant of θ_{23} . These fundamental questions motivate the next generation of experiments. DUNE [26],

Fig. 3 A comparison of the energy and baselines of various accelerator-driven long-baseline experiments. The different lines for T2HKK correspond to various potential baselines, all targeting the second oscillation maximum. The figure is taken from Ref. [50]



scheduled to commence operations in the late 2020s, will feature a deep underground detector in South Dakota to study long-baseline oscillations over 1300 km, with unprecedented sensitivity to CP violation in the neutrino sector. T2HK [25], the successor to T2K, will benefit from increased beam power and an enlarged detector, enabling more precise determinations of oscillation parameters—particularly CP violation and the neutrino mass ordering. In addition, ESSνSB, based in Europe, aims to exploit the European Spallation Source to generate an intense neutrino beam for investigations over a 540 km baseline. Collectively, these forthcoming experiments will provide deeper insights into the fundamental properties of neutrinos, potentially elucidating the origins of the matter–antimatter asymmetry in the Universe and offering valuable constraints on BSM physics, including the possibility of sterile neutrinos and non-standard interactions.

A substantial body of literature is devoted to sensitivity studies under both standard and non-standard interaction scenarios. For instance, Ref. [57] presents a detailed investigation of the complementarity between DUNE and T2HK for constraining CP violation. Moreover, Ref. [58] projects the expected bounds at the 95% confidence level on off-diagonal CPT-violating and CPT-conserving Lorentz invariance violating parameters, using data from DUNE, T2HK, their combination, and the existing measurements from T2K and NOνA.

8 Astrophysical neutrinos

Neutrinos are produced by a wide array of astrophysical processes throughout the Universe. In contrast to other cosmic messengers that are deflected by magnetic fields, neutrinos travel immense distances along nearly unaltered trajectories before reaching the Earth. Astrophysical neutrinos are generated in extremely high-energy environments, giving them energies much greater than those of neutrinos produced in the Sun, supernovae, Earth’s atmosphere, particle accelerators, or nuclear reactors, ranging from hundreds of TeV to tens of PeV range. While the production mechanisms for astrophysical neutrinos are not yet fully understood, potential sources include AGN, GRBs, supernovae, black holes, pulsars, and others. Neutrinos emitted from these sources constitute a diffuse neutrino flux. The energy spectrum of the diffuse neutrino flux follows a power law, $\phi_\nu \propto E^{-\gamma}$. The analysis of the data from the IceCube observatory suggests the value of the spectral index γ in the range [2.0,3.0]. The best-fit value of the spectral index measured from the combined analysis of all the IceCube data is $\gamma = 2.50 \pm 0.09$ above 20 TeV [61].

Within these sources, neutrinos are primarily generated through three possible mechanisms. The most widely discussed mechanism is pion decay, where pions are produced via the collisions of high-energy protons with ambient protons (pp) or photons ($p\gamma$). The decay of pions yields muons and muon neutrinos, with the muons further decaying to produce one additional muon neutrino and one electron neutrino (Eq. 1), resulting in a flavor composition of $f_{\nu_e} : f_{\nu_\mu} : f_{\nu_\tau} \equiv 1 : 2 : 0$ at the source. The other two mechanisms include the muon-damped scenario and neutron decay. In the muon-damped scenario, strong magnetic fields within the source cause the muons produced in pion decay to lose energy through synchrotron radiation, preventing further decay. This results in a source flavor

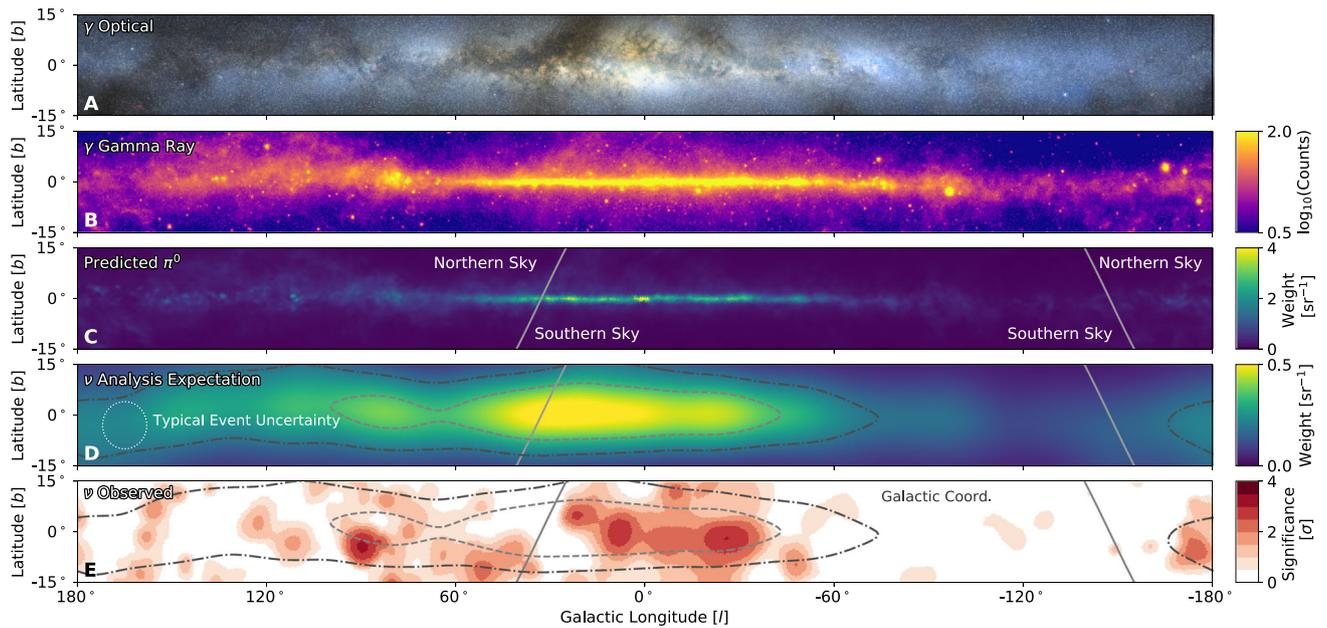


Fig. 4 Galactic plane of the Milky Way galaxy from observation of photons and neutrinos. The first row corresponds to the optical color image of the galactic plane [59], while the second row is the measurement of gamma rays from the Fermi Large Area Telescope (Fermi-LAT) 12-year data at energies greater than 1 GeV. The third and fourth panels show the expected/projected observation of the neutrino flux, derived from the π^0 template that matches the Fermi-LAT observation of gamma rays (third) and adding the sensitivity of the IceCube detector (fourth). The fifth panel is from the IceCube neutrino events calculated from an all-sky scan for point-like sources using 10 years of data. This figure is taken from Ref. [60]

composition of $0 : 1 : 0$. Neutrinos can also originate from the beta decay of neutrons within astrophysical bodies, producing only ν_e with a source composition of $1 : 0 : 0$.

The existence of high-energy neutrino candidates was first experimentally confirmed by the IceCube Neutrino Observatory in 2013 [62, 63]. Since then, IceCube has detected hundreds of astrophysical neutrino events, predominantly in the TeV to PeV energy range. The observatory has been at the forefront of groundbreaking discoveries in high-energy particle astrophysics, including evidence for the Glashow resonance [64], observing neutrinos from the blazar TXS 0506+056 [65], and the Seyfert galaxy NGC 1068 [66]. High-energy astrophysical neutrinos now play a crucial role in multi-messenger astrophysics, offering excellent opportunities for complementary studies with other cosmic messengers and providing a unique window into the Universe. Figure 4 illustrates the view of the Galactic plane based on photon and neutrino observations. Using a decade of data, IceCube has confirmed the emission of high-energy neutrinos from the Milky Way galaxy with a significance of 4.5σ , complementing gamma-ray measurements.

Astrophysical neutrinos also provide an excellent opportunity to study fundamental physics and the various BSM scenarios at high-energy scales. Neutrinos in the TeV-PeV range, produced in various galactic and extragalactic sources, travel distances on the order of megaparsecs (Mpc) to gigaparsecs (Gpc) before reaching the Earth. During this journey, they carry valuable imprints of their source environments and the physical processes occurring within them. Furthermore, minute physics effects that accumulate over these vast propagation paths may become observable at the detector, making astrophysical neutrinos powerful tools for studying both astrophysical phenomena and fundamental physics.

While the field of neutrino astrophysics has advanced significantly over the past two decades, many challenges remain. These include uncovering the exact mechanisms behind neutrino production at astrophysical sources and measuring the neutrino flavor composition at source, identifying the origins of ultra-high-energy cosmic rays and neutrinos [67–69], measuring neutrino cross-sections at extremely high energies [70–72], measuring spectral index of the neutrino flux with high-precision [73, 74]. In addition, high-energy astrophysical neutrinos are expected to play a crucial role in addressing pressing questions in BSM physics, such as the nature of dark matter [75, 76], existence of sterile neutrino states [77, 78], testing the stability of neutrinos [79, 80], and searching for potential new neutrino interactions [81, 82], and many others. In the coming decades, significant progress is anticipated as more data is accumulated from existing detectors like IceCube and KM3NeT-ARCA [34], alongside the deployment of next-generation observatories such as IceCube-Gen2 [83], Baikal-GVD [84], P-ONE [36], ARIANNA-200 [85],

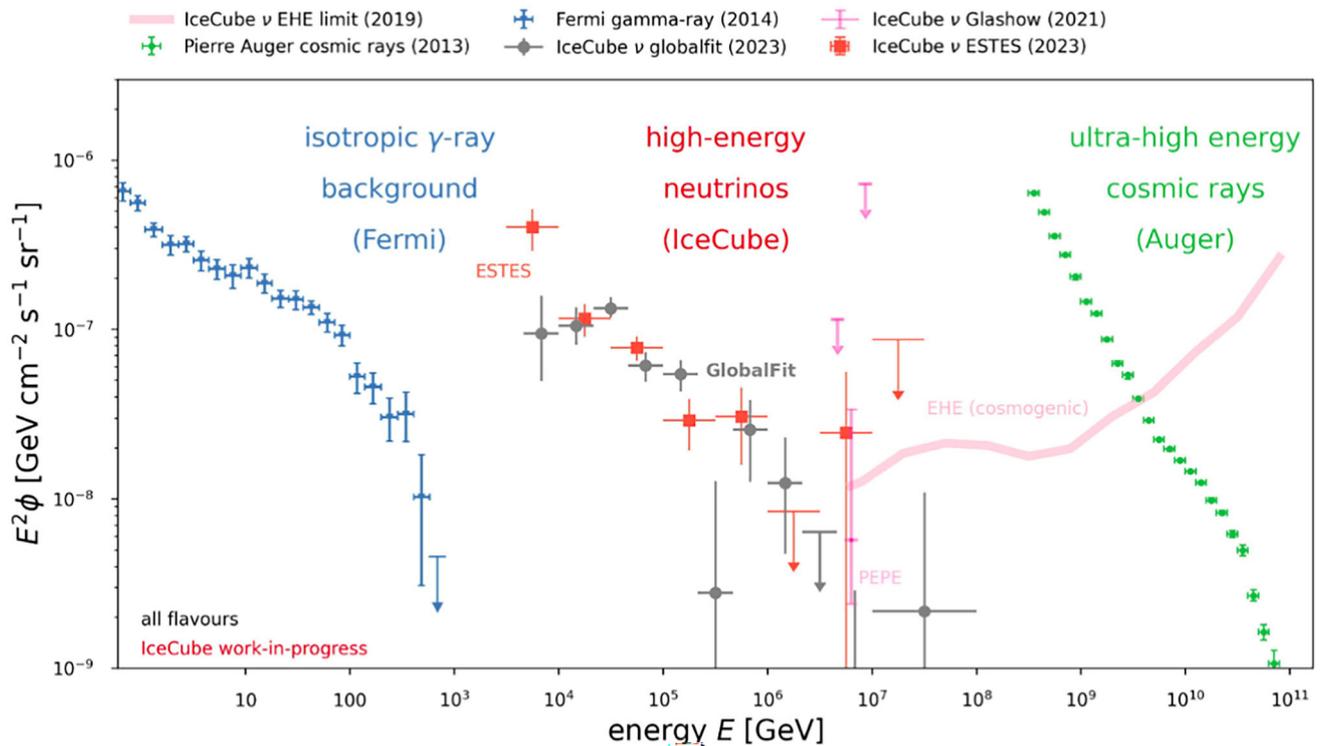


Fig. 5 A comprehensive overview of isotropic γ -ray background from Fermi Gamma-ray Space Telescope, very-high-energy (VHE) astrophysical neutrino measurements as observed by the IceCube Neutrino Observatory, and the ultra-high-energy cosmic ray spectrum as measured at the Pierre Auger Observatory. The figure is taken from [90]

and POEMMA [86], RNO-G [87], RET-CR, and RET-N [88, 89]. Equipped with cutting-edge experimental techniques, these telescopes are poised to address numerous unresolved astrophysical queries, thereby yielding enhanced insights into the fundamental dynamics and constituents of the Universe.

9 Cosmogenic neutrinos

Cosmogenic neutrinos, also known as ultra-high-energy neutrinos, are generated when ultra-high-energy cosmic rays interact with CMB photons through a process known as the Greisen–Zatsepin–Kuzmin (GZK) process. These interactions lead to the production of pions, which subsequently decay into neutrinos and other particles. Cosmogenic neutrinos serve as invaluable messengers of some of the Universe’s most energetic astrophysical phenomena, which occur in AGN blazars or GRBs. These neutrinos can travel immense distances without being affected by intergalactic magnetic fields or experiencing significant attenuation. Detecting these neutrinos offers insights into the origins of cosmic rays and the physical processes occurring at extreme energy scales, thus enhancing our understanding of particle physics and cosmology (Fig. 5).

Research on cosmogenic neutrinos is being conducted at large-scale neutrino observatories, including ARA [91], ARIANNA [92], ANITA [93], the Pierre Auger Observatory [94], and the proposed Giant Radio Array for Neutrino Detection [95]. Additionally, IceCube-Gen2 [96], Baikal-GVD [97], KM3NeT [34], P-ONE [36], and TAMBO [98] will also probe ultra-high-energy neutrinos.

10 Summary and Conclusions

Research on neutrinos from various sources—natural ones such as solar, atmospheric, astrophysical, and geoneutrinos, as well as artificial sources from accelerator and reactor experiments, has significantly enhanced our understanding of fundamental physics. These studies have confirmed the existence of neutrino mass, improved our knowledge of neutrino flavor oscillations and various aspects of BSM physics, and provided insights into Earth’s internal structure and astrophysical phenomena. However, many questions remain unanswered.

The detection of relic neutrinos would be a groundbreaking achievement, confirming a fundamental prediction of the Big Bang model and providing unparalleled insights into the early Universe's conditions and evolution. Geoneutrino studies provide critical insights into Earth's radiogenic heat production and interior composition. In the future, tasks will remain to accurately isolate mantle signals, improve detection technology for potassium geoneutrinos, and achieve precise directional measurements. The study of solar neutrinos has deepened our understanding of both solar fusion processes and neutrino physics, yet challenges remain, including detecting *hep* neutrinos, measuring CNO electron content, and probing potential new physics such as the Gallium anomaly.

Atmospheric neutrinos have been pivotal in neutrino oscillation studies, offering a broad spectrum for testing new physics, and can uniquely probe Earth's internal structure through their interactions as they traverse its layers. However, challenges remain in refining the atmospheric mixing angle and achieving precise Earth modeling. Reactor neutrinos have been crucial in advancing neutrino physics by enabling precise measurements of mixing angles and testing neutrino flux models, but key issues such as the Reactor Antineutrino Anomaly and unexplained spectral deviations, like the "5-MeV bump" remain unresolved, posing challenges to our understanding of antineutrino flux and reactor models.

Accelerator neutrino experiments have significantly advanced our understanding of neutrino oscillations, yet open issues remain, including the precise determination of CP violation, the neutrino mass ordering, and the potential existence of sterile neutrinos; the complementarity between different ongoing experiments: T2K, NO ν A. In the last few decades, there has been rapid progress in the field of neutrino astrophysics. Still, there are many open questions related to the spectrum of astrophysical neutrinos, their production mechanism and flavor composition at the source, the origin of cosmogenic neutrinos, and many others.

Future experiments that build on these complementary sources have the potential to reveal more mysteries and enhance our understanding of neutrino properties and their role in the Universe. Advances in detection techniques will open the door to exploring neutrinos from new sources, such as neutrino factories, which promise further breakthroughs in this field.

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References

1. M.F.H. Seikh, Askaryan radio array: searching for the highest energy neutrinos. (2024). [arXiv:2411.01761](https://arxiv.org/abs/2411.01761) [astro-ph.HE]
2. E. Vitagliano, I. Tamborra, G. Raffelt, Grand unified neutrino spectrum at Earth: sources and spectral components. *Rev. Mod. Phys.* **92**, 45006 (2020). <https://doi.org/10.1103/RevModPhys.92.045006>. [arXiv:1910.11878](https://arxiv.org/abs/1910.11878) [astro-ph.HE]
3. A.A. Penzias, R.W. Wilson, A measurement of excess antenna temperature at 4080-Mc/s. *Astrophys. J.* **142**, 419–421 (1965). <https://doi.org/10.1086/148307>
4. F.P. An et al., Observation of electron-antineutrino disappearance at Daya Bay. *Phys. Rev. Lett.* **108**, 171803 (2012). <https://doi.org/10.1103/PhysRevLett.108.171803>. [arXiv:1203.1669](https://arxiv.org/abs/1203.1669) [hep-ex]
5. J.K. Ahn et al., Observation of reactor electron antineutrino disappearance in the RENO Experiment. *Phys. Rev. Lett.* **108**, 191802 (2012). <https://doi.org/10.1103/PhysRevLett.108.191802>. [arXiv:1204.0626](https://arxiv.org/abs/1204.0626) [hep-ex]
6. Y. Abe et al., Reactor electron antineutrino disappearance in the double Chooz Experiment. *Phys. Rev. D* **86**, 052008 (2012). <https://doi.org/10.1103/PhysRevD.86.052008>. [arXiv:1207.6632](https://arxiv.org/abs/1207.6632) [hep-ex]

7. R. Hodák, F. Šimkovic, S. Kovalenko, A. Faessler, Towards the detection of light and heavy relic neutrinos. *Prog. Part. Nucl. Phys.* **66**(2), 452–456 (2011). <https://doi.org/10.1016/j.pnpnp.2011.01.050>
8. E. Baracchini et al., PTOLEMY: a proposal for thermal relic detection of massive neutrinos and directional detection of MeV dark matter. (2018). [arXiv:1808.01892](https://arxiv.org/abs/1808.01892) [physics.ins-det]
9. M. Aker et al., New constraint on the local relic neutrino background overdensity with the first KATRIN data runs. *Phys. Rev. Lett.* **129**(1), 011806 (2022). <https://doi.org/10.1103/PhysRevLett.129.011806>. [arXiv:2202.04587](https://arxiv.org/abs/2202.04587) [nucl-ex]
10. G. Bellini, K. Inoue, F. Mantovani, A. Serafini, V. Strati, H. Watanabe, Geoneutrinos and geoscience: an intriguing joint-venture. *Riv. Nuovo Cim.* **45**(1), 1–105 (2022). <https://doi.org/10.1007/s40766-021-00026-7>. [arXiv:2109.01482](https://arxiv.org/abs/2109.01482) [physics.geo-ph]
11. T. Araki et al., Experimental investigation of geologically produced antineutrinos with KamLAND. *Nature* **436**, 499–503 (2005). <https://doi.org/10.1038/nature03980>
12. G. Bellini et al., Measurement of geo-neutrinos from 1353 days of Borexino. *Phys. Lett. B* **722**, 295–300 (2013). <https://doi.org/10.1016/j.physletb.2013.04.030>. [arXiv:1303.2571](https://arxiv.org/abs/1303.2571) [hep-ex]
13. G. Bellini et al., Observation of geo-neutrinos. *Phys. Lett. B* **687**, 299–304 (2010). <https://doi.org/10.1016/j.physletb.2010.03.051>. [arXiv:1003.0284](https://arxiv.org/abs/1003.0284) [hep-ex]
14. V. Albanese et al., The SNO+ experiment. *JINST* **16**(08), 08059 (2021). <https://doi.org/10.1088/1748-0221/16/08/P08059>. [arXiv:2104.11687](https://arxiv.org/abs/2104.11687) [physics.ins-det]
15. F. An et al., Neutrino physics with JUNO. *J. Phys. G* **43**(3), 030401 (2016). <https://doi.org/10.1088/0954-3899/43/3/030401>. [arXiv:1507.05613](https://arxiv.org/abs/1507.05613) [physics.ins-det]
16. A. Allega et al., Initial measurement of reactor antineutrino oscillation at SNO+. (2024). [arXiv:2405.19700](https://arxiv.org/abs/2405.19700) [hep-ex]
17. A. Abusleme et al., JUNO physics and detector. *Prog. Part. Nucl. Phys.* **123**, 103927 (2022). <https://doi.org/10.1016/j.pnpnp.2021.103927>. [arXiv:2104.02565](https://arxiv.org/abs/2104.02565) [hep-ex]
18. L. Zhao et al., Measurement of muon-induced neutron yield at the China Jinping Underground Laboratory *. *Chin. Phys. C* **46**(8), 085001 (2022). <https://doi.org/10.1088/1674-1137/ac66cc>. [arXiv:2108.04010](https://arxiv.org/abs/2108.04010) [hep-ex]
19. H. Watanabe, K. Inoue, T. Sakai, W.F. McDonough, N. Abe, E. Araki, T. Kasaya, M. Kyo, N. Sakurai, K. Ueki, H. Yoshida, Snowmass2021-Letter of Interest: ocean bottom detector. Snowmass LOI. (2021). https://www.snowmass21.org/docs/files/summaries/NF/SNOWMASS21-NF4_NF10_OceanBottomDetector-201.pdf
20. A. Cabrera et al., Probing Earth’s missing potassium using the unique antimatter signature of geoneutrinos. (2023). [arXiv:2308.04154](https://arxiv.org/abs/2308.04154) [physics.geo-ph]
21. G. Fiorentini, G.L. Fogli, E. Lisi, F. Mantovani, A.M. Rotunno, Mantle geoneutrinos in KamLAND and Borexino. *Phys. Rev. D* **86**, 033004 (2012). <https://doi.org/10.1103/PhysRevD.86.033004>. [arXiv:1204.1923](https://arxiv.org/abs/1204.1923) [hep-ph]
22. O. Sramek, W.F. McDonough, E.S. Kite, V. Lekic, S. Dye, S. Zhong, Geophysical and geochemical constraints on geoneutrino fluxes from Earth’s mantle. *Earth Planet. Sci. Lett.* **361**, 356–366 (2013). <https://doi.org/10.1016/j.epsl.2012.11.001>. [arXiv:1207.0853](https://arxiv.org/abs/1207.0853) [physics.geo-ph]
23. Y. Herrera, A. S, Standard solar models B23/SF-III (v1.2). Zenodo. (2023). <https://doi.org/10.5281/zenodo.10822316>
24. M. Agostini et al., Experimental evidence of neutrinos produced in the CNO fusion cycle in the Sun. *Nature* **587**, 577–582 (2020). <https://doi.org/10.1038/s41586-020-2934-0>. [arXiv:2006.15115](https://arxiv.org/abs/2006.15115) [hep-ex]
25. K. Abe et al., Hyper-Kamiokande Design Report. (2018). [arXiv:1805.04163](https://arxiv.org/abs/1805.04163) [physics.ins-det]
26. B. Abi et al., Deep Underground Neutrino Experiment (DUNE), far detector technical design report, volume I introduction to DUNE. *JINST* **15**(08), 08008 (2020). <https://doi.org/10.1088/1748-0221/15/08/T08008>. [arXiv:2002.02967](https://arxiv.org/abs/2002.02967) [physics.ins-det]
27. M. Sajjad Athar, M. Honda, T. Kajita, K. Kasahara, S. Midorikawa, Atmospheric neutrino flux at INO, South Pole and Pyhasalmi. *Phys. Lett. B* **718**, 1375–1380 (2013). <https://doi.org/10.1016/j.physletb.2012.12.016>. [arXiv:1210.5154](https://arxiv.org/abs/1210.5154) [hep-ph]
28. M. Honda, M. Sajjad Athar, T. Kajita, K. Kasahara, S. Midorikawa, Atmospheric neutrino flux calculation using the NRLMSISE-00 atmospheric model. *Phys. Rev. D* **92**(2), 023004 (2015). <https://doi.org/10.1103/PhysRevD.92.023004>. [arXiv:1502.03916](https://arxiv.org/abs/1502.03916) [astro-ph.HE]
29. J.P. Yañez, A. Fedynitch, Data-driven muon-calibrated neutrino flux. *Phys. Rev. D* **107**(12), 123037 (2023). <https://doi.org/10.1103/PhysRevD.107.123037>. [arXiv:2303.00022](https://arxiv.org/abs/2303.00022) [hep-ph]
30. J.G. Learned, The atmospheric neutrino anomaly: muon neutrino disappearance. 89–130 (2000). [arXiv:hep-ex/0007056](https://arxiv.org/abs/hep-ex/0007056)
31. Y. Suzuki, The Super-Kamiokande experiment. *Eur. Phys. J. C* **79**(4), 298 (2019). <https://doi.org/10.1140/epjc/s10052-019-6796-2>
32. R. Abbasi et al., Measurement of atmospheric neutrino mixing with improved IceCube DeepCore calibration and data processing. *Phys. Rev. D* **108**(1), 012014 (2023). <https://doi.org/10.1103/PhysRevD.108.012014>. [arXiv:2304.12236](https://arxiv.org/abs/2304.12236) [hep-ex]
33. A. Ishihara, The IceCube upgrade – design and science goals. *PoS ICRC2019*, 1031 (2021). <https://doi.org/10.22323/1.358.1031>. [arXiv:1908.09441](https://arxiv.org/abs/1908.09441) [astro-ph.HE]
34. S. Adrian-Martinez et al., Letter of intent for KM3NeT 2.0. *J. Phys. G* **43**(8), 084001 (2016). <https://doi.org/10.1088/0954-3899/43/8/084001>. [arXiv:1601.07459](https://arxiv.org/abs/1601.07459) [astro-ph.IM]
35. C.A. Argüelles, P. Fernández, I. Martínez-Soler, M. Jin, Measuring oscillations with a million atmospheric neutrinos. *Phys. Rev. X* **13**(4), 041055 (2023). <https://doi.org/10.1103/PhysRevX.13.041055>. [arXiv:2211.02666](https://arxiv.org/abs/2211.02666) [hep-ph]
36. M. Agostini et al., The Pacific Ocean Neutrino Experiment. *Nat. Astron.* **4**(10), 913–915 (2020). <https://doi.org/10.1038/s41550-020-1182-4>. [arXiv:2005.09493](https://arxiv.org/abs/2005.09493) [astro-ph.HE]

37. A.K. Upadhyay, A. Kumar, S.K. Agarwalla, A. Dighe, Constraining the core radius and density jumps inside Earth using atmospheric neutrino oscillations. (2024). [arXiv:2405.04986](https://arxiv.org/abs/2405.04986) [hep-ph]
38. S. Ahmed et al., Physics potential of the ICAL detector at the India-based Neutrino Observatory (INO). *Pramana* **88**(5), 79 (2017). <https://doi.org/10.1007/s12043-017-1373-4>. [arXiv:1505.07380](https://arxiv.org/abs/1505.07380) [physics.ins-det]
39. A. Kumar, A. Khatun, S.K. Agarwalla, A. Dighe, A new approach to probe non-standard interactions in Atmospheric Neutrino Experiments. *JHEP* **04**, 159 (2021). [https://doi.org/10.1007/JHEP04\(2021\)159](https://doi.org/10.1007/JHEP04(2021)159). [arXiv:2101.02607](https://arxiv.org/abs/2101.02607) [hep-ph]
40. K. Anderson et al., White paper report on using nuclear reactors to search for a value of θ_{13} . (2004). [arXiv:hep-ex/0402041](https://arxiv.org/abs/hep-ex/0402041)
41. K. Abe et al., Indication of electron neutrino appearance from an accelerator-produced off-axis muon neutrino beam. *Phys. Rev. Lett.* **107**, 041801 (2011). <https://doi.org/10.1103/PhysRevLett.107.041801>. [arXiv:1106.2822](https://arxiv.org/abs/1106.2822) [hep-ex]
42. P. Adamson et al., Improved search for muon-neutrino to electron-neutrino oscillations in MINOS. *Phys. Rev. Lett.* **107**, 181802 (2011). <https://doi.org/10.1103/PhysRevLett.107.181802>. [arXiv:1108.0015](https://arxiv.org/abs/1108.0015) [hep-ex]
43. Y. Abe et al., Indication of reactor $\bar{\nu}_e$ disappearance in the Double Chooz Experiment. *Phys. Rev. Lett.* **108**, 131801 (2012). <https://doi.org/10.1103/PhysRevLett.108.131801>. [arXiv:1112.6353](https://arxiv.org/abs/1112.6353) [hep-ex]
44. S.K. Agarwalla, T. Li, A. Rubbia, An incremental approach to unravel the neutrino mass hierarchy and CP violation with a long-baseline Superbeam for large θ_{13} . *JHEP* **05**, 154 (2012). [https://doi.org/10.1007/JHEP05\(2012\)154](https://doi.org/10.1007/JHEP05(2012)154). [arXiv:1109.6526](https://arxiv.org/abs/1109.6526) [hep-ph]
45. S. Pascoli, T. Schwetz, Prospects for neutrino oscillation physics. *Adv. High Energy Phys.* **2013**, 503401 (2013). <https://doi.org/10.1155/2013/503401>
46. S.K. Agarwalla, Physics potential of long-baseline experiments. *Adv. High Energy Phys.* **2014**, 457803 (2014). <https://doi.org/10.1155/2014/457803>. [arXiv:1401.4705](https://arxiv.org/abs/1401.4705) [hep-ph]
47. G. Mention, M. Fechner, T. Lasserre, T.A. Mueller, D. Lhuillier, M. Cribier, A. Letourneau, The reactor antineutrino anomaly. *Phys. Rev. D* **83**, 073006 (2011). <https://doi.org/10.1103/PhysRevD.83.073006>. [arXiv:1101.2755](https://arxiv.org/abs/1101.2755) [hep-ex]
48. IAEA: Technical Meeting on Nuclear Data Needs for Antineutrino Spectra Applications. Organized by the Nuclear Data Section of the IAEA, Vienna, 16–20 Jan (2023). <https://conferences.iaea.org/event/337/>
49. C. Zhang, X. Qian, M. Fallot, Reactor antineutrino flux and anomaly. *Prog. Part. Nucl. Phys.* **136**, 104106 (2024). <https://doi.org/10.1016/j.pnpnp.2024.104106>. [arXiv:2310.13070](https://arxiv.org/abs/2310.13070) [hep-ph]
50. K. Abe et al., Physics potentials with the second hyper-Kamiokande detector in Korea. *PTEP* **2018**(6), 063–01 (2018). <https://doi.org/10.1093/ptep/pty044>. [arXiv:1611.06118](https://arxiv.org/abs/1611.06118) [hep-ex]
51. P. Adamson et al., Measurement of neutrino and antineutrino oscillations using beam and atmospheric data in MINOS. *Phys. Rev. Lett.* **110**(25), 251801 (2013). <https://doi.org/10.1103/PhysRevLett.110.251801>. [arXiv:1304.6335](https://arxiv.org/abs/1304.6335) [hep-ex]
52. M.H. Ahn et al., Measurement of neutrino oscillation by the K2K Experiment. *Phys. Rev. D* **74**, 072003 (2006). <https://doi.org/10.1103/PhysRevD.74.072003>. [arXiv:hep-ex/0606032](https://arxiv.org/abs/hep-ex/0606032)
53. M.A. Acero et al., Improved measurement of neutrino oscillation parameters by the NOvA experiment. *Phys. Rev. D* **106**(3), 032004 (2022). <https://doi.org/10.1103/PhysRevD.106.032004>. [arXiv:2108.08219](https://arxiv.org/abs/2108.08219) [hep-ex]
54. K. Abe et al., Constraint on the matter-antimatter symmetry-violating phase in neutrino oscillations. *Nature* **580**(7803), 339–344 (2020). <https://doi.org/10.1038/s41586-020-2177-0>. [arXiv:1910.03887](https://arxiv.org/abs/1910.03887) [hep-ex]. [Erratum: *Nature* 583, E16 (2020)]
55. Z. Vallari, NOvA-T2K joint analysis results. Talk given on behalf of NOvA & T2K Collaborations Joint Experimental-Theoretical Physics Seminar, Fermilab. https://indico.fnal.gov/event/62062/contributions/279004/attachments/175258/237774/021624_NOvAT2K_JointFitResults_ZV.pdf (2024)
56. S.K. Agarwalla, S. Prakash, S.U. Sankar, Resolving the octant of θ_{23} with T2K and NOvA. *JHEP* **07**, 131 (2013). [https://doi.org/10.1007/JHEP07\(2013\)131](https://doi.org/10.1007/JHEP07(2013)131). [arXiv:1301.2574](https://arxiv.org/abs/1301.2574) [hep-ph]
57. S.K. Agarwalla, S. Das, A. Giarnetti, D. Meloni, M. Singh, Enhancing sensitivity to leptonic CP violation using complementarity among DUNE, T2HK, and T2HKK. *Eur. Phys. J. C* **83**(8), 694 (2023). <https://doi.org/10.1140/epjc/s10052-023-11863-7>. [arXiv:2211.10620](https://arxiv.org/abs/2211.10620) [hep-ph]
58. S.K. Agarwalla, S. Das, S. Sahoo, P. Swain, Constraining Lorentz invariance violation with next-generation long-baseline experiments. *JHEP* **07**, 216 (2023). [https://doi.org/10.1007/JHEP07\(2023\)216](https://doi.org/10.1007/JHEP07(2023)216). [arXiv:2302.12005](https://arxiv.org/abs/2302.12005) [hep-ph]
59. A. Mellinger, A color all-sky panorama image of the milky way. *Publ. Astron. Soc. Pac.* **121**(885), 1180 (2009). <https://doi.org/10.1086/648480>
60. R. Abbasi et al., Observation of high-energy neutrinos from the Galactic plane. *Science* **380**(6652), 9818 (2023). <https://doi.org/10.1126/science.adc9818>. [arXiv:2307.04427](https://arxiv.org/abs/2307.04427) [astro-ph.HE]
61. M.G. Aartsen et al., A combined maximum-likelihood analysis of the high-energy astrophysical neutrino flux measured with IceCube. *Astrophys. J.* **809**(1), 98 (2015). <https://doi.org/10.1088/0004-637X/809/1/98>. [arXiv:1507.03991](https://arxiv.org/abs/1507.03991) [astro-ph.HE]
62. M.G. Aartsen et al., First observation of PeV-energy neutrinos with IceCube. *Phys. Rev. Lett.* **111**, 021103 (2013). <https://doi.org/10.1103/PhysRevLett.111.021103>. [arXiv:1304.5356](https://arxiv.org/abs/1304.5356) [astro-ph.HE]
63. M.G. Aartsen et al., Evidence for high-energy extraterrestrial neutrinos at the IceCube detector. *Science* **342**, 1242856 (2013). <https://doi.org/10.1126/science.1242856>. [arXiv:1311.5238](https://arxiv.org/abs/1311.5238) [astro-ph.HE]
64. M.G. Aartsen et al., Detection of a particle shower at the Glashow resonance with IceCube. *Nature* **591**(7849), 220–224 (2021). <https://doi.org/10.1038/s41586-021-03256-1>. [arXiv:2110.15051](https://arxiv.org/abs/2110.15051) [hep-ex]. [Erratum: *Nature* 592, E11 (2021)]
65. M.G. Aartsen et al., Multimessenger observations of a flaring blazar coincident with high-energy neutrino IceCube-170922A. *Science* **361**(6398), 1378 (2018). <https://doi.org/10.1126/science.aat1378>. [arXiv:1807.08816](https://arxiv.org/abs/1807.08816) [astro-ph.HE]

66. R. Abbasi et al., Evidence for neutrino emission from the nearby active galaxy NGC 1068. *Science* **378**(6619), 538–543 (2022). <https://doi.org/10.1126/science.abg3395>. [arXiv:2211.09972](https://arxiv.org/abs/2211.09972) [astro-ph.HE]
67. P. Meszaros, Astrophysical sources of high energy neutrinos in the IceCube era. *Annu. Rev. Nucl. Part. Sci.* **67**, 45–67 (2017). <https://doi.org/10.1146/annurev-nucl-101916-123304>. [arXiv:1708.03577](https://arxiv.org/abs/1708.03577) [astro-ph.HE]
68. M. Bustamante, M. Ahlers, Inferring the flavor of high-energy astrophysical neutrinos at their sources. *Phys. Rev. Lett.* **122**(24), 241101 (2019). <https://doi.org/10.1103/PhysRevLett.122.241101>. [arXiv:1901.10087](https://arxiv.org/abs/1901.10087) [astro-ph.HE]
69. Q. Liu, D.F.G. Fiorillo, C.A. Argüelles, M. Bustamante, N. Song, A.C. Vincent, Identifying energy-dependent flavor transitions in high-energy astrophysical neutrino measurements. (2023). [arXiv:2312.07649](https://arxiv.org/abs/2312.07649) [astro-ph.HE]
70. I. Alikhanov, Hidden Glashow resonance in neutrino-nucleus collisions. *Phys. Lett. B* **756**, 247–253 (2016). <https://doi.org/10.1016/j.physletb.2016.03.009>. [arXiv:1503.08817](https://arxiv.org/abs/1503.08817) [hep-ph]
71. R. Gauld, Precise predictions for multi-TeV and PeV energy neutrino scattering rates. *Phys. Rev. D* **100**(9), 091301 (2019). <https://doi.org/10.1103/PhysRevD.100.091301>. [arXiv:1905.03792](https://arxiv.org/abs/1905.03792) [hep-ph]
72. B. Zhou, J.F. Beacom, W-boson and trident production in TeV-PeV neutrino observatories. *Phys. Rev. D* **101**(3), 036010 (2020). <https://doi.org/10.1103/PhysRevD.101.036010>. [arXiv:1910.10720](https://arxiv.org/abs/1910.10720) [hep-ph]
73. M. Silva, S. Mancina, J. Osborn, Measurement of the cosmic neutrino flux from the Southern Sky using 10 years of IceCube starting track events. *PoS ICRC2023*, 1008 (2023). <https://doi.org/10.22323/1.444.1008>. [arXiv:2308.04582](https://arxiv.org/abs/2308.04582) [astro-ph.HE]
74. R. Abbasi et al., Characterization of the astrophysical diffuse neutrino flux using starting track events in IceCube. *Phys. Rev. D* **110**(2), 022001 (2024). <https://doi.org/10.1103/PhysRevD.110.022001>. [arXiv:2402.18026](https://arxiv.org/abs/2402.18026) [astro-ph.HE]
75. M.G. Aartsen et al., All-flavour search for neutrinos from dark matter annihilations in the Milky Way with IceCube/DeepCore. *Eur. Phys. J. C* **76**(10), 531 (2016). <https://doi.org/10.1140/epjc/s10052-016-4375-3>. [arXiv:1606.00209](https://arxiv.org/abs/1606.00209) [astro-ph.HE]
76. S. Pandey, S. Karmakar, S. Rakshit, Interactions of astrophysical neutrinos with dark matter: a model building perspective. *JHEP* **01**, 095 (2019). [https://doi.org/10.1007/JHEP11\(2021\)215](https://doi.org/10.1007/JHEP11(2021)215). [arXiv:1810.04203](https://arxiv.org/abs/1810.04203) [hep-ph]. [Erratum: *JHEP* **11**, 215 (2021)]
77. C.A. Argüelles, K. Farrag, T. Katori, R. Khandelwal, S. Mandalia, J. Salvado, Sterile neutrinos in astrophysical neutrino flavor. *JCAP* **02**, 015 (2020). <https://doi.org/10.1088/1475-7516/2020/02/015>. [arXiv:1909.05341](https://arxiv.org/abs/1909.05341) [hep-ph]
78. M. Ahlers, M. Bustamante, N.G.N. Willesen, Flavors of astrophysical neutrinos with active-sterile mixing. *JCAP* **07**, 029 (2021). <https://doi.org/10.1088/1475-7516/2021/07/029>. [arXiv:2009.01253](https://arxiv.org/abs/2009.01253) [hep-ph]
79. A. Abdullahi, P.B. Denton, Visible decay of astrophysical neutrinos at IceCube. *Phys. Rev. D* **102**(2), 023018 (2020). <https://doi.org/10.1103/PhysRevD.102.023018>. [arXiv:2005.07200](https://arxiv.org/abs/2005.07200) [hep-ph]
80. V.B. Valera, D.F.G. Fiorillo, I. Esteban, M. Bustamante, New limits on neutrino decay from high-energy astrophysical neutrinos. *Phys. Rev. D* **110**(4), 043004 (2024). <https://doi.org/10.1103/PhysRevD.110.043004>. [arXiv:2405.14826](https://arxiv.org/abs/2405.14826) [astro-ph.HE]
81. K. Ioka, K. Murase, IceCube PeV-EeV neutrinos and secret interactions of neutrinos. *PTEP* **2014**(6), 061–01 (2014). <https://doi.org/10.1093/ptep/ptu090>. [arXiv:1404.2279](https://arxiv.org/abs/1404.2279) [astro-ph.HE]
82. S.K. Agarwalla, M. Bustamante, S. Das, A. Narang, Present and future constraints on flavor-dependent long-range interactions of high-energy astrophysical neutrinos. *JHEP* **08**, 113 (2023). [https://doi.org/10.1007/JHEP08\(2023\)113](https://doi.org/10.1007/JHEP08(2023)113). [arXiv:2305.03675](https://arxiv.org/abs/2305.03675) [hep-ph]
83. M.G. Aartsen et al., IceCube-Gen2: the window to the extreme Universe. *J. Phys. G* **48**(6), 060501 (2021). <https://doi.org/10.1088/1361-6471/abbd48>. [arXiv:2008.04323](https://arxiv.org/abs/2008.04323) [astro-ph.HE]
84. A.D. Avrorin et al., The Baikal-GVD neutrino telescope: first results of multi-messenger study. *PoS ICRC2019*, 1013 (2020). <https://doi.org/10.22323/1.358.1013>. [arXiv:1908.05450](https://arxiv.org/abs/1908.05450) [astro-ph.HE]
85. A. Anker et al., White Paper: ARIANNA-200 high energy neutrino telescope. (2020). [arXiv:2004.09841](https://arxiv.org/abs/2004.09841) [astro-ph.IM]
86. A.V. Olinto et al., The POEMMA (Probe of Extreme Multi-Messenger Astrophysics) observatory. *JCAP* **06**, 007 (2021). <https://doi.org/10.1088/1475-7516/2021/06/007>. [arXiv:2012.07945](https://arxiv.org/abs/2012.07945) [astro-ph.IM]
87. J.A. Aguilar et al., Design and sensitivity of the Radio Neutrino Observatory in Greenland (RNO-G). *JINST* **16**(03), 03025 (2021). <https://doi.org/10.1088/1748-0221/16/03/P03025>. [arXiv:2010.12279](https://arxiv.org/abs/2010.12279) [astro-ph.IM]. [Erratum: *JINST* **18**, E03001 (2023)]
88. S. Prohira et al., The Radar Echo Telescope for cosmic rays: pathfinder experiment for a next-generation neutrino observatory. *Phys. Rev. D* **104**(10), 102006 (2021). <https://doi.org/10.1103/PhysRevD.104.102006>. [arXiv:2104.00459](https://arxiv.org/abs/2104.00459) [astro-ph.IM]
89. D. Frikken, The Radar Echo Telescope for neutrinos: contribution to ICRC 2023. *PoS ICRC2023*, 1135 (2023). <https://doi.org/10.22323/1.444.1135>
90. C. Haack, Current state of neutrino astronomy IceCube and beyond. Talk given on behalf of IceCube Collaboration at the 43rd International Symposium on Physics in Collision PIC 2024. https://indico.cern.ch/event/1414470/contributions/6157638/attachments/2951408/5188130/IceCube_PIC2024_CH.pdf (2024)
91. P. Allison et al., Constraints on the diffuse flux of ultrahigh energy neutrinos from four years of Askaryan radio array data in two stations. *Phys. Rev. D* **102**(4), 043021 (2020). <https://doi.org/10.1103/PhysRevD.102.043021>. [arXiv:1912.00987](https://arxiv.org/abs/1912.00987) [astro-ph.HE]
92. A. Anker et al., Targeting ultra-high energy neutrinos with the ARIANNA experiment. *Adv. Space Res.* **64**, 2595–2609 (2019). <https://doi.org/10.1016/j.asr.2019.06.016>. [arXiv:1903.01609](https://arxiv.org/abs/1903.01609) [astro-ph.IM]

93. P.W. Gorham et al., Constraints on the diffuse high-energy neutrino flux from the third flight of ANITA. *Phys. Rev. D* **98**(2), 022001 (2018). <https://doi.org/10.1103/PhysRevD.98.022001>. [arXiv:1803.02719](https://arxiv.org/abs/1803.02719) [astro-ph.HE]
94. A. Aab et al., The Pierre Auger Cosmic Ray Observatory. *Nucl. Instrum. Methods A* **798**, 172–213 (2015). <https://doi.org/10.1016/j.nima.2015.06.058>. [arXiv:1502.01323](https://arxiv.org/abs/1502.01323) [astro-ph.IM]
95. K. Fang et al., The giant radio array for neutrino detection (GRAND): present and perspectives. *PoS ICRC2017*, 996 (2018). <https://doi.org/10.22323/1.301.0996>. [arXiv:1708.05128](https://arxiv.org/abs/1708.05128) [astro-ph.IM]
96. A. Ishihara, et al., The next generation neutrino telescope: IceCube-Gen2. *PoS ICRC2023*, 994 (2023). <https://doi.org/10.22323/1.444.0994>. [arXiv:2308.09427](https://arxiv.org/abs/2308.09427) [astro-ph.HE]
97. V.A. Allakhverdyan et al., Overview of the Baikal-GVD neutrino telescope: 2024 status. *EPJ Web Conf.* **319**, 04002 (2025). <https://doi.org/10.1051/epjconf/202531904002>
98. W. Thompson et al., TAMBO: searching for Tau neutrinos in the Peruvian Andes. *PoS ICRC2023*, 1109 (2023). <https://doi.org/10.22323/1.444.1109>