

Astrophysics Uniquely Enabled by Observations of High-Energy Cosmic Neutrinos

Thematic Area: Multi-Messenger Astronomy and Astrophysics

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Abstract

High-energy cosmic neutrinos carry unique information about the most energetic non-thermal sources in the Universe. This white paper describes the outstanding astrophysics questions that neutrino astronomy can address in the coming decade. A companion white paper discusses how the observation of cosmic neutrinos can address open questions in fundamental physics. Detailed measurements of the diffuse neutrino flux, measurements of neutrinos from point sources, and multi-messenger observations with neutrinos will enable the discovery and characterization of the most energetic sources in the Universe.

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The Unique Tool of Neutrino Astronomy

Neutrino astronomy allows us to discover and characterize the most energetic non-thermal sources in the Universe. Despite observations of cosmic rays (charged nuclei), which reach energies that are ten million times higher than those achievable in the Large Hadron Collider [1, 2], and observations of γ -rays [3] and astrophysical neutrinos [4–10], we do not yet know where or how these particles are accelerated. Neutrino astronomy is a key to directly answering the question of how particles are accelerated to these extreme energies. Cosmic rays can collide with gas and radiation in their sources or while propagating over cosmic distances until they reach Earth. A “smoking-gun” signal of such interactions is the production of high-energy neutrinos.

Astrophysical neutrinos provide insight into source characteristics not accessible through the observation of other messengers. Due to their low cross sections, neutrinos can escape dense astrophysical environments that are opaque to photons. In contrast to γ -rays, neutrinos travel almost unimpeded through the Universe, allowing direct observation of their sources at high redshifts with sub-degree-scale pointing. Unlike cosmic rays, neutrinos are not deflected in magnetic fields and can be observed in spatial and temporal coincidence with photons and gravitational waves [11, 12], which is a key prerequisite to reap the scientific rewards of multi-messenger astronomy. In addition, neutrinos come in different flavors — electron, muon, and tau neutrinos (ν_e , ν_μ , & ν_τ) — and the flavor ratios observed at Earth give insight into the environment of cosmic-ray sources.

The last decade ushered in high-energy neutrino astronomy, with the discovery of an astrophysical neutrino flux in the 10 TeV – 10 PeV energy range [4–10]. The arrival directions of the most energetic neutrinos are shown in Fig. 1 and are consistent with a uniform distribution across the sky after accounting for detector acceptance. Neutrino emission at the observed flux level has been predicted from a variety of source classes, including γ -ray bursts, blazars, starburst galaxies, galaxy clusters, and others (see, *e.g.* [13, 14]). Recently, coincident observations of neutrinos and γ -rays from the blazar TXS 0506+056 presented evidence of the first extragalactic neutrino source [15, 16]. However, this cannot be the entire story: multiple independent analyses indicate that only a fraction of the diffuse neutrino flux can come from γ -ray blazars [17–22].

In the next decade, the development, construction, and operation of multiple neutrino detectors that cover complementary parts of the sky, have a wide range of neutrino energies, and have sensitivity to different flavors, will disentangle the complexities of the neutrino sky. Real-time multi-messenger campaigns, in collaboration with multi-wavelength (radio to γ -ray) and gravitational-wave astronomers, could prove crucial in unveiling the sources of the most energetic particles and the acceleration mechanisms at work. Neutrinos would provide insights into the physics of stellar explosions, compact object mergers, and relativistic jets, as well as particle acceleration processes.

Discovering and Characterizing the Most Energetic Sources in the Universe

The goal of discovering the most energetic non-thermal sources in the Universe can be approached through multiple observational avenues. Detailed observations of all cosmic messengers, including neutrinos, are needed to fully understand the processes at work. Precision measurements of the diffuse neutrino spectrum will shed light on the physics of the most energetic non-thermal sources and their host environments. High-resolution neutrino data from observatories with deep exposure and wide sky coverage will allow us to identify the source population(s) responsible for the diffuse neutrino emission. Combining observations of these neutrinos and other cosmic messengers will provide the optimal strategy of identifying these sources and determining the governing physics.

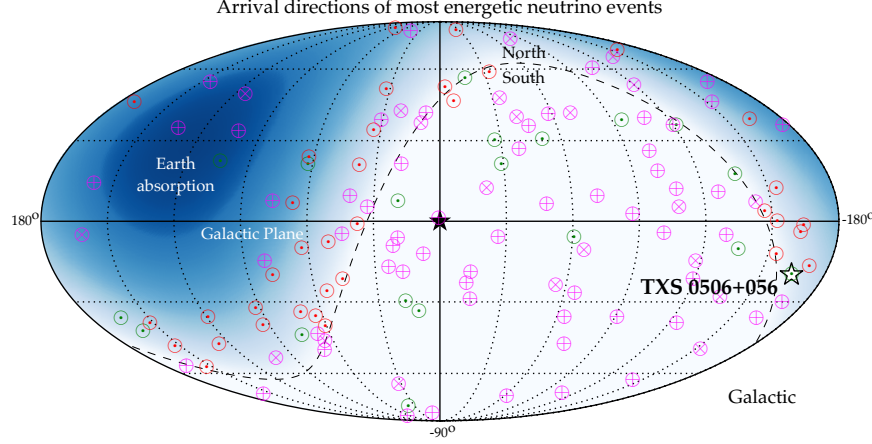


Figure 1: Arrival directions of neutrino events from IceCube. Shown are upgoing track events [8,9] ($\odot$), the high-energy starting events (HESE) (tracks $\otimes$ and cascades $\oplus$) [6, 7, 10], and additional track events published as public alerts ($\odot$) [23, 24]. The blue-shaded region indicates where the Earth absorption of 100-TeV neutrinos becomes important. The dashed line indicates the equatorial plane. We also indicate the location of the blazar TXS 0506+056 ($\star$).

The current lack of established neutrino point sources — despite a firm detection of a diffuse neutrino flux — indicates a population of weak extragalactic sources. This is illustrated in Fig. 2, which shows a parametrization of the diffuse flux (magenta bands) in terms of the local density and luminosity of steady source populations [17] (left plot) or local density rate and bolometric energy for transient source populations [27] (right plot). The lack of neutrino sources after ten years of observations by IceCube translates into the dark-blue shaded exclusion regions. Source populations with sufficiently large local densities — like starburst galaxies [29–38], galaxy clusters and groups [31, 39–41], low-luminosity AGN [42], radio-quiet AGN [43–45], or star-forming galaxies with AGN outflows [34, 46–49] — or with high local rate densities — like (extragalactic) jet-powered SNe including hypernovae [50–53] and interaction-powered SNe [54, 55] — are presently consistent with the observations. Observatories with improvements in point-source sensitivity over current detectors would greatly expand the discovery potential for the brightest sources of these candidate populations (see Fig. 2) and other candidate sources like TXS 0506+056.

Current measurements of the isotropic neutrino flux (ϕ) are shown in Fig. 3, along with the observed isotropic γ -ray background (IGB) and the UHE cosmic-ray flux. The correspondence among the energy densities, proportional to $E^2\phi$, observed in neutrinos, γ -rays, and cosmic rays suggests a strong multi-messenger relationship that offer intriguing prospects for deeper observations with a new generation of instruments.

A) The simultaneous production of neutral and charged pions in cosmic-ray interactions suggests that the sources of high-energy neutrinos could also be strong 10 TeV – 10 PeV γ -ray emitters. For extragalactic scenarios, this γ -ray emission is not directly observable because of the strong absorption of photons by e^+e^- pair production in extragalactic background photons. High-energy γ -rays initiate electromagnetic cascades of repeated inverse-Compton scattering and pair production that eventually contribute to the diffuse γ -rays below 100 GeV, which provides a theoretical upper limit to the diffuse neutrino flux [56, 57]. The detected flux of > 100 TeV neutrinos with the hadronuclear origin is saturated by the diffuse γ -ray data [31] (see blue lines in Fig. 3). Intriguing

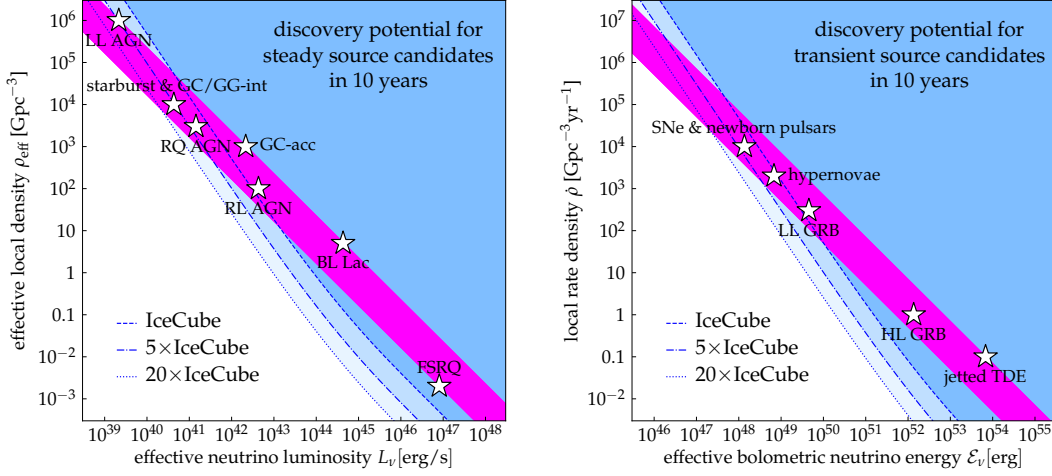


Figure 2: **Left:** Comparison of the diffuse neutrino emission (solid magenta band) to the effective local density and luminosity of extragalactic neutrino source populations. We indicate several candidate populations (☆) by the required neutrino luminosity to account for the full diffuse flux [17] (see also [25]). The lower (upper) edge of the band assumes rapid (no) redshift evolution. The dark-blue-shaded region indicates IceCube’s discovery potential of the closest source of the population ($E^2 \phi_{\nu_\mu + \bar{\nu}_\mu} \simeq 10^{-12}$ TeV/cm²/s in the Northern Hemisphere [26]). **Right:** The same comparison for transient neutrino sources parametrized by their local density rate and bolometric energy [27]. The discovery potential of the closest source is based on 10 years of livetime ($E^2 F_{\nu_\mu + \bar{\nu}_\mu} \simeq 0.1$ GeV/cm² in the Northern Hemisphere [28]).

ingly, several IceCube analyses [10, 58] show an excess of neutrinos below 100 TeV, indicating that the sources are opaque to γ -rays, as expected, *e.g.*, for intense X-ray and soft γ -ray sources [59].

B) Precision measurements of the neutrino flux can test the idea of cosmic particle unification, in which sub-TeV γ -rays, PeV neutrinos, and UHE cosmic rays can be explained simultaneously [17, 41, 60, 61]. If the neutrino flux is related to the sources of UHE cosmic rays, then there is a different theoretical upper limit (the dashed green line in Fig. 3) to the neutrino flux [62, 63]. UHE cosmic ray sources can be embedded in environments that act as “cosmic-ray reservoirs” where magnetic fields trap cosmic rays with energies far below the highest cosmic-ray energies. The trapped cosmic rays collide with gas and produce a flux of γ -rays and neutrinos. The measured IceCube flux is consistent with predictions of some of these models [29, 39, 40]; see, however, [64].

C) The attenuation of UHE cosmic rays through resonant interactions with cosmic microwave background photons results in the production of UHE neutrinos. This mechanism, first pointed out by Greisen, Zatsepin and Kuzmin [67, 68] (GZK), causes a suppression of the UHE cosmic ray proton flux beyond 5×10^{10} GeV [67, 68] and gives rise to a flux of UHE neutrinos [69], not yet detected, shown in Fig. 3. The observation of these cosmogenic neutrinos at $\sim$ EeV, or a stringent upper limit on their flux, will severely restrict models of acceleration, source evolution, cosmic ray composition, and transition from Galactic to extragalactic components, and serve as a complement to cosmic-ray measurements to limit possible sources (*e.g.*, [56, 69–87]).

The strong correspondence of high-energy messengers — suggested by the diffuse data in Fig. 3 — provides excellent motivation for multi-messenger observations. Linking together observations of multiple messengers in time and space will allow direct correlation of neutrino sources

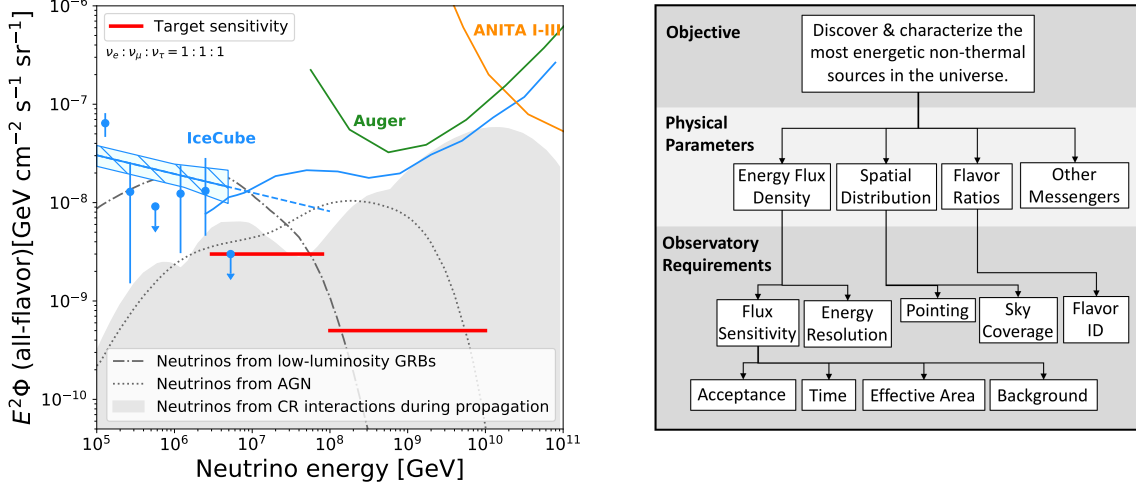


Figure 4: **Left:** Current experimental limits and detections in neutrino astronomy from IceCube [9,10,221], the Pierre Auger Observatory [222], and ANITA [223]. Also shown are low-luminosity GRB [111] (see [50, 52] for similar spectra) and AGN models [224], and an extrapolation of the IceCube flux, which suggests target sensitivities for the next observatories. **Right:** Observatory requirements for neutrino astronomy targeting different physical parameters.

tion [17, 225–227]. At energies between 10 TeV – 10 PeV, an order-of-magnitude improvement in point-source sensitivity will be needed to discover neutrino point sources consistent with the flux discovered by IceCube [17, 225] (see Fig. 2).

For energies 1 – 100 PeV, an order-of-magnitude improvement in the diffuse neutrino flux sensitivity is needed to identify a break, a cutoff, or a new component, to probe diffuse model predictions (*e.g.*, [31, 50, 64, 107, 224, 228]). An energy resolution of $\Delta E/E \lesssim 0.5$ is required to distinguish between model fluxes. At $E \gtrsim 100$ PeV, two orders of magnitude improvement in the diffuse flux sensitivity is needed to test whether particle accelerators in the Universe have similar characteristics to those in our local ($\lesssim 100$ Mpc) neighborhood [83, 84, 229] (see left panel in Fig. 4).

The observed ratios of neutrino flavors and the observed ratio of neutrinos to anti-neutrinos provides a complementary probe of neutrino production mechanisms and the physical conditions at the sources [230, 231]. The identification of per-flavor neutrino fluxes require large event statistics at observatories that can identify flavor-specific signals.

Multi-messenger observations that include neutrinos will provide additional information to localize and characterize sources. This requires the ability to both send and receive real-time alerts to and from other telescopes and gravitational wave detectors [23].

We advocate a staged, multi-observatory approach that will extend the science reach of neutrino observatories throughout the next decade. Complementary approaches that target a broad range of energies (from the TeV scale up through the EeV scale) are useful for determining the nature of these high energy sources. Multiple detectors will be required to measure the per-flavor flux, cover large fractions of the sky, and provide complementary sky coverage in the North and South to increase the exposure for multi-messenger observations. Multiple detectors, preferably with different detection mechanisms to reduce systematic effects, will also be required to confirm results. We advocate for strong cooperation with multi-messenger partners across the electromagnetic spectrum, cosmic rays, and gravitational waves.

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