

Snowmass2021 - Letter of Interest

Target of Opportunity Observations with Next-Generation High-energy Neutrino Observatories

Thematic Areas: (check all that apply ☐/☒)

- ☐ (CF1) Dark Matter: Particle Like
- ☐ (CF2) Dark Matter: Wavelike
- ☐ (CF3) Dark Matter: Cosmic Probes
- ☐ (CF4) Dark Energy and Cosmic Acceleration: The Modern Universe
- ☐ (CF5) Dark Energy and Cosmic Acceleration: Cosmic Dawn and Before
- ☐ (CF6) Dark Energy and Cosmic Acceleration: Complementarity of Probes and New Facilities
- ☒ (CF7) Cosmic Probes of Fundamental Physics
- ☒ (Other) NF04, NF10, TF11

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Abstract:

The recent IceCube detection of a neutrino event coincident with a flaring blazar underscores the enormous potential of target-of-opportunity (ToO) observations in identifying sources of high-energy astrophysical neutrinos. The coming decade will bring to fruition a suite of next-generation high-energy neutrino experiments that will provide the groundbreaking sensitivity needed to detect TeV–PeV neutrinos from nearby astrophysical transients, paving the way for a new understanding of hadronic physics as it occurs in astrophysical phenomena. The combined unique qualities of these experiments, in terms of energy range and sky coverage, will allow them to fully leverage the ToO follow-up capacity of the neutrino sector and emerge as a key pillar of the multi-messenger network to come.

Introduction

Even after more than 80 years since the first measurements of extensive air showers¹, the origins of the highest-energy cosmic rays remain elusive. With the recent discovery of a diffuse flux of TeV–PeV astrophysical neutrinos by IceCube,^{2,3} a newfound and likely related mystery has emerged in the origins of these neutrinos. Various astrophysical source candidates have been invoked as possibly exhibiting conditions that could accelerate cosmic rays to high energies, interact within their sources or their surrounding environments, and produce high-energy neutrinos. In many proposed scenarios, astrophysical neutrino production is linked with transient phenomena,⁴ including compact object mergers,^{5–8} gamma-ray bursts,^{9,10} tidal disruption events,^{11–14} blazar flares,^{15,16} and others. In fact, for transient phenomena involving hadronic acceleration, high-energy neutrinos are the ideal messengers, since they are an unambiguous signal of hadronic interactions. Furthermore, their low cross section and electrical neutrality ensure that they will travel unimpeded over cosmological distances and will be well-localized in space and time with a transient event. In turn, multi-messenger campaigns launched in response to transient alerts will allow for more robust associations between even small numbers of neutrinos and candidate astrophysical sources, as recently demonstrated with the IceCube detection of a 290-TeV neutrino coincident with a γ -ray flare from blazar TXS0506+056¹⁶ and a separate 200-TeV neutrino event coincident with the radio emission from tidal disruption event AT2019dsg.¹⁷ The prospect of detecting neutrinos from a binary neutron star merger galvanized searches by ANTARES, IceCube, and Pierre Auger for candidate neutrino events coincident with GW170817¹⁸. Within this landscape, *such target-of-opportunity (ToO) campaigns are becoming key to identifying the sources of high-energy astrophysical neutrinos, paving the way for a new understanding of hadronic physics as it occurs in astrophysical phenomena.* With simultaneous electromagnetic and/or gravitational wave measurements, neutrino ToO observations will be a key component in the future multi-messenger network with next-generation high-energy neutrino observatories.

The Current and Future Landscape of Neutrino ToO Observations

High-energy astrophysical neutrinos, with energies in the TeV scale and beyond, are produced in the decay of pions, kaons, and secondary muons created in high-energy cosmic-ray interactions with matter and radiation in powerful astrophysical sources.¹⁹ During their journey to Earth, over cosmological distances, neutrino oscillations alter the flavor composition of the neutrino flux, i.e., the proportion of ν_e , ν_μ , and ν_τ , but it retains information about neutrino production at the sources.²⁰ At Earth, neutrino interactions, underground or in the atmosphere, create particle showers that emit Cherenkov light, fluorescence light, or coherent radio signals detectable from the ground and aloft, that are targeted by a variety of detectors with different strategies, and that provide opportunities for ToO neutrino detection across a wide range of energies. Neutrinos of TeV–10-PeV are regularly observed, while neutrinos of 10-PeV–EeV, predicted^{19,21–24} but undiscovered, are targeted by current and upcoming detectors.

— **TeV–10-PeV Neutrinos** — The interaction of TeV–PeV neutrinos in water or ice emit Cherenkov light that is collected by arrays of photomultipliers deployed in-medium. They are capable of detecting neutrinos of all flavors, coming from all directions. However, geometrical constraints arise through selection cuts on low-energy events coming from above to reduce the atmospheric background and attenuation by the Earth for events coming from below. Nonetheless, these detectors have an instantaneous field of view that covers large portions of the sky, making them well-suited to detect short- and long-duration transient events. ToO observations by these detectors use mainly track-like events, primarily from ν_μ interactions, that point back to their sources with sub-degree angular resolution. Thus, for ToO observations, the detectors are sensitive to one third of the neutrino flux, assuming flavor equipartition at Earth. Current examples of this type of detector are IceCube²⁵, presently the largest neutrino telescope, and ANTARES²⁶. Planned detectors include IceCube-Gen2²⁷, KM3NeT²⁸, Baikal-GVD²⁹, and P-ONE³⁰.

— **10-PeV–EeV Neutrinos** — The interactions of neutrinos with energies $\gtrsim 10$ PeV in ice also trigger particle showers that emit Cherenkov light or radio emission. Neutrino interactions in the atmosphere, or underground near the surface, trigger extensive air showers in the atmosphere that emit radio, Cherenkov,

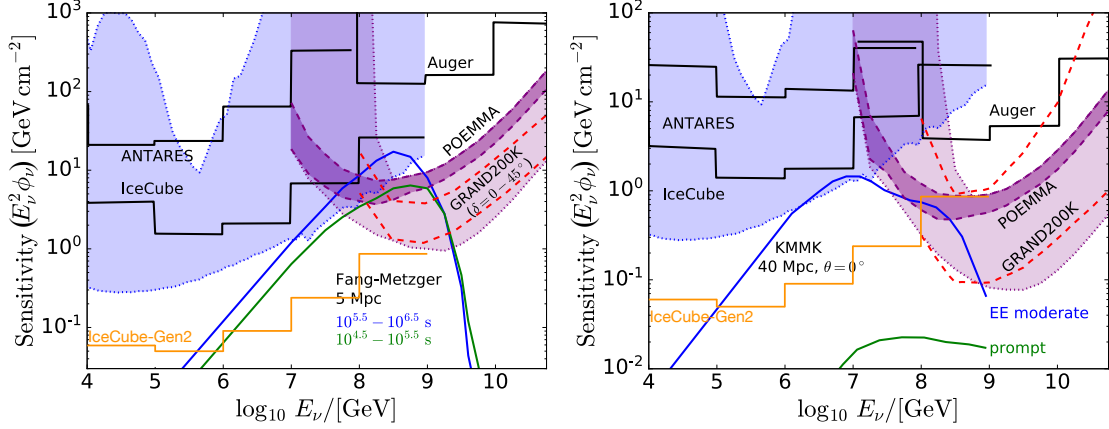


Figure 1: *Next-generation neutrino experiments will achieve the sensitivity needed to detect neutrinos from nearby sources.* Left: Long-duration event. Right: Short-duration event. See Venters et al. 2020³¹ for details.

and fluorescence signals. These detectors have angular resolutions of $\lesssim 1^\circ$, so they can trace the detected neutrinos back to their sources in the sky. A host of existing and upcoming detectors target these signals, and have varying ToO capabilities. Towards the EeV scale, they become especially sensitive to ν_τ , partially due to ν_τ regeneration^{32–36} inside the Earth, which helps preserve their flux, compared to ν_e and ν_μ . For detectors that target ν_τ , the accessible region of the sky is determined by the probability of a τ lepton emerging from underground and into the atmosphere at accessible angles.^{35–39}

In-ice and in-water optical Cherenkov detectors sensitive to TeV–PeV neutrinos are also sensitive to neutrinos above 10 PeV. Surface Cherenkov and radio detectors are sensitive mainly to neutrinos from the horizon. A current example is Auger⁴⁰, with Telescope Array⁴¹ and HAWC⁴² employing similar strategies. Planned detectors include AugerPrime⁴³ and TAMBO.⁴⁴ Ground-based imaging atmospheric Cherenkov telescopes (IACTs) look for the Cherenkov and fluorescence light from ν_τ -induced air showers.^{45–49} MAGIC⁴⁵ and CTA⁴⁹ have only limited sensitivity, but planned dedicated detectors such as Trinity⁵⁰ and Ashra-NTA⁵¹ will feature significant improvements. Radio detectors monitor much larger target volumes owing to the long attenuation length of radio signals. Current radio detectors include the underground detectors ARA⁵² and ARIANNA,⁵³ the balloon-borne ANITA,⁵⁴ and the high-elevation TAROGE-M⁵⁵ and BEACON prototype⁵⁶. Planned radio detectors include IceCube-Gen2,²⁷ RNO-G,⁵⁷ ARIANNA-200,⁵⁸ PUEO,⁵⁹ TAROGE,⁶⁰ BEACON,⁵⁶ GRAND,⁶¹ and SWORD.⁶²

For ToOs, the main limitation of surface and underground detectors is that slewing to other sky locations is constrained by the Earth’s motion. This makes rapid follow-up of short-duration transients infeasible for sources that are not already inside or close to the instantaneous field of view (FoV). Because detectable τ -leptons emerge at shallow angles (typically $\lesssim 6^\circ$),³⁹ the instantaneous FoV is small. Still, radio detectors and in-ice/in-water Cherenkov detectors scan a large fraction of the sky in ~ 1 day, making them well-suited for transient events lasting hours or longer. Because IACTs require moonless nights, they take longer to achieve full-sky coverage and are best suited for long-duration transients lasting weeks or longer.

Suborbital and space-based detectors address the above issues.^{62–64} Cherenkov detectors monitor the Earth’s limb for ν_τ -initiated air showers.^{31,65} They have the unique capability to re-point, allowing them to slew to and track neutrino sources. While the sub-orbital slewing capability is constrained by the Earth’s motion, slewing in azimuth and being able to detect higher-angle events provides access to larger regions of the sky than near-ground detectors. Space-based detectors orbit the Earth at high speed ($T_{\text{orb}} \sim 95$ mins.), providing access to large regions of the sky in minutes, making them best suited for following up short-duration events. Planned detectors are the sub-orbital EUSO-SPB2,⁶³ and the space-based POEMMA.⁶⁴

The coming decade will bring a suite of next-generation high-energy neutrino detectors with TeV–EeV ToO follow-up capacity sensitivity to detect neutrinos from nearby sources (see Fig. 1).

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