Snowmass2021 - Letter of Interest

The IceCube Neutrino Observatory

Thematic Areas:
■ (CF1) Dark Matter: Particle Like
■ (CF7) Cosmic Probes of Fundamental Physics
■ (NF1) Neutrino oscillations
■ (NF2) Sterile neutrinos
■ (NF3) Beyond the Standard Model
■ (NF4) Neutrinos from natural sources
■ (NF5) Neutrino properties
■ (NF6) Neutrino cross sections
■ (NF08/TF11) Theory of Neutrino Physics
■ (NF10) Neutrino detectors

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IceCube Neutrino Observatory
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Abstract: The past decade has welcomed the emergence of cosmic neutrinos as a probe of the fundamental properties of neutrinos at the energy frontier and as a new messenger to explore the most extreme environments of the universe. The discovery measurement of cosmic neutrinos, announced by IceCube in 2013, has revealed a natural beam for neutrino physics with unmatched energies and baselines that holds the potential to answer key questions associated with the high-energy universe, including: are there signatures of new physics at GeV-PeV energies and above; what are the sources in the PeV sky and how do they drive particle acceleration; where are cosmic rays of extreme energies produced? The planned advancements in neutrino telescope arrays in the next decade, in conjunction with continued progress in broad multimessenger astrophysics, promise to elevate the cosmic neutrino field from the discovery to the precision era, enabling a survey of the sources in the neutrino sky. The planned detector upgrades to the IceCube Neutrino Observatory, culminating in IceCube-Gen2, an envisaged $350M facility with anticipated operation in the next decade, are the cornerstone that will drive the evolution and advancement of neutrino astrophysics measurements.

With the discovery of high-energy neutrinos of cosmic origin in 2013[1], the IceCube Neutrino Observatory — just 3 years after its completion — opened a new window onto some of the most extreme phenomena of our universe. Neutrinos interact only weakly with matter and therefore escape energetic and dense astrophysical environments that are opaque to electromagnetic radiation. In addition, at PeV (10^{15} eV) energies, extragalactic space becomes opaque to electromagnetic radiation due to the interaction of high-energy photons (γ-rays) with the extragalactic background light (EBL), predominantly with cosmic microwave photons. This leaves neutrinos as the only astronomical messengers to search for the most extreme particle accelerators in the cosmos—the sources of the ultra-high-energy cosmic rays (CRs). The observed neutrinos have reached energies beyond 10^{16} eV, ten thousand times more energetic than the neutrinos produced at the most powerful particle accelerator facilities on Earth, and first evidence has been realized as to their sources[2–4].

IceCube has transformed a cubic kilometer of deep natural Antarctic ice into a Cherenkov detector[5]. Two principal methods have been used to identify cosmic neutrinos. **Earth-crossing muon neutrinos above atmospheric background —** The first method reconstructs up-going muon tracks initiated by muon neutrinos. The multi-kilometer-long muon range in ice makes it possible to identify neutrinos that interact outside the detector and to separate them from the the background of atmospheric muons [1]. Using this method, IceCube has measured the background flux of atmospheric neutrinos over more than five orders of magnitude in energy with a result that is consistent with theoretical calculations. However, with eight years of data, IceCube has observed an excess of neutrino events at energies beyond 100 TeV[6–8] that cannot be accounted for by the atmospheric flux. Although the detector only records the energy of the secondary muon inside the detector, from Standard Model physics we can infer the energy spectrum of the parent neutrino. The high-energy cosmic muon neutrino flux is well described by a power law with a spectral index of 2.19 ± 0.10 and a normalization at 100 TeV neutrino energy of $(1.01^{+0.26}_{-0.23}) \times 10^{-18}\,\mathrm{GeV}^{-1}\mathrm{cm}^{-2}\mathrm{sr}^{-1}$ [8].

High-energy neutrinos interacting inside the detector — The second method exclusively identifies high-energy neutrinos interacting inside the detector, so-called high-energy starting events. It divides the instrumented volume of ice into an outer veto shield and a $\sim$ 500-megaton inner fiducial volume. The advantage of focusing on neutrinos interacting inside the instrumented volume of ice is that the detector functions as a total absorption calorimeter[9] allowing for a good energy measurement that separates cosmic neutrinos from lower-energy atmospheric neutrinos. Additionally, background atmospheric neutrinos reaching us from the Southern Hemisphere can be rejected because they are accompanied by particles produced in the same air shower where the atmospheric neutrinos originate. With this method, neutrinos from all directions in the sky and of all flavors can be identified, which include both muon tracks as well as secondary showers produced by charged-current interactions of electron and tau neutrinos and neutral current interactions of neutrinos of all flavors.

Both methods yield consistent determinations of the cosmic neutrino flux; see Fig. 1. It was the sample of events starting inside the detector that revealed the first evidence for neutrinos of cosmic origin[1,10]. Events with PeV energies, and no trace of accompanying muons from an atmospheric shower, are highly unlikely to be of atmospheric origin. The seven-year data set contains a total of 60 neutrino events with deposited energies ranging from 60 TeV to 10 PeV. The data are consistent with an astrophysical component with a spectrum close to $E^{-2.2}$ above an energy of ~ 200 TeV[8].

Observation of high-energy tau neutrinos — There is yet another method to conclusively identify cosmic neutrinos: the observation of very high energy tau neutrinos. Tau neutrinos produce two spatially separated showers in the detector, one from the interaction of the tau neutrino and the second one from the decay of the tau produced in the first interaction; the mean tau lepton decay length is about 50 m/PeV. Two such candidate events have been recently identified with IceCube[12,13]. In addition to the double-

[1]The Earth acts as a filter blocking background muons produced by cosmic ray interactions in the atmosphere in the northern hemisphere that range out before reaching IceCube.

cascade candidates, a first candidate event has been attributed to the Glashow resonance: an anti-electron neutrino interacting with an atomic electron produced an event with an energy of 6.3 PeV, characteristic of the resonant production of a weak intermediate W boson[8,12]. With two independent methods and two confirmations, the observation of a cosmic neutrino flux is fully established.

The energy densities of the diffuse extragalactic gamma-ray flux detected by Fermi and the high-energy neutrino flux measured by IceCube show a matching at the similar levels. After propagation through the EBL, the photon flux accompanying IceCube neutrinos is at the same level as the diffuse extragalactic flux observed by Fermi [2]. The implication is that, rather than detecting some exotic sources, it is more likely that IceCube to a large extent observes the same universe astronomers do. The finding implies that a significant fraction of the energy in the nonthermal universe originates in hadronic processes, indicating a larger role than previously thought. Accordingly, IceCube developed methods, most promisingly real-time multiwavelength observations with astronomical telescopes, to identify the sources and build on the discovery of cosmic neutrinos to launch a new era in astronomy.

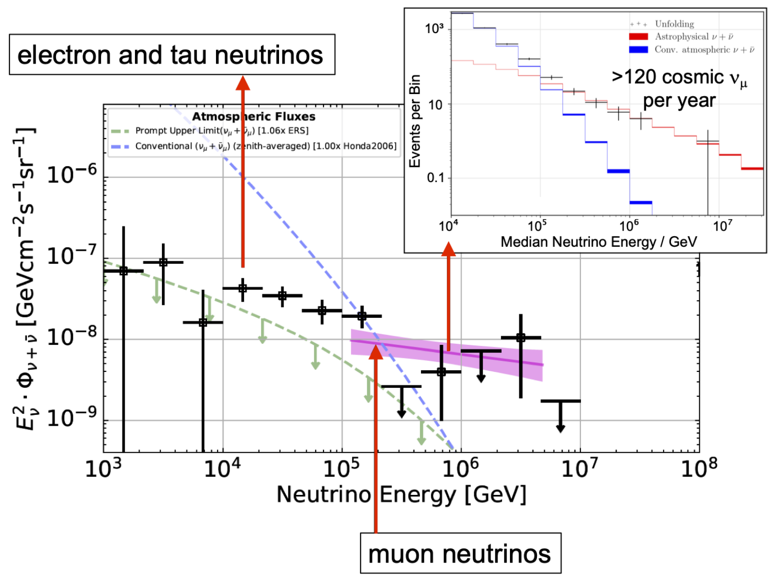

Figure 1: The flux of cosmic muon neutrinos[8] inferred from the eight-year upgoing-muon track analysis (red solid line) with 1σ uncertainty range (shaded range; from fit shown in upper-right inset) is compared with the flux of showers initiated by electron and tau neutrinos (points with error bars)[11]. The measurements are consistent assuming that each flavor contributes the same flux to the diffuse spectrum. The green line also shows the prompt neutrino upper limit from charm production.

The current IceCube detector, with the infill DeepCore subarray, provides 4π coverage with better than 99.5% up-time, delivering O(10^5) atmospheric neutrinos (5 GeV - 200 TeV) and more than 300 cosmic neutrinos per year. [3] Icecube provides precision measurements of atmospheric neutrino oscillations[14], world-leading indirect dark matter searches[15], and crucial tests of the Standard Model as previously unaccessible energies[16,17]. An accompanying surface array, IceTop, is uniquely capable of measuring the cosmic spectrum from below the knee to the ankle[18], as well as acting as a partial veto for atmospheric neutrinos. Compared to typical astronomical instruments the angular resolution of IceCube introduces a large uncertainty when identifying single sources, in particular in heavily populated regions of the sky. The IceCube Upgrade[19], fully funded and currently under construction, provides for improvements that would significantly enhance the sensitivity of past and future data sets via an advanced calibration program that also targets a definitive measurement of the tau neutrino normalization. Finally, IceCube-Gen2, which would increase the sensitivity to astrophysical neutrinos nearly tenfold[20,21], plays an essential role in shaping the new era of multimessenger astronomy into the next decade to resolve a number of the most pressing questions of the high-energy universe.

[2] The photon flux accompanying IceCube neutrinos from π^0 decays is downshifted to lower energies.

[3] Approximately 20 well-reconstructed high-energy astrophysical events – within 1° angular resolution – are issued within less than 1 minute of detection as real-time alerts each year.

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Cross-references to related Snowmass 2021 LOIs:

Frontiers in Neutrino Physics

- Monitoring Near-Galactic Core Collapse Supernovae with IceCube and IceCube-Gen2 — Segev Ben-Zvi et al.
- BSM Neutrino Oscillation Searches with 1-100 TeV Atmospheric Neutrinos at IceCube — B. Jones et al.
- New physics with astrophysical neutrino flavour — T. Katori et al.
- Neutrino cross-sections and interaction physics — S. Klein et al.
- IceCube-Gen2: The Window to the Extreme Universe — M. Kowalski et al.
- Neutrino oscillations with IceCube-DeepCore and the IceCube Upgrade — T. Stuttard et al.

Cosmic Frontier

- Observing the High-Energy Sun — C. Arguelles et al.
- Highest Energy Galactic Cosmic Rays — A. Haungs et al.
- Searches for exotic particles with the IceCube Neutrino Observatory — A. Pollmann et al.
- Letter of Interest in Dark Matter Physics with the IceCube Neutrino Observatory — C. Rott et al.
- Radio Detection of Cosmic Rays — F. Schroeder et al.
- IceCube and Cosmic Rays — D. Seckel et al.
- Studies of the Muon Excess in Cosmic Ray Air Showers — D. Soldin et al.
- Opportunities for multi-messenger observations with neutrinos and tests of fundamental physics over the next decade — I. Taboada et al.

Computational Frontier

- IceCube and IceCube-Gen2: Quantum computing applications — C. Arguelles et al.
- IceCube and IceCube-Gen2 Long Term Preservation — P. Desiati et al.
- IceCube and IceCube-Gen2 Simulations — J. C. Diaz Velez et al.
- IceCube and IceCube-Gen2 Machine Learning — C. Kopper et al.

- IceCube and IceCube-Gen2 User Analysis Computing — K. Meagher et al.
- IceCube and IceCube-Gen2 Storage and Processing Resources — B. Riedel et al.
- IceCube and IceCube-Gen2 Event Management Service — B. Riedel et al.
- IceCube and IceCube-Gen2 Experimental Algorithm Parallelization — A. Olivas et al.

Instrumentation Frontier

- IceCube-Gen2: the next generation wide band neutrino observatory — A. Karle et al.