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Recent High Energy Neutrino Results from the IceCube Collaboration

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The IceCube Neutrino Observatory, located at the geographic South Pole, has detected a significant number of neutrinos consistent with astrophysical sources over its lifetime of more than 12 years. These high energy neutrinos indicate the existence of highly energetic neutrino factories and provide opportunities to study the properties of neutrinos which exceed energies currently available through human-made means. This flux of astrophysical neutrinos has been observed with world-leading sensitivity, leading to strong indications of the flux shape deviating from a single powerlaw model. Recent results and efforts utilising high energy neutrinos include next-generation cross section sensitivities spanning 200 GeV to 10^7 GeV, the detection of a significant number of high energy ν_τ events, observation of neutrinos consistent with the galactic centre, and leading limits on neutrino fluxes up to 10^{11} GeV.

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Executive Summary and Discussion

Astrophysical neutrinos are expected to arise from energetic phenomena such as active galactic nuclei and gamma-ray bursts, and IceCube's detection of a diffuse spectrum of high-energy neutrinos is opening a window to study violent astrophysical processes. Neutrinos provide access to astrophysical regions obscured by dust and gas, such as the Galactic plane, and open up opportunities to test fundamental physics at energies far beyond those accessible in terrestrial experiments. Detection of neutrinos associated with the Galactic plane at 4.5σ confidence [1] represents a significant step towards the goal of identifying individual sources contributing to the diffuse astrophysical neutrino flux - the underlying shape of which is still relatively unknown. These measurements complement broader multi-messenger efforts, where neutrino signals are combined with electromagnetic [2][3] and gravitational wave [4] observations to unlock a more comprehensive picture of cosmic accelerators.

IceCube's capability to measure neutrino cross-sections at energies up to several PeV has profound implications for both particle physics and astrophysics. These measurements test predictions of the Standard Model in uncharted regimes and provide critical benchmarks for other neutrino telescopes, such as KM3NeT [5], Baikal-GVD [6], P-ONE [7], and TRIDENT [8], which share complementary energy ranges. Incorporating modern corrections like nuclear shadowing [9], heavy quark contributions [10], and diffractive interactions [11], future IceCube cross-section results endeavour to provide even better constraints and a more robust framework for interpreting high-energy events.

Astrophysical neutrino flavour ratios, such as the 1:1:1 ν_e:ν_μ:ν_τ expectation, are being directly tested with the detection of high energy ν_τs [12]. These measurements not only validate oscillation physics over cosmic baselines, but also provide insights into models predicting deviations due to exotic physics [13] or source-specific processes [14].

Event-by-event differentiation of ν and $\bar{\nu}$ in IceCube is extremely challenging. However such distinctions are critical for probing the particle composition of astrophysical sources, as the relative abundance of ν and $\bar{\nu}$ can reflect underlying production mechanisms, such as hadronic processes in cosmic accelerators. For instance, proton-proton interactions are expected to produce nearly equal numbers of neutrinos and antineutrinos, while proton-photon interactions may favour neutrino production. Although current high-statistics measurements are limited by the rate, the ability to detect $\overline{\nu_e}$ interactions via the Glashow Resonance [15] offers a clear pathway for understanding highly energetic source properties. Additional methods could include careful measurements of the inelasticity profiles[16].

IceCube's results reaffirm the growing importance of neutrino telescopes in the multi-messenger era. By connecting cosmic-ray acceleration, electromagnetic emissions, and neutrino fluxes, IceCube not only advances our understanding of high-energy astrophysics but also paves the way for future discoveries in both the local universe and beyond. The continued synergy between IceCube and other observatories will ensure its pivotal role in addressing fundamental questions about the universe's most extreme environments.

Astrophysical All-Sky Searches: Historically measurements of the astrophysical neutrino flux have included two free parameters (normalisation, spectral shape) under a single powerlaw (SPL) assumption [17]. Even with IceCube's size, the rate of astrophysical neutrinos is only a few per week, making characterisations of the flux challenging. The results presented at *NOW* 2024 come from two different studies. One uses so-called "starting tracks", primarily ν_μ charged current (CC) events with strong background-rejection potential [18]. The other study uses a "Global Fit" approach, which merges samples looking for ν_μ CC events with ν_e CC, ν_τ CC, & neutral current (NC) events to maximise information [19]. Figure 1 displays the results for both of these techniques, where the starting track sample maintains strongest agreement with the SPL assumption, while the Global Fit results weakly favour some shape, ex. a broken powerlaw (BPL).

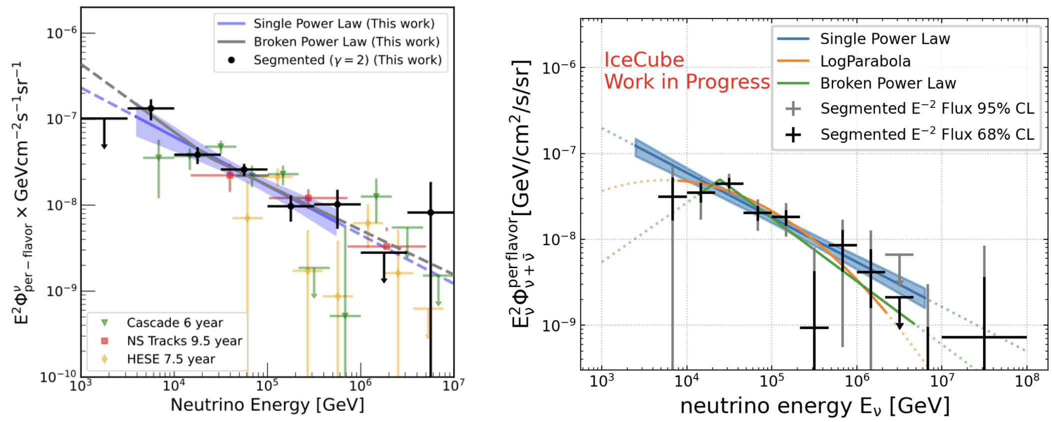

Figure 1: Recent measurements of the astrophysical neutrino flux from IceCube using two independent samples, starting tracks (left)[18] and Global Fit (right)[19]

Neutrinos from the Galactic Plane: The previous section discussed the "diffuse" flux of astrophysical neutrinos, though this diffuse flux is expected to be constructed from a variety of unidentified sources. By using neutrinos to probe regions with strong magnetic fields and/or those obscured by dust and gas, we can look to gain insights into the galactic plane. Through application of template fluxes, derived from Fermi-LAT observations of the galactic plane [20], an expectation of neutrinos is constructed. This analysis is conceptually summarised in Figure 2, where neutrino emission from the Galactic plane has been identified with 4.5σ confidence [1].

Extremely High Energy (EHE) Neutrinos: At energies beyond 10 PeV, these EHE neutrinos probe the most energetic objects in the universe, potentially beyond the Greisen-Zatsepin-Kuz'min (GZK) cut-off [21]. Figure 3 shows updated limits to the EHE neutrino flux with improved rejection of highly energetic muon bundles and 12 years of IceCube data [22]. For the first time, this measurement has sufficient sensitivity to challenge GZK flux models. Inclusion of radio detectors in the future IceCube-Gen2 [23] detector would significantly enhance our search for GZK neutrinos increasing our sensitivity by another order of magnitude.

High-Energy ν_τ Observations: Traditionally detection of ν_τ has been extremely challenging due in-part to the τ mass (threshold energy) and that given IceCube's inter-module separation, the deep-inelastic scattering ν_τ CC interaction cannot be trivially differentiated from a ν_e CC or NC interaction. Using a convolutional neural network has significantly improved IceCube's ability to identify ν_τ CC events, creating a statistically significant sample of astrophysical ν_τ events with a median energy of 200 TeV. These results reject the absence of astrophysical ν_τ with 5σ confidence [12].

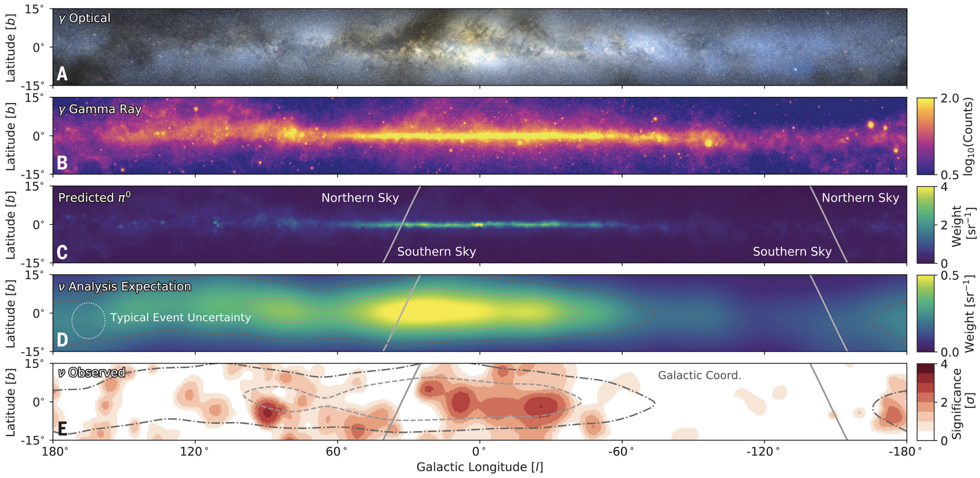

Figure 2: The plane of the Milky Way shown for photons and neutrinos. As shown in **(A)**, gas and dust partially obscure the galactic centre (*Credit A. Mellinger*). For 1 GeV+ gamma rays in **(B)**, some features are visible in the Fermi Large Area Telescope (Fermi-LAT) 12-year survey integrated flux. In **C** the predicted π^0 flux from the gamma ray flux is used to calculate the expected neutrino flux including detector sensitivity in **D**. The white dotted circle displays the angular uncertainty for signal cascade-like events (7°). **(E)** shows the pre-trial significance of the IceCube neutrino observations, calculated from the all-sky scan for point-like sources [1].

Glashow Resonance Event: Proposed in 1959, the Glashow Resonance is a process where a W boson is created from the interaction of a $\overline{\nu_e} + e^-$ [15]. A neutrino event with energy consistent with the Glashow resonance (~6.3 PeV) was detected in 2021 to 2.3σ confidence. This observation opens potential avenues to probe $\nu/\overline{\nu}$ flux ratios and test electroweak interaction predictions at extreme energies [15].

Cross-Section Measurements: At neutrino energies above $\sim$ 20 GeV, the νN cross section is dominated by deep-inelastic scattering (DIS). The most widely-used prediction is the "CSMS" cross section [24], though this model lacks several modern corrections which can modify the prediction. More recent models include contributions from heavy quark (c, b, t) production at higher energies, NNLO QCD calculations, and considerations for non-isoscalar targets [25], which can be significant. Further corrections from final state radiation [26] and diffractive interactions [11] have additional percent-level impacts. In energies relevant for IceCube, overall deviations from CSMS can be upwards of 20%.

Compared to energies accessible by traditional π-based neutrino beamlines, cross section measurements beyond 1 TeV are very limited. Recent results from FASERν utilise the high energy proton beam at the LHC, measuring the ν_μ and ν_e cross sections at 1 TeV [27]. Published results from IceCube begin around 10 TeV and constituted the first ever measurements of the cross section at such high energies (ν_μ CC [28] & all-flavour [29]).

This work in-progress measurement (Figure 3), uses both track-like and cascade-like events, and combines them in a multi-dimensional likelihood framework, to maximise the physics potential of the samples. IceCube achieves sub-10% sensitivity between 300 GeV and 100 TeV, overlapping at lower energies with previously measured cross sections from other experiments. Contributions from non-isoscalar targets and nuclear (anti-)shadowing are included for the first time. Sensitivity

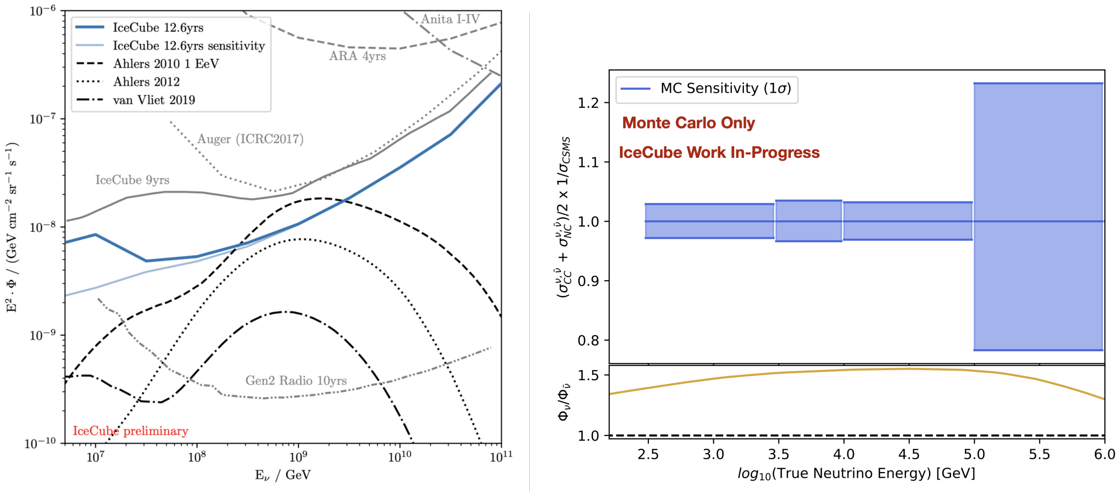

Figure 3: *Left:* Latest EHE neutrino flux limits have some sensitivity to the Ahlers 2010 model [30]. IceCube-Gen2 Radio indicates future ability to strongly constrain different GZK flux models [22]. *Right:* Sensitivity to the all-flavour averaged neutrino DIS cross section under the assumption of a CSMS-like shape, including additional terms for a non-isoscalar target and nuclear (anti-)shadowing. The total ν:$\overline{\nu}$ ratio is included for reference.

at higher energies is strongly limited by the choice of astrophysical neutrino flux model (broken-powerlaw up to 1 PeV, then a segmented normalisation between 1 and 10 PeV).

Future Prospects with IceCube Upgrade & Gen2: The IceCube Upgrade [31], scheduled for 2025/2026 deployment, will enhance sensitivity to few GeV-scale interactions by an order of magnitude through deployment of new highly sensitive optical modules (D-Eggs [32], mDOMs [33]). These new modules have calibration subsystems specially designed to characterise optical properties of the ice, leading to an expected reduction in angular reconstruction uncertainties. This will have broad benefits also for astrophysical neutrino analyses and their searches for point-sources. In the 2030s, the high energy IceCube-Gen2 extension is planned, and will expand sensitivities upwards to EeV energy neutrinos, opening up a new high energy frontier.

References

[1] R. Abbasi et al. Observation of high-energy neutrinos from the Galactic plane. *Science*, 380(6652):1338–1343, June 2023.

[2] M. G. Aartsen et al. Very High-Energy Gamma-Ray Follow-Up Program Using Neutrino Triggers from IceCube. *JINST*, 11(11):P11009, 2016.

[3] R. Abbasi, others, Adam Goldstein, Joshua Wood, and for the Fermi Gamma-ray Burst Monitor. Searches for neutrinos from gamma-ray bursts using the icecube neutrino observatory. *The Astrophysical Journal*, 939(2):116, nov 2022.

[4] R. Abbasi et al. IceCube search for neutrinos coincident with gravitational wave events from LIGO/Virgo Run O3. *The Astrophysical Journal*, 944(1):80, February 2023.

[5] S. Aiello et al. Astronomy potential of KM3NeT/ARCA. *Eur. Phys. J. C*, 2024.

[6] A.V. Avrorin et al. Baikal-GVD Experiment. *Phys. Atom. Nuclei*, 2020.

[7] Matteo Agostini et al. The Pacific Ocean Neutrino Experiment. *Nature Astronomy*, 4(10):913–915, September 2020.

[8] Z. P. Ye et al. A multi-cubic-kilometre neutrino telescope in the western Pacific Ocean, 2024.

[9] Spencer R. Klein, Sally A. Robertson, and Ramona Vogt. Nuclear effects in high-energy neutrino interactions. *Physical Review C*, 102(1), July 2020.

[10] Keping Xie et al. High-energy neutrino deep inelastic scattering cross sections. *Phys. Rev. D*, 109:113001, Jun 2024.

[11] Anh Dung Le and Heikki Mäntysaari. Inclusive and diffractive neutrino-nucleus scattering at high energy, 2024.

[12] R. Abbasi et al. Observation of seven astrophysical tau neutrino candidates with IceCube. *Physical Review Letters*, 132(15), April 2024.

[13] Carlos A. Argüelles, Kareem Farrag, and Teppei Katori. Ultra-light Dark Matter Limits from Astrophysical Neutrino Flavor, 2024.

[14] P. S. Bhupal Dev, Sudip Jana, and Yago Porto. Flavor matters, but matter flavors: Matter effects on flavor composition of astrophysical neutrinos, 2023.

[15] M. G. Aartsen et al. Detection of a particle shower at the Glashow resonance with IceCube. *Nature*, 591(7849):220–224, March 2021.

[16] M. G. Aartsen et al. Measurements using the inelasticity distribution of multi-TeV neutrino interactions in IceCube. *Physical Review D*, 99(3), February 2019.

[17] R. Abbasi et al. Improved characterization of the astrophysical muon–neutrino flux with 9.5 years of IceCube data. *The Astrophysical Journal*, 928(1):50, March 2022.

[18] R. Abbasi et al. Characterization of the astrophysical diffuse neutrino flux using starting track events in IceCube. *Physical Review D*, 110(2), July 2024.

[19] R. Naab, E. Ganster, and Z. Zhang. Measurement of the astrophysical diffuse neutrino flux in a combined fit of IceCube's high energy neutrino data, 2023.

[20] NASA Goddard Space Flight Center. Fermi's 12-year View of the Gamma-ray Sky, 2022.

[21] Markus Ahlers. High-energy cosmogenic neutrinos. *Physics Procedia*, 61:392–398, 2015. 13th International Conference on Topics in Astroparticle and Underground Physics, TAUP 2013.

[22] M. Meier and B. Clark. Search for Extremely High Energy neutrinos with IceCube, 2023.

[23] M G Aartsen et al. IceCube-Gen2: the window to the extreme Universe. *Journal of Physics G: Nuclear and Particle Physics*, 48(6):060501, April 2021.

[24] A. Cooper-Sarkar, P. Mertsch, and S. Sarkar. The high energy neutrino cross-section in the Standard Model and its uncertainty. *Journal of High Energy Physics*, 2011(8), August 2011.

[25] P. L. R. Weigel, J. M. Conrad, and A. Garcia-Soto. Cross sections and inelasticity distributions of high-energy neutrino deep inelastic scattering, 2024.

[26] Ryan Plestid and Bei Zhou. Final state radiation from high and ultrahigh energy neutrino interactions, 2024.

[27] Roshan Mammen Abraham et al. First measurement of the ν_e and ν_μ interaction cross sections at the LHC with FASER's emulsion detector. *Physical Review Letters*, 133(2), July 2024.

[28] The IceCube Collaboration. Measurement of the multi-TeV neutrino interaction cross-section with IceCube using Earth absorption. *Nature*, 2017.

[29] R. Abbasi et al. Measurement of the high-energy all-flavor neutrino-nucleon cross section with IceCube. *Physical Review D*, 104(2), July 2021.

[30] M. Ahlers, L.A. Anchordoqui, M.C. Gonzalez–Garcia, F. Halzen, and S. Sarkar. GZK neutrinos after the Fermi-LAT diffuse photon flux measurement. *Astroparticle Physics*, 34(2):106–115, September 2010.

[31] Aya Ishihara. The IceCube Upgrade – Design and Science Goals, 2019.

[32] R. Abbasi et al. D-Egg: a dual pmt optical module for IceCube. *Journal of Instrumentation*, 18(04):P04014, April 2023.

[33] T. Anderson, L. Classen, A. T. Fienberg, S. Mechbal, J. Schneider, K. H. Sulanke, M. A. Unland Elorrieta, and C. Wendt. Design and performance of the multi-pmt optical module for Icecube Upgrade, 2021.