Snowmass2021 - Letter of Interest

New physics with astrophysical neutrino flavor

NF Topical Groups: (check all that apply □/■)

■ (NF1) Neutrino oscillations
■ (NF2) Sterile neutrinos
■ (NF3) Beyond the Standard Model
■ (NF4) Neutrinos from natural sources
■ (NF5) Neutrino properties
□ (NF6) Neutrino cross sections
□ (NF7) Applications
■ (TF11) Theory of neutrino physics
□ (NF9) Artificial neutrino sources
■ (NF10) Neutrino detectors
■ (Other) CF1 (Dark Matter: Particle-Like), CF2 (Dark Matter: Wave-like), CF6 (Dark Energy and Cosmic Acceleration: Complementarity), CF7 (Cosmic Probes of Fundamental Physics), TF02 (Effective field theory techniques), TF08 (BSM model building), TF09 (Astro-particle physics and cosmology)

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Abstract:

The high-energy astrophysical neutrinos discovered by IceCube offer powerful probes of fundamental physics. Because they have the highest neutrino energies observed —from TeV to PeV— they can probe fundamental physics at new energy scales, where new physics may become evident. Because they travel the longest distances —up to a few Gpc— they are sensitive to even tiny effects that, although individually undetectable, may compound and accumulate to detectable levels during the long trip to Earth. The flavor composition of high-energy astrophysical neutrinos —i.e., the proportion of ν_e, ν_μ, and ν_τ in their flux— is a particularly rich probe of neutrino physics beyond the Standard Model (BSM). In this letter of interest, we highlight the potential of measurements of flavor composition to probe diverse models of new physics, and point out the theoretical and experimental requirements needed to tap into this potential in the next 10–20 years.

New-physics potential of flavor composition: Neutrinos carry a quantum number that other cosmic messengers do not have —second and third family flavor— that is a rich probe of fundamental physics. In particular, the high-energy astrophysical neutrinos discovered by IceCube[1–3] offer the opportunity to test fundamental physics,[4–9] at very high energies and that acts over cosmological-scale distances. Even tiny coupling of neutrinos with backgrounds en route to Earth could modify their mixing and energy patterns.[4–6] In terms of effective operators, the sensitivity of high-energy astrophysical neutrinos to a new dimension-three operator that can modify flavor mixing is $\sim 10^{-26}$ GeV, comparable to the highest-precision atomic experiments searching for new effects in vacuum.[10] The sensitivity to dimension-six operators is $\sim 10^{-42}$ GeV^{-2},[11] which is beyond any known technology: from table-top experiments to cosmology. With this unique sensitivity, astrophysical neutrino flavor measurements may reveal a variety of BSM processes: sterile neutrinos, new neutrino interactions, broken or new symmetries, or other exotic neutrino properties.[4–9]

Measuring flavor in IceCube: The IceCube Neutrino Observatory[16] is an underground array of photomultiplier tubes that instrument 1 km^3 of Antarctic ice and collects the Cherenkov light from particle showers initiated by high-energy neutrino interactions. Since the detector instrumentation is coarse, particle identification is challenging, which makes neutrino flavor identification difficult. Charged-current interactions of ν_μ produce high-energy muons that can be identified as elongated light profiles (tracks). In contrast, distinguishing ν_e from ν_τ is challenging because they produce similar event morphologies (cascades). One discriminator are Glashow resonance events.[17–25] All in all, flavor measurements are possible[26–32], although so far, with large uncertainties.[33–35]

Fig. 1 shows that upcoming improvements in flavor measurement in IceCube and IceCube-Gen2 will grant the sensitivity needed to perform precise tests of new physics[4;13;14;36;37] and of neutrino flavor composition at sources.[19;26;36–58]

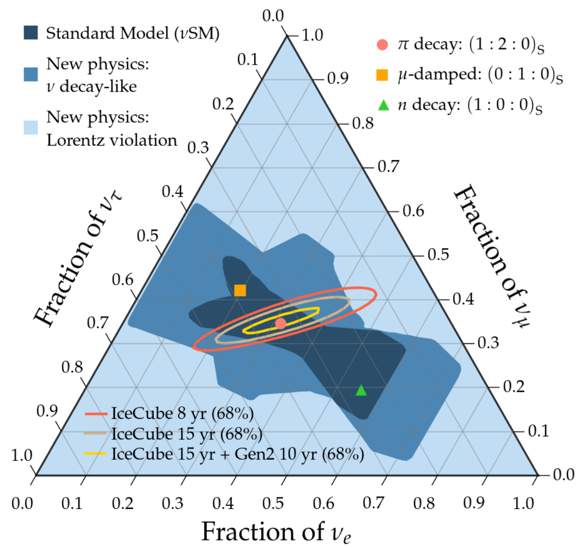

Figure 1: Present and future flavor composition measurements with IceCube and IceCube-Gen2, compared to theory expectations. Neutrinos are assumed to be emitted with flavor composition $\nu_e : \nu_\mu : \nu_\tau = 1 : 2 : 0$. Reproduced from[12]; see also.[4;13–15]

Tests of neutrino properties:

- **Neutrino lifetime:** Propagation distances of cosmological scale provide an ideal opportunity to search for neutrino decay.[53;59–64] Neutrino decays could modify the flavor composition of the flux of astrophysical neutrinos in different ways, and the ratio of detected track and cascade events at different energies can be used to study these scenarios.[14;65–71]
- **Number and nature of neutrinos:** As astrophysical neutrinos propagate over cosmic distances, oscillation probabilities are averaged out,[72] so the resulting flavor composition depends on the mixing angles, but not on the mass splittings. Unitarity of the mixing matrix is usually assumed to predict the flavor composition at Earth,[37;57;73;74] so the lack of three-flavor unitarity could manifest as anomalous flavor ratios.[5;15;75] On the other hand, if sterile and active neutrinos are almost degenerate in mass, the oscillation length between these states would be very long. Cosmic distances offer a unique opportunity to probe these tiny mass splittings, by modifying the flavor composition at Earth.[76–79]
- **Mass-varying neutrinos:** If neutrino masses are related to the dark energy, they could vary in time and induce an effective Hamiltonian, altering the flavor composition of astrophysical neutrinos.[80]

Tests of signatures of a dark Universe:

- **Dark matter as source:** Decays (or annihilation) of heavy dark matter (DM) to SM particles could contribute to the astrophysical neutrino flux. This possibility has been considered to explain IceCube high-energy data.[81–102] Different decay (annihilation) channels would render different flavor compositions at production, which would result in a flavor structure different from that predicted from standard astrophysics. On the other hand, a very massive relic with a lifetime shorter than the age of the Universe could also contribute to this flux, with similar effects on the flavor composition.[103–106]
- **Dark matter as background:** Interactions between neutrinos and DM could induce an effective matter potential[107;108] or dampen the astrophysical neutrino flux along some directions,[109–116] which could alter the flavor composition at Earth from that expected from neutrino oscillations in vacuum.
- **Dark energy as background:** Interactions between neutrinos and dark energy, if treated as a dynamical field, could also modify neutrino oscillation phenomenology. The introduction of an extra contribution to the Hamiltonian could induce apparent Lorentz invariance-violating effects, which would modify the expected flavor ratios of astrophysical neutrinos.[117;118]

Tests of fundamental physics:

- **Non-standard interactions:** Non-standard interactions of astrophysical neutrinos at production, propagation (through the Earth) or detection could give rise to non-standard flavor compositions.[119;120]
- **Neutrino self-interactions:** If neutrinos experience BSM self-interactions on the relic neutrino background, this could induce an effective matter potential, dampen the high-energy astrophysical neutrino flux (like in the DM case), and modify the flavor composition at Earth.[109;121–135]
- **Long-range forces:** Long-range interactions between neutrinos and electrons (from local and cosmological repositories) could also alter the flavor composition of astrophysical neutrinos.[136]
- **Modified neutrino-nucleus interactions:** The existence of leptoquarks could enhance the cascade event rate.[137–143] In models of TeV gravity, neutrinos may transfer only a small fraction of their energy to the target nucleon.[144–146] These scenarios would lead to anomalous flavor compositions.
- **Quantum decoherence:** Conversion of pure into mixed states by quantum-gravity effects would cause neutrino decoherence during propagation and alter the standard flavor structure.[147–151]
- **Lorentz and CPT invariance violation:** Lorentz invariance and CPT violation in neutrino mixing could modify the flavor composition of astrophysical neutrinos,[10;11;36;117;152–160] which could have angular dependence, be different for neutrinos and antineutrinos, or be detected as neutrino echoes.
- **Extra dimensions:** Astrophysical neutrino flavors could be modified by sterile neutrino altered dispersion relations due to shortcuts in an extra dimension.[161] In scenarios with large extra dimensions, microscopic black holes could be produced in high-energy collisions, giving rise to new signatures. In particular, new event topologies could alter the inferred flavor composition of the neutrino flux.[162]

The road ahead: To reach the sensitivity needed to discover new physics in the flavor composition of high-energy astrophysical neutrinos, a number of efforts are underway. First, next-generation detectors, such as IceCube-Gen2,[12] will provide large samples of events (also to measure flavor composition as a function of energy). Second, improved particle identification algorithms are needed, in particular, efficient charged-current ν_τ and neutral-current interaction identification. Recent progress has led to the first identification of high-energy ν_τ's,[163–165] and further improvements are expected.[166;167] This will be facilitated by improved photo-cathode coverage in the IceCube-Upgrade.[168] Third, detection of higher-energy neutrinos by the radio array of IceCube-Gen2 will extend flavor measurements to the EeV scale[169]. Fourth, the identification of neutrino sources in transient phenomena[170–173] offers a unique opportunity to search for new physics,[114–116] including via flavor information. Fifth, improvements in the modeling of high-energy astrophysical sources, and further multimessenger observations of them, should shrink the uncertainties in the neutrino production mechanism that presently plague analyses of fundamental physics that use high-energy neutrinos.

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