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Theoretically palatable flavor combinations of astrophysical neutrinos

Mauricio Bustamante,[1,2] John F. Beacom,[1,2,3] and Walter Winter[4]

[1]*Center for Cosmology and AstroParticle Physics (CCAPP), Ohio State University, Columbus, OH 43210, USA*
[2]*Department of Physics, Ohio State University, Columbus, OH 43210, USA*
[3]*Department of Astronomy, Ohio State University, Columbus, OH 43210, USA*
[4]*DESY, Platanenallee 6, D-15738 Zeuthen, Germany*
bustamanteramirez.1@osu.edu, beacom.7@osu.edu, walter.winter@desy.de

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The flavor composition of high-energy astrophysical neutrinos can reveal the physics governing their production, propagation, and interaction. The IceCube Collaboration has published the first experimental determination of the ratio of the flux in each flavor to the total. We present, as a theoretical counterpart, new results for the allowed ranges of flavor ratios at Earth for arbitrary flavor ratios in the sources. Our results will allow IceCube to more quickly identify when their data imply standard physics, a general class of new physics with arbitrary (incoherent) combinations of mass eigenstates, or new physics that goes beyond that, *e.g.*, with terms that dominate the Hamiltonian at high energy.

Introduction.— The discovery of astrophysical neutrinos with energies up to a few PeV by the IceCube Collaboration [1–4] is tremendously important for multimessenger astronomy as well as for new tests of neutrino properties. While the origin of these neutrinos is still unclear, there are important clues in the energy spectrum and sky distribution, and a component from cosmic distances ($\sim$ Gpc) is required [5–24]. These are the most extreme energies and distances for detected neutrinos.

The flavor composition is also expected to be important, because the ratio of flux in each flavor to the total cancels the unknown normalization. The ratios depend on the physical conditions at the source, the effects of standard flavor mixing, and on potential new physics [5, 25–36].

The first IceCube results on flavor composition have been published recently [35], and results with more statistics will soon follow [37]. Accordingly, there has been intense interest in deducing flavor ratios from IceCube data [9, 31, 34, 38, 39].

In this Letter, we use ternary plots or "flavor triangles" to show the flavor composition at Earth. We systematically explore which regions of this plot can be populated from theoretical perspectives —without or with new physics— including the uncertainties in source flavor composition and neutrino mixing parameters. We also note prospects for the proposed volume upgrade, IceCube-Gen2 [40].

We make no distinction between ν and $\bar{\nu}$, because, except for yet-unobserved high-energy events, IceCube cannot distinguish between them. (In addition, their cross sections agree to better than $\simeq 5\%$ in this energy range [41, 42].)

All plots shown in the main text are for the normal neutrino mass hierarchy (NH), in which ν_1 is the lightest mass eigenstate. Corresponding plots for the inverted hierarchy (IH), in which ν_3 is lightest, are given in the Supplemental Material; the differences are modest.

Flavor identification in IceCube.— IceCube can discriminate between muon tracks (from ν_μ, mostly) and cascades (from charged-current interactions of ν_e and ν_τ, mainly, and from neutral-current interactions of all flavors). If higher-energy events are observed, it will be possible to isolate $\bar{\nu}_e$ cascades via the Glashow resonance [43–45], and ν_τ and $\bar{\nu}_\tau$ via double-bang and lollipop topologies [46–48]. In their absence, there is an experimental degeneracy between the electron and tau neutrino flavor content at Earth [34, 35]. In contrast, theoretically predicted flavor ratios, even in models with new physics, have a μ-τ symmetry due to that mixing angle being near-maximal.

Flavor composition at the source.— The flavor composition at the source could be quite different depending on the physical conditions. For the pion decay chain, which is often used as standard ("pion beam"), one expects a composition $(f_{e,\text{S}} : f_{\mu,\text{S}} : f_{\tau,\text{S}}) = (\frac{1}{3} : \frac{2}{3} : 0)_\text{S}$, with $f_{\alpha,\text{S}}$ the ratio of $\nu_\alpha + \bar{\nu}_\alpha$ to the total flux, where $f_{e,\text{S}} + f_{\mu,\text{S}} + f_{\tau,\text{S}} = 1$. Synchrotron cooling of secondary muons in strong magnetic fields leads to a transition to $(0 : 1 : 0)_\text{S}$ ("muon damped") at higher energies, which depends on the field strength; see, *e.g.*, Refs. [5, 38, 49–51]. If these muons pile up at lower energies [51], or if there are contributions from charmed meson decays [29, 52, 53], then $(\frac{1}{2} : \frac{1}{2} : 0)_\text{S}$ is expected. Neutron decays [5] lead to $(1 : 0 : 0)_\text{S}$. Small deviations, $\lesssim 5\%$ in the ν_e/ν_μ ratio, are expected from effects such as the helicity dependence of muon decays [5, 54]. If several of the above processes in the source compete, arbitrary flavor compositions $(f_{e,\text{S}} : 1 - f_{e,\text{S}} : 0)$ can be obtained [51]. If, in addition, ν_τ are produced, such as by oscillations in a matter envelope [55–57], even $(f_{e,\text{S}} : f_{\mu,\text{S}} : 1 - f_{e,\text{S}} - f_{\mu,\text{S}})$ (with $0 \leq f_{\mu,\text{S}} \leq 1 - f_{e,\text{S}}$) could be possible. Dark matter annihilation or decay could yield any mixture, but $(\frac{1}{3} : \frac{1}{3} : \frac{1}{3})_\text{S}$ is the most natural.

Flavor composition at Earth.— Here we focus on a diffuse flux, which is composed of small contributions from many sources over a wide range of distances, and detected with energy resolution $\gtrsim 10\%$ (and binned

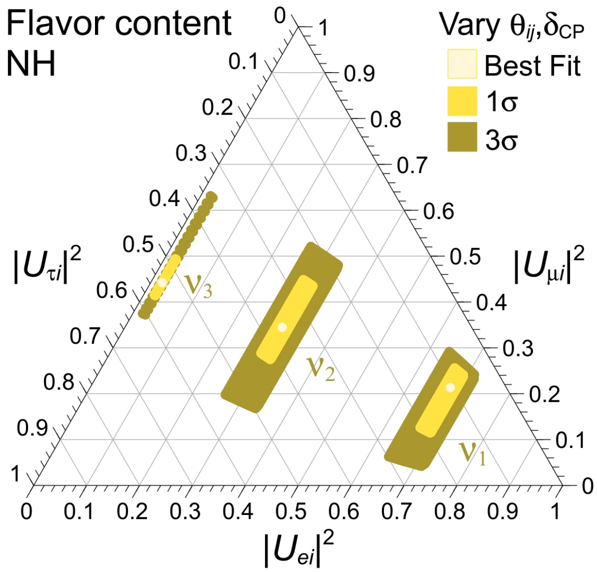

FIG. 1. Flavor content of the three active mass eigenstates. The regions are given by the best-fit values of the mixing parameters (light yellow), and their 1σ (darker) and 3σ (darkest) uncertainty regions [62], assuming a normal mass hierarchy (NH). The tilt of the tick marks indicates the orientation with which to read the flavor content.

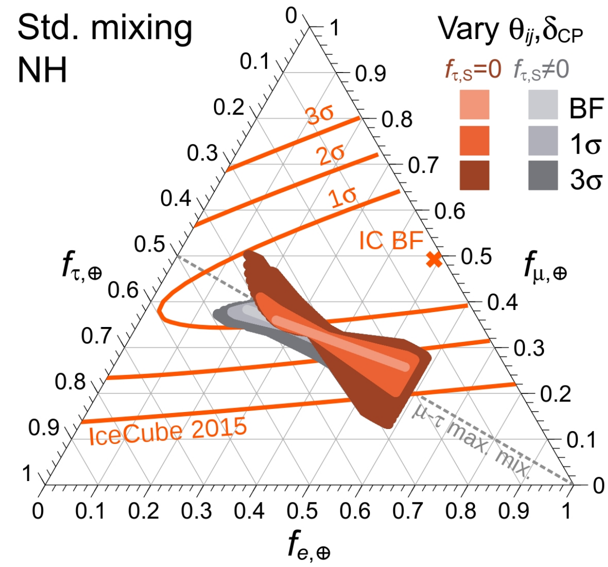

FIG. 2. Allowed flavor ratios at Earth with no new physics. The flavor ratios at the source are arbitrary (gray) or contain no tau flavor (red). The IceCube results are from Ref. [37].

more coarsely). In this case, the neutrinos are, at least effectively, an incoherent mixture of mass eigenstates. Even for the solar $\Delta m^2_\odot \approx 8 \cdot 10^{-5}$ eV^2 and PeV energies, the vacuum oscillation length is only $\sim 10^{-13}$ Gpc, much smaller than the complete baseline. (Depending on the physics in the production region, there can be also wave packet decoherence in the source [58–60].) As a consequence, the flavor composition at Earth [58] is $f_{\beta,\oplus} = \sum_{i,\alpha} |U_{\beta i}|^2 \, |U_{\alpha i}|^2 \, f_{\alpha,\mathrm{S}}$, with U the PMNS matrix [61], implying $\sum_\beta f_{\beta,\oplus} = 1$. For a pion beam, the flavor composition evolves roughly into flavor equipartition at the detector, $(\frac{1}{3} : \frac{1}{3} : \frac{1}{3})_\oplus$.

New physics in neutrino propagation might modify the flavor composition. We categorize classes of new-physics models below. Their effects have to be discriminated from the energy-dependent flavor composition at the source [63].

Flavor content of the mass eigenstates.—
Figure 1 shows the flavor content $|U_{\alpha i}|^2$ of the mass eigenstates, which is the fundamental input that determines flavor ratios at Earth without or with new physics. It also illustrates the underlying three-flavor unitarity of our analysis, *i.e.*, $|U_{\alpha 1}|^2 + |U_{\alpha 2}|^2 + |U_{\alpha 3}|^2 = 1$, which allows the flavor content to be displayed in a ternary plot [64]. This is appropriate because the mixing angles to sterile neutrinos must be quite small [65, 66].

The long axis of each region is set by the uncertainty in θ_{23} and δ_{CP}, while the short axis is set by the uncertainty in θ_{12}. The effect of the uncertainty in θ_{13} is tiny. Even if θ_{23} were to be precisely determined soon, it is less likely that δ_{CP} will be, and the uncertainty in the latter will still span a large range in $|U_{\tau 1}|^2$ and $|U_{\tau 2}|^2$.

Standard flavor mixing.— Figure 2 shows the allowed region for the flavor composition at Earth assuming arbitrary flavor composition at the source and standard neutrino mixing (including parameter uncertainties). The region is quite small: even at 3σ it covers only about 10% of the available space. There is little difference between $f_{\tau,\mathrm{S}} = 0$ and $f_{\tau,\mathrm{S}} \neq 0$.

There is a theoretical symmetry along the line $(f_{e,\oplus} : (1 - f_{e,\oplus})/2 : (1 - f_{e,\oplus})/2)$ coming from nearly-maximal mixing. On the other hand, the experimental degeneracy pulls towards $(f_{e,\oplus} : 1 - 2f_{e,\oplus} : f_{e,\oplus})$, on account of the difficulty of distinguishing between electromagnetic and hadronic cascades. Thus, theory and experiment are complementary, which enhances the discriminating power of flavor ratios.

The region shown includes the possibility of energy-dependent flavor composition at the source; see the Supplemental Material for examples. It also includes the possibility that the diffuse flux has contributions from sources with different flavor compositions, because of the linear mapping between those at the source and those at Earth. The possibility of measuring δ_{CP} from the flavor ratios is explored in the Supplemental Material.

Figure 3 shows that if the flavor composition at the source could be restricted from astrophysical arguments, the allowed regions at Earth could become tiny (and will shrink when the mixing parameters are better known). A source composition of $(1:0:0)_\mathrm{S}$ is already disfavored at $\gtrsim 2\sigma$. While the current IceCube fit is compatible with the standard $\left(\frac{1}{3} : \frac{1}{3} : \frac{1}{3}\right)_\oplus$ at 1σ, the best-fit point cannot

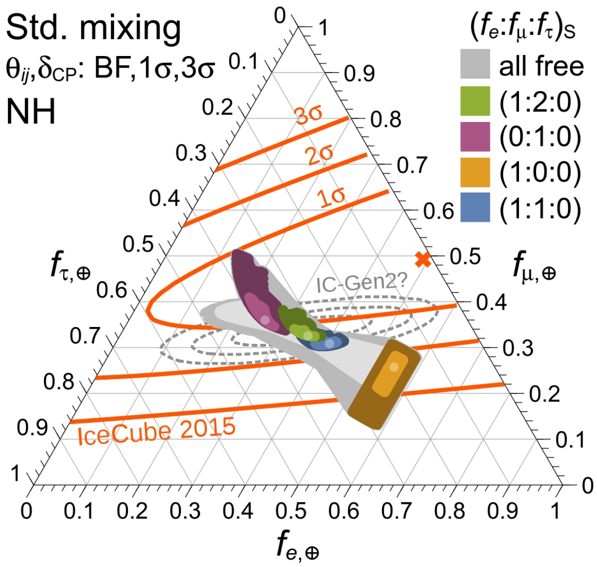

FIG. 3. Allowed flavor ratios at Earth for different choices of source ratios, assuming standard mixing. Projected 1σ, 2σ, and 3σ exclusion curves from IceCube-Gen2 are included for comparison (gray, dotted); see main text.

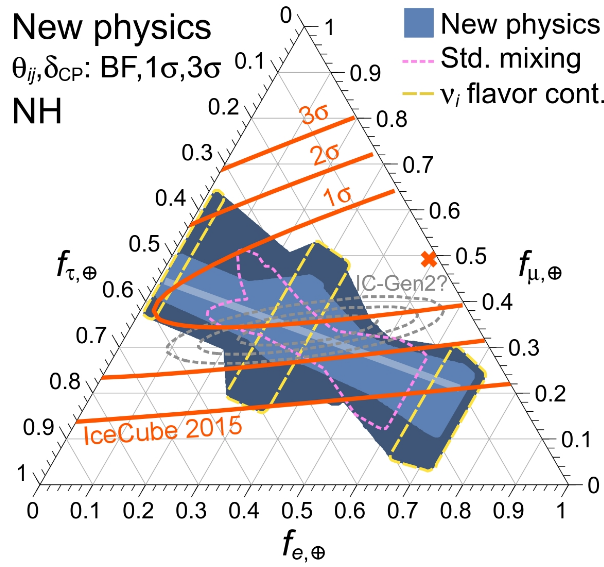

FIG. 4. Allowed flavor ratios at Earth in a general class of new-physics models. These produce linear combinations of the flavor content of ν_3, ν_2, and ν_1, shown as yellow (dashed) curves, from left to right. The standard mixing 3σ region from Fig. 2 is shown as a magenta (dotted) curve.

be reached within the Standard Model.

An upgrade of IceCube would have excellent discrimination power, as indicated by the projected sensitivity curves we estimate for IceCube-Gen2 and show in Fig. 3. We reduced the IceCube uncertainties by a factor 5, corresponding to an exposure increased by a factor ~ 25 (~ 6 times larger effective area [40] and twelve years instead of three). The true sensitivity might be worse (due to sparser instrumentation) or better (due to new techniques or to the discovery of flavor-identifying signals [43, 44, 46, 48, 51, 67–75]). To be conservative, we assumed the best fit will correspond to the most-frequently considered composition, $(\frac{1}{3} : \frac{1}{3} : \frac{1}{3})_\oplus$, for which it will be most difficult to test for new physics.

Flavor ratios with new physics.— New physics can modify the flavor composition at production, during propagation, or in interaction. In the first two cases, it will affect the flavor composition that reaches the detector; this is our focus. In the last case —which includes, *e.g.*, non-standard interactions [76] and renormalization group running of the mixing parameters [77]— we assume that new physics can be separated by probing the interaction length in Earth via the angular dependence of the neutrino flux [78–81].

In extreme scenarios, there could be only one mass eigenstate present at detection, and the flavor composition would correspond to that of one eigenstate. This could happen if all but one mass eigenstate completely decays or if matter-affected mixing at the source singles out a specific one for emission.

Figure 4 shows the allowed region if we restrict ourselves to a general class of new-physics models —those in which arbitrary combinations of incoherent mass eigenstates are allowed. The most dramatic examples include all variants of neutrino decay, both partial and complete [25, 82–85], and secret neutrino interactions [86–91]. Other examples are pseudo-Dirac neutrinos [92–94] and decoherence on the Planck-scale structure of spacetime [95–101]. The shape of the blue region comes from superposing the flavor content of the ν_i calculated with the same values of the mixing parameters.

Even with this general class of new-physics models, only about 25% of the flavor triangle can be accessed. The current IceCube best fit cannot be reached even by invoking this class of physics models. IceCube-Gen2 will be needed to strongly constrain such new-physics models.

Interestingly, there is more than one way in which the standard $\left(\frac{1}{3} : \frac{1}{3} : \frac{1}{3}\right)_\oplus$ composition can be generated, such as through the standard mixing of $\left(\frac{1}{3} : \frac{2}{3} : 0\right)_\text{S}$, or through a fortuitous incoherent mix of mass eigenstates due to decay.

Already, complete decay in the most often used neutrino decay scenario (only ν_1 stable) for the NH can be ruled out at $\gtrsim 2\sigma$ (see Ref. [85] for a weaker exclusion at 1σ based on their own analysis of tracks and cascades), and bounds on the neutrino lifetimes can be set [102].

To access the white region in Fig. 4, a broader class of new-physics models is required. Possible examples are models with violation of CPT and/or Lorentz invariance (which alter the dispersion relations) [25, 100, 103–106], or the equivalence principle [107–109], and coupling to a torsion field [110].

All these have in common that they either invalidate the concept of decoherence in the astrophysical neutrino flavor composition or they change the values of the mixing parameters. Ref. [111] adopted a generic effective theory approach in which the new-physics terms dominate the propagation Hamiltonian at high energies, and showed that such models are indeed able to populate almost the full triangle.

Another possibility is the existence of extra dimensions, which could lead to matter-like resonant mixing between active and sterile flavors [112]. Boosted dark matter [19, 113, 114] could generate neutrino-like events, even mimicking pure-flavor signatures.

Conclusions.— We have demonstrated that the allowed region of neutrino flavor composition at Earth under standard mixing is quite small, in spite of the uncertainties in the mixing parameters and flavor composition at the sources. The allowed region remains small even in the presence of a general class of new-physics models whose effect is to change the incoherent mix of mass eigenstates during propagation (*e.g.*, neutrino decay and secret interactions). These results hardly depend on the mass hierarchy, and they hold for energy-dependent flavor compositions at the source or energy-dependent new physics; see the Supplemental Material.

In order to access the larger space of possible flavor combinations, a broader class of new physics during propagation —flavor-violating or capable of modifying the values of the mixing parameters— or at detection is required. Interestingly, the current IceCube best-fit composition lies in this region, though the standard $(\frac{1}{3}:\frac{1}{3}:\frac{1}{3})_\oplus$ case is not excluded.

The power of IceCube to determine the composition is enhanced by the complementarity between its experimental ν_e-ν_τ degeneracy and the theoretical ν_μ-ν_τ symmetry coming from nearly-maximal mixing. The current bounds are not only compatible with most source compositions, but also with many potential new physics effects. However, the most favored neutrino decay scenario (only ν_1 stable) can be already ruled out at $\gtrsim 2\sigma$.

The smaller the allowed region with only standard mixing shown in Fig. 2 and Fig. 3, the more sensitive IceCube is to new physics. Likewise, the smaller the new-physics region shown in Fig. 4, the more sensitive IceCube is to the broader class of new physics. The recent successes in measuring neutrino mixing parameters have been essential to making these regions small. Our results provide new perspectives that will sharpen and accelerate tests of flavor ratios.

Ideally, flavor ratios would be determined using a single class of point sources at known distances. No high-energy astrophysical sources have been resolved yet, however. We have shown that, even using a diffuse flux, flavor ratios can reveal information about source conditions and neutrino properties.

Data from a volume upgrade of IceCube in combination with improved measurements of the mixing parameters, including $\delta_{\rm CP}$, have the potential to nail down the flavor composition at the source or to identify new physics in propagation. However, it is not possible to extract the value of $\delta_{\rm CP}$ from astrophysical data alone if the flavor composition at the source is not known; see the Supplemental Material.

To fully exploit the power of neutrino flavors, advances in four directions are needed:

1. A volume upgrade of IceCube (IceCube-Gen2 [40]) or a corresponding experiment in seawater (*e.g.*, KM3NeT [115]).

2. Reduction of the uncertainties in the values of the mixing parameters (especially θ_{23} and $\delta_{\rm CP}$).

3. Improvements in experimental techniques to reconstruct neutrino flavor and energy.

4. More systematic model building to better understand, or constrain, the region of flavor ratios at Earth that could be accessed by new physics.

Given the wealth of information about neutrino production, propagation, and interaction that the flavor composition provides, its precise determination should become a high-priority goal of ongoing and near-future experimental analyses.

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Supplemental Material

Appendix A: Plots for inverted mass hierarchy

We repeat the figures shown in the main text of the paper, but now for the inverted hierarchy (IH) instead of the normal hierarchy. The differences are modest and are vanishing for the 3σ regions.

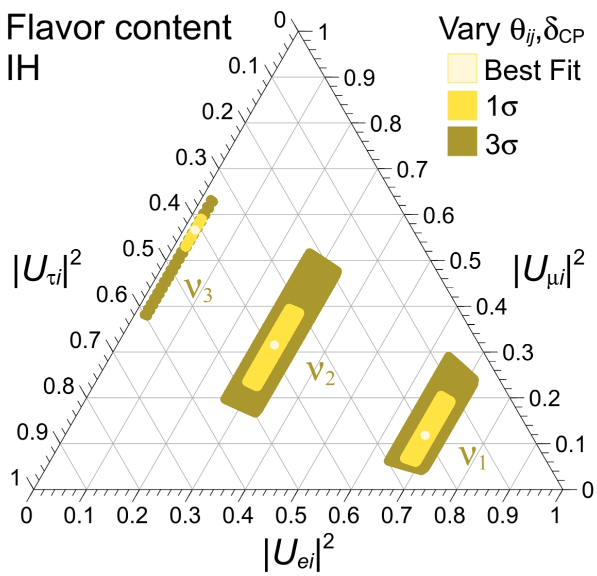

FIG. 5. Same as Fig. 1, but for an inverted mass hierarchy.

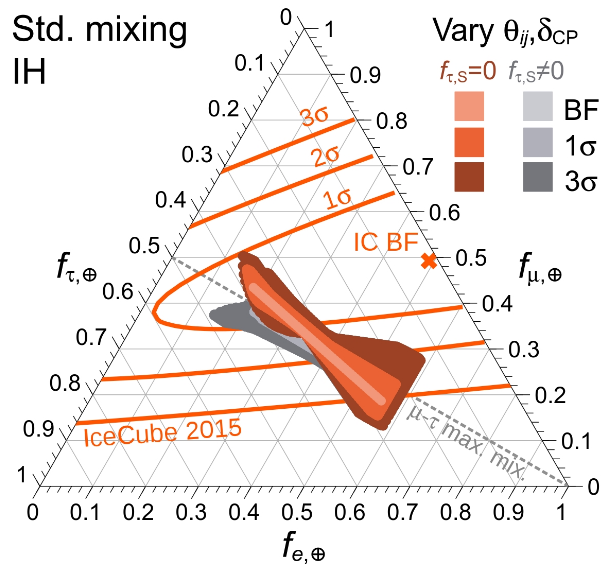

FIG. 7. Same as Fig. 2, but for an inverted mass hierarchy.

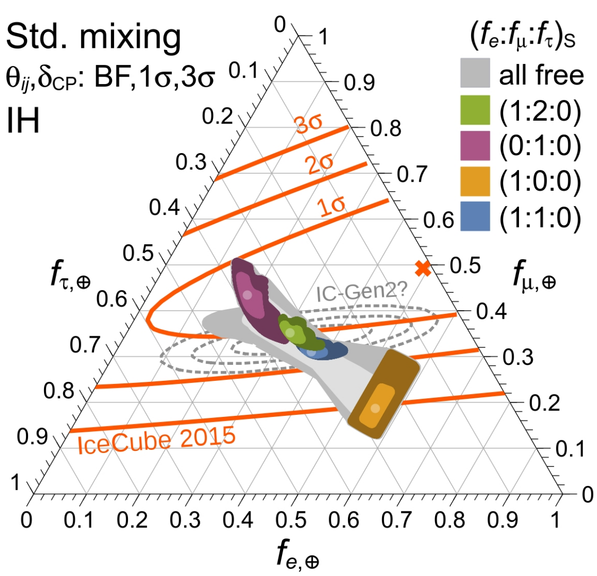

FIG. 6. Same as Fig. 3, but for an inverted mass hierarchy.

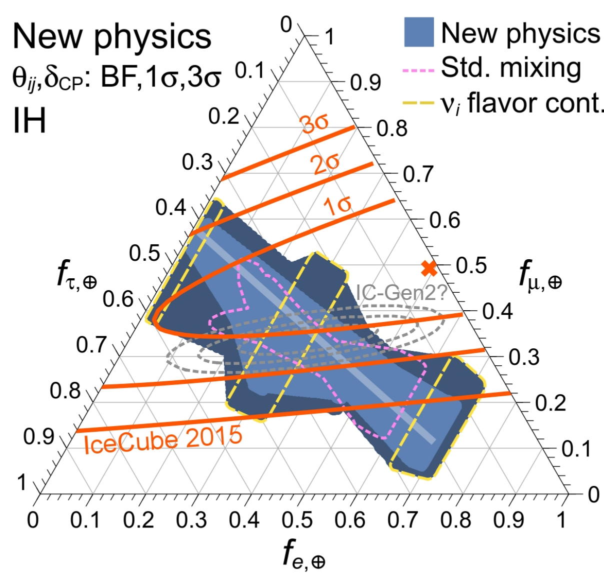

FIG. 8. Same as Fig. 4, but for an inverted mass hierarchy.

Appendix B: Energy dependence of the flavor composition at the source

The energy dependence of the flavor composition at the source has been considered in, *e.g.*, Refs. [49–52]. At lower energies, a $(1:2:0)_S$ composition is expected, coming from the full pion decay chain. At higher energies, where the synchrotron losses of the muons created by the pion decays become larger and where additional neutrino production channels become accessible, the source flavor composition changes. Non-trivial flavor compositions are obtained if several processes compete or the cooled muons pile up at lower energies [51].

If neutrinos in a broad energy interval are considered, then the inferred flavor composition at Earth will be a superposition of those at different energies. It will be challenging for IceCube to pinpoint the exact flavor ratios unless a large volume of data is available for fine energy binning to be feasible.

Let us assume that such a binning is in fact feasible. In that case, by assuming that the energy dependence of the source flavor composition is the same for all of the sources contributing to the neutrino diffuse flux, we can predict the ratios at Earth at different energies.

Figure 9 shows the variation of the flavor ratios at Earth from a source with emission parameters given by a "classical" pion beam source evolving into a muon-damped source at higher energies (test point TP13 from Ref. [51], a photohadronic model where the target photons come from synchrotron emission of co-accelerated electrons). As expected, the trajectory in flavor space lies within the Standard Model region shown in Fig. 2.

Figure 10 shows the results for a different parameter set (test point TP3 from Ref. [51], corresponding to AGN cores, a mixed source at low energies, where muon pile-ups add to the pion decay chain, evolving into muon damped source at high energies), this time taking into account in addition invisible decays of ν_2 and ν_3, and a stable ν_1, *i.e.*, in the normal hierarchy. The fact that decays are invisible means that the decay products of ν_2 and ν_3 do not contribute to the ν_1 flux.

In this example, the energy dependence of the flavor composition at the source competes with the energy dependence of the new physics effect; see discussion in Ref. [63]. We have fixed the decay damping parameter to $\hat{\alpha} L = 10^5\,\mathrm{GeV}$, following the notation in Eq. (18) of Ref. [63]. As expected, the trajectory in flavor space now leaves the Standard Model region at the lowest energies, where the suppression from decay is stronger, and reaches the region corresponding to the flavor content of ν_1 (see Fig. 1). The full trajectory is still completely contained within the new physics region from Fig. 4.

Figure 11 shows complementary results for test point TP3 in the inverted hierarchy case, when ν_3 is stable while ν_1 and ν_2 decay. In this case, the trajectory leaves the Standard Model region and reaches the region corresponding to the flavor content of ν_3. Note that this case may be disfavored by the observation of neutrinos from SN 1987A.

If the experimental determination of the flavor ratios finds no energy dependence, then we could interpret this as a hint that neutrino production occurs in a narrow energy window, inside of which the flavor composition at the sources is approximately constant.

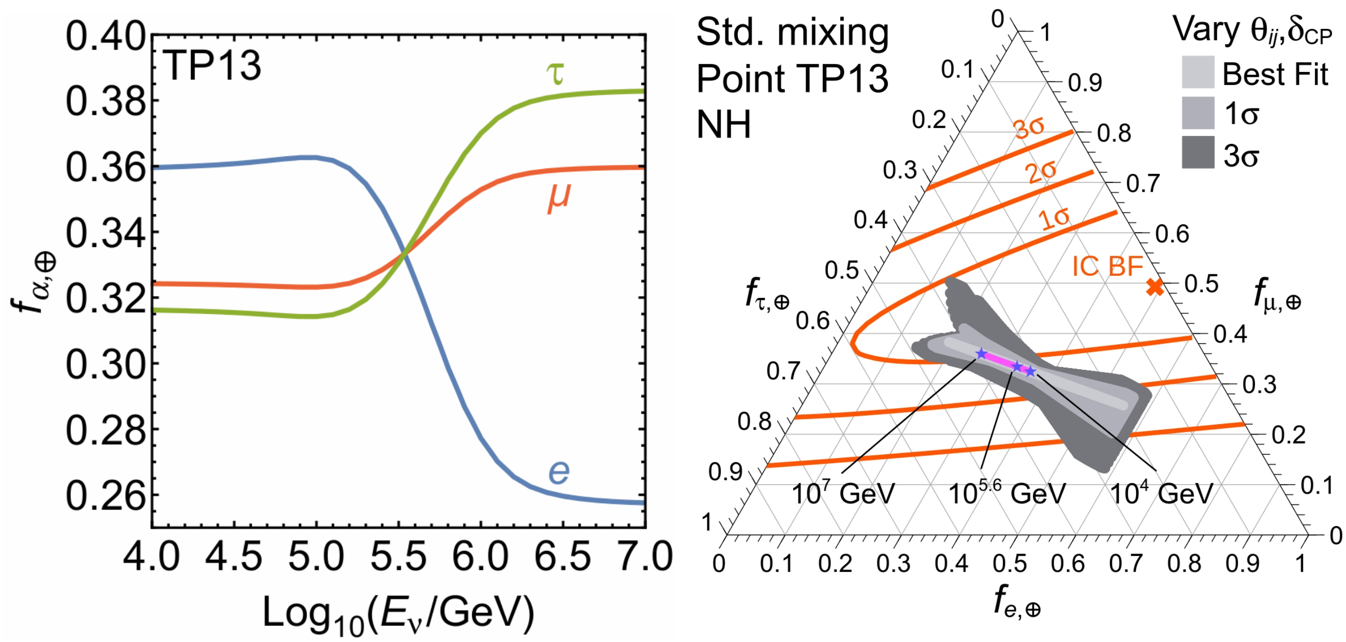

FIG. 9. *Left:* Variation with energy of the flavor ratios at Earth, for neutrinos coming from a source with emission parameters given by test point TP13 from Ref. [51]. The neutrinos were produced in $p\gamma$ interactions, calculated using NeuCosmA [54, 116]. *Right:* Ternary plots showing the trajectory of the flavor ratios of the same source, marking the values at different energies.

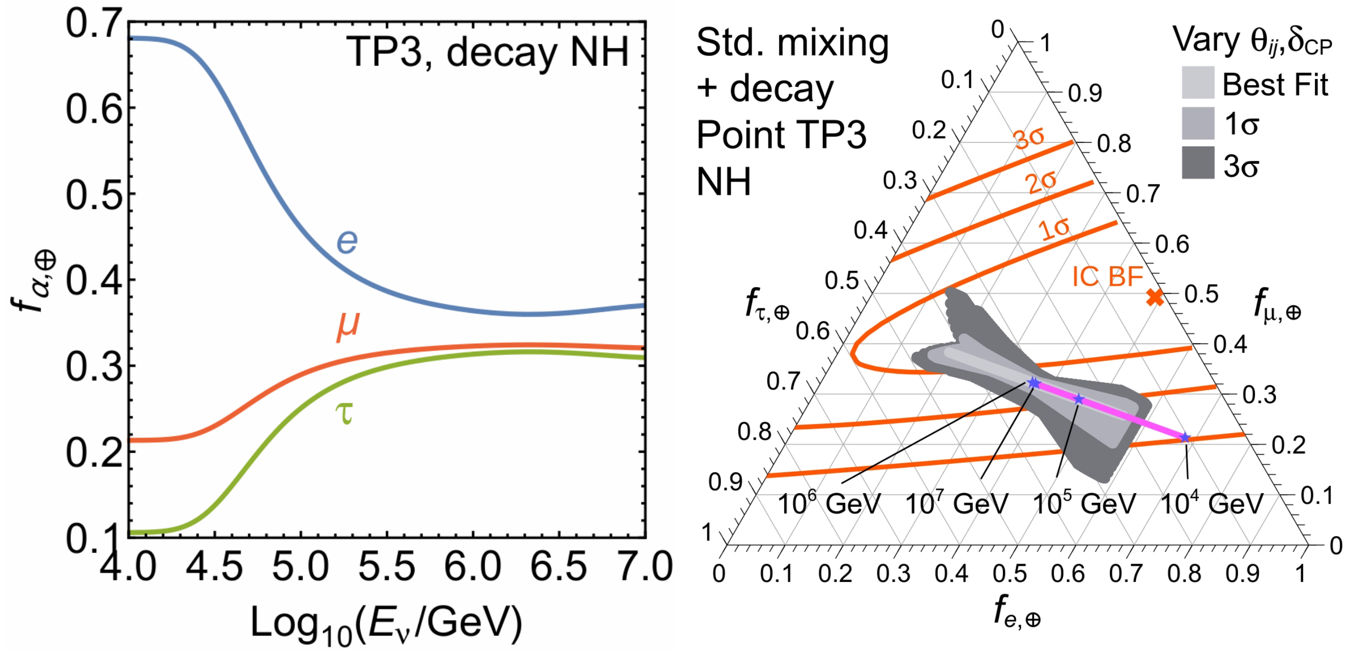

FIG. 10. *Left:* Variation with energy of the flavor ratios at Earth, for neutrinos coming from a source with emission parameters given by test point TP3 from Ref. [51], including decay of ν_2 and ν_3. The neutrinos were produced in $p\gamma$ interactions, calculated using NeuCosmA [54, 116]. *Right:* Ternary plots showing the trajectory of the flavor ratios of the same source, marking the values at different energies.

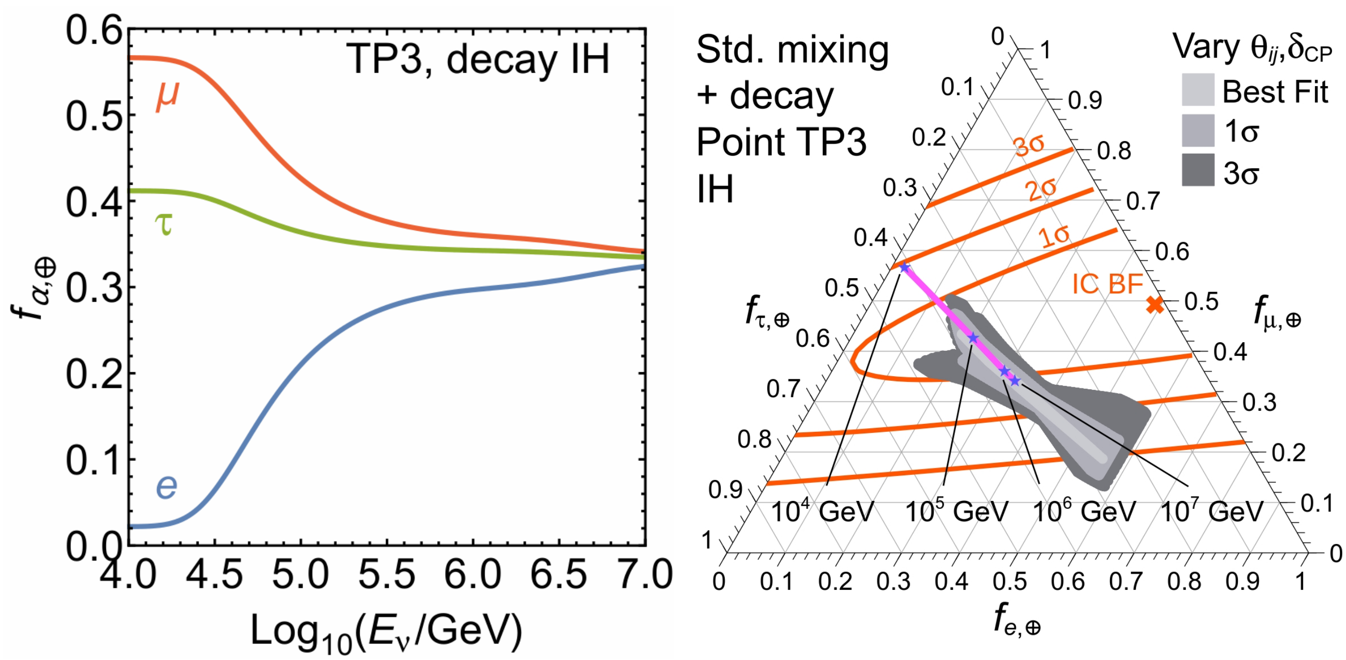

FIG. 11. *Left:* Variation with energy of the flavor ratios at Earth, for neutrinos coming from a source with emission parameters given by test point TP3 from Ref. [51], including decay of ν_1 and ν_2. The neutrinos were produced in $p\gamma$ interactions, calculated using NeuCosmA [54, 116]. *Right:* Ternary plots showing the trajectory of the flavor ratios of the same source, marking the values at different energies.

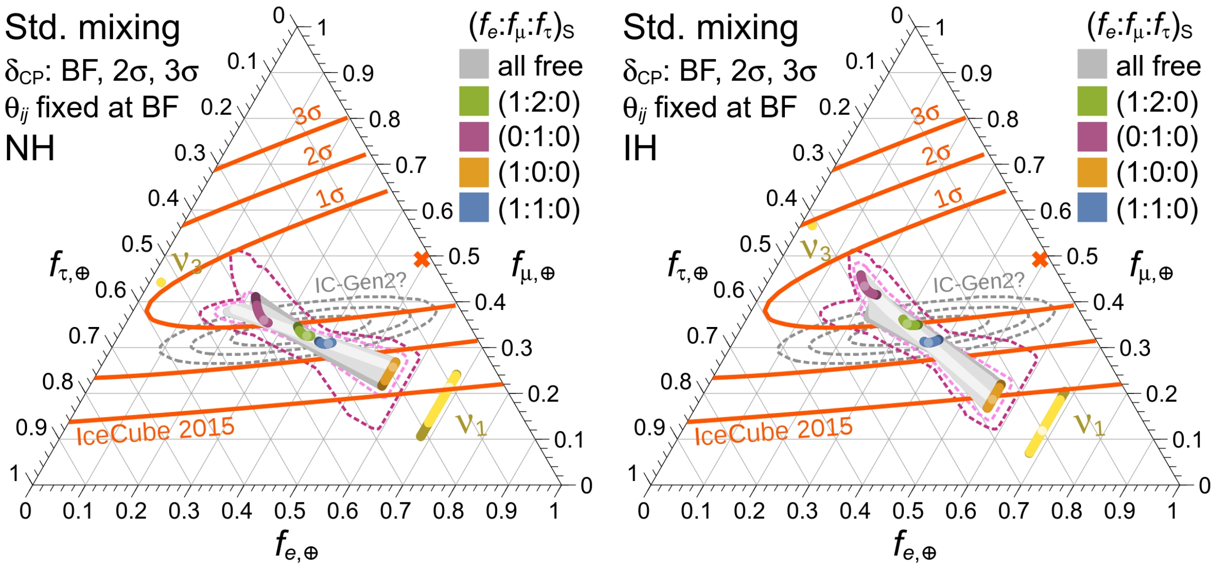

FIG. 12. Flavor ratios at Earth with unconstrained source flavor ratios and four particular choices of source flavor ratios. The mixing angles are kept fixed at their current best-fit values; the CP-violation phase $\delta_{\rm CP}$ is the only mixing parameter that has been varied to create the colored regions. The regions corresponding to the flavor content of ν_1 and ν_3 at the 1σ and 3σ regions are also shown; note that the flavor content of ν_3 has no dependence on $\delta_{\rm CP}$.

Appendix C: Measurement of $\delta_{\rm CP}$?

There have been proposals to determine $\delta_{\rm CP}$ using high-energy astrophysical neutrinos; see, *e.g.*, Refs. [117–122]. If neutrinos decay, this possibility may even be more attractive [123]. We therefore show in Fig. 12 the allowed regions of flavor composition if all of the mixing parameters except $\delta_{\rm CP}$ are fixed to their current best-fit values. This assumption corresponds to future improved measurements of the mixing angles coming from other experiments, whereas $\delta_{\rm CP}$ is to be determined from neutrino telescope data. For comparison, we include the outlines of the regions generated when the mixing angles are also allowed to vary within their 1σ and 3σ regions.

The comparison of Figs. 3 & 6 and Fig. 12 shows that, in the absence of knowledge of the flavor composition at the source, $\delta_{\rm CP}$ cannot be extracted. However, if the source flavor composition were known to be muon-damped ($(0:1:0)_{\rm S}$) or neutron source ($(1:0:0)_{\rm S}$), then, given the statistics of IceCube-Gen2, one would expect a marginal statistically significant contribution to the mass hierarchy or CP violation sensitivities of T2K and NOvA [118]. A new long-baseline experiment, such as DUNE [124], would be more precise. A special case is the one of neutrino decay, in which IceCube-Gen2 could actually measure the leptonic CP phase [123]; see lower right yellow region, if only ν_1 is stable. This case is, however, disfavored by current IceCube data at $\gtrsim 2\sigma$; see Fig. 4.