

Measuring neutrino mixing above 1 TeV with astrophysical neutrinos

Mauricio Bustamante^{1,*} Qinqin Liu^{2,3,4,5,†} and Gabriela Barenboim^{6,‡}

¹*Niels Bohr International Academy, Niels Bohr Institute, University of Copenhagen, 2100 Copenhagen, Denmark*

²*Department of Physics, Engineering Physics and Astronomy, Queen's University, Kingston, Ontario K7L 3N6, Canada*

³*Arthur B. McDonald Canadian Astroparticle Physics Research Institute, Kingston, Ontario K7L 3N6, Canada*

⁴*Perimeter Institute for Theoretical Physics, Waterloo, Ontario N2L 2Y5, Canada*

⁵*Department of Physics, Simon Fraser University, Burnaby, British Columbia V5A 1S6, Canada*

⁶*Departament de Física Teòrica and IFIC, Universitat de València-CSIC, E-46100, Burjassot, Spain*



(Received 14 March 2026; revised 16 July 2026; accepted 8 September 2026; published 2 October 2026)

Neutrino mixing parameters are measured exclusively below 1 TeV. We show, for the first time, how to translate the flavor composition of TeV-PeV astrophysical neutrinos into direct constraints on the standard mixing parameters, placing the high-energy regime on the same quantitative footing as sub-TeV global fits. Present 11.4-year IceCube Medium-Energy Starting Events data leave these parameters unconstrained, limited by flavor-measurement uncertainties, and an irreducible degeneracy between θ_{12} and the unknown astrophysical neutrino production mechanism. However, upcoming multitelescope observations will resolve θ_{23} and θ_{13} with 17%–50% precision. While coarser than terrestrial precision, this marks the transition of TeV-PeV neutrinos from a qualitative consistency check to a genuine measurement of three-flavor mixing. Finally, we establish concrete benchmarks for detecting beyond-Standard-Model effects, providing a roadmap to probe new physics that grows with energy and remains invisible to terrestrial neutrino experiments.

DOI: [10.1103/76bd-86sg](https://doi.org/10.1103/76bd-86sg)

I. INTRODUCTION

Neutrino oscillations—the transformations of one neutrino flavor into another—have been extensively studied for decades using solar, atmospheric, reactor, and accelerator neutrinos with energies from about 10 MeV to 1 TeV. Together, these observations [1–3] support a description of mixing between three active flavors—electron (ν_e), muon (ν_μ), and tau (ν_τ)—occurring at rates driven by mass differences [4]. Today, the “mixing parameters” governing oscillations are known to within a few to tens of percent [1–3], offering nascent insight into the origins of neutrino mass, mixing, and the matter-antimatter asymmetry.

Yet, this high-precision framework is built exclusively upon sub-TeV measurements. Above 1 TeV, it remains largely unexplored—a regime where a plethora of new

neutrino physics that grows with energy could modify neutrino mixing, including via new neutrino interactions, mixing with sterile neutrinos, or violations of fundamental symmetries. Their detection would signal the long-sought discovery of physics beyond the Standard Model (BSM).

At these energies, atmospheric neutrinos are abundant, but they are unaffected by oscillations while traversing the Earth, eliminating their sensitivity to standard mixing [5,6]. High-energy astrophysical neutrinos, discovered comparatively more recently [7], provide the only viable probe of both standard and nonstandard mixing above 1 TeV. Their potential to do so was recognized early [8–26], but because these analyses preceded or immediately followed their discovery, they were necessarily exploratory. Now, growing measurement precision is poised to bring > 1 TeV mixing tests within reach.

A. Overview of results

We quantify how TeV-PeV astrophysical neutrinos constrain the mixing parameters above 1 TeV; concretely, three mixing angles, θ_{12} , θ_{23} , and θ_{13} , and one CP -violation phase, δ_{CP} . We show that inverting the measured flavor composition of these neutrinos—i.e., the proportions of ν_e , ν_μ , and ν_τ , affected by oscillations en route to Earth—yields

*Contact author: mbustamante@nbi.ku.dk

†Contact author: qinqin_liu@sfu.ca

‡Contact author: gabriela.barenboim@uv.es

Published by the American Physical Society under the terms of the [Creative Commons Attribution 4.0 International](https://creativecommons.org/licenses/by/4.0/) license. Further distribution of this work must maintain attribution to the author(s) and the published article's title, journal citation, and DOI. Funded by SCOAP³.

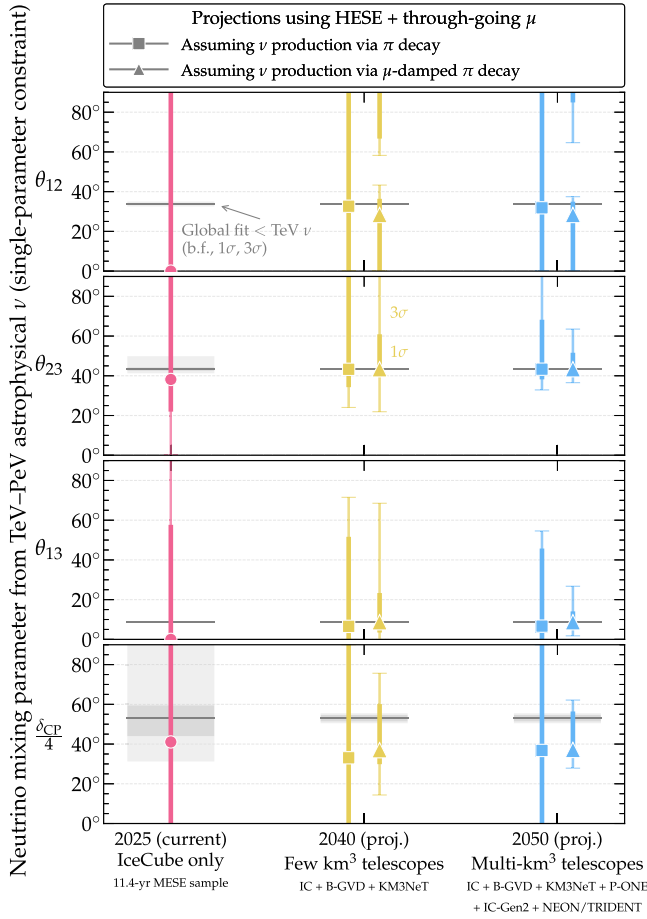


FIG. 1. Evolution of measurements of neutrino mixing parameters above 1 TeV. Present results are derived from IceCube observations of the flavor composition of high-energy astrophysical neutrinos (11.4-yr MESE sample). Projections (2040/2050) combine HESE and through-going muon samples across multiple detectors under two production scenarios. Each parameter is constrained individually, profiling over the remaining parameters within current global sub-TeV ranges. Future neutrino telescopes will constrain θ_{23} and θ_{13} (and, via $\cos \delta_{\text{CP}}$, the value of δ_{CP}) above 1 TeV for the first time.

constraints on the same mixing parameters measured by sub-TeV experiments, making the two energy regimes *quantitatively* comparable.

Figure 1 shows our results. Present flavor-composition measurements by the IceCube Neutrino Observatory [27] leave the mixing angles unconstrained, not only due to limited statistics, but to a degeneracy between θ_{12} and the unknown flavor composition with which neutrinos are produced ($f_{e,S}$, more on this below). Nevertheless, multitelescope networks operating already today will resolve it, reaching 17%–50% precision by 2050. Although orders-of-magnitude coarser than sub-TeV global fits [1–3], this is enough to mark the difference between a consistency check and an actual measurement above 1 TeV, and it establishes a probe of the detectability of BSM physics.

II. HIGH-ENERGY NEUTRINO FLAVOR: FROM SOURCES TO EARTH

A. Producing astrophysical neutrinos

In cosmic accelerators—e.g., active galaxies, γ -ray bursts, supernovae—PeV-scale protons interact with ambient matter [28–30] and radiation [29,31–33] to produce pions. Pions decay via $\pi^+ \rightarrow \mu^+ + \nu_\mu$, followed by $\mu^+ \rightarrow \bar{\nu}_\mu + \nu_e + e^+$ (and charge conjugates), yielding TeV-PeV neutrinos with flavor ratios $(f_e, f_\mu, f_\tau)_S = (\frac{1}{3}, \frac{2}{3}, 0)$ at the sources, where $f_{\alpha,S} \in [0, 1]$ is the ratio of $\nu_\alpha + \bar{\nu}_\alpha$ to the total flux (hereafter ν_α denotes $\nu_\alpha + \bar{\nu}_\alpha$, since telescopes cannot distinguish them). Interactions with matter inside the sources are unlikely to modify the flavor ratios [34–38] (see, however, Ref. [39]).

Alternative production mechanisms are possible (see, e.g., Ref. [40]): muon-damped scenarios with intense magnetic fields yield $(0, 1, 0)_S$, while β decay in neutron-rich sources yields $(1, 0, 0)_S$ (though at lower energies). Flavor ratios likely evolve with energy [41,42], but resolving this evolution is challenging [43]; we therefore assume energy-independent, isotropic [44,45] flavor ratios, representing energy- and sky-averaged values.

Because ν_τ production requires rare mesons [46,47], it is expected to compose less than 10% of the emitted flux. Following standard practice (e.g., Refs. [40,43,48,49]), we fix $f_{\tau,S} = 0$. The source composition is thus entirely parametrized by the ν_e fraction as $(f_{e,S}, 1 - f_{e,S}, 0)$. To account for production uncertainty, we allow $f_{e,S}$ to vary freely across $[0, 1]$. Appendix B shows that relaxing $f_{\tau,S} = 0$ does not weaken our conclusions.

We assume the mixing parameters remain identical from production at the sources to detection at Earth—i.e., that mixing does not run between the sub-TeV and TeV-PeV scales. This is not a mere simplification, but the exact null hypothesis under test. If new physics modifies mixing at high energies, or if mixing is nonuniversal between production and propagation, our extracted parameters simply become *effective*, energy-averaged values. Consequently, any genuine deviation from established sub-TeV measurements constitutes the very BSM signature we aim to quantify—rather than a flaw in the method. (References [50–52] explicitly explore the effects of renormalization-group running of the mixing parameters for high-energy astrophysical neutrinos.)

B. Neutrino oscillations

A neutrino flavor state is a superposition of mass eigenstates, ν_i , i.e.,

$$\nu_\alpha = \sum_{i=1}^3 U_{\alpha i}^* \nu_i, \quad (1)$$

where $U_{\alpha i}$ are elements of the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) mixing matrix. We parametrize

[4] the PMNS matrix using the mixing parameters θ_{12} , θ_{23} , θ_{13} , and δ_{CP} .

For TeV-PeV neutrinos traveling Mpc-Gpc distances from their astrophysical sources to Earth, oscillation lengths are tiny compared to the baselines, leading to rapid oscillations. This, combined with the spread in baselines and limited energy resolution, makes neutrino telescopes sensitive only to the average $\nu_\alpha \rightarrow \nu_\beta$ flavor-transition probabilities, as follows:

$$P_{\alpha\beta} = \sum_i |U_{\alpha i}|^2 |U_{\beta i}|^2. \quad (2)$$

Unlike terrestrial experiments restricted primarily to transitions between two flavors due to shorter baselines, astrophysical neutrinos undergo full three-flavor mixing over cosmological-scale distances, marking the first rigorous test of three-flavor mixing at these energies.

A critical consequence of Eq. (2) is that $P_{\alpha\beta}$ is invariant under $\delta_{\text{CP}} \rightarrow -\delta_{\text{CP}}$. Expanding $|U_{\alpha i}|^2$ in Eq. (2) reveals that δ_{CP} enters $P_{\alpha\beta}$ exclusively through the *CP-conserving* term, $\cos \delta_{\text{CP}}$. The *CP-odd* term proportional to $\sin \delta_{\text{CP}}$ —which drives genuine *CP* violation by distinguishing ν from $\bar{\nu}$ probabilities—decoheres to zero when averaged over astrophysical baselines. Consequently, as advanced in Ref. [49], these measurements are sensitive to $|\delta_{\text{CP}}|$, but remain *blind to CP violation itself*. We report δ_{CP} constraints throughout with this caveat in mind.

C. Flavor composition at Earth

Figure 2 shows the allowed flavor composition at Earth. For a flavor composition at the sources of $(f_e, f_\mu, f_\tau)_S$, this is

$$f_{\alpha,\oplus} = \sum_\beta P_{\beta\alpha} f_{\beta,S}. \quad (3)$$

The nominal expectation, for neutrino production via pion decay and assuming known values of the mixing parameters [3], is approximately $(\frac{1}{3}, \frac{1}{3}, \frac{1}{3})_\oplus$.

The “theoretically palatable” region [40,49] in Fig. 2 varies the mixing parameters entering Eq. (3) within current global sub-TeV uncertainties [3] and $f_{e,S} \in [0, 1]$. The “unitarity-allowed” region spans the full physically allowed ranges while preserving unitarity of flavor transitions [53]; our predictions of $f_{\alpha,\oplus}$ lie within it.

The flavor composition offers different sensitivity to different mixing parameters [40]: the long axis of the theoretically palatable region aligns with $\mu - \tau$ maximal mixing [3] ($\theta_{23} \approx 45^\circ$); its short-axis width reflects θ_{23} uncertainty (and, more weakly, δ_{CP}); its long-axis width reflects θ_{12} uncertainty and the variation of $f_{e,S}$; and θ_{13} sets its tilt. Because flavor measurements are roughly orthogonal to this region, sensitivity is primarily to θ_{23}

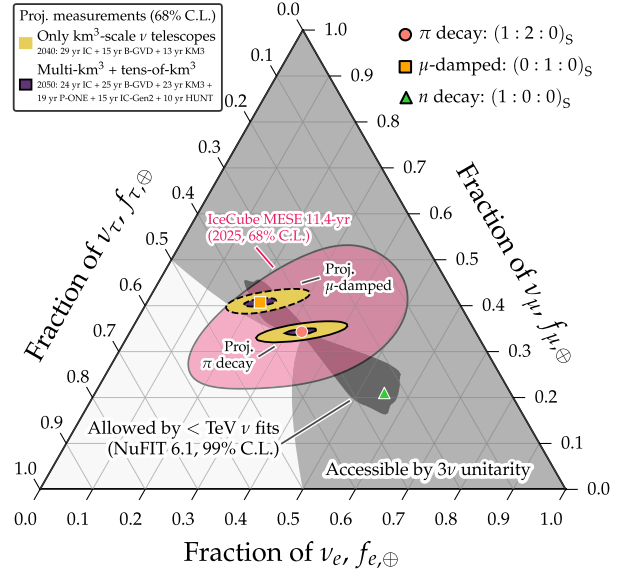


FIG. 2. High-energy neutrino flavor composition at Earth. Theory-allowed regions vary $f_{e,S} \in [0, 1]$ and mixing parameters within experimental uncertainties (theoretically palatable [40,49]) or unitarity constraints (unitarity-allowed [53]). No ν_τ production is assumed. Present IceCube MESE measurements [27] have large uncertainty; they are consistent with standard mixing but cannot constrain mixing parameters. Projected multitelescope combinations, assuming production via full pion decay and muon-damped decay, reveal a path to improved precision.

and θ_{13} (and $f_{e,S}$ [48,49]). This differentiated sensitivity carries through to the unitarity-allowed region.

D. Measuring the flavor composition

TeV-PeV neutrino telescopes such as IceCube detect Cherenkov light from neutrino interactions, identifying primarily tracks, mostly from ν_μ , and cascades, mostly from ν_e and ν_τ , creating a $\nu_e - \nu_\tau$ experimental degeneracy. Additional signatures include double cascades from energetic ν_τ [54] and Glashow resonance enhancement from 6.3 PeV $\bar{\nu}_e$ [55,56].

Rather than determining the flavors of individual events, analyses infer the flavor composition of the diffuse neutrino flux by comparing the number of detected tracks, cascades, and double cascades [27,57–65]. For present results, we use the 11.4-year IceCube Medium-Energy Starting Events (MESE) flavor composition [27] (Fig. 2), the first measurement reporting nonzero content of all flavors at 68% C.L. MESE events have energies from 1 TeV to 10 PeV and high astrophysical purity [66,67].

For our projections, we follow Ref. [43] to infer flavor-composition measurements from a combination of High-Energy Starting Events (HESE) [7,68–72] (tracks, cascades, and double cascades above 60 TeV) and through-going muons [73,74]. We forecast multitelescope detection combining existing IceCube, Baikal-GVD [75], and KM3NeT [76] with future [77,78] P-ONE [79],

IceCube-Gen2 [80], NEON [81], TRIDENT [82], and HUNT [83]—up to 30 times the size of IceCube (see also Refs. [43,44,49,84,85]). Section III A details how we turn these samples into a flavor-composition likelihood.

Figure 2 illustrates the improvement in flavor-composition measurements. Projected uncertainties shrink substantially compared to present ones due to increased statistics as multiple detectors accumulate larger event samples. We consider two possible future measurements: one centered on the nominal expectation from full pion decay and one on muon-damped pion decay.

III. INFERRING THE MIXING PARAMETERS

Translating flavor-composition measurements into constraints on the mixing parameters requires two ingredients: the experimental likelihood of the flavor composition measured at Earth, and a statistical procedure to invert it. We describe them in turn.

A. The flavor-composition likelihood

We use the experimental flavor-composition likelihood, $\mathcal{L}$, to constrain the neutrino mixing parameters. This likelihood represents how compatible a test flavor composition at Earth, $(f_e, f_\mu, f_\tau)_\oplus$, is with the flavor composition inferred from neutrino-initiated events detected by IceCube or by combinations of neutrino telescopes. It also represents the precision with which neutrino telescopes can measure the flavor composition.

We compute all of our projections from the collective detection of HESE plus through-going muons by the telescopes listed in Sec. II D, following the methods of Ref. [43]. We do not use MESE in our projections because its detector effective area and detailed detector response to do so are unavailable publicly. Appendix A shows the resulting forecast likelihoods.

In the projections, we make the simplifying assumption that each neutrino telescope is a scaled version of IceCube, i.e., we scale the event rates of the telescope by its size relative to IceCube, using Table I in Ref. [85]. We estimate the year in which these projections might become possible by adopting the tentative detector start dates from the same table, ignoring contributions of intermediate construction stages.

The projected flavor measurements are centered either at $(0.32, 0.34, 0.36)_\oplus$, as expected from neutrino production by full pion decay, or at $(0.22, 0.41, 0.37)_\oplus$, as expected from muon-damped pion decay. We assume the astrophysical neutrino energy spectrum is a simple power law $\propto E^{-2.5}$, where E is the neutrino energy, consistent with the IceCube measurement of the spectrum combining multiple event samples [61].

We consider four observation eras:

- (i) Present. Figure 3 shows the flavor-composition likelihood inferred by Ref. [27] from the 11.4-year

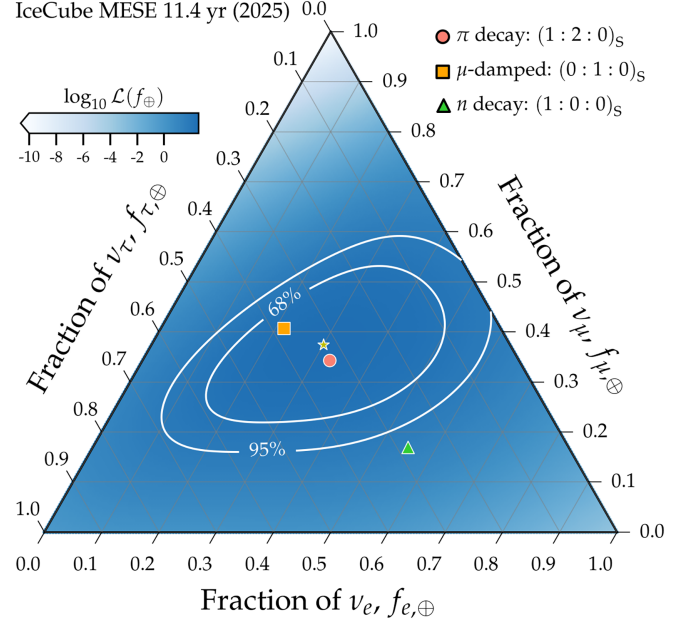


FIG. 3. Present experimental likelihood of flavor-composition measurements. This likelihood, $\mathcal{L}$, is a parametric form of the allowed contours reported in Ref. [27], inferred from the 11.4-yr IceCube MESE sample [67].

IceCube MESE sample [67]. We use this likelihood to extract present-day measurements of the neutrino mixing parameters. (To derive our results, we use a close analytical approximation to the results reported by the IceCube Collaboration [27].)

- (ii) Projected, km³-scale telescopes. Figure 7, top row, shows the year-2040 likelihood obtained by combining observations made by existing neutrino telescopes IceCube (29 years of exposure), Baikal-GVD (15 yr), and KM3NeT (13 yr), each with a volume of roughly 1 km³.
- (iii) Projected, multi-km³ telescopes. Figure 7, central row, shows the year-2050 likelihood obtained by combining observations made by existing and future detectors of km-scale size: IceCube (24 yr), Baikal-GVD (25 yr), KM3NeT (23 yr), P-ONE (19 yr)—and of about 8-km³: IceCube-Gen2 (15 yr) and either NEON or TRIDENT (10 yr).
- (iv) Projected, one tens-of-km³ telescope. Figure 7, bottom row, shows the year-2050 likelihood obtained by combining observations made by existing and future detectors of km-scale size: IceCube (24 yr), Baikal-GVD (25 yr), KM3NeT (23 yr), P-ONE (19 yr)—of about 8-km³: IceCube-Gen2 (15 yr)—and of 30 km³: HUNT (10 yr).

B. Profiled-likelihood analysis

We adopt a frequentist approach and compute a χ^2 function to assess the sensitivity to the mixing parameters $\theta = (\theta_{12}, \theta_{23}, \theta_{13}, \delta_{CP})$. This marks a fundamental shift

from previous flavor-composition analyses. Whether extracting the source flavor composition or exploring other phenomenology, prior analyses [27,43,48,49] have treated the standard mixing parameters purely as nuisance parameters to be marginalized over, making no attempt to measure them.

We pivot to ask the inverse question: taking standard oscillations as given, what do these data say about θ directly? To do so, we build upon the statistical machinery developed in Ref. [43] to combine the HESE and through-going muons detected across multiple telescopes, computing

$$\chi^2_{\text{total}}(\theta, f_{e,S}) = \chi^2_{\text{data}}(\theta, f_{e,S}) + \chi^2_{\text{prior}}(\theta, f_{e,S}), \quad (4)$$

$$\chi^2_{\text{data}}(\theta, f_{e,S}) = -2 \ln \mathcal{L}(f_{e,S} | \theta, f_{e,S}). \quad (5)$$

Here, $\mathcal{L}$ is the experimental likelihood of present or future flavor-composition measurements (shown in Appendix A), and χ^2_{prior} represents penalty terms (*pulls*) from sub-TeV oscillation measurements, which affect only the unmeasured parameters.

For present results, the pull terms χ^2_{prior} in Eq. (4) are χ^2 functions from the NuFIT 6.1 [3] global fit (assuming normal mass ordering with Super-Kamiokande data; other choices change results negligibly). We account for correlations (θ_{12} vs θ_{13} and θ_{23} vs δ_{CP}), substituting a one-dimensional pull term for the unmeasured partner whenever a parameter is measured. For projections, the pull terms are Gaussians centered on NuFIT 6.1 best fits with narrower widths from Ref. [49]. Throughout, $f_{e,S}$ floats unconstrained in $[0, 1]$, reflecting production uncertainty.

We measure one parameter of interest at a time, μ , profiling over nuisance parameters ν , i.e.,

$$\Delta\chi^2(\mu) = \min_{\nu} [\chi^2_{\text{total}}(\mu, \nu)] - \chi^2_{\text{global min}}, \quad (6)$$

using Wilks' theorem for confidence intervals. We find no sensitivity to constrain all parameters simultaneously. (Bayesian results, seemingly more restrictive, are sensitive to the choice of priors, especially today; see Appendix C.)

IV. RESULTS

A. Present status: IceCube

Figure 4 and Table I show the allowed ranges of the TeV-PeV mixing parameters inferred from the 11.4-yr IceCube MESE sample. These intervals span nearly the entire physically allowed ranges, leaving the parameters currently unconstrained.

This lack of sensitivity arises from three factors: (1) statistics that, despite reaching about 10,000 MESE events with high astrophysical purity, yield large errors in flavor measurements, (2) challenges in flavor identification, and (3) theoretical uncertainty in $f_{e,S}$, which allows for degeneracies with different mixing parameters.

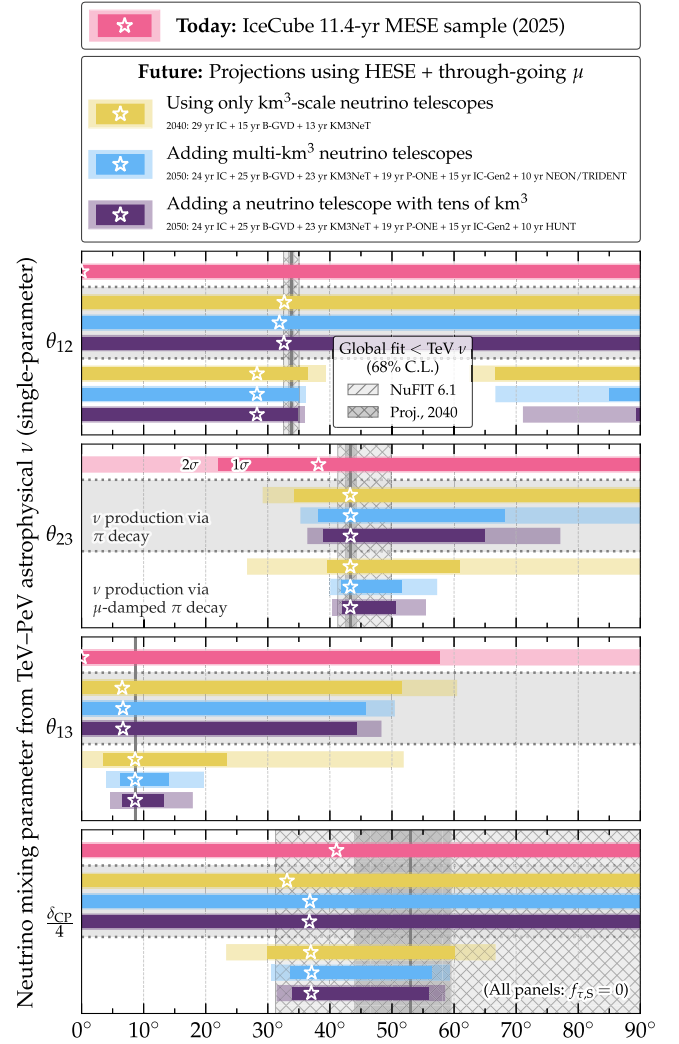


FIG. 4. Constraints on neutrino mixing parameters with high-energy astrophysical neutrinos. Present constraints from the 11.4-yr IceCube MESE sample [27] are consistent with three-flavor mixing but cannot constrain individual parameters. Projected measurements from multitelescope observations show sensitivity to θ_{23} and θ_{13} (and, via $\cos \delta_{\text{CP}}$, to δ_{CP} under muon-damped production; see Sec. II B). For comparison, we show current [3] and projected [49] sub-TeV global-fit ranges. This is the first rigorous assessment of mixing-parameter sensitivity at TeV-PeV energies.

Despite this lack of precision, the consistency of the observed flavor composition with standard expectations delivers physical insight. It rules out BSM scenarios that predict dramatically different flavor ratios [40,86], establishing the first empirical consistency check of the mixing framework at TeV energies.

B. Multitelescope projections

Figure 4 and Table I show projections using HESE plus through-going muon observations from existing (IceCube, Baikal-GVD, KM3NeT) and next-generation detectors

TABLE I. Sensitivity to neutrino mixing parameters from high-energy astrophysical neutrinos. Measurements are derived for each parameter individually while profiling over the others using present (NuFIT 6.1 [3]) and future [49] sub-TeV global-fit constraints. Present results rely on the 11.4-year IceCube MESE sample [27]. Projections using multitelescope detection of HESE plus through-going muons consider two production scenarios (full vs muon-damped pion decay). The sensitivity to δ_{CP} is via $\cos \delta_{\text{CP}}$, not via CP violation; see Sec. II B. See Fig. 4 for comparison with sub-TeV fits and Table II for expanded results.

Parameter	Present (IceCube MESE 11.4 yr)	Future (HESE + thr. μ) ^a	
		π decay	μ -damped
$\theta_{12} [^\circ]$	$0.00^{+90.00}_{-0.00}$	$32.59^{+57.41}_{-32.59}$	$28.26^{+6.57}_{-28.26}$
$\theta_{23} [^\circ]$	$38.16^{+51.84}_{-16.19}$	$43.32^{+21.61}_{-4.38}$	$43.29^{+7.33}_{-1.28}$
$\theta_{13} [^\circ]$	$0.00^{+57.66}_{-0.00}$	$6.67^{+37.64}_{-6.67}$	$8.63^{+4.57}_{-2.06}$
$\delta_{\text{CP}} [^\circ]$	164^{+196}_{-164}	147^{+213}_{-147}	148^{+76}_{-12}
$f_{e,S}$	$0.04^{+0.49}_{-0.04}$	$0.33^{+0.02}_{-0.02}$	$0.00^{+0.03}_{-0.00}$

^aEstimated year 2050, using 24 yr of IceCube + 25 yr of Baikal-GVD + 23 yr of KM3NeT + 19 yr of P-ONE + 15 yr of IceCube-Gen2 + 10 yr of HUNT. Similar results are achievable by 2040 (Appendix B).

(P-ONE, IceCube-Gen2, NEON/TRIDENT, HUNT), accumulated until 2040 and 2050 [85]. Appendix A contains simulation details.

Our projections reveal future sensitivity to θ_{23} and θ_{13} , aligned with pioneering work [8–26] but strengthened by improved sub-TeV global fits and realistic simulations. Assuming production via pion decay, future 2σ intervals remain one-sided except for θ_{23} in our farthest projections, reaching 50% precision on θ_{23} and factor-of-6 sensitivity on θ_{13} . Assuming muon-damped production, constraints are a factor-of-3 tighter, reaching 17% precision on θ_{23} , 53% on θ_{13} , and 51% on the value of δ_{CP} (via $\cos \delta_{\text{CP}}$; see Sec. II B). The weaker results assuming pion decay stem from it yielding about $(\frac{1}{3}, \frac{1}{3}, \frac{1}{3})_{\oplus}$ at Earth, which, as explained in Ref. [48], maps back into $(\frac{1}{3}, \frac{1}{3}, \frac{1}{3})_S$ at the sources regardless of the mixing parameters, diluting the sensitivity to specific values.

Broadly stated, improving the measurement of the ν_μ and ν_τ content tightens constraints on θ_{23} and θ_{13} (and, via $\cos \delta_{\text{CP}}$, on δ_{CP} in the muon-damped case); improving the ν_e measurement would nominally tighten θ_{12} , but in practice this sensitivity is washed out by the large uncertainty in $f_{e,S}$, which mimics the effect of θ_{12} on the flavor composition at Earth.

The one-dimensional intervals in Table I and Fig. 4 do not reveal how the constraints on different parameters are correlated with each other. Figures 5 and 6 show projected pairwise profiled likelihood functions, under our single-parameter approach while keeping the others

constrained with sub-TeV pull terms, using km^3 -scale neutrino telescopes and adding a tens-of- km^3 telescope, respectively. The pairwise profiled likelihood is a straightforward generalization of the one-dimensional profiled likelihood of Eq. (6), for 2 degrees of freedom instead of one.

Finally, our conclusions do not hinge on the choice of statistical framework. Repeating the analysis in a Bayesian framework—computing posterior densities of the mixing parameters under the priors detailed in Appendix C—yields broadly comparable constraints and, in addition, quantifies the global evidence for three-flavor mixing. Quantitatively, the Bayes factor $\mathcal{B}$ comparing the statistical evidence (i.e., the fully integrated posterior) with flavor mixing vs without it is about 16 today, lending strong—but not decisive [87]—evidence for three-flavor mixing. In our projections, $\mathcal{B}$ grows to 10^{56} – 10^{61} , depending on the neutrino production assumed, lending incontrovertible evidence for three-flavor mixing.

Progress may be accelerated through improvements in flavor identification in water-based detectors (e.g., Baikal-GVD, KM3NeT)—less affected than ice-based detectors by light scattering [76]—dedicated event templates [64,65], and novel techniques such as muon and neutron echoes [88–91], not considered here. Better understanding of astrophysical sources would tighten constraints on $f_{e,S}$; future MESE measurements, more abundant than HESE, will further accelerate progress.

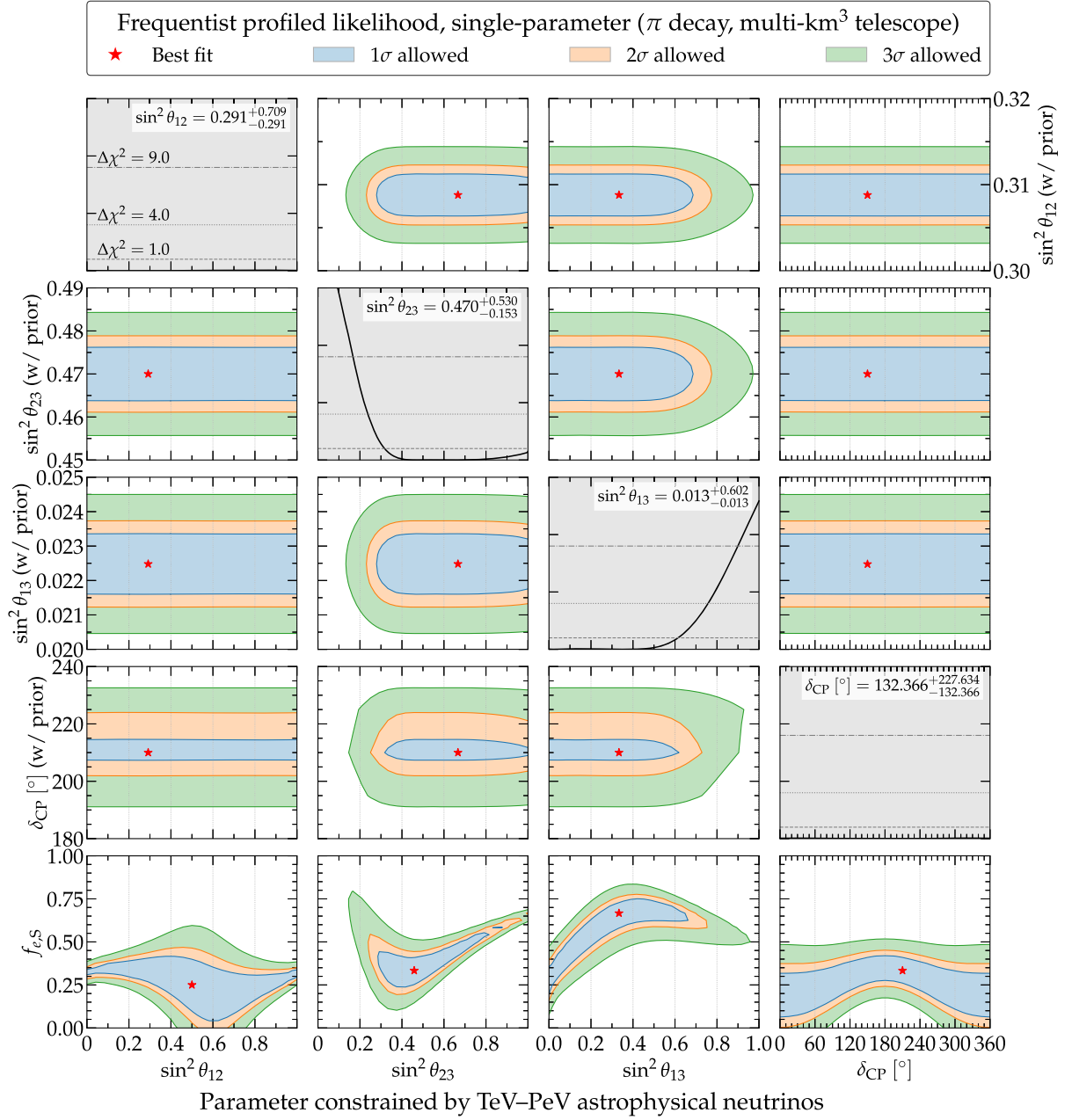


FIG. 5. Future pairwise frequentist profiled likelihood, km³-scale detectors (2040). The flavor-measurement likelihood uses the combined exposure of IceCube, Baikal-GVD, and KM3NeT to the year 2040, assuming neutrino production via full pion decay and $f_{\tau,S} = 0$. See Appendix A for detector details.

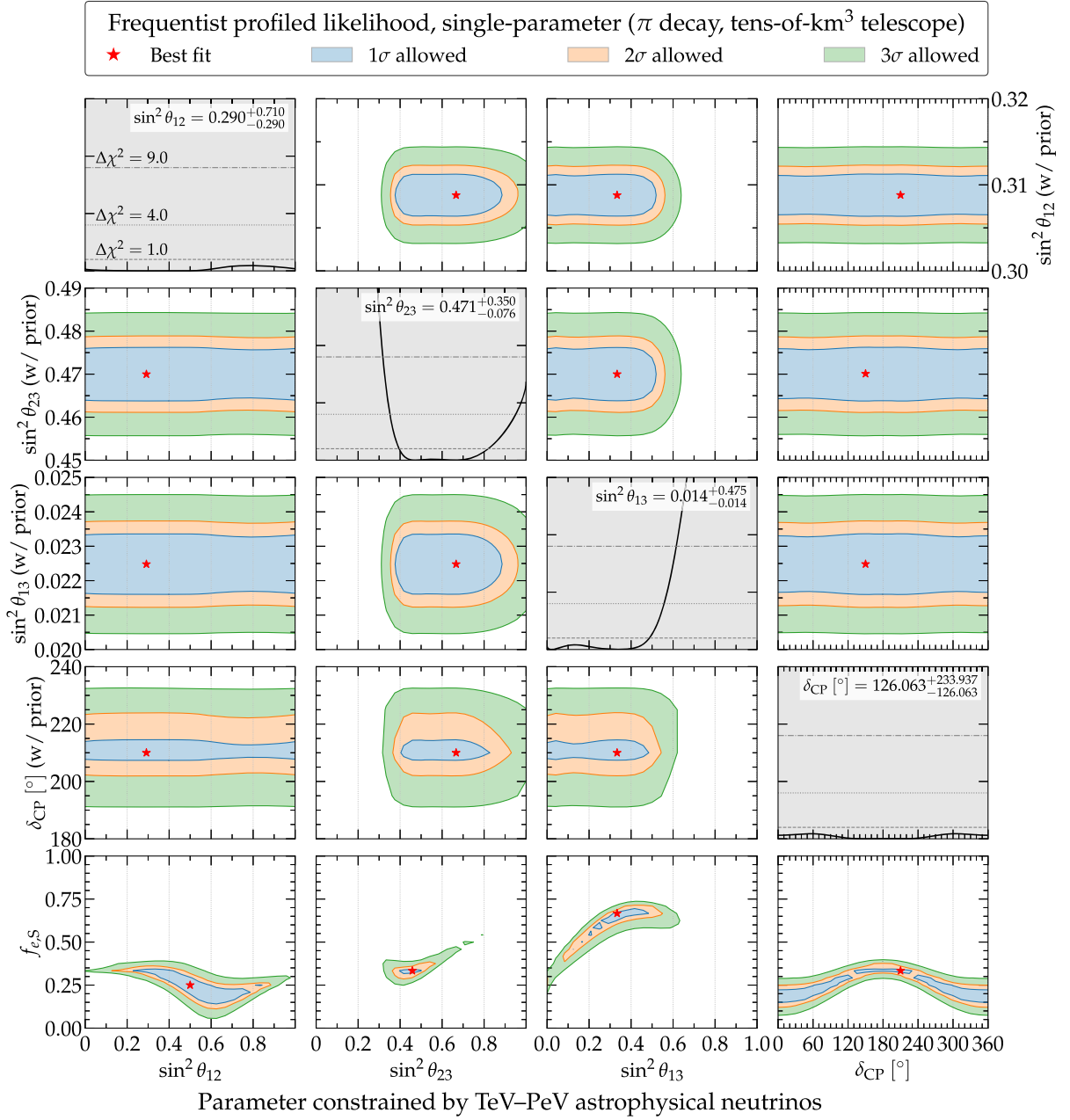


FIG. 6. Future pairwise frequentist profiled likelihood, adding a tens-of-km³ detector (2050). Same as Fig. 5, but the flavor-measurement likelihood uses the combined exposure of IceCube, Baikal-GVD, KM3NeT, P-ONE, IceCube-Gen2, and HUNT to the year 2050, assuming neutrino production via full pion decay and $f_{\tau,S} = 0$. See Appendix A for detector details.

V. IMPLICATIONS, INCLUDING FOR BSM PHYSICS

Astrophysical-neutrino telescopes will never surpass the subpercent precision of terrestrial reactor and accelerator experiments [3]. As our farthest projections show (Fig. 4), future astrophysical constraints will reach tens-of-percent precision. However, the value of mixing-angle language is not competitive precision, but comparability.

First, expressing constraints as mixing angles directly tests whether the *same* mixing parameters describing sub-MeV-GeV oscillations also describe Mpc-Gpc-baseline, TeV-PeV ones. This is a much sharper test than simply stating “the flavor ratios are consistent with $(1:1:1)_\oplus$,” since many BSM scenarios—and even mundane source uncertainties—can mimic near-democratic flavor ratios without preserving the underlying mixing matrix. While the flavor triangle (Fig. 2) remains the appropriate representation of the raw measurement, the mixing-parameter extraction (Fig. 4, Table I) is its physics-motivated interpretation.

Second, BSM effects that modify mixing are typically computed as shifts, $\Delta\theta_{ij}$ or $\Delta\delta_{CP}$ [92–95]. By reporting our sensitivity in these terms, our allowed intervals establish immediately usable benchmarks for detecting BSM neutrino physics at TeV energies. At present, no size of modification is detectable. Future multitelescope observations will be sensitive to modifications of 15° – 20° for θ_{23} and θ_{13} , and to comparably sized shifts in $\cos\delta_{CP}$ under muon-damped production—applicable to scenarios that shift the CP -conserving mixing structure (e.g., new mixing with a sterile or dark sector).

By the close of the coming decade, this will constrain scenarios positing large changes to neutrino mixing, including Lorentz-invariance violation [40,92,93], active-sterile mixing [94,96], and new interactions [95,97,98]. The unique value of TeV-PeV mixing measurements is sensitivity to BSM effects that grow with energy, undetectable at lower energies. Beyond 100 PeV, such effects may become prominent, detectable via flavor measurements in ultrahigh-energy detectors [99–101].

VI. SUMMARY AND OUTLOOK

TeV-PeV astrophysical neutrinos provide the only empirical window into neutrino mixing above 1 TeV. We have demonstrated how to translate flavor-composition measurements into constraints on the mixing parameters—so far inferred only from sub-TeV neutrinos—quantifying realistic prospects using present data and multitelescope projections.

Present IceCube data leave the parameters unconstrained—not for lack of statistics, but because of a θ_{12} – $f_{e,S}$ degeneracy that no increase in exposure alone

can break. However, multitelescope observations by 2040 will resolve θ_{23} and θ_{13} to within tens of degrees. While coarser than sub-TeV global fits by orders of magnitude, these measurements place the three-flavor paradigm on a quantitative footing at high energies, and establish rigorous BSM-sensitivity benchmarks that account for astrophysical unknowns.

Realizing these projections relies on two experimental advances: increased statistics and improved flavor reconstruction. Unlocking θ_{12} demands a distinct advance: better astrophysical source characterization. Together, they will transform high-energy astrophysical neutrinos into robust probes of mixing beyond terrestrial reach.

This work used the Tycho supercomputer hosted at the SCIENCE High Performance Computing Center at the University of Copenhagen, and equipment funded by the Canada Foundation for Innovation and the Province of Ontario, and housed at the Queen’s Centre for Advanced Computing.

ACKNOWLEDGMENTS

The authors are grateful for the contribution of Bernanda Telalovic in the early stages of this work and for the feedback of Subir Sarkar on the manuscript. M.B. is supported by Villum Fonden under Project No. 29388. Q.L. is supported by CFREF and NSERC of Canada through the Arthur B. McDonald Canadian Astroparticle Physics Research Institute. Research at Perimeter Institute is supported by the Government of Canada through the Department of Innovation, Science, and Economic Development, and by the Province of Ontario. G.B. is supported by the Spanish Grants No. CIPROM/2021/054 (Generalitat Valenciana), No. PID2023-151418NB-I00 funded by MCIU/AEI/10.13039/501100011033/, and by the European ITN Project HIDEeN (No. H2020-MSCA-ITN-2019/860881-HIDEeN).

DATA AVAILABILITY

The data that support the findings of this article are not publicly available. The data are available from the authors upon reasonable request.

APPENDIX A: FORECAST FLAVOR-COMPOSITION LIKELIHOODS

Figure 7 shows the forecast flavor-composition likelihoods for the three projected observation eras defined in Sec. III A, for each of the two neutrino-production scenarios that we consider. These likelihoods are the input to the projected constraints reported in Sec. IV B and Appendix B.

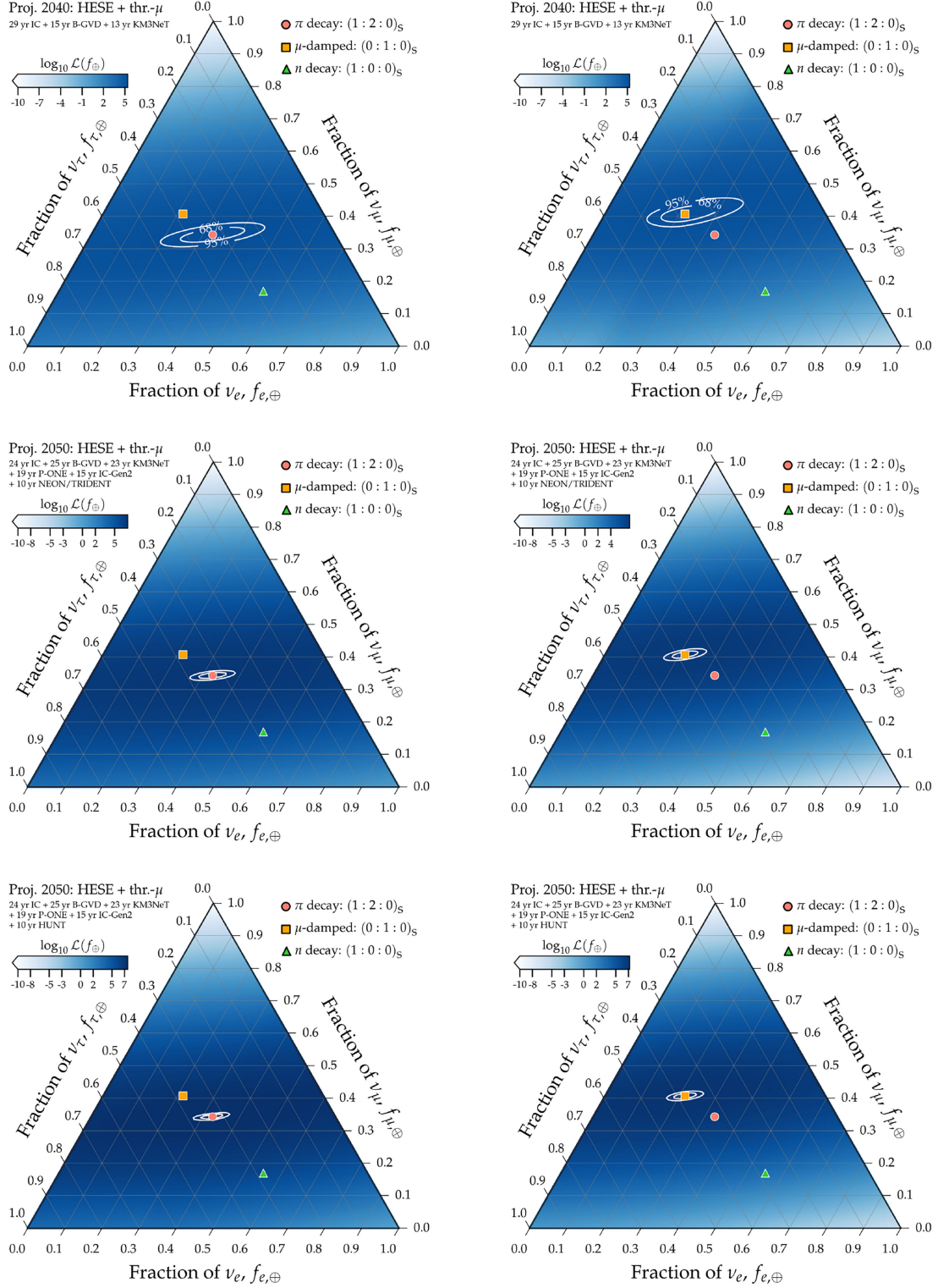


FIG. 7. Forecasts of experimental likelihood of flavor-composition measurements. Same as Fig. 3, but for forecasts using HESE plus through-going muons and assuming (left column) neutrino production via pion decay, i.e., $(\frac{1}{3}, \frac{2}{3}, 0)_S$, and (right column) via muon-damped pion decay, i.e., $(0, 1, 0)_S$. Top row: Using combined observations by multiple existing neutrino telescopes with km³ size. Center row: Combination of existing and future neutrino telescopes, including telescopes of 8 km³. Bottom row: Combination including one telescope with tens of km³.

APPENDIX B: DETAILED RESULTS

This appendix presents comprehensive numerical results and joint parameter distributions for our frequentist analysis, expanding on the condensed results shown in Sec. IV.

Table II shows detailed numerical results for the constraints on the mixing parameters, expanding on Table I. Table II reveals an important prospect: achieving a measurement error of 10% or better will require combining

measurements by existing km³-scale neutrino telescopes and upcoming multi-km³ ones.

Figure 8 shows that the parameter constraints obtained allowing for ν_τ production at the sources are not significantly weaker than our main ones, obtained assuming $f_{\tau,S} = 0$. This is to be expected, since the allowed region of flavor composition at Earth grows only slightly when allowing for $f_{\tau,S} \neq 0$ [40].

TABLE II. Frequentist sensitivity to neutrino mixing parameters from high-energy astrophysical neutrinos. Expanded version of Table I. All results shown are obtained by constraining one parameter at a time while keeping the others controlled via pull terms informed by present (NuFIT 6.1 [3]) and future [49] sub-TeV global oscillation fits. We assume no ν_τ production (i.e., $f_{\tau,S} = 0$). Figures 5 and 6 show joint parameter distributions. The values are stacked: for each parameter, the top line shows the best fit $\pm 1\sigma$, and the bottom line (in brackets) shows the 3σ range, profiled over all the other parameters. See Sec. III for details.

Parameter	Present (IceCube MESE 11.4 yr)	Future (multidetector projections using HESE plus through-going muons)						Global ($< \text{TeV}$) NuFIT 6.1
		Only km ³ -scale telescopes ^a		Plus multi-km ³ telescopes ^b		Plus tens-of-km ³ telescopes ^c		
		π decay	μ -damped	π decay	μ -damped	π decay	μ -damped	
$\sin^2 \theta_{12}$	$0.000^{+1.000}_{-0.000}$ [0.000, 1.000]	$0.291^{+0.709}_{-0.291}$ [0.000, 1.000]	$0.224^{+0.128}_{-0.224}$ [0.000, 1.000]	$0.279^{+0.721}_{-0.279}$ [0.000, 1.000]	$0.224^{+0.104}_{-0.224}$ [0.000, 1.000]	$0.290^{+0.710}_{-0.290}$ [0.000, 1.000]	$0.224^{+0.102}_{-0.224}$ [0.000, 1.000]	$0.303^{+0.012}_{-0.012}$ [0.270, 0.341]
$\theta_{12} [^\circ]$	$0.00^{+90.00}_{-0.00}$ [0.00, 90.00]	$32.66^{+57.34}_{-32.66}$ [0.00, 90.00]	$28.26^{+8.13}_{-28.26}$ [0.00, 90.00]	$31.86^{+58.14}_{-31.86}$ [0.00, 90.00]	$28.26^{+6.68}_{-28.26}$ [0.00, 90.00]	$32.59^{+57.41}_{-32.59}$ [0.00, 90.00]	$28.26^{+6.57}_{-28.26}$ [0.00, 90.00]	$33.40^{+0.74}_{-0.75}$ [31.31, 35.73]
$\sin^2 \theta_{23}$	$0.382^{+0.618}_{-0.242}$ [0.000, 1.000]	$0.470^{+0.530}_{-0.153}$ [0.166, 1.000]	$0.470^{+0.293}_{-0.065}$ [0.139, 1.000]	$0.471^{+0.391}_{-0.088}$ [0.295, 1.000]	$0.470^{+0.144}_{-0.025}$ [0.354, 0.801]	$0.471^{+0.350}_{-0.076}$ [0.318, 1.000]	$0.470^{+0.127}_{-0.022}$ [0.374, 0.758]	$0.451^{+0.019}_{-0.016}$ [0.408, 0.603]
$\theta_{23} [^\circ]$	$38.16^{+51.84}_{-16.19}$ [0.00, 90.00]	$43.26^{+46.74}_{-8.99}$ [24.06, 90.00]	$43.29^{+17.60}_{-3.74}$ [21.91, 90.00]	$43.32^{+24.89}_{-5.13}$ [32.89, 90.00]	$43.29^{+8.29}_{-1.43}$ [36.54, 63.50]	$43.32^{+21.61}_{-4.38}$ [34.31, 90.00]	$43.29^{+7.33}_{-1.28}$ [37.70, 60.51]	$42.19^{+1.09}_{-0.92}$ [39.70, 50.94]
$\sin^2 \theta_{13}$	$0.000^{+0.714}_{-0.000}$ [0.000, 1.000]	$0.013^{+0.602}_{-0.013}$ [0.000, 0.899]	$0.023^{+0.134}_{-0.019}$ [0.000, 0.866]	$0.014^{+0.499}_{-0.014}$ [0.000, 0.664]	$0.023^{+0.037}_{-0.011}$ [0.001, 0.203]	$0.014^{+0.475}_{-0.014}$ [0.000, 0.616]	$0.023^{+0.030}_{-0.009}$ [0.002, 0.156]	$0.02248^{+0.00055}_{-0.00059}$ [0.02064, 0.02418]
$\theta_{13} [^\circ]$	$0.00^{+57.66}_{-0.00}$ [0.00, 90.00]	$6.55^{+45.08}_{-6.55}$ [0.00, 71.52]	$8.63^{+14.71}_{-5.19}$ [0.00, 68.53]	$6.67^{+39.05}_{-6.67}$ [0.00, 54.58]	$8.63^{+5.45}_{-2.37}$ [1.81, 26.74]	$6.67^{+37.64}_{-6.67}$ [0.00, 51.69]	$8.63^{+4.57}_{-2.06}$ [2.69, 23.30]	$8.54^{+0.11}_{-0.12}$ [8.19, 8.90]
$\delta_{\text{CP}} [^\circ]$	164^{+196}_{-164} [0, 360]	132^{+228}_{-132} [0, 360]	148^{+93}_{-28} [57, 303]	147^{+213}_{-147} [0, 360]	148^{+77}_{-14} [111, 249]	147^{+213}_{-147} [0, 360]	148^{+76}_{-12} [116, 244]	232^{+36}_{-26} [133, 368]
f_{eS}	$0.043^{+0.492}_{-0.043}$ [0.000, 1.000]	$0.334^{+0.053}_{-0.053}$ [0.174, 0.491]	$0.000^{+0.061}_{-0.000}$ [0.000, 0.185]	$0.334^{+0.026}_{-0.026}$ [0.256, 0.409]	$0.000^{+0.028}_{-0.000}$ [0.000, 0.084]	$0.334^{+0.019}_{-0.020}$ [0.273, 0.389]	$0.000^{+0.026}_{-0.000}$ [0.000, 0.076]	$\dots$ $\dots$

^aProjections for 2040 using 29 yr of IceCube + 15 yr of Baikal-GVD + 13 yr of KM3NeT.

^bProjections for 2050 using 24 yr of IceCube + 25 yr of Baikal-GVD + 23 yr of KM3NeT + 19 yr of P-ONE + 15 yr of IceCube-Gen2 + 10 yr of NEON or TRIDENT.

^cProjections for 2050 using 24 yr of IceCube + 25 yr of Baikal-GVD + 23 yr of KM3NeT + 19 yr of P-ONE + 15 yr of IceCube-Gen2 + 10 yr of HUNT.

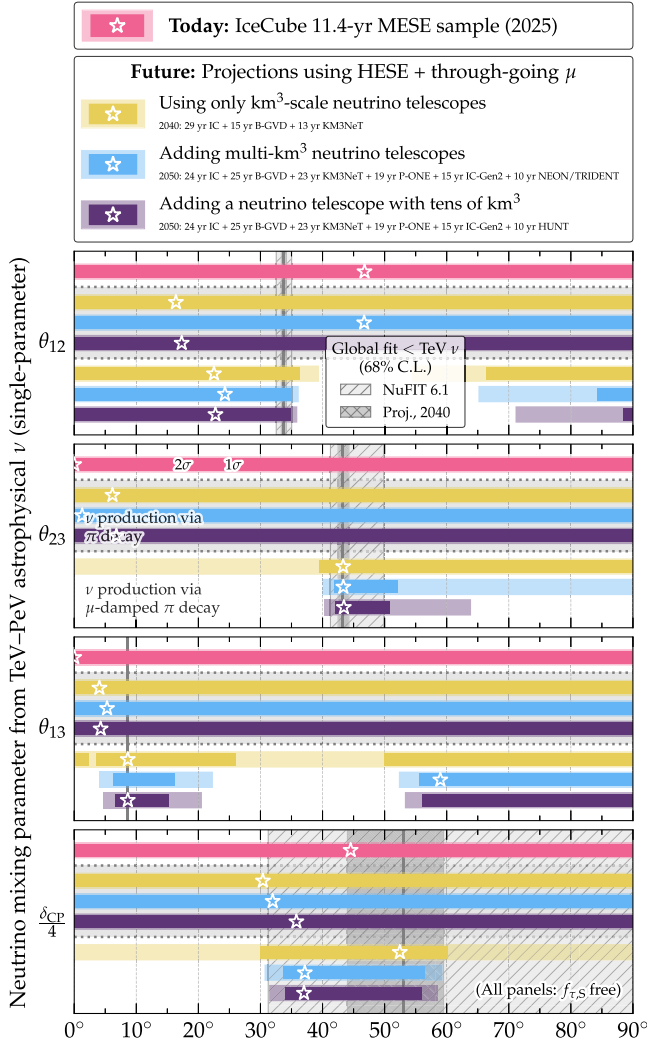


FIG. 8. Prospects for constraining neutrino mixing parameters with high-energy astrophysical neutrinos. Same as Fig. 4, but allowing for ν_τ production at the astrophysical sources, i.e., allowing $f_{\tau,S}$ to vary between 0 and 1. The results do not change significantly compared to our main results obtained with $f_{\tau,S} = 0$.

APPENDIX C: BAYESIAN RESULTS

This appendix presents complementary Bayesian constraints on the neutrino mixing parameters, providing an alternative statistical perspective to the frequentist analysis shown in Sec. IV and Appendix B.

We compute Bayesian posterior probability densities to assess the sensitivity to mixing parameters, $\theta = (\theta_{12}, \theta_{23}, \theta_{13}, \delta_{CP})$, i.e.,

$$\mathcal{P}(\theta, f_{e,S}) = \pi(\theta) \pi(f_{e,S}) \mathcal{L}[f_{e,S}(\theta), f_{\mu,S}(f_{e,S}, \theta)], \quad (C1)$$

where $\pi(\theta)$ is the prior probability distribution on the mixing parameters, $\pi(f_{e,S})$ is uniform in $[0, 1]$, and $\mathcal{L}$ is the likelihood of flavor-composition measurements, present or future, as in the frequentist approach. We assume no ν_τ production (i.e., $f_{\tau,S} = 0$).

We produce Bayesian results under two approaches. First, we follow the same approach as in the frequentist analysis and measure a single parameter at a time while marginalizing over all the other parameters, using for them tight sub-TeV NuFIT 6.1 or projected priors. Second, separately, we measure all of the mixing parameters and $f_{e,S}$ simultaneously, using uninformed priors for all of them. When measuring $\sin^2(\theta_{ij})$, we use for it a uniform prior in $[0, 1]$; when measuring δ_{CP} , we use for it a uniform prior in $[0, 2\pi]$.

Table III and Fig. 9 show our Bayesian results. Present constraints from the 11.4-year IceCube MESE sample [27] show wide posteriors spanning most of the allowed range, indicating insufficient constraining power. Future multi-telescope projections show improved sensitivity, particularly for θ_{23} , as in the frequentist case.

Broadly stated, the frequentist and Bayesian results agree. Yet, there are important differences that make us select the former as our main results, as we explain next.

The frequentist constraints are more conservative than the baseline Bayesian ones. This is clearest when comparing present-day results between Tables II and III. While 1σ frequentist constraints span the entire allowed physical range of most parameters, representing a complete lack of sensitivity, the 68% C.L. Bayesian constraints are narrower, representing nascent sensitivity.

However, this is deceptive, and merely an artifact of our choice of priors. This is conveyed by the fact that in Table III the best-fit values (i.e., the median) for $\sin^2 \theta_{12}$, $\sin^2 \theta_{23}$, and δ_{CP} are merely the mid-points of their uniform priors, i.e., 0.5 for the mixing angles and 180° for δ_{CP} . (There is marginally more sensitivity to $\sin^2 \theta_{13}$.) In turn, this is a reflection of the large errors in the present-day flavor-composition measurements from the 11.4-year IceCube MESE sample. Using different priors on the parameters, e.g., log-uniform ones that can more efficiently sample their lowest allowed values, widens their posteriors and washes away any present Bayesian sensitivity.

This contrast between the frequentist and Bayesian approaches is mitigated in our forecasts. In them, their constraints become more alike as a result of the improved flavor-composition measurements, reducing the impact of our choice of priors on the Bayesian posteriors. This justifies why, to be conservative in our claims and consistent between our present and projected results, we choose to show frequentist constraints rather than Bayesian ones as our main results. In the future, once flavor-composition measurements improve, the choice between these approaches will become less impactful.

TABLE III. Bayesian sensitivity to neutrino mixing parameters from high-energy astrophysical neutrinos. Similar to Table II, but obtained using the Bayesian prescription and priors described in Appendix C. We assume no ν_τ production (i.e., $f_{\tau,S} = 0$). The values are stacked: for each parameter, the top line shows the best fit (“BF”) $\pm 68\%$ C.L., and the bottom line (in brackets) shows the 95% C.L. range. Best-fit values are the medians of the one-dimensional parameter posteriors. The Bayes factor, $\mathcal{B}$, represents the strength of the evidence in favor of three-flavor mixing.

Parameter	Conservative: All mixing parameters free (BF $\pm 68\%$ C.L. / [95% C.L.])			Aggressive: Single-parameter constraints (BF $\pm 68\%$ C.L. / [95% C.L.])			Global (< TeV) NuFIT 6.1 (B.f. $\pm 68\%$ C.L. /[3 σ])
	Present ($\mathcal{B} \approx 16$)	Future ^a ($\mathcal{B} \sim 10^{56}, 10^{61}$)		Present	Future ^a		
		π decay	μ -damped		π decay	μ -damped	
$\sin^2 \theta_{12}$	0.503 ^{+0.304} _{-0.312} [0.033, 0.970]	0.498 ^{+0.284} _{-0.283} [0.037, 0.962]	0.506 ^{+0.397} _{-0.405} [0.013, 0.986]	0.507 ^{+0.279} _{-0.278} [0.043, 0.957]	0.531 ^{+0.210} _{-0.243} [0.071, 0.935]	0.209 ^{+0.088} _{-0.123} [0.018, 0.976]	0.303 ^{+0.012} _{-0.012} [0.270, 0.341]
$\theta_{12} [^\circ]$	45.18 ^{+18.77} _{-19.26} [10.47, 80.03]	44.89 ^{+17.28} _{-17.26} [11.09, 78.76]	45.34 ^{+26.51} _{-26.81} [6.55, 83.20]	45.40 ^{+17.04} _{-16.81} [11.97, 78.03]	46.78 ^{+12.63} _{-14.32} [15.45, 75.23]	27.20 ^{+5.82} _{-10.15} [7.71, 81.09]	33.40 ^{+0.74} _{-0.75} [31.63, 35.95]
$\sin^2 \theta_{23}$	0.509 ^{+0.313} _{-0.326} [0.031, 0.971]	0.497 ^{+0.220} _{-0.224} [0.049, 0.923]	0.452 ^{+0.203} _{-0.230} [0.044, 0.920]	0.454 ^{+0.304} _{-0.255} [0.053, 0.954]	0.541 ^{+0.172} _{-0.113} [0.370, 0.863]	0.535 ^{+0.067} _{-0.049} [0.451, 0.670]	0.451 ^{+0.019} _{-0.016} [0.435, 0.585]
$\theta_{23} [^\circ]$	45.52 ^{+19.53} _{-20.19} [10.14, 80.20]	44.83 ^{+13.03} _{-13.33} [12.79, 73.89]	42.25 ^{+11.78} _{-14.14} [12.11, 73.57]	42.36 ^{+18.17} _{-15.87} [13.31, 77.62]	47.35 ^{+10.26} _{-6.49} [37.47, 68.28]	47.01 ^{+3.88} _{-2.81} [42.19, 54.94]	42.19 ^{+1.09} _{-0.92} [39.70, 50.94]
$\sin^2 \theta_{13}$	0.427 ^{+0.296} _{-0.256} [0.021, 0.932]	0.390 ^{+0.253} _{-0.193} [0.037, 0.888]	0.761 ^{+0.151} _{-0.638} [0.015, 0.983]	0.389 ^{+0.293} _{-0.250} [0.025, 0.915]	0.247 ^{+0.167} _{-0.172} [0.011, 0.513]	0.047 ^{+0.033} _{-0.020} [0.015, 0.128]	0.02248 ^{+0.00055} _{-0.00059} [0.02064, 0.02418]
$\theta_{13} [^\circ]$	40.80 ^{+17.44} _{-16.38} [8.33, 74.88]	38.65 ^{+14.66} _{-12.30} [11.09, 70.45]	60.73 ^{+12.01} _{-40.20} [7.03, 82.51]	38.59 ^{+17.09} _{-16.70} [9.10, 73.05]	29.80 ^{+10.25} _{-13.91} [6.02, 45.74]	12.52 ^{+3.91} _{-3.06} [7.03, 20.96]	8.62 ^{+0.11} _{-0.11} [8.26, 8.95]
$\delta_{\text{CP}} [^\circ]$	185.34 ^{+114.63} _{-124.13} [9.79, 350.07]	182.66 ^{+104.12} _{-110.08} [18.79, 343.44]	178.01 ^{+111.13} _{-106.16} [15.39, 344.01]	179.15 ^{+122.81} _{-120.30} [10.22, 350.84]	179.15 ^{+131.38} _{-131.21} [6.98, 352.43]	180.16 ^{+25.27} _{-24.93} [138.05, 222.47]	212 ⁺²⁶ ₋₃₆ [125, 365]
f_{eS}	0.446 ^{+0.304} _{-0.265} [0.039, 0.951]	0.382 ^{+0.298} _{-0.215} [0.028, 0.920]	0.143 ^{+0.063} _{-0.091} [0.010, 0.250]	0.339 ^{+0.293} _{-0.214} [0.024, 0.886]	0.332 ^{+0.019} _{-0.020} [0.293, 0.368]	0.017 ^{+0.019} _{-0.012} [0.001, 0.056]	$\dots$ $\dots$

^aMultidetector projections of HESE plus through-going muons using 24 yr of IceCube + 25 yr of Baikal-GVD + 23 yr of KM3NeT + 19 yr of P-ONE + 15 yr of IceCube-Gen2 + 10 yr of HUNT.

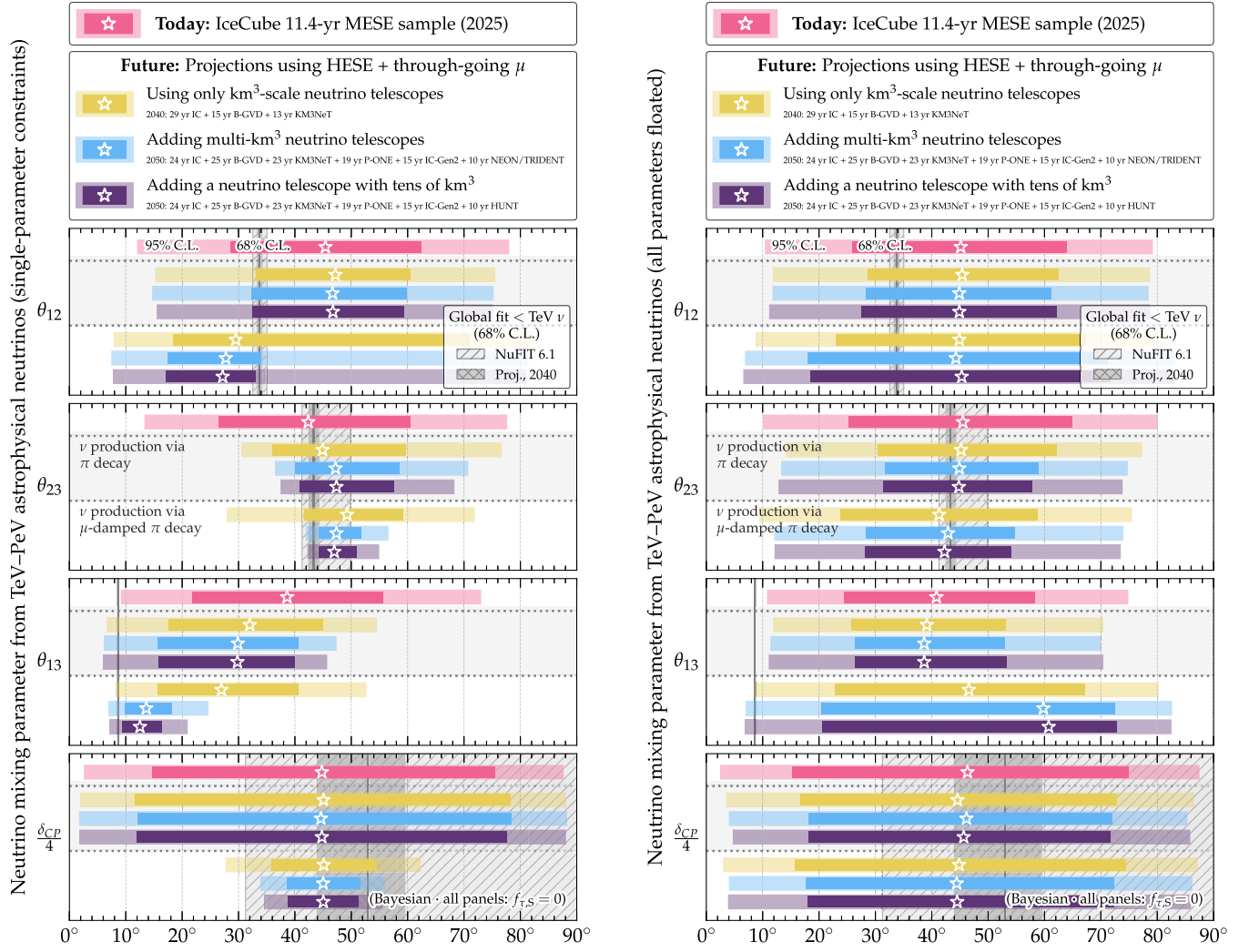


FIG. 9. Bayesian prospects for constraining neutrino mixing parameters with high-energy astrophysical neutrinos. Similar to Fig. 4, but with intervals obtained via a Bayesian analysis instead of the frequentist analysis of our main results. Results are obtained by constraining a single parameter at a time (left panel), as in the main text, and all of them simultaneously (right panel).

- [1] P. F. de Salas, D. V. Forero, S. Gariazzo, P. Martínez-Miravé, O. Mena, C. A. Ternes, M. Tórtola, and J. W. F. Valle, 2020 global reassessment of the neutrino oscillation picture, *J. High Energy Phys.* **02** (2021) 071.
- [2] F. Capozzi, E. Di Valentino, E. Lisi, A. Marrone, A. Melchiorri, and A. Palazzo, Unfinished fabric of the three neutrino paradigm, *Phys. Rev. D* **104**, 083031 (2021).
- [3] I. Esteban, M. C. González-García, M. Maltoni, I. Martínez-Soler, J. P. Pinheiro, and T. Schwetz, NuFit-6.0: Updated global analysis of three-flavor neutrino oscillations, *J. High Energy Phys.* **12** (2025) 216.
- [4] S. Navas *et al.* (Particle Data Group), Review of particle physics, *Phys. Rev. D* **110**, 030001 (2024).
- [5] C. K. Jung, C. McGrew, T. Kajita, and T. Mann, Oscillations of atmospheric neutrinos, *Annu. Rev. Nucl. Part. Sci.* **51**, 451 (2001).
- [6] T. Kajita, The measurement of neutrino properties with atmospheric neutrinos, *Annu. Rev. Nucl. Part. Sci.* **64**, 343 (2014).
- [7] M. G. Aartsen *et al.* (IceCube Collaboration), Evidence for high-energy extraterrestrial neutrinos at the IceCube detector, *Science* **342**, 1242856 (2013).

- [8] J. F. Beacom, N. F. Bell, D. Hooper, S. Pakvasa, and T. J. Weiler, Sensitivity to θ_{13} and δ in the decaying astrophysical neutrino scenario, *Phys. Rev. D* **69**, 017303 (2004).
- [9] P. Bhattacharjee and N. Gupta, Probing neutrino mixing angles with ultrahigh energy neutrino telescopes, [arXiv:hep-ph/0501191](#).
- [10] P. D. Serpico and M. Kachelriess, Measuring the 13-mixing angle and the CP phase with neutrino telescopes, *Phys. Rev. Lett.* **94**, 211102 (2005).
- [11] P. D. Serpico, Probing the 2-3 leptonic mixing at high-energy neutrino telescopes, *Phys. Rev. D* **73**, 047301 (2006).
- [12] K. R. S. Balaji, G. Couture, and C. Hamzaoui, Canonical constraints on leptonic CP violation using UHCR neutrino fluxes, *Phys. Rev. D* **74**, 033013 (2006).
- [13] Z.-z. Xing, Neutrino telescopes as a probe of broken $\mu - \tau$ symmetry, *Phys. Rev. D* **74**, 013009 (2006).
- [14] D. Meloni and T. Ohlsson, Neutrino flux ratios at neutrino telescopes: The role of uncertainties of neutrino mixing parameters and applications to neutrino decay, *Phys. Rev. D* **75**, 125017 (2007).
- [15] W. Winter, How astrophysical neutrino sources could be used for early measurements of neutrino mass hierarchy and leptonic CP phase, *Phys. Rev. D* **74**, 033015 (2006).
- [16] W. Rodejohann, Neutrino mixing and neutrino telescopes, *J. Cosmol. Astropart. Phys.* **01** (2007) 029.
- [17] K. Blum, Y. Nir, and E. Waxman, Probing CP violation in neutrino oscillations with neutrino telescopes, [arXiv:0706.2070](#).
- [18] G.-R. Hwang and K. Siyeon, Conflict between the identification of cosmic neutrino source and the sensitivity to mixing angles in neutrino telescope, *Phys. Rev. D* **78**, 093008 (2008).
- [19] S. Pakvasa, W. Rodejohann, and T. J. Weiler, Flavor ratios of astrophysical neutrinos: Implications for precision measurements, *J. High Energy Phys.* **02** (2007) 005.
- [20] S. Choubey, V. Niro, and W. Rodejohann, On probing θ_{23} in neutrino telescopes, *Phys. Rev. D* **77**, 113006 (2008).
- [21] M. Maltoni and W. Winter, Testing neutrino oscillations plus decay with neutrino telescopes, *J. High Energy Phys.* **07** (2008) 064.
- [22] Z.-z. Xing and S. Zhou, Implications of leptonic unitarity violation at neutrino telescopes, *Phys. Lett. B* **666**, 166 (2008).
- [23] A. Esmaili and Y. Farzan, An analysis of cosmic neutrinos: Flavor composition at source and neutrino mixing parameters, *Nucl. Phys.* **B821**, 197 (2009).
- [24] D. Meloni and T. Ohlsson, Leptonic CP violation and mixing patterns at neutrino telescopes, *Phys. Rev. D* **86**, 067701 (2012).
- [25] K.-C. Lai, G.-L. Lin, and T.-C. Liu, Probing neutrino flavor transition mechanism with ultrahigh energy astrophysical neutrinos, *Phys. Rev. D* **89**, 033002 (2014).
- [26] A. Chatterjee, M. M. Devi, M. Ghosh, R. Moharana, and S. K. Raut, Probing CP violation with the first three years of ultrahigh energy neutrinos from IceCube, *Phys. Rev. D* **90**, 073003 (2014).
- [27] R. Abbasi *et al.* (IceCube Collaboration), Characterization of the three-flavor composition of cosmic neutrinos with IceCube, *Phys. Rev. Lett.* **137**, 081002 (2026).
- [28] S. H. Margolis, D. N. Schramm, and R. Silberberg, Ultra-high-energy neutrino astronomy, *Astrophys. J.* **221**, 990 (1978).
- [29] F. W. Stecker, Diffuse fluxes of cosmic high-energy neutrinos, *Astrophys. J.* **228**, 919 (1979).
- [30] S. R. Kelner, F. A. Aharonian, and V. V. Bugayov, Energy spectra of gamma-rays, electrons and neutrinos produced at proton-proton interactions in the very high energy regime, *Phys. Rev. D* **74**, 034018 (2006); *Phys. Rev. D* **79**, 039901(E) (2009).
- [31] A. Mücke, R. Engel, J. P. Rachen, R. J. Protheroe, and T. Stanev, SOPHIA: Monte Carlo simulations of photohadronic processes in astrophysics, *Comput. Phys. Commun.* **124**, 290 (2000).
- [32] S. R. Kelner and F. A. Aharonian, Energy spectra of gamma-rays, electrons and neutrinos produced at interactions of relativistic protons with low energy radiation, *Phys. Rev. D* **78**, 034013 (2008); *Phys. Rev. D* **82**, 099901(E) (2010).
- [33] S. Hümmer, M. Ruger, F. Spanier, and W. Winter, Simplified models for photohadronic interactions in cosmic accelerators, *Astrophys. J.* **721**, 630 (2010).
- [34] O. Mena, I. Mocioiu, and S. Razzaque, Oscillation effects on high-energy neutrino fluxes from astrophysical hidden sources, *Phys. Rev. D* **75**, 063003 (2007).
- [35] S. Razzaque and A. Y. Smimov, Flavor conversion of cosmic neutrinos from hidden jets, *J. High Energy Phys.* **03** (2010) 031.
- [36] S. Sahu and B. Zhang, Effect of resonant neutrino oscillation on TeV neutrino flavor ratio from choked GRBs, *Res. Astron. Astrophys.* **10**, 943 (2010).
- [37] K. Varela, S. Sahu, A. F. Osorio Oliveros, and J. C. Sanabria, High energy neutrinos from choked GRBs and their flavor ratio measurement by the IceCube, *Eur. Phys. J. C* **75**, 289 (2015).
- [38] D. Xiao and Z. G. Dai, TeV-PeV Neutrino oscillation of low-luminosity gamma-ray bursts, *Astrophys. J.* **805**, 137 (2015).
- [39] P. S. B. Dev, S. Jana, and Y. Porto, Matter effects on flavor composition of astrophysical neutrinos, *Phys. Rev. D* **112**, 093003 (2025).
- [40] M. Bustamante, J. F. Beacom, and W. Winter, Theoretically palatable flavor combinations of astrophysical neutrinos, *Phys. Rev. Lett.* **115**, 161302 (2015).
- [41] T. Kashti and E. Waxman, Flavoring astrophysical neutrinos: Flavor ratios depend on energy, *Phys. Rev. Lett.* **95**, 181101 (2005).
- [42] P. Lipari, M. Lusiignoli, and D. Meloni, Flavor composition and energy spectrum of astrophysical neutrinos, *Phys. Rev. D* **75**, 123005 (2007).
- [43] Q. Liu, D. F. G. Fiorillo, C. A. Argüelles, M. Bustamante, N. Song, and A. C. Vincent, Identifying energy-dependent flavor transitions in high-energy astrophysical neutrino measurements, *Phys. Rev. D* **112**, 043019 (2025).
- [44] B. Telalovic and M. Bustamante, Flavor anisotropy in the high-energy astrophysical neutrino sky, *J. Cosmol. Astropart. Phys.* **05** (2025) 013.
- [45] B. Telalovic and M. Bustamante, No flavor anisotropy in the high-energy neutrino sky upholds Lorentz invariance, *J. High Energy Phys.* **02** (2026) 024.

- [46] H. Athar, C. S. Kim, and J. Lee, The Intrinsic and oscillated astrophysical neutrino flavor ratios, *Mod. Phys. Lett. A* **21**, 1049 (2006).
- [47] Y. Farzan, On the τ flavor of the cosmic neutrino flux, *J. High Energy Phys.* **07** (2021) 174.
- [48] M. Bustamante and M. Ahlers, Inferring the flavor of high-energy astrophysical neutrinos at their sources, *Phys. Rev. Lett.* **122**, 241101 (2019).
- [49] N. Song, S. W. Li, C. A. Argüelles, M. Bustamante, and A. C. Vincent, The future of high-energy astrophysical neutrino flavor measurements, *J. Cosmol. Astropart. Phys.* **04** (2021) 054.
- [50] M. Bustamante, A. M. Gago, and J. Jones Perez, SUSY renormalization group effects in ultra high energy neutrinos, *J. High Energy Phys.* **05** (2011) 133.
- [51] S. R. Mir, C. A. Argüelles, K. S. Babu, and V. Brdar, Double bangs at IceCube as a window to the neutrino mass origin, *Phys. Lett. B* **875**, 140322 (2026).
- [52] M. Bustamante, Q. Liu, and G. Barenboim, Astrophysical bounds on the high-energy evolution of neutrino mixing, [arXiv:2604.14409](https://arxiv.org/abs/2604.14409).
- [53] M. Ahlers, M. Bustamante, and S. Mu, Unitarity bounds of astrophysical neutrinos, *Phys. Rev. D* **98**, 123023 (2018).
- [54] J. G. Learned and S. Pakvasa, Detecting ν_τ oscillations at PeV energies, *Astropart. Phys.* **3**, 267 (1995).
- [55] S. L. Glashow, Resonant scattering of antineutrinos, *Phys. Rev.* **118**, 316 (1960).
- [56] M. G. Aartsen *et al.* (IceCube Collaboration), Detection of a particle shower at the Glashow resonance with IceCube, *Nature (London)* **591**, 220 (2021); *Nature (London)* **592**, E11(E) (2021).
- [57] O. Mena, S. Palomares-Ruiz, and A. C. Vincent, Flavor composition of the high-energy neutrino events in IceCube, *Phys. Rev. Lett.* **113**, 091103 (2014).
- [58] S. Palomares-Ruiz, A. C. Vincent, and O. Mena, Spectral analysis of the high-energy IceCube neutrinos, *Phys. Rev. D* **91**, 103008 (2015).
- [59] A. Palladino, G. Pagliaroli, F. L. Villante, and F. Vissani, What is the flavor of the cosmic neutrinos seen by IceCube?, *Phys. Rev. Lett.* **114**, 171101 (2015).
- [60] M. G. Aartsen *et al.* (IceCube Collaboration), Flavor ratio of astrophysical neutrinos above 35 TeV in IceCube, *Phys. Rev. Lett.* **114**, 171102 (2015).
- [61] M. G. Aartsen *et al.* (IceCube Collaboration), A combined maximum-likelihood analysis of the high-energy astrophysical neutrino flux measured with IceCube, *Astrophys. J.* **809**, 98 (2015).
- [62] A. C. Vincent, S. Palomares-Ruiz, and O. Mena, Analysis of the 4-year IceCube high-energy starting events, *Phys. Rev. D* **94**, 023009 (2016).
- [63] M. G. Aartsen *et al.* (IceCube Collaboration), Measurements using the inelasticity distribution of multi-TeV neutrino interactions in IceCube, *Phys. Rev. D* **99**, 032004 (2019).
- [64] R. Abbasi *et al.* (IceCube Collaboration), Detection of astrophysical tau neutrino candidates in IceCube, *Eur. Phys. J. C* **82**, 1031 (2022).
- [65] N. Lad, T. J. van Eeden, and M. Ackermann, Neutrino flavor composition using high energy starting events with IceCube, *Proc. Sci., ICRC2025* (2025) 1198 [[arXiv:2507.06835](https://arxiv.org/abs/2507.06835)].
- [66] M. G. Aartsen *et al.* (IceCube Collaboration), Atmospheric and astrophysical neutrinos above 1 TeV interacting in IceCube, *Phys. Rev. D* **91**, 022001 (2015).
- [67] R. Abbasi *et al.* (IceCube Collaboration), Evidence for a spectral break or curvature in the spectrum of astrophysical neutrinos from 5 TeV–10 PeV, *Phys. Rev. Lett.* **136**, 121002 (2026).
- [68] S. Schönert, T. K. Gaisser, E. Resconi, and O. Schulz, Vetoing atmospheric neutrinos in a high energy neutrino telescope, *Phys. Rev. D* **79**, 043009 (2009).
- [69] T. K. Gaisser, K. Jero, A. Karle, and J. van Santen, Generalized self-veto probability for atmospheric neutrinos, *Phys. Rev. D* **90**, 023009 (2014).
- [70] M. G. Aartsen *et al.* (IceCube Collaboration), Observation of high-energy astrophysical neutrinos in three years of IceCube data, *Phys. Rev. Lett.* **113**, 101101 (2014).
- [71] C. A. Argüelles, S. Palomares-Ruiz, A. Schneider, L. Wille, and T. Yuan, Unified atmospheric neutrino passing fractions for large-scale neutrino telescopes, *J. Cosmol. Astropart. Phys.* **07** (2018) 047.
- [72] R. Abbasi *et al.* (IceCube Collaboration), The IceCube high-energy starting event sample: Description and flux characterization with 7.5 years of data, *Phys. Rev. D* **104**, 022002 (2021).
- [73] M. G. Aartsen *et al.* (IceCube Collaboration), Time-integrated neutrino source searches with 10 years of IceCube data, *Phys. Rev. Lett.* **124**, 051103 (2020).
- [74] R. Abbasi *et al.* (IceCube Collaboration), IceCube data for neutrino point-source searches years 2008–2018, [10.21234/CPKQ-K003](https://arxiv.org/abs/2102.1234) (2021).
- [75] V. A. Allakhverdyan *et al.* (Baikal-GVD Collaboration), Overview of the Baikal-GVD neutrino telescope: 2024 status, *EPJ Web Conf.* **319**, 04002 (2025).
- [76] S. Adrián-Martínez *et al.* (KM3Net Collaboration), Letter of intent for KM3Net 2.0, *J. Phys. G* **43**, 084001 (2016).
- [77] R. Mammen Abraham *et al.*, Tau neutrinos in the next decade: From GeV to EeV, *J. Phys. G* **49**, 110501 (2022).
- [78] M. Ackermann *et al.*, High-energy and ultra-high-energy neutrinos: A Snowmass white paper, *J. High Energy Astrophys.* **36**, 55 (2022).
- [79] M. Agostini *et al.* (P-ONE Collaboration), The Pacific Ocean neutrino experiment, *Nat. Astron.* **4**, 913 (2020).
- [80] M. G. Aartsen *et al.* (IceCube-Gen2 Collaboration), IceCube-Gen2: The window to the extreme Universe, *J. Phys. G* **48**, 060501 (2021).
- [81] H. Zhang, Y. Cui, Y. Huang, S. Lin, Y. Liu, Z. Qiu, C. Shao, Y. Shi, C. Xie, and L. Yang, A proposed deep sea Neutrino Observatory in the Nanhai, *Astropart. Phys.* **171**, 103123 (2025).
- [82] Z. P. Ye *et al.* (TRIDENT Collaboration), A multi-cubic-kilometre neutrino telescope in the western Pacific Ocean, *Nat. Astron.* **7**, 1497 (2023).
- [83] T.-Q. Huang, Z. Cao, M. Chen, J. Liu, Z. Wang, X. You, and Y. Qi, Proposal for the high energy neutrino telescope, *Proc. Sci. ICRC2023* (2023) 1080.
- [84] D. F. G. Fiorillo and M. Bustamante, Bump hunting in the diffuse flux of high-energy cosmic neutrinos, *Phys. Rev. D* **107**, 083008 (2023).

- [85] L. J. Schumacher, M. Bustamante, M. Agostini, F. Oikonomou, and E. Resconi, Beyond first light: Global monitoring for high-energy neutrino astronomy, *Phys. Rev. D* **112**, 083027 (2025).
- [86] R. W. Rasmussen, L. Lechner, M. Ackermann, M. Kowalski, and W. Winter, Astrophysical neutrinos flavored with Beyond the Standard Model physics, *Phys. Rev. D* **96**, 083018 (2017).
- [87] H. Jeffreys, *The Theory of Probability*, Oxford Classic Texts in the Physical Sciences (Clarendon Press, Oxford University Press, Oxford, England, 1939).
- [88] S. W. Li, M. Bustamante, and J. F. Beacom, Echo technique to distinguish flavors of astrophysical neutrinos, *Phys. Rev. Lett.* **122**, 151101 (2019).
- [89] A. Steuer and L. Köpke (IceCube Collaboration), Delayed light emission to distinguish astrophysical neutrino flavors in IceCube, *Proc. Sci. ICRC2017* (**2018**) 1008.
- [90] K. Farrag *et al.*, Distinguishing ν_τ neutrinos using the neutron echo technique with next generation ice Cherenkov telescopes, *Proc. Sci. ICRC2023* (**2023**) 1211.
- [91] K. Dutta, S. Böser, and M. Rongen, Very late afterpulses and search for the neutron echo in IceCube, *Proc. Sci. ICRC2025* (**2025**) 1030 [arXiv:2507.07042].
- [92] G. Barenboim and C. Quigg, Neutrino observatories can characterize cosmic sources and neutrino properties, *Phys. Rev. D* **67**, 073024 (2003).
- [93] C. A. Argüelles, T. Katori, and J. Salvadó, New physics in astrophysical neutrino flavor, *Phys. Rev. Lett.* **115**, 161303 (2015).
- [94] M. Ahlers, M. Bustamante, and N. G. N. Willesen, Flavors of astrophysical neutrinos with active-sterile mixing, *J. Cosmol. Astropart. Phys.* **07** (2021) 029.
- [95] M. Bustamante and S. K. Agarwalla, Universe’s worth of electrons to probe long-range interactions of high-energy astrophysical neutrinos, *Phys. Rev. Lett.* **122**, 061103 (2019).
- [96] C. A. Argüelles, K. Farrag, T. Katori, R. Khandelwal, S. Mandalia, and J. Salvadó, Sterile neutrinos in astrophysical neutrino flavor, *J. Cosmol. Astropart. Phys.* **02** (2020) 015.
- [97] Y. Bai, K. Xie, and B. Zhou, Large neutrino “collider”, [arXiv:2510.13948](https://arxiv.org/abs/2510.13948).
- [98] P. A. N. Machado, I. R. Wang, X.-J. Xu, and B. Zhou, Widen the resonance at ultra-high energies: Novel probes of neutrino self-interactions in the high-mass regime, *J. Cosmol. Astropart. Phys.* **07** (2026) 064.
- [99] F. Testagrossa, D. F. G. Fiorillo, and M. Bustamante, Two-detector flavor sensitivity to ultrahigh-energy cosmic neutrinos, *Phys. Rev. D* **110**, 083026 (2024).
- [100] A. Coleman, O. Ericsson, C. Glaser, and M. Bustamante, Flavor composition of ultrahigh-energy cosmic neutrinos: Measurement forecasts for in-ice radio-based EeV neutrino telescopes, *Phys. Rev. D* **110**, 023044 (2024).
- [101] A. L. Cummings, C. Welling, and R. Scrandis, Neutrino flavor identification at the highest energies with PUEO, *Proc. Sci. ICRC2025* (**2025**) 1020.