

Searches for nonstandard neutrino oscillations at neutrino telescopes with a TeV muon accelerator source

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Muon accelerators, a potential technology for enabling $\mathcal{O}(10 \text{ TeV})$ parton center of mass energy collisions, would also source an intense, collimated beam of neutrinos at TeV energies. The energy and size of this beam would be excellently matched as a source for existing and planned neutrino telescopes: gigaton-sized detectors of astrophysical neutrinos at and above TeV energies. In this paper, we introduce the technical considerations and scientific reach of pairing a muon accelerator source of neutrinos with a neutrino telescope detector, a combination we dub the “Neutrino Kaleidoscope.” In particular, such a pairing would enable searches for non-standard oscillations of the beam neutrinos as they traverse the earth between source and detector. These nonstandard neutrino oscillations could be sourced by Lorentz invariance violation, which a neutrino kaleidoscope could probe up to the Planck scale. Such a search would also have a reach on sterile neutrinos orders of magnitude beyond existing terrestrial limits. Finally, we touch on the nonoscillation physics case for a neutrino kaleidoscope.

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I. INTRODUCTION

Neutrino telescopes are among the largest particle physics detectors ever built. The IceCube observatory specifically instruments approximately one metric gigaton of South Pole ice [1]. These telescopes observe atmospheric and astrophysical neutrino interactions with energies from $\mathcal{O}(10 \text{ GeV})$ [2] up to $\mathcal{O}(1 \text{ EeV})$ [3,4]. Atmospheric neutrinos with TeV energies have been used by these detectors to search for eV-scale sterile neutrinos [5,6], Lorentz violation [7,8], and nonstandard neutrino-matter interactions [9]. A TeV neutrino beam would have the potential to make these searches orders of magnitude more sensitive through higher interaction rates and greater systematic control.

Such a neutrino beam would be sourced by TeV muon accelerators, a novel technology proposed to enable high energy particle collisions with a parton center-of-mass energy $\gtrsim 2\text{--}10 \text{ TeV}$ [10–14]. The decay of the beam muons would source an intense, collimated flux of electron and muon (anti)neutrinos [15,16]. This neutrino flux could be utilized in a variety of measurements by a detector at the accelerator site [17–20], and also would remain intense far away from the accelerator [21–23].

In this study, we investigate the feasibility and scientific reach of pairing a TeV muon accelerator source of neutrinos with a neutrino telescope detector (see Fig. 1). We dub

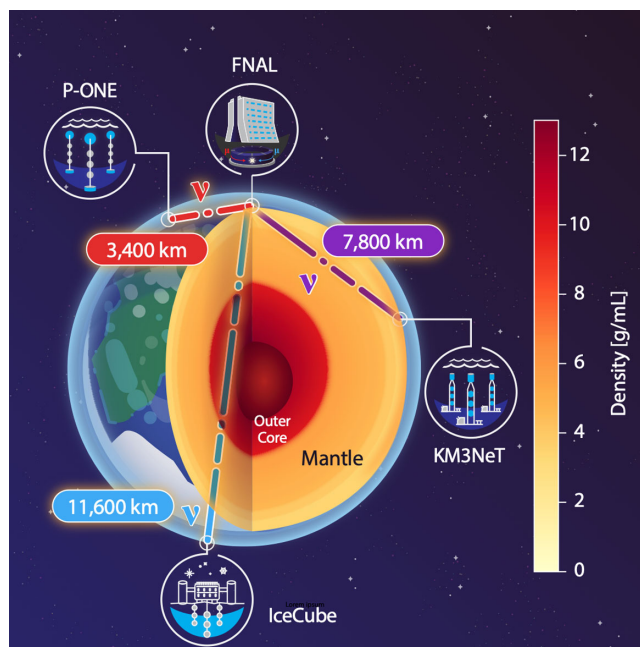


FIG. 1. Baseline scenarios of pairings of muon accelerators and neutrino telescopes as a neutrino kaleidoscope. As is discussed in the text, other scenarios have analogous baselines to those depicted here. Density is taken from PREM [24].

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this combination the neutrino kaleidoscope (alternatively, “collide”-o-scope). As long as the beam dispersion is kept small, the angular size of the neutrino beam spot is proportional to $1/\gamma$, where γ is the boost factor of the muons in decay [17]. For a 5 TeV muon source over an Earth diameter baseline, this angular size translates to a spatial size of $\mathcal{O}(100 \text{ m})$, similar to the telescope radius. Furthermore, the cross section and detector are large enough that a significant fraction of the neutrino flux would interact in the telescope: about 1 in 10^6 neutrinos for a 1 Gt detector.

We consider three baseline pairing scenarios of source and detector: Fermilab to P-ONE [25], KM3NeT [26], or IceCube [1]. These three scenarios match to three qualitatively different neutrino trajectories through the crust, mantle or core (respectively). They also match well onto other possible pairings with existing [1,26,27] or proposed [25,28–31] neutrino telescopes, as well as CERN to KM3NeT (crust crossing) or IceCube (core crossing). Long-baseline neutrino far detectors could also be utilized as the detector [32,33], though with a significantly smaller target mass.

We study the nonstandard neutrino oscillation scenarios that could be probed by a neutrino kaleidoscope. At the relevant baseline and energy ($\sim 10000 \text{ km}/1 \text{ TeV}$), there are various new physics scenarios that would induce novel neutrino oscillations between the accelerator source and neutrino detector. These scenarios arise in the presence of right-handed sterile neutrino states [34,35], neutrino non-standard interactions (NSI) [9,36], and Lorentz invariance violation [37–39], which a neutrino kaleidoscope could probe up to the Planck scale. In addition, there would be a high rate of rare neutrino interactions producing dimuons [40–43], which are in principle observable in neutrino telescopes [40].

II. EXPERIMENTAL CONCEPT

A. Accelerator

There are two primary requirements that a muon accelerator must meet for it to support a neutrino kaleidoscope. First, some section of the accelerator must be engineered to point at the telescope. This would require achieving a descent angle of 13° (Fermilab to P-ONE), 34° (Fermilab to KM3NeT), or 66° (Fermilab to IceCube). Whether the accelerator tunnel can be constructed at such an angle is a critical question underlying experimental design. This challenge stands alongside the many developments necessary to enable a muon collider in the first place [16,44]. Ultimately, we leave these questions outside the scope of this work, and instead focus on the scientific reach of the setup. We do note that it would not be necessary to construct a full circular “racetrack” at this descent angle, as is needed by neutrino factories [20]. Even just building a one-way beam dump at this angle would provide a large enough neutrino flux from muon decays upstream of the target to enable this experiment. Such a muon collider beam

dump would also enable a variety of new physics searches on its own [45,46]. We include this scenario in our projection of the flux and event rates below.

A secondary challenge on the muon beam design is that the beam divergence of the muon beam must be kept small. For a 5 TeV accelerator, the inherent spread of the neutrino beam ($1/\gamma$) is about 0.02 m rad . Any beam divergence larger than this will attenuate the flux observed in the telescope. Furthermore, there are spectral features in the decay angle that enhance the ability of a neutrino kaleidoscope to search for oscillations (these are similar in nature to the PRISM effect in neutrino super beams [47]). Muon collider designs have established a goal for the transverse beam emittance of $25 \text{ } \mu\text{m rad}$ [16,44]. For a beam spot size of 5 mm (away from the interaction point), this corresponds to a beam divergence of $5/\gamma \text{ mrad}$ [48], or $0.1 \text{ } \mu\text{rad}$ for a 5 TeV muon beam. In the vicinity of the interaction point, the beam is squeezed into a smaller spot size which corresponds to a much larger divergence and therefore a less useful neutrino beam [16,17]. Outside the interaction point, movers will likely be necessary to spread the neutrino beam by about 1 m rad to reduce the impact of neutrino radiation near the accelerator [16]. Although this will reduce the total neutrino flux, the instantaneous (turn-by-turn, i.e.,) beam divergence would still be $0.1 \text{ } \mu\text{rad}$, and the key spectral features in the beam would be retained.

We estimate a baseline number of muon decays from a few scenarios for the beam. In the first, the beamline is engineered so that a single straight section is pointed to the telescope. For a baseline muon accelerator scenario [16,44]— 2×10^{12} muons per bunch, a 10 km circumference ring, 30 cm straight section, mover reduction of $50\times$ —there would be 5×10^{14} muon decays per year of total beam operation. In the second, the beam dump is directed toward the telescope. For a 5 Hz repetition (and dump) rate and a 25 m decay tunnel (that is not subject to movers), there would be 2×10^{14} muon decays per year of total beam operation. We assume the muon angular divergence in the beam dump scenario is similar to that of the collider ring itself: $0.1 \text{ } \mu\text{rad}$ at 5 TeV. We consider the smaller beam dump scenario (2×10^{14}) as a nominal yearly rate. As an alternative scenario, the interaction point (IP) could be oriented toward the detector. This would enable a larger 100 m straight section with an intrinsic angular spread of 0.6 mrad (due to the spatial focusing at the IP [16]). In this case, there would be $8 \times 10^{18} \text{ } \mu$ decays per year, reduced by $30\times$ by the angular spread, and with the spectral features lost. We consider this scenario for only the P-ONE (crust-crossing) scenario, due to the challenge of orienting the slope of the IP.

B. Telescope

Neutrino telescopes are an ideal far detector for the intense flux of TeV energy neutrinos from a muon collider [49]. The extreme collimation of these neutrinos means that

the majority of the flux is contained within $\mathcal{O}(100 \text{ m})$ over Earth-diameter-scale baselines; thus, we benefit directly from the large active mass of neutrino telescopes. Neutrino interactions in these detectors generally fall under two morphological categories: *tracks* from high-energy muons and and *cascades* from hadronic and electromagnetic showers. For a μ^+ (μ^-) accelerator, charged-current $\bar{\nu}_\mu$ (ν_μ) interactions would result in tracks, while charged-current ν_e ($\bar{\nu}_e$) interactions and neutral-current interactions of all flavors would result in cascades. Track samples tend to have a $\bar{\nu}_\mu$ purity $\gtrsim 99\%$ [52], while cascade samples are comprised of similar contributions from all flavors [53]. Tracks have great angular resolution ($\lesssim 1^\circ$ [54]) but relatively poor resolution on the muon energy (~ 0.22 in $\log_{10}(E_\mu)$ [55]). Cascades have much better resolution on the deposited energy (~ 0.1 in $\log_{10}(E)$ [56]). This can also improve the energy reconstruction of ν_μ interactions inside the detector, which create a hadronic cascade at the start of the track [52]. Tracks have the added benefit that TeV muons will typically travel a few kilometers in ice before stopping [57]. This allows neutrino telescopes to observe charged-current ν_μ interactions outside of the active volume, increasing event rates by a factor of ~ 3 [52].

Currently operating neutrino telescopes include IceCube [1], KM3NeT [26], and Baikal-GVD [27]. There are multiple proposals for future neutrino telescopes [25,28–31], including P-ONE [25], IceCube-Gen2 [28], TRIDENT [29], NEON [30], and HUNT [31]. While any of these existing or future telescopes could operate as a neutrino kaleidoscope, we consider IceCube, KM3NeT, and P-ONE as they cover a representative range of baselines.

III. STERILE NEUTRINO OSCILLATIONS

A new right-handed (nonweakly interacting, or sterile) neutrino state would induce oscillations from the active beam neutrinos into the sterile state. The energy and baseline of neutrino kaleidoscopes would be precisely matched to probe oscillations at an active-sterile mass splitting of about 1 eV^2 . In particular, at TeV neutrino energies and eV^2 splittings there is a matter resonance, most prominent through the core of the earth, that would magnify the oscillation of muon antineutrinos and electron neutrinos into the sterile state [34,35,58–60].

In the case of a discovery of an eV^2 -scale sterile neutrino by the existing program of experiments investigating the “short-baseline” neutrino anomalies [61–63], a neutrino kaleidoscope could be a follow on to study the oscillation. The small systematic uncertainties inherent to this setup should allow for higher precision in measurement in addition to the significant discovery sensitivity we demonstrate here. In addition, many theoretical models capable of explaining eV^2 -scale sterile neutrinos predict or otherwise allow for additional light sterile states [64,65], which

would be motivated targets to search for down to smaller mixing if a short-baseline neutrino oscillation is definitively observed.

Furthermore, the existence of neutrino mass merits the search for right-handed neutrino states across the full range of masses. Neutrino kaleidoscopes offer orders-of-magnitude improvement over current and planned short-baseline neutrino oscillation searches, and are therefore motivated independent of any experimental anomaly. In this Section, we focus on the sensitivity to a single new sterile neutrino state to demonstrate the performance of the kaleidoscope.

An active-sterile oscillation can be described in the “3+1” picture (approximating the electron and neutron number densities in the earth as equal) as

$$i \frac{d}{dx} \begin{pmatrix} \nu_\alpha \\ \nu_S \end{pmatrix} = \begin{pmatrix} -\frac{\Delta m^2}{4E} \cos 2\theta_{\alpha\alpha} \pm_\alpha G_F N_e / \sqrt{2} & \frac{\Delta m^2}{4E} \sin 2\theta_{\alpha\alpha} \\ \frac{\Delta m^2}{4E} \sin 2\theta_{\alpha\alpha} & \frac{\Delta m^2}{4E} \cos 2\theta_{\alpha\alpha} \end{pmatrix} \begin{pmatrix} \nu_\alpha \\ \nu_S \end{pmatrix}, \quad (1)$$

where $\alpha \in \{e, \mu\}$ is either an electron or muon neutrino, S represents the sterile state, $\theta_{\alpha\alpha}$ is the effective active-sterile neutrino mixing angle (in terms of the mass-mixing matrix U , $\sin^2 2\theta_{\alpha\alpha} \equiv 4|U_\alpha|^2[1 - |U_\alpha|^2]$), Δm^2 is the new mass splitting, G_F is the Fermi constant, and $N_e (\approx N_n)$ is the number density of electrons [66]. The sign of the matter potential term ($\pm_\alpha$) is $+1$ for electron neutrinos and muon antineutrinos, and -1 for electron antineutrinos and muon neutrinos. When the matter potential is positive, the resonance is achieved when $\frac{\Delta m^2}{4E} \cos 2\theta_{\alpha\alpha} = G_F N_e / \sqrt{2}$.

Figure 2 shows the distribution of muon antineutrino events by the neutrino energy and interaction radius at the IceCube baseline, with an example sterile neutrino point injected. Because different annular radii contain different

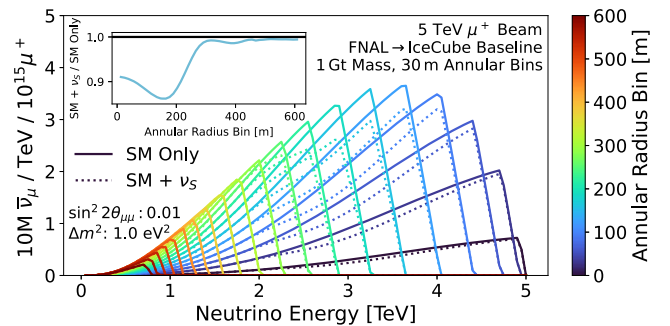


FIG. 2. Neutrino interaction rates, per 30 m annular radius bin, at the Fermilab to IceCube baseline. Shown with and without an example injected sterile neutrino (ν_S) model point. The inset shows the fractional rate of $\bar{\nu}_\mu$ interactions with the sterile neutrino (relative to without) as a function of the annular radius.

energy distributions, an oscillation effect is observable even in the vertex position of the neutrino interaction. This is useful because reconstructing the energy of $\mathcal{O}(\text{TeV})$ “tracklike” neutrino interactions is challenging in neutrino telescopes [55].

We estimated the sensitivity of neutrino kaleidoscopes with a binned likelihood analysis performed on the neutrino interaction annular radius in bins of 10 m, matching the interaction vertex spatial resolution of neutrino telescopes [67]. A threshold of 1 TeV is applied on the neutrino energy. Otherwise, no direct information on the neutrino energy is incorporated into the analysis. Oscillations are computed by numerically integrating Eq. (1) with the earth density taken from PREM [24]. The resulting sensitivity is shown in Fig. 3. Depending on the baseline and systematic uncertainties, the sensitivity reaches up to multiple orders of magnitude beyond any existing or planned search for eV-scale sterile neutrinos.

A normalization systematic uncertainty of 1% is included, accounting for possible uncertainties into the flux or cross section. The cross-section of neutrino-nucleus interactions is very well understood from a theoretical perspective, with residual uncertainties at the percent level [71]. Similarly, the neutrino flux from muon decay is very well understood, and the dominant relevant uncertainty would likely be counting the number of muons in the beam. In existing neutrino super beams, the uncertainty in the number of protons in the beam (protons on target) is similarly at the percent level [72,73]. This systematic mostly impacts the large Δm^2 region where the oscillation largely arises as a normalization shift. It does not significantly impact the bulk of the sensitivity (around $\Delta m^2 \sim 1 \text{ eV}^2$), which is largely driven by the shape of the oscillation pattern in the vertex distribution (see Fig. 2).

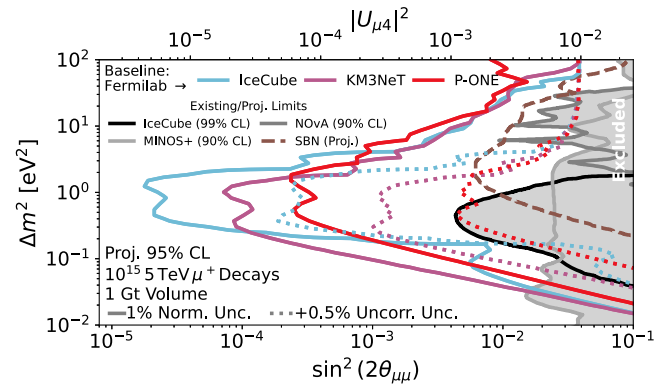


FIG. 3. Projected sensitivity of a neutrino kaleidoscope to an eV²-scale, muon-coupled sterile neutrino, compared to existing and projected terrestrial limits [6,68–70]. Shown at various source-detector baselines with an integrated flux of $10^{15} \mu^+$ decays at an energy of 5 TeV. The sensitivity is calculated with a 1% normalization uncertainty (solid line) and an additional 0.5% uncorrelated systematic uncertainty in each annular bin (dashed line).

These uncertainties could be constrained through comparison with ν_μ data (which would not experience an Mikheyev–Smirnov–Wolfenstein resonance). Furthermore, they could also be reduced by the use of a near detector. Although it would be challenging to place a near detector at the end of a steeply descending beamline (likely deep underground), a detector placed on a different segment of the muon ring (at the surface) would be able to play largely the same role. Since the flux from a muon beam is so simple, it could in-principle be replicated at different sites in the accelerator complex, unlike in current experiments. Ultimately, a near detector may also be less critical than in existing oscillation experiments, owing to the small systematic uncertainties relevant for a muon beam induced neutrino flux interacting at the TeV scale.

Figure 3 also shows the impact of a possible uncorrelated systematic uncertainty which, for example, could arise from nonuniformities in the detector response. It is hard to predict the size of any uncorrelated uncertainties between different annular bins, given the novel nature of this analysis. This uncertainty is included rather to demonstrate the impact of such a systematic, in the case that it is similar in magnitude to the uncorrelated uncertainties at present short-baseline neutrino oscillation searches. For example, one can see that in the presence of a 0.5% uncorrelated systematic, the P-ONE baseline (which gets almost no boost from the matter resonance) obtains a similar sensitivity to previous searches. Even in such a “high-systematic” scenario, the KM3Net and IceCube baselines obtain a significant improvement in reach, owing to the matter resonance.

Neutrino kaleidoscopes would also have a similar reach to electron-coupled sterile neutrinos. In this case, the resonant oscillation mode would arise in the ν_e flux from μ^+ decays. At the telescope, the corresponding “shower-like” reconstructed topology would include both ν_e charged-current and neutral-current events. Figure 4 shows the sensitivity to electron-coupled sterile neutrinos compared to existing constraints. The same likelihood analysis as for the muon-coupled case is applied, except here the events include both ν_e charged-current interactions and $\bar{\nu}_\mu$ and ν_e neutral-current interactions. As charged-current and neutral-current interactions have different cross sections with different underlying uncertainties, we apply an 1% uncertainty both on the overall rate (which is mostly charged current) as well as an independent 1% uncertainty on the neutral-current rate [71]. Again, the projected sensitivity reaches many orders of magnitude beyond existing and projected limits [74–81].

The incredible reach of neutrino kaleidoscopes to sterile neutrinos is underlaid by numerous advantages over existing searches. The neutrino energy is at the TeV scale, and is therefore not subject to the large systematic uncertainties that impact GeV-scale neutrino experiments [82]. The search also gets a significant boost from the matter

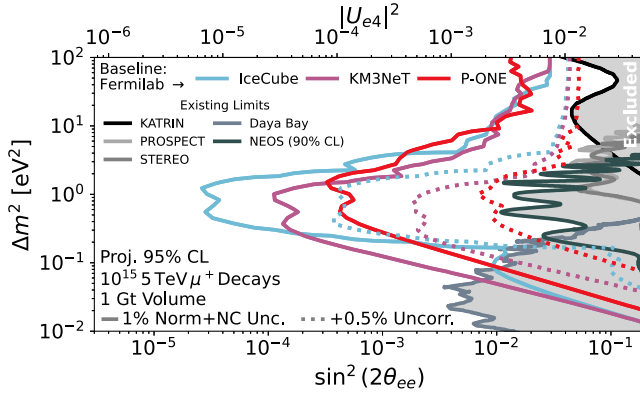


FIG. 4. Projected sensitivity of a neutrino kaleidoscope to an eV^2 -scale, electron-coupled sterile neutrino, compared to existing terrestrial limits [74–78]. Shown at various source-detector baselines with an integrated flux of $10^{15} \mu^+$ decays at an energy of 5 TeV. The sensitivity is calculated with separate 1% uncertainties on the total normalization, as well as the neutral-current rate (solid line) and an additional 0.5% uncorrelated systematic uncertainty in each annular bin (dashed line).

resonance which, unlike in searches with TeV atmospheric neutrinos, is probed with a pure $\bar{\nu}_\mu$ or ν_e beam with all of the neutrinos experiencing the same density profile. Finally, the rates in the telescope are large enough (100s of millions) to search for very small oscillation effects, as long as systematic effects can be mitigated.

In both the muon-coupled and electron-coupled cases, we have considered the sterile neutrino mixing “one at a time,” and therefore neglect the possible impact of degeneracies from mixed muon- and electron-sterile couplings. Such degeneracies have limited the reach of previous sterile neutrino searches [83,84]. However, even weak simultaneous information on muon and electron neutrino rates are able to break these degeneracies [85,86]. In the case of the neutrino kaleidoscope, a complete analysis would have access to a powerful set of samples, especially if data from a μ^- beam is also incorporated. In this case, there would be track events (ν_μ charged current) for both muon-neutrino and anti-muon-neutrino fluxes, and the shower sample (ν_e charged current and ν neutral current) for both $\nu_\mu/\bar{\nu}_e$ and $\bar{\nu}_\mu/\nu_e$ fluxes. Across these samples, $\bar{\nu}_\mu$ and ν_e (from the μ^+ beam) fluxes would be subject to resonant oscillations from the matter effect. And ν_μ and $\bar{\nu}_e$ fluxes (from the μ^- beam) would be subject to a different oscillation pattern from nonresonant sterile oscillations. The combination of these samples would be able to break degeneracies in the oscillation pattern from mixed couplings, and therefore should obtain a similar overall sensitivity to our projection.

Furthermore, one could imagine leveraging information on the neutrino interactions beyond what we include in this analysis. The neutrino energy can be reconstructed directly with some precision, especially in ν_e charged-current interactions, complementing the annular radius

reconstruction. One could also imagine expanding the reach of the search for sterile neutrinos by incorporating nonfiducial ν_μ charged current interactions. Reconstructing ν_τ interactions would provide a powerful additional sample in the analysis with a unique (relative to existing short-baseline oscillation searches) sensitivity to the sterile- τ mixing. We leave the ν_τ appearance case out of this analysis as isolating ν_τ interactions in neutrino telescopes at TeV energies has not been demonstrated, although there are some ideas [87]. The extension to include the features, as well as the full set of possible samples and mixed-coupling scenarios, merits future study.

IV. ACTIVE NEUTRINO OSCILLATIONS

Neutrino kaleidoscopes would also be able to probe oscillations between the active neutrino states in the beam. At TeV energies, the matter potential in the earth effectively decouples the ν_e flavor from ν_μ and ν_τ [88]. We therefore focus on oscillations in the μ - τ sector. Including the possibility of a nonstandard neutrino potential V , the μ - τ oscillation master equation is

$$i \frac{d}{dx} \begin{pmatrix} \nu_\mu \\ \nu_\tau \end{pmatrix} = \left[\frac{\Delta m_{31}^2}{4E} \begin{pmatrix} -\cos 2\theta_{23} & \sin 2\theta_{23} \\ \sin 2\theta_{23} & \cos 2\theta_{23} \end{pmatrix} + \begin{pmatrix} V_{\mu\mu} & V_{\mu\tau} \\ V_{\mu\tau}^* & V_{\tau\tau} \end{pmatrix} \right] \begin{pmatrix} \nu_\mu \\ \nu_\tau \end{pmatrix}, \quad (2)$$

where θ_{23} and Δm_{31}^2 are the standard neutrino oscillation parameters. The sign of the potential V is flipped for antineutrinos. In the limit where the baseline is short ($\frac{\Delta m_{31}^2}{4E} L, VL \ll 1$), for a position-independent potential, the transition probability becomes [89]

$$P_{\nu_\mu \rightarrow \nu_\tau} = L^2 \left| \frac{\Delta m_{31}^2}{4E} \sin 2\theta_{23} + V_{\mu\tau} \right|^2 + \mathcal{O}(L^4). \quad (3)$$

There are therefore two channels to observe active neutrino oscillations: muon neutrino disappearance and tau neutrino appearance. These channels would probe the product $\Delta m_{31}^2 \sin 2\theta_{23}$, as well as the nonstandard neutrino potential $V_{\mu\tau}$, which could be generated by new physics. Standard vacuum oscillations alone would induce a muon-to-tau neutrino oscillation probability of about $0.1\% \times \left(\frac{1 \text{ TeV}}{\text{Neutrino Energy}} \times \frac{\text{Neutrino Baseline}}{10,000 \text{ km}} \right)^2$. A measurement of this rate would be complimentary to those in GeV-scale long baseline neutrino experiments. Such a measurement is most straightforward through the ν_μ disappearance channel, though the ν_τ appearance channel could also be possible depending on the ability of future neutrino telescopes to identify tau neutrinos, an area of active research [90].

A. Oscillations from Lorentz invariance violation

The potential $V_{\mu\tau}$ in Eq. (3) can be generated by neutrino interactions with a background field that violate Lorentz invariance [37,38,91–93]. Such violations can occur in theories of quantum gravity [94], for example, which unify general relativity with the Standard Model at the Planck scale ($E_P = 1.22 \times 10^{19}$ GeV) [95]. While Planck-scale quantum gravity cannot presently be probed directly, it can lead to Planck-suppressed effects on observables at lower energy scales [96], including small violations of Lorentz symmetry [20,95,97–99]. Lorentz-violating neutrino oscillations can also arise in alternative scenarios, such as nonstandard neutrino interactions with dark energy [100] or ultralight bosonic dark matter [101]. The strongest constraints on Lorentz violation in the neutrino sector come from IceCube measurements of atmospheric [102–104] and astrophysical [105] neutrinos, as they probe the highest energies and longest baselines of all neutrino experiments. Neutrino kaleidoscopes have typical energies and baselines similar to that of IceCube atmospheric neutrino searches, with the added benefit of unprecedented event rates. Thus, they are an ideal experimental configuration to search for Lorentz violation.

The imprint of Planck-scale Lorentz violation on the Standard Model is described by an effective field theory, the Standard-Model extension (SME) [97,106], which includes operators that govern neutrino interactions with a new Lorentz-violating background field. The renormalizable μ - τ operators of this group are of mass dimension three and four and are parameterized by the Wilson coefficients $(a_L^\mu)_{\mu\tau}$ and $(c_L^{\mu\nu})_{\mu\tau}$, respectively. Unlike typical Wilson coefficients, these carry Lorentz indices, which leads to frame-dependent neutrino interactions. This effect is conventionally studied within a Sun-centered celestial-equatorial frame, in which the Earth's rotation causes the direction of a neutrino beam to vary over the course of a sidereal day, i.e., with a frequency $\omega_\oplus = 2\pi/(23 \text{ h } 56 \text{ min})$ [93]. This leads to a potential $V_{\mu\tau}$ with an explicit sidereal time dependence,

$$V_{\mu\tau} = (\mathcal{C})_{\mu\tau} + (\mathcal{A}_s)_{\mu\tau} \sin \omega_\oplus T_\oplus + (\mathcal{A}_c)_{\mu\tau} \cos \omega_\oplus T_\oplus + (\mathcal{B}_s)_{\mu\tau} \sin 2\omega_\oplus T_\oplus + (\mathcal{B}_c)_{\mu\tau} \cos 2\omega_\oplus T_\oplus, \quad (4)$$

where, dropping the flavor indices, $\mathcal{C}$, $\mathcal{A}_s$, $\mathcal{A}_c$, $\mathcal{B}_s$, and $\mathcal{B}_c$ are energy-dependent linear combinations of the a_L^μ and $c_L^{\mu\nu}$ coefficients. The specific linear combination depends on the geometry of the neutrino beam with respect to the Earth; explicit expressions can be found in Eqs. (4)–(13) of Ref. [93].

Sidereal variations from Lorentz violation have been perviously investigated in neutrino experiments [102,107–110]. In this Letter, we study the expected sensitivity of neutrino kaleidoscopes to sidereal variations. This analysis benefits directly from the high event rates of

neutrino kaleidoscopes, as systematic uncertainties tend to be negligible [102,107]. We consider the beam dump scenario for IceCube and KM3NeT and the 100 m IP straight section scenario for P-ONE, denoted P-ONE (IP), as energy-radial correlations are not important in the sidereal variation analysis. We focus on ν_μ disappearance from μ - τ SME coefficients, as tracks provide a pure sample of ν_μ interactions. We also consider ν_τ appearance in hypothetical ν_τ -enriched sample with a benchmark signal-to-background ratio of 0.1. Event-by-event ν_τ identification is difficult at TeV energies [111], but techniques such as the neutron/muon echo [87] and the isolation of track events from muonic tau decays with high apparent inelasticity or muon angles may enable the identification of a ν_τ -enriched sample. While such a ν_τ -enriched sample has yet to be demonstrated experimentally, the benchmark signal-to-background ratio of 0.1 is intended to identify the classification capability required to achieve unprecedented laboratory reach on Lorentz violating neutrino oscillations, motivating further investigation of the tau identification techniques discussed above.

In principle, SME coefficients in the e - μ and e - τ sector can also impact oscillations. However, unlike in the sterile neutrino case, these SME coefficients cannot lead to degeneracies in the oscillation probabilities in the μ - τ sector. This is because, as mentioned above, the matter potential of the Earth decouples electron neutrinos from the other flavors at TeV energies and thus suppresses the impact of e - μ and e - τ SME coefficients. Therefore, we only consider oscillations from μ - τ SME coefficients.

Figure 5 shows the expected interaction rate in each detector for the ν_μ and ν_τ -enriched sample over one sidereal day for characteristic values of c_L^{TY} , as a ratio to the Standard Model expectation. We perform the Fourier analysis outlined in Ref. [107] to assess our sensitivity to the a_L^μ and $c_L^{\mu\nu}$ coefficients. Table I suggests that the ν_μ

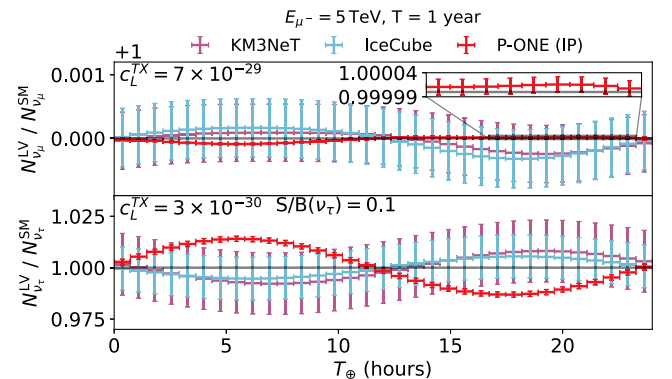


FIG. 5. Ratio of muon (top) and tau (bottom) neutrino interactions with and without Lorentz violation as a function of sidereal time, considering a single nonzero SME Wilson coefficient. Error bars indicate the expected statistical uncertainty after one year of accelerator operation.

TABLE I. The sensitivity of the ν_μ sample in each kaleidoscope configuration to three different a_L and c_L SME coefficients at the 3σ C.L., considering one year of data at a muon energy of 5 TeV. The current limits on each coefficient are also shown, which come from sidereal variation searches at either IceCube [102] or MINOS [108].

Coefficient	KM3NeT	IceCube	P-ONE (IP)	Current limit
$a_L^X/10^{-25}$ GeV	8.2	5.8	1.0	1.7×10^2 ([102])
$c_L^{TX}/10^{-28}$	1.6	1.1	0.2	79 ([102])
$c_L^{XX}/10^{-28}$	4.0	2.4	0.7	2.5×10^5 ([108])

“track” sample of a neutrino kaleidoscope can improve upon current limits from IceCube [102] and MINOS [108] by two or more orders of magnitude.

Many theories of quantum gravity [99,112–114] predict higher-order Lorentz-violating operators with mass dimension $d > 4$. The simple power-counting analysis suggests that the SME coefficients associated with higher-order operators take on a value of approximately E_p^{4-d} [96]. Furthermore, these operators induce oscillations at a frequency proportional to LE^{d-3} [115], such that high-energy neutrinos are more sensitive to higher-dimension operators. Recent IceCube constraints using high-energy astrophysical neutrino flavor have reached the E_p^{-2} regime of the isotropic $d = 6$ operators for the first time [105]. However, these constraints depend on the unknown flavor composition of neutrinos at the source. Neutrino kaleidoscopes can probe higher-dimensional Lorentz-violating operators without such model dependence.

We can estimate the sensitivity to higher-dimensional operators by the relation [115]

$$|\mathbf{p}|^{d-3}|A_c^d| \approx |A_c^3|, \quad (5)$$

where $\mathbf{p}$ is the average neutrino energy, A_c^3 is the dimension three coefficient appearing in Eq. (4), and A_c^d is an experiment-dependent linear combination of d -dimensional SME coefficients. We consider three different kaleidoscope configurations to probe dimension six operators,

- (i) Nominal: ν_μ sample, $T = 1$ yr, $E_\mu = 5$ TeV
 - (ii) Tau enriched: ν_τ -enriched sample with a signal-to-background ratio of 10%, $T = 10$ yrs, $E_\mu = 5$ TeV
 - (iii) High energy: ν_μ sample, $T = 10$ yrs, $E_\mu = 50$ TeV.
- Table II shows that the tau-enriched and high-energy neutrino kaleidoscope configurations can reach the double-Planck-suppressed regime of A_c^6 . Thus, a neutrino kaleidoscope with either a 50 TeV muon beam or improved ν_τ tagging at the detector is likely the only terrestrial (and thus model-independent) probe of the double-Planck suppressed imprint of quantum gravity.

TABLE II. Sensitivity of each kaleidoscope to A_c^6 , in units of $E_p^{-2} = 6.7 \times 10^{-39}$ GeV $^{-2}$, at the 90% CL, considering the three different experimental configurations in the text.

Configuration	KM3NeT	IceCube	P-ONE (IP)
Nominal	$2.8 \times 10^3/E_p^2$	$1.2 \times 10^3/E_p^2$	$5.3 \times 10^2/E_p^2$
Tau-enriched	$26/E_p^2$	$17/E_p^2$	$2.1/E_p^2$
High-energy	$11/E_p^2$	$5.3/E_p^2$	$1.9/E_p^2$

B. Oscillations from anomalous matter potentials

In addition to Lorentz invariance violation, $\nu_\mu - \nu_\tau$ oscillations would also be able to probe other nonstandard oscillation scenarios. For example, the oscillation could be generated by a matter potential from NSIs experienced by the neutrinos traveling through the earth [9,36,116–118]. Such NSI potentials arise naturally in certain radiative neutrino mass models [119] such as the Zee model [120]. Unlike the Lorentz-violating oscillations of the previous section, nonstandard oscillations from NSIs would not induce a sidereal variation, but would still induce anomalous ν_μ disappearance and ν_τ appearance. To leverage the latter, neutrino kaleidoscopes would need to search for ν_τ interactions on top of large ν_μ and ν_e backgrounds. As discussed in Sec. IV, this may be possible at the TeV scale by searching for muon and neutron “echoes” in hadronic cascades [87]. In addition, μ -decaying τ leptons from ν_τ interactions would have higher inelasticity and larger muon angles than ν_μ interactions due to the missing energy from the neutrinos in the τ decay, which could be used to identify ν_τ interactions statistically.

Figure 6 shows the rate of ν_τ and $\bar{\nu}_\tau$ interactions at a range of anomalous matter potential values ($\epsilon_{\mu\tau}$, where $V_{\mu\tau} \equiv \sqrt{2}G_F N_e \epsilon_{\mu\tau}$), as well as for standard oscillations

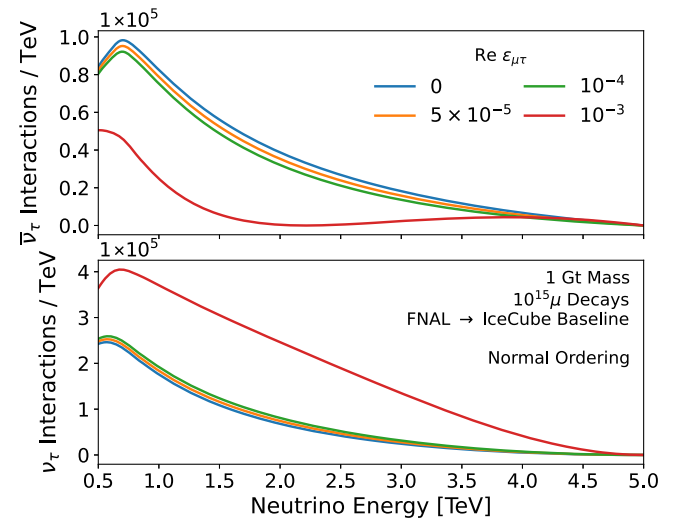


FIG. 6. Interaction rate of $\bar{\nu}_\tau$ (top) and ν_τ (bottom) for standard oscillations ($\epsilon_{\mu\tau} = 0$), as well as a few nonstandard scenarios.

($\epsilon_{\mu\tau} = 0$). There would be hundreds of thousands of ν_τ interactions in the telescope to observe such an oscillation effect even without an anomalous matter potential. However, due to the challenge of selecting a pure sample of ν_τ events, it is difficult to estimate how well the rate of interactions in the telescope could be determined. A value of $\epsilon_{\mu\tau} = 5 \times 10^{-5}$ has an $\mathcal{O}(10\%)$ effect on the ν_τ rate, differing in direction between tau neutrinos and antineutrinos. The relative direction of the change in the interaction rate flips if the sign of the potential flips or, equivalently, in the case of the inverted mass ordering. An imaginary $\epsilon_{\mu\tau}$ would instead impact the ν_τ and $\bar{\nu}_\tau$ rates in the same direction.

A sensitivity at $\epsilon_{\mu\tau} = 5 \times 10^{-5}$ would surpass the reach on any nonstandard matter potential term from existing and planned measurements [9,36,116–118]. In the case of a heavy mediator, NSI potentials generically have a magnitude on the order of M_W^2/M_χ^2 [116], where M_W is the mass of the W boson and M_χ is the new physics scale. This reach therefore corresponds to a sensitivity on such a new scale up to about 10 TeV. (Neutrino NSI models are often constructed with a light mediator to avoid bounds from charged lepton flavor violation [121–125]; in such models, the scale comparison does not apply.) Even without a ν_τ -enriched sample, a similar reach on any new physics potential can also be obtained in principle through very precise measurements of muon neutrino disappearance.

V. RARE NEUTRINO INTERACTIONS

Neutrino kaleidoscopes can also search for rare neutrino interactions. Specifically, neutrino production of muon pairs can lead to double track signatures in neutrino telescopes [40], which can in principle be distinguished from the typical track and cascade signatures. These “dimuon” events can arise from charm production, W-boson production (WBP), and trident interactions. The cross sections for these processes are shown in Fig. 7. We use the charged-current ν_μ charm-production cross section

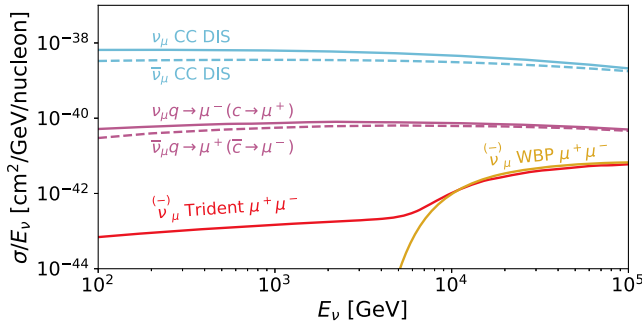


FIG. 7. Total CC DIS cross section for muon neutrinos [71], and cross sections for rare neutrino interactions producing dimuons in the final state, through charm production [41,126], tridents, and WBP [127].

TABLE III. Number of ν_μ interactions per year, including rare interactions with dimuons in the final state, for each kaleidoscope configuration. Event rates are computed using the cross sections in Fig. 7.

Process	KM3NeT	IceCube	P-ONE (IP)
ν_μ CC DIS	1.7×10^8	1.6×10^8	1.3×10^{11}
$\nu_\mu q \rightarrow \mu^- (c \rightarrow \mu^+)$	2.2×10^6	2.1×10^6	1.8×10^9
ν_μ Trident $\mu^+ \mu^-$	5.2×10^3	5×10^3	4.2×10^6
ν_μ WBP $\mu^+ \mu^-$	3.6	3.6	2.8×10^3

computed in Ref. [126] and account for the muon branching ratio of the outgoing charm hadron according to the fragmentation fractions of the outgoing charm quark [41]. W-boson production and trident dimuon cross sections are taken from Refs. [127,128]. Table III reports the expected rate per year from these dimuon processes in each kaleidoscope configuration. The large dimuon event rates, which enable powerful probes of the strong force [129] and new lepton flavor symmetries [130], are directly a consequence of the large active mass of neutrino telescopes. This is a unique feature of the kaleidoscope proposal, as a neutrino detector near the interaction point will necessarily have smaller active mass. Such an enhancement is only possible due to the high collimation of neutrino beams from a muon collider, as discussed in Sec. II. We leave a detailed investigation of the physics capabilities of a dimuon measurement in neutrino kaleidoscopes to future work.

VI. CONCLUSION

We have introduced the “neutrino kaleidoscope,” combining a TeV-scale muon accelerator with a gigaton neutrino telescope to deliver, for the first time, a high-energy, long-baseline neutrino experiment with an intense and precisely controlled flux. The unprecedented event rates enable orders-of-magnitude improvement over existing and planned experiments in sensitivity to nonstandard neutrino oscillations from eV-scale sterile neutrinos, nonstandard neutrino interactions, and Lorentz-violating effects. Notably, this approach provides the first terrestrial access to double-Planck suppressed sidereal variations from Lorentz violation in theories of quantum gravity. Our proposal is also an excellent probe of rare neutrino interactions with dimuons in the final state. The neutrino kaleidoscope thereby offers a powerful, generalizable platform to probe new physics and fundamental symmetries with precision. We encourage further exploration of this paradigm as a flagship opportunity for future accelerator and neutrino detector facilities.

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DATA AVAILABILITY

The data that support the findings of this article are openly available [133].

APPENDIX: MORE DETAILS ON THE LORENTZ VIOLATION SENSITIVITY

1. Theory

The imprint of Planck-scale Lorentz violation on the Standard Model is described by an effective field theory, the SME [97,106], in which neutrino flavor evolution is governed by the effective Hamiltonian h_{eff} such that

$$i \frac{d}{dx} \begin{pmatrix} \nu_\alpha \\ \nu_\beta \end{pmatrix} = \begin{bmatrix} (h_{\text{eff}})_{\alpha\alpha} & (h_{\text{eff}})_{\alpha\beta} \\ (h_{\text{eff}})_{\alpha\beta}^* & (h_{\text{eff}})_{\beta\beta} \end{bmatrix} \begin{pmatrix} \nu_\alpha \\ \nu_\beta \end{pmatrix},$$

$$(h_{\text{eff}})_{\alpha\beta} = \frac{1}{E} \left[(a_L)_{\alpha\beta}^\mu p_\mu - (c_L)_{\alpha\beta}^{\mu\nu} p_\mu p_\nu \right], \quad (\text{A1})$$

where p_μ is the neutrino four-momentum, and $(a_L)_{\alpha\beta}^\mu$ and $(c_L)_{\alpha\beta}^{\mu\nu}$ are the flavor-dependent SME coefficients associated with operators of mass dimension 3 and 4, respectively. Here we have assumed neutrino oscillations from mass-mixing are negligible compared to those from Lorentz-violation, which is valid when $\Delta m^2/(4E) \ll h_{\text{eff}}$. When the baseline L is small compared to $h_{\text{eff}}/(\hbar c)$, neutrino oscillation probabilities are given by

$$P_{\nu_\alpha \rightarrow \nu_\beta} \approx |(h_{\text{eff}})_{\alpha\beta}|^2 L^2 / (\hbar c)^2, \quad (\text{A2})$$

where $\alpha \neq \beta$.

Two effects are important to note in Eq. (A1). First, the a_L and c_L coefficients have mass dimension 1 and 0, resulting in neutrino oscillations that depend on L and LE , respectively, in contrast to the standard L/E dependence of mass-generated oscillations. Oscillations from Lorentz violation can thus dominate over mass-generated oscillations at high energies, even for Planck-suppressed SME coefficients. Second, the nontrivial dependence on p_μ leads to frame-dependent oscillations. As discussed in Sec. IV, the conventional choice is a Sun-centered celestial-equatorial frame, in which the Earth's rotation causes the direction of a neutrino beam to vary over the course of a sidereal day, i.e., with a frequency $\omega_\oplus = 2\pi/(23 \text{ h } 56 \text{ min})$. This leads to the explicit sidereal time dependence in the effective Hamiltonian as shown in Eq. (4) and reproduced here,

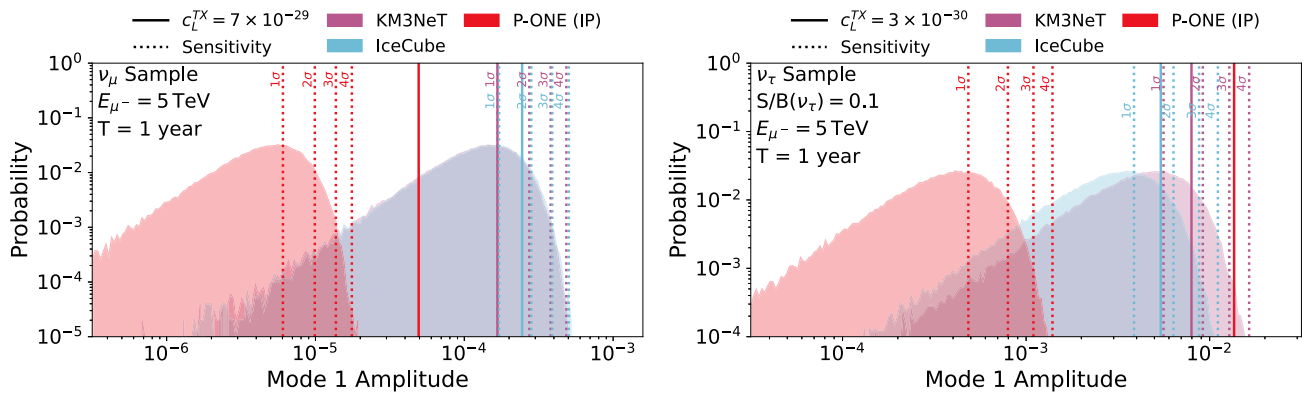


FIG. 8. Expected distributions of first mode amplitudes under the null hypothesis for the ν_μ (left) and ν_τ -enriched (right) sample in each experimental configuration, with sensitivities indicated by the dotted lines. The solid lines indicated the expected first harmonic amplitude for the indicated value of $c_L^{TX} = 1$. Here we consider one year of data at a muon energy of 5 TeV.

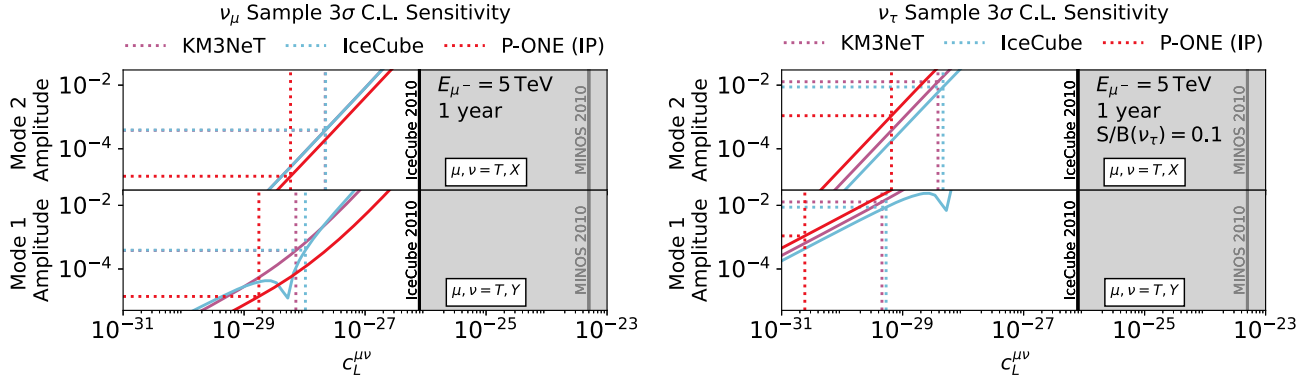


FIG. 9. Expected 3σ exclusion sensitivity to c_L^{TX} and c_L^{TY} for the ν_μ (left) and ν_τ -enriched (right) sample in each kaleidoscope, determined by corresponding quantile of the second and first mode amplitude distributions, respectively. Here we consider one year of data at a muon energy of 5 TeV. The shaded regions correspond to existing constraints from IceCube [102] and MINOS [108].

$$(h_{\text{eff}})_{\alpha\beta} = (\mathcal{C})_{\alpha\beta} + (\mathcal{A}_s)_{\alpha\beta} \sin \omega_\oplus T_\oplus + (\mathcal{A}_c)_{\alpha\beta} \cos \omega_\oplus T_\oplus + (\mathcal{B}_s)_{\alpha\beta} \sin 2\omega_\oplus T_\oplus + (\mathcal{B}_c)_{\alpha\beta} \cos 2\omega_\oplus T_\oplus, \quad (\text{A3})$$

where $\mathcal{C}$, $\mathcal{A}_s$, $\mathcal{A}_c$, $\mathcal{B}_s$, and $\mathcal{B}_c$ are energy-dependent linear combinations of the a_L^μ and $c_L^{\mu\nu}$ coefficients. The specific linear combination depends on the geometry of the neutrino beam with respect to the Earth $\vec{N}$; explicit expressions can be found in Eqs. (4)–(13) of Ref. [93]. The directional vectors in the Sun-centered celestial-equatorial frame for each kaleidoscope configuration are

$$\begin{pmatrix} \hat{N}_X \\ \hat{N}_Y \\ \hat{N}_Z \end{pmatrix}_{\text{KM3}} = \begin{pmatrix} 0.1836 \\ 0.5876 \\ 0.788 \end{pmatrix}, \quad \begin{pmatrix} \hat{N}_X \\ \hat{N}_Y \\ \hat{N}_Z \end{pmatrix}_{\text{IC}} = \begin{pmatrix} 0.0124 \\ 0.4079 \\ -0.9129 \end{pmatrix}, \quad \begin{pmatrix} \hat{N}_X \\ \hat{N}_Y \\ \hat{N}_Z \end{pmatrix}_{\text{P-ONE}} = \begin{pmatrix} 0.1099 \\ -0.9591 \\ 0.2609 \end{pmatrix}. \quad (\text{A4})$$

2. Analysis

We begin by using Eq. (4) to determine the expected sidereal oscillation signal at each neutrino telescope as a function of the SME coefficients. Supplemental Fig. 5 shows the expected rate in the ν_μ sample and the ν_τ -enriched sample in each kaleidoscope over one sidereal day for different values of c_L^{TX} , as a ratio to the Standard Model expectation. Statistical uncertainties reflect predicted event rates after one year of neutrino kaleidoscope operation. In the ν_μ sample, the largest variations occur in IceCube due to the long baseline, while the variations are the same size in the ν_τ -enriched sample as the Standard Model prediction also depends linearly on the baseline. In both samples, the smallest statistical uncertainties occur in P-ONE due to the event rate enhancement from the 100 m decay region. For

this specific Lorentz violation scenario, oscillations occur at the first harmonic of the sidereal frequency. In general, SME-induced oscillations can occur as any integer harmonic of the sidereal frequency. We follow the procedure outlined in Ref. [107] to assess our sensitivity. For each detector, we generate 10^5 pseudoexperiments from the null hypothesis (no sidereal variations) and take the Fourier transform of the sidereal time distribution to determine the amplitude of each mode corresponding to the first four harmonics of the sidereal frequency. The first harmonic distributions for the ν_μ and ν_τ -enriched samples are shown in Fig. 8. As we are looking for amplitudes in excess of the null expectation, the vertical dotted lines show the one-tailed sensitivity at the $\{1, 2, 3, 4\}\sigma$ confidence level. The solid vertical lines indicate the expected amplitude of the first harmonic for the indicated values of c_L^{TX} . In this example, the ν_μ sample

TABLE IV. Sensitivity of the ν_μ sample in each kaleidoscope configuration to all relevant μ - τ a_L^μ and $c_L^{\mu\nu}$ SME coefficients at the 3σ C.L., considering one year of data at a muon energy of 5 TeV. The current limits on each coefficient are also shown, which come from sidereal variation searches at either IceCube [102] or MINOS [108].

Coefficient	P-ONE			
	KM3NeT	IceCube	(IP)	Current limit
$a_L^X/10^{-25}$ GeV	8.2	5.8	1.0	1.7×10^2 ([102])
$a_L^Y/10^{-25}$ GeV	8.2	5.8	1.0	1.7×10^2 ([102])
$c_L^{TX}/10^{-28}$	1.6	1.1	0.2	79 ([102])
$c_L^{TY}/10^{-28}$	0.7	1.0	0.2	79 ([102])
$c_L^{XX}/10^{-28}$	4.0	2.4	0.7	2.5×10^5 ([108])
$c_L^{XY}/10^{-28}$	5.2	5.4	0.4	1.2×10^5 ([108])
$c_L^{XZ}/10^{-28}$	2.0	1.2	0.7	7×10^4 ([108])
$c_L^{YY}/10^{-28}$	4.2	2.4	0.6	2.4×10^5 ([108])
$c_L^{YZ}/10^{-28}$	2.0	1.2	0.7	7×10^4 ([108])

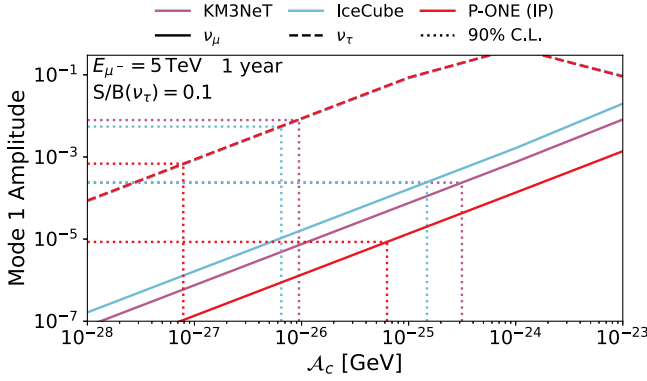


FIG. 10. Top: Sensitivity of each kaleidoscope to $\mathcal{A}_c$ at dimension 3 for ten years of data with a muon energy of 5 TeV. Separate results for a ν_μ and ν_τ -enriched sample are shown.

of the P-ONE (IP) neutrino kaleidoscope would rule out $c_L^{TX} = 7 \times 10^{-29}$ at $> 4\sigma$.

We repeat this exercise to determine the value of each SME coefficient that results in an amplitude at the 3σ sensitivity of the three neutrino kaleidoscopes. This analysis is carried out for each of the first four harmonics of the sidereal frequency, and the strongest constraint over the four modes is taken as the 3σ sensitivity of a given kaleidoscope to a given SME coefficient. Figure 9 depicts this analysis for c_L^{TX} and c_L^{TY} in both the ν_μ and ν_τ -enriched samples. The sensitivity of the ν_μ sample for all relevant a_L^μ and $c_L^{\mu\nu}$ coefficients is shown in Table IV. As discussed in Sec. IV, neutrino kaleidoscopes can improve upon existing limits on μ - τ SME coefficients by multiple orders of magnitude.

We now touch on analysis of higher-dimensional SME operators. As indicated by Eq. (5), in order to compute the sensitivity of each kaleidoscope to $\mathcal{A}_c^d$ from operators of mass-dimension d , we must first compute the sensitivity to

TABLE V. Sensitivity of each kaleidoscope configuration to $\mathcal{A}_c^d$ at the 90% CL, considering a ν_μ sample with one year of data at a muon energy of 5 TeV.

Dimension	$\mathcal{A}_c^d$ Units	KM3NeT	IceCube	P-ONE
ν_μ sample, $E_\mu = 5$ TeV, 1 year				
$d = 3$	GeV^1	3.1×10^{-25}	1.5×10^{-25}	6.3×10^{-26}
$d = 4$	GeV^0	1.2×10^{-28}	5.7×10^{-29}	2.3×10^{-29}
$d = 5$	GeV^{-1}	4.7×10^{-32}	2.2×10^{-32}	8.7×10^{-33}
$d = 6$	GeV^{-2}	1.8×10^{-35}	8.3×10^{-36}	3.2×10^{-36}
ν_τ sample, $S/B(\nu_\tau) = 0.1$, $E_\mu = 5$ TeV, 10 years				
$d = 3$	GeV^1	3×10^{-27}	2.1×10^{-27}	2.4×10^{-28}
$d = 4$	GeV^0	1.2×10^{-30}	7.8×10^{-31}	9.4×10^{-32}
$d = 5$	GeV^{-1}	4.5×10^{-34}	2.9×10^{-34}	3.7×10^{-35}
$d = 6$	GeV^{-2}	1.7×10^{-37}	1.1×10^{-37}	1.4×10^{-38}
ν_μ Sample, $E_\mu = 50$ TeV, 10 years				
$d = 3$	GeV^1	1.2×10^{-24}	5.4×10^{-25}	2.5×10^{-25}
$d = 4$	GeV^0	4.8×10^{-29}	2.2×10^{-29}	9.2×10^{-30}
$d = 5$	GeV^{-1}	1.9×10^{-33}	8.8×10^{-34}	3.4×10^{-34}
$d = 6$	GeV^{-2}	7.3×10^{-38}	3.6×10^{-38}	1.3×10^{-38}

A_c^3 and scale by the average neutrino energy $|\mathbf{p}| \approx E_\mu/2$. According to Eq. (A3), A_c^3 represents the amplitude of first-harmonic sidereal variations. Figure 10 shows the induced first harmonic amplitude as a function of A_c^3 for the ν_μ and ν_τ -enriched sample in each kaleidoscope. The dotted lines in Fig. 10 indicate the 90% CL sensitivity to A_c^3 computed using the psuedoexperiments described above. Table V shows the sensitivity of the nominal, tau-enriched, and high-energy kaleidoscope configurations introduced in Sec. IV to $\mathcal{A}_c^d$, for $d \in \{3, 4, 5, 6\}$. The $d = 6$ sensitivities in particular suggest sensitivity near the double-Planck suppressed regime.

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