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Fuzzy dark matter and nonstandard neutrino interactions

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We discuss novel ways in which neutrino oscillation experiments can probe dark matter. In particular, we focus on interactions between neutrinos and ultralight ("fuzzy") dark matter particles with masses of order 10^{-22} eV. It has been shown previously that such dark matter candidates are phenomenologically successful and might help ameliorate the tension between predicted and observed small scale structures in the Universe. We argue that coherent forward scattering of neutrinos on fuzzy dark matter particles can significantly alter neutrino oscillation probabilities. These effects could be observable in current and future experiments. We set new limits on fuzzy dark matter interacting with neutrinos using T2K and solar neutrino data, and we estimate the sensitivity of reactor neutrino experiments and of future long-baseline accelerator experiments. These results are based on detailed simulations in GLoBES. We allow the dark matter particle to be either a scalar or a vector boson. In the latter case, we find potentially interesting connections to models addressing various B physics anomalies.

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I. INTRODUCTION

Our ignorance about the particle physics nature of dark matter (DM) is so vast that viable candidate particles span more than 90 orders of magnitude in mass. At the heavy end of the spectrum are primordial black holes [1–5]. On the low end of the DM mass spectrum are models of "fuzzy dark matter" with a mass of order $m_\phi \sim 10^{-22}$ eV. The term "fuzzy" refers to the huge Compton wavelength $\lambda = 2\pi/m_\phi \simeq 0.4\ \mathrm{pc} \times (10^{-22}\ \mathrm{eV}/m_\phi)$ of such DM particles. Fuzzy DM has been studied mostly in the context of axions or other extremely light scalar fields [6–13]. Such DM candidates can be searched for in laboratory experiments using cavity-based haloscopes [14–16], helioscopes [17–20], LC circuits [21], atomic clocks [22,23], atomic spectroscopy [24] and interferometry [25], as well as accelerometers [26] and magnetometry [27–29]. Constraints on their parameter space can also be set using current gravitational wave detectors [30–32]. However, ultralight vector bosons are also conceivable fuzzy DM candidates [7,33–44]. The tightest constraints on the mass of fuzzy DM come from observations of large scale structure in the Universe, and very recent studies suggest that $m_\phi > 10^{-21}$ eV may be required [10,12,45].

Because of its macroscopic delocalization, fuzzy DM has the potential to resolve several puzzles related to structure formation in the Universe: (i) DM delocalization can explain the observed flattening of (dwarf) galaxy rotation curves towards their center [6], which is in tension with predictions from N-body simulations [46–48] ("cusp vs. core problem"); (ii) the lower than expected abundance of dwarf galaxies [49] ("missing satellites problem") can be understood in fuzzy DM scenarios because of the higher probability for tidal disruption of DM subhalos and because of the suppression of the matter power spectrum at small scales [9,50]; (iii) the apparent failure of many of the most massive Milky Way subhalos to host visible dwarf galaxies [51,52] ("too big to fail problem") is ameliorated since fuzzy DM predicts fewer such subhalos [9,50]. While it is conceivable that these galactic anomalies will disappear with a more refined treatment of baryonic physics in simulations [53–55], the possibility that DM physics plays a crucial role is far from excluded.

Our goal in the present paper is to highlight the tremendous opportunities for probing interactions of fuzzy DM in current and future neutrino oscillation experiments. These opportunities exist, in particular, in scenarios in which DM–neutrino interactions are flavor nonuniversal or flavor violating. In this case, even very feeble couplings between neutrinos and dark matter are sufficient for coherent forward scattering to induce a non-negligible

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potential for neutrinos, which affects neutrino oscillation probabilities and will thus alter the expected event rates and spectra in current and future neutrino oscillation experiments [56,57]. We will, in particular, derive constraints from T2K and solar neutrino neutrino data, and we will determine the sensitivities of DUNE and RENO. Similar effects have been considered previously in Ref. [56], where the focus has been on anomalous temporal modulation of neutrino oscillation probabilities.

II. DARK MATTER–NEUTRINO INTERACTIONS

Fuzzy DM can consist either of scalar particles ϕ or of vector bosons ϕ^μ. In the scalar case, the relevant terms in the Lagrangian are given by [58]

$$\mathcal{L}_{\text{scalar}} = \bar{\nu}_L^\alpha i\partial\!\!\!/ \nu_L^\alpha - \frac{1}{2} m_\nu^{\alpha\beta} \overline{(\nu_L^c)^\alpha} \nu_L^\beta - \frac{1}{2} y^{\alpha\beta} \phi \overline{(\nu_L^c)^\alpha} \nu_L^\beta, \quad (1)$$

where α, β are flavor indices and $y^{\alpha\beta}$ are the coupling constants. For vector DM, the Lagrangian is

$$\mathcal{L}_{\text{vector}} = \bar{\nu}_L^\alpha i\partial\!\!\!/ \nu_L^\alpha - \frac{1}{2} m_\nu^{\alpha\beta} \overline{(\nu_L^c)^\alpha} \nu_L^\beta + g Q^{\alpha\beta} \phi^\mu \bar{\nu}_L^\alpha \gamma_\mu \nu_L^\beta, \quad (2)$$

with the coupling constant g and the charge matrix $Q^{\alpha\beta}$. In both Lagrangians, m_ν is the effective Majorana neutrino mass matrix. The interaction term in Eq. (1) can be generated in a gauge-invariant way by coupling the scalar DM particle ϕ to heavy right-handed neutrinos in a seesaw scenario [58]. The interaction in Eq. (2) could arise, for instance, if the DM is the feebly coupled gauge boson corresponding to a local $L_\mu - L_\tau$ lepton family number symmetry, defined via $Q^{ee} = 0$, $Q^{\mu\mu} = 1$, $Q^{\tau\tau} = -1$. Alternatively, the DM particle could couple to the SM via mixing with a much heavier gauge boson Z' with flavor nonuniversal couplings. If the Z' boson has a mass of order $m_{Z'} \sim$ TeV, we expect the mixing-induced coupling g in Eq. (2) to be of order $g \sim m_\phi / m_{Z'}$. Intriguingly, we will see below that such tiny couplings may be within reach of neutrino oscillation experiments. Interesting candidates for a TeV-scale Z' boson mediating interactions of ultralight vector DM and neutrinos include an $L_\mu - L_\tau$ gauge boson, or a new gauge boson coupled predominantly to the second family of leptons. The latter possibility is of particular interest as such a particle could explain several recent anomalies in B physics [59]. We defer a detailed discussion of possible UV completions of Eqs. (1) and (2) to a forthcoming publication [60]. The mass of ϕ^μ can be generated either through the Stückelberg mechanism [61] or from spontaneous symmetry breaking in a dark Higgs sector.

III. PRODUCTION OF ULTRALIGHT DM PARTICLES

DM particles with masses $m_\phi \ll$ keV must have been produced nonthermally in the early Universe to avoid constraints on hot (i.e., relativistically moving) DM. The most popular way to achieve this is with the misalignment mechanism, which was first introduced in the context of QCD axion models [62–64] but can also be applied to other ultralight fields. For vector bosons, the misalignment mechanism has been discussed in Refs. [7,34,39]. In this case, the mechanism may also require a nonminimal coupling of ϕ^μ to the Ricci scalar to avoid the need for super-Planckian field excursions [7,39]. It might be possible to avoid these extra couplings in certain UV completions of the model [39]. The misalignment mechanism for vector bosons is more constrained if the bosons obtain their mass through a Higgs mechanism than in models with Stückelberg masses. In particular, it is required that the boson is massive at the temperature T_{osc} at which ϕ^μ begins to oscillate about its minimum [34]. This temperature is given by $T_{\text{osc}} \sim \sqrt{m_\phi M_{\text{Pl}}}$, where M_{Pl} is the Planck mass. We see that the dark Higgs boson thus needs to acquire a vacuum expectation value (vev) v at a critical temperature T_c much larger than $m_\phi \simeq gv$. Since typically $T_c \simeq v$ [65], this implies $g \lesssim \sqrt{m_\phi / M_{\text{Pl}}}$. We will, however, see that neutrino oscillation experiments are sufficiently sensitive to probe the relevant parameter region. As an alternative to the misalignment mechanism, the authors of Ref. [39] propose production of vector DM from quantum fluctuations during inflation, but argue that this mechanism can only account for all the DM in the Universe if $m_\phi > 10^{-6}$ eV.

IV. COHERENT FORWARD SCATTERING OF NEUTRINOS ON FUZZY DM

By inspecting Eqs. (1) and (2), we observe that scalar DM ϕ, treated as a classical field, alters the neutrino mass matrix, $m_\nu \to m_\nu + y\phi$, while vector DM ϕ^μ alters their effective 4-momenta, $p_\mu \to p_\mu + gQ\phi_\mu$. This can be seen as dynamical Lorentz violation [66]. For implementing these effects in simulation codes, we parametrize them in terms of a Mikheyev-Smirnov-Wolfenstein-like potential V_{eff} [67–70]. To do so, we use the equations of motion derived from Eqs. (1) and (2) (treating ϕ and ϕ^μ as classical fields) to derive a modified neutrino dispersion relation in the form

$$(E_\nu - V_{\text{eff}})^2 = \mathbf{p}_\nu^2 + m_\nu^2. \quad (3)$$

Here, E_ν, V_{eff}, and m_ν should be understood as 3×3 matrices. Neglecting the V_{eff}^2 term in Eq. (3), we read off that

$$V_{\text{eff}} = \frac{1}{2E_\nu} (\phi(y m_\nu + m_\nu y) + \phi^2 y^2) \qquad \text{(scalar DM)}, \quad (4)$$

$$V_{\text{eff}} = -\frac{1}{2E_\nu} (2(p_\nu \cdot \phi) gQ + g^2 Q^2 \phi^2) \qquad \text{(vector DM)}. \quad (5)$$

These expressions for $V_{\rm eff}$ should now be added to the Hamiltonian on which the derivation of neutrino oscillation probabilities is based. The classical DM field can be expressed as $\phi = \phi_0 \cos(m_\phi t)$ for scalar DM and as $\phi^\mu = \phi_0 \xi^\mu \cos(m_\phi t)$ for vector DM, where ξ^μ is a polarization vector. The oscillation amplitude ϕ_0 is related to the local DM energy density $\rho_\phi \sim 0.3\ {\rm GeV/cm^3}$ via [7,34,71]

$$\phi_0 = \frac{\sqrt{2\rho_\phi}}{m_\phi}. \qquad (6)$$

For the tiny DM masses we are interested in here, the period τ of field oscillations is macroscopic, $\tau \simeq 1.3\ {\rm yrs} \times (10^{-22}\ {\rm eV}/m_\phi)$ [72–75]. Note that in Eqs. (4) and (5), the terms linear in the coupling constants are valid when the DM mass is so low that the DM field can be treated as classical; the quadratic terms are approximately valid for any DM mass.

In deriving numerical results, we will, for definiteness, assume that the neutrino-DM couplings have a flavor structure given by $y = y_0(m_\nu/0.1\ {\rm eV})$ for scalar DM, where y_0 is a constant for scalar DM. This choice is motivated by the assumption of universal couplings of ϕ to right-handed neutrinos. For vector DM, we assume $Q = {\rm diag}(0,1,-1)$, as motivated by $L_\mu - L_\tau$ symmetry. We will moreover assume that contributions to the neutrino oscillation probabilities proportional to powers of $\cos(m_\phi t)$ are averaged. In other words, we assume the running time of the experiment to be much larger than τ. Equation (5) shows that for vector DM, $V_{\rm eff}$ depends on the polarization of the field. As it is unclear whether the initial polarization survives structure formation or is completely randomized even on scales ~1000 km relevant to long-baseline experiments, we will consider both the case of fully polarized and fully unpolarized DM. In the former case, we assume the polarization axis to be parallel to the ecliptic plane for definiteness. For fully polarized DM, the leading contribution to $V_{\rm eff}$ is linear in the small coupling g, while for unpolarized DM, ξ^μ varies randomly along the neutrino trajectory, so the leading contribution to $V_{\rm eff}$ is $\mathcal{O}(g^2)$. The same would be true for DM polarized in a direction transverse to the neutrino trajectory.

V. MODIFIED NEUTRINO OSCILLATION PROBABILITIES

We have implemented the potential from Eqs. (1) and (2) in GLoBES [76–79]. To facilitate integration of the predicted event rates over time, we evaluate the oscillation probabilities at several fixed times and interpolate them using a second-order polynomial in $\cos(m_\phi t)$. The latter can then be integrated analytically. We do not include long-term temporal modulation effects in our fits because the available long-baseline data are presented in time-integrated form. We have checked that including modulation with time in the fit does not significantly improve our results [60].

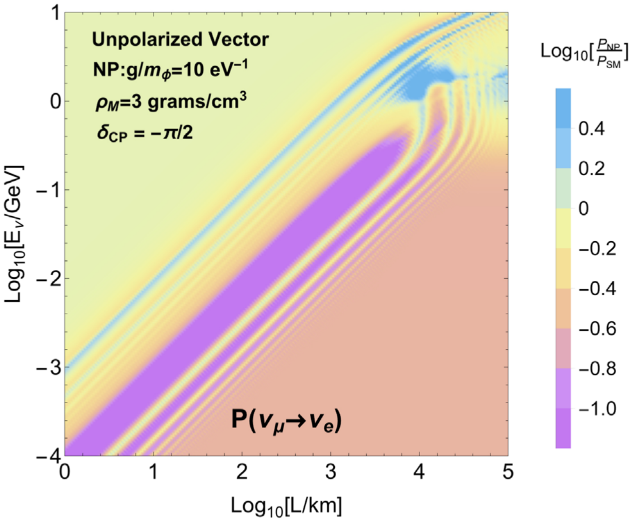


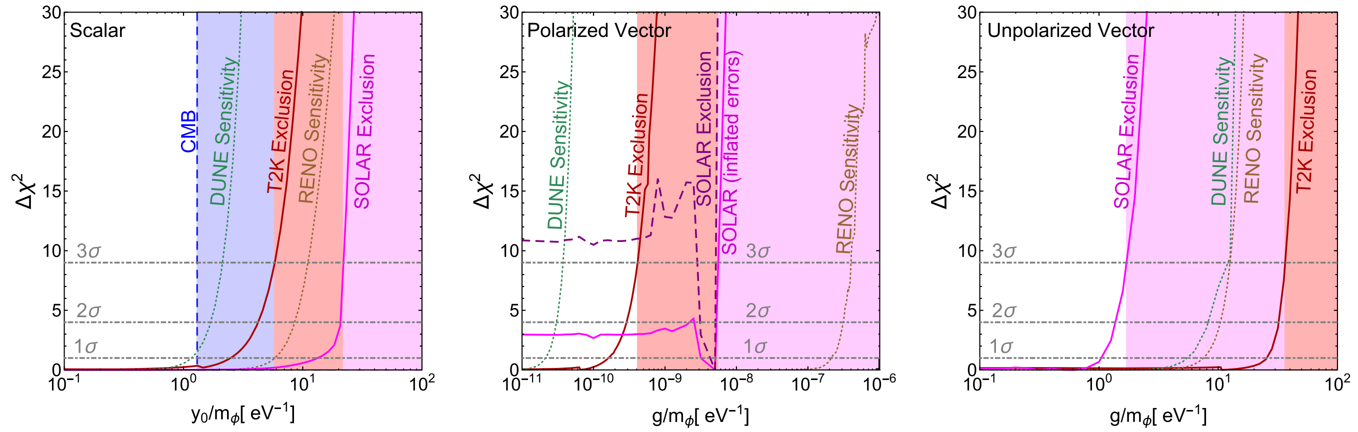
FIG. 1. Impact of neutrino-DM interactions on neutrino oscillation probabilities in $\nu_\mu \to \nu_e$, shown as a function of baseline L and energy E_ν. The color code shows the ratio $P_{\rm NP}/P_{\rm SM}$, where $P_{\rm NP}$ is the oscillation probability in the presence of unpolarized fuzzy vector DM coupled to neutrinos with $Q^{ee} = 0$, $Q^{\mu\mu} = 1$, $Q^{\tau\tau} = -1$, and $P_{\rm SM}$ is the standard oscillation probability.

In Fig. 1 we show the impact of neutrino-DM interactions on the oscillation probabilities as a function of neutrino energy E_ν and baseline L. We see that even for tiny couplings, substantial modifications are possible.

VI. SIGNALS IN LONG-BASELINE EXPERIMENTS

In Fig. 2 we collect various limits and future sensitivities on neutrino-DM interactions. For the T2K experiment we have developed a new GLoBES implementation [80,81], which we use to fit data based on an integrated luminosity of 6.6×10^{20} protons on target (pot) [82,83]. We have verified that we reproduce T2K's standard oscillation results to high accuracy before setting limits on DM. For the projected sensitivity of DUNE [84], we use the simulation code released with Ref. [85], corresponding to 14.7×10^{20} pot for neutrinos and antineutrinos each. To determine the sensitivity of RENO, we rely on a simulation based on Refs. [86–88] and corresponding to 3 years of data taking.

We observe that experimental sensitivities are superb, thanks to the scaling of $V_{\rm eff}$ with $1/m_\phi$; see Eqs. (4)–(6). For vector DM the sensitivity is more than 10 orders of magnitude better in the polarized case (left panel of Fig. 2) than in the unpolarized case. In the former case the sensitivity comes from the term linear in g, which is enhanced by $E_\nu/(g\phi)$ compared to the quadratic one. In general, experiments exclude values of the coupling



(a) (b) (c)

FIG. 2. $\Delta\chi^2$ curves from existing (thick solid curves) and future (thin dotted curves) analyses of neutrino oscillation data. Shaded parameter regions are excluded by the current data. Panel (a) applies to scalar DM, panel (b) is for vector DM with fixed polarization parallel to the ecliptic plane, and panel (c) is for unpolarized vector DM. For scalar DM, we have assumed $y = y_0(m_\nu/0.1\ \text{eV})$, while for vector DM, we use a coupling structure inspired by $L_\mu - L_\tau$ symmetry, namely, $Q^{ee} = 0$, $Q^{\mu\mu} = 1$, $Q^{\tau\tau} = -1$. In panel (a), we also show a limit based on the cosmological constraint on $\sum m_\nu$.

constant for which V_{eff} is much larger than the oscillation frequency $\sim m_\nu^2/(2E)$. For scalar or polarized vector DM, long-baseline experiments have a significant edge over reactor experiments, while for unpolarized DM, RENO is able to compete even with DUNE. The reason is the scaling of V_{eff} with $1/E$ according to Eqs. (4) and (5).

VII. SIGNALS IN SOLAR NEUTRINO EXPERIMENTS

Since solar neutrinos evolve adiabatically as they propagate out of the Sun, their survival probability in the electron flavor is given by

$$P_{ee}(E_\nu) = \sum_i |U^{\odot}_{ei}|^2 |U^{\oplus}_{ei}|^2, \qquad (7)$$

where $U^{\odot}$ and $U^{\oplus}$ are the effective leptonic mixing matrices at the center of the Sun and at Earth, respectively. Note that $U^{\odot}$ is strongly affected by both SM matter effects and DM-neutrino interactions, while $U^{\oplus}$ differs from the vacuum mixing matrix mainly through the DM term in our scenario. We neglect Earth matter effects as their impact on our results would be negligible [89].

We fit solar neutrino data from Borexino [90], Super-Kamiokande [91], and SNO [92,93], as collected in Ref. [89]. We illustrate in Fig. 3 how the presence of DM-neutrino interactions could improve the fit to solar neutrino data. For lstandard oscillations, we find $\chi^2/\text{dof} \simeq 22/20$, while the best-fit point for polarized vector DM yields $\chi^2/\text{dof} \simeq 12/19$. Even though we find in both cases an acceptable goodness of fit, standard oscillations are disfavored compared to the new physics hypothesis. This is a reflection of the fact that the upturn of the survival probability at low energy has not been observed yet [89]. As the preference for new physics in our fit is somewhat stronger than in a fit including full spectral data [94], we also show in Fig. 2 conservative constraints obtained by artificially inflating the error bars of all solar data points by a factor of 2.

Comparing limits from solar neutrino observations to those from long-baseline experiments, we see from Fig. 2 that for unpolarized vector DM, solar neutrinos offer the most powerful constraints. This is once again due to the $1/E_\nu$ dependence of V_{eff} in this case. Even though the same scaling applies to scalar DM, solar limits are much weaker because

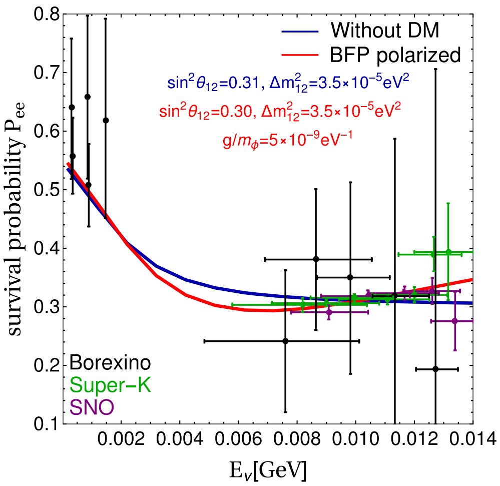


FIG. 3. Predicted ν_e survival probability for solar neutrinos at the SM best-fit point (blue) and at the best-fit point including neutrino interactions with polarized vector DM (red). The best-fit curves for unpolarized vector DM and for scalar DM are similar to the SM curve. We compared to data from Borexino [90], Super-Kamiokande [91], and SNO [92,93].

in our benchmark scenario, neutrino-DM interactions alter only neutrino masses (to which solar neutrinos have poor sensitivity) but not the mixing angles. This is also the reason why the limits from Ref. [56], which rely on variations in the mixing angle θ_{12}, are not applicable here.

VIII. COSMOLOGICAL CONSTRAINTS ON $\sum m_\nu$

As pointed out in Ref. [58], interactions between neutrinos and ultralight scalar DM are constrained by the requirement that the DM-induced contribution to the neutrino mass term does not violate the cosmological limit on the sum of neutrino masses, $\sum m_\nu$. We estimate this constraint in Fig. 2(a) by requiring that, at recombination (redshift $z = 1100$), the correction to the heaviest neutrino mass (taken at 0.05 eV) should not be larger than 0.1 eV.

IX. ASTROPHYSICAL NEUTRINOS

One may wonder whether neutrino-DM interactions could inhibit the propagation of astrophysical neutrinos [95] from distant sources [96]. The optical depth for such neutrinos is given by [97] $\tau_\nu(E_\nu) = \sigma_{\nu\phi}(E_\nu) X_\phi m_\phi^{-1}$, with the DM column density $X_\phi \equiv \int_{\mathrm{l.o.s}} dl \rho_\phi$, where the integral runs along the line of sight. For both galactic and extragalactic neutrino sources, we typically have $X_\phi \sim 10^{22}$–10^{23} GeV/cm^2 [97]. The scattering cross section for vector DM is approximately

$$\sigma_{\nu\phi}^T \simeq \frac{g^4}{8\pi} \frac{m_\nu^2}{E_\nu^2 m_\phi^2} \qquad \text{(vector DM)}, \tag{8}$$

where the superscript T indicates that, for simplicity, we have only considered the transverse polarization states of DM. For scalar DM the corresponding expression is

$$\sigma_{\nu\phi} \simeq \frac{g^4}{36\pi m_\nu^2} \qquad \text{(scalar DM)}. \tag{9}$$

Requiring $\tau_\nu < 1$, we obtain the constraints

$$\frac{g}{m_\phi} < 3 \times 10^8\ \mathrm{eV}^{-1} \left(\frac{E_\nu}{\mathrm{PeV}}\right)^{\frac{1}{2}} \left(\frac{0.1\ \mathrm{eV}}{m_\nu}\right)^{\frac{1}{2}} \left(\frac{10^{-22}\ \mathrm{eV}}{m_\phi}\right)^{\frac{1}{4}} \qquad \text{(vector DM)}, \tag{10}$$

$$\frac{y}{m_\phi} < 1.3 \times 10^{11}\ \mathrm{eV}^{-1} \left(\frac{m_\nu}{0.1\ \mathrm{eV}}\right)^{\frac{1}{2}} \left(\frac{10^{-22}\ \mathrm{eV}}{m_\phi}\right)^{\frac{3}{4}} \qquad \text{(scalar DM)}. \tag{11}$$

We see that these limits are much weaker than the constraints imposed by oscillation experiments (see Fig. 2) except for DM masses much larger than the ones considered here and for very low neutrino energies. At low energy, however, astrophysical neutrinos cannot be observed because of prohibitively large atmospheric backgrounds.

X. SUMMARY

To conclude, we have demonstrated that unique opportunities exist at current and future neutrino oscillation experiments to probe interactions between neutrinos and ultralight DM particles. The latter are an interesting alternative to weakly interacting massive particle DM, avoiding many of the phenomenological challenges faced by weakly interacting massive particles. A particularly interesting possibility, which we plan to explore further in an upcoming publication [60], is a possible connection to flavor nonuniversal new physics at the TeV scale, as motivated by recent anomalies in quark flavor physics.

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Note added.—Recently, Ref. [58] appeared, addressing similar questions. While the main focus of Ref. [58] (and also of the earlier Ref. [56]) is on scalar DM, we also consider DM in the form of ultralight gauge bosons. The authors of Ref. [58] have considered a larger range of experiments for setting limits than us, while our results are based on more detailed numerical simulations of the few most relevant experiments. Where our results are comparable to those of Ref. [58], they are in good agreement.

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