

Neutrino Lorentz invariance violation and ultralight axionlike dark matter searches at the European Spallation Source

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The dark matter conundrum stands out as one of the central challenges to understand in both particle physics and cosmology. The ultralight axionlike particle (UALP) is an appealing dark matter candidate that can be searched for in neutrino oscillation experiments. In this work, we examine the interaction among neutrinos and a UALP—such interaction might induce violations of the Lorentz and *CPT* symmetries. We assess the sensitivity to both the isotropic *CPT*-odd standard model extension coefficients $(a_L)^T$ and effective neutrino-UALP couplings $\tilde{g}$ at the next-to-next-generation neutrino oscillation experiment at the European Spallation Source.

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I. INTRODUCTION

One of the greatest mysteries of nature that has to be resolved is the dark matter (DM) dilemma. A plethora of proposals have been suggested in the literature. As an illustration, consider weakly interacting massive particles (WIMPs), including neutralinos, gravitinos, and sneutrinos in supersymmetric extensions of the standard model (SM) [1], as well as ultralight, weakly interacting particles, such as axions, which, as in the case of WIMPs, are appealing dark matter proposals due to their theoretical motivation and potential observational and experimental prospects to search for them [2,3].

The axion (a neutral pseudoscalar boson) was postulated as a solution to the so-called strong *CP* problem in the theory of strong interactions in QCD [4–7]. For reviews on axion and ultralight axionlike particles (UALPs) as dark matter and cosmology, see, e.g., Refs. [3,8–10]. An ALP is phenomenologically similar to the QCD axion, without solving the strong *CP* problem [10]. As in the case of the QCD axion, ultralight ALPs can behave as cosmological dark matter [11] and, in some scenarios, they can generate the correct DM abundance [2,9,10]. For instance, several ultralight scalars appear in some string theories [12–18]. Some searches of ALPs as dark matter include the

following: 21 cm intensity mapping (IM) [19,20], gravitational waves [21,22], electromagnetic radiation [23], Lyman- α forest [24], velocity acoustic oscillations (VAOs) [25], Hubble and Webb galaxy UV luminosities [26], axion star explosions [27], dwarf galaxies [28], time-dependent magnetic fields [29], pulsar timing array [30], as well as solid-state nuclear magnetic resonance [31].¹

As far as searches of ALPs as DM in the neutrino sector are concerned, in Ref. [39], the authors studied the phenomenology and astrophysical constraints derived from a neutrino interaction with a UALP as dark matter. The authors set limits on the neutrino-UALP couplings from the oscillations of neutrinos at several experimental configurations, including deep underground neutrino experiment (DUNE). Furthermore, the implications of this type of coupling with an axionlike particle as DM (with mass $m \sim 10^{-22}$ eV) were studied in the context of high-energy neutrinos from extragalactic sources [40]. Recently, there has been an interest in searches of neutrino nonstandard interactions with scalar fields at the European Spallation Source neutrino super beam (ESSnuSB) experiment [41,42]. Besides, in Ref. [43], the authors explore the potential to search for ultralight axionlike dark matter interactions with neutrons produced at the European Spallation Source.

From a phenomenological point of view, it has been argued that potential Lorentz invariance violations (LIVs) and violations of the *CPT* symmetry in the neutrino sector could emerge from neutrino nonstandard interactions with

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¹Further searches of ultralight scalars as DM candidates include atomic clocks [32], resonant-mass detectors [33], axion-photon couplings [34–37], and atomic gravitational wave detectors [38].

scalar fields [44–54]. For some reviews regarding Lorentz invariance and CPT violations in the neutrino sector, we refer the reader to Refs. [55–58]. Besides, for some studies regarding potential violations of the Lorentz and CPT symmetries in neutrino oscillation experiments, see, e.g., Refs. [59–66]. In this paper, we study the sensitivity to the isotropic CPT -odd SME coefficients $(a_L)^T$ and effective neutrino-UALP couplings $\tilde{g}$ at the proposed ESSnuSB experiment. Furthermore, we outline some cosmological implications of the neutrino-ultralight axionlike dark matter interaction.

The manuscript is organized as follows: in Sec. II, we introduce the theoretical framework and phenomenology of Lorentz invariance violation and the neutrino-ultralight axionlike dark matter coupling. In Sec. III, we discuss some cosmological aspects of the neutrino-UALP interaction. In Sec. IV, we describe the experimental configuration and methodology regarding searches of the aforementioned scenarios in the ESSnuSB proposal. In Sec. V, we show our results of the potential signatures of Lorentz violation and ultralight axionlike dark matter couplings via oscillations of neutrinos at the ESSnuSB experiment. Finally, in Sec. VI, we give our conclusions and comment on future assessments in this direction.

II. THEORY PRELIMINARIES

Within the standard model extension (SME) framework [67], LIV effects in the fermion sector are parametrized by the effective Lagrangian [68]

$$\mathcal{L}_{\text{eff}}^{\text{Fermion}} = \mathcal{L}_{\text{SM}}^{\text{Fermion}} + \mathcal{L}_{\text{LIV}} + \text{H.c.}, \quad (1)$$

$$\begin{aligned} \mathcal{L}_{\text{LIV}} = & -\frac{1}{2} \{ p_{\alpha\beta}^{\mu} \bar{\psi}_{\alpha} \gamma_{\mu} \psi_{\beta} + q_{\alpha\beta}^{\mu} \bar{\psi}_{\alpha} \gamma_5 \gamma_{\mu} \psi_{\beta} - i r_{\alpha\beta}^{\mu\nu} \bar{\psi}_{\alpha} \gamma_{\mu} \partial_{\nu} \psi_{\beta} \\ & - i s_{\alpha\beta}^{\mu\nu} \bar{\psi}_{\alpha} \gamma_5 \gamma_{\mu} \partial_{\nu} \psi_{\beta} \}, \end{aligned} \quad (2)$$

and in the case of neutrinos, it is convenient to define

$$(a_L)_{\alpha\beta}^{\mu} = (p + q)_{\alpha\beta}^{\mu}, \quad (c_L)_{\alpha\beta}^{\mu\nu} = (r + s)_{\alpha\beta}^{\mu\nu}, \quad (3)$$

where the $(a_L)_{\alpha\beta}^{\mu}$ coefficients are CPT -odd and break the CPT symmetry, while the $(c_L)_{\alpha\beta}^{\mu\nu}$ coefficients are CPT -even, preserving the CPT symmetry [55,62].

Nevertheless, if we are interested in examining the isotropic ($\mu = \nu = T$) LIV contributions in neutrino oscillation experiments, either the CPT -even SME coefficients $(c_L)_{\alpha\beta}^{TT} = c_{\alpha\beta}$ or the CPT -odd SME coefficients $(a_L)_{\alpha\beta}^T = a_{\alpha\beta}$, we can consider the corresponding Hamiltonian

$$H = H_{\text{vacuum}} + H_{\text{matter}} + H_{\text{LIV}}, \quad (4)$$

where H_{vacuum} and H_{matter} represent the neutrino Hamiltonian in vacuum and matter, respectively. Additionally, the contribution from the LIV sector is

$$H_{\text{LIV}} = \begin{pmatrix} a_{ee} & a_{e\mu} & a_{e\tau} \\ a_{e\mu}^* & a_{\mu\mu} & a_{\mu\tau} \\ a_{e\tau}^* & a_{\mu\tau}^* & a_{\tau\tau} \end{pmatrix} - \frac{4}{3} E_{\nu} \begin{pmatrix} c_{ee} & c_{e\mu} & c_{e\tau} \\ c_{e\mu}^* & c_{\mu\mu} & c_{\mu\tau} \\ c_{e\tau}^* & c_{\mu\tau}^* & c_{\tau\tau} \end{pmatrix}, \quad (5)$$

with E_{ν} being the neutrino energy, $a_{\alpha\beta} = |a_{\alpha\beta}| e^{i\phi_{\alpha\beta}}$, and $c_{\alpha\beta} = |c_{\alpha\beta}| e^{i\phi_{\alpha\beta}^c}$, accordingly. The factor $-4/3$ arises from the nonobservability of the Minkowski trace of the CPT -even SME coefficients $(c_L)_{\alpha\beta}^{\mu\nu}$ [62,68].

A. Impact of LIV parameters on the oscillation probability

In this subsection, we consider the impact of the isotropic LIV parameters $a_{\alpha\beta} = |a_{\alpha\beta}| e^{i\phi_{\alpha\beta}}$ on the neutrino oscillation probability in the context of the ESSnuSB experimental proposal. To illustrate such LIV effects at the probability level, we have employed the analytical expressions for both the $P(\nu_{\mu} \rightarrow \nu_e)$ appearance channel and $P(\nu_{\mu} \rightarrow \nu_{\mu})$ disappearance channel, as given in Sec. II of Ref. [63].

1. Electron neutrino appearance channel

As discussed in Refs. [63,64], the electron neutrino appearance probability is mostly sensitive to LIV effects from the $e - \mu$ and $e - \tau$ sectors, accordingly. Modifications of the standard neutrino oscillation probability (SM) in the presence of LIV parameters will show a significant deviation from the SM case depending on the value of the associated phase $\phi_{\alpha\beta}$.

The left panel of Fig. 1 considers the impact of LIV on the $P(\nu_{\mu} \rightarrow \nu_e)$ oscillation probability from the $e - \mu$ sector. We have fixed the magnitude $|a_{e\mu}| = 2 \times 10^{-23}$ GeV and chosen four values of the LIV phases $\phi_{e\mu}$: ($\phi_{\mu\tau} = 0, \pi/2, \pi, 3\pi/2$), displayed in brown-, blue-, orange-, and green-dashed lines, accordingly. Furthermore, the purple contour shows the neutrino flux times' cross section at the electron neutrino appearance channel, as presented in Fig. 1 of Ref. [69].

2. Muon neutrino disappearance channel

On the other hand, the muon neutrino disappearance probability is mostly sensitive to LIV effects from the $\mu - \tau$ sector [63].

The left panel of Fig. 2 considers the impact of LIV on the $P(\nu_{\mu} \rightarrow \nu_{\mu})$ oscillation probability from the $\mu - \tau$ sector. We set the magnitude $|a_{\mu\tau}| = 2 \times 10^{-23}$ GeV and choose four values of the LIV phases $\phi_{\mu\tau}$: ($\phi_{\mu\tau} = 0, \pi/2, \pi, 3\pi/2$), shown in brown-, blue-, orange-, and green-dashed lines, accordingly. Moreover, the purple contour displays the neutrino flux times' cross section at the muon neutrino disappearance channel, as presented in Fig. 1 of Ref. [71]. Besides, in the right panel of Fig. 2, we show our simulated electron and muon neutrino events, considering the standard

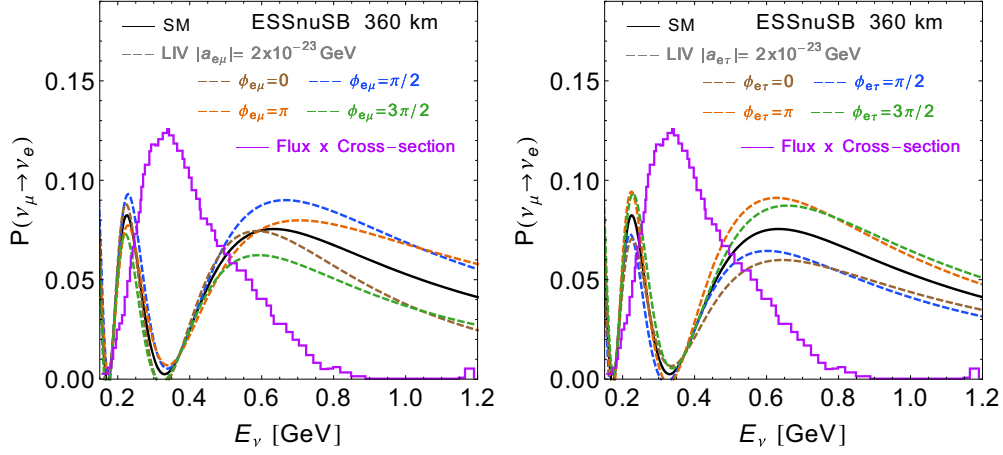


FIG. 1. $\nu_\mu \rightarrow \nu_e$ appearance probability as a function of the neutrino energy E_ν in the presence of LIV from the $e - \mu$ (left panel) and $e - \tau$ (right panel) sectors, respectively. All the oscillation parameters are fixed to their normal mass ordering (NO) best-fit values [70].

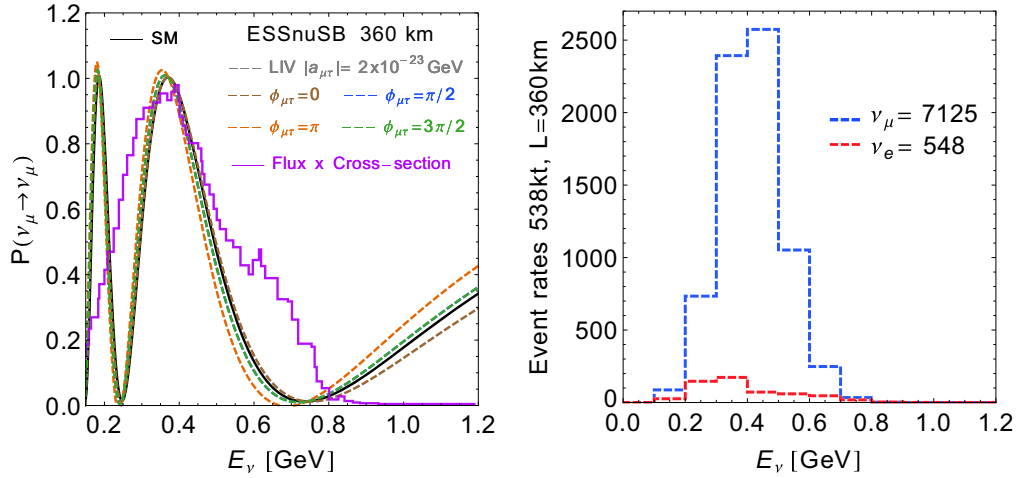


FIG. 2. $\nu_\mu \rightarrow \nu_\mu$ disappearance probability as a function of the neutrino energy E_ν in the presence of LIV from the $\mu - \tau$ sector (left panel). Expected reconstructed electron neutrino (ν_e) and muon neutrino (ν_μ) events at the ESSnuSB setup (right panel). All the oscillation parameters are fixed to their NO best-fit values [70] (see Sec. IV for details regarding the ESSnuSB experimental setup and simulation).

three-neutrino oscillations picture at the ESSnuSB $L = 360$ km configuration.

Although the effect of LIV from the $\mu - \tau$ sector appears to be marginal compared with those from the $e - \mu$ and $e - \tau$ sectors (Fig. 1), the sensitivity to the $a_{\mu\tau}$ parameter will be compensated by larger statistics from the muon neutrino disappearance channel, as displayed in the right panel of Fig. 2.

B. Neutrinophilic axionlike dark matter

The derivative interaction among neutrinos with a pseudoscalar ALP is given as [39,40,51]

$$-\mathcal{L}_{\text{eff}} = \tilde{g}_{\alpha\beta} \partial_\mu \varphi \bar{\nu}_L \alpha \gamma^\mu \gamma_5 \nu_L \beta, \quad (6)$$

where φ is a pseudoscalar ALP field, $\tilde{g}_{\alpha\beta} = \tilde{g}_{\beta\alpha}^*$ are the effective couplings among the ALP and the left-handed active neutrinos ν_L , and $\alpha, \beta = (e, \mu, \tau)$ are flavor indices. For instance, in some models, this type of interaction emerges [72–74].² In this scenario, by considering ultra-relativistic neutrinos and $\varphi \simeq \varphi(t)$, an axionlike particle, we can obtain the following relationship among the CPT -odd SME coefficients $(a_L)_{\alpha\beta}^\mu = a_{\alpha\beta}^\mu$ and the effective neutrino-ALP interaction [39,52]:

²Besides, within the M -theory axiverse [9,16], an ultralight ($m_\varphi \sim 10^{-15}$ eV) axionlike particle arises, with decay constant $F_\varphi \sim 10^{16}$ GeV.

$$a_{\alpha\beta}^{\mu} \bar{\nu}_{L\alpha} \gamma_{\mu} \gamma^5 \nu_{L\beta} \rightarrow \tilde{g}_{\alpha\beta} \partial^{\mu} \varphi \bar{\nu}_{L\alpha} \gamma_{\mu} \gamma^5 \nu_{L\beta}, \quad (7)$$

and the pseudoscalar field $\varphi \simeq \varphi(t)$ can be identified as a dark matter candidate (see Sec. III). Furthermore, in this scenario, violations of the Lorentz and *CPT* symmetries emerge via the *CPT*-odd SME coefficients $a_{\alpha\beta}^{\mu} \rightarrow \tilde{g}_{\alpha\beta} \partial^{\mu} \varphi$ [52]. For the case of φ with potential $V(\varphi) \simeq m_{\varphi}^2 \varphi^2$, locally, this field can be expressed as [75–78]

$$\varphi(t, X) \simeq \frac{\sqrt{2\rho_{\varphi,\odot}}}{m_{\varphi}} \sin(m_{\varphi}(t - \langle v_{\varphi} \rangle X)), \quad (8)$$

with $\rho_{\varphi,\odot}$ being the local UALP field density, $X = (x, y, z)$ the spatial components, and $\langle v_{\varphi} \rangle$ the virialized UALP velocity [which is of the order $\mathcal{O}(10^{-3})c$, see, e.g., Refs. [39,46,53]] in the Milky Way (MW).

In this study, we will consider a UALP density of $\rho_{\varphi} \simeq \rho_{\text{DM}} \simeq 2 \times 10^{-11} \text{ eV}^4$ (locally $\rho_{\text{DM},\odot} \sim 10^5 \rho_{\text{DM}}$ [79]).³ Thus, depending on the ALP mass m_{φ} , density, and effective couplings $\tilde{g}_{\alpha\beta}$ ($\tilde{g}_{ee} \lesssim 10^{-9} \text{ GeV}^{-1}$ for electron-ALP couplings [40]), for ultrarelativistic neutrinos, one can obtain bounds for the *CPT*-odd SME coefficients $a_{\alpha\beta}^{\mu}(t)$, as in the case where φ is considered to be scalar field dark matter [51,52].

The effective Lagrangian in Eq. (6) could induce violations of Lorentz invariance and *CPT* at neutrino oscillation experiments via the *CPT*-odd SME coefficients $a_{\alpha\beta}^{\mu} \rightarrow \tilde{g}_{\alpha\beta} \partial^{\mu} \varphi$, for instance, for the case of an ALP field φ with mass $m_{\varphi} \sim 10^{-15} \text{ eV}$. Hence, at present, the local value of the field amplitude in the MW would be $|\varphi_{\odot}| \sim 10^{12} \text{ eV}$ and, therefore, $|\dot{\varphi}_{\odot}| \simeq m_{\varphi} |\varphi_{\odot}| \simeq \sqrt{2\rho_{\varphi,\odot}} \sim 10^{-21} \text{ GeV}^2$. Thus, from Eqs. (7) and (8), the isotropic SME coefficients $a_{\alpha\beta}(t)$ are

$$a_{\alpha\beta}(t) = a_{\alpha\beta} \cos(m_{\varphi} t) \simeq \tilde{g}_{\alpha\beta} |\dot{\varphi}_{\odot}| \cos(m_{\varphi} t). \quad (9)$$

Comparably to the situation examined in [46], directional-dependent contributions ($a_{\alpha\beta}^X$) will be subleading due to the small virialized UALP velocity $\langle v_{\varphi} \rangle$

$$\begin{aligned} |a_{\alpha\beta}^X| &\simeq \tilde{g}_{\alpha\beta} |\nabla \varphi_{\odot} \cdot \hat{p}_{\nu}| \simeq \tilde{g}_{\alpha\beta} m_{\varphi} |\phi_{\odot} \langle v_{\varphi} \rangle \hat{v}_{\varphi} \cdot \hat{p}_{\nu}| \\ &\sim \tilde{g}_{\alpha\beta} \sqrt{2\rho_{\varphi,\odot}} \langle v_{\varphi} \rangle \sim 10^{-3} |a_{\alpha\beta}|, \end{aligned} \quad (10)$$

and these coefficients have been investigated within the framework of active-sterile neutrino oscillations and supernovae neutrino emission [52].

³From recent analyses, the estimation of the local DM density coincides within a range of $\rho_{\text{DM},\odot} \simeq 0.3\text{--}0.6 \text{ GeV}/\text{cm}^3$ [80–82].

III. COSMOLOGICAL ASPECTS OF THE NEUTRINO-UALP INTERACTION

At the cosmological level, the evolution of the interacting ALP field φ with neutrinos can be described through energy exchange among the two fluids [83,84],

$$\dot{\rho}_{\nu} + 4H\rho_{\nu} = Q, \quad (11)$$

$$\dot{\rho}_{\varphi} + 3H(\rho_{\varphi} + P_{\varphi}) = -Q, \quad (12)$$

where the explicit form of the energy exchange term, Q , is model dependent.⁴ In addition, the evolution of the Hubble parameter H can be obtained from the Friedmann equation

$$H^2 = \frac{8\pi G}{3} (\rho_r + \rho_b + \rho_{\varphi} + \rho_{\Lambda}), \quad (13)$$

where ρ_r , ρ_b , and ρ_{Λ} are the energy densities associated with radiation, nonrelativistic baryonic matter, and dark energy, respectively.

Furthermore, the evolution of the ALP field φ can be determined from its equation of motion

$$\ddot{\varphi} + 3H\dot{\varphi} + \frac{dV(\varphi)}{d\varphi} = -\frac{Q}{\dot{\varphi}}, \quad (14)$$

with $H = \dot{a}/a$ being the Hubble parameter, and a is the scale factor of the Universe. However, the corresponding energy exchange term Q for the case of the neutrino-UALP interaction would be [86]

$$Q \simeq \frac{d}{dt} (\partial_0 \varphi \langle \bar{\nu}_{L\alpha} \gamma^0 \gamma^5 \nu_{L\beta} \rangle) \simeq \frac{d}{dt} \left(\dot{\varphi} \left\langle \frac{\vec{\sigma}_{\nu} \cdot \vec{p}_{\nu}}{m_{\nu}} \right\rangle \right) \simeq 0, \quad (15)$$

where $\vec{\sigma}_{\nu}$ is the average spin of the neutrinos [87], and $\vec{\sigma}_{\nu} \simeq 0$ [88], unless we consider a neutrino beam with a particular spin orientation. Furthermore, the equation of motion for the ALP field would be

$$\ddot{\varphi} + 3H\dot{\varphi} + \frac{dV(\varphi)}{d\varphi} = -\frac{Q}{\dot{\varphi}} \simeq 0. \quad (16)$$

Therefore, in this scenario, the ALP may evolve as a free particle and could be considered a DM candidate, e.g., ultralight axionlike dark matter, with mass m_{φ} in the range $10^{-24} \text{ eV} \lesssim m_{\varphi} \lesssim 1 \text{ eV}$ [2,40,78].

⁴For instance, in the scenario explored by the authors of Ref. [85], the energy exchange term is $Q = \tilde{g} n_{\nu} \dot{\varphi}$, with $\tilde{g}$ being an effective coupling constant, φ a scalar field, and n_{ν} the neutrino number density. Within this scenario, φ can behave as dark energy [85]. However, if the energy exchange term is $Q \propto \dot{\varphi}$, the scalar field could act as dark matter [53].

IV. EXPERIMENTAL SETUP AND METHODOLOGY

Long-baseline neutrino oscillation experiments play a central role in both elucidating the mysteries within the standard three-neutrino oscillation paradigm and exploring other novel physics scenarios, including the potential breaking of the Lorentz and CPT symmetries, as well as the possibility of ultralight dark matter interactions with neutrinos.

In this section of the manuscript, we will focus on a long-baseline experimental configuration, the ESSnuSB initiative [89], which is a proposed next-to-next-generation accelerator-based neutrino oscillation experiment at the ESS, envisioned to determine and measure the leptonic CP -violating phase δ_{CP} [89,90]. It will consist of a water Cerenkov detector with a total mass of up to 538 kt, placed inside a deep mine in Sweden [69,89–92]. Moreover, within the ESSnuSB+ proposal [93], a monitored neutrino beam (based on the Enhanced Neutrino BEams from kaon Tagging (ENUBET) technology [94]) to improve neutrino cross section measurements at the ESS is contemplated [95].

From the ESSnuSB initiative, two potential locations have been investigated: $L \simeq 540$ km (Garpenberg mine) and $L \simeq 360$ km (Zinkgruvan mine) [90]; however, in this work, we will consider the configuration at a distance of $L \simeq 360$ km from the beam source (on-axis) at Lund [42,69,91,96]. Moreover, within this experimental setup, the mean neutrino energy would be around $E_\nu \sim 0.4$ GeV [69,89–91,96]. Searches of beyond the standard model (BSM) scenarios at ESSnuSB include sterile neutrinos [97,98], source and detector nonstandard neutrino interactions (NSI) [99], neutrino decay [100], nonunitary lepton mixing [101,102], leptonic flavor models [103,104], ultralight scalar dark matter [41], scalar-mediated neutrino nonstandard interactions [42], as well as quantum decoherence in neutrino oscillations [71].

In order to obtain sensitivities to the LIV coefficients using an ESSnuSB-like experimental setup, we use the GLOBES software [105,106] and its additional NSI tool *snu.c* [107,108], which was modified to implement the CPT -odd coefficients of the SME at the Hamiltonian level. Moreover, we use the ESSnuSB experimental configuration, as developed in Refs. [41,109], which considers a 10-year running time, evenly distributed among neutrino and antineutrino modes. In this analysis, we have considered the following Hamiltonian, $\tilde{H}(t)$, which in the presence of the CPT -odd LIV coefficients is

$$\tilde{H}(t) = H_0 + V_{\text{MSW}} + a_{\alpha\beta}(t), \quad (17)$$

where H_0 is the neutrino Hamiltonian in vacuum, V_{MSW} is the Mikheyev-Smirnov-Wolfenstein (MSW) potential, and the last term corresponds to the CPT -odd LIV Hamiltonian

$$a_{\alpha\beta}(t) = \tilde{g}_{\alpha\beta} \frac{\partial \varphi(t, X)}{\partial t} \simeq \tilde{g}_{\alpha\beta} \sqrt{2\rho_{\varphi,\odot}} \cos(m_\varphi t_\varphi). \quad (18)$$

Besides, for simplicity, we will consider an approach performed by the authors of Ref. [110], such that we will fix $\cos(m_\varphi t_\varphi) = 1$. Therefore, the isotropic CPT -odd SME coefficients will be related to the effective neutrino-UALP couplings as $a_{\alpha\beta} \simeq \tilde{g}_{\alpha\beta} \sqrt{2\rho_{\varphi,\odot}}$. To obtain sensitivities for the effective neutrino-UALP couplings, $\tilde{g}_{\alpha\beta}$, we consider a local DM density of $\rho_{\varphi,\odot} = 2 \times 10^{-6}$ eV⁴. For instance, at the ESSnuSB configuration ($L = 360$ km), the expected ultralight field mass sensitivity is 2.0×10^{-23} eV $\leq m_\varphi^{360 \text{ km}} \leq 8.5 \times 10^{-15}$ eV [41]. However, we should point out that the sensitivities derived for the effective couplings $\tilde{g}_{\alpha\beta}$ might change when averaging over the ALP oscillation time t_φ [39].

Moreover, to quantify the statistical significance of CPT -odd SME coefficients $a_{\alpha\beta}$ and effective couplings $\tilde{g}_{\alpha\beta}$, we set up a chi-square test analysis employing both neutrino and antineutrino datasets. The total χ^2 function is given as in Ref. [41]

$$\chi^2 = \sum_c \tilde{\chi}_c^2 + \chi_{\text{prior}}^2, \quad (19)$$

where the corresponding $\tilde{\chi}_c^2$ function stands for each channel c , with $c = (\nu_\mu(\bar{\nu}_\mu) \rightarrow \nu_e(\bar{\nu}_e), \nu_\mu(\bar{\nu}_\mu) \rightarrow \nu_\mu(\bar{\nu}_\mu))$, and is provided as in Ref. [111]

$$\tilde{\chi}_c^2 = \min_{\eta_j} \left[\sum_i^{n_{\text{bin}}} 2 \left\{ N_{i,\text{test}}^{3\nu+\text{LIV}}(\Omega, \Theta, \{\eta_j\}) - N_{i,\text{true}}^{3\nu} + N_{i,\text{true}}^{3\nu} \log \frac{N_{i,\text{true}}^{3\nu}}{N_{i,\text{test}}^{3\nu+\text{LIV}}(\Omega, \Theta, \{\eta_j\})} \right\} + \sum_j^{n_{\text{syst}}} \left(\frac{\eta_j}{\sigma_j} \right)^2 \right]. \quad (20)$$

Here, $N_{i,\text{true}}^{3\nu}$ are the simulated events at the i -th energy bin, considering the standard three-neutrino oscillations framework, $N_{i,\text{test}}^{3\nu+\text{LIV}}(\Omega, \Theta, \{\eta_j\})$ are the computed events at the i -th energy bin, including CPT -odd SME coefficients (one parameter at a time). In addition, $\Omega = \{\theta_{12}, \theta_{13}, \theta_{23}, \delta_{CP}, \Delta m_{21}^2, \Delta m_{31}^2\}$ is the set of neutrino oscillation parameters, while $\Theta = \{|a_{\alpha\beta}|, \phi_{\alpha\beta}, a_{\alpha\alpha}\}$ is the set of isotropic SME coefficients (nondiagonal $a_{\alpha\beta} = |a_{\alpha\beta}|e^{i\phi_{\alpha\beta}}$, diagonal $a_{\alpha\alpha}$), where $\{\eta_j\}$ are the nuisance parameters to account for the systematic uncertainties. Furthermore, σ_j are the systematic uncertainties, as described in Sec. III of Refs. [41,109]. Besides, to obtain our simulated events, we consider the neutrino oscillation parameters from Ref. [70] as *true* values. We show those values in Table I. In addition, the implementation of external input for the standard oscillation parameters on the χ^2 function is performed via Gaussian priors [111]

$$\chi_{\text{prior}}^2 = \sum_p^{n_{\text{priors}}} \frac{(\Omega_{p,\text{true}} - \Omega_{p,\text{test}})^2}{\sigma_p^2}. \quad (21)$$

TABLE I. Standard oscillation parameters used in our analysis [70]. We consider the NO throughout this study.

Oscillation parameter	Best-fit NO
θ_{12}	34.3°
θ_{23}	49.26°
θ_{13}	8.53°
Δm_{21}^2 [10^{-5} eV 2]	7.5
$ \Delta m_{31}^2 $ [10^{-3} eV 2]	2.55
δ_{CP}/π	1.08

The central values of the oscillation parameter priors, $\Omega_{p,\text{true}}$, are fixed to their best-fit values from Ref. [70], considering the normal mass ordering of neutrino masses, and σ_p corresponds to the 1σ confidence level (CL) of each parameter p .

V. RESULTS

In this section, we present our results of the projected sensitivities to the isotropic CPT -odd SME coefficients $a_{\alpha\beta}$ and the effective couplings of the neutrino-ultralight axion-like dark matter interaction $\tilde{g}_{\alpha\beta}$,⁵ considering the ESSnuSB 360 km ($L = 360$ km) configuration.

In Fig. 3, we display the projected 95% CL and 3σ sensitivities to the isotropic CPT -odd SME coefficients $a_{\alpha\beta}$, and the effective couplings of the neutrino-ultralight axionlike dark matter interaction $\tilde{g}_{\alpha\beta}$, at the ESSnuSB 360 km configuration. The left panel shows the sensitivities to the nondiagonal isotropic SME coefficients: $|a_{\alpha\beta}| \simeq [5-7] \times 10^{-23}$ GeV [red-, blue-, and green-solid lines ($\alpha\beta = e\mu, \mu\tau, e\tau$)], at 95% CL. Here, we have marginalized over the corresponding LIV phases, $\phi_{\alpha\beta}$, in the interval $[0-2\pi]$, as well as the standard oscillation parameters θ_{23} and δ_{CP} . Besides, the right panel displays the sensitivities to the nondiagonal effective neutrino-UALP couplings: $|\tilde{g}_{\alpha\beta}| \simeq 3 \times 10^{-11}$ eV $^{-1}$, at 95% CL. We observe that the expected sensitivities to these effective couplings at the ESSnuSB setup are comparable with limits ($\tilde{g}_{\alpha\beta} < 2 \times 10^{-11}$ eV $^{-1}$ [39]) from the proposed Jiangmen Underground Neutrino Observatory (JUNO) experiment [112].

In Fig. 4, we show the projected 95% CL and 3σ sensitivities to the flavor-conserving SME coefficients $a_{\alpha\alpha}$ and effective couplings $\tilde{g}_{\alpha\alpha}$, considering the ESSnuSB 360 km setup. The left panel displays the sensitivities to the isotropic (diagonal) SME coefficients: $a_{\alpha\alpha} \in (-4.4, 4.4) \times 10^{-23}$ GeV [red-, blue-, and green-solid lines ($\alpha\alpha = ee, \mu\mu, \tau\tau$)], at 95% CL, and we marginalized over the standard oscillation parameters θ_{23} and δ_{CP} , accordingly. Moreover, the right panel shows the sensitivities to the effective

couplings: $\tilde{g}_{\alpha\alpha} \in (-2.2, 2.2) \times 10^{-11}$ eV $^{-1}$, at 95% CL. As in the case of the nondiagonal effective couplings $\tilde{g}_{\alpha\beta}$, the expected sensitivities from the flavor-conserving sector at ESSnuSB are comparable with limits ($\tilde{g}_{\alpha\alpha} < 2 \times 10^{-11}$ eV $^{-1}$) from JUNO [39]. Besides, from Figs. 3 and 4, we observe that the ESSnuSB 360 km setup will be slightly more sensible to both the SME coefficients and effective couplings from the flavor-changing ($e - \tau$) and flavor-conserving ($\tau - \tau$) sectors.

A. Sensitivity impact by improved oscillation parameter measurements

In this subsection, we will discuss how the sensitivity to the LIV parameters $(a_L)^T$ may be affected by better measurements of the neutrino oscillation parameters. For example, the sensitivity may be slightly enhanced for the case of the nondiagonal $e - \mu$ sector, depending on the values of the leptonic CP phase. Furthermore, if we consider the scenario of maximal mixing for the atmospheric mixing angle, which is $\theta_{23} = 45^\circ$, the estimated sensitivities for the $e - \mu$ and $e - \tau$ sectors may be improved correspondingly.

In Fig. 5, we present the projected 95% CL sensitivities to the isotropic nondiagonal LIV coefficients $a_{\alpha\beta} = |a_{\alpha\beta}|e^{i\alpha\beta}$, considering the ESSnuSB 360 km setup. The left panel displays the projected sensitivities assuming two different values of the leptonic CP phase δ_{CP} : ($\delta_{CP} = 1.08\pi$, $\delta_{CP} = 1.5\pi$), presented as solid, dashed lines. Moreover, the right panel shows the expected sensitivities in the case of two distinct values for θ_{23} and δ_{CP} : ($\theta_{23} = 45^\circ$, $\theta_{23} = 49.26^\circ$) and ($\delta_{CP} = 1.08\pi$, $\delta_{CP} = 0$), displayed as solid, dashed lines. All the remaining oscillation parameters are fixed to their NO best-fit values, as shown in Table I. We observe that the projected sensitivities to the nondiagonal LIV parameters will be almost unaffected by assuming distinct values of δ_{CP} , exhibiting a mild sensitivity enhancement from the $e - \mu$ sector in the case of $\delta_{CP} = 0$, as displayed in the right panel of Fig. 5. The sensitivities to the other nondiagonal sectors are not modified in comparison with our benchmark value of $\delta_{CP} = 1.08\pi$. As a result, the effect of considering distinct values of the CP phase does not have a considerable influence for this particular type of new physics. A similar discussion follows for the case of the effective neutrino-UALP couplings $\tilde{g}_{\alpha\beta}$.

In Fig. 6, we consider the case of future improvements on the measurements of the neutrino mixing parameters θ_{23} and δ_{CP} , accordingly.⁶ In order to examine such impacts,

⁵Nevertheless, for relativistic neutrinos, the analysis with ultralight axionlike dark matter will be equivalent to the ultralight scalar dark matter (ULDM) case [51,52].

⁶At present, out of the complete set of neutrino oscillation mixing parameters, the oscillation parameters θ_{23} and δ_{CP} are the largest sources of uncertainties [70]. The current uncertainty in the measurement of the reactor mixing angle θ_{13} is at the percent level, while for the solar mixing parameters ($\Delta m_{21}^2, \theta_{12}$), particularly the solar mixing angle θ_{12} , uncertainty is considerable. These mixing parameters play a subleading role in accelerator-based oscillation experiments, such as the ESSnuSB proposal. As far as the atmospheric mass-squared difference Δm_{31}^2 is concerned, we fix it to its present NO best-fit value [70].

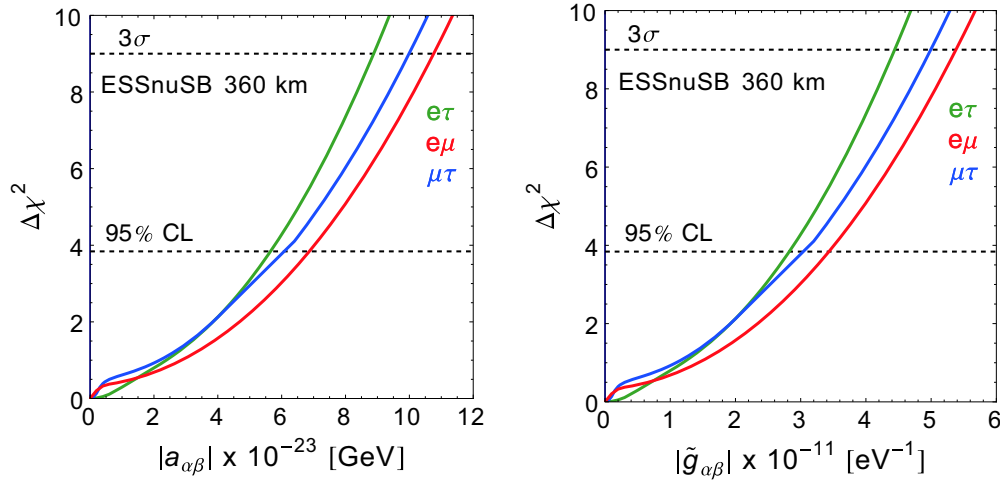


FIG. 3. The expected sensitivity regions: SME coefficients $|a_{\alpha\beta}|$ (left panel) and effective couplings $|\tilde{g}_{\alpha\beta}|$ (right panel), accordingly. We have marginalized over the corresponding LIV phases, $\phi_{\alpha\beta}$, in the interval $[0 - 2\pi]$, as well as θ_{23} and δ_{CP} , around their 1σ uncertainty [70]. All the remaining oscillation parameters are fixed to their NO best-fit values. See the text for a detailed explanation.

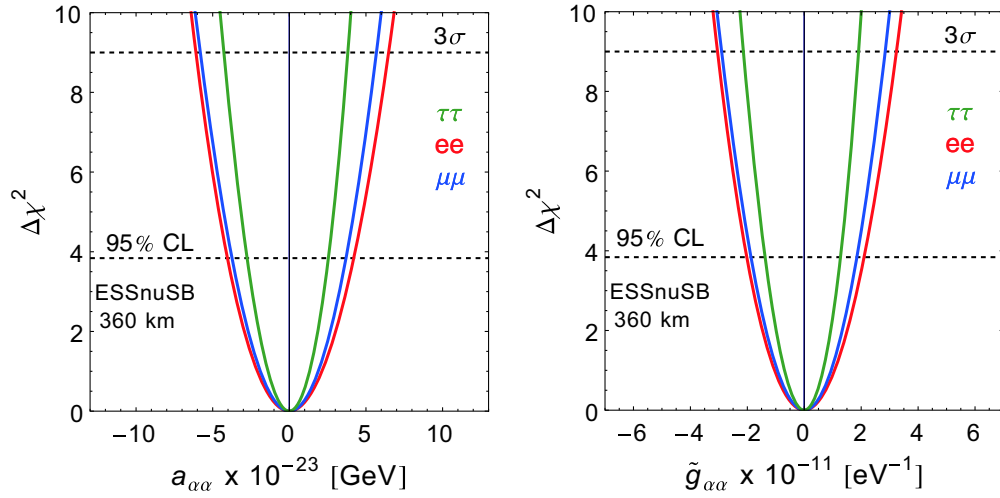


FIG. 4. The expected sensitivity regions: SME coefficients $a_{\alpha\alpha}$ (left panel) and effective couplings $\tilde{g}_{\alpha\alpha}$ (right panel), accordingly. We marginalize over θ_{23} and δ_{CP} around their 1σ uncertainty [70]. All the remaining oscillation parameters are fixed to their NO best-fit values. See the text for a detailed explanation.

we will assume a future 1σ uncertainty of 3% for the atmospheric mixing angle θ_{23} and 5% for the case of the leptonic CP -violating phase δ_{CP} . The left panel displays the projected sensitivities to the nondiagonal LIV coefficients $|a_{\alpha\beta}|$, where dotted lines correspond to $\theta_{23} = 45^\circ$, while dashed lines consider our benchmark values from Table I. In contrast, the right panel shows the expected sensitivities to the diagonal LIV coefficients $a_{\alpha\alpha}$, where dashed lines consider $\theta_{23} = 45^\circ$, while solid lines assume our standard oscillation values from Table I.

From the left panels of Figs. 3 and 6 (dashed lines), we observe that for our standard benchmark values, the

impact of improved oscillation parameter measurements on the future sensitivities to the nondiagonal LIV coefficients $|a_{\alpha\beta}|$ is marginal. However, if we consider the case with $\theta_{23} = 45^\circ$ (dotted lines), there could be a considerable enhancement of the sensitivities from the $e - \mu$ and $\mu - \tau$ sectors, while the sensitivity in the $e - \tau$ sector shows only a mild improvement. Besides, in the case of the diagonal LIV coefficients $a_{\alpha\alpha}$ (right panel of Fig. 6), only a significant sensitivity improvement may be expected from the $\mu - \mu$ sector. A similar discussion applies to the case of the effective neutrino-UALP couplings: $\tilde{g}_{\alpha\beta}$ and $\tilde{g}_{\alpha\alpha}$.

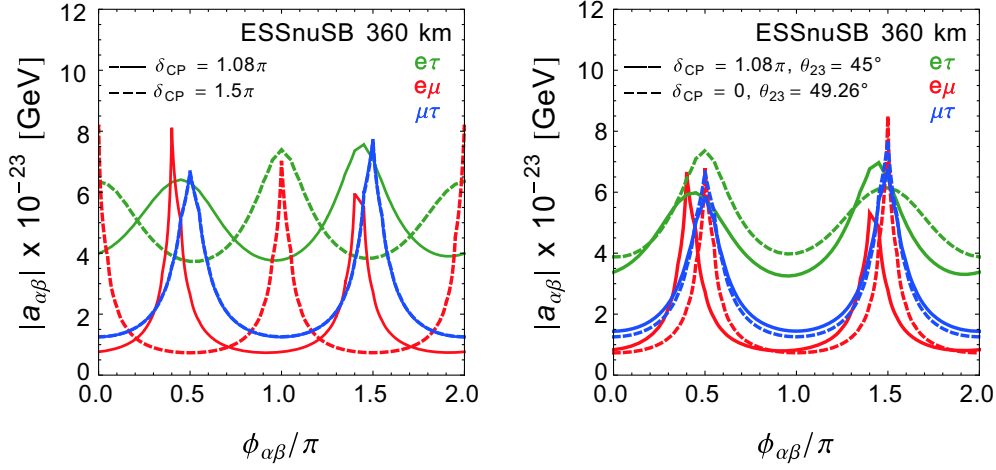


FIG. 5. Expected sensitivity regions in the $a_{\alpha\beta}$ vs $|\phi_{\alpha\beta}|$ projection plane. The red, green, and blue lines correspond to the LIV coefficients from the $\alpha\beta = (e\mu, e\tau, \mu\tau)$ sectors, respectively. The left panel considers the sensitivity influence of assuming different values of the leptonic CP phase δ_{CP} : ($\delta_{CP} = 1.08\pi, \delta_{CP} = 1.5\pi$), displayed as solid, dashed lines. The right panel considers the sensitivity impact in the case of two distinct values for θ_{23} and δ_{CP} : ($\theta_{23} = 45^\circ, \theta_{23} = 49.26^\circ$) and ($\delta_{CP} = 1.08\pi, \delta_{CP} = 0$), shown as solid, dashed lines. All the remaining oscillation parameters were fixed to their NO best-fit values from Ref. [70].

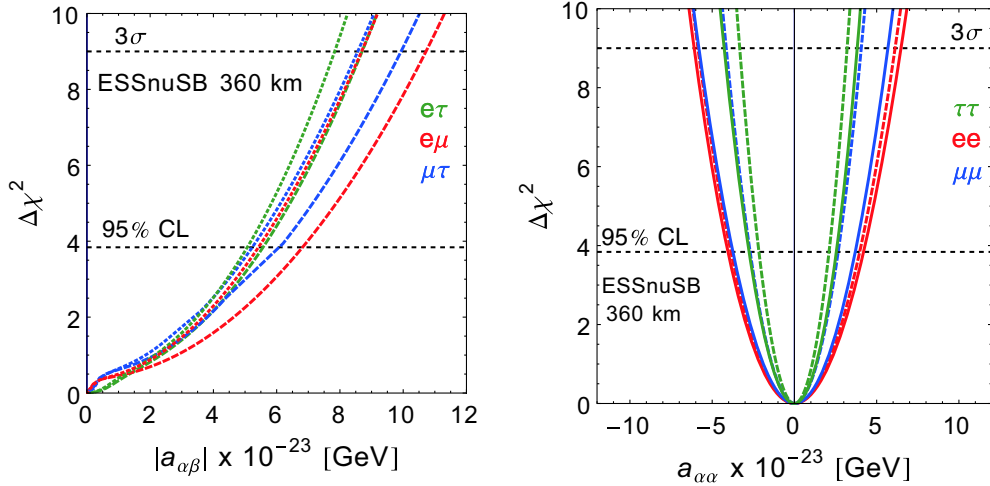


FIG. 6. Expected sensitivity regions in the $|a_{\alpha\beta}|$ (left panel) and $a_{\alpha\alpha}$ (right panel) projection planes, accordingly. The red, green, and blue lines correspond to the LIV coefficients from the $\alpha\beta = (e\mu, e\tau, \mu\tau)$ and $\alpha\alpha = (ee, \tau\tau, \mu\mu)$ sectors, respectively. We marginalize over θ_{23} and δ_{CP} assuming future 1σ uncertainties of 3% and 5%, accordingly. For the nondiagonal LIV coefficients, we marginalize over the corresponding LIV phases, $\phi_{\alpha\beta}$, in the full $[0 - 2\pi]$ range. All the remaining oscillation parameters are fixed to their NO best-fit values from [70]. Refer to the text for a detailed explanation.

Regarding astrophysical limits on the effective neutrino-UALP couplings $\tilde{g}_{\alpha\beta}$, the most restrictive constraints originate from the decay process: $\nu_\alpha \leftrightarrow \nu_\beta + \varphi$, which establishes $\tilde{g}_{\alpha\beta} \lesssim 10^{-10} \text{ eV}^{-1}$ [39]. For a summary of current limits and projected sensitivities to the isotropic SME coefficients ($a_{\alpha\beta}$, $a_{\alpha\alpha}$) and the effective neutrino-UALP couplings ($\tilde{g}_{\alpha\beta}$, $\tilde{g}_{\alpha\alpha}$) at ESSnuSB 360 km, and other experimental configurations, see Table II.

VI. CONCLUSION

The dark matter puzzle stands out as one of the main challenges to understand in both particle physics and cosmology. UALP is an appealing dark matter candidate that can be searched for in neutrino oscillation experiments. Besides, this type of neutrino-UALP interaction could induce breakdowns of the Lorentz and CPT symmetries in the neutrino sector. At the cosmological level, the ALP

TABLE II. Summary of current limits and projected sensitivities (shown in parentheses) from beyond the standard model: neutrino LIV, neutrino-UALP interaction, and neutrino-UALP decay processes relevant to this study.

BSM process	Limit (Future sensitivity)
Neutrino LIV	$ a_{e\mu} < 1.8 \times 10^{-23}$ GeV, Super-Kamiokande [113]
Neutrino LIV	$ a_{e\tau} < 2.8 \times 10^{-23}$ GeV, Super-Kamiokande [113]
Neutrino LIV	$ a_{\mu\tau} < 2.9 \times 10^{-24}$ GeV, IceCube [114]
Neutrino LIV	$a_{\tau\tau} < 2 \times 10^{-26}$ GeV, IceCube [110]
Neutrino LIV	$(a_{\alpha\beta} \simeq 1 \times 10^{-23} \text{ GeV})$, DUNE [59,63,64]
Neutrino LIV	$(a_{\alpha\beta} \simeq 5 \times 10^{-23} \text{ GeV})$, Hyper-K [63]
Neutrino LIV	$(a_{\alpha\beta} \simeq [1 - 4] \times 10^{-23} \text{ GeV})$, ICAL [64]
Neutrino LIV	$(a_{\alpha\beta} \simeq [2 - 7] \times 10^{-23} \text{ GeV})$, T2HK [64]
Neutrino LIV	$(a_{\alpha\beta} \lesssim 10^{-30} \text{ GeV})$, UHE neutrinos [45,46]
Neutrino LIV	$(a_{\alpha\beta} \simeq [5 - 7] \times 10^{-23} \text{ GeV})$, ESSnuSB 360 km
Neutrino LIV	$(a_{\alpha\alpha} \in (-4.4, 4.4) \times 10^{-23} \text{ GeV})$, ESSnuSB 360 km
Neutrino-UALP	$(\tilde{g}_{\alpha\beta} \simeq 10^{-11} - 10^{-12} \text{ eV}^{-1})$, DUNE [39]
Neutrino-UALP	$\tilde{g}_{\tau\tau} < 3 \times 10^{-13} \text{ eV}^{-1}$, IceCube [110]
Neutrino-UALP	$\tilde{g}_{\alpha\beta} \lesssim 10^{-13} \text{ eV}^{-1}$ [53]
Neutrino-UALP	$(\tilde{g}_{\alpha\beta} < 2 \times 10^{-11} \text{ eV}^{-1})$, JUNO [39]
Neutrino-UALP	$(\tilde{g}_{\alpha\beta} \simeq 3 \times 10^{-11} \text{ eV}^{-1})$, ESSnuSB 360 km
Neutrino-UALP	$(\tilde{g}_{\alpha\alpha} \in (-2.2, 2.2) \times 10^{-11} \text{ eV}^{-1})$, ESSnuSB 360 km
$\nu_\alpha \leftrightarrow \nu_\beta + \varphi$	$\tilde{g}_{\alpha\beta} \lesssim 10^{-10} \text{ eV}^{-1}$ [39]

can act as DM, and this is because the neutrino-UALP energy exchange term is $Q \simeq 0$, as described in Sec. III.

In this paper, we have studied the sensitivity to the isotropic CPT -odd SME coefficients $(a_L)^T$ and the effective couplings $(\tilde{g})$ of the neutrino-ultralight ALP interaction at the next-to-next-generation long-baseline neutrino experiment ESSnuSB, and our results are summarized in Table II. However, improved measurements of the neutrino oscillation parameters, such as the atmospheric mixing angle θ_{23} , may enhance the projected sensitivity of the LIV parameters $(a_L)^T$. Therefore, the ESSnuSB configuration represents an appealing platform to investigate both LIV and potential neutrino-UALP interactions. For instance, the expected sensitivity at the ESSnuSB 360 km configuration is comparable with limits from JUNO [39]. It would be

interesting to study the complementarity among the upcoming ESSnuSB and JUNO experiments within this scenario.

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