

Ultralight dark matter in long-baseline accelerator neutrino oscillations

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(Received 17 April 2026; accepted 9 June 2026; published 8 July 2026)

We present a systematic study of the effects of ultralight dark matter (ULDM) on neutrino oscillations using the latest long-baseline data from the T2K and NO ν A experiments. Our analysis covers both flavor-universal and flavor-general scalar interactions as well as vector interactions associated with the $L_e - L_\mu$ and $L_\mu - L_\tau$ gauge symmetries. Importantly, we explicitly consider the coherence properties of the ULDM by incorporating the resulting stochastic fluctuations into our statistical analysis. We find that in the low-mass regime, $m_\phi \lesssim 10^{-17}$ eV, where the stochastic effects are maximal, the constraints on the ULDM couplings are relaxed by roughly an order of magnitude compared to those in the high-mass regime, $m_\phi \gtrsim 10^{-15}$ eV, where such fluctuations are effectively averaged out. While the combined T2K and NO ν A datasets impose nontrivial exclusion limits on the ULDM interactions, we do not find statistically significant evidence that these effects can alleviate the current tension in determining the charge-parity (CP) violating phase δ_{CP} between the two experiments. Therefore, it will be essential for future high-precision facilities to further probe the ULDM scenarios and achieve a definitive measurement of δ_{CP} .

DOI: [10.1103/twkz-l635](https://doi.org/10.1103/twkz-l635)

I. INTRODUCTION

Neutrino physics has now entered the era of precision measurements [1]. The recent release of observational datasets from the Tokai-to-Kamioka (T2K) [2] and NuMI Off-axis ν_e Appearance (NO ν A) [3] experiments, culminating in a joint analysis presented in Ref. [4], signifies that the measured precision of some key oscillation parameters—most notably the atmospheric mass-squared splitting Δm_{32}^2 and the mixing angle θ_{23} —has reached an unprecedented level, crossing the sub-2% threshold. These stringent experimental constraints not only provide a decisive foundation for addressing unresolved standard oscillation questions, such as the CP -violating phase δ_{CP} and the neutrino mass ordering, but also offer an exceptionally sensitive platform for probing subtle signals of physics beyond the Standard

Model (SM). In particular, recent phenomenological analyses further exploit the T2K and NO ν A datasets to probe dark-sector physics through neutrino oscillations [5,6], including the ultralight dark matter (ULDM) with a mass of about $m_\phi \sim 10^{-22}$ eV [7,8].

The nature of dark matter (DM), whose existence is supported by robust evidence of galactic rotation curves [9], galaxy cluster movement [10,11], and cosmic microwave background (CMB) radiation [12,13], remains one of the most compelling puzzles in modern physics. Although the weakly interacting massive particles have long been regarded as the leading candidates [14], their parameter space has been stringently constrained by the null results of direct detection experiments, such as LUX [15] and PandaX-II [16]. Furthermore, the conventional DM models have encountered problems at the small-scale level [17]. In order to tackle these issues, numerous alternatives have been proposed, including the primordial black holes [18] and the axions [19], as well as the very light particles [20,21]. A good review on recent advances could be found, e.g., in Ref. [22].

The ULDM regime is a highly motivated topic within the DM community [23]. In addition to its implications in cosmology, the ultralight bosonic DM has been shown to aid with the questions of supermassive black holes [24], pulsar timing arrays [25], Stückelberg axions [26], and the age-velocity dispersion relation of the Milky Way disk [27].

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The ULDM could have further interesting effects in neutrino oscillation experiments, where even feeble couplings could lead to notable signatures in neutrino oscillations in terrestrial experiments [7,8,28–30]. Such effects have been analyzed in various contexts, including an improved fit to the reactor neutrino data from KamLAND [31], as well as the sensitivity projections for next-generation facilities, such as DUNE and JUNO [7,8,31] and the proposed ESS ν SB experiment [32]. Beyond static matter-like effects, the ULDM interactions may induce observable temporal variations [33–35]. The ULDM effect has also been considered in neutrino experiments in the case of pseudoscalar [36,37] and vector fields [7,38–41], which hold similarly promising prospects for future experiments.

Although extensive research has explored the ULDM constraints in neutrino experiments, certain physical nuances within the prevailing analytical frameworks warrant more rigorous scrutiny. First, due to its macroscopic de Broglie wavelength, the ULDM at local galactic densities can be approximated as a classically oscillating background field [42,43]. Most existing studies model this field as a single-mode background with static amplitude and phase and remove phase-dependent contributions in observables through time averaging. In this article, we argue that the realistic DM field is constrained by its finite coherence and should instead be regarded as a superposition of multiple near-degenerate frequency modes, which in turn leads to stochastic fluctuations in its effective amplitude and phase. When the experimental measurement or exposure time is significantly shorter than the DM coherence time, these fluctuations cannot be efficiently averaged out and, thus, constitute a non-negligible physical effect [44,45]. Second, with respect to the construction of the scalar ULDM potential term, and assuming an independent (non-ULDM) origin for neutrino masses, the induced potential is inherently coupled to the intrinsic neutrino mass matrix [46,47]. Although this connection has been theoretically noticed, the extent to which the absolute neutrino mass scale m_ν directly influences the magnitude of the ULDM-induced potential—and consequently the robustness of the resulting experimental limits—has not been systematically scrutinized in previous phenomenological studies. This simplification potentially neglects a nontrivial physical dependence that extends beyond the standard oscillation parameters.

To address these scientific nuances, we perform in this work a systematic exclusion analysis of the ULDM parameter space across a broad mass range from 10^{-23} to 10^{-12} eV, utilizing the most recent joint datasets from T2K [2] and NO ν A [3]. We aim to establish the most rigorous constraints to date by incorporating updated experimental observations. Crucially, our analysis explicitly incorporates the stochastic fluctuations of the DM field and examines their impact across different mass regimes, as determined by the interplay between the DM coherence

time and the experimental exposure window. Operating within a joint likelihood framework, we extend our investigation across scalar and multiple vector-field models (including $L_e - L_\mu$ and $L_\mu - L_\tau$) and investigate how the absolute neutrino mass scale m_ν leads to a systematic shift in the exclusion limits for the scalar scenario.

This article is organized as follows. In Sec. II, the theoretical formalism for neutrino interactions with the ULDMs is reviewed in light of the neutrino matter potentials. The datasets from the T2K and NO ν A experiments and also the analysis methods are described in Sec. III. We present our phenomenological analysis of scalar and vector ULDMs in Sec. IV. The conclusion made in Sec. V synthesizes the results of the joint analysis and discusses future experimental prospects.

II. ULTRALIGHT DARK MATTER IN NEUTRINO OSCILLATIONS

In this section, we review the theoretical framework for the scalar and vector DM fields in the ultralight regime and discuss their phenomenological implications on the neutrino matter potentials in terrestrial experiments.

A. Ultralight dark matter background

When the ULDM is present, neutrinos in terrestrial experiments can be seen to drift in a dark sea. The ULDM particles exhibit high occupation numbers and sufficiently low velocities to be treated as a classical coherent field [47]:

$$\phi(t) = \phi_0 \cos(m_\phi t + \alpha), \quad (1)$$

where m_ϕ is the DM mass, t denotes the laboratory time, and α is an arbitrary initial phase. Given the Solar System’s nonrelativistic velocity $v \sim 10^{-3}$ relative to the Galactic Center, this field is dominated by the temporal term $m_\phi t$. We can therefore drop the spatial dependence. The DM field $\phi(t)$ can be regarded as a superposition of many field modes with randomly distributed phases. The resulting oscillation amplitude ϕ_0 emerges from the interference among these modes and can be statistically understood as a random walk in the complex plane, leading to a Rayleigh distribution [45]

$$p(\phi_0) = \frac{2\phi_0}{\phi_{\text{DM}}^2} \exp\left(-\frac{\phi_0^2}{\phi_{\text{DM}}^2}\right), \quad (2)$$

where $\phi_{\text{DM}} = \frac{\sqrt{2\rho_{\text{DM}}}}{m_\phi}$ is determined by the local DM average density $\rho_{\text{DM}} \simeq 0.3 \text{ GeV/cm}^3$ [48,49]. The sampling number N_{DM} is determined by the ratio of the experimental exposure time T_{exp} to the coherence time $\tau_c \equiv 2\pi/(m_\phi v^2)$ [50], which characterizes the dephasing of the net field.

When the running time of an experiment is $T_{\text{exp}} \sim 10$ yr, the DM fields with mass $m_\phi \gtrsim 10^{-23}$ eV complete many oscillation cycles during the data-taking period. Accordingly, phase averaging can be applied when computing event rates or oscillation probabilities, and this treatment will be adopted throughout our analysis. For long-baseline neutrino experiments with propagation distances of the order of a few hundred kilometers, neutrinos will undergo one or multiple oscillation periods of the DM fields for $m_\phi \gtrsim 10^{-12}$ eV. In this regime, the time-dependent perturbation is averaged over a period at the level of the time integral in the evolution operator, so that the contribution that is linear in ϕ does not enter the effective Hamiltonian. Thus, in this work, we will not address the DM mass region with $m_\phi \gtrsim 10^{-12}$ eV.

B. Effective interactions with neutrinos

Neutrino propagations in the dark medium can subsequently affect the oscillation probabilities. In the case of scalar DM, the relevant Lagrangian can be written as [47]

$$\mathcal{L}_{\text{eff}}^{\text{scalar}} = \bar{\nu}_L^\alpha i \partial \nu_L^\alpha - \frac{1}{2} m_\nu^{\alpha\beta} (\bar{\nu}_L^c)^\alpha \nu_L^\beta - \frac{1}{2} y^{\alpha\beta} \phi (\bar{\nu}_L^c)^\alpha \nu_L^\beta, \quad (3)$$

where ν_L is the left-handed neutrino field, m_ν is the effective neutrino mass matrix, y contains the coupling constants of the neutrino and DM interactions, and α, β are the flavor indices for neutrinos.

The scalar field in Eq. (1) can have notable implications in neutrino experiments where neutrinos propagate underground. The effective neutrino Lagrangian specified by Eq. (3) corresponds to the transformation $m_\nu \rightarrow m_\nu + y\phi$, where m_ν receives an additional contribution $y\phi$ from the neutrino-DM interaction. When the scalar mass m_ϕ matches the propagation length of the neutrinos, coherent scattering between the DM and neutrino fields can lead to observable distortions in the oscillation probabilities. Furthermore, the time dependency of ϕ means that this distortion varies over time. This modulation may be testable in neutrino experiments where the lifetime is sufficiently long. The oscillation distortion and time modulation of the ULDM scalar fields have previously been contemplated, e.g., in Refs. [34,35].

It is also possible to write the neutrino-DM interactions in vector form. In such a case, the DM field alters the neutrino four-momentum as $p_\mu \rightarrow p_\mu + gQ\phi_\mu$, where ϕ_μ represents the vectorlike DM field. The corresponding version of the effective Lagrangian is then given by [7]

$$\mathcal{L}_{\text{eff}}^{\text{vector}} = \bar{\nu}_L^\alpha i \partial \nu_L^\alpha - \frac{1}{2} m_\nu^{\alpha\beta} (\bar{\nu}_L^c)^\alpha \nu_L^\beta + gQ^{\alpha\beta} \phi^\mu \bar{\nu}_L^\alpha \gamma_\mu \nu_L^\beta, \quad (4)$$

where g and $Q^{\alpha\beta}$ stand for the effective neutrino-DM coupling and the charge matrix, respectively. The ULDM field ϕ^μ is defined as a vector with its total

magnitude given by Eq. (1). As noted in Ref. [38], the vector DM can also be studied through its time-varying effects.

C. Neutrino matter potentials with different scenarios

Neutrino oscillations are affected by the presence of DM particles. The effective Hamiltonian is given by

$$\mathcal{H}_{\text{eff}} = \frac{1}{2E_\nu} (U_\nu M^2 U_\nu^\dagger) + V_{\text{CC}} + V_{\text{dark}}, \quad (5)$$

where $M^2 = \text{diag}(0, \Delta m_{21}^2, \Delta m_{31}^2)$, U_ν is the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix, and V_{CC} denotes the standard matter potential from charged-current interactions. The additional matter potential V_{dark} results from neutrino interactions with DM.

Depending on the Lorentz structures of the neutrino-DM interactions, the DM potential V_{dark} can take different forms. In the case of scalar interactions, this potential can be written as [7]

$$V_{\text{dark}}^{\text{scalar}} = \frac{1}{2E_\nu} [\phi(y m_\nu + m_\nu y) + \phi^2 y^2], \quad (6)$$

where $\phi^2 y^2$ dominates at low values of m_ϕ while $\phi(y m_\nu + m_\nu y)$ at high values of m_ϕ . It should be noted that the DM affects neutrino oscillations in two different ways: the time modulation and the nontrivial matter effects. The time modulation arises from the classical field definition [cf. Eq. (1)] and the strength of the modulation depends primarily on the neutrino time of flight. The matter effect, on the other hand, is influenced by the matter potential $V_{\text{dark}}^{\text{scalar}}$, which can be calculated from Eq. (6).

The couplings between neutrinos and the scalar ULDM are given by the 3×3 matrix y , which is defined as

$$y = \begin{pmatrix} y_{ee} & y_{e\mu} & y_{e\tau} \\ y_{ee}^* & y_{\mu\mu} & y_{\mu\tau} \\ y_{e\tau}^* & y_{\mu\tau}^* & y_{\tau\tau} \end{pmatrix}, \quad (7)$$

where y_{ee} , $y_{\mu\mu}$ and $y_{\tau\tau}$ are real while $y_{e\mu}$, $y_{e\tau}$ and $y_{\mu\tau}$ are complex parameters. These couplings can follow a specific pattern, as is the flavor-universal case with $y_{ee} = y_{\mu\mu} = y_{\tau\tau}$. The coupling parameters may also be unstructured, in which case any of the diagonal and nondiagonal parameters can acquire different nonzero values. We define the off-diagonal parameters as $y_{\ell\ell'} = |y_{\ell\ell'}| e^{-i\phi_{\ell\ell'}}$, where $|y_{\ell\ell'}|$ and $\phi_{\ell\ell'}$ represent the magnitude and complex phase of the given coupling, respectively, for which $\ell, \ell' = e, \mu$ or τ .

In DM models that involve vectorlike interactions, the neutrino matter potential is expressed in terms of the charge matrix Q and the effective neutrino-DM coupling g as [7]

$$V_{\text{dark}}^{\text{vector}} = -\frac{1}{2E_\nu} [2(p_\nu \cdot \phi)gQ + g^2 Q^2 \phi^2]. \quad (8)$$

Although its elements can in principle take any values, the charge matrix Q often has, in practice, a structure that follows from the DM model. In this work, we are mainly interested in the DM candidates that are charged under the $L_e - L_\mu$ or $L_\mu - L_\tau$ gauge symmetry. In the former case, the charge matrix is defined as $Q = \text{diag}(1, -1, 0)$, while in the latter case $Q = \text{diag}(0, 1, -1)$. For clarity, we denote the effective coupling by g in the $L_e - L_\mu$ case and by g' in the $L_\mu - L_\tau$ case, respectively.

In this work, we consider the scalar ULDM in the mass range $m_\phi \in [10^{-23}, 10^{-12}]$ eV and study its effects on long-baseline neutrino oscillations with both flavor-universal and flavor-general couplings. We also investigate the effects of the vector ULDM fields in the $L_e - L_\mu$ and $L_\mu - L_\tau$ cases, with a similar mass range.

III. ANALYSIS OF THE LONG-BASELINE NEUTRINO OSCILLATION DATA

In this work, we investigate two different datasets from the ongoing long-baseline neutrino oscillation experiments. The first dataset comes from the T2K experiment [2], which is currently taking data in Japan. The second dataset is taken from NO ν A [3] in USA. In this section, we briefly introduce the experimental setups of T2K and NO ν A and describe the analysis methods used in this work.

A. T2K dataset

The T2K is a long-baseline accelerator neutrino experiment currently taking data in Japan. It operates a proton linac with 770 kW average power output. The accelerator produces a high-purity neutrino beam, of which 96%–98% are muon neutrinos or muon antineutrinos. The experiment also has three detector facilities. The main detector, Super-Kamiokande, is a large water Cherenkov vessel located 295 km from the accelerator with a 2.5° off-axis angle. The other two detectors, ND280 and INGRID, are placed near the accelerator to monitor the neutrino beam and constrain its beam-related systematic uncertainties. The T2K produces a narrow-band beam, which peaks at about 600 MeV in the far detector facility. The main goal of T2K experiment is to find evidence for leptonic CP violation and improve measurements of other neutrino oscillation parameters and neutrino-nucleus cross sections [2].

We analyze the latest neutrino oscillation dataset from the T2K experiment [2], which accounts for neutrino events from 1.97×10^{21} protons-on-target (POT) in neutrino mode and 1.63×10^{21} POT in antineutrino mode, respectively. The dataset comprises five interaction samples: the charged-current quasielastic (CCQE) ν_μ and ν_e events obtained in neutrino mode, the CCQE $\bar{\nu}_\mu$ and $\bar{\nu}_e$ events in antineutrino mode, and the resonant charged-current

pion production (CC1 π) ν_e events in neutrino mode. The neutrino and antineutrino events that make up these samples correspond to the oscillation channels $\nu_\mu \rightarrow \nu_e$, $\nu_\mu \rightarrow \nu_\mu$, $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$, and $\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$. We analyze neutrino and antineutrino events assuming 36 energy bins over the [0.2, 2.0] GeV interval in both ν_μ and $\bar{\nu}_\mu$ CCQE samples and 23 bins within the [0.1, 1.25] GeV energy range for ν_e and $\bar{\nu}_e$ CCQE samples, respectively. We also include the ν_e CC1 π^+ sample events with 19 energy bins over the [0.45, 1.25] GeV energy range.

B. NO ν A dataset

The NO ν A is a long-baseline neutrino oscillation experiment currently operating in USA. Akin to the T2K experiment, the NO ν A generates intensive beams of muon neutrinos and antineutrinos using accelerated protons. The neutrino beam facility NuMI operates at 700 kW average beam power and its output is monitored by a near detector located 1 km away from the beam line. The far detector is located 810 km from the source and is a segmented active calorimeter consisting of highly reflective PVC cells. The total fiducial mass of the far detector is 14 kt. Both detector facilities are placed 0.8° off axis. The NO ν A beam facility generates a wide range of energies with 2 GeV average. The main objectives of NO ν A experiment include probing the violation or conservation of leptonic CP and establishing the correct ordering of neutrino masses [3].

The NO ν A dataset [3] consists of six event samples that correspond to 26.6×10^{20} POT in neutrino mode and 12.5×10^{20} POT in antineutrino mode, respectively. Due to the wide neutrino energy range, neutrino events belonging to the NO ν A dataset include various types of neutrino charged-current interactions. The first four samples are the electronlike events that undergo $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations. Depending on the purity level of particle identification used in the convolutional neural network (CNN) algorithm, the electronlike samples are further divided into the so-called low-CNN_{evt} and high-CNN_{evt} bins. The remaining two data samples correspond to the muonlike events that characterize the disappearance channels $\nu_\mu \rightarrow \nu_\mu$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$. Whereas the electronlike events are distributed in six same-sized bins over [1.0, 4.0] GeV energies, the muonlike events are binned over [0.0, 5.0] GeV energy range with 22 bins of unequal size.

C. Data analysis

The analysis of the T2K and NO ν A datasets is performed with a modified version of the General Long-Baseline Experiment Simulator (GLOBES) [51,52]. To this end, we have altered the GLOBES package to calculate oscillation probabilities with scalar and vector ULDM parameters discussed in Sec. II B. The full description of the analysis methods can be found in Ref. [53].

The GLOBES package calculates the neutrino events by integrating fluxes, cross sections, and oscillation probabilities over neutrino energies [51]:

$$N_i = N_{\text{nuc}} T \epsilon \int_{E_{\text{min}}}^{E_{\text{max}}} \int_{E'_{\text{min}}}^{E'_{\text{max}}} dE dE' \Phi_\nu(E) \sigma(E) \times R(E, E') P_{\nu_e \rightarrow \nu_{e'}}(E), \quad (9)$$

where the indices $i = 1, 2, 3, \dots$ run over the neutrino energy bins and $\Phi_\nu(E)$, $\sigma(E)$, and $R(E, E')$ represent the neutrino fluxes, the neutrino-nucleus cross sections, and the energy resolution function, respectively. The oscillation probabilities $P_{\nu_e \rightarrow \nu_{e'}}(E)$ are computed as a function of the true neutrino energy E , including both matter effects and neutrino-DM interactions. The double integration in Eq. (9) is carried out over the true neutrino energy E and the reconstructed neutrino energy E' . The final result is multiplied by N_{nuc} , T , and ϵ , which represent the number of nucleons in the detector, the total lifetime of the experiment, and the efficiency of the detector, respectively.

The analysis of the T2K and NO ν A datasets is conducted with the following formula [52,54]:

$$\chi^2 = \sum_i 2 \left[T_i - O_i \left(1 + \ln \frac{O_i}{T_i} \right) \right] + \frac{\zeta_{\text{sg}}^2}{\sigma_{\zeta_{\text{sg}}}^2} + \frac{\zeta_{\text{bg}}^2}{\sigma_{\zeta_{\text{bg}}}^2} + \text{priors}, \quad (10)$$

where T_i and O_i represent the theoretically predicted and experimentally observed events, respectively. ζ_{sg} and ζ_{bg} are the nuisance parameters representing systematic errors in signal and background normalizations, with the corresponding 1σ confidence-level (CL) uncertainties given by $\sigma_{\zeta_{\text{sg}}}$ and $\sigma_{\zeta_{\text{bg}}}$, respectively. The predicted events T_i are obtained from Eq. (9) as $T_i = (1 + \zeta_{\text{sg}}) N_i^{\text{sg}} + (1 + \zeta_{\text{bg}}) N_i^{\text{bg}}$, where N_i^{sg} and N_i^{bg} denote the signal and background events, respectively. We adopt 5% signal and 10% background errors for the T2K dataset and 5% errors for signal and background events in the NO ν A dataset. These choices of systematic uncertainties are consistent with those in Ref. [53]. We have also confirmed that they can reproduce the numerical results reported in Refs. [2,3].

The stochastic fluctuations are incorporated for the ULDM within a Bayesian framework [55,56]. The marginalized likelihood chi-square with $N_{\text{DM}} = \lfloor T_{\text{exp}}/\tau_c \rfloor + 1$ independent samples can be written as

$$\chi_{\text{stoch}}^2(y) = -2 \ln \int \exp \left[-\frac{1}{2} \chi^2(y, \phi_0^1, \dots, \phi_0^{N_{\text{DM}}}) \right] \times \prod_{i=1}^{N_{\text{DM}}} p(\phi_0^i) d\phi_0^i. \quad (11)$$

Since the stochastic field amplitude affects observables only via the energy density $\rho_\phi \propto \phi^2$, which enters through

the product $y\sqrt{\rho_\phi}$ with the coupling constant y , the expression in Eq. (11) can be simplified by introducing a dimensionless and normalized density variable $x = \bar{\rho}_\phi/\rho_{\text{DM}}$ as

$$\chi_{\text{stoch}}^2(y) = -2 \ln \int_0^\infty \exp \left[-\frac{1}{2} \chi_{\text{det}}^2(y\sqrt{x}, \rho_{\text{DM}}) \right] \times \Gamma(x; N_{\text{DM}}, 1/N_{\text{DM}}) dx, \quad (12)$$

where $\Gamma(x; k, \theta)$ denotes a Gamma distribution with shape parameter k and scale parameter θ . Here $\chi_{\text{det}}^2(y\sqrt{x}, \rho_{\text{DM}})$ denotes the deterministic chi-square computed for a fixed (nonstochastic) field amplitude, evaluated at an effective coupling $y\sqrt{x}$. The simplification to Eq. (12) is possible because, under the classical field approximation, the coupling constant always appears in the Hamiltonian multiplied by the DM field amplitude (i.e., $y\phi_0$ in the scalar case and $g\phi_0$ in the vector case). Since $\phi_0 \propto \sqrt{\rho_\phi}$, Eqs. (11) and (12) take a similar form for the vector DM, with the simple replacement $y \rightarrow g$.

In the limit where the experimental exposure time is much longer than the coherence time, $N_{\text{DM}} \gg 1$, x will concentrate around its expectation value $x = 1$. The central limit theorem then implies that the width of the distribution shrinks as $N_{\text{DM}}^{-1/2}$, so that the Gamma distribution becomes sharply peaked and approaches a Dirac delta function:

$$\Gamma(x; N_{\text{DM}}, 1/N_{\text{DM}}) \longrightarrow \delta(x - 1). \quad (13)$$

Consequently, Eq. (11) reduces exactly to the deterministic likelihood $\chi_{\text{det}}^2(y, \rho_{\text{DM}})$.

The combined neutrino oscillation datasets from T2K and NO ν A are analyzed with the following restrictions on the standard oscillation parameters. The solar parameters θ_{12} and Δm_{21}^2 are fixed at 33.76° and $7.54 \times 10^{-5} \text{ eV}^2$, respectively, adopting the best-fit values from the NuFit-6.1 database [57,58], as their uncertainties have a negligible impact on the observables in T2K and NO ν A. Furthermore, we apply a prior to the reactor mixing angle θ_{13} by demanding that $\sin^2 2\theta_{13} = 0.0851 \pm 0.0024$ at 1σ CL [59]. The χ^2 function defined in Eq. (10) is minimized over the atmospheric parameters θ_{23} and Δm_{31}^2 and also the Dirac CP -violating phase δ_{CP} . Throughout this work, we assume normally ordered neutrino masses, which are currently favored by the experimental data [58].

IV. NUMERICAL RESULTS

We now present our results from a numerical analysis of the combined T2K and NO ν A datasets, first for the scalar DM in Sec. IV A and then for the vector DM in the $L_e - L_\mu$ and $L_\mu - L_\tau$ cases in Sec. IV B.

A. Ultralight scalar dark matter

We analyze the joint datasets from the T2K and NO ν A experiments within the framework of scalar DM. Two distinct coupling scenarios are explored: a flavor-universal pattern and a set of general (nonuniversal) patterns. The resulting constraints on the coupling strengths $y_{\alpha\beta}$ and the DM mass m_ϕ , spanning the range $10^{-23} \text{ eV} \leq m_\phi \leq 10^{-10} \text{ eV}$, are summarized in Fig. 1.

In the flavor-universal scenario, the neutrino-DM couplings are assumed to be flavor-blind, such that the coupling matrix takes the form $y = y_0 \mathbb{I}_{3 \times 3}$, where y_0 denotes the universal coupling strength and $\mathbb{I}_{3 \times 3}$ the 3×3 identity matrix. This benchmark case is well motivated by flavor symmetries and has been extensively investigated in the context of neutrino oscillation experiments [7,47,60]. Conversely, for the general coupling patterns, we adopt a parameter-by-parameter approach, varying a single coupling constant $y_{\alpha\beta}$ at a time while setting all other off-diagonal and diagonal entries to zero. Since y_{ee} effectively contributes as an additional term to the matter potential and is therefore weakly constrained by the T2K and NO ν A datasets, the resulting exclusion curves exhibit some spurious features. The leading experimental constraint in this ULDM mass regime arises from the CMB measurements [8], which set a stringent upper limit on the sum of neutrino masses $\sum m_\nu$. To be consistent with the analysis performed in Ref. [7], we reproduce this cosmological bound by adopting the conservative criteria detailed in Ref. [8].

As illustrated in Eq. (6), the effective potential induced by the scalar DM field contains a cross term proportional to the neutrino mass, rendering the interaction sensitive to the absolute neutrino mass scale. Given the well-measured mass-squared differences, the entire neutrino mass spectrum can be uniquely determined by specifying the mass of the lightest neutrino (m_1 in the case of normal ordering). Our benchmark analysis assumes a vanishing lightest neutrino mass ($m_1 = 0$), a configuration that is theoretically well motivated by the minimal seesaw model [61–63].

To evaluate sensitivity to the absolute mass scale, we also investigate a scenario with $m_1 = 1.0 \times 10^{-2} \text{ eV}$ (represented by the red dashed line in Fig. 1), a value that approaches the current experimental upper bounds. Our results indicate that the specific choice of the lightest neutrino mass does not significantly alter the overall constraints, resulting only in a marginal relaxation of the excluded regions.

In our statistical framework, the stochastic nature of the scalar DM field is rigorously incorporated. Given a characteristic experimental exposure time (T_{exp}) of approximately 10 yr, the stochastic fluctuations manifest most significantly in the ULDM mass regime of $m_\phi \lesssim 10^{-17} \text{ eV}$, where the coherence time τ_c is comparable to or exceeds T_{exp} . In this maximum fluctuation region, the 3σ exclusion limit for the flavor-universal scenario approximately follows the scaling relation $y_0/m_\phi \simeq 19.4 \text{ eV}^{-1}$.

As the DM mass m_ϕ increases, the coherence time $\tau_c \propto (m_\phi v^2)^{-1}$ decreases, leading to a higher number of

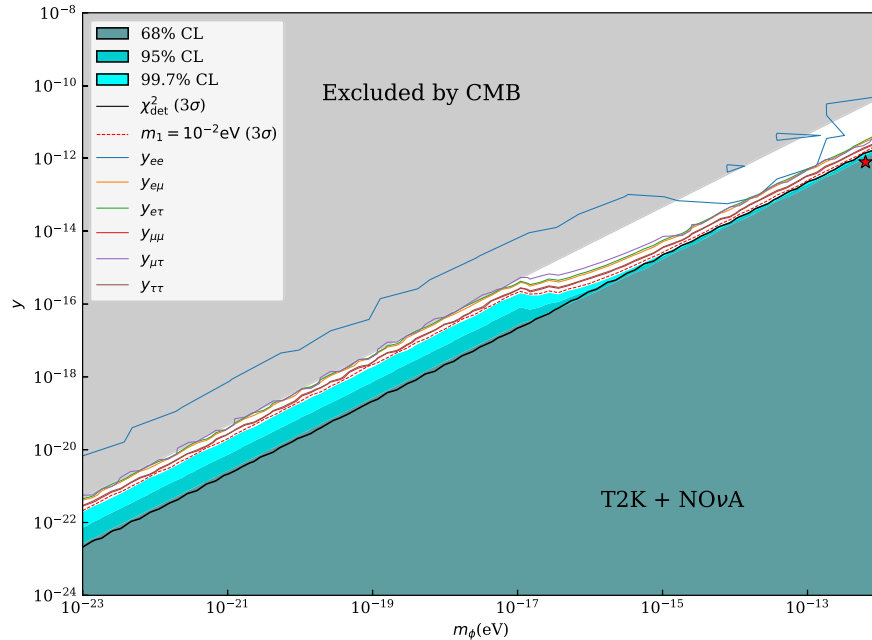


FIG. 1. Joint T2K and NO ν A constraints on the scalar DM. The color map shows the χ^2 distribution for the flavor-universal scenario, with the black solid and red dashed lines representing the 3σ boundaries for the deterministic and the $m_0 = 10^{-2} \text{ eV}$ case, respectively. The individual 3σ upper limits for general scalar couplings are shown as solid curves ($y_{\alpha\beta}$). The gray region indicates the conservative CMB exclusion [8]. The best-fit point is located at $m_\phi \simeq 6.31 \times 10^{-13} \text{ eV}$ and $y_0 \simeq 7.93 \times 10^{-13}$. Unless noted otherwise, the normal ordering and $m_1 = 0$ are assumed for neutrinos.

independent stochastic samples ($N_{\text{DM}} \simeq T_{\text{exp}}/\tau_c$) within the observation window. This results in a statistical averaging of the field's fluctuations, making the constraints progressively converge toward the deterministic limit. In this high-mass regime where fluctuations are fully averaged, the 3σ boundary follows a more stringent scaling of $y_0/m_\phi \simeq 2.26 \text{ eV}^{-1}$. The discrepancy between these two regimes quantifies the order-of-magnitude relaxation (a factor of ~ 8.6) in the sensitivity induced by the stochastic nature of the net DM field.

Finally, a global scan across both flavor-universal and general coupling patterns yields a best-fit point at $m_\phi \simeq 6.31 \times 10^{-13} \text{ eV}$ and $y_0 \simeq 7.93 \times 10^{-13}$. However, this result exhibits less than 1σ improvement ($\Delta\chi^2 \sim 0.4$) relative to the standard neutrino oscillation hypothesis (i.e., excluding the DM background), indicating that there is no statistically significant preference for the scalar DM model by the current T2K and NO ν A datasets.

Next, we investigate the effects of neutrino-DM couplings in the measurement of standard parameters $\sin^2 \theta_{23}$ and δ_{CP} . Figure 2 illustrates the joint fit results for $\sin^2 \theta_{23}$ and δ_{CP} at 90% CL, with the analysis presented separately for T2K (blue) and NO ν A (red). The dashed contours represent the standard oscillation framework, while the shaded regions denote the flavor-universal scalar DM scenario. Incorporating the DM coupling leads to a slight downward shift in the preferred values of $\sin^2 \theta_{23}$ for both T2K and NO ν A. Additionally, the best-fit regions for δ_{CP} show marginal convergence to each other compared to the

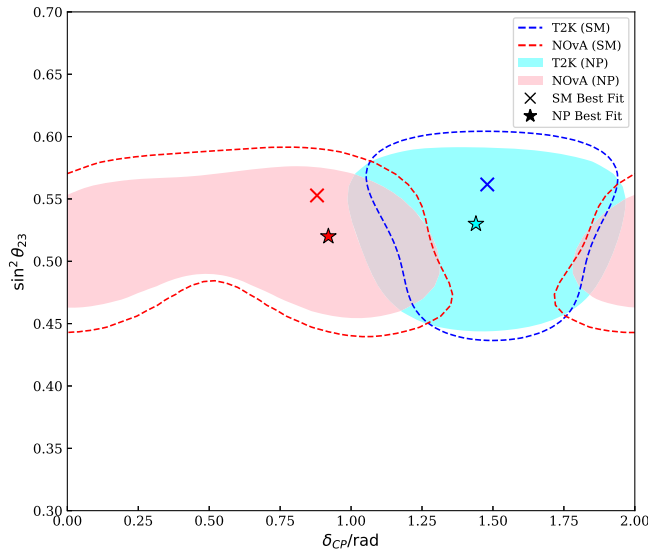


FIG. 2. Effects of the flavor-universal scalar ULDM in the combined analysis of T2K and NO ν A datasets. The results are presented at 90% CL for the normal neutrino mass ordering with the assumption of $m_1 = 0$. The new physics (NP) contours (shaded regions) are computed at the scalar DM best-fit point, corresponding to $m_\phi \simeq 6.31 \times 10^{-13} \text{ eV}$ and $y_0 \simeq 7.93 \times 10^{-13}$. Normal ordering and $m_1 = 0$ are assumed for neutrinos.

SM predictions. However, the overall parameter spaces for both experiments remain largely consistent with their SM counterparts. Consequently, based on the current available data, the scalar ULDM model does not appear to provide a significant contribution toward alleviating the existing tension between T2K and NO ν A.

B. Ultralight vector dark matter with $L_e - L_\mu$ and $L_\mu - L_\tau$

The ULDM may also couple with active neutrinos via vector interactions. In such a case, the effects on neutrino oscillations are induced by the DM polarization, which is not present in the scalar case. Thus, the vector ULDM may be studied in neutrino oscillation experiments by daily modulation [38]. As Earth's rotation changes the angle at which neutrino and vector DM may interact, the subsequent effect on the neutrino matter potential also depends on the time at which the interaction occurs. In this work, we focus primarily on the polarized vector DM scenario while also extending our analysis to the unpolarized scenario. Physically, the unpolarized scenario characterizes a regime dominated by multimode random wave interference, producing a robust isotropic background due to high particle occupations. In the polarized scenario, on the other hand, it is assumed that the vector DM field possesses a specific preferred orientation, for which we conservatively adopt the configuration that maximizes the interaction strength as a phenomenological benchmark.

Constraints on the interactions of vector ULDM with neutrinos have been derived previously, with the leading constraints coming from black hole superradiance [64] and atmospheric neutrinos [38]. Other sources of experimental constraints include the search for the fifth force [65,66], the cosmological bounds on neutrino decay [67], and the tests of the equivalence of gravitational mass and inertial mass [68]. There is also a model-dependent constraint from searches for monoleptons and missing energy at the Large Hadron Collider (LHC) [69]. These constraints have been collected in Ref. [38] and are reproduced in the present work.

We begin by analyzing the vector DM scenario, where the model is charged under the $L_e - L_\mu$ gauge symmetry. Figure 3 shows the fit results under the combined constraints from T2K and NO ν A datasets in this scenario. The coupling parameter g represents the coupling strength between neutrinos and the vector DM, whereas the charge matrix is given as $Q = \text{diag}(+1, -1, 0)$. The allowed values of g and m_ϕ are shown for 68%, 95% and 3σ CL in the T2K and NO ν A datasets with the red, dark red and light red regions, respectively.

The fit is presented for the polarized DM case, where its effect on the neutrino matter potential is maximal. The figure also shows the present experimental constraints from the atmospheric neutrinos (SuperK), the fifth force searches [65,66], the cosmological limits from solar and atmospheric

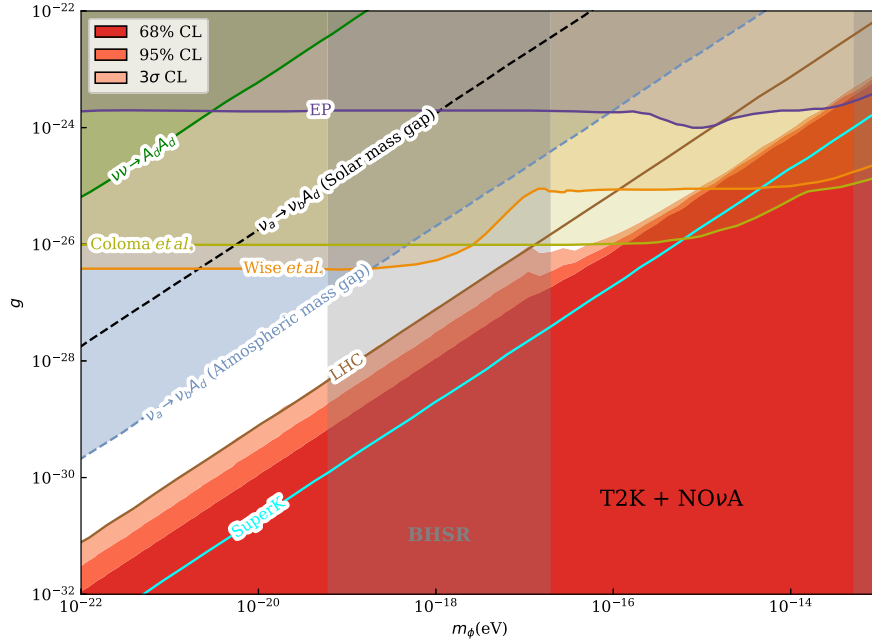


FIG. 3. Vector DM fit with neutrino-DM coupling g under the $L_e - L_\mu$ charge. The allowed values for g and m_ϕ arising from the joint T2K and NO ν A datasets are presented at 68%, 95% and 3σ CL. External constraints are taken from Ref. [38]. The best-fit point, located at $g \simeq 7.93 \times 10^{-24}$ and $m_\phi \simeq 1.58 \times 10^{-13}$ eV, lies near the right boundary of the parameter space shown, assuming the normal mass ordering.

masses ($\nu_a \rightarrow \nu_b A_d$ for the solar and $\nu_a \rightarrow \nu_b A_d$ for the atmospheric mass gap, respectively), and the equivalence principle (EP) tests [70]. We also show the limits from the LHC and black hole superradiance (BHSR).

In terms of experimental sensitivity, the combined constraints from T2K and NO ν A on the $L_e - L_\mu$ parameter space fall between the limits set by the LHC and the Super-Kamiokande atmospheric neutrino data. The best-fit point exhibits a marginal improvement in the fit ($\Delta\chi^2 \sim 0.5$ within the 1σ CL) and is situated in a region already excluded by existing experimental bounds. Notably, our T2K and NO ν A limits appear relatively relaxed in the low-mass regime due to the incorporation of stochastic fluctuations. It is important to emphasize that if other external constraints were consistently treated under the classical field framework, they would similarly be subject to such stochastic effects, leading to a corresponding reassessment of their exclusion boundaries.

We further explore the $L_e - L_\mu$ case within the unpolarized scenario. In this regime, the first-order correction to the neutrino matter potential is averaged out, making only the second-order terms provide a nonvanishing contribution; consequently, the resulting effect on neutrino oscillation probabilities is significantly suppressed compared to the polarized case. Due to this weakened sensitivity, the constraints on unpolarized DM are considerably relaxed. The corresponding best-fit point fails to yield a significant improvement in the fit and is subsequently excluded by all experimental constraints considered in this work.

Next, we examine the combined T2K and NO ν A datasets in the $L_\mu - L_\tau$ case. The results are shown in Fig. 4. In this case, the charge matrix of the ULDM field ϕ is given by $Q = \text{diag}(0, +1, -1)$. The leading experimental constraints are the same as those in the $L_e - L_\mu$ case, except for the bounds coming from the fifth force and the violation of EP searches, which are replaced with constraints from the neutron star (NS) binaries [73]. The allowed values for the T2K and NO ν A datasets are presented at 68%, 95% and 3σ CL by red, dark red and light red regions, respectively, and the best-fit point by black star. The fit results are obtained for the polarized DM.

At 3σ CL, the neutrino oscillation datasets from T2K and NO ν A experiments provide stringent constraints on the vector ULDM parameter space in the $L_\mu - L_\tau$ sector. Specifically, in the low-mass regime where stochastic fluctuations are maximal, we find $g'/m_\phi \lesssim 4.08 \times 10^{-10}$ eV $^{-1}$. In the high-mass region where fluctuations are effectively averaged out, on the other hand, the constraint is tightened to $g'/m_\phi \lesssim 4.82 \times 10^{-11}$ eV $^{-1}$. The best-fit point, denoted by a black star in the figure, is located at $m_\phi \simeq 3.98 \times 10^{-13}$ eV and $g' \simeq 7.93 \times 10^{-24}$. These limits are slightly less stringent than those reported in Ref. [5], although they remain consistent in terms of orders of magnitude. This discrepancy primarily stems from our explicit treatment of stochastic fluctuation effects and the incorporation of phase averaging within the oscillation probabilities, as discussed in Sec. II A.

Similarly to the $L_e - L_\mu$ case, the black hole superradiance bounds truncate certain portions of the parameter

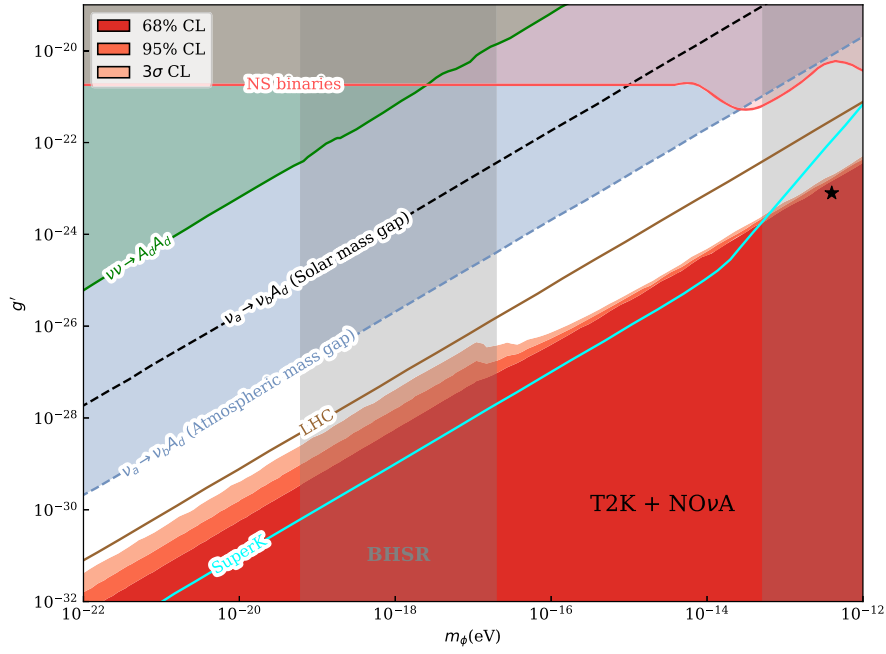


FIG. 4. Vector DM fit with neutrino-DM coupling g' under the $L_\mu - L_\tau$ charge. The allowed values of g' and m_ϕ are presented for the combined T2K and NO ν A datasets at 68%, 95% and 3σ CL, assuming the normal mass ordering. Constraints from other experiments are taken from Ref. [38].

space while leaving several regions of interest intact, and the best-fit point fails to yield a statistically significant improvement ($\Delta\chi^2 \sim 0.2$) to the overall fit. The results for the unpolarized scenario are omitted from the figure as they are robustly excluded and their corresponding limits are entirely overshadowed by other constraints.

As the last step of this work, we study the effect of the vector ULDM on the parameter discrepancy in the T2K and

NO ν A datasets. Figure 5 shows the individual fits to the T2K and NO ν A datasets in the vector ULDM models. The neutrino oscillation probabilities are computed by assuming the best-fit values that were previously obtained for the vector DM parameters with $L_e - L_\mu$ and $L_\mu - L_\tau$ charges. Under the hypothesis of vector DM, the neutrino oscillation parameter fits for T2K remain largely robust. For NO ν A, while the 90% CL allowed regions exhibit substantial

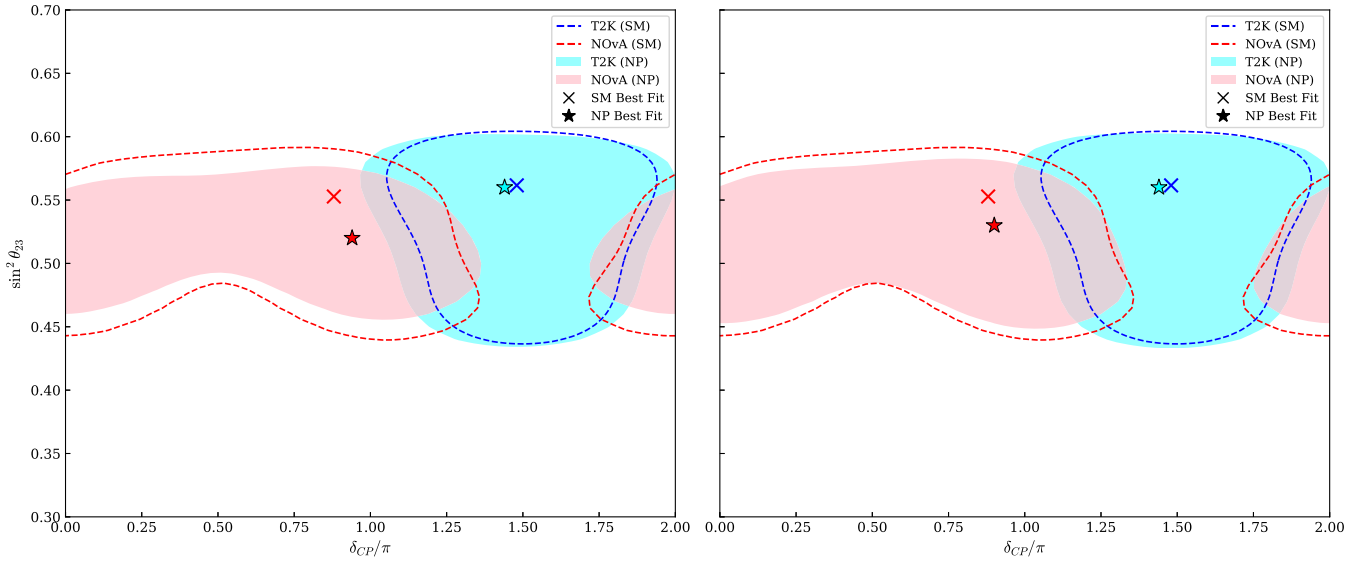


FIG. 5. Discrepancies in T2K and NO ν A fits for the vector ULDM with $L_e - L_\mu$ (left panel) and $L_\mu - L_\tau$ (right panel) charges. The vector couplings g and g' and DM mass m_ϕ are fixed to their best-fit points in both panels. Sensitivities are presented for T2K and NO ν A at 90% CL assuming normally ordered neutrino masses.

overlap with the SM contours, a discernible shift is observed in the fitting results: the preferred value of $\sin^2 \theta_{23}$ decreases and δ_{CP} shifts slightly toward the region favored by T2K. Despite these localized adjustments, the inclusion of DM does not yield a significant alleviation of the persistent tension between the T2K and NO ν A datasets. These results are qualitatively consistent with those obtained in flavor-universal scenarios.

V. CONCLUSIONS

In the work, we have performed a comprehensive analysis of the ULDM signatures in long-baseline neutrino oscillations, utilizing the latest joint datasets from the T2K and NO ν A experiments. We investigated the phenomenological implications of several ULDM coupling scenarios, including flavor-universal and flavor-general couplings in the scalar sector, as well as the $L_e - L_\mu$ and $L_\mu - L_\tau$ gauge symmetries in the vector sector.

Crucially, our analysis explicitly incorporates the stochastic nature of the ULDM field. We introduce a Bayesian statistical treatment to account for the amplitude fluctuations determined by the ratio of the experimental exposure time to the DM coherence time. Our results show that in the low-mass regime ($m_\phi \lesssim 10^{-17}$ eV), where the stochastic effects are maximal, the constraints derived on coupling constants are relaxed by approximately one order of magnitude compared to the deterministic case, specifically by factors of ~ 8.6 for the scalar, ~ 8.0 for the $L_e - L_\mu$ and ~ 8.5 for the $L_\mu - L_\tau$ case, respectively. The mass range of 10^{-17} eV $\lesssim m_\phi \lesssim 10^{-15}$ eV serves as a transition away from the stochastic-dominated regime. Conversely, for $m_\phi \gtrsim 10^{-15}$ eV, the system enters a multisample regime ($N_{\text{DM}} \gg 1$) where the stochastic fluctuations are effectively suppressed, recovering the deterministic limits. In addition, we also find that the choice of the lightest neutrino mass has little impact on the overall constraints, leading only to a marginal relaxation of the excluded regions.

The joint T2K and NO ν A datasets yield the following substantial 3σ exclusion limits in the maximal fluctuation region ($m_\phi \lesssim 10^{-17}$ eV):

- (i) *scalar (flavor-universal)*: $y_0/m_\phi \lesssim 19.4$ eV $^{-1}$;
- (ii) *vector ($L_e - L_\mu$)*: $g/m_\phi \lesssim 7.41 \times 10^{-10}$ eV $^{-1}$;
- (iii) *vector ($L_\mu - L_\tau$)*: $g'/m_\phi \lesssim 4.08 \times 10^{-10}$ eV $^{-1}$.

Regarding the model preference, the identified best-fit points obtained from a global scan over the full mass range for each scenario read

- (i) *scalar (flavor-universal)*: $m_\phi \simeq 6.31 \times 10^{-13}$ eV, $y_0 \simeq 7.93 \times 10^{-13}$;
- (ii) *vector ($L_e - L_\mu$)*: $m_\phi \simeq 1.58 \times 10^{-13}$ eV, $g \simeq 7.93 \times 10^{-24}$;
- (iii) *vector ($L_\mu - L_\tau$)*: $m_\phi \simeq 3.98 \times 10^{-13}$ eV, $g' \simeq 7.93 \times 10^{-24}$.

Although the inclusion of ULDM couplings leads to slight shifts in the preferred oscillation parameters, the statistical improvement over the standard oscillation is marginal ($\Delta\chi^2 < 1$). Consequently, we do not find compelling evidence that the current ULDM models provide a viable resolution to the existing parameter tension between T2K and NO ν A. This limited numerical sensitivity could be qualitatively understood from the algebraic structures of the effective potentials. Unlike conventional mechanisms such as nonstandard interactions [74,75] that introduce a new complex phase via off-diagonal elements, the vector ULDM potential is generally diagonal, whereas the scalar ULDM modifications are inherently entangled with the neutrino mass and the PMNS mixing matrix. Such structural constraints make it less straightforward to effectively provide the independent phase degrees of freedom required to reconcile the δ_{CP} discrepancy.

Looking ahead, we anticipate that future high-precision facilities, such as DUNE and JUNO, will be instrumental in further clarifying the δ_{CP} landscape and providing more decisive probes of the ULDM parameter space.

ACKNOWLEDGMENTS

S. V. is grateful to Tommy Ohlsson and Pedro Pasquini for fruitful discussions during this project. This work is supported in part by the National Natural Science Foundation of China under Grants No. 12347105, No. 12475094, and No. 12135006, as well as the Fundamental Research Funds for the Central Universities (No. 23xkjc017) in Sun Yat-sen University.

DATA AVAILABILITY

The data that support the findings of this article are openly available [2,3].

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- [1] P. Huber *et al.*, Snowmass neutrino frontier report, in *Snowmass 2021* (2022); [arXiv:2211.08641](https://arxiv.org/abs/2211.08641).
 - [2] K. Abe *et al.* (T2K Collaboration), Measurements of neutrino oscillation parameters from the T2K experiment

using 3.6×10^{21} protons on target, *Eur. Phys. J. C* **83**, 782 (2023).

- [3] S. Abubakar *et al.* (NO ν A Collaboration), Precision measurement of neutrino oscillation parameters with 10 years of

- data from the NOvA experiment, *Phys. Rev. Lett.* **136**, 011802 (2026).
- [4] S. Abubakar *et al.* (T2K and NOvA Collaborations), Joint neutrino oscillation analysis from the T2K and NOvA experiments, *Nature (London)* **646**, 818 (2025).
- [5] G. Alonso-Álvarez, J. M. Cline, B. Laurent, and U. Rahaman, Dark photon distortions of NOvA and T2K neutrino oscillations, *Eur. Phys. J. C* **85**, 635 (2025).
- [6] A.-Y. Bai, A. Chatrabhuti, Y.-Y. Huang, H. Isono, and J. Tang, Dark dimension right-handed neutrinos confronted with long-baseline oscillation experiments, *J. High Energy Phys.* **05** (2026) 196.
- [7] V. Brdar, J. Kopp, J. Liu, P. Prass, and X.-P. Wang, Fuzzy dark matter and nonstandard neutrino interactions, *Phys. Rev. D* **97**, 043001 (2018).
- [8] G. Krnjaic, P. A. N. Machado, and L. Necib, Distorted neutrino oscillations from time varying cosmic fields, *Phys. Rev. D* **97**, 075017 (2018).
- [9] V. C. Rubin, N. Thonnard, and W. K. Ford, Jr., Rotational properties of 21 SC galaxies with a large range of luminosities and radii, from NGC 4605 ($R = 4$ kpc) to UGC 2885 ($R = 122$ kpc), *Astrophys. J.* **238**, 471 (1980).
- [10] M. Bartelmann and P. Schneider, Weak gravitational lensing, *Phys. Rep.* **340**, 291 (2001).
- [11] D. J. Eisenstein *et al.* (SDSS Collaboration), Detection of the baryon acoustic peak in the large-scale correlation function of SDSS luminous red galaxies, *Astrophys. J.* **633**, 560 (2005).
- [12] G. Hinshaw *et al.* (WMAP Collaboration), Nine-year Wilkinson microwave anisotropy probe (WMAP) observations: Cosmological parameter results, *Astrophys. J. Suppl. Ser.* **208**, 19 (2013).
- [13] N. Aghanim *et al.* (Planck Collaboration), Planck 2018 results. VI. Cosmological parameters, *Astron. Astrophys.* **641**, A6 (2020); *Astron. Astrophys.* **652**, C4(E) (2021).
- [14] G. Jungman, M. Kamionkowski, and K. Griest, Supersymmetric dark matter, *Phys. Rep.* **267**, 195 (1996).
- [15] D. S. Akerib *et al.* (LUX Collaboration), First results from the LUX dark matter experiment at the Sanford Underground Research Facility, *Phys. Rev. Lett.* **112**, 091303 (2014).
- [16] X. Cui *et al.* (PandaX-II Collaboration), Dark matter results from 54-ton-day exposure of PandaX-II experiment, *Phys. Rev. Lett.* **119**, 181302 (2017).
- [17] B. Moore, Evidence against dissipationless dark matter from observations of galaxy haloes, *Nature (London)* **370**, 629 (1994).
- [18] B. Carr, F. Kuhnel, and M. Sandstad, Primordial black holes as dark matter, *Phys. Rev. D* **94**, 083504 (2016).
- [19] R. D. Peccei and H. R. Quinn, CP conservation in the presence of instantons, *Phys. Rev. Lett.* **38**, 1440 (1977).
- [20] P. Fayet, Effects of the spin 1 partner of the goldstino (gravitino) on neutral current phenomenology, *Phys. Lett.* **95B**, 285 (1980).
- [21] P. Fayet, On the search for a new spin 1 boson, *Nucl. Phys.* **B187**, 184 (1981).
- [22] E. Oks, Brief review of recent advances in understanding dark matter and dark energy, *New Astron. Rev.* **93**, 101632 (2021).
- [23] D. Antypas *et al.*, New horizons: Scalar and vector ultralight dark matter, *arXiv:2203.14915*.
- [24] H. Davoudiasl, P. B. Denton, and J. Gehrlein, Supermassive black holes, ultralight dark matter, and gravitational waves from a first order phase transition, *Phys. Rev. Lett.* **128**, 081101 (2022).
- [25] D. Chowdhury, A. Hait, S. Mohanty, and S. Prakash, Ultralight dark matter explanation of NANOGrav observations, *Phys. Rev. D* **110**, 083023 (2024).
- [26] C. Corianò, P. H. Frampton, N. Irges, and A. Tatullo, Dark matter with Stückelberg axions, *Front. Phys.* **7**, 36 (2019).
- [27] B. T. Chiang, J. P. Ostriker, and H.-Y. Schive, Can ultralight dark matter explain the age-velocity dispersion relation of the Milky Way disc: A revised and improved treatment, *Mon. Not. R. Astron. Soc.* **518**, 4045 (2023).
- [28] J. Liao, D. Marfatia, and K. Whisnant, Light scalar dark matter at neutrino oscillation experiments, *J. High Energy Phys.* **04** (2018) 136.
- [29] K.-Y. Choi, J. Kim, and C. Rott, Constraining dark matter-neutrino interactions with IceCube-170922A, *Phys. Rev. D* **99**, 083018 (2019).
- [30] G. M. Salla, Characterising dark matter-induced neutrino potentials, *Eur. Phys. J. C* **83**, 204 (2023).
- [31] M. Losada, Y. Nir, G. Perez, I. Savoray, and Y. Shpilman, Parametric resonance in neutrino oscillations induced by ultra-light dark matter and implications for KamLAND and JUNO, *J. High Energy Phys.* **03** (2023) 032.
- [32] R. Cordero, L. A. Delgadillo, and O. G. Miranda, European spallation source as a searching tool for an ultralight scalar field, *Phys. Rev. D* **107**, 075023 (2023).
- [33] A. Dev, P. A. N. Machado, and P. Martínez-Miravé, Signatures of ultralight dark matter in neutrino oscillation experiments, *J. High Energy Phys.* **01** (2021) 094.
- [34] M. Losada, Y. Nir, G. Perez, and Y. Shpilman, Probing scalar dark matter oscillations with neutrino oscillations, *J. High Energy Phys.* **04** (2022) 030.
- [35] M. Losada, Y. Nir, G. Perez, I. Savoray, and Y. Shpilman, Time dependent CP -even and CP -odd signatures of scalar ultralight dark matter in neutrino oscillations, *Phys. Rev. D* **108**, 055004 (2023).
- [36] G.-Y. Huang and N. Nath, Neutrinophilic axion-like dark matter, *Eur. Phys. J. C* **78**, 922 (2018).
- [37] R. Brandenberger, J. Fröhlich, and H. Jiao, Cosmological magnetic fields from ultralight dark matter, *Phys. Rev. Lett.* **136**, 031001 (2026).
- [38] D. Brzemiński, S. Das, A. Hook, and C. Ristow, Constraining vector dark matter with neutrino experiments, *J. High Energy Phys.* **08** (2023) 181.
- [39] T. Gherghetta and A. Shkerin, Probing a local dark matter halo with neutrino oscillations, *Phys. Rev. D* **108**, 095009 (2023).
- [40] C. A. Argüelles, K. Farrag, and T. Katori, Ultra-light dark matter limits from astrophysical neutrino flavour, *Proc. Sci. ICRC2023* (2023) 1415.
- [41] Y. Chen, X. Xue, and V. Cardoso, Black holes as fermion factories, *J. Cosmol. Astropart. Phys.* **02** (2025) 035.
- [42] W. Hu, R. Barkana, and A. Gruzinov, Cold and fuzzy dark matter, *Phys. Rev. Lett.* **85**, 1158 (2000).

- [43] L. Hui, J. P. Ostriker, S. Tremaine, and E. Witten, Ultralight scalars as cosmological dark matter, *Phys. Rev. D* **95**, 043541 (2017).
- [44] G. P. Centers *et al.*, Stochastic fluctuations of bosonic dark matter, *Nat. Commun.* **12**, 7321 (2021).
- [45] J. W. Foster, N. L. Rodd, and B. R. Safdi, Revealing the dark matter halo with axion direct detection, *Phys. Rev. D* **97**, 123006 (2018).
- [46] S.-F. Ge and S. J. Parke, Scalar nonstandard interactions in neutrino oscillation, *Phys. Rev. Lett.* **122**, 211801 (2019).
- [47] A. Berlin, Neutrino oscillations as a probe of light scalar dark matter, *Phys. Rev. Lett.* **117**, 231801 (2016).
- [48] A. E. Nelson and J. Scholtz, Dark light, dark matter and the misalignment mechanism, *Phys. Rev. D* **84**, 103501 (2011).
- [49] P. Arias, D. Cadamuro, M. Goodsell, J. Jaeckel, J. Redondo, and A. Ringwald, WISPy cold dark matter, *J. Cosmol. Astropart. Phys.* **06** (2012) 013.
- [50] H.-Y. Schive, T. Chiueh, and T. Broadhurst, Cosmic structure as the quantum interference of a coherent dark wave, *Nat. Phys.* **10**, 496 (2014).
- [51] P. Huber, M. Lindner, and W. Winter, Simulation of long-baseline neutrino oscillation experiments with GLOBES (General Long Baseline Experiment Simulator), *Comput. Phys. Commun.* **167**, 195 (2005).
- [52] P. Huber, J. Kopp, M. Lindner, M. Rolinec, and W. Winter, New features in the simulation of neutrino oscillation experiments with GLOBES 3.0: General Long Baseline Experiment Simulator, *Comput. Phys. Commun.* **177**, 432 (2007).
- [53] H.-X. Lin, J. Tang, S. Vihonen, and P. Pasquini, Non-minimal Lorentz invariance violation in light of the muon anomalous magnetic moment and long-baseline neutrino oscillation data, *Phys. Rev. D* **105**, 096029 (2022).
- [54] G. L. Fogli, E. Lisi, A. Marrone, D. Montanino, and A. Palazzo, Getting the most from the statistical analysis of solar neutrino oscillations, *Phys. Rev. D* **66**, 053010 (2002).
- [55] A. Derevianko, Detecting dark-matter waves with a network of precision-measurement tools, *Phys. Rev. A* **97**, 042506 (2018).
- [56] P. Gregory, *Bayesian Logical Data Analysis for the Physical Sciences: A Comparative Approach with Mathematica Support* (Cambridge University Press, Cambridge, England, 2005).
- [57] I. Esteban, M. C. Gonzalez-Garcia, M. Maltoni, T. Schwetz, and A. Zhou, The fate of hints: Updated global analysis of three-flavor neutrino oscillations, *J. High Energy Phys.* **09** (2020) 178.
- [58] I. Esteban *et al.* (NuFIT Collaboration), Nufit 6.1 (2025) (2025), <http://www.nu-fit.org/?q=node/309> accessed: 2026-03-29.
- [59] F. P. An *et al.* (Daya Bay Collaboration), Precision measurement of reactor antineutrino oscillation at kilometer-scale baselines by Daya Bay, *Phys. Rev. Lett.* **130**, 161802 (2023).
- [60] F. Capozzi, I. M. Shoemaker, and L. Vecchi, Solar neutrinos as a probe of dark matter-neutrino interactions, *J. Cosmol. Astropart. Phys.* **07** (2017) 021.
- [61] S. F. King, Large mixing angle MSW and atmospheric neutrinos from single right-handed neutrino dominance and U(1) family symmetry, *Nucl. Phys.* **B576**, 85 (2000).
- [62] P. H. Frampton, S. L. Glashow, and D. Marfatia, Zeroes of the neutrino mass matrix, *Phys. Lett. B* **536**, 79 (2002).
- [63] S. F. King, Minimal predictive see-saw model with normal neutrino mass hierarchy, *J. High Energy Phys.* **07** (2013) 137.
- [64] M. Baryakhtar, R. Lasenby, and M. Teo, Black hole superradiance signatures of ultralight vectors, *Phys. Rev. D* **96**, 035019 (2017).
- [65] M. B. Wise and Y. Zhang, Lepton flavorful fifth force and depth-dependent neutrino matter interactions, *J. High Energy Phys.* **06** (2018) 053.
- [66] P. Coloma, M. C. Gonzalez-Garcia, and M. Maltoni, Neutrino oscillation constraints on U(1)' models: From non-standard interactions to long-range forces, *J. High Energy Phys.* **01** (2021) 114; *J. High Energy Phys.* **11** (2022) 115 (E).
- [67] J. Z. Chen, I. M. Oldengott, G. Pierobon, and Y. Y. Y. Wong, Weaker yet again: Mass spectrum-consistent cosmological constraints on the neutrino lifetime, *Eur. Phys. J. C* **82**, 640 (2022).
- [68] S. Schlamminger, K. Y. Choi, T. A. Wagner, J. H. Gundlach, and E. G. Adelberger, Test of the equivalence principle using a rotating torsion balance, *Phys. Rev. Lett.* **100**, 041101 (2008).
- [69] M. Ekhterachian, A. Hook, S. Kumar, and Y. Tsai, Bounds on gauge bosons coupled to nonconserved currents, *Phys. Rev. D* **104**, 035034 (2021).
- [70] Violation of the equivalence principle has also been studied in MICROSCOPE space mission, which sets an independent upper limit of 1.3×10^{-25} on the couplings relevant for the $L_e - L_\mu$ gauge symmetry [71,72].
- [71] P. Fayet, MICROSCOPE limits for new long-range forces and implications for unified theories, *Phys. Rev. D* **97**, 055039 (2018).
- [72] P. Fayet, MICROSCOPE limits on the strength of a new force, with comparisons to gravity and electromagnetism, *Phys. Rev. D* **99**, 055043 (2019).
- [73] J. A. Dror, R. Laha, and T. Opferkuch, Probing muonic forces with neutron star binaries, *Phys. Rev. D* **102**, 023005 (2020).
- [74] P. B. Denton, J. Gehrlein, and R. Pestes, CP -violating neutrino nonstandard interactions in long-baseline-accelerator data, *Phys. Rev. Lett.* **126**, 051801 (2021).
- [75] S. S. Chatterjee and A. Palazzo, Status of tension between NOvA and T2K after Neutrino 2024 and possible role of nonstandard neutrino interactions, *Phys. Rev. D* **110**, 113002 (2024).