

Scalar nonstandard neutrino interactions in galactic supernovae

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We analyze the prospects for studying scalar nonstandard interactions (SNSI) using the neutrino burst from a galactic supernova (SN). SNSI modifies the resonant flavor conversion and, correspondingly, the neutronization burst signal, and may be identifiable in future multi-tonne-scale experiments, such as Deep Underground Neutrino Experiment (DUNE). Notably, in the normal mass ordering, SNSI can lead to an anomalous (re)appearance of the neutronization-burst ν_e peak at Earth, a feature otherwise strongly suppressed in the Standard Model. We show that, in the presence of SNSI, neutrinos propagating out of the dense SN environment acquire a density-squared-dependent contribution to their mass-squared differences, which in turn modifies the energy levels of the neutrino matter eigenstates. This density-squared effect is absent in less dense environments such as the Earth or the Sun and is precisely what enables SN neutrinos to probe SNSI parameters up to 4 orders of magnitude below the values accessible to solar or terrestrial neutrino sources.

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I. INTRODUCTION

The observation of neutrinos from SN1987A [1–3] confirmed the basic picture of core-collapse SNe, in which more than 99% of the released gravitational binding energy is emitted in the form of neutrinos of all flavors [4,5]. Since then, neutrino detectors have operated continuously without observing another galactic event [6–9]. The next nearby SN will provide unprecedented statistics in current and future detectors such as Super-Kamiokande [6], DUNE [10], JUNO [11], and hyper-Kamiokande [12], enabling precision tests of neutrino emission, flavor conversion, and fundamental neutrino properties [5,13]. In addition, multi-ton-scale dark matter detectors will reach comparable sensitivity [14].

Neutrinos from SNe provide a unique laboratory for physics beyond the Standard Model. Since the origin of

neutrino masses and mixings requires new interactions, nonstandard neutrino interactions (NSI) with matter have been widely studied, especially for vector and axial-vector couplings [15–19] and for their impact on scattering rates [20–23]. In this work, we focus on scalar-mediated nonstandard interactions (SNSI), which naturally arise in extended Higgs sectors [24–26] and modify the neutrino mass matrix directly [27–29]. This behavior is fundamentally different from vector NSI, which modifies only the matter potential [30–33]. In the Earth and Sun, the leading SNSI effects scale linearly with the ambient matter density [34,35]. In contrast, we demonstrate that in SNe, the dominant SNSI contribution scales quadratically with density, leading to qualitatively new flavor evolution phenomena in the extreme SN environment.

The impact of SNSI in SNe has previously been explored in the context of collective oscillations [36–38], as well as through constraints based on potentially large medium-induced neutrino masses in the SN core [28,29]. Large induced masses could strongly affect neutrino production and the emitted spectra. In this work, we present the first study of SNSI effects on neutrino flavor evolution during the neutronization burst phase of a future galactic SN. This early-time ν_e flash has robust temporal and spectral features and is comparatively insensitive to astrophysical uncertainties that can strongly affect the flavor composition at Earth [39]. A key signature is the anomalous preservation of the neutronization-burst ν_e peak in the normal mass ordering

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(NMO), in contrast to the standard Mikheyev-Smirnov-Wolfenstein (MSW) [40–43] expectation of a suppressed peak. Using realistic SN profiles and the expected capabilities of DUNE [44], we show that flavor conversion during the neutronization burst can probe SNSI couplings 2 to 4 orders of magnitude below existing terrestrial and solar bounds, while accessing parameter regions not covered by studies relying on large induced masses.

II. NEUTRONIZATION BURST

The neutronization burst is the earliest and most sharply defined phase of neutrino emission from a core-collapse SN [4,5]. It is driven by electron capture on free protons behind the shock front, producing an intense and short-lived ν_e flash within the first ~ 50 ms after core bounce, with typical energies of 10–20 MeV and a luminosity exceeding that of the other flavors by 1 to 2 orders of magnitude. Owing to its short duration, high ν_e purity, and weak dependence on the progenitor and equation of state, this burst provides a particularly clean probe of flavor conversion and new physics [45–52]. Throughout this work, we assume a fiducial supernova-Earth distance of $R = 10$ kpc. The time evolution and integrated spectra for the $12M_\odot$ progenitor adopted in this work [53], as well as the benchmark density profile at ~ 5 ms postbounce [54,55], are shown in the Supplemental Material [56]. These sharp temporal and spectral features make the burst especially well suited for detection in ν_e -sensitive experiments such as DUNE [44,57,58].

III. SCALAR NONSTANDARD INTERACTIONS

SNSI arise when a new scalar mediator ϕ couples to neutrinos and matter fermions, modifying neutrino propagation in dense media [27–29]. The relevant Lagrangian is

$$\mathcal{L} \supset -\frac{1}{2}(\partial_\mu \phi)^2 - \frac{1}{2}m_\phi^2 \phi^2 + \bar{\nu}_\alpha i \not{\partial} \nu_\beta - m_{\alpha\beta} \bar{\nu}_\alpha \nu_\beta - y_{\alpha\beta} \bar{\nu}_\alpha \nu_\beta \phi - y_f \bar{f} f \phi, \quad (1)$$

where m_ϕ is the scalar mass, and $y_{\alpha\beta}$ and y_f denote the Yukawa couplings to neutrinos and matter fermions.

In the contact-interaction limit assumed here, the scalar can be integrated out, yielding the effective interaction,

$$\mathcal{L}^{\text{eff}} \supset -\frac{y_f y_{\alpha\beta}}{m_\phi^2} (\bar{\nu}_\alpha \nu_\beta) (\bar{f} f). \quad (2)$$

This induces a medium-dependent correction to the neutrino mass matrix,

$$\delta M_{\alpha\beta} = \sum_f \frac{N_f y_f y_{\alpha\beta}}{m_\phi^2}, \quad (3)$$

where $N_f \simeq \langle \bar{f} f \rangle$ is the fermion number density. Restricting to universal couplings to u and d quarks with

strength y_q , one obtains

$$\delta M_{\alpha\beta} = \frac{3y_q y_{\alpha\beta}}{m_\phi^2} (N_p + N_n) = \sqrt{\Delta m_{21}^2} \eta_{\alpha\beta}^\odot \frac{\rho}{\rho_\odot}. \quad (4)$$

Here, $\rho_\odot = 100 \text{ g/cm}^3$ is the characteristic solar density scale. Couplings to electrons or other matter fermions would lead to analogous qualitative behavior, with the scalar source term rescaled by the corresponding matter density and coupling. For electron couplings, this source is reduced relative to the quark benchmark by $N_e/[3(N_p + N_n)] = Y_e/3$, for the same assumed coupling strength.¹ The dimensionless solar-normalized SNSI parameter is defined as [34],²

$$\eta_{\alpha\beta}^\odot = \frac{3y_q y_{\alpha\beta} \rho_\odot}{\sqrt{\Delta m_{21}^2} m_\phi^2 m_N}. \quad (5)$$

Numerically,

$$\frac{y_{\alpha\beta} y_q}{m_\phi^2} = 6.3 \times 10^{-15} \text{ eV}^{-2} \eta_{\alpha\beta}^\odot. \quad (6)$$

The flavor-basis evolution Hamiltonian including SNSI is, therefore,

$$\mathcal{H}_F = \frac{1}{2E} ([U \text{diag}(m_1, m_2, m_3) U^\dagger + \delta M] \times [U \text{diag}(m_1, m_2, m_3) U^\dagger + \delta M]^\dagger) + \text{diag}(V, 0, 0), \quad (7)$$

where δM is defined above. Unlike vector NSI, which modify only the matter potential, SNSI directly alter the neutrino mass matrix and introduce a dependence on the absolute neutrino mass scale. In the analysis below, we activate one $\eta_{\alpha\beta}^\odot$ parameter at a time to isolate its impact on SN flavor evolution.

IV. IMPACT OF A NONZERO $\eta_{\tau\tau}^\odot$

We begin by activating a single parameter and consider the case where only $\eta_{\tau\tau}^\odot$ (or $\delta M_{\tau\tau}$) is nonzero. The full Hamiltonian becomes

¹Possible scalar neutrino self-interactions [38] constitute an additional effect not included in the Hamiltonian above. Since the neutronization burst is initially dominated by ν_e , a flavor-nonuniversal $\tau\tau$ feedback develops only after the additional conversion has generated a ν_τ component. As discussed in the Supplemental Material [56], such feedback can shift the conversion to larger radii, but does not generically spoil the adiabatic flavor-conversion signature studied in this work.

²The superscript $\odot$ indicates normalization to the solar density scale and solar mass-squared differences [34]. This definition may differ from those adopted in other works in the literature.

$$\mathcal{H}_F = \frac{1}{2E} U \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m_{21}^2 & 0 \\ 0 & 0 & \Delta m_{31}^2 \end{pmatrix} U^\dagger + \frac{1}{2E} \begin{pmatrix} 2EV & 0 & c_{e\tau}\delta M_{\tau\tau} \\ 0 & 0 & c_{\mu\tau}\delta M_{\tau\tau} \\ c_{\tau e}\delta M_{\tau\tau} & c_{\tau\mu}\delta M_{\tau\tau} & \delta M_{\tau\tau}^2 + 2c_{\tau\tau}\delta M_{\tau\tau} \end{pmatrix}, \quad (8)$$

where $c_{\alpha\beta} = \sum_j m_j U_{\alpha j} U_{\beta j}^*$ are the elements of the vacuum neutrino mass matrix in the flavor basis. Unlike standard matter effects, which depend linearly on the density ρ , the SNSI terms introduce both a dependence on the absolute neutrino mass scale through $c_{\alpha\beta}$ and quadratic-density contributions through $\delta M_{\tau\tau}^2$. Depending on the strength of $\eta_{\tau\tau}^\circ$, these terms can rearrange the level ordering, modify the MSW structure, or induce new resonances at small radii. An analogous evolution is obtained for $\eta_{\mu\mu}^\circ$, as discussed later.

V. DIFFERENT REGIMES WITH A NONZERO $\eta_{\tau\tau}^\circ$

The evolution governed by $\mathcal{H}_F$ exhibits distinct regimes controlled by the local matter density and the SNSI parameter $\eta_{\tau\tau}^\circ$. At densities $\rho \gtrsim 10^4$ g/cm³ ($r \lesssim 10^4$ km), vacuum terms are negligible and will be omitted in the following estimates. Since both the standard matter potential and the linear SNSI terms proportional to $c_{\alpha\beta}\delta M_{\tau\tau}$ scale linearly with ρ , their ratio is density independent. For instance,

$$\frac{2c_{\tau\tau}\delta M_{\tau\tau}}{2EV} \approx 6\eta_{\tau\tau}^\circ, \quad (9)$$

where we adopt $E = 10$ MeV, $\Delta m_{21}^2 = 7.5 \times 10^{-5}$ eV² [59], and $m_1 < 0.01$ eV, yielding $c_{\tau\tau} \approx 0.025$ eV, 0.001 eV $\lesssim c_{e\tau} \lesssim 0.008$ eV (varying δ_{CP}), and $c_{\mu\tau} \approx 0.025$ eV. The standard matter potential therefore dominates over linear SNSI terms as long as $|\eta_{\tau\tau}^\circ| \lesssim 0.1$.

The assumption $m_1 < 0.01$ eV is consistent with the cosmological bound $\sum m_\nu < 0.072$ eV [60] for NMO. With this assumption, the coefficients $c_{\alpha\beta}$ depend only weakly on the absolute neutrino mass scale. This constraint is substantially stronger than the kinematic bound from KATRIN, $m_1 < 0.45$ eV [61]. The implications of relaxing this assumption are discussed in the Supplemental Material [56].

The ratio between the standard matter potential and the quadratic SNSI term is instead

$$\frac{2EV}{\delta M_{\tau\tau}^2} \approx \frac{1}{\eta_{\tau\tau}^{\circ 2}(\rho/\rho_\odot)}, \quad (10)$$

which varies with density/radius. Since neutrinos are emitted at $\rho \sim 10^{11}$ g/cm³ ($r \sim 50$ – 100 km), for $|\eta_{\tau\tau}^\circ| \gtrsim 10^{-4}$

the quadratic term initially dominates over $2EV$ and later becomes subdominant, potentially inducing an additional inner resonance between ν_e and ν_τ prior to the standard MSW transitions. This will be discussed in the following sections.

By contrast, for $|\eta_{\tau\tau}^\circ| \gtrsim 0.1$, the linear SNSI term $2c_{\tau\tau}\delta M_{\tau\tau}$ becomes comparable to, or larger than, $2EV$, modifying the MSW structure, with a strong dependence on the sign of $\eta_{\tau\tau}^\circ$ (this is explained in the Supplemental Material [56]). Finally, for $|\eta_{\tau\tau}^\circ| \ll 10^{-4}$, all SNSI terms are negligible and $\mathcal{H}_F$ reduces to the standard oscillation in matter.

For clarity, a visual comparison of the radial behavior of $2EV$, $2c_{\tau\tau}\delta M_{\tau\tau}$, and $\delta M_{\tau\tau}^2$, and of how they determine the different flavor-conversion regimes, is provided in the Supplemental Material [56].

VI. ADDITIONAL $\nu_e \leftrightarrow \nu_\tau$ RESONANT CONVERSION INDUCED BY SNSI

An additional resonance appears for $10^{-4} \lesssim |\eta_{\tau\tau}^\circ| < 0.1$. In this regime, the new inner resonance involves the ν_e and ν_τ states, while the ν_μ state acts essentially as a spectator, so the problem can be reduced to the following effective ν_e – ν_τ 2×2 Hamiltonian:

$$\mathcal{H}_F^{2 \times 2} \approx \frac{1}{2E} \begin{pmatrix} 2EV & c_{e\tau}\delta M_{\tau\tau} \\ c_{\tau e}\delta M_{\tau\tau} & \delta M_{\tau\tau}^2 \end{pmatrix}. \quad (11)$$

Since $\delta M_{\tau\tau}^2$ initially exceeds $2EV$ and decreases more rapidly with radius, a resonance occurs when $2EV = \delta M_{\tau\tau}^2$. This occurs at $\rho \gtrsim 10^4$ g/cm³ ($r \lesssim 10^4$ km), prior to the standard MSW layers.

The resonance density is

$$\rho_{\text{res}} \approx \frac{\rho_\odot^2}{\Delta m_{21}^2 \eta_{\tau\tau}^{\circ 2}} \left(\frac{2\sqrt{2}EG_F Y_e}{m_N} \right). \quad (12)$$

Efficient flavor conversion requires the resonance to be adiabatic, with the adiabaticity condition given by

$$\gamma = \left| \frac{4|\mathcal{H}_{e\tau}|^2}{\dot{\mathcal{H}}_{\tau\tau} - \dot{\mathcal{H}}_{ee}} \right|_{\text{res}} \approx \frac{2|c_{e\tau}|^2}{E} \left| \frac{1}{\rho} \frac{d\rho}{dr} \right|_{\text{res}}^{-1} > 1, \quad (13)$$

which depends sensitively on δ_{CP} through $c_{e\tau}$.

To make the dependence of γ on δ_{CP} explicit, we write

$$|c_{e\tau}|^2 = c_{13}^2(A^2 + B^2 - 2AB \cos \delta_{\text{CP}}), \quad (14)$$

with $A \equiv c_{23}s_{13}(c_{12}^2 m_1 + s_{12}^2 m_2 - m_3)$ and $B \equiv c_{12}s_{12}s_{23} \times (m_1 - m_2)$. For $m_1 = 0$, NMO, and $E = 10$ MeV, both A and B are negative, so that $|c_{e\tau}|$ is maximized for $\delta_{\text{CP}} = \pi$ and minimized near $\delta_{\text{CP}} = 0$.

Approximating the neutronization-burst density profile as $\rho \propto r^{-3}$, one finds

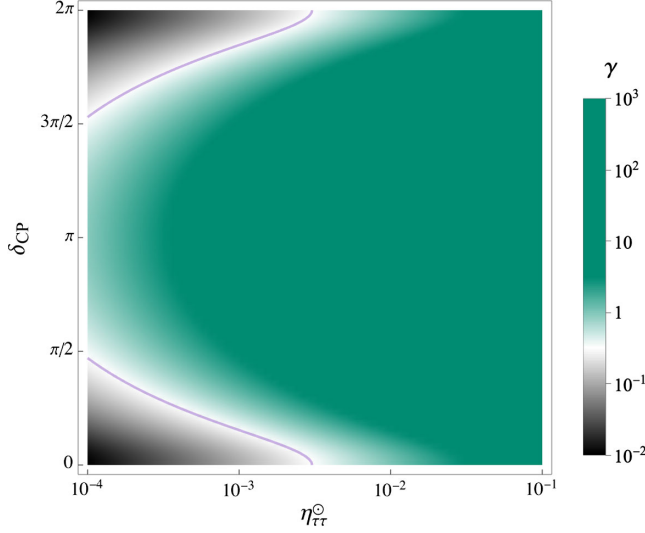
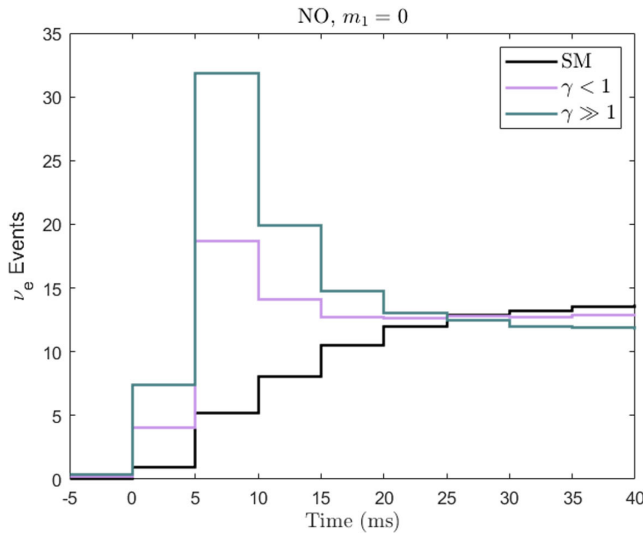


FIG. 1. Adiabaticity parameter γ as a function of $\eta_{\tau\tau}^{\odot}$ and δ_{CP} , assuming $m_1 = 0$ and $E = 10$ MeV. Black regions correspond to fully nonadiabatic propagation ($\gamma \ll 1$), green regions to fully adiabatic propagation ($\gamma \gg 1$), and the color gradient denotes the transition regime. The purple contour marks the half-adiabatic condition $\gamma \simeq 0.45$.

$$\left| \frac{1}{\rho} \frac{d\rho}{dr} \right|_{\text{res}}^{-1} = \frac{r_{\text{res}}}{3}, \quad (15)$$

with $r_{\text{res}} \approx 6.5 \times 10^4 \eta_{\tau\tau}^{2/3}$ km. Since $\gamma \propto |c_{e\tau}|^2 r_{\text{res}}$, adiabaticity increases both with $\eta_{\tau\tau}^{\odot}$ and as $\delta_{\text{CP}} \rightarrow \pi$.

The resulting adiabatic, non-adiabatic, and transition regimes are summarized in Fig. 1. The corresponding impact on detector event rates is shown in Fig. 2.



VII. SNSI EFFECTS ON DUNE EVENT RATES

We now assess the observable consequences of a nonzero $\eta_{\tau\tau}^{\odot}$ on the ν_e flux at Earth and the corresponding DUNE event rates. For $|\eta_{\tau\tau}^{\odot}| < 10^{-4}$, SNSI effects are negligible and the neutronization-burst ν_e is produced as the heaviest matter eigenstate, ν_3^m , which propagates adiabatically and arrives at Earth as ν_3 . Since ν_3 contains only a small ν_e component, the ν_e flux at a terrestrial detector is

$$\begin{aligned} \Phi_{\nu_e}^{\text{std}} &= |U_{e3}|^2 \Phi_{\nu_e}^i + (|U_{e1}|^2 + |U_{e2}|^2) \Phi_{\nu_x}^i \\ &\approx 0.02 \Phi_{\nu_e}^i + 0.98 \Phi_{\nu_x}^i, \end{aligned} \quad (16)$$

where $\Phi_{\nu_x}^i$ denotes the common unoscillated ν_μ and ν_τ flux. Although $\Phi_{\nu_e}^i \approx 10 \Phi_{\nu_x}^i$ at the neutronization peak, the ν_e contribution remains subdominant, and the peak is therefore suppressed for NMO. This standard case is shown by the black curve in Fig. 2 (details of the DUNE event-rate calculation and detector modeling are given in the Supplemental Material [56]).

For $|\eta_{\tau\tau}^{\odot}| \gtrsim 10^{-4}$, the SNSI contribution to the ν_τ potential dominates near the neutrinosphere, and ν_e is instead produced as the second-heaviest eigenstate, ν_2^m . If the propagation is adiabatic, the initial ν_e flux arrives at Earth as ν_2 , yielding

$$\begin{aligned} \Phi_{\nu_e}^{\text{SNSI}} &= |U_{e2}|^2 \Phi_{\nu_e}^i + (|U_{e1}|^2 + |U_{e3}|^2) \Phi_{\nu_x}^i \\ &\approx 0.3 \Phi_{\nu_e}^i + 0.7 \Phi_{\nu_x}^i. \end{aligned} \quad (17)$$

Since during the neutronization burst $\Phi_{\nu_e}^i \gg \Phi_{\nu_x}^i$, the peak remains partially visible. This behavior is illustrated by the

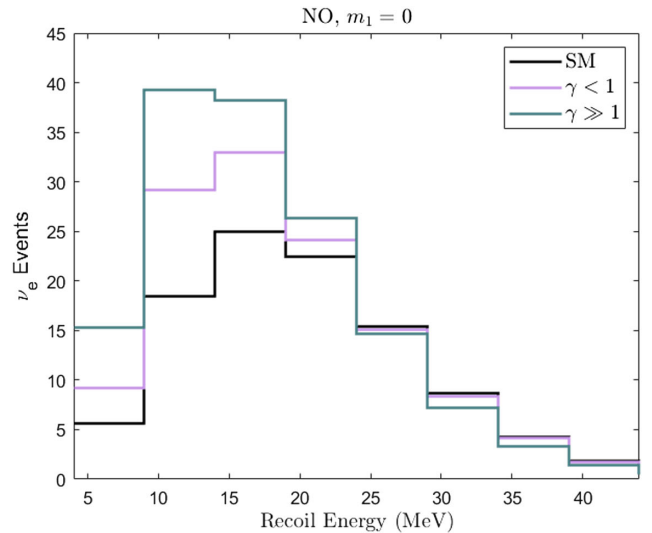


FIG. 2. Expected ν_e event rates in DUNE for a $12M_{\odot}$ progenitor during the neutronization burst for NMO and $m_1 = 0$. The black curve corresponds to the standard MSW scenario (no SNSI or $\gamma \ll 1$). The green curve shows the fully adiabatic SNSI regime ($\gamma \gg 1$), where the neutronization peak is partially preserved, while the purple curve corresponds to the partially adiabatic SNSI regime ($\gamma \lesssim 1$), in which the peak is partially washed out. The three cases correspond to the adiabaticity regimes identified in Fig. 1. The left (right) panel shows the time (recoil-energy) distribution of events.

green curves in Fig. 2. For best-fit oscillation parameters [59], the propagation is fully adiabatic for all $\eta_{\tau\tau}^{\odot}$ shown.

If the SNSI-induced resonance is not fully adiabatic, the initially produced ν_2^m can partially convert to ν_3^m , and the final flux interpolates between the SNSI and standard cases,

$$\Phi_{\nu_e} = (1 - P_f)\Phi_{\nu_e}^{\text{SNSI}} + P_f\Phi_{\nu_e}^{\text{std}}, \quad (18)$$

with the Landau-Zener flip probability $P_f = e^{-\frac{\pi}{2}\gamma}$ [62–64]. This intermediate regime is illustrated by the purple curve in Fig. 2. In this case, the neutronization peak is partially suppressed but remains distinguishable. For $|\eta_{\tau\tau}^{\odot}| \gtrsim 0.1$, Eq. (18) is effectively realized with $P_f = 0$; see the Supplemental Material [56].

Theoretical uncertainties in the ν_e – ^{40}Ar cross section [65] and in the overall supernova flux normalization may affect the absolute normalization of the DUNE event rates, but they do not alter the main signature studied here, namely the presence or absence of the neutronization-burst peak in time. To quantify this point, we perform a shape-only comparison of the time distributions in the left panel of Fig. 2, fully marginalizing over the overall normalization; details are given in the Supplemental Material [56]. Relative to the standard MSW prediction, we find $\chi^2 \simeq 38$ for the fully adiabatic SNSI case and $\chi^2 \simeq 17$ for the partially adiabatic case. The dominant contribution comes from the neutronization-burst peak around 5–10 ms, showing that the SNSI-induced restoration of the peak remains distinguishable even without relying on the absolute event normalization.

VIII. PARAMETER REGION AND EXISTING CONSTRAINTS

Fig. 3 shows the parameter region in which the additional SNSI-induced flavor conversion discussed in this work occurs, projected through Eq. (5) onto the parameter space of scalar mass and coupling $(m_\phi, \sqrt{y_{\tau\tau}y_q})$, alongside existing constraints and projections from other searches. Here, we use $y_u = y_d = y_q$. In the same parameter space, we depict the constraints on the in-medium mass of neutrinos in the Sun and SN1987A [29], which directly probes $\sqrt{y_{\tau\tau}y_q}$ as a function of the scalar mass. The bounds labeled as “others” depict bounds from fifth-force experiments [66] as well as other cosmological bounds. We also depict the most stringent bound on $|\eta_{\tau\tau}^{\odot}| = 0.06$ from combined solar and KamLAND data [34]. Alongside, we also show the projected sensitivity of the long-baseline DUNE experiment [26]. We restrict our analysis to scalar masses $m_\phi > 10^{-16}$ MeV. Scalars lighter than this would mediate forces with macroscopic ranges ($\gtrsim 10$ km) comparable to the size of the SN core, leading to additional long-range contributions to the matter potential that require a dedicated treatment. We also refrain from including the parameter space for $m_\phi > 10^{-10}$ MeV and $\sqrt{y_{\tau\tau}y_q} > 10^{-12}$

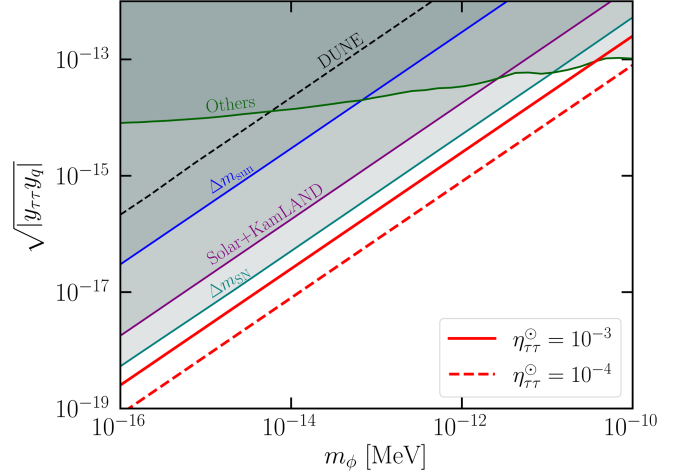


FIG. 3. Parameter region in which the additional SNSI-induced flavor conversion discussed in this work occurs, shown in the scalar mass–coupling plane $(m_\phi, \sqrt{y_{\tau\tau}y_q})$ using the relation in Eq. (5), with $y_u = y_d = y_q$. The two dashed lines correspond to $|\eta_{\tau\tau}^{\odot}| = 10^{-3}$ and 10^{-4} . The bounds Δm_{sun} and Δm_{SN} depict constraints from in-medium neutrino masses inside the Sun and SN1987A, respectively [29]. We also show constraints from BBN, ΔN_{eff} , and fifth-force experiments, collectively labeled as “others” [26], as well as the current 95% C.L. bound on $\eta_{\tau\tau}^{\odot}$ from combined solar and KamLAND data [34]. Additionally, we show the projected 95% C.L. sensitivity of the upcoming long-baseline DUNE experiment [26]. The region with $m_\phi > 10^{-10}$ MeV and $\sqrt{y_{\tau\tau}y_q} > 10^{-12}$ is omitted for presentation purposes only, since the relevant bounds there are strongly model dependent, and this does not reflect a limitation of the validity of our analysis.

where nontrivial model-dependent bounds from BBN, SN1987A, and stellar cooling [67], SN1987A trapping [68], and neutrino self interactions [69–73] become relevant.

IX. SN VERSUS SOLAR NEUTRINOS IN PROBING SNSI

Exploiting the neutronization burst, SN neutrinos can probe $|\eta_{\tau\tau}^{\odot}|$ down to $\sim 10^{-4}$, well below the values currently accessible to solar neutrinos, $|\eta_{\tau\tau}^{\odot}| \sim O(1)$ [34]. For solar neutrinos, rewriting Eq. (9) yields

$$\frac{2c_{\tau\tau}\delta M_{\tau\tau}}{2EV} \approx 12\eta_{\tau\tau}^{\odot}, \quad (19)$$

where the numerical factor reflects a characteristic solar neutrino energy of 5 MeV. As a result, SNSI effects become relevant only for $|\eta_{\tau\tau}^{\odot}| \gtrsim 0.1$, consistent with existing solar bounds. In this regime, the quadratic term remains subdominant, as

$$\frac{2c_{\tau\tau}\delta M_{\tau\tau}}{\delta M_{\tau\tau}^2} \approx \frac{6}{\eta_{\tau\tau}^{\odot}(\rho/\rho_{\odot})} \gg 1 \quad (20)$$

at solar densities and grows further as ρ decreases. Solar sensitivity is therefore controlled by the linear SNSI term.

By contrast, the SN reach is driven by the quadratic term $\delta M_{\tau\tau}^2$, strongly enhanced by the extreme densities near the neutrinosphere. This qualitative difference in density scaling underlies the orders-of-magnitude improvement of SN neutrinos over solar probes.

X. FINAL REMARKS

We have shown that neutrinos from a future galactic core-collapse SN provide an exceptional probe of SNSI. Owing to the quadratic density scaling of SNSI effects, the neutronization burst can exhibit an anomalous ν_e peak in the NMO, even for couplings well below the current reach of solar and terrestrial experiments. With its excellent time and energy resolution, DUNE can test values as small as $|\eta_{\tau\tau}^{\odot}| \sim 10^{-4}$, highlighting the next nearby SN as a unique natural laboratory for scalar-mediated new physics. For vector NSI, the density-squared contribution studied in this work is absent; an analogous burst-revival signature would instead require non-electron flavor diagonal NSI above $O(0.1)$, together with off diagonal entries sufficient for adiabatic conversion [33], parameter combinations constrained or directly tested by non-supernova oscillation and CE ν NS data [74].

In the inverted mass ordering, both the Standard Model and SNSI predict the presence of a neutronization peak, leading to a strong degeneracy and a substantially reduced ability to distinguish SNSI from the standard expectation.

As a result, the discriminating power of the neutronization burst is maximized in the NMO, where the appearance of the peak would constitute a clear signal of beyond-Standard-Model physics.

During the period of our publication, a complementary study of SNSI in SN neutrinos also appeared in Ref. [75], with emphasis on detector event rates and the associated mass-ordering ambiguity.

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DATA AVAILABILITY

The data that support the findings of this article are not publicly available because they are owned by a third party and the terms of use prevent public distribution. The data are available from the authors upon reasonable request.

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