Oscillations of high-energy cosmic neutrinos in the copious MeV neutrino background

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The core-collapse of massive stars and the merger of neutron star binaries are among the most promising candidate sites for the production of high-energy cosmic neutrinos. We demonstrate that the high-energy neutrinos produced in such extreme environments can experience efficient flavor conversions on scales much shorter than those expected in vacuum, due to their coherent forward scatterings with the bath of decohered low-energy neutrinos emitted from the central engine. These low-energy neutrinos, which exist as mass eigenstates, provide a very special and peculiar dominant background for the propagation of the high-energy ones. We point out that the high-energy neutrino flavor ratio is modified to a value independent of neutrinos energies, which is distinct from the conventional prediction with the matter effect. We also suggest that the signals can be used as a novel probe of new neutrino interactions beyond the Standard Model. This is yet another context where neutrino-neutrino interactions can play a crucial role in their flavor evolution.

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I. INTRODUCTION

Core-collapse supernovae (CCSNe) and neutron star mergers (NSMs) commonly lead to a burst of thermal neutrinos in the MeV range, with a very active literature on the physics of their oscillations. These environments are considered as the central engine of not only supernovae but also gamma-ray bursts (GRBs) and other energetic or transrelativistic supernovae driven by outflows such as jets and winds (i.e., engine-driven supernovae). It has been suggested that GeV–TeV neutrinos can be produced in such environments if neutron-loaded outflows are launched from a black hole with an accretion disk and/or a newborn magnetar [1–5]. Even TeV–PeV neutrinos can be generated inside the outflows through shock acceleration or magnetic reconnections [6–10].

The IceCube discovery of high-energy neutrinos (HEνs) has opened a new avenue to investigate the physics of neutrino oscillations and related neutrino physics (see Refs. [11–13] and references therein). In this article, we investigate a novel effect caused by the interplay between the HEνs produced in outflows and low-energy neutrinos (LEνs) directly from the central engine (see Fig. 1 for the schematic picture). Indeed, the decohered LEνs, which are in mass eigenstates, can provide a *dominant* unusual background for the propagation of the HE ones. In particular, we show that the resulting neutrino self-interactions (νSI) lead to a very intriguing phenomenon in which the HEνs experience short-scale flavor oscillations in such a way that, on average, they end up in the mass eigenstates. This phenomenon is noncollective in spirit and differs remarkably from the well-known phenomenon of *collective oscillations* of MeV neutrinos occurring in dense neutrino environments such as CCSNe and NSM remnants [14–16].

II. HE NEUTRINO INTERACTIONS IN JETS OR WINDS

Various scenarios for HEν production in GRBs, CCSNe, and NSMs have been suggested. In this work, we are interested in the fate of HEνs so we assume that they are produced at the dissipation radius $R_{\rm diss} \sim 10^8$–10^{10} cm, which is much larger than the engine radius $R_{\rm eng} \sim 10^6$ cm.

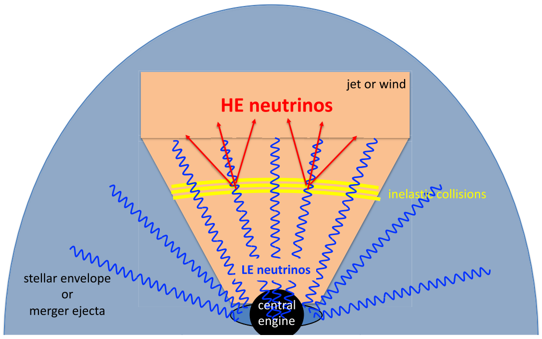

FIG. 1. Schematic picture of HEν (GeV–PeV) production and their interactions with LEνs (MeV–GeV) from the central engine such as a black hole with an accretion disk or a newborn magnetar. HEν production occurs at $R_{\rm diss} \gg R_{\rm eng}$, which may be beamed with the opening angle $\sim 1/\Gamma$, with $R_{\rm diss}$, $R_{\rm eng}$, and Γ being the dissipation radius, engine radius, and outflow Lorentz factor, respectively. Note that the opening angle of the LEν beams is exaggerated for illustration purposes.

Then, an interesting interplay is particularly plausible when the HEν production occurs within the duration of LEν emission. It should also occur before the outflow breakouts (where the outflow breakout time is longer than the light crossing time). Note that (as seen below) the effect on neutrino oscillation is largely model independent as long as $R_{\rm diss}$ is so small that LEνs govern the neutrino potential.

Although the proposed mechanism works in pretty general setups, for illustrative purposes, we consider models of GeV–TeV neutrinos. Quasithermal neutrinos can naturally be produced in the GeV–TeV range through inelastic neutron-proton collisions when neutrons decouple from protons or neutron-loaded outflows make collisions with the surrounding environment [1–3,5], and higher-energy nonthermal neutrinos may also be produced through neutron-proton-converter acceleration [3,4]. For these neutrinos, the dissipation may occur at $R_{\rm diss} \sim 10^8$–10^{10} cm [1,5]. Protons could be further accelerated to higher energies via shock acceleration or magnetic reconnections, and nonthermal TeV neutrinos can be efficiently produced via inelastic pp and/or $p\gamma$ interactions [6–10]. These neutrinos are associated with the dissipation at internal, collimation, and termination shocks [5,6,9,17,18]. For example, the internal dissipation radius is estimated to be $R_{\rm diss} \approx 2\Gamma^2 c\delta t \sim 6\times 10^8$ cm $(\Gamma/3)^2(\delta t/1~{\rm ms})$, where δt is the variability time.

The number density of LEνs at $R_{\rm diss}$ (in the engine frame) is

$$n_{{\rm LE}\nu} = \frac{L_{\nu_e}}{4\pi R_{\rm diss}^2 c\langle E_\nu\rangle} \simeq 1.7\times 10^{27}~{\rm cm}^{-3}\left(\frac{L_{\nu_e}}{10^{52}~{\rm erg~s^{-1}}}\right) \times\left(\frac{R_{\rm diss}}{10^9~{\rm cm}}\right)^{-2}\left(\frac{\langle E_\nu\rangle}{10~{\rm MeV}}\right)^{-1}, \quad (1)$$

which can be much larger than the expected number density of HEνs therein, $n_{{\rm HE}\nu} \lesssim 10^{24}$ cm^{-3} at 10^9 cm. Here L_{ν_e} and $\langle E_\nu\rangle$ are the electron neutrino luminosity and average energy, respectively. In addition, the electron number density in the outflow is

$$n_e \approx \frac{\Gamma L}{4\pi R_{\rm diss}^2\Gamma^2 m_p c^3} \simeq 5.9\times 10^{23}~{\rm cm}^{-3}\left(\frac{L}{10^{52}~{\rm erg~s^{-1}}}\right) \times\left(\frac{R_{\rm diss}}{10^9~{\rm cm}}\right)^{-2}\left(\frac{\Gamma}{30}\right)^{-1} \ll n_{{\rm LE}\nu}. \quad (2)$$

Unlike the flavor evolution of the LEνs, which is dominated by the mass Hamiltonian at such neutrino number densities, the evolution of HEνs can be dominated by their coherent scattering with the bath of the LEνs. This simply comes from the fact that for the HEνs, the strength of νSI [see Eq. (5)],

$$\mu \approx \sqrt{2}G_{\rm F} n_\nu \hbar^2 c^2 \xi \simeq 6.4\times 10^{-6}~{\rm cm}^{-1}\left(\frac{n_\nu}{10^{27}~{\rm cm}^3}\right)\xi, \quad (3)$$

can be much larger than their vacuum wavelength, $\omega \approx \Delta m^2_{\rm atm}c^3/(2\hbar E_\nu) \simeq 6\times 10^{-10}~{\rm cm}^{-1}\,(100~{\rm GeV}/E_\nu)$, with $G_{\rm F}$ being the Fermi constant. In the above equation, $\xi = 1-\cos\Theta$, where Θ is the opening angle of the neutrino beams, which is determined here mainly by the opening angle of HEνs. Note that as soon as the parameter μ is known, ξ and ν do not provide any more relevant information. For relativistic flows with $\Gamma \sim 2$–100, one has $\xi \approx \Theta^2/2 \sim 1/(2\Gamma^2)$. Note that the optical depth to incoherent neutrino scatterings is so small that the electron-positron pair production is negligible. Moreover, given the fact that the number density of LEνs is much larger than that of HEνs, one can assume that n_ν here is exclusively determined by the LEνs.

Although the number density of the LEνs within the zones of interest is expected to be too small to allow for the νSI Hamiltonian to compete with or dominate their vacuum Hamiltonian, the evolution of HEνs is almost completely governed by the interaction term for appropriate LEν number densities ($\omega_{{\rm HE}\nu} \ll \mu \lesssim \omega_{{\rm LE}\nu}$).

III. TWO-BEAM MODEL

In order to demonstrate how the flavor content of HEνs is impacted by their propagation in the bath of the LEνs, we study neutrino-flavor conversions in a one-dimensional two-beam model, which consists of *two* energy bins, and a *three-flavor* neutrino gas with two angular beams. The neutrino energies are taken to be $E_\nu = 10$ MeV and 100 GeV for the bins representing the LEνs and the HEνs, respectively, unless otherwise stated. Thus, in brief, our model consists of two angle beams each including neutrinos and antineutrinos with two energies representing high- and low-energy neutrinos. We also assume that the neutrino density is constant within the bath of LEνs.

In order to study the flavor evolution of neutrinos in our model, we solve the Liouville–von Neumann equation for the neutrino density matrix, ϱ ($c = \hbar = 1$) [19],

$$i d_t \varrho_{\mathbf{p}} = \left[\frac{\mathsf{UM^2U^\dagger}}{2E_\nu} + \mathsf{H}_{\rm m} + \mathsf{H}_{\nu\nu,\mathbf{p}}, \varrho_{\mathbf{p}}\right], \quad (4)$$

with

$$\mathsf{H}_{\nu\nu,\mathbf{p}} = \sqrt{2}G_{\rm F}\int \frac{d^3 p'}{(2\pi)^3}(1-\mathbf{v}\cdot\mathbf{v}')(\varrho_{\mathbf{p}'} - \bar{\varrho}_{\mathbf{p}'}) \quad (5)$$

being the neutrino potential stemming from the neutrino-neutrino forward scattering [20–22]. Here $\mathbf{p}$ is the neutrino momentum, $E_\nu = |\mathbf{p}|$, $\mathbf{v} = \mathbf{p}/E_\nu$, and M^2 are the energy, velocity, and mass-square matrix of the neutrino, respectively, and U is the Pontecorvo-Maki-Nakagawa-Sakata matrix. Moreover, $\mathsf{H}_{\rm m}$ is the contribution from the matter term which is proportional to the matter (electron) density [23,24], which is ignored in our calculations due to the relatively small matter density inside the outflow. Hence, there are only two nonzero terms in H (vacuum and νSI) which are both diagonal in the mass basis and constant (see below), but with different eigenvalues.

As mentioned above, here $\mathsf{H}_{\nu\nu}$ is almost exclusively determined by LEνs due to their much larger number densities. In this study, we assume that LEνs are in mass eigenstates because they are expected to be already decohered within the zones of interests, which are very far from their emission region (with a typical coherence length of a few 10^6 cm for the atmospheric mass difference) [25–27]. In addition, the HEνs do not significantly disturb the flavor state of the LEν bath due to their much smaller number densities. This implies that the LEνs do not evolve since their evolution is dominated by the mass term and they are already in the mass eigenstates. Consequently, $\mathsf{H}_{\nu\nu}$ remains approximately constant. (We will discuss later how the neutrino-flavor evolution changes once the oscillations of LEνs are taken into account.) On the other hand, the HEνs find themselves in the bath of the LEνs as soon as they are produced, and start flavor conversions on relatively short scales due to their interactions with the LEνs. It should be kept in mind that the coherence length of HEνs are expected to be much longer than those of the LE ones [28].

IV. RESULTS

In the top panel of Fig. 2, we show the survival probabilities of HEν_e's propagating in vacuum (dashed curve) and in the bath of the LEνs (solid curve). As can be clearly seen, the oscillation scales of HEνs can change by orders of magnitude when coherent scatterings with LEνs are taken into account. As a matter of fact, the oscillation scale of HEνs in a bath of the LE ones is determined by the number density of the LEνs, namely, $l_{\rm osc} \sim |\mathsf{H}_{\nu\nu}|^{-1} \sim \mu^{-1}$ ($\sim 10^5$ cm for this simulation). This scaling behavior can be immediately deduced from Eq. (4) given the fact that for the HEνs the dominant contribution to the Hamiltonian comes from coherent scatterings with LEνs as long as $\omega_{{\rm HE}\nu} \ll \mu$

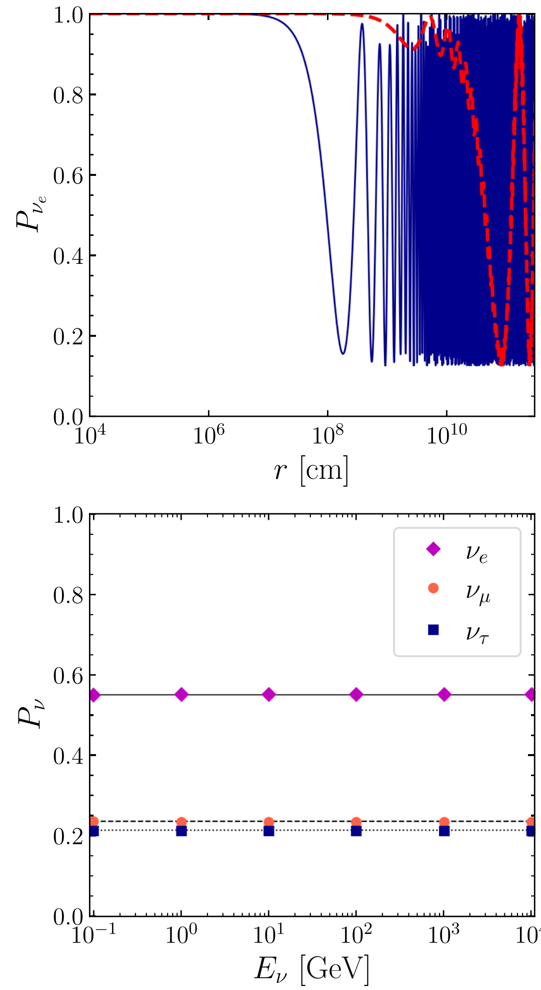

FIG. 2. Top: survival probability of HEν_e's propagating in vacuum (dashed red curve), and in the bath of the LEνs (solid blue curve). HEνs can experience flavor conversions on scales much shorter than those expected in vacuum. Here, for illustrative purposes, we assume $\mu = 10^{-7}$ cm^{-1}, $E_{{\rm LE}\nu} = 10$ MeV, and $E_{{\rm HE}\nu} = 100$ GeV. For the LEν bath, $n_{\bar{\nu}_e}/n_{\nu_e} = 1.3$ is also fixed, although the survival probabilities are independent of $n_{\bar{\nu}_e}/n_{\nu_e}$ as long as it is not too close to 1. Bottom: survival probabilities as a function of the HEν energy, where the diamonds, points, and squares are the survival probabilities of ν_e, ν_μ, and ν_τ obtained from the simulations, respectively, and the black lines are the corresponding analytical solutions. We assume an initial flavor ratio of $\nu_e:\nu_\mu:\nu_\tau = 1:0:0$. Here we set $\theta_{12} = 33.6°$, $\theta_{23} = 47.2°$, $\theta_{13} = 8.5°$, and $\delta_{\rm CP} = 0$. Antineutrinos behave in exactly the same manner.

(we indeed observe this behavior for $10\ \omega_{\mathrm{HE}\nu} \lesssim \mu$). Note that here the only relevant physical parameter is $\mu/\omega_{\mathrm{HE}\nu}$, and therefore one can play with μ in Fig. 2 as long as this ratio is constant (provided that r is also appropriately rescaled for the top panel).

The fact that HEνs oscillate on scales $\sim\mu^{-1}$ might remind an astute reader of the phenomenon of *fast* flavor conversions occurring for MeV neutrinos in dense neutrino media [29,30]. This similarity becomes more obvious once one notes that the oscillations of HEνs can even occur when $\omega_{\mathrm{HE}\nu} = 0$. However, and in spite of this resemblance, it should be kept in mind that these two phenomena completely differ in spirit and *have nothing to do with each other*. Although for the occurrence of fast conversions certain criteria need to be fulfilled [31], the short-scale conversions of HEνs in a bath of the LE ones is a generic phenomenon provided that there are two populations of neutrinos of which one is dominant.

Flavor conversions of HEνs induced by the static bath of the LEνs are also distinct from the phenomenon of ordinary collective oscillations in dense neutrino media. While the latter is a nonlinear phenomenon with a high level of coupling, the former is a linear phenomenon where $\mathsf{H}_{\nu\nu}$ solely provides a constant background for the flavor evolution of HEνs. This implies that such flavor conversions of HEνs are a noncollective phenomenon. Also note that the relevant n_ν's can be many orders of magnitude smaller than the values for which collective oscillations of MeV neutrinos are expected, due to the much smaller $\omega_{\mathrm{HE}\nu}$.

In order to see how the short-scale flavor conversions of HEνs change the expected $\nu_e:\ \nu_\mu:\nu_\tau$ ratio on Earth, one can average the survival probabilities over a few oscillations. As we will indicate in our upcoming work [32], such an averaging process in our two-beam model corresponds to averaging over the neutrino angular distribution in a more realistic, multiangle neutrino gas. The average survival probabilities then reach a steady state which does not depend on the details of the simulation (apart from the neutrino mixing parameters, as discussed in the following), shown in the bottom panel of Fig. 2. This behavior can be understood analytically as follows. In the mass basis, the νSI Hamiltonian is diagonal with its kk-th component being $h_k \propto \sum_\alpha |U_{\alpha k}|^2(\rho_{\alpha\alpha} - \bar{\rho}_{\alpha\alpha})$, where $\overset{(-)}{\rho}_{\alpha\alpha}$ are the initial (anti) neutrino occupation numbers in flavor α. This comes from the fact that $\mathsf{H}_{\nu\nu}$ is nearly determined only by the LEνs which are in the mass eigenstates. Then the HEν density matrix in the mass basis, $\tilde{\rho}$, evolves as,

$$\tilde{\rho}_{ij}(t) = \tilde{\rho}_{ij}(0)e^{-\mathrm{i}(h_i - h_j)t}, \tag{6}$$

implying that the averaged flavor ratio, $\nu_e:\ \nu_\mu:\nu_\tau$, can be written as,

$$|U_{ek}|^2|U_{\alpha k}|^2 f_\alpha : |U_{\mu k}|^2|U_{\alpha k}|^2 f_\alpha : |U_{\tau k}|^2|U_{\alpha k}|^2 f_\alpha, \tag{7}$$

where there is a summation over α and k, and $f_e:\ f_\mu:f_\tau$ is the initial flavor ratio at the production region. The black lines in the lower panel of Fig. 2 indicate the analytical flavor ratios in Eq. (7), which show a perfect agreement with the numerical results.

Note that the average density matrix in the flavor basis is equal to the one expected after the neutrino decoherence, and is also independent of the neutrino energy. This behavior indeed results from the fact that the HEνs oscillate very quickly about $\mathsf{H}_{\nu\nu}$ and, consequently, they end up in the mass eigenstates (on average). Hence, in summary, short-scale conversions of HEνs induced by the ambient gas of the LEνs lead to their decoherence on scales that can be shorter than their natural decoherence length [28] by *many orders of magnitude*.

Although such short-scale oscillations and the resulting decoherence of HEνs is an interesting phenomenon by itself and could in principle impact the physics of their propagation by modifying their flavor ratio at the source, here we discuss a few important cases in which the induced conversions of HEνs can be observable on Earth.

Once HEνs leave the LEν bath, they should propagate in the dense ejecta, where $n_e \gg n_\nu$ [33–37]. In particular, for engine-driven transients, the HEν production region is surrounded by the stellar or merger ejecta, whose density is much larger than that in the production region. This means that in solving Eq. (4) for the neutrino propagation in this region, we ignore the $\mathsf{H}_{\nu\nu}$ term. In order to account for the decoherence experienced by neutrinos in the LEν bath, we start with an initial density matrix which is a time average of the one in Eq. (6). In addition, for the H_m term we consider a blue supergiant matter profile from Ref. [38] as an example ($30M_\odot$ BSG in Ref. [37]). Needless to say, the short-scale conversions of HEνs will impact the outcome of the matter effect and, correspondingly, their flavor ratio on Earth. This is clearly illustrated in Fig. 3 for a case with the initial flavor ratio $\nu_e:\nu_\mu:\nu_\tau = 1:2:0$ in the normal mass ordering. This is particularly interesting considering the energy-independent nature of the LEν-induced short-scale oscillations of HEνs. Although the pure matter effect shows a clear sign of energy dependence here [37], it is almost independent of the neutrino energy in the presence of νSI. This is even the case at high energies where the muon damping is expected to occur in such dense environments [39,40]. This can provide one with a new observable indication of neutrino flavor mixing caused by νSI.

So far, we have assumed that the bath of the LEνs is completely decohered. However, the situation could be different. On the one hand, since R_diss can be as low as 10^8 cm, the solar-mass-channel LEνs could still be in phase since $l_{\mathrm{coh},\odot} \sim \sigma_x E_\nu^2/\Delta m^2_\mathrm{sol} \gtrsim 10^8$ cm. Moreover, due to the possibility for the existence of $\mu \gtrsim 10^{-4}\ \mathrm{cm}^{-1}$, the decoherence of LE$\nu$s *might* be suppressed [41] in the atmospheric channel as well and LEνs can experience a sort

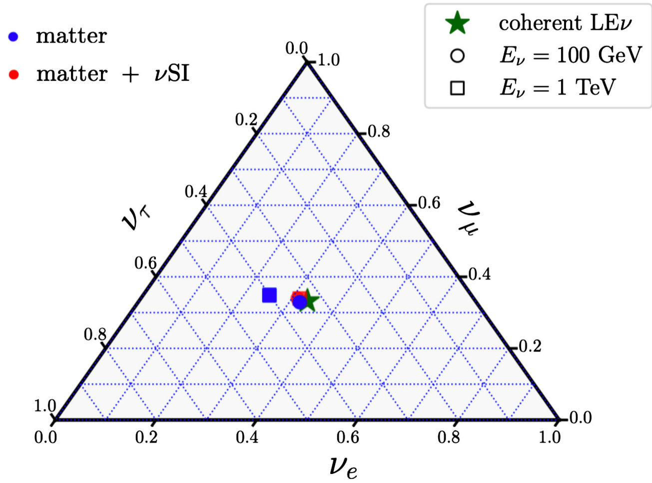

FIG. 3. Expected $\nu_e:\nu_\mu:\nu_\tau$ ratio on Earth in the absence and presence of νSI for different neutrino energies. Note that the matter effect is included in both cases, assuming the density profile of a blue supergiant, and the ratio with νSI is very close to the total flavor equipartition. In addition, the green star indicates the total flavor equipartition expected from the propagation of HEνs in a bath of *oscillating* LEνs, as discussed in the text. Note that, apart from the matter-only case for the 1 TeV neutrinos, the other ones are almost on top of each other. It is also illuminating to keep in mind that the final flavor states are specific to the initial flavor composition of 1:2:0 and can vary under different circumstances.

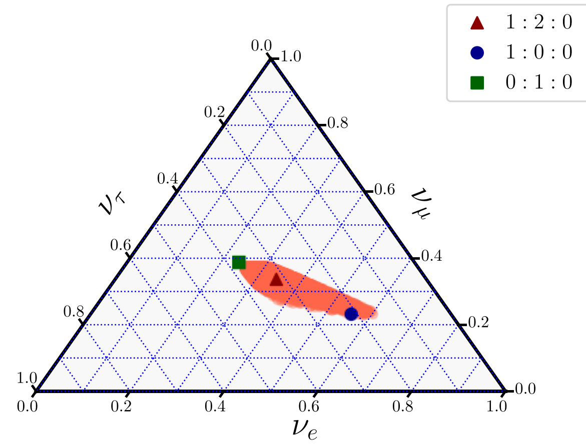

FIG. 4. Expected $\nu_e:\nu_\mu:\nu_\tau$ ratio after HEνs escape their production region, in the presence of νNSSI. The triangle, circle, and square indicate the ratio in the SM while the red region shows how the ratio changes in the presence of νNSSI for the 1:2:0 case. Here the red region is created by choosing a large set of randomly populated $\hat{G}^{\alpha\beta}$ assuming that $|\hat{G}^{\alpha\beta}| < 1$ (for $\alpha \neq \beta$). Via coherent νSI, the final HEν flavor ratio is very sensitive to the νNSSI.

of (partial) collective oscillations in the production region of HE ones. Such erratic conversions of LEνs will lead to the total flavor equipartition of HEνs regardless of their initial flavor content, as indicated by the green star in Fig. 3. This phenomenon will be discussed in more detail in our upcoming work [32].[1]

In some of the beyond-the-Standard-Model (SM) theories of particle physics, neutrinos can experience neutrino nonstandard self-interactions (νNSSI) [42,43]. Such νNSSI modify Eq. (5) to [44–46]

$$\mathsf{H}_{\nu\nu,\mathbf{p}} = \sqrt{2}G_\mathrm{F}\int \frac{\mathrm{d}^3 p'}{(2\pi)^3}(1-\mathbf{v}\cdot\mathbf{v}')\{\hat{G}(\varrho_{\mathbf{p}'}-\bar{\varrho}_{\mathbf{p}'})\hat{G} + \hat{G}\mathrm{Tr}[(\varrho_{\mathbf{p}'}-\bar{\varrho}_{\mathbf{p}'})\hat{G}]\}, \tag{8}$$

where $\hat{G}$ contains information about νNSSI ($\hat{G} = \mathbb{1}$ in the SM). For example, in the vector mediator scenario, we may have $\mathcal{L}_\mathrm{eff} \supset G_\mathrm{F}[\hat{G}^{\alpha\beta}\bar{\nu}_\alpha\gamma^\mu\nu_\beta][\hat{G}^{\xi\eta}\bar{\nu}_\xi\gamma_\mu\nu_\eta]$, and its νNSSI components are related to the vector mediator mass m_V and the coupling strength g by $|\hat{G}^{\alpha\beta}| \propto g^2/m_V^2$. The current constraints on νNSSI are model dependent and strong for the mediator mass below MeV energies. For heavier mediators, the constraints from the early Universe are rather weak, e.g., $|\hat{G}^{\alpha\beta}| \lesssim 10^7$ [47], although laboratory constraints can be stronger in the limited parameter space [48]. It has been suggested that spectral modulations and time delays of HEνs enable us to study the unexplored parameter space of νNSSI [49–54]. We point out that coherent νSI-induced oscillations of HEνs can be used as a novel probe of νNSSI. This is illustrated in Fig. 4 where the red region shows the impact of νNSSI. The flavor content is expected to have observable sensitivity to νNSSI, i.e., a $\sim$10% change of flavor ratio is caused by $|\hat{G}^{\alpha\beta}| \sim 0.1$. This means that one could probe such weak couplings with this effect.

[1]The only difference between this case and the results shown in Fig. 2 is that here we allow for flavor oscillations of the LEν gas rather than fix it to be in the mass state.

V. CONCLUSION

We have brought to light a novel phenomenon in which a class of high-energy cosmic neutrino emissions can experience flavor conversions induced by the copious LEν background, on scales much shorter than their intrinsic vacuum oscillation wavelengths. Unlike the celebrated phenomenon of collective oscillations of MeV neutrinos in a dense neutrino medium, the unearthed flavor conversions of high-energy cosmic neutrinos is a noncollective phenomenon in spirit.

This intriguing phenomenon can occur when HEνs from relativistic outflows launched from the core-collapse of massive stars or from mergers propagate in the bath of the already-decohered lower-energy neutrinos from the central engine. Despite the small number density of HEνs which can be insufficient to result in their own collective oscillations, their presence can lead to short-scale conversions of HEνs on scales determined by the density of LEνs.

The background-induced conversions of HEνs change their flavor content in an energy-independent manner and take the HEν gas to a state that is diagonal in the mass basis. This way, they cause an induced decoherence of HEνs on scales that are many orders of magnitude shorter than their natural decoherence lengths. Such a modification of the HEνs at the source can impact the physics of the phenomena occurring during their propagation, such as neutrino decay, scattering, etc. We also pointed out a few possibilities where such short-scale-induced decoherence can directly impact the flavor ratio of HEν on Earth, including the matter effect of HEνs, the νNSSI, and the total flavor equipartition due to an oscillating ambient LEν gas.

Our study provides the first step toward understanding this intriguing phenomenon, and further exploration is needed to better understand its implications. This is yet another context where neutrino-neutrino interactions can play a crucial role in their flavor evolution, and also motivates further investigations into *multimessenger* high-energy emission from GRBs, CCSNe, and NSMs.

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