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Suppression of fast neutrino flavor conversions occurring at large distances in core-collapse supernovae

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Abstract. Neutrinos propagating in dense neutrino media such as core-collapse supernovae and neutron star merger remnants can experience the so-called *fast* flavor conversions on scales much shorter than those expected in vacuum. A very generic class of fast flavor instabilities is the ones which are produced by the backward scattering of neutrinos off the nuclei at relatively large distances from the supernova core. In this study we demonstrate that despite their ubiquity, such fast instabilities are unlikely to cause significant flavor conversions if the population of neutrinos in the backward direction is not large enough. Indeed, the scattering-induced instabilities can mostly impact the neutrinos traveling in the backward direction, which represent only a small fraction of neutrinos at large radii. We show that this can be explained by the shape of the unstable flavor eigenstates, which can be extremely peaked at the backward angles.

Keywords: supernova neutrinos, core-collapse supernovae, neutrino astronomy, supernovas

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1 Introduction

Neutrino emission is a major effect in the most extreme astrophysical settings, such as core-collapse supernova (CCSN) explosions. The density of neutrinos in such environments is so high that the neutrino self-interactions can play an important role in their flavor evolution. In particular, it leads to a nonlinear and rich phenomenon in which the whole neutrino gas can oscillate collectively [1–7].

Collective neutrino oscillations can influence the physics of CCSNe by modifying the spectra of neutrinos and antineutrinos. On the one hand, they can influence the nucleosynthesis of heavy elements by shifting the neutron-to-proton ratio. On the other hand, they can affect the SN dynamics by changing the neutrino energy deposition into the stalling shock wave. Apart from these, they can also modify the SN neutrino signal detectable from a galactic CCSN.

The first studies on collective neutrino oscillations were centered around what we now call *slow* flavor conversions. Slow modes occur on scales determined by the neutrino vacuum frequency, $\omega = \Delta m^2/2E$, which are $\sim \mathcal{O}(1)$ km for a typical SN neutrino energy and atmospheric mass splitting. However, it was then perceived that a dense neutrino gas can also experience *fast* flavor conversions on extremely short scales [8–46]. Unlike the slow modes, the fast conversions scale as $\sim G_{\text{F}}^{-1}n_{\nu}^{-1}$, with n_{ν} and G_{F} being the neutrino number density and the Fermi coupling constant, respectively.

The necessary and sufficient condition for the occurrence of fast flavor instabilities is that the angular distribution of the neutrino electron lepton number (ELN) defined as,

$$G_{\mathbf{v}} = \sqrt{2}G_{\text{F}} \int_0^{\infty} \frac{E_{\nu}^2 dE_{\nu}}{(2\pi)^3} [f_{\nu_e}(E_{\nu}, \mathbf{v}) - f_{\bar{\nu}_e}(E_{\nu}, \mathbf{v})], \quad (1.1)$$

changes its sign at some directions [35]. In other words, fast instabilities exist provided that the ELN angular distribution possesses a crossing. Here E_{ν} , \mathbf{p} , and \mathbf{v} are the neutrino energy, momentum, and velocity, respectively, and f_{ν} 's are the neutrino occupation numbers with G_{F} being the Fermi constant. Note that here we assume $f_{\nu_{\mu}} = f_{\nu_{\tau}} = f_{\bar{\nu}_{\mu}} = f_{\bar{\nu}_{\tau}}$, otherwise there can exist crossings in the other leptonic channels, which can similarly lead to fast conversion modes [18, 41].

It has been demonstrated that ELN crossings and their associated fast instabilities can occur in different SN regions via different mechanisms. The deepest region where fast instabilities can appear is within the convective layer of the proto-neutron star (PNS), well below the neutrinospheres of neutrinos and antineutrinos. These instabilities occur due to a shallow

crossing between the angular distributions of ν_e and $\bar{\nu}_e$, which are almost isotropic [47–49]. As a matter of fact, large amplitude modulations in the spatial distributions of ν_e and $\bar{\nu}_e$ number densities can be caused by the strong convective activities. This implies that deep SN zones can always exist for which the number densities of ν_e and $\bar{\nu}_e$ can be extremely close to each other and an ELN crossing can occur regardless of the isotropic nature of neutrino angular distributions. Though fascinating, the nearly equal distributions of neutrinos and antineutrinos of all flavors prevents a significant amount of flavor conversion resulted from such fast instabilities.

ELN crossings and their associated fast instabilities can also occur within the neutrino decoupling region, just above the PNS [36, 48, 50, 51]. In the SN zones above the neutrinospheres, the angular distributions of $\bar{\nu}_e$ are more peaked in the forward direction than those of ν_e , due to their decoupling at smaller radii. This leads to a high chance of the occurrence of ELN crossings in the zones where $\nu_e - \bar{\nu}_e$ asymmetry is small [50, 52]. Given this observation, the asymmetry in the neutrino emission caused by LESA (lepton-emission self-sustained asymmetry) [53, 54] plays a pivotal role in this context (see also ref. [55] for other relevant effects).

Finally, a very generic class of ELN crossings and fast instabilities can occur farther away from the SN core. Though they were first discovered in the pre-shock SN region [56], it was then understood that they can occur in the post-shock region, as well [40, 41]. This type of ELN crossings is generated by the backward scatterings of neutrinos off heavy nuclei or nucleons. Generally speaking, $\bar{\nu}_e$ has a larger cross section than ν_e . This implies that at larger distances where the backward direction is almost empty, $\bar{\nu}_e$ can become the dominant type due to the higher scattering rate and an ELN crossing can occur.

In the present work, we study neutrino flavor conversions due to such scattering-induced fast instabilities. Despite being ubiquitous at large distances from the SN core, we show that they can not, in general, lead to significant neutrino flavor conversions if the population of neutrinos in the backward direction is not large enough. Our results are consistent with the ones provided in ref. [57], which appeared while this work was under preparation. However, we here take a step forward and give an explanation of this observation based on the shape of unstable eigenstates in the linear regime. We also provide a rough estimate of the depth of the ELN crossing below which significant flavor conversions are suppressed.

The paper is organized as follows. In section 2, we introduce our model and present our results of the linear stability analysis and we develop some useful insights regarding the form of the unstable wave functions. We then discuss neutrino flavor evolution in the nonlinear regime before the conclusion.

2 Time-dependent one-dimensional neutrino gas model

In this section, we discuss our time-dependent one-dimensional (1D) neutrino gas and we present our results in the linear and nonlinear regimes, respectively.

We consider a time-dependent gas of neutrinos, whose conditions are axially symmetric around the z axis. We set to zero the neutrino mass splittings so that the evolution of the system is energy-independent. We also neglect the matter potential due to neutrino coherent forward scattering on electrons and also neutrino inelastic collisions. Under these conditions, the flavor evolution of the neutrino gas is governed by the following Liouville-von Neumann equation [58–62] ($c = \hbar = 1$)

$$i(\partial_t + v\partial_z)\varrho_v = [\mathbf{H}_{\nu\nu}^v, \varrho_v], \quad (2.1)$$

where $\varrho_v(t, z)$ represents the usual density matrix for neutrinos with velocity v along the z axis, and

$$\mathbf{H}_{\nu\nu}^v = \sqrt{2}G_F \int_{-1}^{+1} dv' (1 - v v') (\varrho_{v'} - \bar{\varrho}_{v'}). \quad (2.2)$$

is the potential stemming from the neutrino-neutrino forward scattering [63–65].

2.1 Flavor instabilities in the linear regime

In the two-flavor scenario (e and x), the density matrix can be written as [66],

$$\varrho = \frac{f_{\nu_e} + f_{\nu_x}}{2} + \frac{f_{\nu_e} - f_{\nu_x}}{2} \begin{bmatrix} s & S \\ S^* & -s \end{bmatrix}, \quad (2.3)$$

in the weak-interaction basis where the complex and real scalar fields S and s describe the flavor coherence and the flavor conversion of the neutrino gas, respectively.

In the linear regime before any significant flavor conversions occur, one has $|S_v| \ll 1$ and $s \approx 1$, and eq. (2.1) can be written as [11, 66, 67],

$$i(\partial_t + v\partial_z)S_v = (\epsilon_0 + v\epsilon)S_v - \int dv' (1 - v v') G_{v'} S_{v'}, \quad (2.4)$$

where $\epsilon_0 = \int dv' G_{v'}$, $\epsilon = \int dv' G_{v'} v'$, and we have only retained the terms linear in S_v . We look for plane wave solutions obeying

$$S_v(t, z) = Q_v e^{-i\Omega t + iKz}. \quad (2.5)$$

An eigenmode of flavor conversion can be identified by its frequency and wavevector, Ω and K , respectively.

The neutrino gas is stable in the flavor space and the flavor mixing amplitude S_v remains small unless for a real wave vector K , the corresponding Ω has a positive imaginary component, i.e. $\Omega_i = \text{Im}(\Omega) > 0$, referred to as temporal instabilities which is also the focus of this study. If such a condition is satisfied, S_v can grow exponentially and the neutrino medium can, in principle, experience non-negligible flavor conversions. As discussed previously, such instabilities exist if, and only if, the angular distribution of ELN possesses a crossing.

In the following, we focus on two special classes of angular distributions which mimic crossings in the backward direction. We first consider a pure $\nu_e - \bar{\nu}_e$ neutrino gas with schematic distributions of the form:

$$f_{\nu_e} \propto \begin{cases} 1 & \text{for } v > v_c, \\ \delta & \text{for } v < v_c. \end{cases}, \quad f_{\bar{\nu}_e} \propto \begin{cases} 1 & \text{for } v > v_c, \\ 2\delta & \text{for } v < v_c. \end{cases} \quad (2.6)$$

Here, v_c is the point where the crossing occurs, and δ is the depth of the backward scattering. We also consider the more realistic neutrino angular distributions considered in ref. [57],

$$f_\nu \propto g_b + g'_b(e^{v+1} - 1) + g_f b^{v-1}, \quad (2.7)$$

where the parameters g_b , g'_b , g_f , and b can be different for ν_e and $\bar{\nu}_e$ and are presented in table I of ref. [57]. Note that we here only take the normalized distributions from eqs. (2.6) and (2.7) with fixed $n_{\bar{\nu}_e}/n_{\nu_e} = 0.8$, though the results are independent of this choice. The neutrino distributions are indicated in figure 1

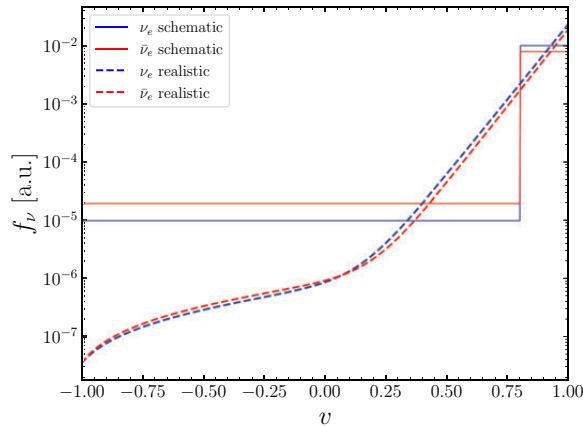


Figure 1. Neutrino angular distributions of realistic (dashed lines) and schematic (solid lines) cases where we have shown the $\delta = 10^{-3}$ and $v_c = 0.8$ case as an example.

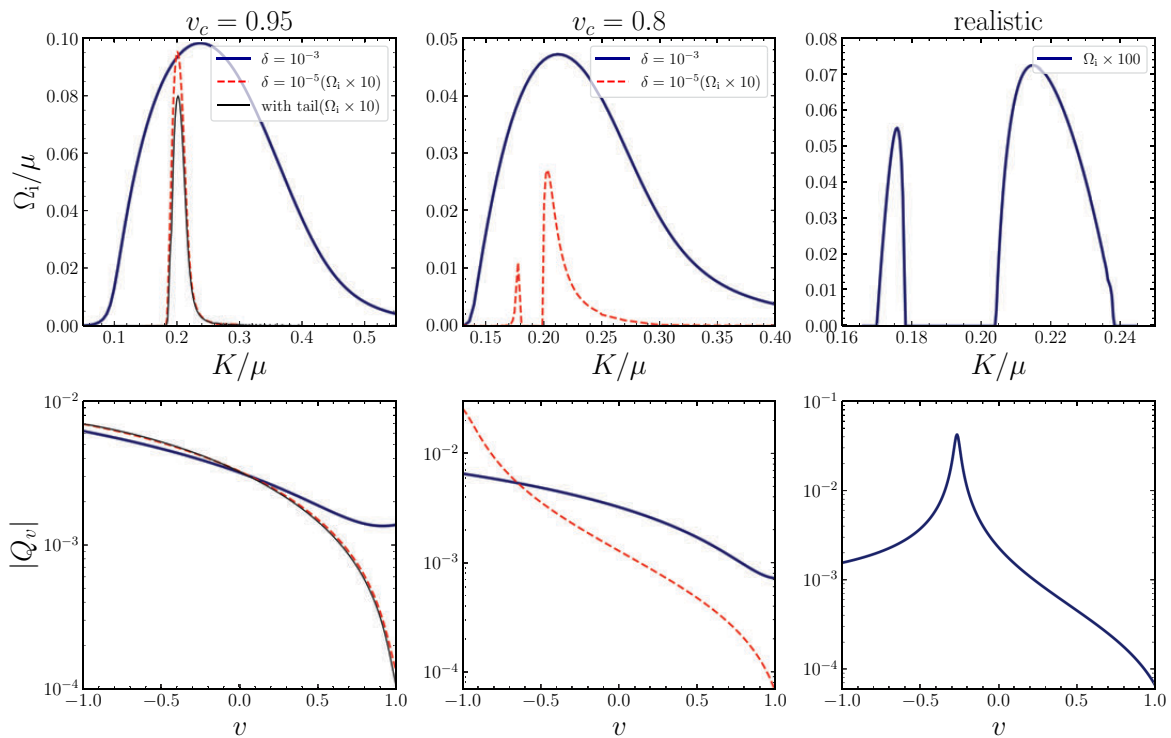


Figure 2. Upper panels: growth rate of temporal fast instabilities as functions of the real wave number K . Lower panel: the normalized angular distributions of the eigenvectors, Q_v , of unstable modes with maximum growth rate. Note that the amplitude of Q_v can be extremely small in the forward direction where the majority of neutrinos are traveling. This implies that the backward instabilities should mainly affect the backward traveling neutrinos, which are a small fraction of neutrinos at large radii. The left and middle panels show the results obtained from our schematic ELN distribution (eq. (2.6)), while the right panels are the ones from the realistic distribution (eq. (2.7)). For the sake of completeness, in the left panels we also study an ELN distribution with two crossings where the second crossing exists in the tail of the distribution, namely for $v < -0.9$ we have a second crossing for which $G(v) = +\delta$.

In the upper panels of figure 2, we indicate the growth rate of temporal fast instabilities, Ω_i , for a number of ELN distributions introduced in eqs. (2.6) and (2.7). Here, we use

$$\mu = \sqrt{2}G_{\text{F}}n_{\nu_e}, \quad (2.8)$$

as a measure of the strength of the weak interactions. Although ELN crossings in the backward direction can be extremely shallow, their corresponding fast growth rates may not be necessarily small [40]. For instance, for $\mu = 10^4 \text{ km}^{-1}$ and $\delta = 10^{-3}$, the growth rate can be as high as 10^3 km^{-1} , which is much larger than the typical growth rates expected for slow modes.

In spite of such significant growth rates, fast instabilities brought about by backward ELN crossings can not induce significant neutrino flavor conversions if the population of backward traveling neutrinos is not large enough. This can be deduced from the lower panels of figure 2, where the eigenvectors of the unstable modes with maximum growth rates are shown. As can be clearly seen, Q_v is highly peaked in the backward direction. This implies that the instabilities can mainly impact the backward traveling neutrinos, which can be a tiny fraction of all neutrinos (at large radii).

2.2 Flavor conversions in the nonlinear regime

We solve numerically the partial differential equation system in eq. (2.1), assuming periodic boundary conditions. We calculate the spatial derivatives using the fast fourier transform based differentiation, whereas we solve temporal evolution using the backward differentiation formulae through the NAG library. Our initial conditions for the diagonal elements of ϱ are independent of z ,

$$\varrho_{v,ee}(0, z) = \xi \times \begin{cases} 1 & \text{for } v > v_c, \\ \delta & \text{for } v < v_c. \end{cases} \quad \bar{\varrho}_{v,ee}(0, z) = \xi \times \begin{cases} 0.8 & \text{for } v > v_c, \\ 2\delta & \text{for } v < v_c. \end{cases} \quad \varrho_{v,xx}(0, z) = 0, \quad (2.9)$$

which, considering $\alpha = 0.8$, allow one to reproduce G_v in eq. (2.6) with $\xi = 4 \times 10^5 \text{ km}^{-1}$. Note that $\mu \simeq (1 - v_c)\xi$ for small δ 's. In terms of initial conditions for the off-diagonal elements, we choose them to be v -independent and we set $\varrho_{ex}(z) = \delta(z)$. This choice allows to give the same seed to all the $S_{v,K}(t)$ defined below and provides the necessary perturbation triggering fast flavor conversions.

In order to extract the eigenvectors of unstable modes Q_v , we first calculate $S_v(t, z)$ as

$$S_v(t, z) = \frac{\varrho_{ex}(t, z)}{\varrho_{ee}(t=0, z) - \varrho_{xx}(t=0, z)} \quad (2.10)$$

and then we perform its Fourier Transform

$$S_{v,K}(t) = \frac{1}{L} \int_0^L dz S_v(t, z) e^{iKz}, \quad (2.11)$$

$S_{v,K}(t)$ then represents an estimate of the eigenvectors Q_v calculated in the linear regime.

Here we focus on the cases of $\delta = 10^{-3}$ and 10^{-5} , and $v_c = 0.95$. Similar results are obtained for $v_c = 0.8$. Figure 3 shows the angular distributions of $S_{v,K}(t)$ at different times for $K = 2 \times 10^3 \text{ km}^{-1}$. We note that the shape of $S_{v,K}$ is similar to that of Q_v , reported in figure 2, as expected. Moreover, we have checked that we are already in the nonlinear regime and thus $|S_{v,K}|$ is not growing exponentially anymore.

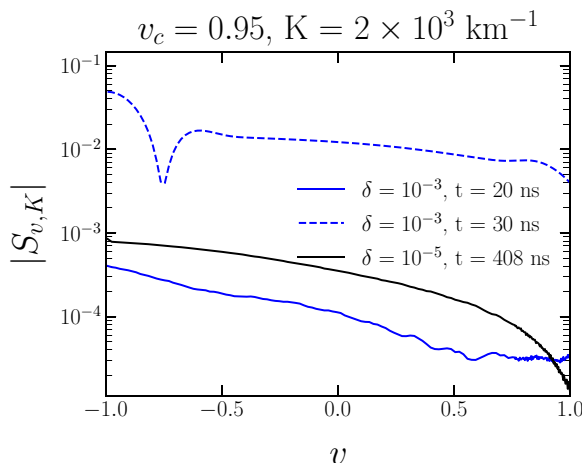


Figure 3. The angular distributions of the eigenvectors of unstable modes, $S_{v,K}$ (eq. (2.11)), for $v_c = 0.95$, and $\delta = 10^{-3}$ and 10^{-5} . The initial perturbations are flat in v .

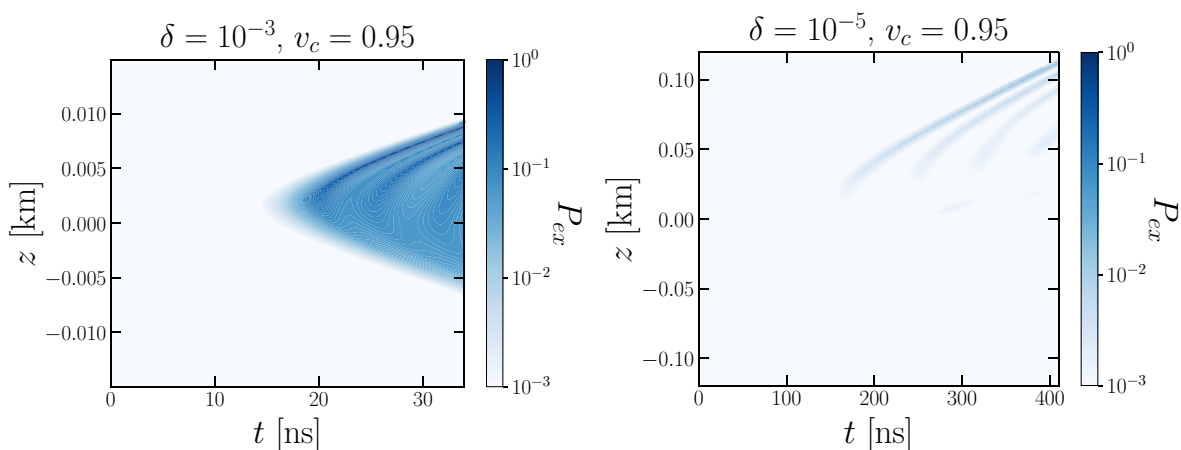


Figure 4. Time and space evolution of the conversion probability between the e and x flavors for $\delta = 10^{-3}$ (left panel) and 10^{-5} (right panel).

Figure 4 displays the time and space evolution of the conversion probability between e and x flavor, defined as

$$P_{ex}(t, z) = 1 - \frac{\langle \varrho_{ee}(t, z) \rangle}{\langle \varrho_{ee}(0, z) \rangle}, \quad (2.12)$$

where $\langle \varrho_{ee}(t, z) \rangle$ is the angle integrated equivalent of ϱ_{ee} ,

$$\langle \varrho_{ee}(t, z) \rangle = \int_{-1}^1 dv \varrho_{v,ee}(t, z). \quad (2.13)$$

While large flavor conversions can exist for the case of $\delta = 10^{-3}$, they are significantly suppressed for $\delta = 10^{-5}$ with the maximum of P_{ex} being $\mathcal{O}(10^{-2})$, despite the presence of fast flavor instabilities with large growth rates. This can be understood by noting that for the $\delta = 10^{-5}$ case, $|Q_{\text{forward}}|/|Q_{\text{backward}}| \lesssim 10^{-2}$. Therefore, the amount of flavor conversion of the forward propagating neutrinos is remarkably small at the onset of the nonlinear regime. Then as the backward traveling neutrinos enters the nonlinear regime, the exponential growth

ceases and the conversion of forward traveling neutrinos is suppressed. Nevertheless, the reason for observing significant conversions for the case of $\delta = 10^{-3}$ is twofold. First of all, the population of the backward traveling neutrinos is relatively large in this case, namely $\sim 5\%$ of the total neutrinos. In addition and as a consequence of this, $|Q_{\text{forward}}|/|Q_{\text{backward}}| \gtrsim 10\%$. Hence, the forward traveling neutrinos can experience significant conversions even at the onset of the nonlinear regime.

This result is indeed consistent with the observation of ref. [57], where realistic ELN distributions of eq. (2.7) were employed. As can be seen in the lower right panel of figure 2, $|Q_{\text{forward}}|/|Q_{\text{backward}}| \lesssim 10^{-3}$ for the realistic distributions. Note that these results are obtained in the absence of slow modes ($\omega = 0$) and one can still observe non-negligible flavor conversions in the presence of slow modes as in ref. [57], which has then little to do with the backward ELN crossings and fast modes.

It is also illuminating to note that while for $\delta = 10^{-3}$ the flavor conversion wave travels both in the backward and forward directions, it mostly affects the forward regions in the $\delta = 10^{-5}$ case. This simply comes from the fact that for latter, there is a smaller number of neutrinos traveling in the backward direction. We have confirmed that there is absolutely no backward traveling conversion wave if one completely removes the backward traveling neutrinos, namely $f_\nu = 0$ for $v < 0$.

Considering the linear stability analysis, our results suggest that the transition between significant and negligible flavor conversions occurs for $\delta \lesssim 10^{-4}$, as a very rough estimate. Needless to say, the precise transition value should depend on the exact angular distribution and the employed neutrino gas model.

3 Conclusions

Fast flavor conversions of SN neutrinos can happen on timescales as short as a few nanoseconds. A very generic class of fast instabilities is the scattering-induced ones which are caused by the backward ELN crossings. They actually occur due to the residual inelastic collisions of neutrinos on nucleons and/or nuclei when they are nearly free-streaming. Such instabilities can appear ubiquitously both in the post-shock and pre-shock SN regions at large distances from the SN core.

Despite their ubiquity in the SN environment, we show that the scattering-induced fast instabilities can not lead to significant flavor conversions if the population of the backward traveling neutrinos is not large enough. This arises from the fact that the unstable flavor states of scattering-induced fast instabilities are extremely peaked at backward angles, meaning that the instability should mainly impact the small fraction of neutrinos traveling in the backward direction. This is quite understandable since backward ELN crossings are themselves generated by that tiny fraction of neutrinos traveling in the backward direction.

Though our study is performed in the two-flavor scenario, one should expect similar results in the three-flavor scenario. This can be simply understood by noting that the shape of the unstable eigenfunctions should be similar in the three-flavor scenario where analogous angular crossings can happen in all the three sectors ($e\mu$, $e\tau$ and $\mu\tau$) [41].

The results we obtained here suggest that one can safely ignore the scattering-induced fast instabilities in the SN environment when the population of the backward traveling neutrinos is $\ll 1\%$.¹ Two important questions still remain to be answered. First and foremost, it

¹Unless the tiny population of the backward traveling neutrinos can lead to some unexpected non-negligible effects.

is not very clear to us if one can always assume that for all SN zones where scattering-induced crossings can occur, the depth of the crossing is such small. If one can find scattering-induced ELN crossings for which the population of the backward traveling neutrinos is \sim a few percents, then the next question would be how the flavor content of the neutrino gas is affected by such instabilities. This is specially interesting given the fact that the scattering-induced fast instabilities seem to be most generic/ubiquitous class of fast instabilities in the SN environment.

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