No collective neutrino flavor conversions during the supernova accretion phase

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We perform a dedicated study of the SN neutrino flavor evolution during the accretion phase, using results from recent neutrino radiation hydrodynamics simulations. In contrast to what expected in the presence of only neutrino-neutrino interactions, we find that the multi-angle effects associated with the dense ordinary matter suppress collective oscillations. The matter suppression implies that neutrino oscillations will start outside the neutrino decoupling region and therefore will have a negligible impact on the neutrino heating and the explosion dynamics. Furthermore, the possible detection of the next galactic SN neutrino signal from the accretion phase, based on the usual Mikheyev-Smirnov-Wolfenstein effect in the SN mantle and Earth matter effects, can reveal the neutrino mass hierarchy in the case that the mixing angle \( \theta_{13} \) is not very small.

PACS numbers: 14.60.Pq, 97.60.Bw

Introduction. — Neutrinos emitted from core-collapse supernovae (SNe) represent a crucial tool to get valuable information about the mixing parameters and an insight into the dynamics of the exploding stellar core [1]. SN neutrinos not only interact with the stellar medium via the Mikheyev-Smirnov-Wolfenstein (MSW) effect [2], but also with other neutrinos (\( \nu \)) and antineutrinos (\( \bar{\nu} \)). It was pointed out that large \( \nu \) densities in the deepest stellar regions can result in significant coherent \( \nu - \nu \) forward scatterings [3, 4], which give rise to collective \( \nu \) flavor oscillations inside the SN [3, 5] (see [8] for a recent review).

The development of these self-induced \( \nu \) transformations crucially depends on the primary SN \( \nu \) spectra (see, e.g., [6, 10]). At this regard the post-bounce accretion phase of core-collapse SNe, lasting few tens of milliseconds (for low mass O-Ne-Mg-core progenitors) up to several hundreds of milliseconds (for more massive iron-core progenitors), might seem the best opportunity to detect signatures of collective \( \nu \) flavor oscillations. Indeed, the absolute \( \nu \) fluxes are large during the accretion phase with significant spectral differences between the different \( \nu \) species, and a flux order \( F_{\nu_e} > F_{\nu_x} \gg F_{\nu_x} \). This scenario has been often taken as a benchmark for the description of the self-induced effects. Notably, these latter would leave the \( \nu \) spectra unaffected in normal mass hierarchy (NH: \( \Delta m_{\text{atm}}^2 = m_2^2 - m_1^2 > 0 \)). In the inverted \( \nu \) mass hierarchy (IH: \( \Delta m_{\text{atm}}^2 < 0 \)), they would produce a complete exchange of the \( \bar{\nu}_e \) and \( \bar{\nu}_x \) spectra, and a spectral split in the energy distributions of the \( \nu \)‘s [8]. This seemingly robust and clear behavior has been proposed as an unique way to determine the \( \nu \) mass hierarchy even if the leptonic 1–3 mixing angle \( \theta_{13} \) is too small to be detected in terrestrial \( \nu \) oscillation experiments [11, 12].

The implicit assumption in this picture is related to the flavor evolution in the deepest SN regions being driven by only large neutrino densities \( n_\nu \). However, during the accretion phase also the net electron density \( n_e \) is expected to be large, as documented by many different SN simulations [12, 10]. This is a generic feature that applies to SNe of massive iron-core progenitors. As recently pointed out in [17] and confirmed in [18], when \( n_e \) is not negligible with respect to \( n_\nu \), the large phase dispersion induced by the matter for \( \nu \)‘s traveling in different directions, will partially or totally suppress the collective oscillations through peculiar multi-angle effects.

Motivated by this insight, we have performed a detailed study of the SN \( \nu \) flavor evolution during the accretion phase, characterizing the \( \nu \) signal and the matter density profiles by means of recent neutrino radiation hydrodynamics simulations. Contrarily to what shown in previous studies based on the only \( \nu - \nu \) interaction effects, we find that the presence of a dominant matter term inhibits the development of collective flavor conversions. The matter suppression ranges from complete to partial, producing intriguing time-dependent features. In particular, when it is complete (for post-bounce times \( t_{\text{ph}} \lesssim 0.2 \) s in iron-core SNe) the \( \nu \) signal will be processed only by the usual MSW effect in the SN mantle and Earth matter effects. This was the usual description before the inclusion of collective phenomena. This \( \text{d} \text{é} \text{j} \text{à} \text{vu} \) \( \nu \nu \) would reopen the possibility, prevented by self-induced effects, to reveal the neutrino mass hierarchy through the Earth matter effect on the next galactic SN neutrino burst, in the case \( \theta_{13} \) is not very small [19].

\( \nu \) signal from the accretion phase. — We take as benchmark for our study the results of the recent long-term SN simulations, described in [20]. These are based on radiation hydrodynamics that employs three flavor Boltzmann neutrino transport in spherical symmetry. Figure 1 shows the evolution of the \( \nu \) number fluxes \( F_{\nu_\alpha} \) for the different neutrino flavors \( \nu_\alpha \), up to 0.6 seconds after core bounce, for the 10.8 M⊙ iron-core progenitor model. Enhanced \( \nu \) heating was applied, because a neutrino-driven explosion cannot be obtained in spherical symmetry for such a progenitor (for details, see [20]). The first phase after core bounce lasts only \( \sim 0.02 \) s, where large numbers of electron captures release a flare of \( \nu_e \) with luminosities on the order of \( 10^{53} \) erg/s. It is followed by the accretion phase
that can last up to several hundred milliseconds. After the onset of the explosion, mass accretion vanishes at the neutrinospheres (i.e., $\nu$ last-scattering surfaces) and the neutrino luminosities are determined by diffusion. It results in a sharp drop of the fluxes after the explosion shock crosses a distance of 500 km, where the fluxes are measured in a co-moving reference frame. The fluxes of all flavors decrease continuously on a longer timescale of $O(10^4)$ s, indicating the beginning of the cooling phase.

**Setup of the flavor evolution.**— Our description of the $\nu$ flavor conversions is based on a two-flavor scenario, driven by the atmospheric mass-square difference $\Delta m^2_{\text{atm}} \simeq 2.6 \times 10^{-3}$ eV$^2$ and by a small (matter suppressed) in-medium mixing $\theta_{\text{eff}} = 10^{-3}$ [21]. Three-flavor effects, associated with the solar sector, are small for the fluxes during the accretion phase [22]. We will always refer to the inverted mass hierarchy where $\nu_e \rightarrow \nu_x$ (left panel) and the ratio $R = n_e/(n_{\mu_e} - n_{\mu_x})$ between electron and neutrino densities entering the potentials (right panel), at selected post-bounce times. One can recognize the abrupt discontinuity in $n_e$, associated with the SN shock-front that propagates in time. From the ratio $R$ at the different post-bounce times, we realize that $n_e$ is always larger than or comparable to $n_{\mu_e} - n_{\mu_x}$, suggesting that matter effects cannot be ignored during the accretion phase. Depending on the strength of the matter density, the matter suppression can be total, when $n_e \gg n_\nu$, or partial when the matter dominance is less pronounced. Finally, when $n_e \gtrsim n_\nu$ the interference of the two comparable potentials leads to a flavor equilibrium with a complete mixture of electron and non-electron species [17].

**Neutrino flavor conversions.**— In order to have a quantitative description of these matter effects, we performed a multi-angle numerical study of the $\nu$ flavor evolution in the schematic model described above. In Fig. 4 we show the radial evolution of the $\nu_\ell$ survival probability $P_{\nu_{\ell e}}$ for the same post-bounce times as in Fig. 2. For comparison, we also show the example of what is expected in the case of $n_e = 0$ (light curve for $t_{\text{pb}} = 0.3$ s). As predicted, we find that matter strongly suppresses the development of the self-induced flavor transformations. In particular, at $t_{\text{pb}} = 0.1, 0.4$ s, when $n_e \gg n_\nu$ the flavor conversions are completely blocked ($P_{ee} = 1$). Conversely, at $t_{\text{pb}} = 0.2$ s when $n_e \simeq 2n_\nu$ in the conversions region, the matter suppression is only partial giving a final $P_{ee} \sim 0.75$. Finally, at $t_{\text{pb}} = 0.3$ s when $n_e \gtrsim n_\nu$, matter effects produce a complete flavor mixture ($P_{ee} = 1/2$). From a systematic study of the flavor evolution at different time snapshots during the accretion phase, we find (i) a complete matter suppression of the self-induced transformations for $t_{\text{pb}} \lesssim 0.2$ s, (ii) partial matter suppression for $0.2$ s $\lesssim t_{\text{pb}} \lesssim 0.35$ s, and (iii) again complete suppression for $0.35$ s $\lesssim t_{\text{pb}} \lesssim 0.6$ s. This feature suggests a time-dependent pattern for the $\nu$ conversions, i.e. complete-partial-complete suppression.

The behavior, analyzed for this specific example of the $10.8 M_\odot$ SN explosion model, is generic also for more massive iron-core SNe. It is independent from the explosion scenarios and applies also for non-exploding models. Indeed, in any case the density of the material, enclosed inside the standing bounce shock, can only increase due to mass accretion from the iron-core envelope. Only after the onset of an explosion, when mass accretion vanishes, the matter density decreases. However, for the low-mass O-Ne-Mg-core SNe, where the matter density profile is very steep, the suppression is never complete. As a consequence, the different features induced by the dense matter effects on the oscillations may allow to distinguish iron-core SNe from O-Ne-Mg-core SNe [23].

Our results have been obtained considering a spherically symmetric neutrino emission. All the previous analysis in the field have relied on this assumption to make the flavor evolution equations numerically tractable. It remains to be investigated if the removal of a perfect spherical symmetry can provide a different behavior in
the flavor evolution \[^{26}\]. Moreover, in multi-dimensional SN models, density fluctuations are expected behind the standing bounce shock, due to the presence of convection and hydro instabilities. These can range at most between 10\% to a factor 2-3 (see, e.g., \[^{14,27}\]). Therefore, even in this case, the matter suppression of the collective oscillations will still remain relevant. This claim is supported by a recent analysis of the matter suppression, performed with two-dimensional SN simulations \[^{28}\].

**Oscillated SN neutrino fluxes** — Figure 2 shows the $\bar{\nu}_e$ distribution function at the neutrinosphere (continuous thin curve) as well as after self-induced and matter effects at $r = 2 \times 10^3$ km (continuous thick curve). We compare the case of complete matter suppression at $t_{pb} = 0.1$ s (left panel, where thin and thick continuous curves coincide) and complete flavor mixture at $t_{pb} = 0.3$ s (right panel). We also show the oscillated flux for $n_e = 0$, where a complete $\bar{\nu}_e \rightarrow \bar{\nu}_x$ swap occurs (dashed curve). The difference in the final $\bar{\nu}_e$ flux with/without matter suppression is striking. It is plausible that a high-statistics detection of a future galactic SN $\nu$ signal would monitor the abrupt spectral changes between the phases of complete and partial matter suppression, probing this scenario. These peculiar time variations in the $\nu$ signal during the accretion would represent also a new tool to extract information on the $\nu$ mass ordering, since the effects of dense matter would show up only in the case of inverted mass hierarchy.

**Earth matter effect.** — A further consequence of the matter suppression is a significant change in the interpretation of the Earth matter effect on the SN $\nu$ signal during the accretion phase, occurring when $\nu$'s oscillate inside the Earth before being detected (see, e.g., \[^{29}\]). In the case of complete matter suppression of the self-induced oscillations (at $t_{pb} \lesssim 0.2$ s for iron-core SNe), the observable SN $\nu$ fluxes at Earth have been already calculated in the literature, antecedent to the inclusion of the collective effects. For definiteness, here we consider the Earth effects on the $\bar{\nu}_e$ spectrum, observable through inverse beta decay reactions $\bar{\nu}_e + p \rightarrow n + e^+$ at large volume Cherenkov or scintillation detectors (see, e.g., \[^{19}\]).

The $\bar{\nu}_e$ flux at Earth $F_{\nu_e}$ in NH for any value of the mixing angle $\theta_{13}$ is given by $F_{\nu_e}^D = \cos^2 \theta_{12} F_{\nu_e} + \sin^2 \theta_{12} F_{\nu_x}$ \[^{19}\], where $\theta_{12}$ is the 1–2 mixing angle, with $\sin^2 \theta_{12} \simeq 0.3$ \[^{21}\]. In the IH case, for "large" $\theta_{13}$ (i.e. for $\sin^2 \theta_{13} \gtrsim 10^{-3}$) $F_{\nu_e}^D = F_{\nu_e}$, while for "small" $\theta_{13}$ (i.e. for $\sin^2 \theta_{13} \lesssim 10^{-5}$) the flux is the same as in the case of NH. Earth effects can be taken into account by mapping $\cos^2 \theta_{12} \rightarrow P(\bar{\nu}_1 \rightarrow \bar{\nu}_e)$ and $\sin^2 \theta_{12} \rightarrow 1 - P(\bar{\nu}_1 \rightarrow \bar{\nu}_e)$, where $P(\bar{\nu}_1 \rightarrow \bar{\nu}_e)$ is the probability that a state entering the Earth as mass eigenstate $\bar{\nu}_1$ is detected as $\bar{\nu}_e$ at the...
detector (see, e.g., [29]).

In this scenario, the presence or absence of Earth matter effects at early times ($t_{pb} \lesssim 0.2$ s) will allow to distinguish the $\nu$ mass hierarchy at large value of the mixing angle $\theta_{13}$. This possibility, presented in the previous scenario with dominant self-induced effects, is particularly attractive since there are already hints for a “large” $\theta_{13}$ [30, 31], promising its possible detection with the current and upcoming reactor and accelerator experiments [32]. Thus for large $\theta_{13}$, the next galactic SN $\nu$ signal would become crucial to get a determination of the $\nu$ mass hierarchy from the sky.

**Impact on SN heating.** — Neutrino flavor oscillations between the neutrinospheres and the standing bounce shock, have long been speculated to influence the $\nu$ heating and hence the SN dynamics [6, 13]. In contrast, we find that the high matter density in the heating region causes complete suppression of the flavor conversion behind the shock-front. Hence, collective $\nu$ flavor oscillations cannot help to increase the $\nu$ heating significantly and an impact on the SN dynamics is not expected. Our result is in agreement with the analysis recently performed in [28]. In order to solve the SN problem, which is related to the revival of the stalled bounce shock, it is possible to decouple the $\nu$ flavor evolution from the hydrodynamics aspects as well as from the $\nu$ transport.

**Conclusions.** — In early, schematic investigations, the accretion phase seemed particularly promising to probe the development of the collective $\nu$ transformations. However, by analyzing state-of-the art simulations, we pointed out that the presence of a large matter density piled-up above the neutrinosphere can take its revenge over the $\nu$-$\nu$ interactions, producing a significant suppression of the self-induced flavor conversions. The presence of a large matter density during the accretion phase is a robust feature of SN simulations [13, 14]. However, its impact on the self-induced oscillations was estimated most often negligible in previous studies (see, e.g., [31]).

Even if the matter suppression would prevent collective effects on the $\nu$ signal during the accretion phase, its presence will result in various benefits. In particular, the detection of the Earth matter effect on the SN $\nu$ burst during the accretion may allow to extract the $\nu$ mass hierarchy, if $\theta_{13}$ is not too small. Moreover, the matter suppression of oscillations at high densities decouples the problem of the $\nu$ flavor mixing in SNe from the $\nu$ transport and impact on the matter heating/cooling.

Collective oscillations may remain possible during the cooling phase, when the matter effects become sub-dominant due to the continuously decreasing matter density. However, the characterization of these effects in the presence of small flux differences and of matter turbulences is far from being settled. Further studies are crucial to understand possible effects of self-induced $\nu$ oscillations and imprinted observable signatures.

**Acknowledgements**

We thank M. Liebendörfer, E. Lisi, C. Ott, G. Raffelt, S. Sarikas, P. D. Serpico, G. Sigl and I. Tamborra for helpful comments on the manuscript. We also acknowledge B. Dasgupta and T. Janka for important discussions. The work of S.C., A.M., N.S. was supported by the German Science Foundation (DFG) within the Collaborative Research Center 676 “Particles, Strings and the Early Universe”. T.F. acknowledges support from HIC for FAIR project no. 62800075.

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