Supernova neutrino oscillations: what do we understand?

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Abstract.
    We summarize our current understanding of the neutrino flavor conversions inside a core collapse supernova, clarifying the important role played by the "collective effects" in determining flavor conversion probabilities. The potentially observable ν_e and $\bar{\nu}_e$ spectra may help us identify the neutrino mixing scenario, distinguish between primary flux models, and learn more about the supernova explosion.

1. Introduction

Neutrino energy spectra exiting a core collapse supernova (SN) are determined by the primary neutrino fluxes, the neutrino mixing scenario as well as the densities encountered by the neutrinos along their path. (For recent overviews, see [1, 2].) In this talk, we explain how the collective effects due to ν-ν interactions and MSW matter effects result in distinctive features in the ν_e and $\bar{\nu}_e$ energy spectra at the detectors. We emphasize some of the recent results involving the collective effects.

2. Primary neutrino fluxes

Neutrinos from a SN are emitted in roughly three phases. The first ~ 10 ms of the SN neutrino signal is the neutronization burst, composed entirely of ν_e. Neutrinos and antineutrinos of all species are emitted during the next ~ 10 s, initially in the accretion phase and later in the Kelvin-Helmholtz cooling phase [3].

    The SN core acts essentially like a neutrino black body source with flavor dependent fluxes. Since the primary fluxes of $\nu_\mu, \bar{\nu}_\mu, \nu_\tau, \bar{\nu}_\tau$ are almost identical, it is convenient to work in terms of the three "flavors": ν_e , $\nu_x \equiv \cos\theta_{23}\, \nu_\mu - \sin\theta_{23}\, \nu_\tau$, $\nu_y \equiv \sin\theta_{23}\, \nu_\mu + \cos\theta_{23}\, \nu_\tau$, which are also the mass eigenstates at large matter densities. Clearly, the primary fluxes of $\nu_x, \nu_y, \bar{\nu}_x, \bar{\nu}_y$ are identical and we denote them as $F^0_{\nu_x}$.

    The primary fluxes $F^0_{\nu_e}, F^0_{\bar{\nu}_e}, F^0_{\nu_x}$ are parameterized by the total number fluxes Φ_0, average energies E_0, and the "pinching parameters" that characterize their spectral shapes [4]. The values of the parameters are highly model dependent, as can be seen from Table 1. In the Table, M1 fluxes represent the predictions of the Livermore model [5]. The predictions of the Garching model [6], on the other hand, are close to M1 during the accretion phase and close to M2 during the cooling phase. As will be seen later, the neutrino flavor conversion probabilities depend on certain features of these primary spectra.

Table 1. Representative predictions of neutrino flux models. E_0 values are given in MeV.

| Flux Model	$E_0(\nu_e)$	$E_0(\bar{\nu}_e)$	$E_0(\nu_x)$	$\frac{\Phi_0(\nu_e)}{\Phi_0(\nu_x)}$	$\frac{\Phi_0(\bar{\nu}_e)}{\Phi_0(\bar{\nu}_x)}$
M1	12	15	24	2.0	1.6
M2	12	15	18	0.85	0.75

3. Neutrino flavor conversions

3.1. Collective effects at large neutrino densities

The extremely high neutrino and antineutrino densities near the neutrinospheres make the ν-ν interactions in this region significant [7, 8] and give rise to "collective effects". Analytic studies of these effects reveal distinctive flavor conversion phenomena that are qualitatively different from the usual vacuum or MSW oscillations. These include "synchronized oscillations" [9] where ν and $\bar{\nu}$ of all energies oscillate with the same frequency, "bipolar/pendular oscillations" [10, 11] that correspond to pairwise conversions $\nu_e\bar{\nu}_e \leftrightarrow \nu_y\bar{\nu}_y$, and "spectral split" [12, 13, 14, 15, 16] where ν_e and ν_y ($\bar{\nu}_e$ and $\bar{\nu}_y$) spectra interchange completely within certain energy ranges. The dynamics in three generations can be factorized into a superposition of multiple two-flavor phenomena [17]. New three flavor effects also emerge: for example in early accretion phase, large μ-τ matter potential may cause interference between MSW and collective effects [18].

The dependence of the flavor evolution on the direction of propagation of the neutrino may give rise to direction-dependent evolution, or "multi-angle effects" [7, 8, 19, 20] that may lead to decoherence [21, 22, 23]. However, for a realistic asymmetry between neutrino and antineutrino fluxes, such multi-angle effects are likely to be small [24, 25] and the "single-angle" approximation can be used. Even for non-spherical geometries, one can study the single-angle evolution along stream lines of neutrino flux, as long as coherence is maintained [26].

The propagation of the neutrinos can be rather cleanly separated into regions where various collective effects dominate individually and hence the neutrinos experience these effects sequentially [17, 24]. When the neutrinos emerge from the region where collective effects dominate, the net effect is a swap between the spectra of ν_e and ν_y ($\bar{\nu}_e$ and $\bar{\nu}_y$) in some energy ranges, as illustrated in Fig. 1. The neutrino (antineutrino) spectra at this point can be divided into two energy regimes: the "swapped" regime where the ν_e and ν_y ($\bar{\nu}_e$ and $\bar{\nu}_y$) spectra have completely interchanged, and the "unswapped" regime where the spectra have remained unchanged. At the boundary between two such regimes, the survival probability changes sharply: this is the "spectral split". This boundary need not be sharp: the spectral split is typically smeared out over a small energy range. In general, there can be zero, one, or multiple spectral splits in ν as well as $\bar{\nu}$ channels [16, 27], and their positions can be approximately predicted depending on the mass ordering and primary spectra [16]. Although the exact evolution of the neutrino state leading to the splits can be calculated numerically (for animated simulations, see `http://www.mppmu.mpg.de/supernova/multisplits`), the current analytic understanding of the dynamics is a bit unsatisfactory. A clear direct mapping between the primary fluxes and split positions is also still lacking.

When the fluxes obey an approximate hierarchy, i.e. $F^0_{\nu_e} > F^0_{\bar{\nu}_e} > F^0_{\nu_x}$ except at high energies, the flux-split mapping is particularly straightforward. All energies in ν as well as $\bar{\nu}$ are unswapped in normal hierarchy, while in inverted hierarchy, only the energy range $E < E_c$ for neutrinos below a certain critical energy E_c remains unswapped [12, 14]. The fluxes in the accretion phase (e.g. M1) typically fall under this catagory. The results in [2, 17, 24, 28], in particular, have been obtained with this flux scenario.
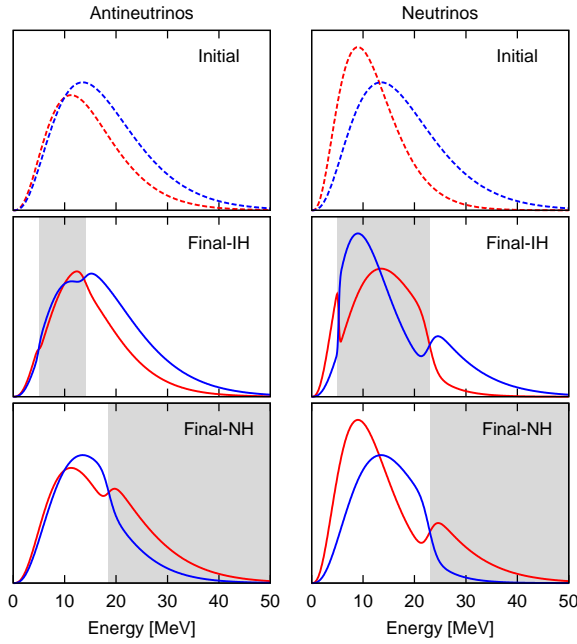
Figure 1. The fluxes of antineutrinos and neutrinos (light grey/ red: e flavor, dark grey/ blue: y flavor) before and after the action of collective effects, in the normal hierarchy (NH) and inverted hierarchy (IH). The shaded regions correspond to the swapped energy regime. Here M2 fluxes from Table 1 have been used. The Figure has been adapted from [16].

3.2. MSW resonances inside the SN and propagation through vacuum

In iron core supernovae, the collective effects have already become insignificant when neutrinos enter the MSW resonance regions. SN neutrinos must pass through two resonance layers: the H-resonance layer at $\rho_{\mathrm{H}} \sim 10^3$ g/cc characterized by $(\Delta m^2_{\mathrm{atm}}, \theta_{13})$, and the L-resonance layer at $\rho_{\mathrm{L}} \sim 10$ g/cc characterized by $(\Delta m^2_{\odot}, \theta_{12})$. The outcoming incoherent mixture of vacuum mass eigenstates travels to the Earth without any further conversions, and is observed at a detector as a combination of primary fluxes of the three neutrino flavors:

$$F_{\nu_e} = p F^0_{\nu_e} + (1-p) F^0_{\nu_x} , \qquad F_{\bar{\nu}_e} = \bar{p} F^0_{\bar{\nu}_e} + (1-\bar{p}) F^0_{\nu_x} ,$$

where p and $\bar{p}$ are the survival probabilities of ν_e and $\bar{\nu}_e$ respectively.

The neutrino survival probabilities are governed by the adiabaticities of the resonances traversed, which are directly connected to the neutrino mixing scheme [29]. Table 2 shows the survival probabilities in swapped and unswapped energy regions in various mixing scenarios. For intermediate values of θ_{13}, i.e. $10^{-5} \lesssim \sin^2\theta_{13} \lesssim 10^{-3}$, the survival probabilities depend on energy as well as details of the SN density profile. Note that though p and $\bar{p}$ entries in scenarios C and D are identical, since the swapped regime is determined by the mass hierarchy, even these scenarios lead to different net flavor conversions. The spectral swaps can occur for values of θ_{13} as low as 10^{-10} [13, 28]. Collective effects are thus sensitive to extremely small (but nonzero) θ_{13}, and can in principle allow identification of hierarchy.

3.3. Propagation through the shock wave near MSW resonances

The passage of the shock wave through the H-resonance ($\rho \sim 10^3$ g/cc) a few seconds after the core bounce may break adiabaticity, thereby modifying the flavor evolution of neutrinos that are emitted during this time interval [30, 31, 32, 33, 34, 35]. Such a situation is possible, even in principle, only in certain mixing scenarios: for neutrinos (antineutrinos), shock effects can be present only in the mixing scenario A (B). As a result, the mere identification of shock wave effects is enough to identify these scenarios, irrespective of the collective effects.

Table 2. Survival probabilities p and $\bar{p}$ in the swapped and unswapped energy regimes, in various mixing scenarios. Terms of $\mathcal{O}(\theta_{13}^2)$ have been neglected.

	Hierarchy	$\sin^2\theta_{13}$	p unswapped	p swapped	$\bar{p}$ unswapped	$\bar{p}$ swapped
A	Normal	$\gtrsim 10^{-3}$	0	$\sin^2\theta_{12}$	$\cos^2\theta_{12}$	0
B	Inverted	$\gtrsim 10^{-3}$	$\sin^2\theta_{12}$	0	0	$\cos^2\theta_{12}$
C	Normal	$\lesssim 10^{-5}$	$\sin^2\theta_{12}$	0	$\cos^2\theta_{12}$	0
D	Inverted	$\lesssim 10^{-5}$	$\sin^2\theta_{12}$	0	$\cos^2\theta_{12}$	0

The shock wave effects can be diluted by stochastic density fluctuations [36] or turbulence [37]. However, recent hydrodynamic simulations [38, 39] suggest that some of the shock wave effects survive in spite of these smearing factors.

3.4. Oscillations inside the Earth matter
If neutrinos travel through the Earth before reaching the detector, they undergo flavor oscillations and the survival probabilities change [40, 41, 42]. This change however occurs only in the energy ranges where $p \neq 0$ (for neutrinos) or $\bar{p} \neq 0$ (for antineutrinos). The presence or absence of Earth effects in the neutrino or antineutrino channels would therefore help in identifying some flux-mixing combination, using Table 2.

4. Observable signals at neutrino detectors
If a SN explodes in our galaxy at ~ 10 kpc from the Earth, we expect $\mathcal{O}(10^4)$ events of $\bar{\nu}_e$ at Super-Kamiokande (SK). With future larger water Cherenkov detectors, large scintillation detectors with better energy resolutions, and liquid Argon detectors sensitive to ν_e, it should be possible to reconstruct the ν_e and $\bar{\nu}_e$ spectra to a good accuracy. SN neutrinos would also enable pointing at the SN in advance of the optical signal [43], with [44] or even without [45, 46, 47] any information on neutrino mixing, and in reconstructing the SN bounce time accurately [48].

4.1. Suppression of ν_e in the neutronization burst
Since the primary signal during the neutronization burst is pure ν_e, the entire energy range is unswapped. Since the model predictions for the energy and luminosity of the burst are fairly robust [49], the observation of the burst signal gives direct information about the survival probability of ν_e. This probability is $\mathcal{O}(\theta_{13}^2)$ in scenario A and $\sin^2\theta_{12}$ in all the other scenarios [29]. Thus, the strong suppression of ν_e burst would be a smoking gun signal for scenario A.

In an O-Ne-Mg supernova, the MSW resonances may lie deep inside the collective regions during the neutronization burst, when the neutrino luminosity is even higher. In such a situation, neutrinos of all energies undergo the MSW resonances together, with the same adiabaticity [50]. As long as this adiabaticity is nontrivial, one gets the "MSW-prepared spectral splits", two for normal hierarchy and one for inverted hierarchy [51, 52, 53]. The positions of the splits can be predicted from the primary spectra [53]. The splits imply ν_e suppression that is stepwise in energy. Such a signature may even be used to identify the O-Ne-Mg supernova, in addition to identifying the hierarchy.

4.2. Shock wave effects
Observables like the number of events, average energy, or the width of the spectrum may display dips or peaks for short time intervals, while the shock wave is passing through the H resonance.

The positions of the dips or peaks in the number of events at different neutrino energies would also allow one to trace the shock propagation while the shock is in the mantle, around densities of $\rho \sim 10^3$ g/cc [34]. This information, by itself or in combination with the corresponding gravitational wave signal, will yield valuable information about the SN explosion, in addition to identifying the scenario A or B.

If light sterile neutrinos exist, they may leave their imprints in the shock wave [54, 55]. For an O-Ne-Mg supernova, passage of the shock wave through the sharp density profile at the resonance leads to distinctive effects [56].

4.3. Spectral split in ν_e

A split in ν_e or $\bar{\nu}_e$ spectrum would manifest itself as a sharp jump at the split energy [13]. It is therefore a smoking gun signal for collective effects and the corresponding flux-mixing combination. However, the sharp split in p is smeared to some extent by the multi-angle effects [24] and its actual observation may be a challenging task.

4.4. Earth matter effects

Earth matter effects can be identified by the comparison of signals at two detectors, only one of which is shadowed by the earth. This could be achieved through the $\bar{\nu}_e$ spectra at two large water Cherenkov detectors [28] or through the time dependent ratio of luminosities at IceCube and Hyper-Kamiokande [57]. The Earth effects can be identified even at a single detector as long as it is capable of determining the neutrino energy. For example, Fourier transform of the "inverse energy" spectrum of $\bar{\nu}_e$ [58] gives peaks (multiple ones if the neutrinos traverse the Earth core) whose positions are independent of the primary neutrino spectra. These would reveal the presence of Earth matter effects [59]. For the typical accretion phase scenario (M1) and $\sin^2 \theta_{13} \lesssim 10^{-5}$, the detection of Earth effects in $\bar{\nu}_e$ can identify normal hierarchy [28].

The presence of spectral splits implies that the Earth effects may be present in only certain energy regimes. The identification of these energy regimes can play a major role in the identification of the corresponding flux-mixing combination.

5. Concluding remarks

The flavor conversion probabilities of neutrinos inside a SN are sensitive to the neutrino mixing scenarios, in particular to the mass hierarchy even at extemely small θ_{13}, thanks to the collective effects and MSW matter effects. In addition, since the collective effects can change the neutrino flavor composition deep inside the core, they may affect the dynamics of the SN explosion.

Smoking gun signals of neutrino mixing scenarios as well as information on primary fluxes and shock wave propagation can be independently obtained through observations like the suppression of neutronization burst, time variation of the signal during shock wave propagation, and Earth matter effects. More reliable predictions of primary fluxes, better understanding of the collective effects, and improved limits on θ_{13} from terrestrial experiments will make our deductions more robust.

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