Supernova observations for neutrino mixing parameters

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Abstract. The neutrino spectra from a future galactic core collapse supernova could reveal information on the neutrino mixing pattern, especially on θ_{13} and the mass hierarchy. I briefly outline our current understanding of neutrino flavor conversions inside a supernova, and point out possible signatures of various neutrino mixing scenarios that the neutrino detectors should look for. Supernova neutrinos provide a probe for θ_{13} and mass hierarchy that is complementary to, and sometimes even better than, the current and proposed terrestrial neutrino oscillation experiments.

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MOTIVATION

Astrophysical observations have historically been the first steps towards the measurements of neutrino mixing parameters, setting the stage for precision measurements by terrestrial experiments. The solar neutrino observations first identified the ranges for Δm^2_{21} and θ_{12}, which guided the design of experiments like KamLAND that in turn confirmed the solution of the solar neutrino problem. Similarly, the values of $|\Delta m^2_{32}|$ and θ_{23} measured by the atmospheric neutrino experiments influenced the design parameters for K2K and MINOS, which later confirmed the oscillation solution to the atmospheric neutrino anomaly. Observations of the neutrino signal from a future galactic core collapse supernova (SN) may be expected to play a similar role for two more neutrino mixing parameters that are hitherto unknown: θ_{13}, and the neutrino mass hierarchy [1, 2].

Unlike the solar or atmospheric neutrinos that keep on bombarding the Earth continuously, the neutrino burst from a galactic SN is a rather rare occurence – estimated to happen only a few times every century. The only SN that we have observed in neutrinos so far was SN1987A [3], which was about 50 kpc away. Therefore, constructing a detector specifically for detecting SN neutrinos may not be practical. On the other hand, the number of neutrinos from such a burst, and the information content therein, is so large that such a golden opportunity should not be missed. Fortunately, many of the large neutrino detectors – designed for solar, atmospheric or terrestrial neutrino experiments – are in principle sensitive to SN neutrinos. All that is needed is the ability and readiness of these detectors to observe the expected salient features of the SN neutrino spectra. As we shall see in this talk, this involves the reconstruction of ν_e and $\bar{\nu}_e$ spectra, the identification of spectral modulations in them, and the detection of time variation of the signal.

The SN neutrino burst arriving at the Earth would be a net product of the primary neutrino fluxes and the neutrino flavor conversions during their travel from the star to the earth. We shall start by exploring the flavor conversions and their dependence on the primary neutrino spectra.

FLAVOR CONVERSIONS INSIDE A SN

The paradigm of neutrino flavor conversions inside a SN has undergone major changes in the past decade. Till a few years ago, it was believed that flavor conversions inside the star occured mainly in the MSW resonance regions H ($\rho \sim 10^4$ g/cc) and L ($\rho \sim 10$ g/cc). These matter-induced flavor conversion probabilities are independent of the primary neutrino fluxes, however they are sensitive to whether $\sin^2\theta_{13}$ is $\gtrsim 10^{-3}$ or $\lesssim 10^{-5}$, and to the mass hierarchy, as long as $\sin^2\theta_{13} \gtrsim 10^{-5}$ [1]. A few years ago it was realized [4] that the neutrino-neutrino interactions near the neutrinosphere ($\rho \sim 10^{10}$ g/cc) are significant enough to give rise to new flavor-changing phenomena ("collective effects") – synchronized oscillations [5], bipolar/pendular oscillations [6] and spectral splits [7] – at such high densities. The net flavor conversion probabilities are then sensitive to the primary fluxes themselves, and to the mass hierarchy, even for a vanishingly small $\sin^2\theta_{13}$, since the pendular oscillations may be triggered by even a small instability [8].

The collective effects are nonlinear phenomena, and hence difficult to handle analytically. Moreover, the dependence of the flavor evolution on the direction of propagation of the neutrino, termed "multi-angle effects" [9], may give rise to decoherence [10]. Such multi-angle effects are expected to be small for a realistic asymmetry between neutrino and antineutrino fluxes [11] and a

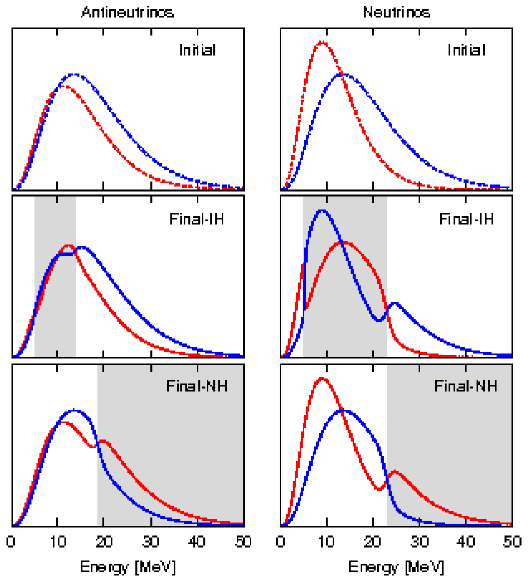

FIGURE 1. The fluxes of antineutrinos and neutrinos (light grey/ red: e flavor, dark grey/ blue: y flavor) before and after the action of collective effects, in the normal hierarchy (NH) and inverted hierarchy (IH). The shaded regions correspond to the swapped energy regime. The average energies of the primary fluxes are taken to be $\langle E_{\nu_e} \rangle = 12$ MeV, $\langle E_{\bar{\nu}_e} \rangle = 15$ MeV, $\langle E_{\nu_\mu} \rangle = 18$ MeV, while their luminosities are $L_{\nu_e} : L_{\bar{\nu}_e} : L_{\nu_\mu} = 1.0 : 1.1 : 1.8$.

so-called "single-angle" approximation can be used. The jury is still out on the importance of multi-angle effects, and most of the available results, including those in this talk, use the single-angle approximation.

The net consequence of the collective effects is that the spectra of ν_e can completely swap with those of certain combinations of ν_μ and ν_τ spectra, but only in certain energy regimes. The boundaries of these regimes, across which the flavor conversion probabilities change abruptly, are termed "spectral splits". In general, multiple spectral splits are present in neutrino as well as antineutrino spectra [12]; see Fig. 1 for an example. The number and positions of the spectral splits depend on the primary neutrino spectra.

Primary fluxes and spectral splits

Our current knowledge of the primary neutrino fluxes is rather incomplete, since the exact dynamics of the SN explosion is not yet well-understood. Moreover, new predictions of the features of these fluxes [13] differ substantially from the older ones. In such a situation, it is prudent not to assume any particular values for the parameters of the primary spectra, but to scan over all the reasonable parameter space and understand the features of flavor conversions as functions of the spectral parameters.

All the simulations of the primary fluxes predict the hierarchy $\langle E_{\nu_e} \rangle < \langle E_{\bar{\nu}_e} \rangle < \langle E_{\nu_\mu} \rangle$ among the average energies of neutrino species. In addition, most of them agree that the luminosities L_{ν_e} and $L_{\bar{\nu}_e}$ are almost equal, while the luminosity L_{ν_μ} may, conservatively, vary between half to twice the ν_e luminosity, depending on the simulation as well as the time after the core collapse even in a single simulation. Note that the energies and luminosities of $\nu_\mu, \nu_\tau, \bar{\nu}_\mu, \bar{\nu}_\tau$ are all equal.

A scan over the parameter space consistent with the above robust predictions yields [14] the following observations. When the electron flavor dominates in the primary fluxes, i.e. $L_{\nu_e} \gtrsim L_{\nu_\mu}$, one obtains (i) in NH: no spectral split in either neutrino or antineutrino channel, and (ii) in IH: single spectral splits in the neutrino and antineutrino channels – corresponding to the swaps $\nu_e \leftrightarrow \nu_y$ and $\bar{\nu}_e \leftrightarrow \bar{\nu}_y$, respectively. Here, $\nu_y \equiv -\sin\theta_{13}\, \nu_\mu + \cos\theta_{13}\, \nu_\tau$, and similarly for antineutrinos. On the other hand, when the non-electron flavors dominate, i.e. $L_{\nu_e} \lesssim L_{\nu_\mu}$, one gets (i) in NH: single spectral splits in the neutrino and antineutrino channels – corresponding to the swaps $\nu_e \leftrightarrow \nu_y$ and $\bar{\nu}_e \leftrightarrow \bar{\nu}_y$, respectively, and (ii) in IH: up to two spectral splits, both in the neutrino and antineutrino channels – corresponding to the swaps $\nu_e \leftrightarrow \nu_y, \nu_e \leftrightarrow \nu_x$, and $\bar{\nu}_e \leftrightarrow \bar{\nu}_y, \bar{\nu}_e \leftrightarrow \bar{\nu}_x$. Here, $\nu_x \equiv \cos\theta_{13}\, \nu_\mu + \sin\theta_{13}\, \nu_\tau$, and similarly for antineutrinos. Some of the splits, especially the $e \leftrightarrow x$ ones, may be incomplete due to non-adiabatic effects. Spectral splits also display three-flavor effects in certain circumstances [15].

Though the above results have been obtained only in the single-angle approximation, and have been stated only in a qualitative language, they still allow us to predict what kind of signals to look for at the neutrino detectors, and guide us towards the disentanglement of the primary spectra and neutrino flavor conversions.

Matter effects on flavor conversions

In the region where the collective effects are dominant, the matter effects suppress the mixing angle θ_{13}, and are not expected to cause any significant additional flavor changes. After the neutrinos exit this region, the flavor conversions occur mainly in the MSW resonance regions H ($\rho \sim 10^4$ g/cc) and L ($\rho \sim 10$ g/cc) [1]. Here the conversion probabilities are independent of the spectra themselves, and are well understood in terms of the neutrino mixing parameters and density profiles.

In particular, the flavor conversion in the H resonance is completely adiabatic (non-adiabatic) for $\sin^2\theta \gtrsim 10^{-3}$ ($\lesssim 10^{-5}$), while the L resonance is always completely adiabatic. These conclusions, however, are altered when the shock wave passes through the resonance regions. It has two main effects: (i) the sharp density fluctuations in the shock wave may cause the adiabatic resonances to become non-adiabatic [16] and (ii) the turbulence that follows the shock wave may, if large enough, cause flavor depolarization, so that the fluxes of all the neutrino species – or all the antineutrino species, depending on the hierarchy – become identical [17]. If the latter effect is small, the former one may become observable as time-dependent sharp changes in quantities like the average energy of the ν_e or $\bar{\nu}_e$ flux [18].

If the detector is shadowed by the earth, i.e. if the neutrinos travel through Earth before reaching the detector, the Earth matter effects on the neutrinos change the flavor conversion probabilities, causing modulations in the observed $\nu_e/\bar{\nu}_e$ spectra [1, 19].

OBSERVABLE SIGNALS

We shall consider three main categories of neutrino detectors: water Cherenkov, carbon-based scintillators, and liquid argon detectors. The major interaction in the first two detectors is the inverse beta decay $\bar{\nu}_e p \to e^+ n$, which helps reconstruct the $\bar{\nu}_e$ spectrum. While the energy resolution of the water Cherenkov detectors is typically a factor of 5-10 worse than that of the liquid scintillators, it is easier to make larger water Cherenkov detectors, so they have the advantage of larger statistics. The liquid argon detector is the best detector for observing the ν_e spectrum; the corresponding reaction is $\nu_e\,^{40}\mathrm{Ar} \to ^{40}\mathrm{K}^* e^-$. The rule-of-thumb estimate for the number of events observed through the above reactions is ~ 300 per kt in the 10 s duration of the neutrino pulse, for a supernova at 10 kpc.

There are also sub-leading interactions like the forward scattering $\nu_e e^- \to \nu_e e^-$ that occurs in all the above detectors, $\nu_e\,^{16}\mathrm{O} \to X e^-$ in water Cherenkov, and the neutral current reaction $\nu\,^{12}\mathrm{C} \to \nu X \gamma(15.11\,\mathrm{MeV})$ in scintillator detectors, which will not be discussed here. We shall focus on the leading charged current reactions above, which enable the reconstruction of the ν_e and $\bar{\nu}_e$ spectra.

Fig. 2 shows these spectra at a liquid scintillator detector (for $\bar{\nu}_e$) and a liquid Argon detector (for ν_e) for a representative set of primary flux parameters when $L_{\nu_e} \lesssim L_{\nu_\mu}$. Following are some of the features of these spectra that can act as smoking gun signals of specific neutrino mixing scenarios.

Detection of the spectral splits

Though the survival probability of ν_e or $\bar{\nu}_e$ changes sharply at the spectral splits, the observed signal is often diluted by the small difference between the swapping spectra. Moreover if the split is at low energies, the small cross sections make the detection of the spectral split difficult. However if the primary fluxes are dominated by non-electron flavors, the splits can be at higher energies and may manifest themselves as shoulders in the ν_e or $\bar{\nu}_e$ spectra [14]. This feature may be seen in Fig. 2.

Earth matter effects

Time-dependent changes in relative luminosities observed at two detectors, only one of which is shadowed by the Earth, are indicators of Earth matter effects. On the other hand, the modulations in the ν_e or $\bar{\nu}_e$ spectra allow one to detect Earth matter effects even at a single detector [20]. While the former method needs two detectors with large fiducial masses (e.g. megaton water Cherenkov, IceCube), the latter method needs detectors with a good energy resolution (e.g. liquid scintillator or liquid Ar); see Fig. 2. In general, one expects more distinctive signatures of Earth effects with a ν_e spectrum, therefore one will have a better chance of detecting these effects with a large liquid Argon detector.

Earth effects allow the identification of mass hierarchy even when θ_{13} is extremely small – much below the reach of the long-baseline experiments – and is perhaps the only probe of mass hierarchy for such small θ_{13} values [21].

If the Earth effects are not detected, it may be due to multi-angle decoherence, turbulent effects, or small differences in primary spectra. However a positive identification of Earth effects would be enough to shortlist specific mixing patterns [14]. The spectral split phenomenon implies that the Earth effect modulations will typically occur only in a part of the spectrum and not in the other, but this feature may be rather hard to identify.

Shock wave effects

The shock wave effects would be typically easy to spot using the time variation of neutrino signal. Sharp changes in the ν_e ($\bar{\nu}_e$) spectra at $t > 3-4$ s testify for NH (IH) and $\sin^2\theta_{13} \gtrsim 10^{-5}$ [16].

If the multi-angle effects cause decoherence at such late times, or if the turbulence that follows the shock wave is large enough to cause flavor depolarization [17], the spectra of all flavors may become identical and no shock effects will be observed. Thus, the non-

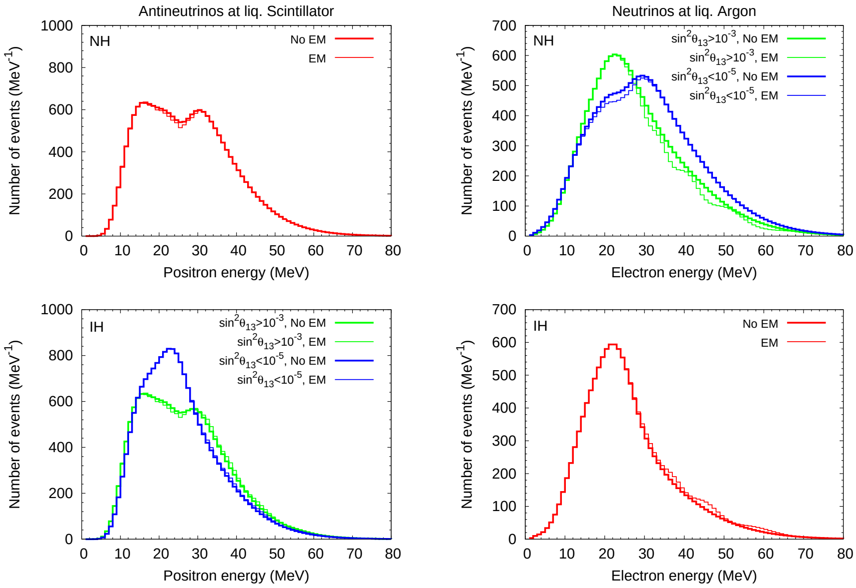

FIGURE 2. $\bar{\nu}_e$ and ν_e energy spectra at 50 kt scintillator and 100 kt LAr TPC detectors, in both the hierarchies: NH (upper panels) and IH (lower panels), with and without oscillations due to Earth matter effects. The spectra with Earth matter effects (EM) have been calculated for $L = 8000$ km through the Earth, and have been denoted by thinner lines. The spectra at a water Cherenkov detector can be obtained by smearing the energy of $\bar{\nu}_e$ at the scintillator detector, and multiply the number of events by an appropriate factor.

observation of shock effects does not convey any concrete information about neutrino mixing. However, a positive observation of these effects can pinpoint the neutrino mixing pattern. Collective effects play no part in deciding whether the shock effects are present or not, so the inferences from this observation are rather robust.

Vanishing neutronization burst

The ~ 10 ms burst of ν_e that occurs immediately after the core bounce has a well-predicted flux [22]. If the hierarchy is normal and $\sin^2\theta_{13} \gtrsim 10^{-3}$, the burst signal is suppressed by a factor of $\sin^2\theta_{13}$ [1]. Such an extreme suppression (almost vanishing) of the neutronization burst signal is a clear signal of this mixing scenario, since it is independent of the collective effects or turbulence. However since this signal is available only in ν_e, one needs a large liquid Argon detector. Also, one needs a good time resolution to be able to distinguish between the ν_e from the neutronization burst and the ν_e from the subsequent accretion phase.

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. Then neutrinos of all energies undergo the MSW resonances together, with the same adiabaticity [23]. As long as this adiabaticity is nontrivial, one gets the "MSW-prepared spectral splits", two for normal hierarchy and one for inverted hierarchy [24, 25]. The positions of the splits can be predicted from the primary spectra [25]. The splits imply a 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. Recent multi-angle results [26] show that the double-swap feature survives only for $\theta_{13} \gtrsim 10^{-3}$.

CONCLUDING REMARKS

In spite of the uncertainties in the primary spectra, and our rather sketchy understanding of collective and turbulent effects, there are potential signals in the ν_e and $\bar{\nu}_e$ spectra that can help in decoding the message in the supernova neutrino spectra. While one still needs to work on the theoretical interpretations of the signals, it is clear what kind of signals will be important, viz. (i) spectral splits, (ii) Earth matter effects, (iii) shock wave effects and (iv) the neutronization burst signal. Future experiments should be designed to optimize the detection of these signals.

The observable effects in the neutrino and antineutrino signals, for various scenarios of primary fluxes and neutrino mixing, have been summarized in Tables 1 and 2. Though these tables are calculated with the single-angle approximation and neglecting turbulent effects,

TABLE 1. Observable effects in the ν_e spectra, for various primary flux scenarios as well as neutrino mixing patterns.

		$L_{\nu_e} \gtrsim L_{\nu_x}$			$L_{\nu_e} \lesssim L_{\nu_x}$		
		ν_e burst	Earth effects	Shock effects	ν_e burst	Earth effects	Shock effects
NH	$\sin^2\theta_{13} \gtrsim 10^{-3}$	Vanishes	Absent	Possible	Vanishes	Only high E	Possible
	$\sin^2\theta_{13} \lesssim 10^{-5}$	Present	All E	Absent	Present	Only intermediate E	Absent
IH	$\sin^2\theta_{13} \gtrsim 10^{-3}$	Present	Absent	Absent	Present	Only high E	Absent
	$\sin^2\theta_{13} \lesssim 10^{-5}$	Present	Absent	Absent	Present	Only high E	Absent

TABLE 2. Observable effects in the $\bar{\nu}_e$ spectra, for various primary flux scenarios as well as neutrino mixing patterns.

		$L_{\nu_e} \gtrsim L_{\nu_x}$		$L_{\nu_e} \lesssim L_{\nu_x}$	
		Earth effects	Shock effects	Earth effects	Shock effects
NH	$\sin^2\theta_{13} \gtrsim 10^{-3}$	All E	Absent	Only intermediate E	Absent
	$\sin^2\theta_{13} \lesssim 10^{-5}$	All E	Absent	Only intermediate E	Absent
IH	$\sin^2\theta_{13} \gtrsim 10^{-3}$	Intermediate and high E	Possible	Intermediate and high E	Possible
	$\sin^2\theta_{13} \lesssim 10^{-5}$	Absent	Absent	Only high E	Absent

they clearly indicate that different neutrino mixing scenarios give rise to distinctive features in the neutrino signal. These features can be used to determine the neutrino mixing scenario, the primary fluxes, as well as some aspects of the supernova shock wave propagation.

If a galactic supernova occurs when we still have not determined θ_{13} or identified the mass hierarchy, it will be our first handle on these quantities. Given the uncertainties on the primary spectra and our current lack of complete understanding of the collective effects and turbulence, the inferences from this observation will most likely need to be verified with terrestrial experiments. Indeed these inferences may even influence our priorities between different long-baseline experiments. On the other hand, if the neutrino mixing parameters are already well known by the time a galactic SN is observed, a lot of concrete information about the primary spectra and the shock wave dynamics can be discerned from it.

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