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On the observability of collective flavor oscillations in diffuse supernova neutrino background

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ABSTRACT

Collective flavor oscillations are known to bring multiple splits in the supernova (SN) neutrino and antineutrino spectra. These spectral splits depend not only on the mass hierarchy of the neutrinos but also on the initial relative flux composition. Observation of spectral splits in a future galactic supernova signal is expected to throw light on the mass hierarchy pattern of the neutrinos. However, since the Diffuse Supernova Neutrino Background (DSNB) comprises of a superposition of neutrino fluxes from all past supernovae, and since different supernovae are expected to have slightly different initial fluxes, it is pertinent to check if the hierarchy dependent signature of collective oscillations can survive this averaging of the flux spectra. Since the actual distribution of SN with initial relative flux spectra of the neutrinos and antineutrinos is unknown, we assume a log-normal distribution for them. We study the dependence of the hierarchy sensitivity to the mean and variance of the log-normal distribution function. We find that the hierarchy sensitivity depends crucially on the mean value of the relative initial luminosity. The effect of the width is to reduce the hierarchy sensitivity for all values of the mean initial relative luminosity. We find that in the very small mixing angle (θ_{13}) limit considering only statistical errors even for very moderate values of variance, there is almost no detectable hierarchy sensitivity if the mean relative luminosities of ν_e and $\bar{\nu}_e$ are greater than 1.

1. Introduction

Neutrinos coming from supernova explosions can give rich information about the explosion mechanism as they are the only particles that come from regions deep inside the core. They are also extremely useful for determining neutrino properties as neutrinos from SN1987A have amply demonstrated [1–3]. In particular, it has been shown that the neutrino mass hierarchy and smallness of θ_{13} can be probed using SN neutrinos [4,5]. In the last few years, focus has been on the effect of neutrino–neutrino interaction in the central regions of the core of supernova, giving rise to the so-called collective effects [6–43].

The 'collective' nature of simultaneous flavor conversions of both neutrinos and antineutrinos give rise to 'splits' in the spectra of the neutrinos and antineutrinos. These splits occur due to sudden change in the oscillation probability, causing spectral swaps which may end up in observable effects. Interestingly the impact of collective oscillations on the spectra are different for the Normal Hierarchy (NH) and the Inverted Hierarchy (IH). This opens up the possibility of identifying the neutrino mass hierarchy via observation of collective effects in the neutrino signal from a future galactic supernova event [30].

However with the very small rate of occurrence of galactic supernova events (a few per century) one is forced to think of strategies of detecting the above mentioned effect otherwise. One of the promising possibilities is the detection of Diffuse Supernova Neutrino Background (DSNB) in the near future [44–46]. The cumulative number of neutrinos and antineutrinos produced by all earlier SN events in the universe result in a cosmic background known as DSNB. Though these neutrinos are yet to be detected, one has reasons to believe that it may be possible to observe them in the near future [47–66]. Present day upper limits are $1.2\bar{\nu}_e\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ with energies above 19.3 MeV for Super-Kamiokande (SK) water Cerenkov detectors [67] and $6.8 \times 10^3\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ with energies between 25 MeV and 50 MeV for Liquid Scintillator Detector (LSD) [68] at 90% C.L. for both.

The two key ingredients in the calculation of DSNB are (i) the SN rate which is proportional to cosmic star formation rate and (ii) the ν and $\bar{\nu}$ energy spectra. Whereas reliable estimates are now available for the star formation rate and the SN rate [69,70], the prediction for the SN neutrino spectra has gone through an evolution over the years. Earlier considerations of matter induced

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resonances were followed by incorporating the 'collective' effects due to interaction amongst the neutrinos themselves in the high density central regions of the core. The first study of the effect of the collective flavor oscillations on DSNB fluxes and the corresponding predicted number of events in terrestrial detectors were carried out in [65] where it was demonstrated that the event rate gets substantially modified by collective effects. The results also showed that observation of the DSNB fluxes at earth could shed light on the neutrino mass hierarchy. However, since then substantial progress has been made in the understanding of the collective effects. In particular, it is now clear that the neutrino and antineutrino survival probability and hence different split patterns depend crucially on the relative luminosities of the initial neutrino fluxes produced inside the exploding star [36–38]. Therefore, one can predict the final neutrino and antineutrino spectra from a given SN with reasonable accuracy only if one already has access to the initial flux conditions. This complication is further compounded for the DSNB, as the DSNB flux comes from a superposition of the fluxes from all past SNe. Since the initial flux conditions are expected to be sensitive to the properties of the progenitor star and since we have a whole distribution of stars which end up being a SN, it is a complicated business to accurately estimate the DSNB spectra after accounting for the collective effects, which are bound to happen in almost every SN.

In this work we incorporate the observation of different split patterns in the spectra for the calculation of DSNB and do not take the relative (anti)neutrino fluxes to have fixed values. The main focus of this work is to check the effect of a distribution of supernovae with initial flux on the measurement of the neutrino mass hierarchy via the observation of the DSNB signal. Since the distribution of the initial fluxes over all past SNe are not available to us, we parametrize this by a log-normal distribution. The log-normal distribution has two parameters which define the mean and width of the distribution. Since they are also unknown, we choose various plausible values for them. We calculate the DSNB event rate averaged over these distributions. We study how the hierarchy measurement is affected when one takes the distribution of initial relative fluxes into account and find situations where the hierarchy determination may be possible.

2. The diffuse supernova neutrino background

The differential number flux of DSNB is

$$F'_\nu(E_\nu) = \frac{c}{H_0}\int_0^{z_{max}} R_{SN}(z)F_\nu(E)\frac{dz}{\sqrt{\Omega_m(1+z)^3+\Omega_\Lambda}}, \qquad (1)$$

where $E_\nu = (1+z)^{-1}E$ is the redshifted neutrino energy observed at earth while E is the neutrino energy produced at the source, F_ν is the neutrino flux for each core collapse SN, $R_{SN}(z)$ the cosmic SN rate at redshift z, and the Hubble constant taken as $H_0 = 70h_{70}\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$. For the standard Λ-CDM cosmology, we have matter and dark energy density $\Omega_m = 0.27$ and $\Omega_\Lambda = 0.73$, respectively [71]. As Eq. (1) suggests the DSNB flux at earth depends on two factors: (i) the cosmic SN rate and (ii) the initial SN neutrino spectrum from each SN.

The cosmic SN rate is related to the star formation rate $R_{SF}(z)$, through a suitable choice of Initial Mass Function (IMF) as $R_{SN}(z) = 0.0132 \times R_{SF}(z)M_\odot^{-1}$ [72,73]. The IMF takes into account that only stars with masses larger than $8M_\odot$ result in supernova explosion. For the cosmic star formation rate per co-moving volume we take

$$R_{SF}(z) = 0.32\ f_{SN}h_{70}\frac{e^{3.4z}}{e^{3.8z}+45}\frac{\sqrt{\Omega_m(1+z)^3+\Omega_\Lambda}}{(1+z)^{3/2}}, \qquad (2)$$

where f_{SN} is normalization of the order of unity and $R_{SF}(z)$ is in units of $M_\odot\ \mathrm{yr^{-1}\,Mpc^{-3}}$ [54,74]. The initial SN neutrino spectrum emitted from the neutrinosphere is parametrized in the form [75]

$$F^0_\nu(E) = \left(\frac{L^0_\nu}{\bar{E}}\right)\times\left(\frac{(1+\alpha)^{1+\alpha}}{\Gamma(1+\alpha)\bar{E}}\left(\frac{E}{\bar{E}}\right)^{\alpha}e^{-(1+\alpha)E/\bar{E}}\right) = \phi^0_\nu \times \psi(E), \qquad (3)$$

where ϕ^0_ν is the total initial flux estimated for the initial luminosity L^0_ν and average energy ($\bar{E}$). The spectral shape also depends on the energy distribution $\psi(E)$, which is parametrized by the pinching parameter α. In this study we use $\bar{E}_{\nu_e} = 12$ MeV, $\bar{E}_{\bar{\nu}_e} = 15$ MeV, $\bar{E}_{\nu_x} = \bar{E}_{\nu_y} = 18$ MeV with $\alpha_{\nu_x} = \alpha_{\bar{\nu}_x} = \alpha_{\nu_y} = \alpha_{\bar{\nu}_y} = 4$ and $\alpha_{\nu_e} = \alpha_{\bar{\nu}_e} = 3$. Here ν_x is a linear combination of ν_μ, ν_τ and ν_y is the combination orthogonal to ν_x; in our case ν_x and ν_y has same flux hence $F_{\nu_x} = F_{\nu_y}$. The average energies of the different flux types will also vary from SN to SN. However for simplicity, in this work we choose to keep the average energies fixed. We assume that 3×10^{53} erg of energy is released in (anti)neutrinos by all SNe.

The emitted spectrum $F_\nu(E)$ is processed by collective flavor oscillation and MSW oscillation effects over the huge drop of matter density inside SN. The collective oscillations are over within a few 100 km from neutrinosphere whereas the MSW oscillation takes place in the region 10^4–10^5 km [76] for the solar and atmospheric mass squared differences. As the collective and MSW oscillations are widely separated in space, they can be considered independent of each other [35]. Thus the flux reaching the MSW resonance region already has the effects of the collective oscillations. This assumption may not hold in SN models [15], where at late times the MSW resonance and the collective effects can be simultaneous as there the matter density falls substantially compared to the early time. In the time integrated DSNB flux it can give rise to some corrections. However we have ignored these effects as in this work we followed matter profile from studies [35] with larger matter density [76,77] finding the two oscillations regimes to be mutually exclusive even at late times.

It has been seen that collective oscillations can give rise to different split patterns of the neutrino spectra depending on the initial relative flux of ν_e and $\bar{\nu}_e$ with respect to flavor ν_x or ν_y, so we define $\phi^r_{\nu_e} = \frac{\phi^0_{\nu_e}}{\phi^0_{\nu_x}}$ and $\phi^r_{\bar{\nu}_e} = \frac{\phi^0_{\bar{\nu}_e}}{\phi^0_{\nu_x}}$ as measures of the relative fluxes [38]. The electron antineutrino flux beyond the collective region can swap to x flavor above some energy (single split) or can swap in some energy interval (double split) or even can remain unchanged (no split) depending on the initial relative flux $\phi^r_{\nu_e}$ and $\phi^r_{\bar{\nu}_e}$ [36–38]. DSNB is affected differently with these different oscillation scenarios. To incorporate the effect of collective oscillations we work in a effective two flavor scenario with single angle approximation.[1]

Recent papers [39,42] have explored the effect of three flavors on the outcome of the split patterns in collective oscillations. The three flavor results differ a bit from the two flavors only for IH and that too in a small region of the initial flux parameter space ($\phi^r_{\nu_e}$,$\phi^r_{\bar{\nu}_e}$), where single split (in 3 flavor) appears instead of the double splits (in 2 flavor). However the observed single split in NH for this region remains unchanged in the 3 flavor treatment [42]. Thus in a small part [37,38] of the parameter space ($\phi^r_{\nu_e}$,$\phi^r_{\bar{\nu}_e}$), where 2 and 3 flavor results differ, both IH and NH have similar

[1] Multi-angle effects can give rise to kinematical decoherence among angular modes and smear the spectral splits [17], however for spherical symmetry the single angle approximation i.e. neutrino–neutrino interactions averaged along a single trajectory comes out to be a fine approximation as the multi angle decoherence in such a case is weak against the collective features [18,36,78].