Study Of EoS Dependence of SNe via Relic Supernova Neutrino Spectrum

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Abstract.

The energy spectrum of relic supernova neutrinos (RSNs) tells us valuable information about neutrinos emitted from the core-collapsed SNe and their cosmological evolution. Recent astronomical observations and theoretical studies of SNe give new insights on stellar evolution, which also influence supernova explosion mechanism. The RSN energy spectrum is an important tool to investigate these findings. We show the results of the RSN spectrum based on a variety of astronomical scenarios, which include different supernova occurrence, the cosmic star formation history, and metallicity dependent initial mass function. They reveal the signature of nuclear EoS dependence, which appears robustly in spite of the different scenarios.

1. Introduction

Recent progress of the numerical simulation provides insight into the SN explosion mechanism. This includes the complicated picture about the criteria for successful explosions in terms of their progenitor mass [1, 2]. We have previously assumed that the successful explosions occur within certain mass range. Many numerical investigations, however, have shown the density profile of progenitor is essential to determine their final outcome, and so-called compactness parameter is proposed to be a key to understand physics behind this situation[3]. We have been studying the relic supernova neutrino spectrum for different types of SNe, and showed that the clear EoS dependence in the spectrum[4, 5]. According to these new finding, it is important to re-investigate the EoS dependence of the RSN spectrum.

Moreover, the RSN spectrum highly depends upon the cosmic star formation rate (SFR). The observational estimation of the SFR relies mostly on the UV light from galaxies. It is, however, pointed out by the recent study that the SFR based on UV underestimates the contribution
from the starburst galaxies, especially at high-z, and a new cosmic SFR is proposed. Therefore it is interesting to see the consequence in RSN spectrum with this SFR.

Star formation rate also depends upon the choice of the initial mass function (IMF), which is usually assumed universal. There is another possibility that IMF varies according to the metallicity. In general the metal works as a coolant, and metal-poor molecular cloud tends to form more massive stellar objects selectively leading to the top-heavy IMF. This could be the case at high-z, and it is worth studying the effect of z-dependent IMF in the RSN spectrum.

In this article we investigate the EoS dependence in the RSN spectrum by applying a variety of scenarios described above and show that the EoS dependence is robust enough to be a useful tool to get insight of the nuclear EoS for the supernova explosion.

2. Detection Rate of RSN

The detection rate of the RSN is given as follows. For each type of SNe, the neutrino number flux per unit energy is written as

\[
\frac{dN_\nu}{dE_\nu} = \frac{c}{H_0} \int_0^{z_{\text{max}}} R_{\text{SN}}(z) \frac{dN_\nu(E'_\nu)}{dE'_\nu} \times \frac{dz}{\sqrt{\Omega_m(1+z)^3 + \Omega_\Lambda}}.
\]

where we adopt \(z_{\text{max}} = 5\) as the redshift at which star formation begins, and \(R_{\text{SN}}\) is the cosmic supernova rate. \(dN_\nu(E'_\nu)/dE'_\nu\) is the neutrino spectrum emitted at the source. \(E'_\nu = (1+z)E_\nu\) is the energy at emission, and \(E_\nu\) is the redshifted energy observed in the detector. We adopt \(H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}\), \(\Omega_m = 0.3\), \(\Omega_\Lambda = 0.7\) [3, 6]. Fermi-Dirac distribution for all neutrino species is assumed and parametrized by the effective neutrino temperature and the total energy of emitted neutrinos as summarized in Table 1. We choose two models of SNe with the different EoS, a soft EoS (LS-EoS [7]) and a stiff EoS (Shen-EoS [8, 9]). The supernova rate \(R_{\text{SN}}\) is given by

\[
R_{\text{SN}}(z) = \Psi_s(z) \times \frac{\int_{M_{\text{SN}}} M \phi_0(M) dM}{\int_{M_{\text{min}}}^{M_{\text{max}}} M \phi_0(M) dM},
\]

where \(\Psi_s(z)\) is the cosmic SFR, and \(\phi_0(M)\) is the initial mass function (IMF). \(M_{\text{SN}}\) is the range of progenitor masses for a type of SN. We assume \(M_{\text{min}} = 0.1 M_\odot\) and \(M_{\text{max}} = 125 M_\odot\). According to these formulae, we can recognize the neutrino flux depends not only upon the cosmic SFR and the IMF, but also upon the mass range of the progenitors for each type of SNe. The event rate at the detector is given by

\[
\frac{dN_{\text{event}}}{dE_{e^+}} = N_{\text{target}} \frac{1}{c} \frac{dN_\nu}{dE_\nu} \sigma(E_\nu) \frac{dE_\nu}{dE_{e^+}},
\]

Table 1. Parameters for the various neutrino sources.

| Detailed | ONeMg | SNe (optically luminous) | fSNe (Shen EoS) | fSNe (LS EoS) |
|----------|-------|--------------------------|-----------------|--------------|
| mass \(M_\odot\) | 8-10  | 10-40(74%) | 10-40(26%), 40-125 | 10-40(26%), 40-125 |
| \(T_{\nu_e}(MeV)\) | 3.0 ± 0.3 | 3.2 ± 0.32 | 7.25 ± 0.73 | 5.58 ± 0.56 |
| \(T_{\nu_x}(MeV)\) | 3.6 ± 0.36 | 4.0 ± 0.50 | 8.25 ± 0.83 | 6.67 ± 0.67 |
| \(T_{\nu_\mu}(MeV)\) | 3.6 ± 0.36 | 6.0 ± 0.60 | 9.27 ± 0.93 | 8.22 ± 0.82 |
| \(E_{\nu_{\text{total}}}(\text{erg})\) | 3.3 \times 10^{52} | 5.0 \times 10^{52} | 13.5 \times 10^{52} | 4.4 \times 10^{52} |
| \(E_{\nu_{e}}^{\text{total}}(\text{erg})\) | 2.7 \times 10^{52} | 5.0 \times 10^{52} | 12.7 \times 10^{52} | 3.7 \times 10^{52} |
| \(E_{\nu_{e}}^{\text{total}}(\text{erg})\) | 1.1 \times 10^{52} | 5.0 \times 10^{52} | 5.3 \times 10^{52} | 1.9 \times 10^{52} |
where $N_{\text{target}}$ is the number of target particles in the detector. $\sigma(E_\nu)$ is the cross section for neutrino interactions within the detector [10]. We assume a water Čerenkov detector, and $\bar{\nu}_e + p \rightarrow e^+ + n$ is considered as the dominant reaction. $E_\nu = E_{e^+} + 1.3$ MeV is used.

As noticed above, the RSN detection rate depends upon SFR, IMF, and $M_{\text{SN}}$. In this work, we adopt a cosmic SFR parametrized by Madau & Dickinson[11], and it is given by

$$\Psi_s(z) = 0.015 \frac{(1 + z)^{2.7}}{1 + [(1 + z)/2.9]^{2.7}} \text{M}_\odot \text{year}^{-1} \text{Mpc}^{-3}. \quad (4)$$

We use this SFR for the fiducial case, in which Salpeter-A IMF is also adopted and written as

$$\phi_0(M) = M^{-\zeta} = M^{-(1+\Gamma)} \quad (5)$$

with $\zeta = 2.35$ for stars with $M \geq 0.5M_\odot$ and $\zeta = 1.5$ ($\Gamma = 0.5$) for stars with $0.1 < M < 0.5M_\odot$[12]. Since each type of SNe emits neutrinos differently, it is crucial to determine the mass range of progenitor for a type of SNe. Most studies of the RSN have been assuming some definitive mass ranges within which a certain type of SNe occurs. Recent numerical simulations, however, show more complicated pictures about the relationship between the progenitors and SN explosions. Here for the fiducial investigation, we adopt a case such that the fraction of fSN, $f_{\text{fSN}} = 0.26$ for the progenitors in the mass range of $10 - 40M_\odot$ and $f_{\text{fSN}} = 1.00$ for $M > 40M_\odot$ based on the study by Pejcha & Thompson[1] (see Table 1).

### 3. Results with a variety of the astronomical scenarios

Figure 1 shows the detector event rate of the fiducial case by assuming 10 years run of the Hyper-Kamiokande detector. No neutrino oscillation is considered. The uncertainty bands are based upon the observed cosmic SFR. Rectangular regions represent the peak of the spectrum and the locations where the neutrino signals start overwhelming the atmospheric neutrino noise. As noticed from the figure, the EoS dependence is clearly seen in the high energy tail of the spectrum as the well-separated rectangles. The locations of these rectangular symbols are used in order to characterize the EoS dependence for other cases described below.

![Figure 1. Predicted $e^+$ energy spectra and uncertainties in the total SRN detections for the fiducial case. The shaded energy range below 10 MeV indicates the region where the background noise due to reactor $\bar{\nu}_e$ may dominate. The shaded energy range that intersects the spectrum at $30$ to $46$ MeV indicates the region where the background may be dominated by noise from atmospheric neutrinos. The figure includes the schematic representation for the the progenitor-SNe relationship.](image_url)
on SFR is, therefore, necessary when we apply the different IMF. In the followings we consider four different cases. All results are included in figure 2 with only rectangular symbols at both the peaks and tails. The fiducial case is labeled by “PT”.

First we investigate the scenario which adopts the different progenitor-SNe relationship which is suggested by so-called the red supergiant problem. In this case, we consider $10 - 18M_\odot$ progenitor stars to become CCSNe, and progenitors in $18 - 125M_\odot$ are taken to be as fSNe. They are labeled by “RSG” in the figure.

As the second case, we consider two phase star formation history. Recently N-body cosmological simulation identifies starburst and quiescent star formation phases, and it reveals that the starburst is dominant phase at high-z while the quiescent one becomes dominant at low-z[13]. Moreover the study shows that top-heavy IMF ($\zeta = 2$ ( or $\Gamma = 1$)) is required in order to recover the SFR by Madau & Dickinson. This result is physically reasonable. The environment of star formation at high-z could be metal poor and lack of coolant for the molecular clouds to be filamented into small scale. This might lead to the top-heavy IMF at high-z. The result of this cosmologically motivated scenario is labeled by “PT, Lacey-SB-Q” in figure 2.

Next we employ another cosmic SFR, which has higher star formation rate comparing with the SFR by Madau & Dickinson especially at high-z. As mentioned earlier, the RSN spectrum is affected by the SFR very much, and we expect to see the difference in the spectrum. This SFR is derived by newly interpreted data based on the idea that the UV luminosity from the starburst galaxies could underestimate the SFR[14]. The analysis of this work also identifies the starburst and quiescent phases. Thus we apply the same IMF used in the second case for each star formation phase. The results are denoted by “PT, IMF-Lacey, RR-SB-Q” in figure 2.

As the last case, we adopt a varying IMF, which is metallicity dependent. Recent observational study of nearby galaxies shows the clear metallicity dependence in the IMF[15], and it is formulated by

$$\Gamma = 2.2(\pm0.1) + 3.1(\pm0.5) \times [M/H].$$

(6)

We apply this varying IMF, instead of Salpeter-A IMF, to the fiducial case. We also adopt the galaxy mass function[16] and the mass-metallicity relation[17] so that we have a z-dependent IMF. Figure 2 includes the results labeled by “PT, varying IMF”.

According to all cases in figure 2, we can see the robustness of EoS dependence in the RSN spectrum. The locations of rectangles in the high energy tail for cases of LS and Shen EoS are well-separated each other. Thus, the RSN spectrum could become a good tool to investigate the nuclear EoS in the supernova explosion.

In addition to the cases without the neutrino oscillation (see figure 2), we also consider the RSN spectrum with two possible cases of the neutrino oscillation[4, 5]. The neutrino oscillation of a normal or inverted mass hierarchy associated with complete non-adiabatic mixing is given by

$$\phi_{\nu_e} = 0.7 \times \phi^0_{\nu_0} + 0.3 \times \phi^0_{\nu_x},$$

(7)

and the RSN spectra of this case are shown in figure 3. Figure 4 shows the results with another cases of the neutrino oscillation, in which an inverted mass hierarchy associated with complete adiabatic mixing through the MSW high-density resonance is considered. It is given by

$$\phi_{\nu_e} = \phi^0_{\nu_x},$$

(8)

where the effect from shock wave propagation is ignored. Figure 2-4 clearly show the EoS dependence in the RSN spectrum in the high energy tail, though the robustness for the case of inverted mass hierarchy becomes slightly weaker since the separation of the locations of rectangles for LS and Shen EoS is smaller than those of two other cases.
Figure 2. Predicted $e^+$ energy spectra for all cases without neutrino oscillation. The figure shows only rectangles for the characteristic locations of both peaks and tails for each cases. As the eye-guide, the lines are included only for the fiducial cases with the best fitted SFR.

Figure 3. Same as figure 2 but with the neutrino oscillation by equation 7.

Figure 4. Same as figure 2 but with the neutrino oscillation by equation 8. The dashed lines, the fiducial cases in figure 3 are also included for comparison.

4. Conclusion
We investigate the RSN spectrum with a variety of astronomical scenarios. We employ the different progenitor-SNe relationship, the cosmic SFR, the star formation phase of starburst and quiescent, and the metallicity-dependent IMF. We found that the appearance of EoS dependence in the spectrum is clearly seen in the high energy tail. We also consider the effects of the neutrino oscillations. Although we have slightly weaker EoS dependence for the case of the inverted mass hierarchy, the EoS dependence still robust to be a good tool in order to get valuable knowledge about the nuclear EoS in the supernova explosion.

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