The 12th Supernova Neutrino Workshop

Neutrino Mean Energy Estimates from Müller's 1D CCSN model and DSNB Spectrum Predictions Based on Population Synthesis

Tokyo University of Science, **Shugo Murakami**, Hideyuki Suzuki

Abstract

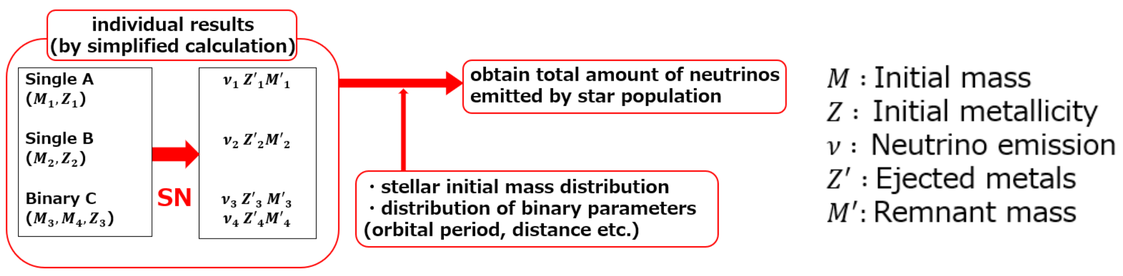
In this study, We improve one-dimensional supernova models to evaluate the mean neutrino energy for various progenitor masses and construct fitting formulae as functions of the pre-supernova CO core mass and radius. Incorporating these results into a population synthesis code, we calculate the DSNB energy spectrum and compare with the previous study.

1.Introduction

■ DSNB Calculation Using Population Synthesis

DSNB : Diffuse Supernova Neutrino Background
Neutrinos from all past supernovae since the birth of the universe, accumulated throughout the universe.

To estimate DSNB , We use stellar population Synthesis. Below is an image diagram.

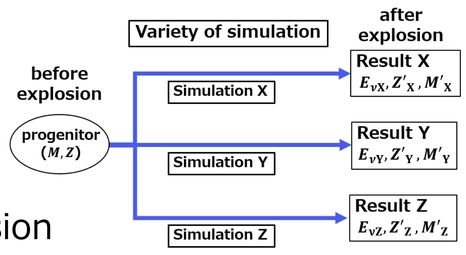


M : Initial mass
Z : Initial metallicity
ν : Neutrino emission
Z' : Ejected metals
M' : Remnant mass

Simplified calculation :
SSE and BSE codes of Hurley et al. (2000, 2002) with improvements based on Müller's 1D CCSN model (Müller et al. (2016))

■ Issues

①Various models of supernova explosions exist, and their predicted outcomes differ from model to model. In the simplified calculation currently used, it is difficult to incorporate results from various supernova explosion models.



②Detailed stellar evolution calculations and multi-dimensional hydrodynamical supernova simulations are too expensive for DSNB calculations.

Using **Müller's 1D CCSN model**

■ Objectives

- To calculate the mean neutrino energy $\langle \epsilon_\nu \rangle$ by improving Müller's 1D CCSN model.
- To fit $\langle \epsilon_\nu \rangle$ as a function of $M_{\rm CO}$ and $R_{\rm CO}$, and to compute the DSNB spectrum for comparison with previous studies.

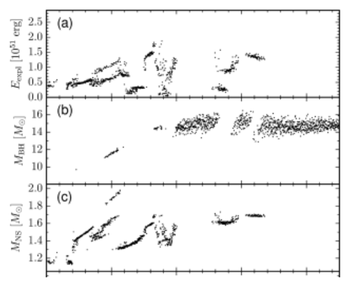
2.Method

■ Müller's 1D CCSN model

A method to estimate the results of CCSN simulations using progenitor structure data without using hydrodynamical calculations.

→ computational cost : $1\ \mathrm{min}/1000$ stars

- Evolves the explosion through 3 phases.
- Reproduces results of multidimensional supernova simulations by incorporating turbulence and other multidimensional effects via 5 parameters.



by Müller et al. (2016)

■ How to estimate $\langle \epsilon_\nu \rangle$

Parameter	Explanation	Standard value	Typical range
$\alpha_{\rm out}$	Volume fraction of outflows	0.5	0.3...0.7
$\alpha_{\rm turb}$	Shock expansion due to turbulent stresses	1.18	1...1.4
$\beta_{\rm expl}$	Shock compression ratio during explosion phase	4	3...7
ζ	Efficiency factor for conversion of accretion energy into ν luminosity	0.8	0.5...1
$\tau_{1.5}$	Cooling time-scale for $1.5\,M_\odot$ neutron star	1.2 s	0.6 s...3 s

by Müller et al. (2016)

$$E_\nu = \int L_\nu(t)\ dt$$

$$N_\nu = \int n_\nu(t)\ dt = \int \frac{L_\nu(t)}{XM(t)}\ dt \qquad \because \langle \epsilon_\nu \rangle(t) \propto M(t)$$

Müller and Janka et al.(2014)

$$\therefore \langle \epsilon_\nu \rangle = \frac{E_\nu}{N_\nu} = \frac{\int L_\nu(t)\ dt}{\int \frac{L_\nu(t)}{XM(t)}\ dt}$$

E_ν : neutrino emission
n_ν : neutrino number emission rate
N_ν : total emitted neutrino number
X : proportionality constant

3.Result and discussion

■ result of $\langle \epsilon_\nu \rangle$

Fig 1 shows $\langle \epsilon_\nu \rangle$ estimated using the improved Müller's 1D CCSN model. In this work, only progenitors that form neutron stars are included in the plot.

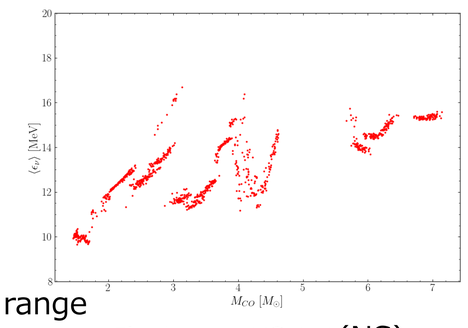


Fig 1 : $M_{\rm co}$ VS $\langle \epsilon_\nu \rangle$(NS)

This graph shape suggests that fitting the entire range with a single function leads to reduced accuracy.

■ Fitting Formulae

The data are grouped into bins with a width of 1.0×10^9 cm in $R_{\rm CO}$

Fitting with

$$\langle \epsilon_\nu \rangle = a\left(\frac{M_{\rm co}}{M_\odot}\right) + b$$

Accuracy varies among bins, which remains a limitation, but implementation was prioritized.
Now, we are exploring more physically motivated fitting methods, such as fitting based on compactness

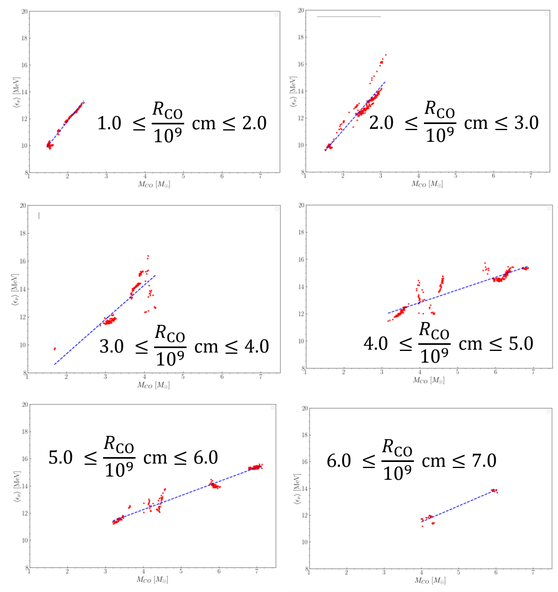


Fig 2 : Fitted graphs

■ Comparison with Previous Study

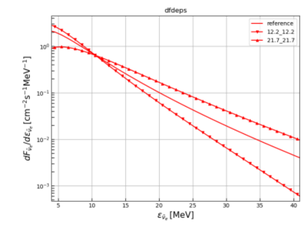


Fig 3 : Effect of $\langle \epsilon_\nu \rangle$ on the DSNB spectrum (by Sugiura (2026))

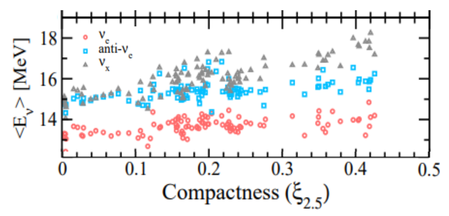


Fig 4 :$\langle \epsilon_\nu \rangle$ by 2D simulation (by Horiuchi et al.(2017))

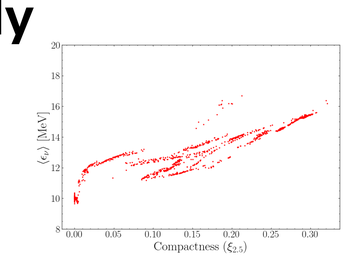


Fig 5 : $\xi_{2.5}$ VS $\langle \epsilon_\nu \rangle$

$$\frac{dF_\nu(\varepsilon_\nu, t_0)}{d\varepsilon_\nu} = c\int_0^{t_0} R_{\rm cc}(z) \int_{M_{\rm min}}^{M_{\rm max}} N(M, Z(z)) \frac{dN_\nu(\varepsilon'_\nu, M, Z(z))}{d\varepsilon'_\nu} \frac{d\varepsilon'_\nu}{d\varepsilon_\nu} dM dt$$

DSNB spectrum strongly depends on the $\langle \epsilon_\nu \rangle$(Fig3), which also varies among models(Fig4,5). Therefore, we compare my result with previous studies.

Fig 6 shows DSNB energy spectrum of our estimate and previous study.

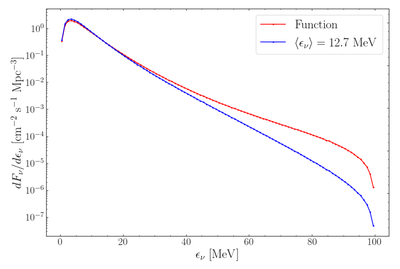


Fig 6 : DSNB spectrum

Compared with the previous study, the spectrum is reduced at low energies (below 13 MeV) and enhanced at higher energies.

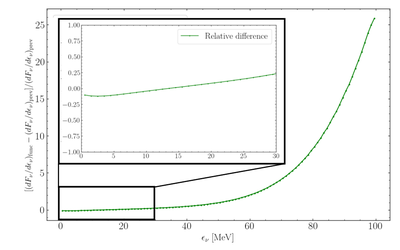


Fig 7 : Relative difference

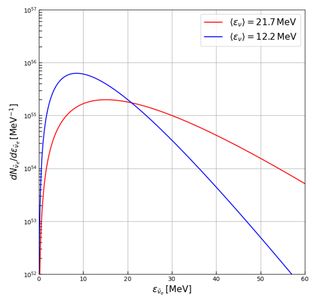


Fig 8 : $30M_\odot$ neutrino energy spectrum (by Sugiura (2026))

This result is likely due to the fitting results, which produce many stars with $\langle \epsilon_\nu \rangle$ exceeding 12.7 MeV, leading to harder spectra that extend to higher energies for individual progenitors.

$$\frac{dN_\nu}{d\varepsilon_\nu} = \frac{1}{E_\nu}\left(\frac{\varepsilon_\nu}{\langle \varepsilon_\nu \rangle}\right)^{\alpha_\nu} \exp\left(-\frac{(\alpha_\nu + 1)\varepsilon_\nu}{\langle \varepsilon_\nu \rangle}\right)$$

【Previous study】
$\langle \epsilon_\nu \rangle$(NS) : 12.7 MeV Fixed
$\langle \epsilon_\nu \rangle$(BH) : 21.7 MeV Fixed

【My estimate】
$\langle \epsilon_\nu \rangle$(NS) : Function
$\langle \epsilon_\nu \rangle$(BH) : 21.7 MeV Fixed

4.Conclusion and Future plans

■ Conclusion

- Improved the Müller's 1D CCSN model to enable the calculation of $\langle \epsilon_\nu \rangle$ for NS formation.
- Calculated the DSNB spectrum using the derived $\langle \epsilon_\nu \rangle$ and compared it with previous studies.

■ Future plan

- Calculate $\langle \epsilon_\nu \rangle$ for black hole formation cases, perform fitting, and calculate the DSNB spectrum for comparison.
- Calculate $\langle \epsilon_\nu \rangle$ by varying five parameters, construct a parameter-dependent functional form of the average energy, and perform population synthesis calculations to compare DSNB spectrum under various parameter sets.