Effects of nucleon recoils for neutrino spectra in core-collapse supernovae

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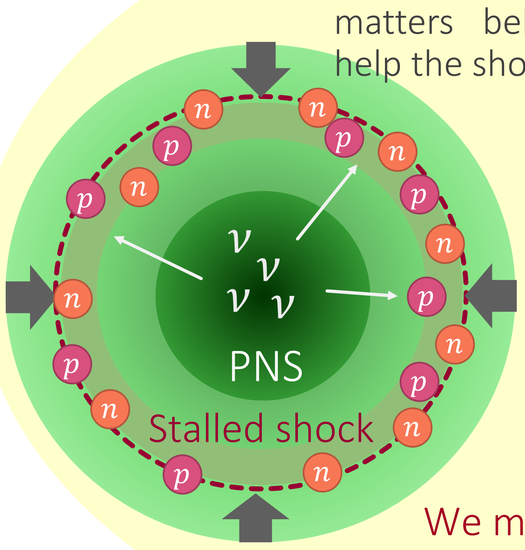
Abstract

The energy exchange by nucleon recoils in neutrino-nucleon scattering is one of the important factors for core-collapse supernovae. It is known that nucleon recoils change neutrino spectra around neutrino sphere due to the numerous number of scatterings. A discretized method is adopted to solving neutrino transport in almost dynamical simulations. Due to their huge computational costs, however, we can not take enough number of energy bins to resolve the small energy exchange and need a special technique. We hence develop a new code for neutrino transport with Monte Carlo (MC) method and investigate the effects of nucleon recoils for neutrino spectra by steady-state calculations on a static background. Finally, We suggest a new way to take nucleon recoils into the discretized method using number and energy conservations in energy bins.

Introduction

▸ Importance of neutrinos in CCSNe

Neutrinos emitted from PNS give energy to matters behind a stalled shock wave and help the shock revival.



✓ electron neutrinos

⇒ Heating behind a shock wave

$$\nu_e + n \rightarrow p + e^-$$

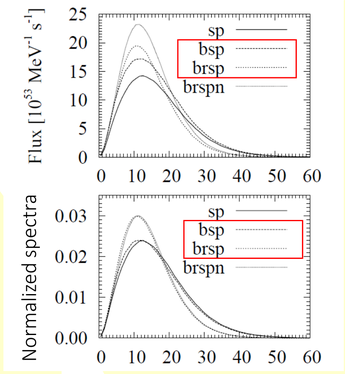
$$\bar{\nu}_e + p \rightarrow n + e^+$$

✓ heavy-lepton neutrinos

⇒ Efficiency of PNS cooling

Neutrino oscillation

We must predict neutrino spectra in all flavor!!



Keil et al. 2003

▸ Importance of nucleon scattering

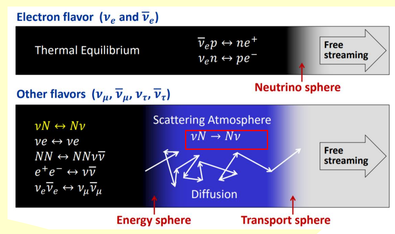
✓ only a few % of initial neutrino energy is exchanged per scattering by nucleon recoils

✓ numerous number of scattering

Neutrino spectra can be changed by nucleon scattering, especially in heavy-lepton flavor

$$\nu + N \rightarrow \nu + N$$

Raffelt 2001, Janka 2017



Purpose of our research

✓ Development of new neutrino transport code with MC method

✓ To investigate the effects of nucleon recoils for neutrino spectra

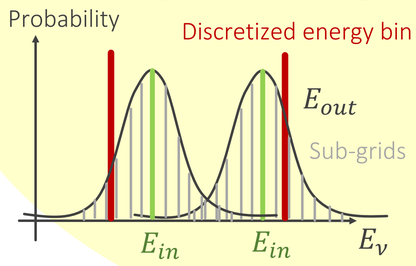
✓ To suggest a new way to incorporate nucleon recoils into the discretized method

▸ Difficulty of nucleon recoils in discretized method

Due to small energy exchange, it is difficult to incorporate nucleon recoils into the discretized solver.

① Estimation of energy flux

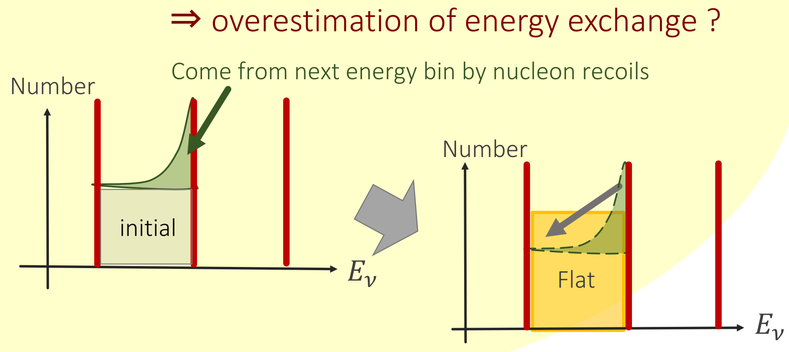
⇒ sub-grid, not-fixed grid



② artificial procedure　ex) flat structure

⇒ overestimation of energy exchange ?

Come from next energy bin by nucleon recoils

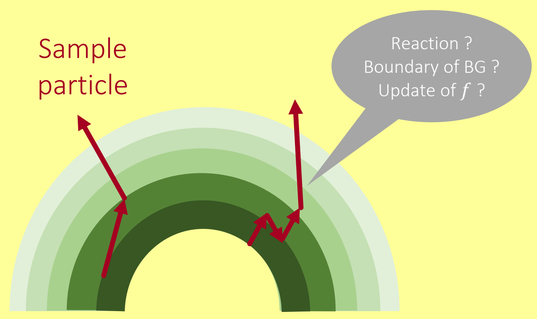


NEW CODE !!

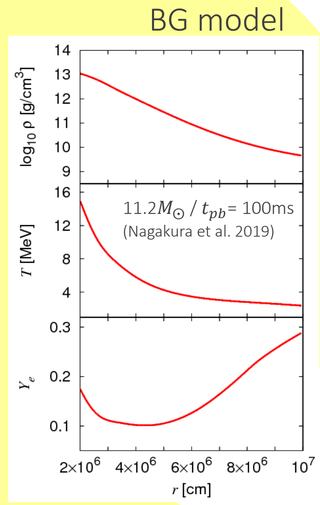
▸ MC transport code

We develop new neutrino transport code on statistical background with MC method.

In MC method, we follow the tracks of "sample particles".



BG model



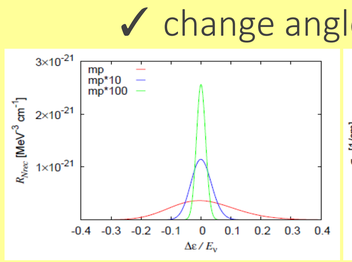
Methods & Results

▸ Iso-energy VS non-iso energy in νN scattering

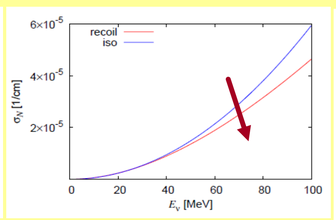
✓ broaden spectra

✓ reduction of reaction rate in high energy

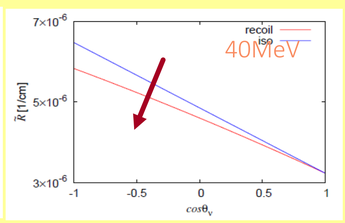
✓ change angle distribution



$m_p \rightarrow \infty$: iso-energy



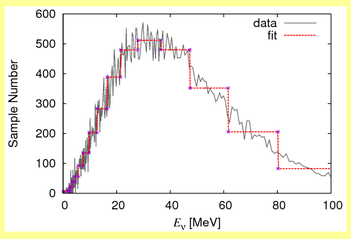
cross section



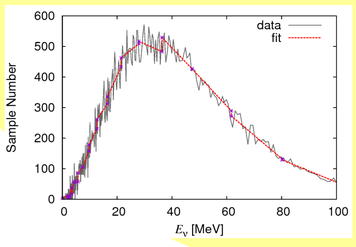
Angular distribution

▸ Suggestion a new way to incorporate nucleon recoils

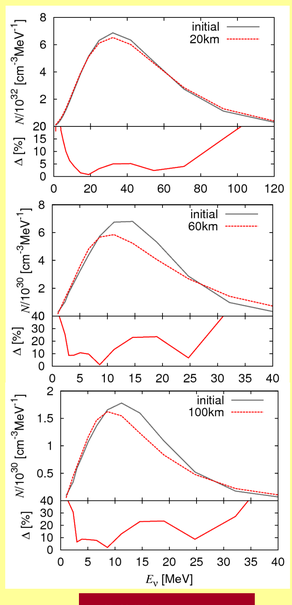
① flat model



② Number & energy conservation (NE model)



①



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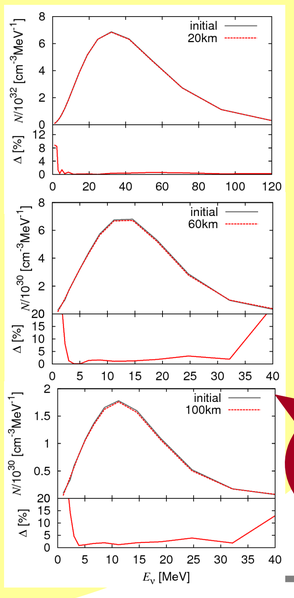
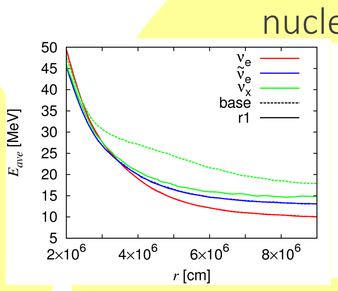


20% errors

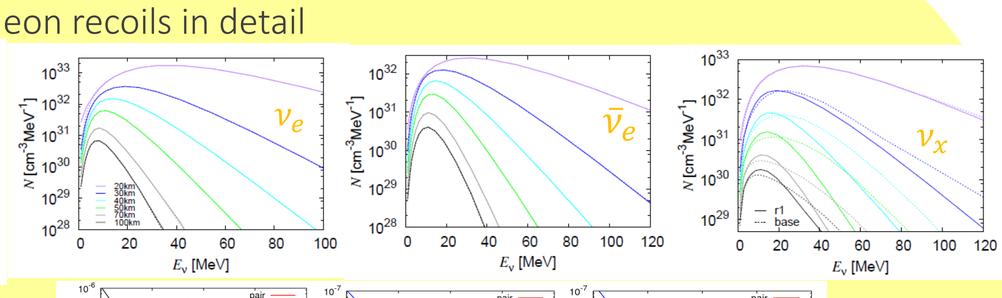
GOOD AGRREMENT!!

▸ Effects of nucleon recoils

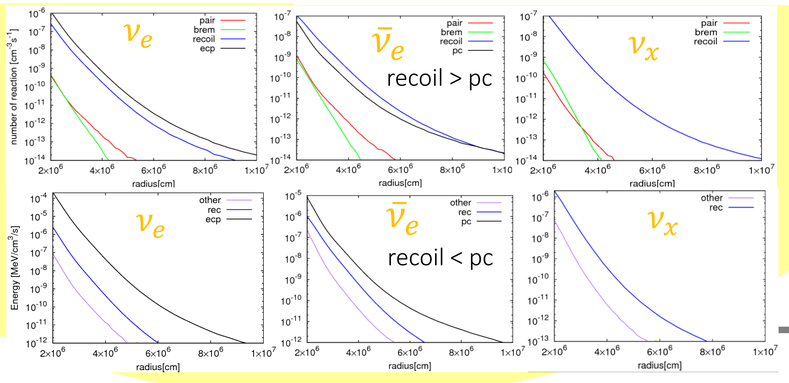
By steady-state calculations, we investigate the effects of nucleon recoils in detail



Radial profile of average energy



Number of reaction



Energy exchange

Summary

We investigate the effects of nucleon recoils in nucleon scatterings for neutrino spectra in detail. We find that the average energy of heavy-lepton neutrinos reduces ～15%. For anti-electron neutrinos, even if the number of nucleon scattering is the largest among neutrino reactions, their spectra are not changed by nucleon recoils due to the small energy exchange. We also suggest a new way to incorporate nucleon recoils into the discretized method. In flat model, spectra deviate from correct ones by ～20% due to the overestimation of energy exchange, whereas in NE model, we can reconstruct spectra within a few % difference.