RIKEN-RESCEU Joint Seminar, March 19th-20th

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

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Historical SN neutrino events

"SN1987A"

- 23th, Feb, 1987
- LMC
- 20 $M_{\odot}$
- ～50kpc

✓11 events @ Kamiokande II

⇒ $L_{\nu} \sim 5 \times 10^{52}$ [ergs]

$E_{\nu} \sim 10 - 15$ [MeV]

✓Neutrinos became a new tool !

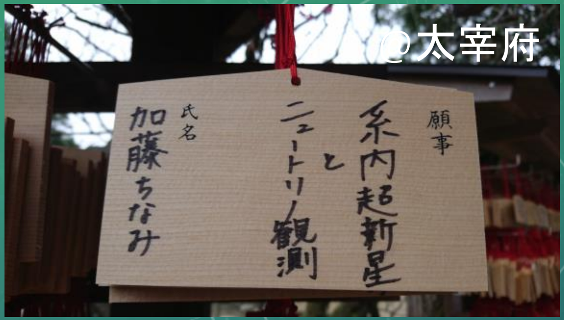
Findings by ν obs.

✓ mechanism
✓ nucleosynthesis
✓ EOS
✓ BH formation
✓ Physics of ν

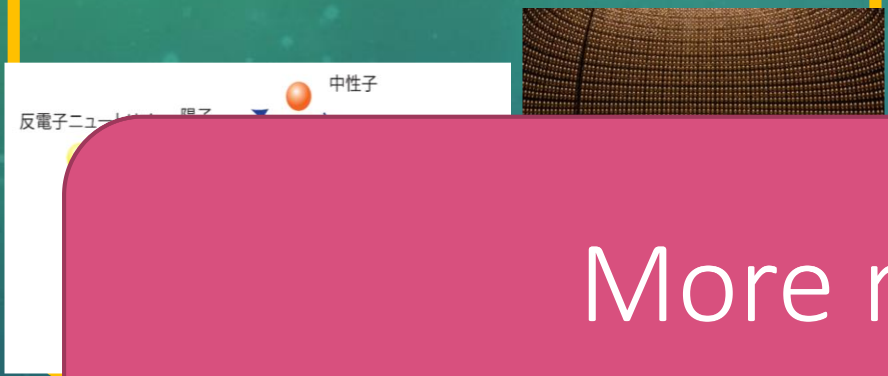
Preparation for next SN

Galactic SN rate : a few / 100-1000 years

⇒ We never miss a next galactic SN !!

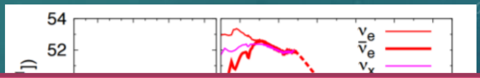


✓ low background technique

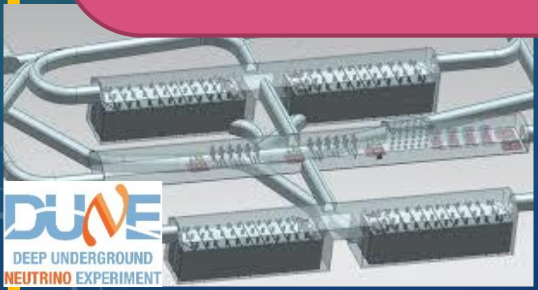


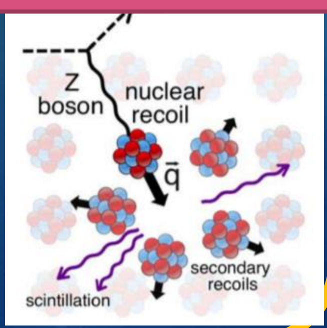
✓ multi-messenger

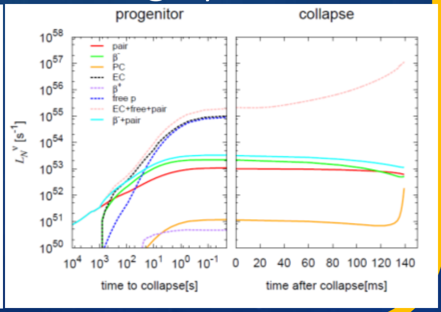
neutrino / GW / EM



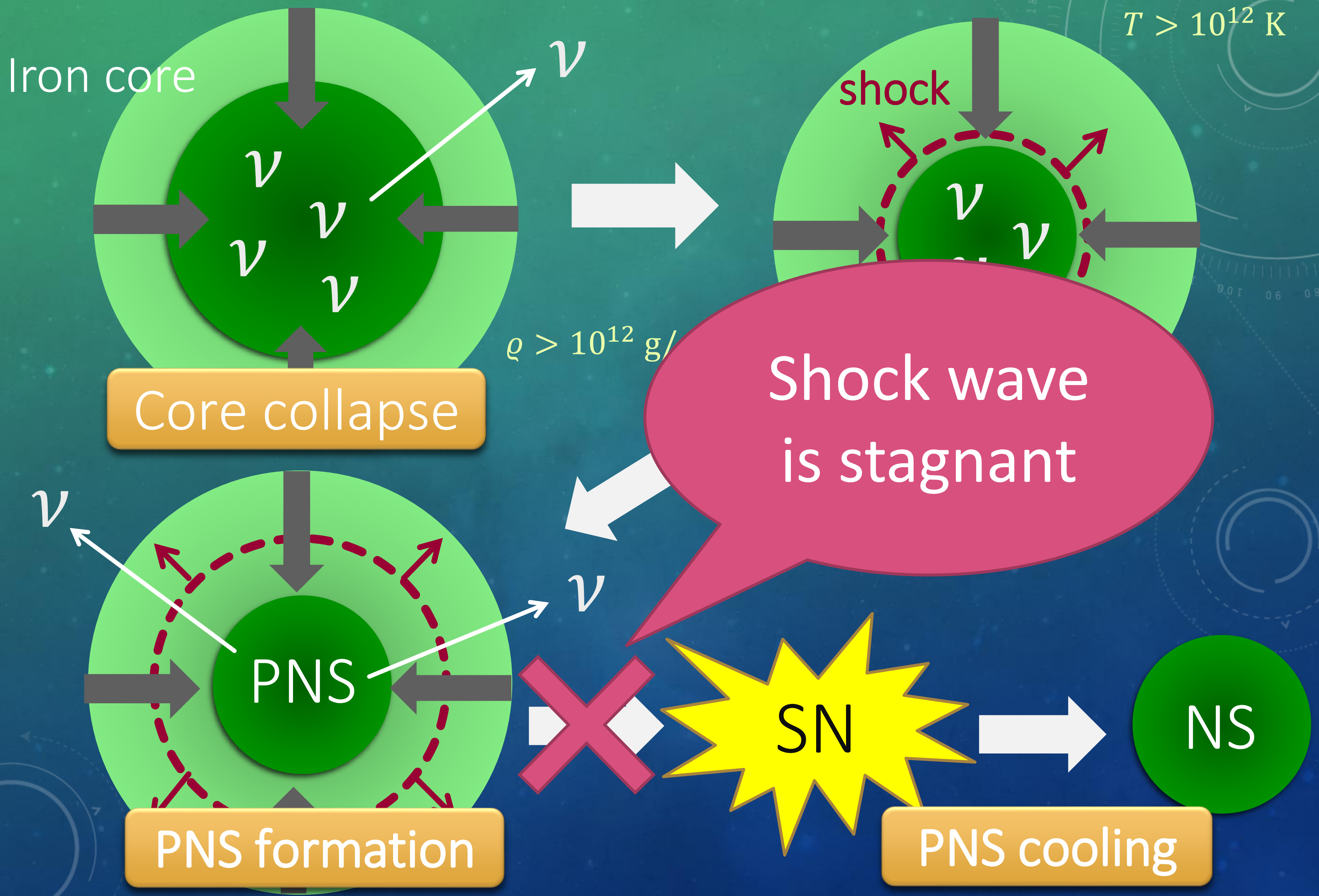
More realistic
theoretical prediction of neutrino







SN mechanism



Importance of neutrino

✓ electron neutrinos

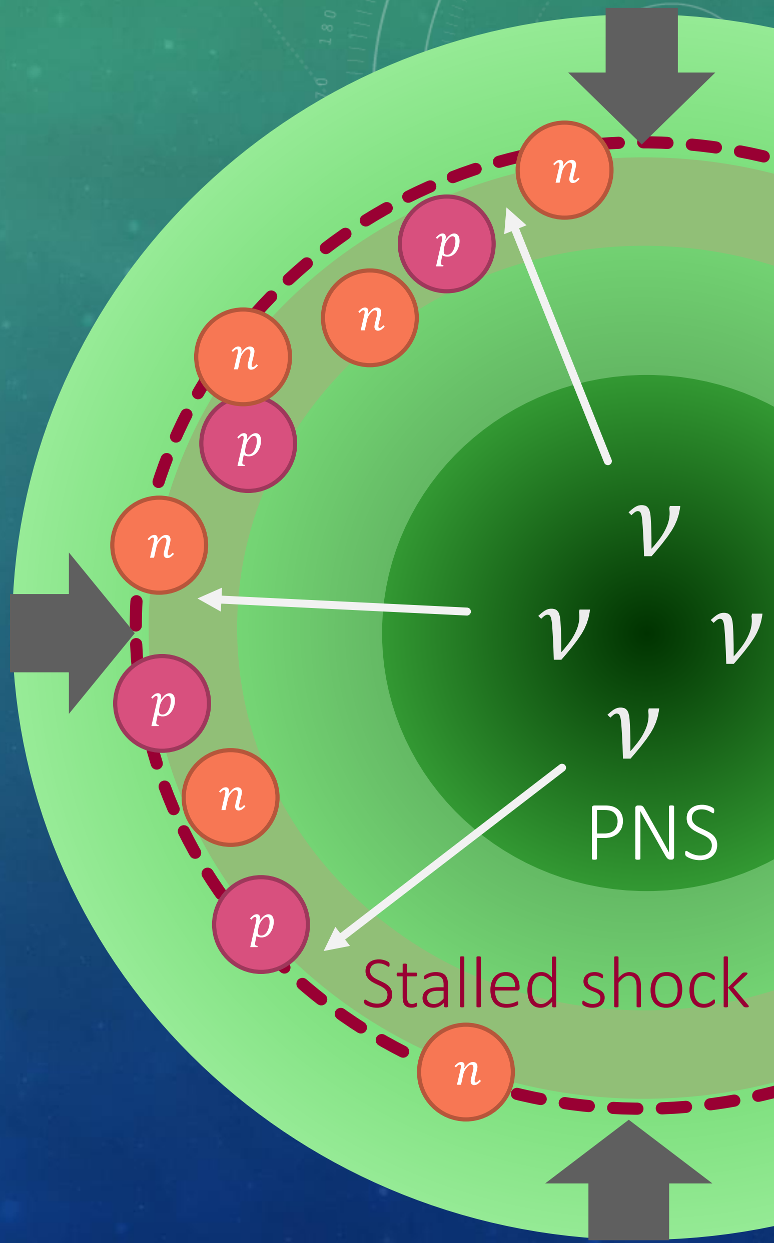
⇒ Heating behind a shock wave

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

✓ heavy-lepton neutrinos

⇒ Efficiency of PNS cooling
neutrino oscillation

We must predict neutrino spectra in all flavor !!



Current problems in SN neutrino

✓ Neutrino reaction ← My talk

Some approximations are used because of CPU cost

Ex.) nucleon recoils / weak magnetism / medium modification etc

✓ Neutrino oscillation

There is possibility that neutrino oscillation occurs inside PNS

⇒ neutrino spectra at shock wave change ?

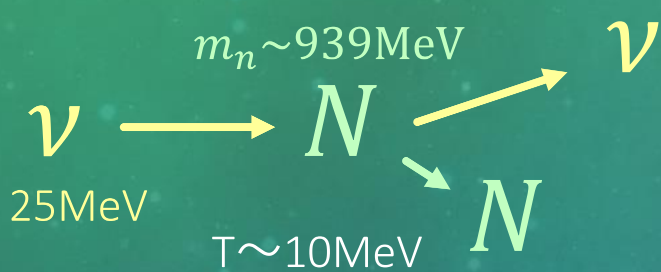
✓ Distinction of heavy-lepton flavor

Heavy-lepton flavors (ν_x) are not distinguished

⇒ Recent study shows the importance of distinction

Ex.) μ creation @ PNS / weak magnetism / oscillation etc

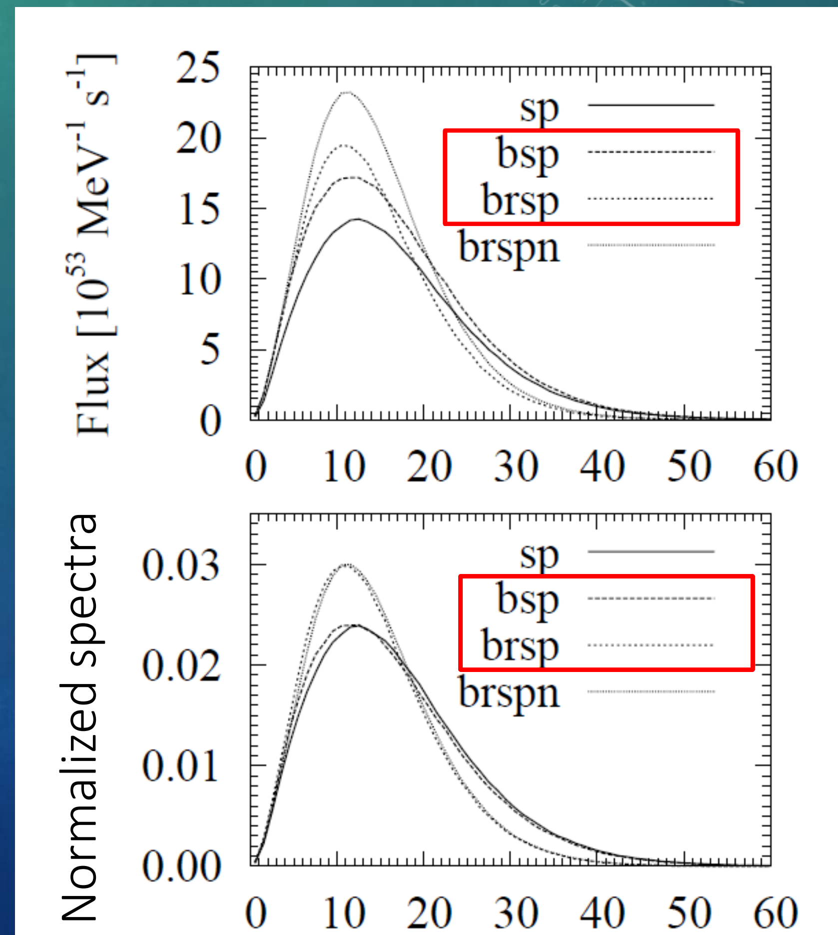
Importance of nucleon scattering

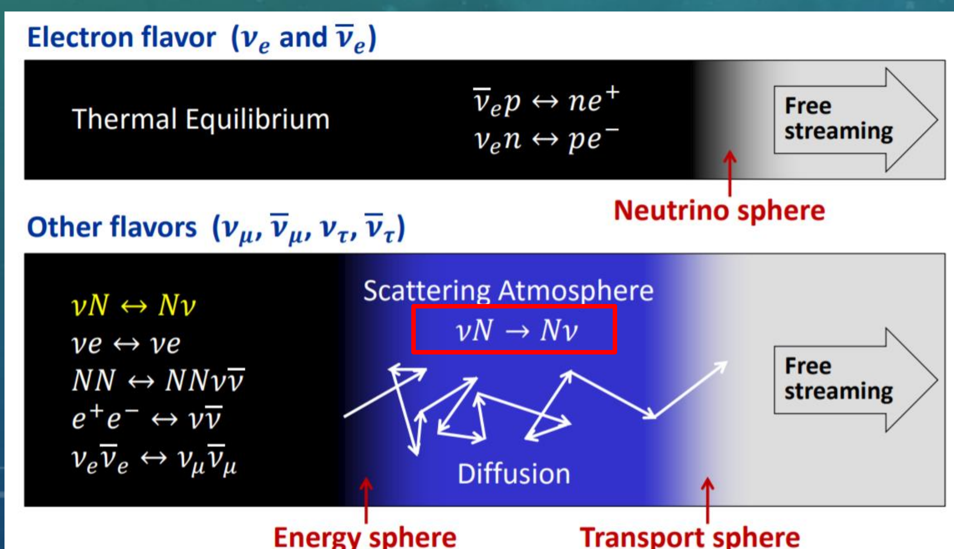


✓Very small energy exchange
✓Number of nucleons is large

Exchange energy : ～2-3 MeV

Keil et al. 2003



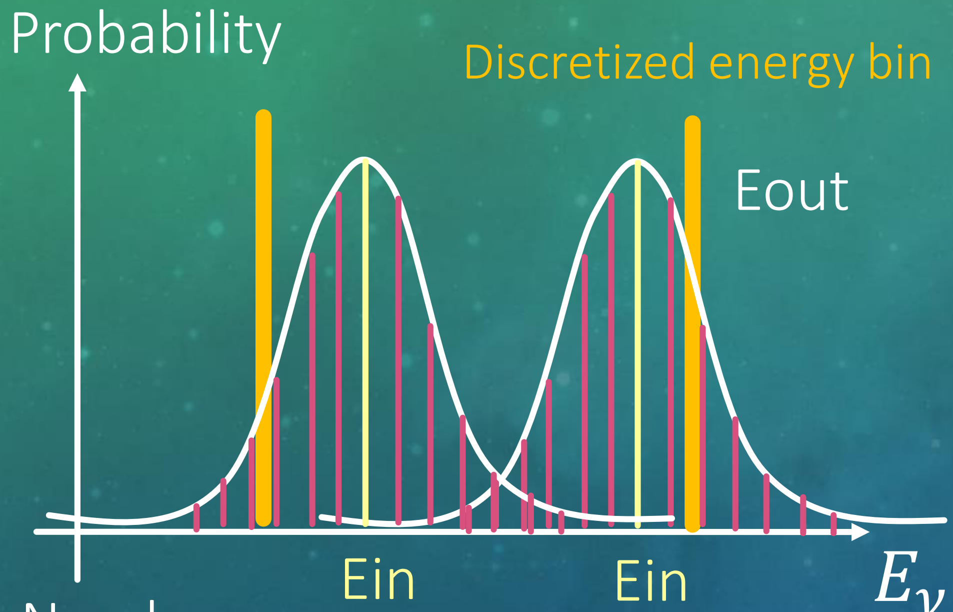


Raffelt 2001, Janka 2017

Difficulty of nucleon recoil

It is very difficult to treat nucleon recoils numerically

Some studies assume iso-energy scattering

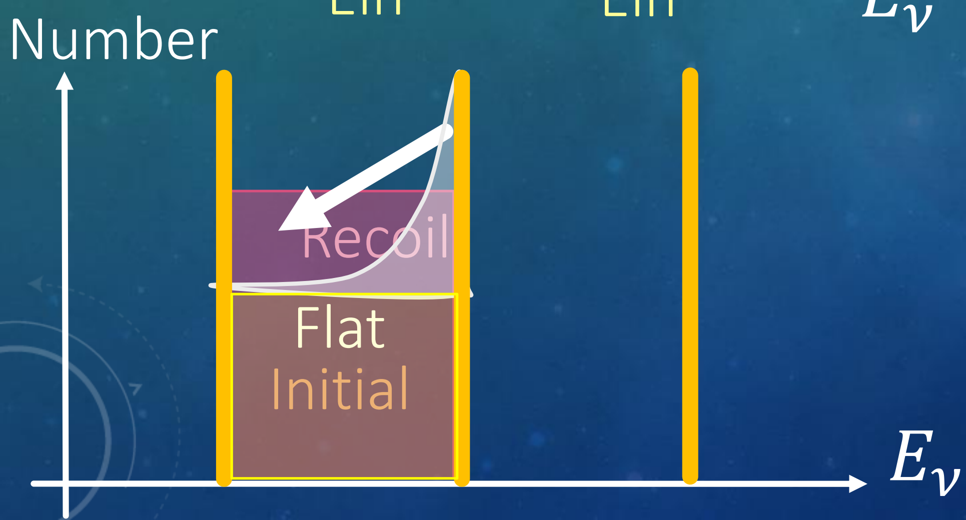


① Estimation of energy flux

⇒ sub-grid

not-fixed grid

(depending on Ein)



② "Flatness" procedure

⇒ overestimation of energy exchange ?

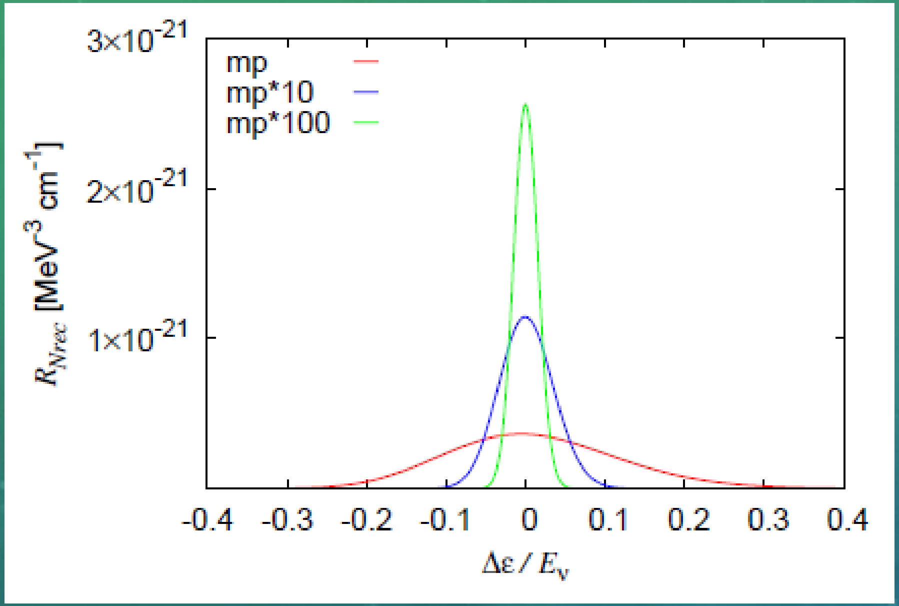
Purpose

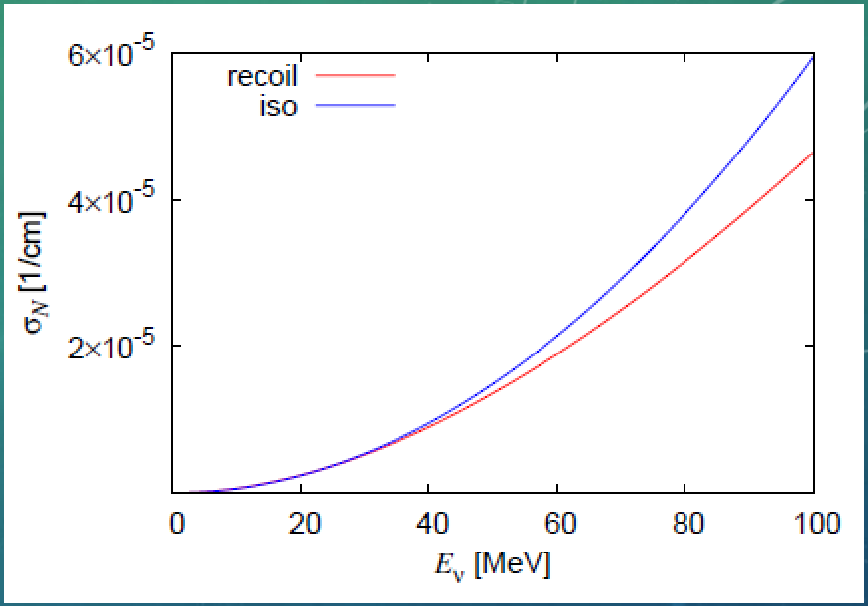
In order to get realistic neutrino spectrum,

We investigate the effects of nucleon recoils for neutrino spectra

✓Which reaction is the most dominant in each flavor ?
✓Nucleon scattering VS Electron scattering
✓How do we take nucleon recoils into numerical simulations ?

Iso-energy scattering & Nucleon recoils

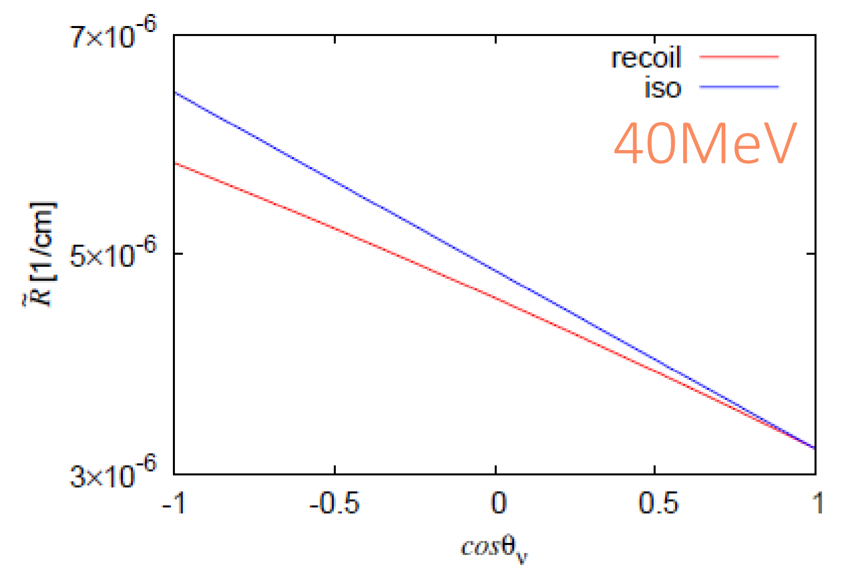




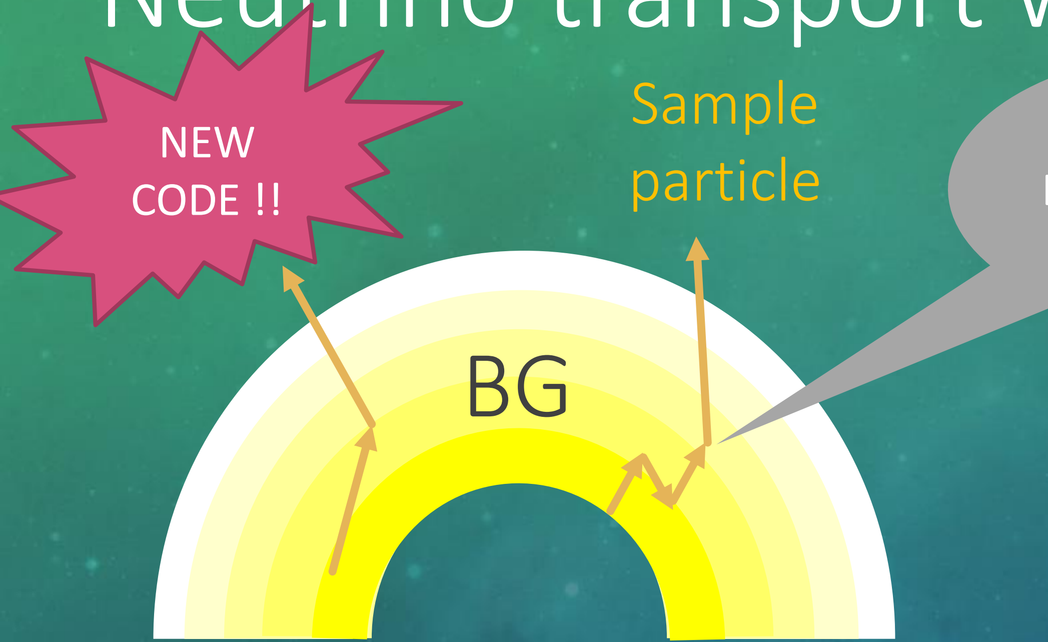
✓If we take a limit $m_N \to \infty$, $\nu - N$ scattering becomes iso-energy (Bruenn 1985)

✓Effects of nucleon recoils

- reduction of opacity
- broadening of spectrum
- change of angle distribution



Neutrino transport with MC method



For neutrinos

Reaction rate includes Fermi blocking $(1-f_\nu)$
⇒update of f_ν

Idea of MC method

- Following tracks of "sample particles" with random numbers
- Taking average of their behavior

Advantage

- Investigation of physical process
- Complex background

✓Our code is consistent with discretized method

✓guarantee the detailed balance

Set up

1D dynamical SN simulation
(Nagakura et al. / full Boltzmann solver)

Steady-state ν transport calculation with MC code

<u>BG model</u>

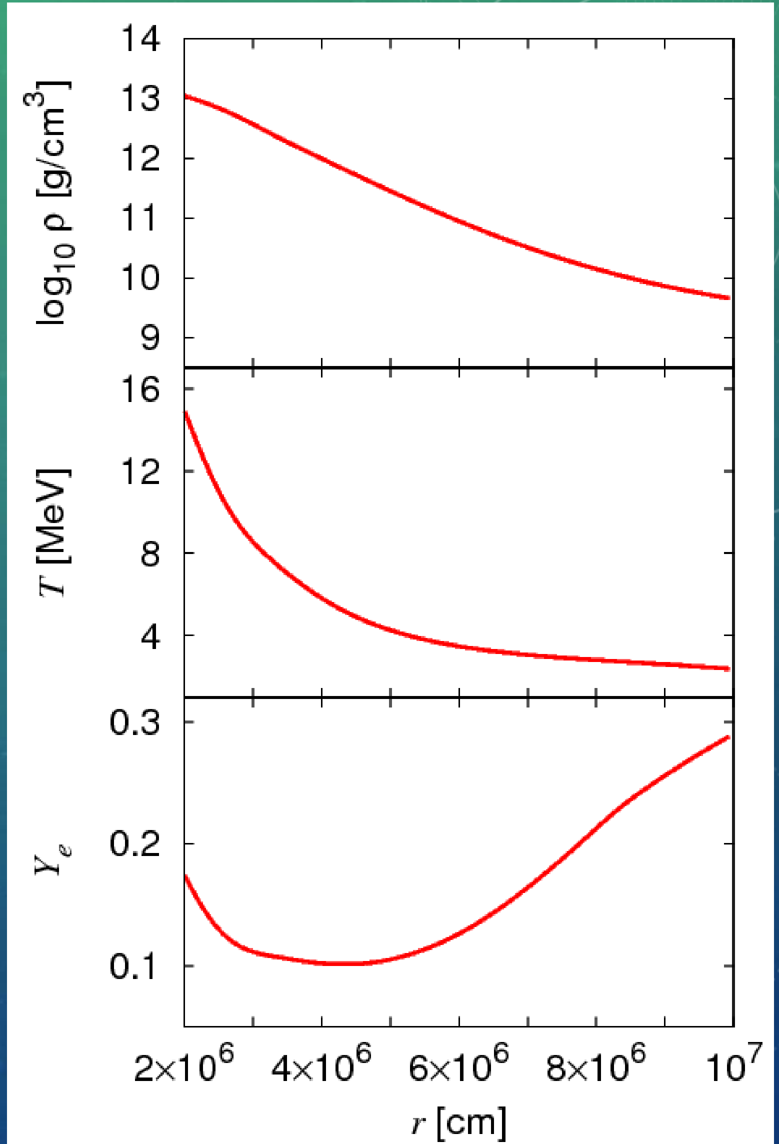
11.2 Msolar without rotation

100ms after post bounce

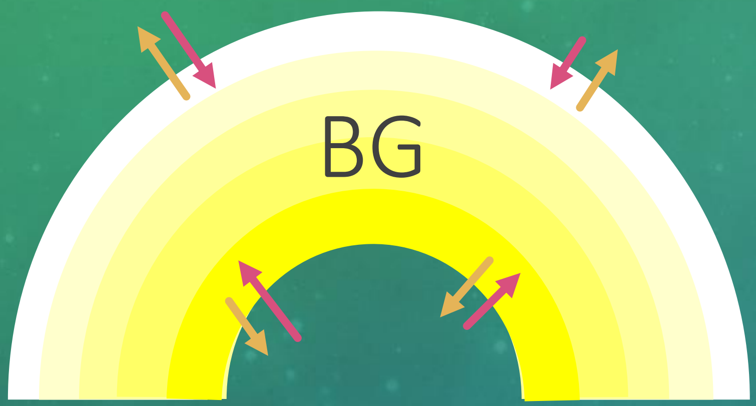
reactions		model
pair	$e^- + e^+ \longrightarrow \nu + \bar{\nu}$	base, r1, e1
brems	$N + N \longrightarrow N + N + \nu + \bar{\nu}$	base, r1, e1
ecp	$p + e^- \longleftrightarrow n + \nu_e$	base, r1, e1
pc	$n + e^+ \longleftrightarrow p + \bar{\nu}_e$	base, r1, e1
Nsc(iso)	$N + \nu \longrightarrow N + \nu$	base
Nsc(rec)		r1, e1
esc	$e^- + \nu \longrightarrow e^- + \nu$	e1

emis・abs

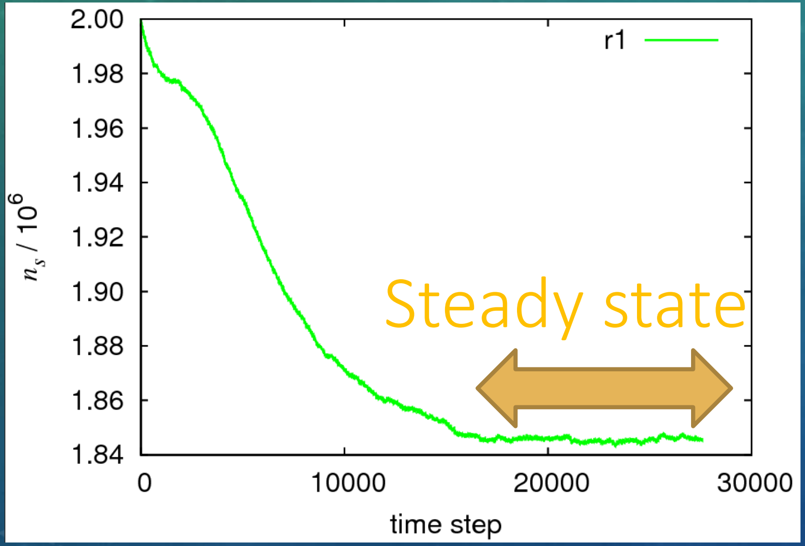
scattering

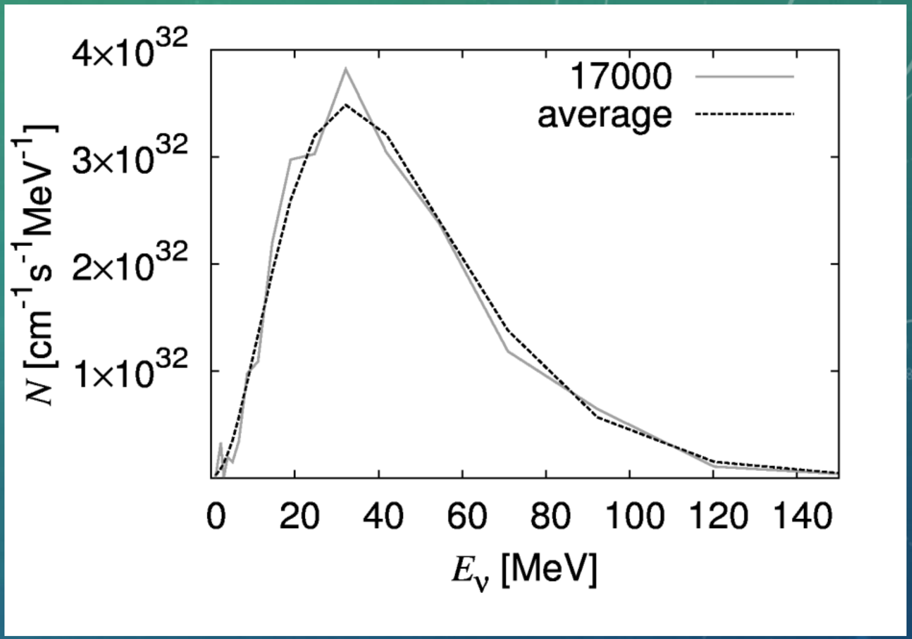


How to construct neutrino spectra



Constant neutrino flux





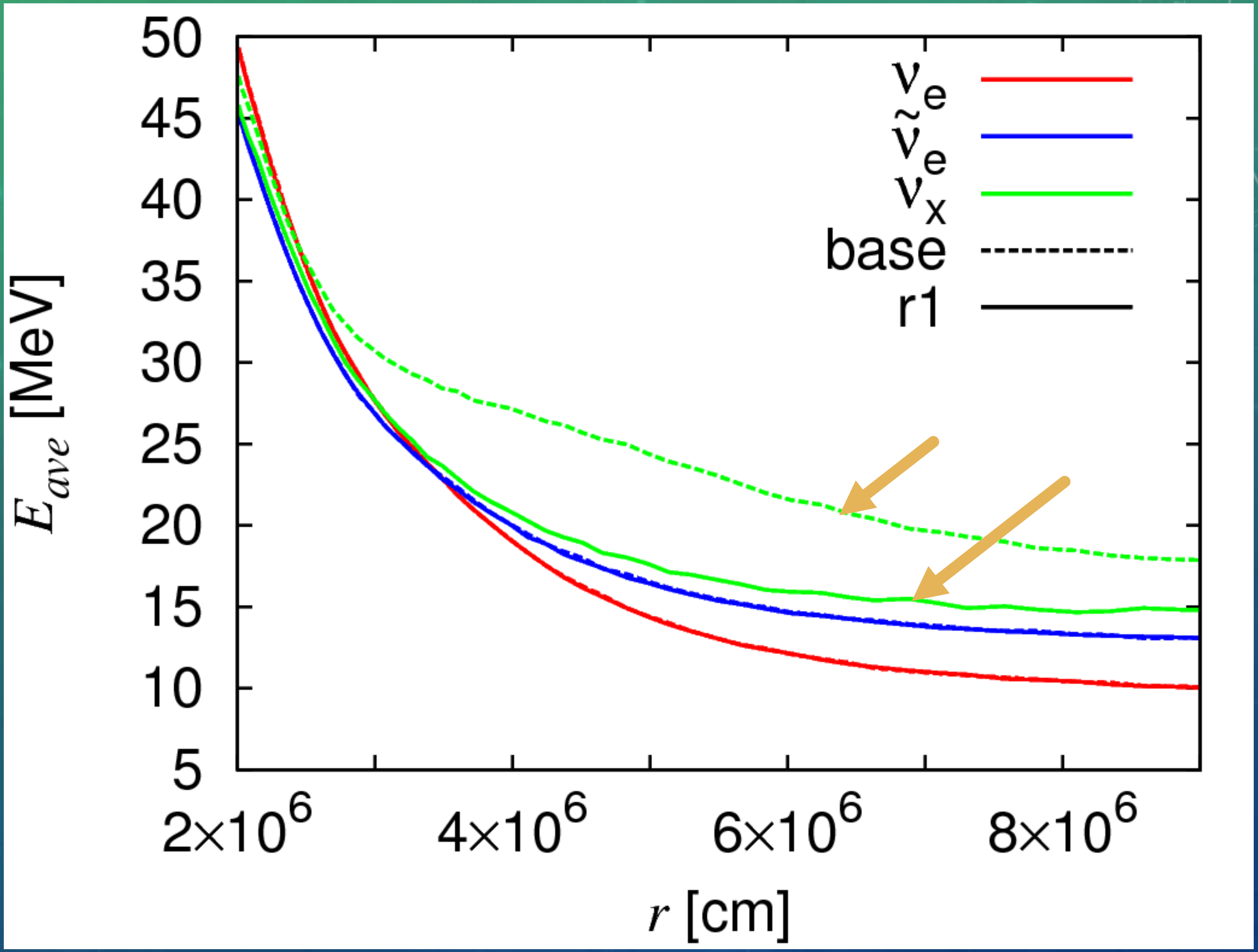
sample ：2×10^6

$\mathrm{d}t = 10^{-7}$

average steps : about 10000 steps

After neutrino becomes steady-state, we take the time average of neutrino distribution function

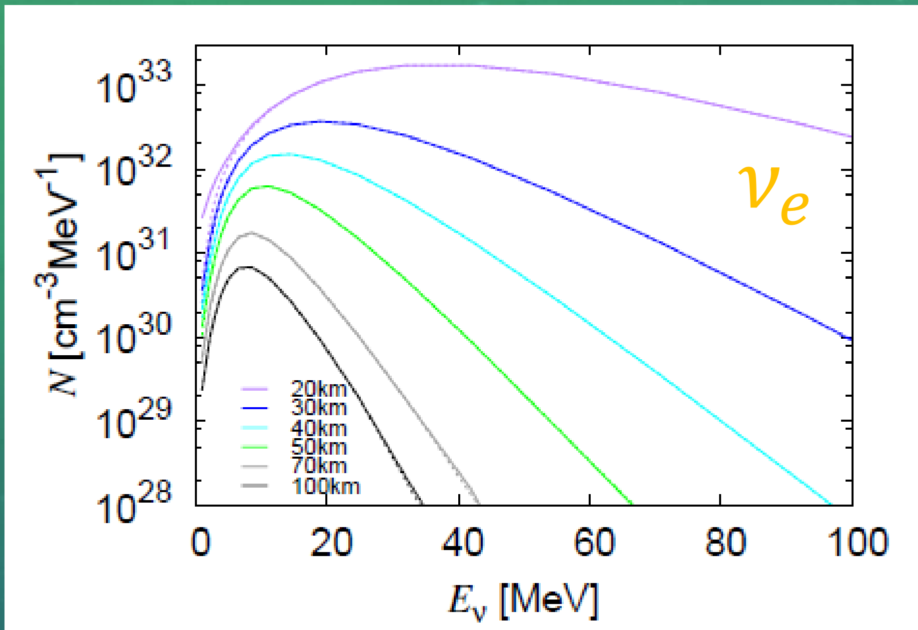
Average energy

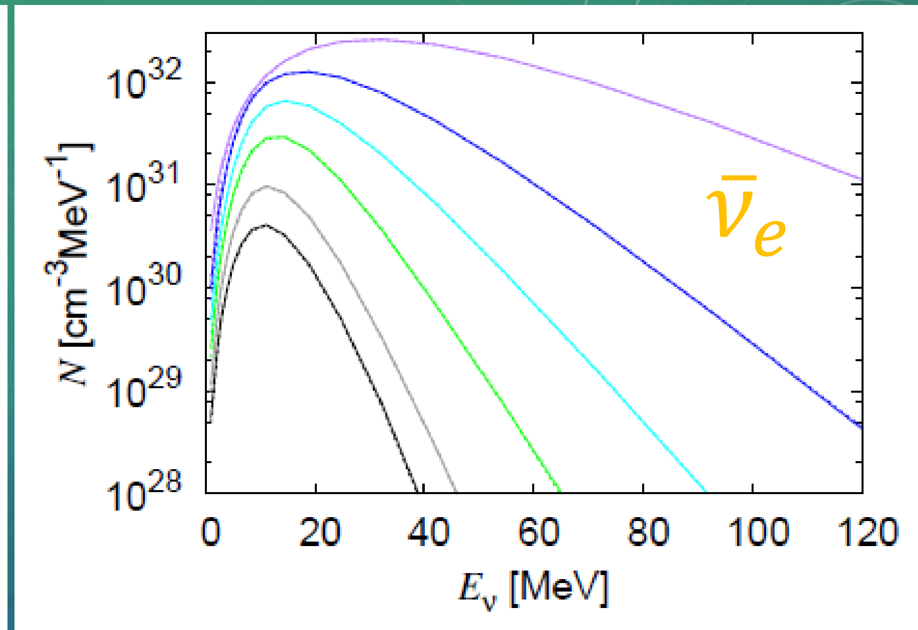


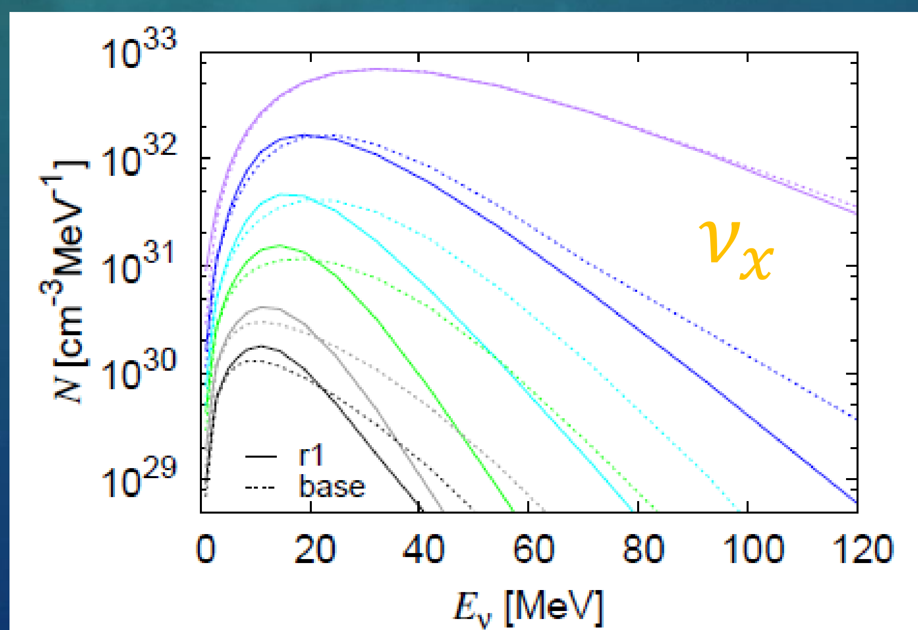
ν_e & $\overline{\nu_e}$: almost no change

ν_x : Average energy decreases about 15%

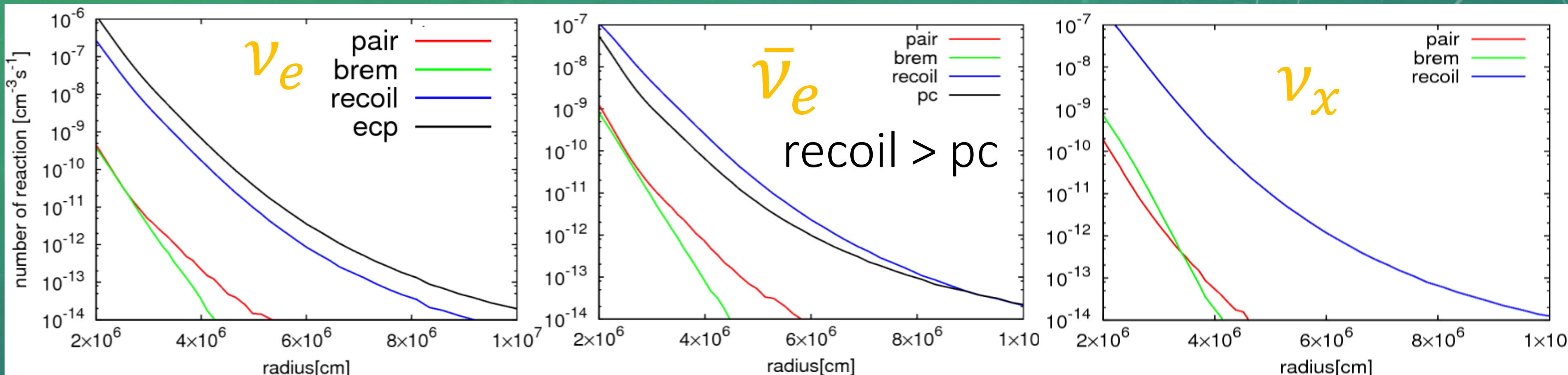
Neutrino spectra





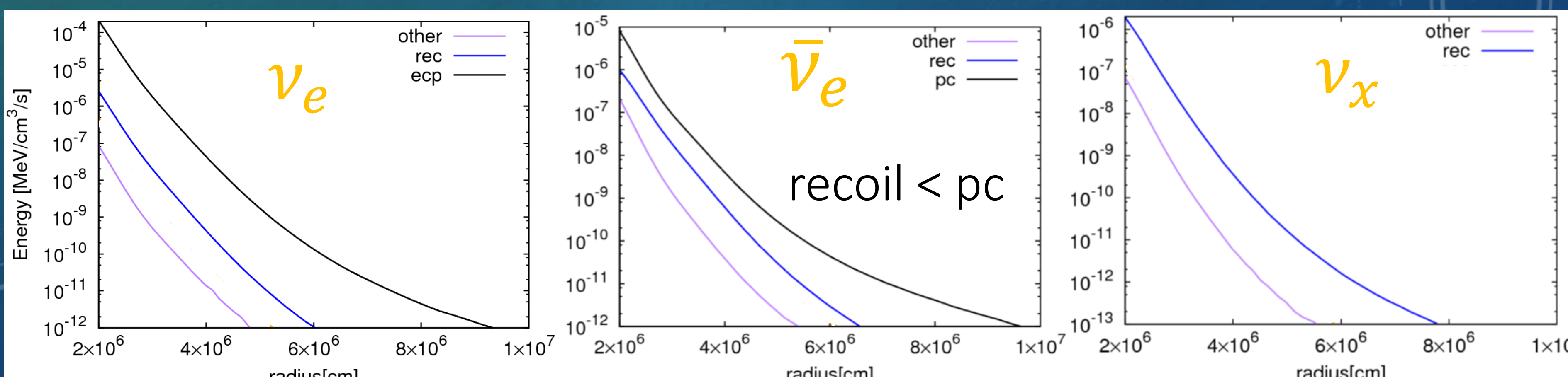


Contribution by each reaction

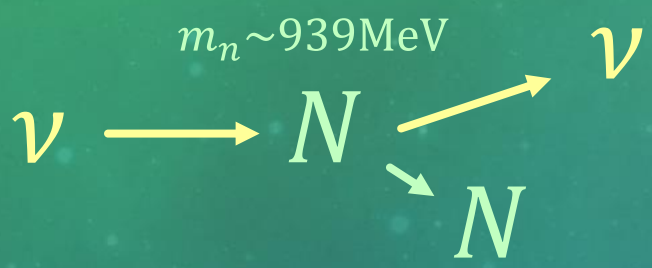


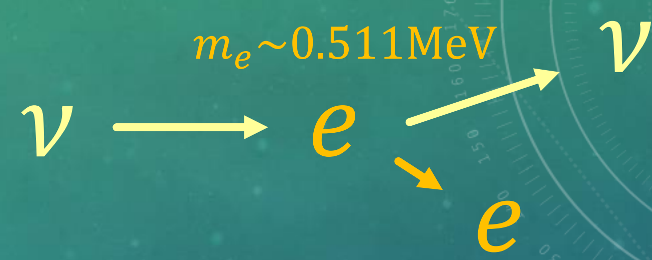
Number of reaction /s/cm^3

Exchange energy MeV/s/cm^3



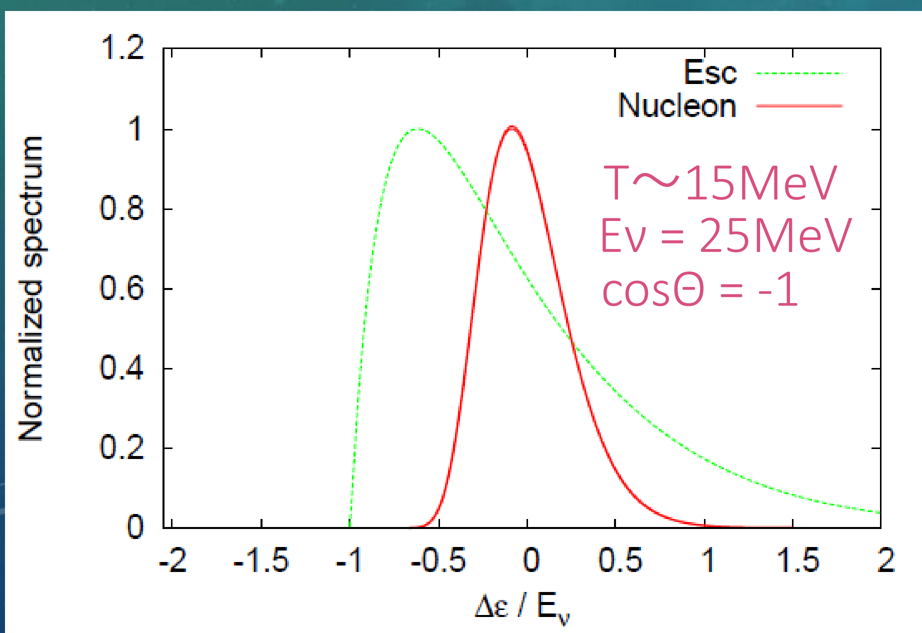
Nucleon scattering VS Electron scattering

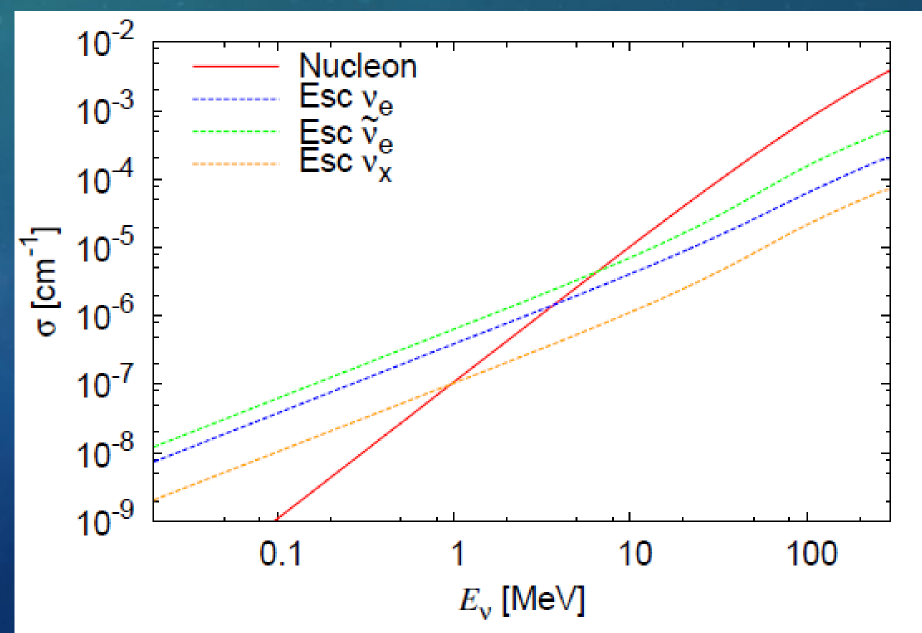




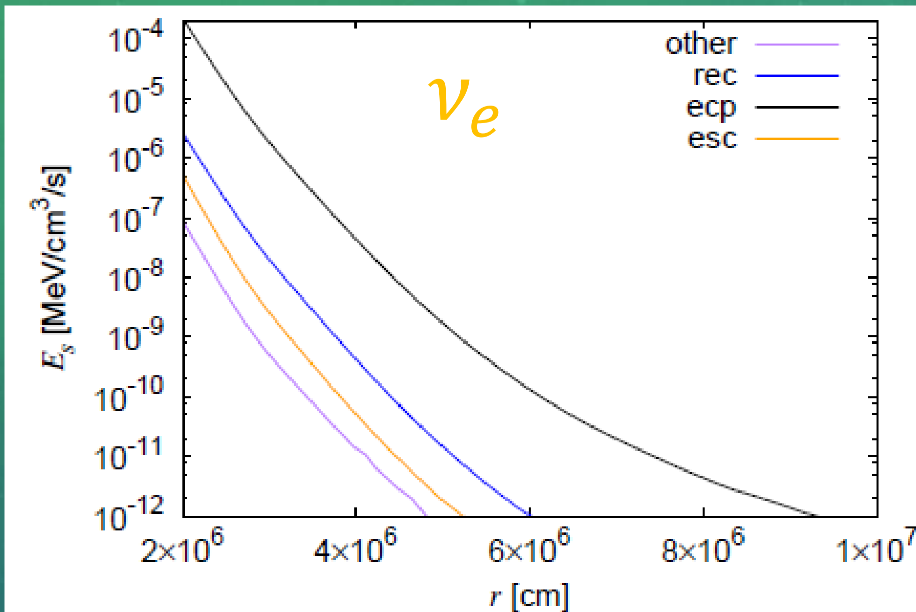
More energy is exchanged in electron scattering

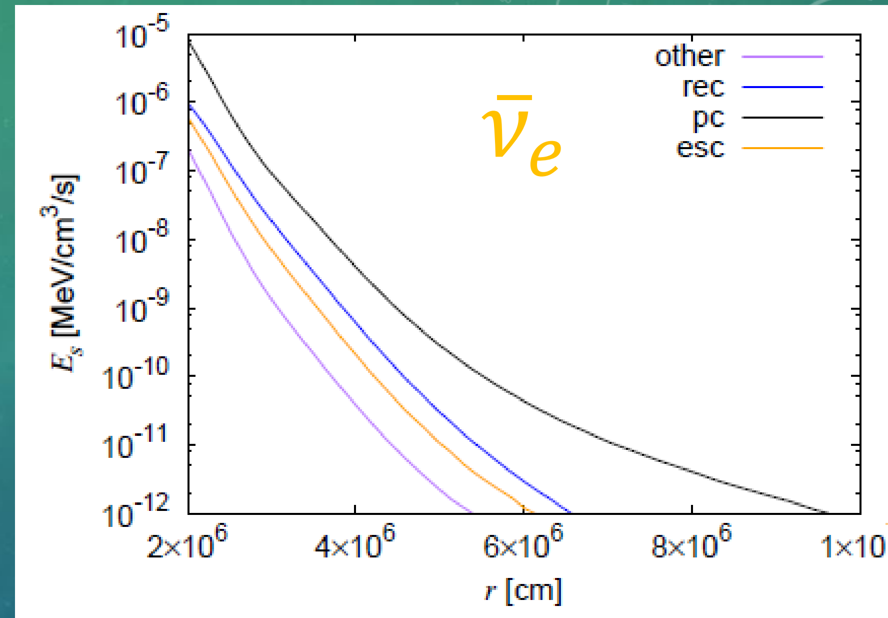
Number of reaction is larger in nucleon scattering

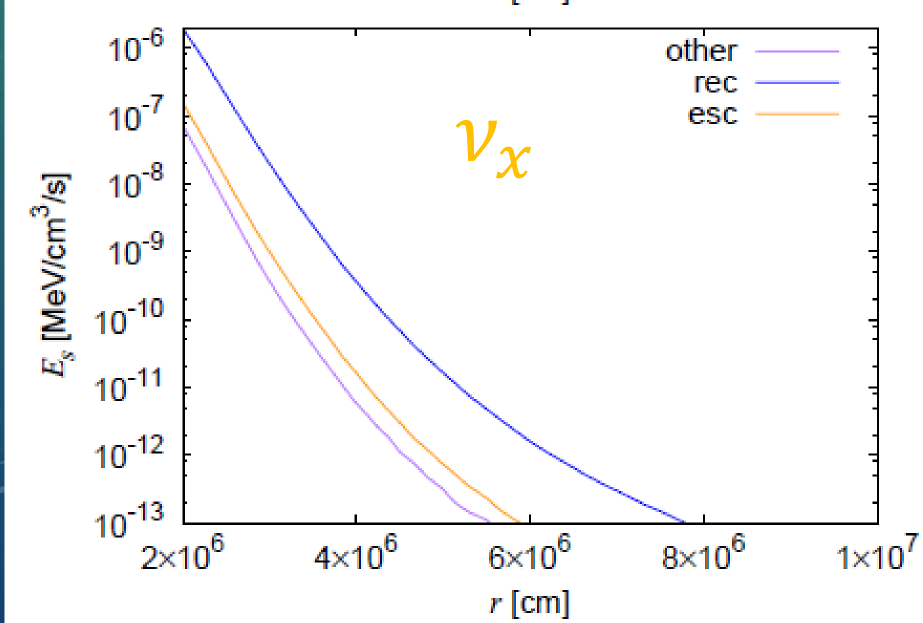




Nucleon scattering VS Electron scattering







Exchange energy
MeV/s/cm^3

recoil > esc

How to incorporate?

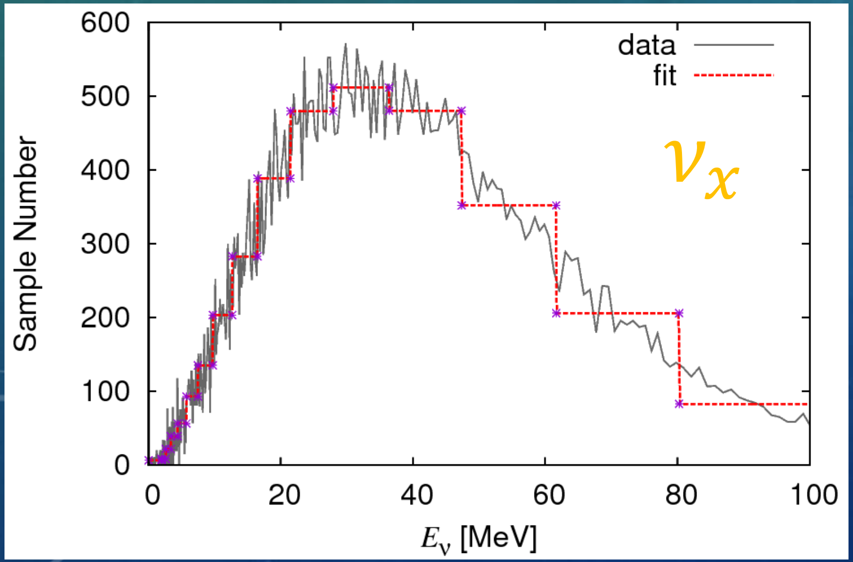
Now we get correct neutrino spectra
⇒ We have to take nucleon recoils into dynamical sim.

<u>SET UP</u>

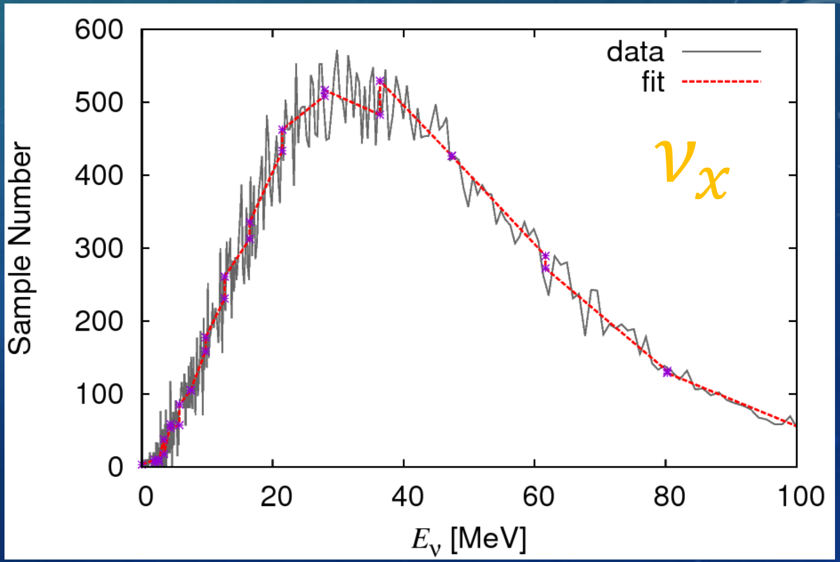
Initial : correct spectra

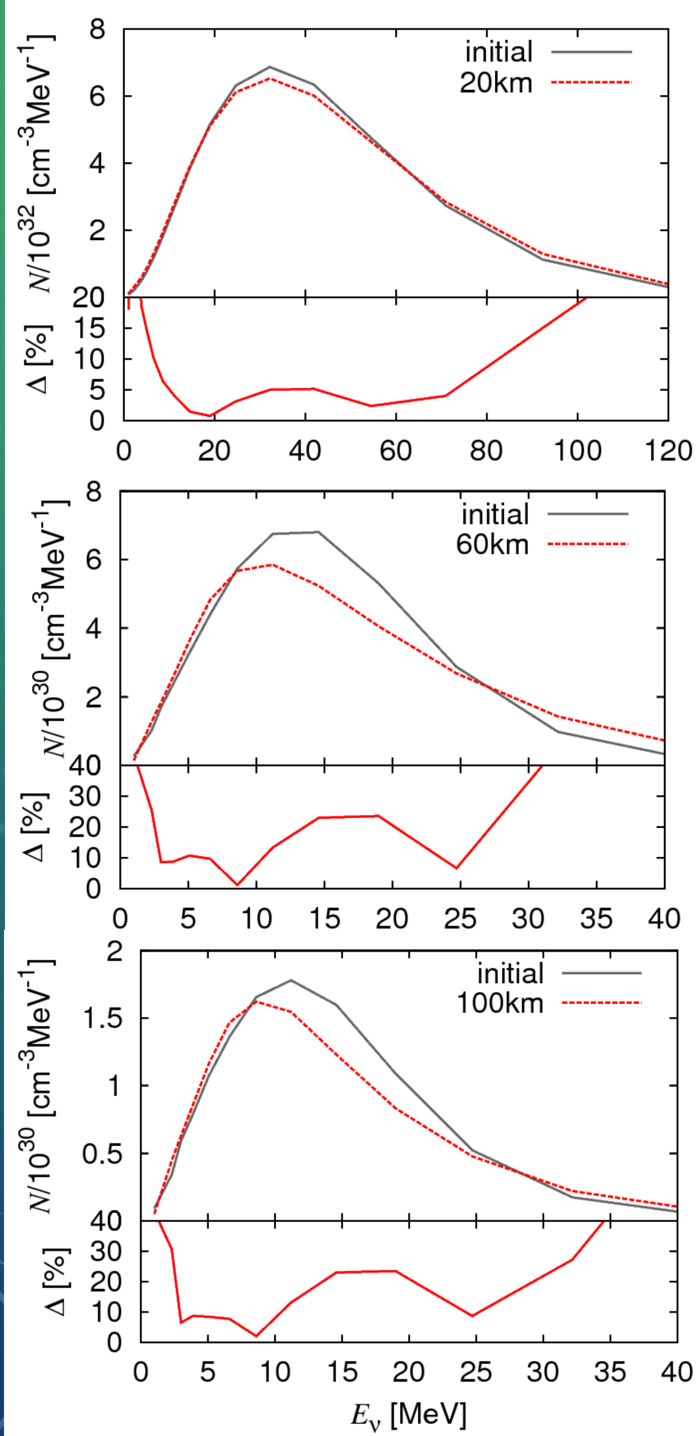
We prepare two fit models for spectra and remake it using fitting at every time step

① flat



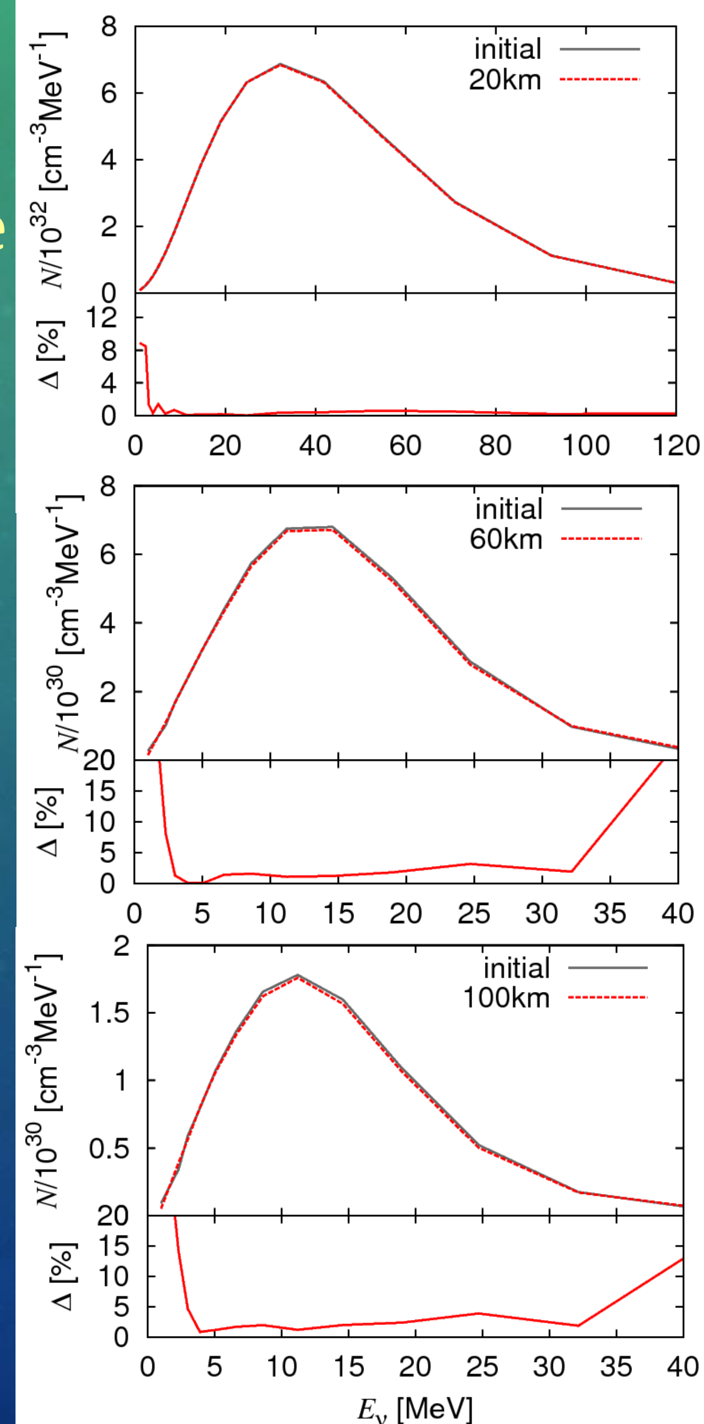
② Number & energy conservation





N&E conserve →

←flat



Summary

✓ For the next supernova event, we have to prepare realistic neutrino spectra theoretically

✓ We investigate nucleon recoils, which are problematic in numerical simulations

★ Spectrum of heavy-lepton neutrinos are changed by nucleon recoils mainly

★ Nucleon scattering dominates electron scattering in thermalization

★ The fitting using number & energy conservation is favorable for incorporation of nucleon recoils