Physics of Core-collapse Supernovae and
Compact Star Formations, Waseda Univ., Mar.19-21

Supernova neutrino oscillations in three-flavor multi angle simulations and their effects on nucleosynthesis

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Phys. Rev. D **96**, 043013, 2017
arXiv:1707.09111

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Neutrinos in core-collapse supernova

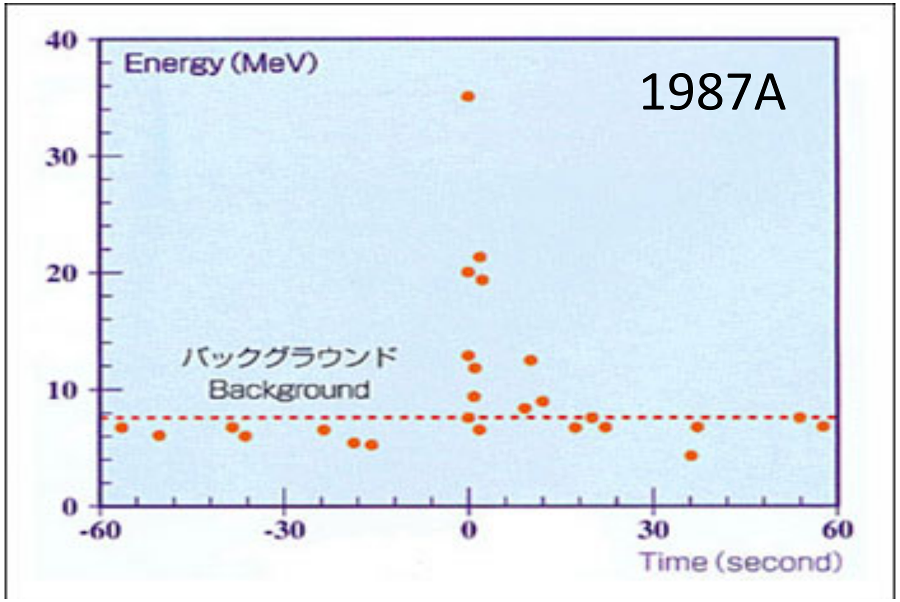
99% of gravitational energy ～10^{53} erg
is carried by neutrinos during ～10 s

Neutrino oscillations inside the supernova could affect neutrino-induced reactions

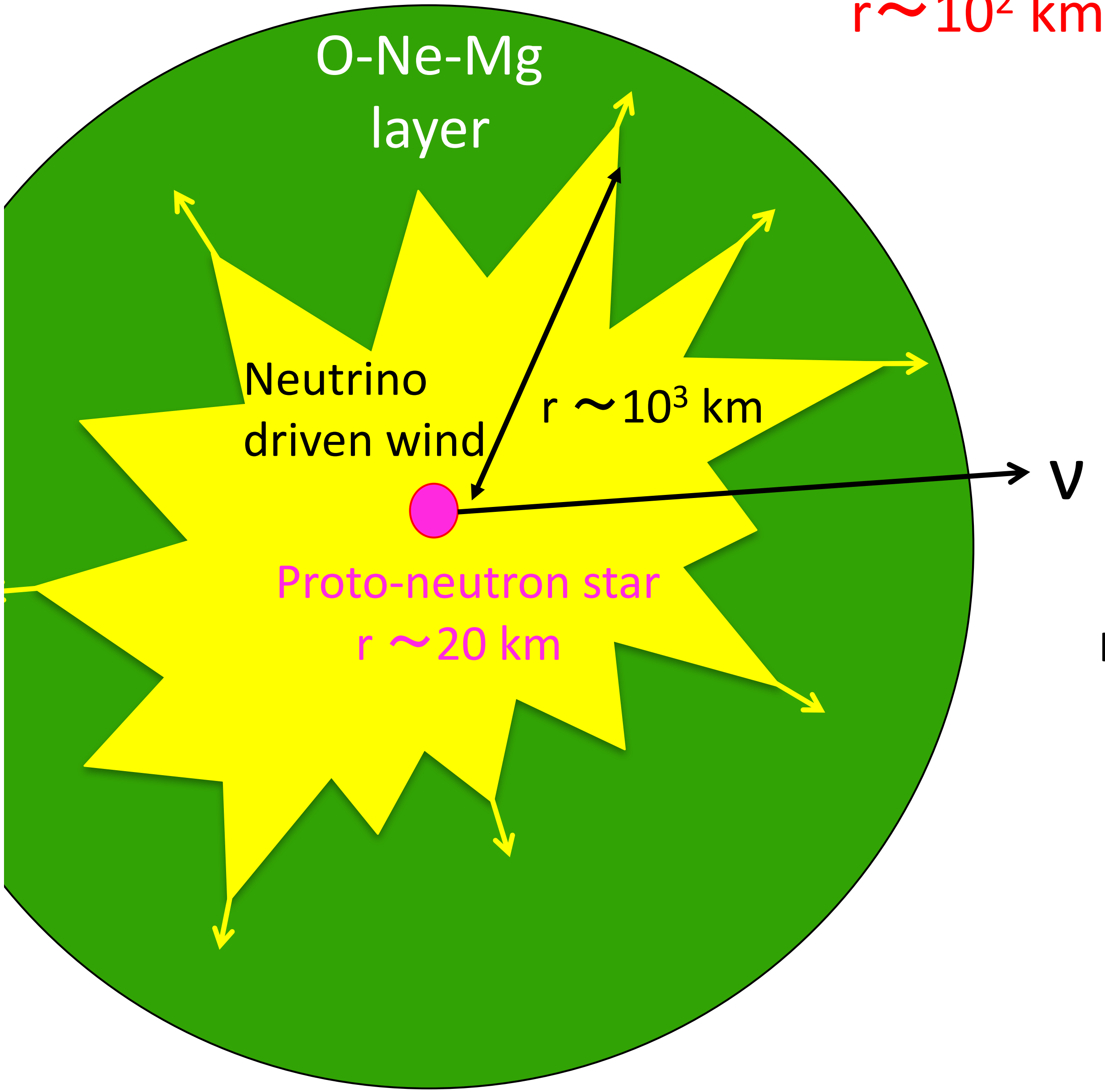
$$\nu_e + n \rightarrow p + e^-$$

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

→ Change explosion mechanism and nucleosynthesis ?

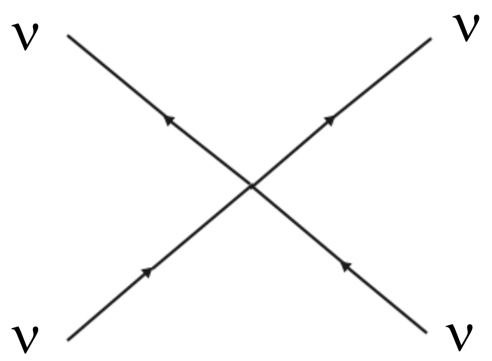


Neutrino oscillations in core-collapse supernovae



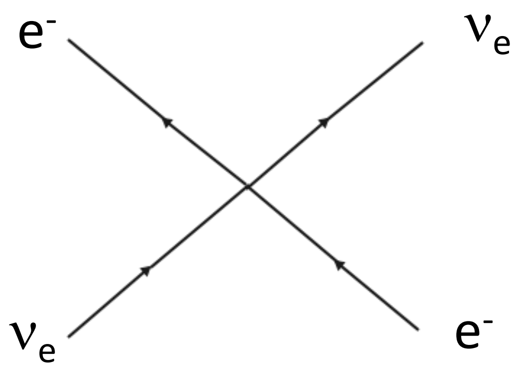
r∼10^2 km: **Neutrino self-interactions**

(ν-ν coherent scatterings)



Duan, et al.,PRD74, 105014, 2006.

r > ∼10^3 km: Matter effects



L. Wolfenstein,PRD17, 2369, 1978.

Numerical simulations of neutrino self interactions in SNe

How to calculate neutrino oscillations

Solve time evolutions of 3 × 3 density matrices $\rho, \quad \bar{\rho}$

Neutrinos, Antineutrinos

$$\frac{\mathrm{d}}{\mathrm{d}t}\rho_{\alpha\beta} = -i\,[H,\rho]_{\alpha\beta}$$

$$\frac{\mathrm{d}}{\mathrm{d}t}\bar{\rho}_{\alpha\beta} = -i\,[H,\bar{\rho}]_{\alpha\beta}$$

$\rho_{\alpha\alpha}$: number of ν_α

$\bar{\rho}_{\alpha\alpha}$: number of $\bar{\nu}_\alpha$

$\alpha, \beta = e, \mu, \tau$

Hamiltonian

$$H = H_{\mathrm{kinetic}} + H_{\mathrm{matter}} + H_{\mathrm{self}}$$

Vacuum Oscillations — Scattering with electrons — Neutrino self interactions

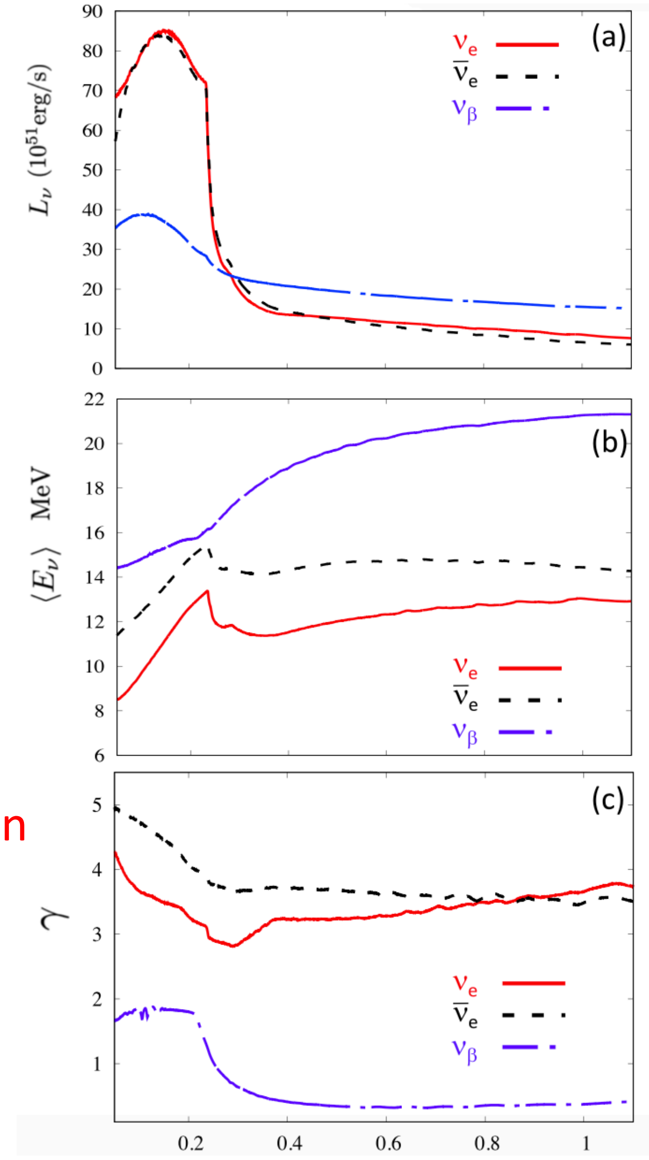
Our model

1. Hydrodynamics

- 1D explosion model
- 40 $M_\odot$ progenitor, 0.6, 1.1 s after core bounce

In this talk

S.E. Woosley and T.A.Weaver,1995,ApJS,101,181
H. Sotani and T. Takiwaki, Phys. Rev. D, 94, 044043,2016



2. Neutrino oscillations

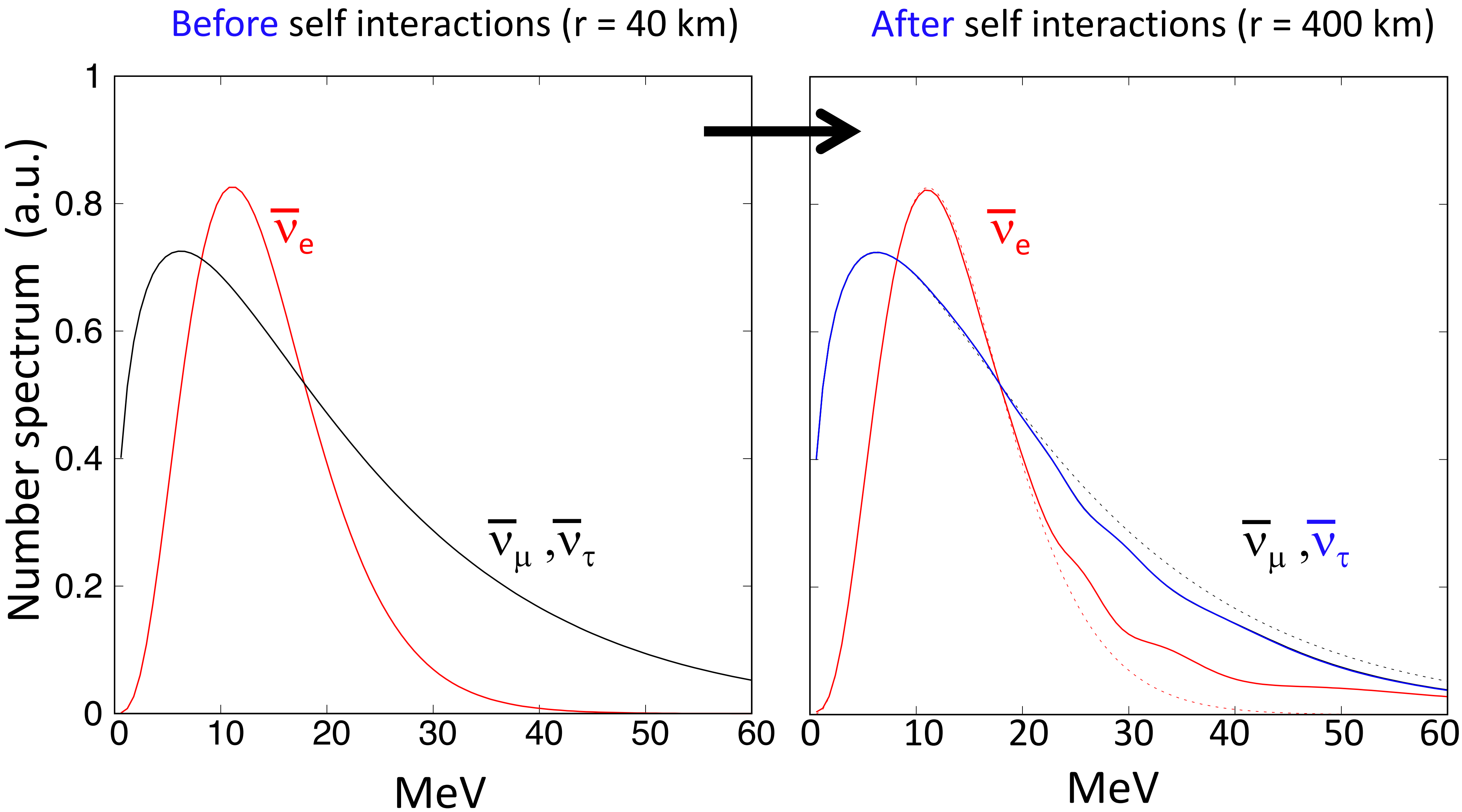
- Spherical symmetric
- Multi angle simulations

Ignored in the single angle approximation

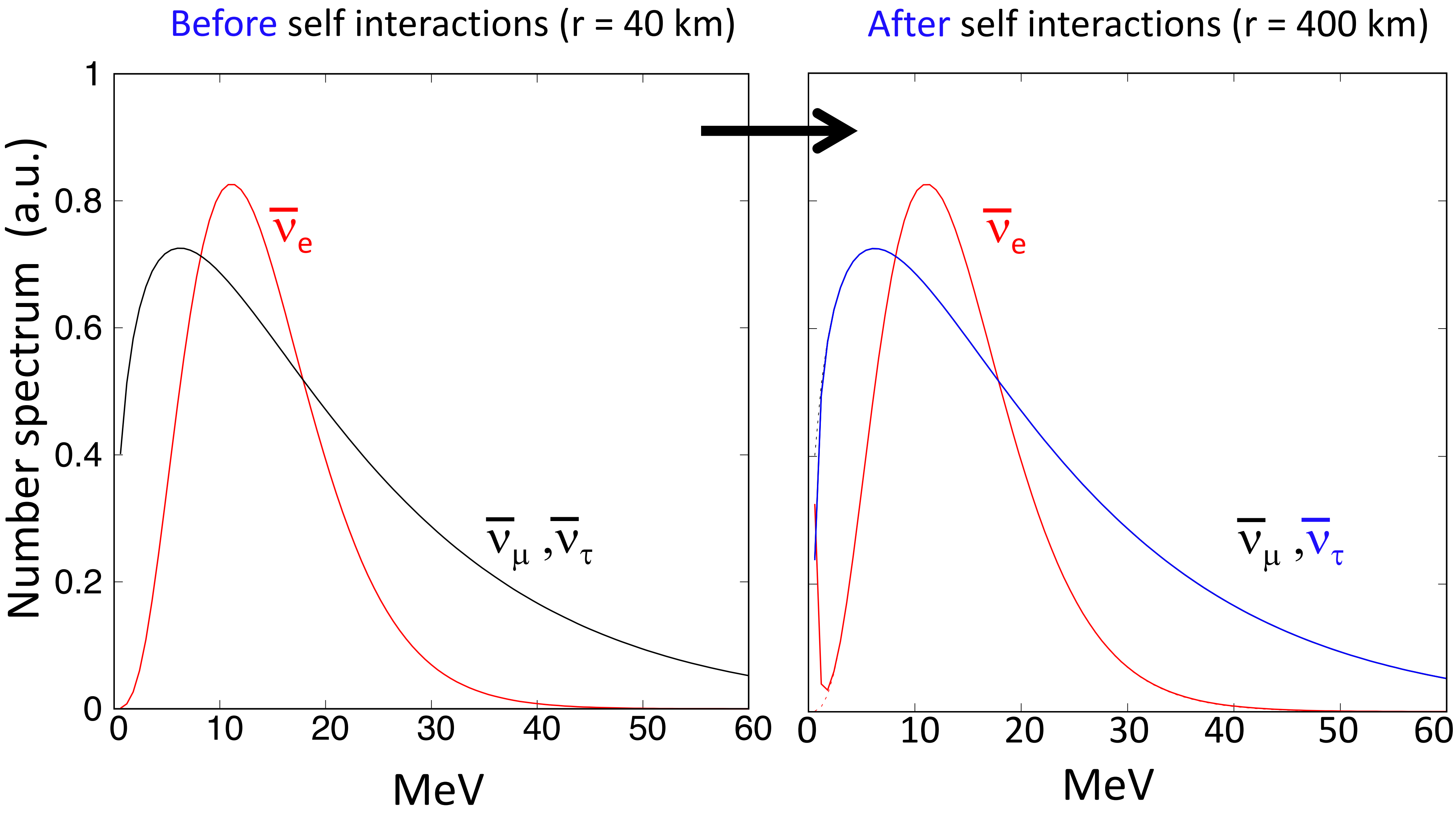
$$H_{\rm self}(r,E,\theta_p)=\frac{\sqrt{2}G_F}{2\pi R_\nu^2}\int {\rm d}E{\rm d}(\cos\theta_q)(1-\cos\theta_p\cos\theta_q)$$
$$\times\sum_{\alpha=e,\mu,\tau}\left\{\frac{L_{\nu_\alpha}}{\langle E_{\nu_\alpha}\rangle}f_{\nu_\alpha}(E)\rho(r,E,\theta_q)\right.$$
$$\left.-\frac{L_{\bar{\nu}_\alpha}}{\langle E_{\bar{\nu}_\alpha}\rangle}f_{\bar{\nu}_\alpha}(E)\bar{\rho}(r,E,\theta_q)\right\}$$

$$f_{\nu_\alpha}(E)=\frac{E^\gamma}{\Gamma(\gamma+1)}\left(\frac{\gamma+1}{\langle E_{\nu_\alpha}\rangle}\right)^{\gamma+1}\exp\left[-\frac{(\gamma+1)E}{\langle E_{\nu_\alpha}\rangle}\right]$$

Self interactions in normal hierarchy $\Delta m_{32}^2 > 0$

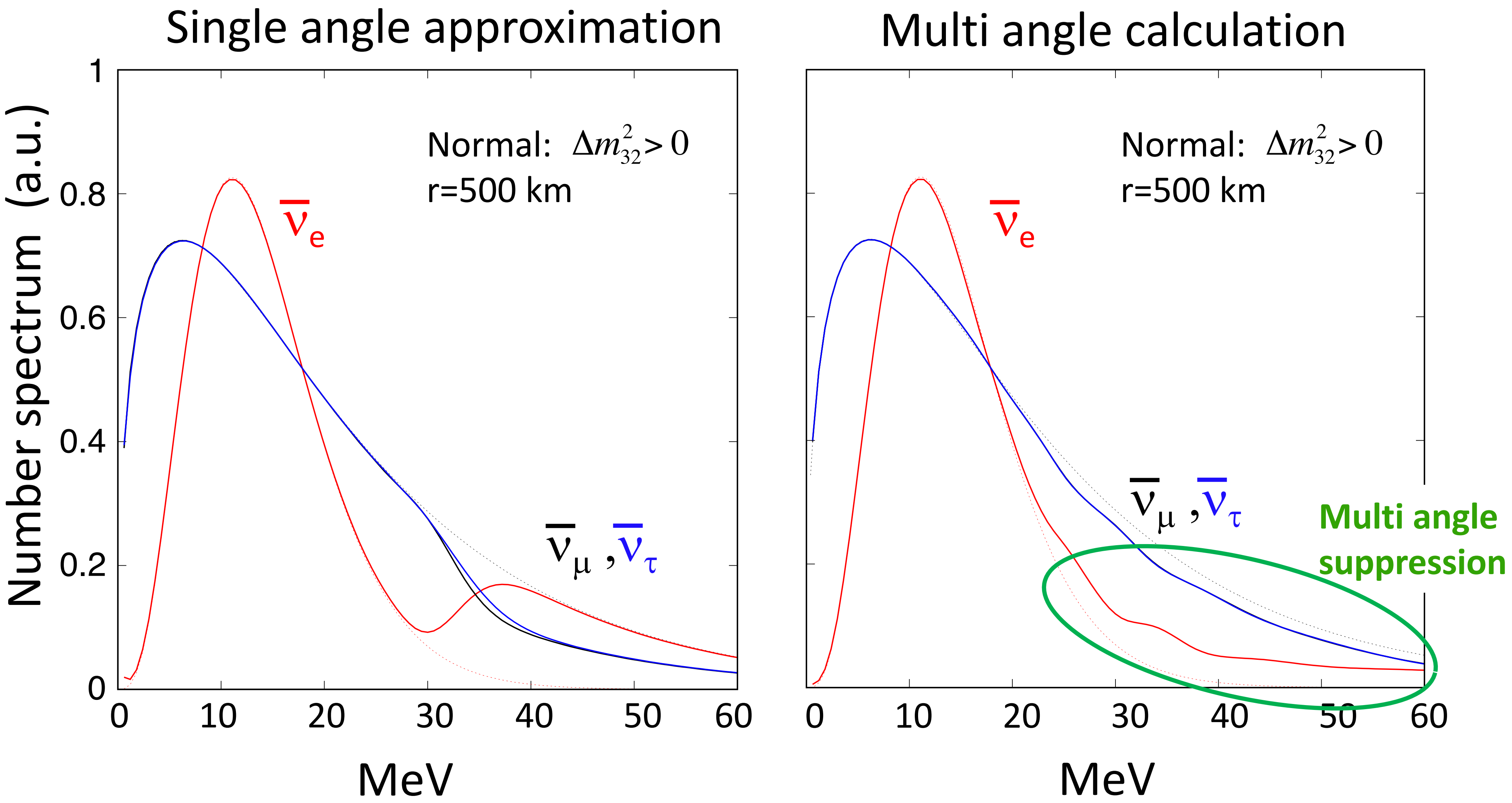


Self interactions in inverted hierarchy $\Delta m^2_{32} < 0$



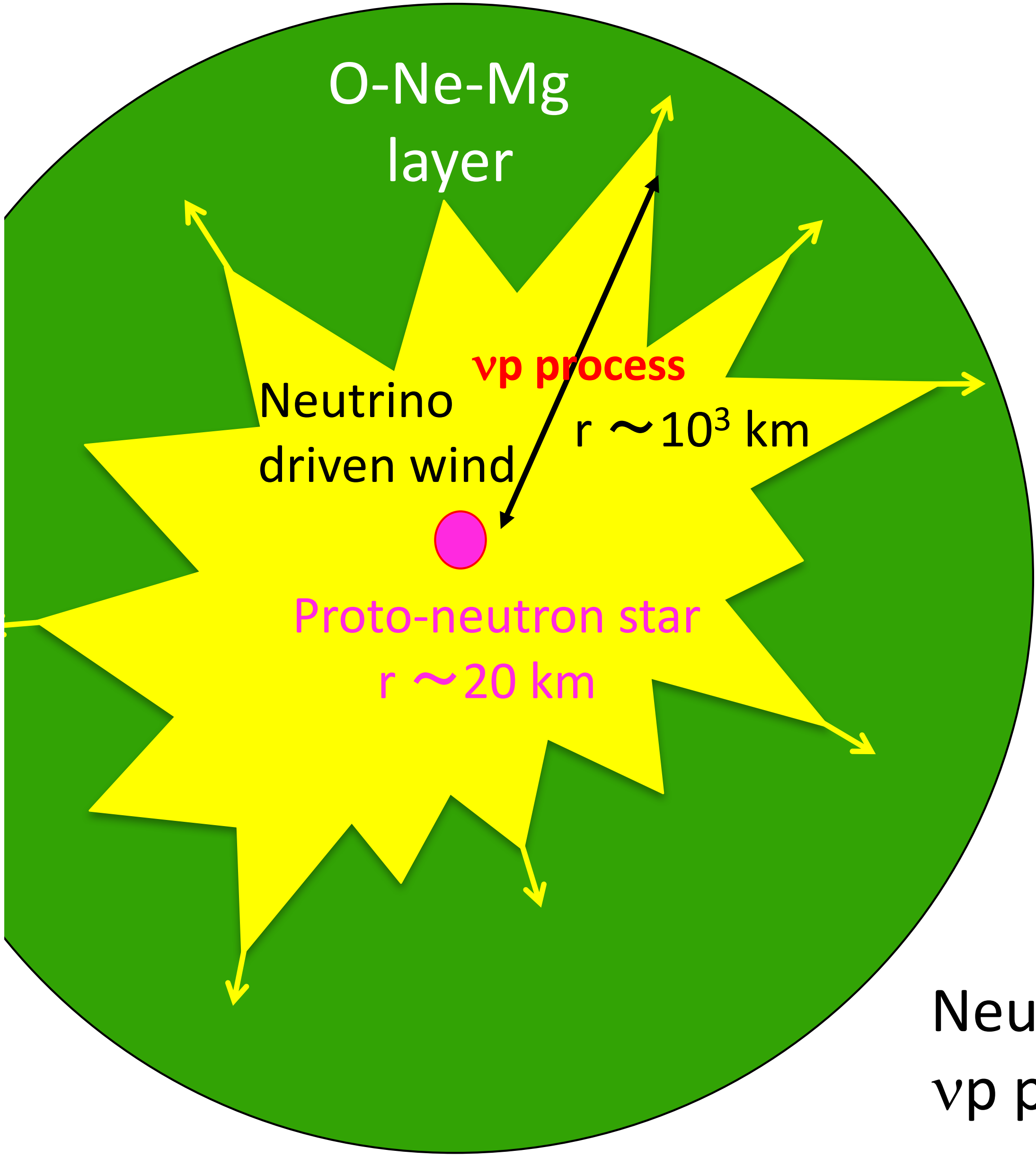
Multi angle suppression

Flavor transitions are weakened in the multi angle calculation



Influence on νp process nucleosynthesis

Nucleosynthesis in neutrino-driven winds



νp process

(T=2-3 × 10⁹ K, Yₑ > 0.5)

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

Supply free neutrons

^{64}Ge (n,p)^{64}Ga(p,γ)…

~~β^+ decay~~

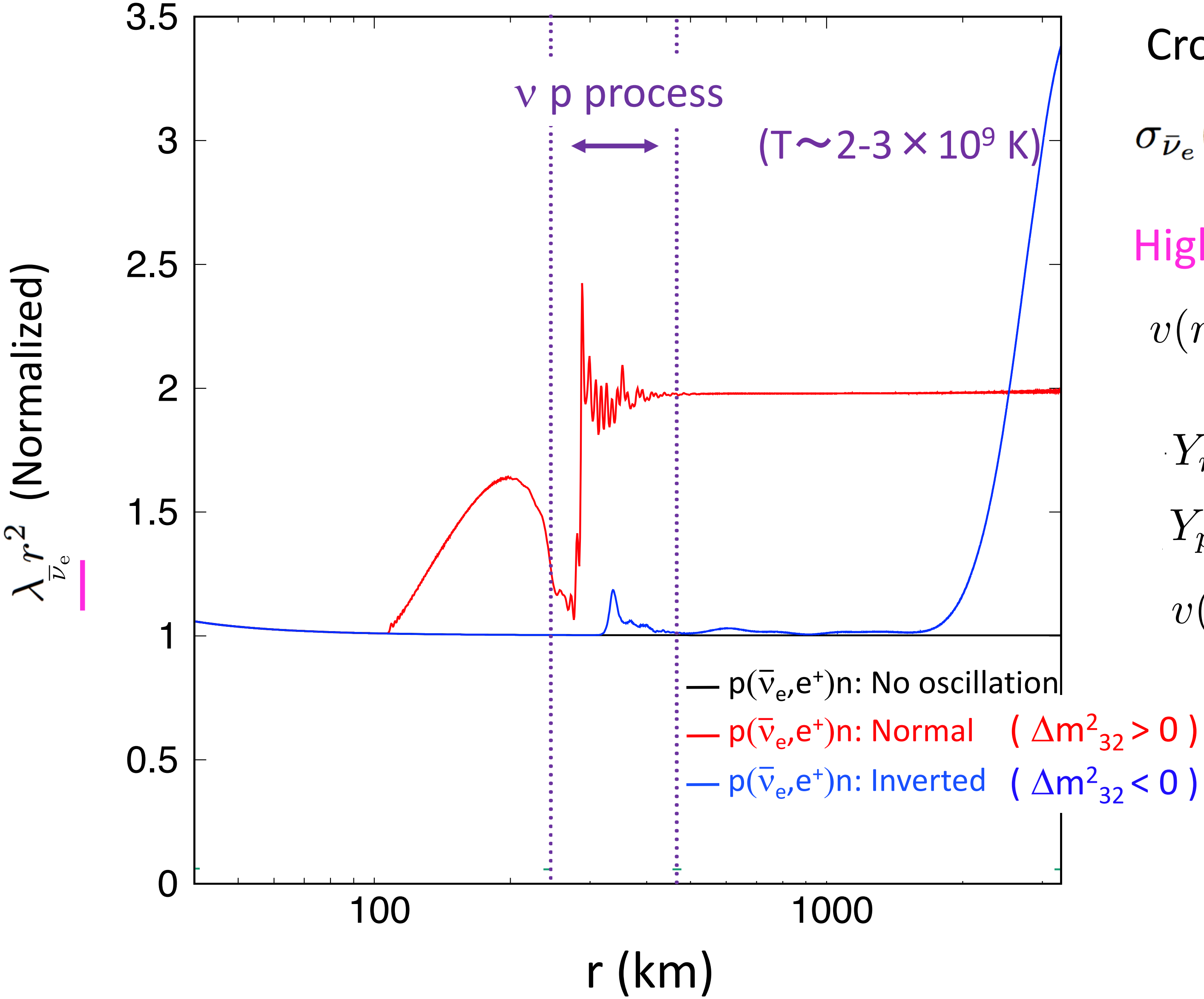
^{92,94}Mo, ^{96,98}Ru,..

p-nuclei

Neutrino self-interactions can affect νp process nucleosynthesis !!

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

$$\lambda_{\bar{\nu}_e} = \int dE\, d\cos\theta \sum_{\alpha=e,\mu,\tau} \frac{L_{\bar{\nu}_\alpha}}{2\pi R_\nu^2 \langle E_{\bar{\nu}_\alpha} \rangle} f_{\bar{\nu}_\alpha}(E) \bar{\rho}_{ee}(E,\theta_R) \sigma_{\bar{\nu}_e}(E)$$



Cross section

$$\sigma_{\bar{\nu}_e}(E) \propto (E/\mathrm{MeV} - 1.293)^2$$

High λ creates more neutrons

$$v(r) \frac{d}{dr} Y_n = \lambda_{\bar{\nu}_e} Y_p + \mathrm{Other}$$

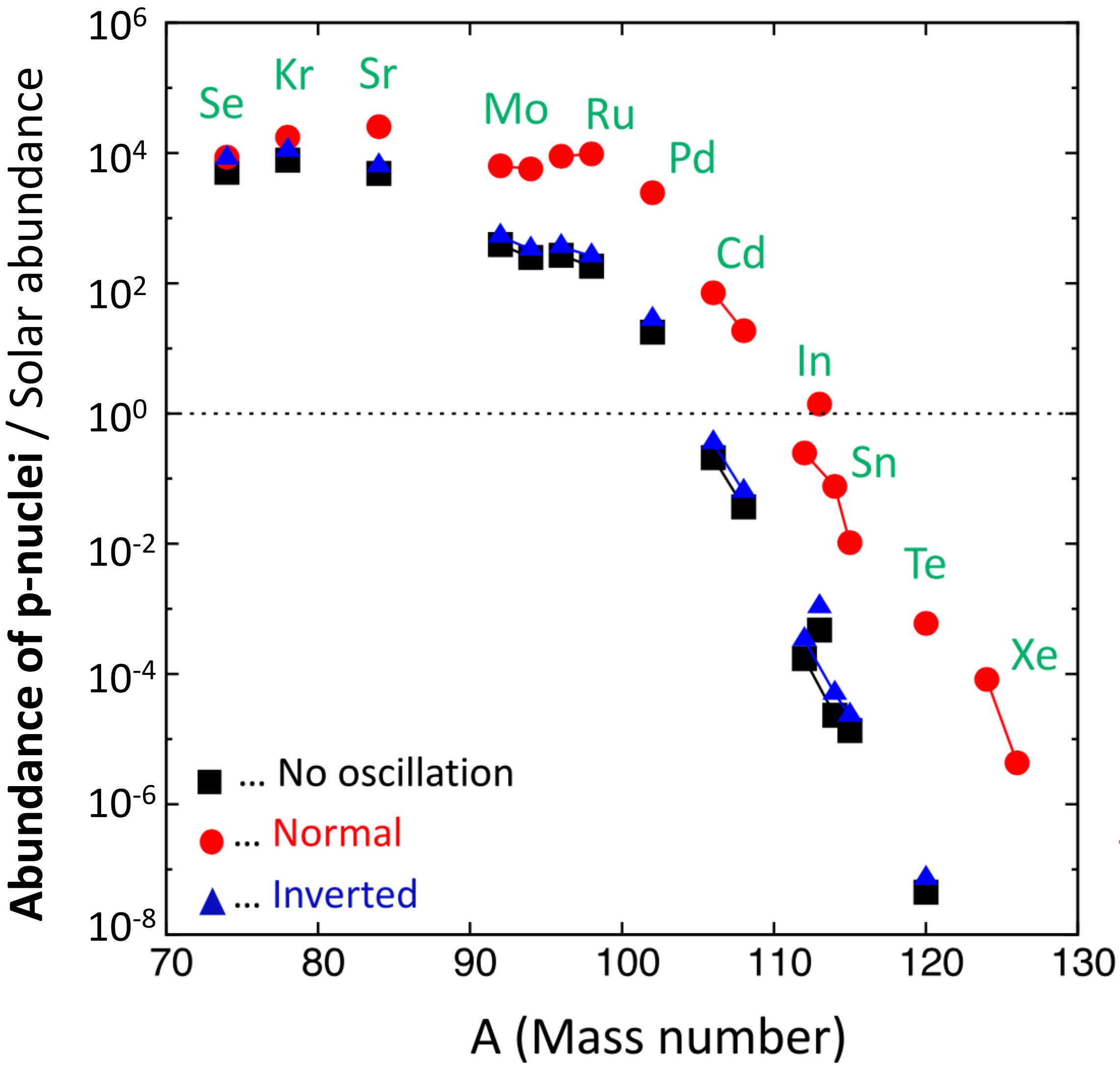
Y_n ... neutron abundance

Y_p ... proton abundance

$v(r)$ ... wind velocity

Enhanced abundances of p-nuclei

$$\Gamma_i = \frac{X_i}{X_{i,\mathrm{solar}}} \Big/ \frac{X_{^{56}\mathrm{Fe}}}{X_{^{56}\mathrm{Fe,solar}}},$$



In normal hierarchy, p-nuclei are increased by ～1-10^4 times

In inverted hierarchy, nearly the same result as that in no oscillation

Neutrino oscillations in T～2-3 × 10^9 K affect abundances of p-nuclei

The necessity of self interactions for the precise nucleosynthesis

Summary

- Neutrino self interactions could affect neutrino spectra and nucleosynthesis in core collapse supernovae

- Neutrino flavor transitions are suppressed by multi angle effects

- In normal hierarchy, the νp process nucleosynthesis is enhanced by increasing electron antineutrinos

- Our simulation results suggest the necessity of neutrino self interactions for the precise nucleosynthesis