Toward Reliable Neutrino Reaction Rates for Core-Collapse Supernova Simulations

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Outline

1 : Introduction

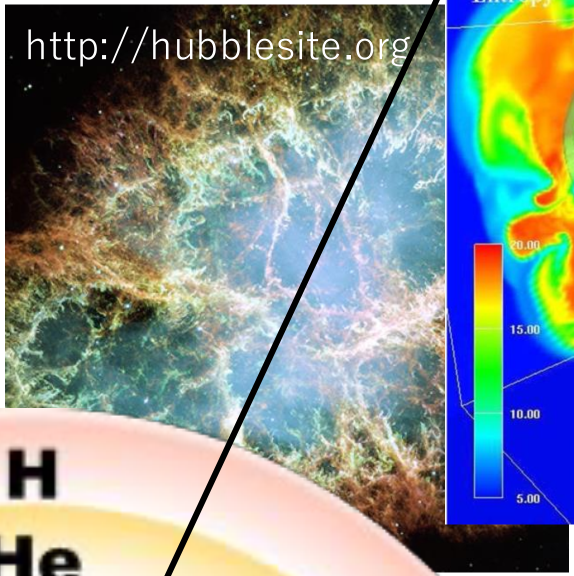
2 : Supernova simulation with standard reaction rates

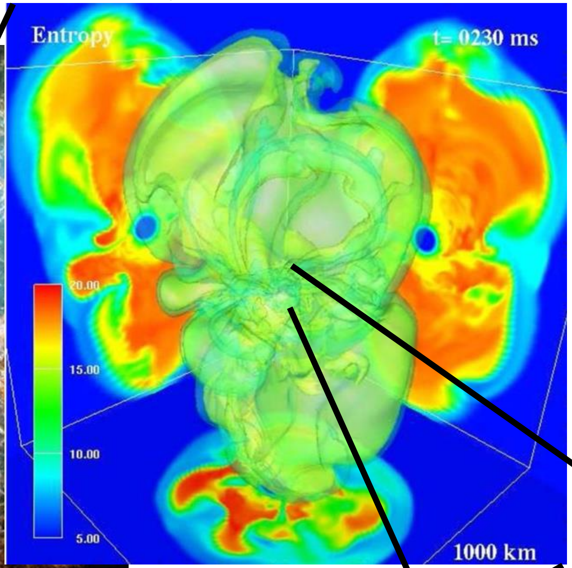
3 : Neutrino-nucleon reaction rates consistent with the EOS

4: Neutrino-nucleus coherent scattering in compact star cooling

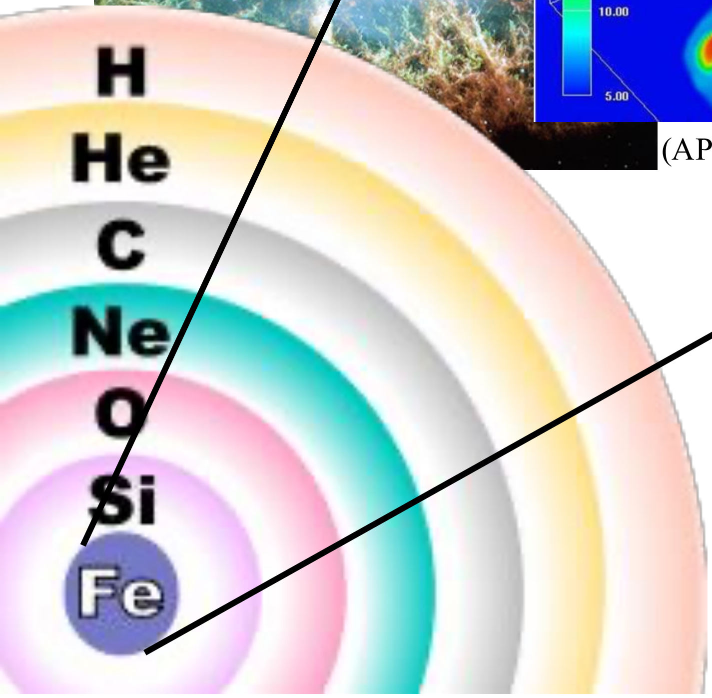
1. Introduction

Core-Collapse Supernovae

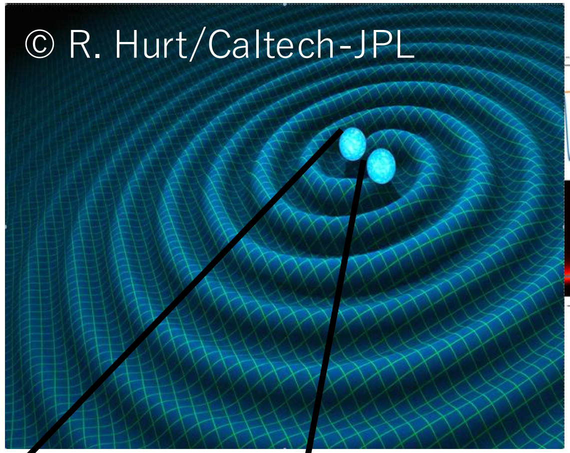


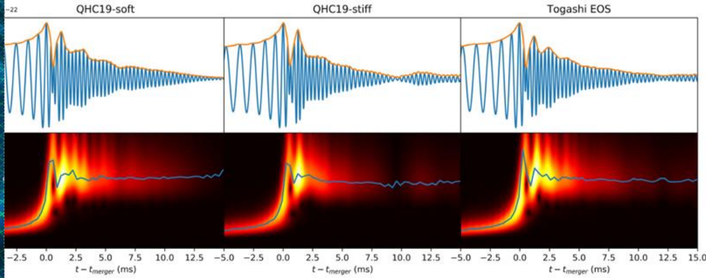


(APJ 786 (2014) 83)

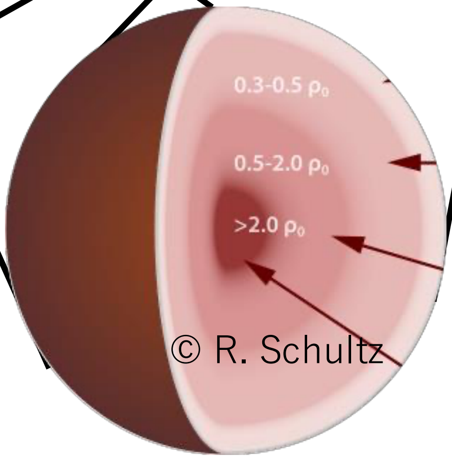


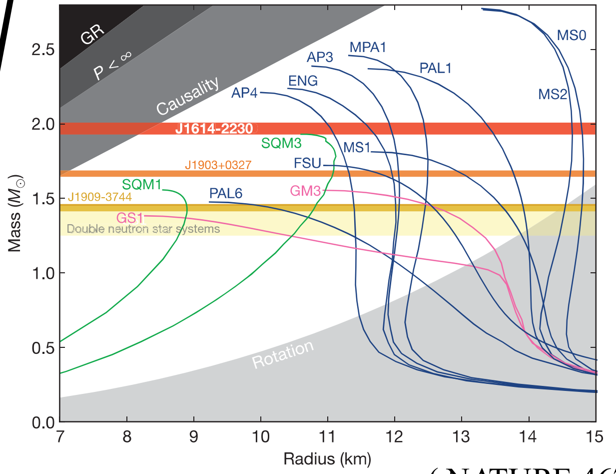
Neutron Star Mergers





(PRL 129 (2022) 181101)





Neutron Stars

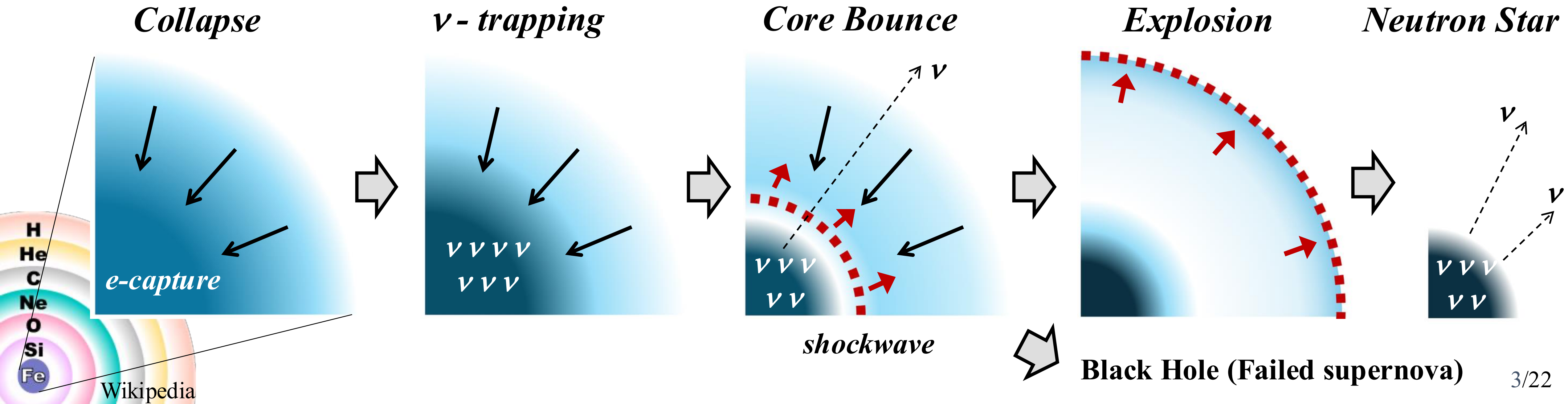
(NATURE 467 (2010) 1081)

Core-collapse supernovae

1. **Nuclear equation of state (EOS) for dense matter**
2. **Nuclear weak reactions with neutrino**

Those are essential ingredients that should be provided by Nuclear Physics for Compact Star studies.

Core-collapse mechanism of massive stars



Current Status of Supernova Simulations

EOS dependence in core-collapse supernova simulations is gradually being investigated.

- More than 20 EOSs applicable to the simulations (only two EOSs were available about 10 years ago)

<u>Variational EOS with realistic nuclear forces</u>

(**HT**, K. Nakazato, Y. Takehara, S. Yamamuro, H. Suzuki, and M. Takano, NPA961 (2017) 78)

*Constructed by **the variational many-body theory** with bare nuclear forces (**AV18+UIX**)*

- This EOS is applicable to the studies for <u>**neutron stars**</u> and <u>**core-collapse supernovae**.</u>
- This EOS table is available on the web: **`http://www.np.phys.waseda.ac.jp/EOS/`**

TODAY'S TALK

- **Overview of neutrino reaction rates adopted in simulations**
- **Recent improvement in those reaction rates**

2. Supernova simulation with standard reaction rates

1. Electron-type neutrino absorption on neutrons

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

2. Electron-type antineutrino absorption on protons

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

3. Neutrino bremsstrahlung in NN collisions

$$N + N' \leftrightarrow N + N' + \nu + \bar{\nu}$$

4. Neutrino scattering on nucleons

$$\nu + N \leftrightarrow \nu + N$$

5. Electron-type neutrino absorption on nuclei

$$\nu_e + A \leftrightarrow A + e^-$$

6. Neutrino coherent scattering on nuclei

$$\nu + A \leftrightarrow \nu + A$$

7. Neutrino scattering on electrons

$$\nu + e^- \leftrightarrow \nu + e^-$$

8. Electron-positron pair annihilation and creation

$$e^- + e^+ \leftrightarrow \nu + \bar{\nu}$$

9. Plasmon decay and creation

$$\gamma^* \leftrightarrow \nu + \bar{\nu}$$

Widely used interaction rates: S.W. Bruenn (APJS 58 (1985) 771)

Neutrino Transport in Supernova Matter

We directly solve the Boltzmann equation for neutrino distributions.

- Neutrino distribution function: $f_\nu\ (t, r, E_\nu, \theta_\nu)$

$$\frac{\partial f_\nu}{c\partial t} + \mu\frac{\partial f_\nu}{\partial r} + \frac{(1-\mu^2)}{r}\frac{\partial f_\nu}{\partial \mu} = \left(\frac{\delta f_\nu}{c\delta t}\right)_{collision}$$

μ=cosθ_ν: angle

Neutrino source term which depends on various neutrino interaction rates

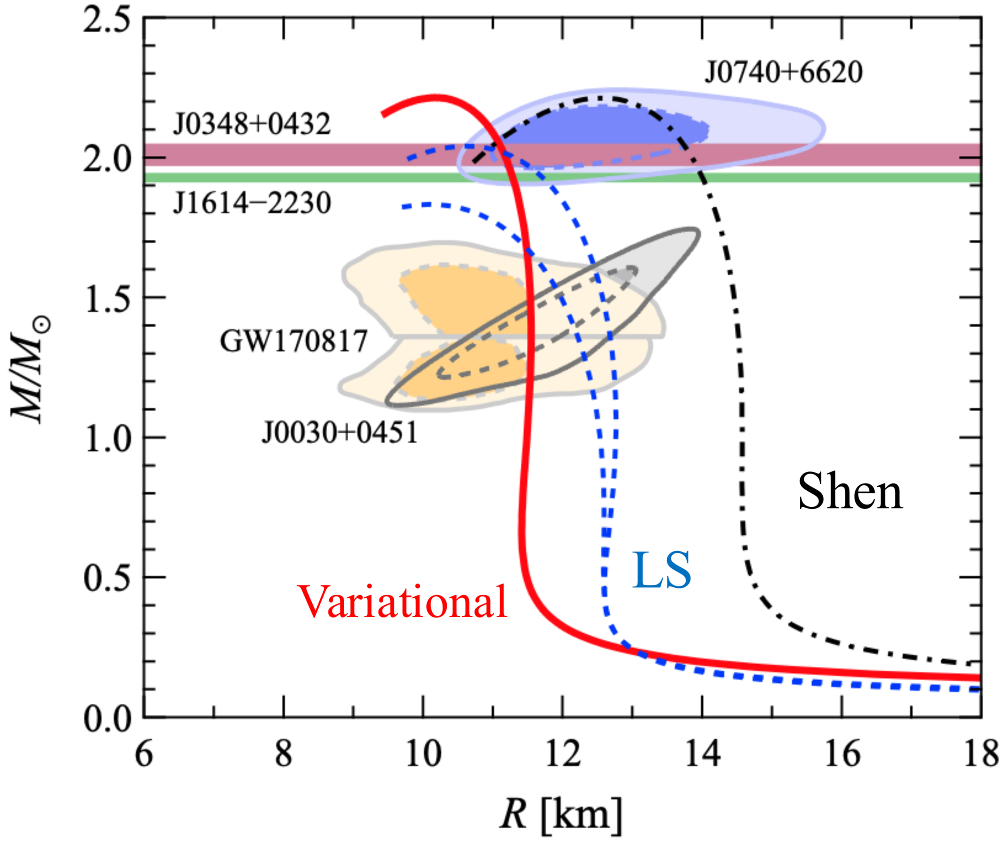
To perform simulations coupled with hydrodynamics,

interaction rates need to be given in analytical forms as functions of T, Y_p, n_B and neutrino energy E_n.

EOSs applicable to supernova simulations

- The following three types of EOSs are adopted.

- **Variational:** Variational method (AV18+UIX)
- **LS EOS**: Skyrme Hartree-Fock
- **Shen EOS**: Relativistic Mean Field (TM1)



- These EOSs provide thermodynamic quantities in the wide ranges.

- Temperature T : $0 \le T \le 400$ MeV
- Density ρ : $10^{5.1} \le \rho_B \le 10^{16.0}\mathrm{g/cm^3}$
- Proton fraction Y_p : $0 \le Y_p \le 0.65$

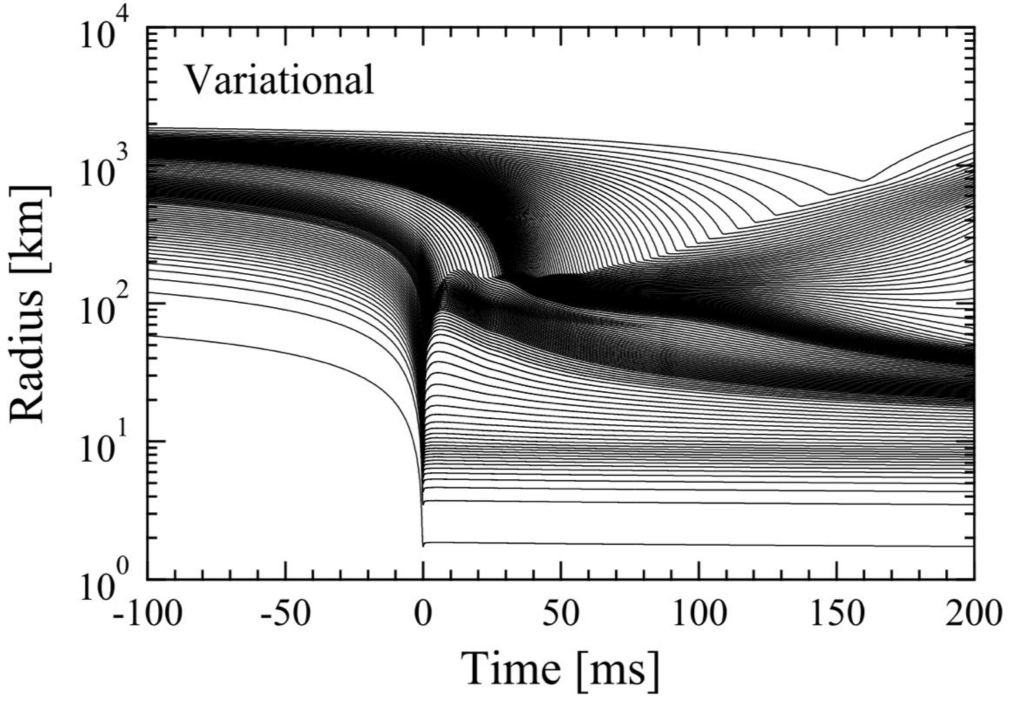
Application to core-collapse simulations

1D neutrino-radiation hydrodynamics simulations

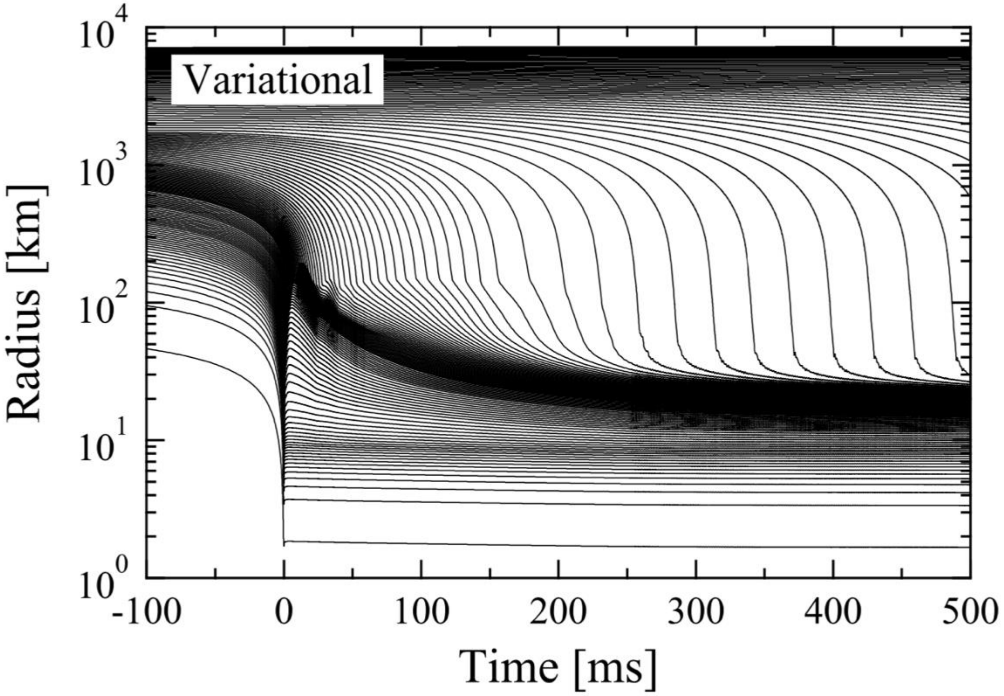
(HT et al., PTEP 023D05 (2014))
(Nakazato, Sumiyoshi & HT, PASJ 73 (2021) 639)

- **EOS: Togashi / Shen / LS220 / LS180**
- Progenitor model : 9.6 $M_\odot$ / 15 $M_\odot$ / 30 $M_\odot$
- Neutrino Transport: Directly solve the Boltzmann equation

Progenitor model : 9.6 $M_\odot$
(provided by A. Heger)

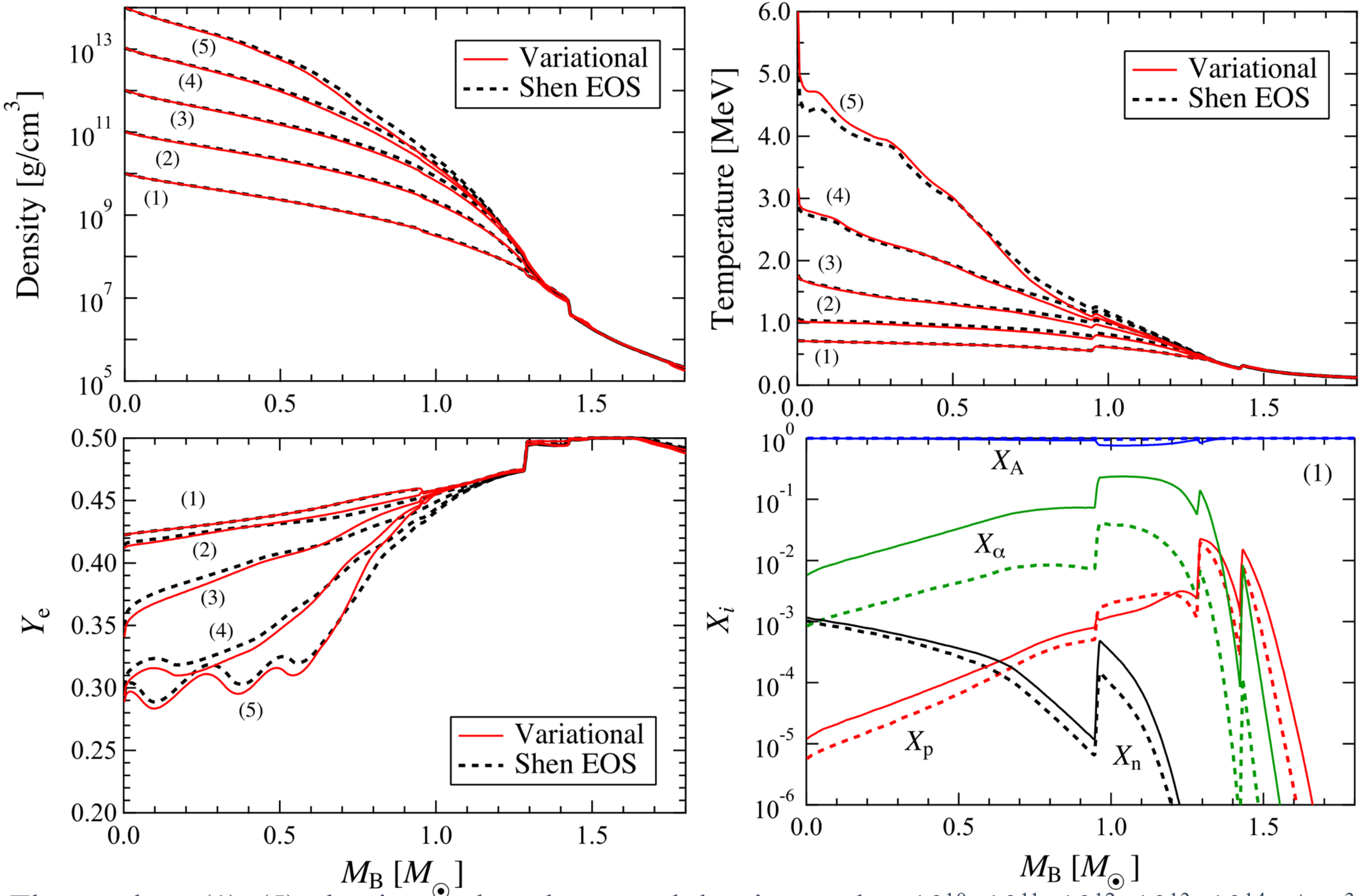


Progenitor model: WW 15$M_\odot$
(Astrophys. J. Suppl. 101 (1995) 181)



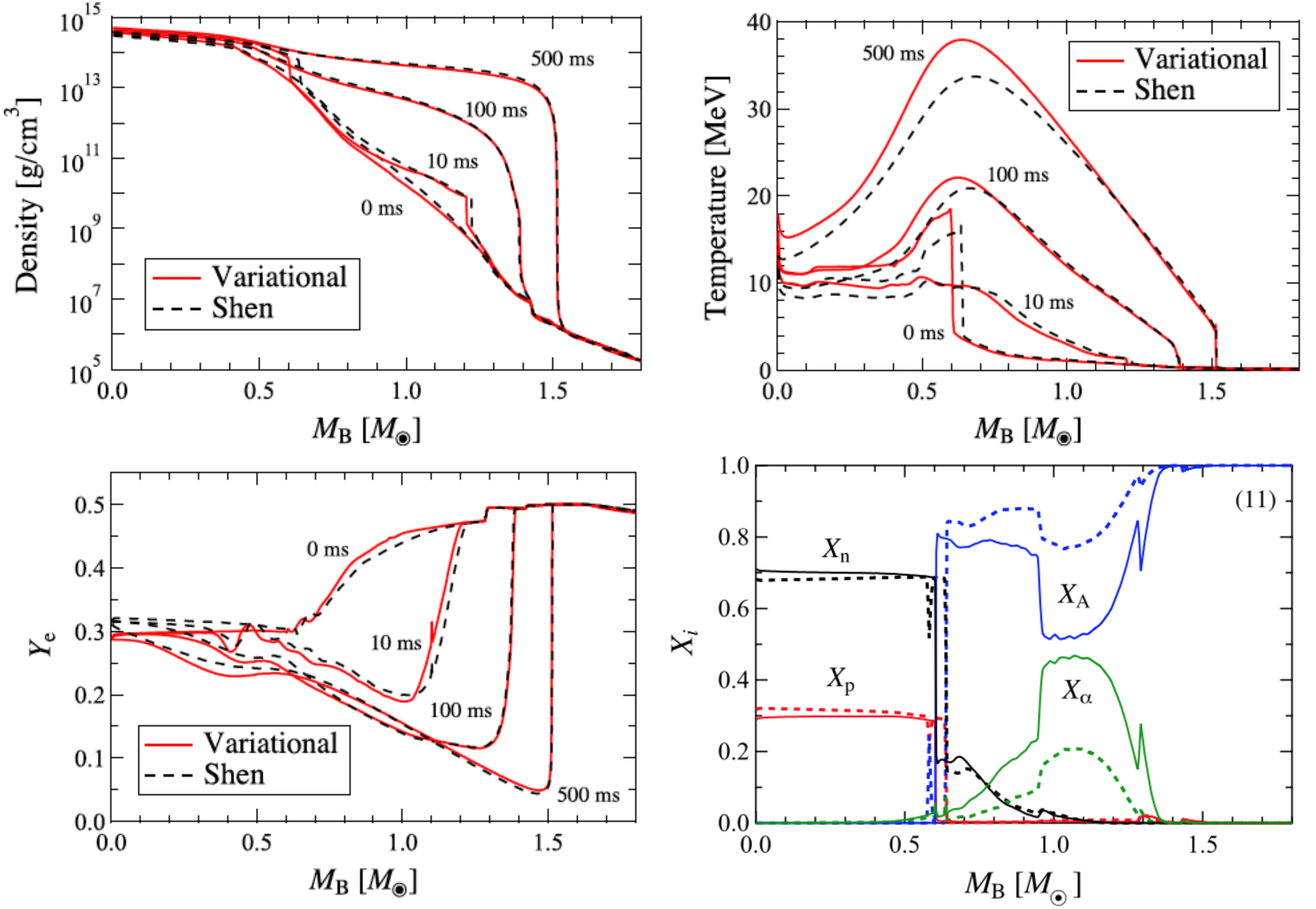
Radial trajectories of mass elements

Thermodynamic Profiles (Collapse Phase)



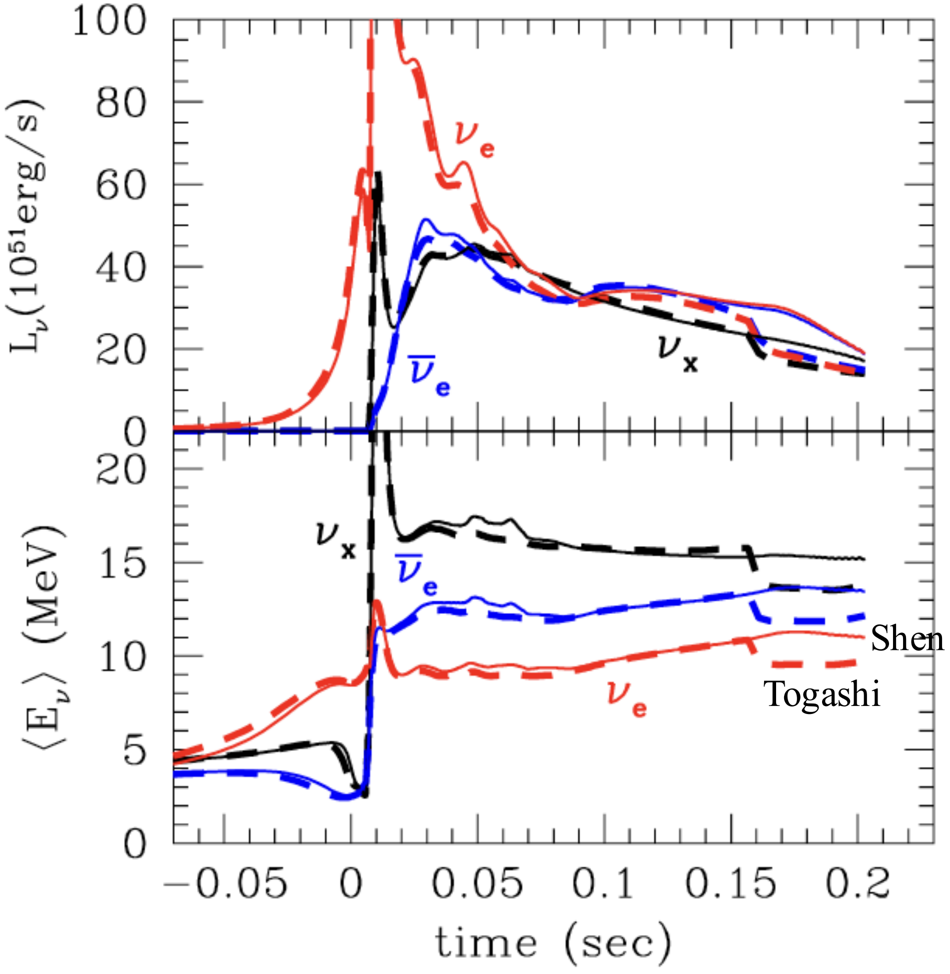
The numbers (1)–(5) :the times when the central density reaches 10^{10}, 10^{11}, 10^{12}, 10^{13}, 10^{14} g/cm^3

Thermodynamic Profiles (Postbounce Phase)

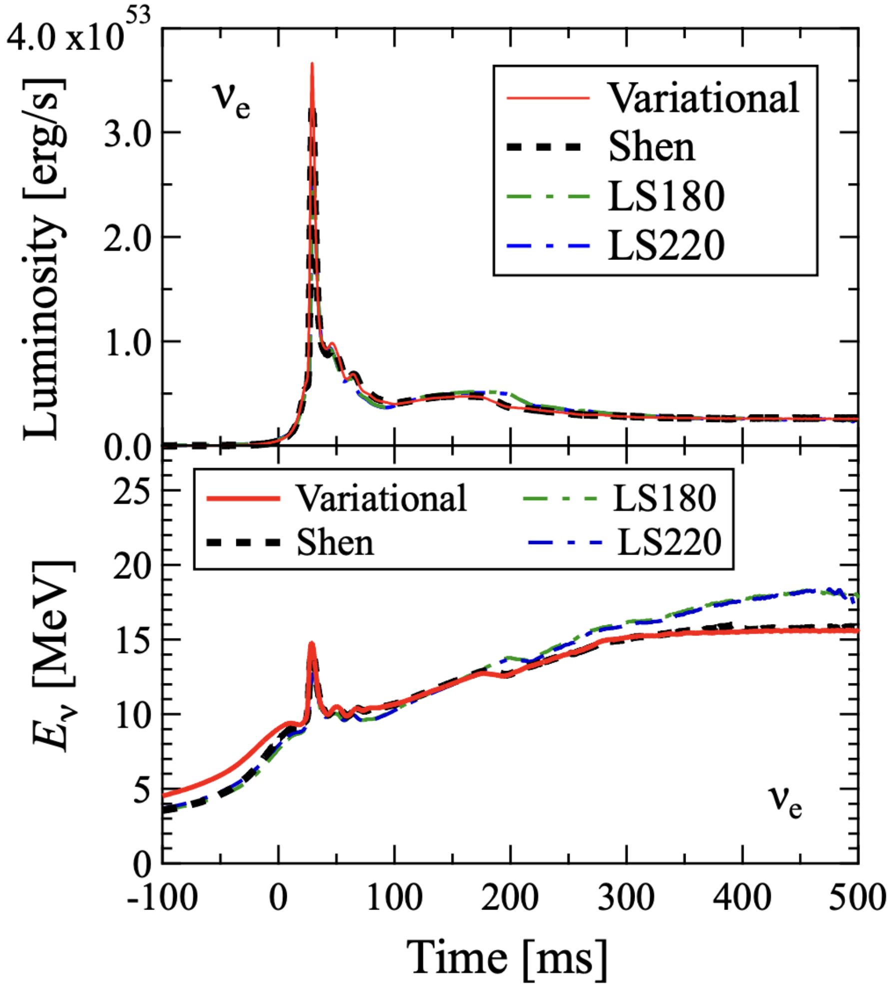


Neutrino Luminosity and average energy

Progenitor model : 9.6 $M_\odot$



Progenitor model : WW 15$M_\odot$



(Nakazato, Sumiyoshi & HT, PASJ 73 (2021) 639)

Effect of the EOS is small in emitted neutrino from supernova (!?)

3. Neutrino-nucleon reaction rates consistent with the EOS

Effect of the EOS is not so large in emitted neutrino from supernova explosion

<u>**Variational EOS with realistic nuclear forces**</u>

(**HT**, K. Nakazato, Y. Takehara, S. Yamamuro, H. Suzuki, and M. Takano, NPA961 (2017) 78)

*Constructed by **the variational many-body theory** with bare nuclear forces (**AV18+UIX**)*

For a more sophisticated simulations to understand the supernova mechanism,
we aim to construct nuclear reaction rates with neutrino in a self-consistent manner.

Difficulties in applying to astrophysical simulations

- Wide range of T, Y_p, n_B and neutrino energy E_ν
- Interaction rates need to be given in analytical forms!
  (Computer memory is already fully occupied by the EOS table)

Neutrino reactions in core-collapse simulations

1. Electron-type neutrino absorption on neutrons

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

2. Electron-type antineutrino absorption on protons

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

3. Neutrino bremsstrahlung in NN collisions

$$N + N' \leftrightarrow N + N' + \nu + \bar{\nu}$$

4. Neutrino scattering on nucleons

$$\nu + N \leftrightarrow \nu + N$$

As a first step of the project

5. Electron-type neutrino absorption on nuclei

$$\nu_e + A \leftrightarrow A + e^-$$

6. Neutrino coherent scattering on nuclei

$$\nu + A \leftrightarrow \nu + A$$

7. Neutrino scattering on electrons

$$\nu + e^- \leftrightarrow \nu + e^-$$

8. Electron-positron pair annihilation and creation

$$e^- + e^+ \leftrightarrow \nu + \bar{\nu}$$

9. Plasmon decay and creation

$$\gamma^* \leftrightarrow \nu + \bar{\nu}$$

We aim to calculate the neutrino reaction rates in a nuclear medium by using the cluster variational method.

I. Neutrino Charged Current Reactions on Nucleons

1. Electron-type neutrino absorption on neutrons

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

2. Electron-type antineutrino absorption on protons

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

Fermi interaction: $M = \frac{G}{\sqrt{2}} \bar{u}_p(p_p)\gamma^\mu(g_V - g_A\gamma_5)u_n(p_n)\bar{u}_e(p_e)\gamma_\mu(1-\gamma_5)u_\nu(q)$

Emissivity [s^{-1}]:

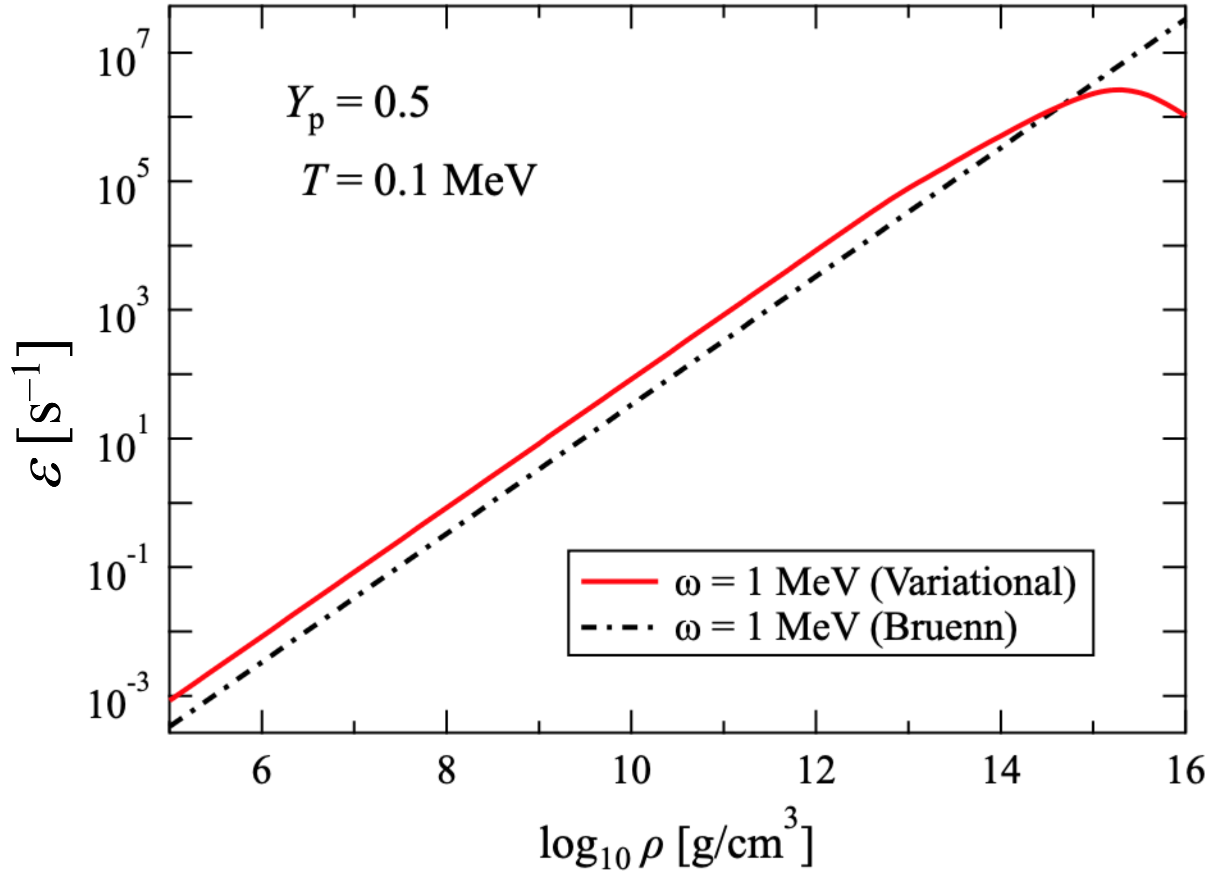
$$\begin{aligned}\epsilon(n_B, Y_p, T, E_\nu) &= 2\hbar^2 G_F^2 \cos^2\theta_c(1+3g_A^2)(2\pi)^4 \int \frac{d\boldsymbol{p}_n}{(2\pi\hbar)^3} \int \frac{d\boldsymbol{p}_p}{(2\pi\hbar)^3} \int \frac{d\boldsymbol{p}_e}{(2\pi\hbar)^3} \\ &\times \delta(E_p + E_e - E_n - E_\nu)\delta^3(\boldsymbol{p}_p + \boldsymbol{p}_e - \boldsymbol{p}_n - \boldsymbol{p}_\nu) f_n(E_n)\left[1 - f_p(E_p)\right)]\left[1 - f_e(E_e)\right)]\end{aligned}$$

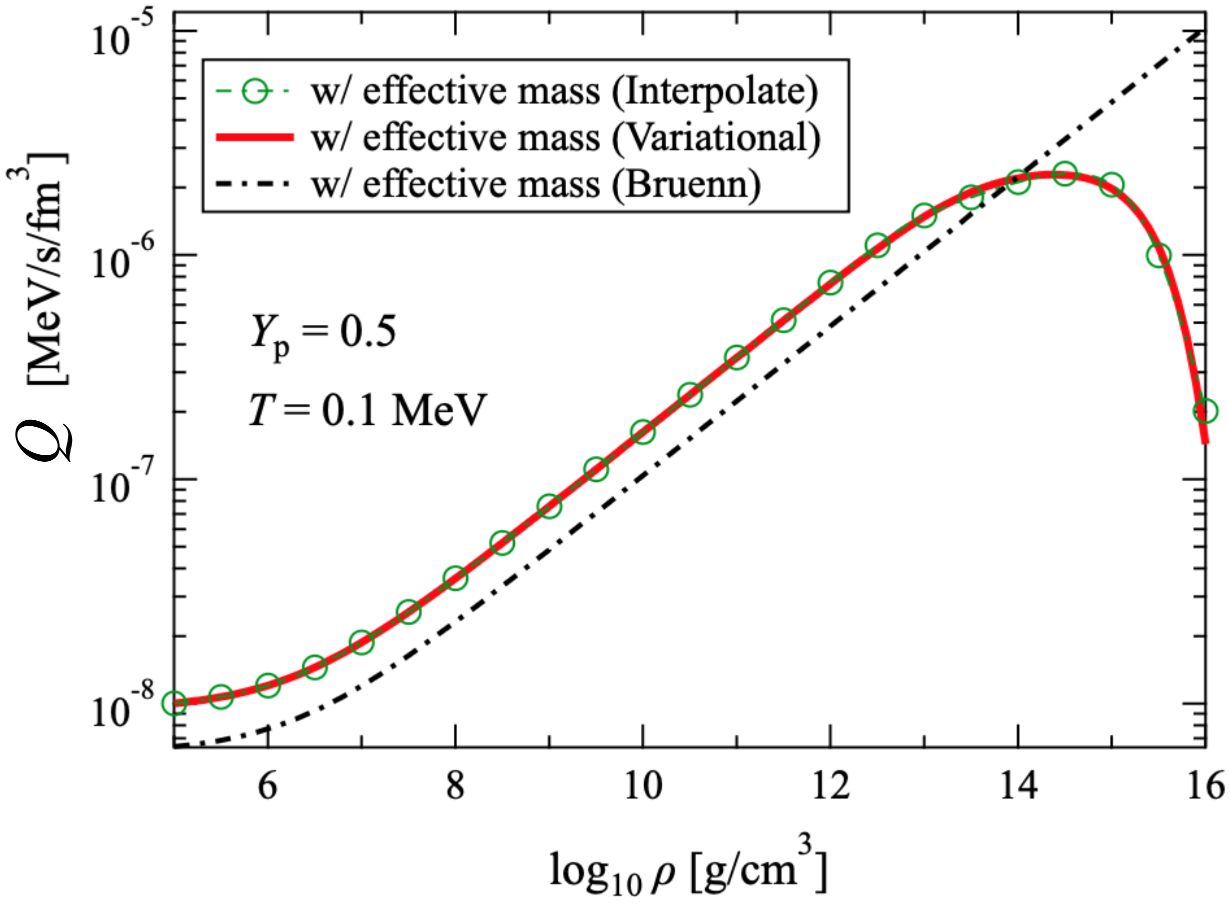
Occupation probabilities obtained from the variational method are applied.

$$f_i(k) = \left\{1 + \exp\left[\frac{\varepsilon_i(k) - \mu_{0i}}{k_B T}\right]\right\}^{-1} \qquad \varepsilon_i(k) = \frac{\hbar^2 k^2}{2m_i^*}$$

Neutrino Emissivity with the variational method

$$Q(n_{\mathrm{B}}, Y_{\mathrm{p}}, T) = \int \frac{d\boldsymbol{p}_\nu}{(2\pi\hbar)^3} \epsilon(n_{\mathrm{B}}, Y_{\mathrm{p}}, T, E_\nu) E_\nu f_\nu$$



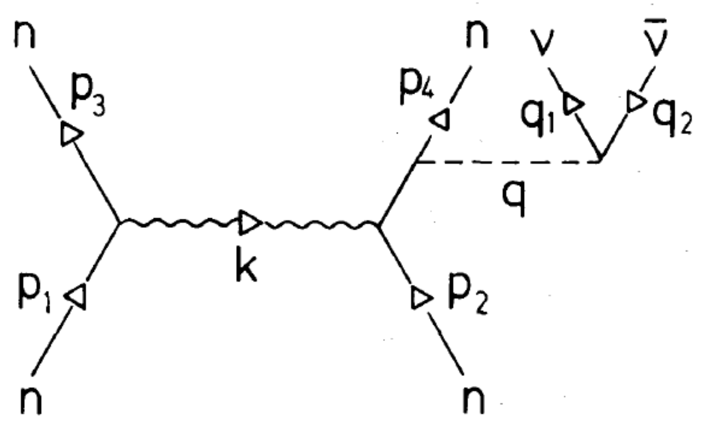


II. Nucleon Bremsstrahlung Process

One-Pion Exchange Potential

B. L. Friman and O. V. Maxwell, Astrophys. J. 232 (1979) 451.

O. V. Maxwell, Astrophys. J. 316 (1987) 691.



$$V_{12}(\mathbf{k}) = -\left(\frac{f}{m_\pi}\right)^2 (\tau_1 \cdot \tau_2) \frac{(\boldsymbol{\sigma_1} \cdot \mathbf{k})(\boldsymbol{\sigma_2} \cdot \mathbf{k})}{k^2 + m_\pi^2}$$

Total Energy Emissivity

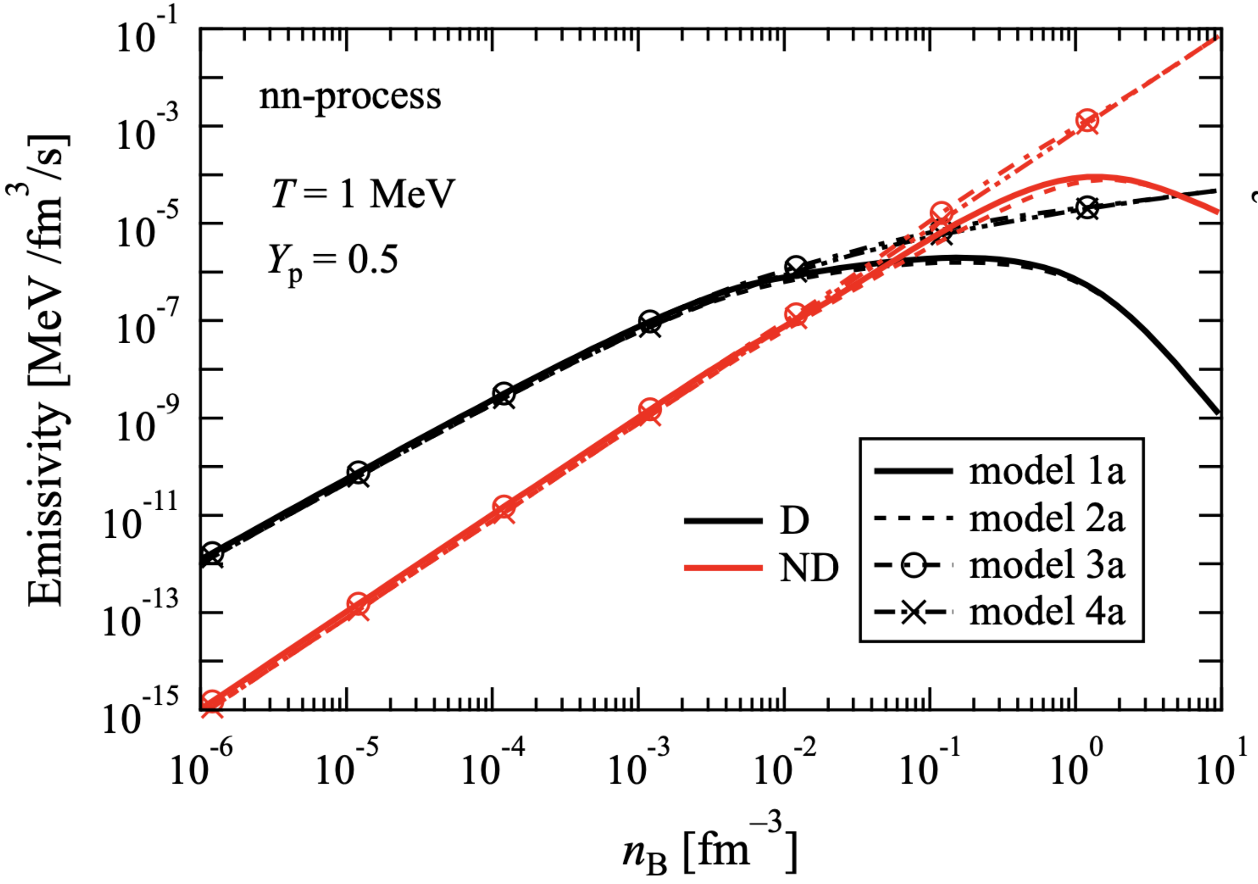
$$Q^{NN}(n_{\mathrm{B}}, Y_{\mathrm{p}}, T) = \frac{\hbar^8}{c^2}(2\pi)^4 \int \prod_{i=1}^{4} \left[\frac{d\boldsymbol{p}_i}{(2\pi\hbar)^3}\right] \frac{d\boldsymbol{q}_1}{(2\pi\hbar)^3 2\omega_1} \frac{d\boldsymbol{q}_2}{(2\pi\hbar)^3 2\omega_2} (\omega_1 + \omega_2)$$

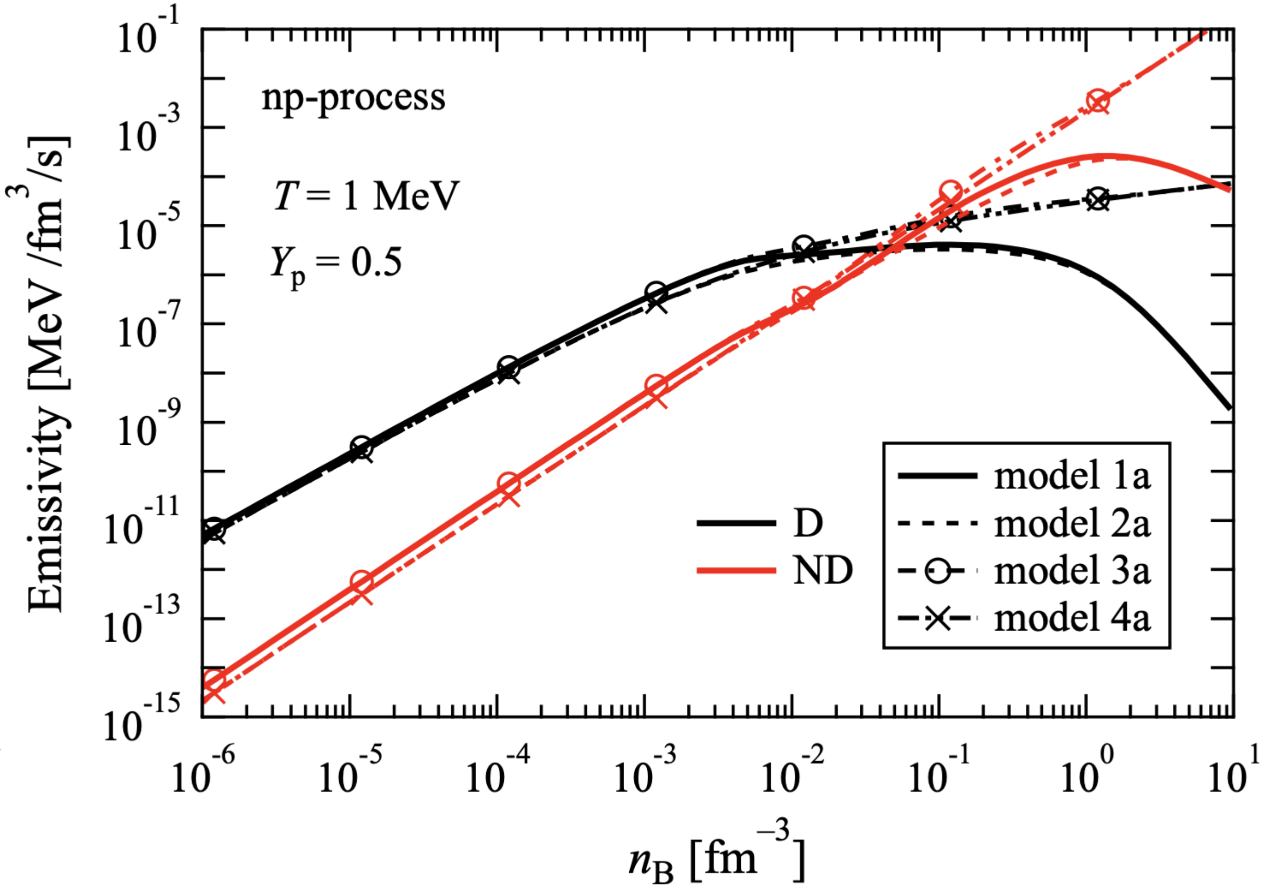
$$\times \quad \delta(E_{\mathrm{fin}} - E_{\mathrm{ini}})\delta^3(\boldsymbol{P}_{\mathrm{fin}} - \boldsymbol{P}_{\mathrm{ini}}) f_1(\epsilon_1) f_2(\epsilon_2) [1 - f_3(\epsilon_3)] [1 - f_4(\epsilon_4)]\, s \sum_{\mathrm{spin}} |M_{NN}|^2$$

Occupation probabilities obtained from the variational method are applied.

Taking into account the correlation between two nucleons

Neutrino Total Energy Emissivity





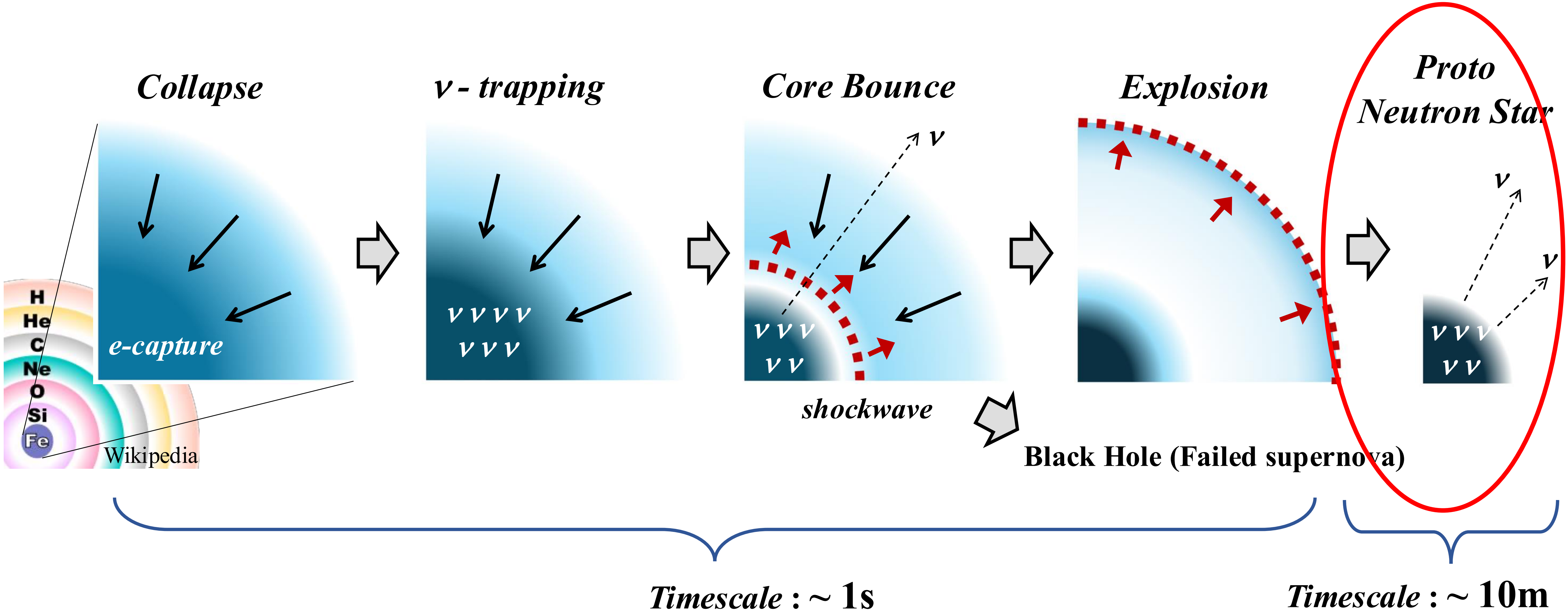
1a: f_i & $|M|$ are improved.

3a: $|M|$ is improved.

2a: f_i is improved.

4a: No improvement

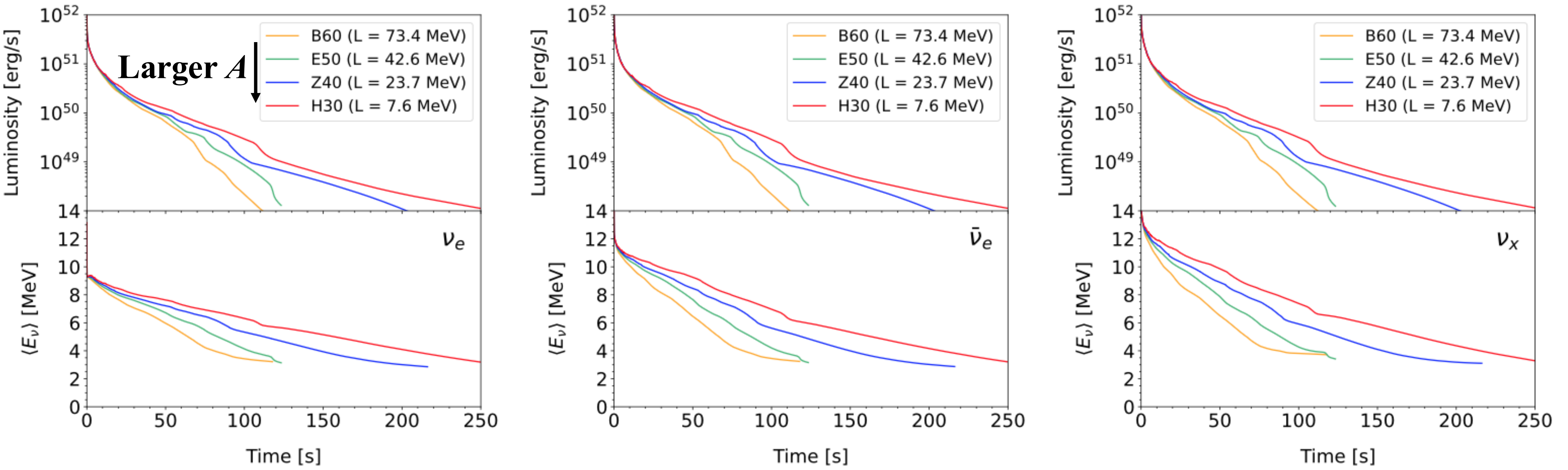
4. Neutrino-nucleus coherent scattering in PNS cooling



We performed proto-neutron star (PNS) cooling simulations using several EOS models that systematically differ in nuclear size.

Neutrino Light Curves from Proto-Neutron Star Cooling

(Nakazato, HT, Sumiyoshi & Suzuki, accepted in PTEP)



(a) ν_e (b) $\bar{\nu}_e$ (c) ν_x

The heavier nuclei have substantially larger scattering cross sections with neutrinos as a result of coherent effects.

Summary

Nuclear EOS and **Neutrino Reaction Rates in nuclear medium** are essential ingredients for core-collapse supernova simulations.

- The EOS dependence in core-collapse supernova simulations is gradually being investigated.
- Uncertainty in neutrino reaction rates in nuclear matter is still large.

We are reformulated neutrino-nucleon rection rates in supernova simulations by using the cluster variational method.

Future Plans

- Supernova simulations with the obtained neutrino reaction rates
- Analytical expression of the interaction rates