Neutrinos from Proto-neutron Star Cooling and Nuclear Equation of State: Effects of Coherent Elastic Scattering

Ken'ichiro Nakazato (Kyushu University)
Hideyuki Suzuki (Tokyo Univ. Sci.)

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Supernovae and Equation of State

- Physics in core-collapse supernovae（SNe）
  - ✓ Gravity（GR）
  - ✓（Magneto）Hydrodynamics
  - ✓ Neutrino Reaction
  - ✓ Nuclear Equation of State

- Tables of Equation of State（EOS）
  - ✓ Skyrme type interaction

    El Eid & Hillebrandt (1980), Lattimer & Swesty (1991)

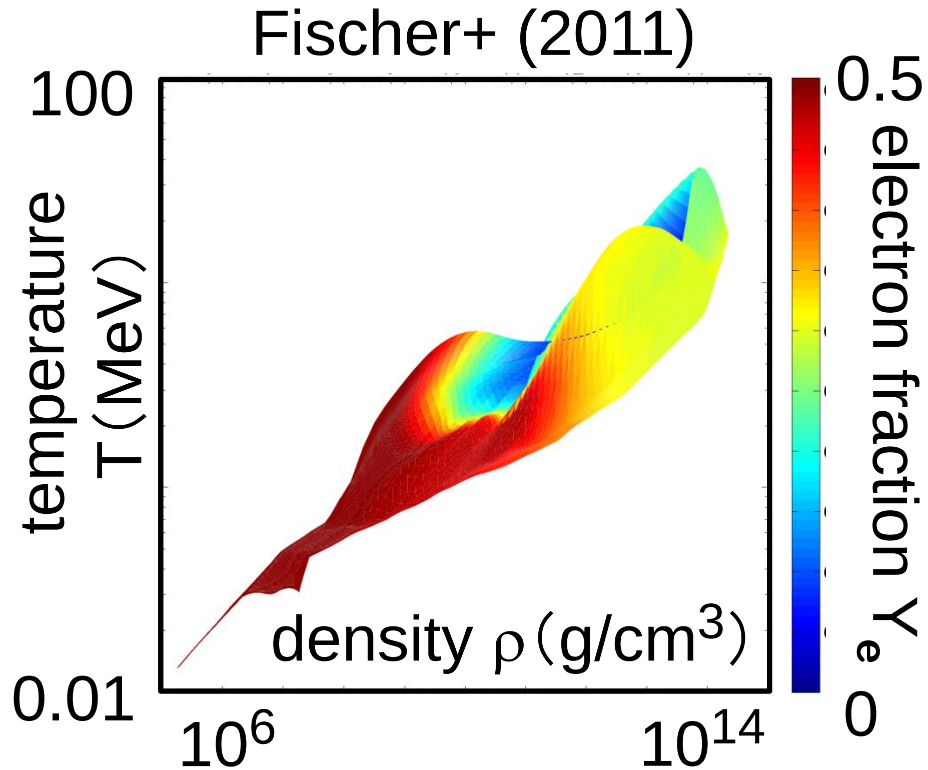
  - ✓ Relativistic mean field model

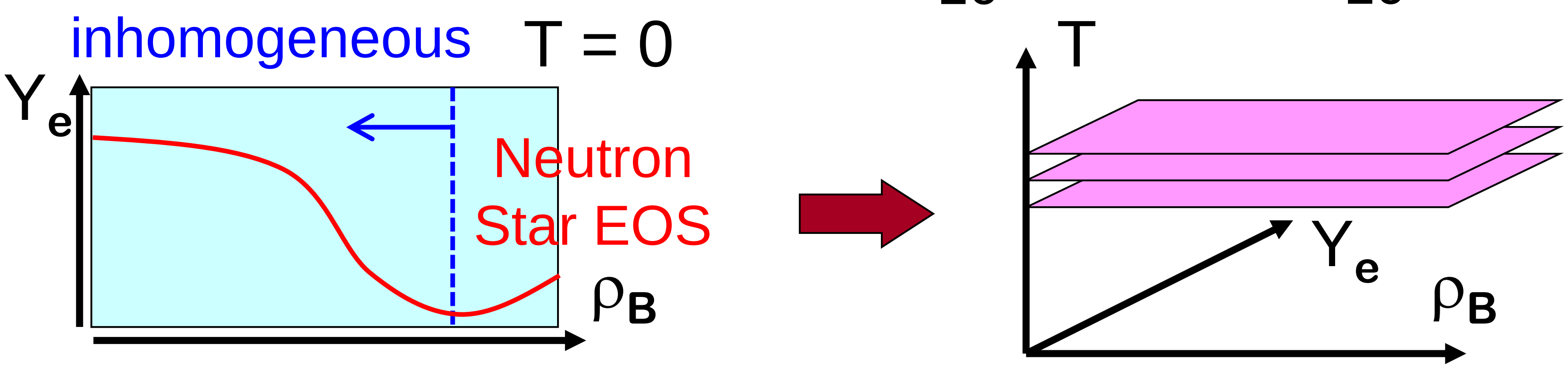
    H. Shen+ (1998, 2011), Hempel & Schaffner-Bielich (2010), G. Shen+ (2011), Steiner+ (2013)

+α： Ishizuka+ (2008), Nakazato+ (2008), Sagert+ (2009)

What is EOS table?

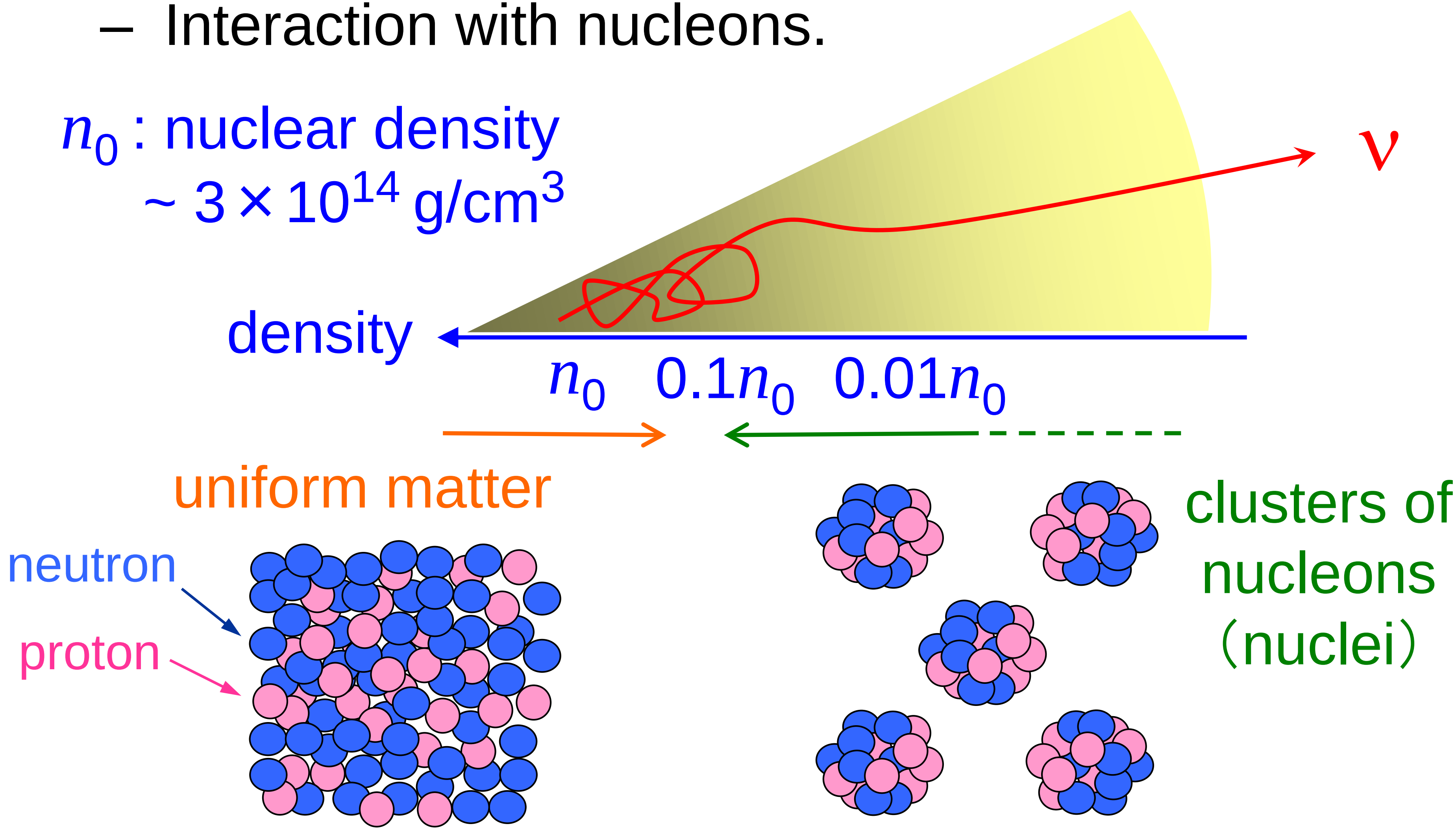
- Thermodynamical variables (e.g., free energy, entropy) should be given as functions of ρ, T and Y_e for wide range as realized in SNe.





Supernova neutrino

- Neutrinos come from deep inside supernova.
  - Interaction with nucleons.

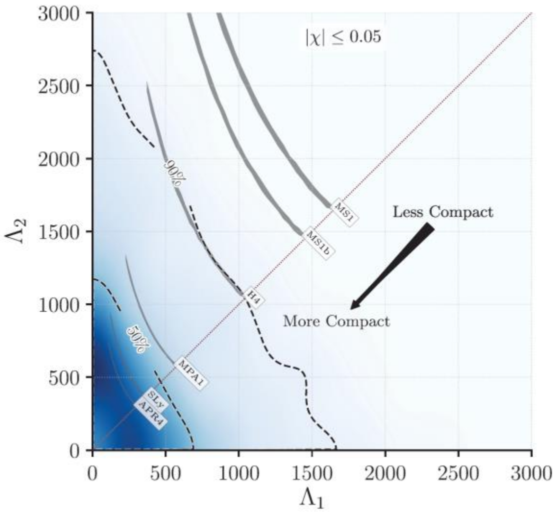


New nuclear EOS table

Togashi, Nakazato et al. NPA 961（2017）78

- Constructed on the basis of the many body theory with the realistic nuclear force
  - variational method（Togashi & Takano 2013）
- EOS of finite temperature and involving the inhomogeneous phase as in Shen EOS
  - local density approximation（Oyamatsu 1993）
  - without pasta phase（e.g. Horowitz et al. arXiv:1611.10226）
- How do uniform and inhomogeneous phases of EOS affect supernova neutrino emission?

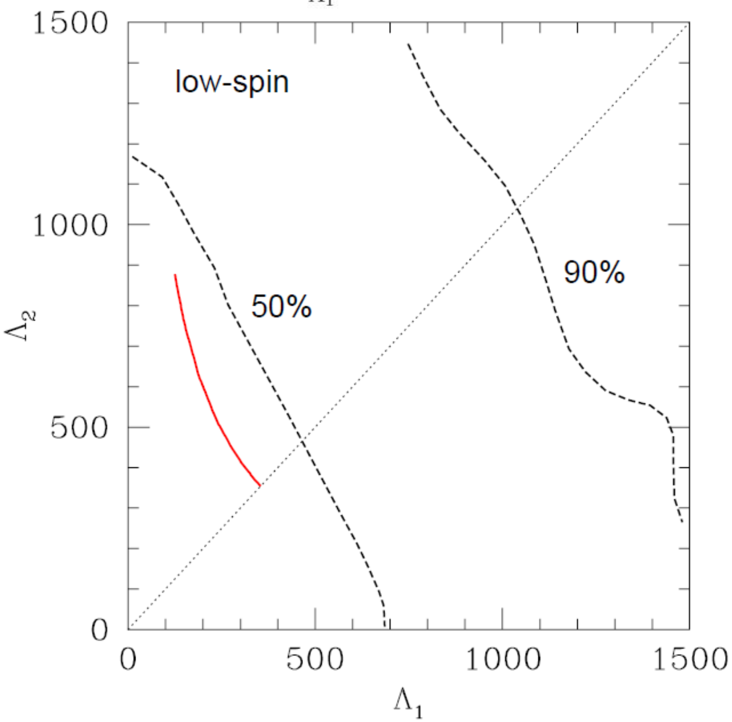
Property of new nuclear EOS



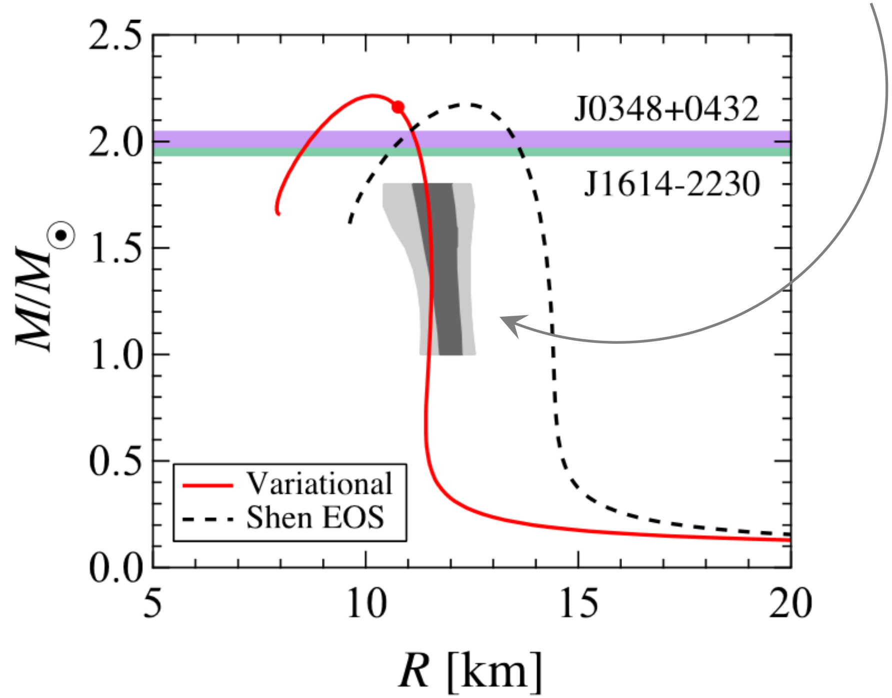
Togashi, Nakazato et al. NPA 961（2017）78

- Consistent with NS radius measurements and tidal deformability from GW170817.

← [PRL **119** (2017), 161101]



（Steiner et al. 2010）



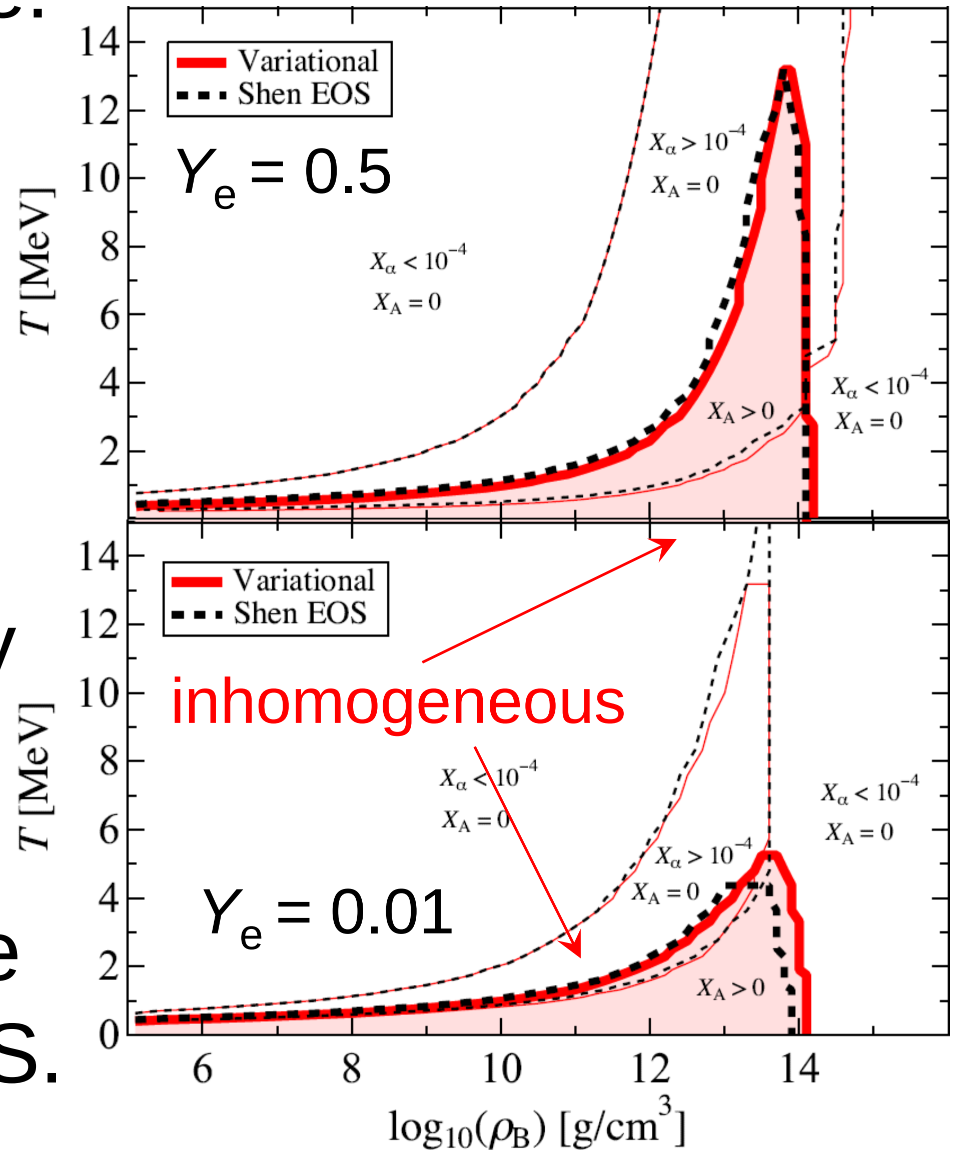
Comparison with other EOSs

EOS	variational	LS220	Shen
K [MeV]	245	220	281
S_0 [MeV]	30.0	28.6	36.9
L [MeV]	35	73.8	111
ρ_0 [10^{14} g/cm^3]	2.66	2.57	2.41
w_0 [MeV]	16.1	16.0	16.3

- Symmetry gradient, L, is lower.
  → large symmetry energy at low densities.
  → small symmetry energy at high densities.

Finite temperature phase diagram

- Inhomogeneous phase: subnuclear densities and T < 10 MeV.
- Low Y_e (elec. fraction) → low critical T and low transition density.
- Reflecting the property of nuclear matter model, the region of inhomogeneous phase is different among EOS.

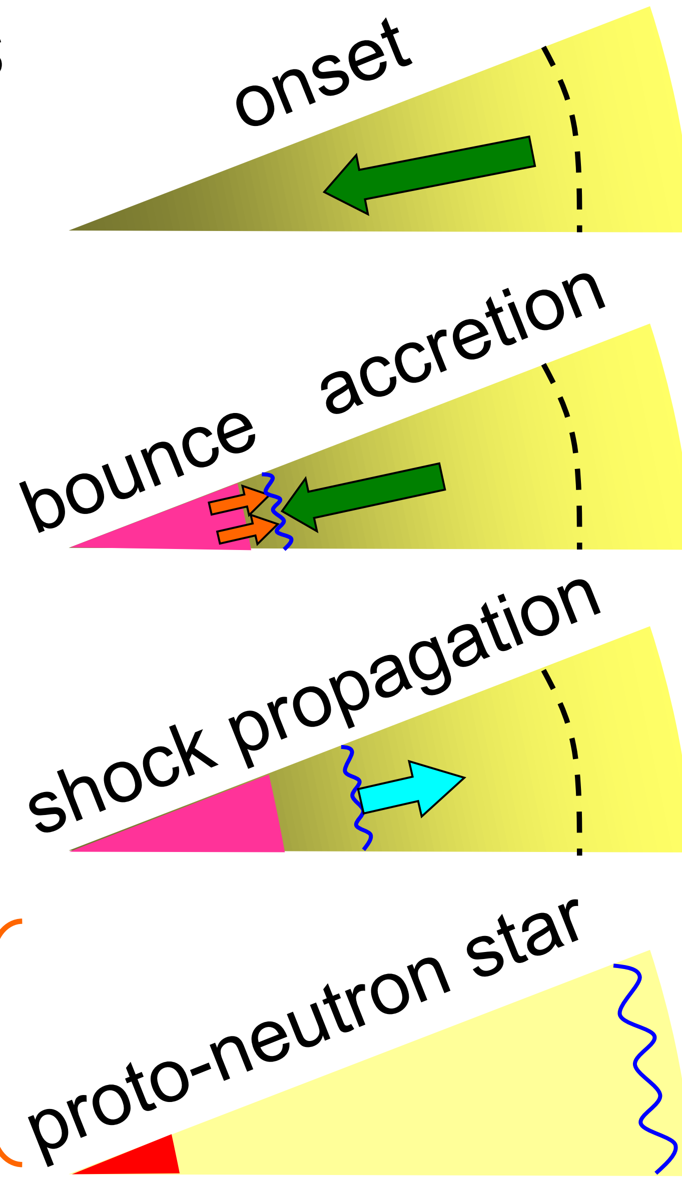


Proto-neutron star cooling

- Proto-neutron star（PNS）is formed at the center of SN.

  → cooled by ν emission.

- EOS dependence of PNS evolution after the shock revival is studied.



this phase

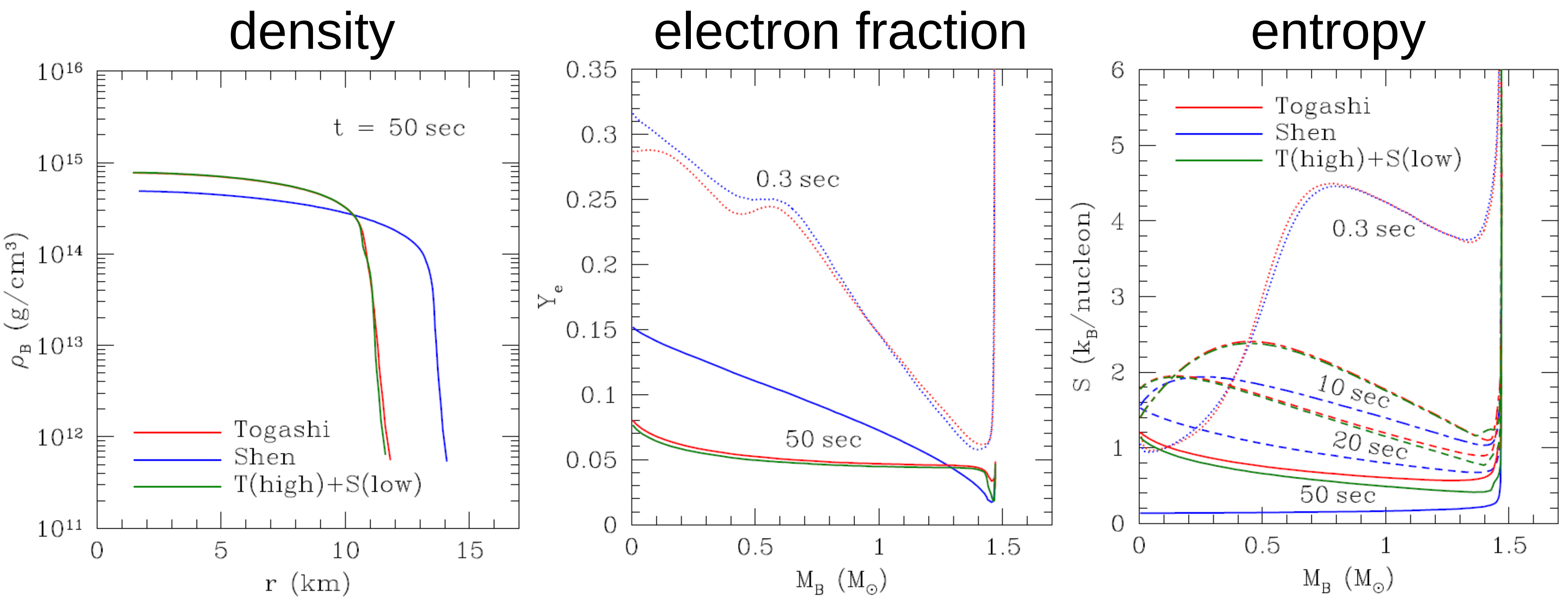
Setup

- Step1: Core-collapse simulation of spherical GR ν radiation hydrodynamical simulation for $15M_{\odot}$ star（Woosley & Weaver 1995）until 0.3 sec.

- Step2: After that, quasi-static evolutionary calculation of PNS（~$1.5M_{\odot}$）cooling.
  - transfer of ν_e, $\bar{\nu}_e$, ν_μ ($= \nu_\tau = \bar{\nu}_\mu = \bar{\nu}_\tau$) is treated in Multigroup Flux Limited Diffusion scheme

- EOS: ① Variational model（Togashi）, ② Shen ③ Mixed（Togashi for $\geq 2 \times 10^{14}$ g/cc, Shen for $\leq 10^{14}$ g/cc, and they are interpolated; T+S）

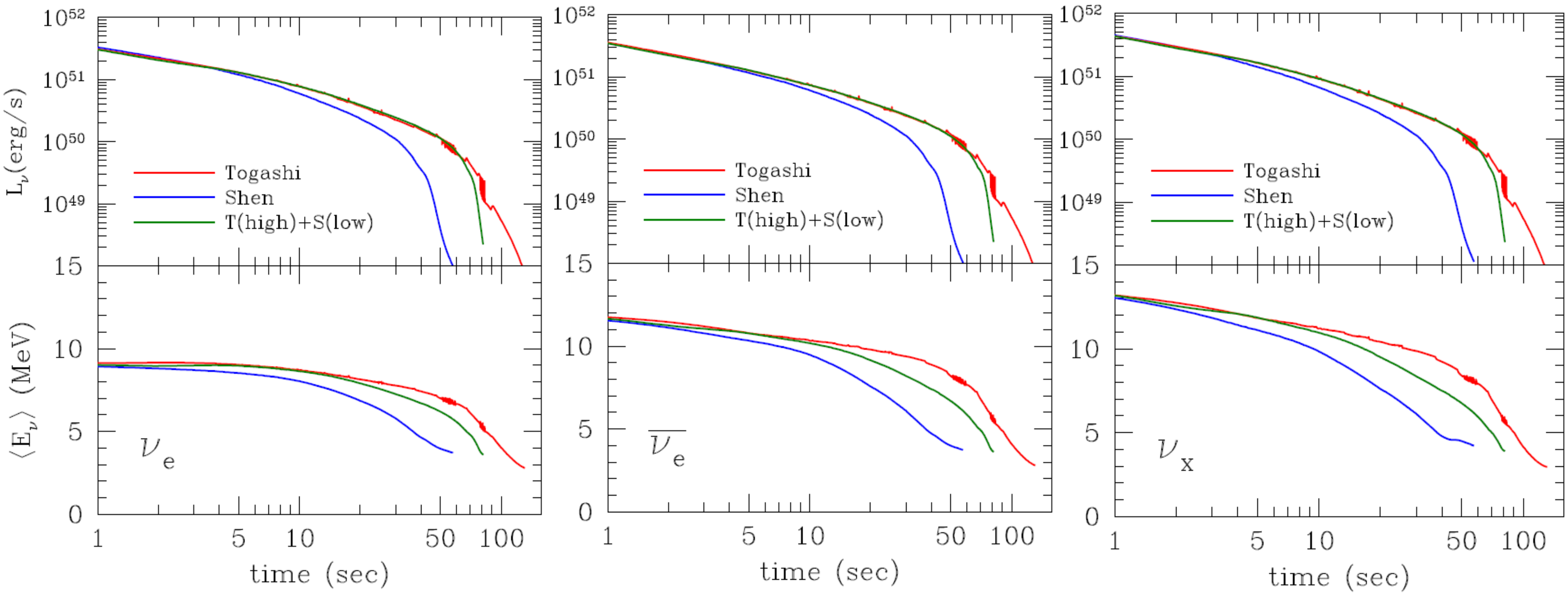
Profiles of PNS



- Soft EOS makes compact PNS.
  → high density and small radius
- Low *L* EOS results in low Y_e due to small symmetry energy at high densities.

Neutrino light curve

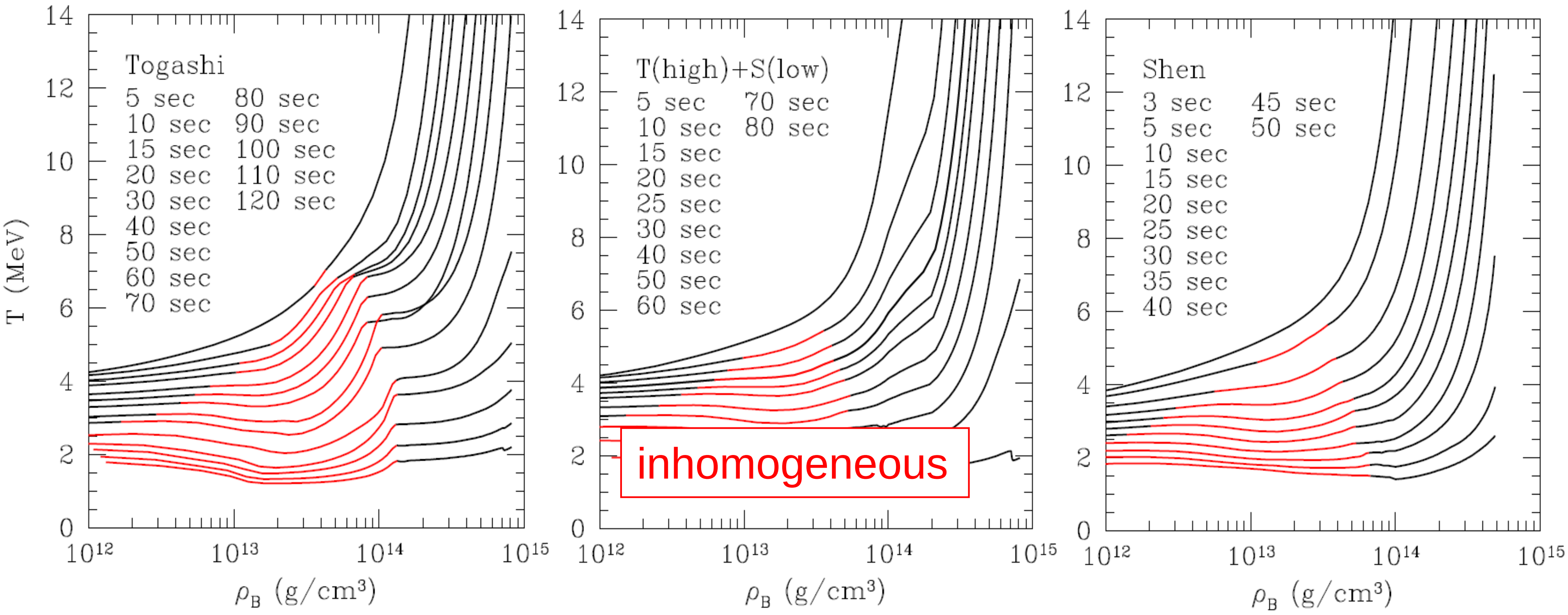
- High density EOS determines luminosity.
  - Luminosity drops steeper for faster cooling
  - Variational EOS results high density / slow cooling
- Av. energy depends also on low density EOS.



Inhomogeneous region

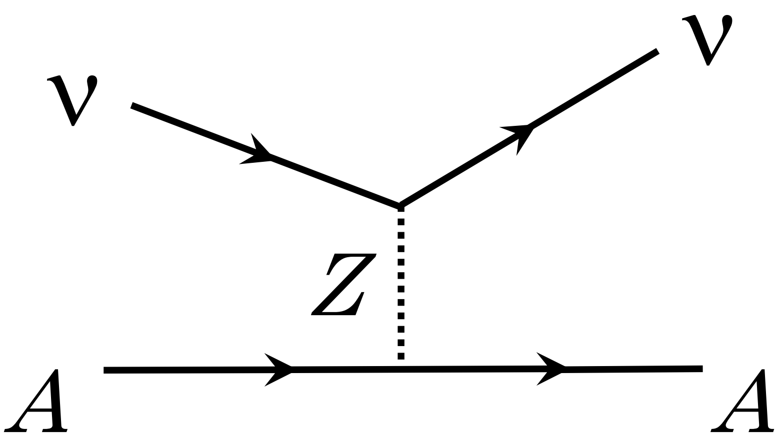
- Variational EOS has inhomogeneous phase for higher density and temperature.

  → In inhomogeneous phase, cooling slows down and the surface is kept hot.



In the inhomogeneous phase…

$$\nu + A \rightarrow \nu + A$$



- Coherent elastic scattering

  → If nuclear size is much lower than neutrino wave length, cross section gets larger.

$$\boldsymbol{\sigma} \sim \frac{G_{\mathrm{F}} E_\nu^2}{4\pi} \left[N - (1 - 4\sin^2\theta_{\mathrm{W}})Z\right]^2$$

neutron rich & $1 - 4\sin^2\theta_{\mathrm{W}} \sim 0$

$$\Rightarrow \ \boldsymbol{\sigma} \propto A^2$$

Coherent effect

- Due to the scattering, neutrino wave number changed $\vec{k} \to \vec{k'}$, state of nucleus unchanged
  $\longrightarrow$ nucleus = sum of nucleons' potentials

$$V(\vec{r}) = \sum_{i=1}^{A} v\delta(\vec{r} - \vec{r_i})$$

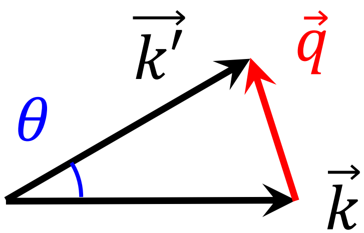
- Fermi's golden rule: $\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} \propto \left| \left\langle \vec{k'} \,\middle|\, V(\vec{r}) \,\middle|\, \vec{k} \right\rangle \right|^2$

- If neutrino wave function is a plane wave …

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} \propto \left| \int \sum_{i=1}^{A} v e^{-i\vec{k'}\cdot\vec{r}} \delta(\vec{r} - \vec{r_i}) e^{\vec{k}\cdot\vec{r}} \, d\vec{r}^3 \right|^2$$

Coherent effect (cont.)

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} \propto \left|\sum_{i=1}^{A} \nu e^{-i\vec{q}\cdot\vec{r_i}}\right|^2 = \nu^2 \sum_{i,j}^{A} e^{i\vec{q}\cdot(\vec{r_i}-\vec{r_j})}$$



$$|\vec{k}| = |\vec{k'}|$$

$$= \nu^2 A + \nu^2 \sum_{i \neq j}^{A} e^{i\vec{q}\cdot(\vec{r_i}-\vec{r_j})}$$

per nucleon

coherence

- Neutrinos' wave length: $120\left(\frac{10\ \mathrm{MeV}}{E_\nu}\right)$ fm
- Radius of nucleus: $5.6\left(\frac{A}{100}\right)^{1/3}$ fm

$$\rightarrow\ |\vec{r_i} - \vec{r_j}| \ll 1/|\vec{q}|\ \rightarrow\ e^{i\vec{q}\cdot(\vec{r_i}-\vec{r_j})} \sim 1$$

$$\rightarrow\ \frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} \propto \nu^2 A + \nu^2 \frac{A(A-1)}{2} \propto A^2$$

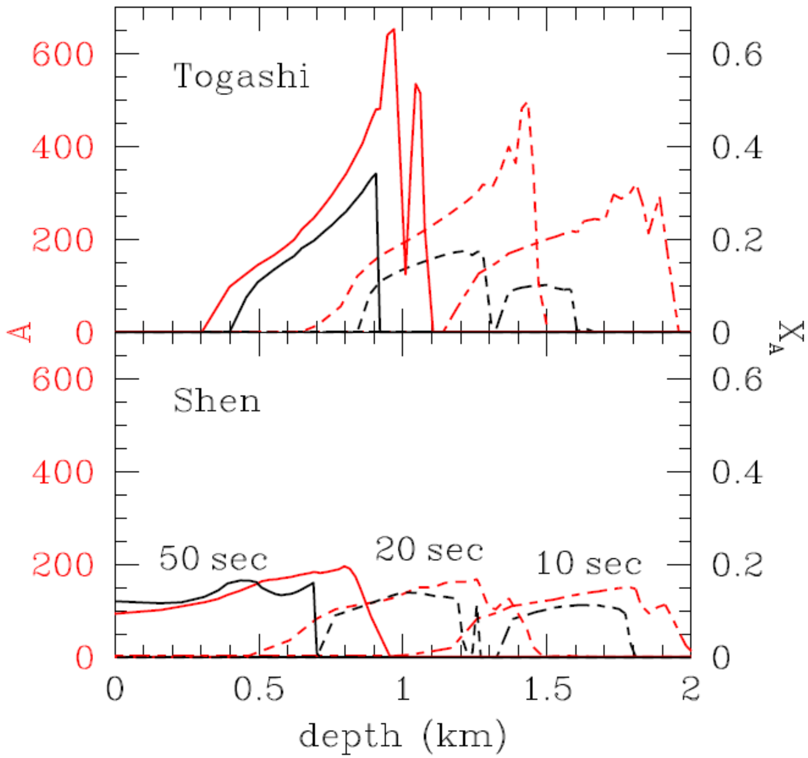
Nuclear size near PNS surface

- Large nuclear mass number is estimated for varational EOS.

  → Cross section of the coherent elastic scattering is enhanced making cooling time scale longer.

- Thermal insulation by heavy nuclei

$$\begin{cases} \sigma \propto A^2 \\ 1/\lambda \propto X_A \cdot A \end{cases}$$



A; mass number

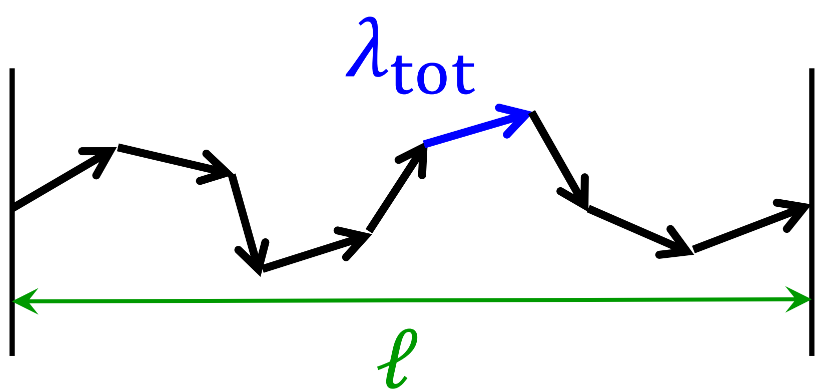
X_A; fraction of nuclei

Neutrino Energy Sphere (1)

- Why thermalization is enhanced by coherent elastic scattering, no energy exchange?
  - neutrino mean free path for all reactions : λ_{tot}
  - " for energy exchange reactions : λ_{th}
  - within 1 energy exchange reaction, neutrinos propagate the distance… ℓ
  - in this way, total reaction number… N

$$\ell = \sqrt{N}\lambda_{\mathrm{tot}}$$

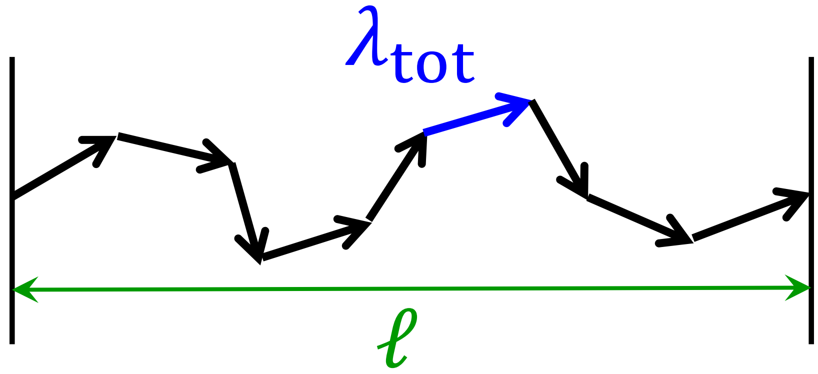
(random walk)



Neutrino Energy Sphere (2)

$$\ell = \sqrt{N}\lambda_{\mathrm{tot}}$$

(random walk)



– In this way, neutrinos travel… $N\lambda_{\mathrm{tot}}$

→ it is nothing but λ_{th}

$$N = \frac{\lambda_{\mathrm{th}}}{\lambda_{\mathrm{tot}}} \quad \Longrightarrow \quad \ell = \sqrt{\lambda_{\mathrm{th}}\lambda_{\mathrm{tot}}}$$

- Thermalization radius : R_{th}

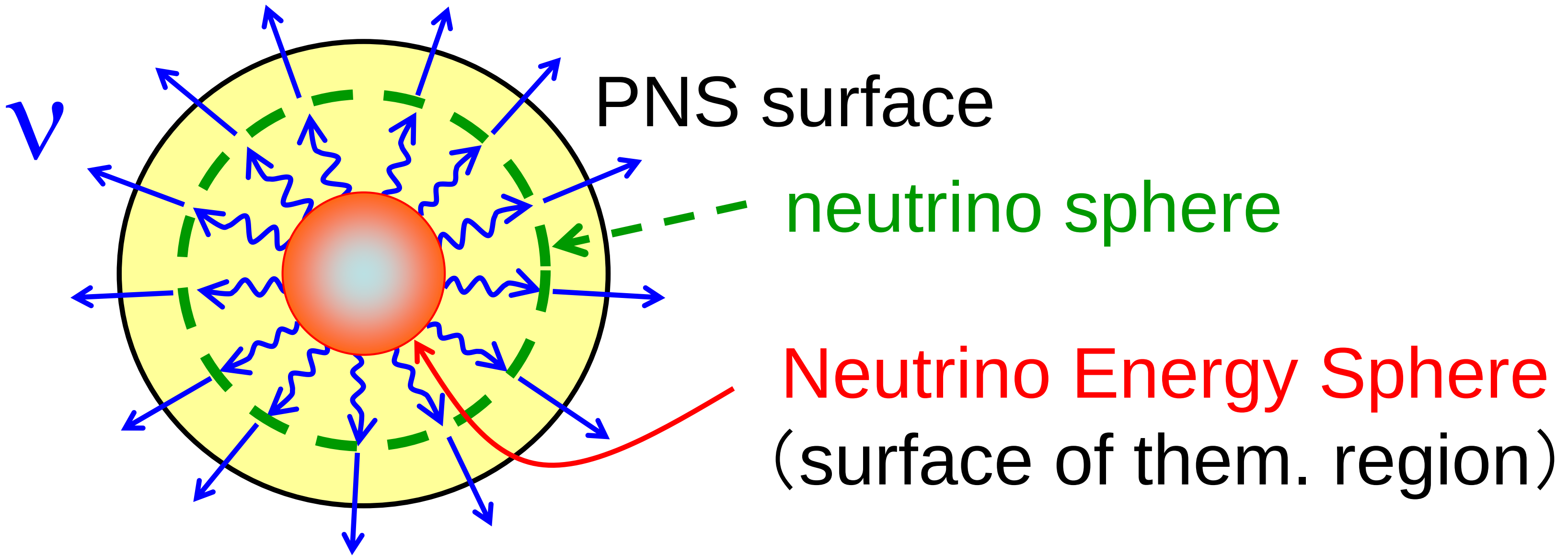
$$\int_{R_{\mathrm{th}}}^{R_{\mathrm{s}}} \frac{\mathrm{d}r}{\ell} = \frac{2}{3} \quad \Longrightarrow \quad \int_{R_{\mathrm{th}}}^{R_{\mathrm{s}}} \frac{\mathrm{d}r}{\sqrt{\lambda_{\mathrm{th}}\lambda_{\mathrm{tot}}}} = \frac{2}{3}$$

Neutrino Energy Sphere (3)

- Thermalization radius : R_{th}

$$\int_{R_{\mathrm{th}}}^{R_{\mathrm{s}}} \frac{\mathrm{d}r}{\sqrt{\lambda_{\mathrm{th}}\lambda_{\mathrm{tot}}}} = \frac{2}{3}$$

→ If λ_{tot} gets lower due to coherent scattering, thermalization radius goes outer.



Summary and Future work

- New EOS based on the variational method is constructed and applied to PNS cooling

  → EOS table: www.np.phys.waseda.ac.jp/EOS/

- Neutrino luminosity is determined by high density EOS and average energy is affected also by low density region due to coherent scattering.

- Future work: impacts on the spectrum of supernova relic neutrino should be studied.