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

Ken'ichiro Nakazato

（Faculty of Arts & Science, Kyushu University）

in collaboration with

H. Suzuki（Tokyo Univ. of Sci.） and H. Togashi（RIKEN）

to appear in PRC, arXiv:1710.10441 [astro-ph.HE].

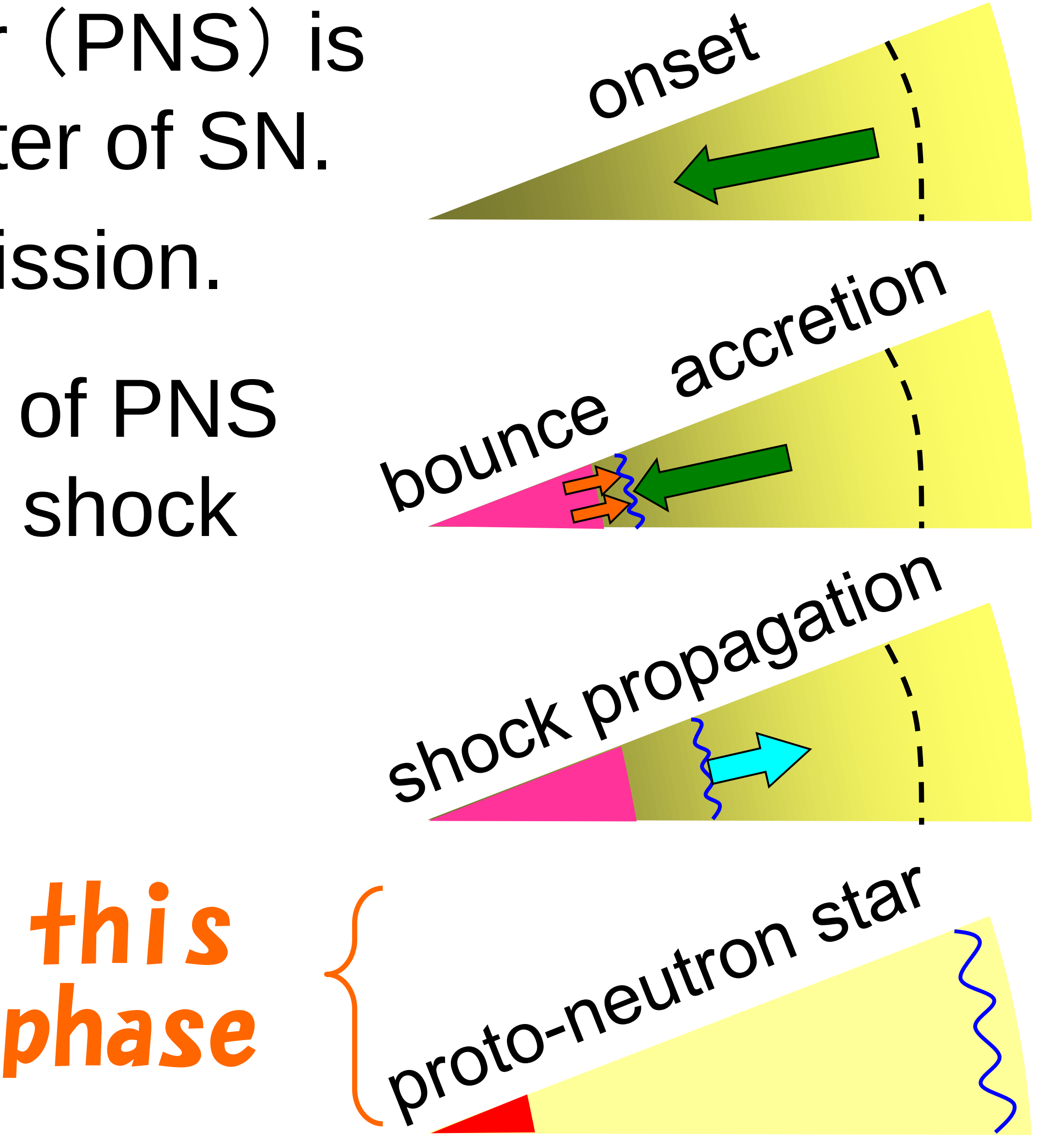
Mar. 19-21, 2018 @ Waseda University.

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.



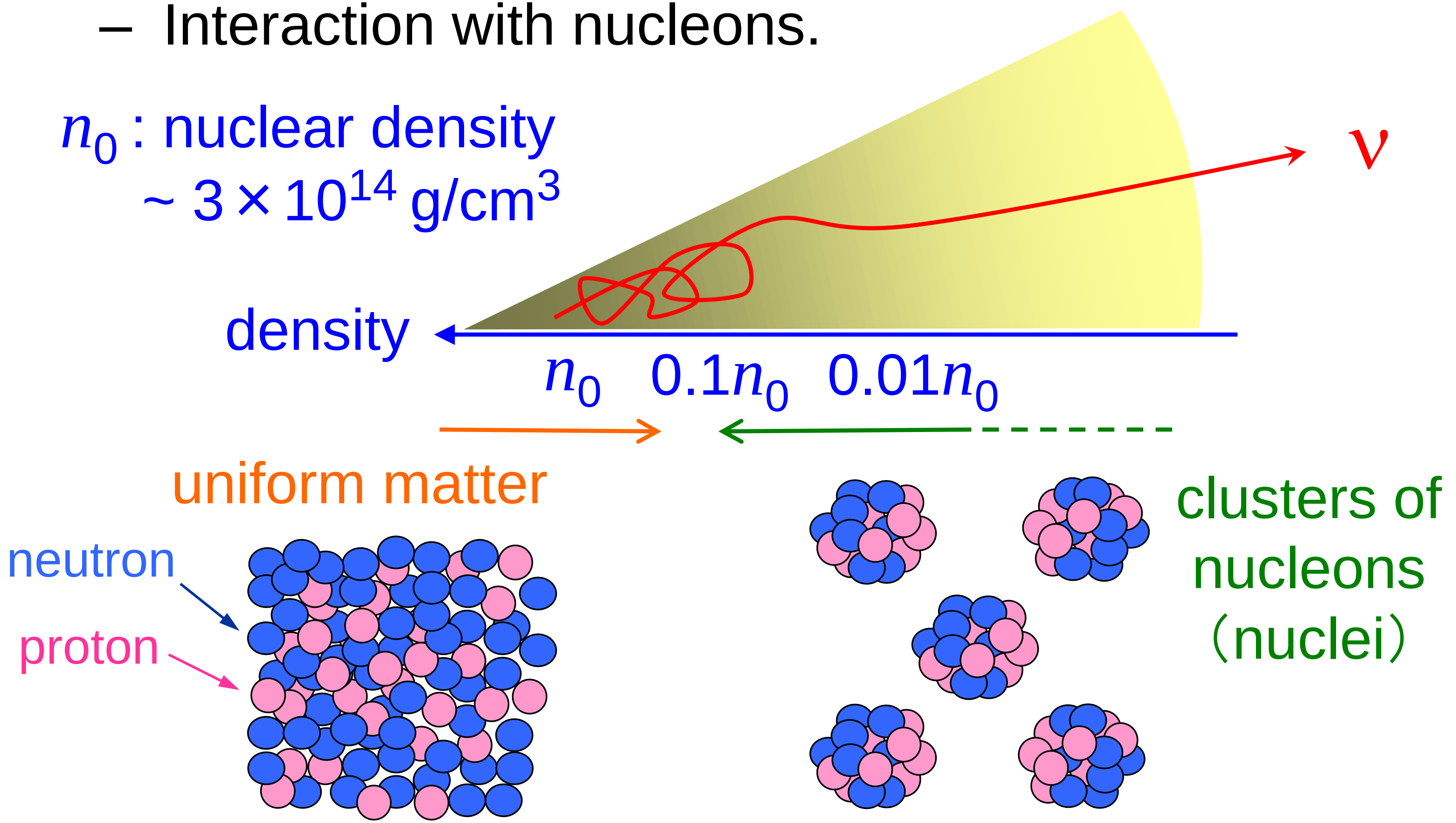
Supernovae and Equation of State

- 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), G. Shen+ (2011), Hempel+ (2012) etc.
  - ✓ Variational method with realistic nuclear force
    Togashi+ (2017)

Supernova neutrino

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



Setup

- Step1: Core-collapse simulation of spherical GR ν radiation hydrodynamics is performed 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

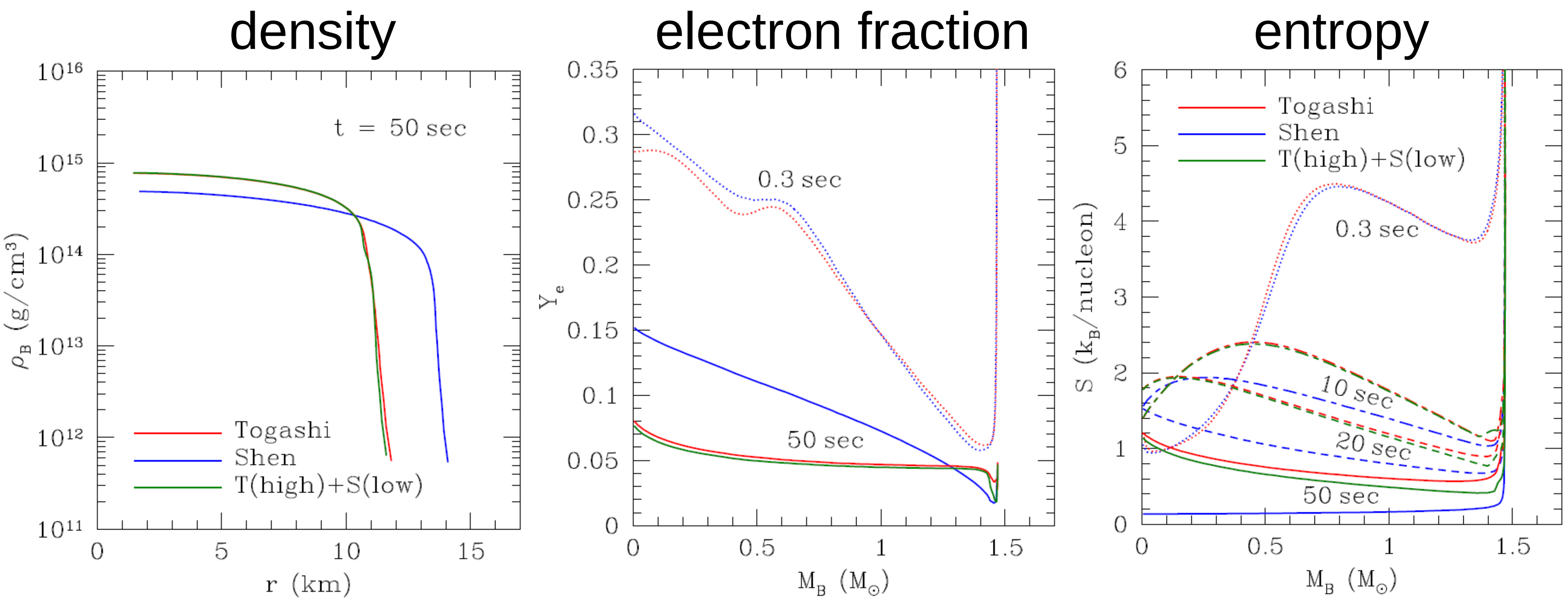
- EOS: ① Togashi（Variational model）, ② Shen ③ Mixed（Togashi for $\geq 2\times10^{14}$ g/cc, Shen for $\leq 10^{14}$ g/cc, and they are interpolated）

Properties of EOSs

EOS	Togashi	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.

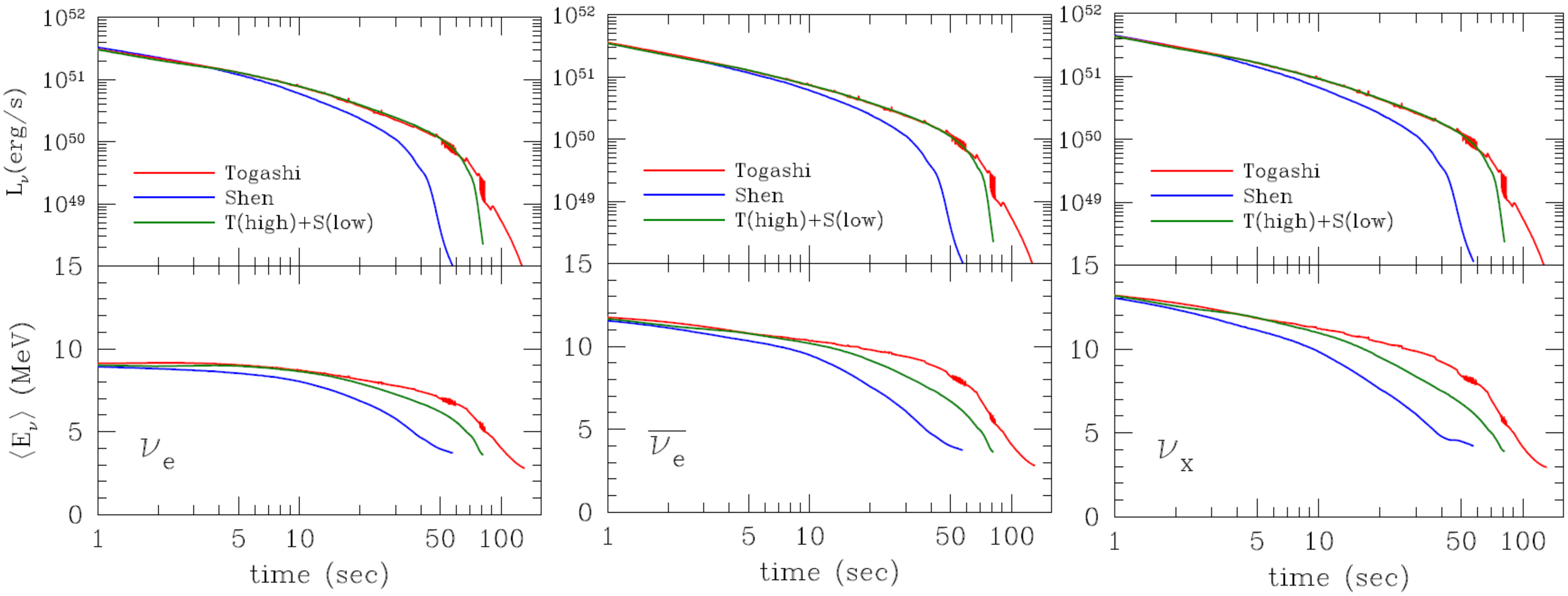
Profiles of PNS



- 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

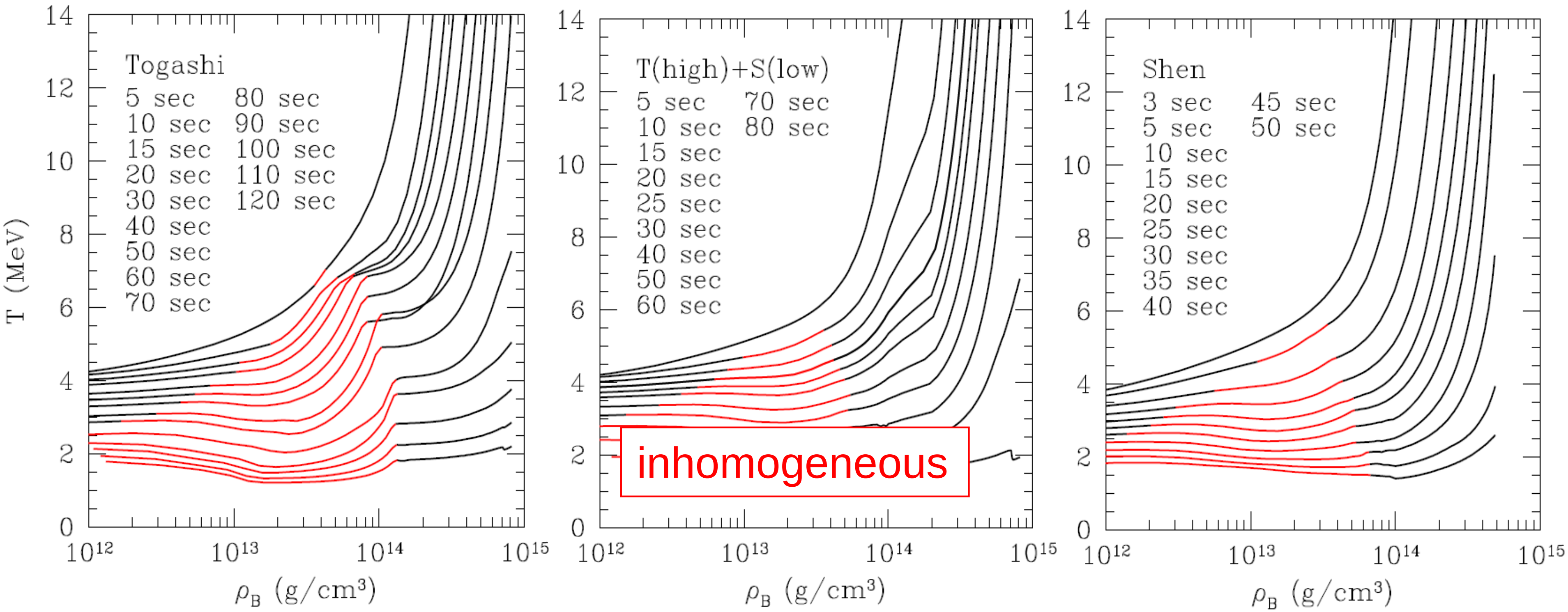
- High density EOS determines luminosity.
  - Luminosity drops steeper for faster cooling
  - Variational EOS results high density / slow cooling
- Av. energy depends also on low density EOS.



Inhomogeneous region

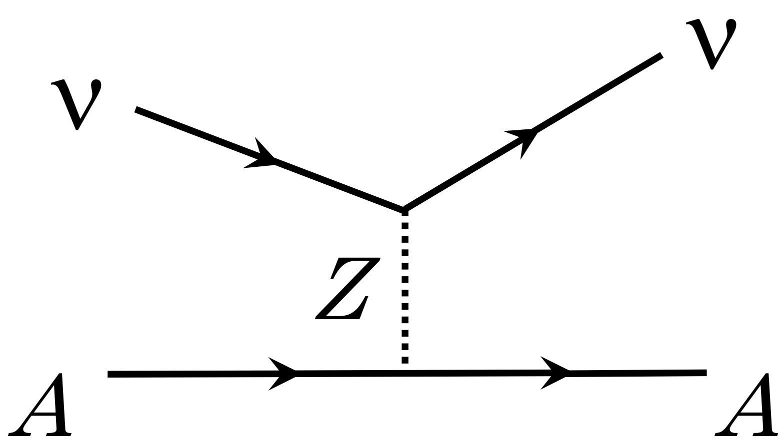
- Togashi EOS has inhomogeneous phase for higher density and temperature.

  → 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.

$$\sigma \sim \frac{G_F E_\nu^2}{4\pi}\left[N - (1 - 4\sin^2\theta_W)Z\right]^2$$

neutron rich & $1 - 4\sin^2\theta_W \sim 0$

$$\Rightarrow \quad \sigma \propto A^2$$

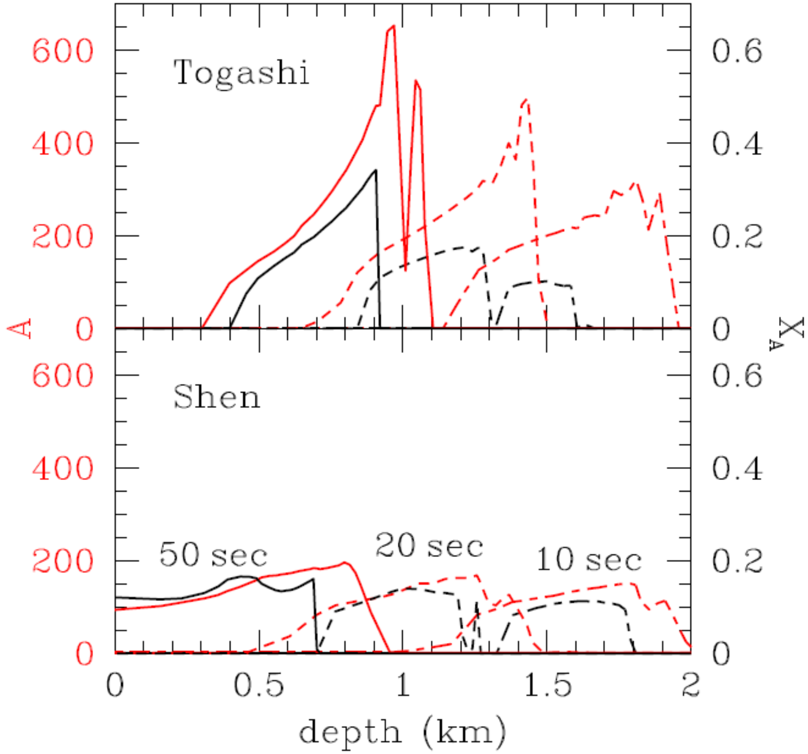
Nuclear size near PNS surface

- Large nuclear mass number is estimated for Togashi EOS.

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

- Thermal insulation by nuclei

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



A; mass number
X_A; fraction of nuclei

Summary and Future work

- The first application of new EOS based on the variational method (Togashi EOS) for astrophysical phenomena (PNS cooling).

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

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

- Future work: Not only coherent scattering but also ion screening effects should be dealt.