10th supernova neutrino workshop

Evolution of Proto-neutron star and the structure near the surface

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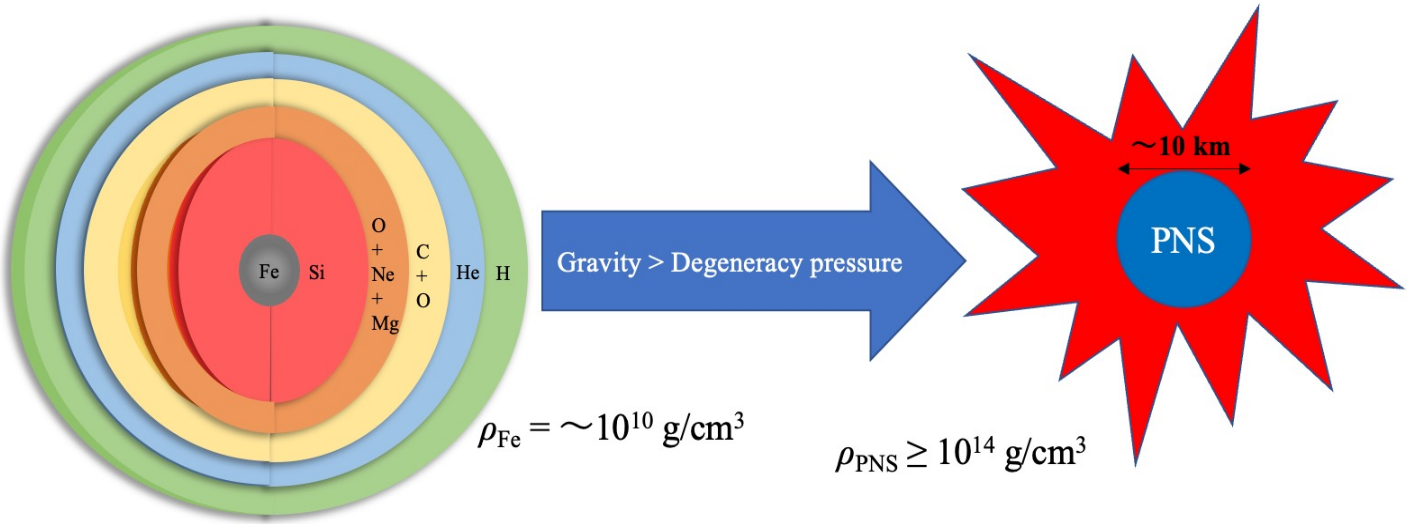
Outline

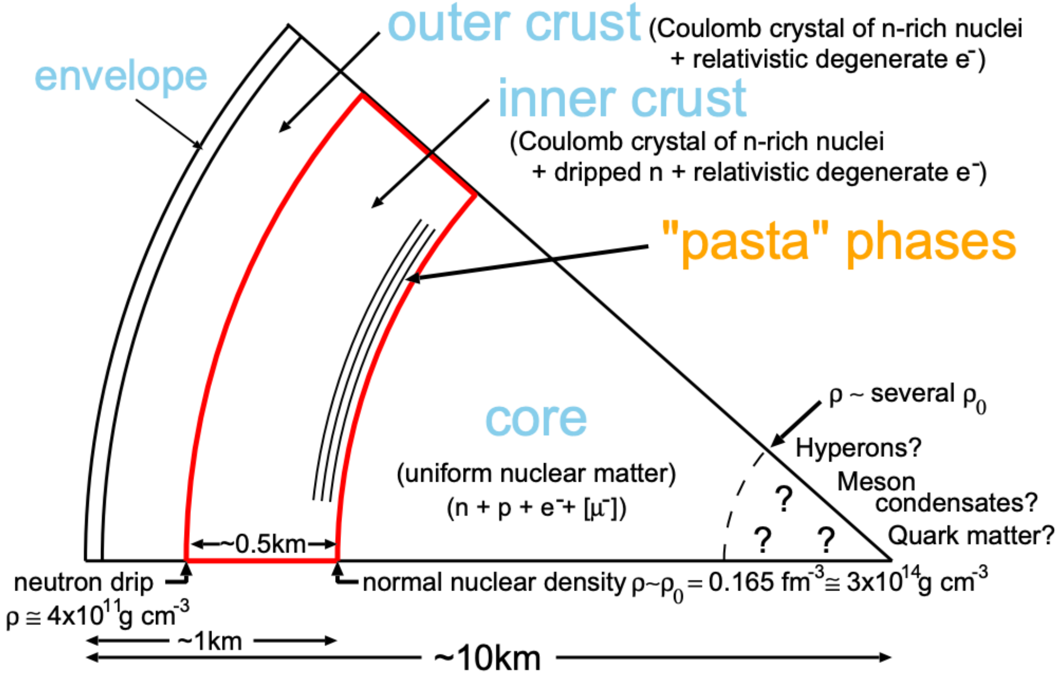
- Note :
  - Neutrino flavor :
    - ν_e : electron neutrino
    - $\bar{\nu}_e$: electron antineutrino
    - ν_μ : muon neutrino
    - $\bar{\nu}_\mu$: muon antineutrino
    - ν_τ : tau neutrino
    - $\bar{\nu}_\tau$: tau antineutrino

Proto-neutron star cooling



- After a supernova explosion(SN), the new-born neutron star left in the central region called proto-neutron star(PNS) evolves while emitting neutrinos.
- The all 6 flavor neutrinos are released at a phase named PNS cooling(PNSC). This process is accompanied by the temperature decreasing and contracting of PNS.

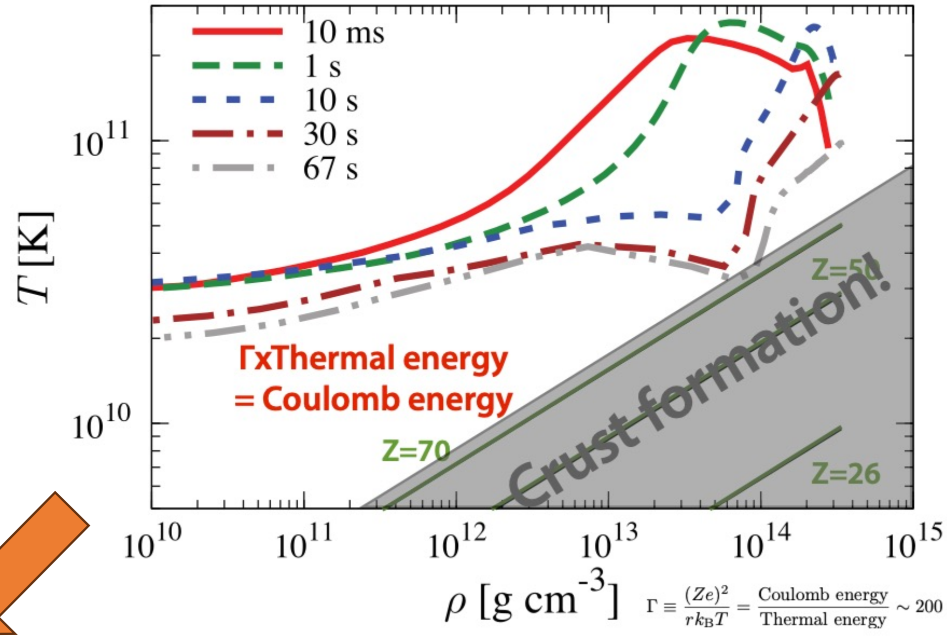
Nuclear matter in neutron star



G. Watanabe & T. Maruyama
arXiv: 1109.3511v2

the typical proton number of the component of the lattice: Z

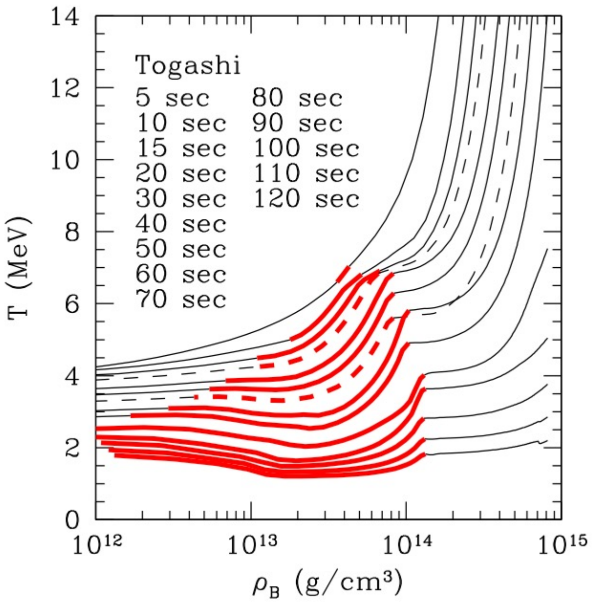
The critical temperature of lattice structure formation: $T_c \approx \frac{Z^2 e^2}{\Gamma k_B}\left(\frac{4\pi}{3}\frac{\rho Y_e x_a}{Z m_u}\right)^{1/3}$

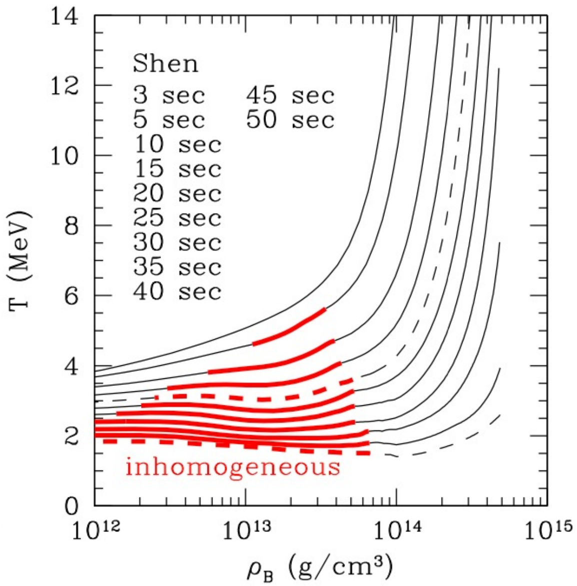


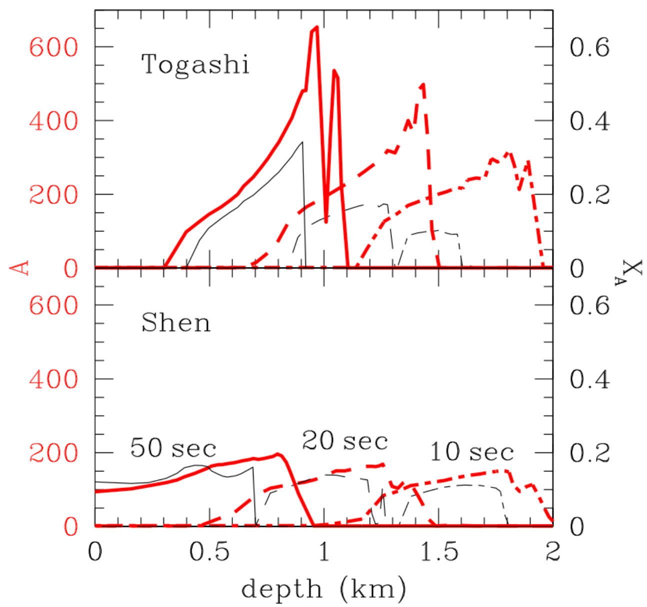
$\Gamma \equiv \frac{(Ze)^2}{r k_B T} = \frac{\text{Coulomb energy}}{\text{Thermal energy}} \sim 200$

the crust forms at ~10–100 s after PNS formation near the center

Y. Suwa
JPS Conf. Proc. **20**, 011020 (2018)







With a comparation of different EOS in simulations,

- Heavy nuclei have a large scattering cross section(∼A^2) with neutrinos owing to the coherent effects.
- A large value of *A* enhances the impact of heavy nuclei. As a result, neutrinos efficiently interact with the matter and keep the matter hot near the PNS surface.

K. Nakazato et al.
PHYSICAL REVIEW C **97**, 035804 (2018)

Objective

This study aims to perform calculations for the cooling of a primitive neutron star over several tens of seconds and analyze how the PNS evolves.

the specific focus was on examining the relationship between thermal evolution and material composition, particularly in regions of low density in the outer layers of the PNS.

Method

Quasi-static evolution code under spherical symmetry with general relativity:

mean free path of neutrino $\lambda\nu$: a statistical measure to describe the average distance traveled by neutrino

PNSC process:

Neutrinos' diffusion timescale:

$$\frac{R^2}{\lambda_\nu c} \gtrsim 10 \text{ sec}$$

The timescale for PNS to reach hydrostatic equilibrium:

$$\frac{1}{\sqrt{G\rho_B}} \sim \text{msec} \quad << \quad \frac{R^2}{\lambda_\nu c}$$

→ **This calculation is assumed to be in hydrostatic equilibrium.**

Neutrino transfer

Multi-energy flux limited diffusion scheme(MGFLD) :

Boltzmann equation:

$$\frac{\partial f_{(\nu)}}{\partial t} + \frac{\mathrm{d}\boldsymbol{r}}{\mathrm{d}t}\frac{\partial f_{(\nu)}}{\partial \boldsymbol{r}} + \frac{\mathrm{d}\boldsymbol{p}}{\mathrm{d}t}\frac{\partial f_{(\nu)}}{\partial \boldsymbol{p}} = \left(\frac{df_{(\nu)}}{dt}\right)_{\mathrm{coll}}$$

Radiant intensity I :

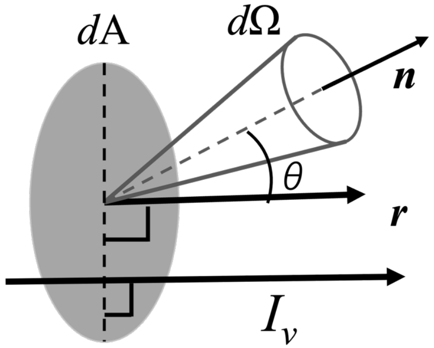
$$\mathcal{I} = \frac{\epsilon^3}{(hc)^3}\, cf$$

Radiant energy E :

$$\frac{1}{4\pi}\int d\Omega\, n^0\, \mathcal{I}(t, \boldsymbol{r}, \epsilon, \boldsymbol{n}) = \frac{c}{4\pi}E$$

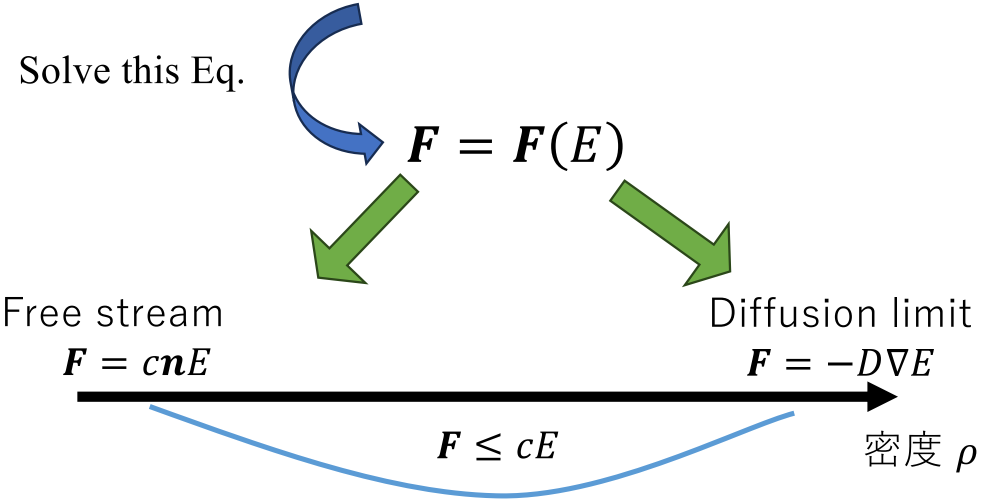
Flux F:

$$\frac{1}{4\pi}\int d\Omega\, n^i\, \mathcal{I}(t, \boldsymbol{r}, \epsilon, \boldsymbol{n}) = \frac{1}{4\pi}F^i$$



Radiant intensity Diagram: The radiation energy passing through the solid angle $d\Omega$, formed by the angle θ with the normal to the area element dA through which radiation perpendicular passes, in the time dt, with an energy width $d\epsilon$, is expressed as $dE = I_\nu cos\theta dAdtd\Omega d\epsilon$, where I_ν is the radiation intensity.

$$\partial_t E + \nabla \cdot \boldsymbol{F} = Q^0$$



Diffusion coefficient $D = \dfrac{c}{3\kappa}$ κ: opacity

Optical thin region: κ→0, D→∞ ☞ $v_\nu > c$

To ensure that the neutrino propagation speed does not exceed the speed of light, a **flux limiting function** Λ is introduced.

$$\boldsymbol{F} = -c\frac{\Lambda}{\kappa}\nabla E$$

Input physics

ν_e $\bar{\nu}_e$ ν_x

(ν_x : ν_μ , ν_τ , $\bar{\nu}_\mu$, $\bar{\nu}_\tau$)

Neutrino reactions

AE (absorption and emission)

$e^- \ p \longleftrightarrow \nu_e \ n$

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

$e^- \ A \longleftrightarrow \nu_e \ A'$

TP (thermal pair)

$e^- \ e^+ \longleftrightarrow \nu \ \bar{\nu}$: PR(pair neutrino)

$\tilde{\gamma} \longleftrightarrow \nu \ \bar{\nu}$: PL(plasmon decay)

$N\,N \leftrightarrow N\,N\,\nu\,\bar{\nu}$ Nucleon Bremsstrahlung

ES (electron scattering)

$\nu \ e^\pm \longleftrightarrow \nu \ e^\pm$

IS (isoenergetic scattering off nucleon)

$\nu \ n \longleftrightarrow \nu \ n$

$\nu \ p \longleftrightarrow \nu \ p$

$\nu \ A \longleftrightarrow \nu \ A$

Mayle & Wilson's flux limiter:

$$\Lambda_{\mathrm{MW}}(R_{\mathrm{MW}}) = \frac{1}{3 + |R_{\mathrm{MW}}|\xi(R_{\mathrm{MW}})}$$

$$R_{\mathrm{MW}} = \frac{\nabla E}{\chi E} \qquad \xi(R_{\mathrm{MW}}) = 1 + \frac{3}{1+\frac{1}{2}|R_{\mathrm{MW}}|+\frac{1}{8}|R_{\mathrm{MW}}|^2}$$

Summary of method

- Code： Quasi-static PNS evolution code under spherical symmetry with general relativity
- Neutrino transfer： multi-energy flux limited diffusion scheme
- PNS structure : TOV equation
- Energy & Charge conservation：equations of entropy and Y_e
- EOS : Shen(1998)、Togashi(2017)
- Neutrino reactions： Bruenn(1985) + Nucleon Bremsstrahlung …
- Lagrangian description

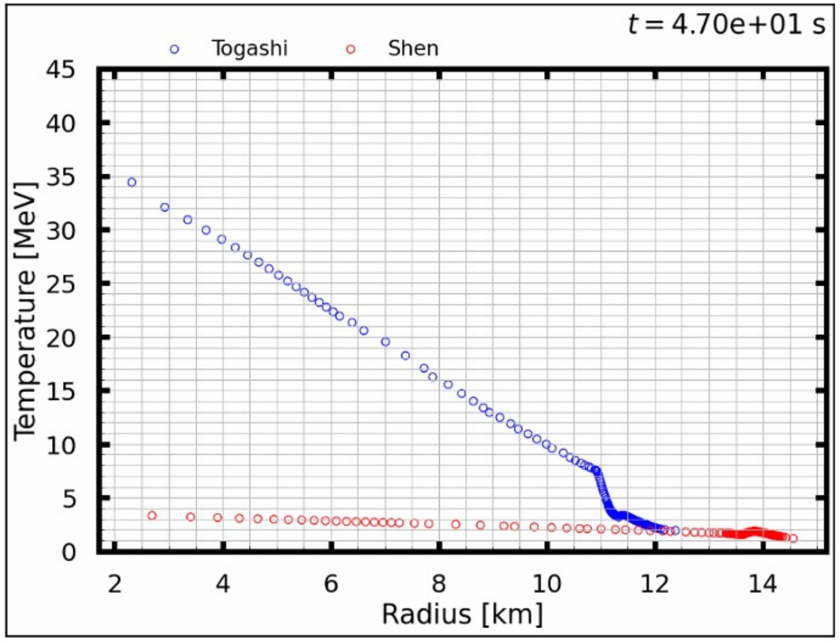
Outline

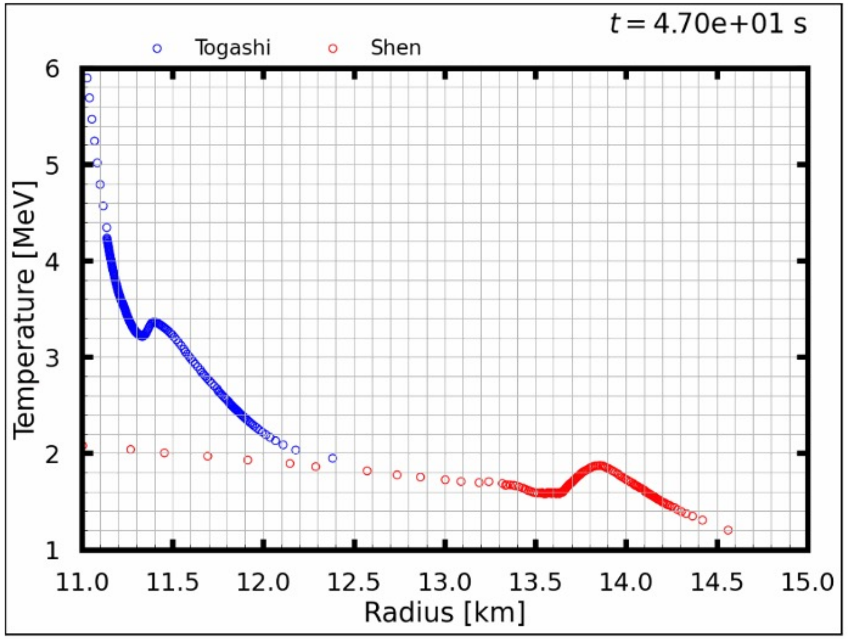
- Introduction
  - Proto-neutron star cooling
  - Nuclear matter near the PNS surface
- Objective
- Method
  - Simulation code
  - Input physics
- Results & Discussion
  - PNS structure & thermal evolution
  - Energy exchange
- Conclusion

PNS structure & thermal evolution

Spatial distribution of temperature

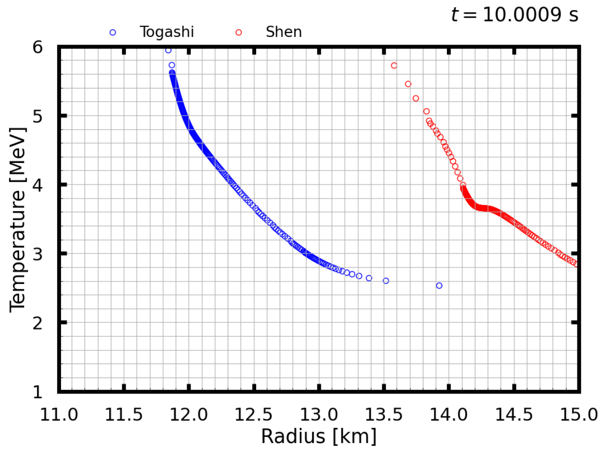
Blue for Togashi EOS
Red for Shen EOS

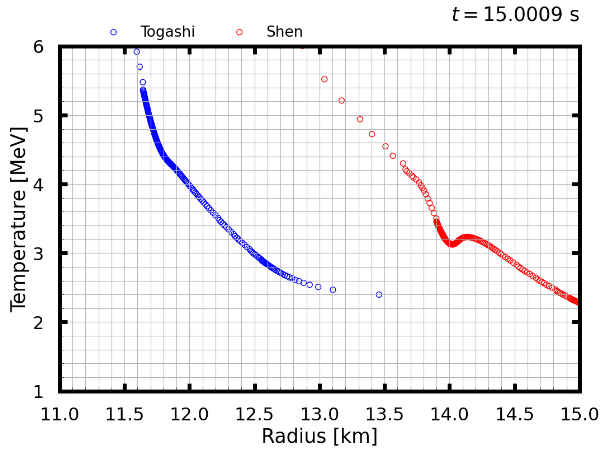


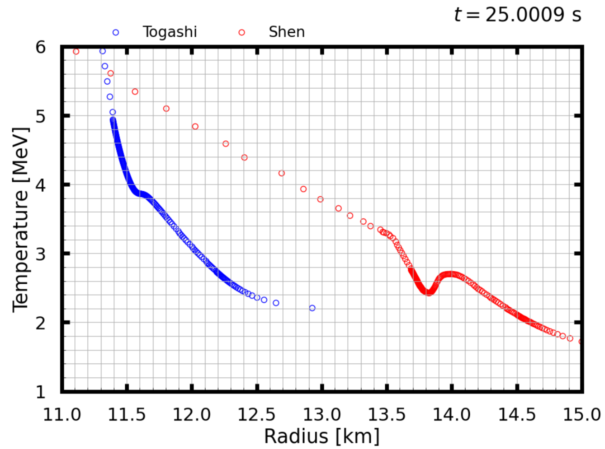


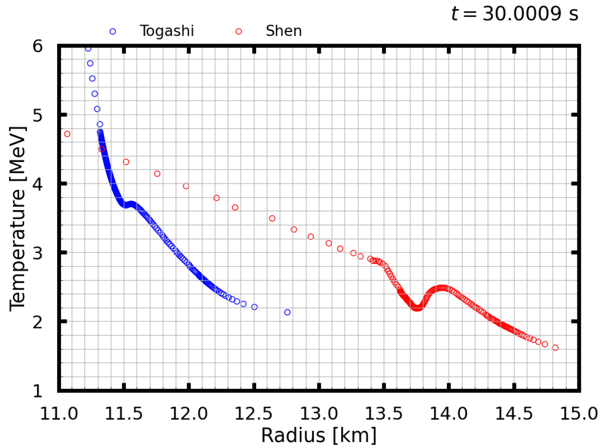
The PNS undergoes radius contraction and continues to cool overall. However, within the region near the surface of the PNS at a depth of 1.5 km, there appears a local maximum value of temperature (T-peak).

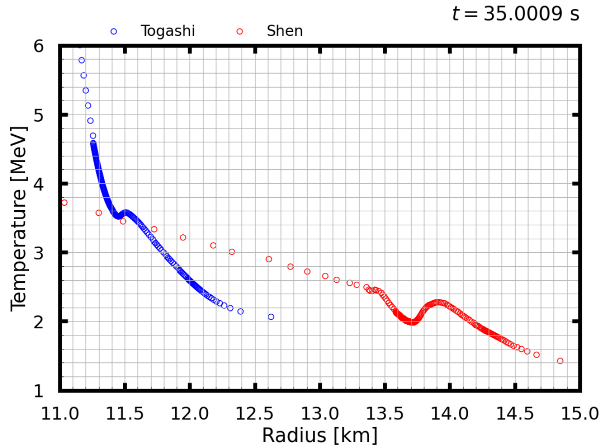
Results from 10 sec. to 35 sec.







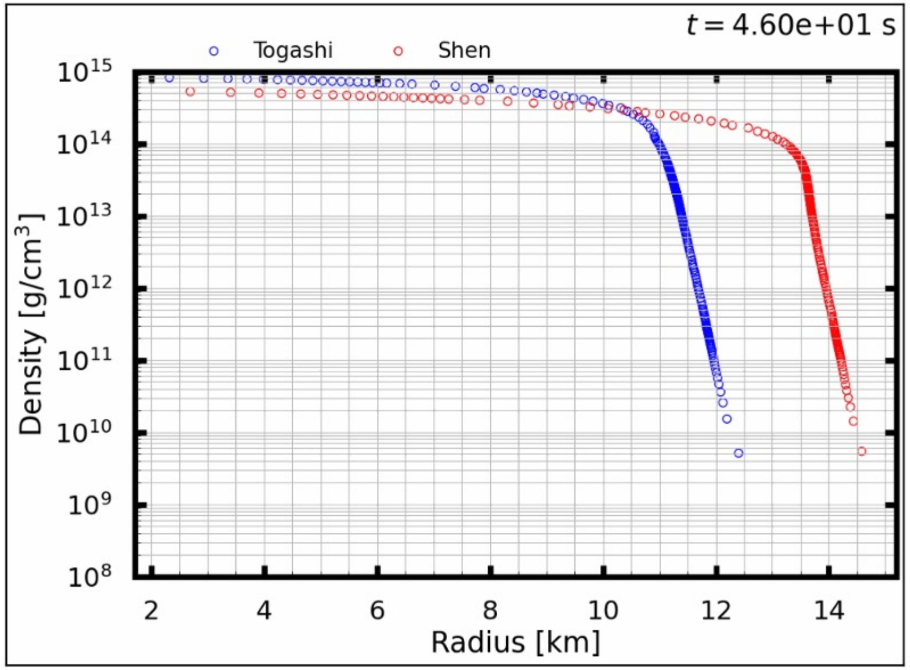


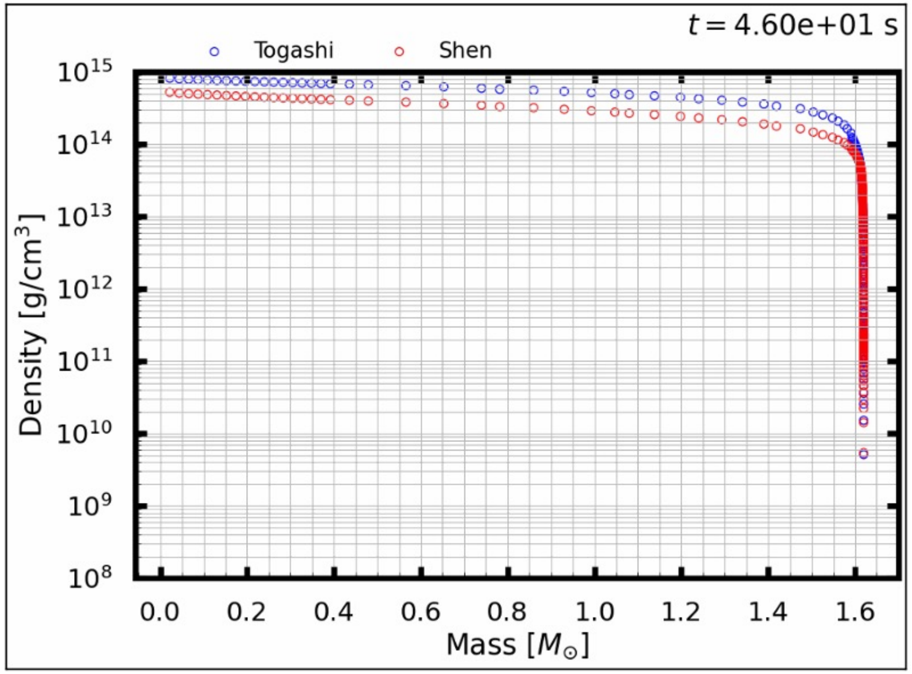


The T-peak appears in different time between two models.

- Togashi EOS： 25 ～ 35 sec.
- Shen EOS： 10 ～ 15 sec.

Spatial distribution of density



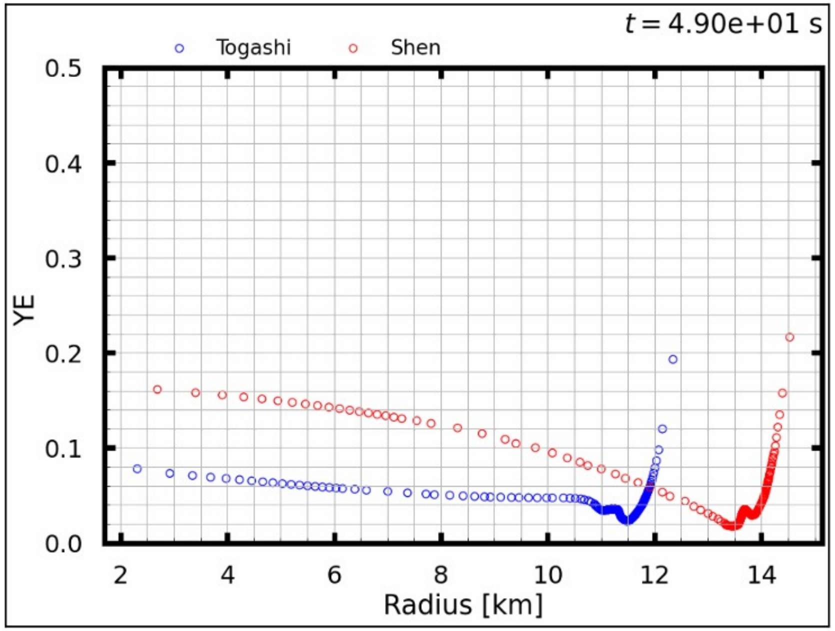


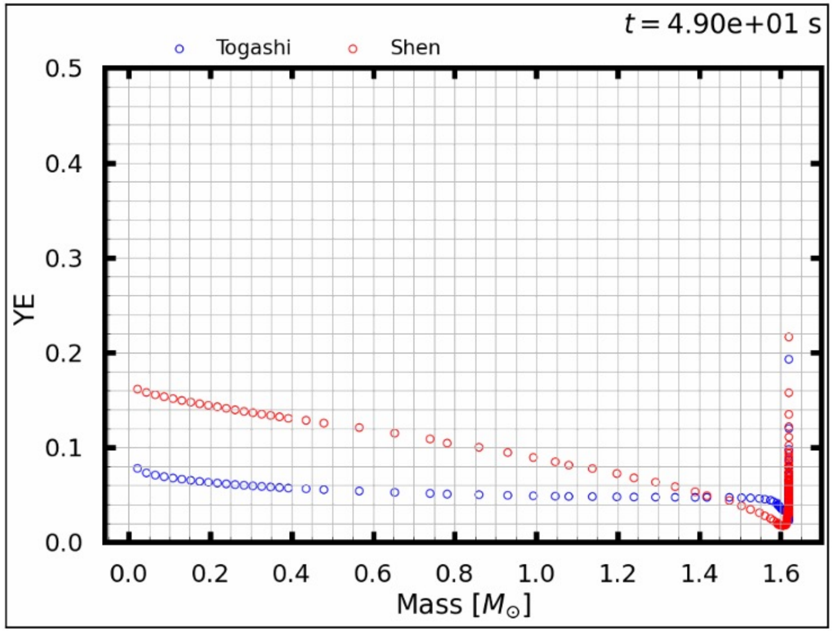
- After the start of the calculation, there is an increase in the density of the PNS by several times to several orders of magnitude within the first 5 seconds, with particularly significant changes observed in the outer layers.
- In terms of the spatial distribution of density, as one approaches the outer layers, the density exponentially decreases. The location of the T-peak corresponds to a region where the density sharply decreases.

Spatial distribution of electron fraction Y_e

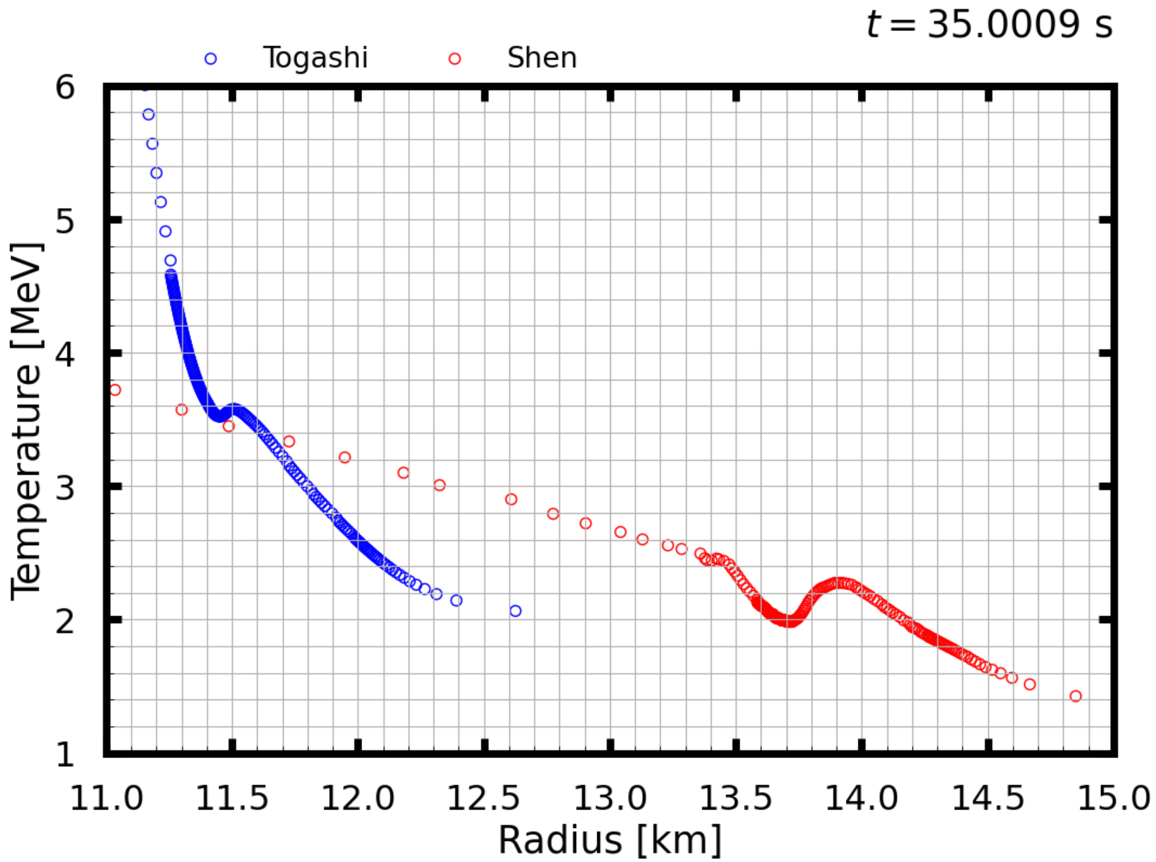
$$Y_e \equiv \frac{n_e}{n_B}$$

the ratio of electron number density to baryon (nucleon) density





In the interior of the PNS, neutronization is progressing.



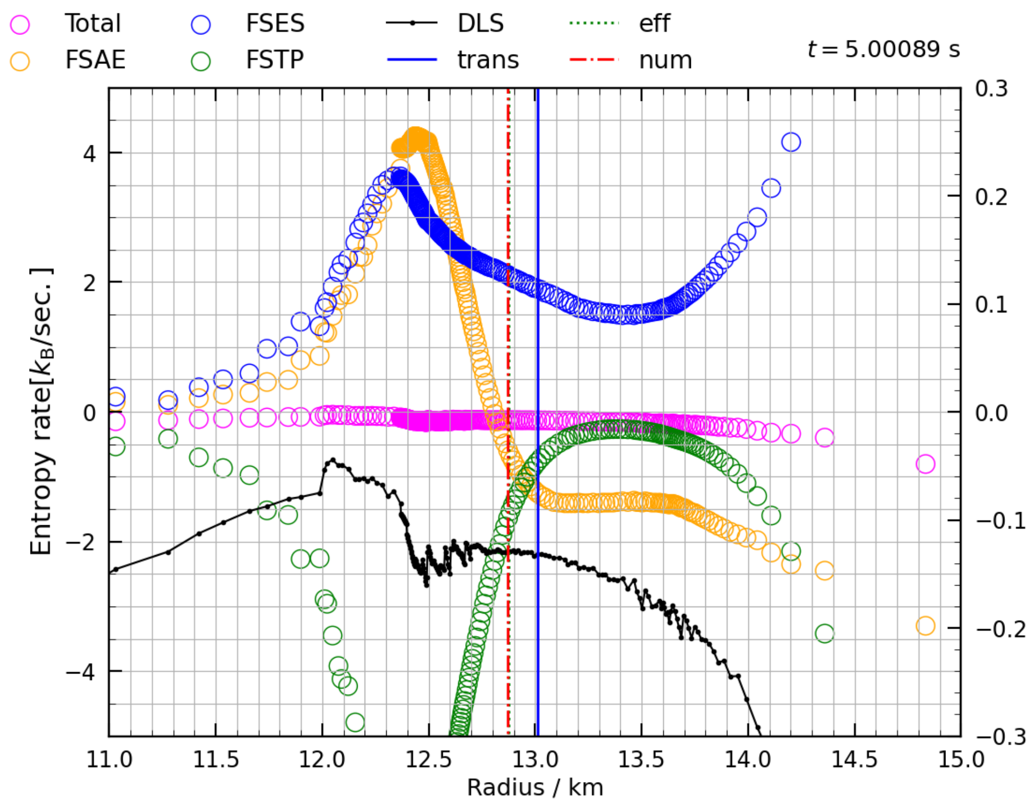
How did the T-peak form?

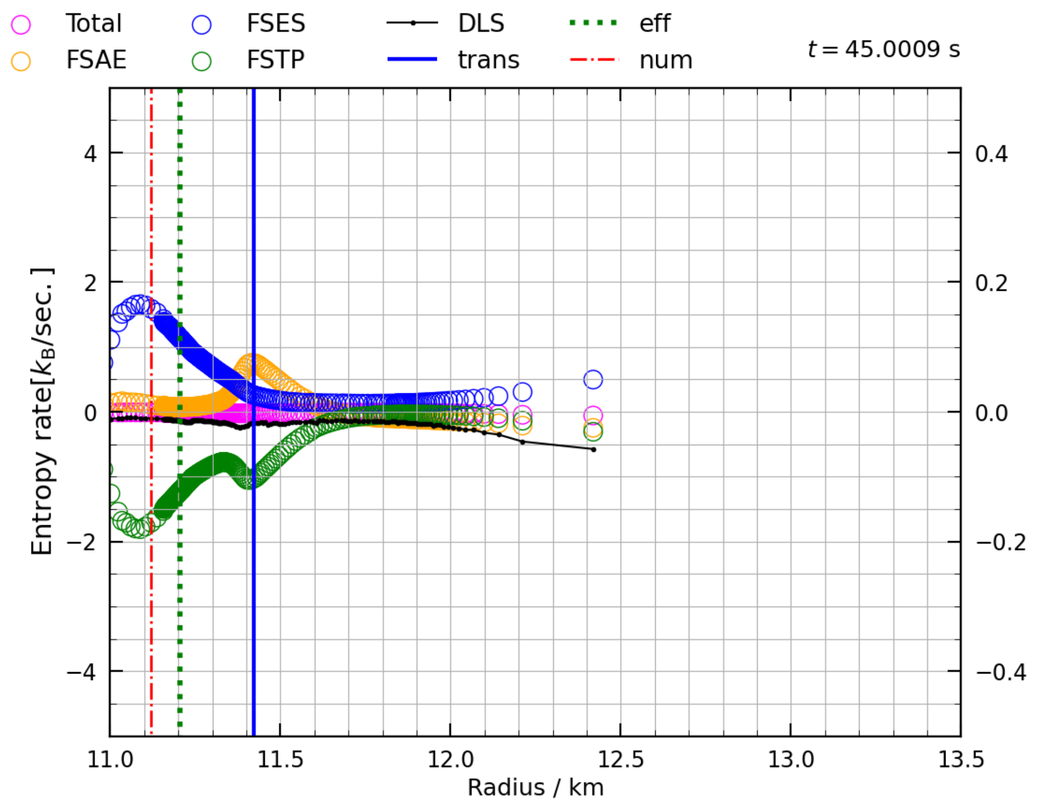
Energy exchange

Togashi

Time derivative of entropy $\dot{s}$

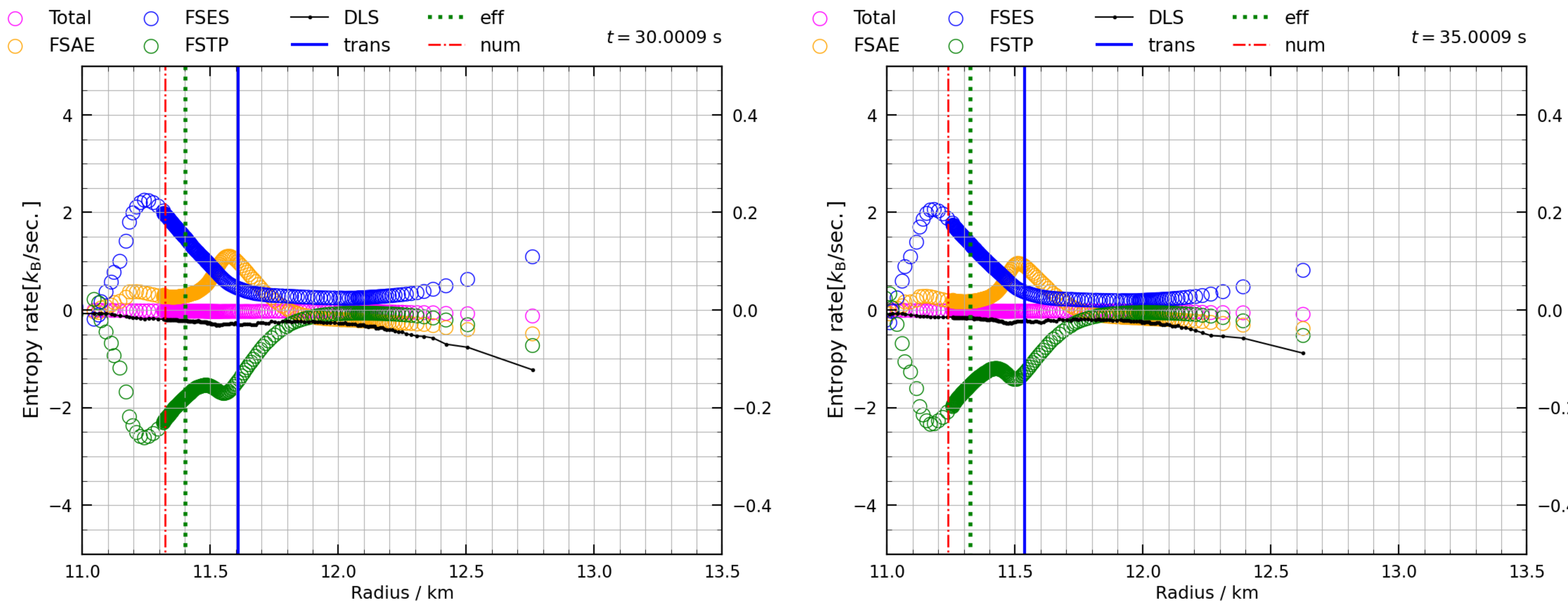
Absorption and emission	AE
Electron scattering	ES
Thermal pair	TP
Isoenergetic scattering off nucleon	IS





Togashi

The $\dot{s}$ does not exhibit a distribution structure like the T-peak around the location where the T-peak exists.



Material composition

$$ds \equiv \frac{dQ}{T}$$
$$C = \frac{dQ}{dT}$$

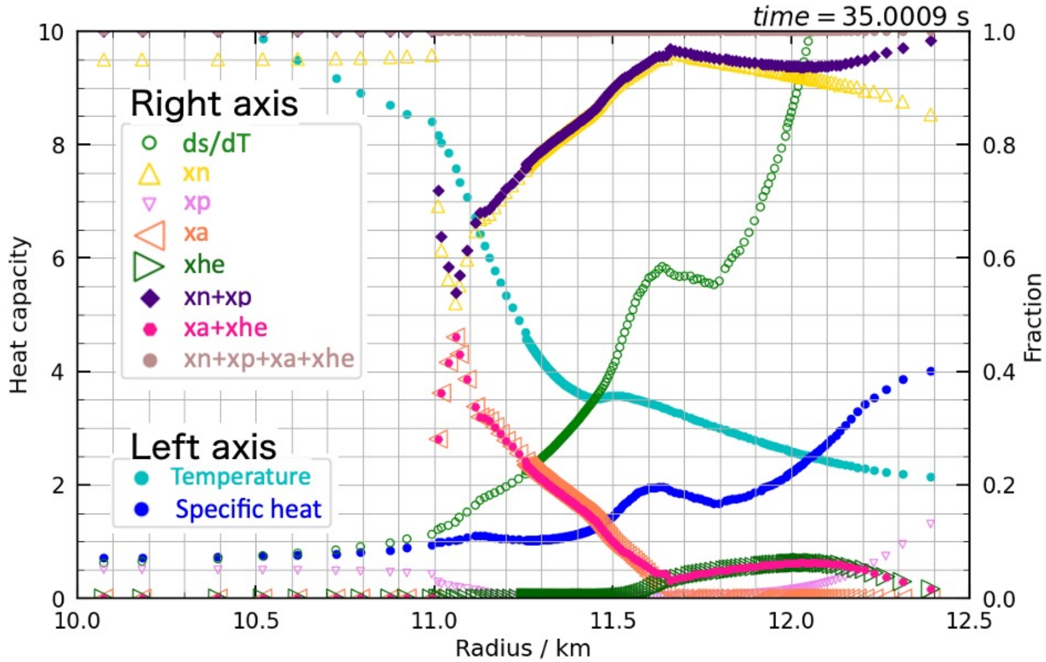
$$C = T\frac{ds}{dt}\frac{dt}{dT} = T\frac{ds}{dT}$$

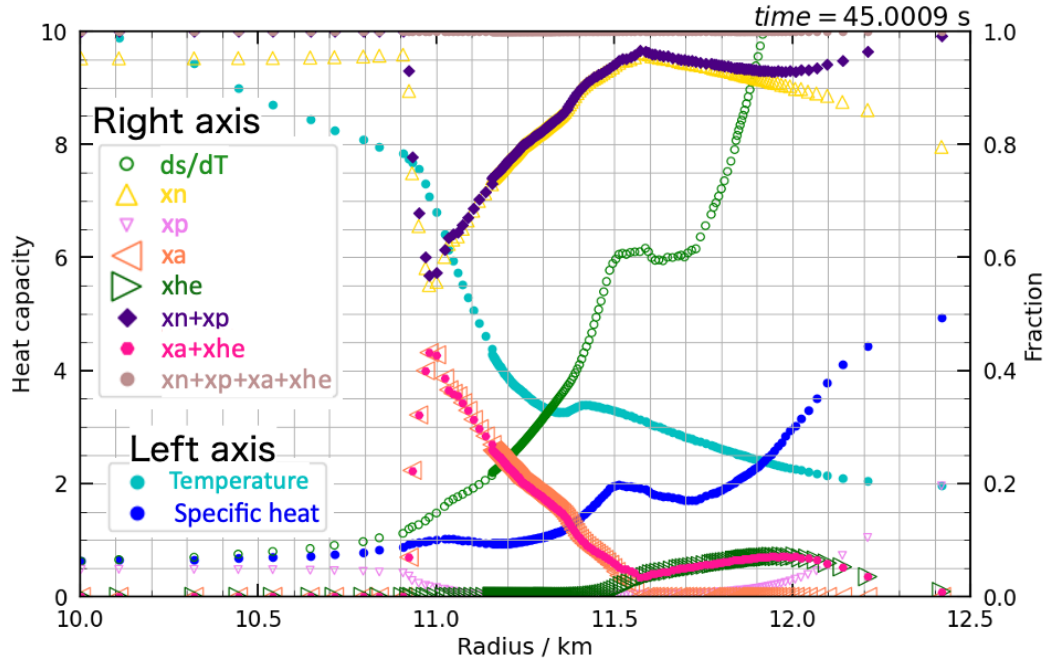
Fraction defined by number density:

- xn: free neutron
- xp: free proton
- xhe: free alpha-particle
- xa: heavy nucleus

Togashi

A local maximum of specific heat capacity appears at the location outside the T-peak.
A large specific heat capacity impedes the cooling of matter outside.

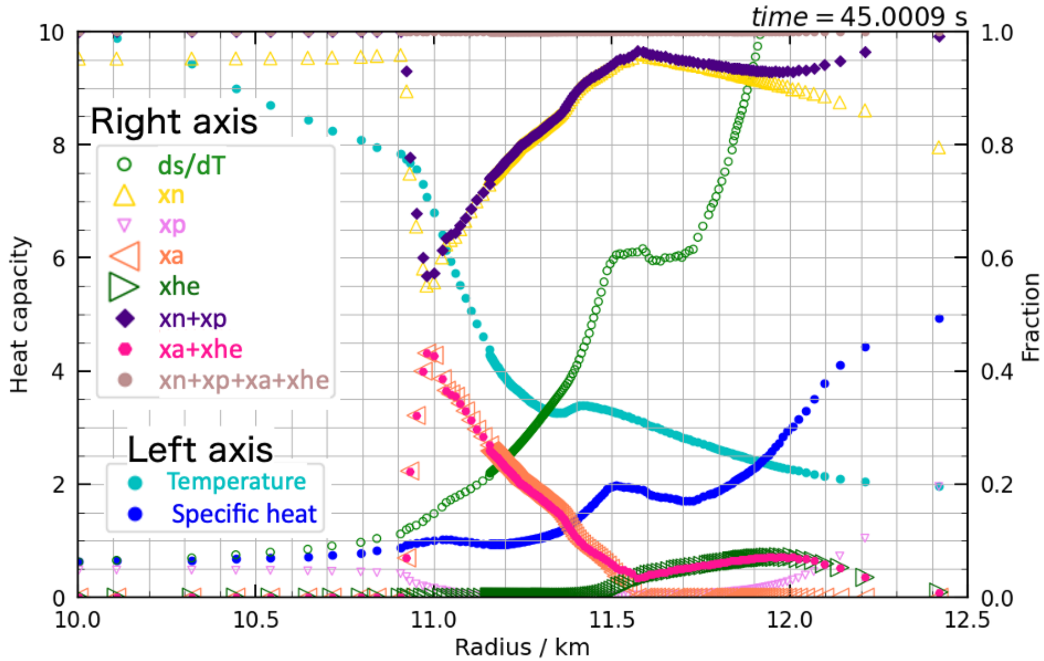




Togashi

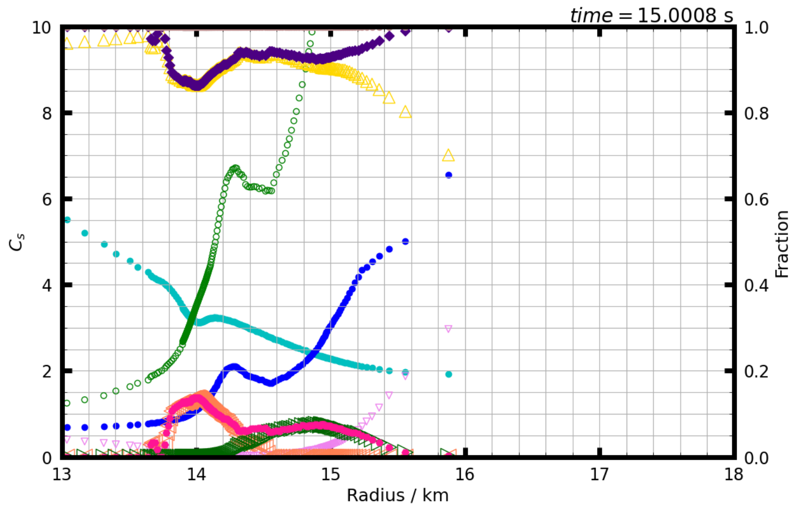
In regions with abundant nucleons, energy is released, leading to the formation of heavy nucleus and helium, making the temperature less prone to change like phase transition.

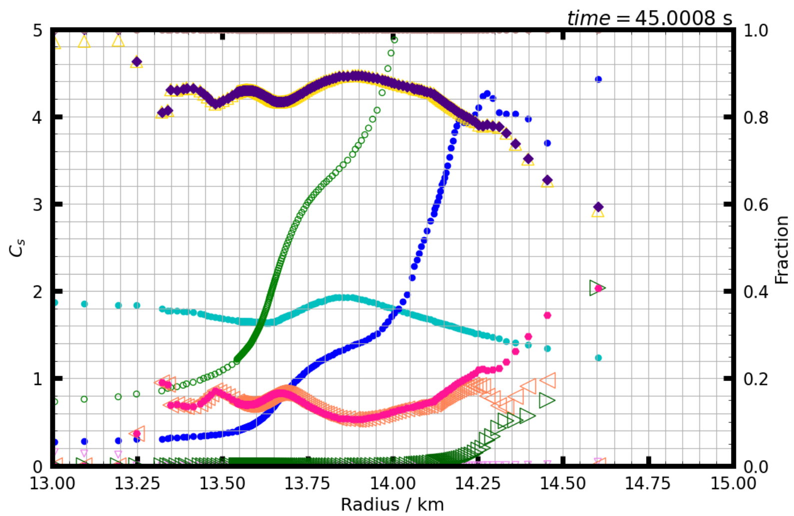
xn: free neutron
xp: free proton
xhe: free alpha-particle
xa: heavy nucleus



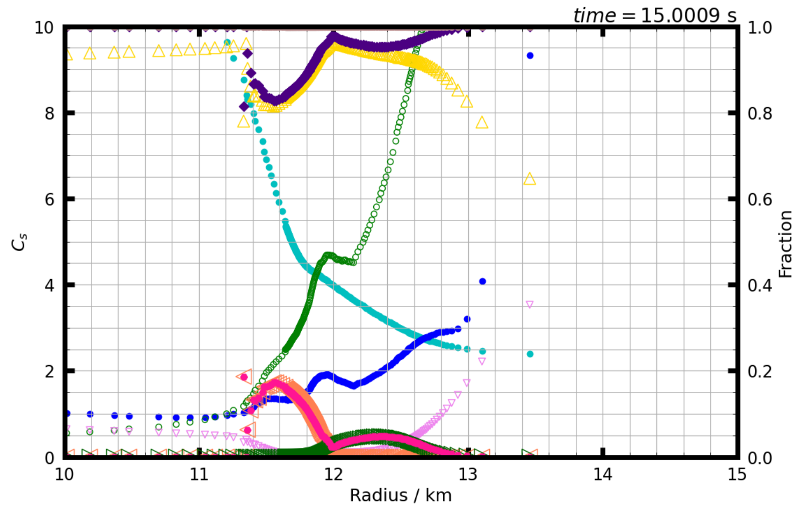
Region	Matter composition
11 km → 11.5 km	Heavy nucleus → Neutron
11.5 km → 11.7 km	Neutron → Helium
11.7 km →	Neutron & Helium → Proton

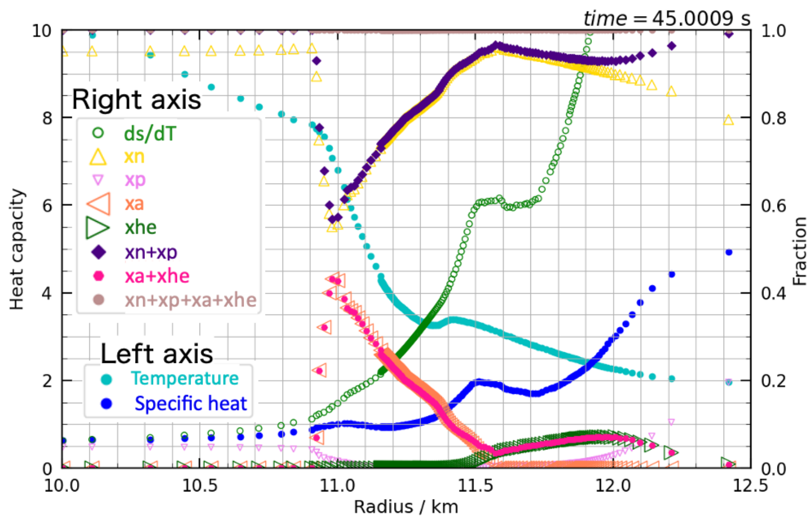
The compositional changes involving helium and heavy nucleus result in a variation in specific heat, hindering cooling beyond the location where the T-peak appears.





Shen





Togashi

Conclusion

In the late thermal evolution of the outer layers of the PNS up to 50 seconds, the appearance of T-peak is attributed to the occurrence of heavy nuclei and helium, resulting in a maximum value of specific heat in the outer layers of the PNS. In those locations, it acts to impede cooling, making them less prone to cooling than the inner regions. Additionally, the simulation with softer EOS will reach non-uniform phase fast.