Jet and Shock Breakouts
in Cosmic Transients

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Early Emission in Shock Breakout of Binary Neutron Star Merger

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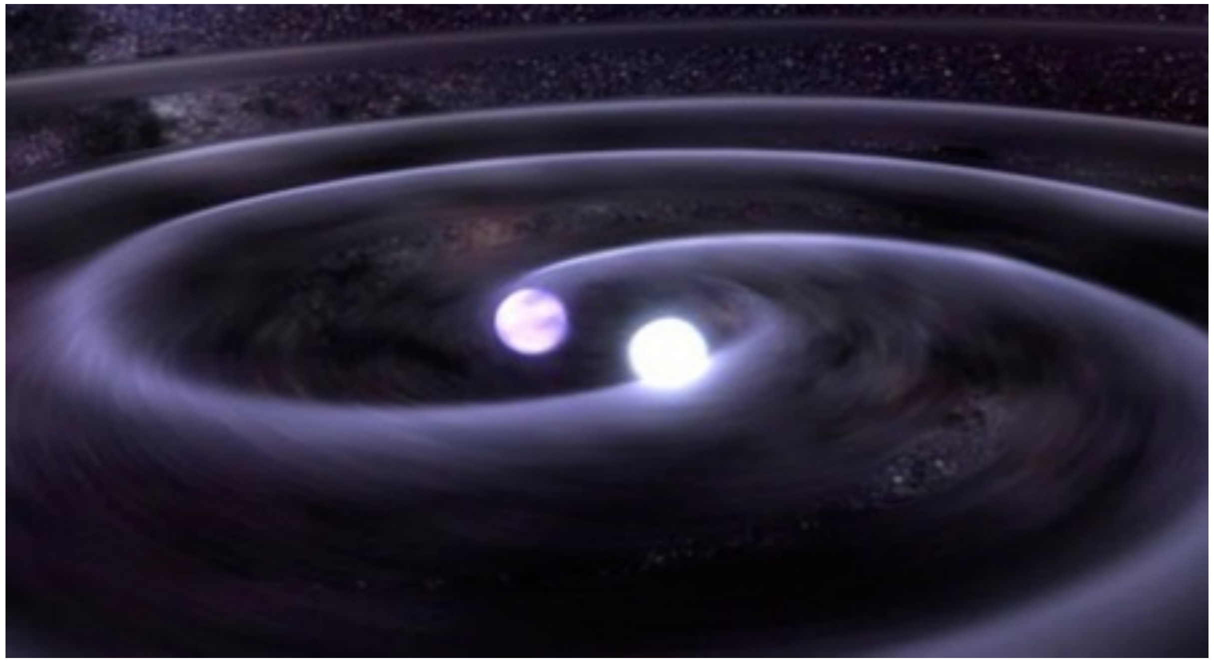
Emission from Binary Neutron Star Merger

(Li & Paczynski 1998, B. D. Metzger et al. 2010, ⋯)

GW170817

Electromagnetic emission was detected over wide wavelength range



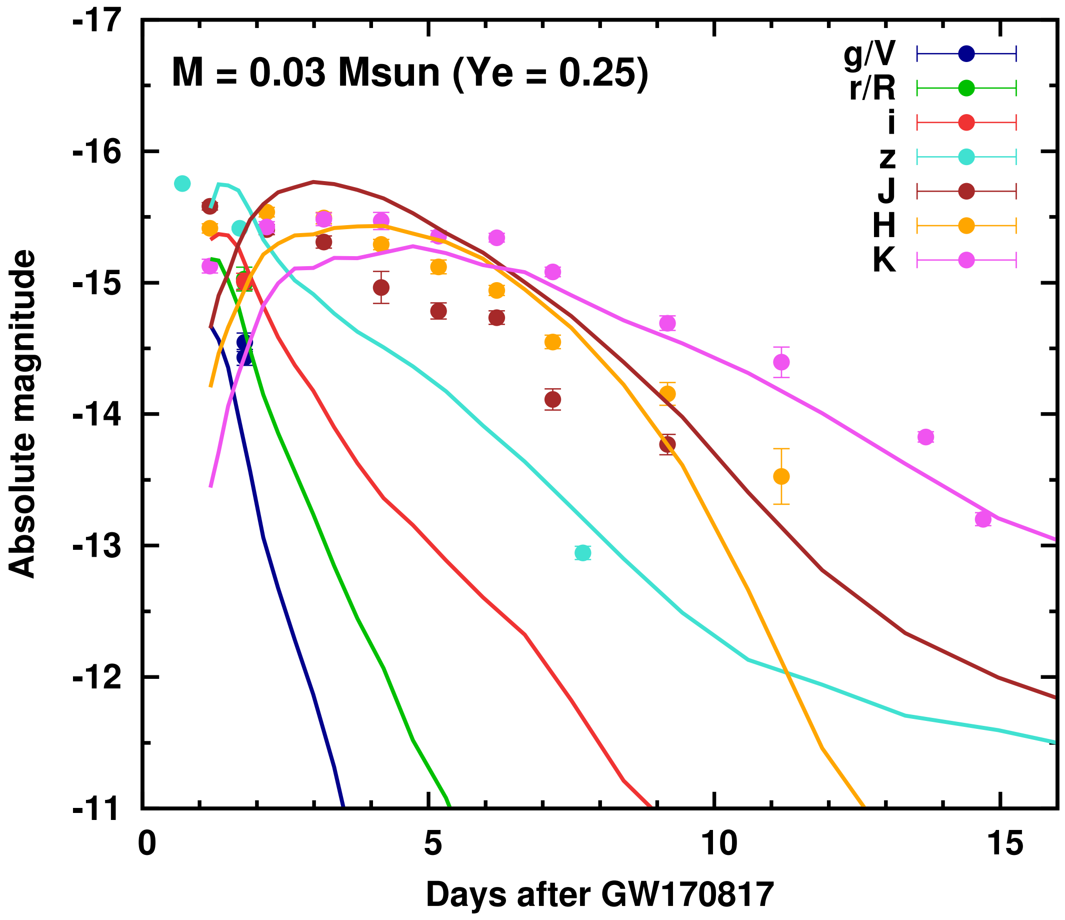
http://aasnova.org/2015/10/28/what-do-you-get-when-two-neutron-stars-merge/

Observed emission could be almost explained by kilonova model

- Neutron star matter is ejected at merging
  (Neutron-rich ejecta for r-process nucleosynthesis)
- Emission by radioactive decay is detected

Early Emission from Neutron Star Merger

(M. Tanaka et al. 2017, Y. Utsumi et al. 2017, I. Arcavi 2018, ⋯)



- Observations started in ~11 h after merging event
- Observed early emission (~1 day) is more luminous and bluer than model computation

Early emission can provide us with rich information

→ It relates to the shock breakout

Emission in Shock Breakout

(C. D. Matzner and C. F. McKee 1999)

	NS merger	Supernova	long GRB
timescale (R/v)	$\sim 10^{-4}$ s	$10 \sim 10^4$ s ? (depends on progenitor)	a few 10^{-2} s ? ($\sim R/c\Gamma$)
nuclear reaction	occur	not occur	not occur
velocity	mildly relativistic	non relativistic	highly relativistic
opacity source	~~heavy elements~~ H or He in outer region	depends on progenitor (H, He, O, C, Si, Fe, Ti, Ca···)	fully ionized gas $e^{\pm}$

- The timescale may relate to the observability
- Radiation mediated shock should be considered
  ($\rightarrow$ it is neglected in subsequent topic for simplicity)

Free Neutron Precursor

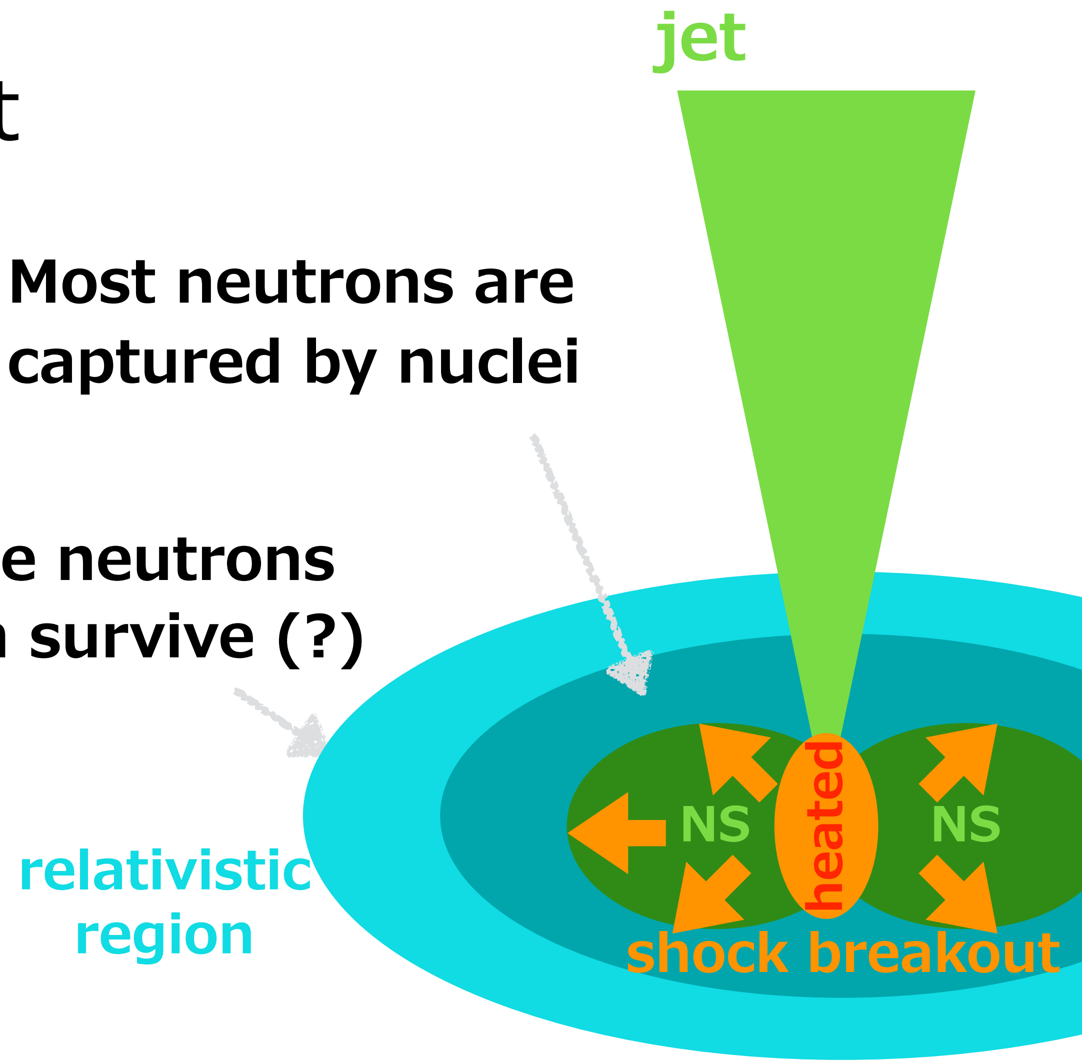
(B. D. Metzger et al. 2015, Metzger 2017)

- Outermost ejecta is accelerated to relativistic speed in shock breakout
  (K. Kyutoku et al. 2014)
- Outermost ejecta expands sufficiently rapidly that neutrons avoid capture ($M \sim 10^{-4}\ M_{sun}$)
  (Goriely et al. 2014, Just et al. 2014)
- β-decay of free neutron powers "precursor" to kilonova

peaks at ~ few hours

Most neutrons are captured by nuclei

Free neutrons can survive (?)



Smoothed Particle Hydrodynamics (SPH) simulation (Just et al. 2015)
→Can the similar result be obtained in grid-based simulations?

Objectives

Examining early emission by free-neutron-powered precursor in shock breakout of binary neutron star merger

Step 1

- Developing relativistic Lagrangian hydrodynamics code and reproducing shock breakout of neutron star merger

Step 2

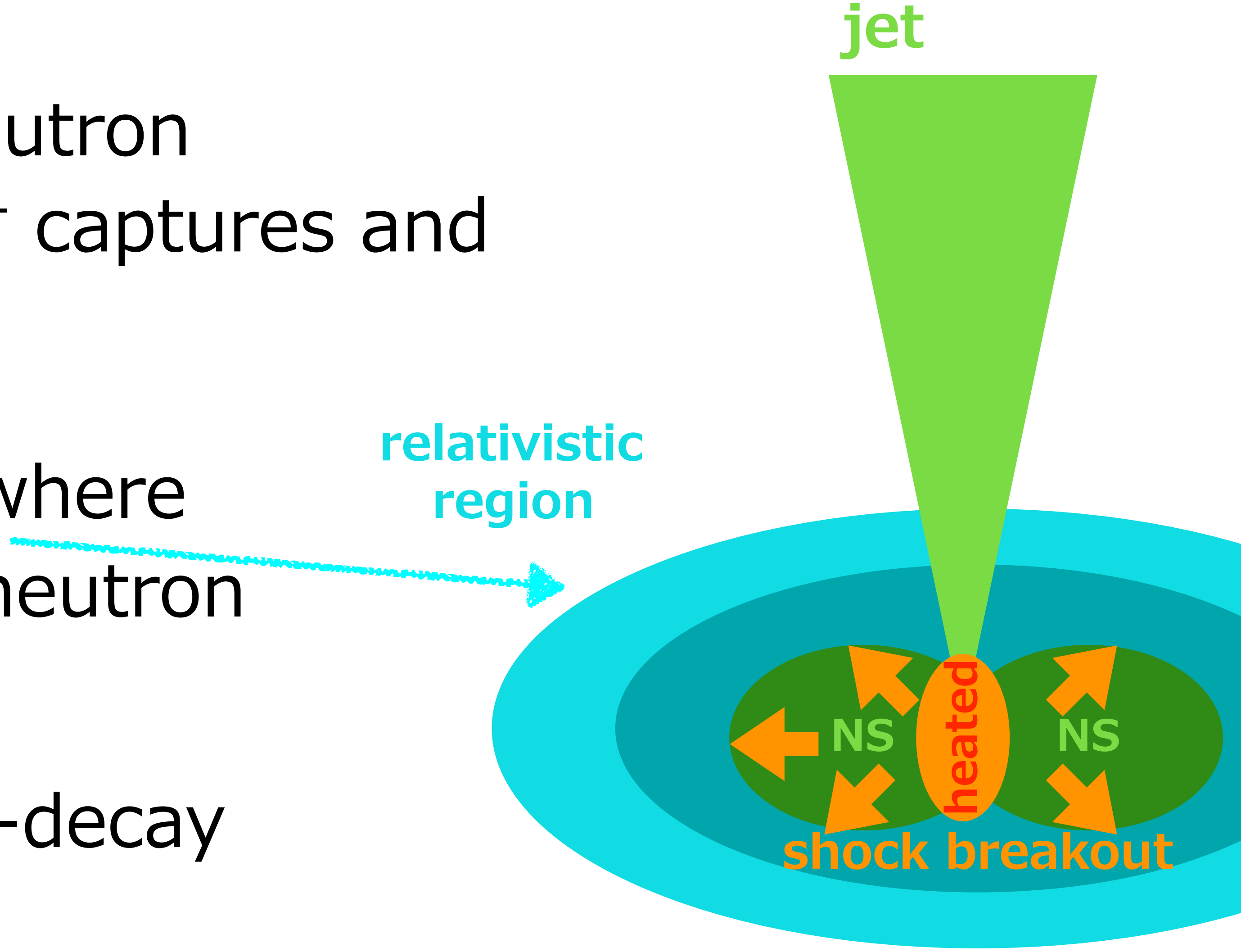
- Estimating surviving free neutron mass fraction with e^+ and e^- captures and some nuclear reactions

Step 3

- Calculating mass of region where reasonable amount of free neutron is surviving

Step 4

- Calculating emission from β-decay of free neutron



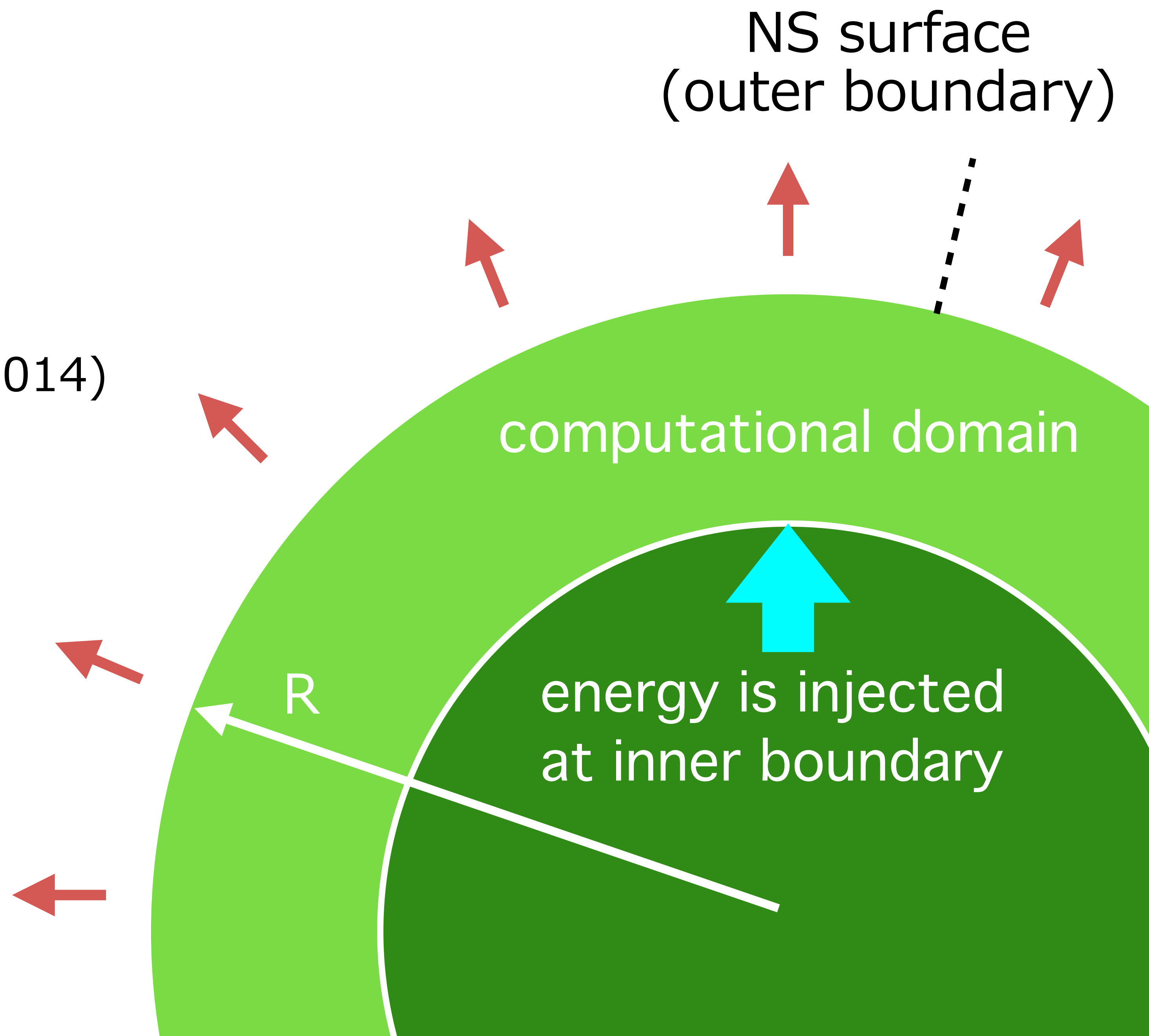
Simulation Condition

- Relativistic Lagrangian hydro simulation
- 1D spherical symmetric coordinate
- 500 computational cells in radial direction
- $E_{\mathrm{final}} = 10^{47} - 10^{50}$ erg
- $R = 15, 20, 25, 30$ km
- $M_{\mathrm{shell}} = 10^{-3}\ M_{\mathrm{sun}}$
- $\rho \propto (R - r)^3$ (K. Kyutoku et al. 2014)

Shock wave propagates through merging NS

↓

Shock breakout occurs when it reaches NS surface



NS surface (outer boundary)

computational domain

R

energy is injected at inner boundary

Estimation of free neutron rate

- Free neutron rate X_n is set to be 0.9 initially (Y_e=0.1) (beta equilibrium of cold dense matter)
- $e^{\pm}$ is generated by shock heating

$$n + e^{+} \rightarrow p + \bar{\nu_e}$$
$$p + e^{-} \rightarrow n + \nu_e$$

- Time scale of positron and electron capture processes are obtained depending on temperature ($\tau_+(T)$, $\tau_-(T)$)
  (L. Kawano 1992, B. D. Metzger et al. 2015)
- Time evolution of X_n is calculated by

$$\frac{dX_{\mathrm{n}}}{dt} = -\frac{X_{\mathrm{n}}}{\Gamma\tau_{+}(T)} + \frac{(1-X_{\mathrm{n}})}{\Gamma\tau_{-}(T)}$$

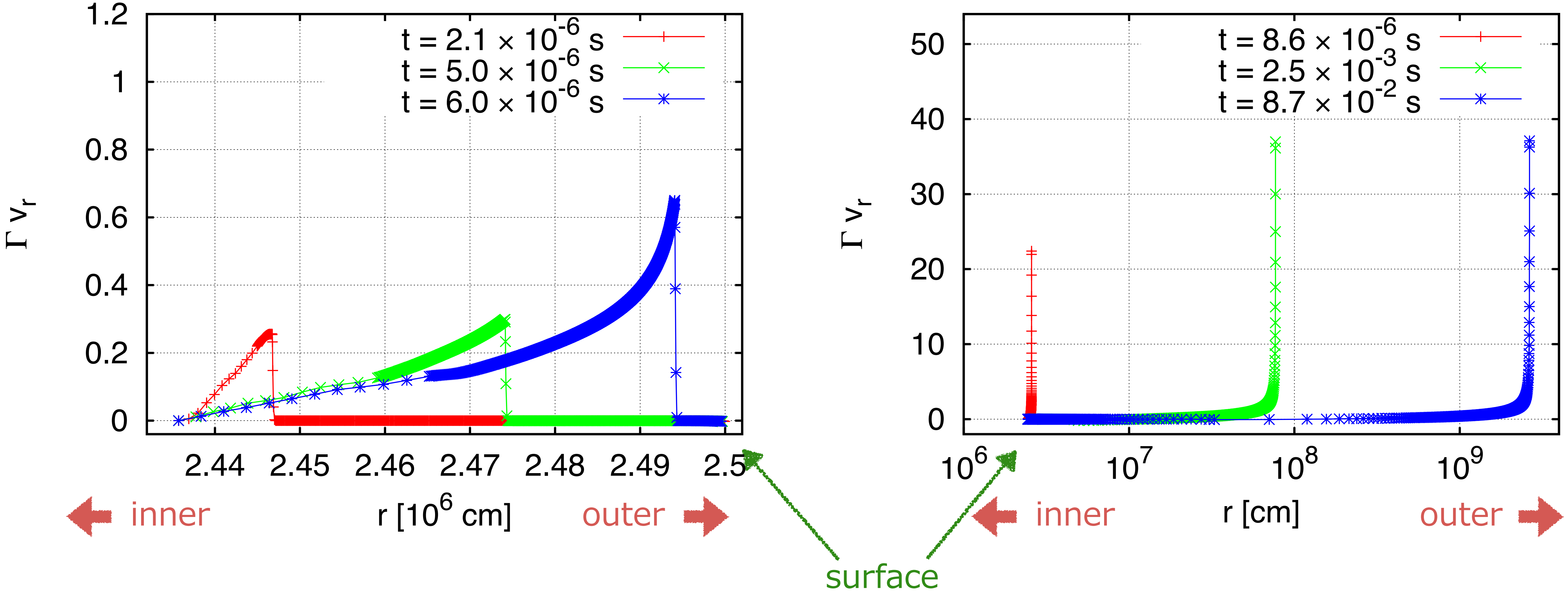
- Nuclear reaction network calculations are performed after temperature decreases down to 10^{10} K (Shigeyama et al. 2010)

Results in Shock Breakout

Before shock breakout

R = 25 km, $E_{\mathrm{final}} = 10^{49}$ erg

After shock breakout



- Accelerated shock wave in breakout can be reproduced
- Ejecta in outermost region has relativistic speed

Results in Shock Breakout

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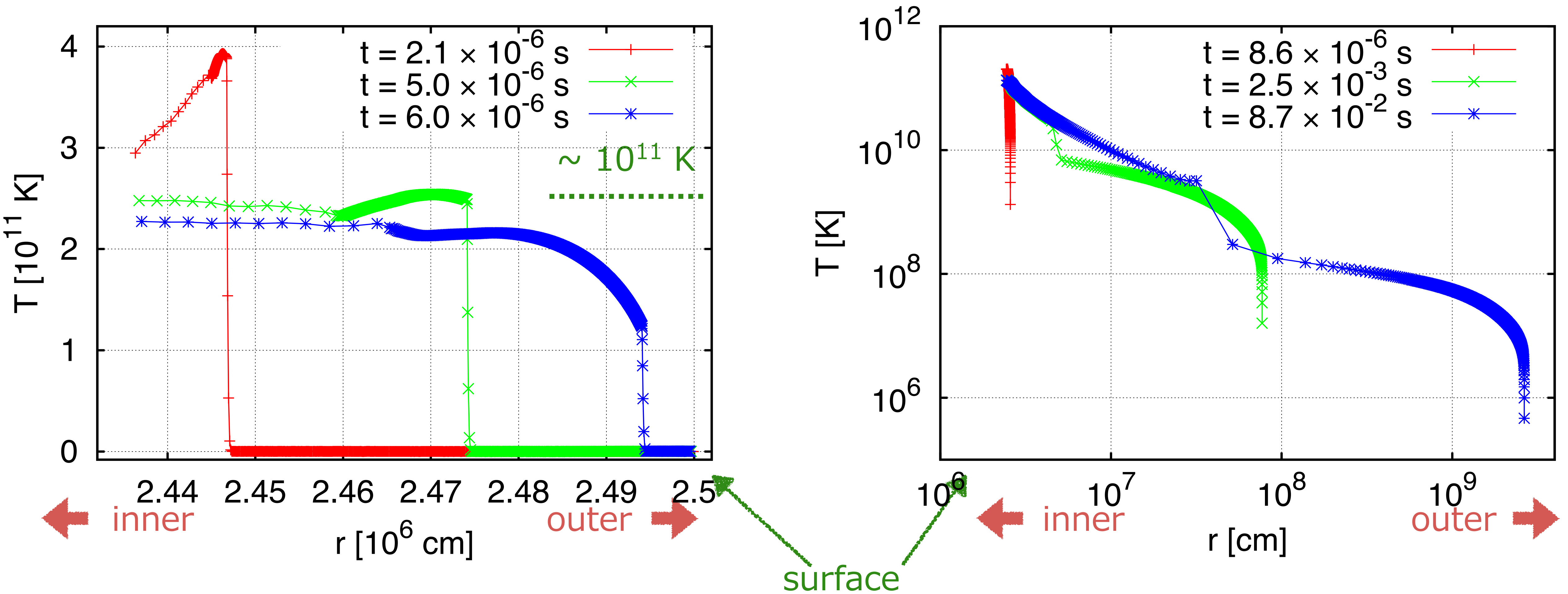
After shock breakout

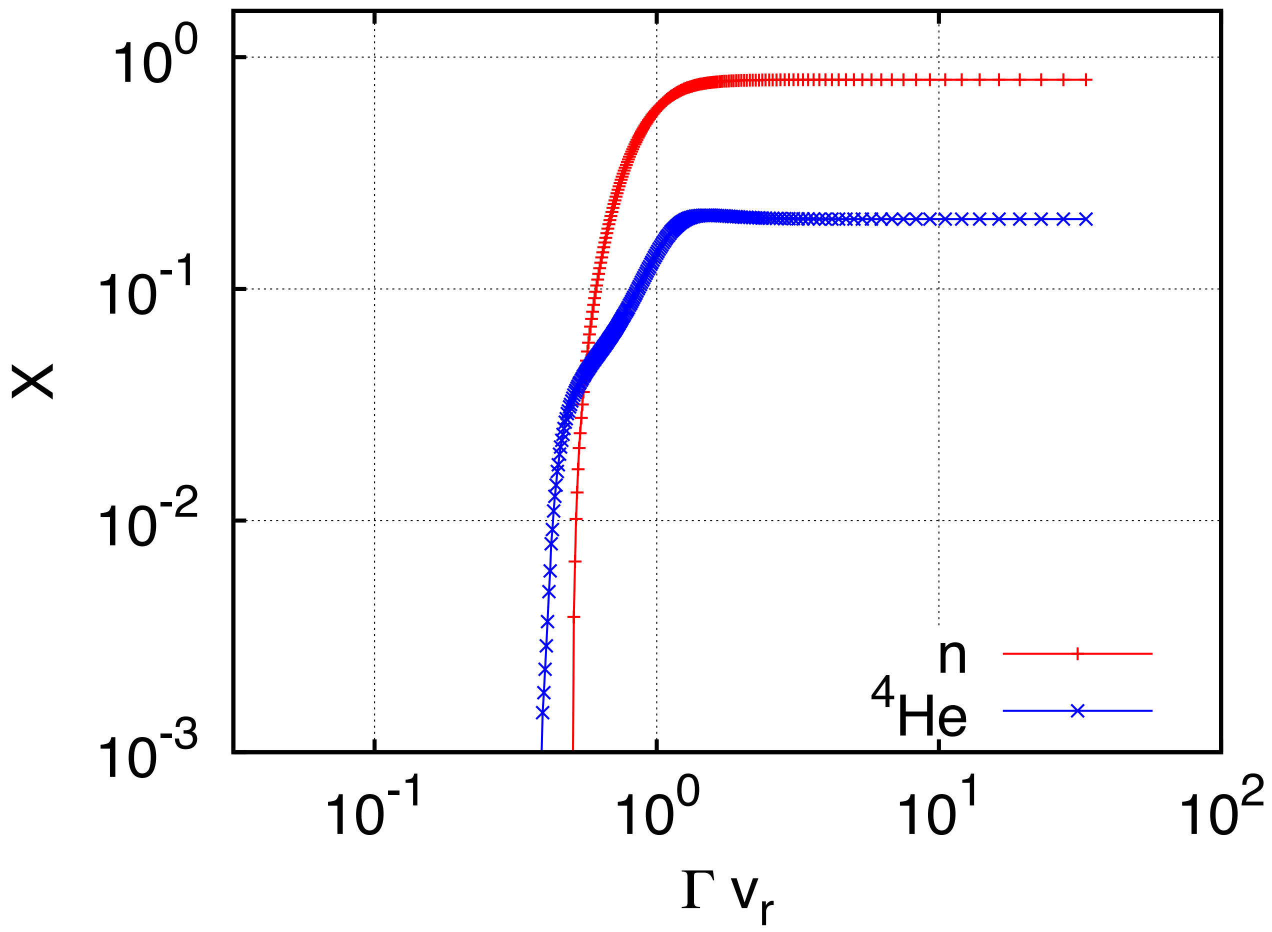


- Radiation pressure is assumed to be dominant ($P = \frac{aT^4}{3}$)
- Temperature decreases rapidly after shock breakout

$$\tau_+ \simeq 2.1(T/\mathrm{MeV})^{-5}\ \mathrm{s} \xrightarrow{10^{11}\ \mathrm{K}} \sim 4.41\times 10^{-5}\ \mathrm{s}$$

Distribution of Mass Fraction

R = 25 km
$E_{\mathrm{final}} = 10^{49}$ erg
$t = 9\times10^{-2}$ s
$T < 10^{8}$ K



Inner region

- Neutrons are captured by nuclei to produce heavy elements

Middle region

- p(n,γ)d reactions consume all neutrons to produce ^{4}He

Outermost region

- Free neutron layer is produced due to low density and temperature

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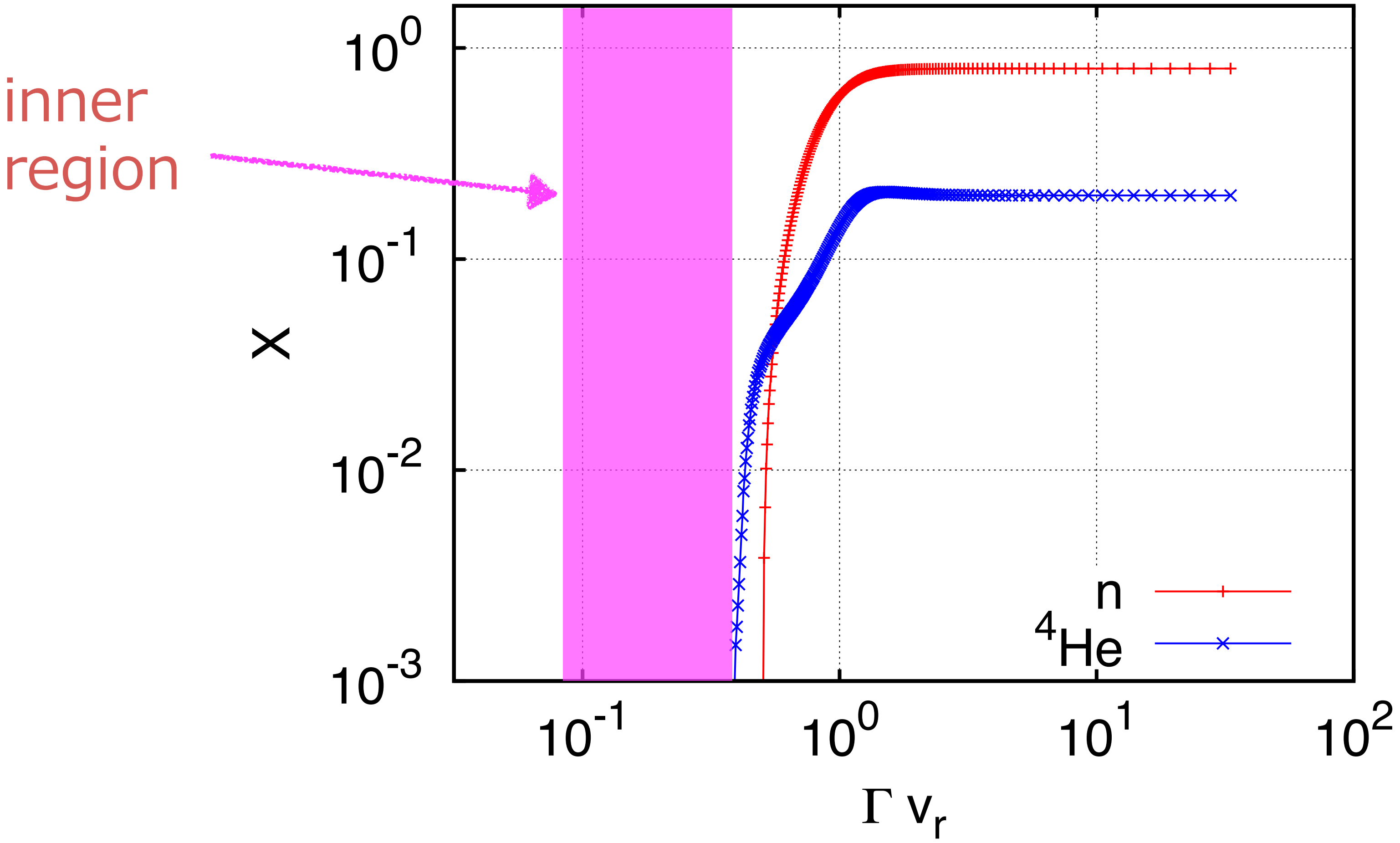

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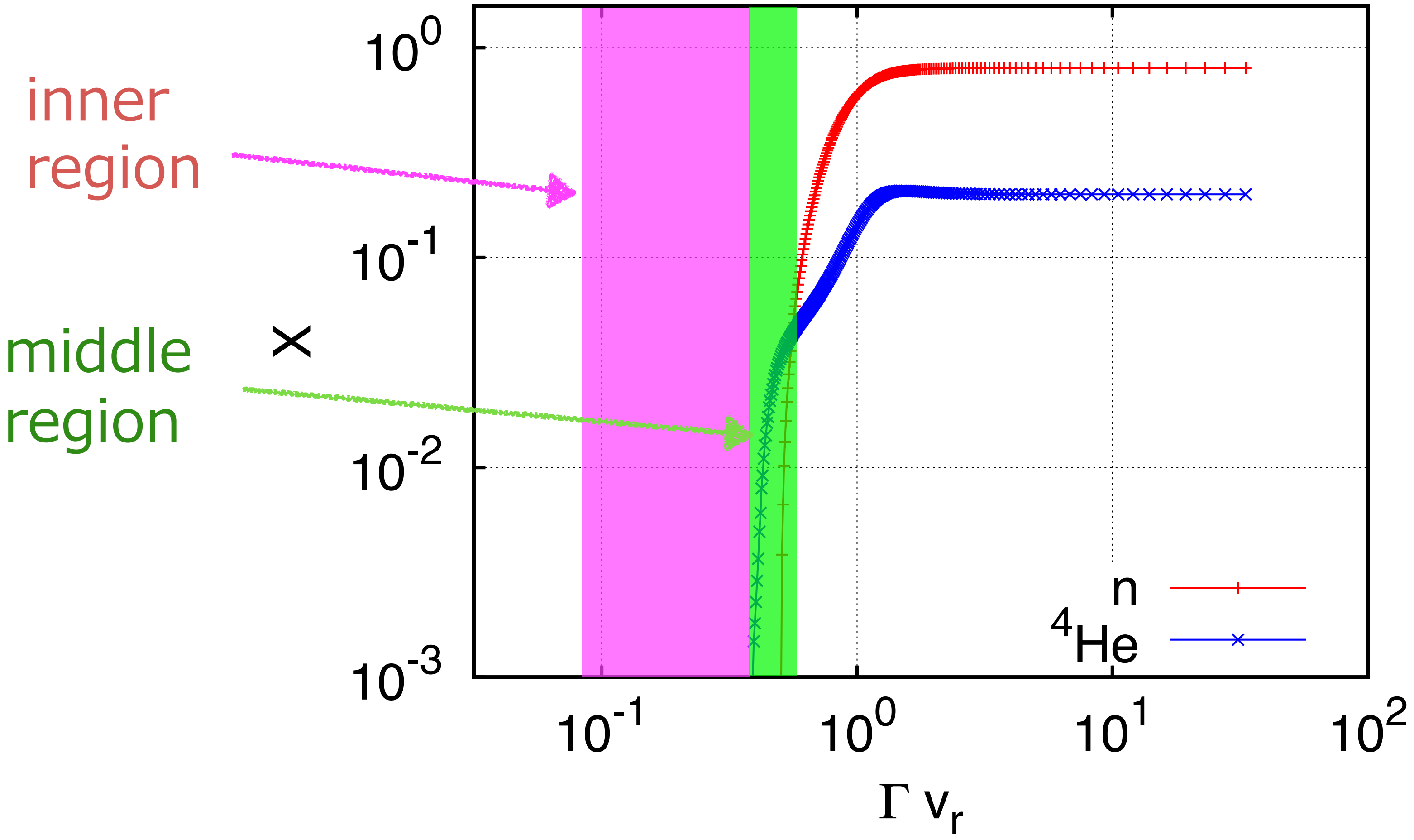

Inner region

- Neutrons are captured by nuclei to produce heavy elements

Middle region

- p(n,γ)d reactions produce ^{4}He with X_n ~0.5

Outermost region

- Free neutron layer is produced due to low density and temperature

Distribution of Mass Fraction

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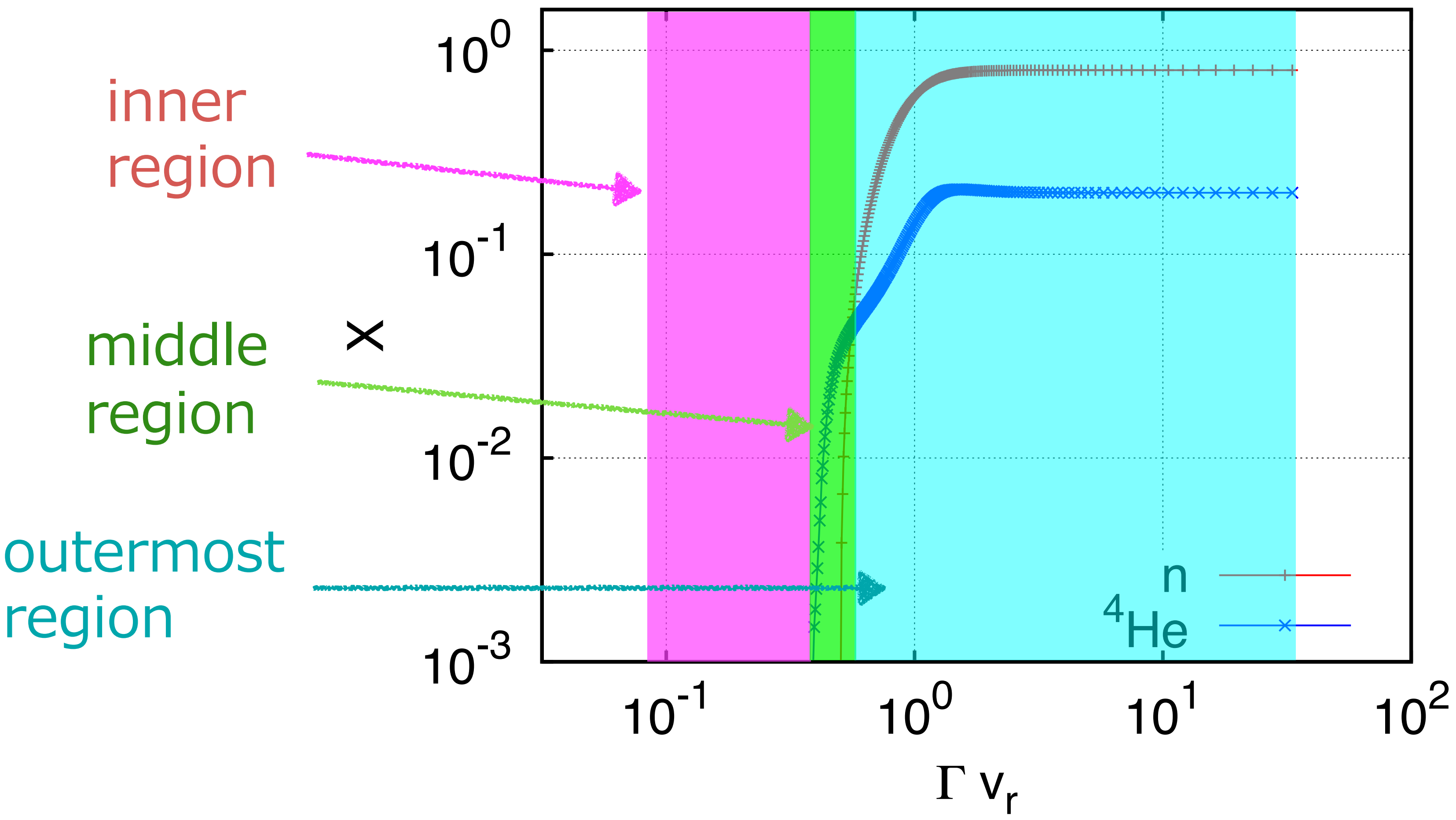

Inner region

- Neutrons are captured by nuclei to produce heavy elements

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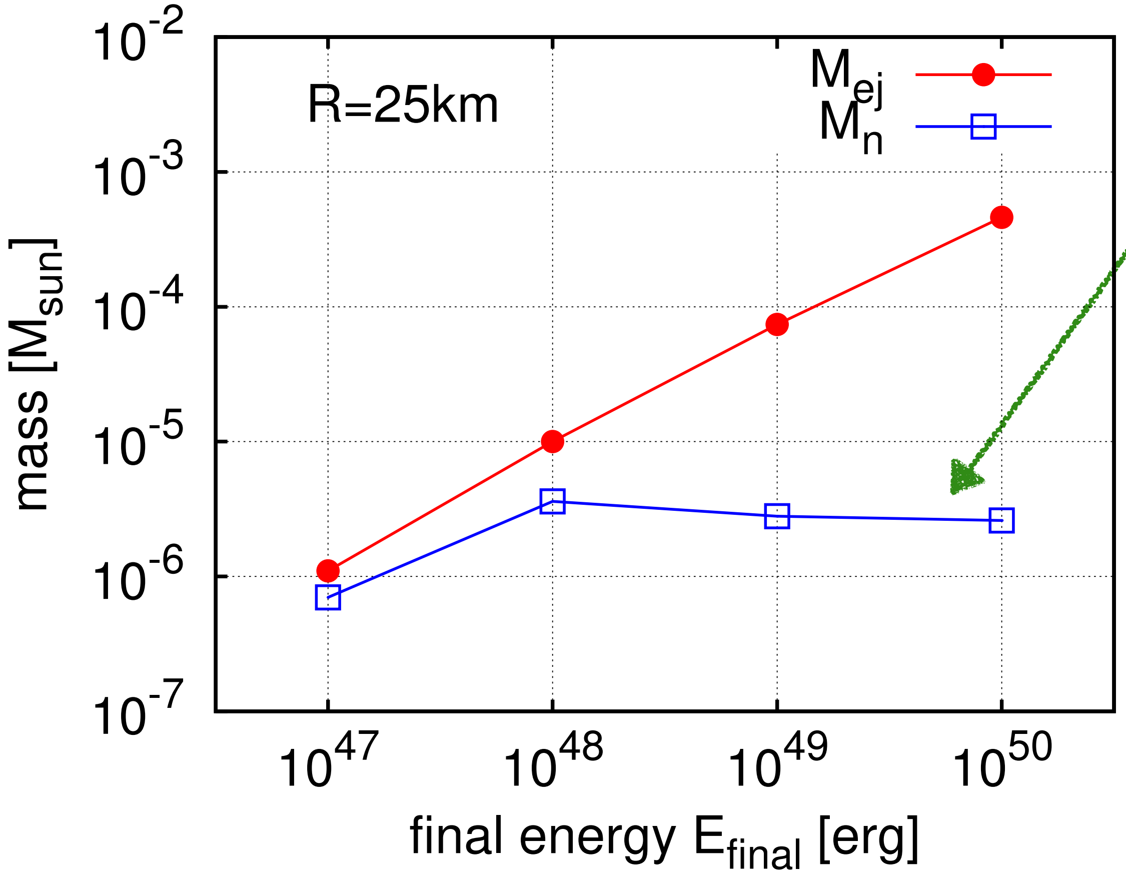
Total Mass of Free Neutron

R = 25 km



$M_n = \Sigma_i (X_{n,i} \times m_i)$
(Total mass of free neutron layer)

- Preferred energy that yields maximum amount of free neutrons is 10^{48} erg
- M_n value is smaller than previous SPH work by more than 2 orders ($\sim 10^{-4}$ M_{sun})

R [km] ($E_f = 10^{48}$ erg)	15	20	25	30
M_n [M_{sun}]	9.2×10^{-7}	2.1×10^{-6}	3.6×10^{-6}	5.2×10^{-6}

Emission from free neutron layer

M_{ej} = 10^{-5} M_{sun}, E_{final} = 10^{48} erg, ejecta velocity ~c/3, opacity ~0.4 cm^2 g^{-1}

- Photon diffusion velocity becomes comparable to expansion velocity (c/3) at ~1,500 s
- Energy density at neutron decay time (~800 s) is

$$\epsilon_0 \sim 10^6 \text{ erg cm}^{-3} \ (M_\mathrm{n}/3.6 \times 10^{-6} \ M_\mathrm{sun})$$

- Considering subsequent adiabatic expansion up to 1,500 s, luminosity L is estimated by

$$L \sim 7.6 \times 10^{41} \text{ erg s}^{-1} \ \left(\frac{t}{1{,}500 \text{ s}}\right)^{-2} \ \left(\frac{M_\mathrm{n}}{3.6{\times}10^{-6} \ M_\mathrm{sun}}\right)$$

(Ultraviolet, timescale of ~30 min)

- This is detectable with Swift if observations start immediately after the merger

Summary

- Shock breakout in neutron star merger was reproduced by relativistic Lagrangian hydrodynamics code
- Free neutrons can survive especially with $E_f \sim 10^{48}$ erg
- Total mass of neutron surviving region is $\sim 10^{-6}$ M_{sun} (two orders smaller than previous SPH work)
  →due to the different ejecta component or low resolution with a small number of SPH particles
- Luminosity of free neutron emission is $\sim 7\times10^{41}$ erg s^{-1} in optical band at ~ 30 min after merger event

Future work

- Monte Carlo Radiative transfer computation (A. Ishii et al. 2017) with thermal photons from free neutron decays

Thank you for your attention!

Reaction timescales

timescale for positron capture

$$\tau_{+} \simeq 2.1\left(\frac{kT}{\mathrm{MeV}}\right)^{-5} \ \mathrm{s}$$

(B. D. Metzger et al. 2015)

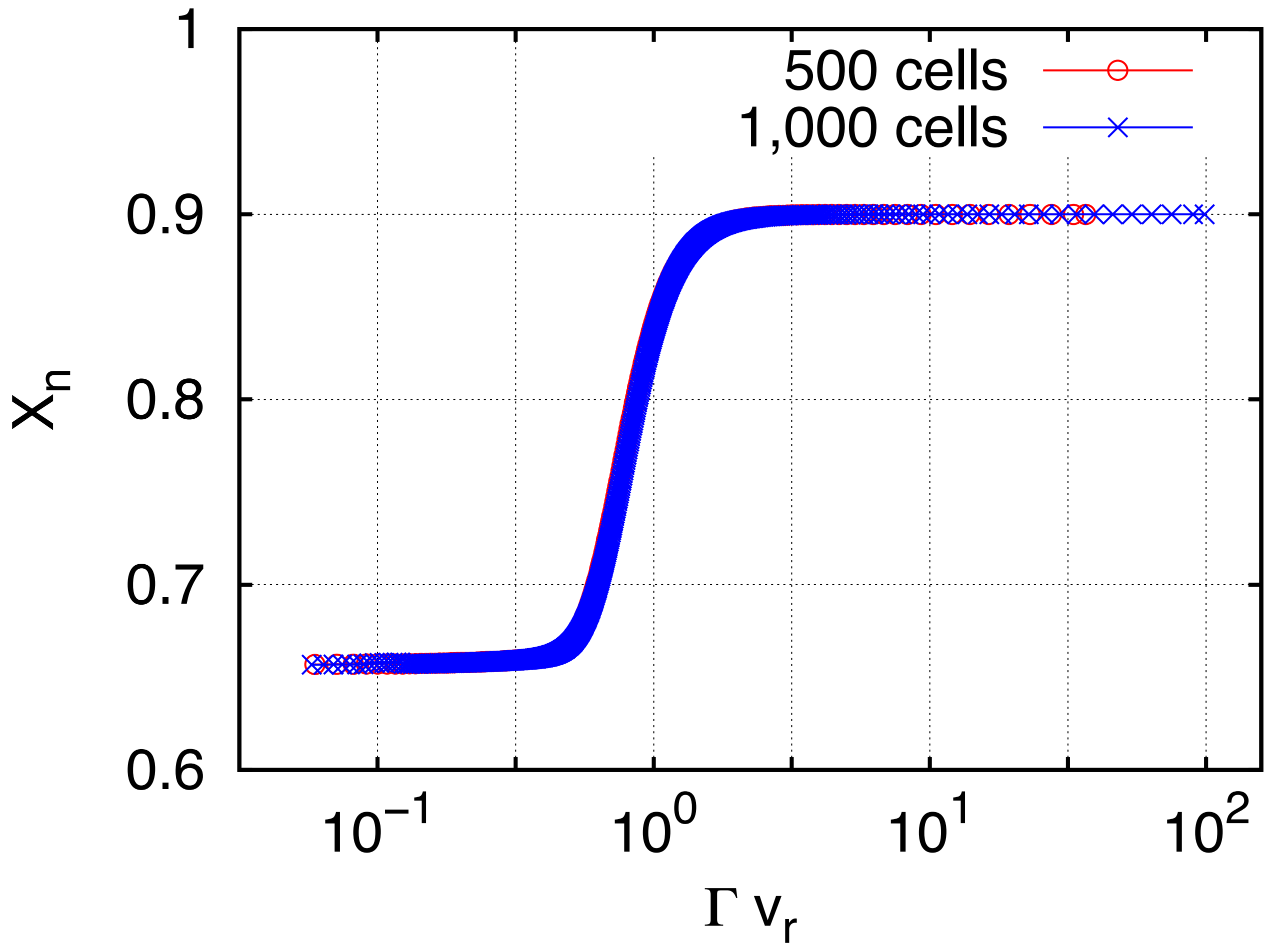
timescale for electron capture

$$\tau_{-} \simeq \frac{\tau e^{qz}}{\left(\frac{5.252}{z}-\frac{16.229}{z^{2}}+\frac{18.059}{z^{3}}+\frac{34.181}{z^{4}}+\frac{27.617}{z^{5}}\right)}$$

τ: neutron lifetime
q: $(m_n - m_p)/m_e$
z: $m_e c^2/kT$

(L. Kawano 1992)

Grid Convergence Test



- Computation was performed with 1,000 cells
- Distribution extends to larger Γv_r region than 500 cells
- M_n values are almost equivalent
  ($1.4 \times 10^{-6}\ M_{sun}$ and $1.3 \times 10^{-6}\ M_{sun}$)
  →Computation with 500 cells are converged

Endothermic reaction

- Disintegration for the heavy element nuclei is endothermic reaction
- The energy density: $a_r T^4/\rho \sim 3 \times 10^{19}$ erg g^{-1} ($T \sim 2.5 \times 10^{11}$ K)
- The energy of the endothermic reaction for Fe: ~9 MeV per nucleon →Energy density for the reaction: 9 MeV/mu $\sim 8.6 \times 10^{18}$ erg g^{-1}
- Thus the energy is brought out by the endothermic reaction by a few tens of a percent
- The expelled energy might be decreased with the realistic composition of the merging neutron stars