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Free Neutron Ejection from Shock Breakout in 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/

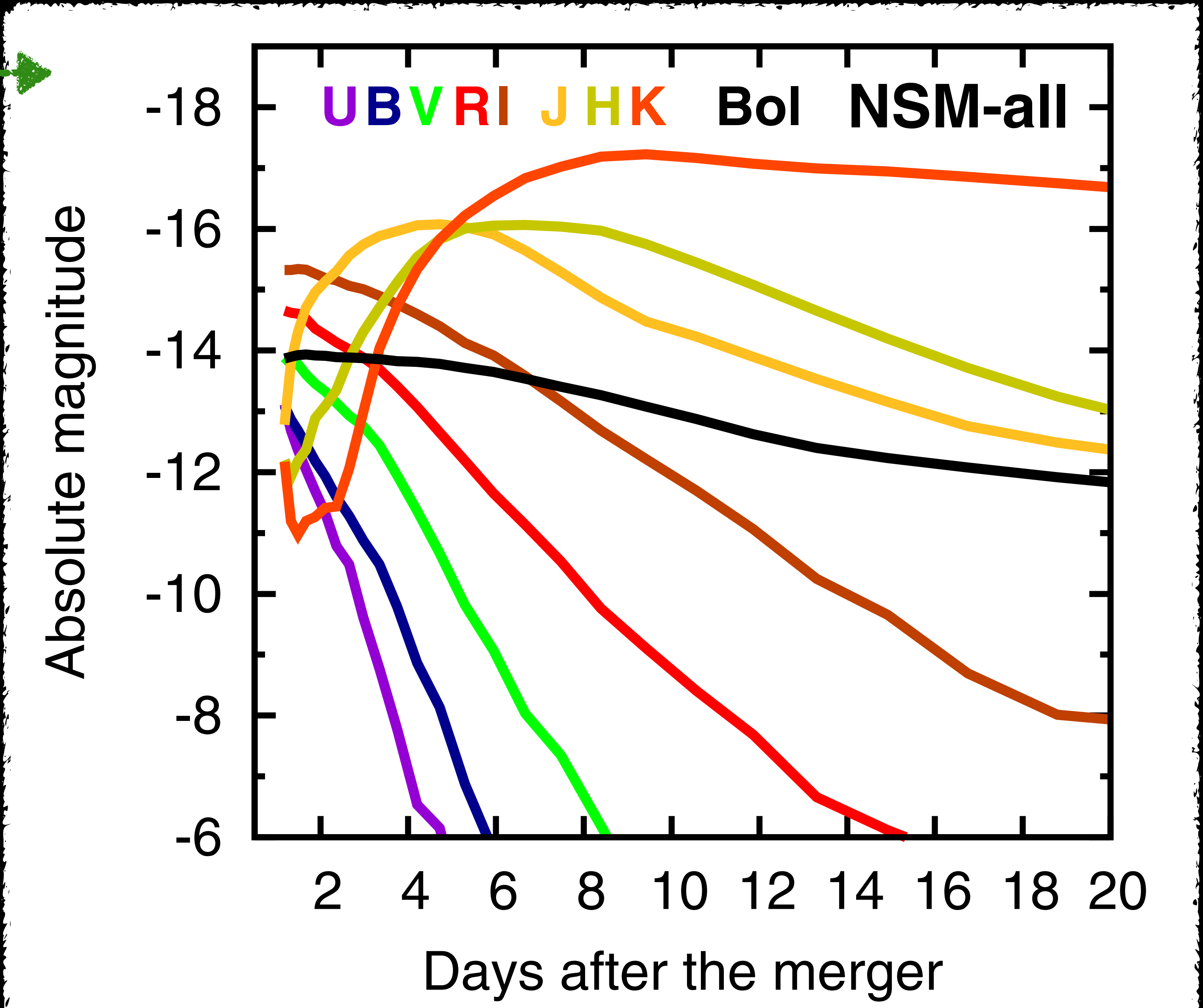
Observed emission could be almost explained by kilonova model

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

Theoretical Study of kilonova

(Goriely et al. 2011, M. Tanaka & K. Hotokezaka 2013)

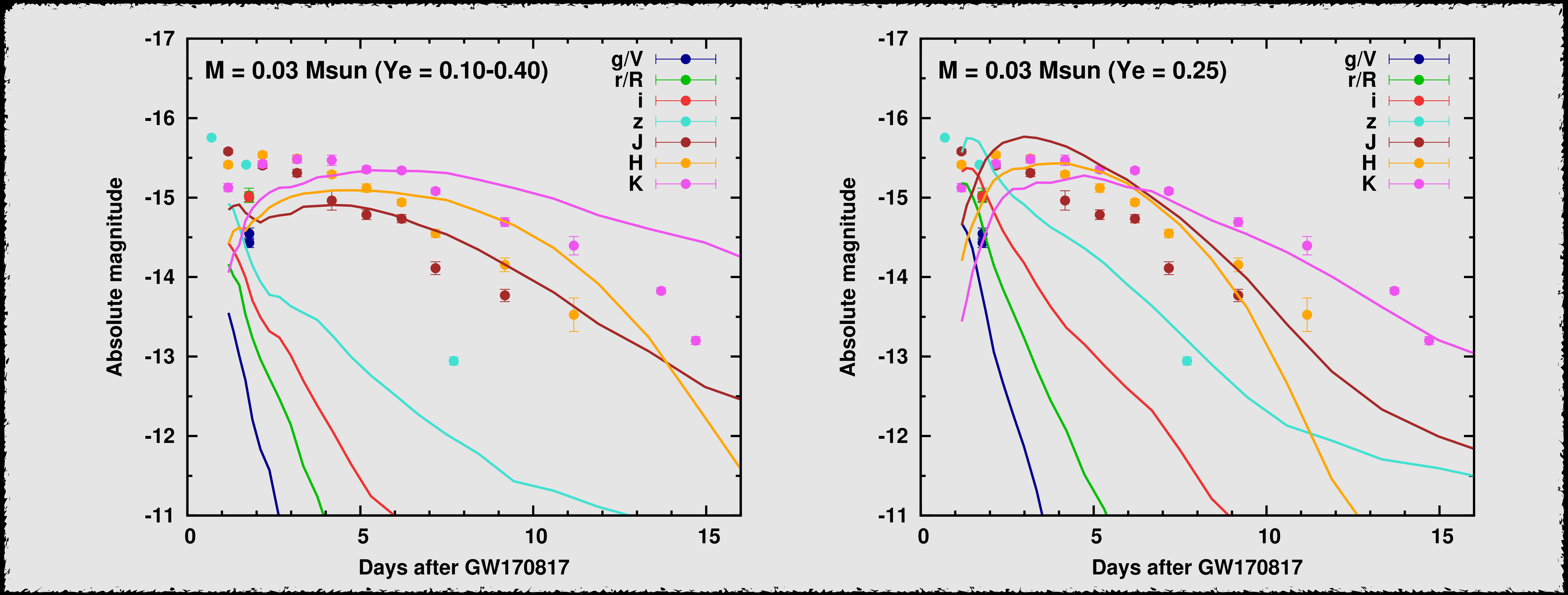
Opacity for 31 < Z < 92 is used



- Emission before ~1 day cannot be computed because of lack of opacity data

Early Emission from Neutron Star Merger

(M. Tanaka et al. 2017, Utsumi et al. 2017, …)



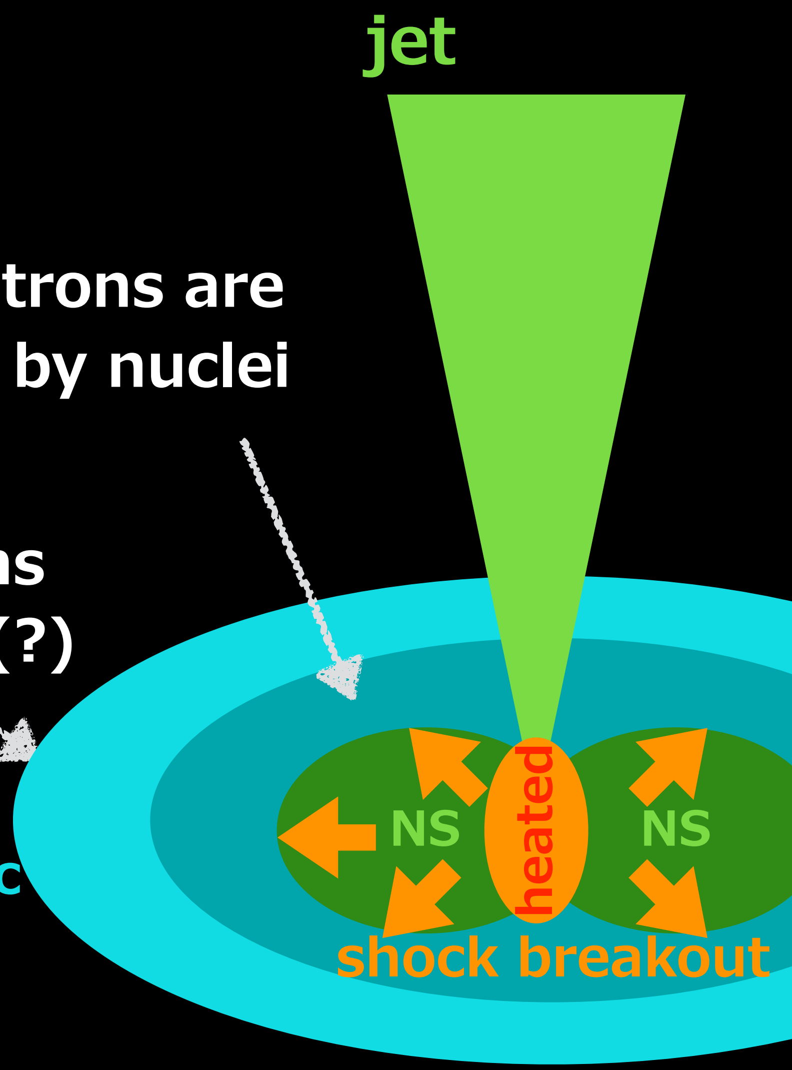
- Observations started in ~11 h after merging event
- Observed early emission (~1 day) is more luminous and bluer than model computation
- Early emission from neutron star merger is unclear
  But it can provide us with rich information about merger event

Free Neutron Precursor

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

- Outermost ejecta is accelerated to relativistic speed
  (K. Kyutoku et al. 2014)
- Outermost ejecta expands sufficiently rapidly that neutrons avoid capture
  (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 (?)

relativistic region

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 binary neutron star merger

Step 1

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

Step 2

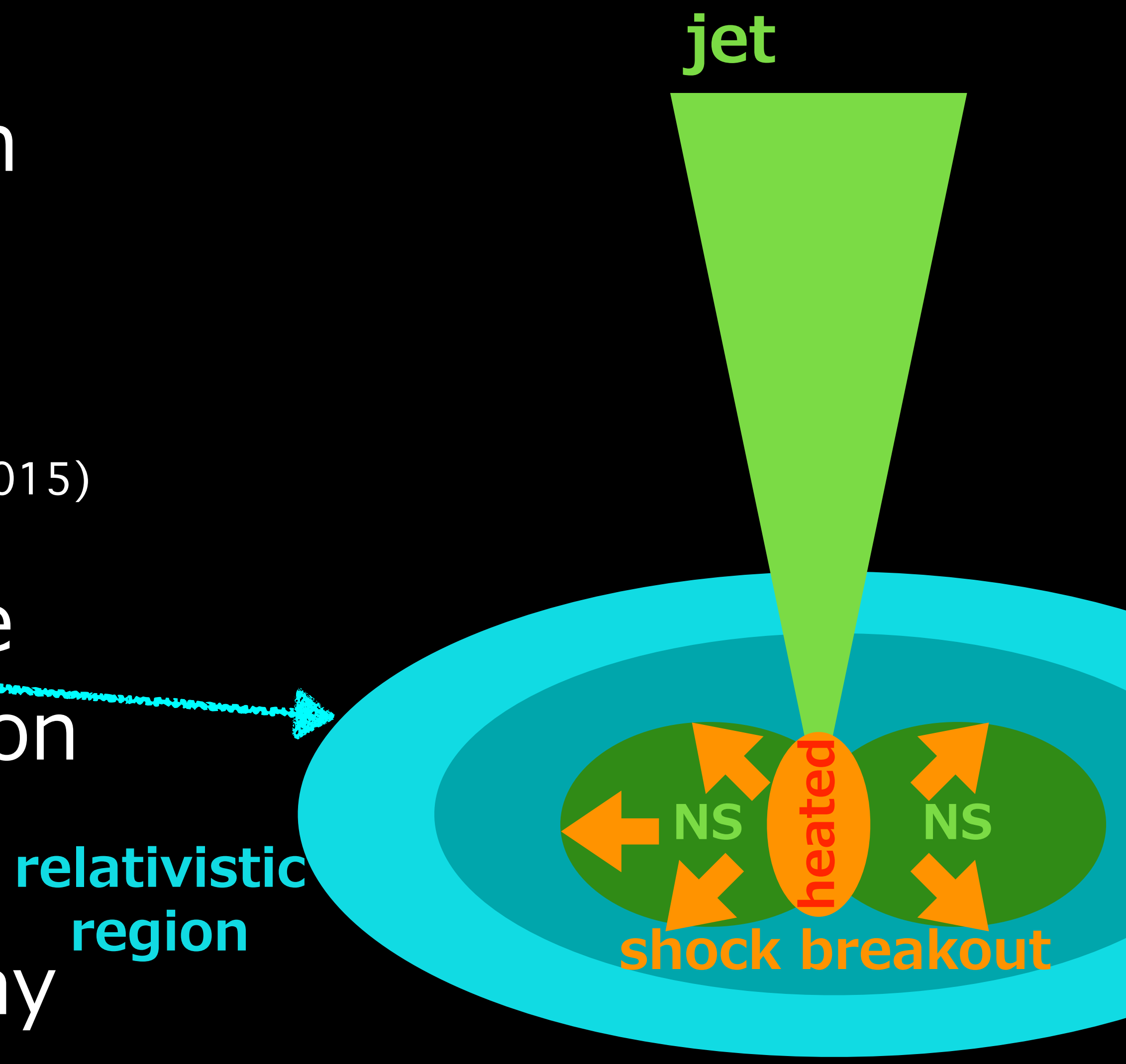
- Estimating surviving free neutron mass fraction

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

$$\tau_{+} \simeq 2.1(T/\mathrm{MeV})^{-5}\ \mathrm{s}$$ (B. D. Metzger et al. 2015)

Step 3

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



Step 4

- Calculating emission from β-decay of free neutron

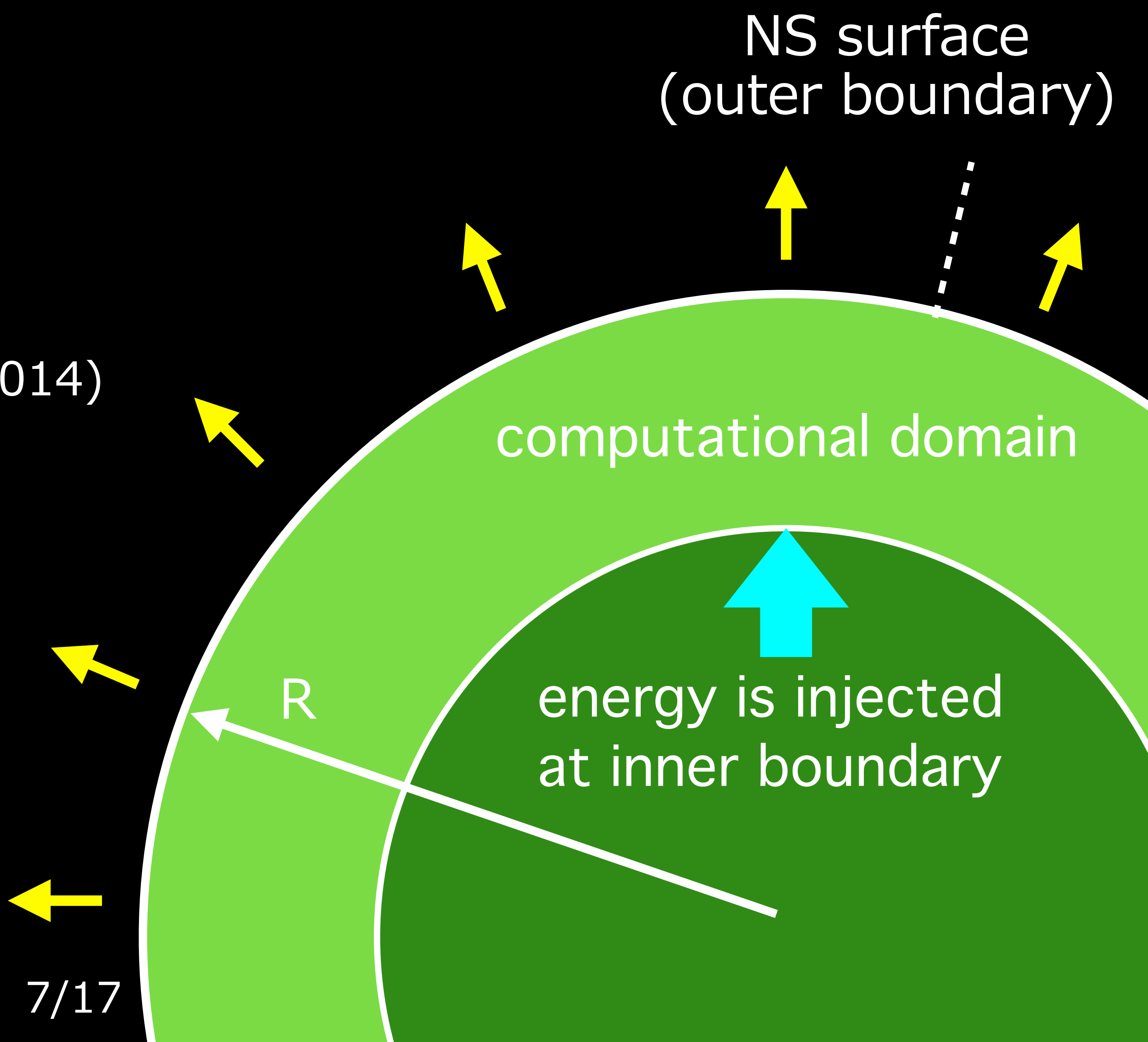
Simulation Condition

- 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 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 (beta equilibrium of cold dense matter)
- $e^{\pm}$ is generated by shock heating

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

← dominant

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

- Time scale of positron capture process is calculated by

$$\tau_{+} \simeq 2.1 (T/\mathrm{MeV})^{-5}\ \mathrm{s}$$

(B. D. Metzger et al. 2015)

- Time evolution of X_n is calculated by

$$\frac{dX_n}{dt} = -\frac{X_n}{\Gamma \tau_{+}(T)}$$

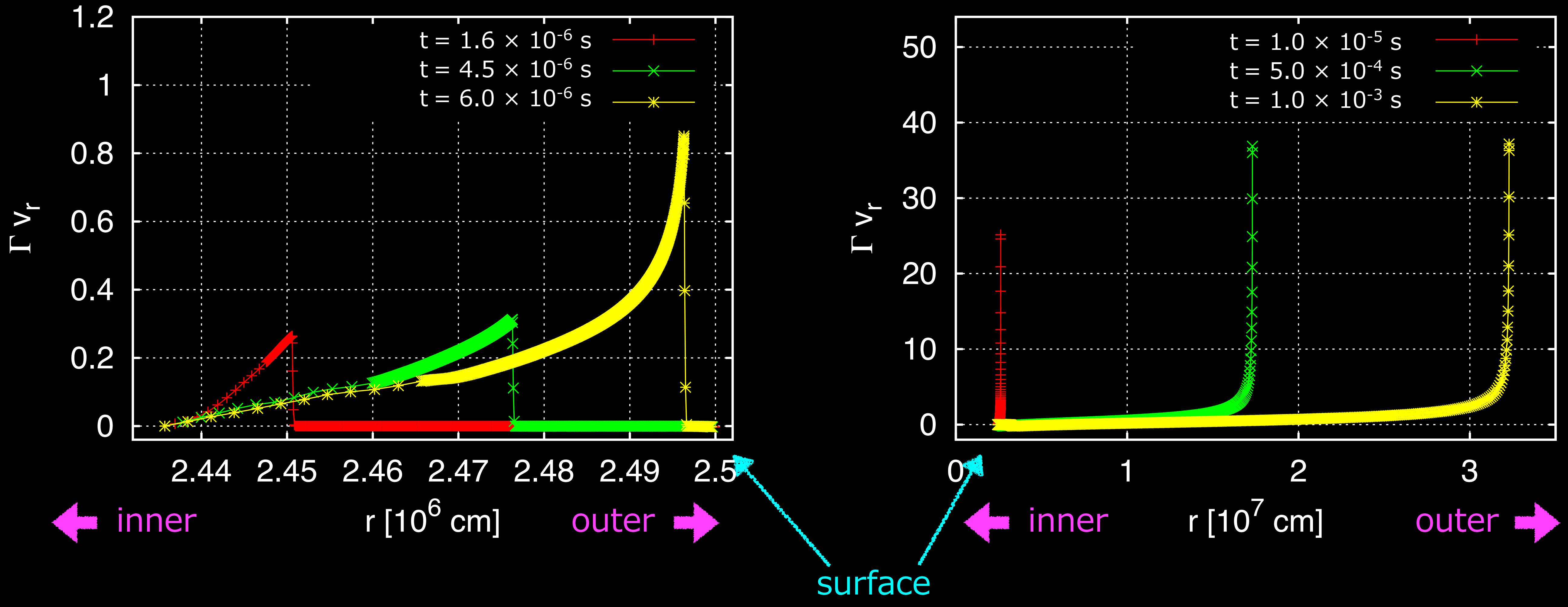
- Nuclear reaction network calculations are performed after temperature decreases down to 10^{10} K (Shigeyama et al. 2010)

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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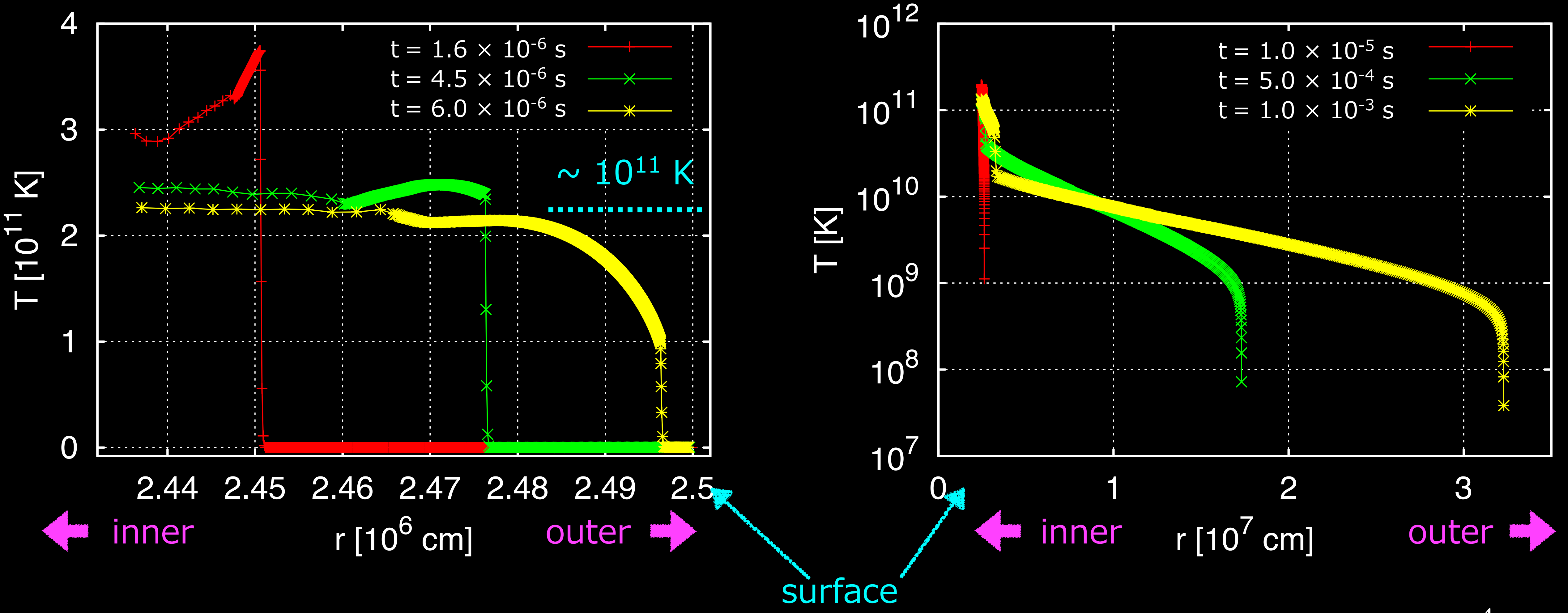
After shock breakout

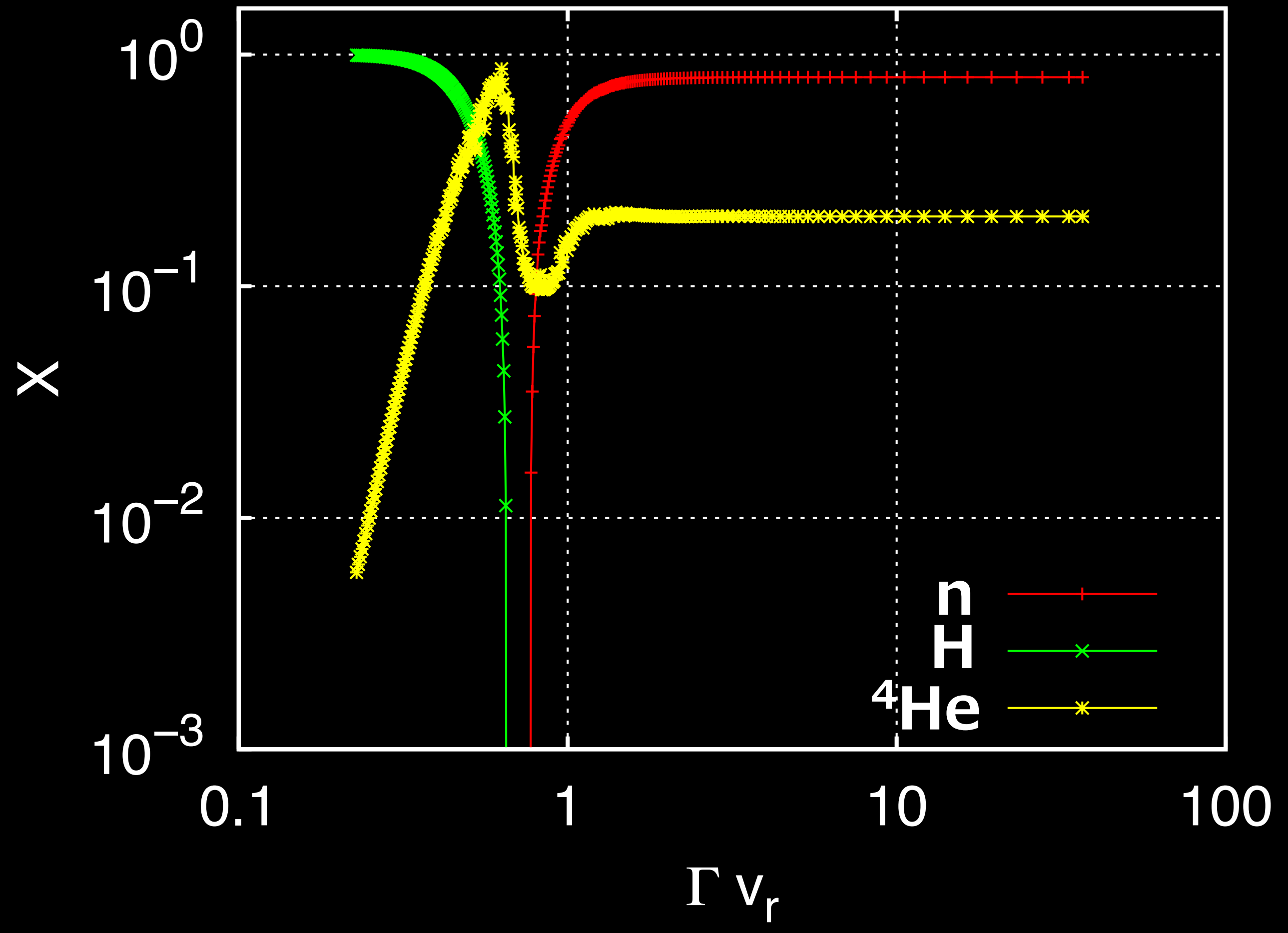


- Radiation pressure is assumed to be dominant ($P = \frac{aT^4}{3}$)
- Temperature decreases rapidly after shock breakout

$$\tau_+ \simeq 2.1(T/\mathrm{MeV})^{-5}\ \mathrm{s} \xrightarrow{10^{11}\ \mathrm{K}} \sim 4.41\times10^{-5}\ \mathrm{s}$$

Distribution of Mass Fraction

$R = 25$ km
$E_{\mathrm{final}} = 10^{49}$ erg
$t = 0.3$ s
$T < 5\times10^{7}$ K



Inner region

- Free proton layer is produced due to active positron captures

Middle region

- p(n,γ)d reactions consume all neutrons to produce ^{4}He if $X_n<0.5$; otherwise, p(n,γ)d reactions produce heavy neutron rich elements

Outermost region

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

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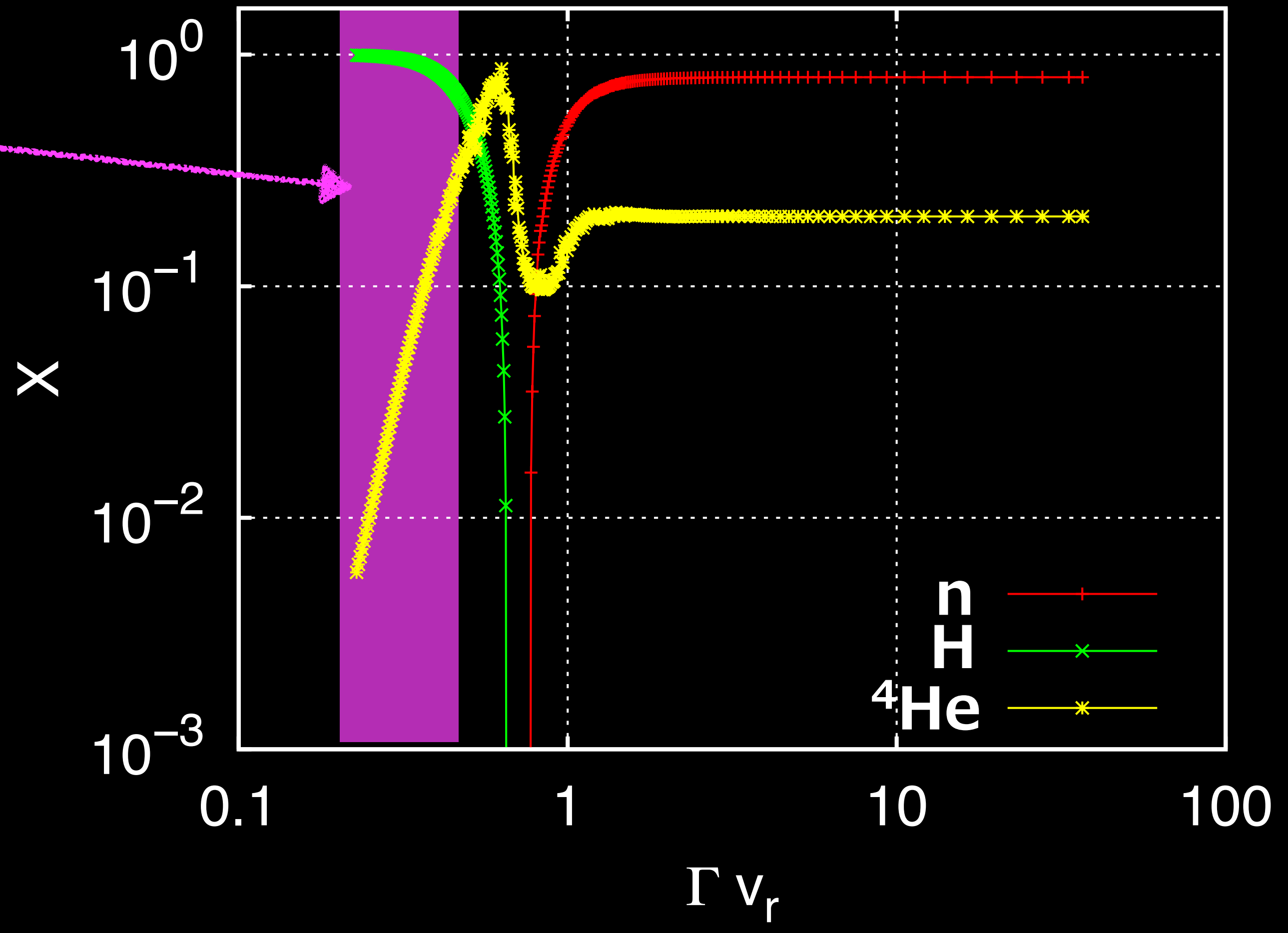

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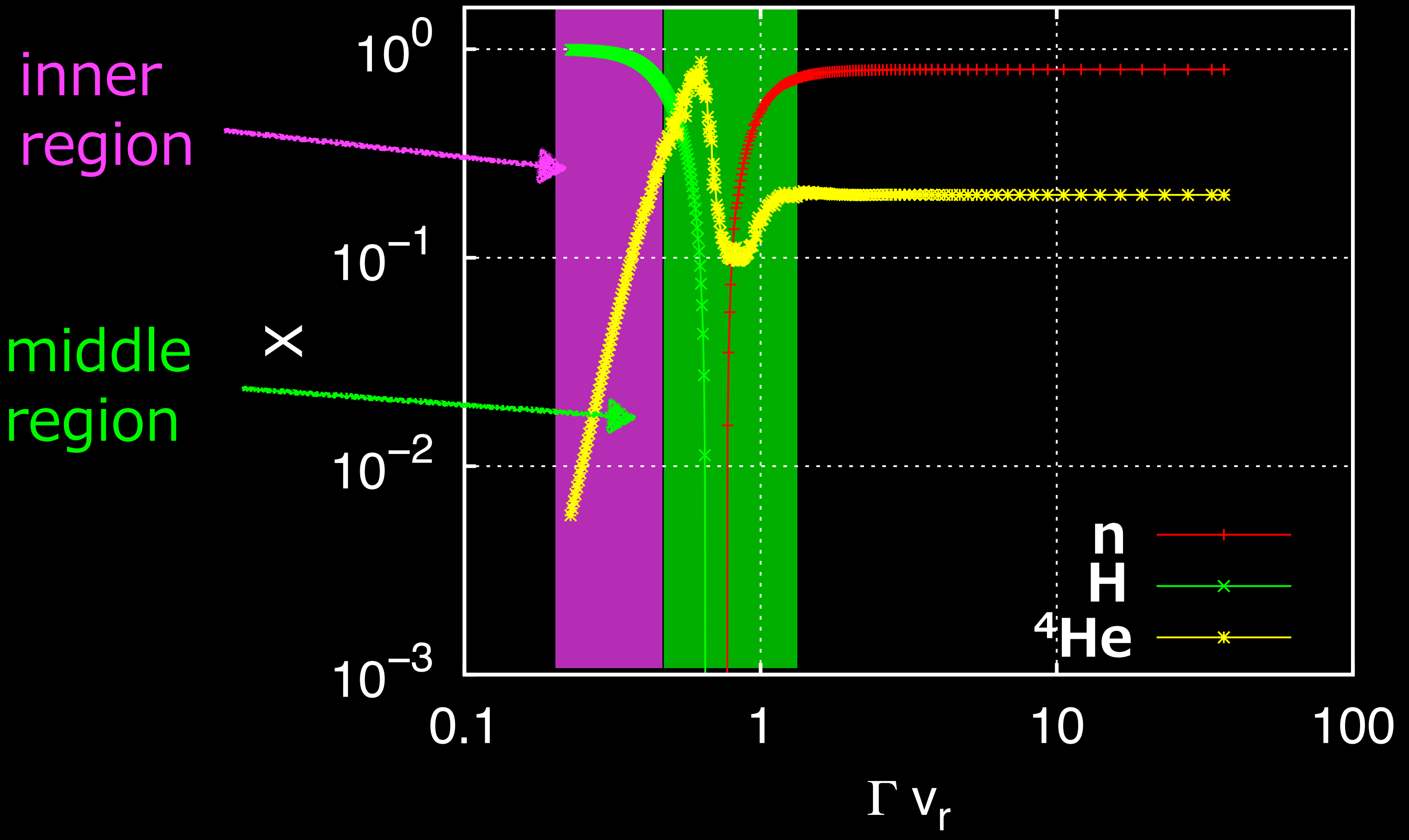

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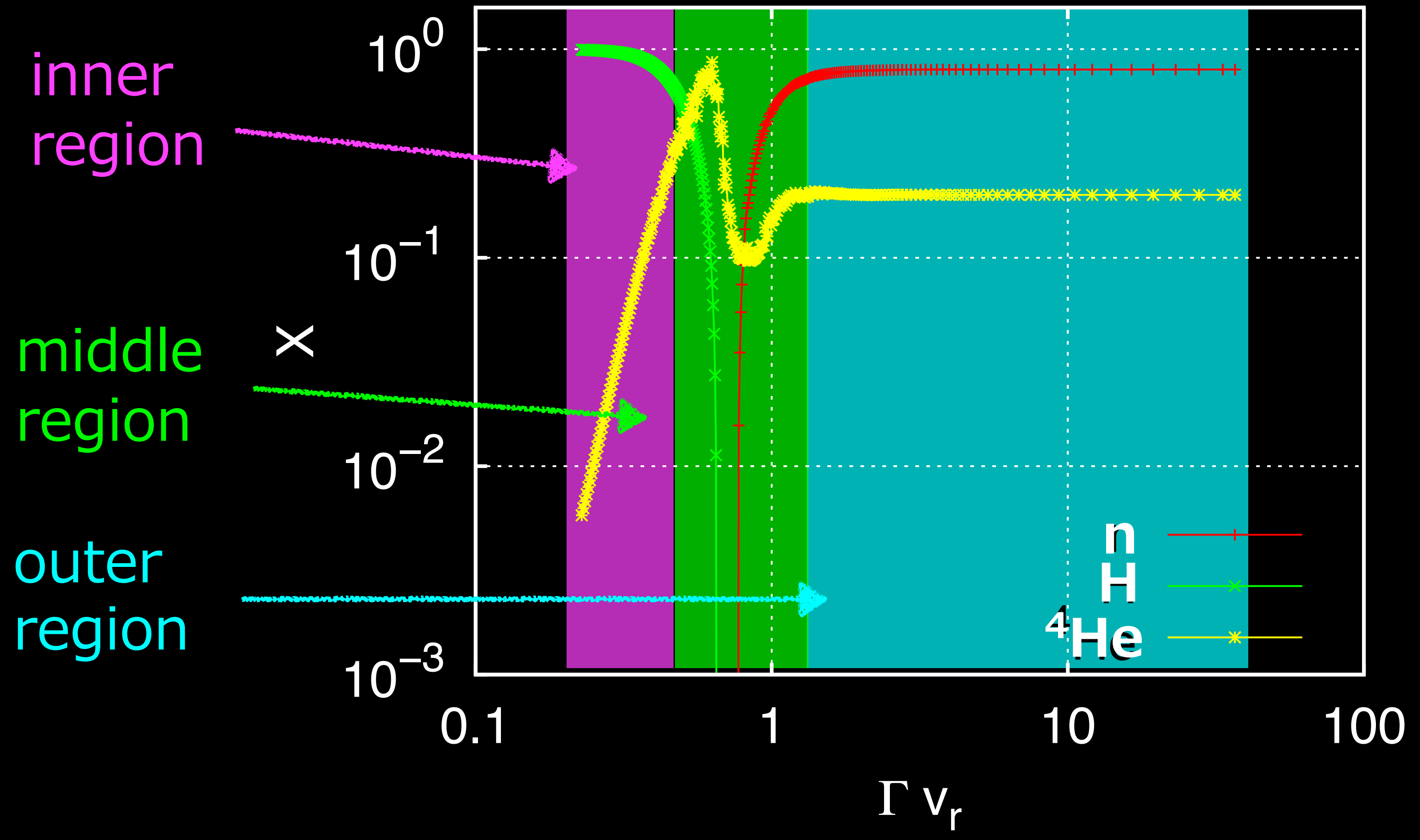

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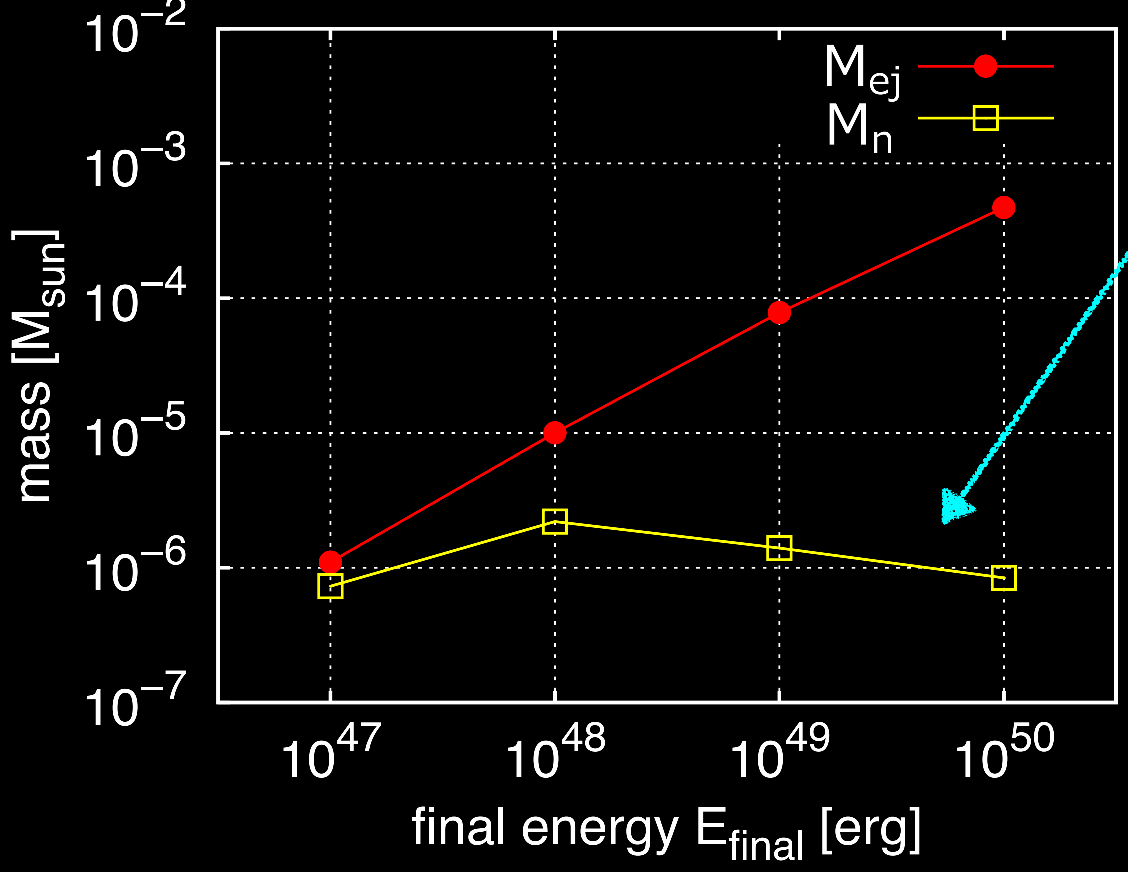
Total Mass of Free Neutron

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 ($\sim 10^{-4}$ M_{sun})

R [km] (E_f = 10^{48} erg)	15	20	25	30
M_n [M_{sun}]	4.5×10^{-7}	1.1×10^{-6}	2.2×10^{-6}	3.8×10^{-6}

Emission from free neutron

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

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

$$\epsilon_0 \sim 6.0 \times 10^5\ \mathrm{erg\ cm^{-3}}\ (M_n/2.2 \times 10^{-6}\ M_{\mathrm{sun}})$$

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

$$L \sim 4.6 \times 10^{41}\ \mathrm{erg\ s^{-1}} \left(\frac{t}{1{,}500\ \mathrm{s}}\right)^{-2} \left(\frac{M_{\mathrm{n}}}{2.2{\times}10^{-6}\ M_{\mathrm{sun}}}\right)$$

(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 low resolution with small number of SPH particles
- Luminosity of free neutron emission is $\sim 4 \times 10^{41}$ erg s^{-1} in optical band at ~ 30 min after merger event

Future work

- Radiative transfer computation with thermal photons from free neutron decays

Thank you for your attention!