Advancing the Understanding of Interaction-Powered Transients through Numerical Modeling

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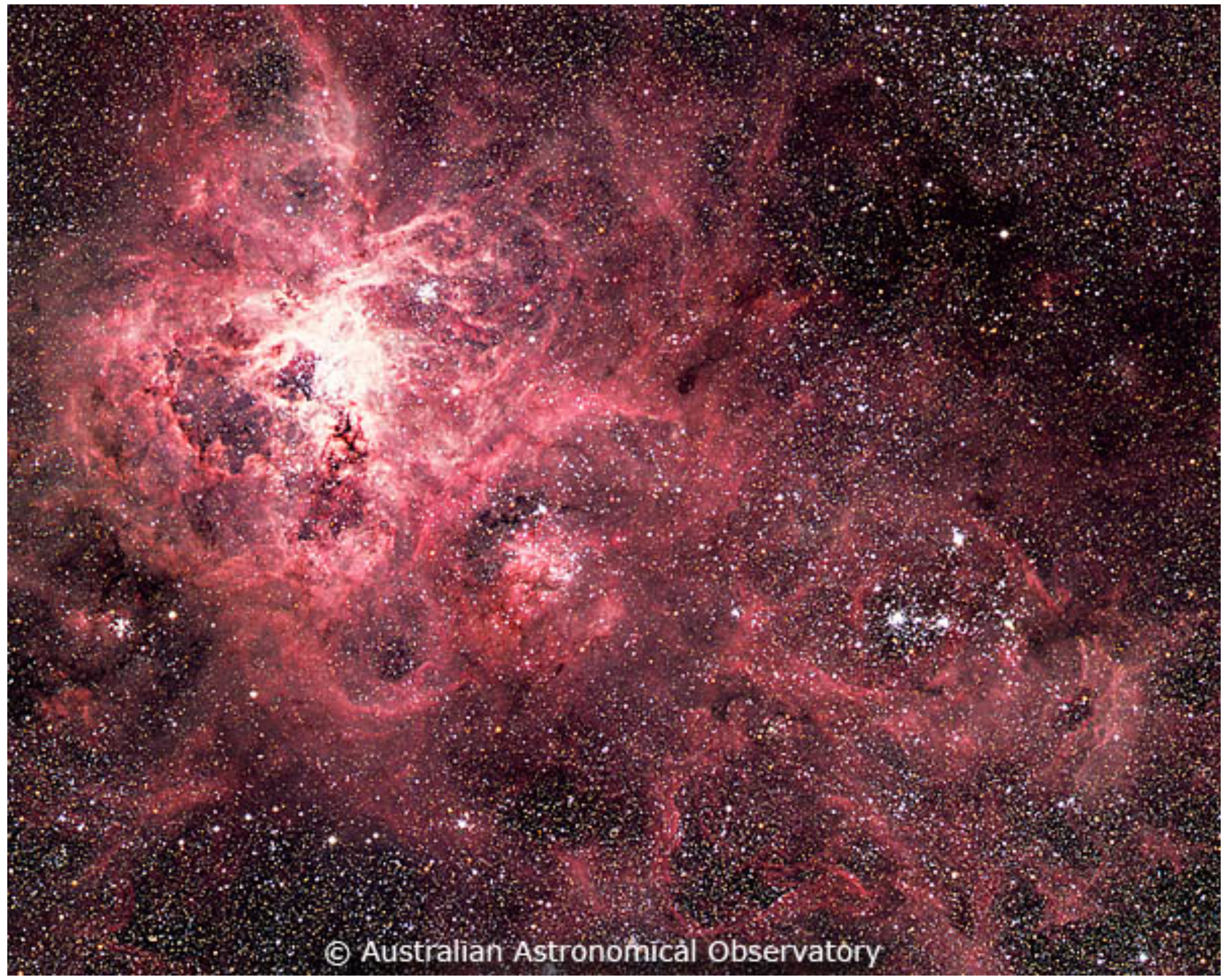
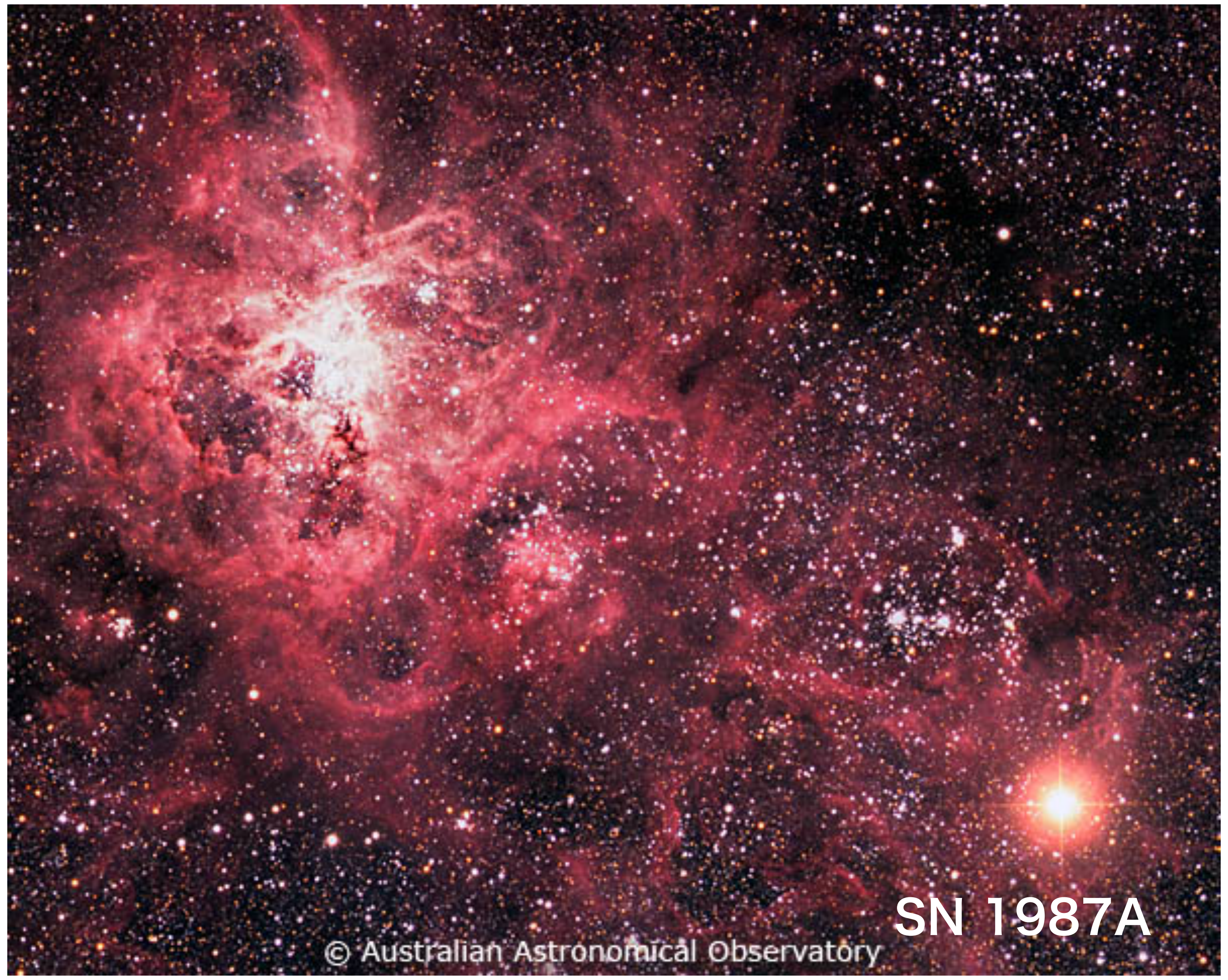
TeV Particle Astrophysics 2026, Tendo Yamagata, 2026/9/1

Supernovae/Transients as a high-energy particle source

- CCSNe: massive star's final evolutionary state
- the explosion forms a compact remnant (NS/BH) and ejects outer envelope
- Most gravitational energy is converted to neutrino emission $E_\nu \sim 10^{53}$erg, while the expanding ejecta carries $E_{exp} \sim 10^{51}$erg



1984

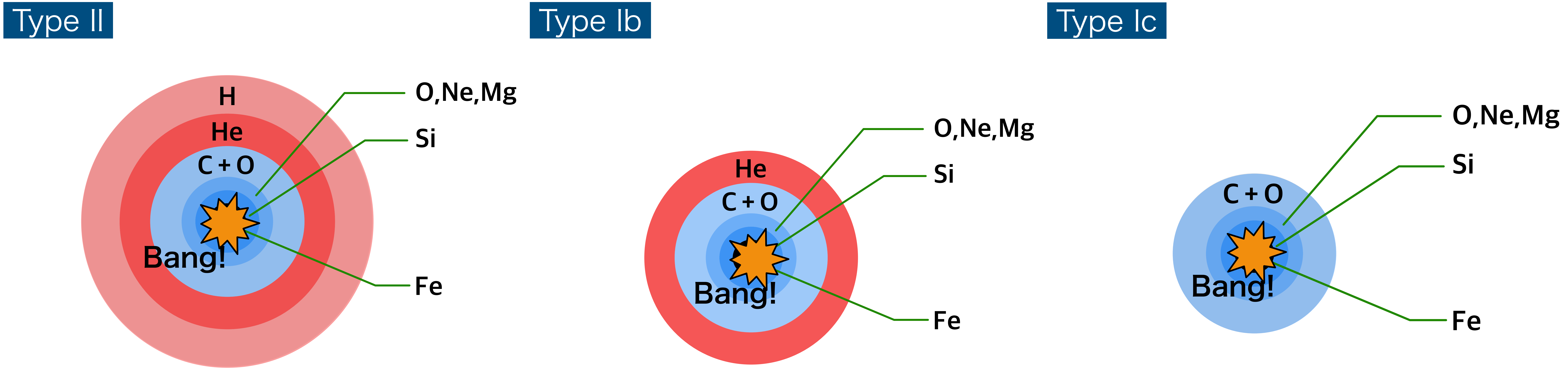


1987

SN 1987A at Magellanic cloud

Interacting supernovae/transients "Zoo"

- diverse populations of SNe showing interaction feature (narrow absorption/emission spectra)
- Hydrogen-rich (IIn), Hydrogen-poor (Ibn, Icn)
- possibly FBOTS (fast blue optical transients) could also be interaction-powered



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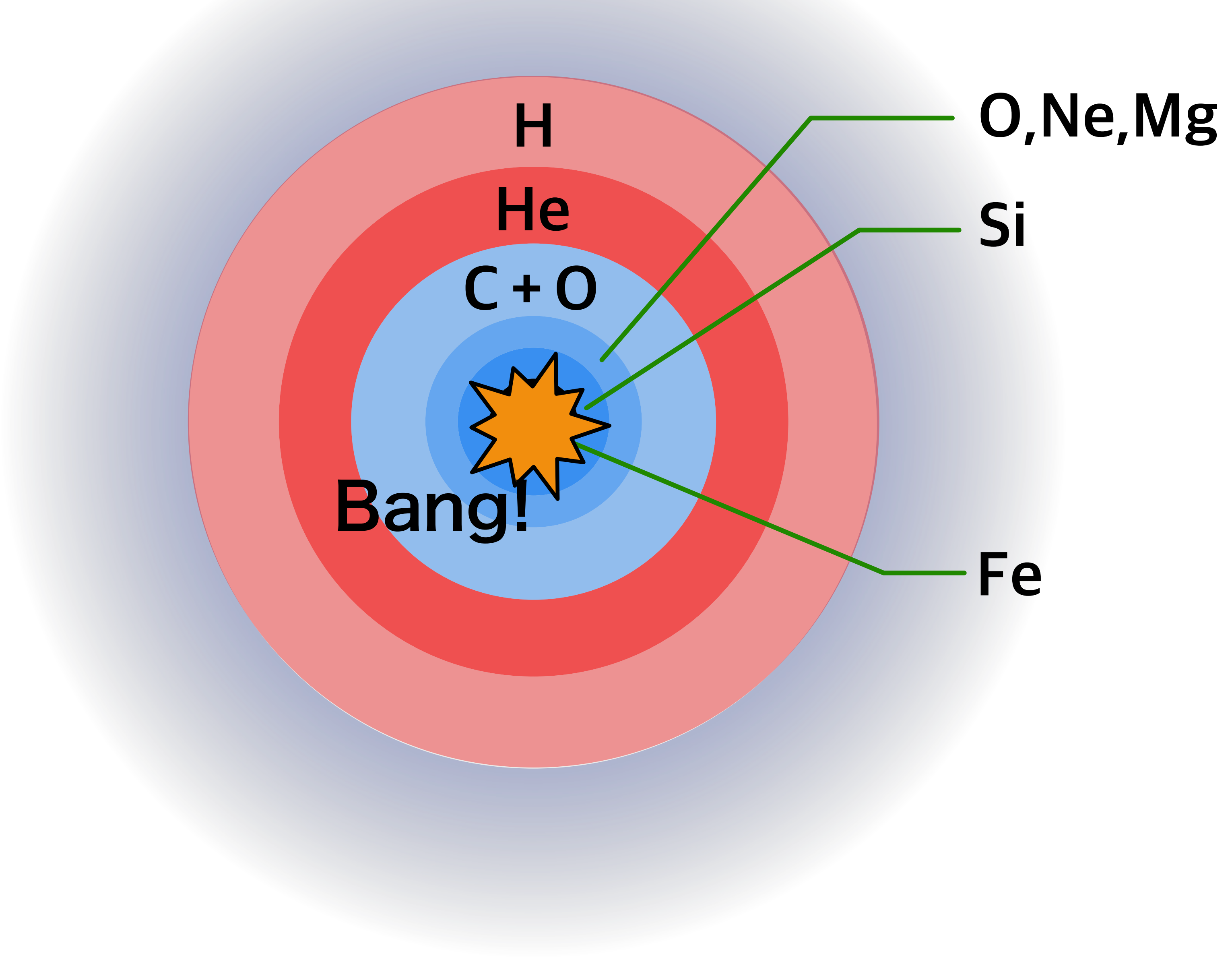
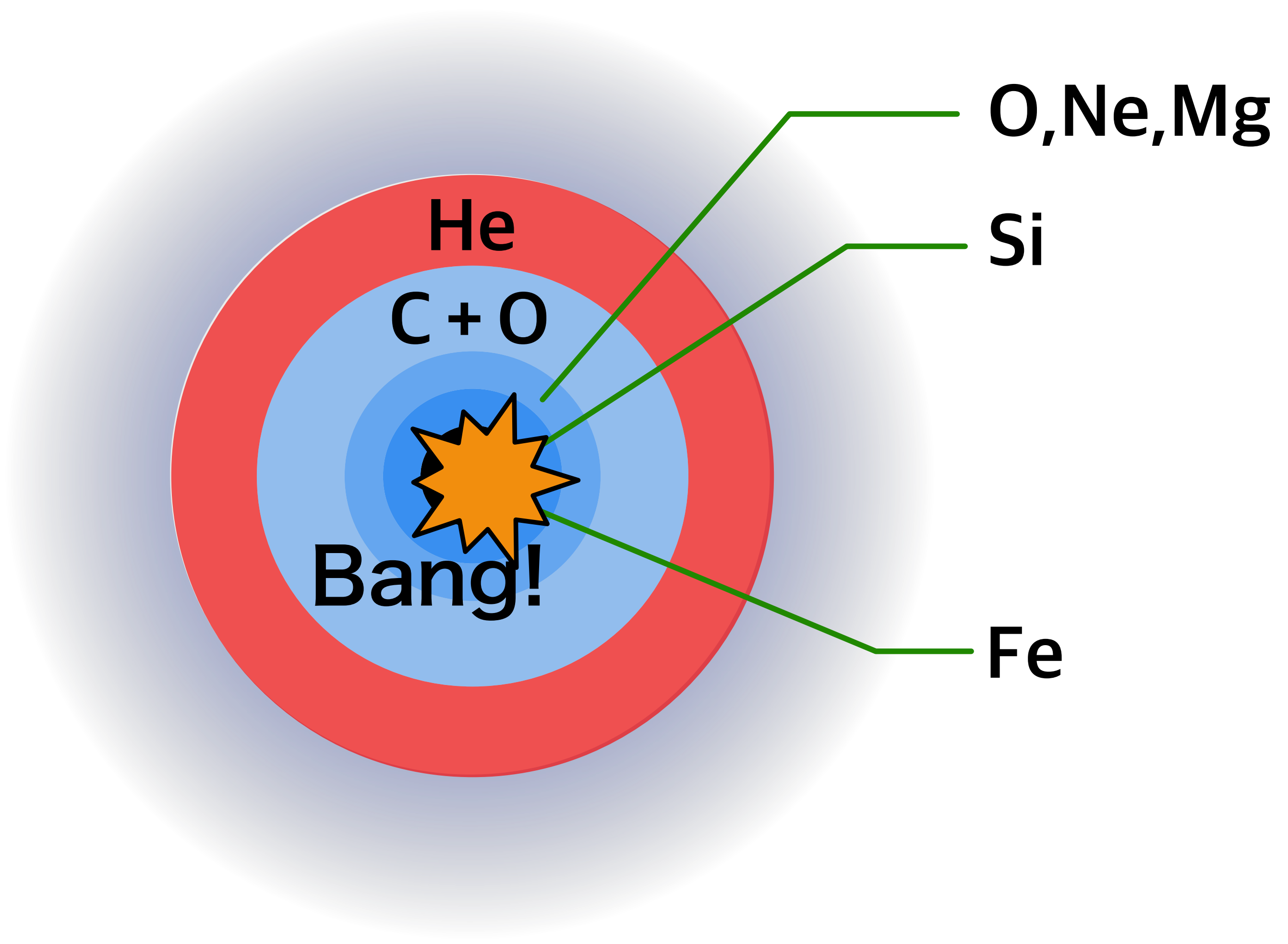
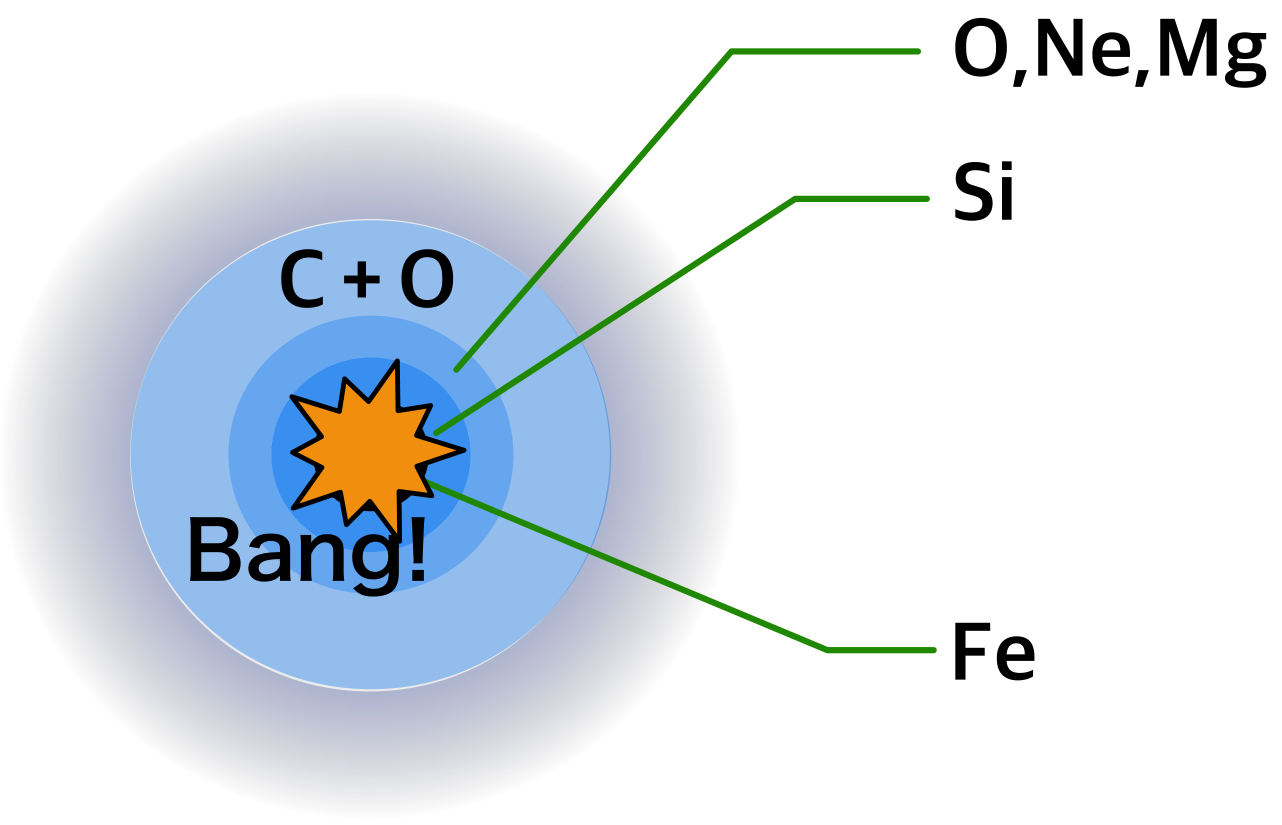
Type II → IIn



Type Ib → Ibn



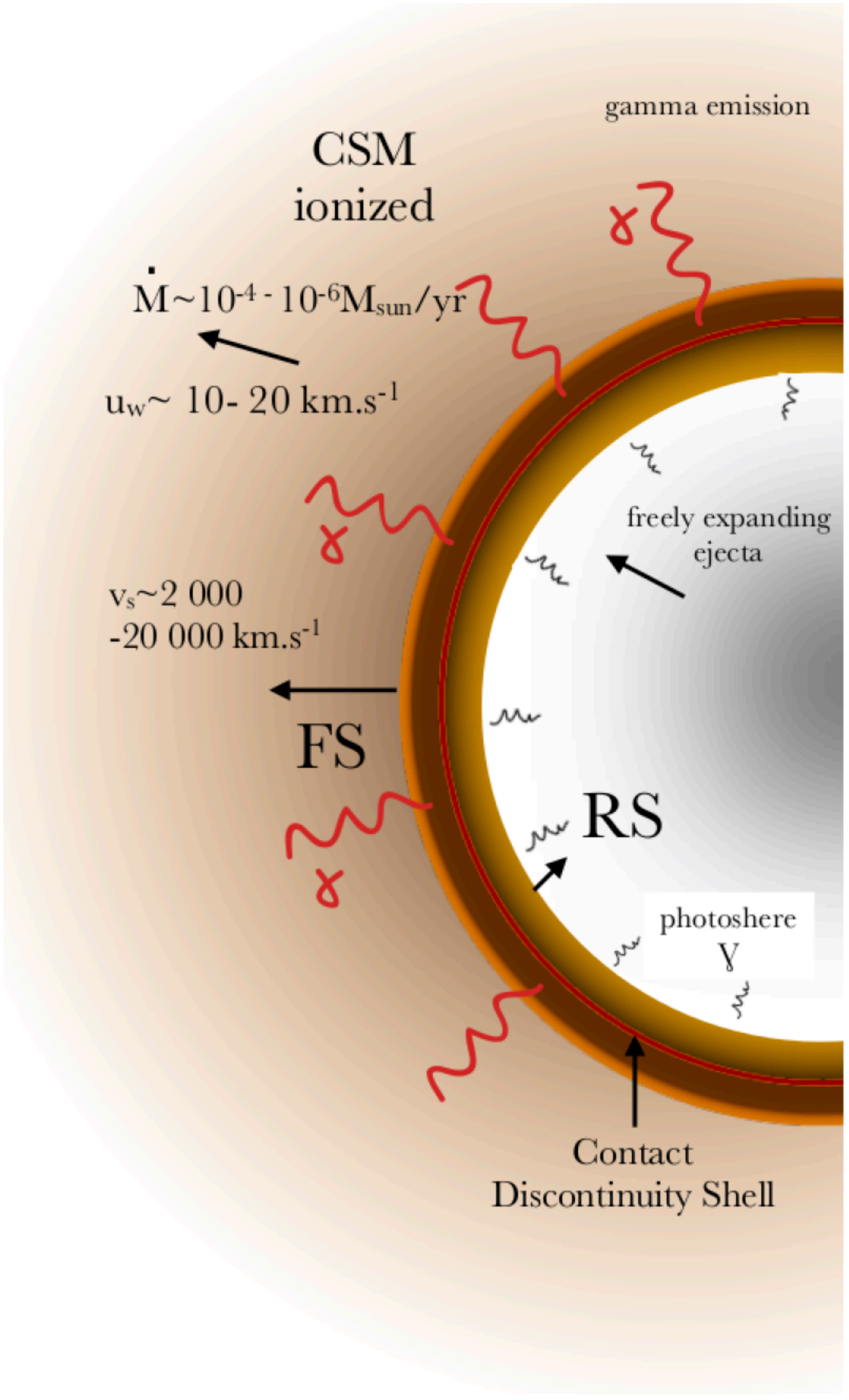
Type Ic → Icn

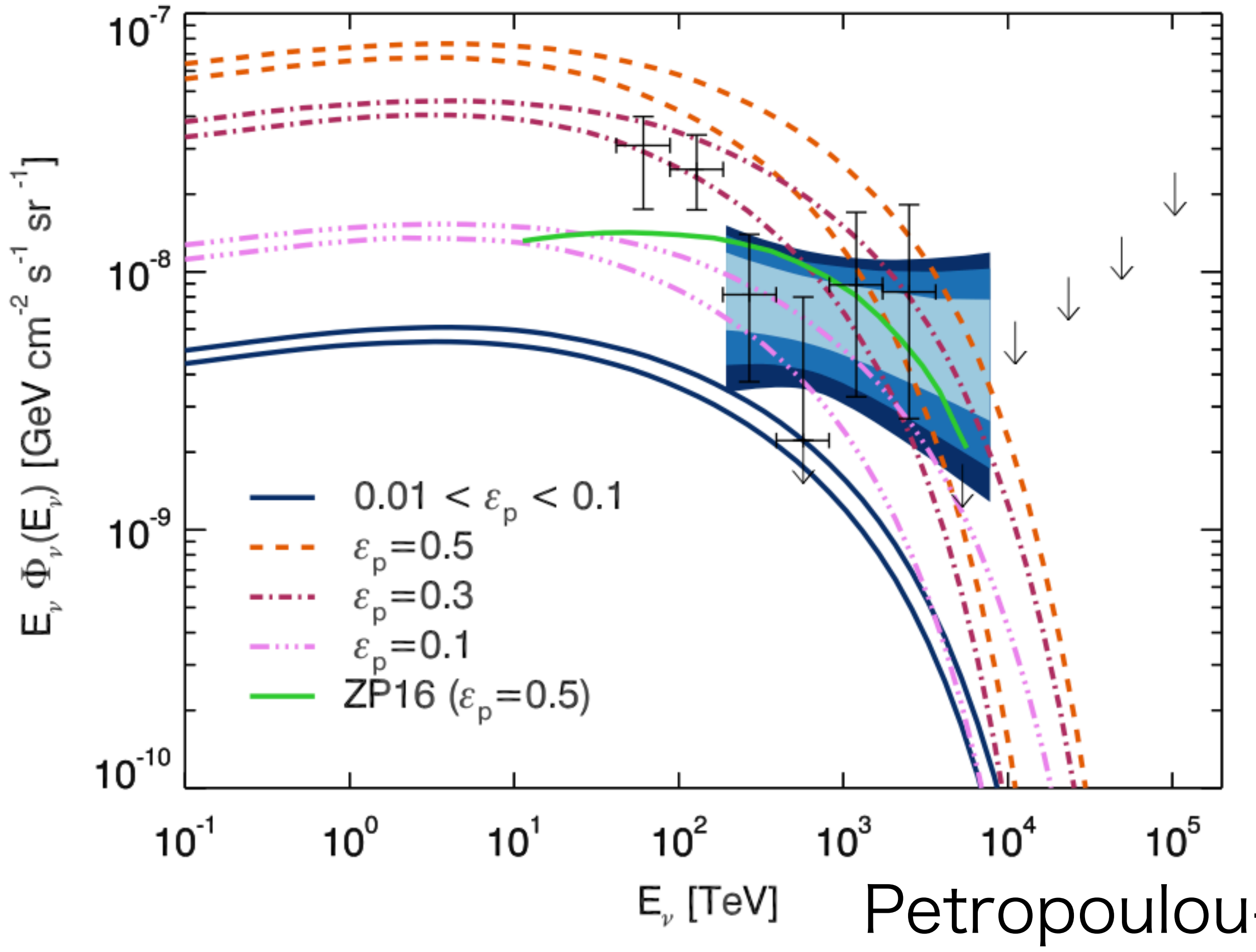


Supernovae/Transients as a high-energy particle source

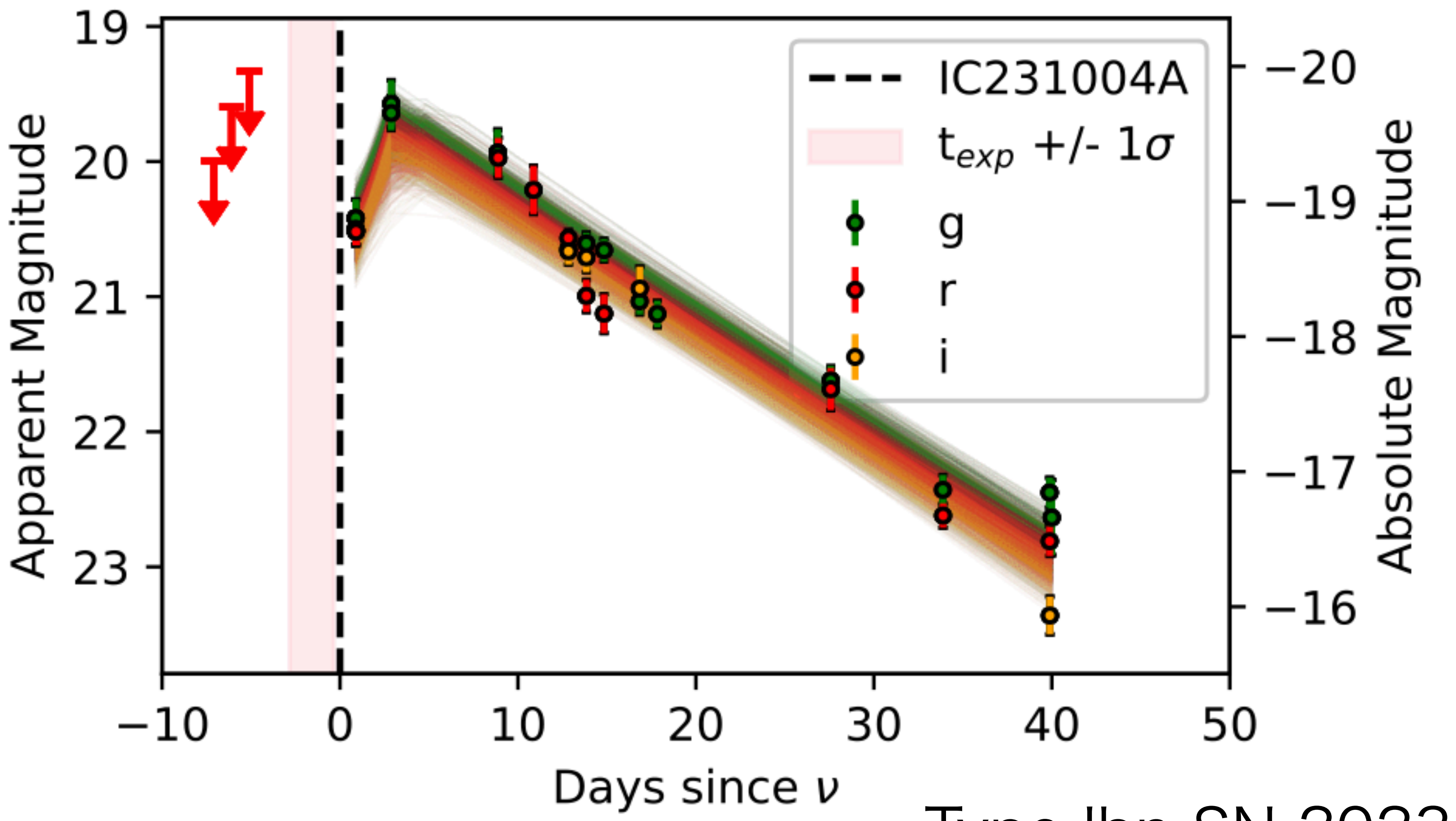
https://www.mpi-hd.mpg.de/HESS/pages/home/som/2019/07/

- interacting SNe: dissipation of the kinetic energy of expanding ejecta
- shock dissipation potentially leads to particle acceleration
- high-energy neutrino/gamma-ray/cosmic-rays expected
  e.g. Murase+(2011), Bell+(2013), Shure&Bell(2014), Marcowith+(2014)
- PeV cosmic-ray source?
  e.g. Marcowith+(2018), but see also Brose+(2020)
- IceCube neutrino source?
  e.g. Ptuskin&Zirakashvili&(2017), Petropoulou+(2017)





Petropoulou+(2017)



Type Ibn SN 2023uqf, Stein+(2025)

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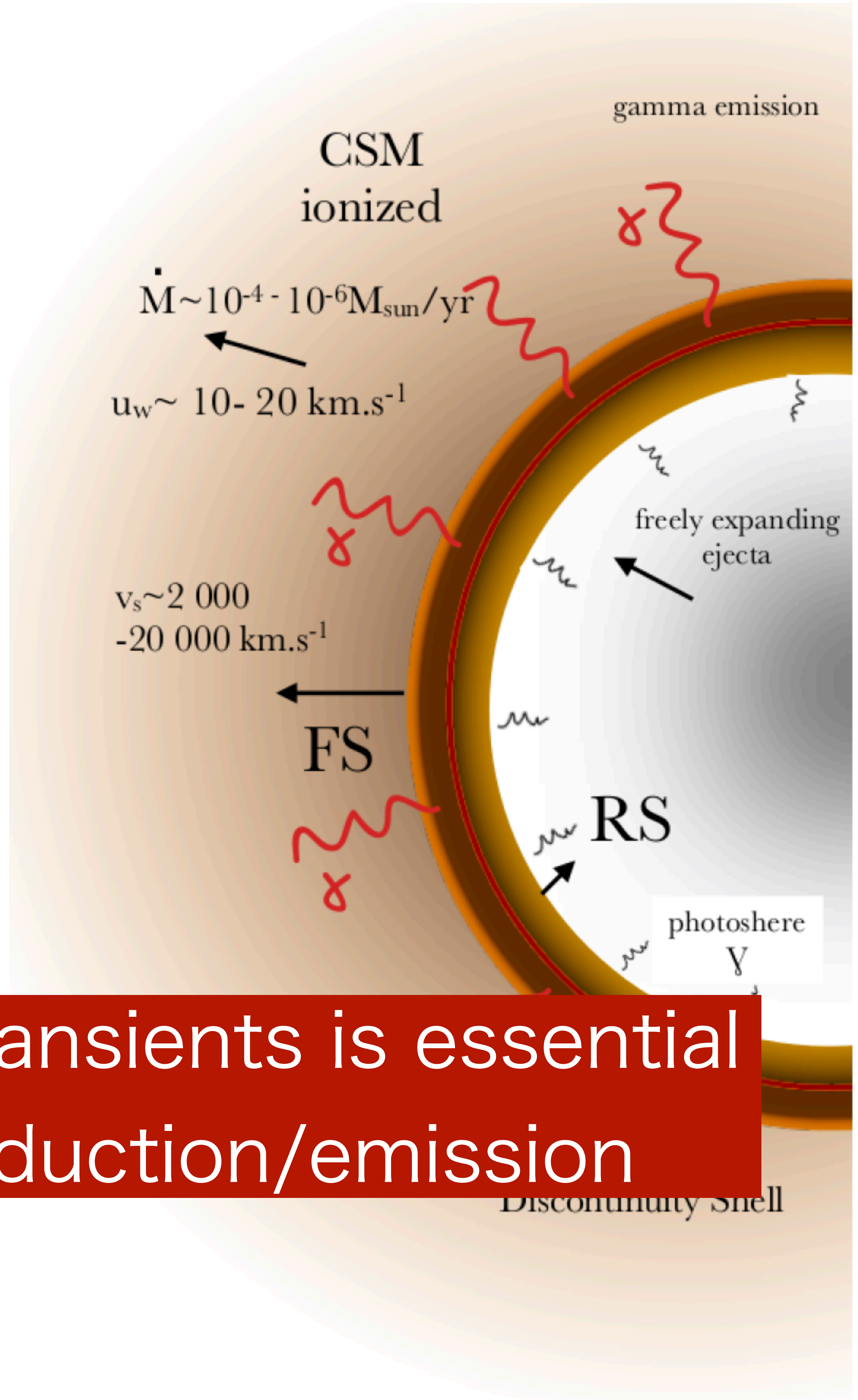

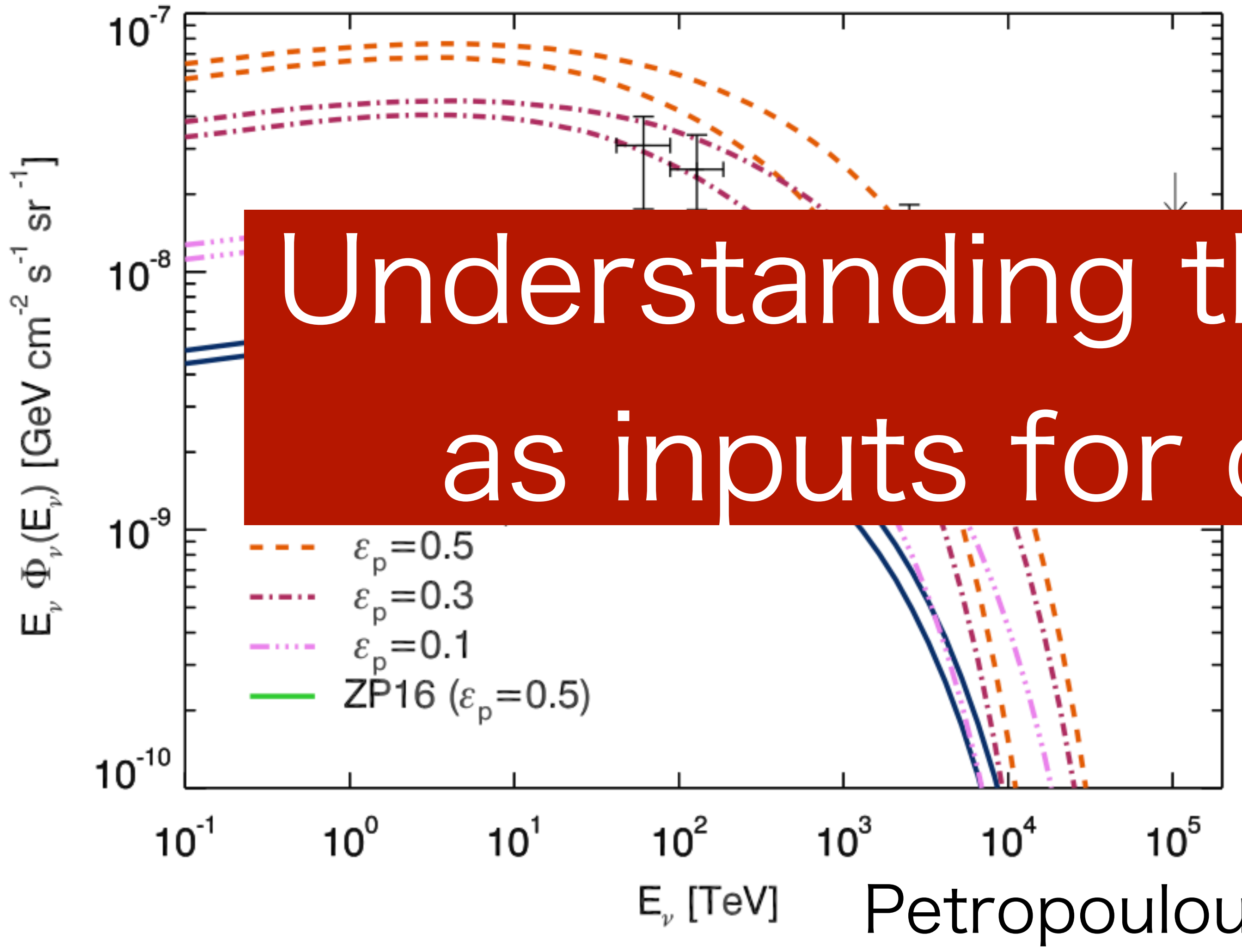

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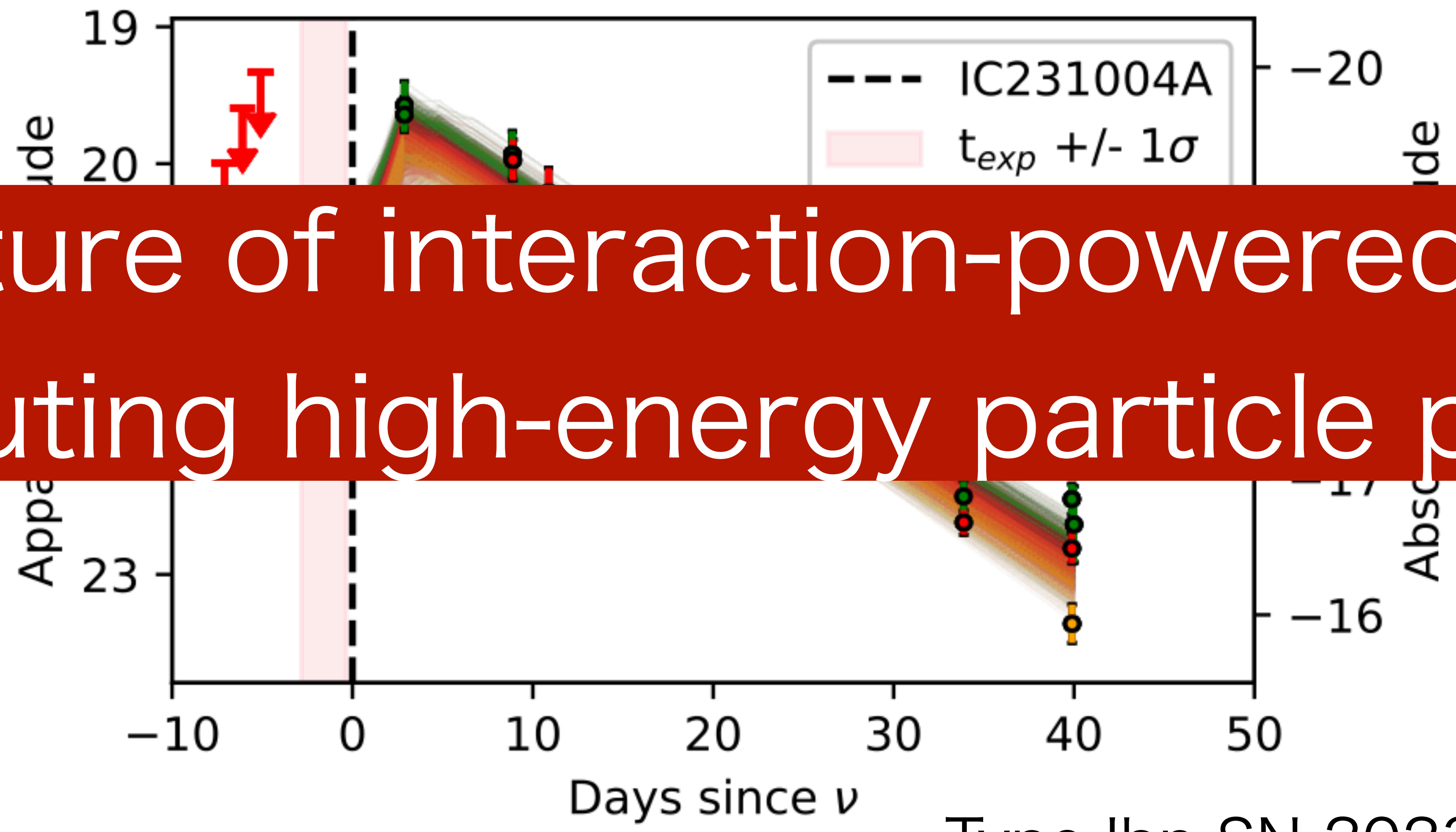

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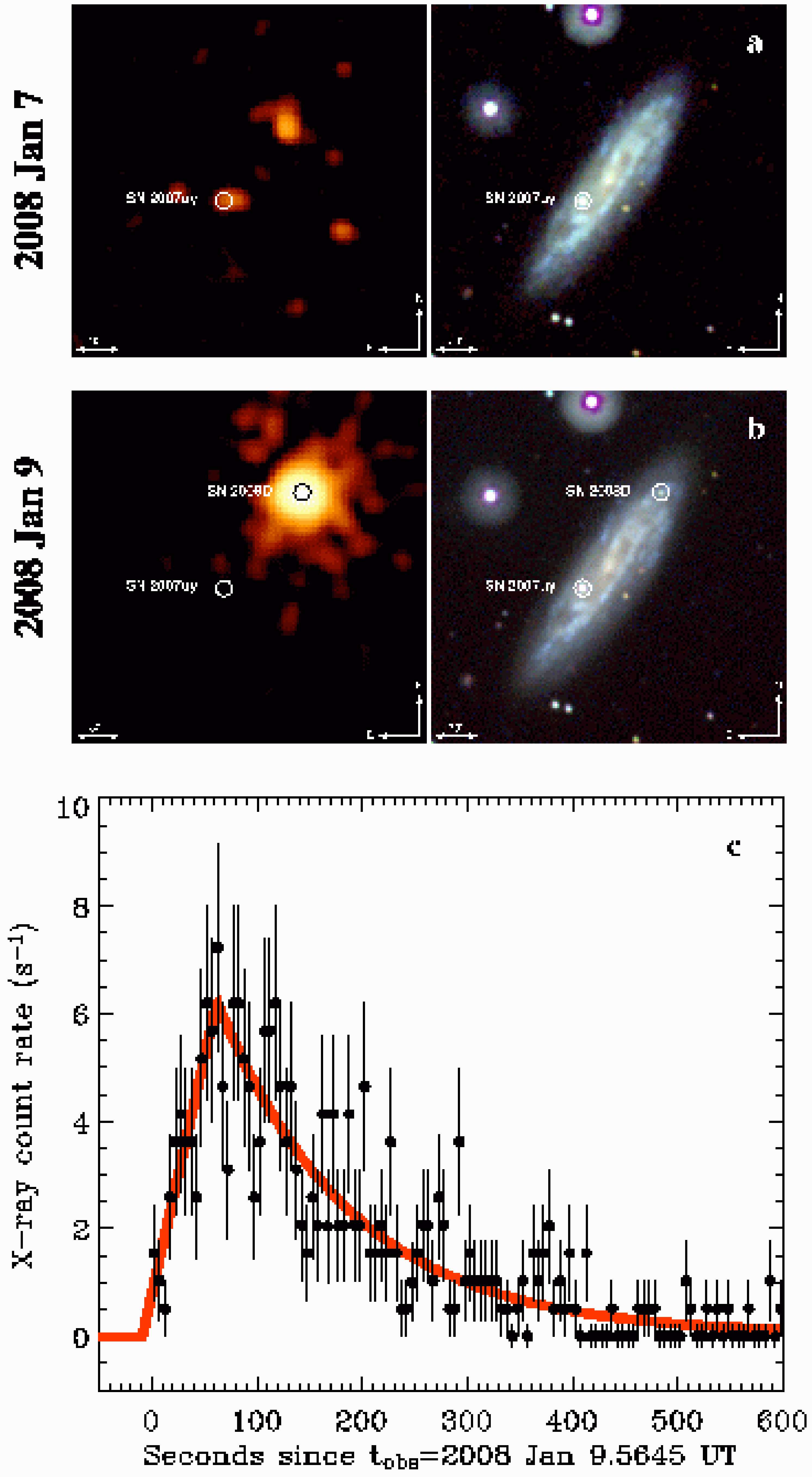
Understanding the nature of interaction-powered transients is essential as inputs for computing high-energy particle production/emission

Early observations of CCSNe

- SN 2008D: first (X-ray) shock breakout (SB; earliest EM emission from SN)
  Sodererg+(2008), Mazzali+(2008), Modjaz+(2009), Tanaka+(2009)
- Type Ibc SNe: He or CO star progenitor having stripped its H-rich envelope
- Small progenitor radius = short emission time scale ($R_{star}/c \sim 1$ s) of SB emission ↔ observed long X-ray emission ($\Delta t > 100$ s)
- dense circum-stellar medium (CSM) enlarge its effective photosphere (wind/CSM shock breakout)



X-ray burst associated with the birth of SN 2008D (Soderberg+2009)

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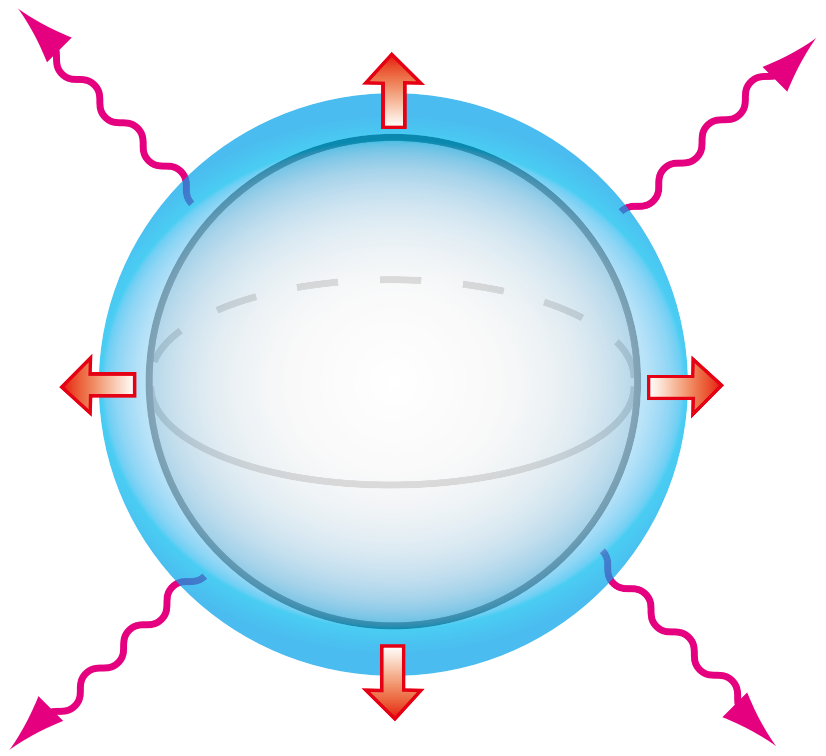
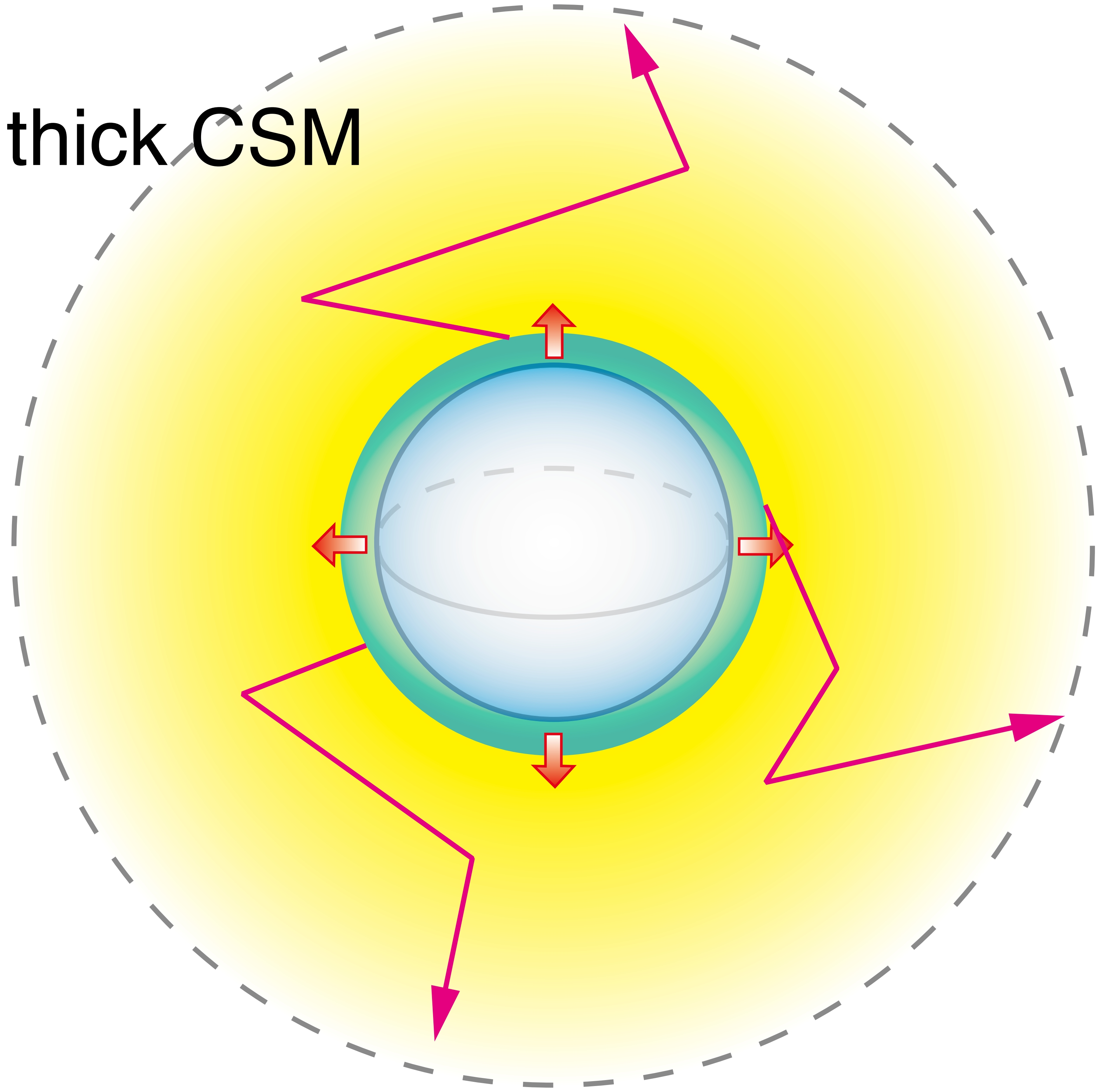
without CSM

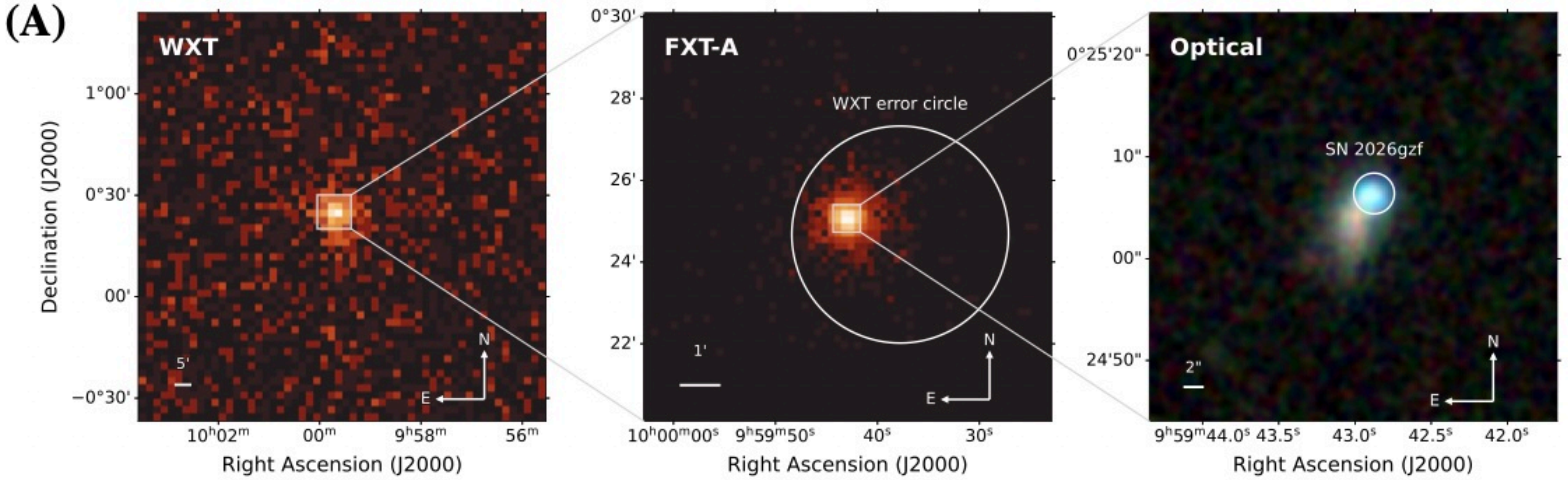


with optically thick CSM



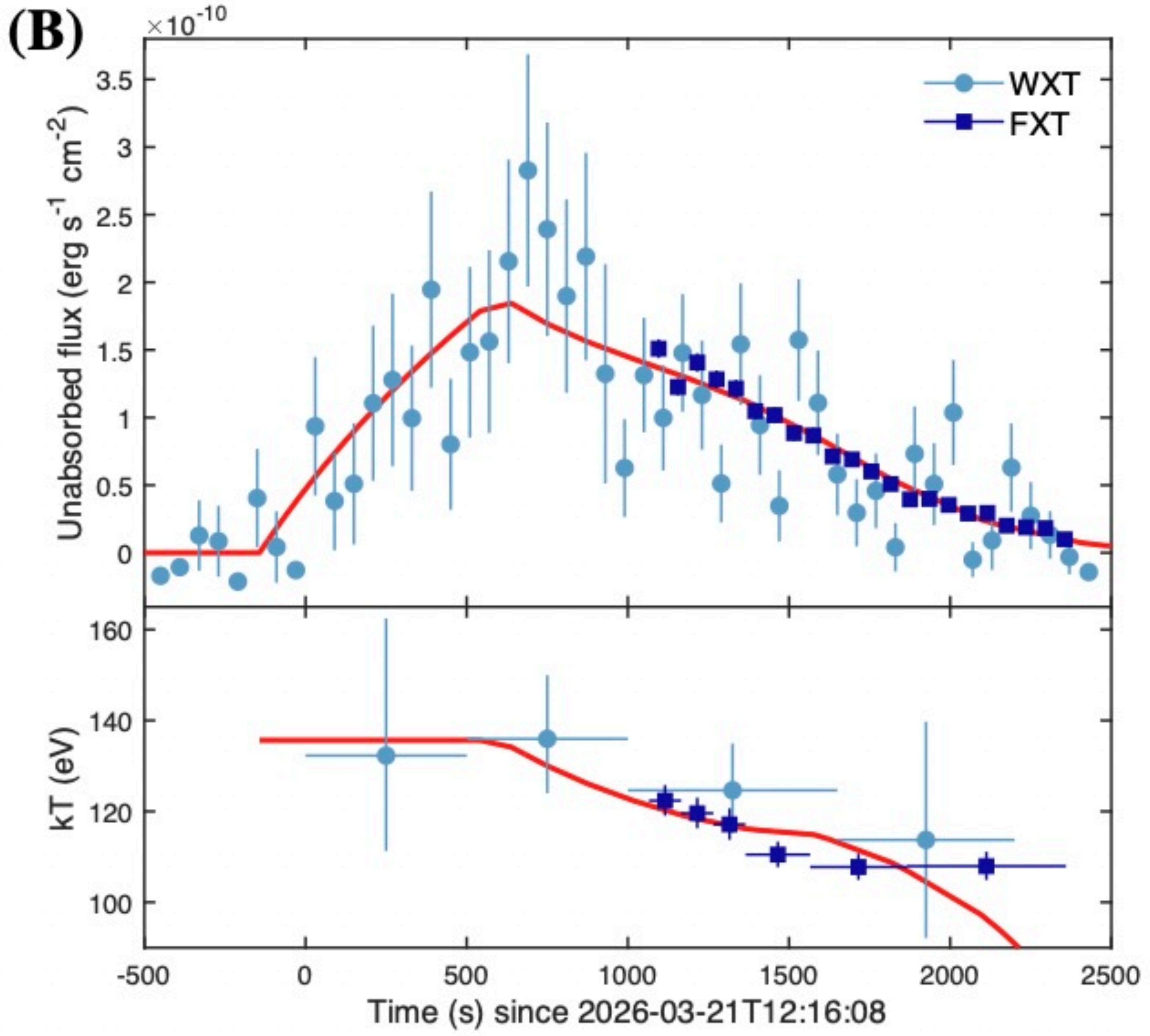
EP260321a/SN 2026gzf

- 2nd unambiguous case of X-ray SN shock breakout detection by Einstein Probe mission Yuan+(2026)

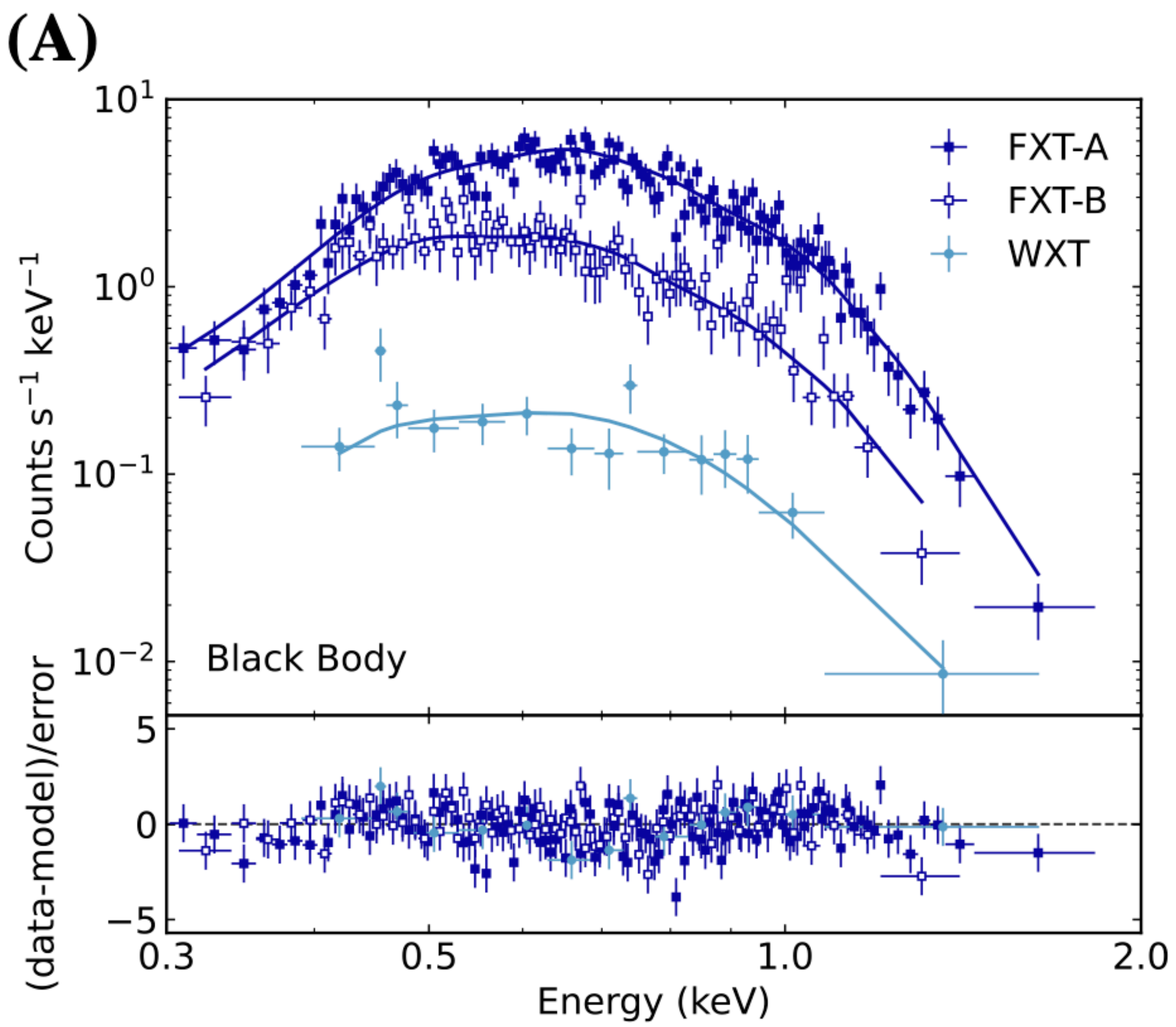


- association with broad-line Ic SN 2026gzf from optical observations

Martin-Carrillo+(2026), Rastinejad+(2026)
Chen+(2026), O'Connor+(2026)



- thermal X-ray emission lasting for ~2000s with kT~0.1-0.2keV



EP260321a detected by Einstein Probe mission (Yuan+2026)

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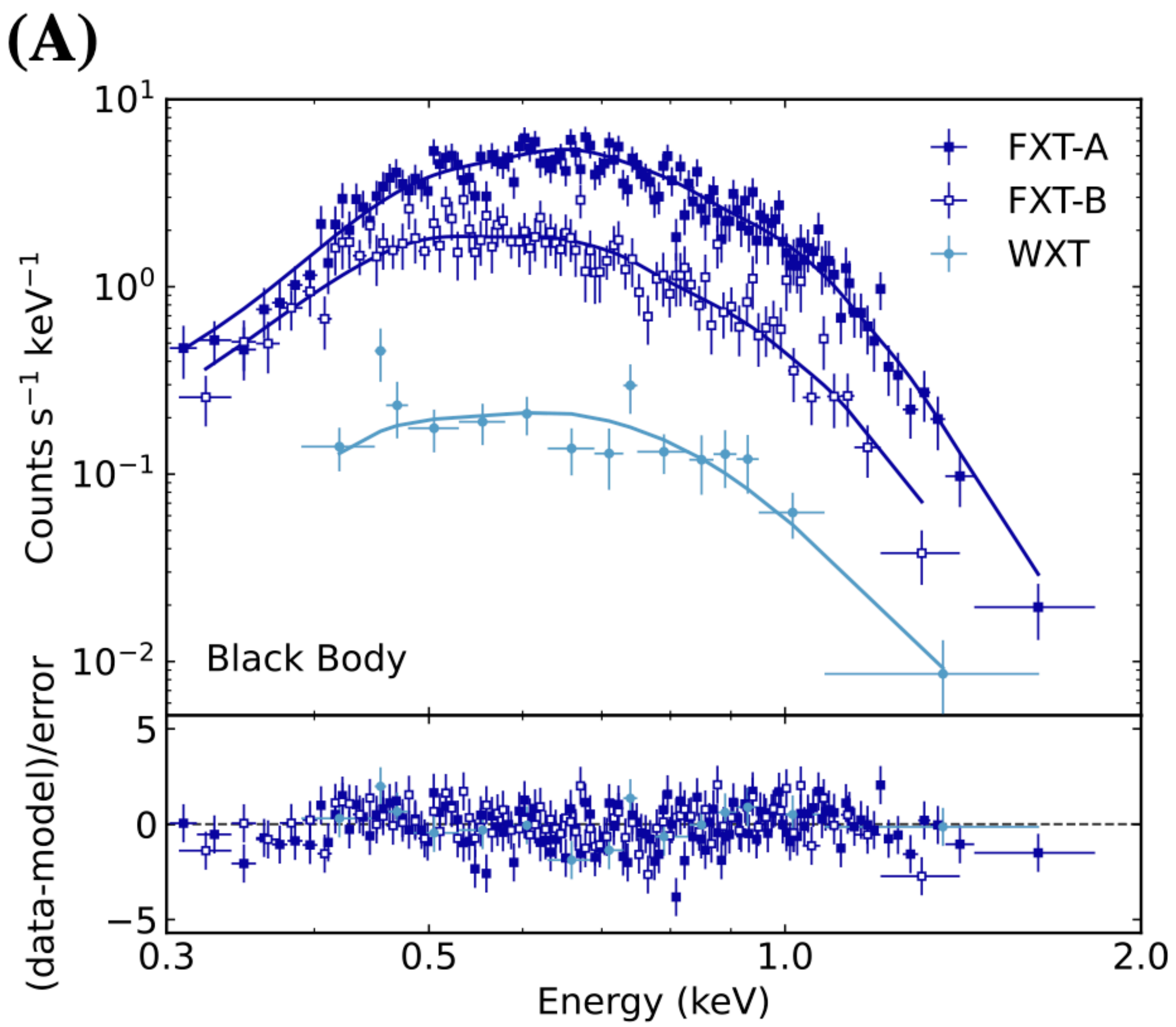

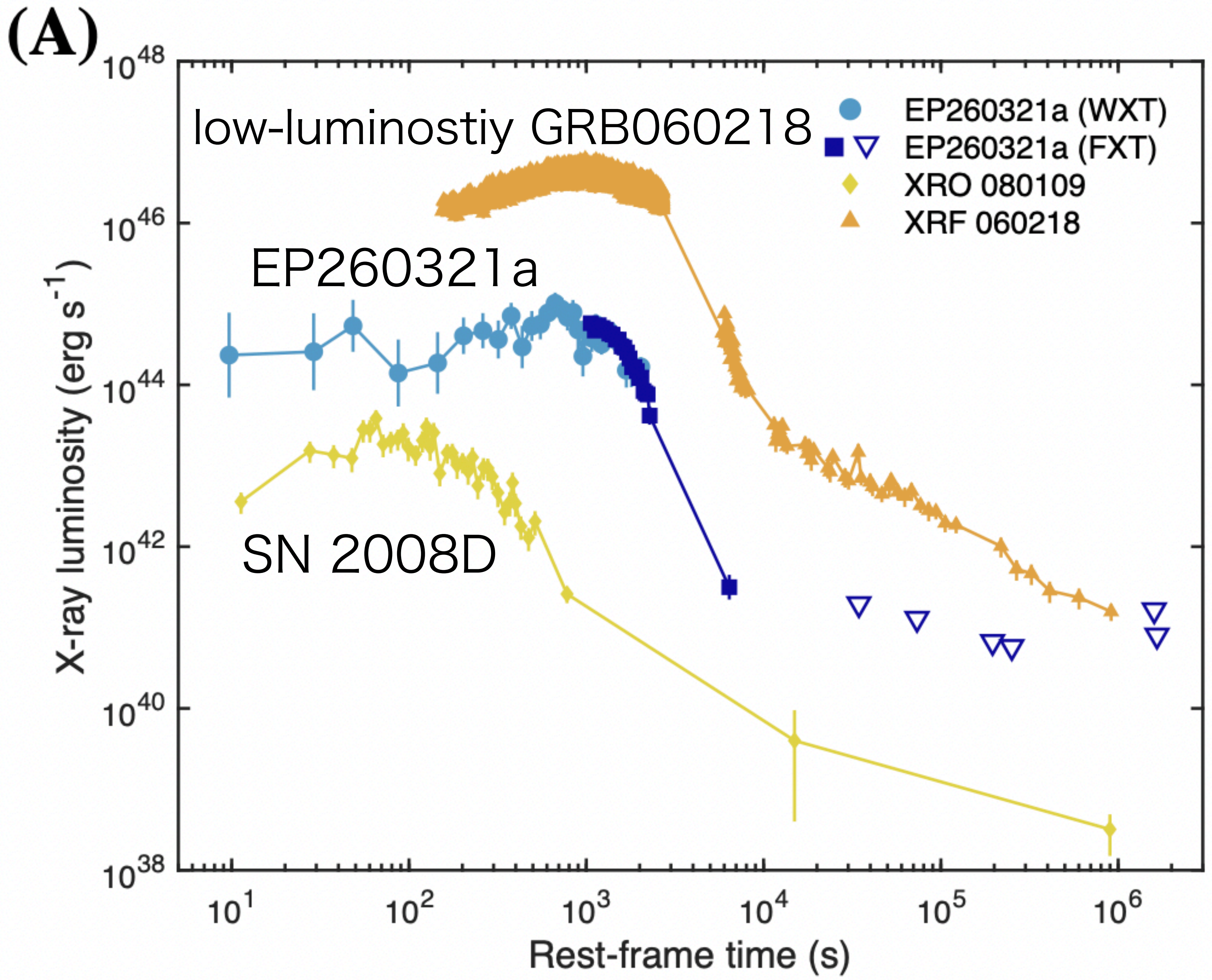

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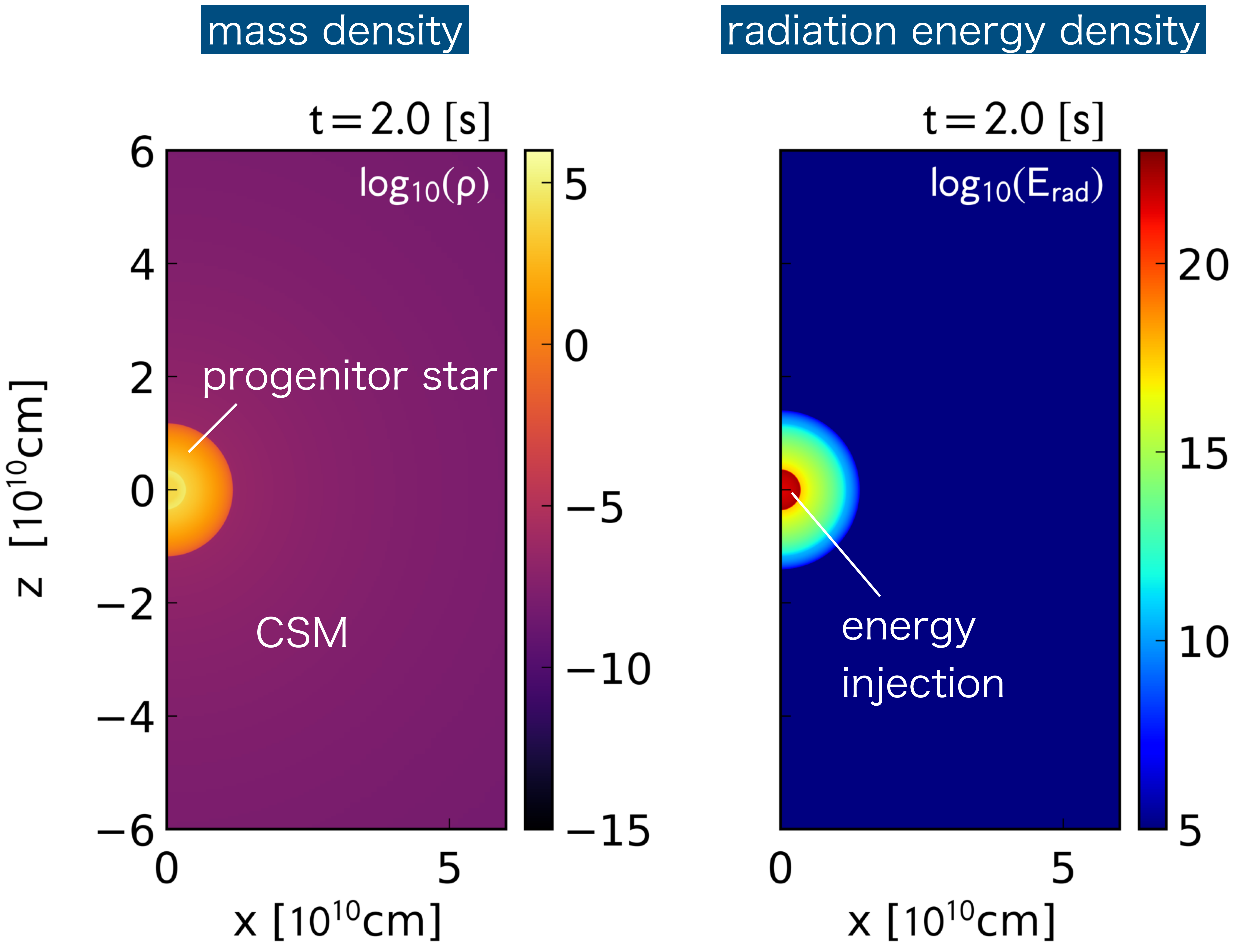
2D RHD simulations

- ~$2.7M_{sun}$ CO star as a pre-SN star ($M_{zams}=14M_{sun}$)
- SN explosion: $E_{exp}= 4x10^{51}$erg, $M_{Ni}=0.7M_{sun}$, M_{ej} ~$1.25M_{sun}$
- wind-like CSM: $M_{csm}=1.7x10^{-5}M_{sun}$, $R_{csm}=500R_{sun}$



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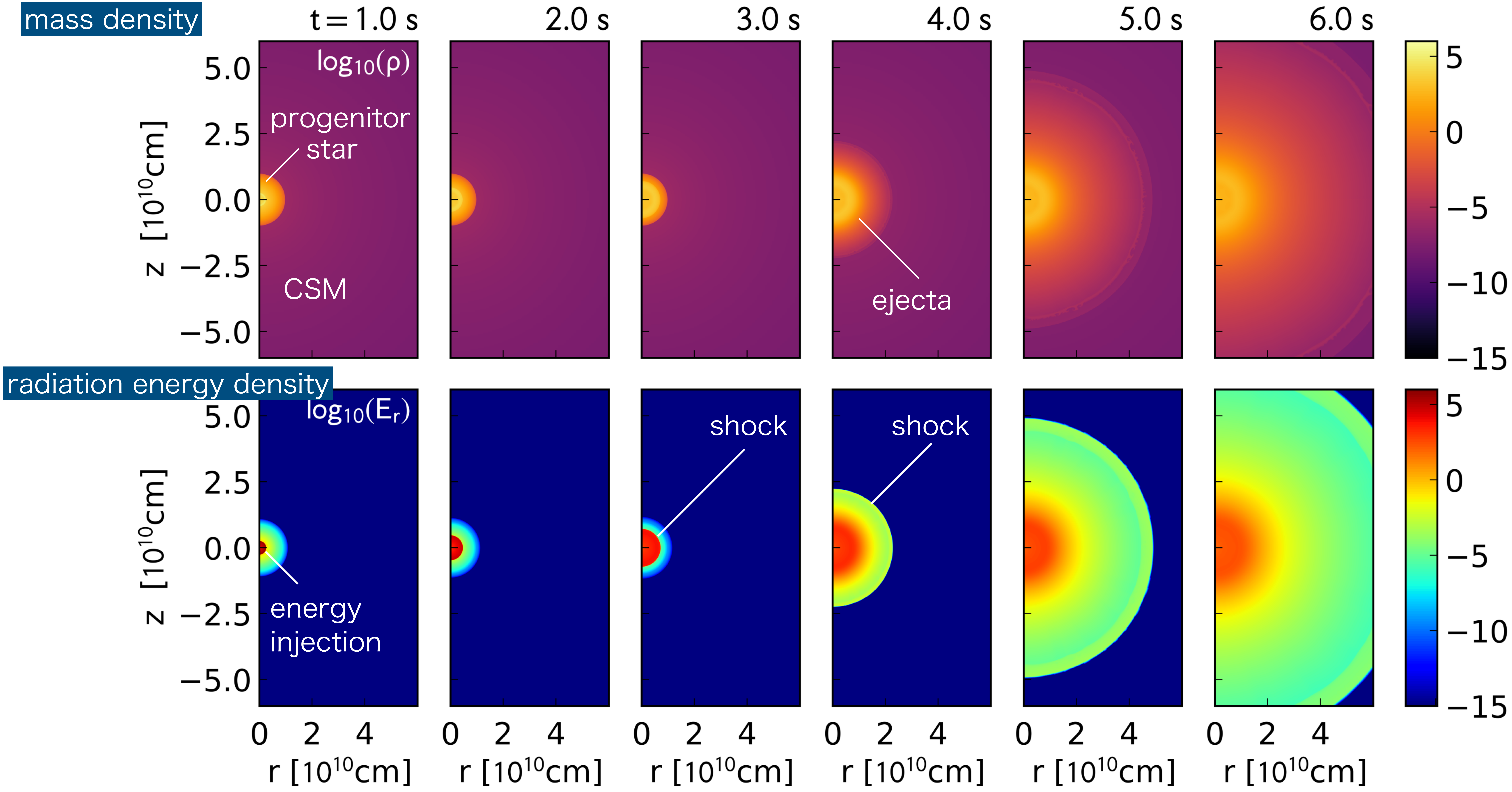

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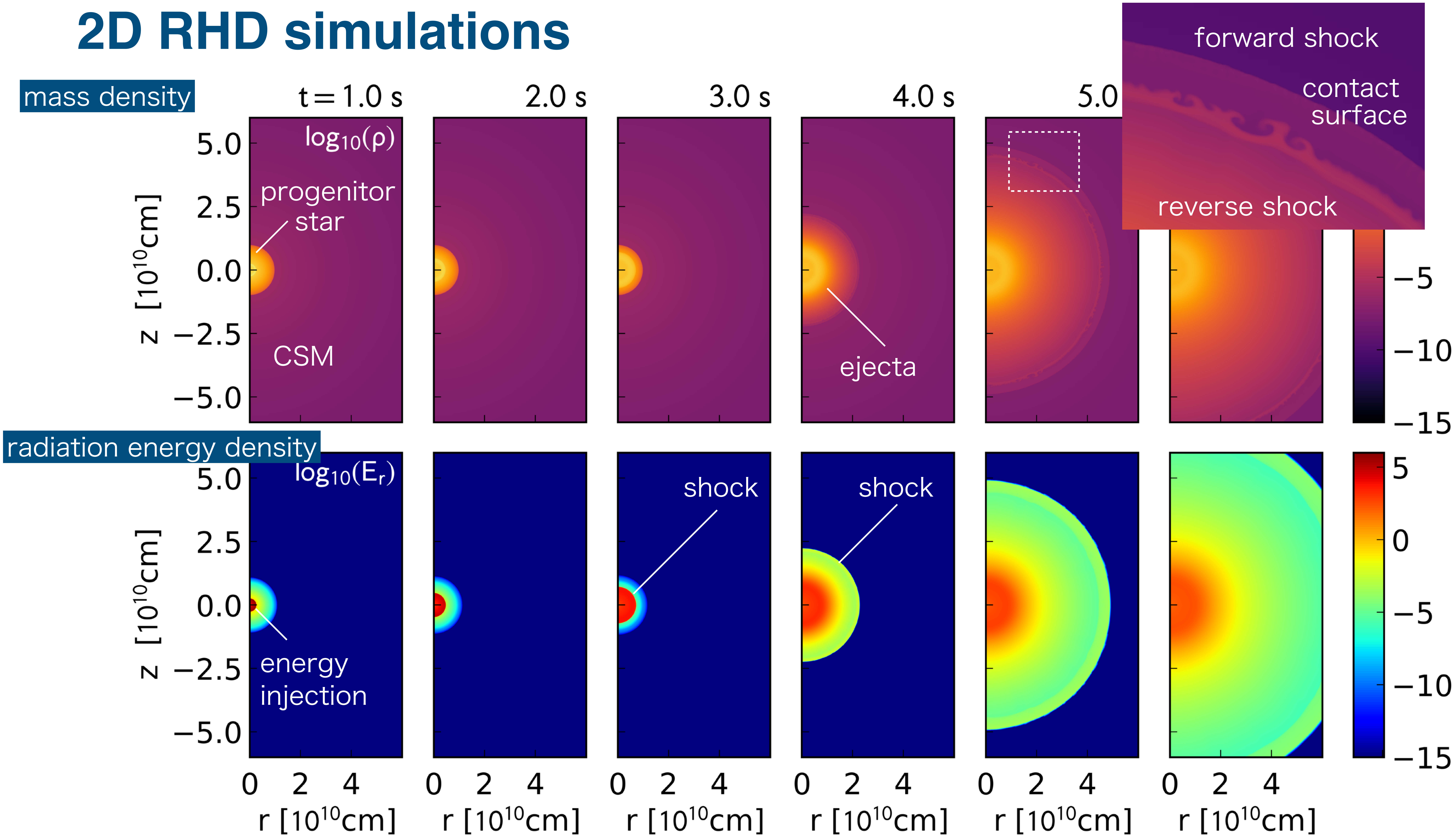

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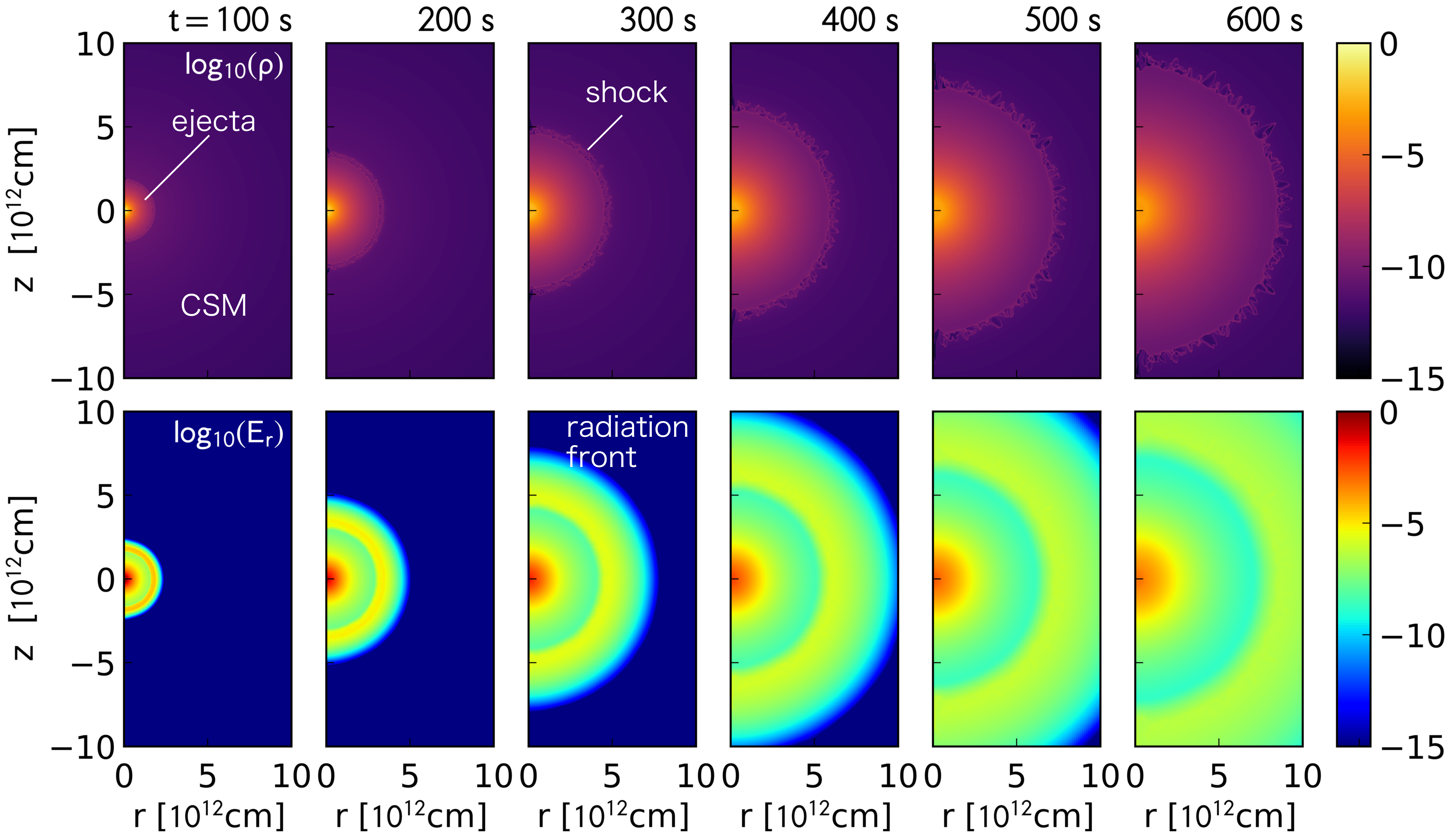

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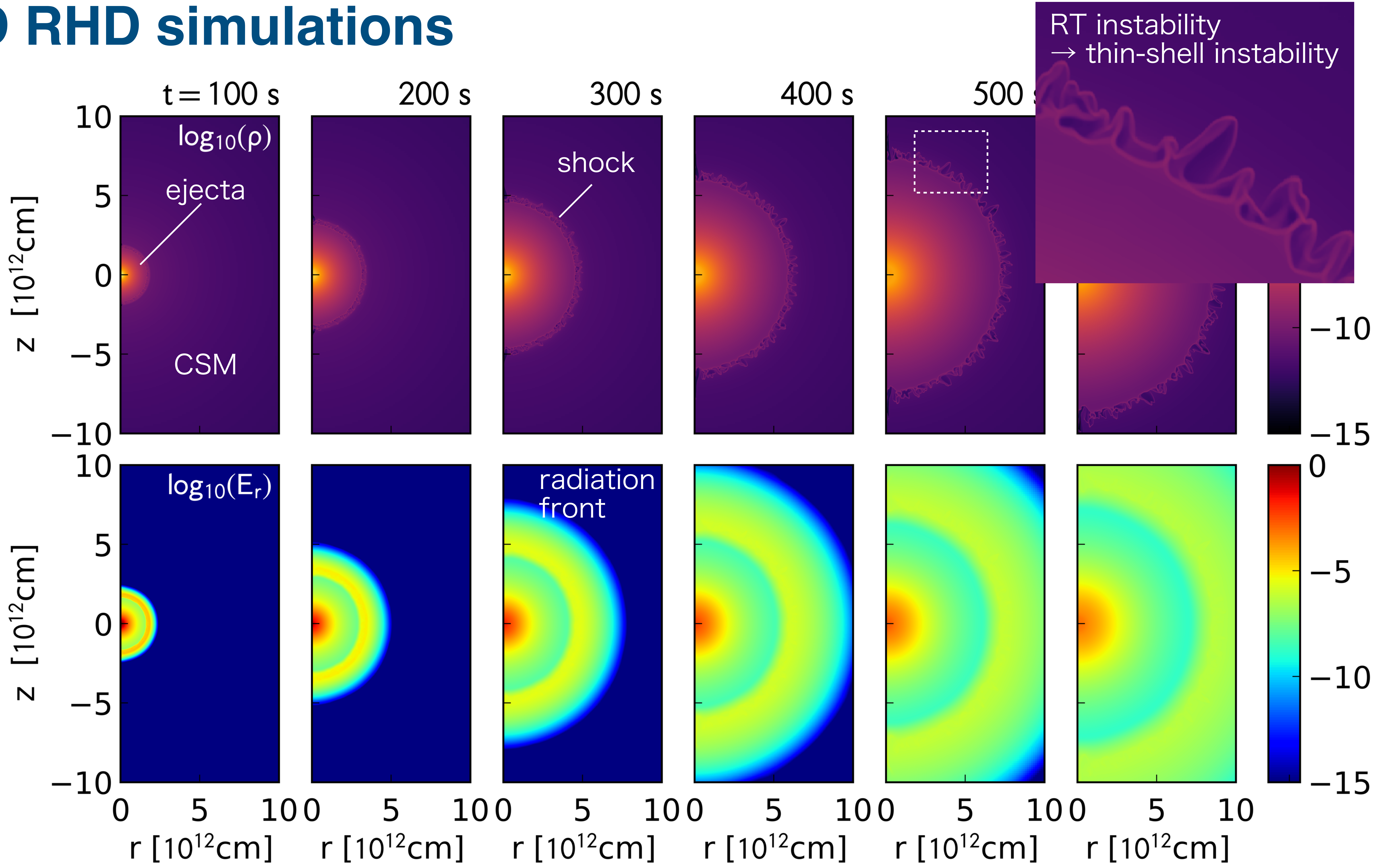

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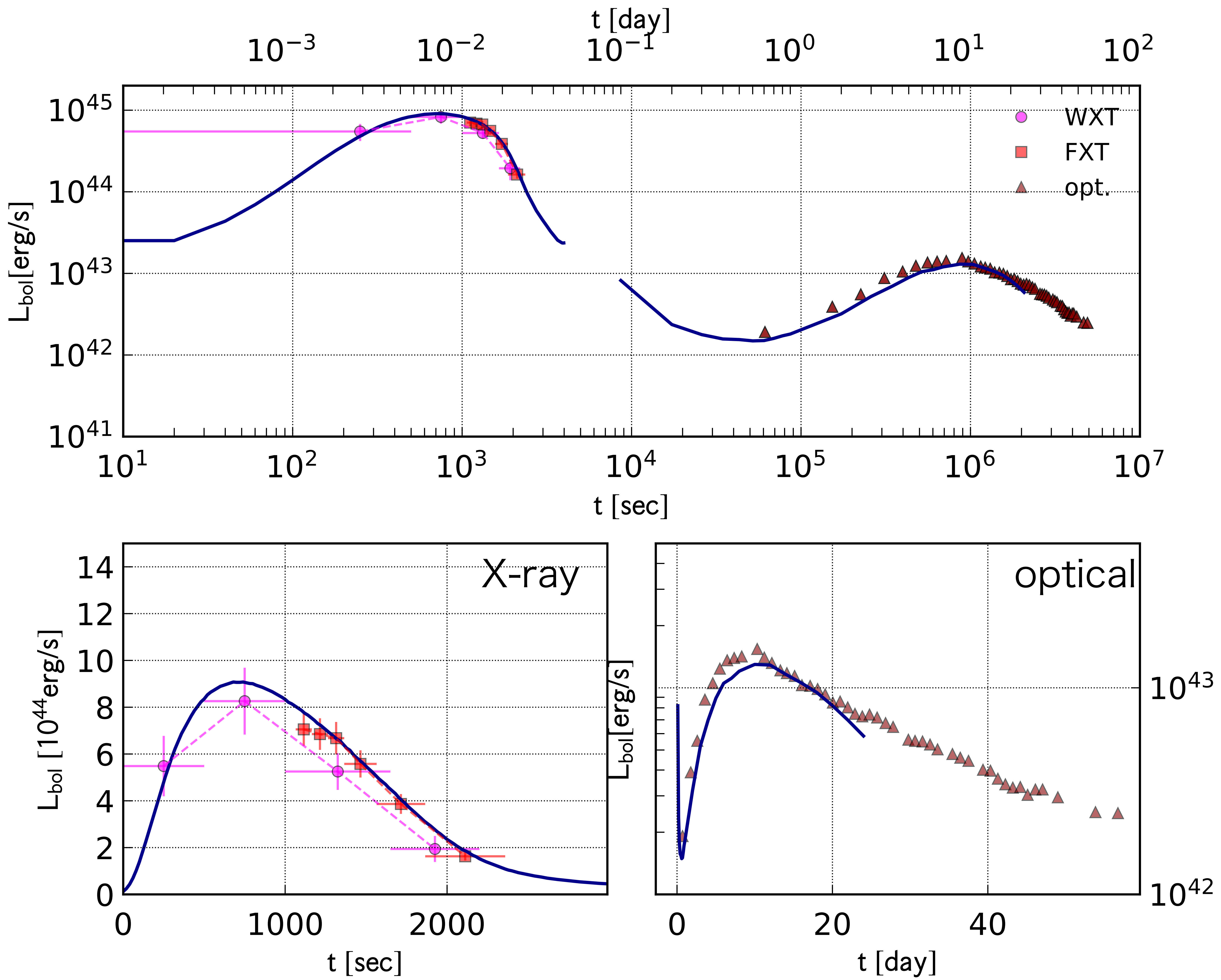
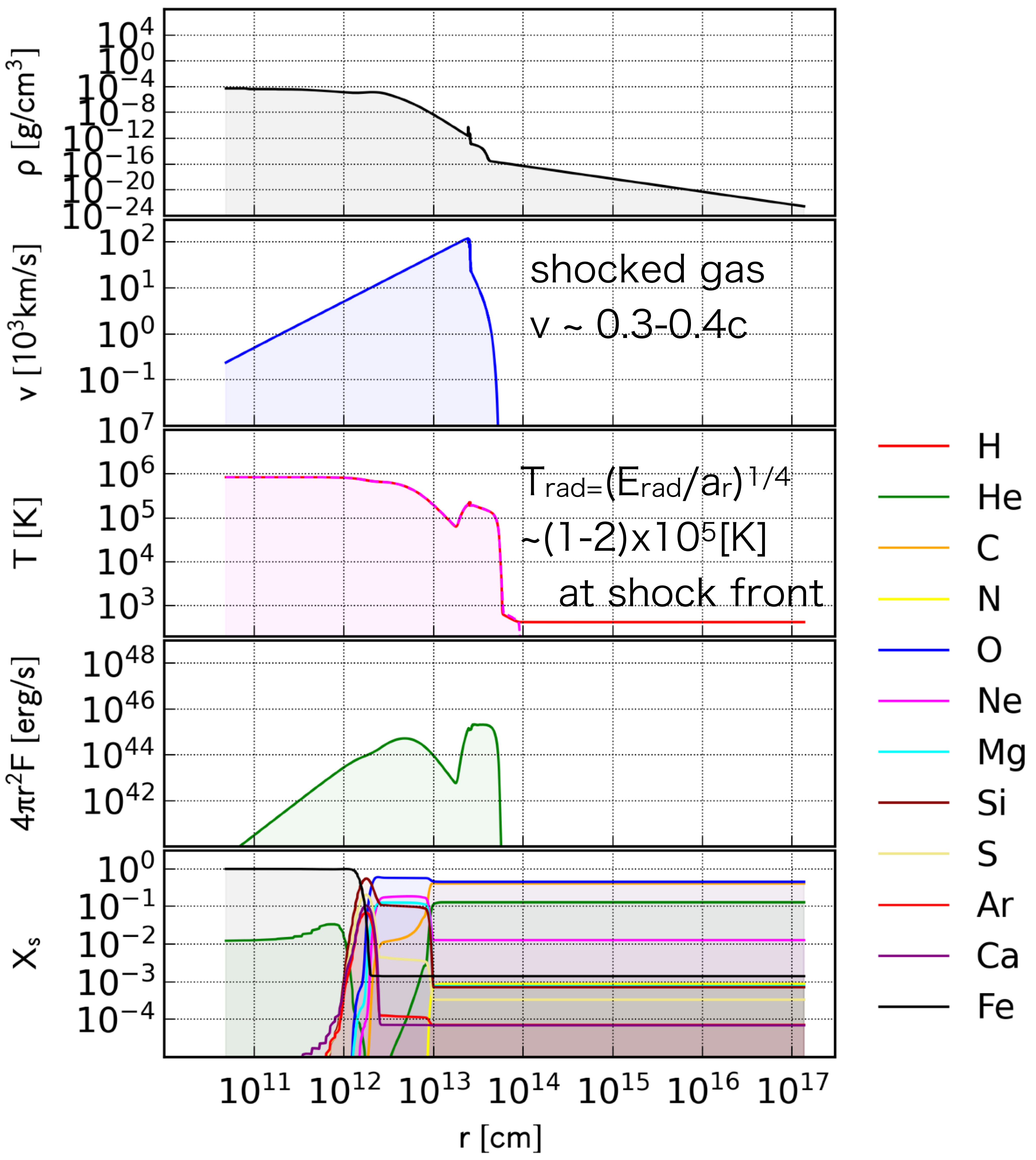
- wind-like CSM: M_{csm}=1.7x$10^{-5}$$M_{sun}$, R_{csm}=500R_{sun}
- synthetic bolometric light curve consistent with observed light curve
- 1000 sec-long X-ray emission + bright optical emission powered by ^{56}Ni



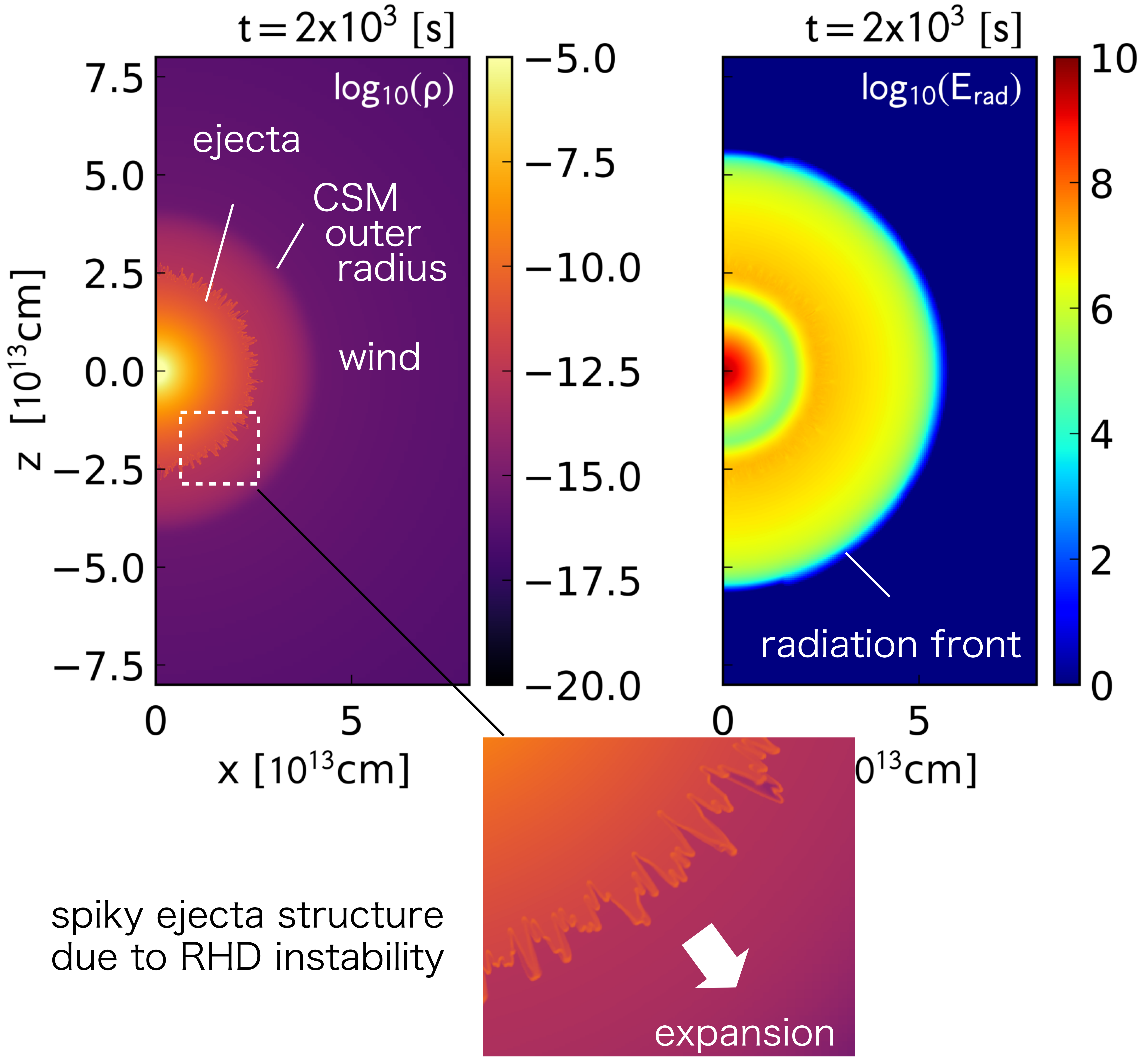
Implications to high-energy particle acceleration

- RHD simulations can constrain the parameters of interaction-powered transients
- ejecta E, M → shock velocity
- CSM M, R → ambient density
- What is typical parameter set?
- this is important for considering conditions/energy budget for high-energy emission/particle production
- What about the rate of potential non-thermal particle accelerators?



Implications to high-energy particle acceleration

- RHD simulations can give an initial set-up for later evolutionary stages
- shock evolution after entering collisionless regime is essential for shock particle acceleration
- (multi-D) shock structure in collisionless regime is governed by the evolution in radiative regime
- shock normal is not necessarily alined with radial direction
- what about the CSM geometry? spherical is good?



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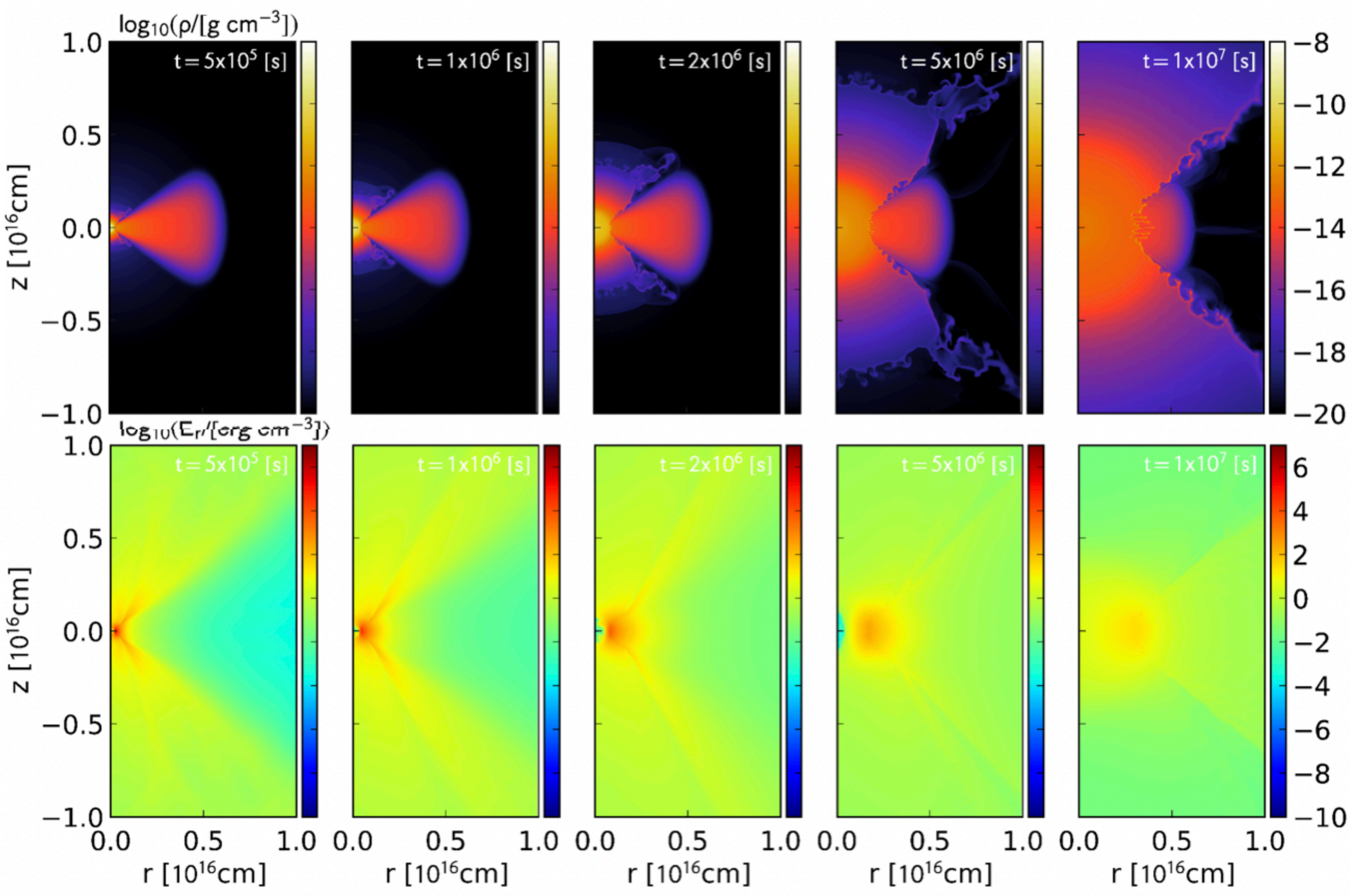
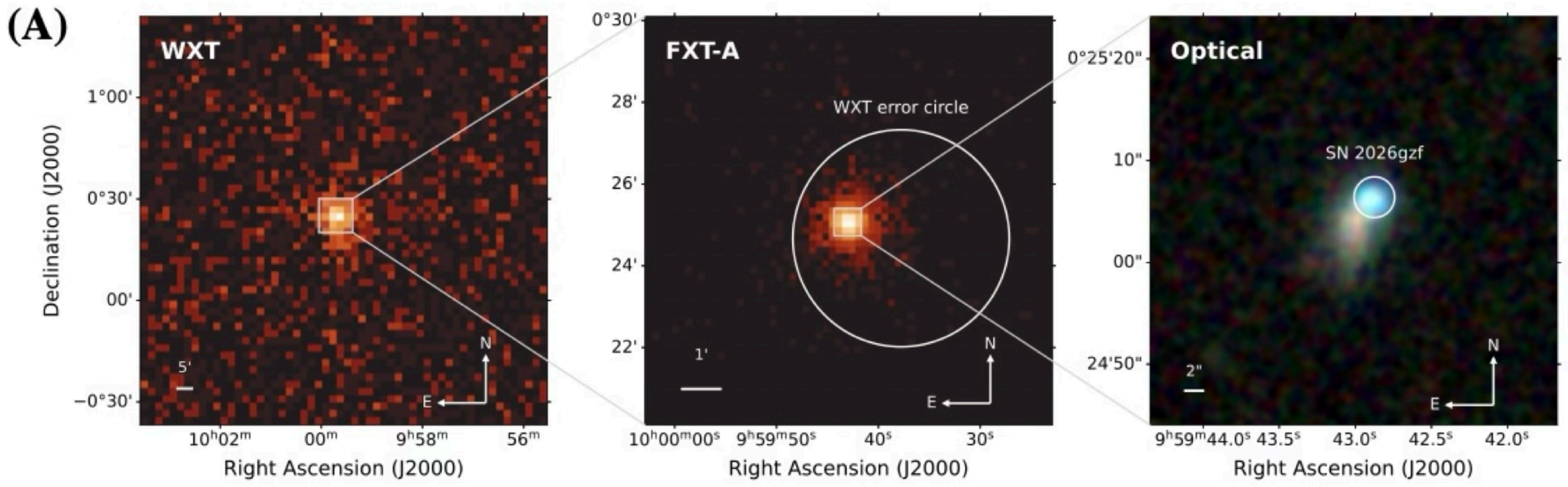
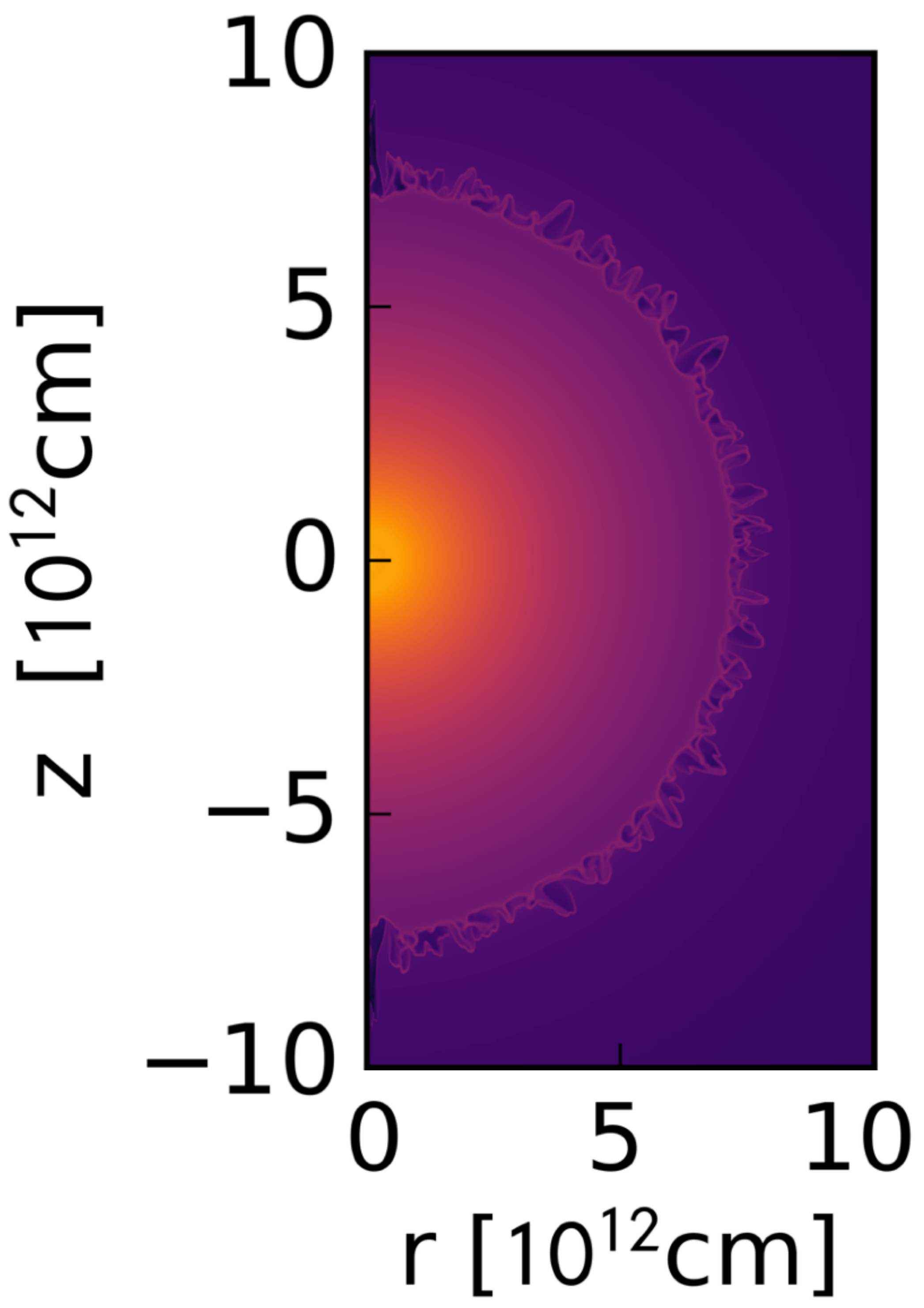


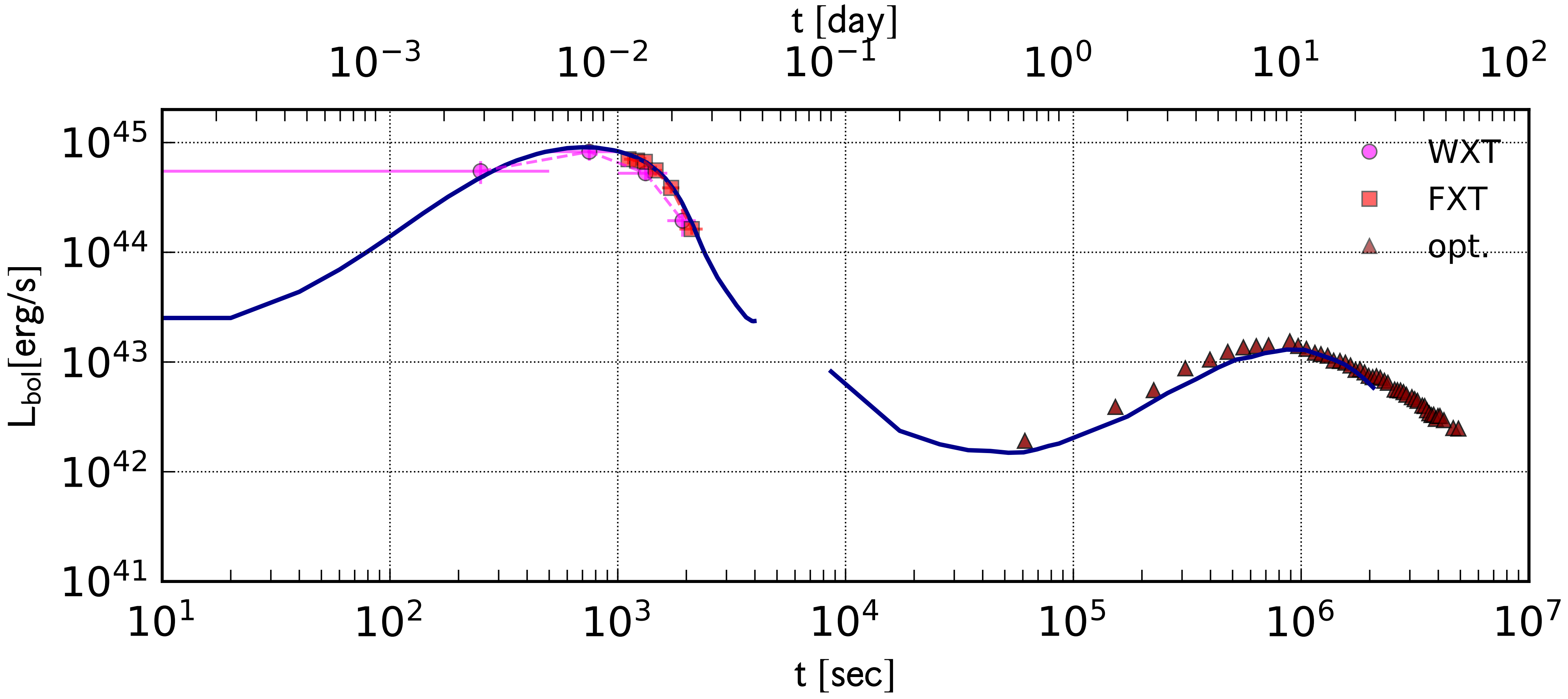
SN ejecta colliding with a disk-like CSM
(Suzuki, Moriya, & Takiwaki 2019)

Summary: interacting SNe as CR accelerators

- interacting SNe: collision between SN ejecta and ambient (dense) gas
- observationally, they are common
- shock dissipation leads to bright EM radiation and potentially accelerates particles to high energy
- theoretical modeling of such events gives us constraints on shock dynamics and ambient gas







Backup slides

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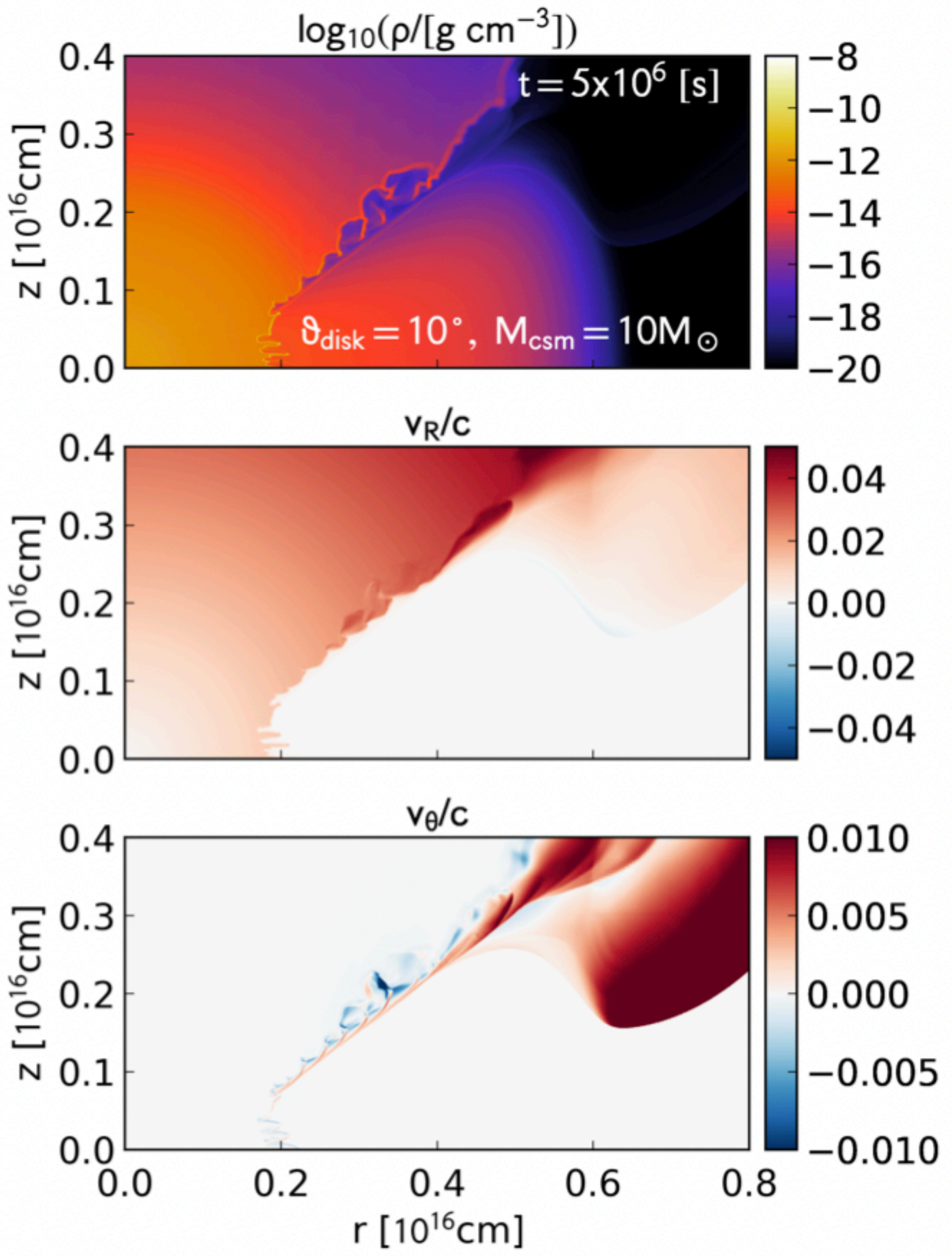

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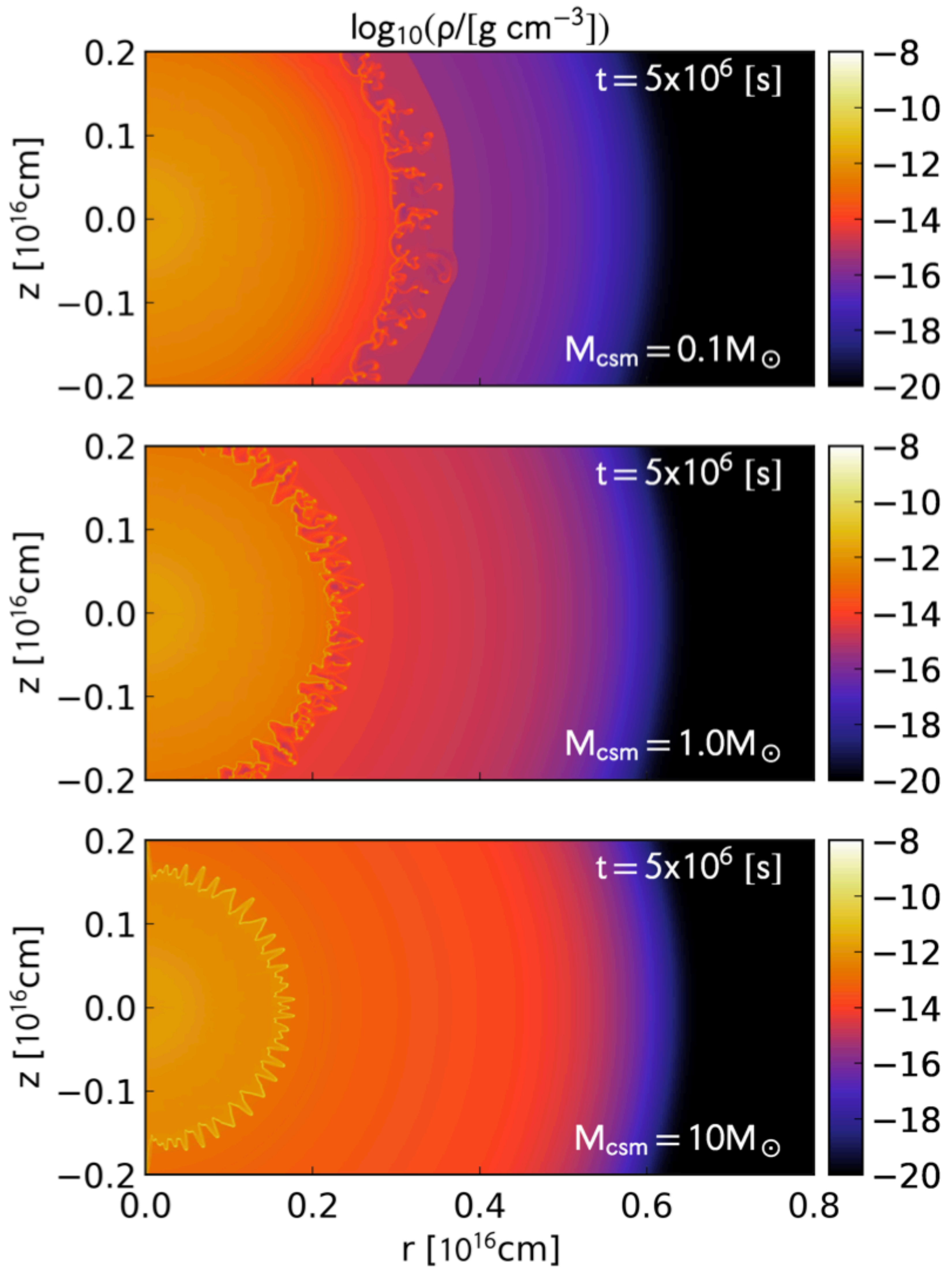

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SR-RHD simulations

- gray approximation (frequency-integrated quantities)
- moment method: temporal evolutions of radiation energy density and flux $(E_\mathrm{r}, F_\mathrm{r}^x, F_\mathrm{r}^y, F_\mathrm{r}^z)$
- M1-closure scheme for the Eddington tensor: $P_\mathrm{r}^{ij} = E_\mathrm{r} D^{ij}$

Radiative transfer equations

$$\frac{\partial E_\mathrm{r}}{\partial t} + \frac{\partial F_\mathrm{r}^i}{\partial x^i} = \Gamma \bar{\rho} \bar{\kappa}_\mathrm{a} (a_\mathrm{r} T_\mathrm{g}^4 - \bar{E}_\mathrm{r}) - \Gamma \bar{\rho} (\bar{\kappa}_\mathrm{a} + \bar{\kappa}_\mathrm{s}) \beta_i \bar{F}_\mathrm{r}^i$$

$$\frac{\partial F_\mathrm{r}^i}{\partial t} + \frac{\partial P_\mathrm{r}^{ij}}{\partial x^j} = -\bar{\rho} (\bar{\kappa}_\mathrm{a} + \bar{\kappa}_\mathrm{s}) \bar{F}_\mathrm{r}^i + \Gamma \bar{\rho} \bar{\kappa}_\mathrm{a} (a_\mathrm{r} T_\mathrm{g}^4 - \bar{E}_\mathrm{r}) \beta^i - \frac{\Gamma^2}{\Gamma + 1} \bar{\rho} (\bar{\kappa}_\mathrm{a} + \bar{\kappa}_\mathrm{s}) \beta^i \beta_j \bar{F}_\mathrm{r}^j$$

M1 closure scheme

$$\frac{P_\mathrm{r}^{ij}}{E_\mathrm{r}} = \frac{1-\chi}{2} \delta^{ij} + \frac{3\chi - 1}{2} \frac{F_\mathrm{r}^i F_\mathrm{r}^j}{|F_\mathrm{r}|^2}$$

$$\chi = \frac{3 + 4 F_\mathrm{r}^i F_{\mathrm{r},i} / E_\mathrm{r}^2}{5 + 2\sqrt{4 - 3 F_\mathrm{r}^i F_{\mathrm{r},i} / E_\mathrm{r}^2}}$$

e.g., Livermore (1984)

$\bar{\rho}, T_\mathrm{g}, \beta^i, \Gamma$: gas density, temperature, velocity, Lorentz factor

$\bar{E}_\mathrm{r}, \bar{F}_\mathrm{r}$: comoving radiation energy density and flux

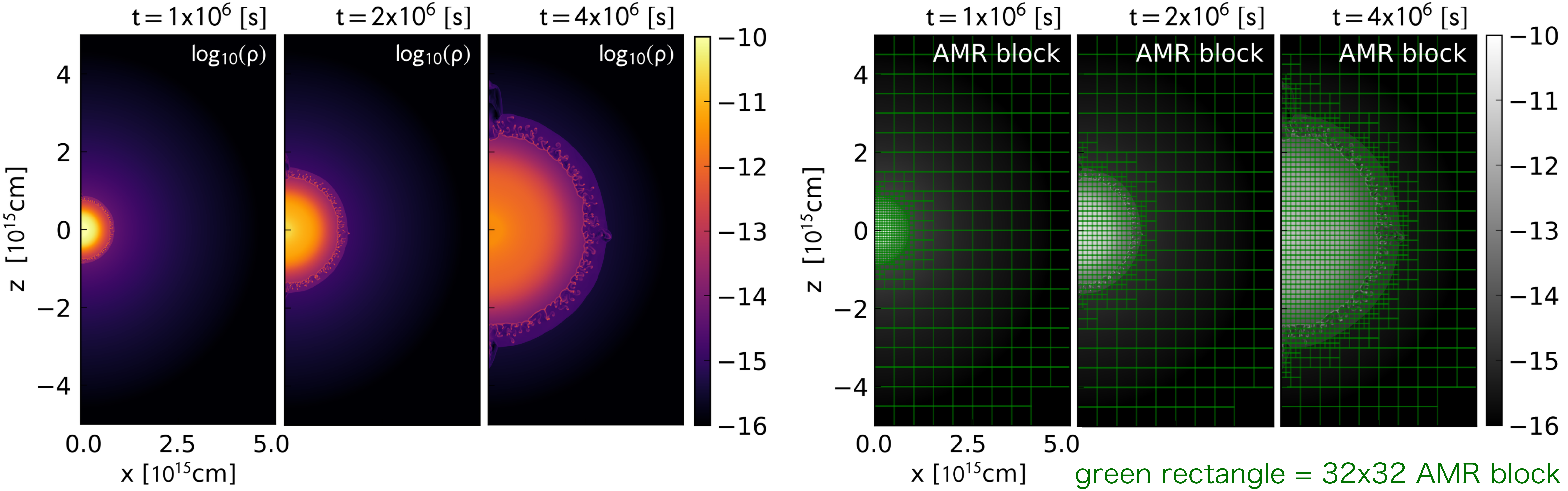
$\bar{\kappa}_\mathrm{a}$: comoving absorption opacity

$\bar{\kappa}_\mathrm{s}$: comoving scattering opacity

+ SR hydro equations

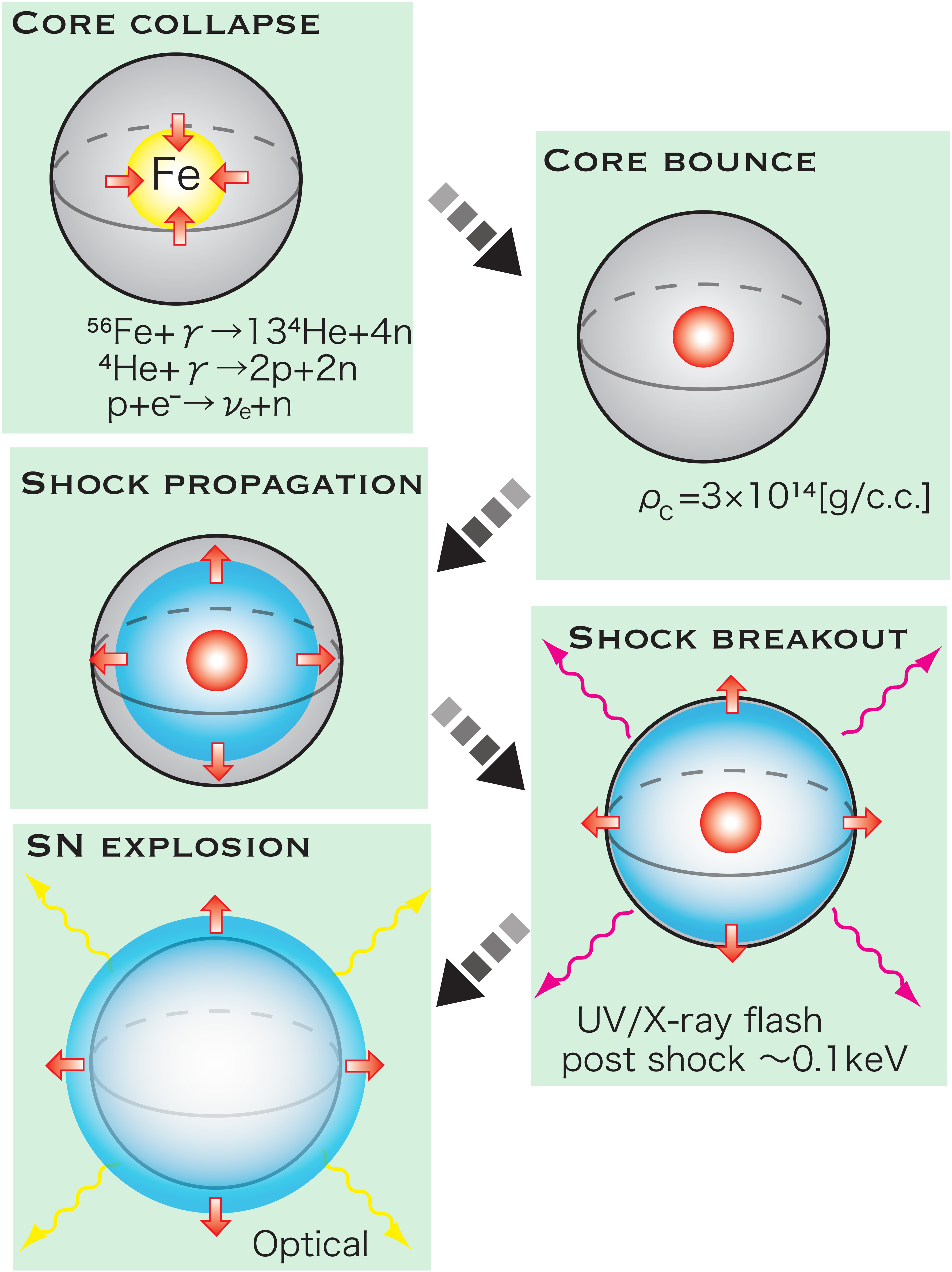
Adaptive Mesh Refinement

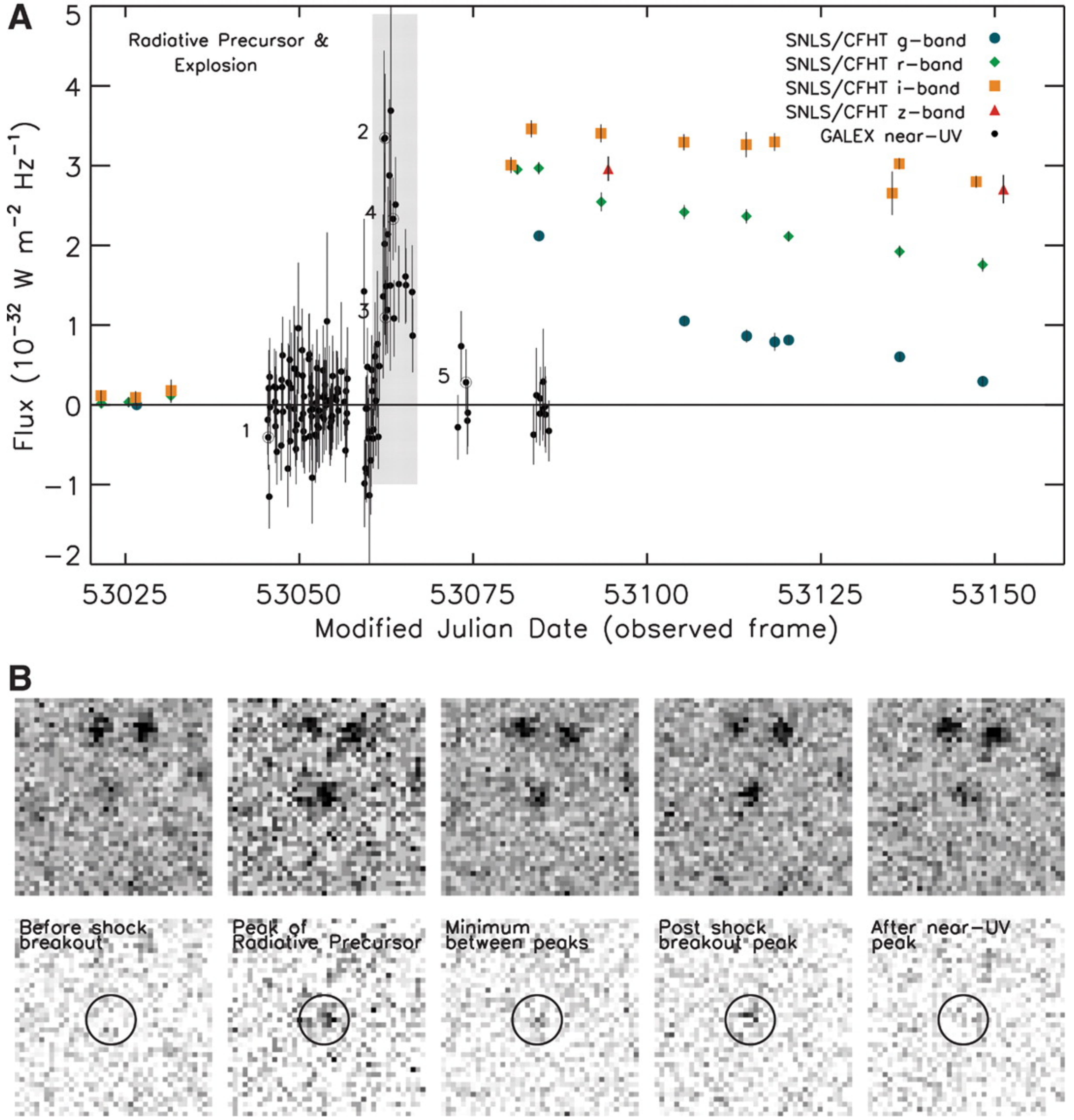
- SN ejecta is gradually expanding in an ambient medium
- Automatic tracking of the ejecta expansion by an adaptive mesh refinement (AMR) technique (Berger & Corella 1989)
- oct-tree block-structure AMR
- MPI + openMP hybrid parallelization



green rectangle = 32x32 AMR block

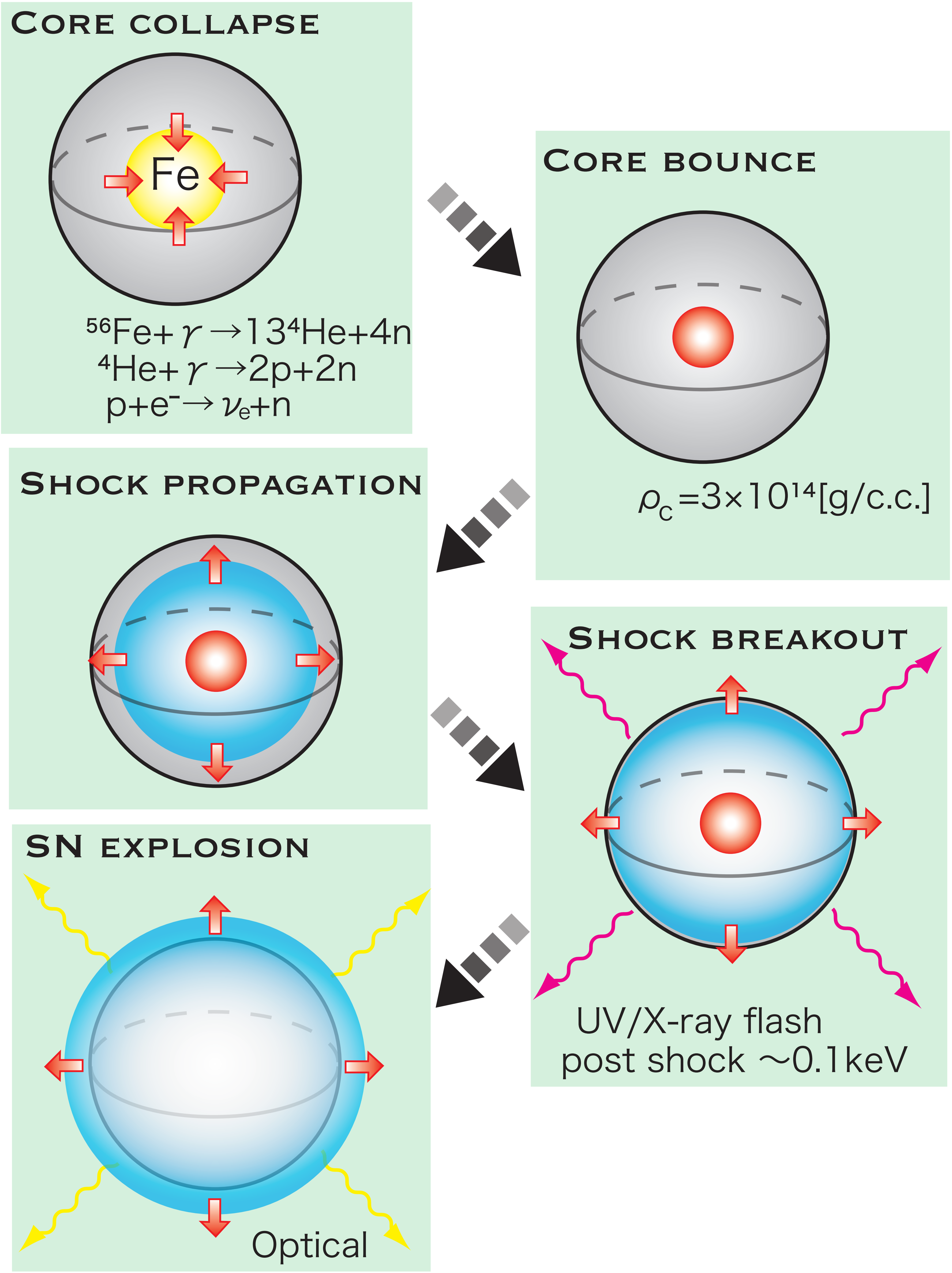
Early observations of CCSNe

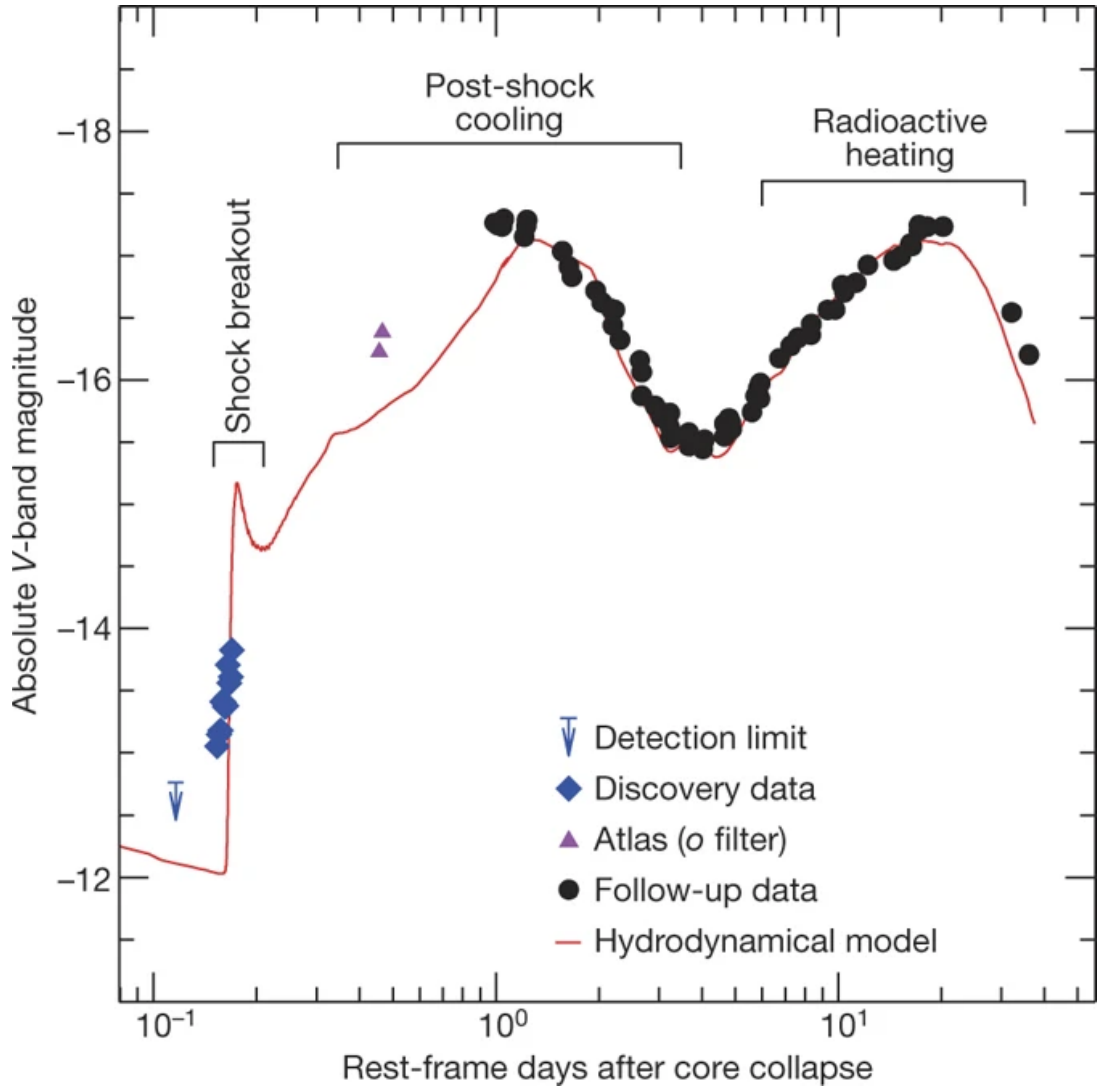




SN breakout emission observed by UV satellite GALEX
(Schwanski+2008)

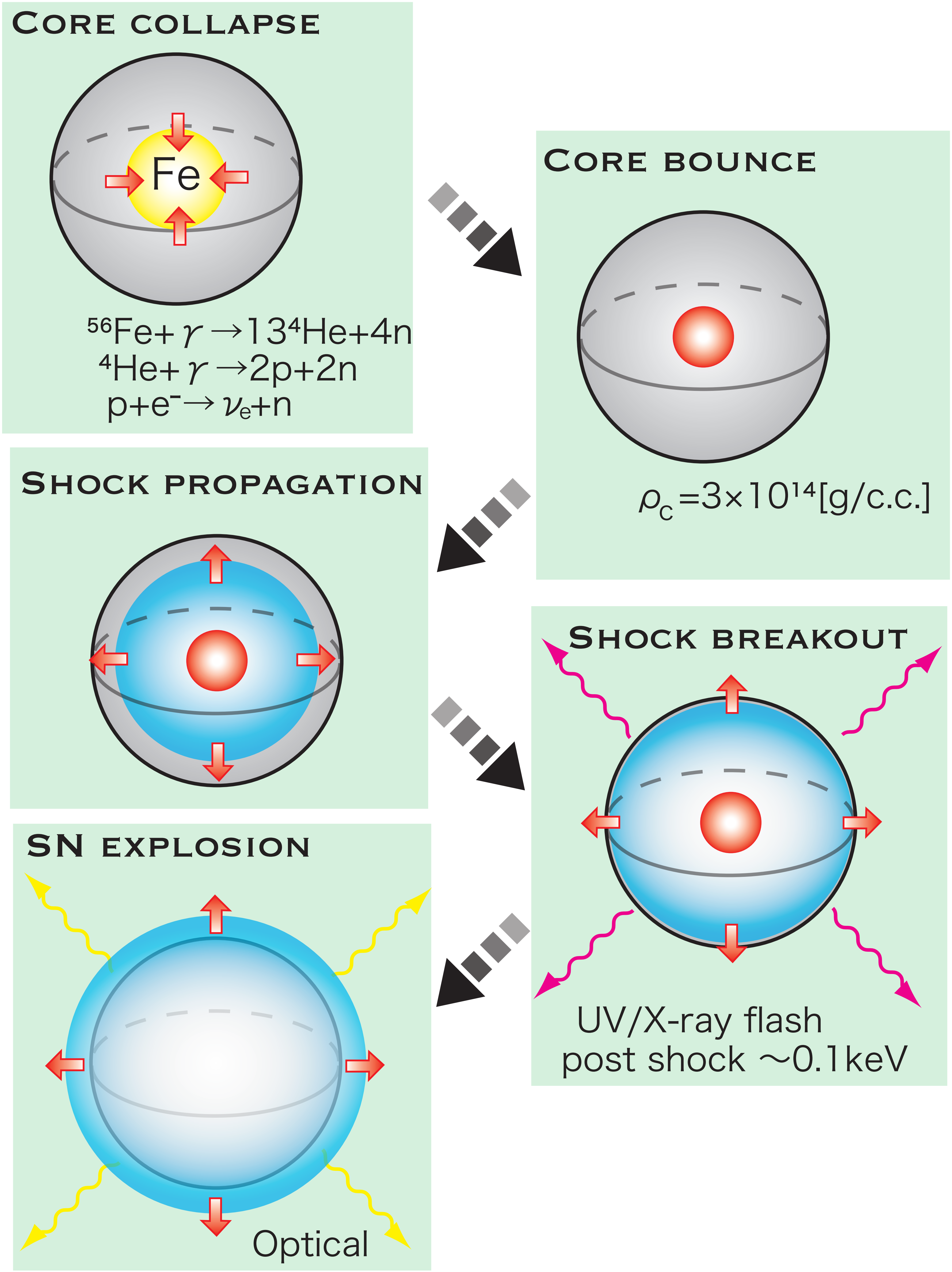
Early observations of CCSNe

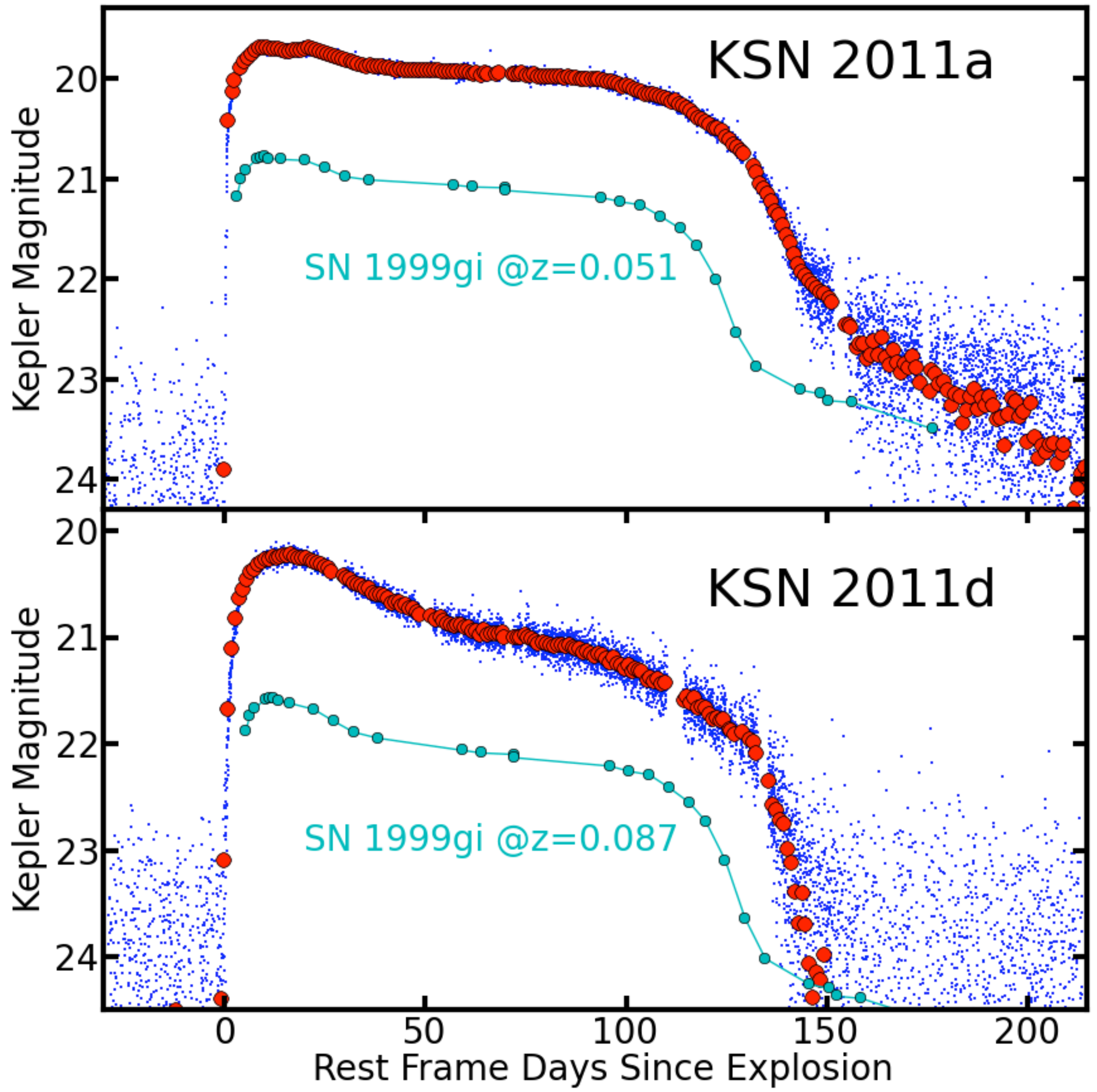


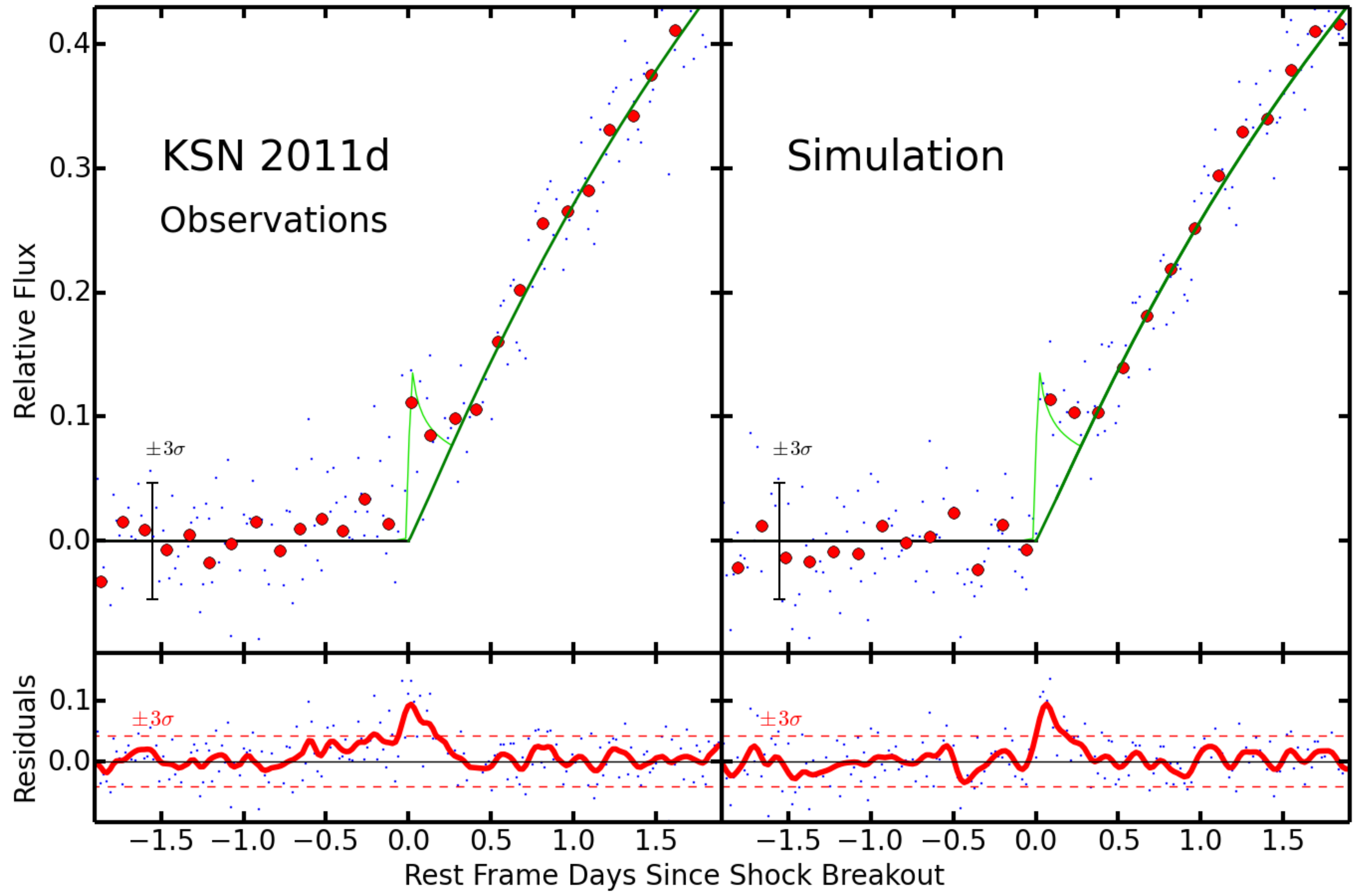


SN breakout emission in type IIb SN2016gkg
(Bersten+2018)

Early observations of CCSNe







SN breakout emission?
in SNe observed by
Kepler satellite
(Garnavich+2019)