重力崩壊型超新星からの
初期電磁波放射

Early electromagnetic signals from core-collapse supernovae

鈴木昭宏 (東京大学RESCEU)

第11回超新星ニュートリノ研究会
東大駒場, 2025/03/03

- Introduction
- Evolution of exploding massive stars
- Early emission and past/recent observations
- Progenitor and pre-supernova activities
- Summary

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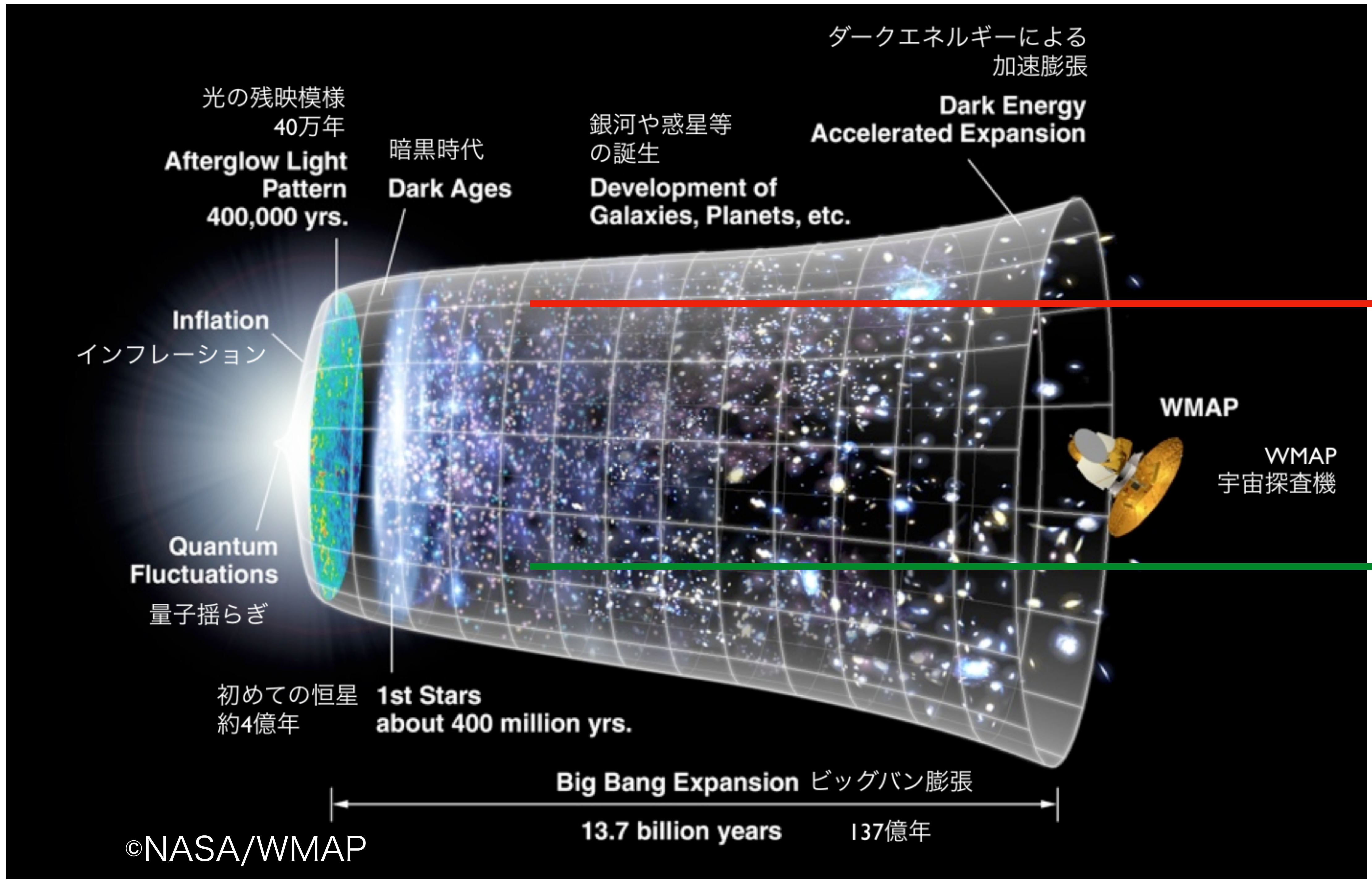
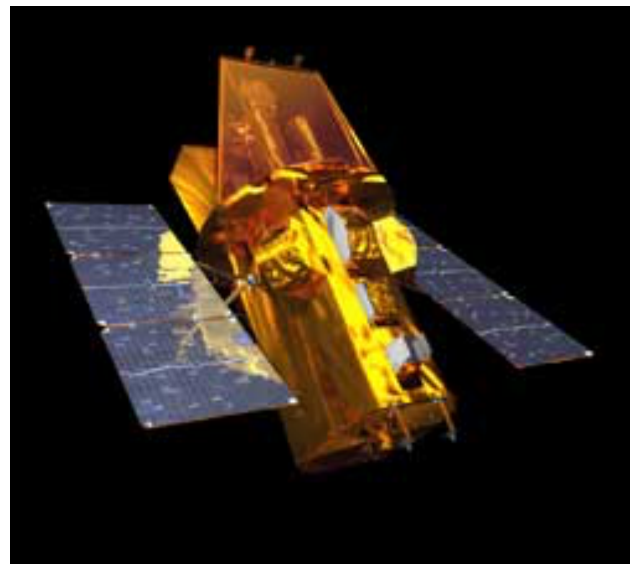
Transient studies and astronomy/astrophysics

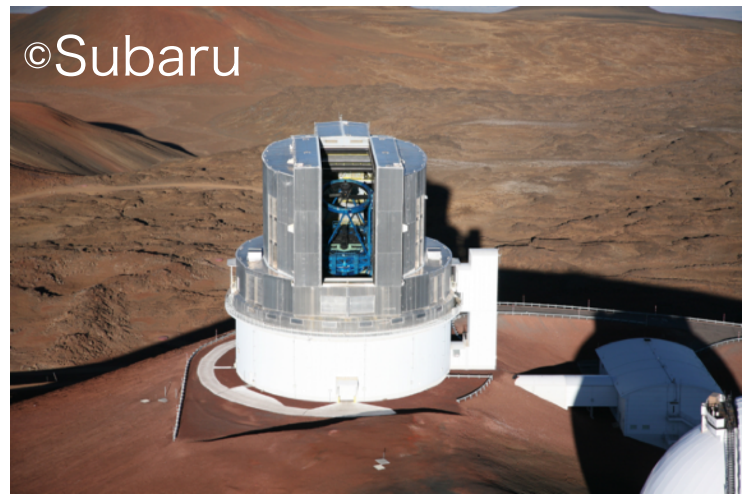
- Various astrophysical object in the universe(stars, star clusters, galaxies, compact objects). Their formation and evolution are interesting problem.
- Massive stars and their activities influence the evolution of galaxies and universe.
- Transient studies: important not only for understanding evolutions and activities of stars, but also for investigating feedback processes to larger scales.



X-ray,
optical,
radio,…

ν, CRs, GW



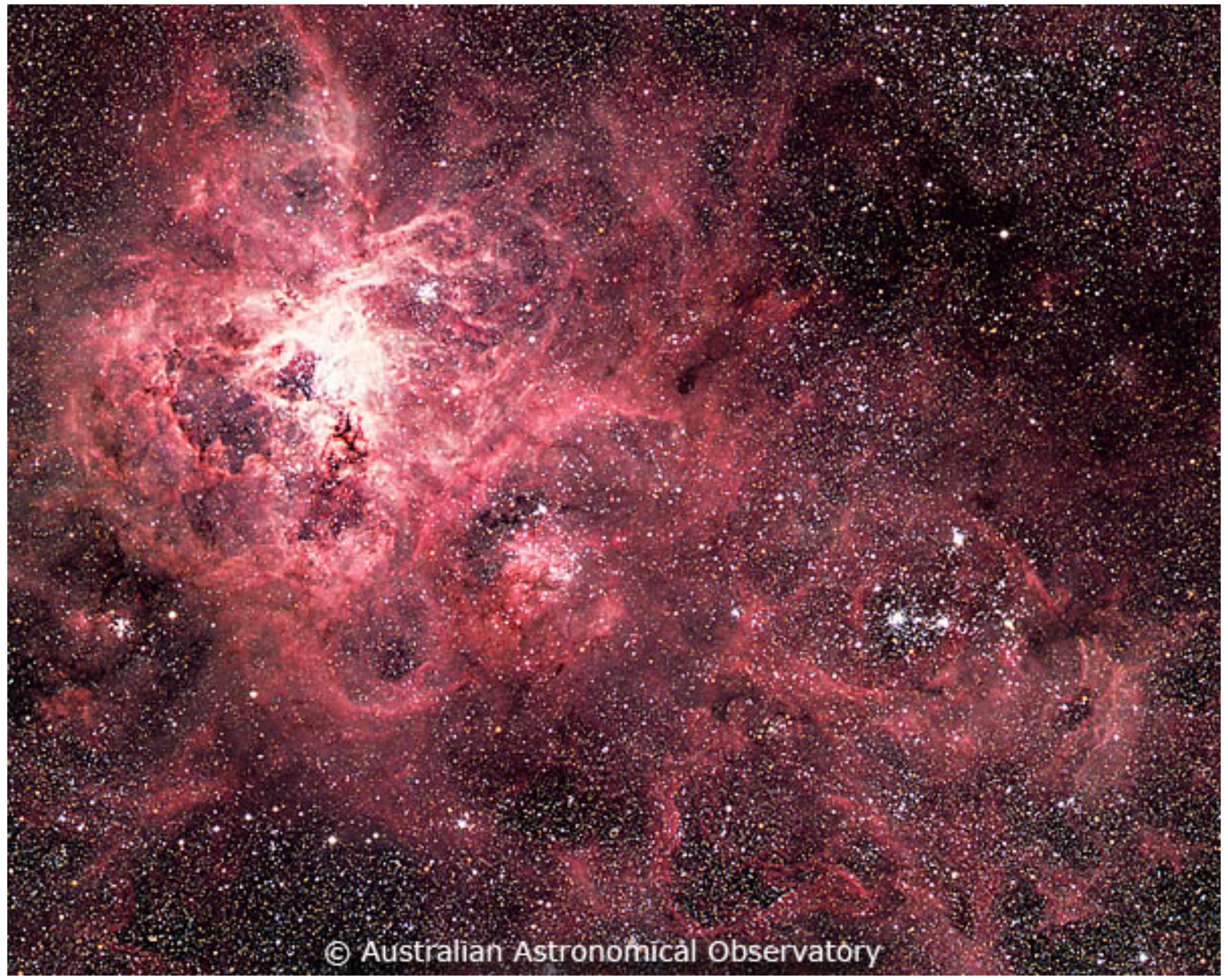


Transient studies and astronomy/astrophysics

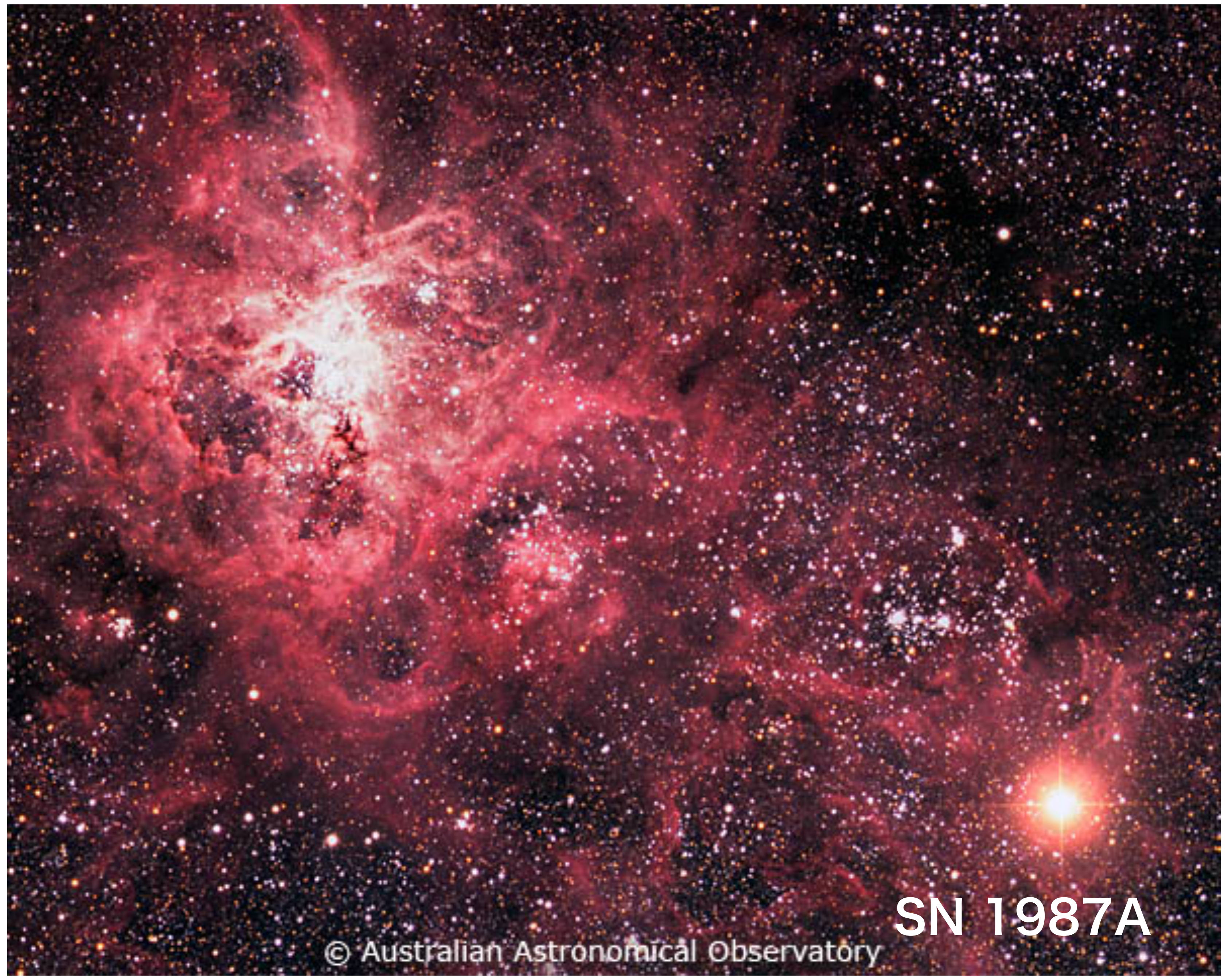
- Traditional extragalactic (optical) transients are often explosions of whole stars: The final stage of stellar evolution

- Massive stars explode as **core-collapse supernova explosions** and brightly outshine.

- White dwarfs in close binaries explode in some way as **thermonuclear supernova explosions**



1984

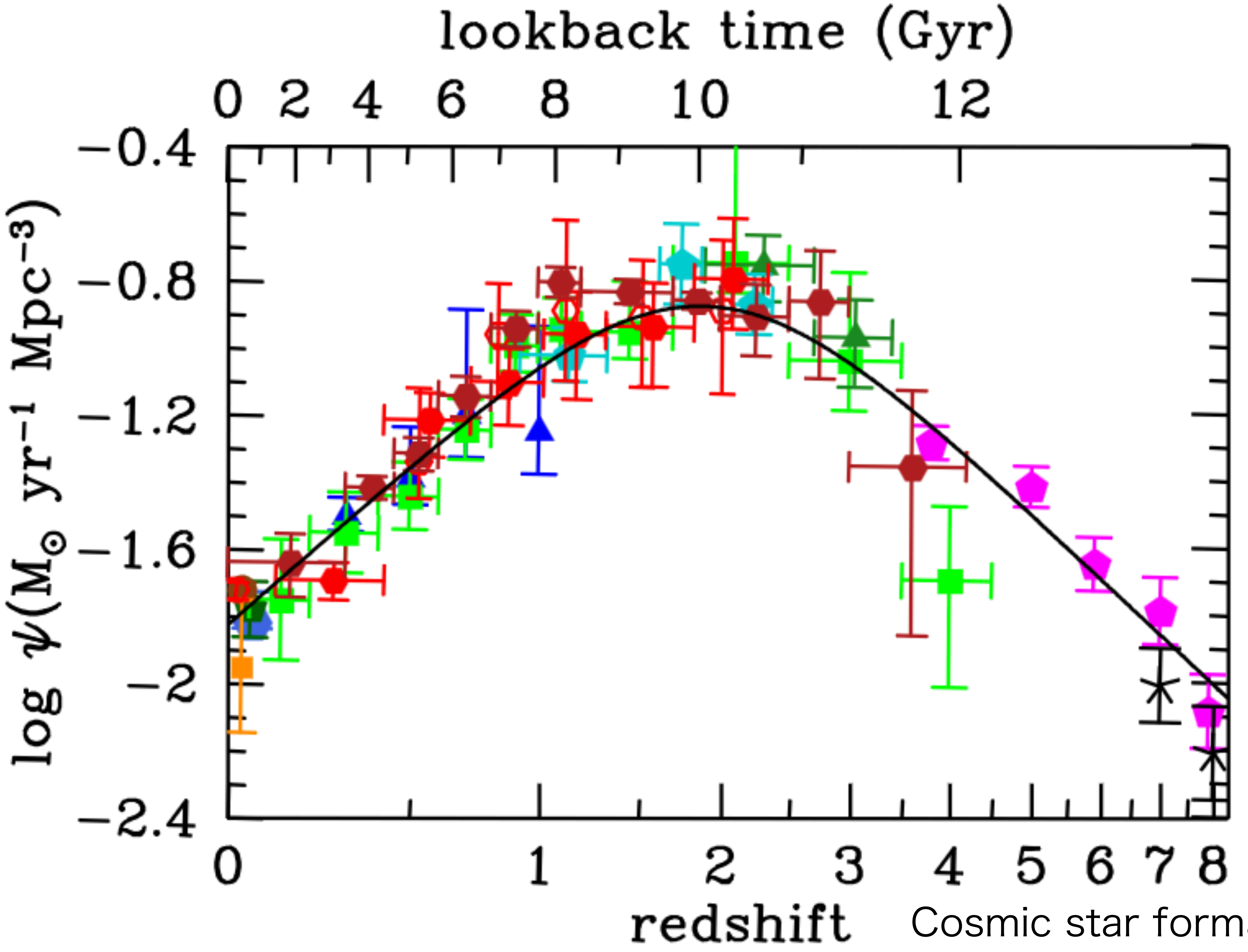


1987

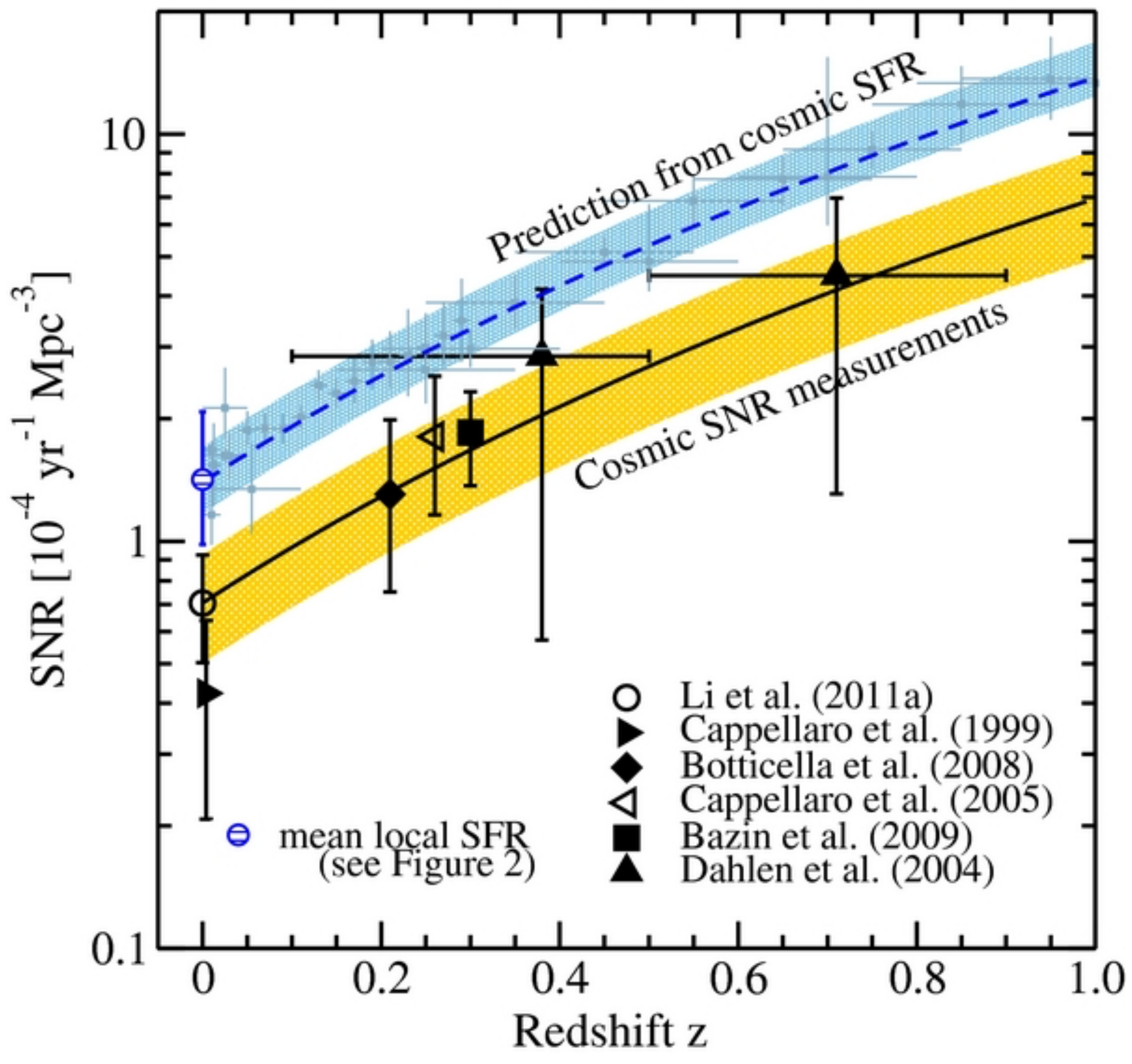
SN 1987A at Magellanic cloud

Gravitational collapse of massive stars and CCSNe

- Feedback processes to interstellar media, galaxy, and larger structures (heavy elements, ionizing photons, mechanical energy injection, cosmic-ray acceleration)



Cosmic star formation history
(Madau&Dickinson 2014)



Supernova rate problem
(Horiuchi+ 2011)

What kinds of stars have formed throughout the cosmic history?

Gravitational collapse of massive stars and CCSNe

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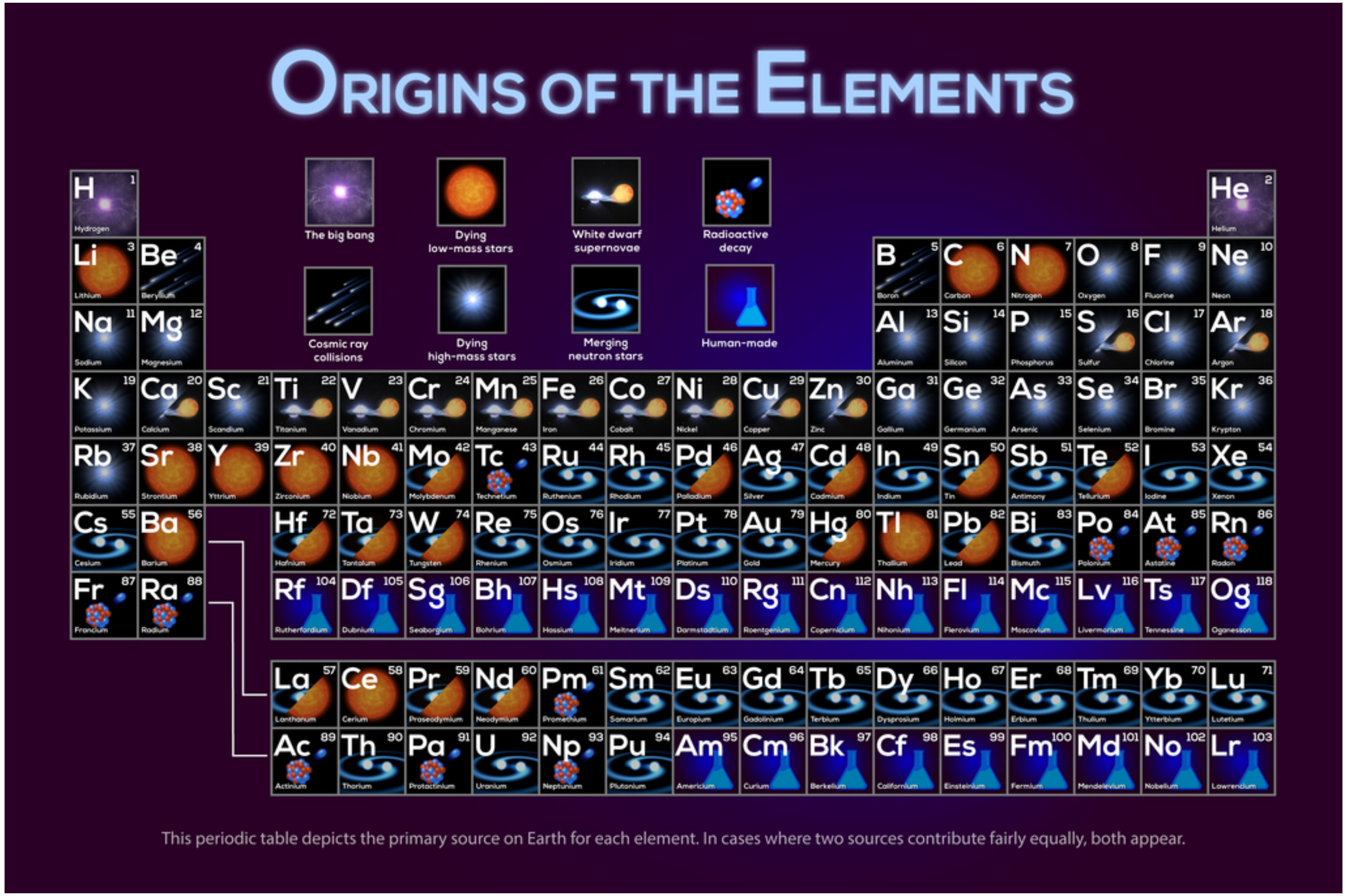
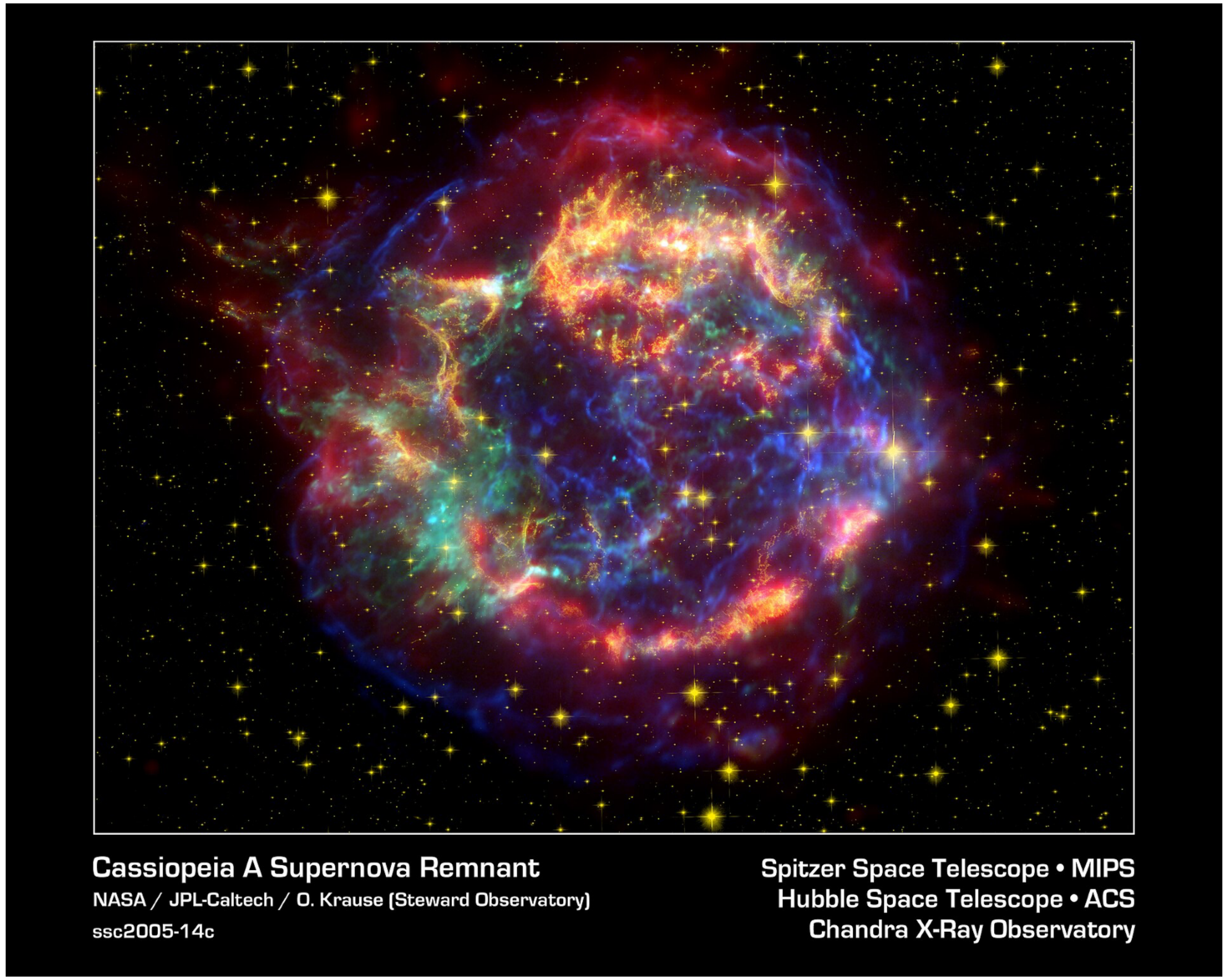


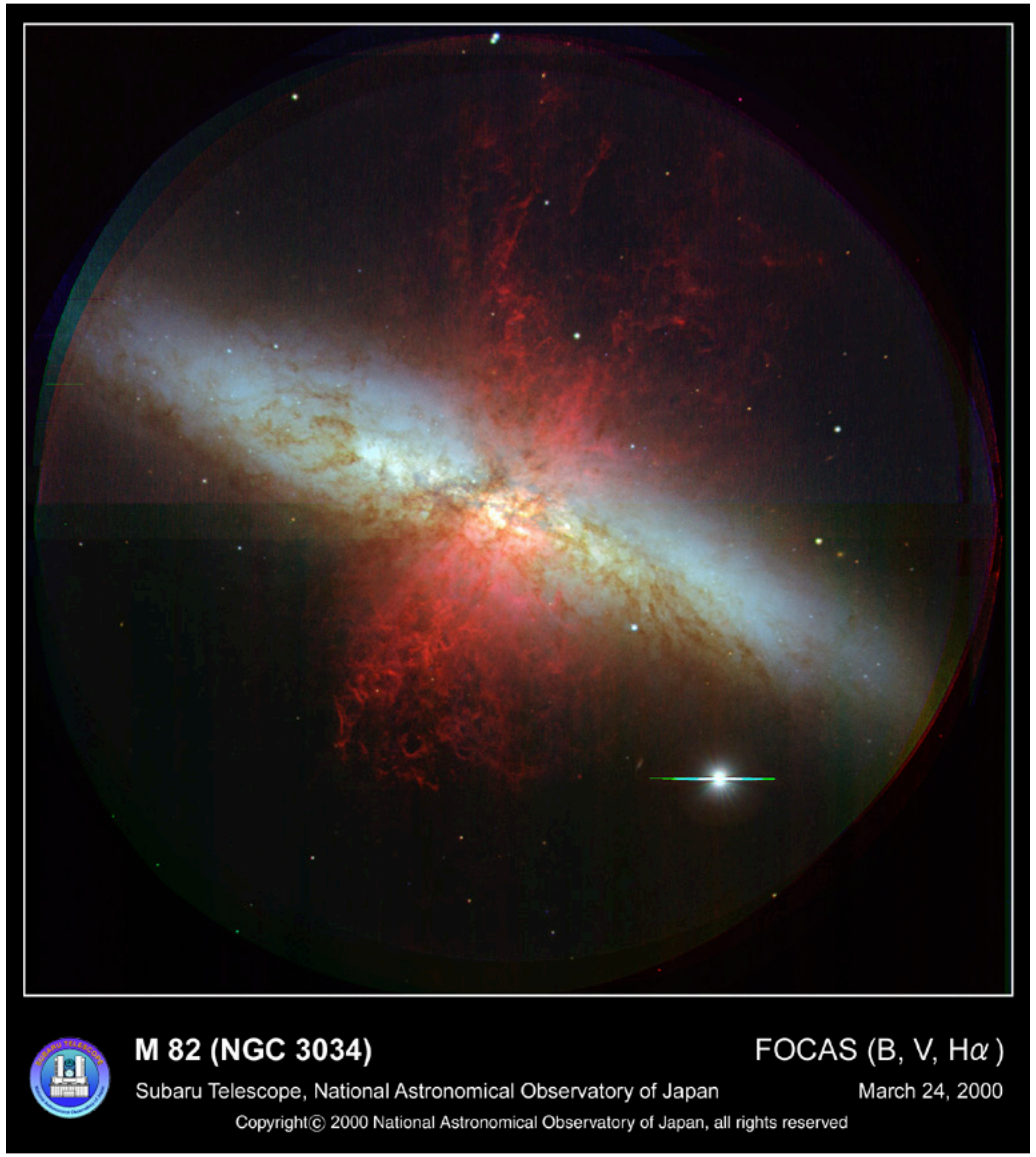
How and when heavy elements are created?

credit: NASA's Goddard Space Flight Center

Gravitational collapse of massive stars and CCSNe

- Feedback processes to interstellar media, galaxy, and larger structures (heavy elements, ionizing photons, mechanical energy injection, cosmic-ray acceleration)



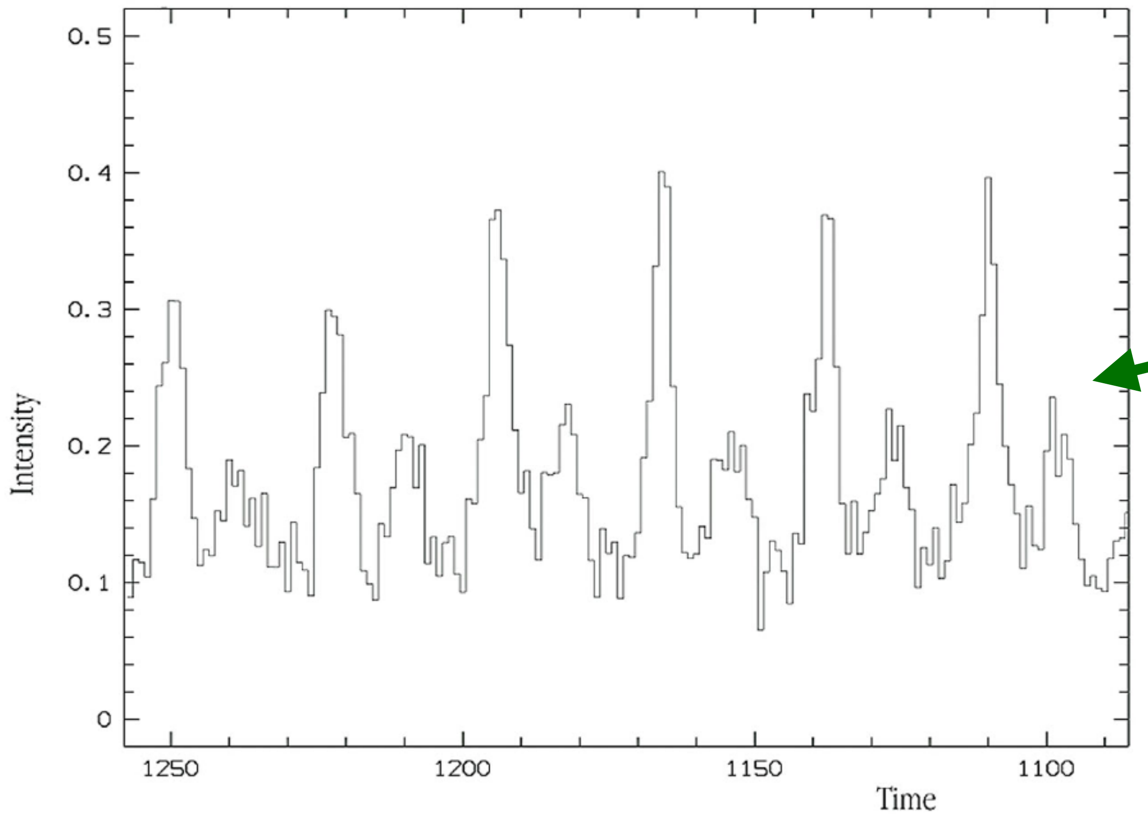


How explosive objects influence the surroundings?

From birth to death of stars

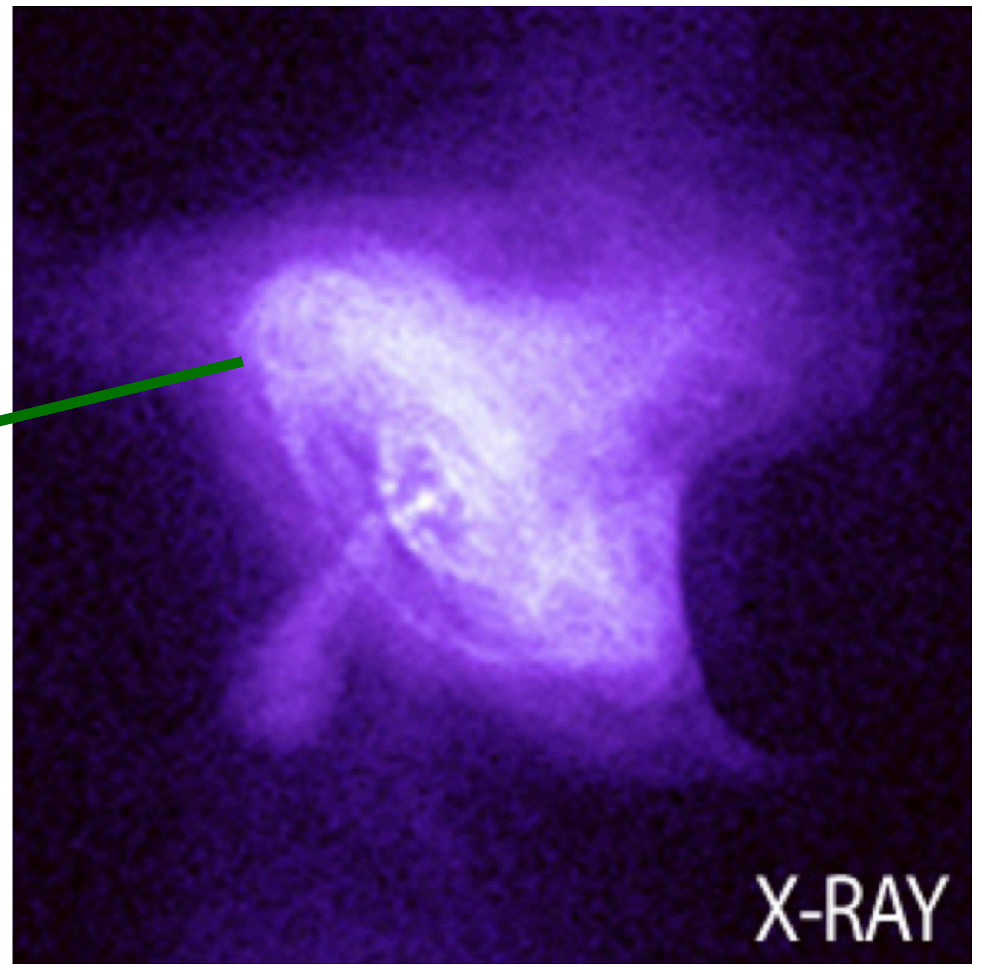
- Collapsing massive stars are birthplaces of compact objects.
- SN1054 (SN that created the Crab nebula)
- ~1000 yrs-old NS sitting at the center.

radio luminosity

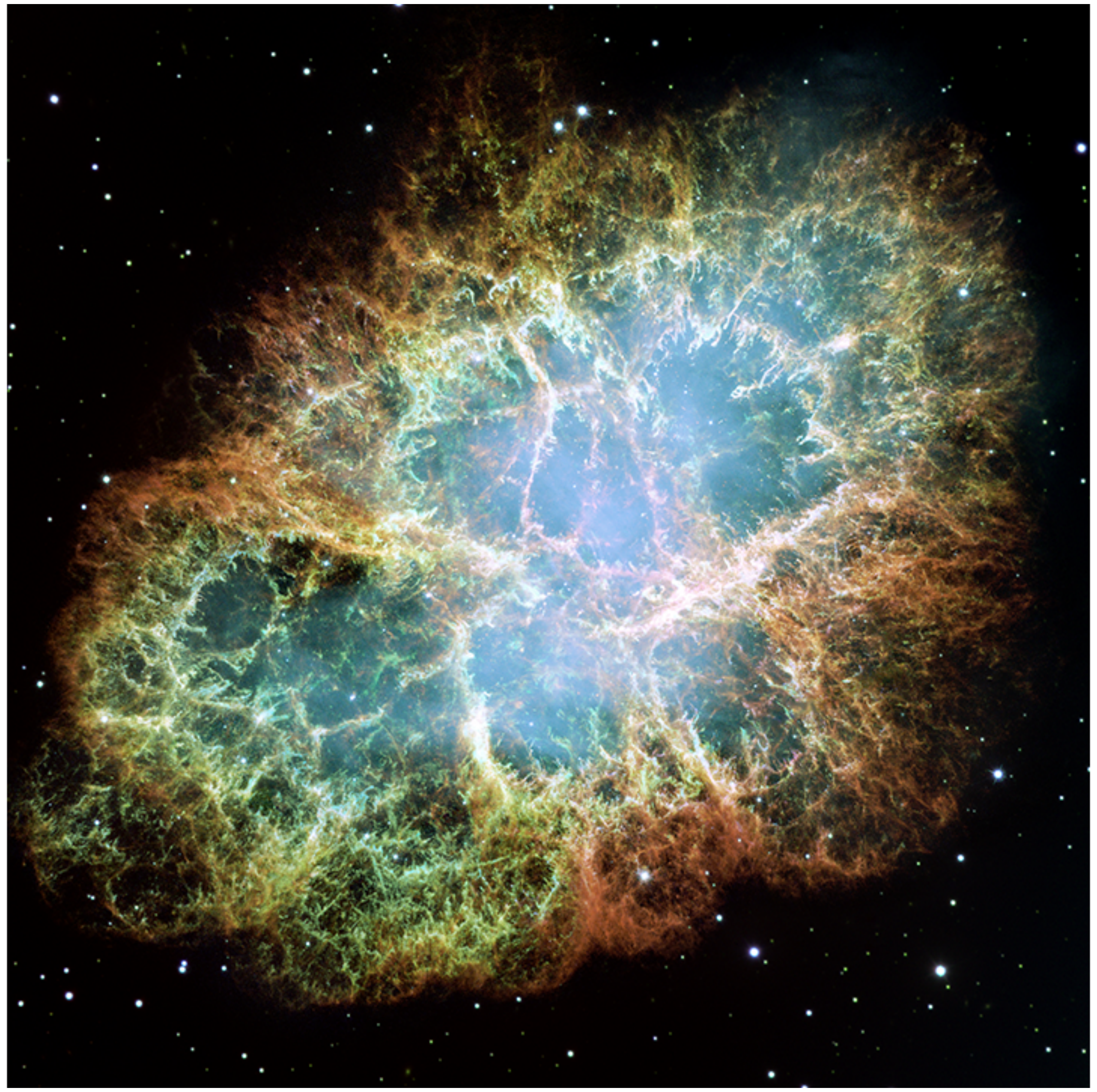


time [msec]

Radio signal from Crab pulsar
credit: ESO
https://www.eso.org/public/images/eso9948i/



credit: Chandra Education Data Analysis Software And Activities

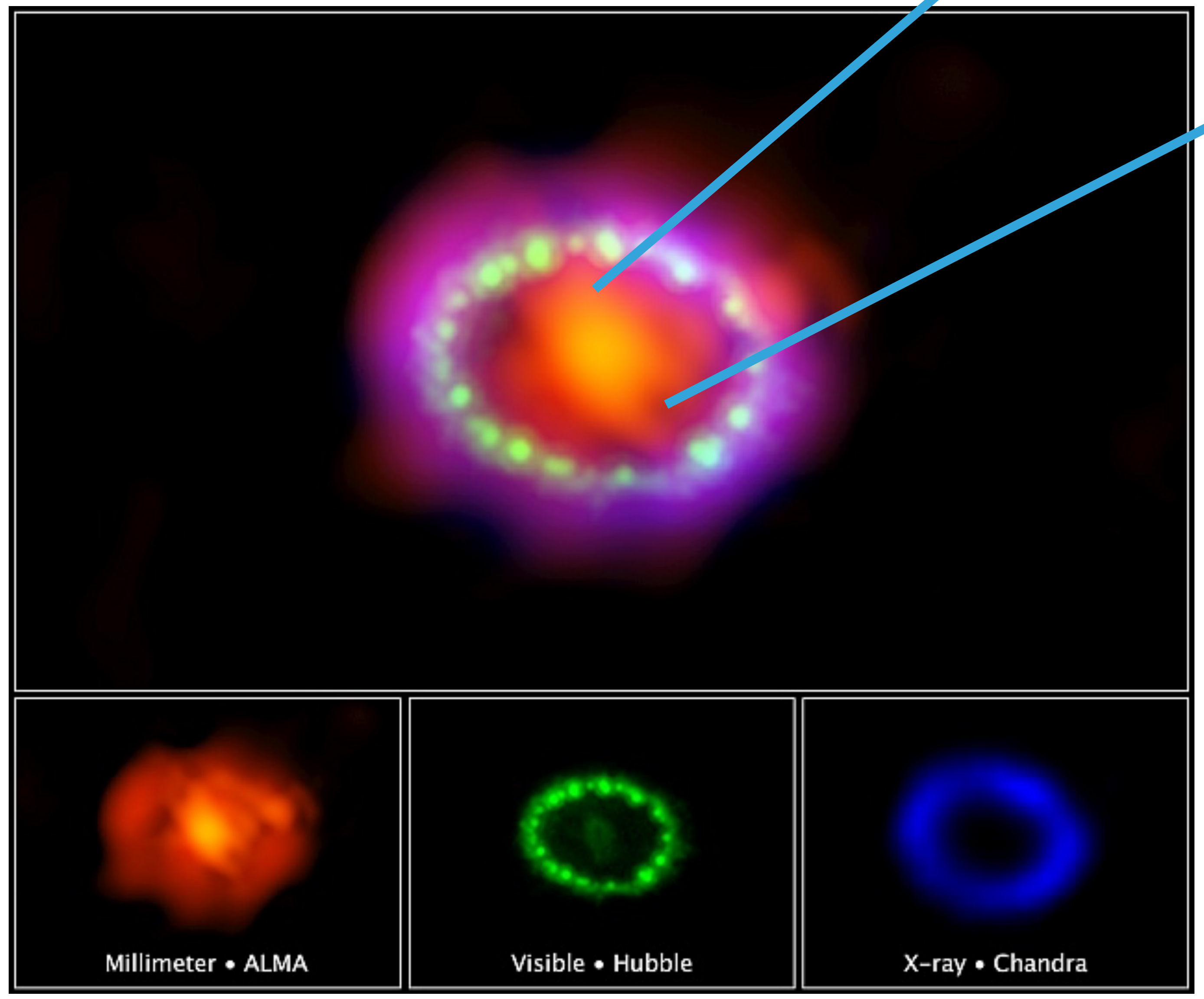


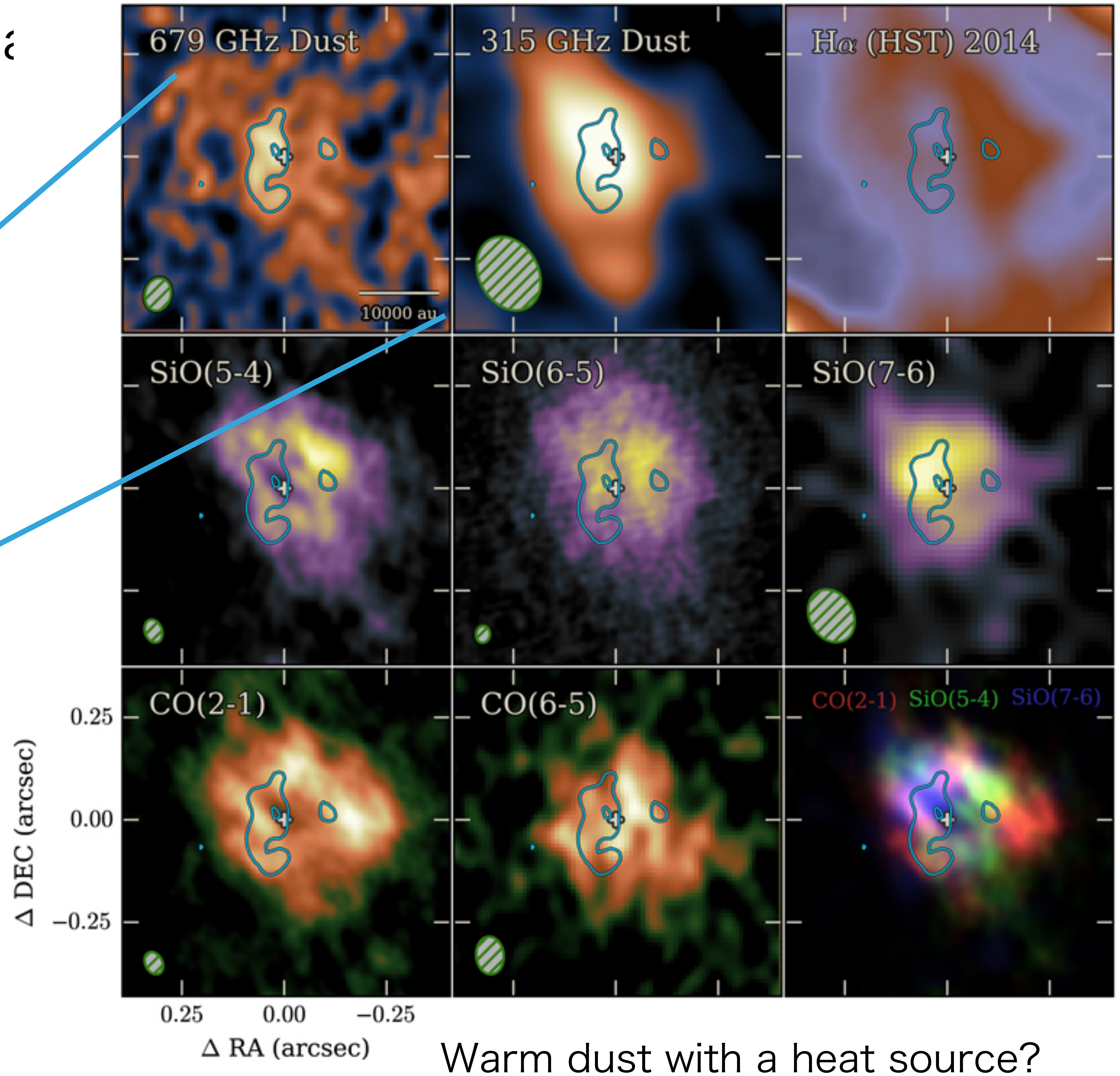
HST image of Crab nebula
https://hubblesite.org/image/3885/category/35-supernova-remnants

How compact objects (NS/BH) are born?

From birth to death of stars

- Collapsing massive stars are birthplaces of compa objects.
- SN1054 (SN that created the Crab nebula)
- ~1000 yrs-old NS sitting at the center.
- NS 1987A in SN 1987A remnant?





Warm dust with a heat source?

(Cigan+2020)

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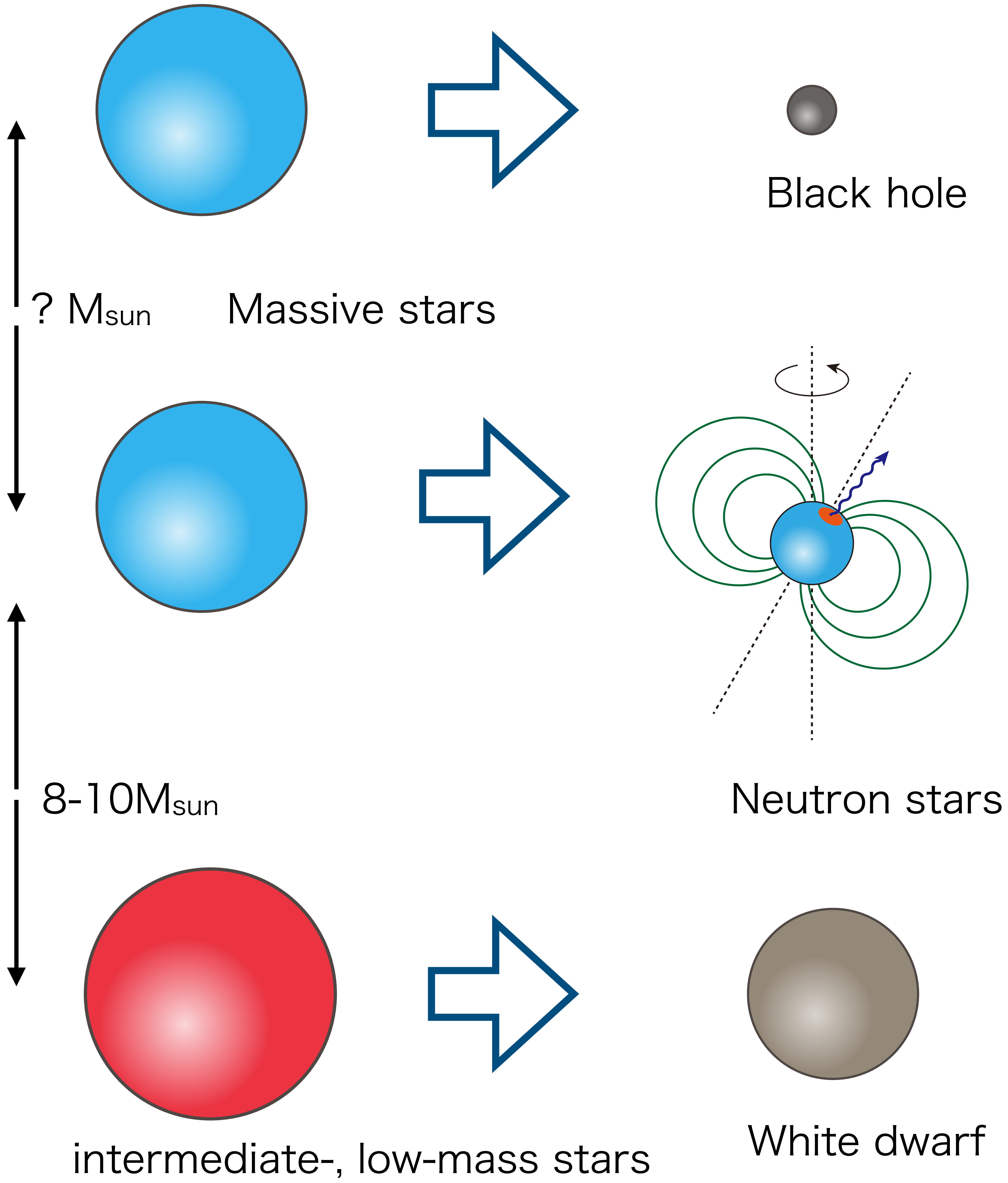


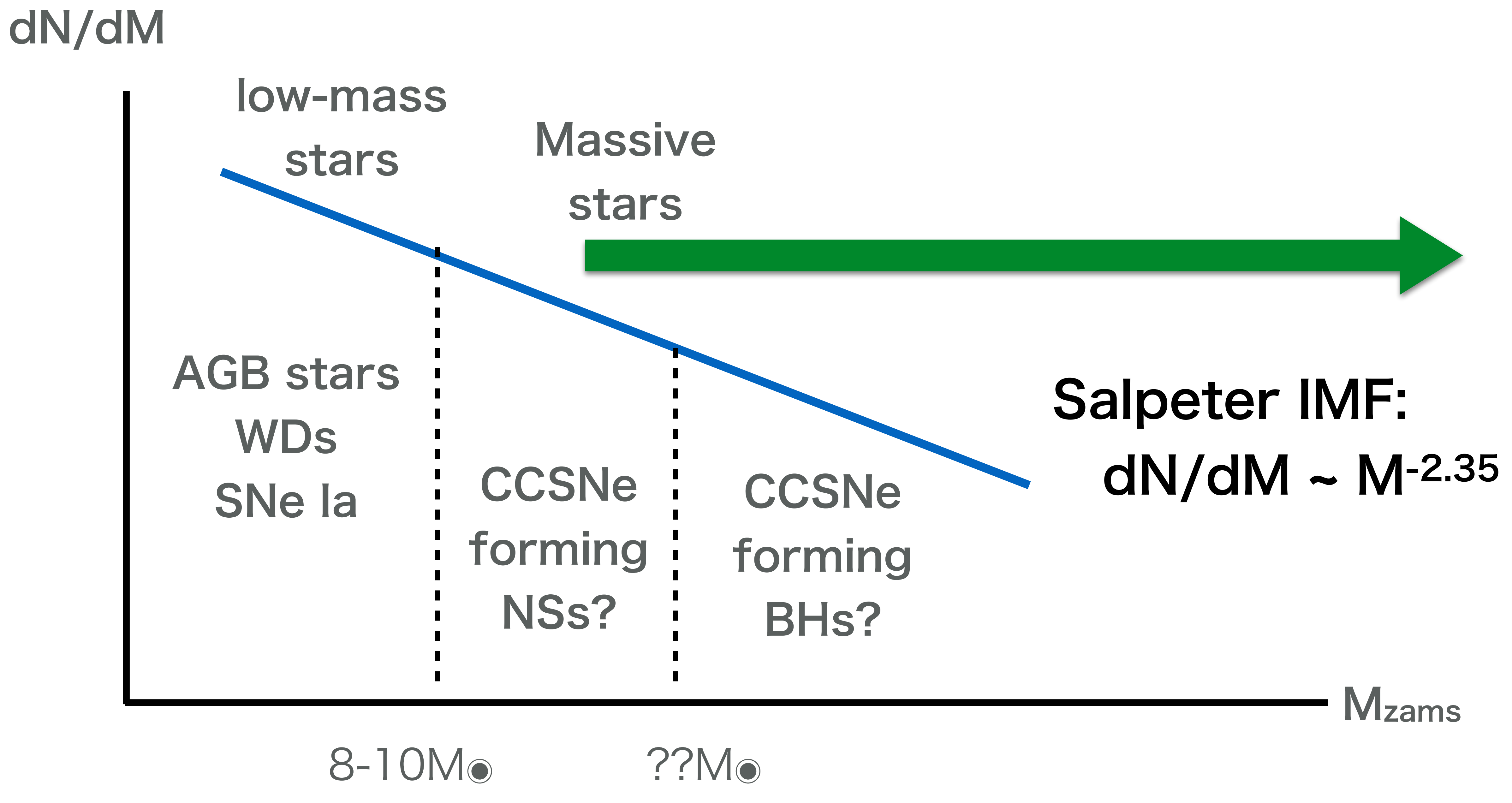
How compact objects (NS/BH) are born?

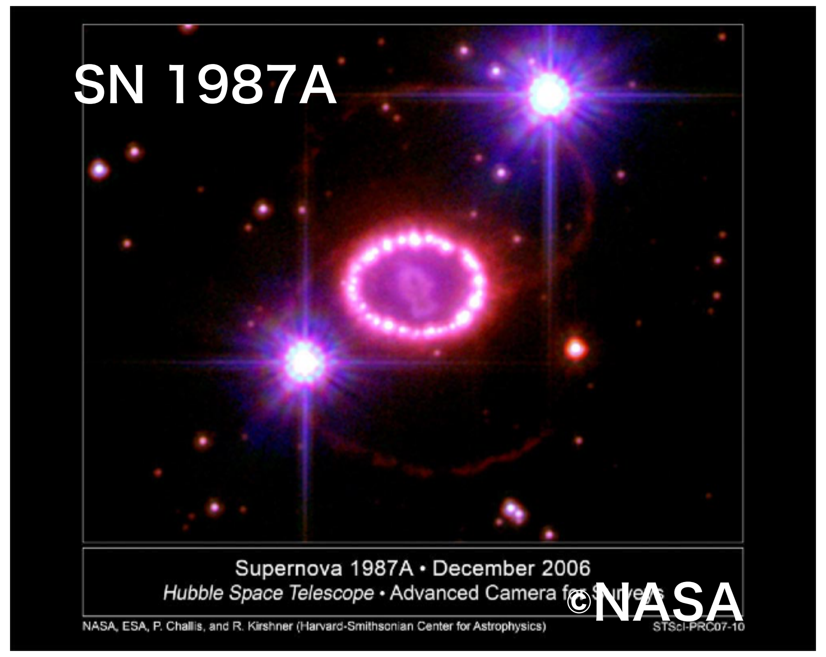
From birth to death of stars

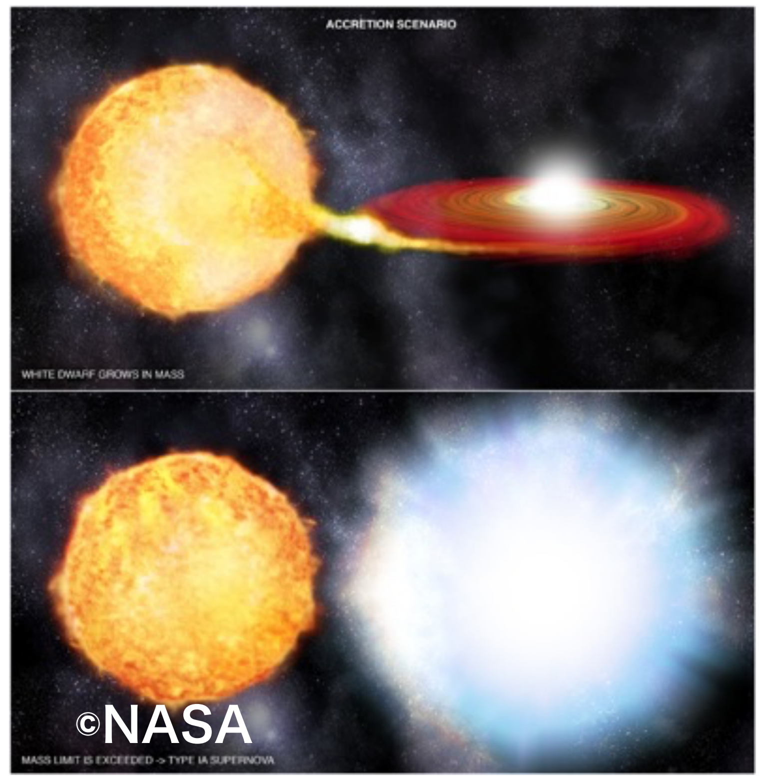
- ZAMS mass(M_{zams}), metallicity(Z), rotation(Ω), magnetic field(B) → various types of CCSNe
- compact object(NS/BH) or no compact object(ECSNe/PISNe)

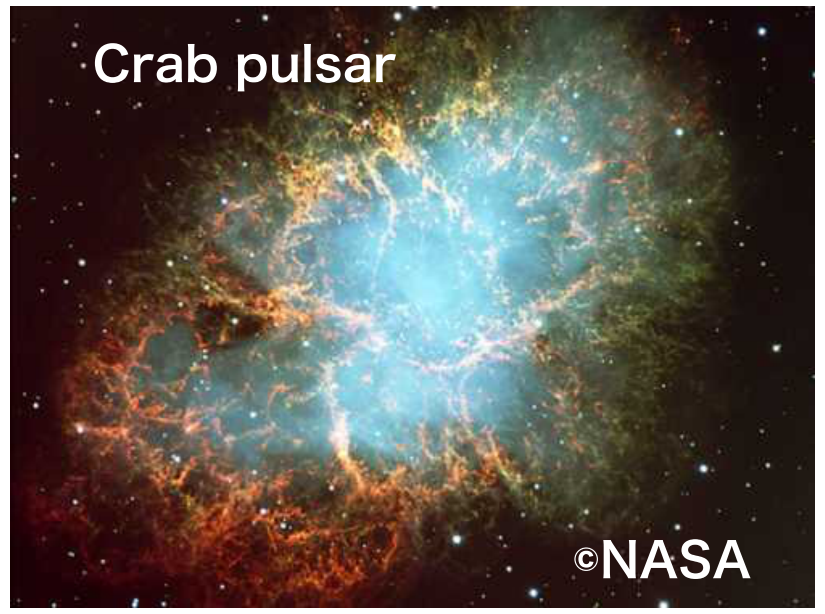
Initial Mass Function (IMF):
probability distribution of the initial stellar mass (or M_{zams})

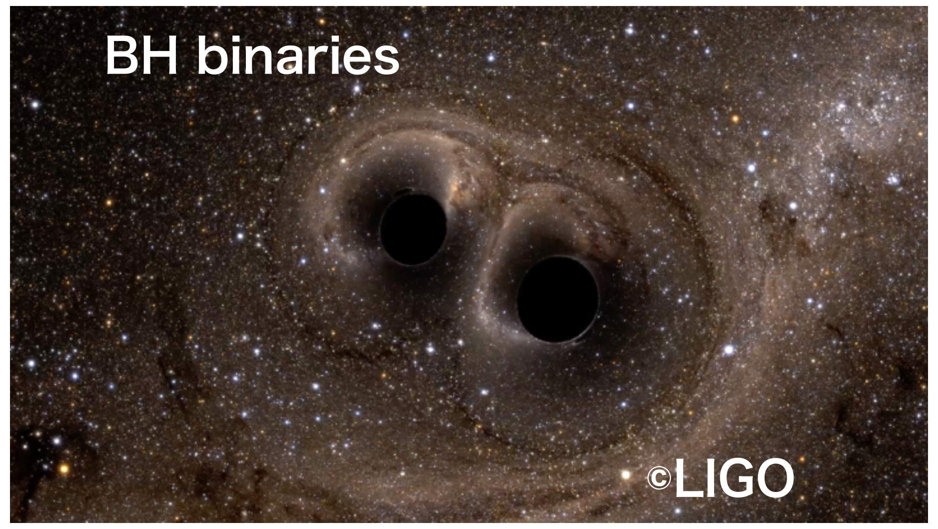
ZAMS=Zero Age Main Sequence(~initial mass)









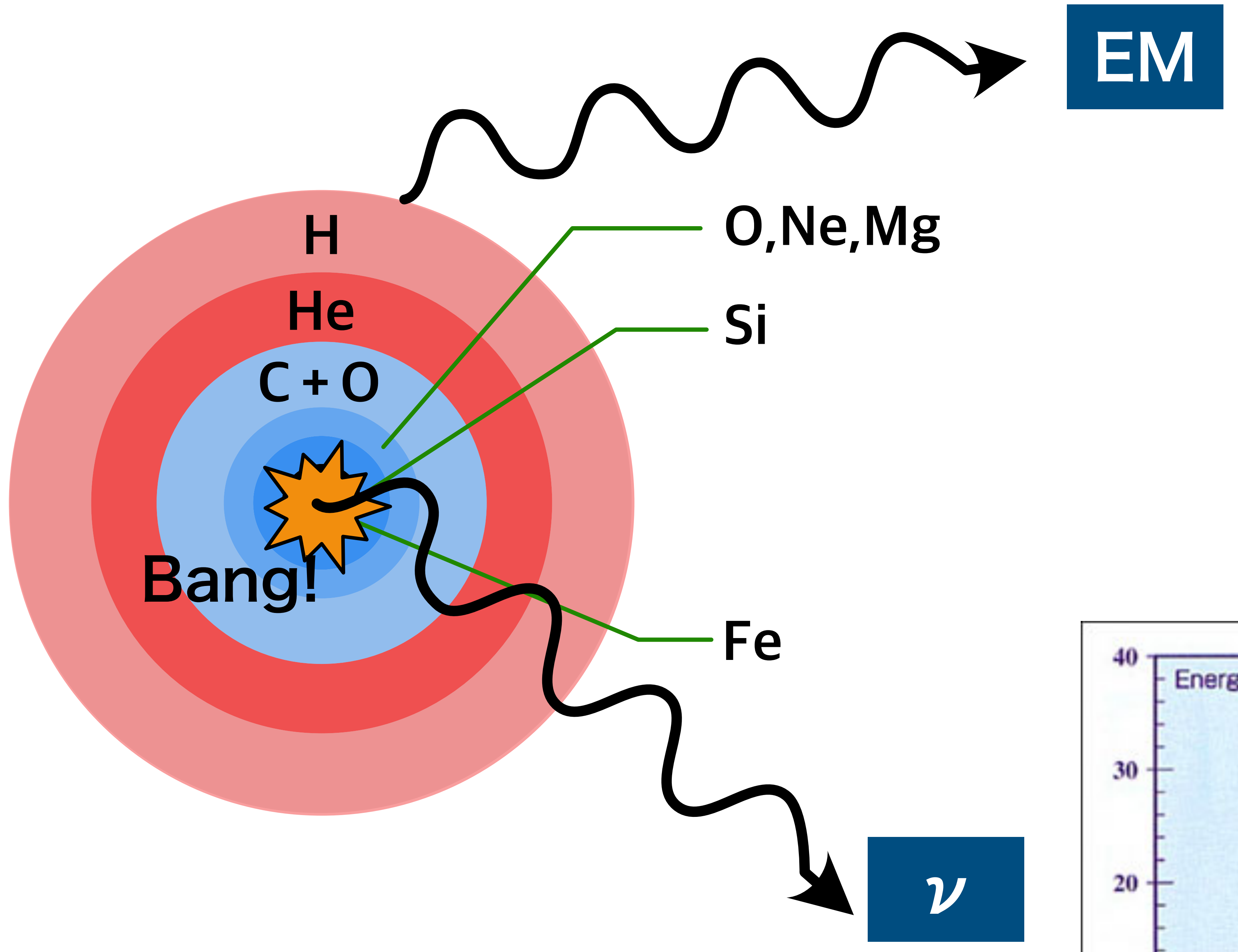


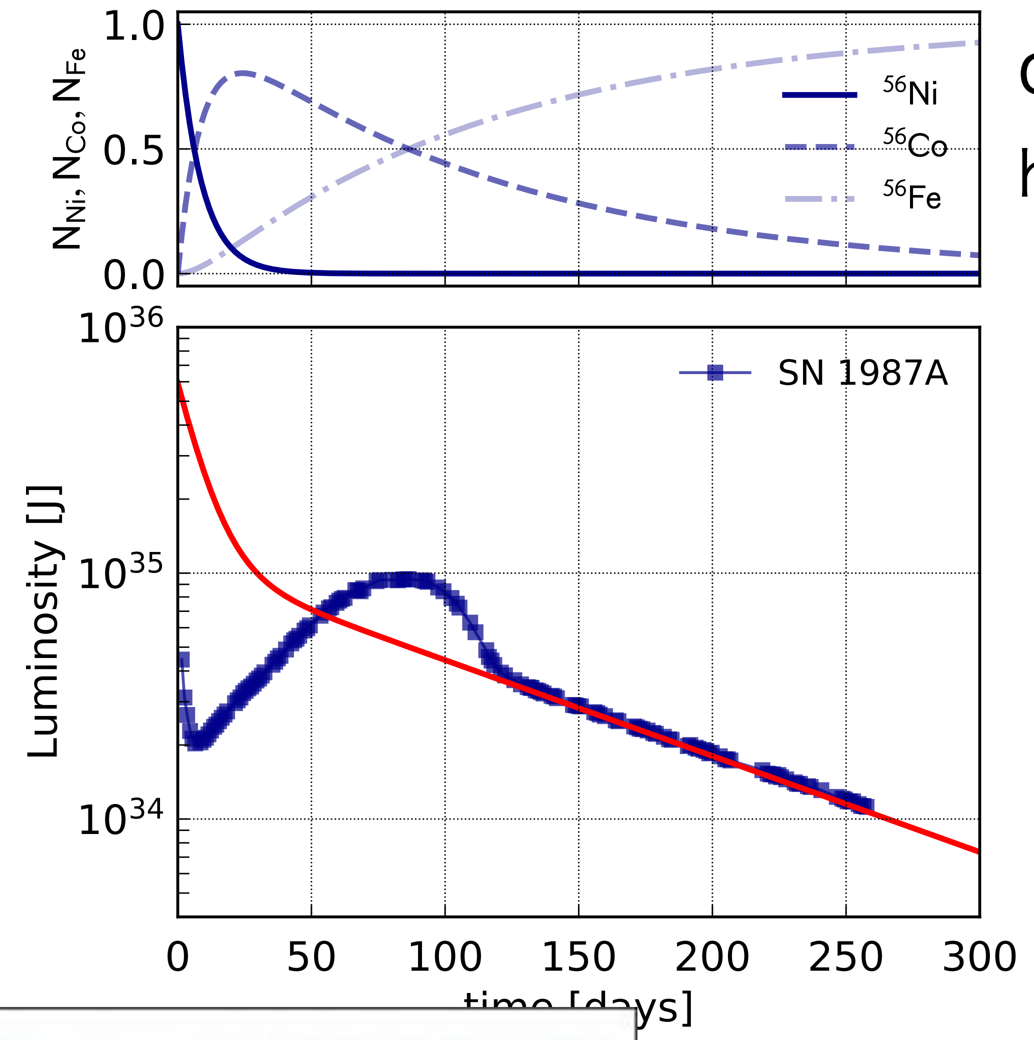
Mapping an IMF to a variety of transients and remnants

EM and ν + GW observations

- Electromagnetic wave obs.(EM): “old good” way. various information across EM spectrum (radio to gamma-ray). But, we cannot see through the photosphere.

- Neutrino obs. (ν): information on stellar cores. But, detections are challenging (SN 1987A). →multi-**messenger** astronomy

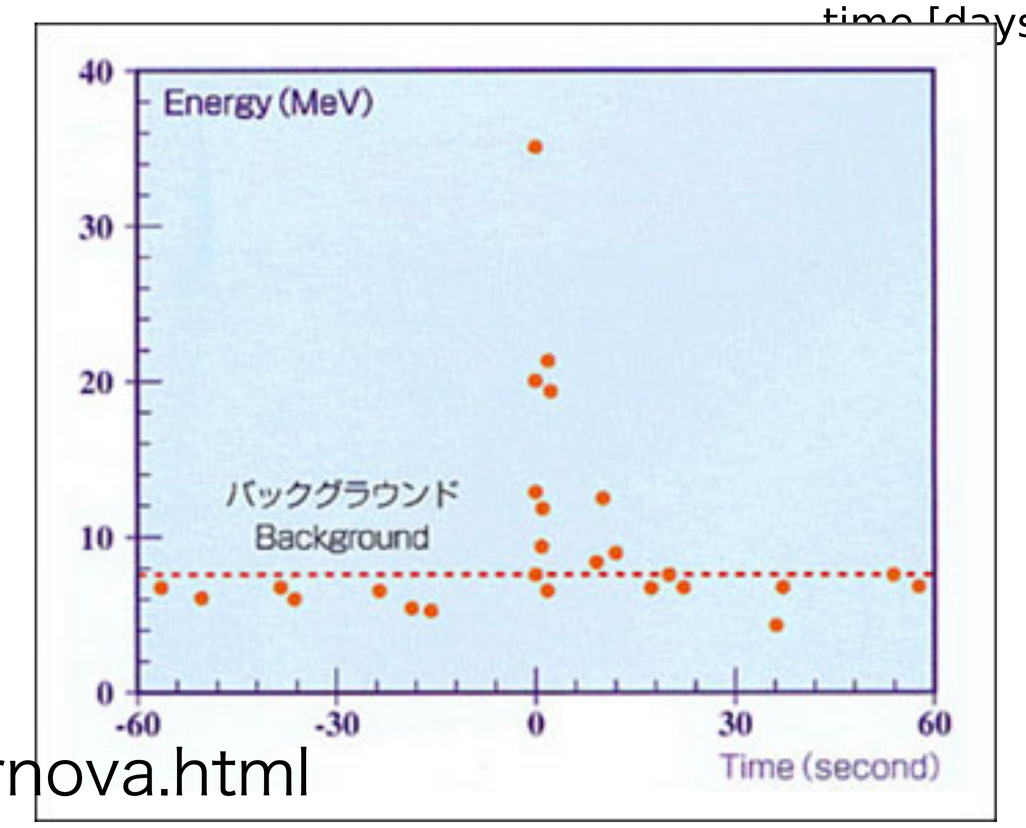




SN1987A light curve

data source: Catchpole et al. (1987,88) MNRAS 229 15

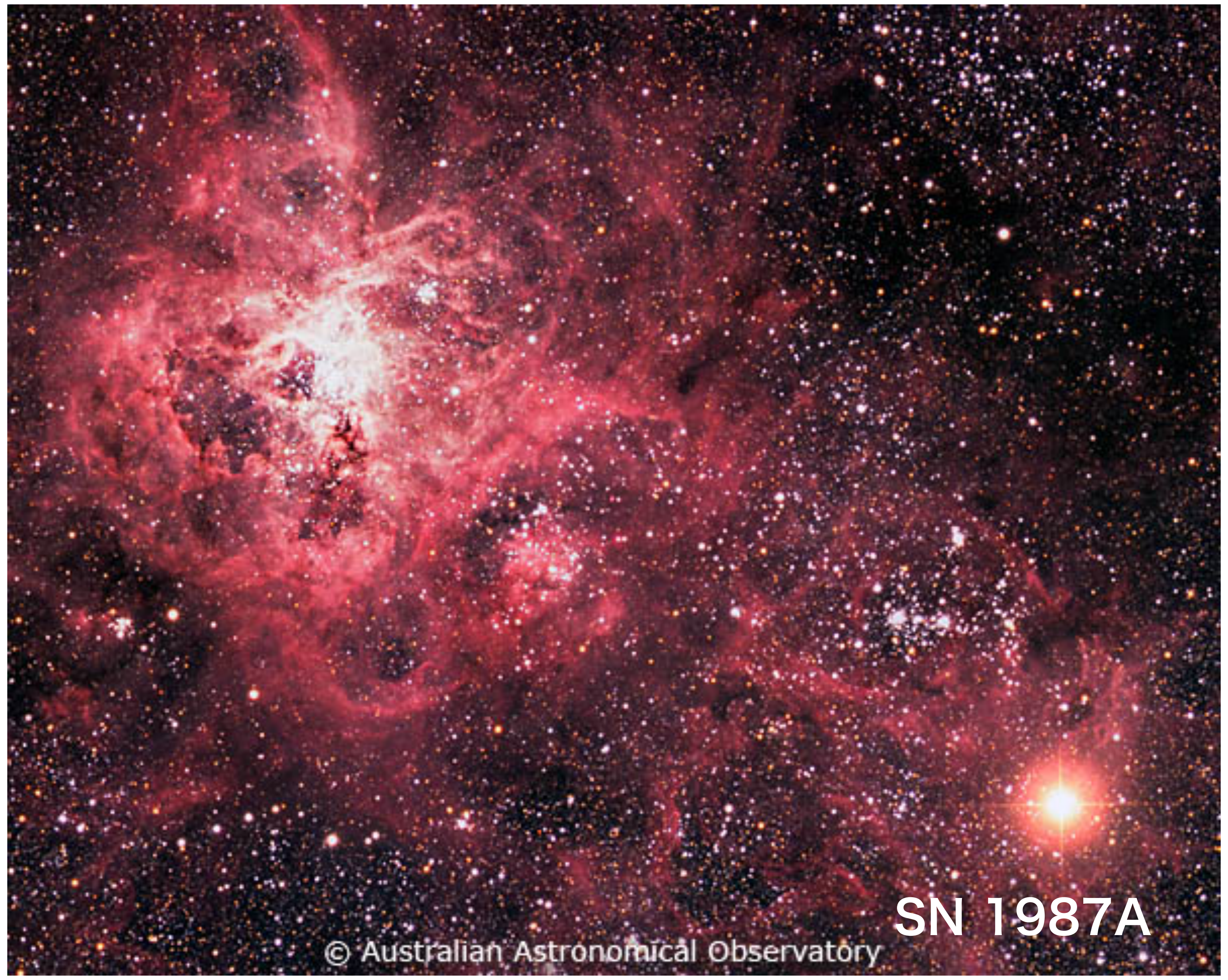
https://ui.adsabs.harvard.edu/abs/1987MNRAS.229P..15C



Neutrino from SN1987A

credit: ICRR, U.Tokyo

http://www-sk.icrr.u-tokyo.ac.jp/sk/physics/supernova.html



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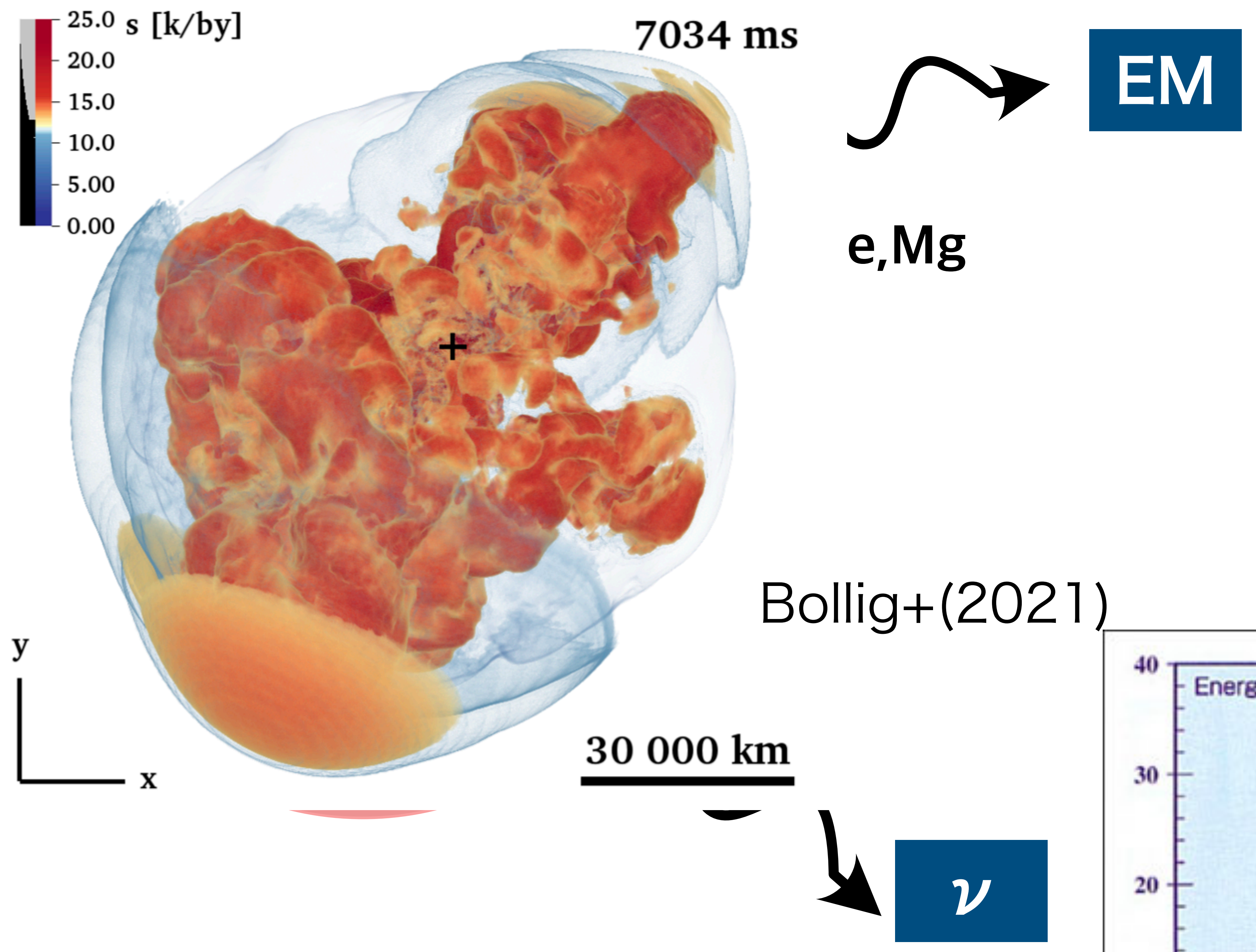
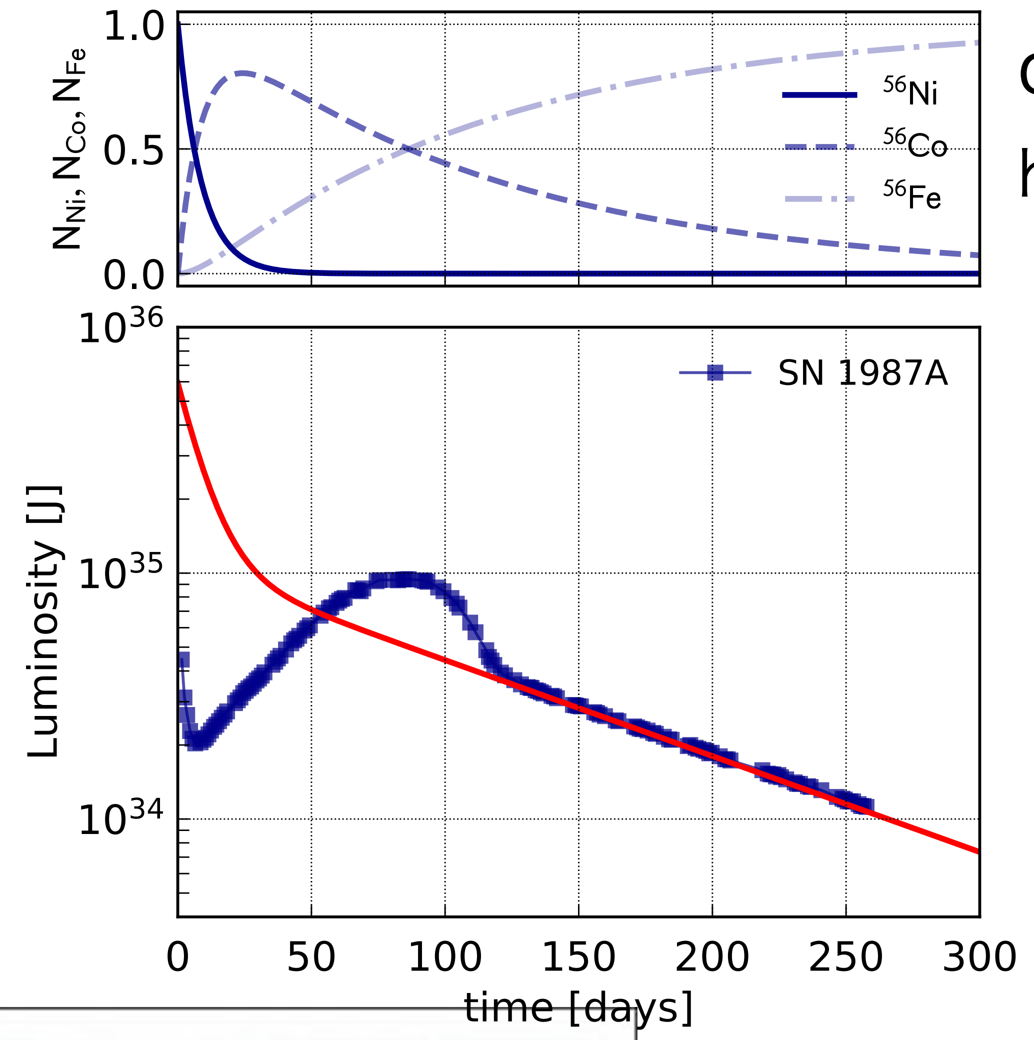


Bollig+(2021)



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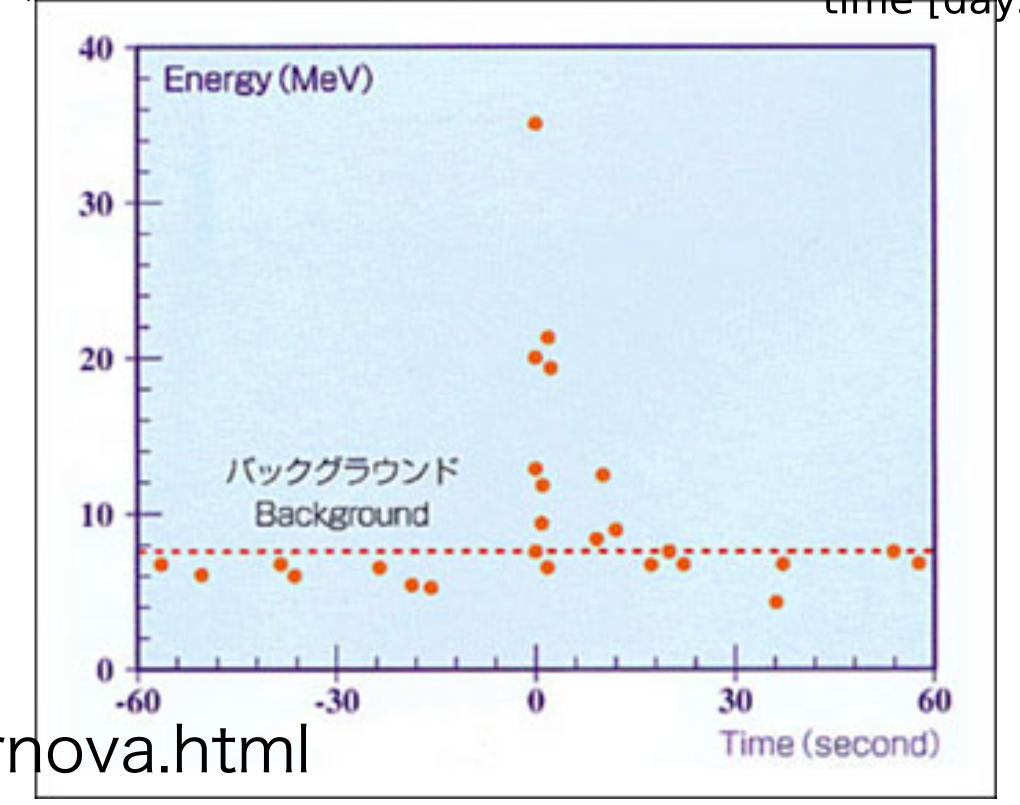

Neutrino from SN1987A
credit: ICRR, U.Tokyo
http://www-sk.icrr.u-tokyo.ac.jp/sk/physics/supernova.html

- observational test for what we believed as the standard explosion mechanism (ν-driven)

- ν luminosity/spectrum → temperature and radius of ν-sphere

- relation between ν properties and progenitor/explosion properties(mass, energy, ,Ni,...)

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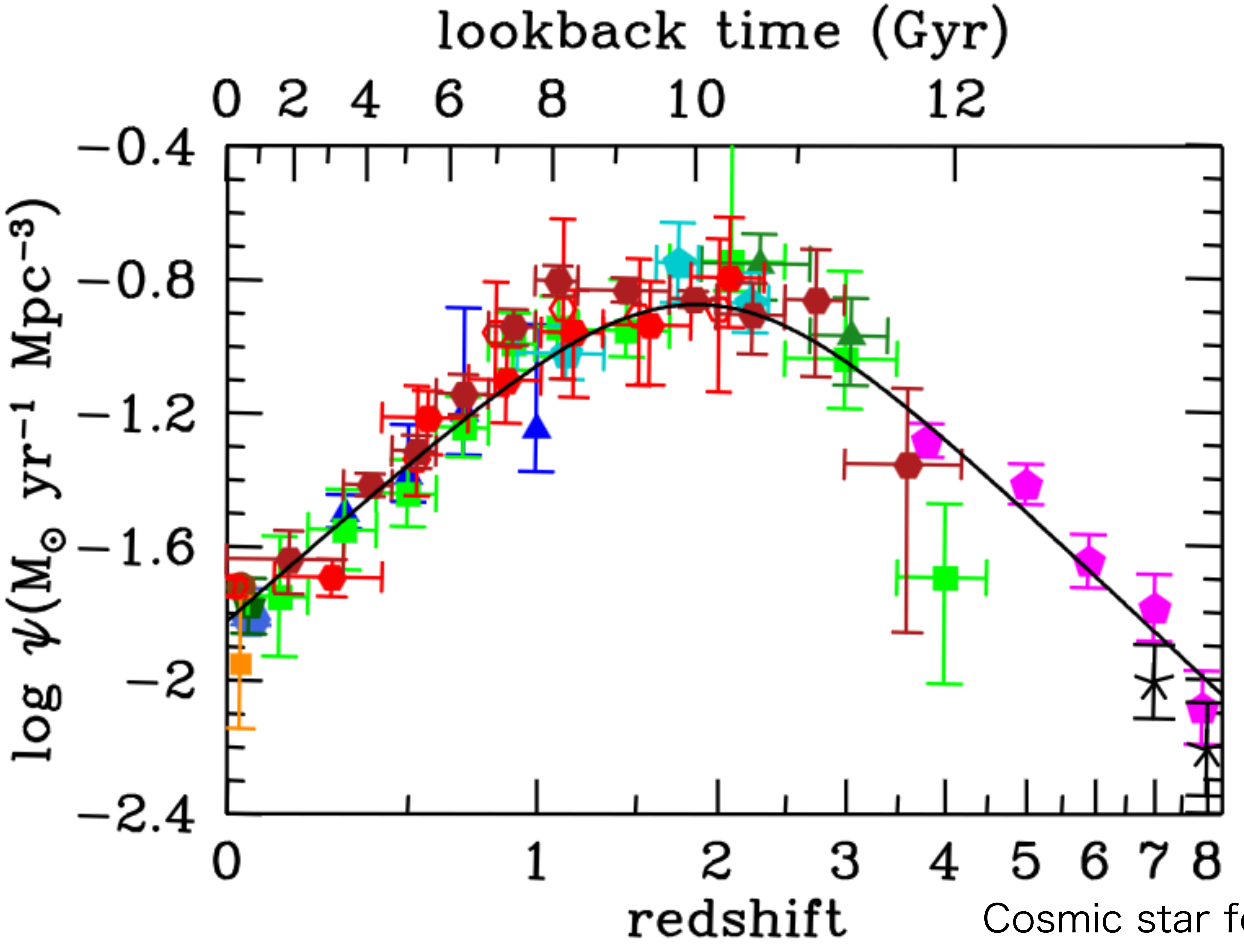

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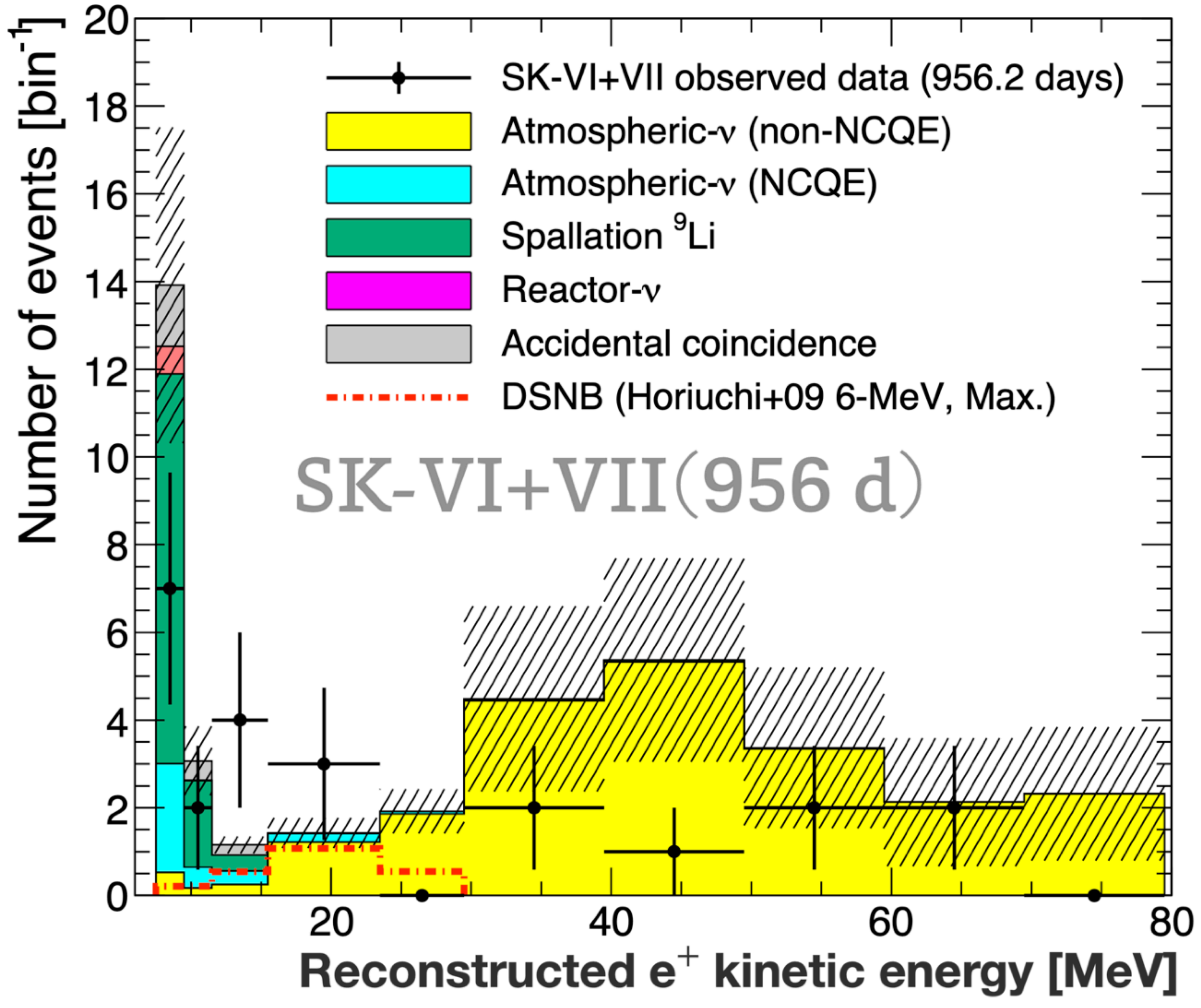
(Madau&Dickinson 2014)



Diffuse SN neutrino background search
(M.Harada, Neutrino 2024)

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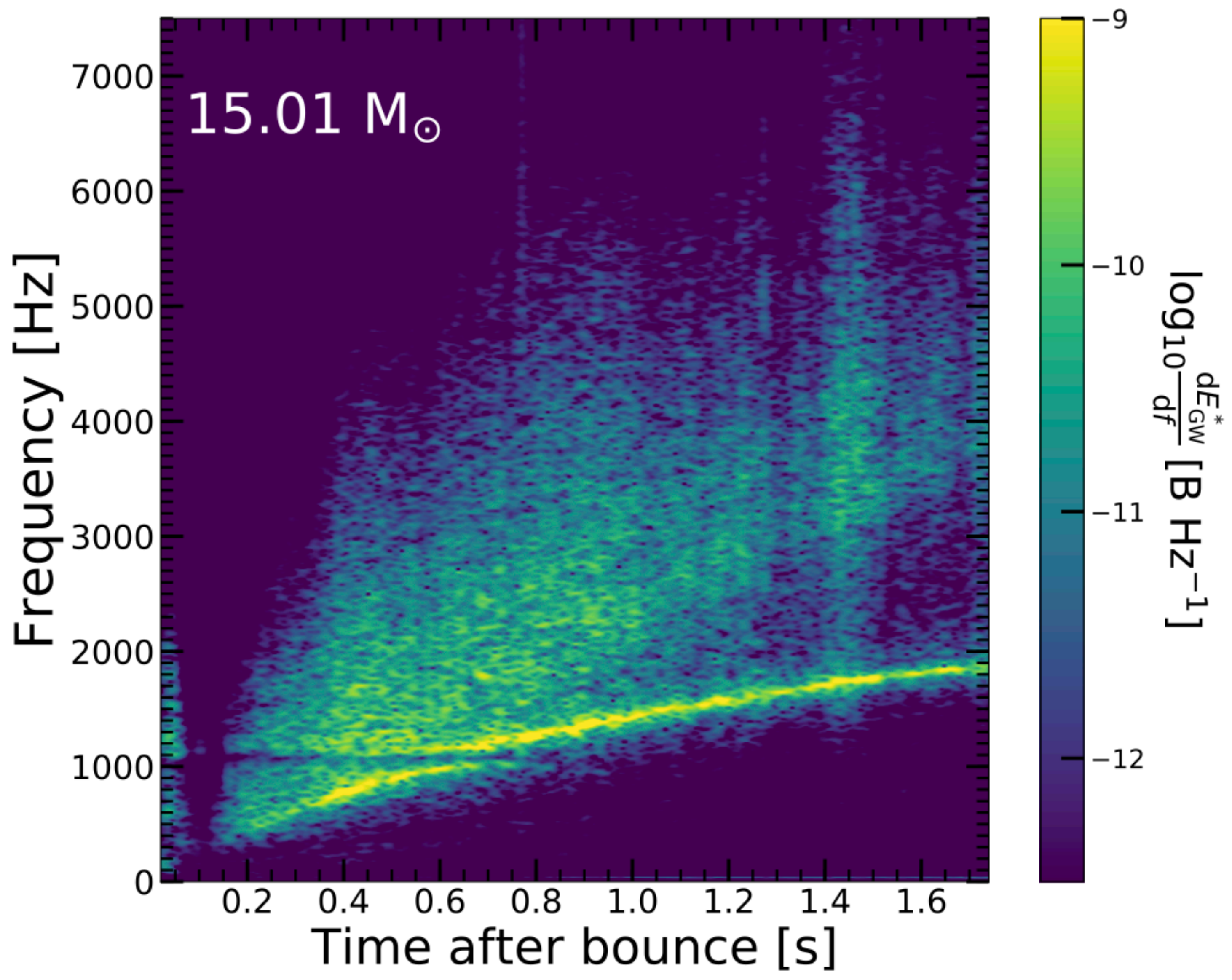
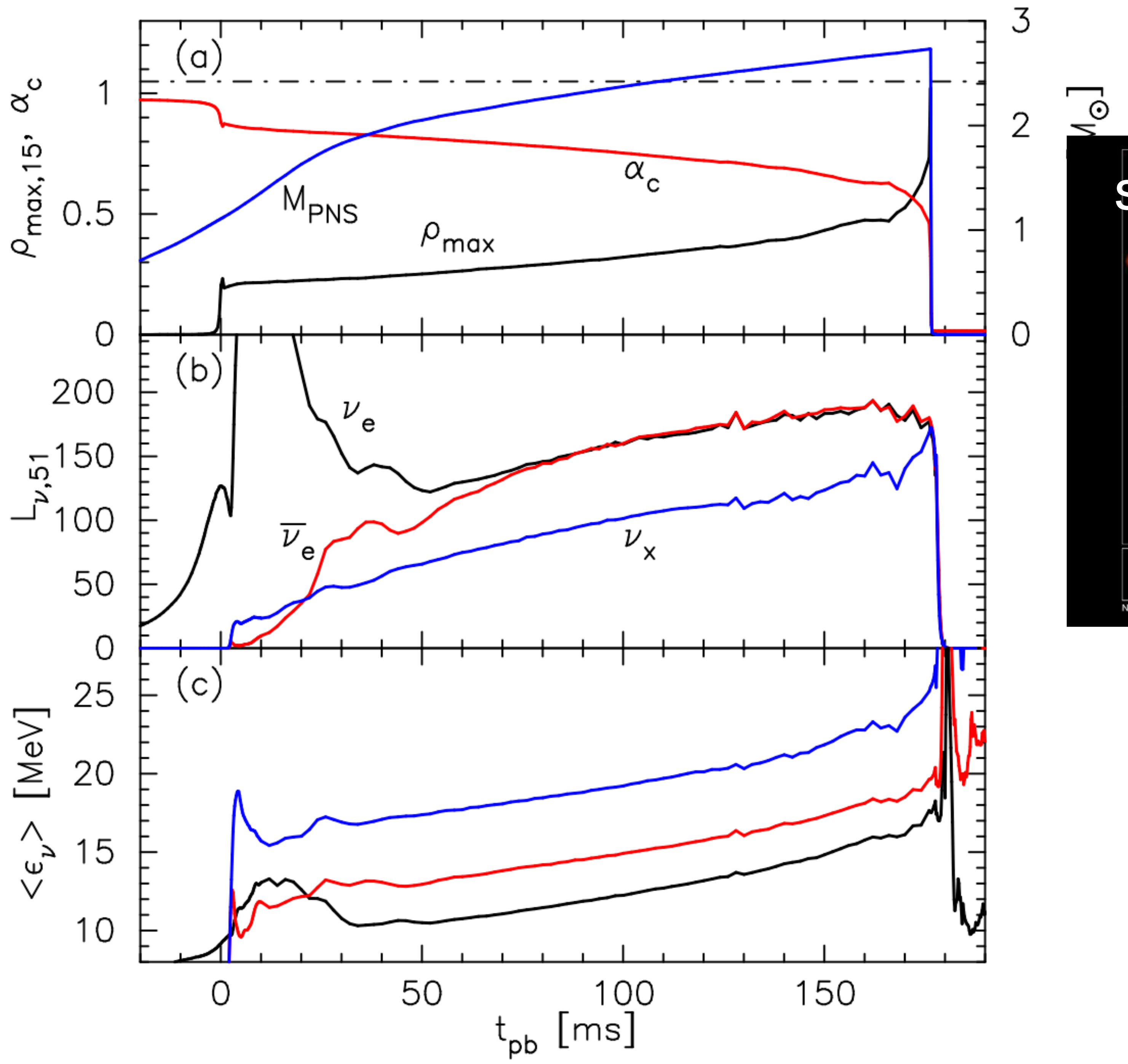
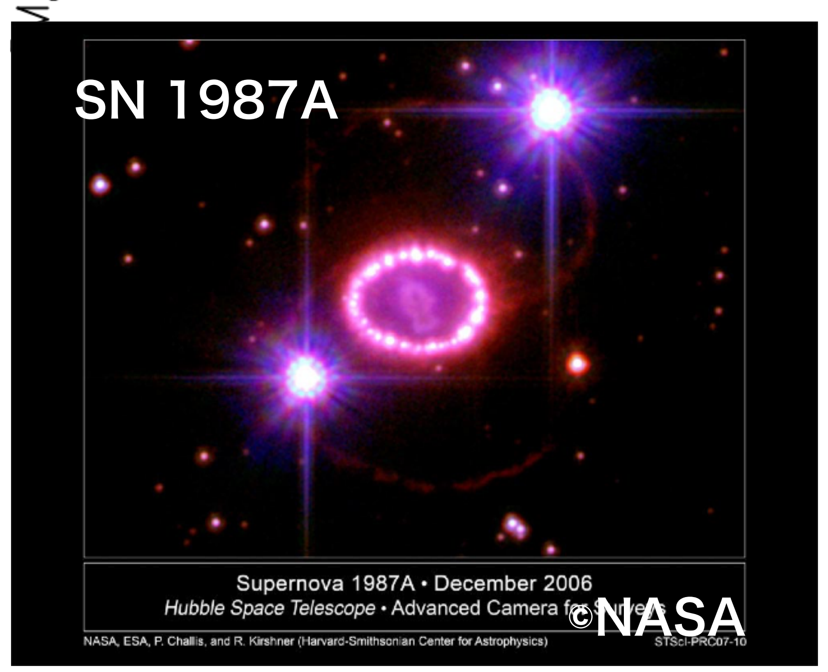
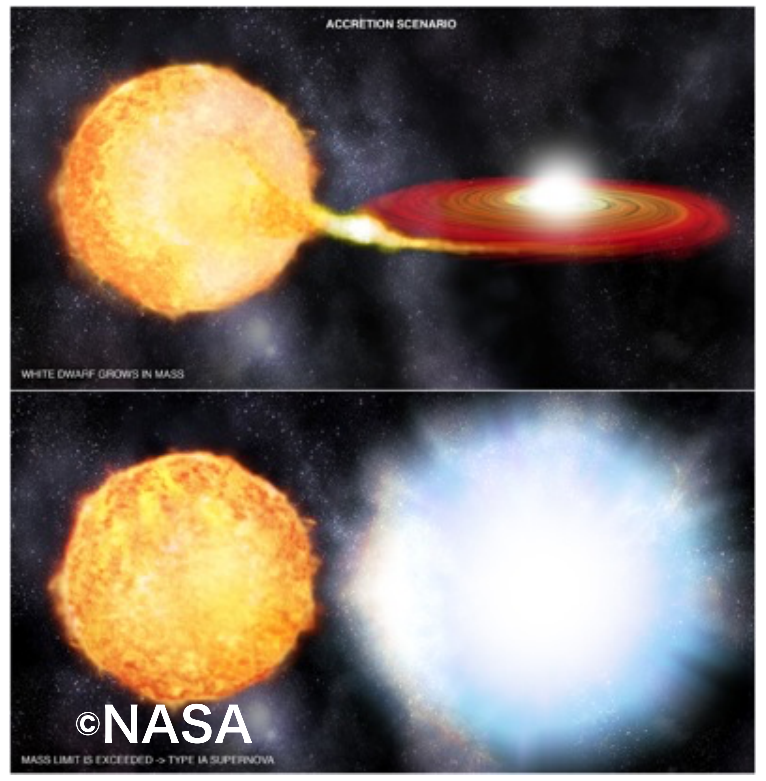


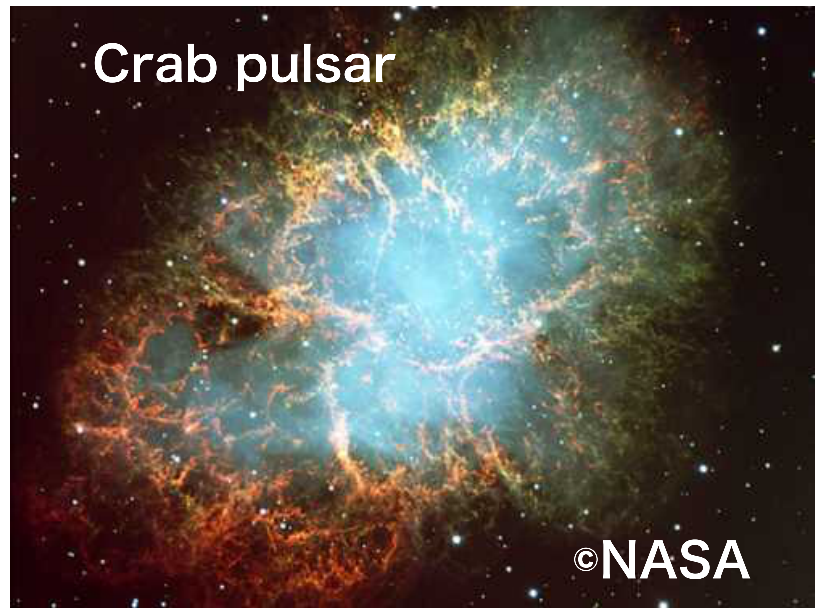
GW signal from CCSN
Vartanyan+ (2023)

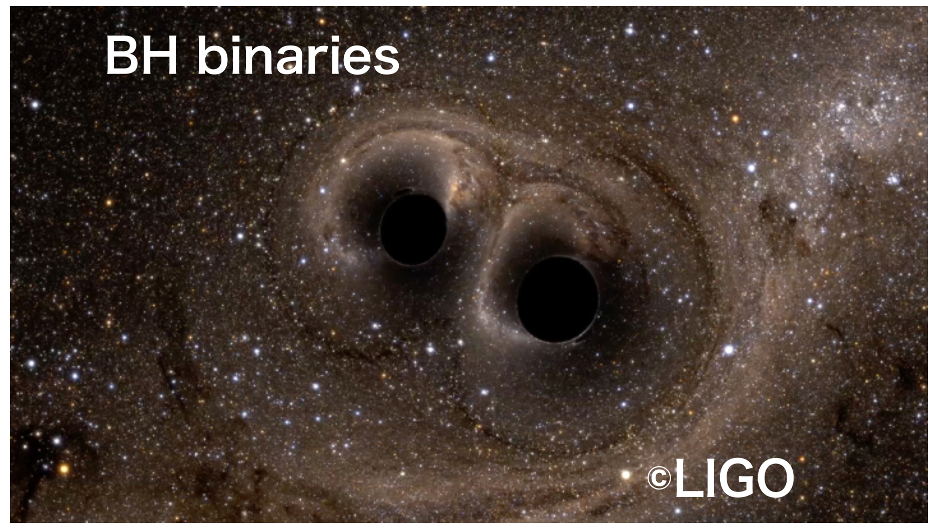


BH formation in failed SN
Kuroda&Shibata (2023)









Mapping an IMF to a variety of transients and remnants

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Spectral classification of SNe and their progenitors

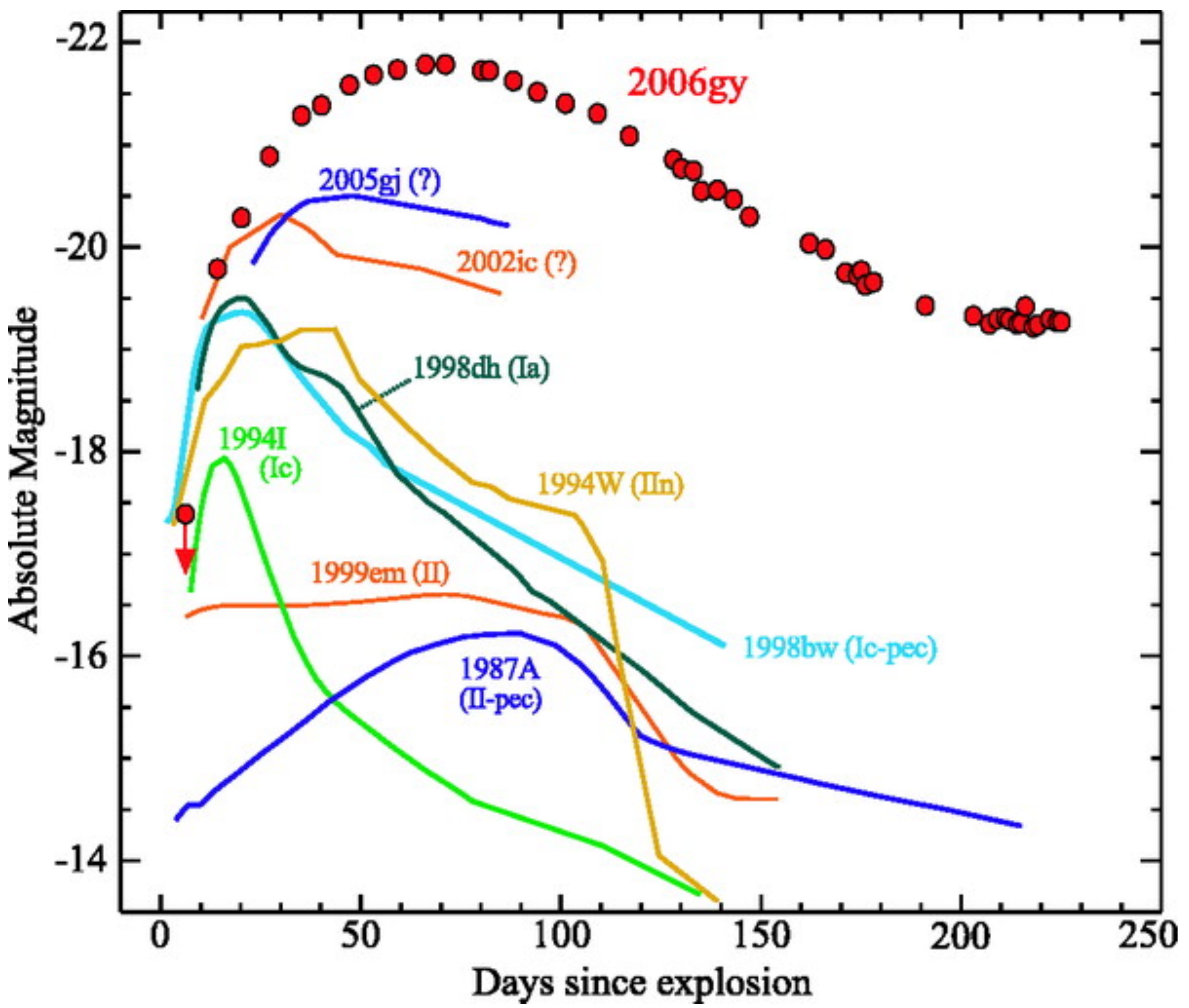
- Light curves+spectra (Ia, Ib, Ic, II)

Hydrogen: no → Type I; yes → Type II — H-rich SNe

Type I — Silicon: no → Helium; yes → Type Ia — thermonuclear SNe

Helium: no → Type Ic; yes → Type Ib — stripped envelope SNe

+broad-lined Ic (Ic-BL)



SN light curves (Smith+2012)

Spectral classification of SNe and their progenitors

- Light curves+spectra (Ia, Ib, Ic, II)

no
yes
Hydrogen
Type II — <u>H-rich SNe</u>

Type I

no
yes
Silicon
Type Ia — <u>thermonuclear SNe</u>

no
yes
Helium
Type Ic
Type Ib — <u>stripped envelope SNe</u>

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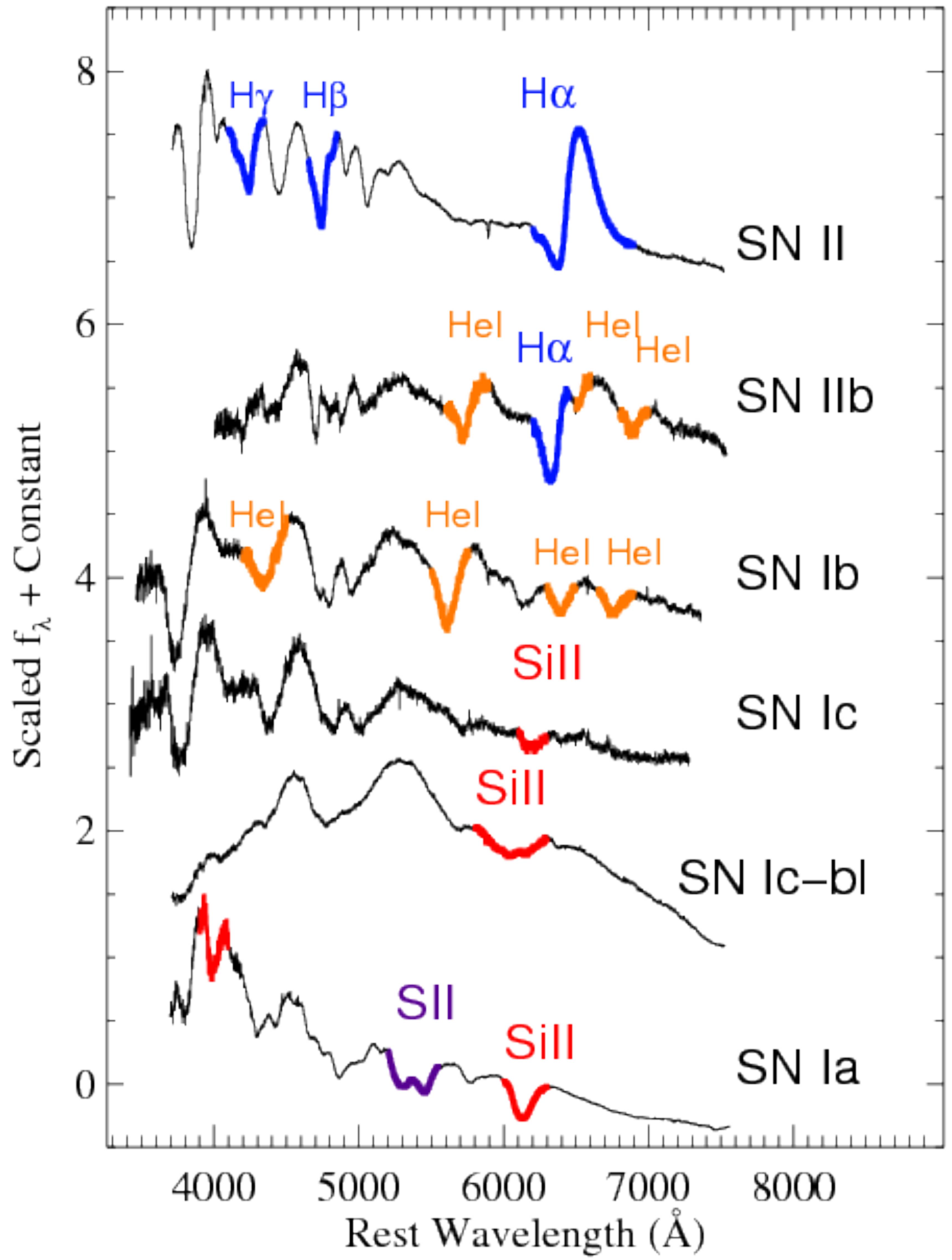

SN spectra (Modjaz+2014)

Spectral classification of SNe and their progenitors

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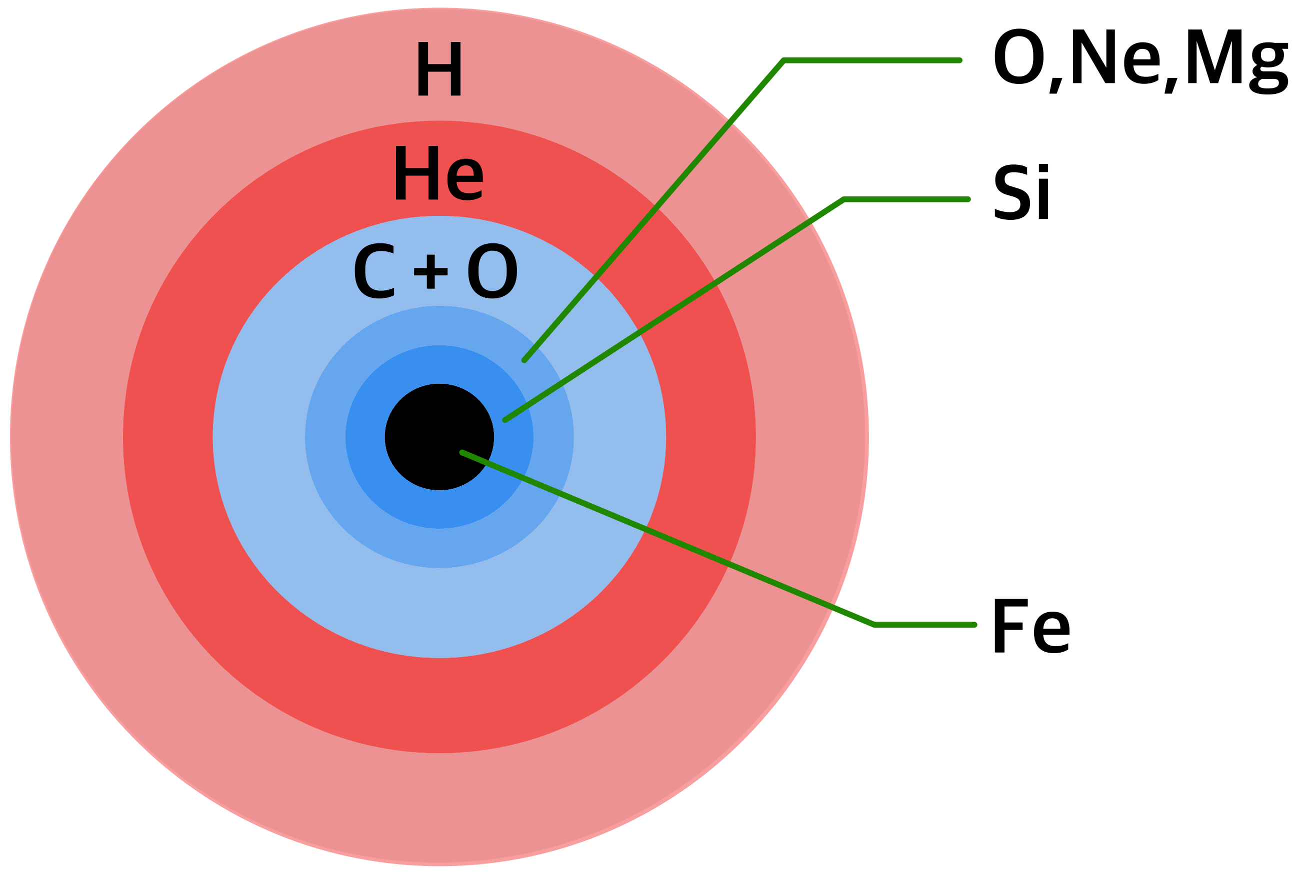
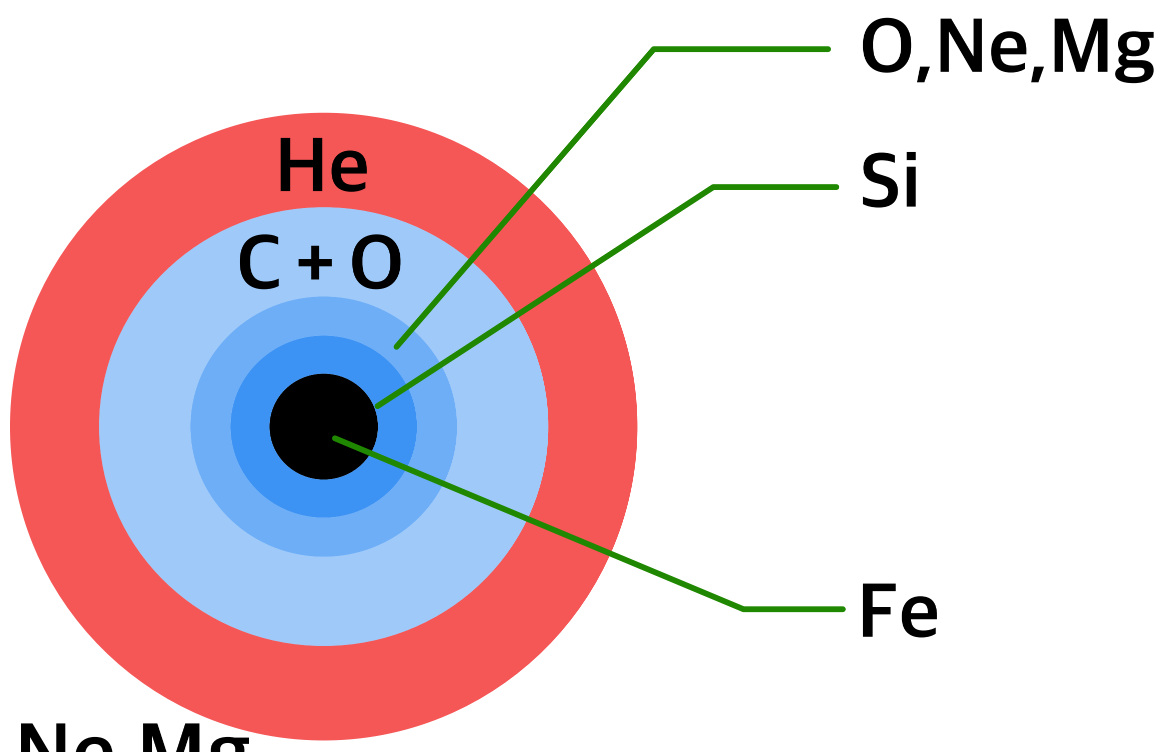
no | Hydrogen | yes

Type I | Type II — H-rich SNe



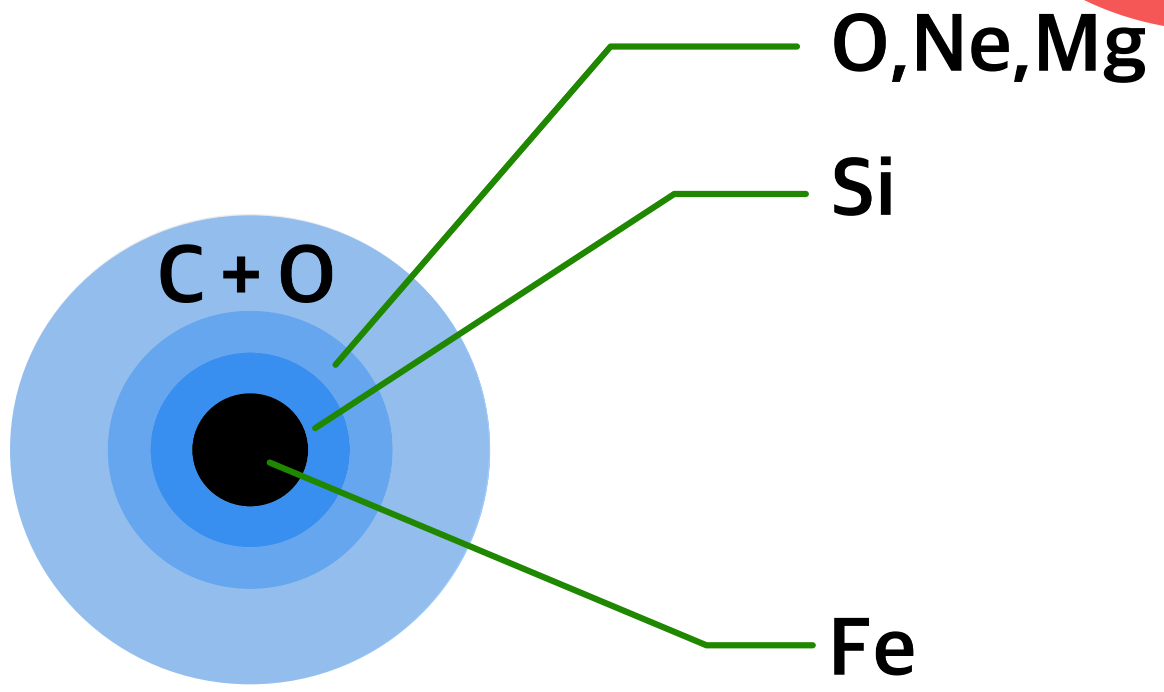
no | Silicon | yes

Type Ia — thermonuclear SNe



no | Helium | yes

Type Ic | Type Ib — stripped envelope SNe



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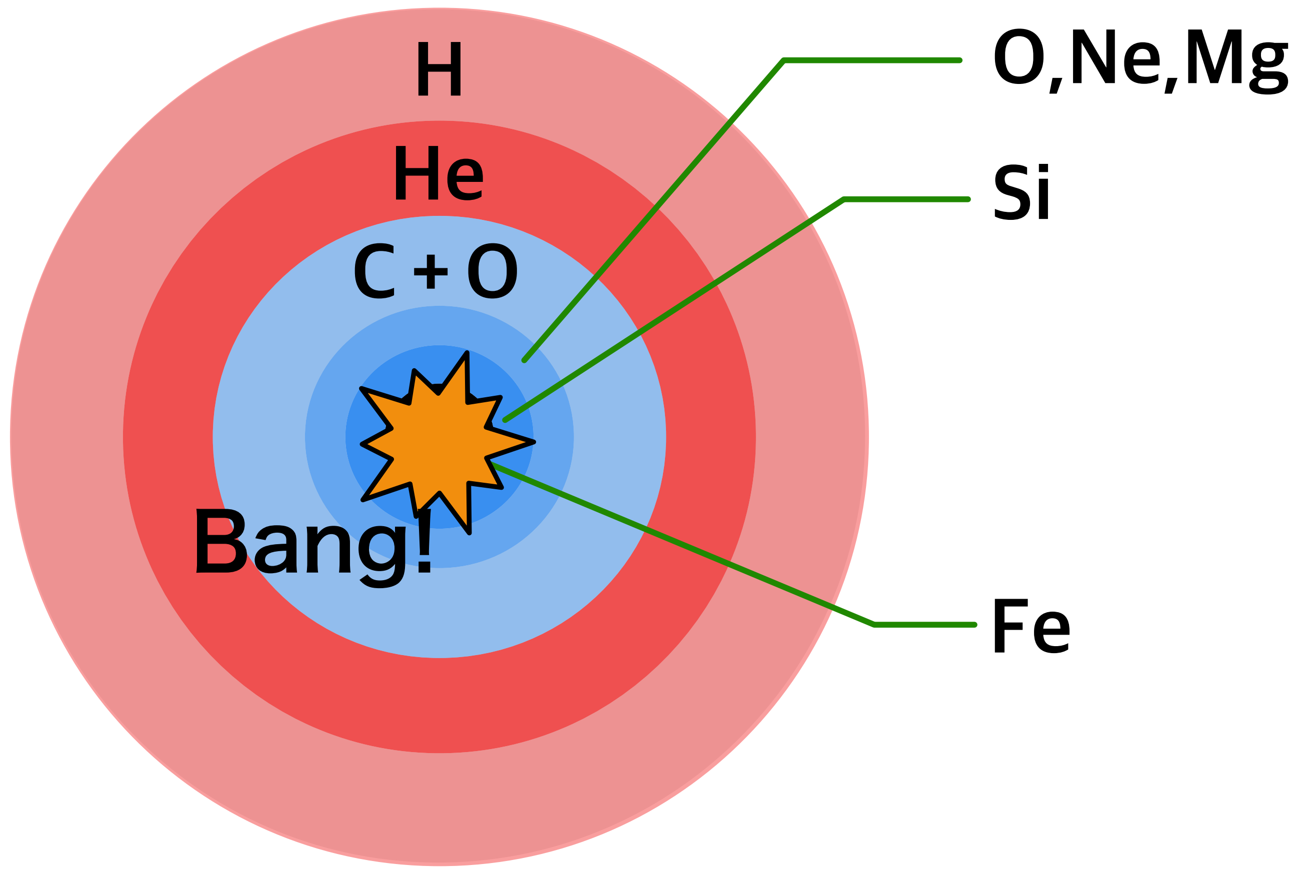
no yes

Hydrogen

Type II

H-rich SNe



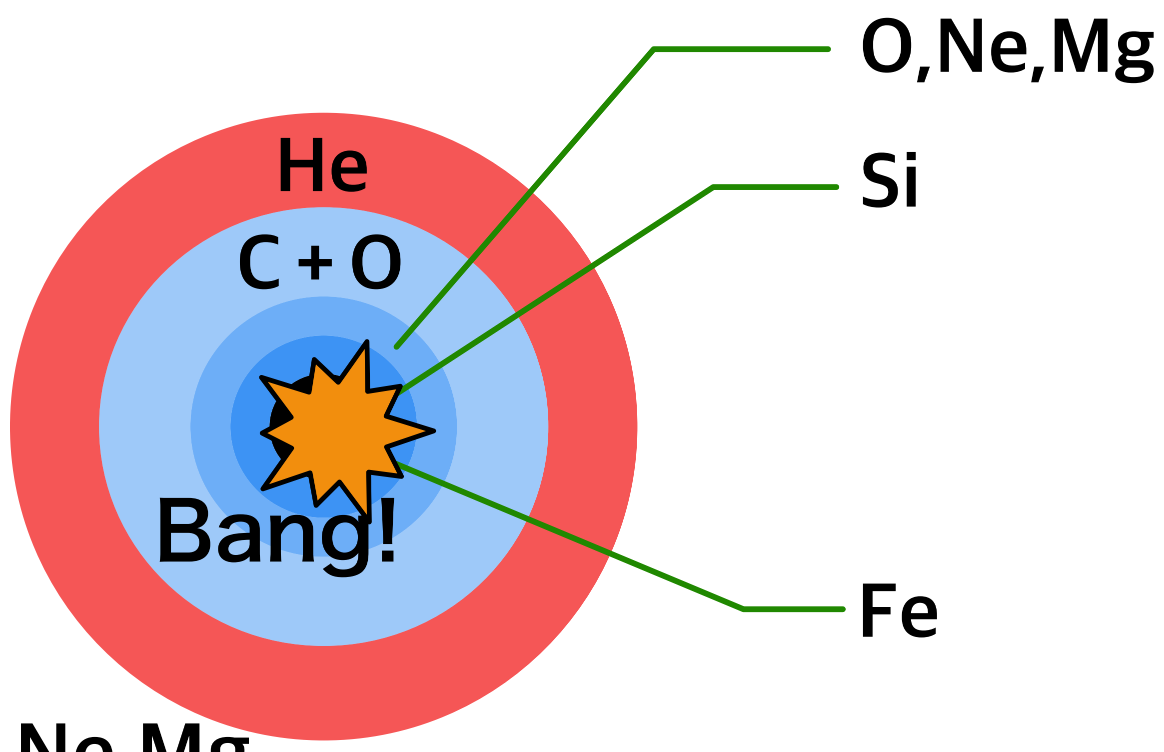
Type I

no yes

Silicon

Type Ia

thermonuclear SNe



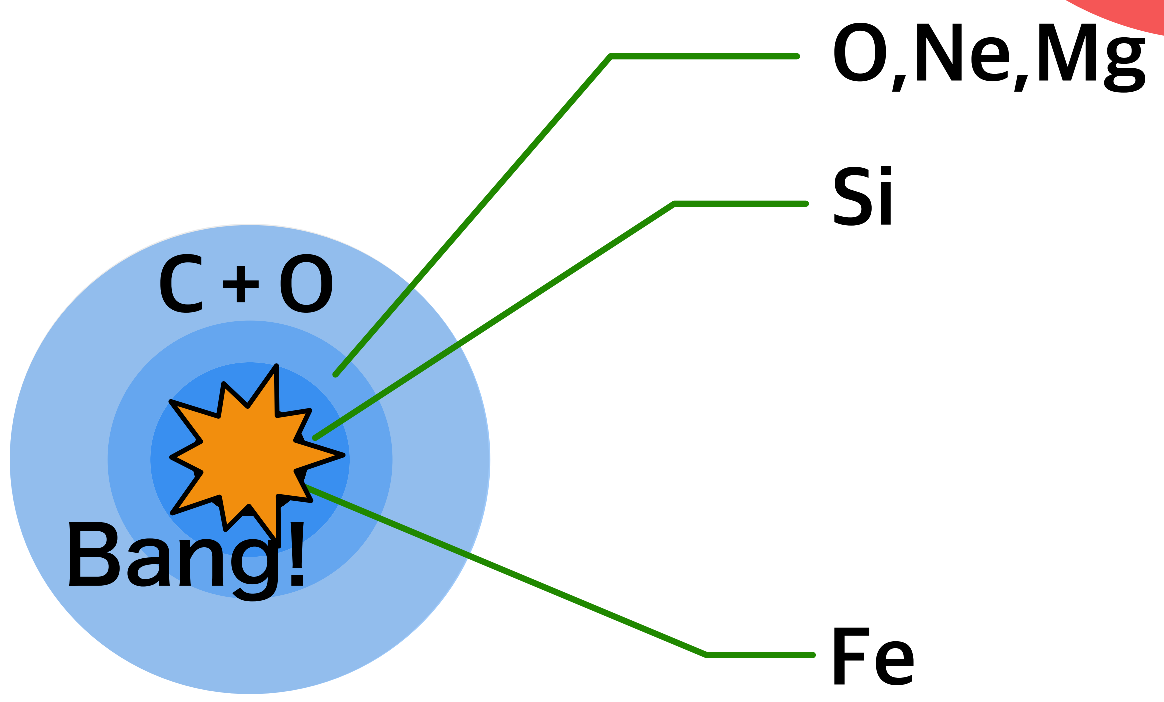
no yes

Helium

Type Ic

Type Ib

stripped envelope SNe



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Spectral classification of SNe and their progenitors

- Light curves+spectra (Ia, Ib, Ic, II)

no yes
Hydrogen
H-rich SNe
Type II
→ Type IIn

Type I
no yes
Silicon
Type Ia
thermonuclear SNe
→ Type Ia-CSM

no yes
Helium
Type Ic
→ Type Icn
Type Ib
→ Type Ibn
stripped envelope SNe

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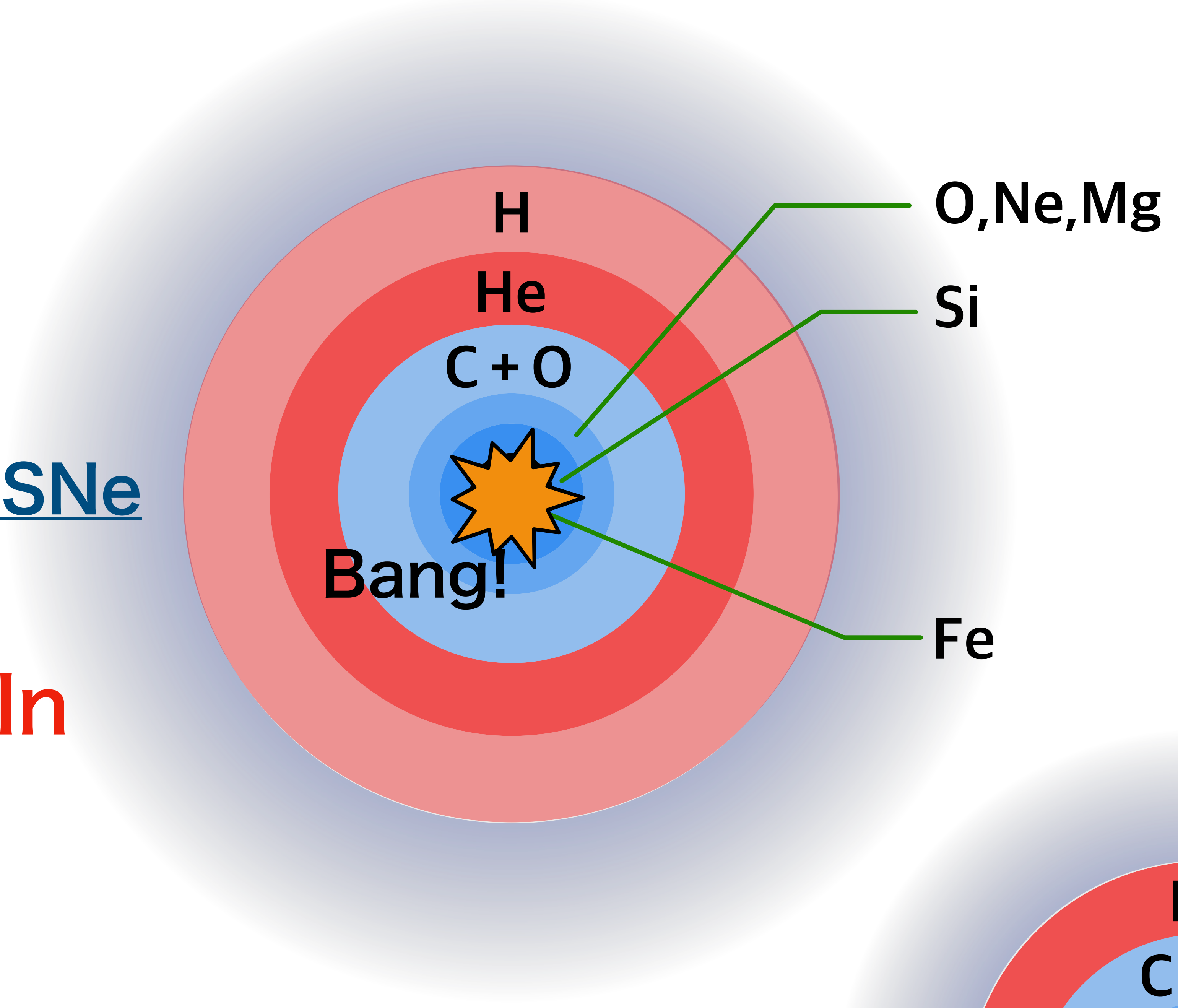
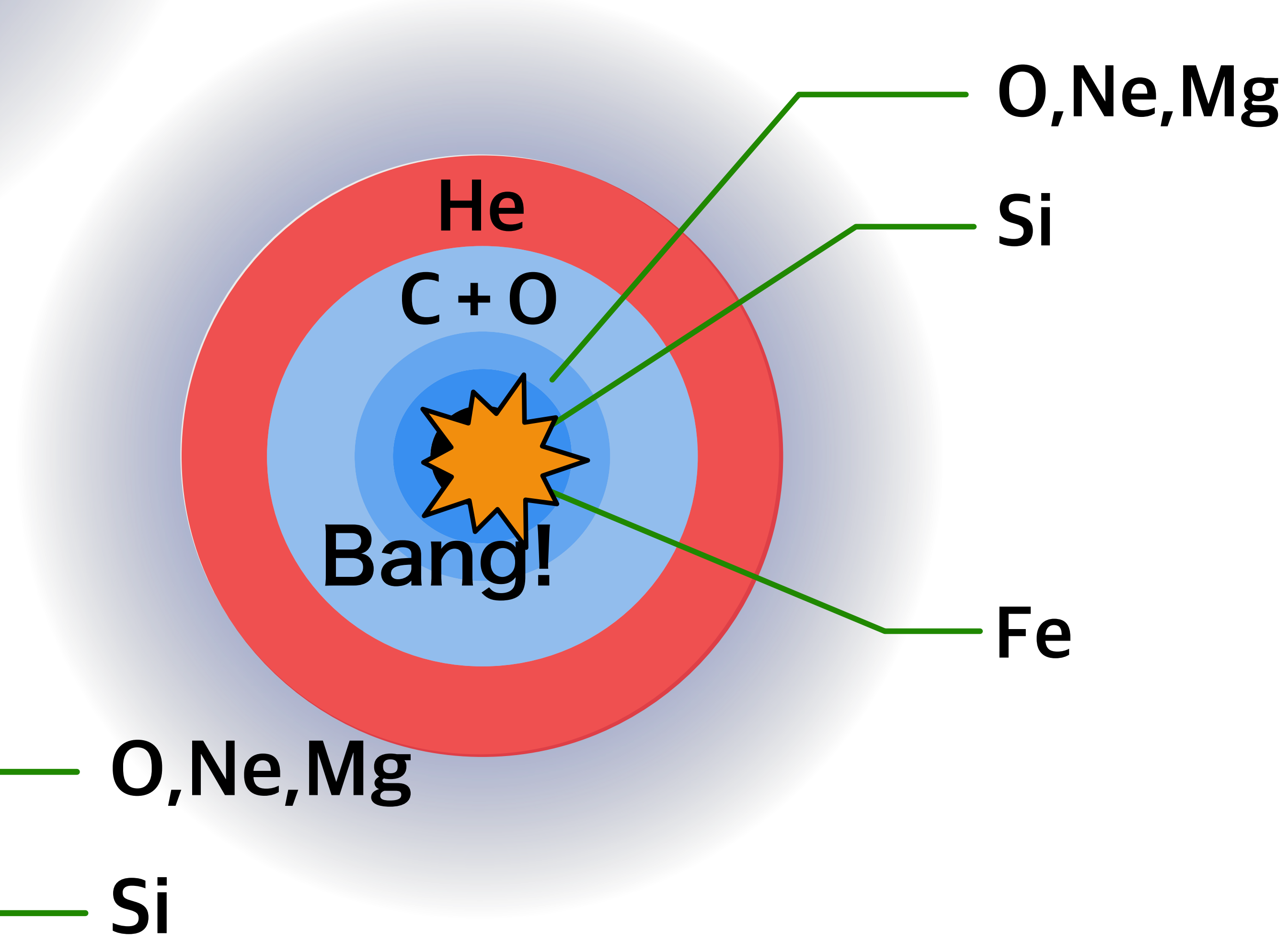
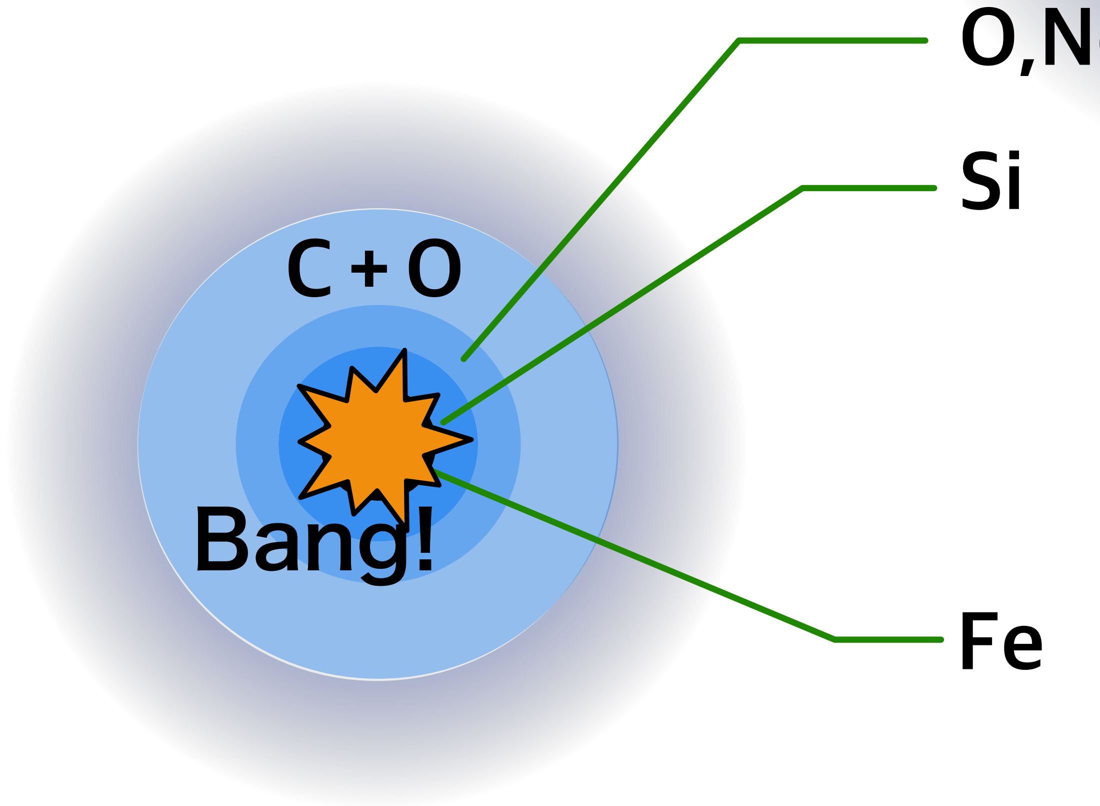
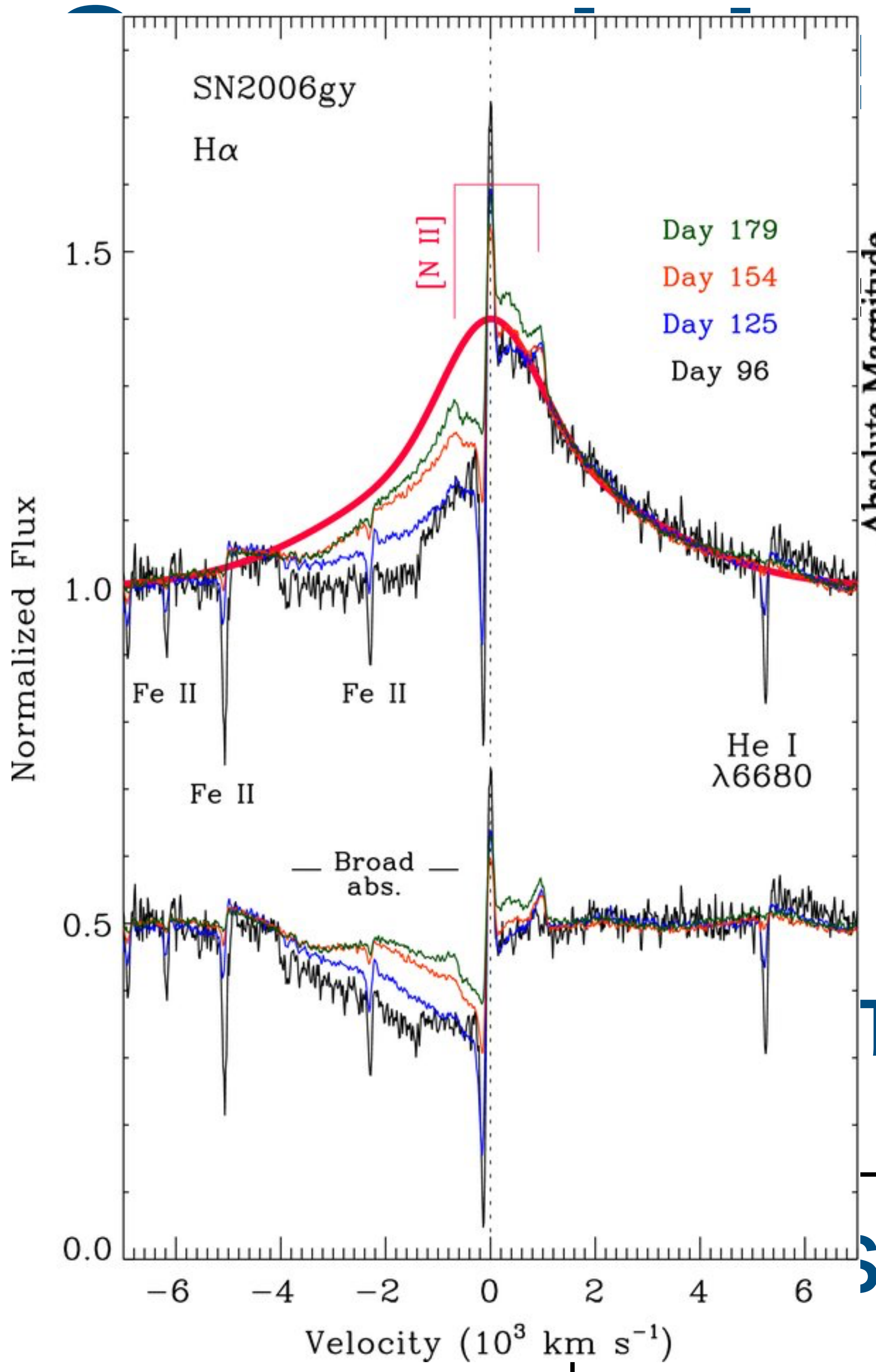
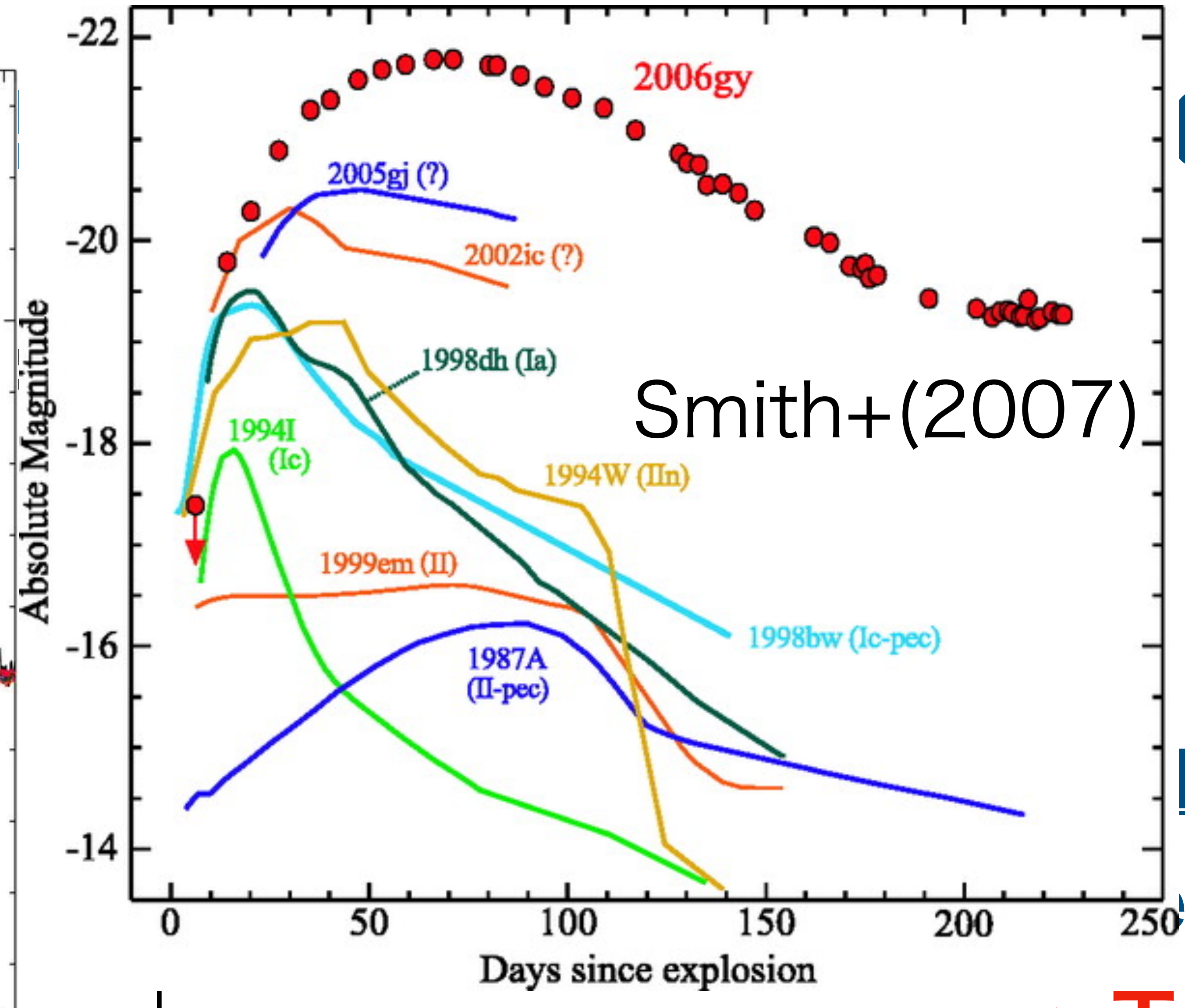






e and their progenitors





l-rich SNe

II

→ Type IIn

I

Type I

yes

Silicon

Type Ia

no

yes

thermonuclear SNe

→ Type Ia-CSM

Helium

Type Ic

Type Ib

stripped envelope SNe

→ Type Icn

→ Type Ibn

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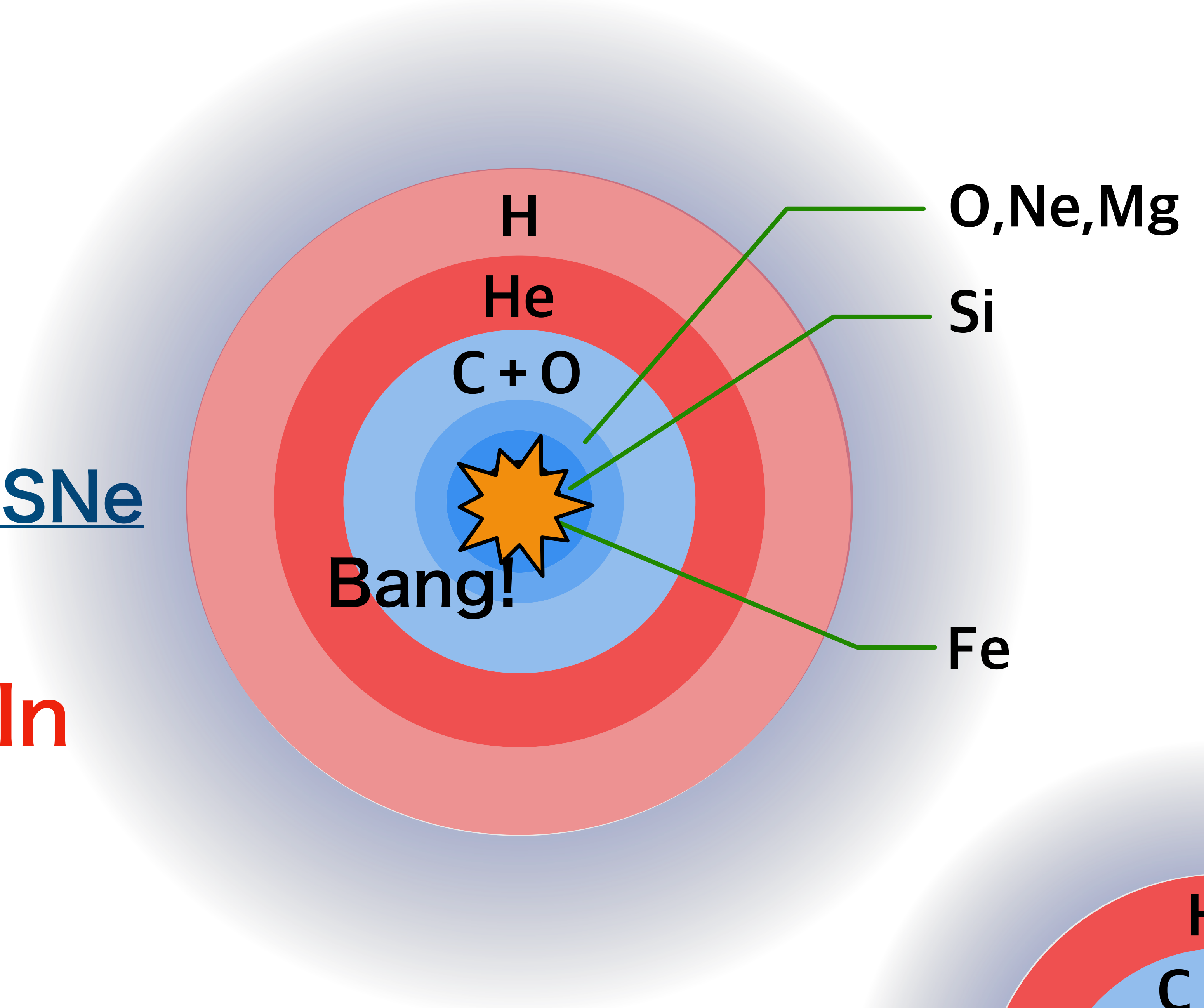

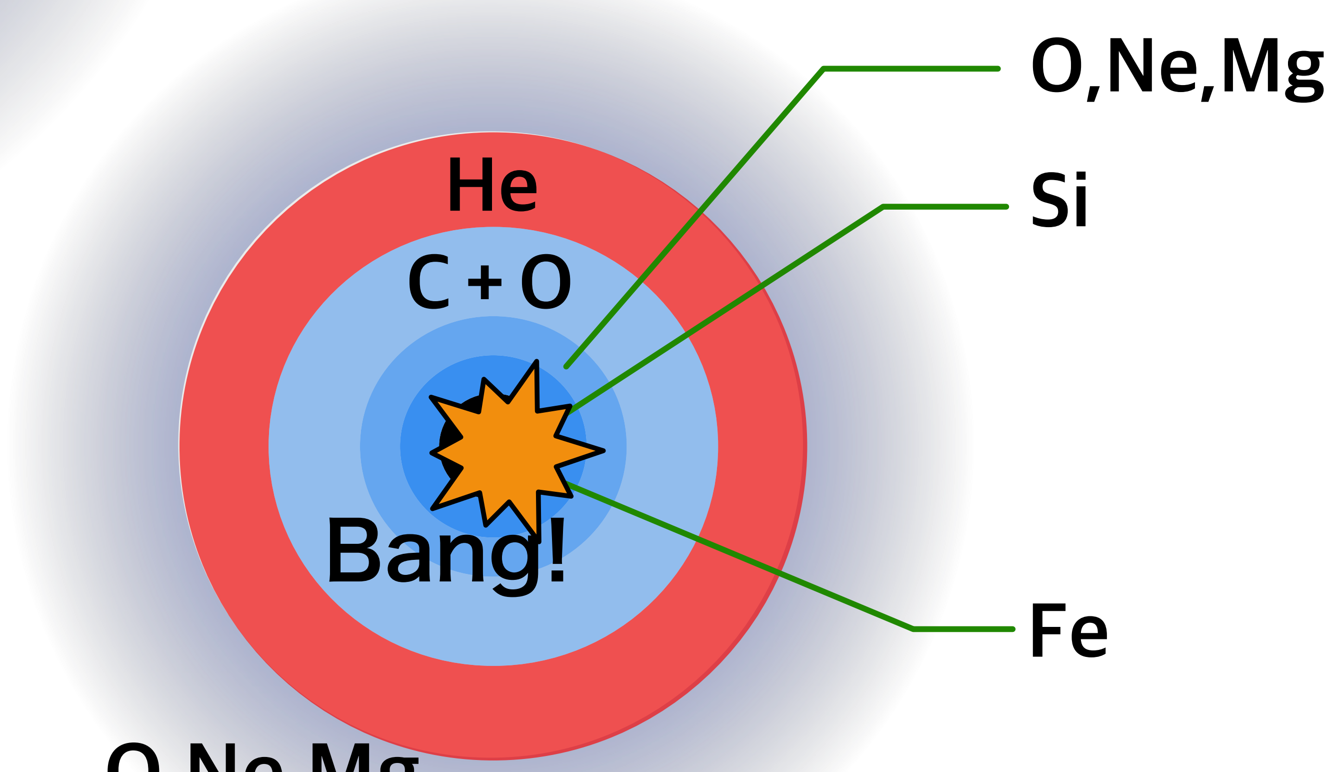

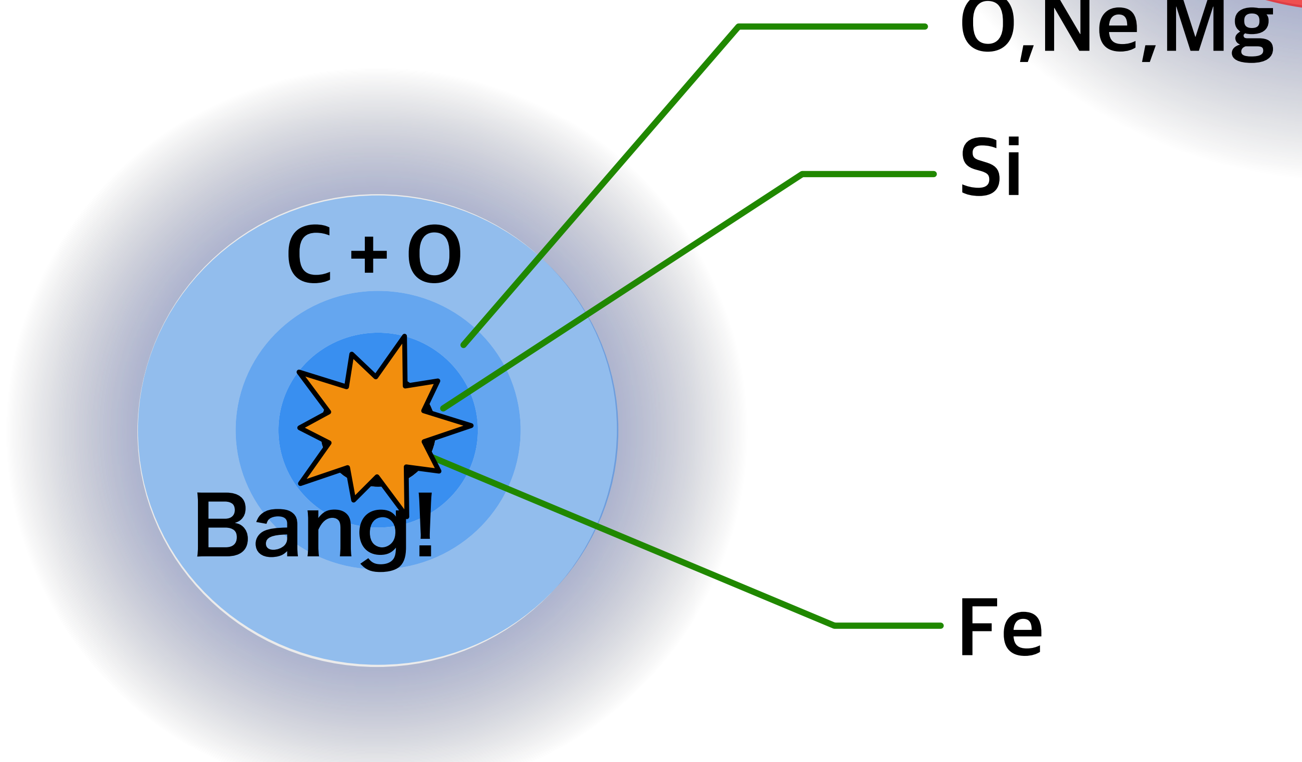

see, also, **AS**, Moriya, Takiwaki (2019,20)

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no | yes

Hydrogen

H-rich SNe

Type II

→ Type IIn

Type I

no | yes

Silicon

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thermonuclear SNe

→ Type Ia-CSM

no | yes

Helium

Type Ic

→ Type Icn

Type Ib

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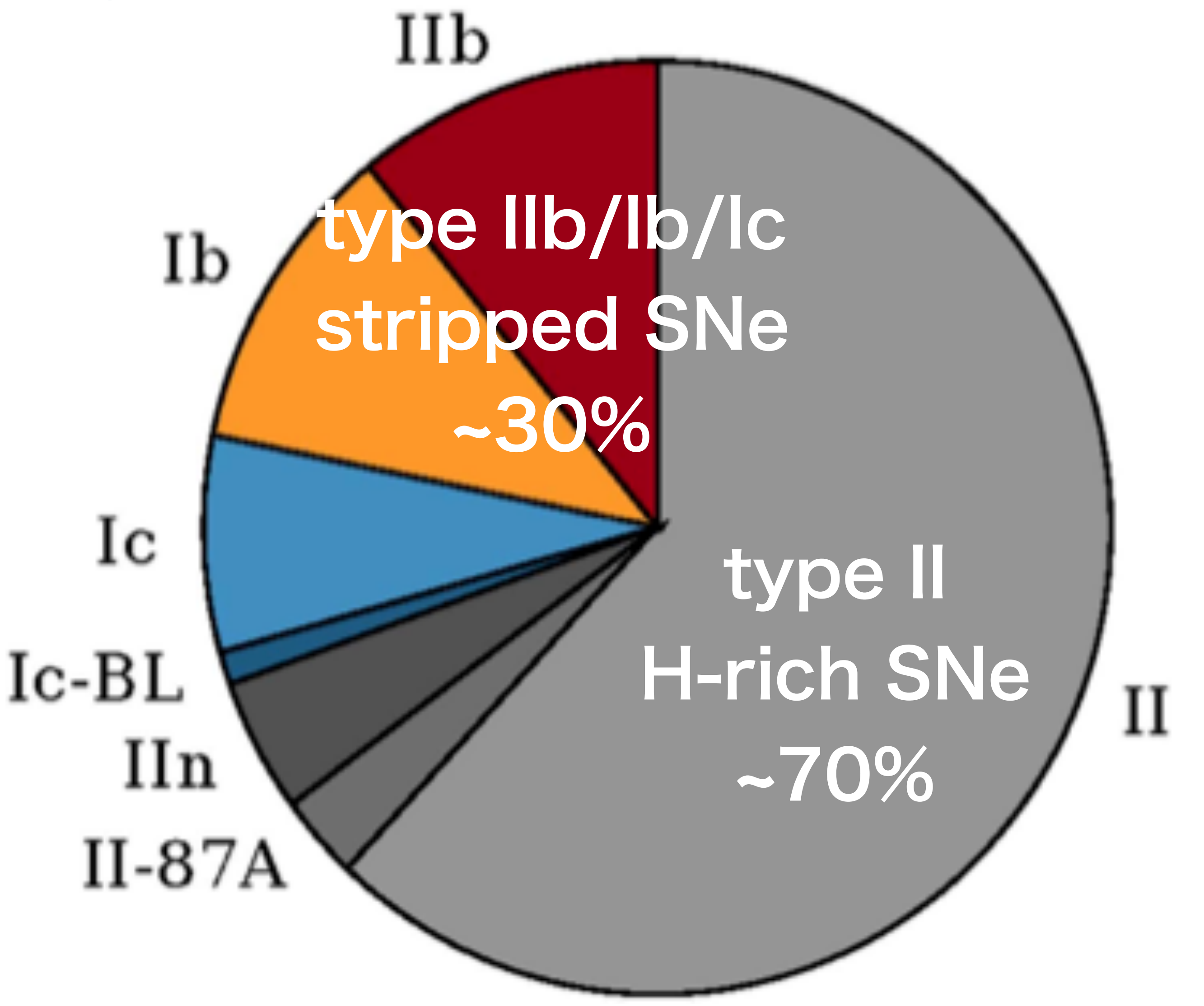


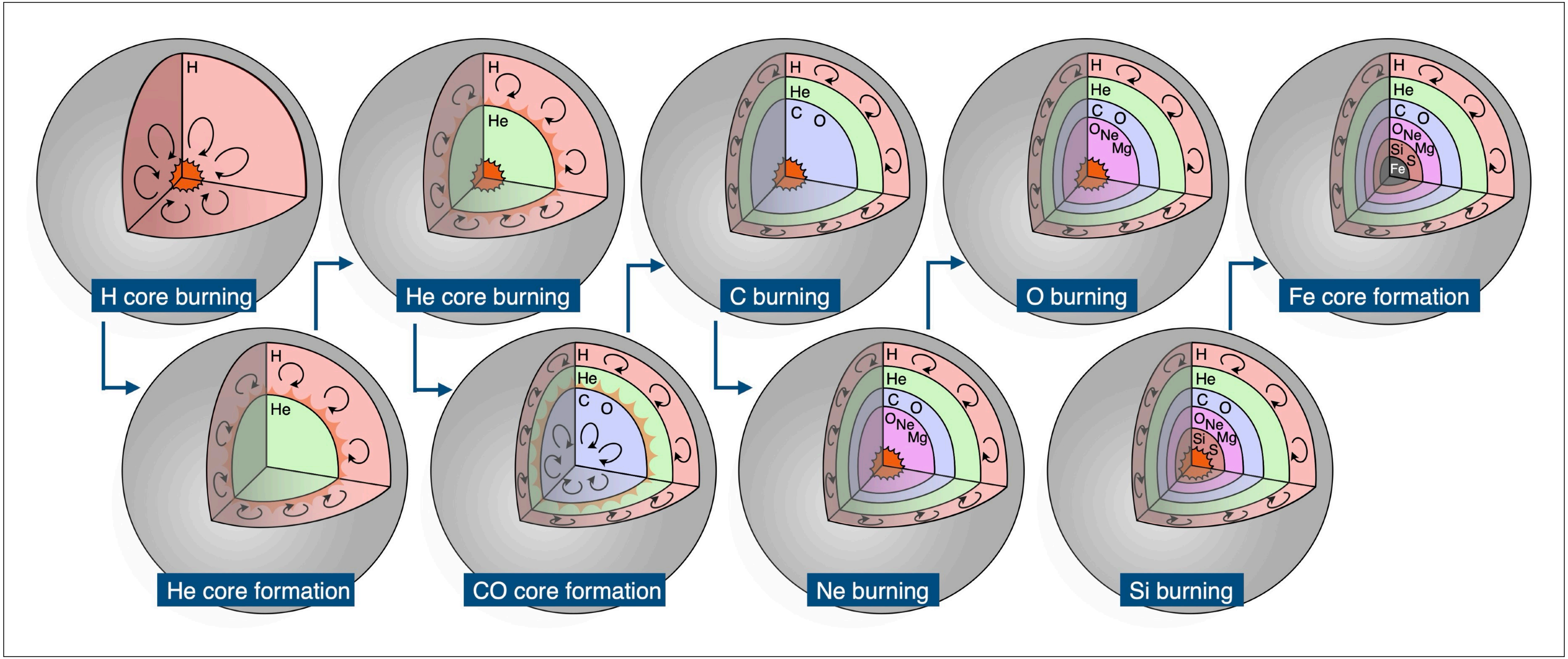
Table 3
Updated Relative SN Fractions in a Volume-limited Survey

Type	Previous	This Work	Difference
Core Collapse			
II	$68.9^{+6.0}_{-6.0}$	$69.6^{+6.7}_{-6.7}$	…
IIb/Ib/Ic	$31.1^{+4.6}_{-4.6}$	$30.4^{+5.0}_{-4.9}$	…
Stripped Envelope			
IIb	$27.6^{+9.1}_{-9.1}$	$34.0^{+11.1}_{-11.1}$	+6.3
IIb-pec	…	$2.0^{+1.5}_{-2.0}$	…
Ib	$16.1^{+6.8}_{-6.6}$	$35.6^{+11.4}_{-11.4}$	+19.5
Ib-pec	…	…	…
Ibc-pec[a]	$12.4^{+5.9}_{-5.6}$	…	…
Ic	$41.1^{+11.5}_{-11.4}$	$21.5^{+8.6}_{-8.6}$	−19.6
Ic-pec	$2.8^{+2.6}_{-2.8}$	$3.2^{+3.1}_{-3.2}$	…
Ic-BL	…	$3.7^{+2.9}_{-3.7}$	…
Hydrogen Rich			
II[b]	$93.2^{+11.5}_{-11.3}$	$89.1^{+10.9}_{-10.9}$	…
II-87A	…	$4.2^{+2.4}_{-2.7}$	…
IIn	$6.8^{+3.0}_{-2.9}$	$6.7^{+3.0}_{-2.9}$	…

CCSNe type fraction based on the volumetric samples in Lick Observatory SN search
Shivvers+(2017)

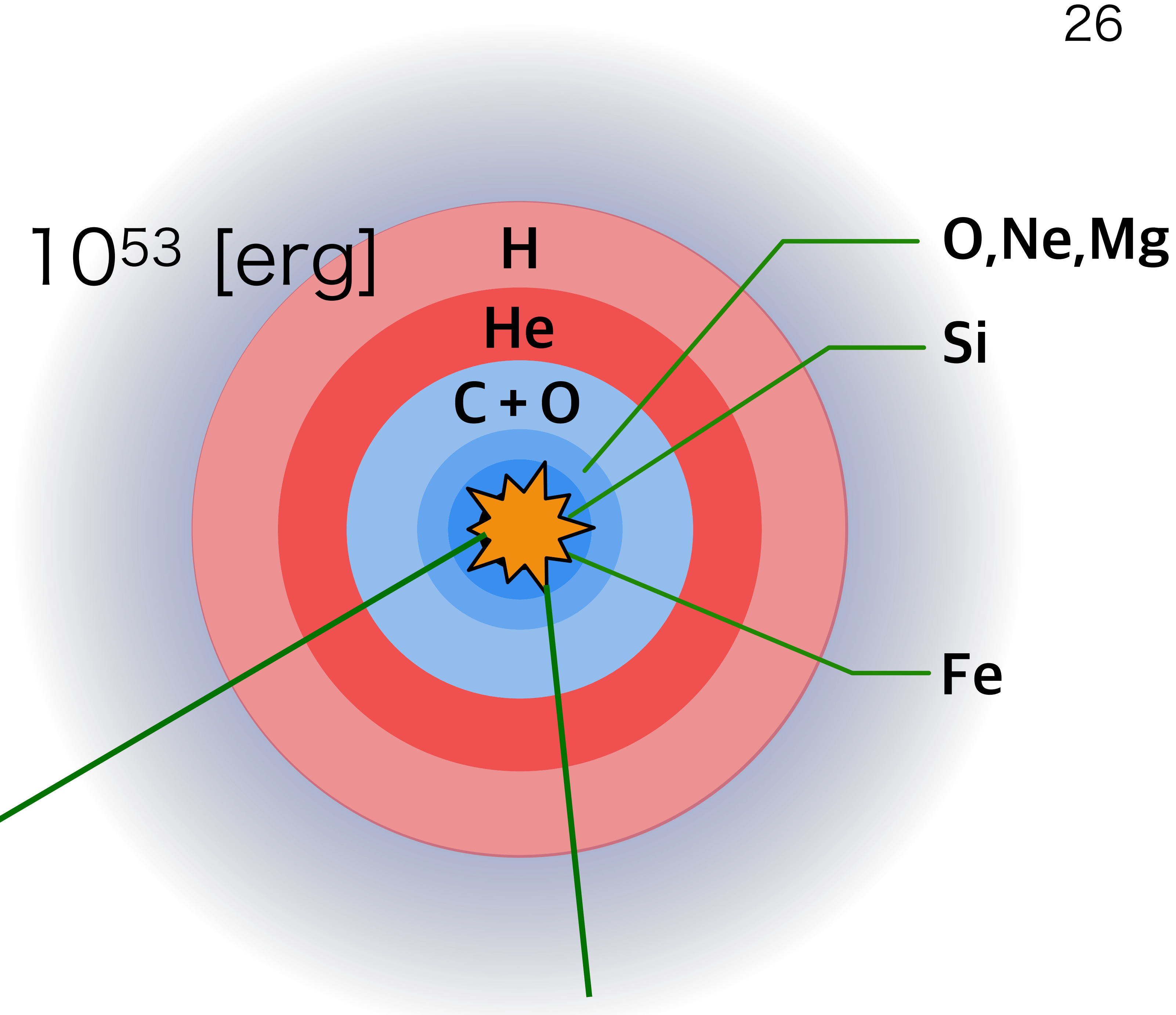
Massive star evolution (M_{ini}> ~10M_{sun})

- successive formation of burning layers and nuclear products (from He to Fe)
- Fe core collapses with its own gravity

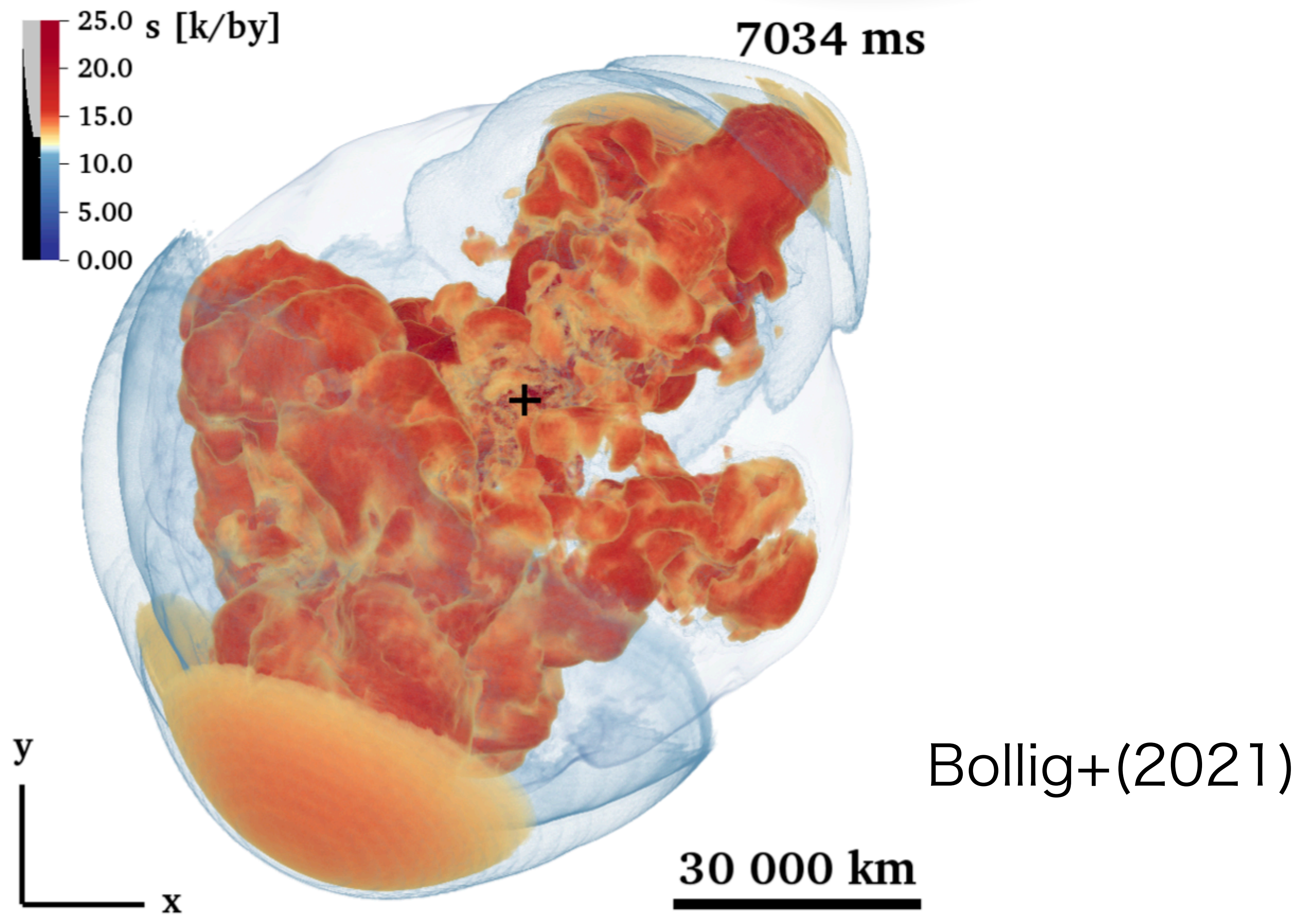


Explosion mechanism of CCSNe

- gravitational energy of iron core-collapse: $|E_{grav}|$ ~ GM_{ns}^2/R_{ns} ~ 10^{53} [erg]
- typical explosion energy: E_{exp} ~ 10^{51}[erg] = 1% of E_{grav}
- how to achieve 1% efficiency → ν heating mechanism is likely
- Can we reproduce typical CCSNe or need any new physics?



- radiated energy from a typical CCSN:
  E_{rad}~10^{49} [erg] = 1% of E_{exp}
- corresponding to ~0.1M_{sun} radioactive ^{56}Ni
- Can we reproduce enough ^{56}Ni to power CCSN emission?



Bollig+(2021)

Shock propagation: explosive nucleosynthesis

- E_{exp}~10^{51}erg injected around Fe core → blast wave propagation in the star
- post-shock temperature: $\frac{4\pi}{3}R^3 a_r T^4 \sim E_{exp} \Rightarrow T \sim 10^{10}\left(\frac{E_{exp}}{10^{51}\mathrm{erg}}\right)^{1/4}\left(\frac{R}{10^8\mathrm{cm}}\right)^{-3/4}$ [K]
- explosive nucleosynthesis: various kinds of nuclei

- T>5x10^9[K]: **complete Si burning**
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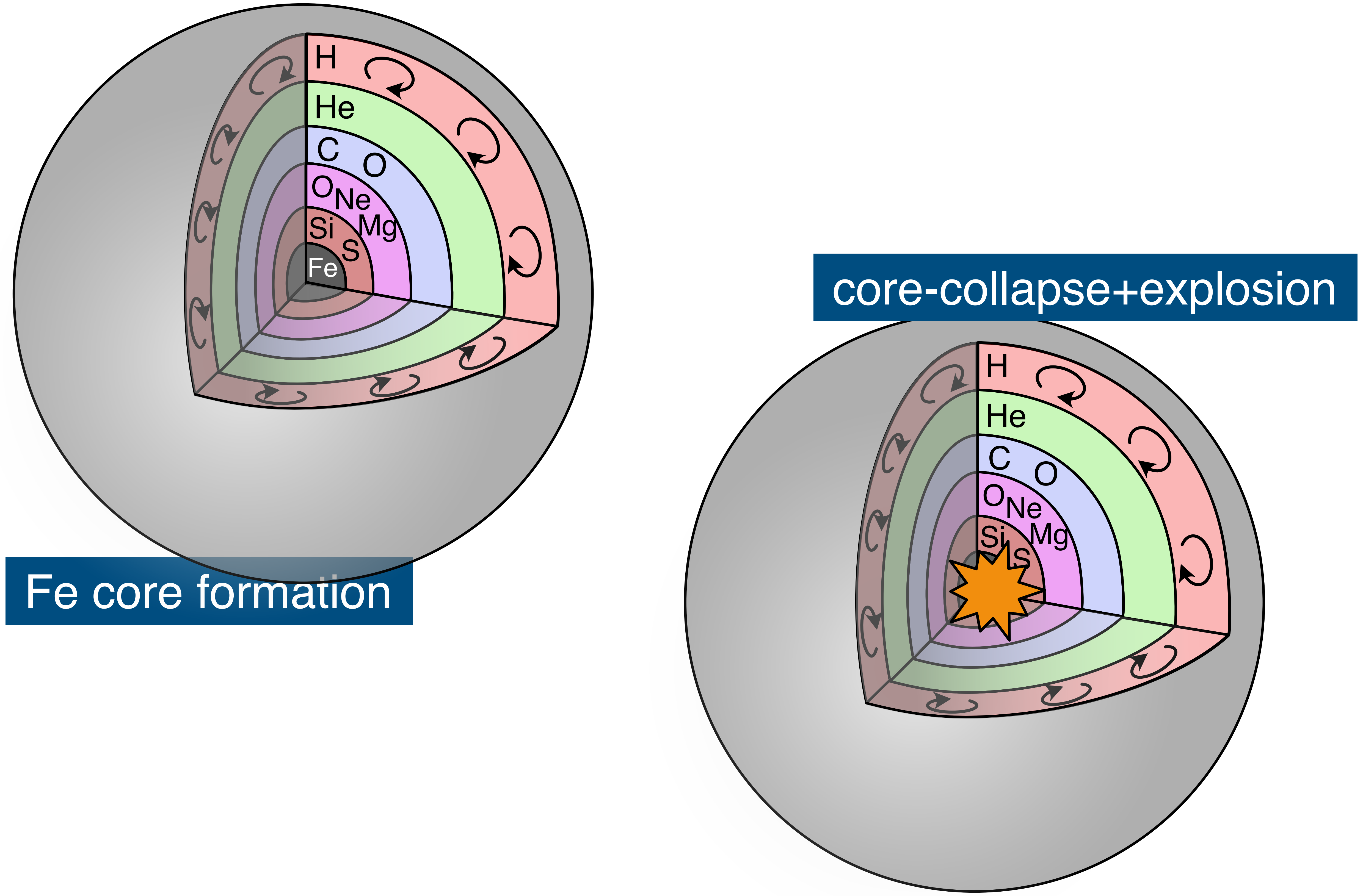

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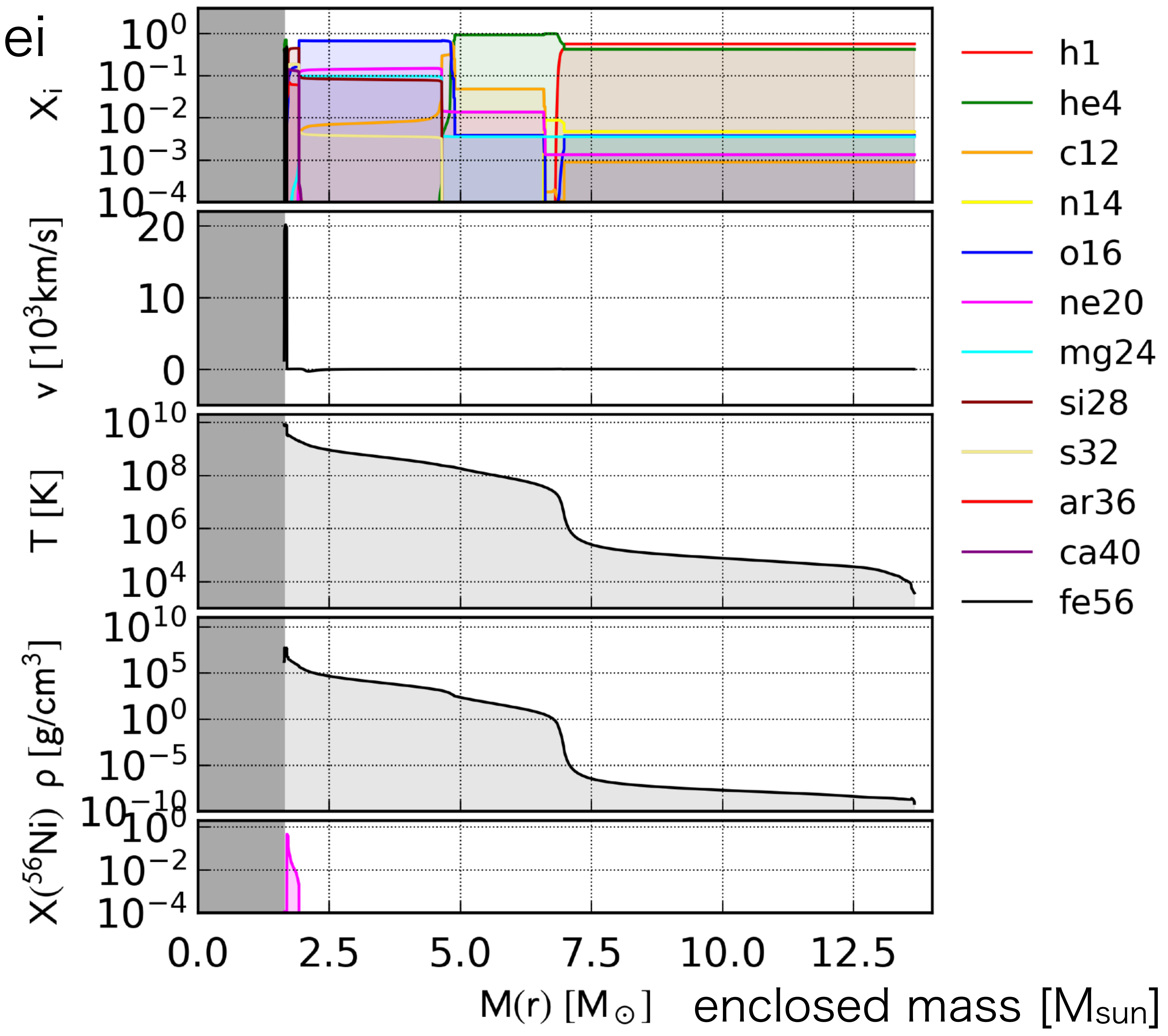

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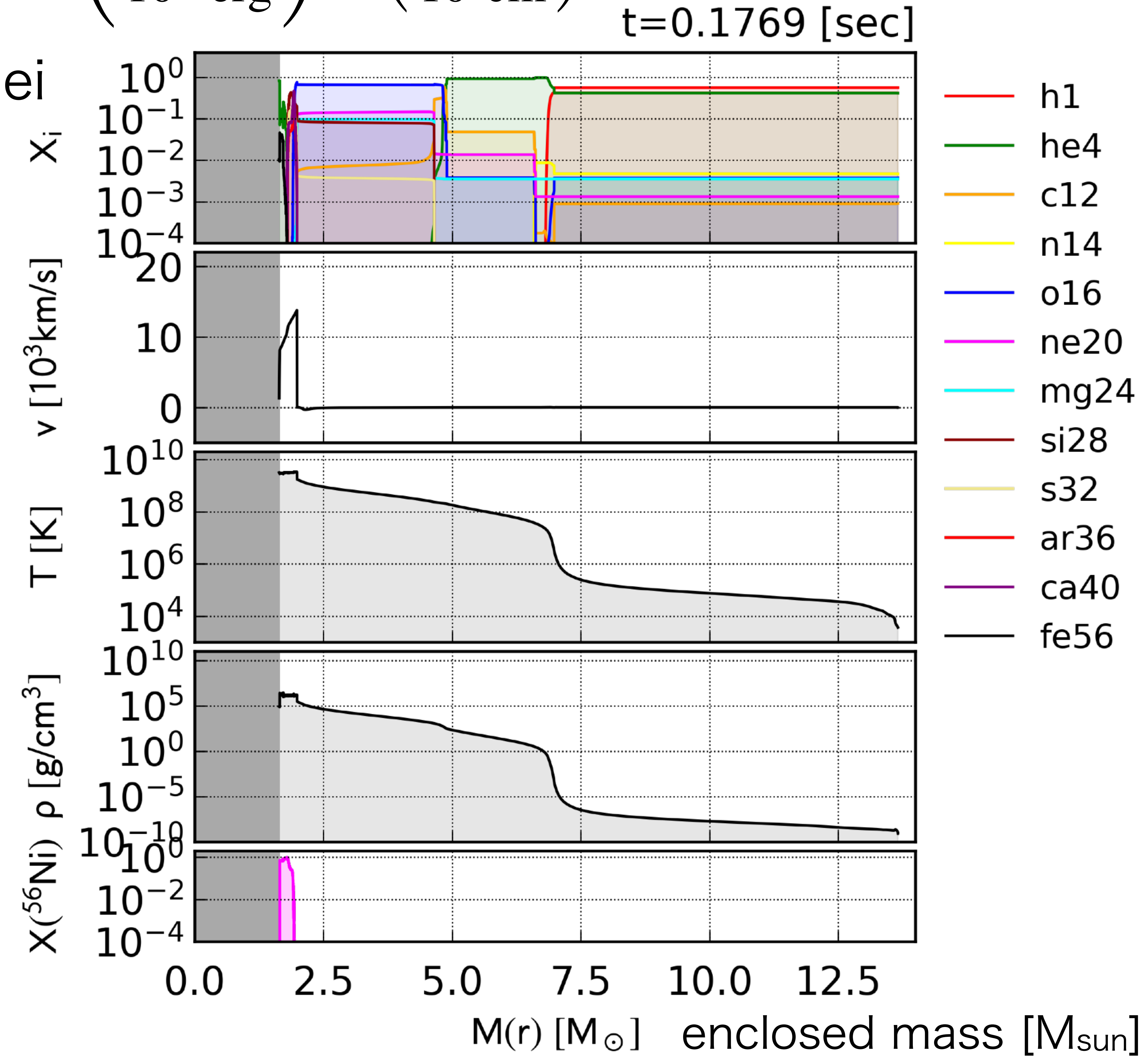

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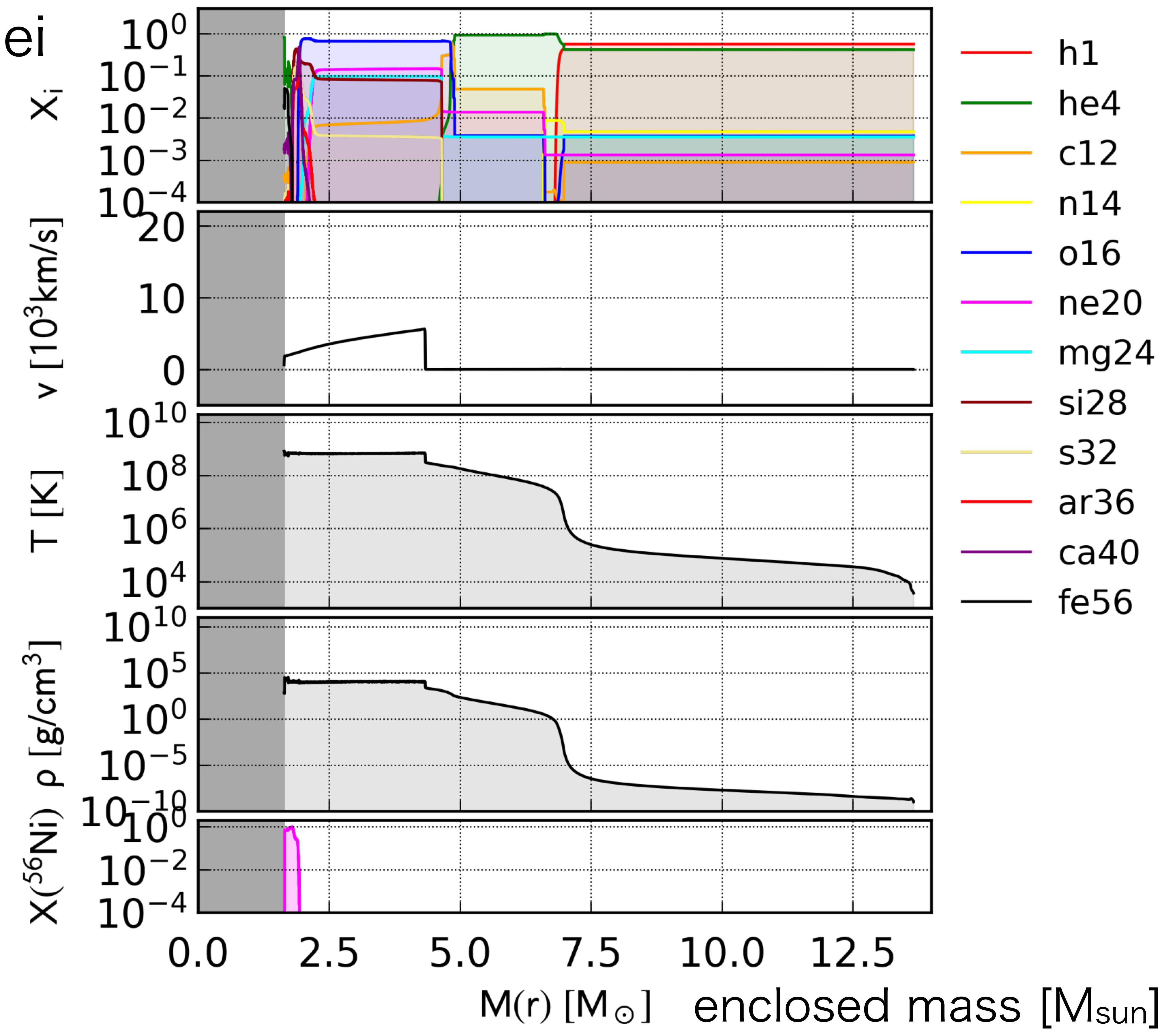

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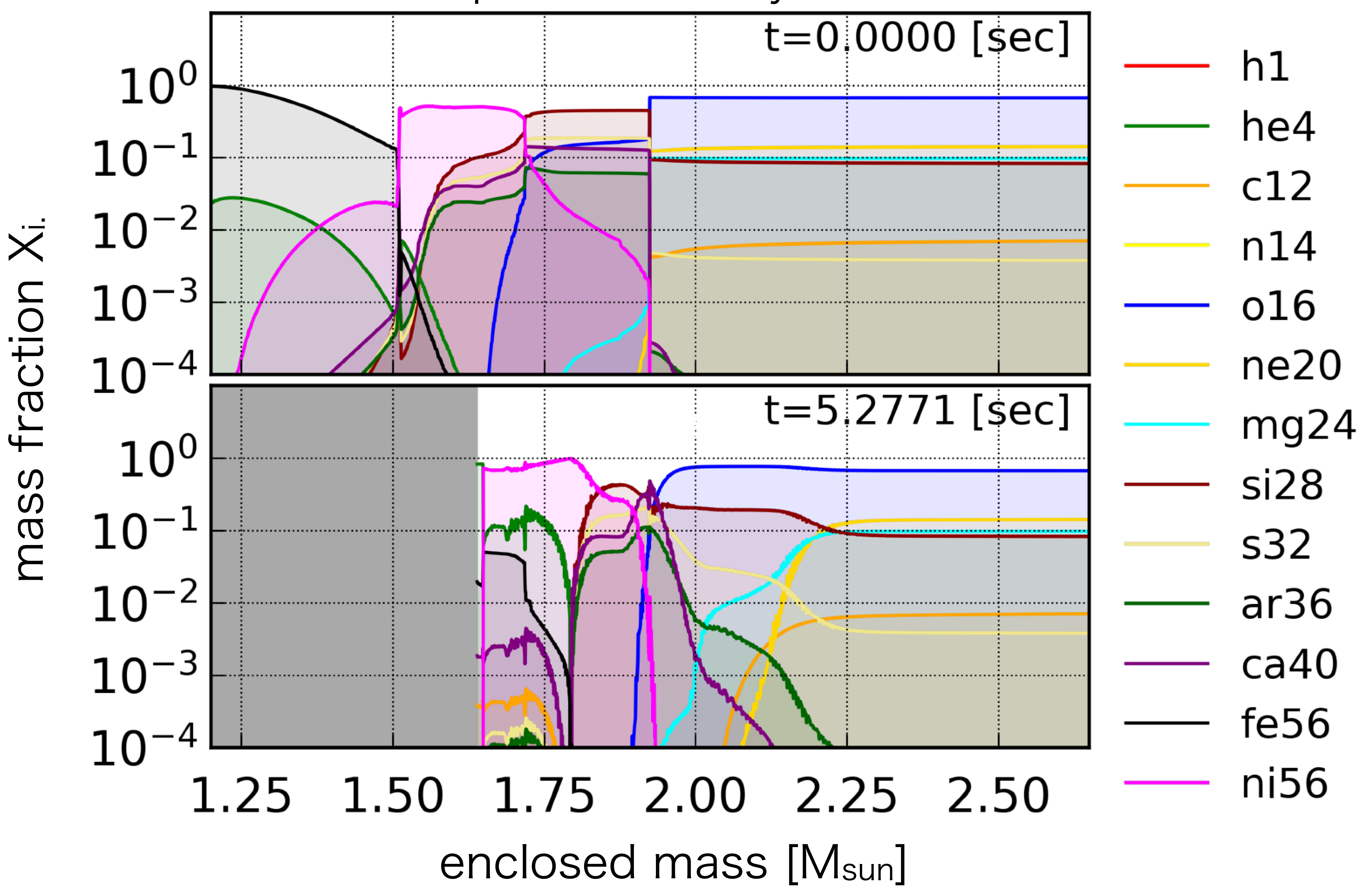
explosive nucleosynthesis in 20Msun star



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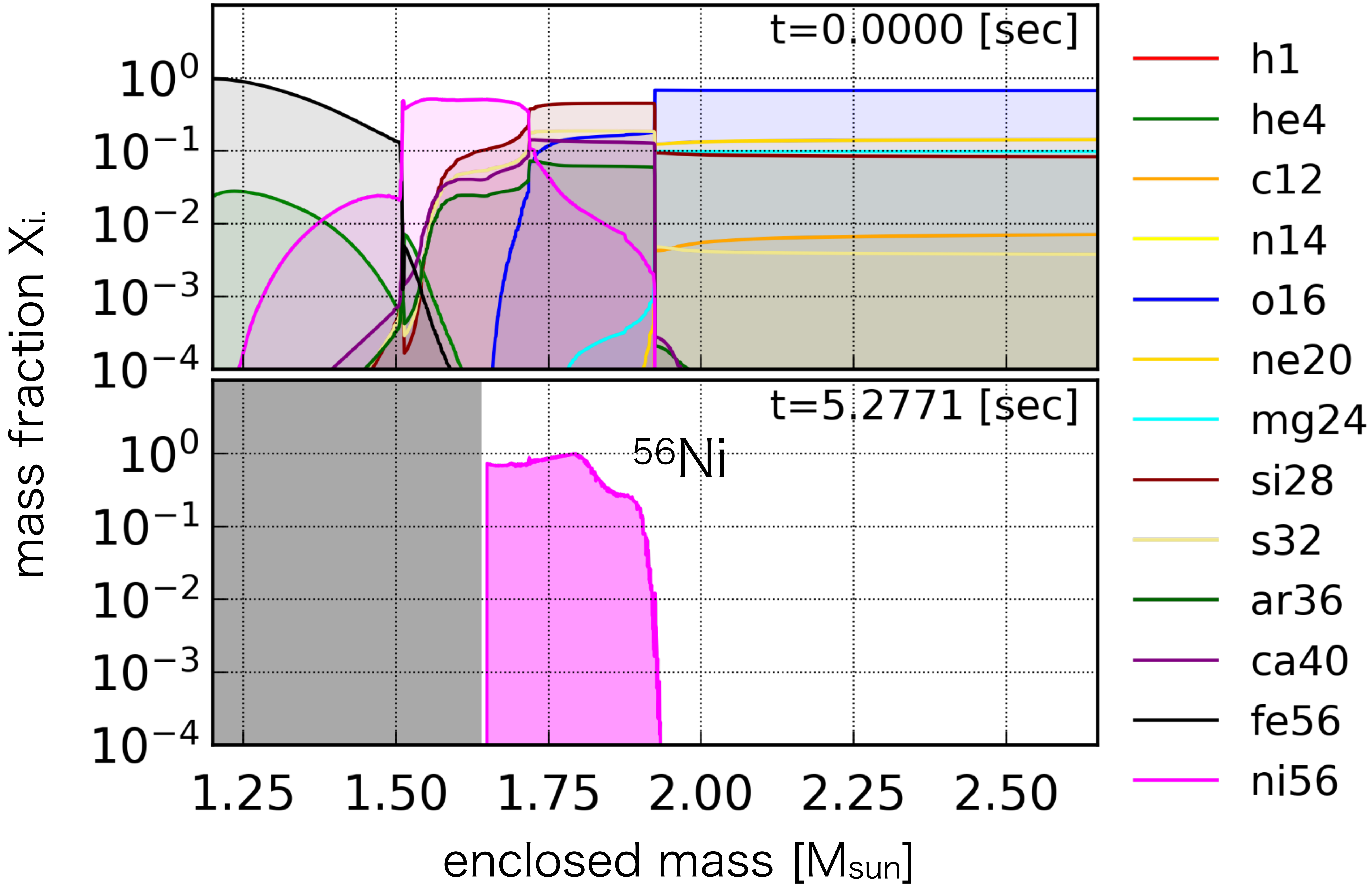

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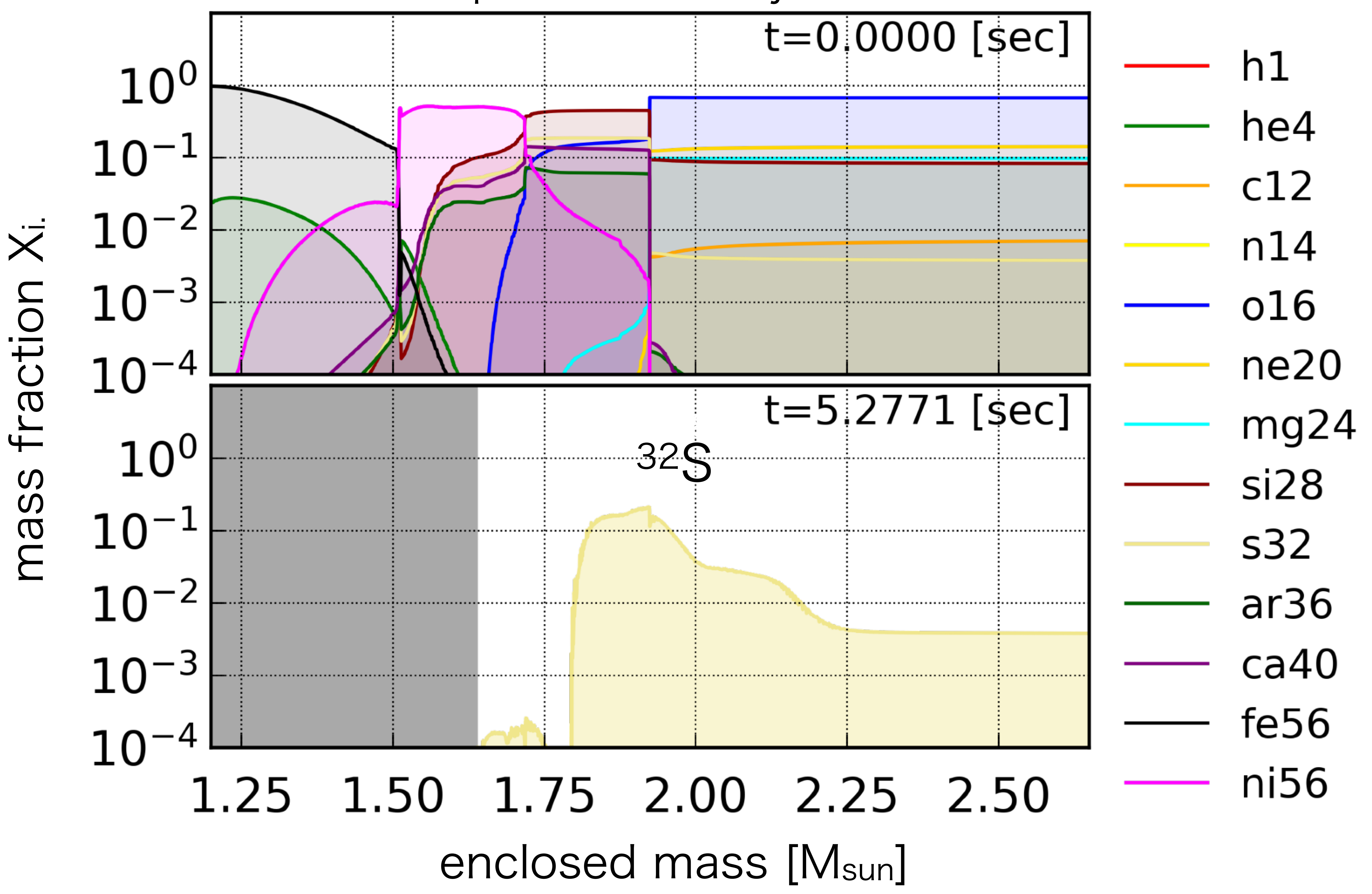

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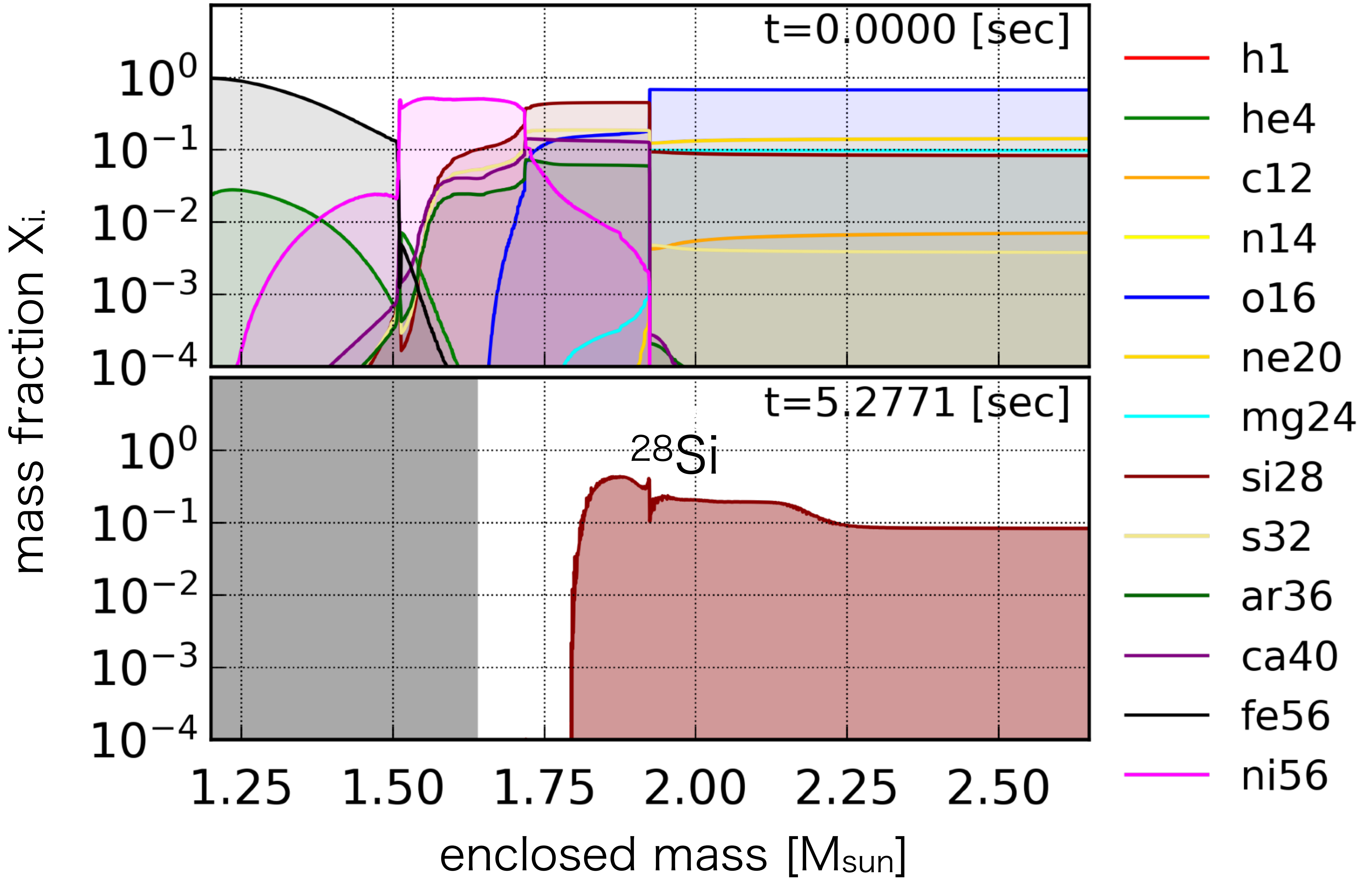

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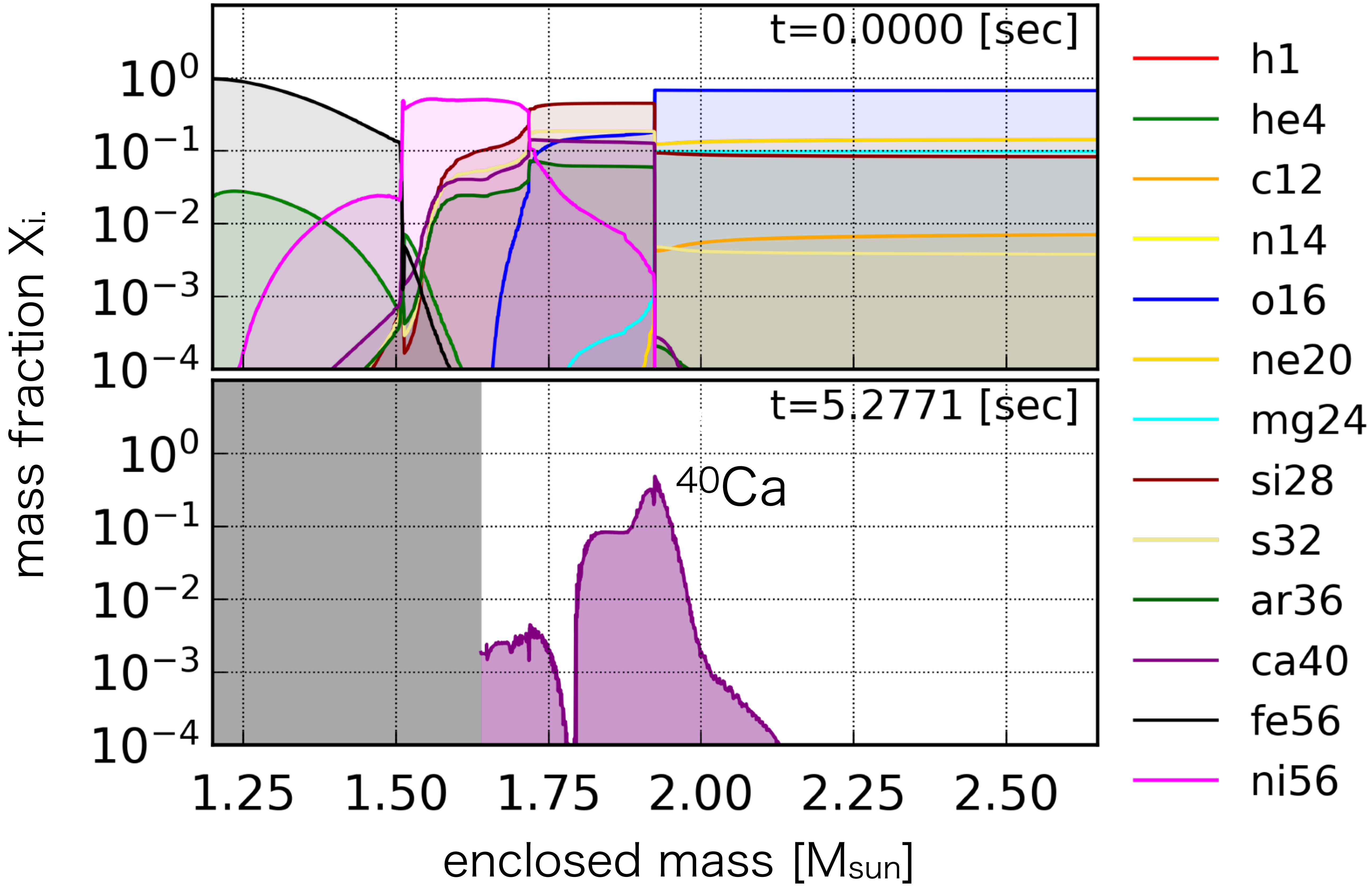

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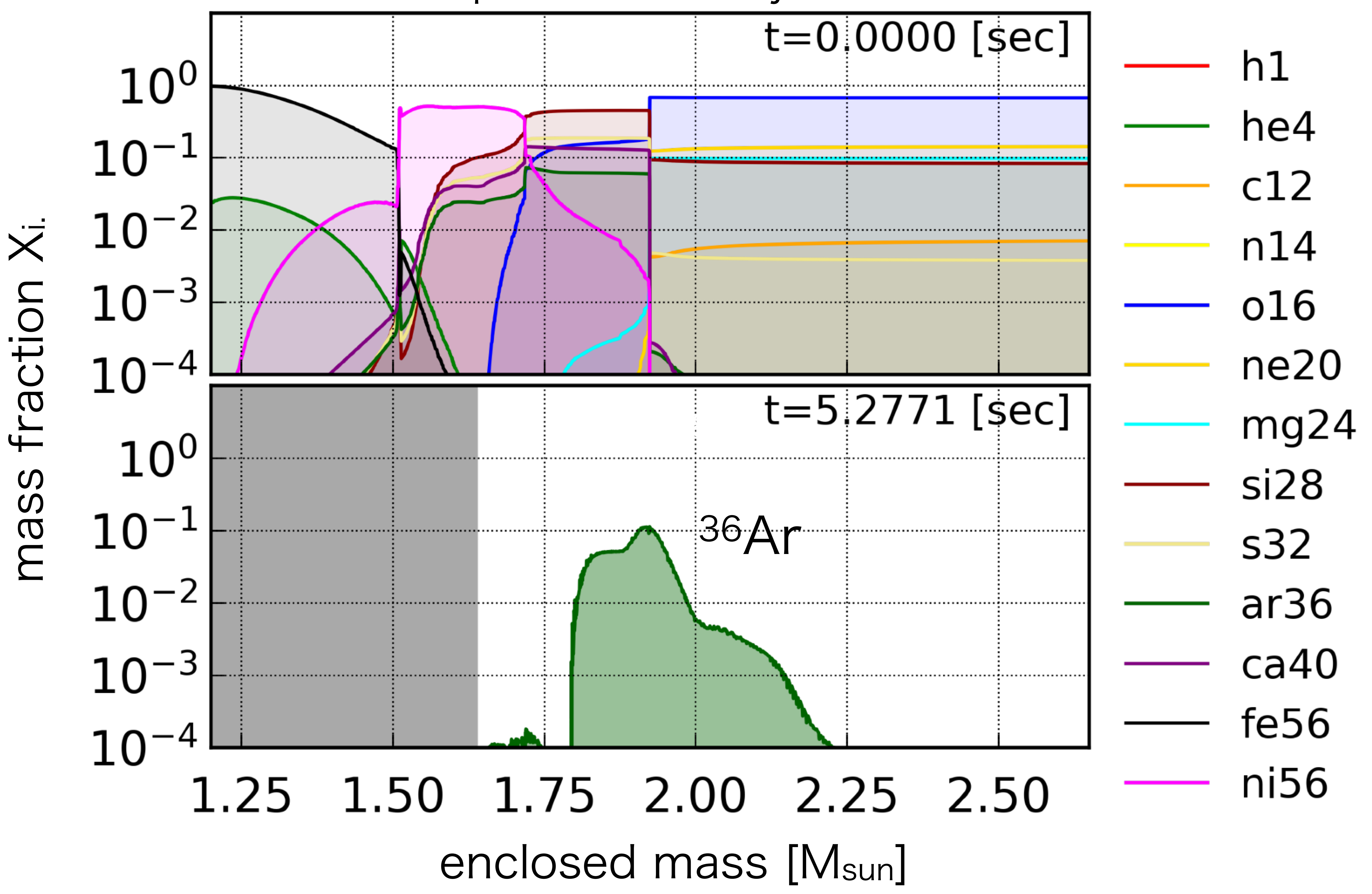

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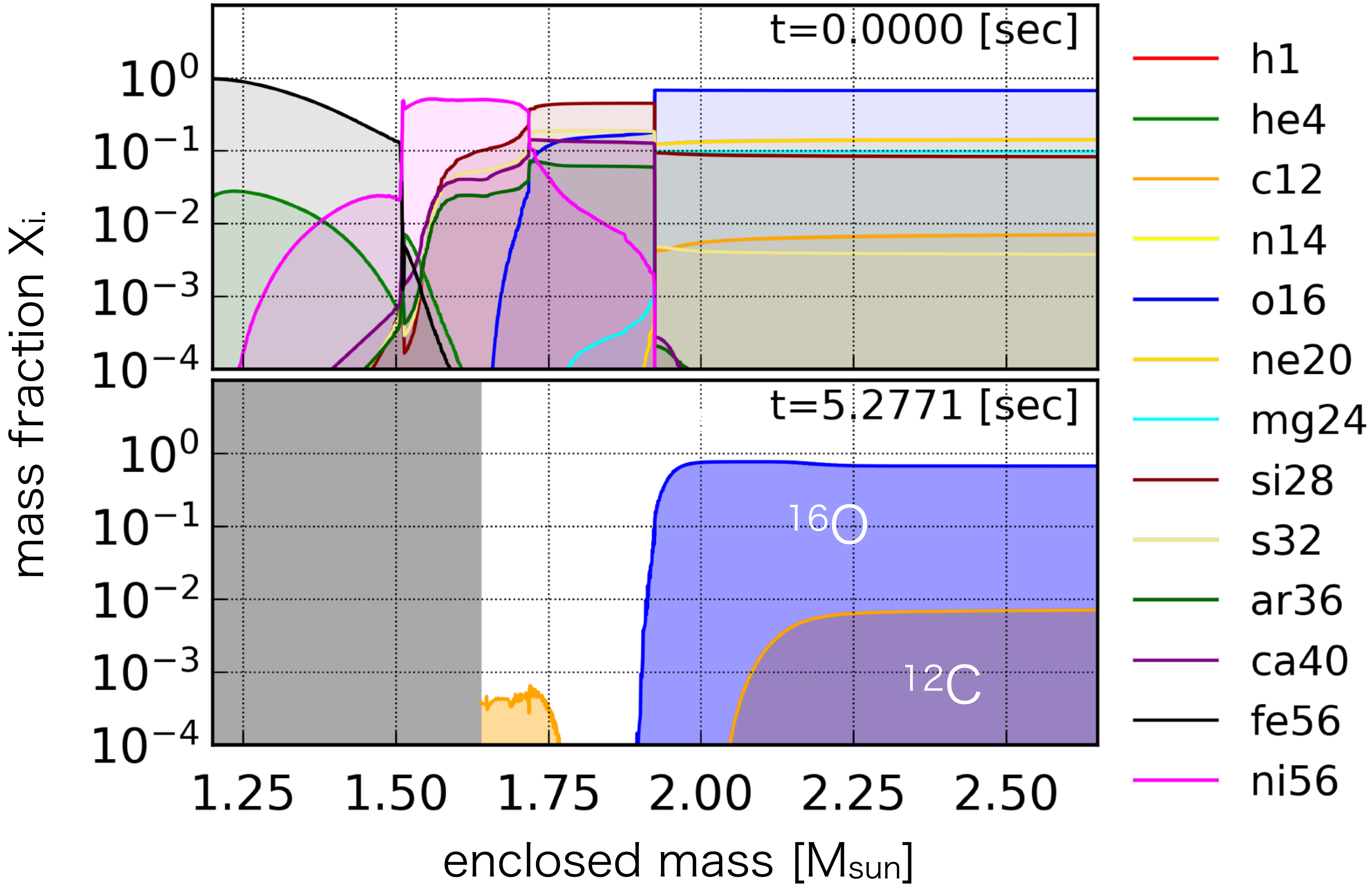
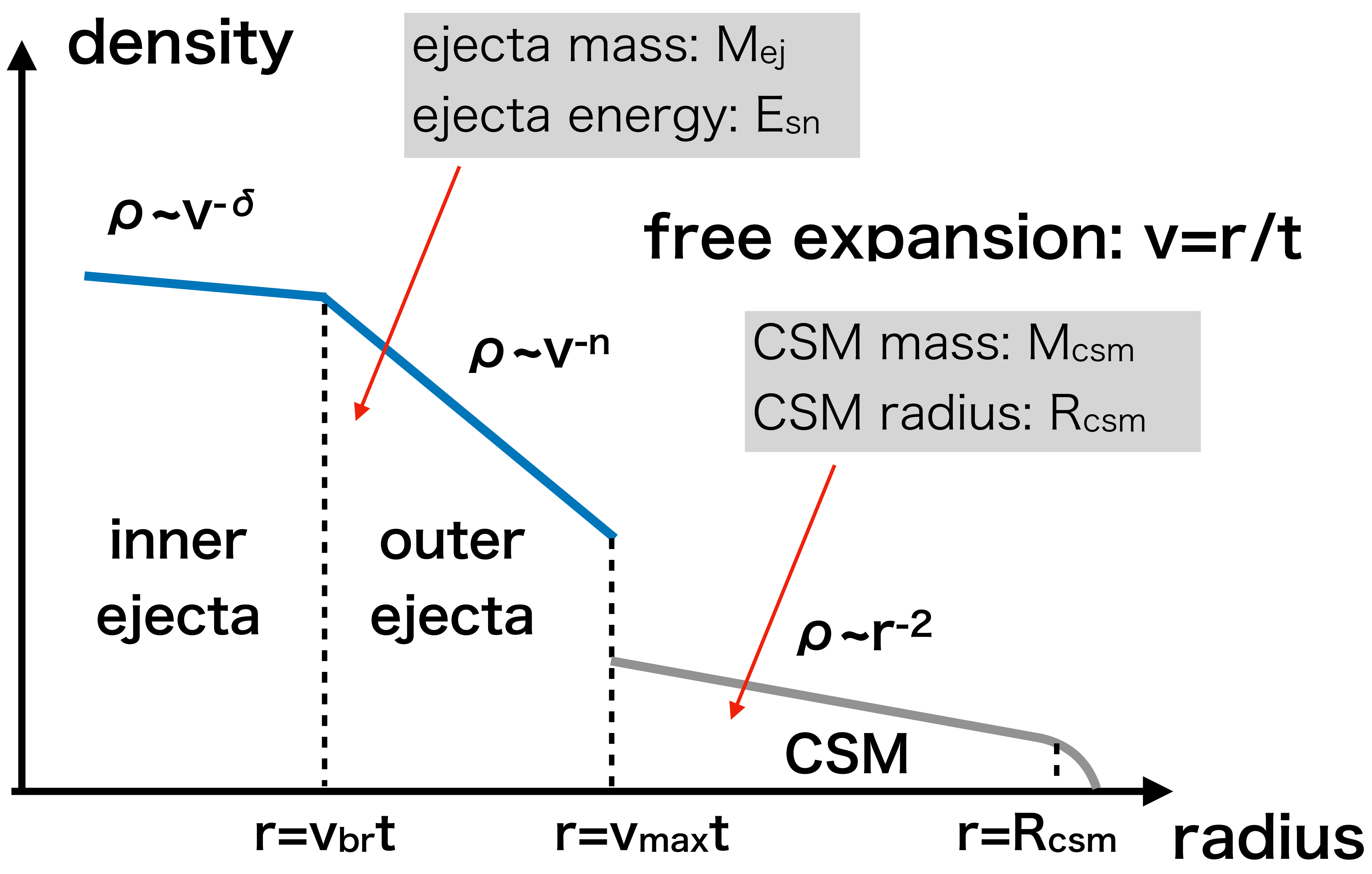
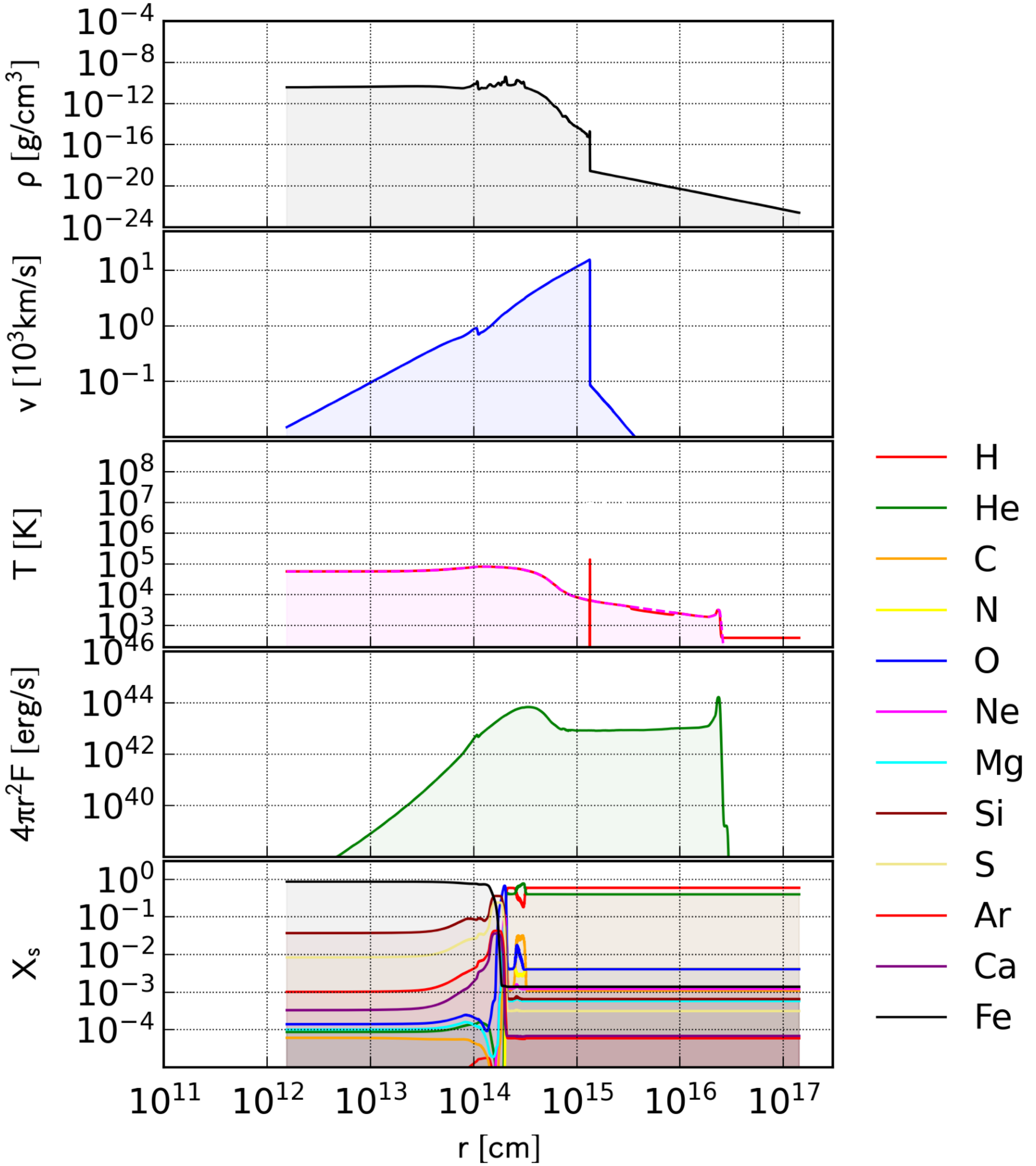
explosive nucleosynthesis in 20Msun star



Shock propagation: shock emergence to expansion

- After the shock emergence from the photosphere, the ejecta rapidly expands
- it starts free expansion, soon after the breakout: v=r/t
- the radial density structure well reproduced by a double-power law (δ=0-2, n=6-10)

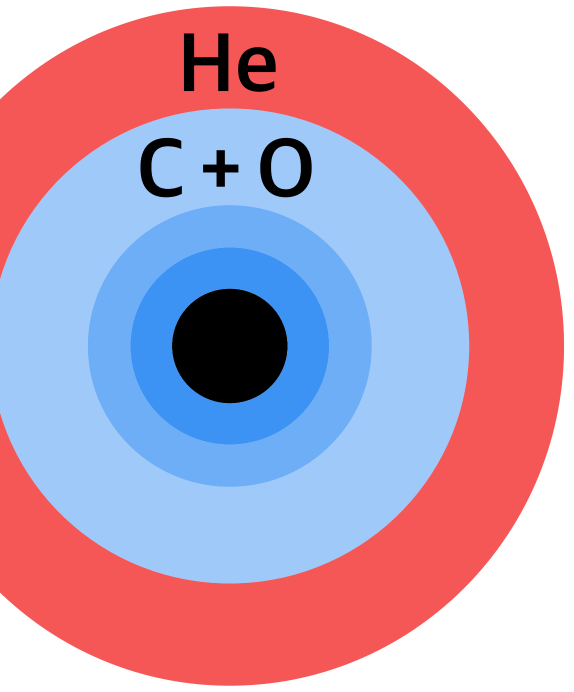


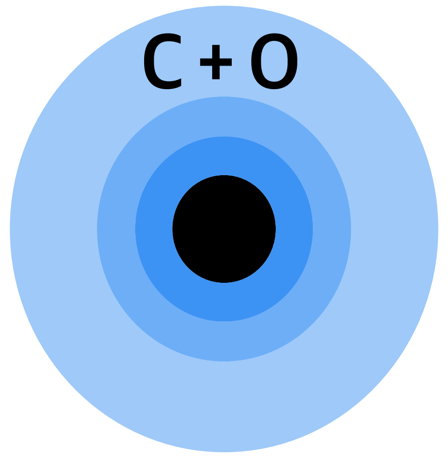


Supernova evolution

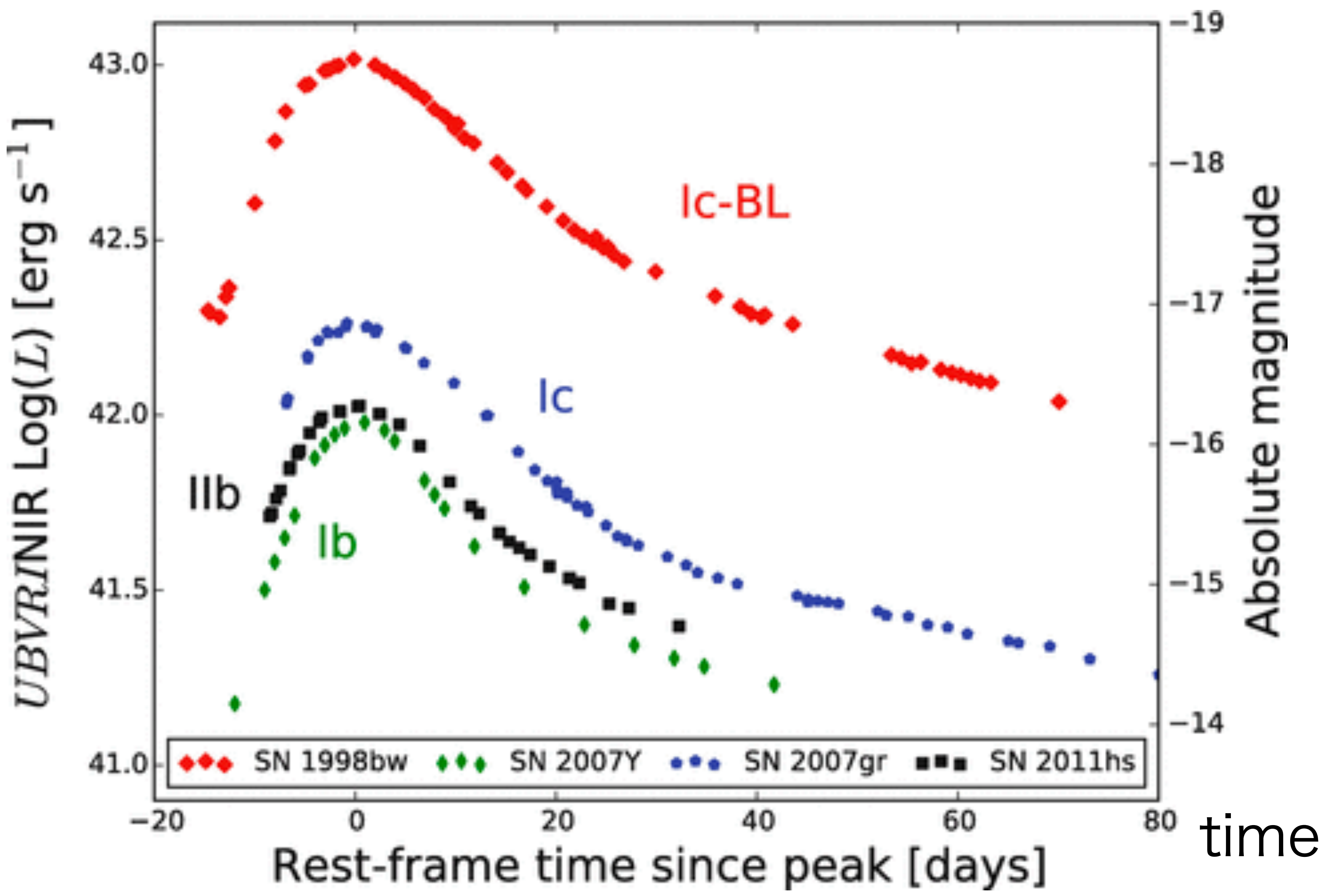
- CCSN light curves (LCs): luminosity evolution determined from ejecta mass, energy, ^{56}Ni mass, ejecta strudture(density/temperature/abundance profiles)

- (We believe) We know how normal SNe behave (LCs+spectral evolutions)





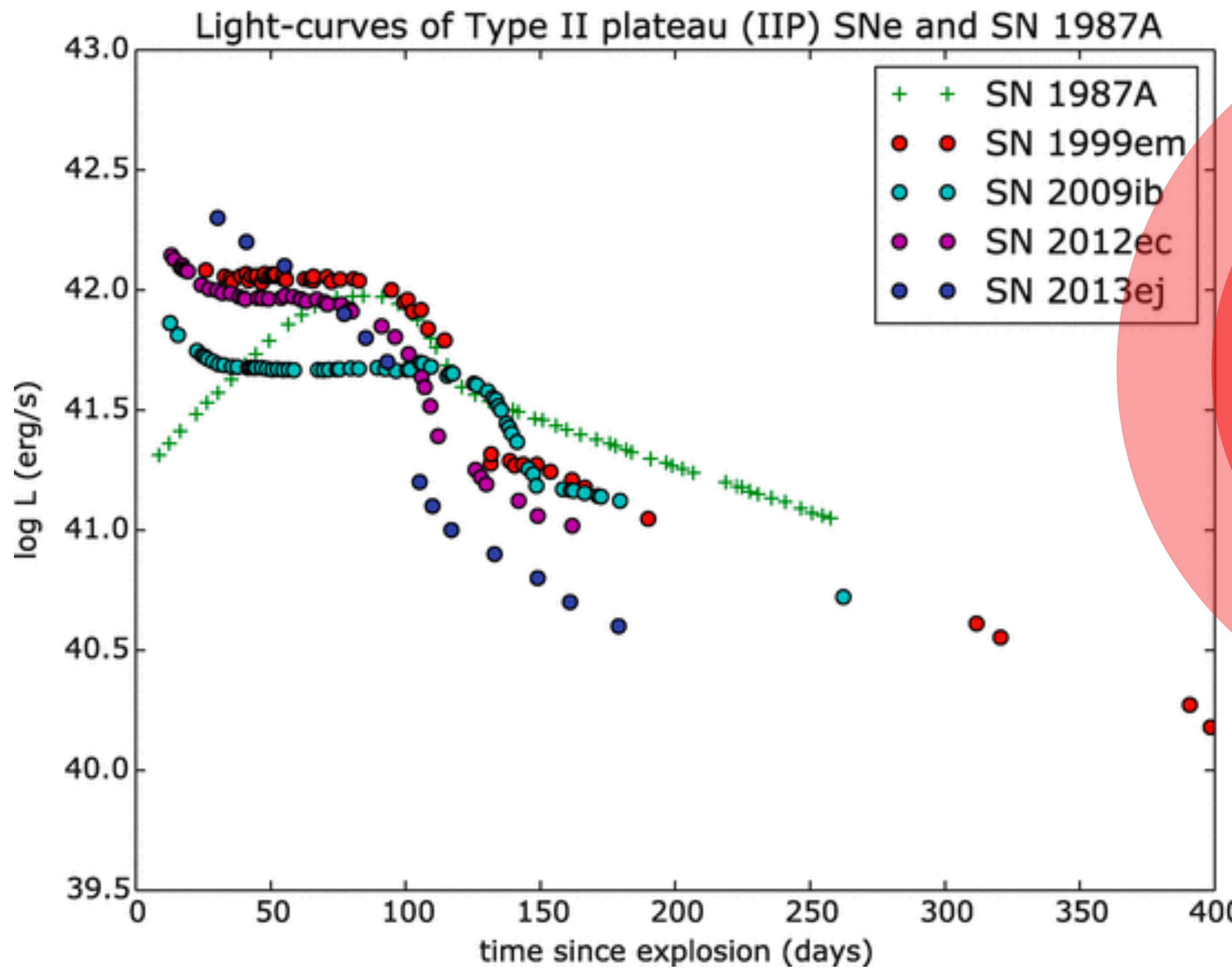
Luminosity

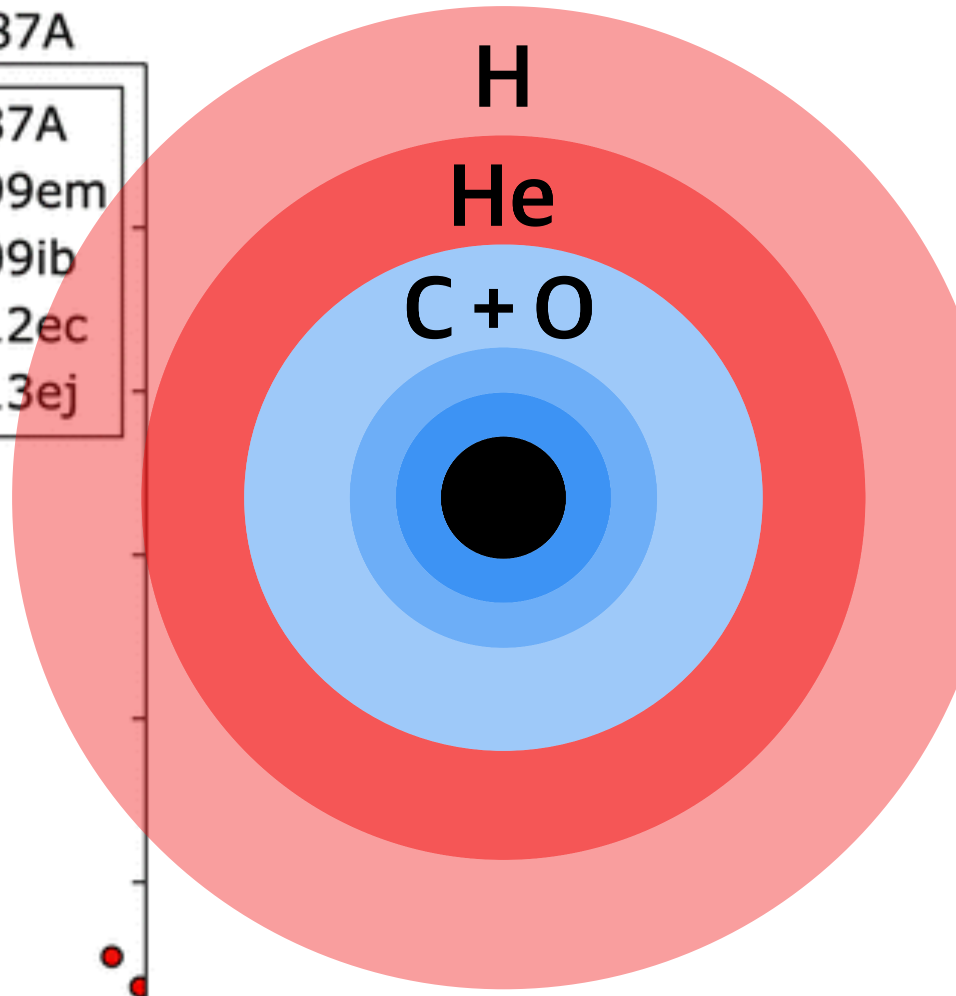


time

Type Ibc SN light curves (Pian&Mazzali2017)

Luminosity





time

Type II SN light curves (Zampieri+2017)

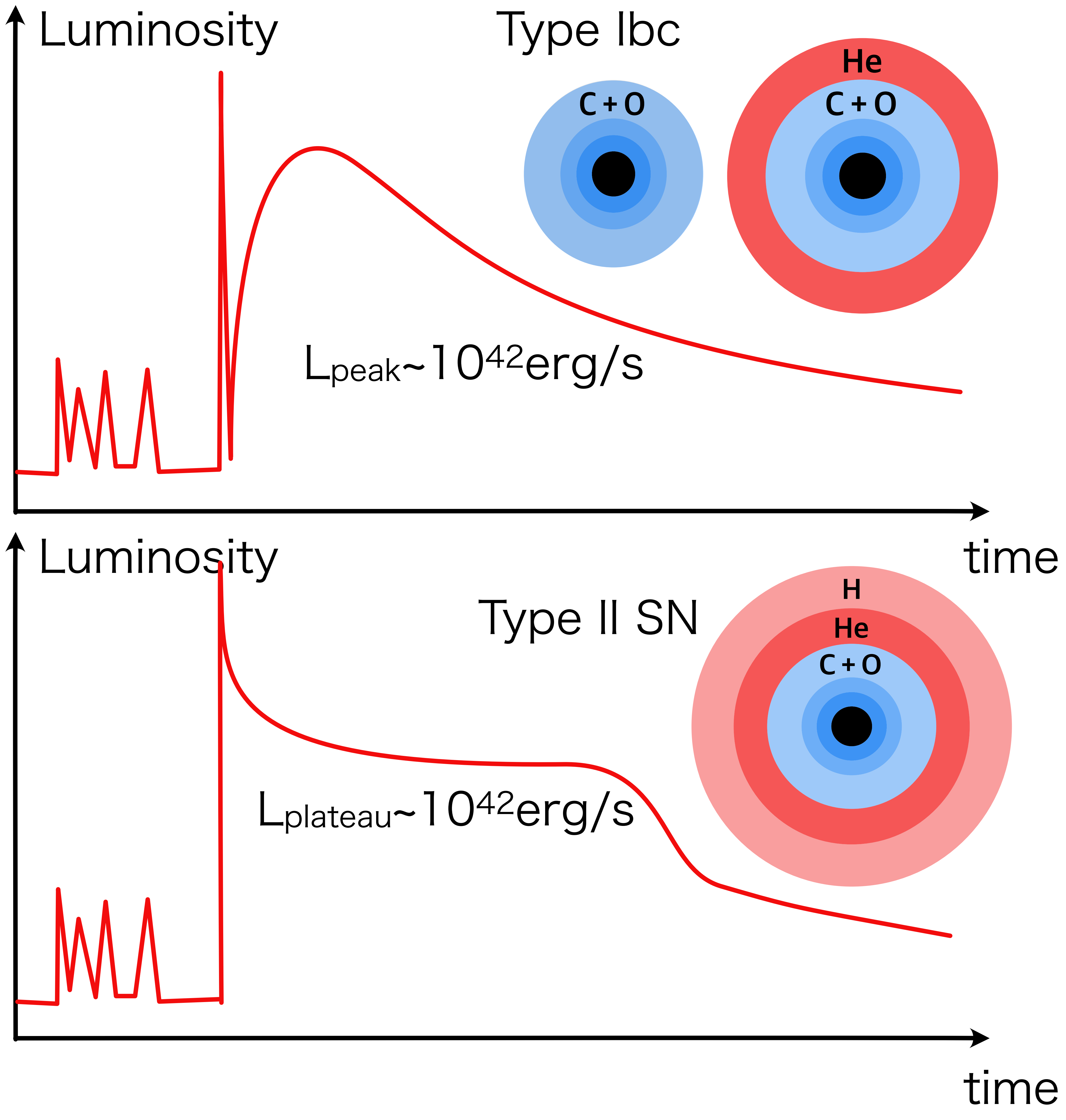
Supernova evolution

- In each phase, properties of exploding stars can be obtained through LCs and spectra (+ multi-λ obs.)

star/ejecta evolution | Research trend

- **pre-supernova image/activity**
  → progenitor properties/activities
- **SN shock breakout/cooling emission**
  → explosion dynamics, stellar radii
- **photospheric/plateau phase**
  → explosion dynamics, stellar mass
- **nebular phase**
  → stellar interior, nucleosynthesis

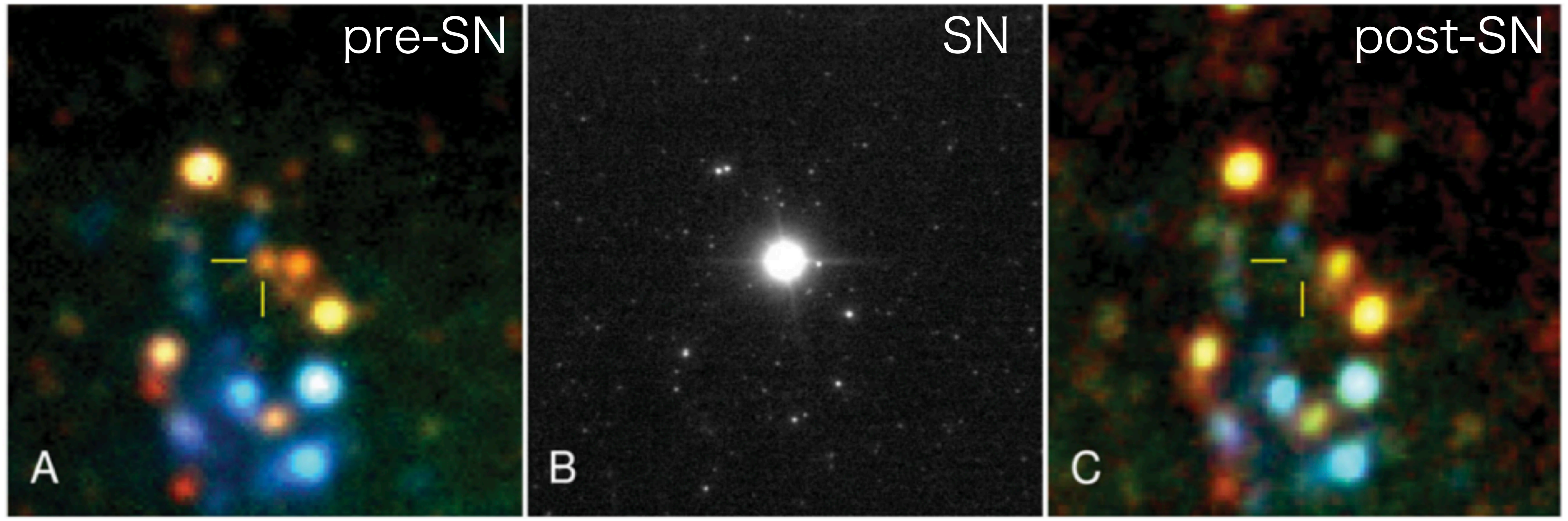
➡ SN remnant phase



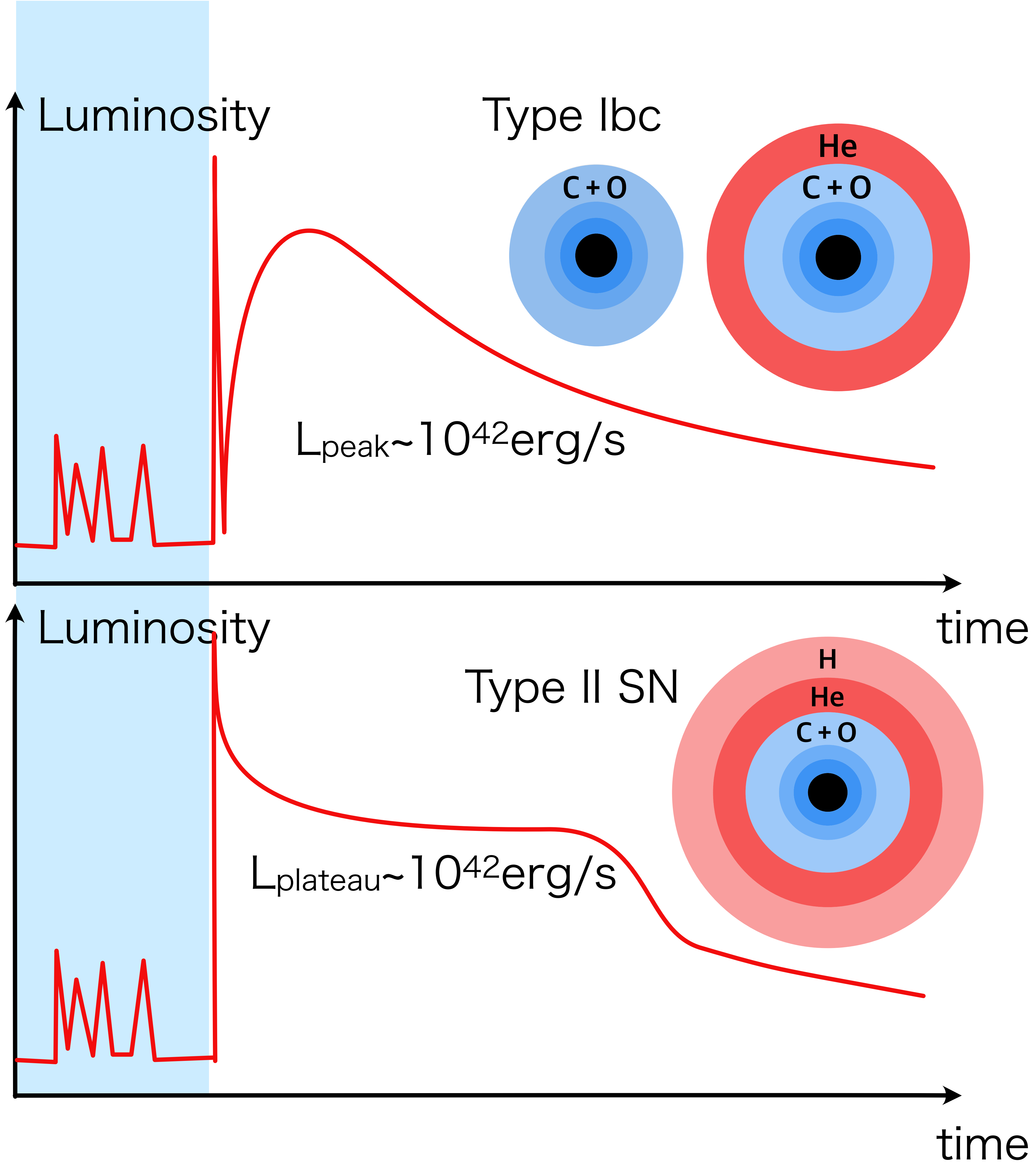
Supernova evolution

- **pre-supernova image**: check archival data(HST, etc) to see if the pre-explosion star is resolved.
  → progenitor luminosity function/mass distribution

- **pre-supernova activity**: check any possible variability/non-variability of the pre-explosion stars in previous transient surveys

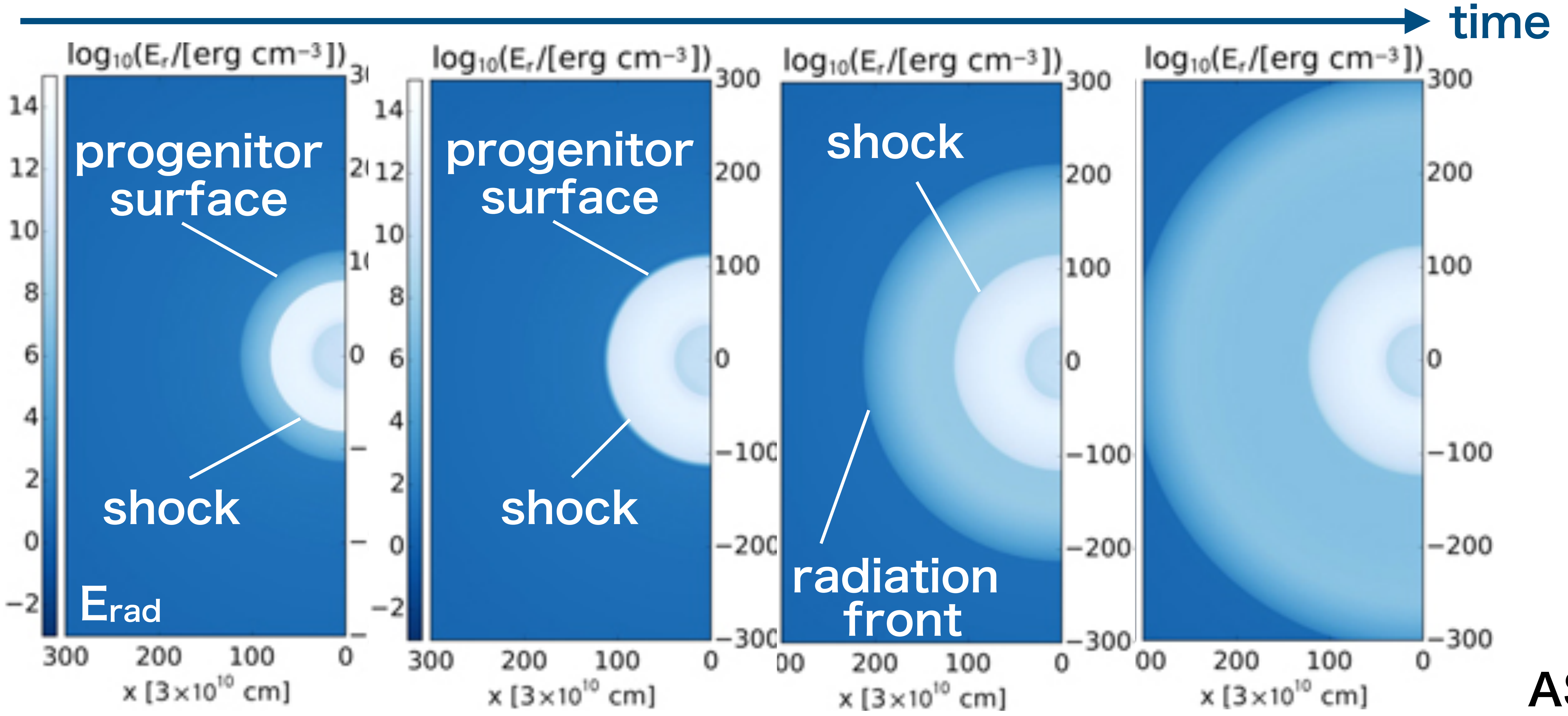


Pre-supernova image
Pre-supernova activity

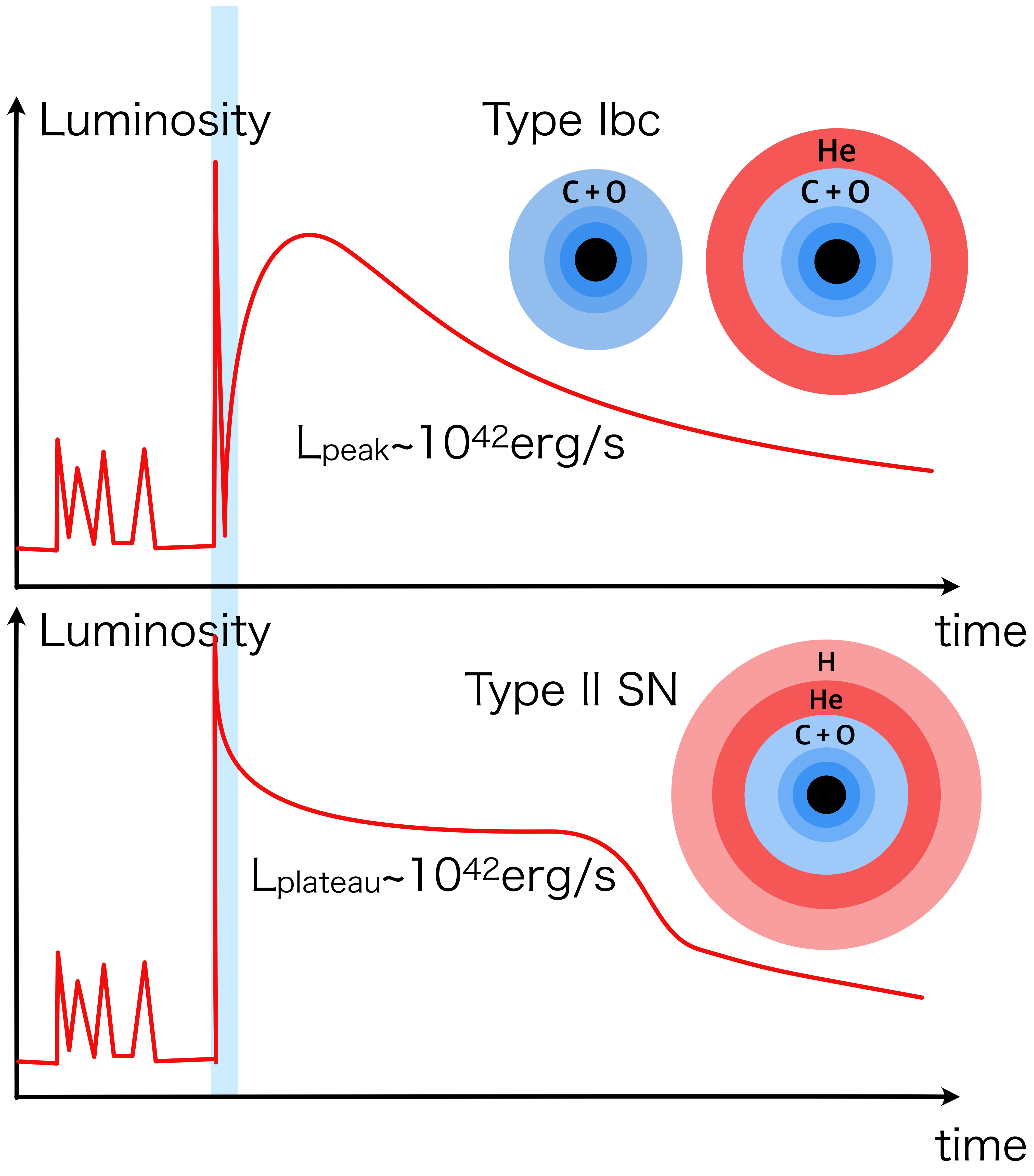


Supernova evolution

- **SN shock breakout**: first EM signal from SNe (thermal UV, X-ray + non-thermal?)
- challenging observations to catch events that we do not know when and where to appear
- followed by **shock cooling emission**
- information on stellar radius/environments



SN shock breakout/cooling



AS, Maeda, Shigeyama (2016)

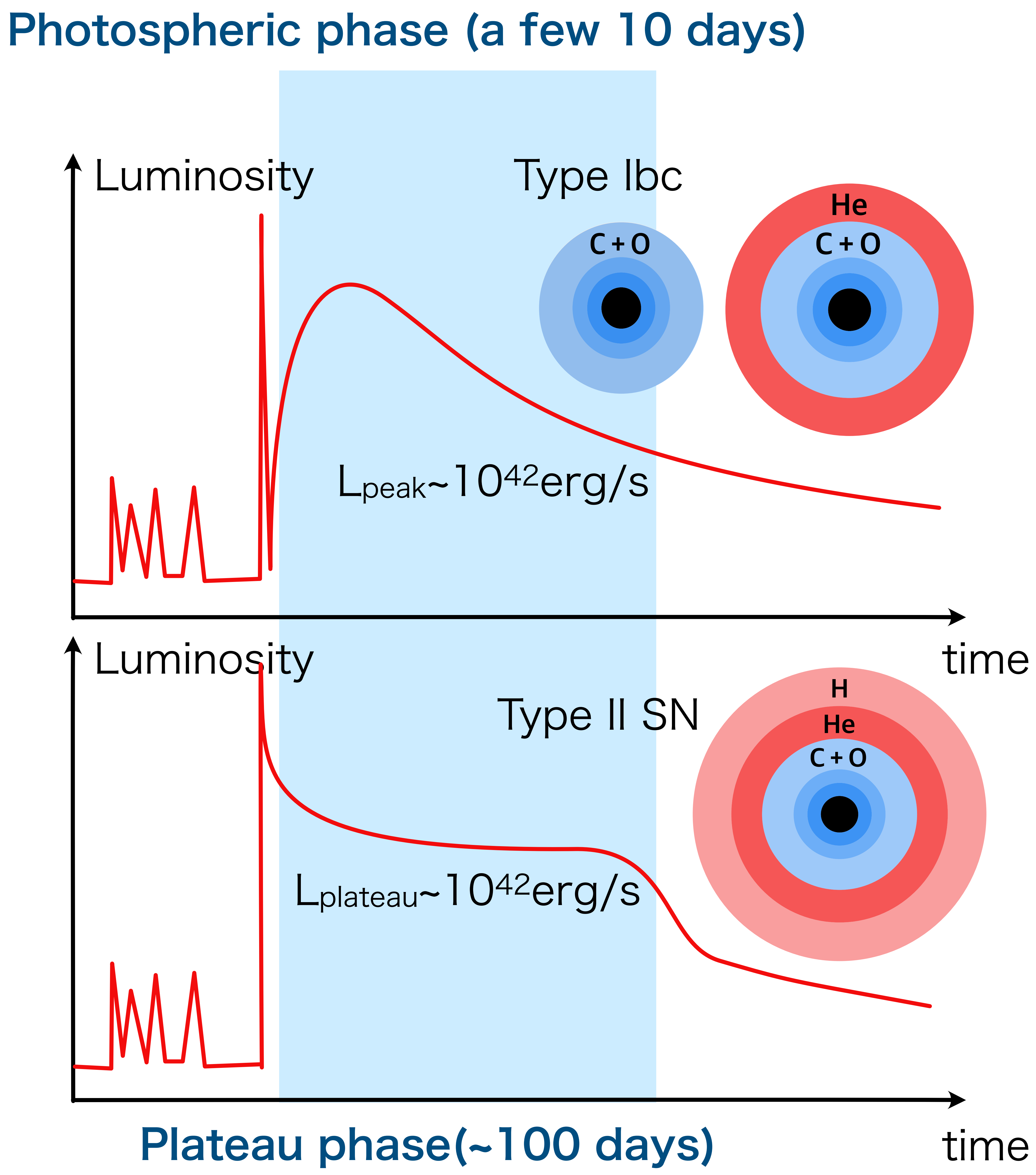
Supernova evolution

- **Photospheric phase**: SN ejecta is still coupled with thermal photons.
- power source is usually thermal energy + nuclear energy $^{56}Ni \rightarrow ^{56}Co \rightarrow ^{56}Fe$ decay chain
- evolutionary timescale = photon diffusion

$$t_{\rm ch} = \left(\frac{\kappa M_{\rm ej}}{c v_{\rm ph}}\right)^{1/2} \propto M_{\rm ej}^{3/4} E_{\rm exp}^{-1/4}$$

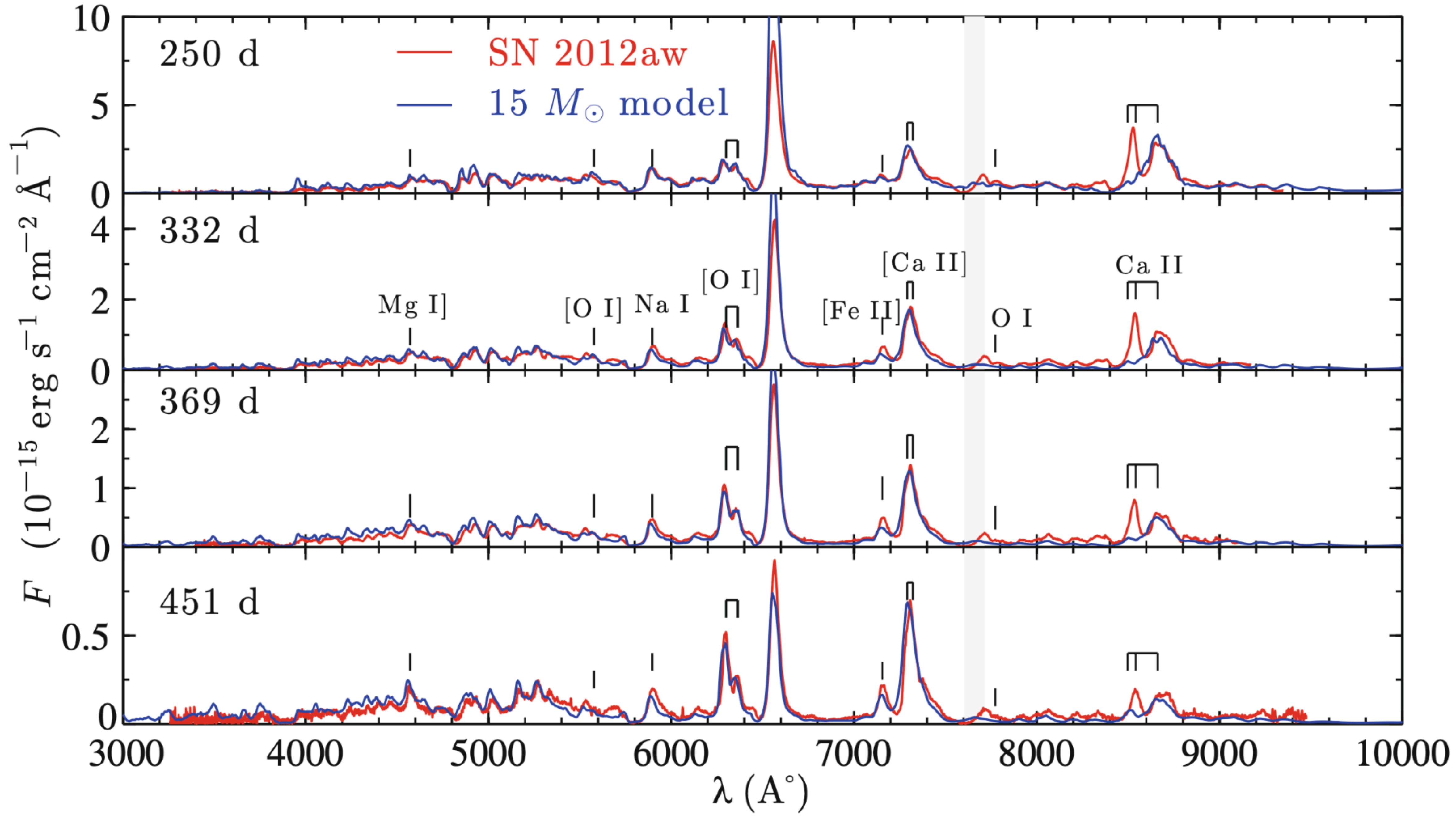
- expansion velocity (photospheric velocity) obtained from spectra

$$E_{\rm exp} \sim \frac{1}{2} M_{\rm ej} v_{\rm ph}^2 \Leftrightarrow v_{\rm ph} \sim \left(\frac{2E_{\rm exp}}{M_{\rm ej}}\right)^{1/2}$$

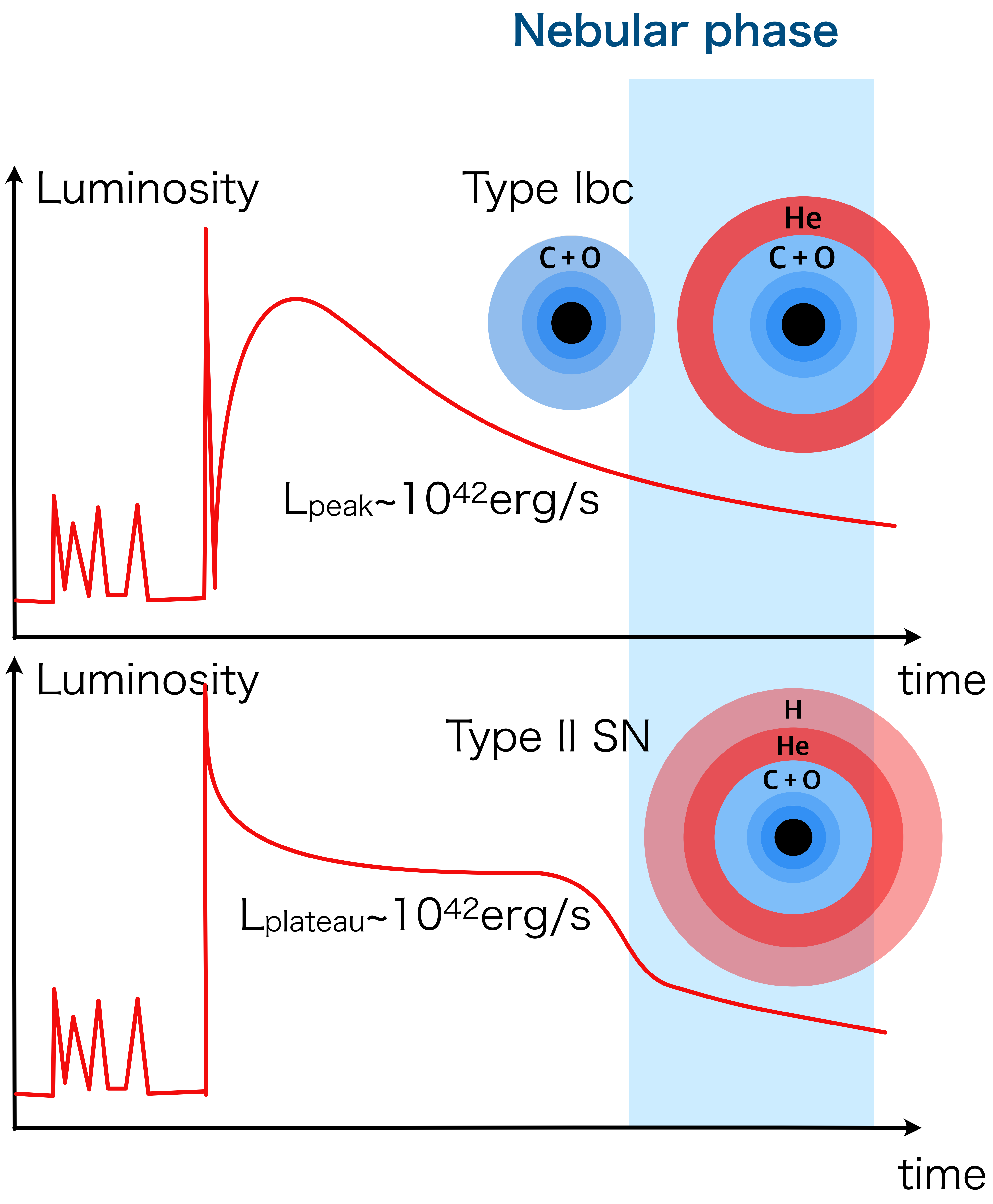


Supernova evolution

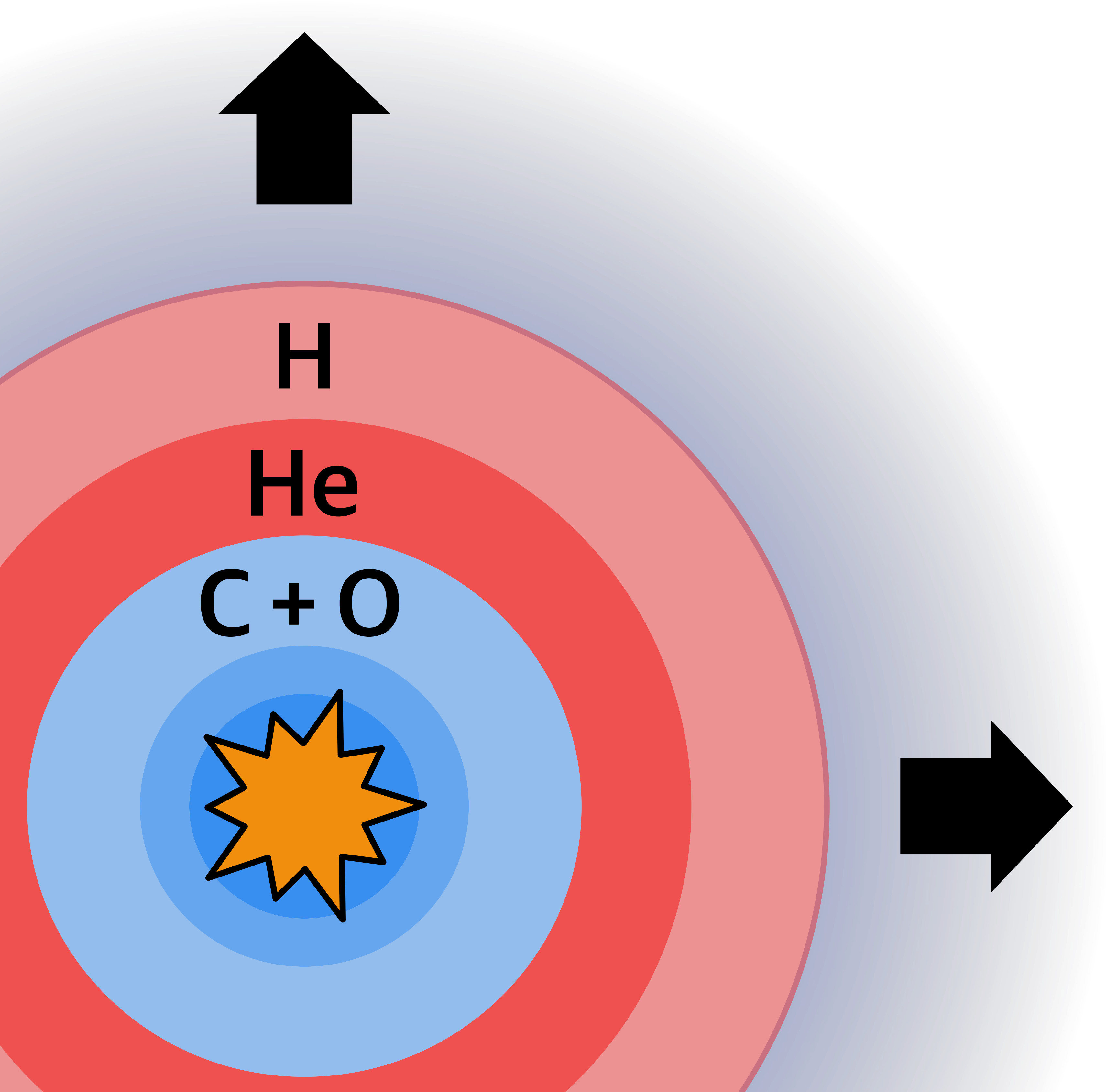
- **Nebular phase**: the whole SN ejecta is now decoupled from photons (optically thin).
- emission lines from metals [OI], [CaII], [FeII], …
- we can "see through" the ejecta



Jerkstrand, A. (2017)

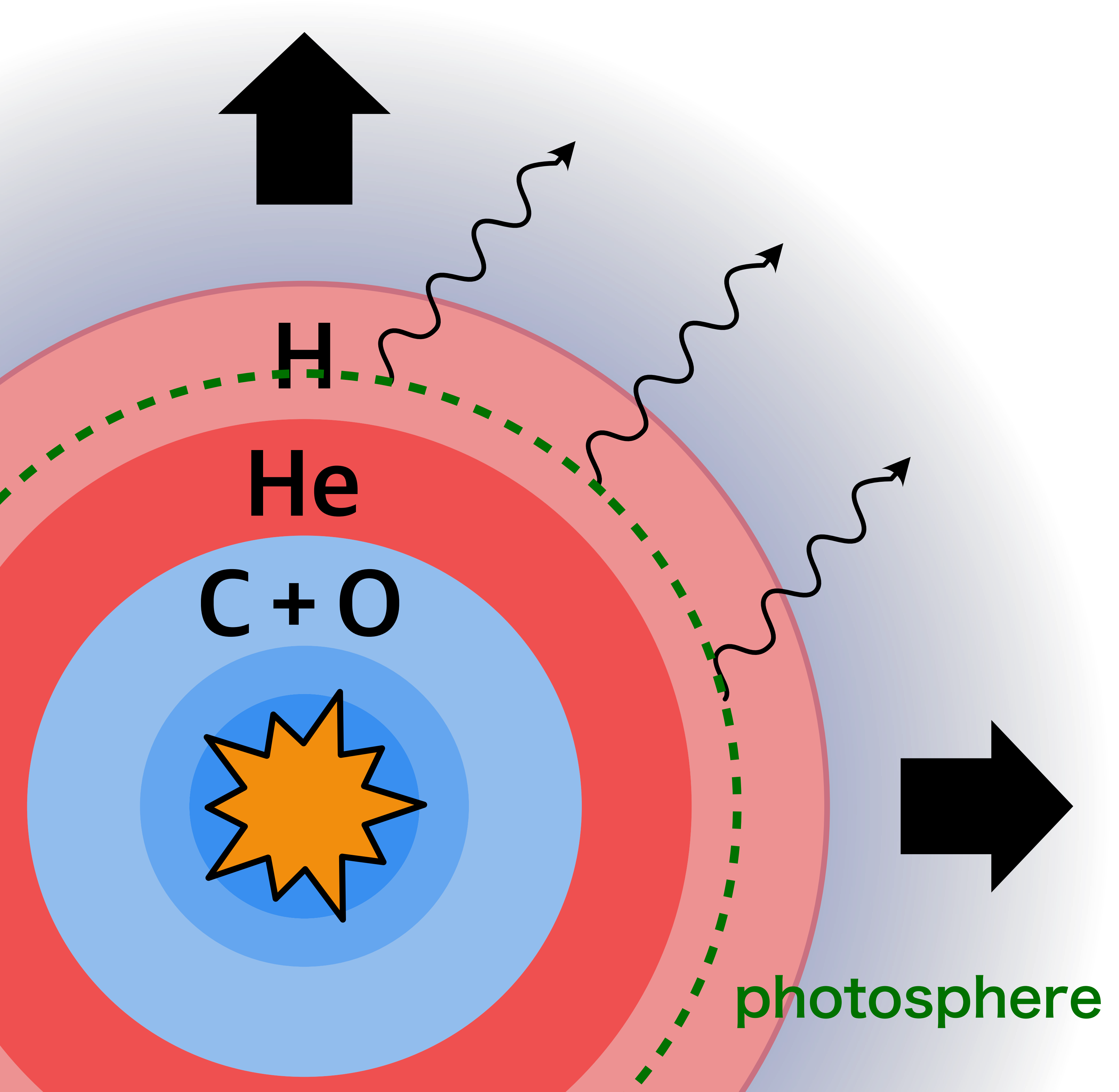


Energy sources of supernova lights



- **thermal energy $E_{\rm th}$**: eventually released in the optically thick to thin transition of the ejecta
  - → all types: shock breakout/shock cooling emission
  - → type IIP: plateau emission
- **kinetic energy $E_{\rm kin} \sim 10^{51}[{\rm erg}]$**: (late) shock conversion into thermal/non-thermal energy
  - → optically thin: thermal (X-ray), non-thermal (synchrotroni/IC)
  - → optically thick: optical
- **nuclear energy $E_{\rm nuc}$**: radioactive ^{56}Ni→^{56}Co→^{56}Fe (half-lives of 6 and 77 days)
  - → stripped-envelope SNe → gamma-ray leakage
- **compact remnant (NS spin/BH accretion)**: some energetic/exotic supernovae (e.g., broad-lined Ic SNe, super-luminous SNe)?

Energy sources of supernova lights



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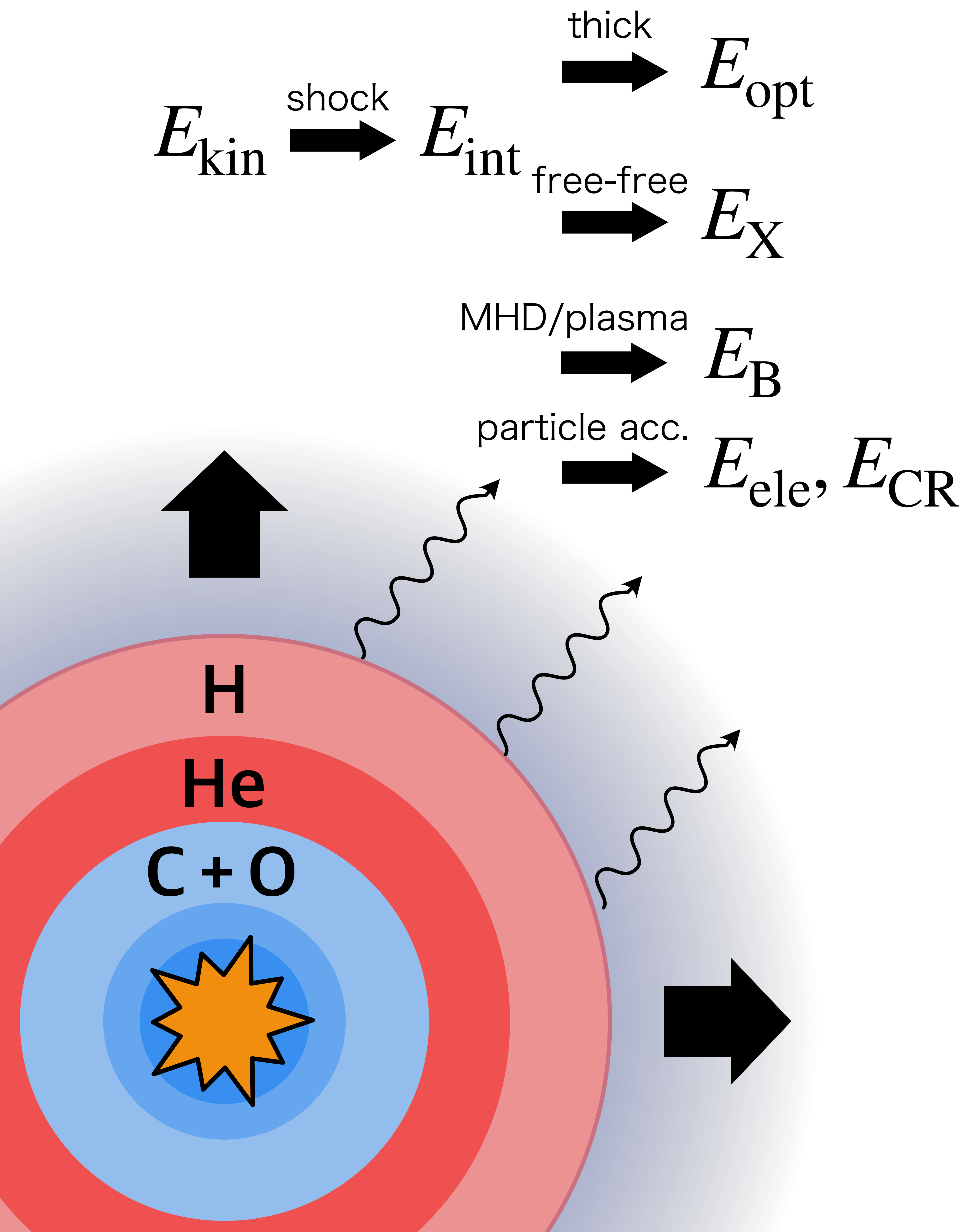
- **nuclear energy** $E_{\rm nuc}$: radioactive ^{56}Ni→^{56}Co→^{56}Fe (half-lives of 6 and 77 days)
  - → stripped-envelope SNe → gamma-ray leakage
- **compact remnant (NS spin/BH accretion)**: some energetic/exotic supernovae (e.g., broad-lined Ic SNe, super-luminous SNe)?

Energy sources of supernova lights



- **thermal energy** $E_{\rm th}$: eventually released in the optically thick to thin transition of the ejecta
  - → all types: shock breakout/shock cooling emission
  - → type IIP: plateau emission
- **kinetic energy** $E_{\rm kin} \sim 10^{51}[{\rm erg}]$: (late) shock conversion into thermal/non-thermal energy
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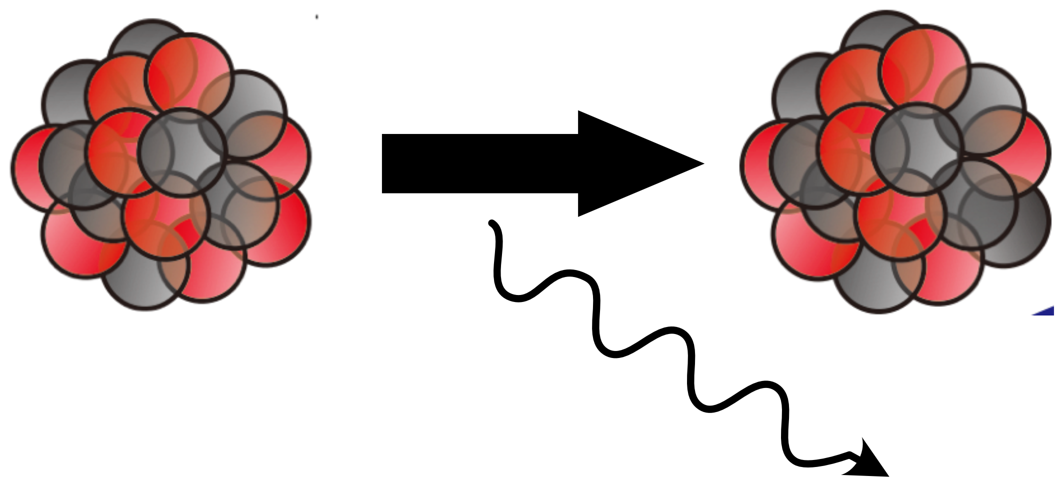
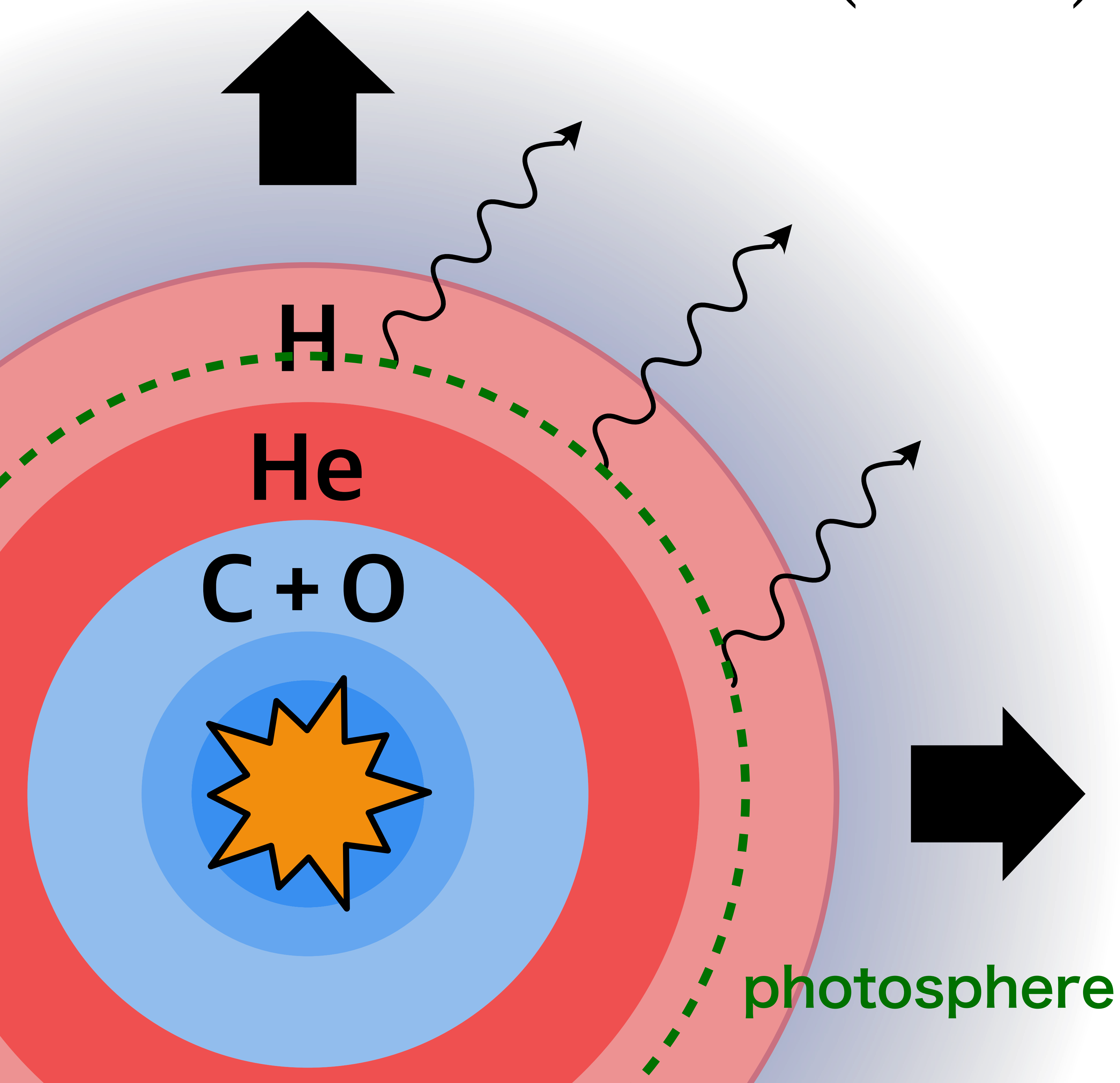


$$E_{\rm Ni} \sim 2.3 \times 10^{49} \left(\frac{M_{\rm Ni}}{0.1 M_{\odot}}\right) [\rm erg]$$



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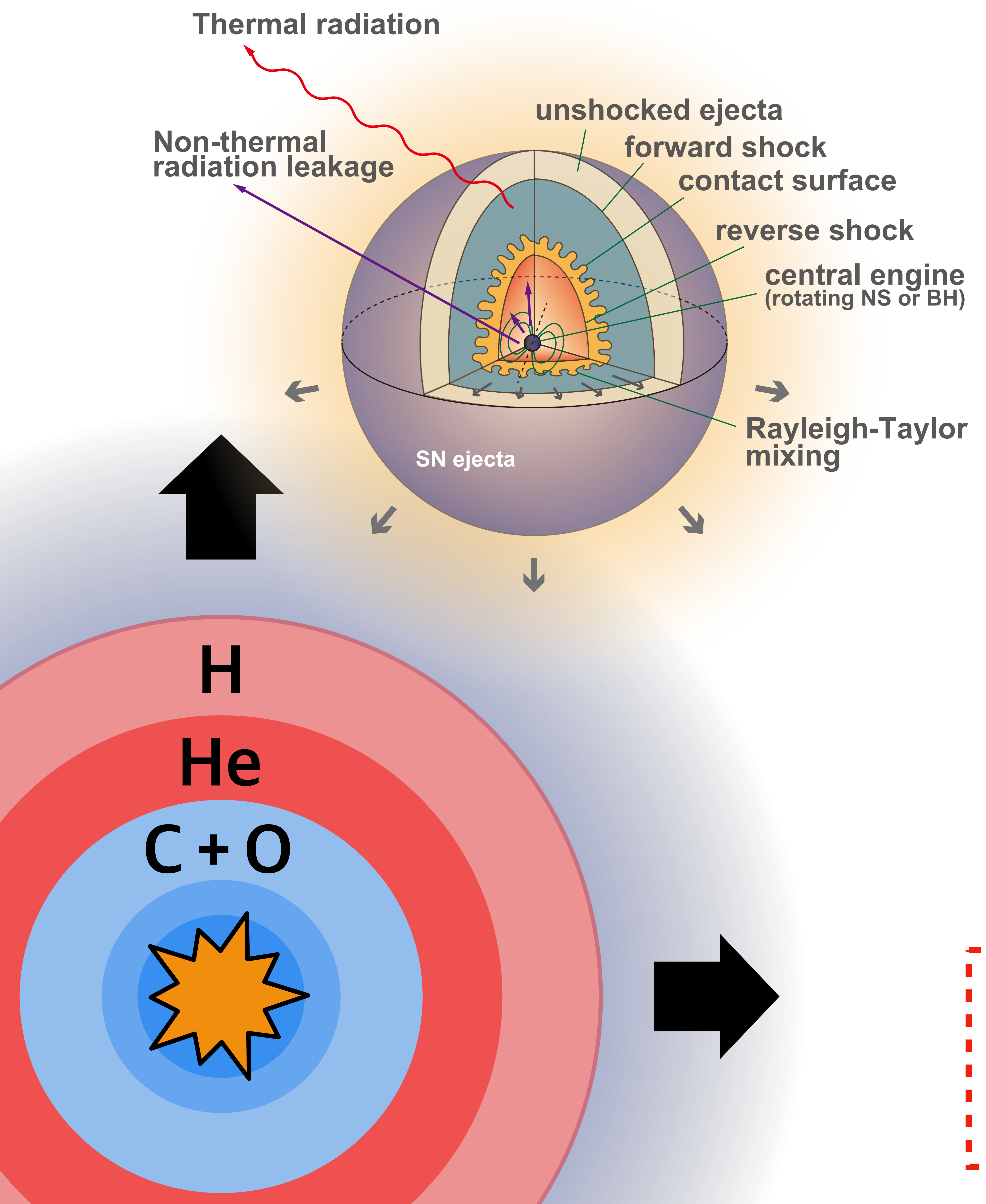

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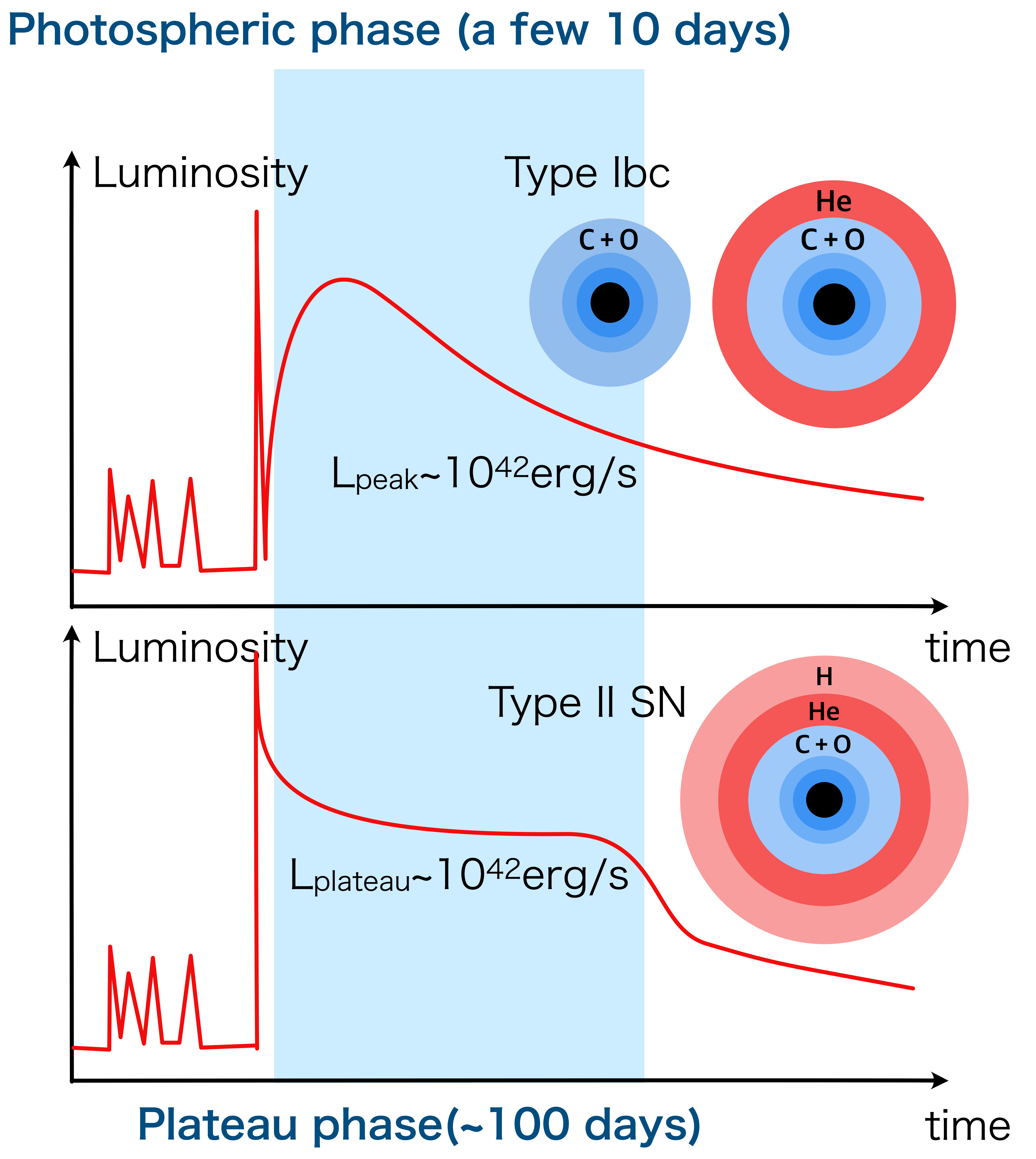
Photospheric phase

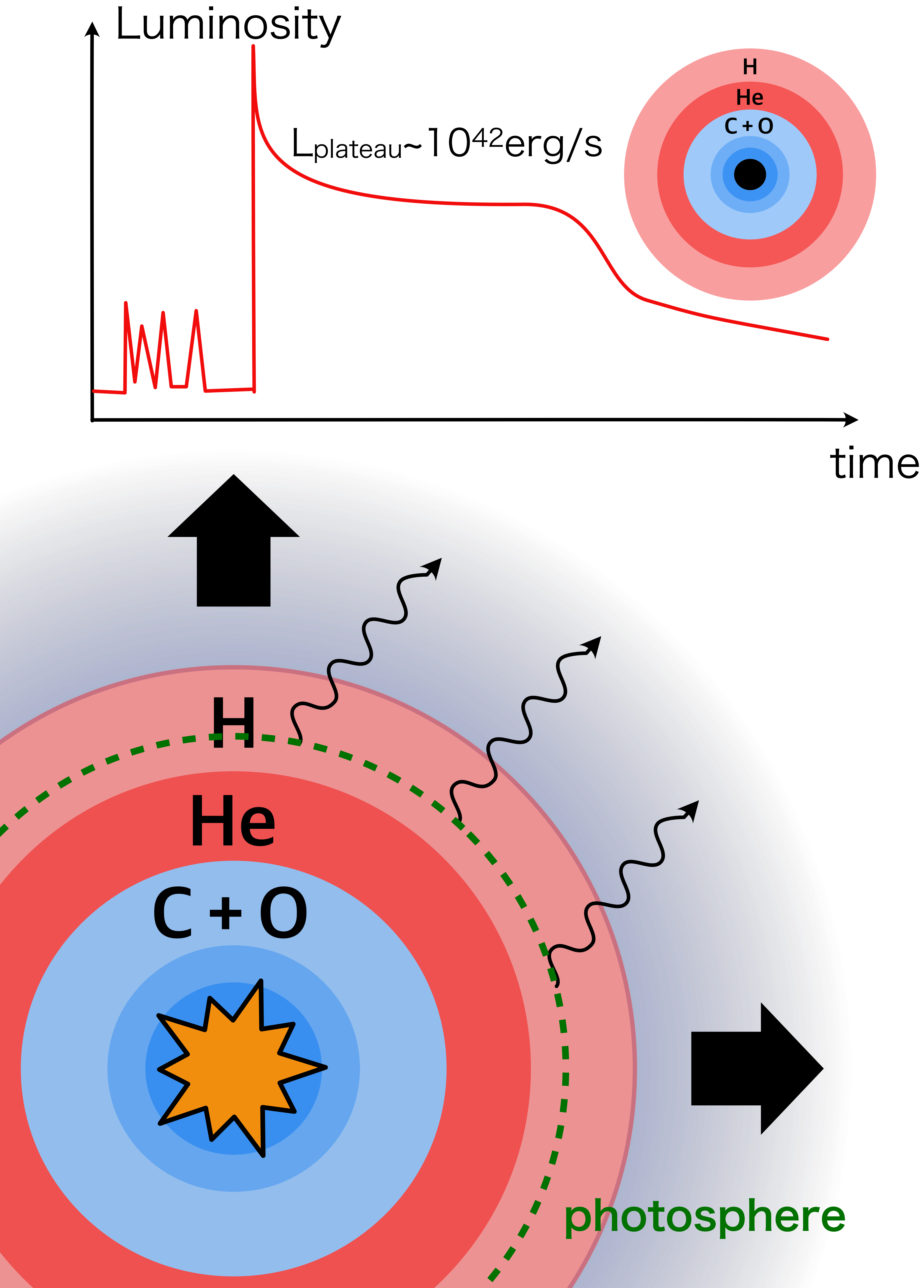
- SN ejecta is still coupled with thermal photons
- photons diffuse throughout the expanding ejecta
- observed spectra characterized by a temperature (Blackbody-like)
- ejecta dynamics (mass, velocity) and photon transport (diffusion/expansion)

→ characteristic time: $t_{\rm ch} = \left(\dfrac{\kappa M_{\rm ej}}{c v_{\rm exp}}\right)^{1/2} \propto M_{\rm ej}^{3/4} E_{\rm exp}^{-1/4}$

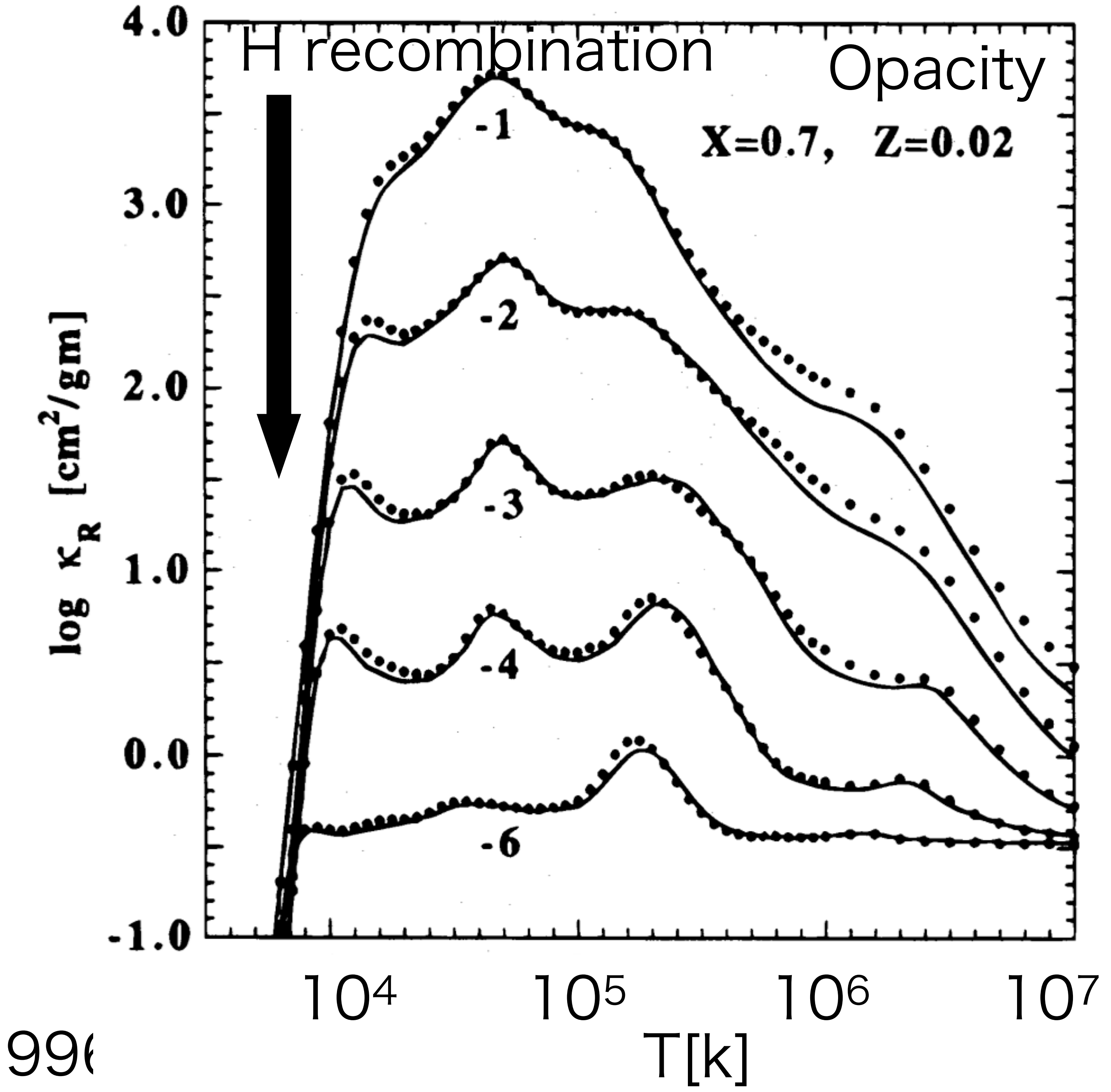
→ expansion velocity: $v_{\rm exp} \sim \left(\dfrac{2E_{\rm exp}}{M_{\rm ej}}\right)^{1/2} \Leftrightarrow E_{\rm exp} \sim \dfrac{1}{2} M_{\rm ej} v_{\rm exp}^2$



Type II-“Plateau” supernovae



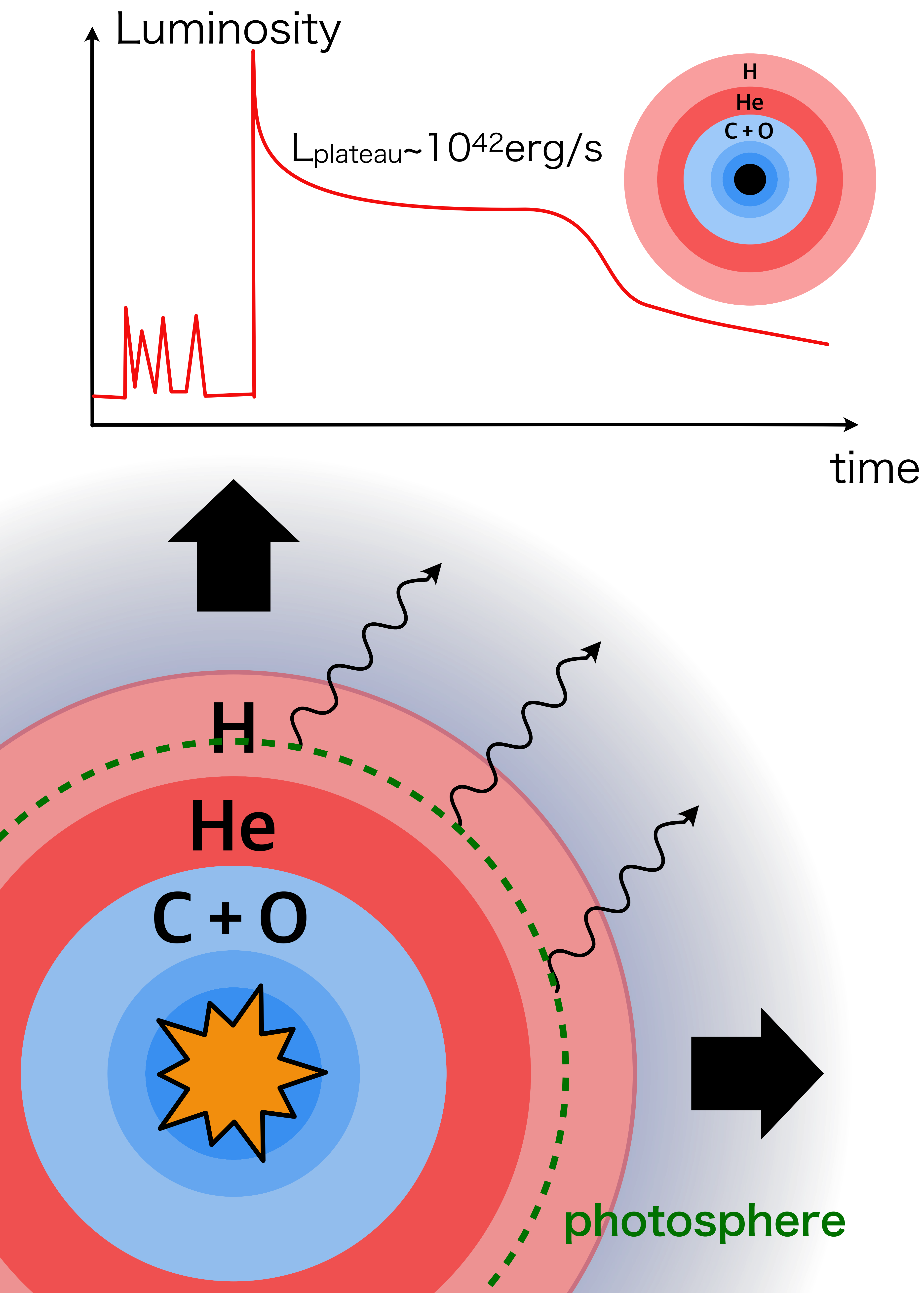
- explosions of red-supergiants (RSG) with typical M~$10M_{sun}$ and R~a few100 - $1000R_{sun}$.
- Plateau emission: gradual release of the thermal energy in the ejecta
- optically thick ⇒ thin transition by H recombination



- free electrons from H as a dominant opacity source(e^--scattering)
- recombination temperature of T_{rec}~6000-7000[K]

OPAL opacity, Iglesias&Rogers (199

Type II-“Plateau” supernovae

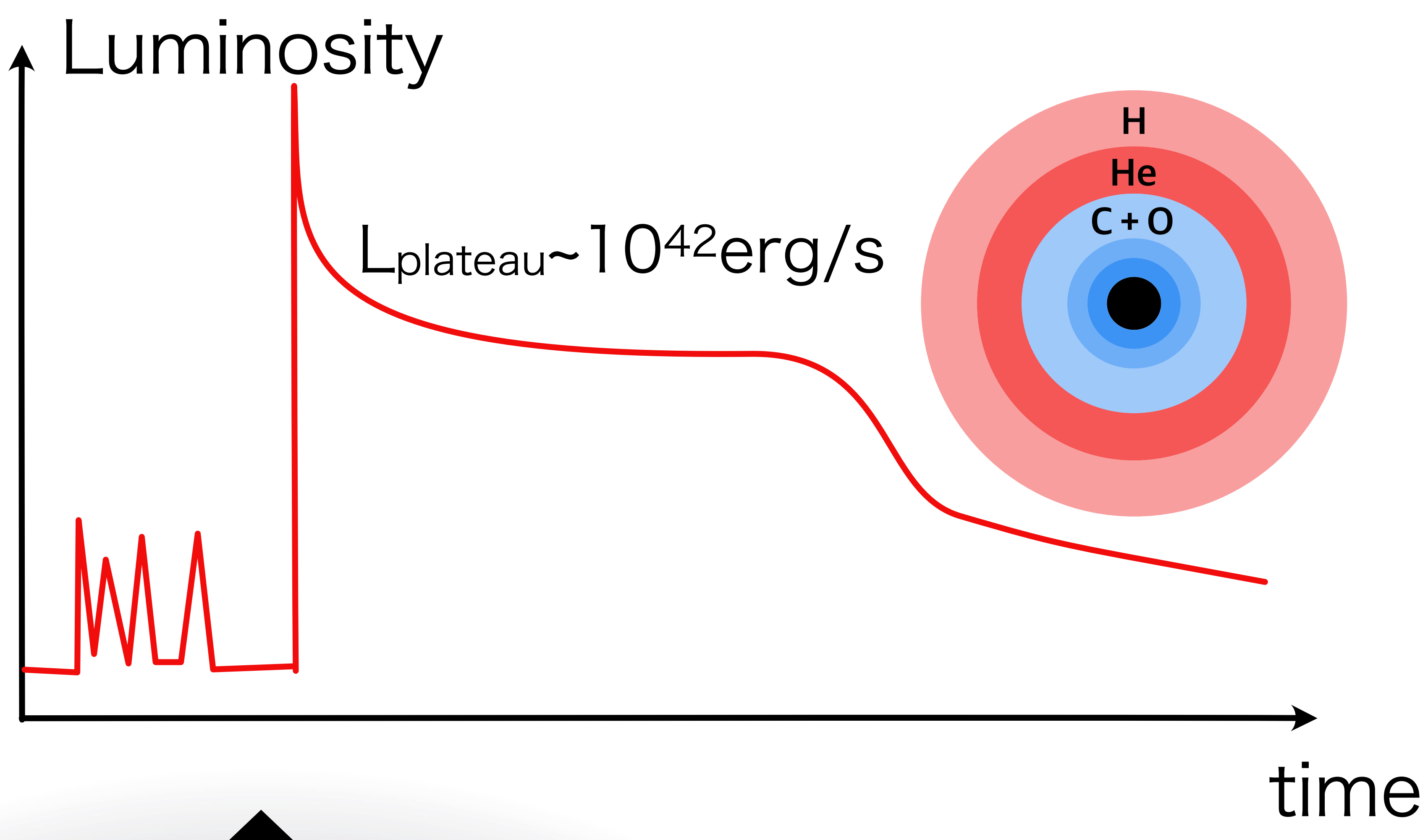


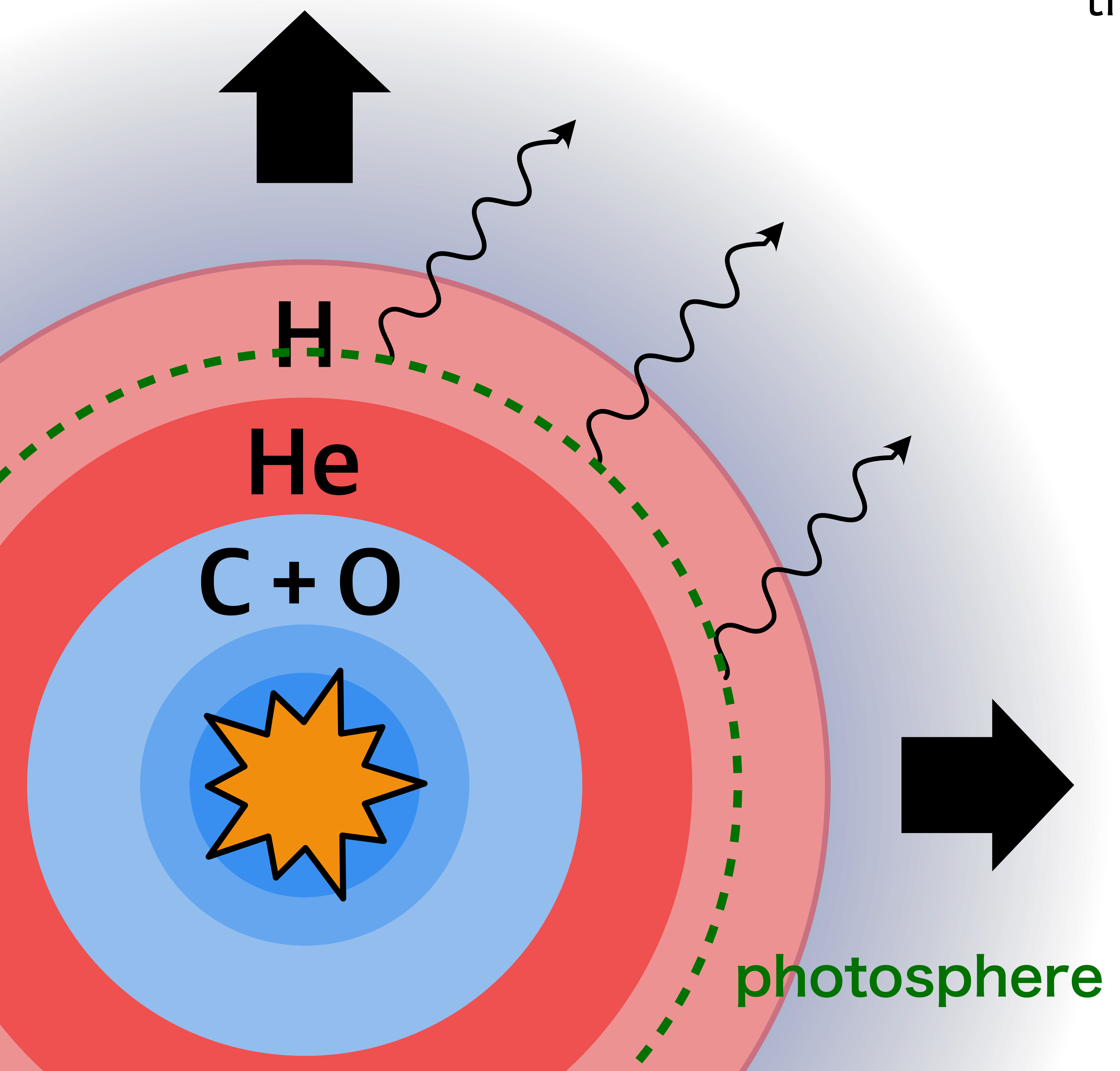
- explosions of red-supergiants (RSG) with typical M~10Msun and R~a few100 - 1000Rsun.
- $R_{\rm star} \sim 700 R_\odot \sim 5\times 10^{13}{\rm cm}$
- $T_0 = \left(\dfrac{3E_{\rm th,0}}{4\pi a_{\rm r} R_{\rm star}^3}\right)^{1/4} = 7\times 10^5 \left(\dfrac{E_{\rm th,0}}{10^{51}{\rm erg}}\right)^{1/4} \left(\dfrac{R_{\rm star}}{5\times 10^{13}{\rm cm}}\right)^{-3/4} [{\rm K}]$
- adiabatic cooling, $T = T_0 \left(R/R_{\rm star}\right)^{-1}$
- $R = \left(\dfrac{T_0}{T_{\rm rec}}\right) R_{\rm star} = 100 R_{\rm star} \left(\dfrac{T_{\rm rec}}{7\times 10^3{\rm K}}\right)^{-1} \left(\dfrac{T_0}{7\times 10^5{\rm K}}\right)$
- on average, the expansion velocity is given by

$$v \sim (2E_{\rm exp}/M)^{1/2} \sim 3\times 10^3 \left(\frac{E_{\rm exp}}{10^{51}{\rm erg}}\right)^{1/2} \left(\frac{M}{10M_\odot}\right)^{-1/2} [{\rm km/s}]$$

- $100 R_{\rm star}/v \sim 200[{\rm d}] \sim \mathcal{O}(100{\rm d})$

Type II-"Plateau" supernovae





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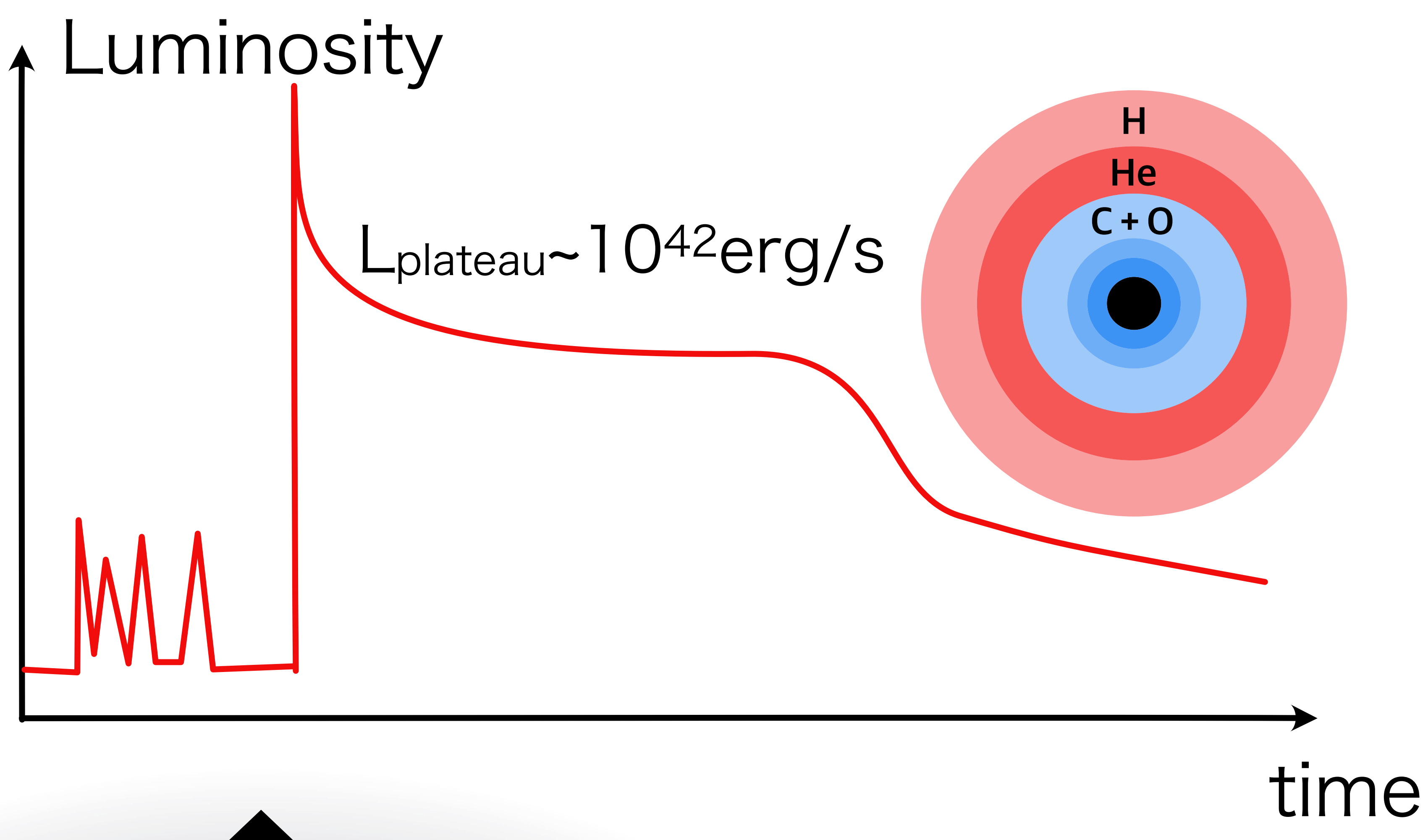
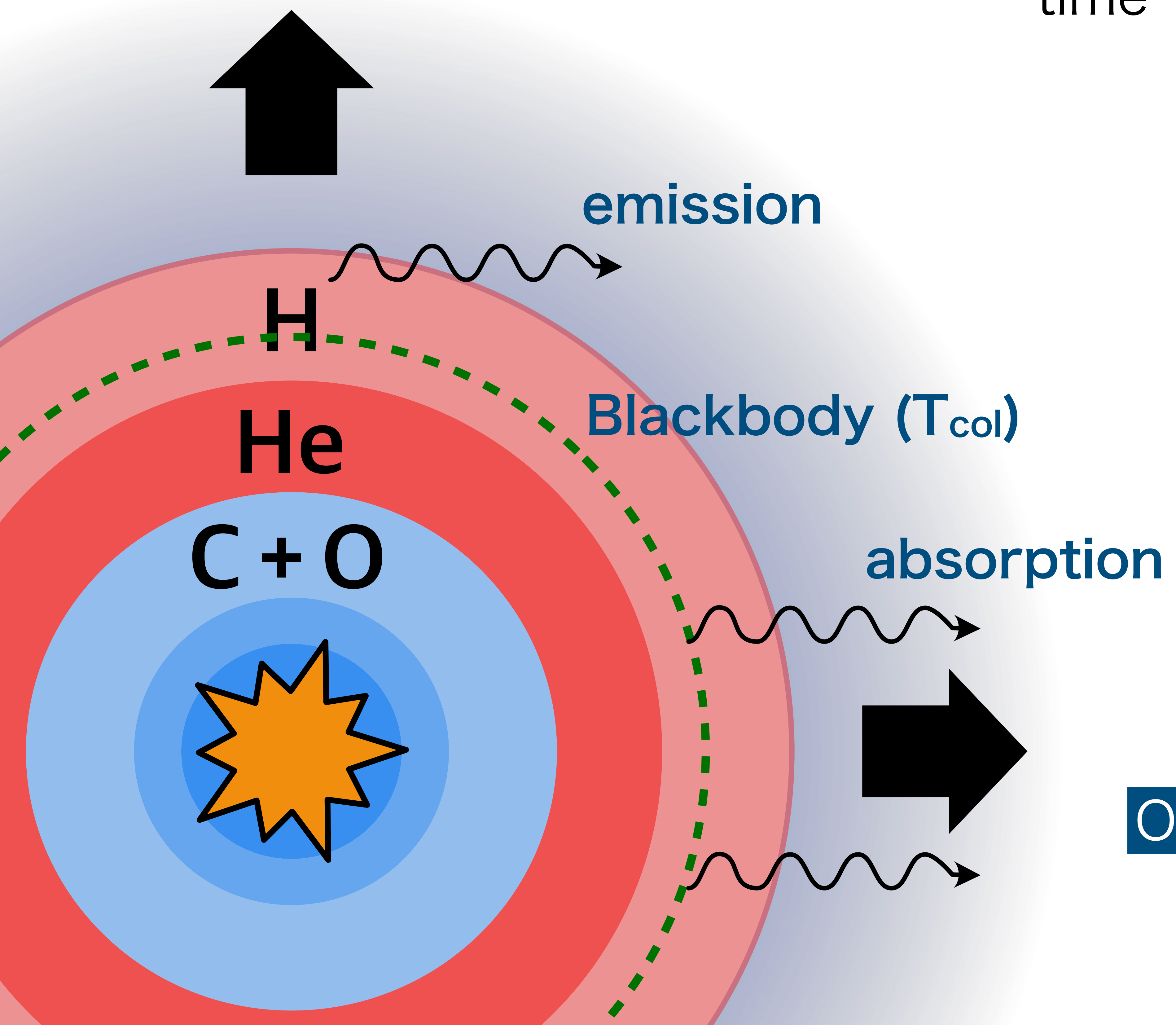
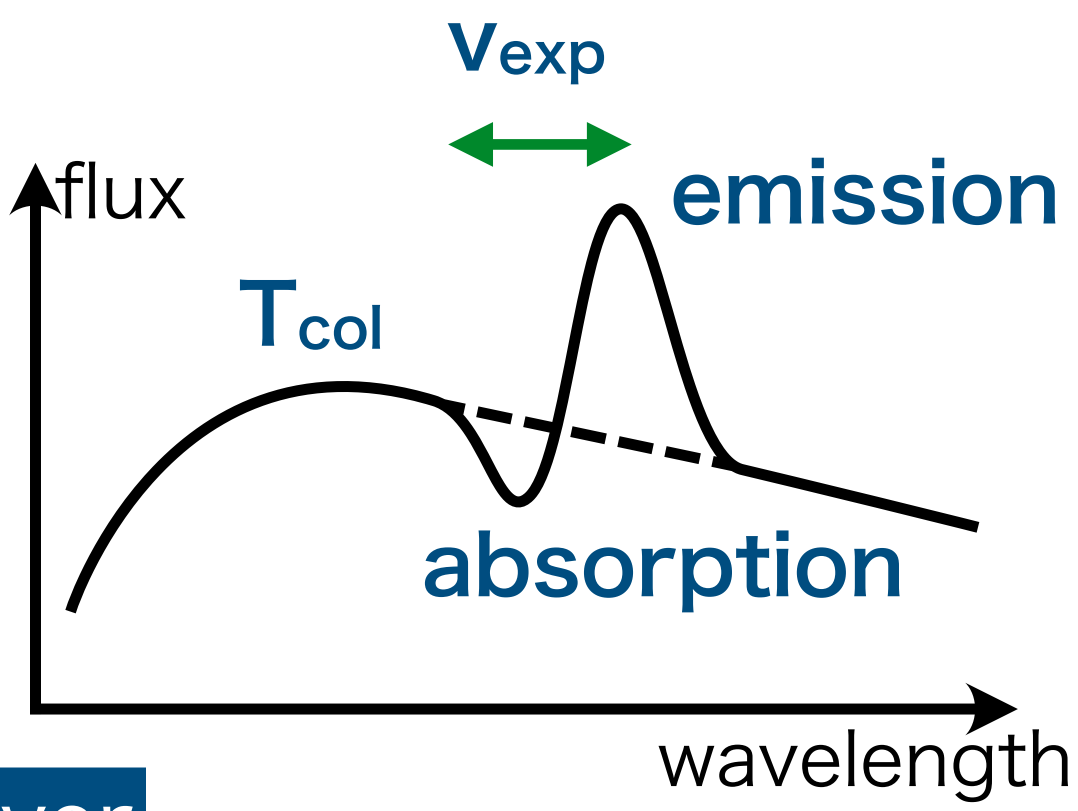
- $R_{\rm star} \sim 700 R_\odot \sim 5\times 10^{13}\,{\rm cm}$
- adiabatic cooling, $T = T_0\left(R/R_{\rm star}\right)^{-1}$
- at $R = 100R_{\rm star}$, $E_{\rm th} = 10^{49}{\rm erg}\left(\frac{E_{\rm th,0}}{10^{51}{\rm erg}}\right)\left(\frac{R}{100R_{\rm star}}\right)$
- L ~ 10^{49}[erg]/100[days] ~ 10^{42}[erg/s]
- order of magnitude estimate
- in reality, the recombination front propagate back from the surface to the center

Type II-“Plateau” supernovae

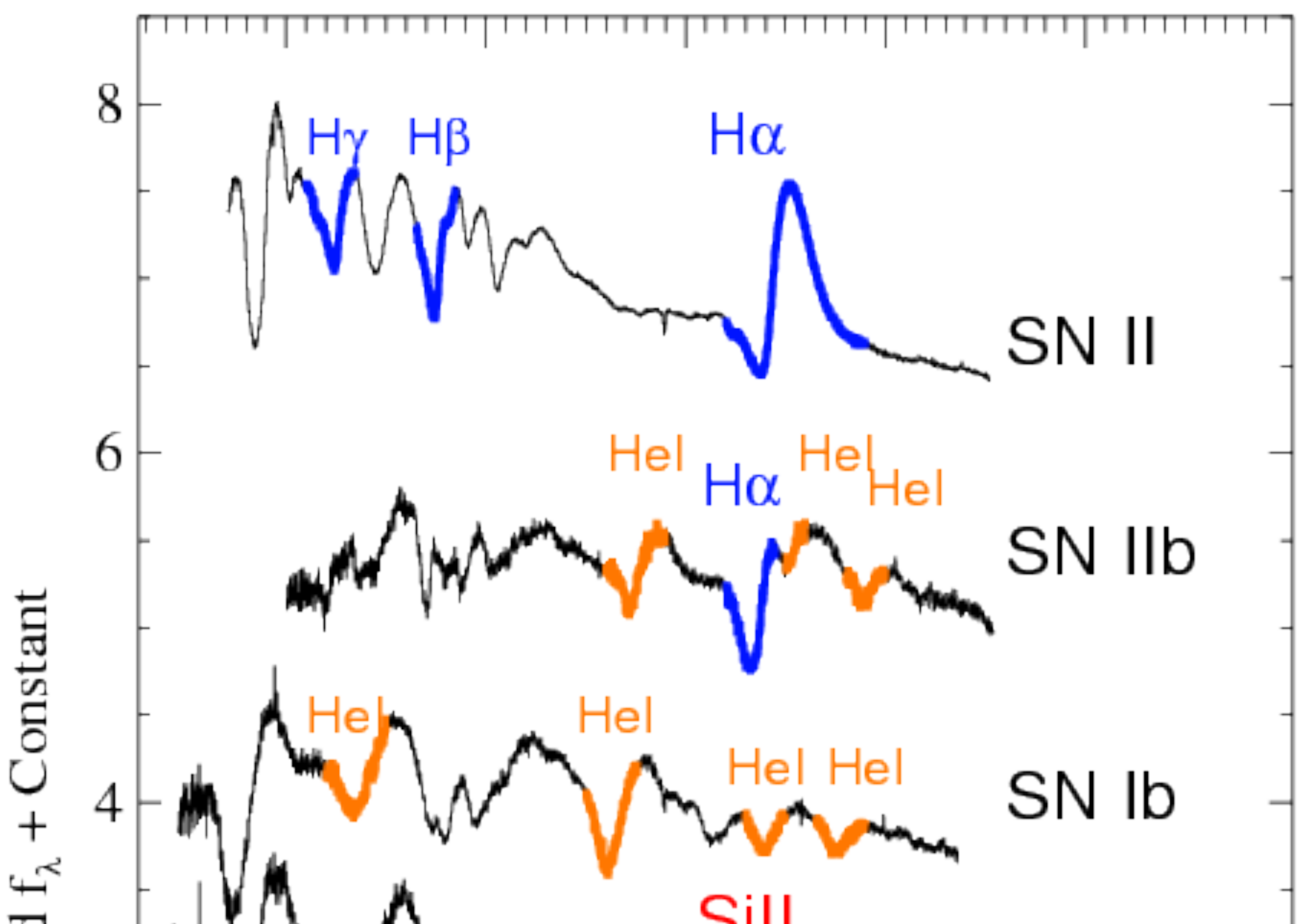


- in reality, the recombination front propagate back from the surface to the center
- accordingly, the thermal energy is released as radiation (with T_{BB}=T_{rec})
- type II SN spectra: temperature and doppler velocity (P-Cygni profile)

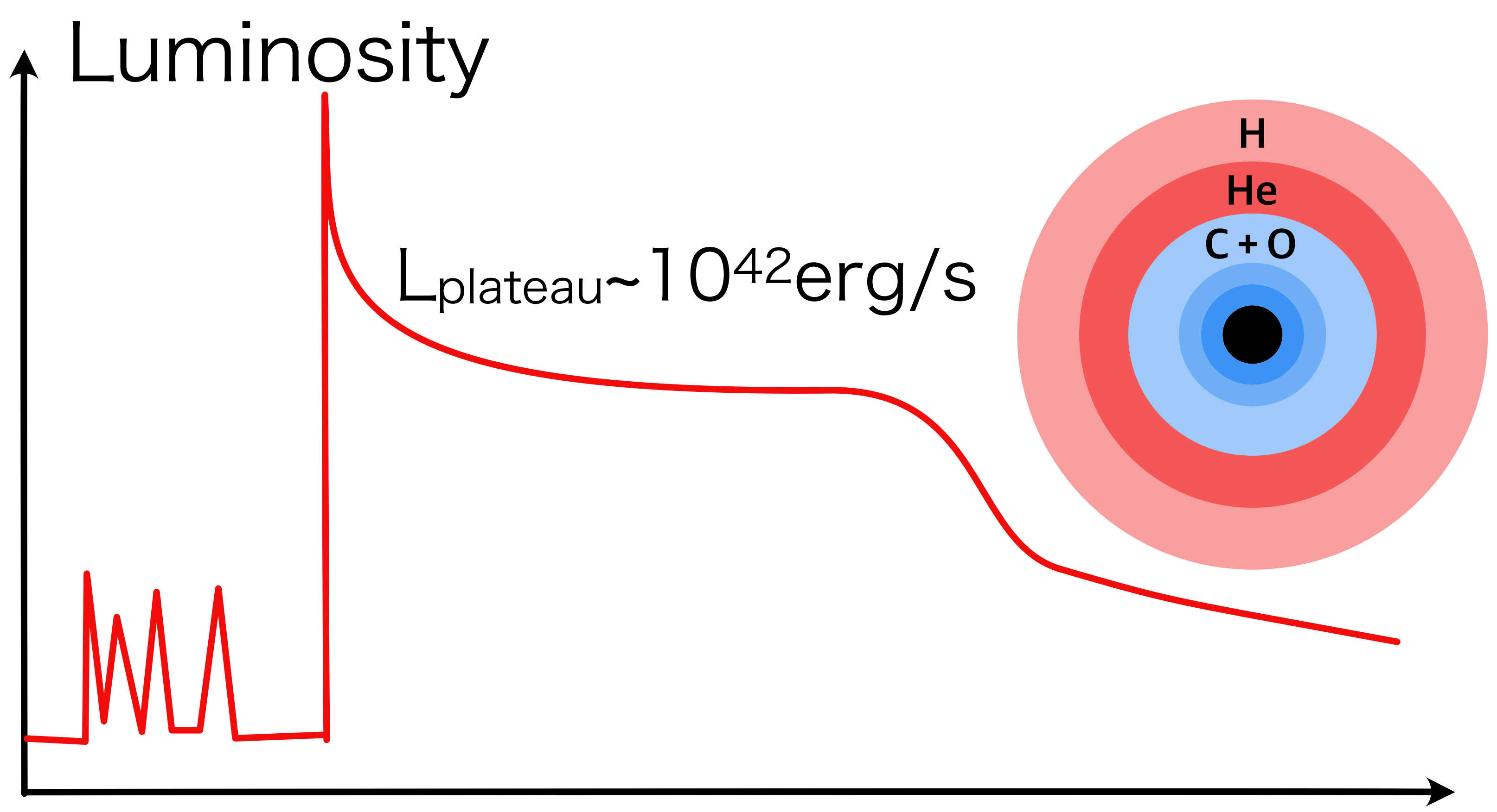


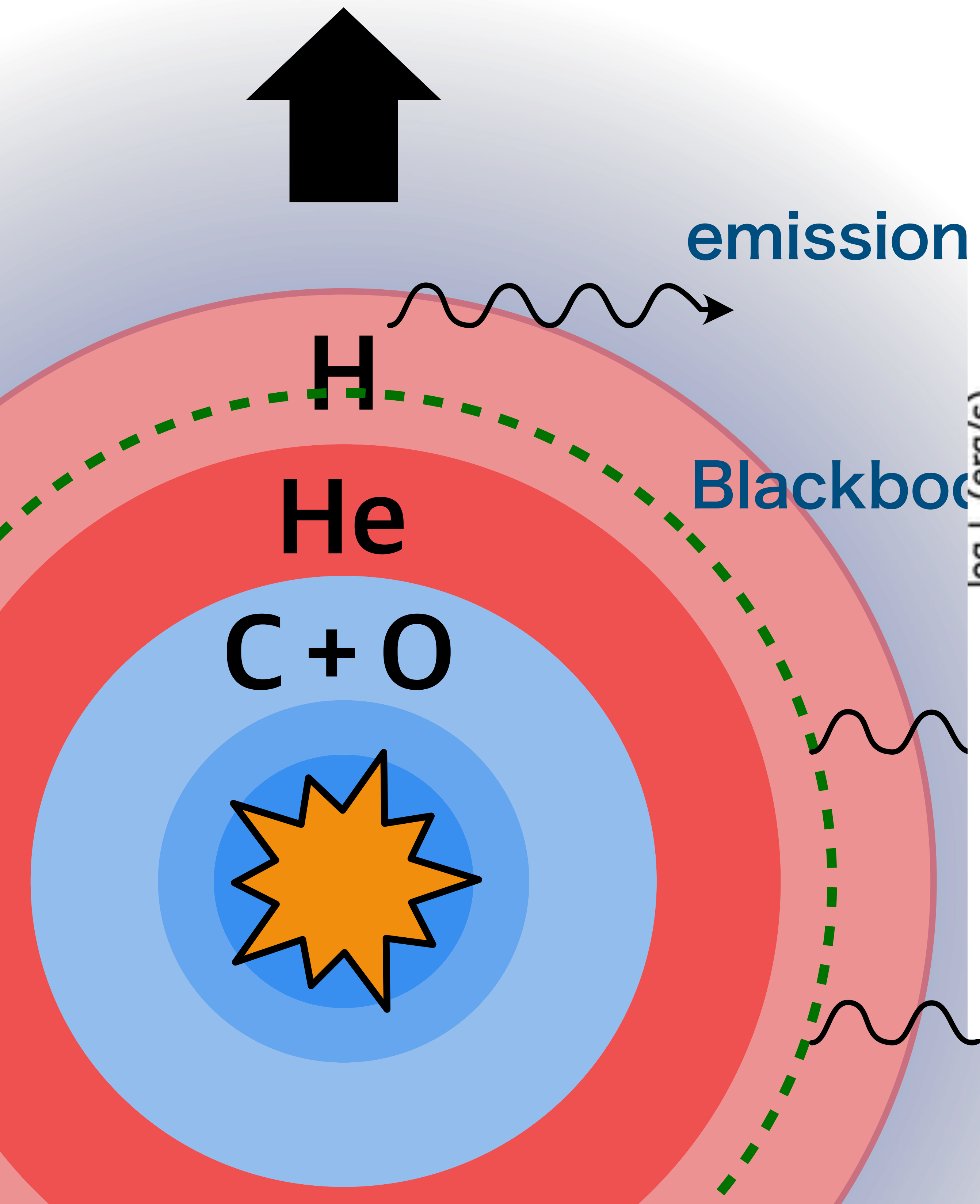


SN spectra (Modjaz+2014)



Type II-“Plateau” supernovae





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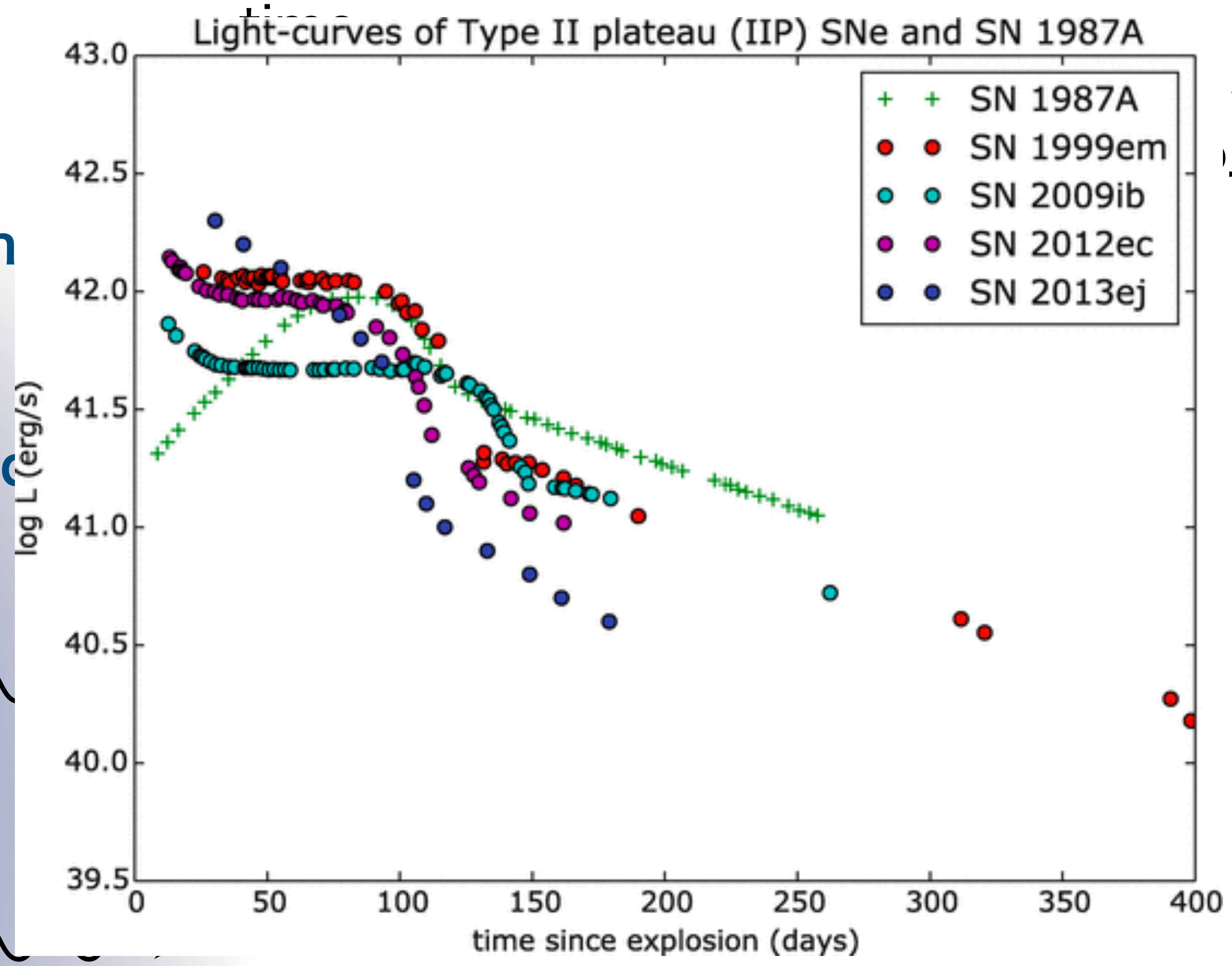
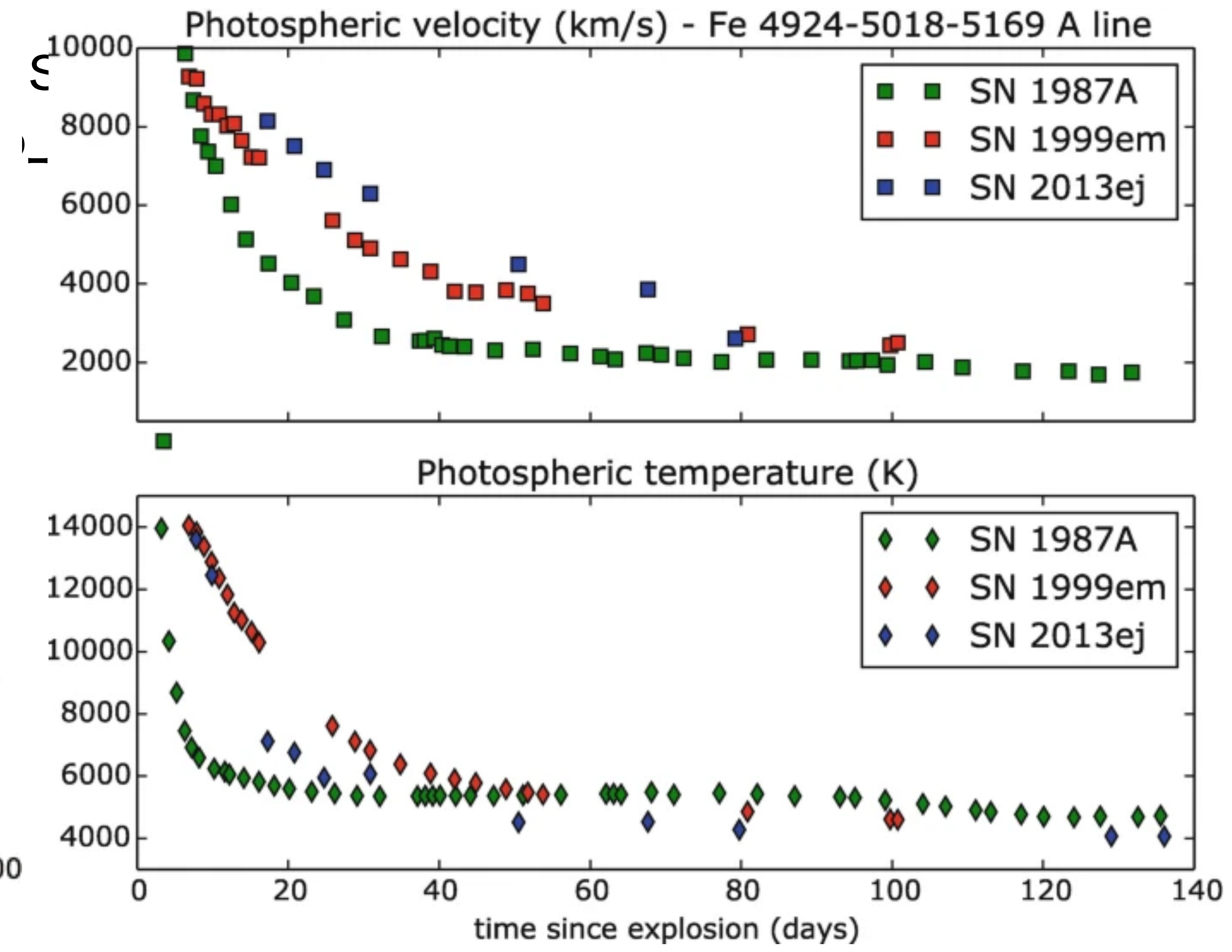
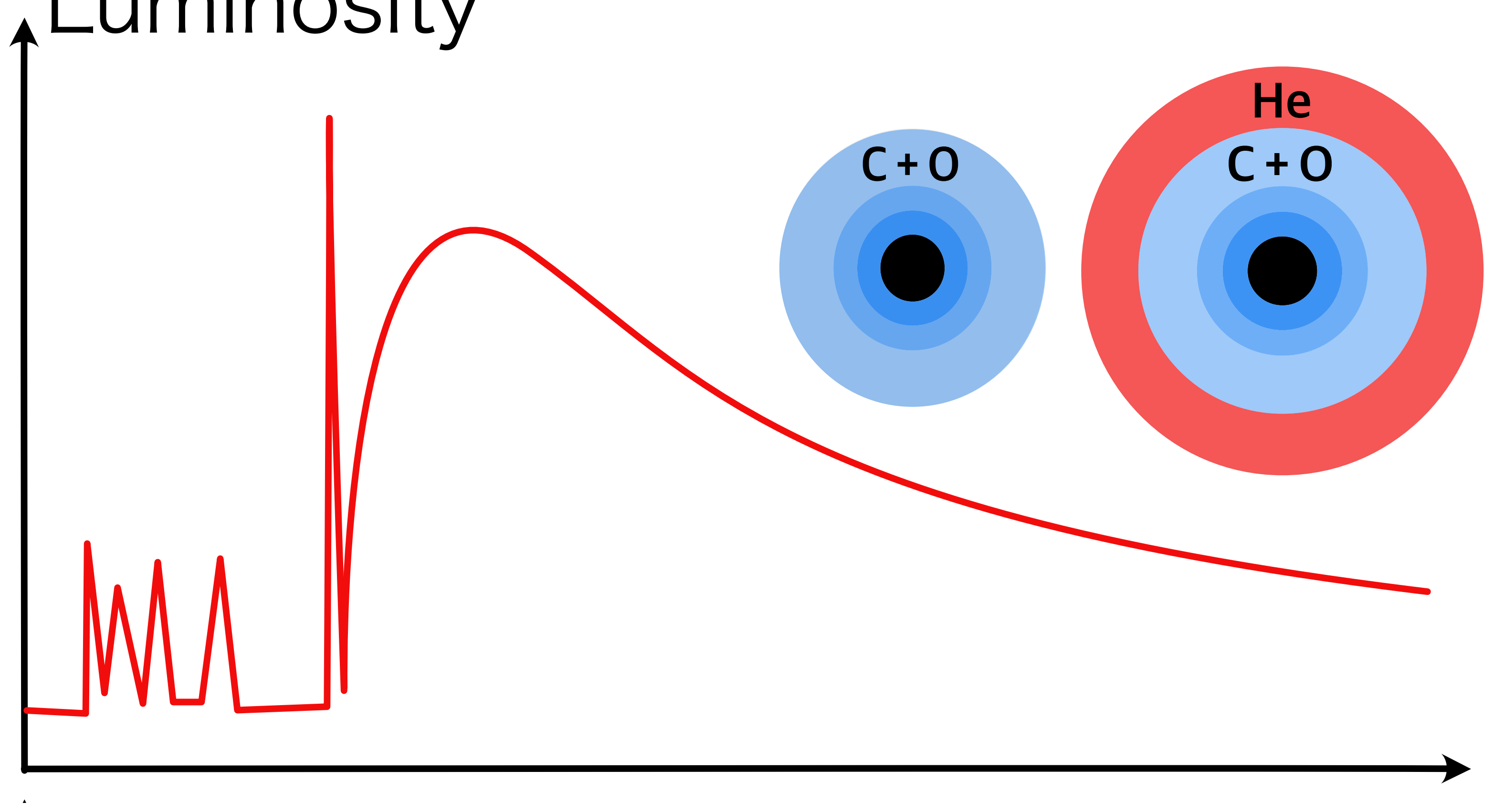
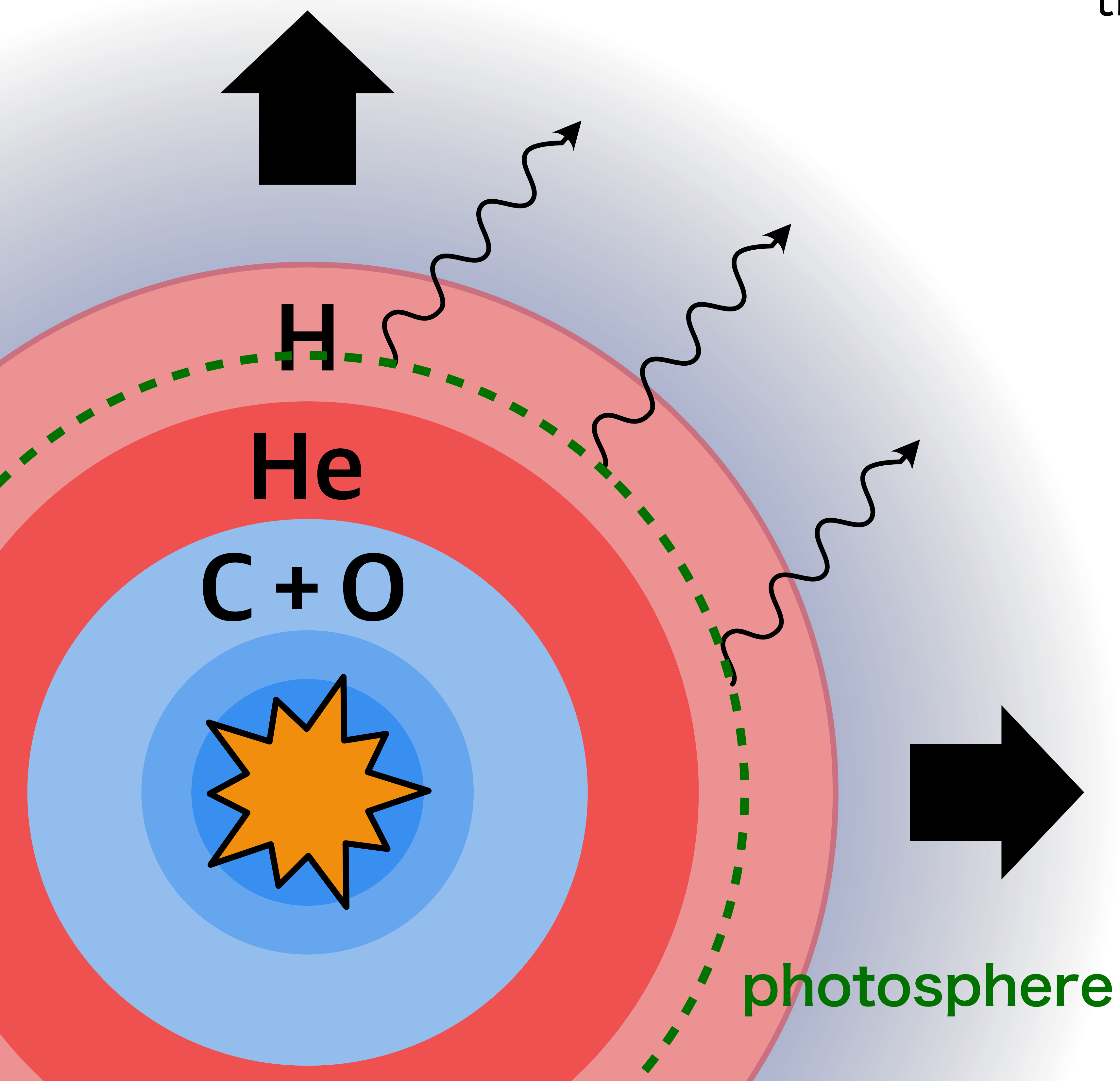




Type II SN light curves (Zampieri+2017)

Type Ibc or stripped-envelope supernovae





- explosions of He or CO star with typical M~ a few M_{sun} and R~ 1-10R_{sun}.
- initial thermal energy suffers from adiabatic cooling (H-poor: $\kappa \sim 0.1 \mathrm{cm^2/g}$)
- radioactive energy instead heats up the ejecta

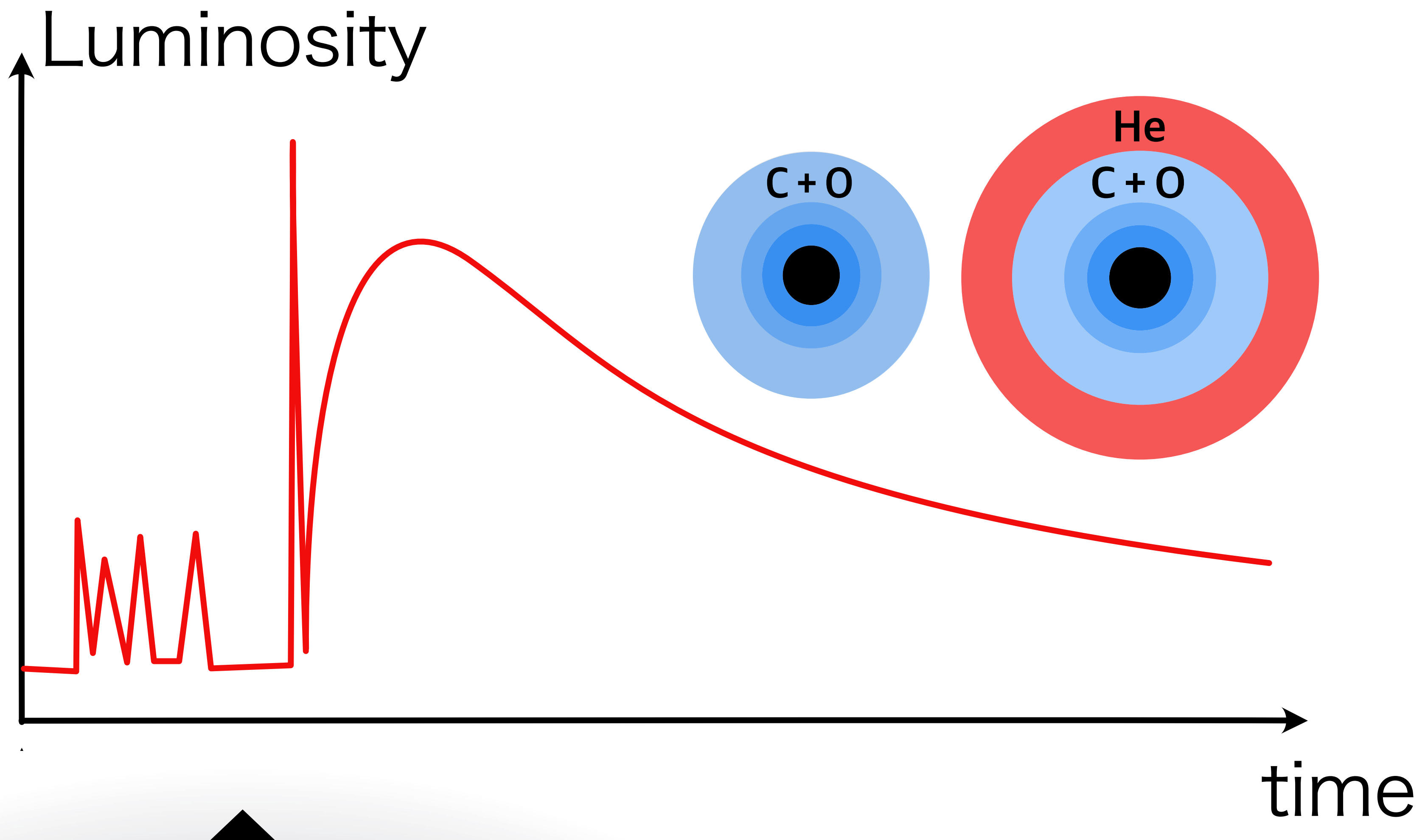
$$M_{\rm Ni}(t) = M_{\rm Ni}(0) e^{-t/\tau_{\rm Ni}}$$

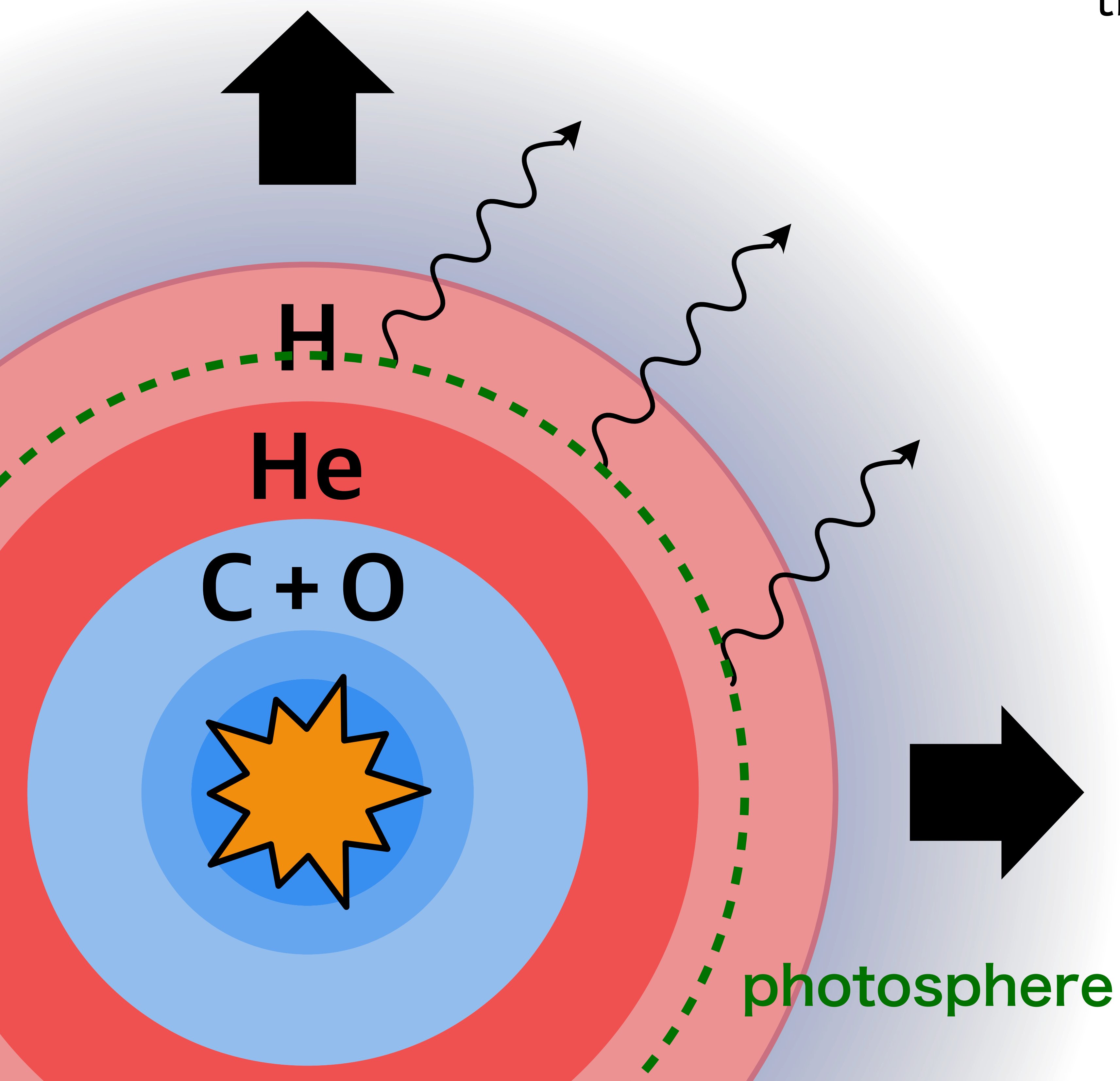
$$M_{\rm Co}(t) = M_{\rm Ni}(0) \frac{\tau_{\rm Co}}{\tau_{\rm Co} - \tau_{\rm Ni}} \left(e^{-t/\tau_{\rm Co}} - e^{-t/\tau_{\rm Ni}} \right)$$

$$M_{\rm Fe}(t) = M_{\rm Ni}(0) \left[1 - \frac{\tau_{\rm Co}}{\tau_{\rm Co} - \tau_{\rm Ni}} e^{-t/\tau_{\rm Co}} + \frac{\tau_{\rm Ni}}{\tau_{\rm Co} - \tau_{\rm Ni}} e^{-t/\tau_{\rm Ni}} \right]$$

$$\tau_{\rm Ni} = 8.8[\mathrm{d}], \quad \tau_{\rm Co} = 111[\mathrm{d}]$$

Type Ibc or stripped-envelope supernovae





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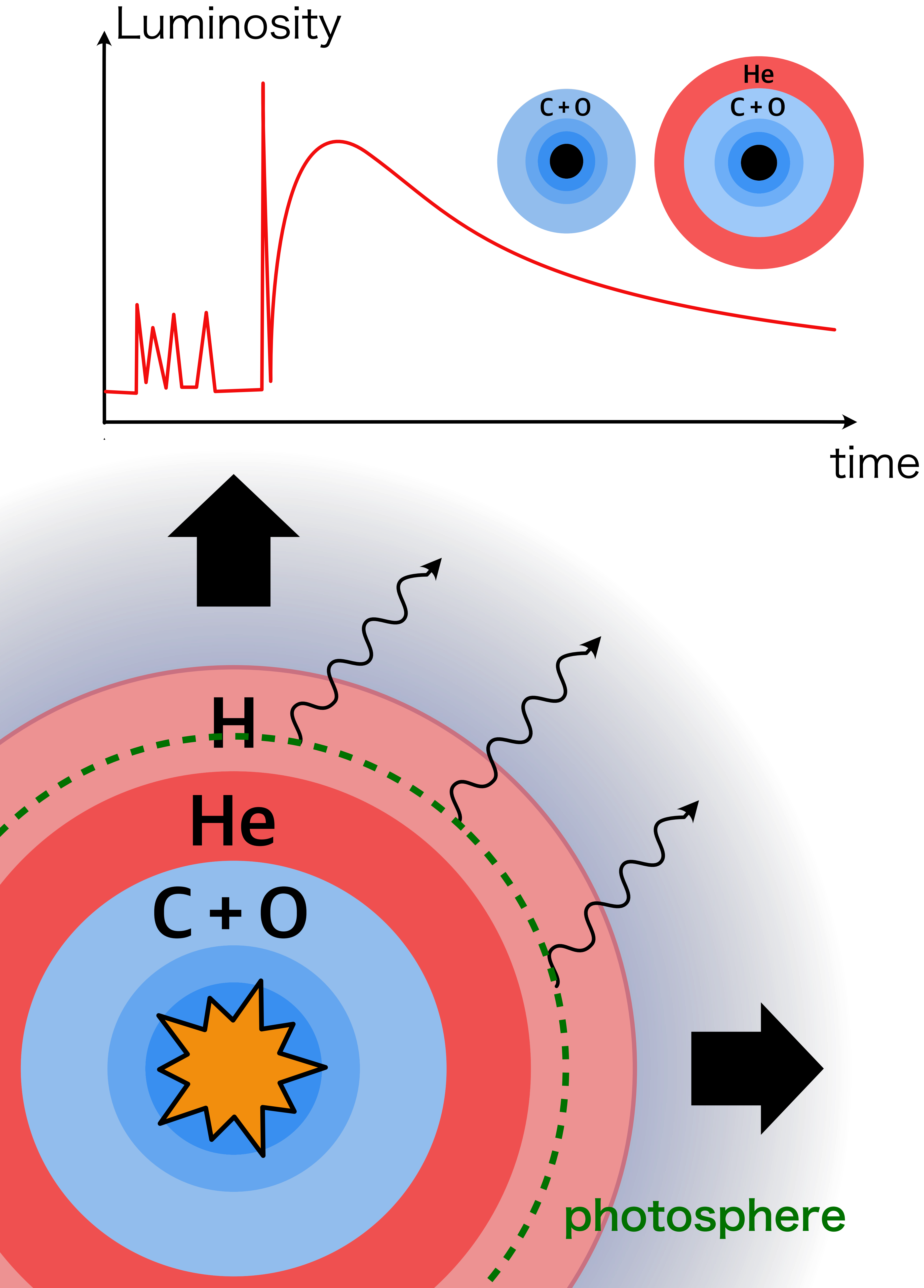
$$\begin{aligned}\dot{E}_{\rm nuc} =& \epsilon_{\rm Ni}\frac{M_{\rm Ni}(t)}{\tau_{\rm Ni}}+\epsilon_{\rm Co}\frac{M_{\rm Co}(t)}{\tau_{\rm Co}},\\ =& \left[\left(\frac{\epsilon_{\rm Ni}}{\tau_{\rm Ni}}-\frac{\epsilon_{\rm Co}}{\tau_{\rm Co}-\tau_{\rm Ni}}\right)e^{-t/\tau_{\rm Ni}}+\frac{\epsilon_{\rm Co}}{\tau_{\rm Co}-\tau_{\rm Ni}}e^{-t/\tau_{\rm Co}}\right]M_{\rm Ni}(0)\end{aligned}$$

$$\begin{aligned}\epsilon_{\rm Ni} =& (1-m_{\rm 56Co}/m_{\rm 56Ni})c^2\\ =& (1-55.939844/55.94214)c^2\\ =& 3.69\times 10^{16}\ \mathrm{erg\ g^{-1}}\end{aligned}$$

$$\begin{aligned}\epsilon_{\rm Co} =& (1-m_{\rm 56Fe}/m_{\rm 56Co})c^2\\ =& (1-55.9349393/55.939844)c^2\\ =& 7.88\times 10^{16}\ \mathrm{erg\ g^{-1}},\end{aligned}$$

Type Ibc or stripped-envelope supernovae



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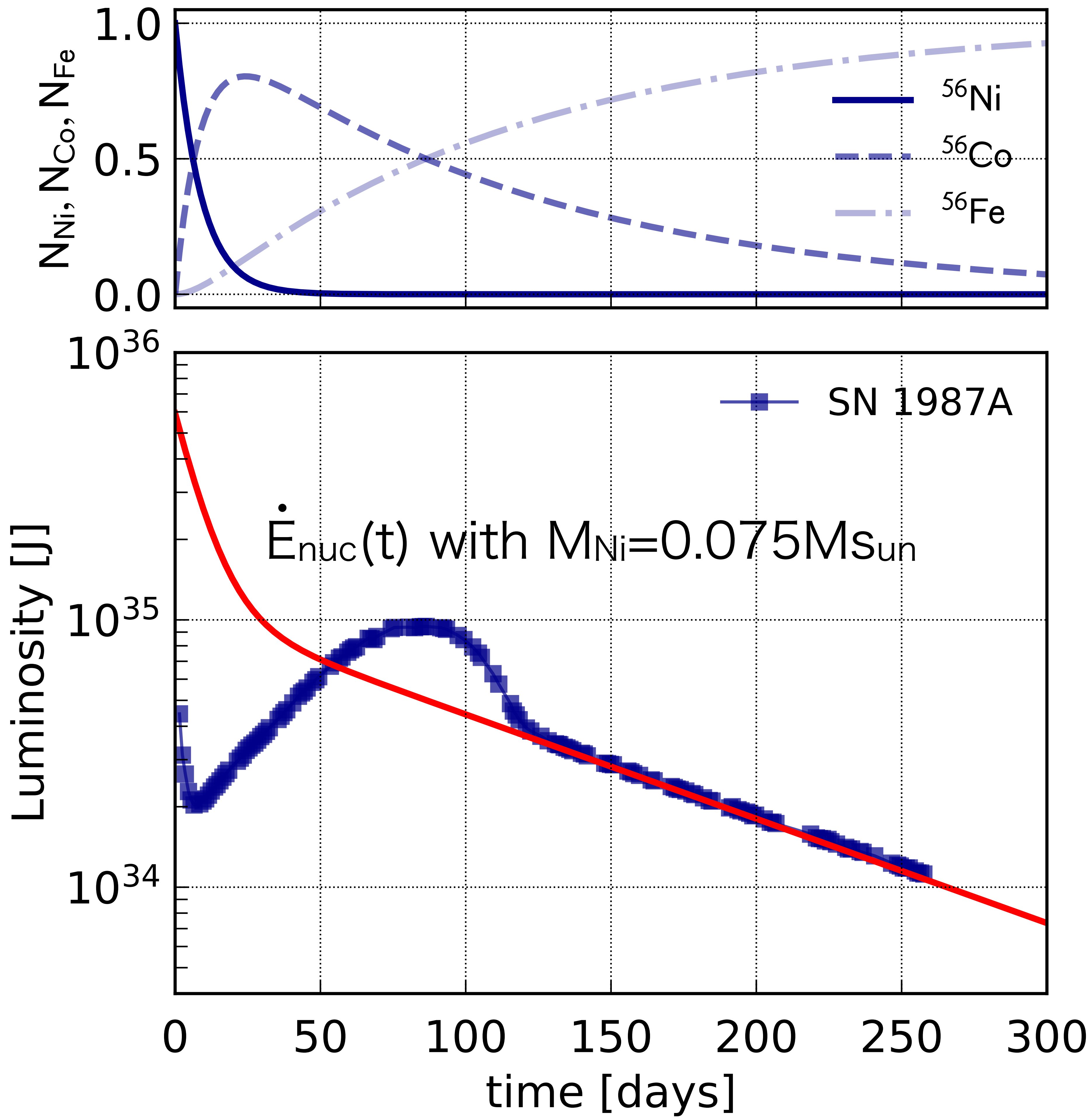

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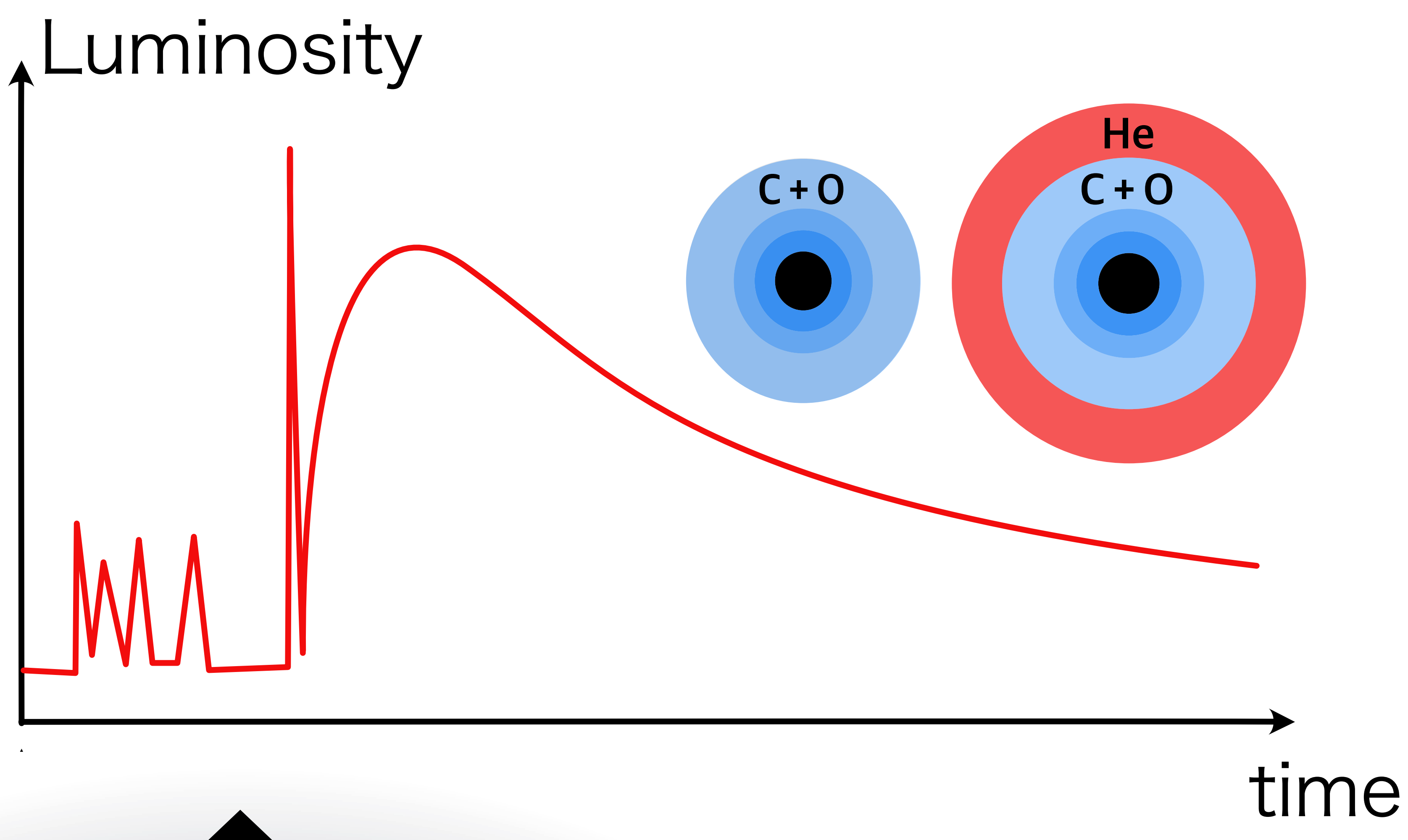

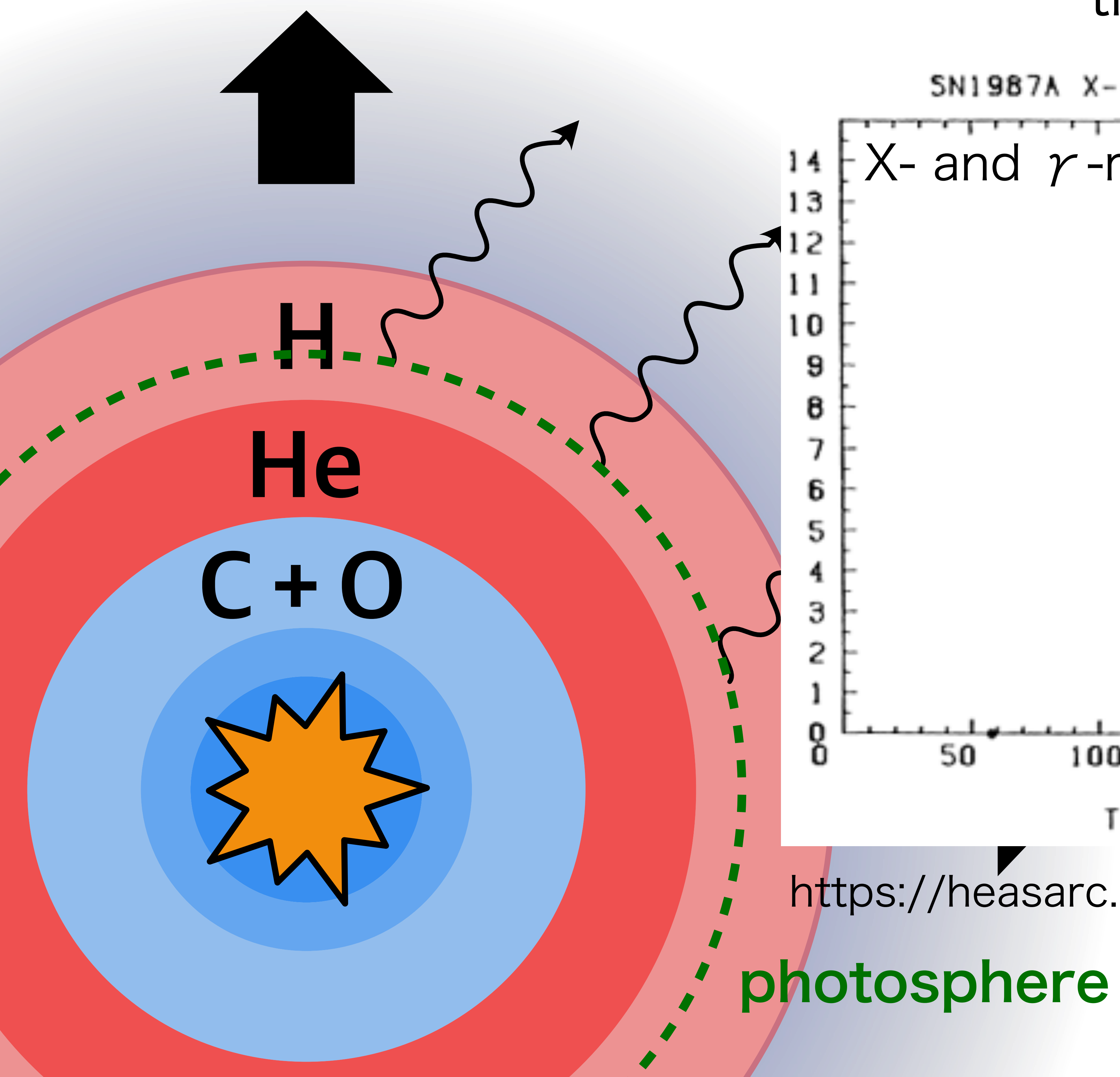

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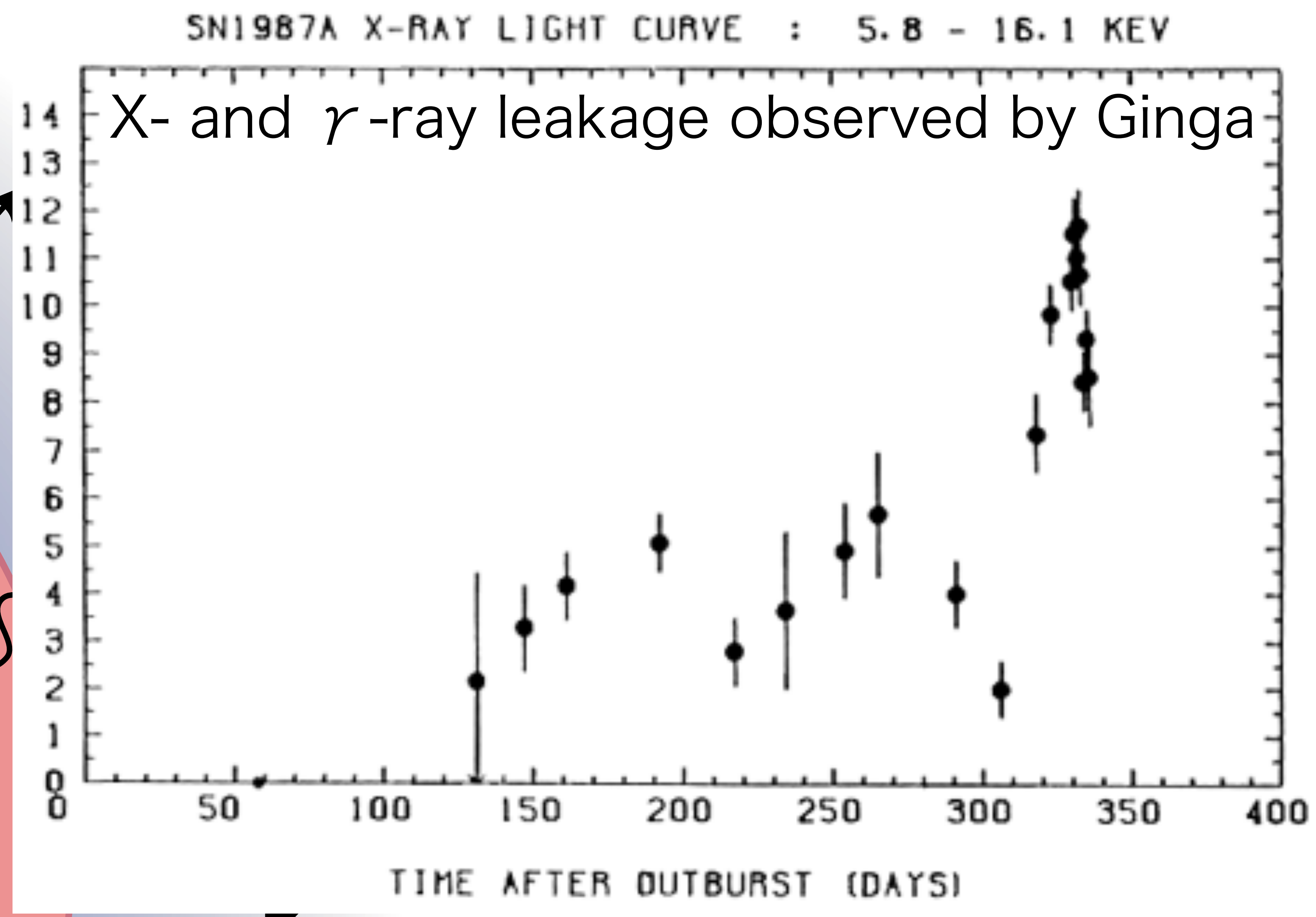
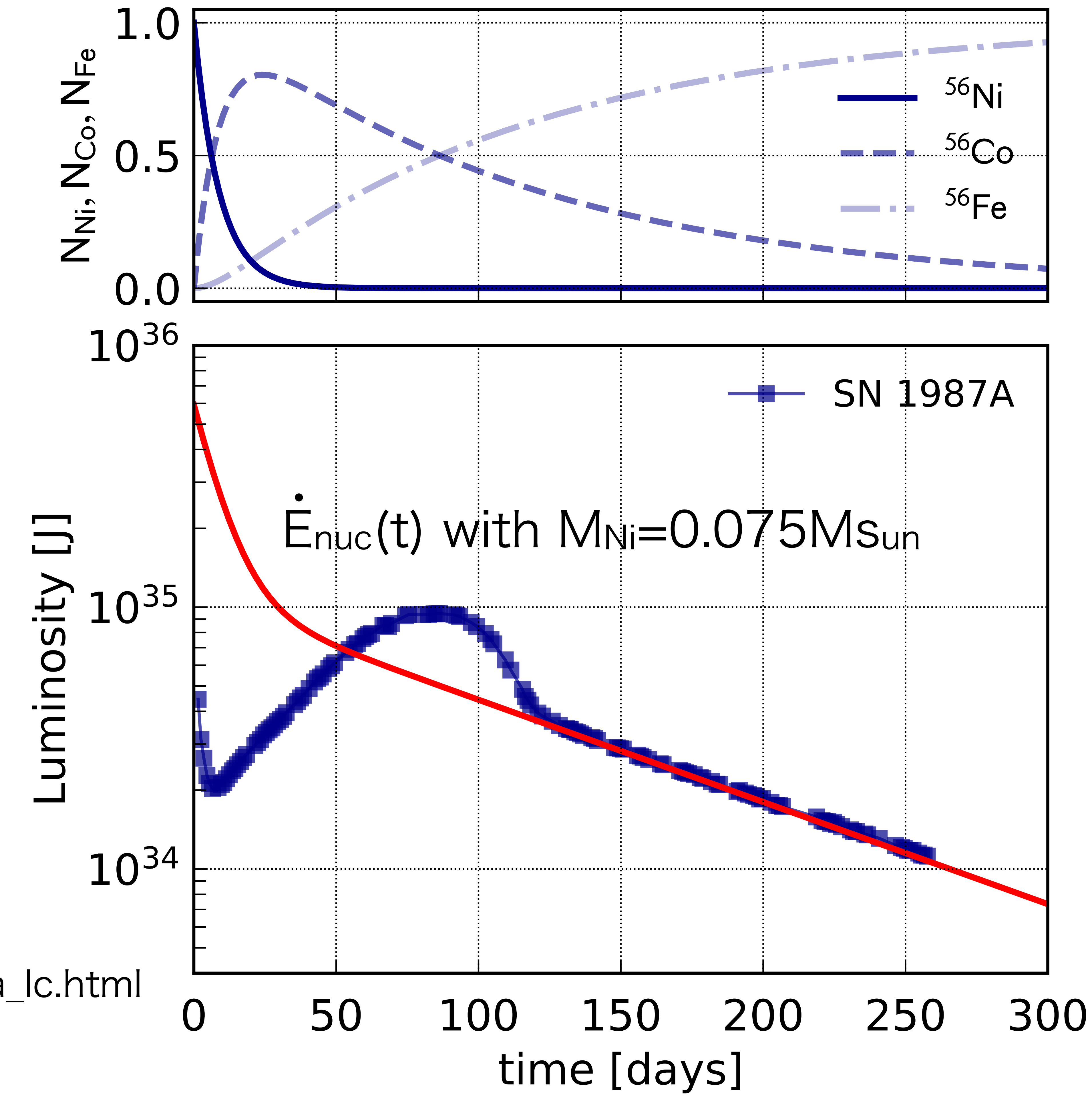


https://heasarc.gsfc.nasa.gov/docs/objects/snrs/sn1987a_lc.html



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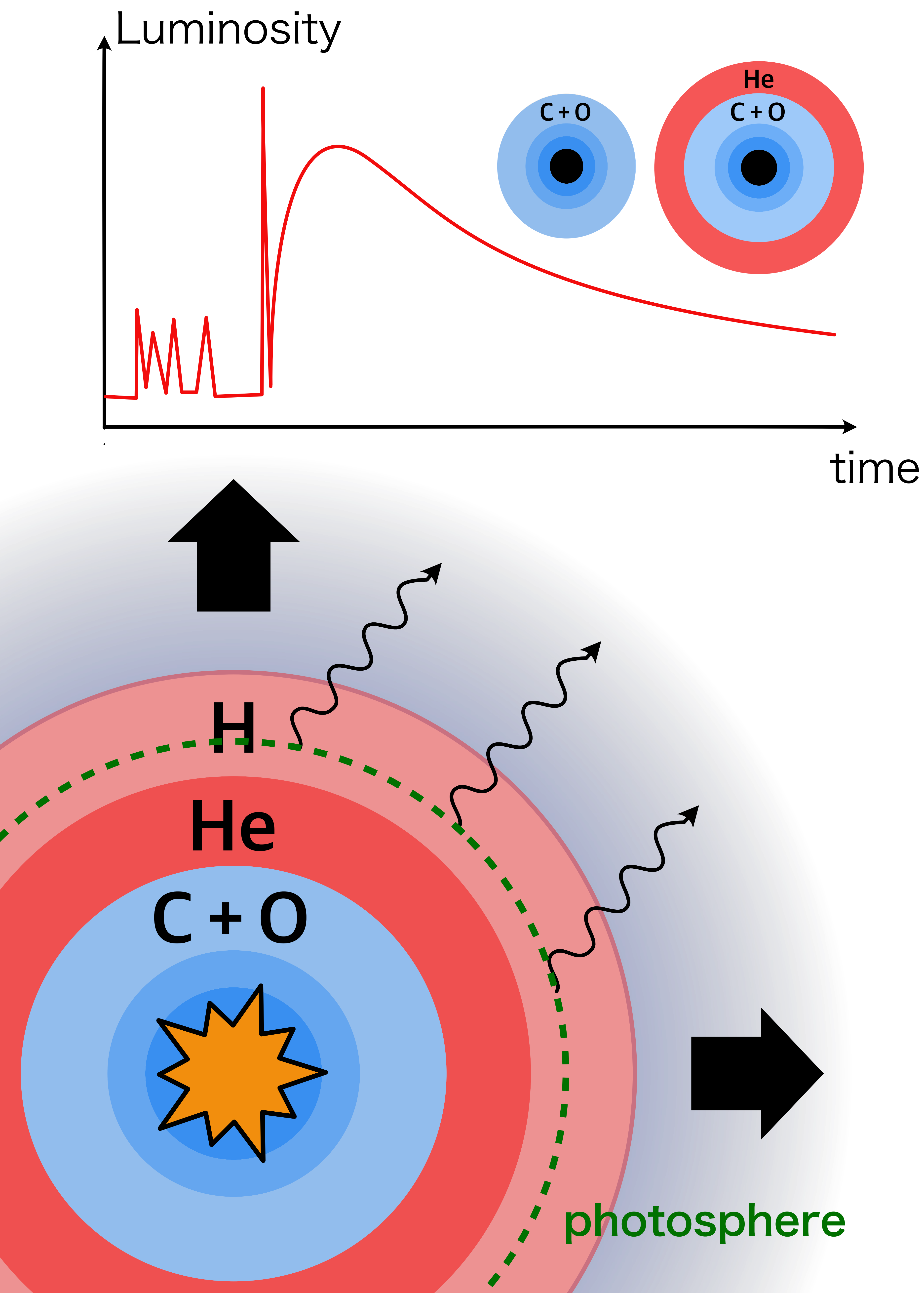
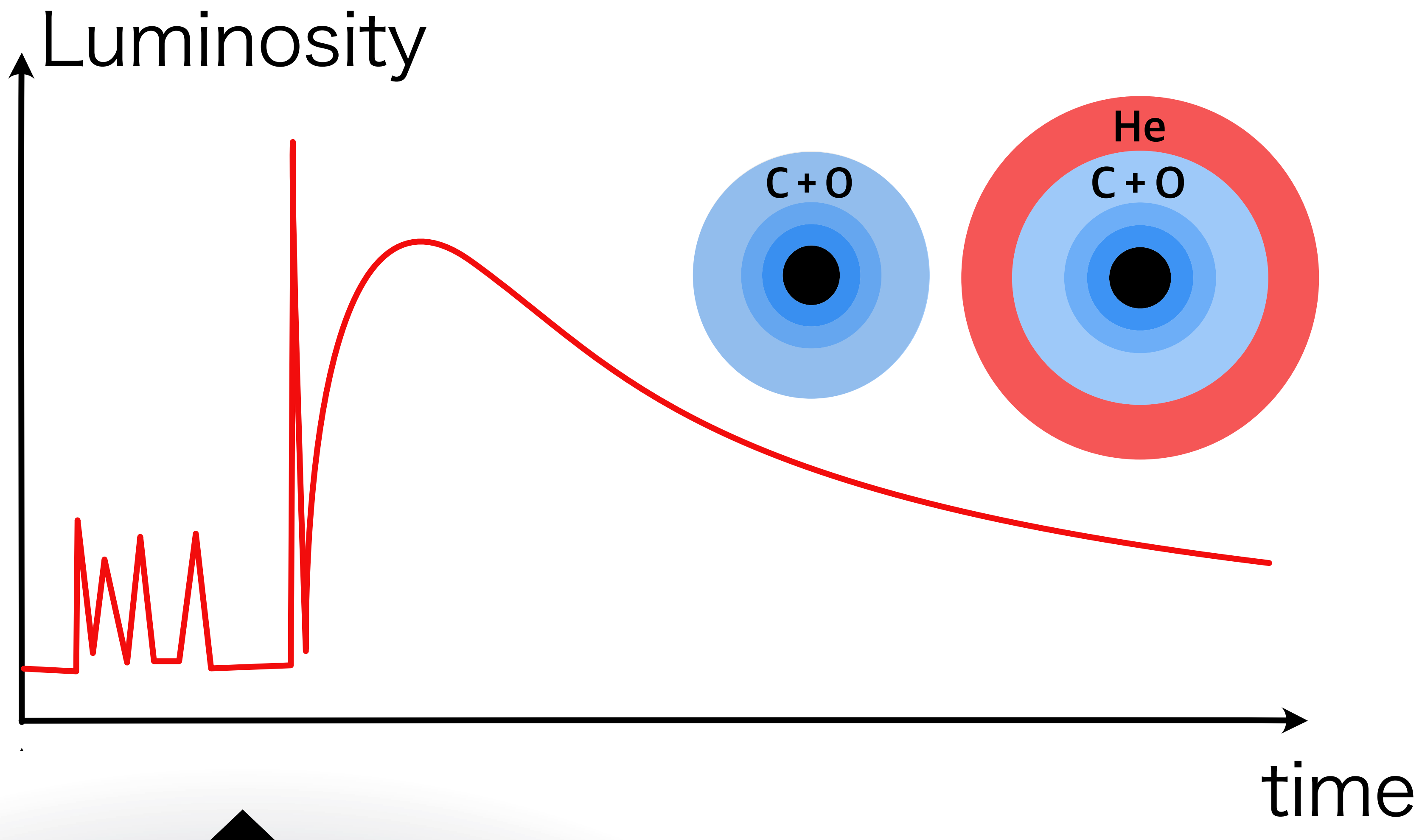
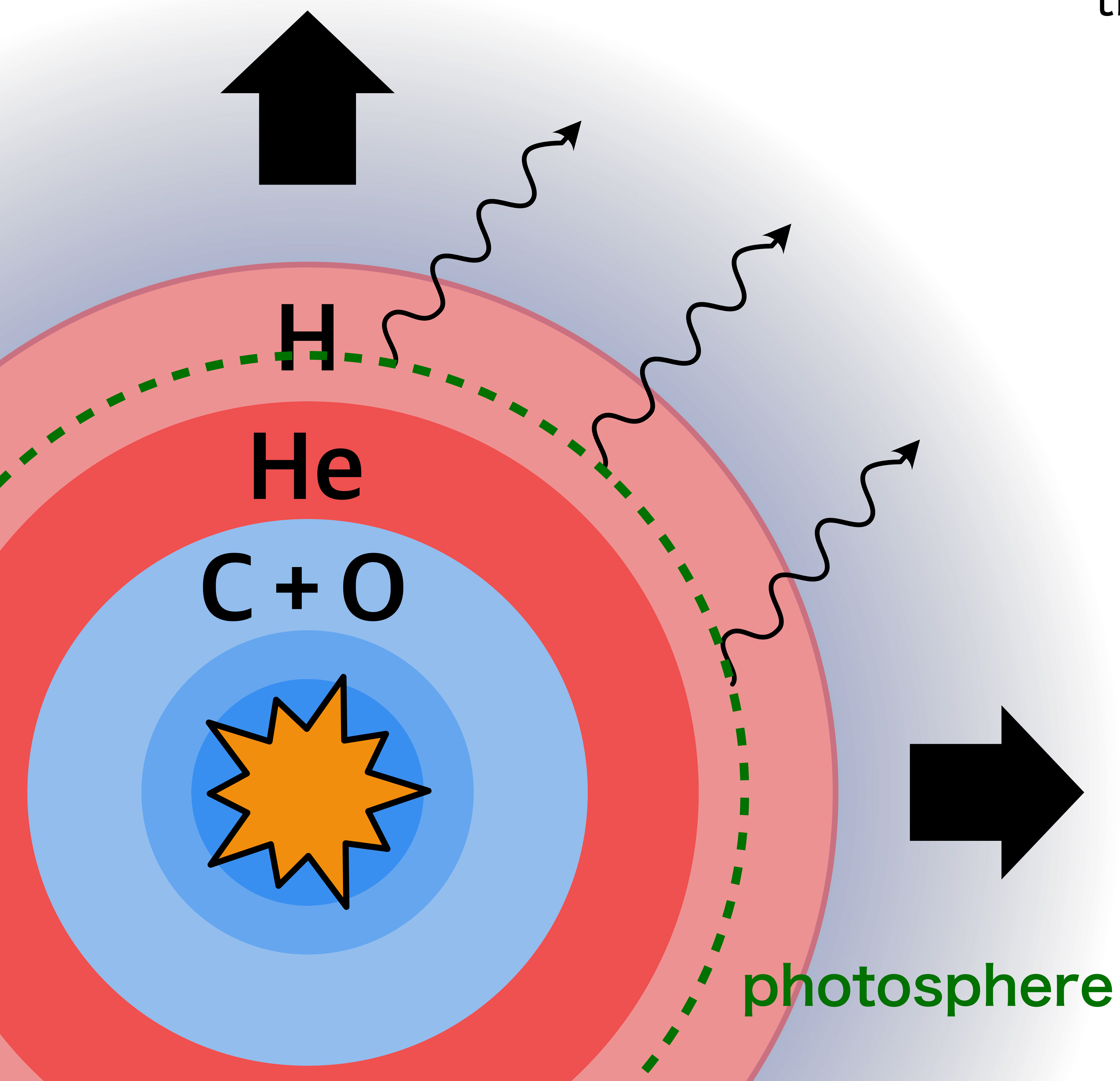


- explosions of He or CO star with typical M~ a few Msun and R~ 1-10Rsun.
- diffusion time: $\tau_{\rm diff} = \dfrac{R}{v_{\rm diff}} = \dfrac{\tau}{c}R = \dfrac{\kappa\rho R^2}{c} \sim \dfrac{\kappa M}{cR}$
- expansion time: $\tau_{\rm exp} = \dfrac{R}{v}$
- Initially, $\tau_{\rm diff} \ll \tau_{\rm exp}$: dragged by expansion
- When $\tau_{\rm diff} \sim \tau_{\rm exp}$, photons efficiently escape through the photosphere (peak L).

$$t_{\rm peak} \propto \left(\frac{\kappa M}{cv}\right)^{1/2} = 40\left(\frac{\kappa}{0.1{\rm cm^2/g}}\right)^{1/2}\left(\frac{M}{2M_\odot}\right)^{1/2}\left(\frac{v}{10^4{\rm km/s}}\right)^{-1/2} [{\rm d}]$$

Type Ibc or stripped-envelope supernovae





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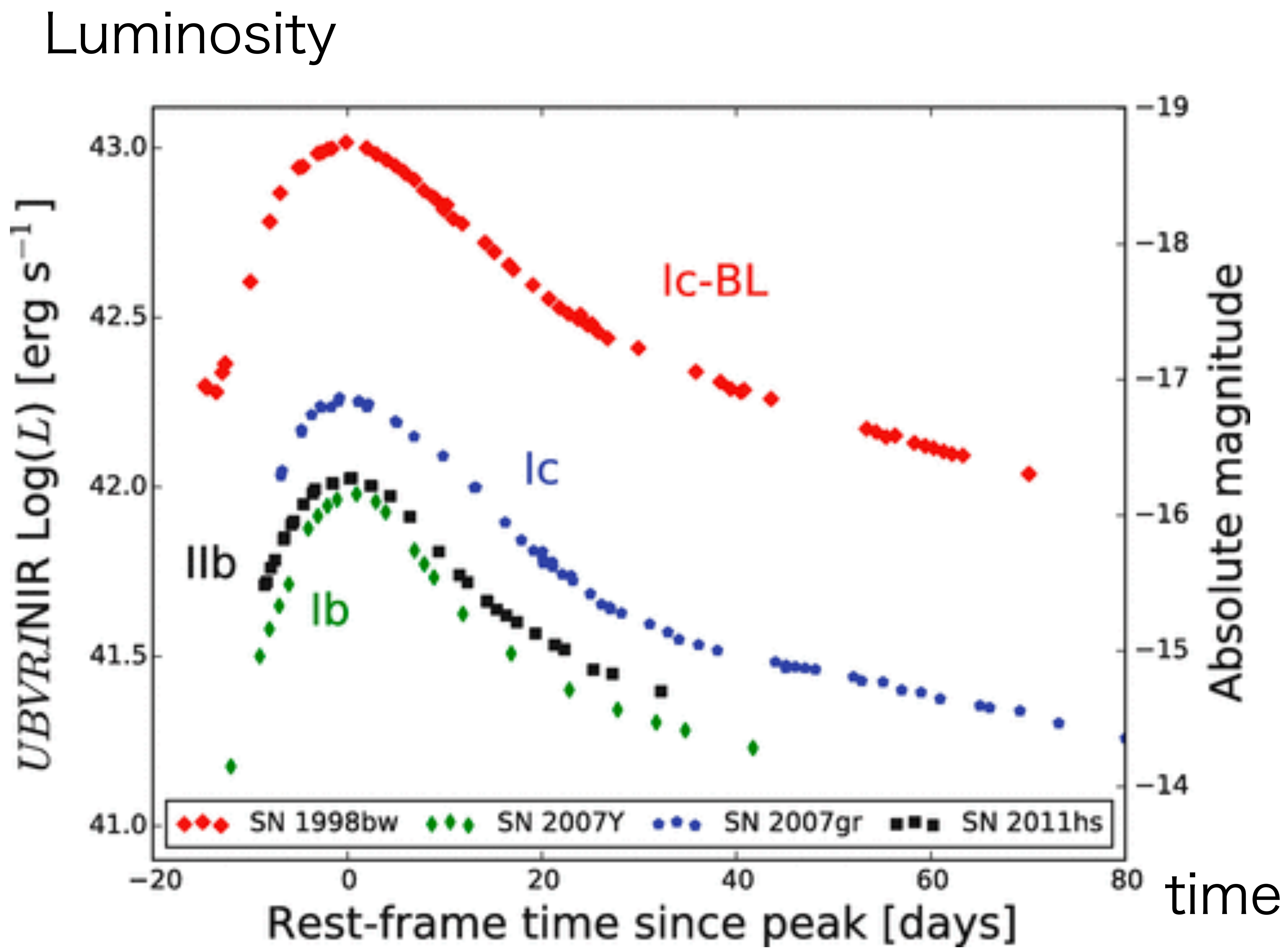
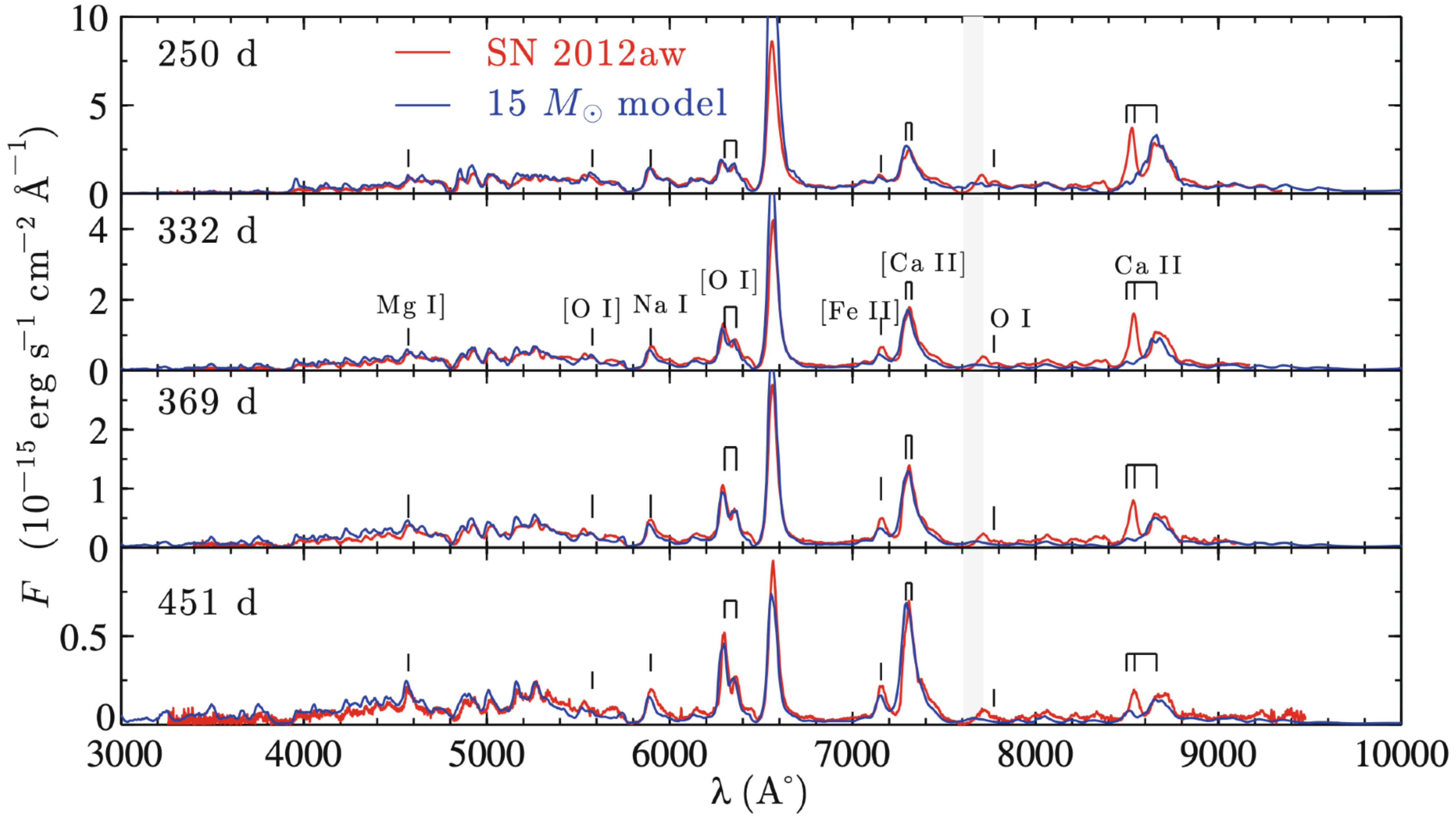
$$L_{\rm peak} = \dot{E}_{\rm nuc}(t_{\rm peak}) \sim 10^{42} [{\rm erg/s}]$$



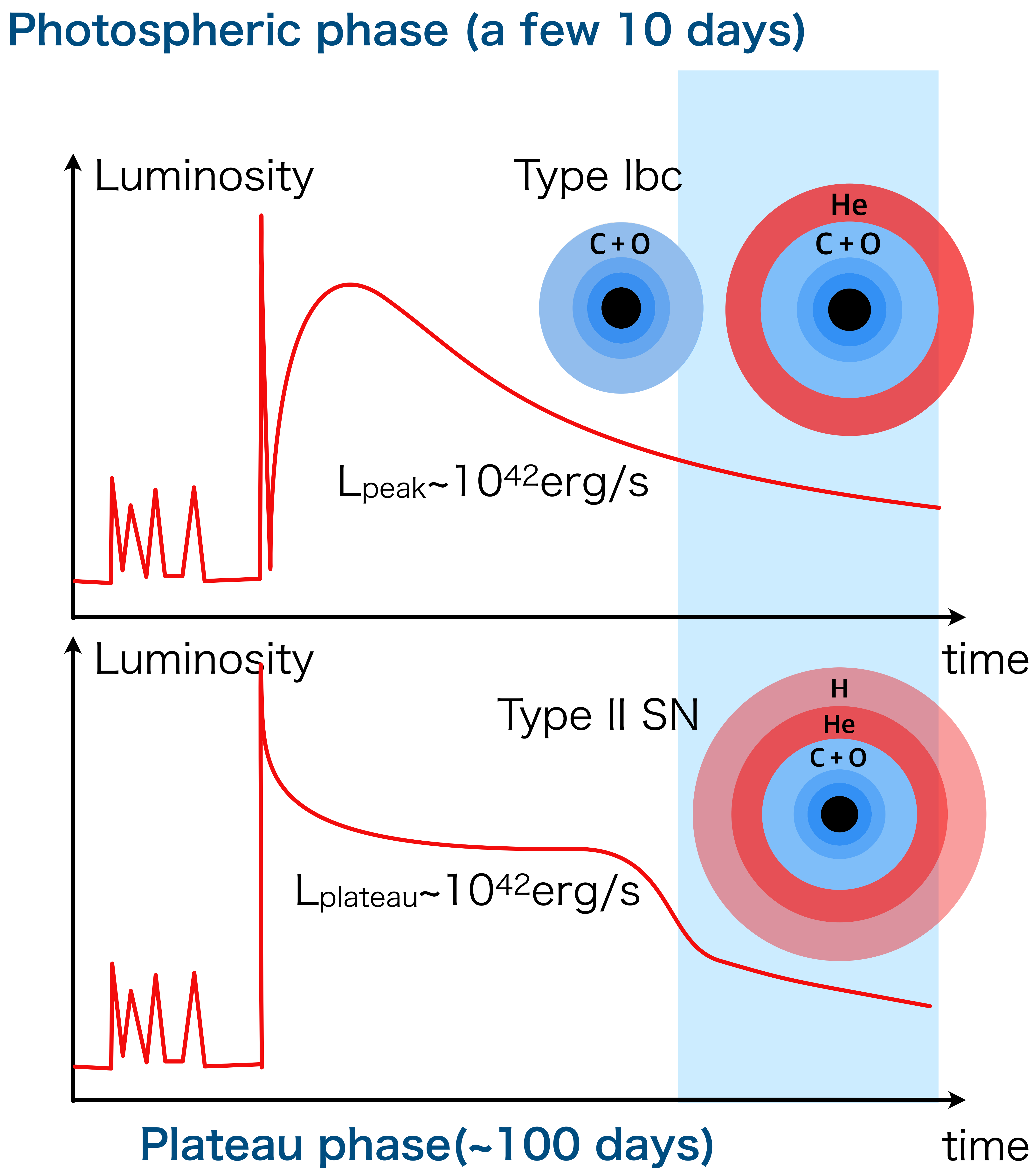
Type Ibc SN light curves (Pian&Mazzali2017)

Nebular phase spectrum

- SN ejecta is transparent to thermal photons
- radioactive tail
- observed spectra show emission lines (nebular-like)
- chemical abundance and distribution + doppler tomography



Jerkstrand, A. (2017)



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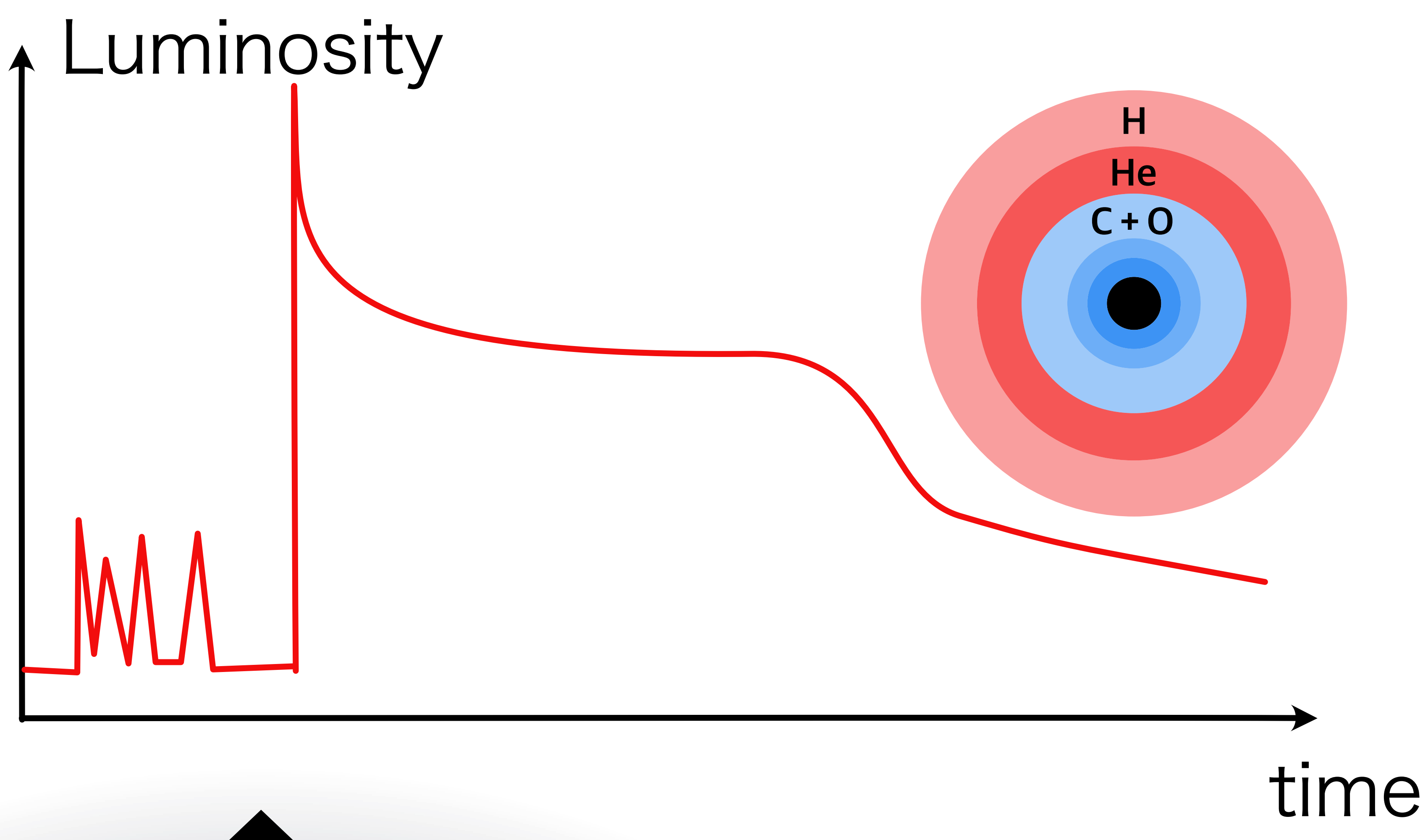

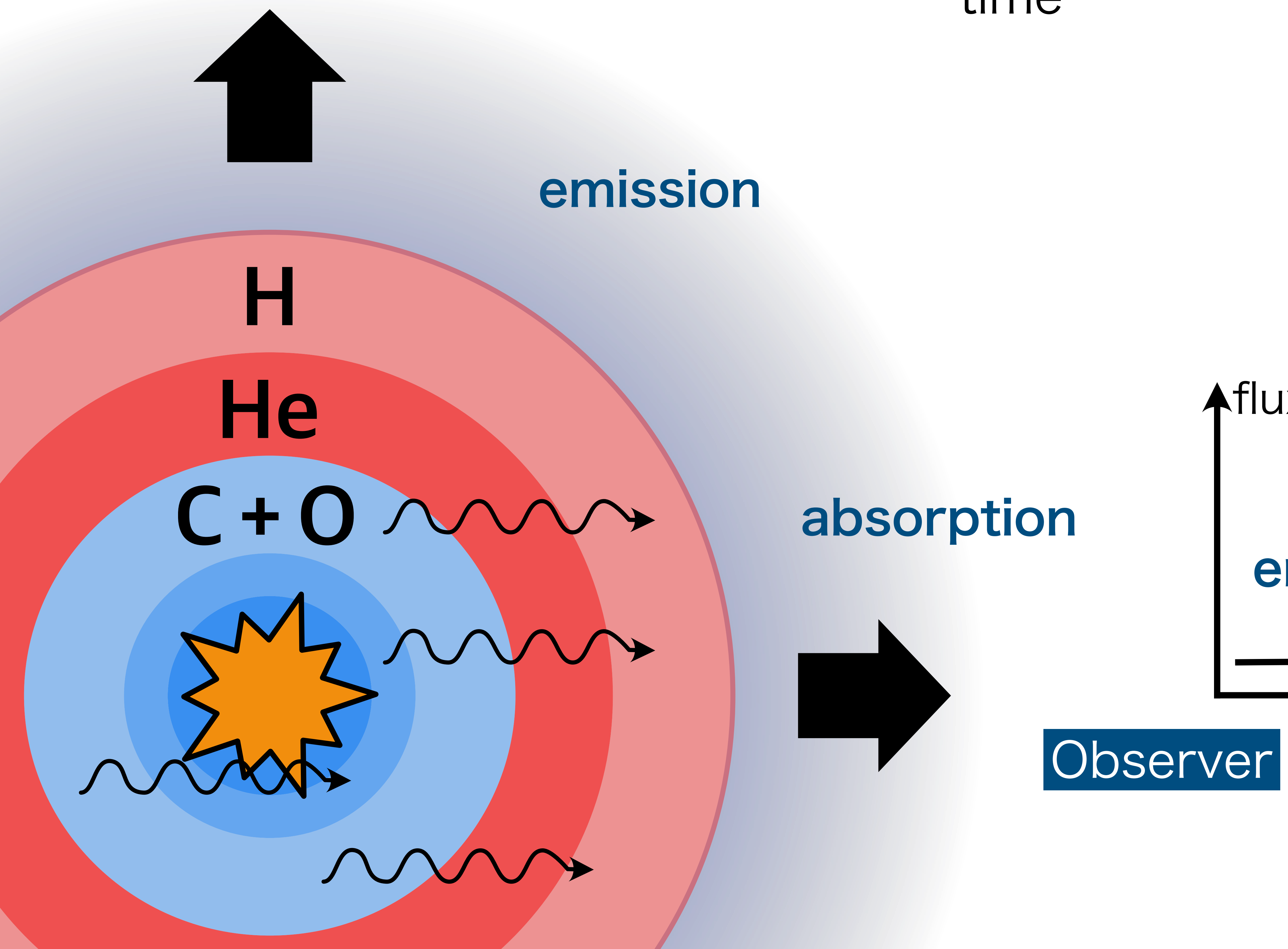

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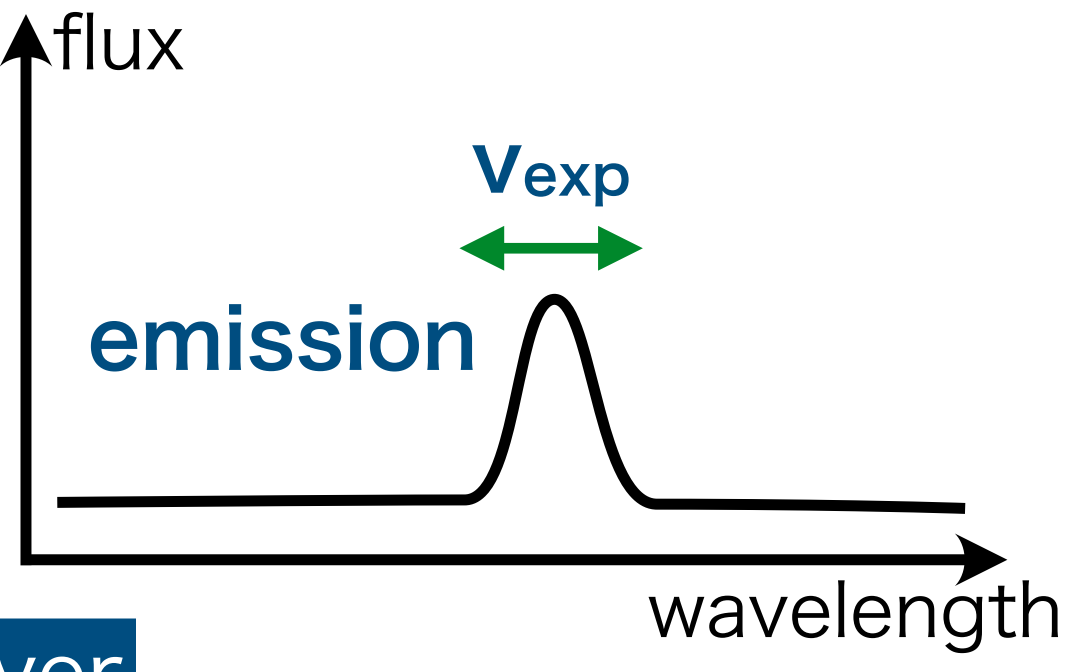
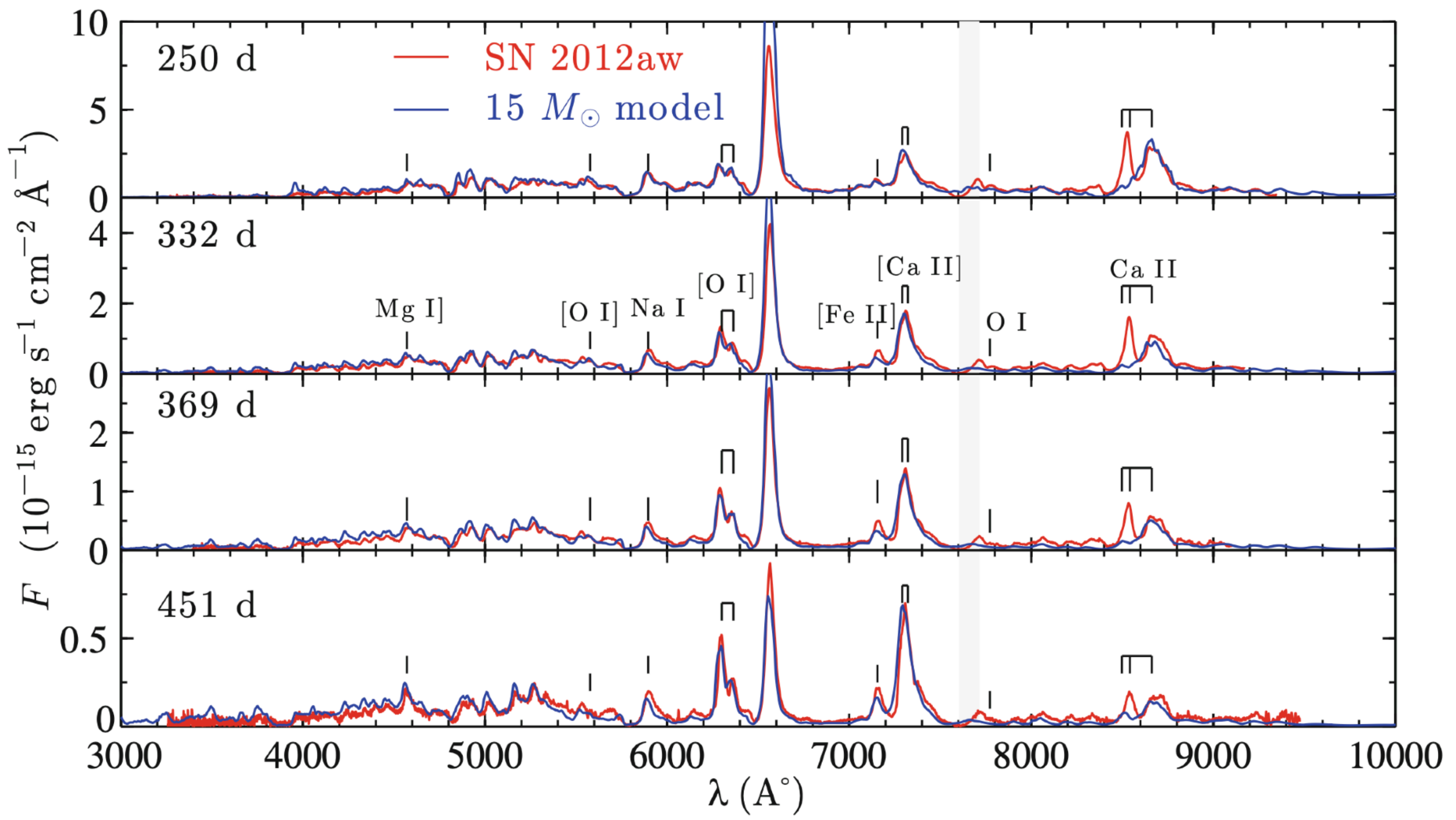




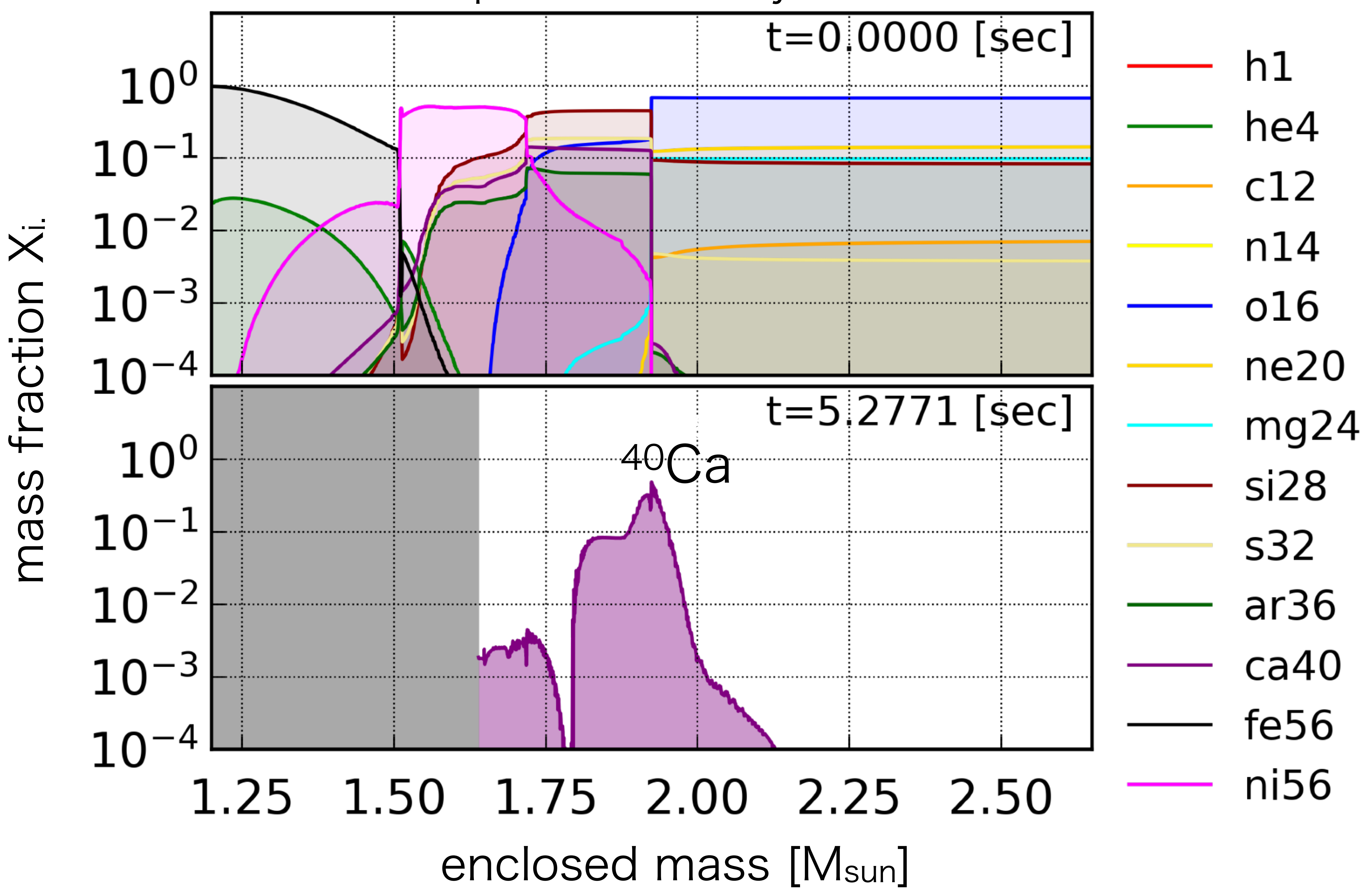
Jerkstrand, A. (2017)

Shock propagation: explosive nucleosynthesis

- E_{exp}~10^{51}erg injected around Fe core → blast wave propagation in the star
- post-shock temperature: $\frac{4\pi}{3}R^3 a_r T^4 \sim E_{exp} \Rightarrow T \sim 10^{10}\left(\frac{E_{exp}}{10^{51}\mathrm{erg}}\right)^{1/4}\left(\frac{R}{10^8\mathrm{cm}}\right)^{-3/4}$ [K]
- explosive nucleosynthesis: various kinds of nuclei

- T>5×10^9[K]: **complete Si burning**
  ➡ ^{56}Ni, Fe-peak
- T=(4-5)$\times10^9$[K]: **incomplete Si burning**
  ➡ Si, S, ^{56}Ni, Ar, Ca
- T=(3-4)$\times10^9$[K]: **O burning**
  ➡ O, Si, S, Ar, Ca
- T=(2-3)$\times10^9$[K]: **C and Ne burning**
  ➡ O, Mg, Si, Ne

explosive nucleosynthesis in 20M_{sun} star



see, Maeda (2022, arXiv 2210.00326) for more detail

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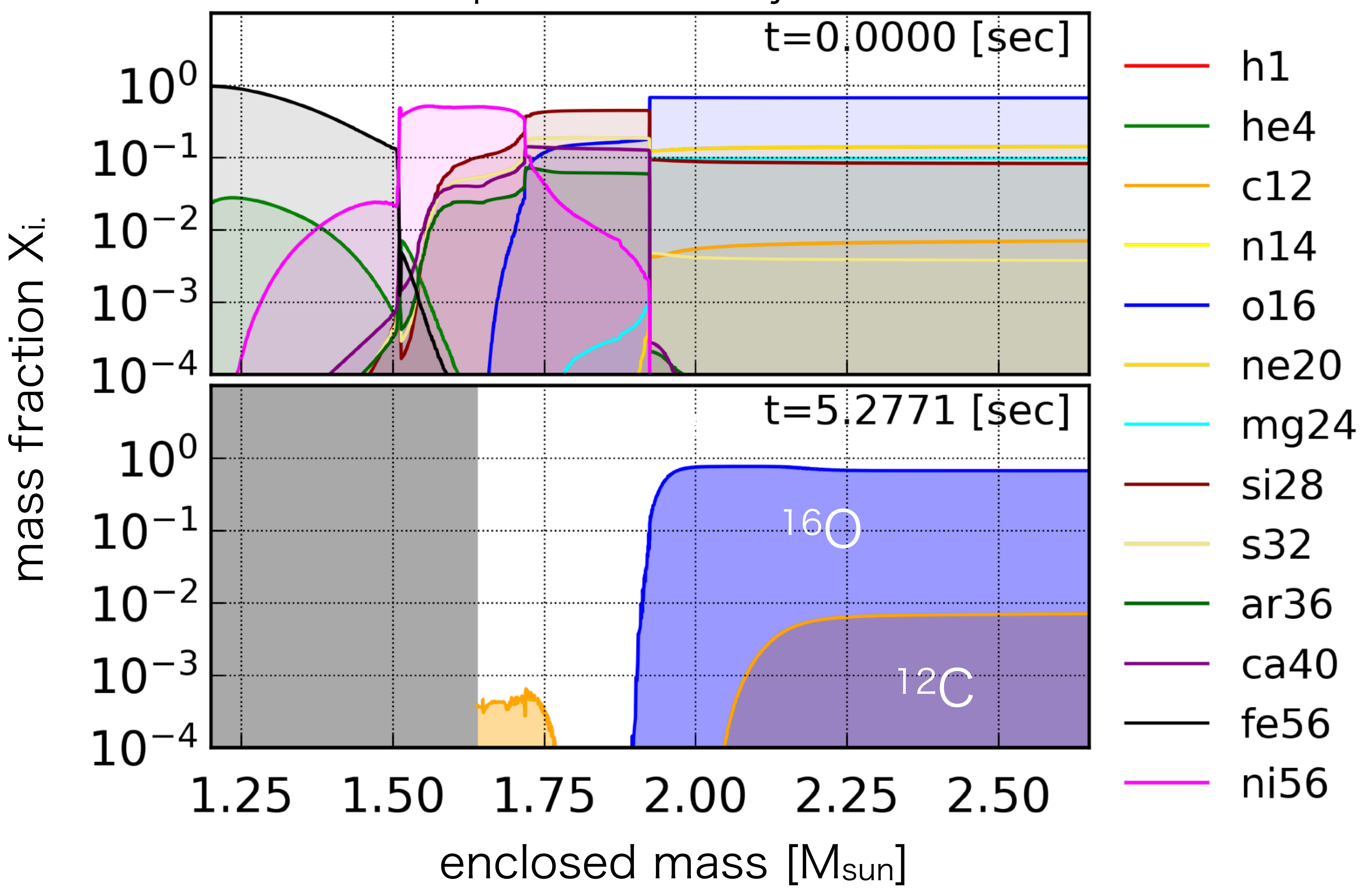
explosive nucleosynthesis in 20M_{sun} star



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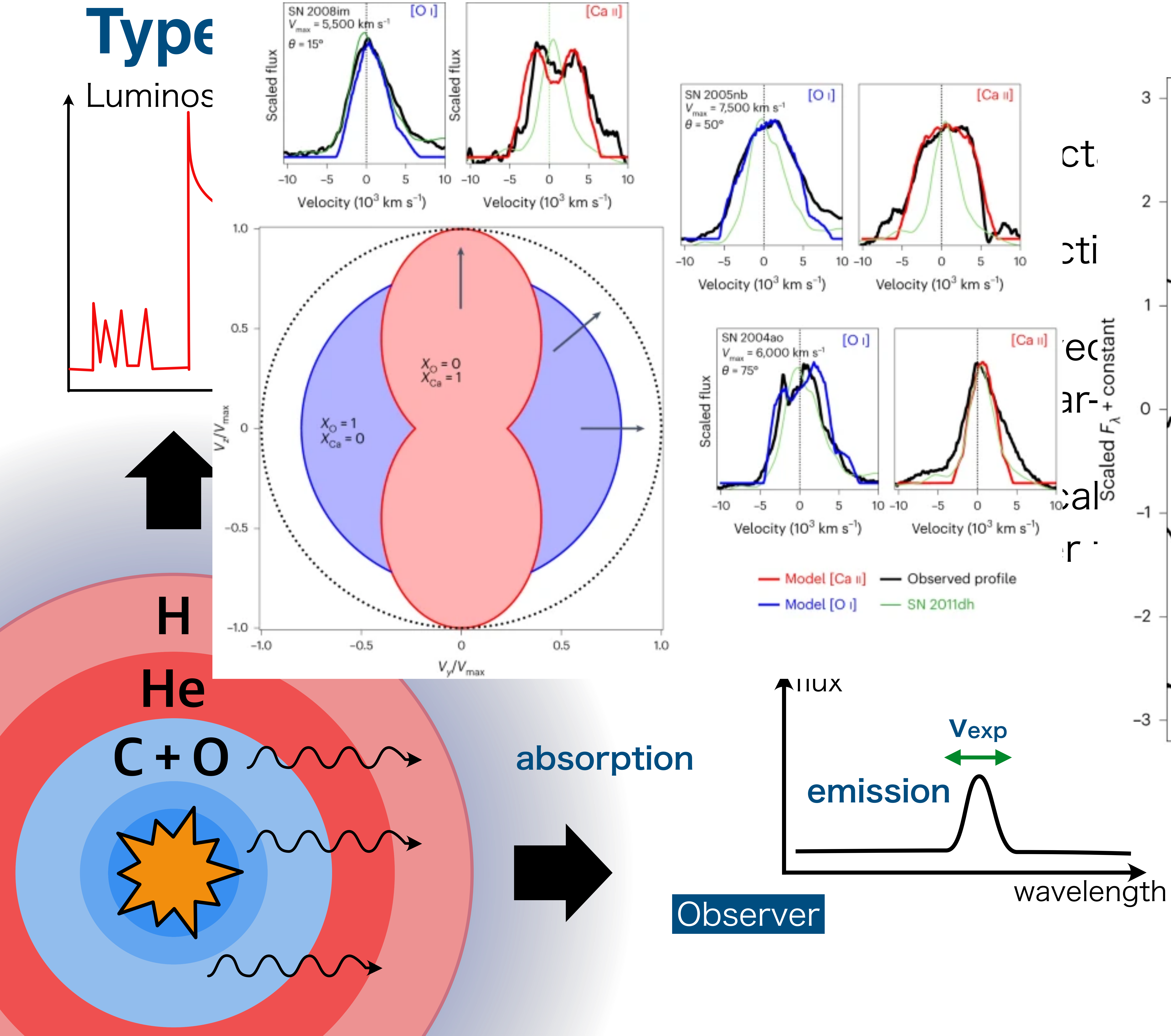
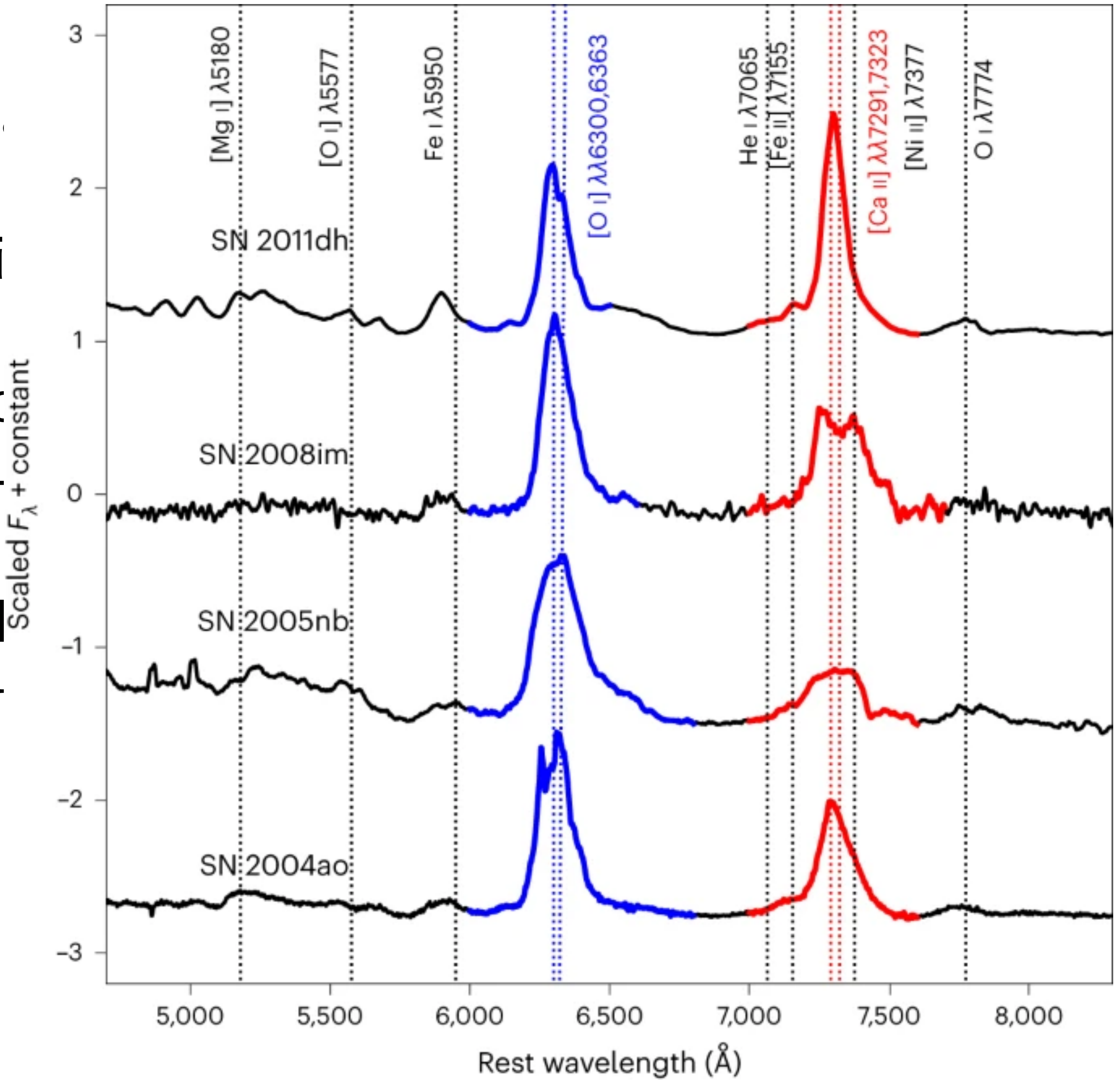
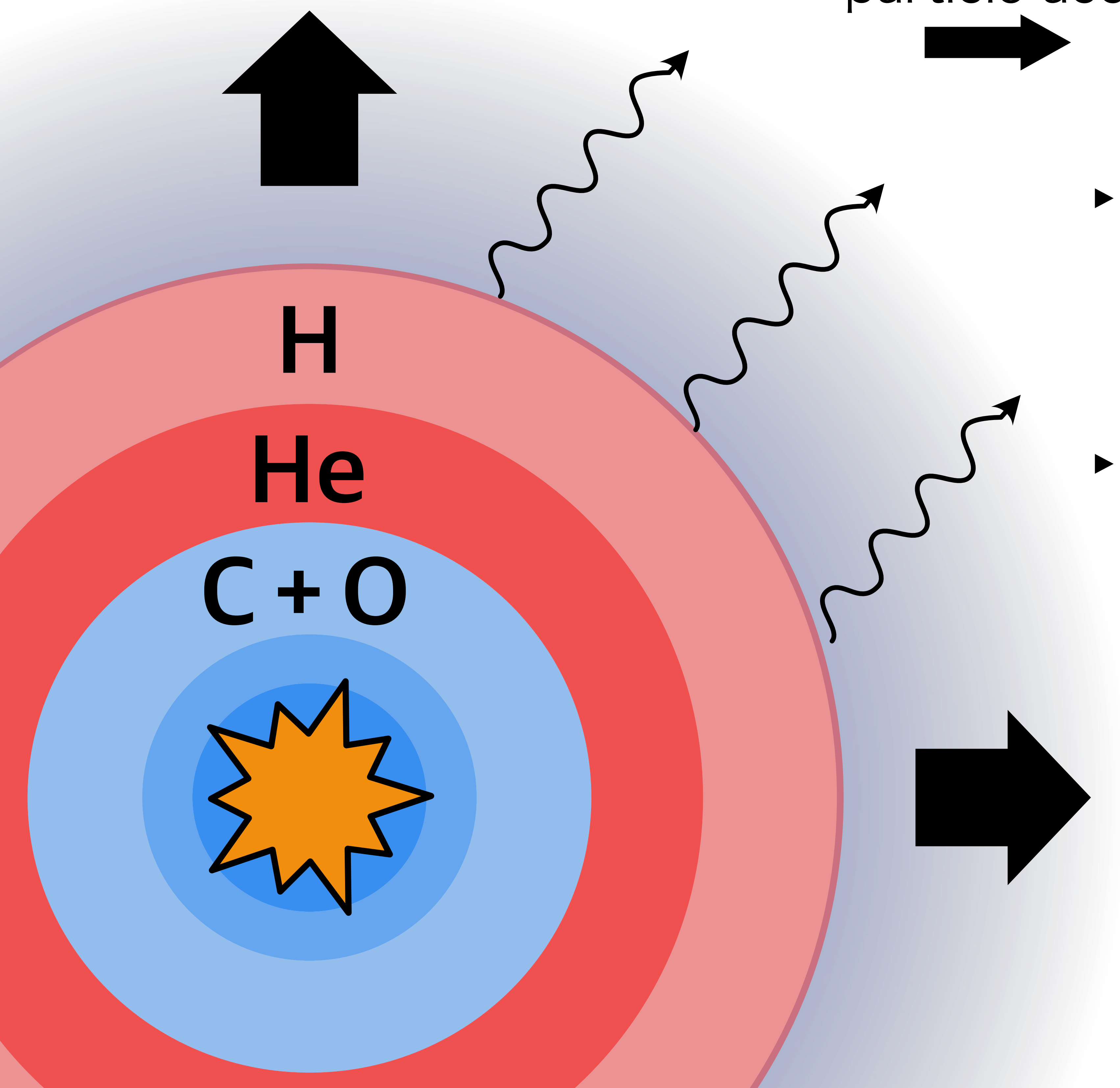

Type
Luminos
SN 2008im
V_{max} = 5,500 km s^{-1}
θ = 15°
[O I]
[Ca II]
Scaled flux
Velocity (10^3 km s^{-1})
SN 2005nb
V_{max} = 7,500 km s^{-1}
θ = 50°
SN 2004ao
V_{max} = 6,000 km s^{-1}
θ = 75°
X_O = 0
X_{Ca} = 1
X_O = 1
X_{Ca} = 0
V_z/V_{max}
V_y/V_{max}
Model [Ca II]
Model [O I]
Observed profile
SN 2011dh
H
He
C + O
absorption
Observer
flux
Vexp
emission
wavelength


[Mg I] λ5180
[O I] λ5577
Fe I λ5950
[O I] λλ6300,6363
He I λ7065
[Fe II] λ7155
[Ca II] λλ7291,7323
[Ni II] λ7377
O I λ7774
SN 2011dh
SN 2008im
SN 2005nb
SN 2004ao
Scaled F_λ + constant
Rest wavelength (Å)

Fang+ (2024)

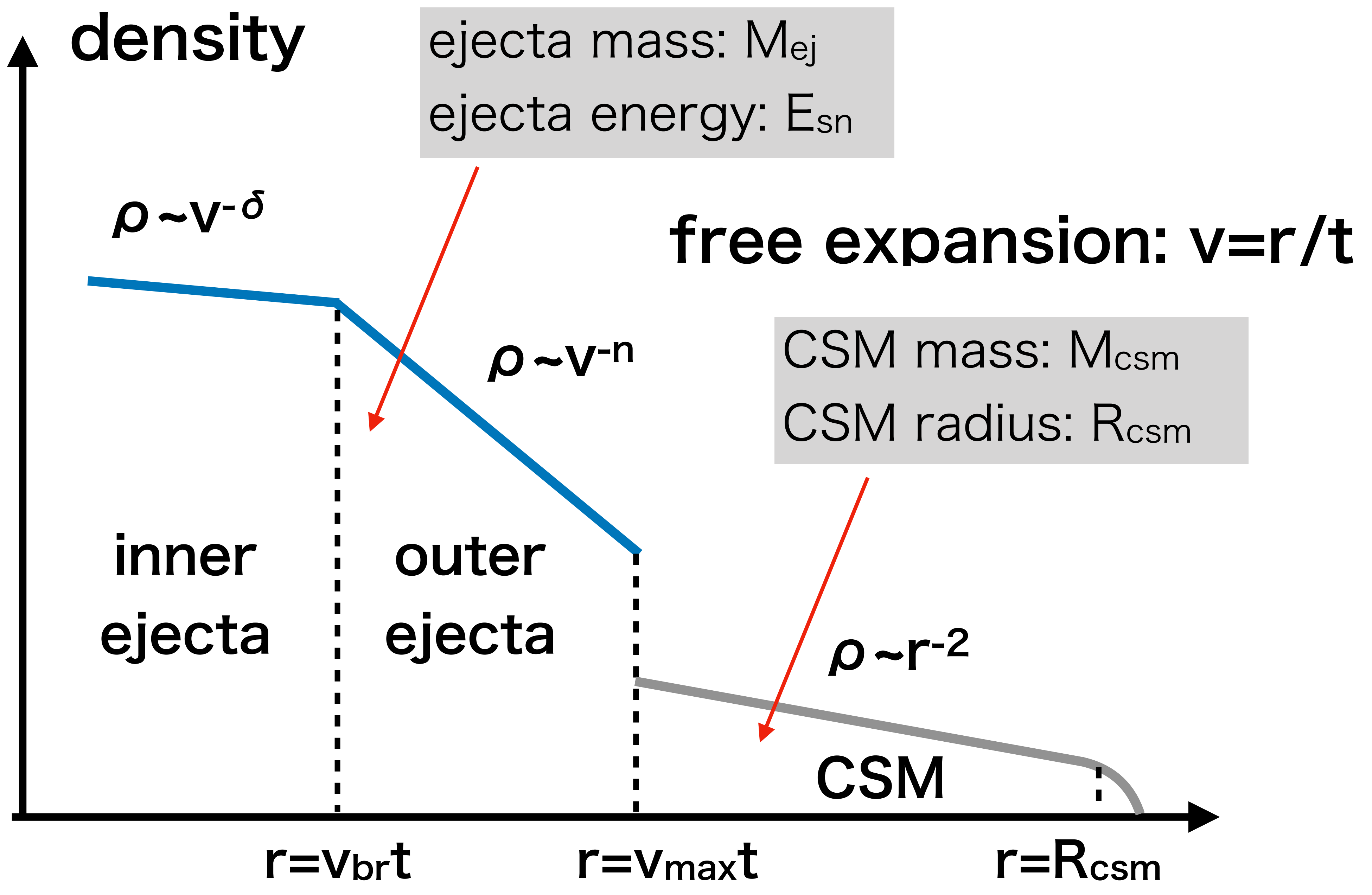
Shock-powered emission

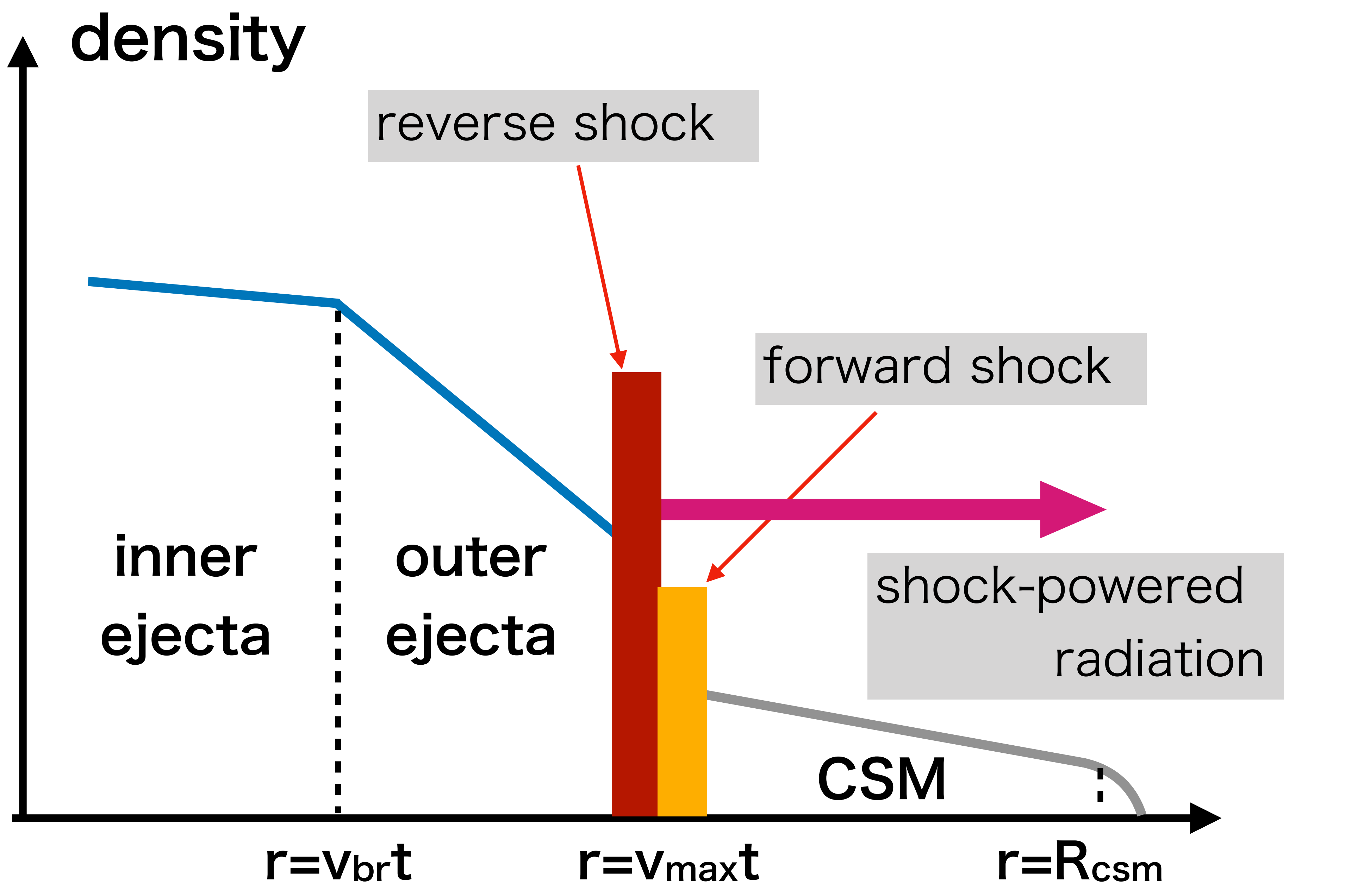
$$E_{\rm kin} \xrightarrow{\text{shock}} E_{\rm int} \begin{cases} \xrightarrow{\text{thick}} E_{\rm opt} \\ \xrightarrow{\text{free-free}} E_{\rm X} \\ \xrightarrow{\text{MHD/plasma}} E_{\rm B} \\ \xrightarrow{\text{particle acc.}} E_{\rm ele}, E_{\rm CR} \end{cases}$$



- SN ejecta: double power-law: $\rho \propto v^{-\delta}$ or $v^{-n}, v = r/t$
- ambient media: $\rho = \dfrac{\dot{M}}{4\pi v_{\rm w} r^2}$

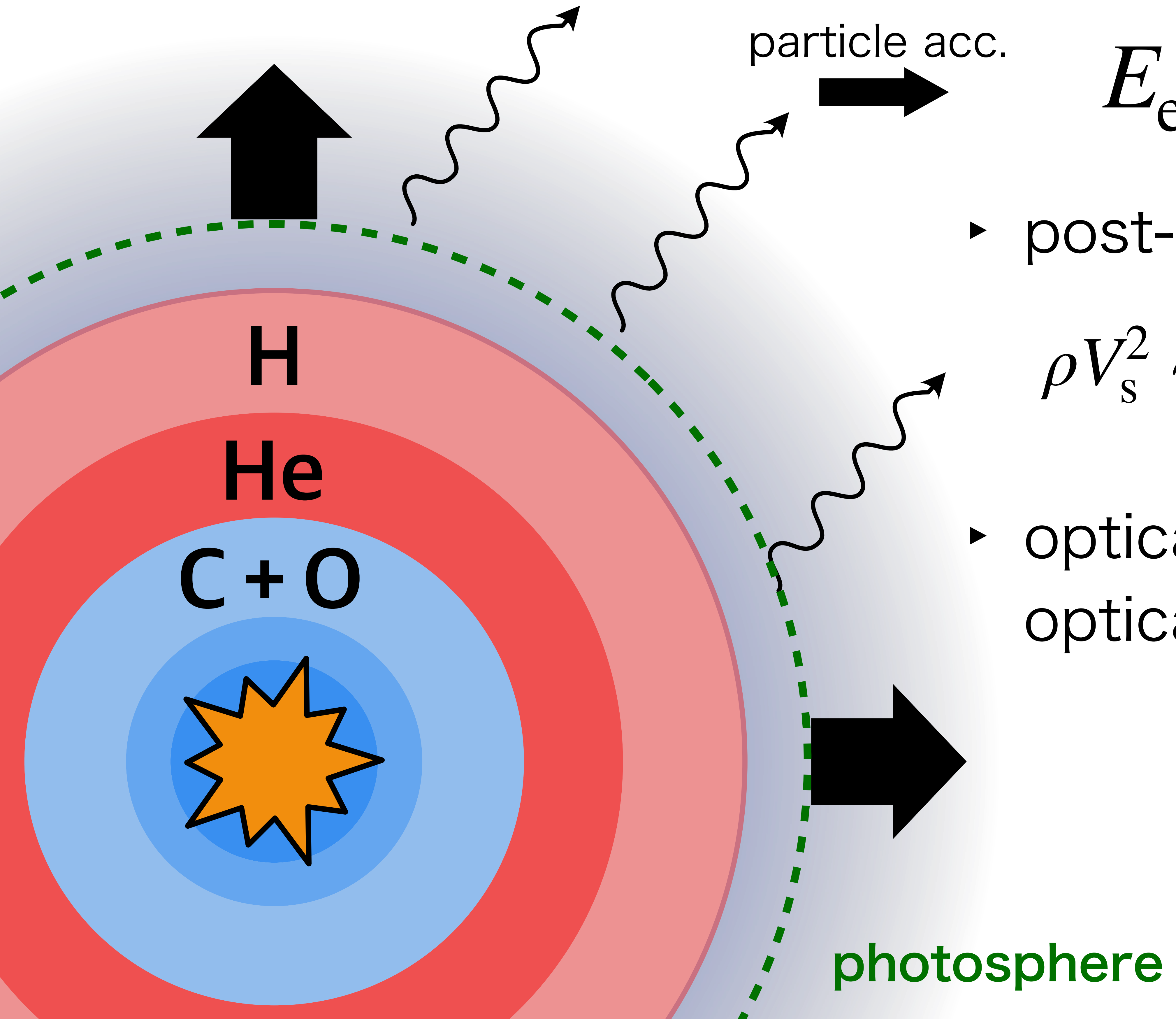
$$\rho r^2 \simeq 5 \times 10^{11} \left(\frac{\dot{M}}{10^{-6} M_\odot/{\rm yr}}\right) \times \left(\frac{v_{\rm w}}{100{\rm km/s}}\right)^{-1} [{\rm g/cm}]$$





Shock-powered emission

$$E_{\rm kin} \xrightarrow{\text{shock}} E_{\rm int} \begin{cases} \boxed{\xrightarrow{\text{thick}} E_{\rm opt}} \\ \xrightarrow{\text{free-free}} E_{\rm X} \\ \xrightarrow{\text{MHD/plasma}} E_{\rm B} \\ \xrightarrow{\text{particle acc.}} E_{\rm ele}, E_{\rm CR} \end{cases}$$

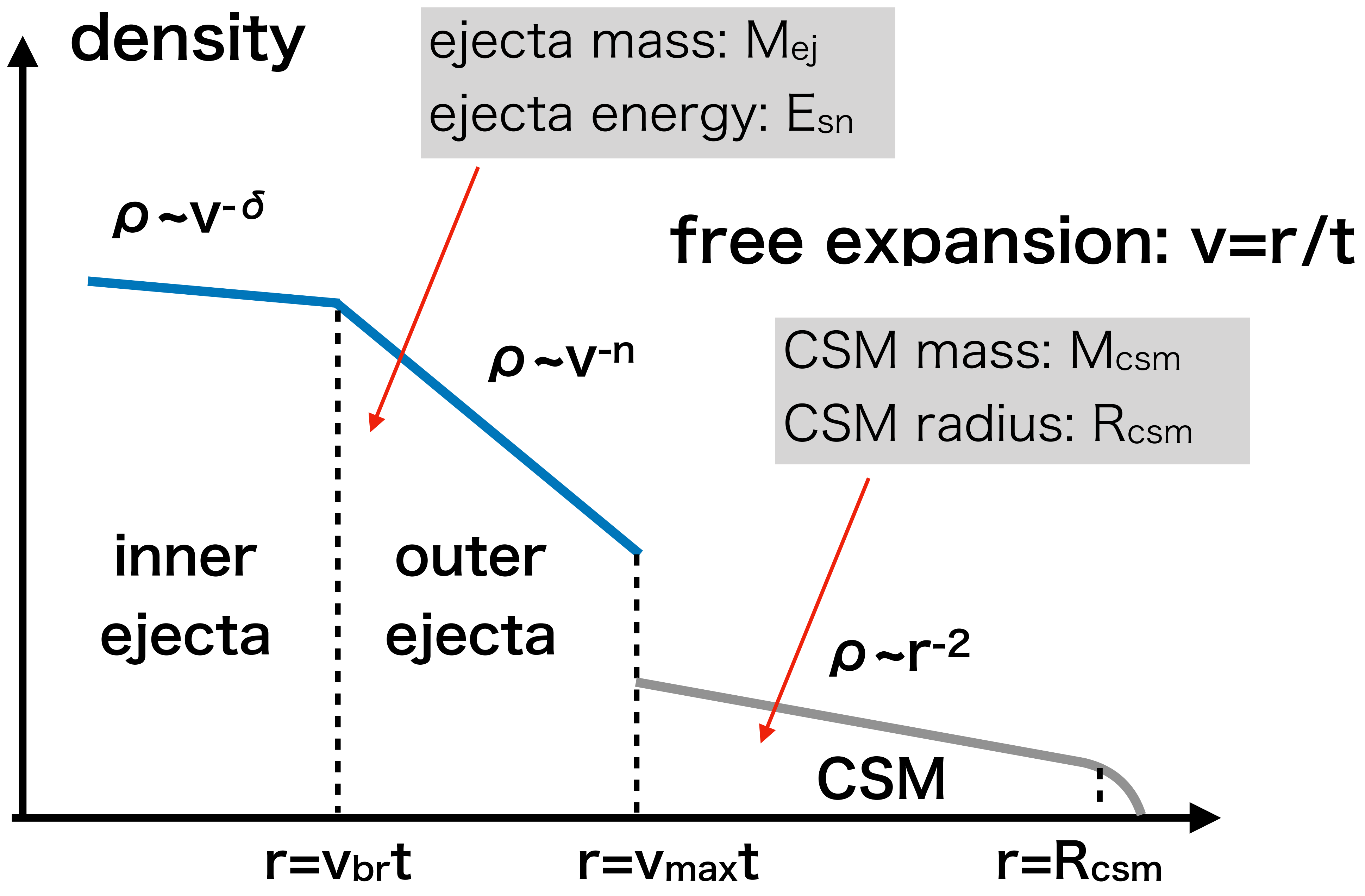


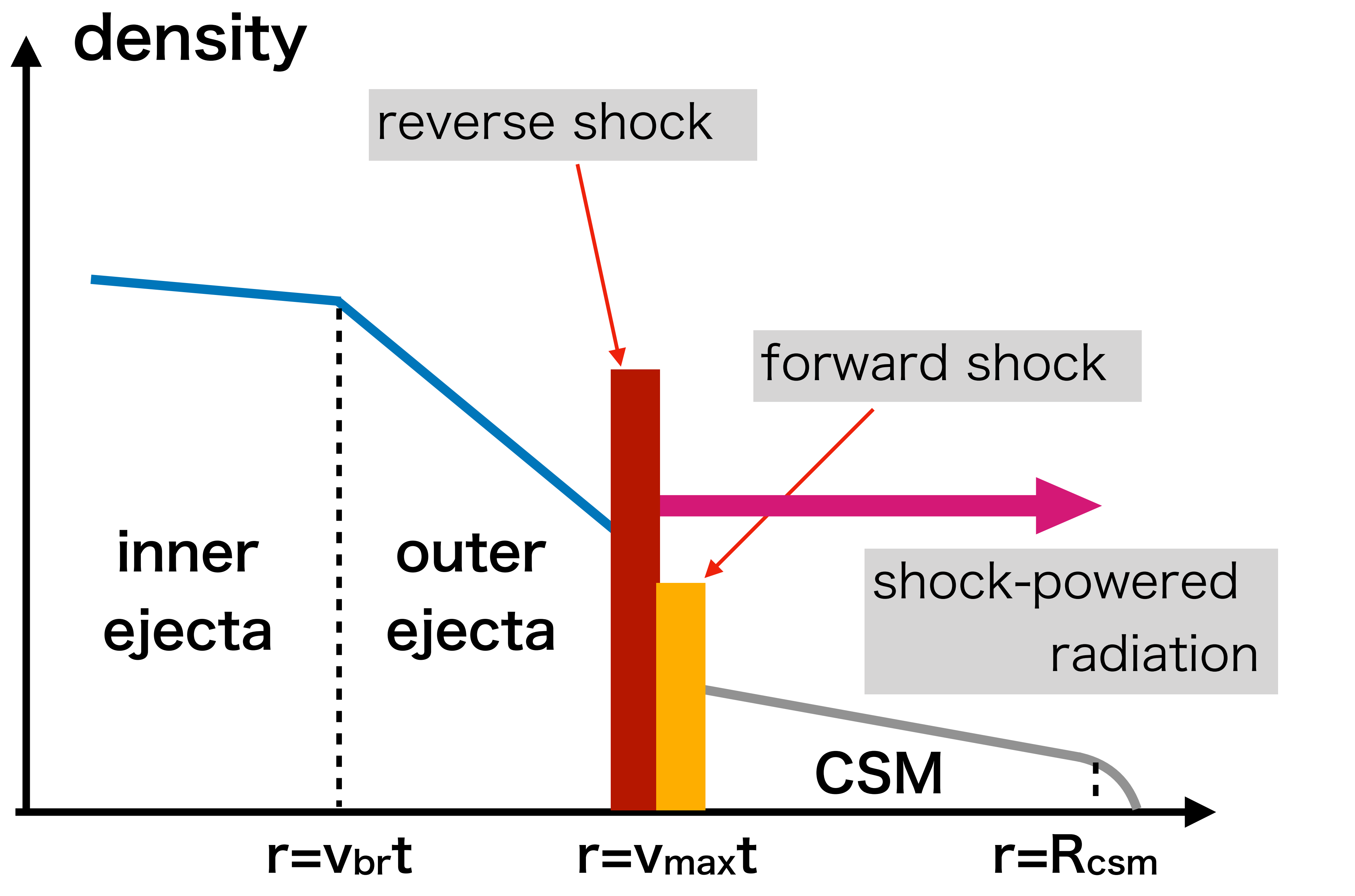
- post-shock temperature

$$\rho V_{\rm s}^2 \sim p_{\rm s} \sim \frac{\rho k_{\rm B} T}{\mu m_{\rm u}} + \frac{a_{\rm r} T^4}{3}$$

- optically thick → thermal optical emission

$$\frac{\rho k_{\rm B} T}{\mu m_{\rm u}} \ll \frac{a_{\rm r} T^4}{3}$$





Shock-powered emission

$$E_{\mathrm{kin}} \xrightarrow{\text{shock}} E_{\mathrm{int}}$$

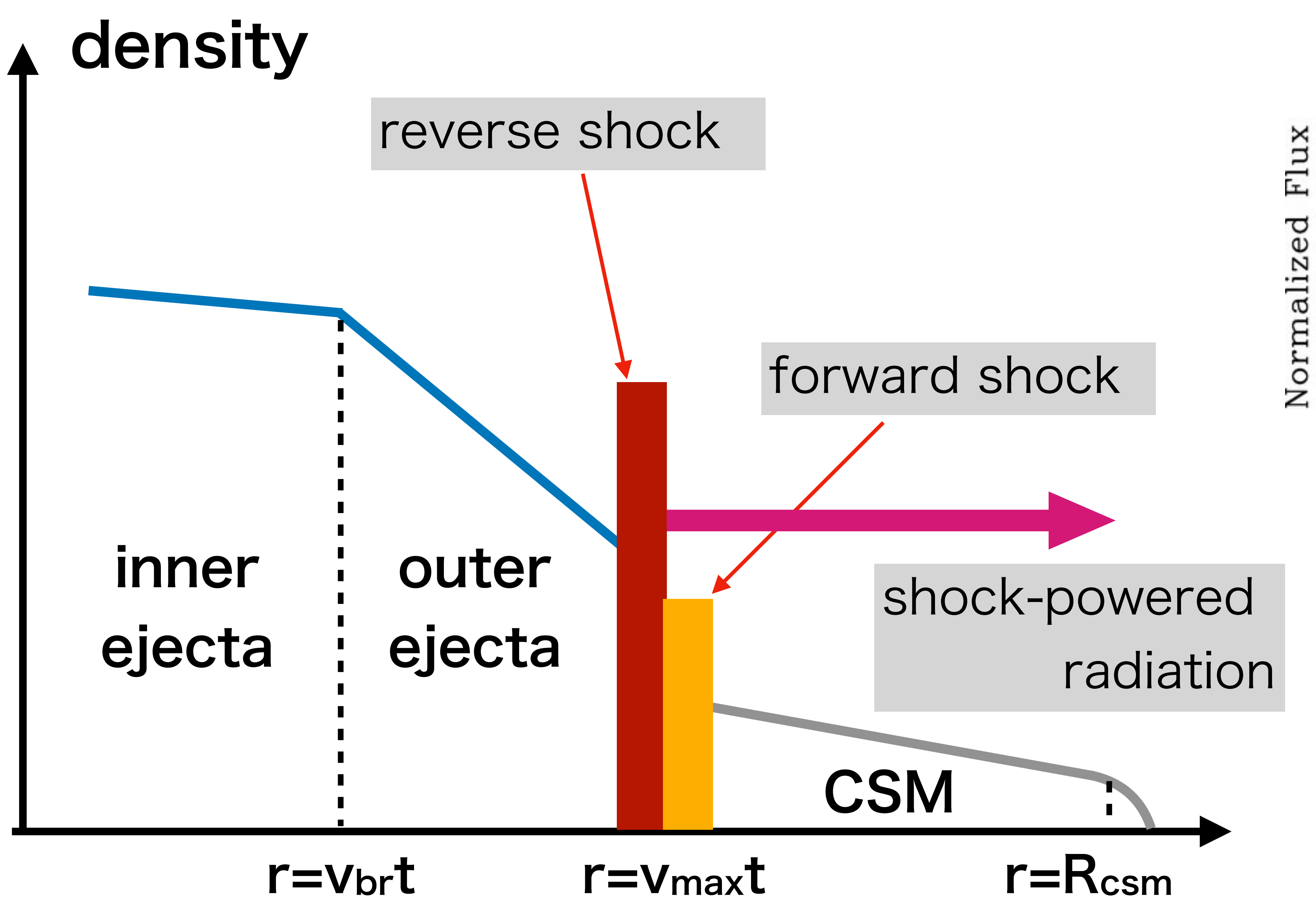
$$\boxed{\xrightarrow{\text{thick}} E_{\mathrm{opt}}}$$

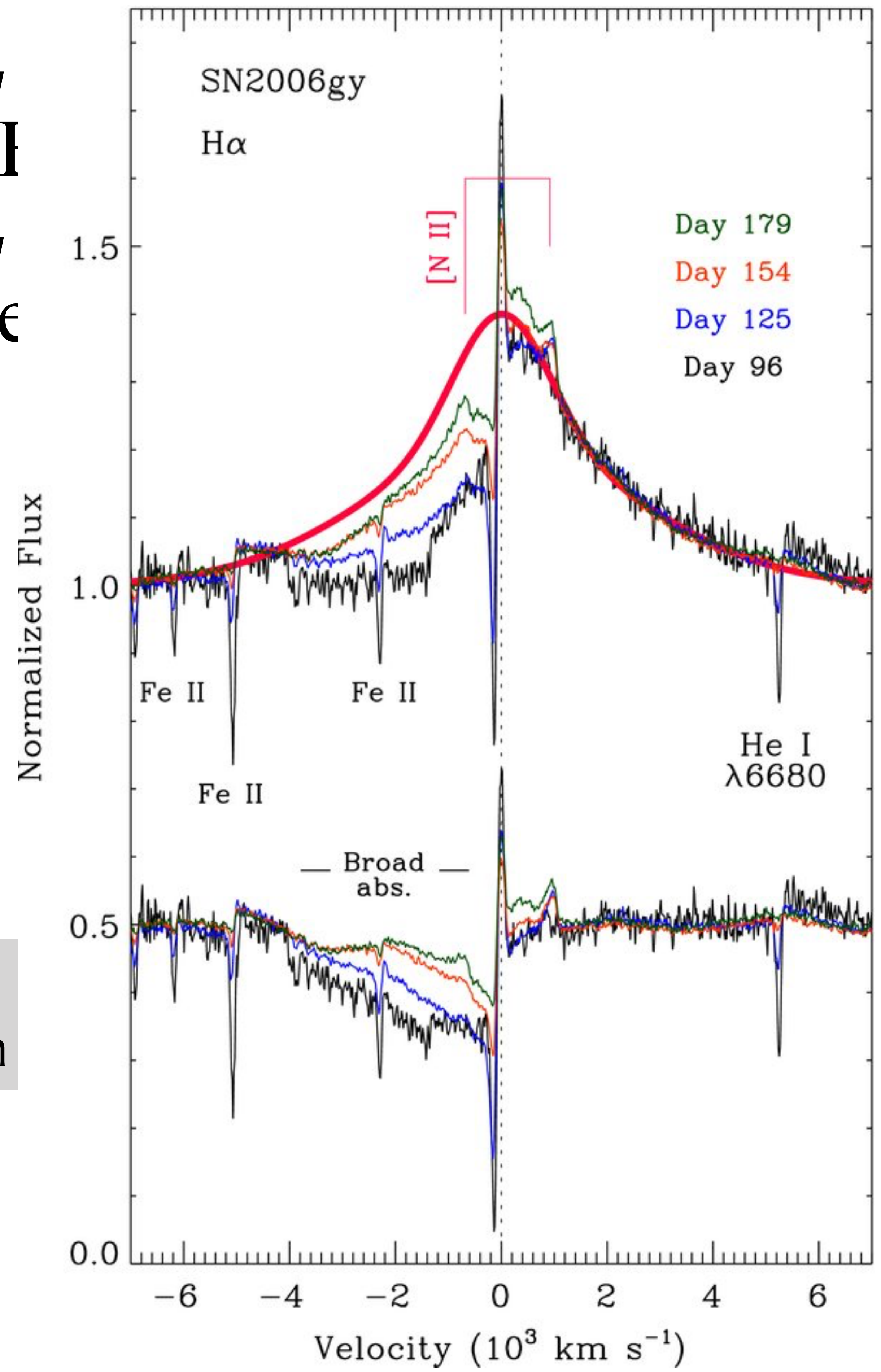
$$\xrightarrow{\text{free-free}} E_{\mathrm{X}}$$

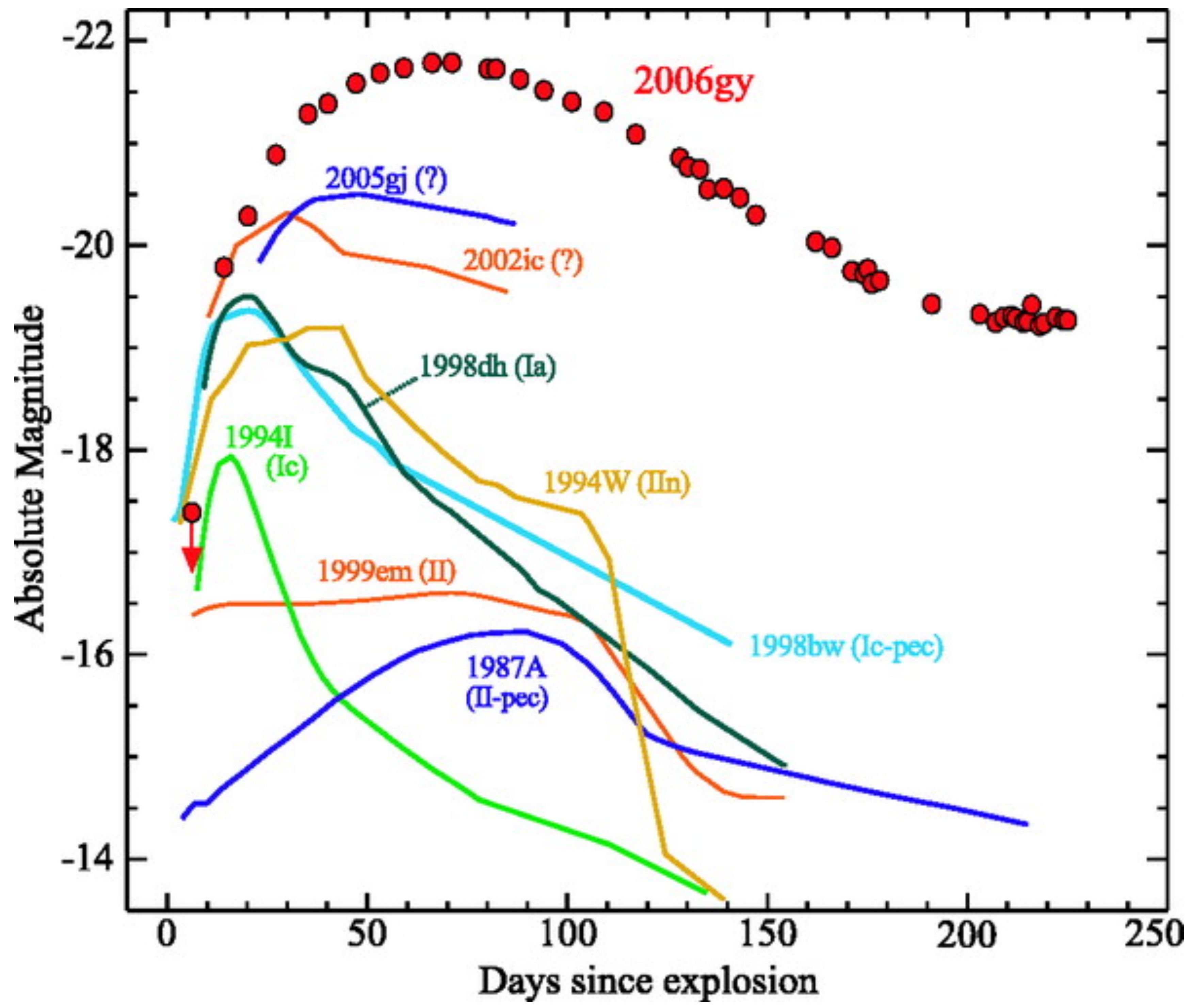
MHD/plasma ➡

particle acc.

- rare luminous events (e.g., type IIn SNe)
- inferred mass-loss rate of 10^{-2}-1 M_{sun}/yr







Smith+(2007)

Shock-powered emission

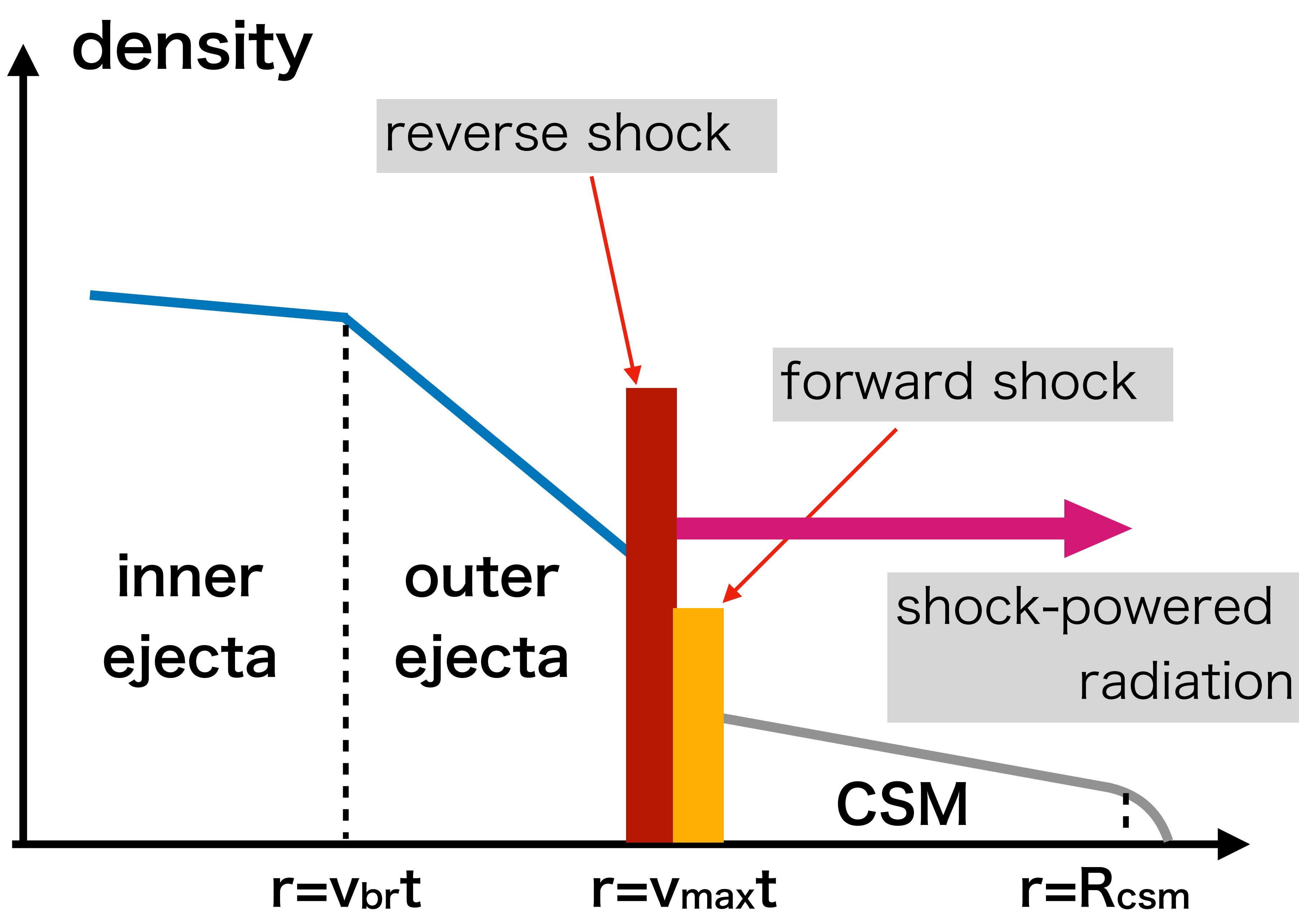
$$E_{\rm kin} \xrightarrow{\text{shock}} E_{\rm int} \xrightarrow{\text{thick}} \boxed{E_{\rm opt}}$$

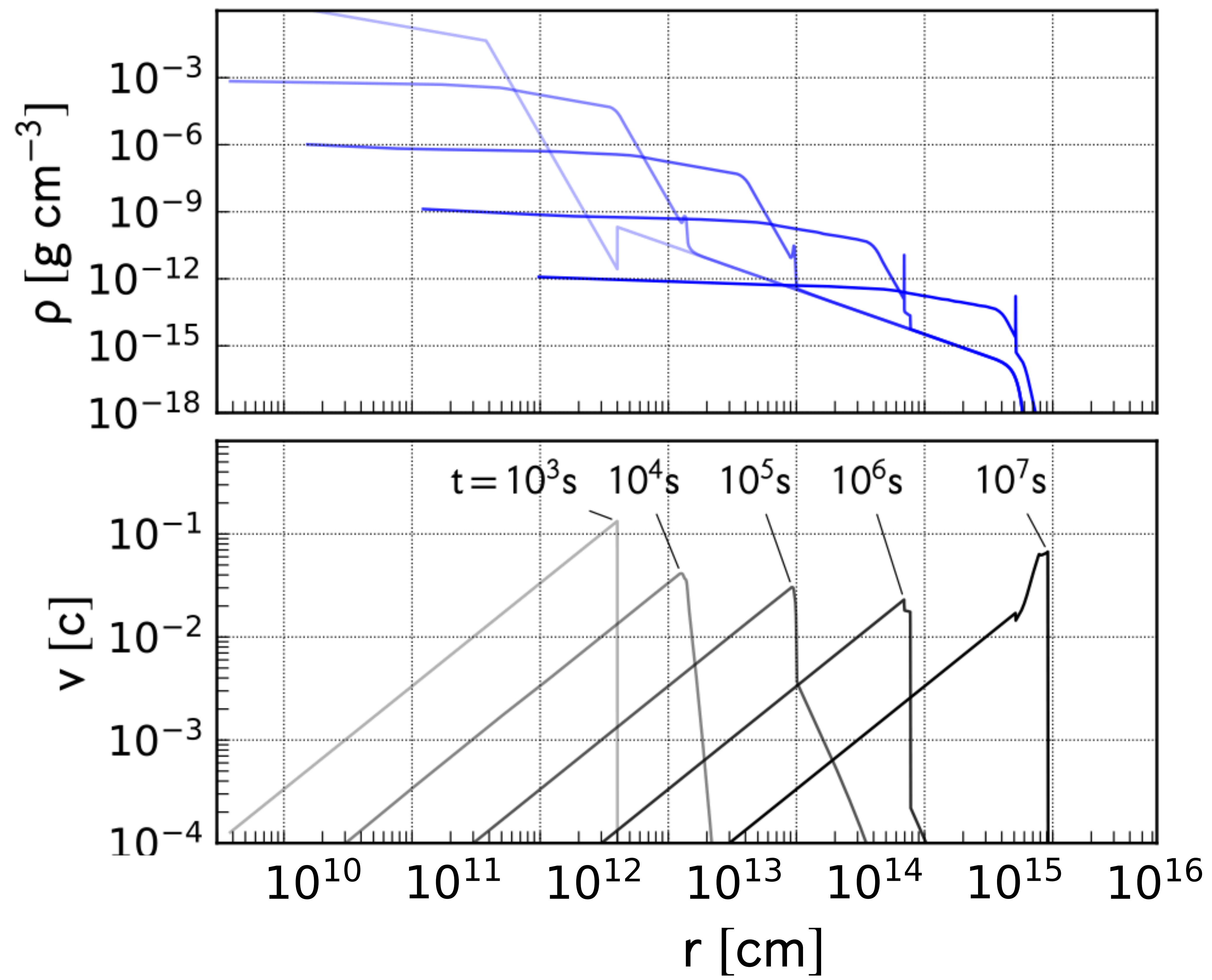
$$E_{\rm int} \xrightarrow{\text{free-free}} E_{\rm X}$$

$$E_{\rm int} \xrightarrow{\text{MHD/plasma}} E_{\rm B}$$

$$E_{\rm int} \xrightarrow[\text{particle acc.}]{} E_{\rm ele}, E_{\rm CR}$$

- rare luminous events (e.g., type IIn SNe)
- inferred mass-loss rate of 10^{-2}-1 $M_{\rm sun}$/yr





1D RHD simulations of type IIn SNe (**AS**, Moriya, Takiwaki 2019)

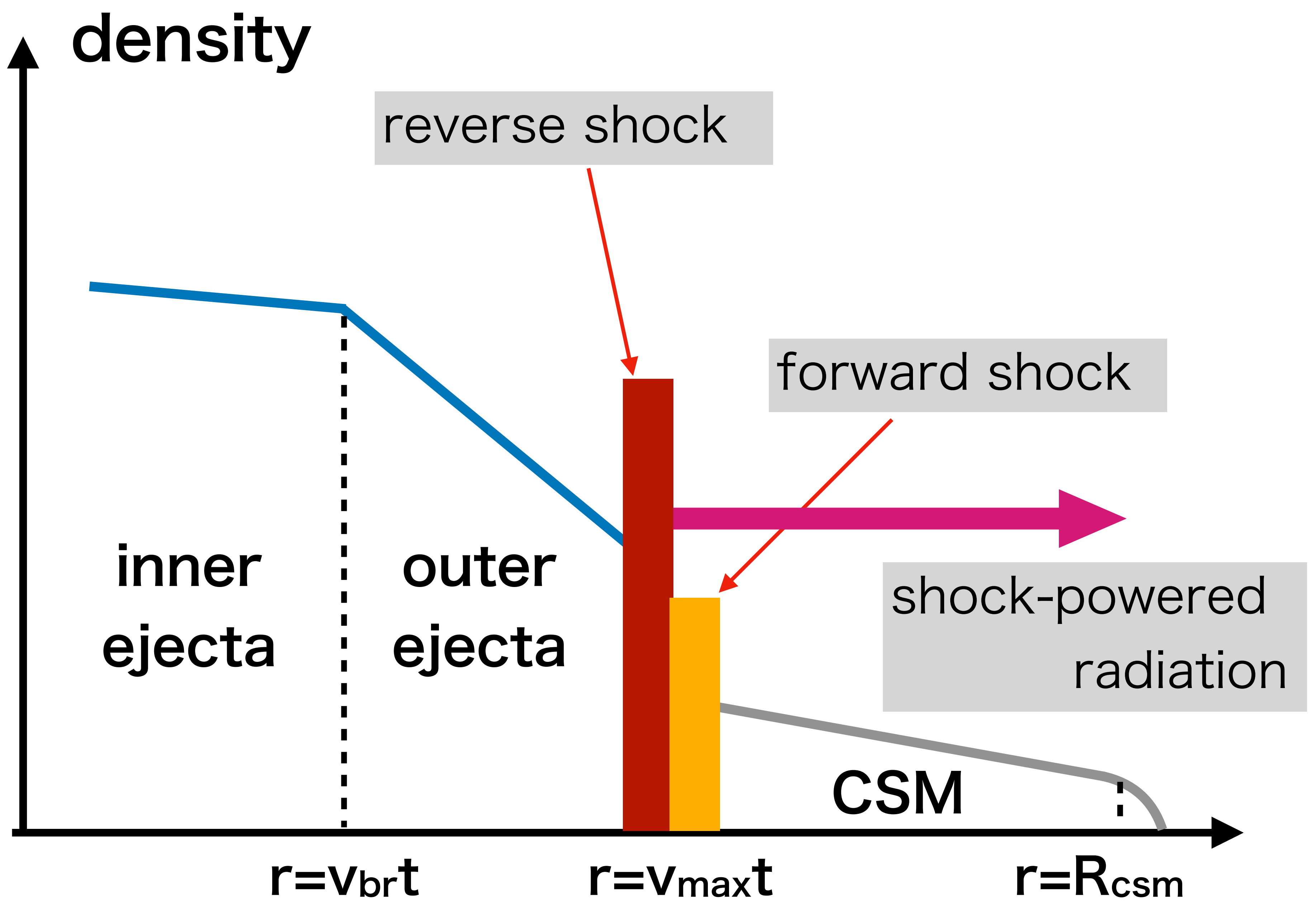
Shock-powered emission

$$E_{\rm kin} \xrightarrow{\text{shock}} E_{\rm int}$$

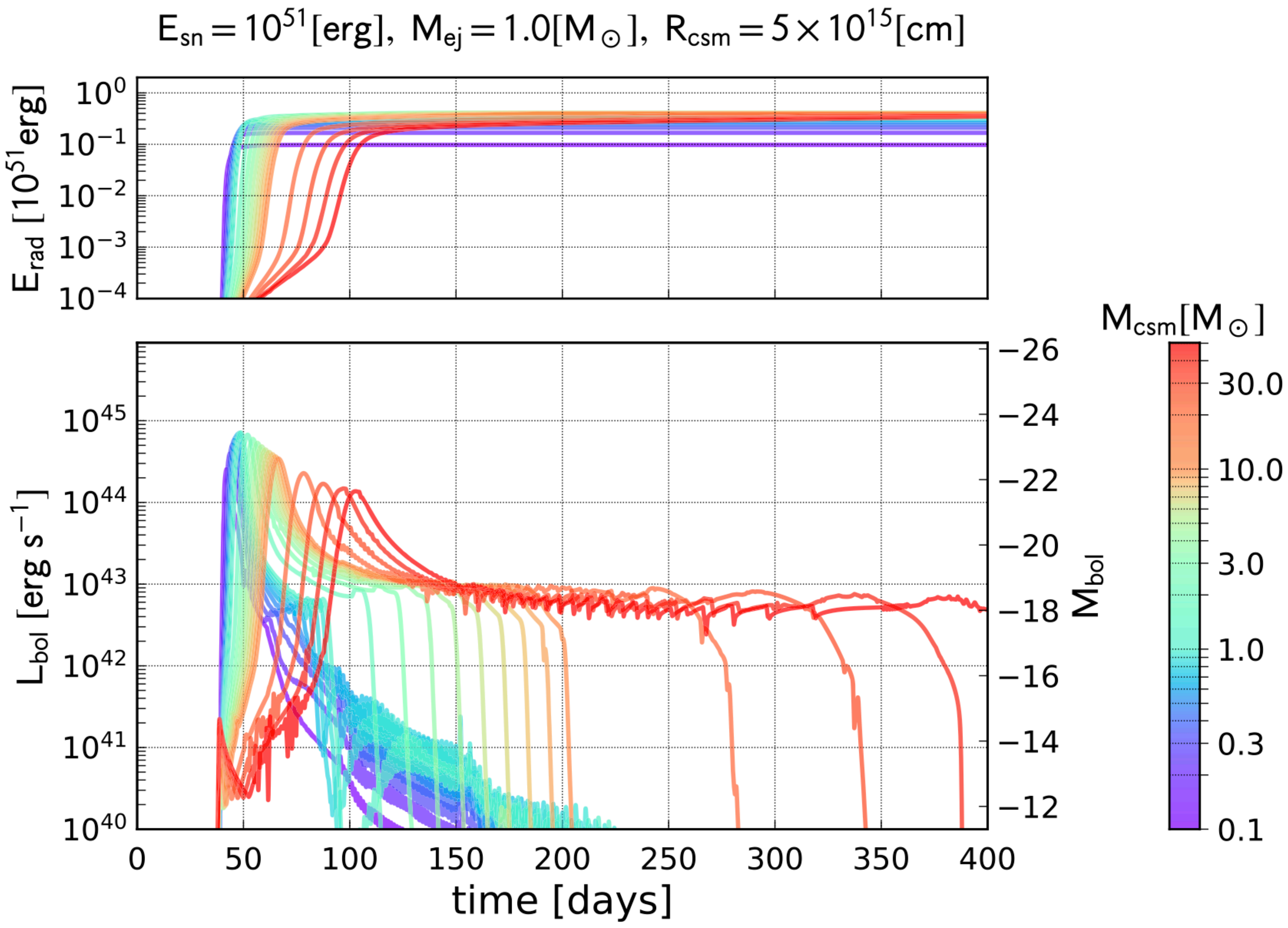
$$E_{\rm int} \xrightarrow{\text{thick}} E_{\rm opt}$$

$$E_{\rm int} \xrightarrow{\text{free-free}} E_{\rm X}$$

$$E_{\rm int} \xrightarrow[\text{particle acc.}]{\text{MHD/plasma}} E_{\rm B}, \quad E_{\rm ele}, E_{\rm CR}$$



- rare luminous events (e.g., type IIn SNe)
- inferred mass-loss rate of 10^{-2}-1 M_{sun}/yr

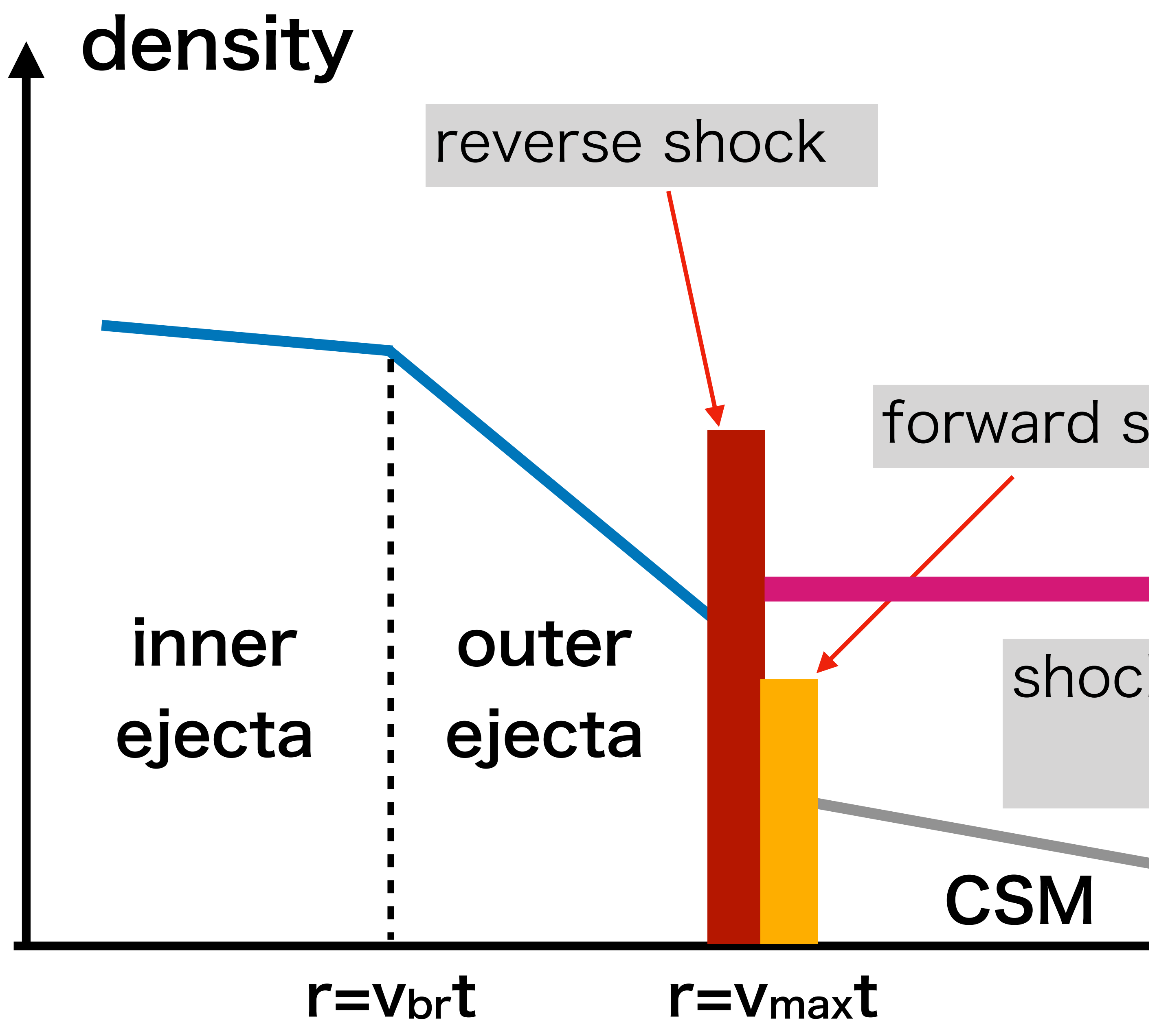


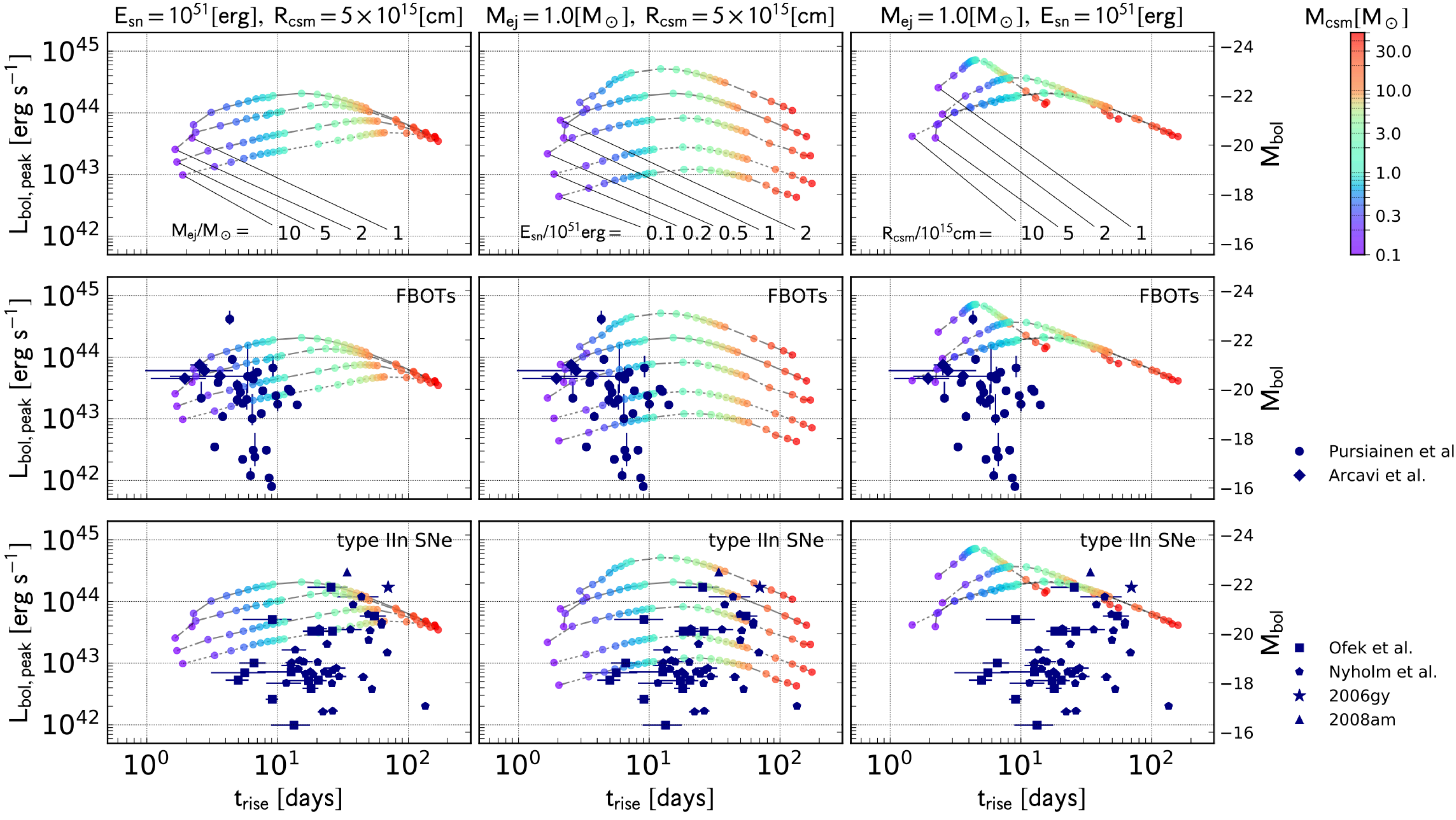
1D RHD simulations of type IIn SNe (**AS**, Moriya, Takiwaki 2019)

Shock-powered emission

$E_{\rm kin} \xrightarrow{\text{shock}} E_{\rm int} \xrightarrow{\text{thick}} E_{\rm opt}$

- rare luminous events (e.g., type IIn SNe)



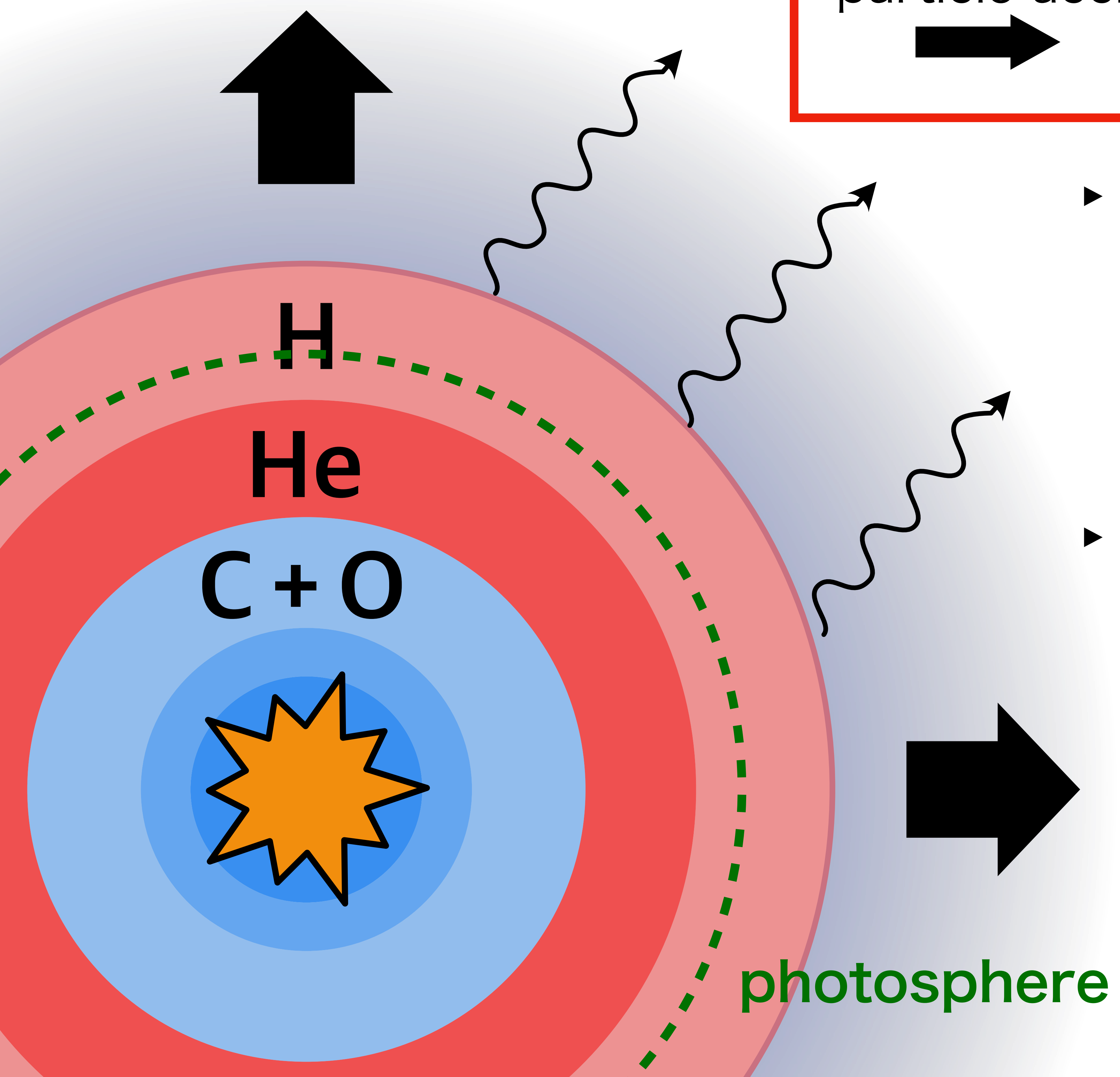


1D RHD simulations of type IIn SNe (**AS**, Moriya, Takiwaki 2019)

Shock-powered emission

$$E_{\rm kin} \xrightarrow{\text{shock}} E_{\rm int} \xrightarrow{\text{thick}} E_{\rm opt}$$

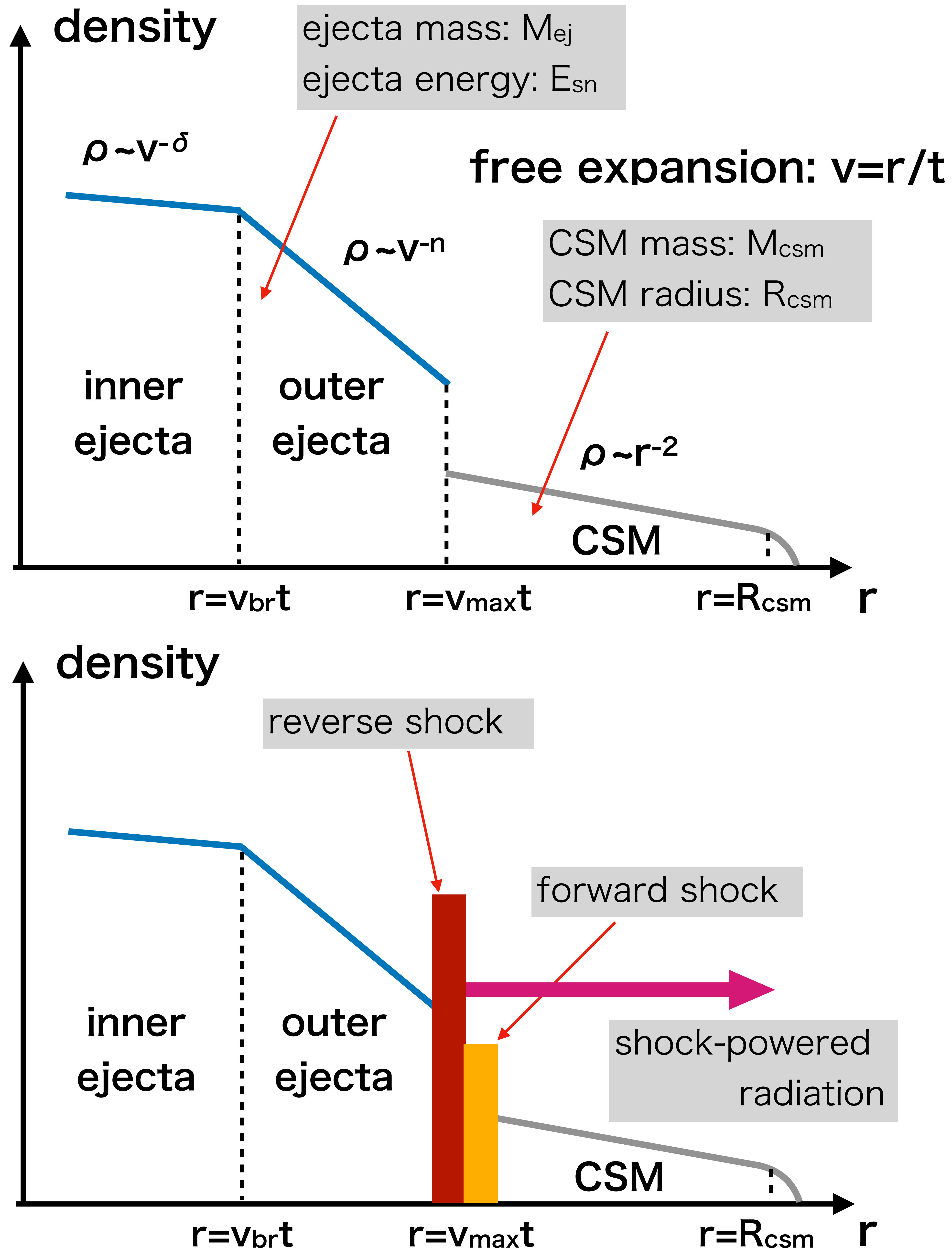
$$\boxed{\begin{aligned} &\xrightarrow{\text{free-free}} E_{\rm X} \\ &\xrightarrow{\text{MHD/plasma}} E_{\rm B} \\ &\xrightarrow{\text{particle acc.}} E_{\rm ele}, E_{\rm CR} \end{aligned}}$$



- post-shock temperature

$$\rho V_{\rm s}^2 \sim p_{\rm s} \sim \frac{\rho k_{\rm B} T}{\mu m_{\rm u}} + \cancel{\frac{a_{\rm r} T^4}{3}}$$

- optically thin → thermal X-ray, synchrotron



Shock-powered emission

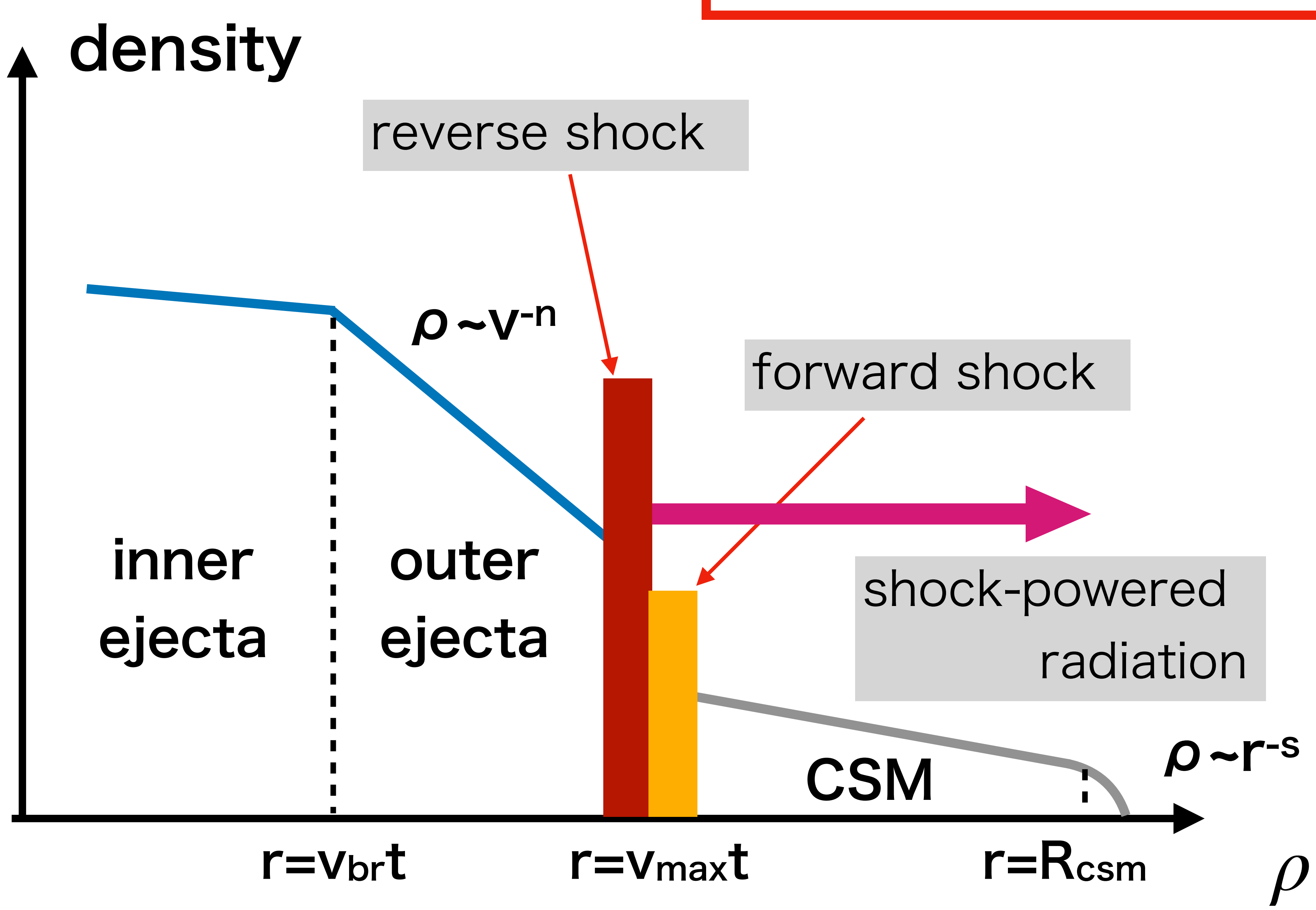
$E_{\rm kin} \xrightarrow{\text{shock}} E_{\rm int}$

$\xrightarrow{\text{thick}} E_{\rm opt}$

$\xrightarrow{\text{free-free}} E_{\rm X}$

$\xrightarrow{\text{MHD/plasma}} E_{\rm B}$

$\xrightarrow{\text{particle acc.}} E_{\rm ele}, E_{\rm CR}$



$$\rho = \frac{\dot{M}}{4\pi v_{\rm w} r^2}$$

- post-shock temperature can be much higher than optically thick case (only depends on the shock velocity and composition)
- shock dissipation: $\rho V_{\rm s}^2 \sim p_{\rm gas} = \dfrac{\rho k_{\rm B} T}{\mu m_{\rm u}}$

$$T_{cs} = 2.27 \times 10^9 \mu_s \frac{(n-3)^2}{(n-s)^2} V_4^2 \ \mathrm{K}$$

$$T_{rev} = \frac{(3-s)^2}{(n-3)^2} T_{cs}$$

$$L_{rev} = \frac{(3-s)^2(n-3)(n-4)}{2(4-s)(n-s)^3} \frac{\dot{M} V^3}{v_w} \left(\frac{r}{r_o}\right)^{2-s}$$

$$= 1.57 \times 10^{41} \frac{2(3-s)^2(n-3)(n-4)}{(4-s)(n-s)^3} \frac{\dot{M}_{-5}}{v_{w1}}$$

$$\times V_4^{5-s} \left(\frac{t}{11.57 \ \mathrm{days}}\right)^{2-s} \mathrm{ergs\ s^{-1}} .$$

(Fransson, Lundqvist, Chevalier 1996)

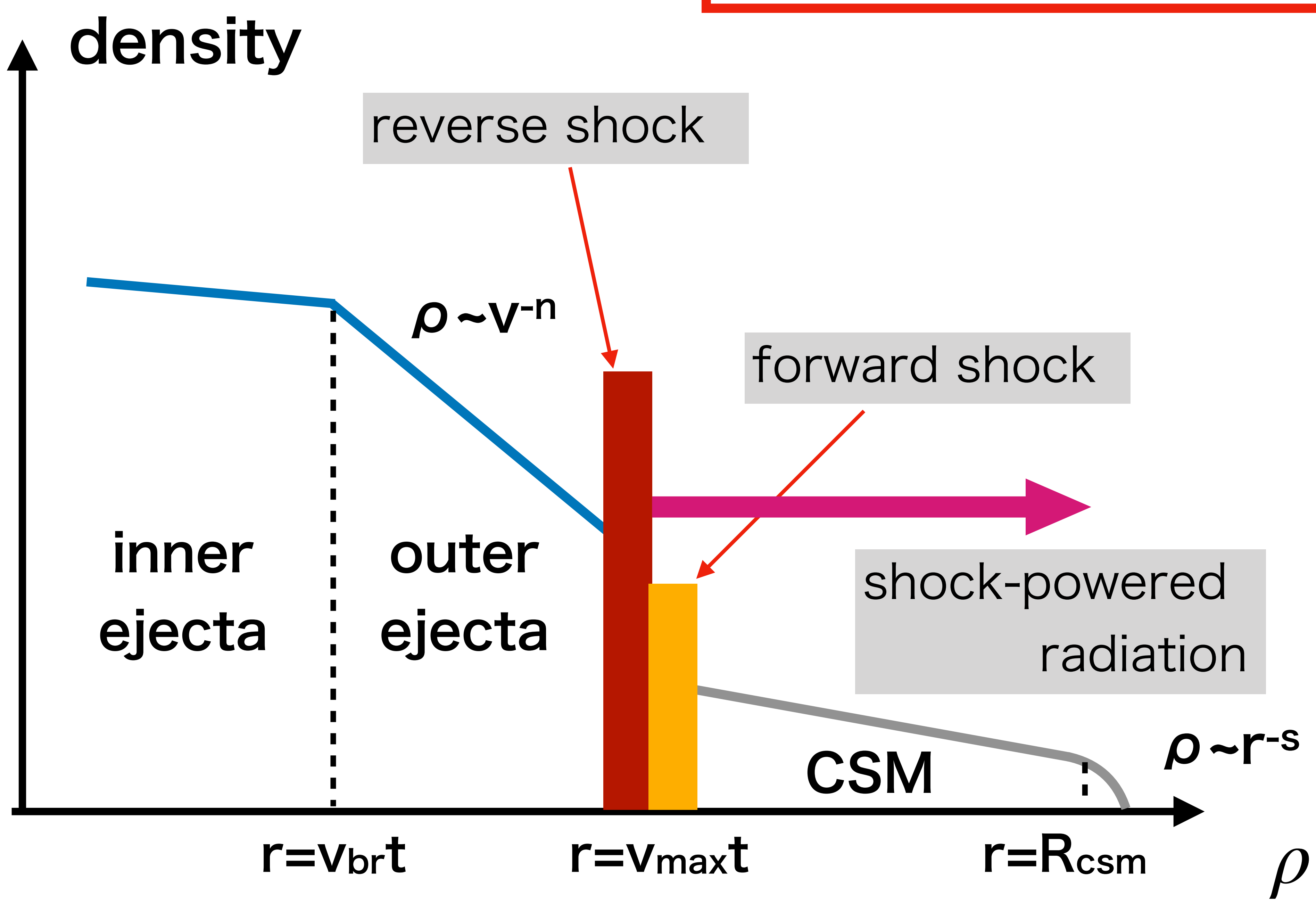
Shock-powered emission

$E_{\rm kin} \xrightarrow{\text{shock}} E_{\rm int}$

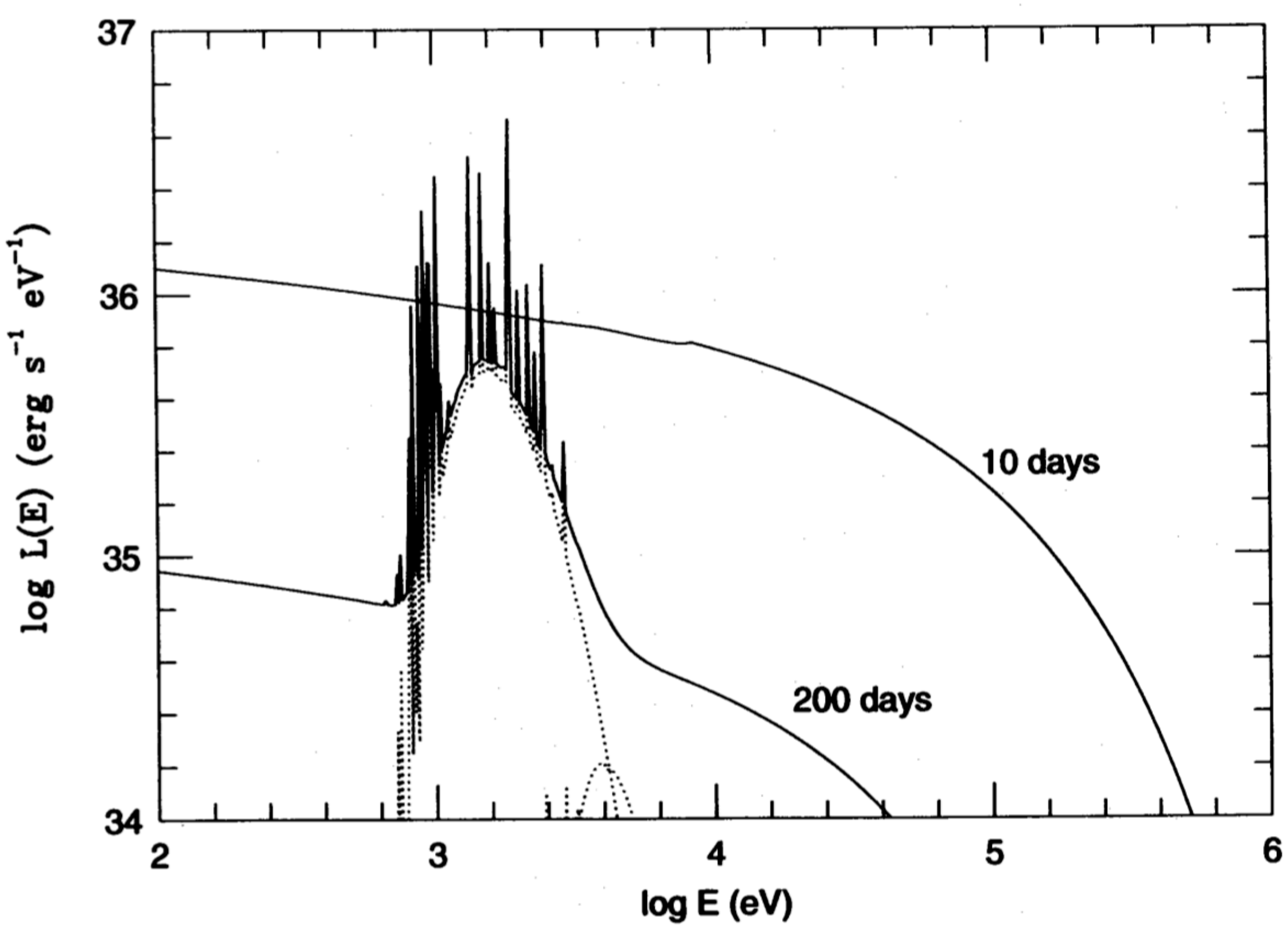
$\xrightarrow{\text{thick}} E_{\rm opt}$

$\boxed{\begin{array}{l} \xrightarrow{\text{free-free}} E_{\rm X} \\ \xrightarrow{\text{MHD/plasma}} E_{\rm B} \\ \xrightarrow{\text{particle acc.}} E_{\rm ele}, E_{\rm CR} \end{array}}$

- post-shock temperature can be much higher than optically thick case (only depends on the shock velocity and composition)
-



$$\rho = \frac{\dot{M}}{4\pi v_{\rm w} r^2}$$



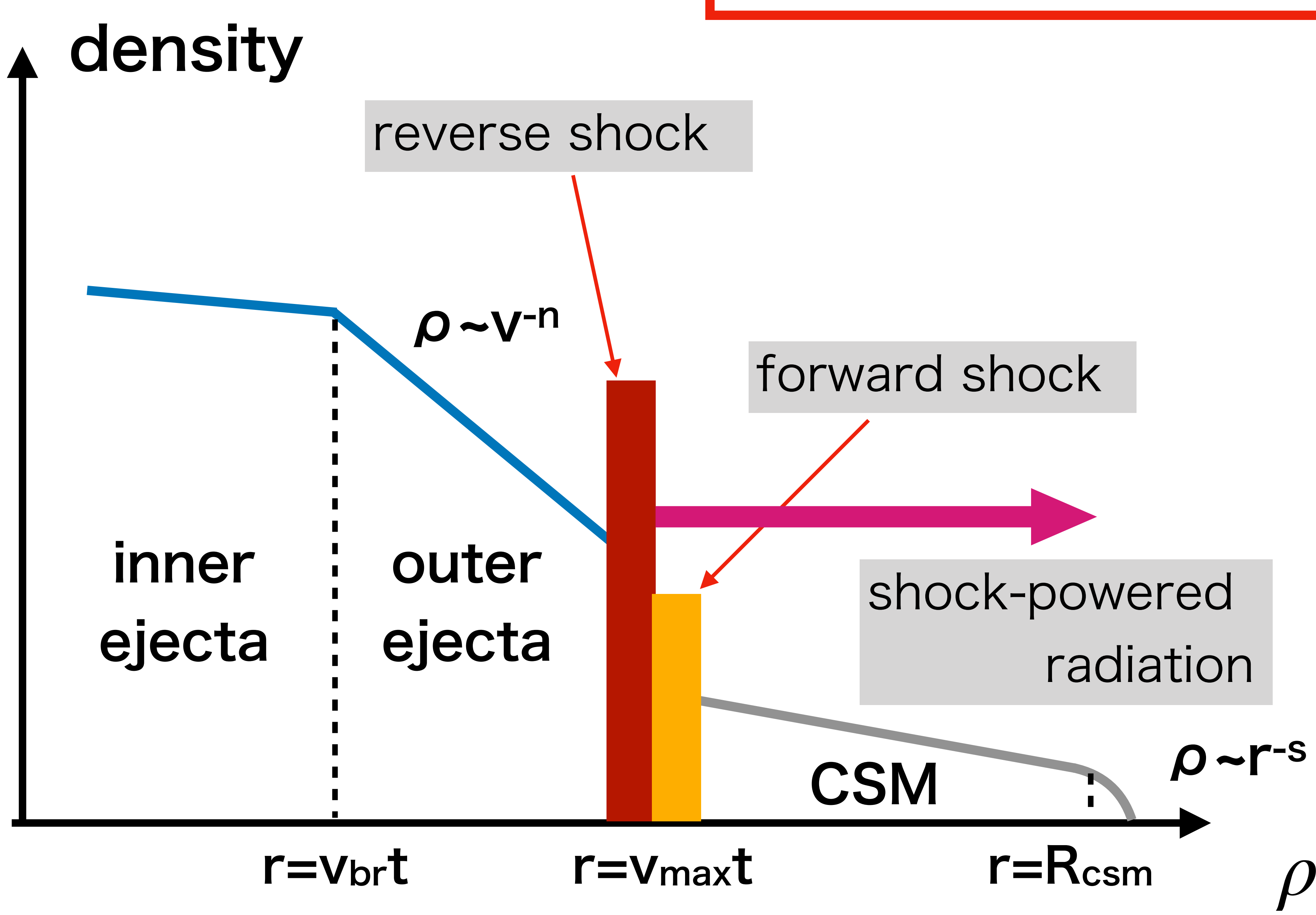
(Fransson, Lundqvist, Chevalier 1996)

Shock-powered emission

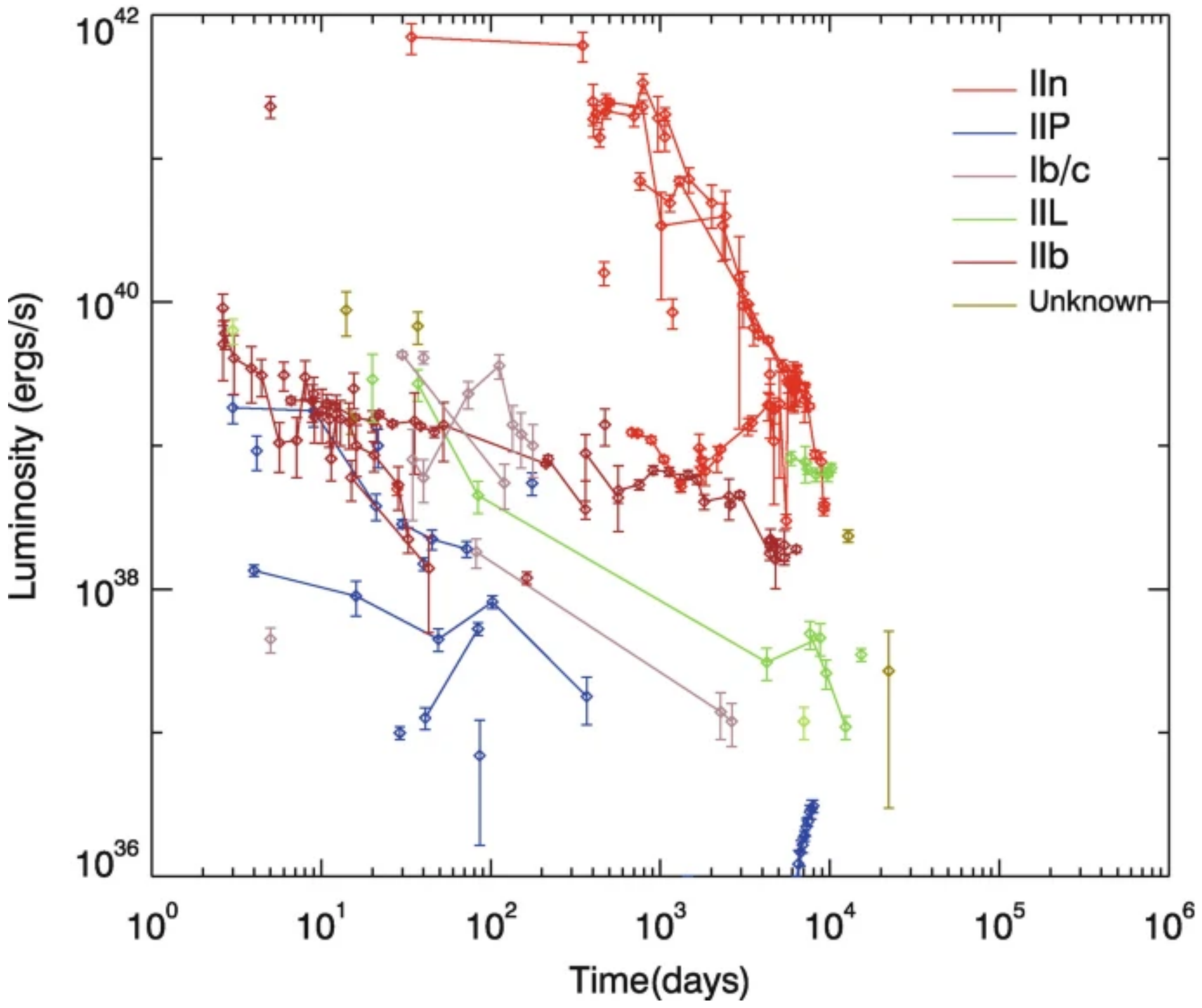
$$E_{\mathrm{kin}} \xrightarrow{\text{shock}} E_{\mathrm{int}} \xrightarrow{\text{thick}} E_{\mathrm{opt}}$$

$$\boxed{\begin{array}{l} \xrightarrow{\text{free-free}} E_{\mathrm{X}} \\ \xrightarrow{\text{MHD/plasma}} E_{\mathrm{B}} \\ \xrightarrow{\text{particle acc.}} E_{\mathrm{ele}}, E_{\mathrm{CR}} \end{array}}$$

- post-shock temperature can be much higher than optically thick case (only depends on the shock velocity and composition)
-



$$\rho = \frac{\dot{M}}{4\pi v_{\mathrm{w}} r^2}$$



X-ray light curves of CCSNe (Dwarkadas 2014)

Shock-powered emission

$$E_{\rm kin} \xrightarrow{\text{shock}} E_{\rm int}$$

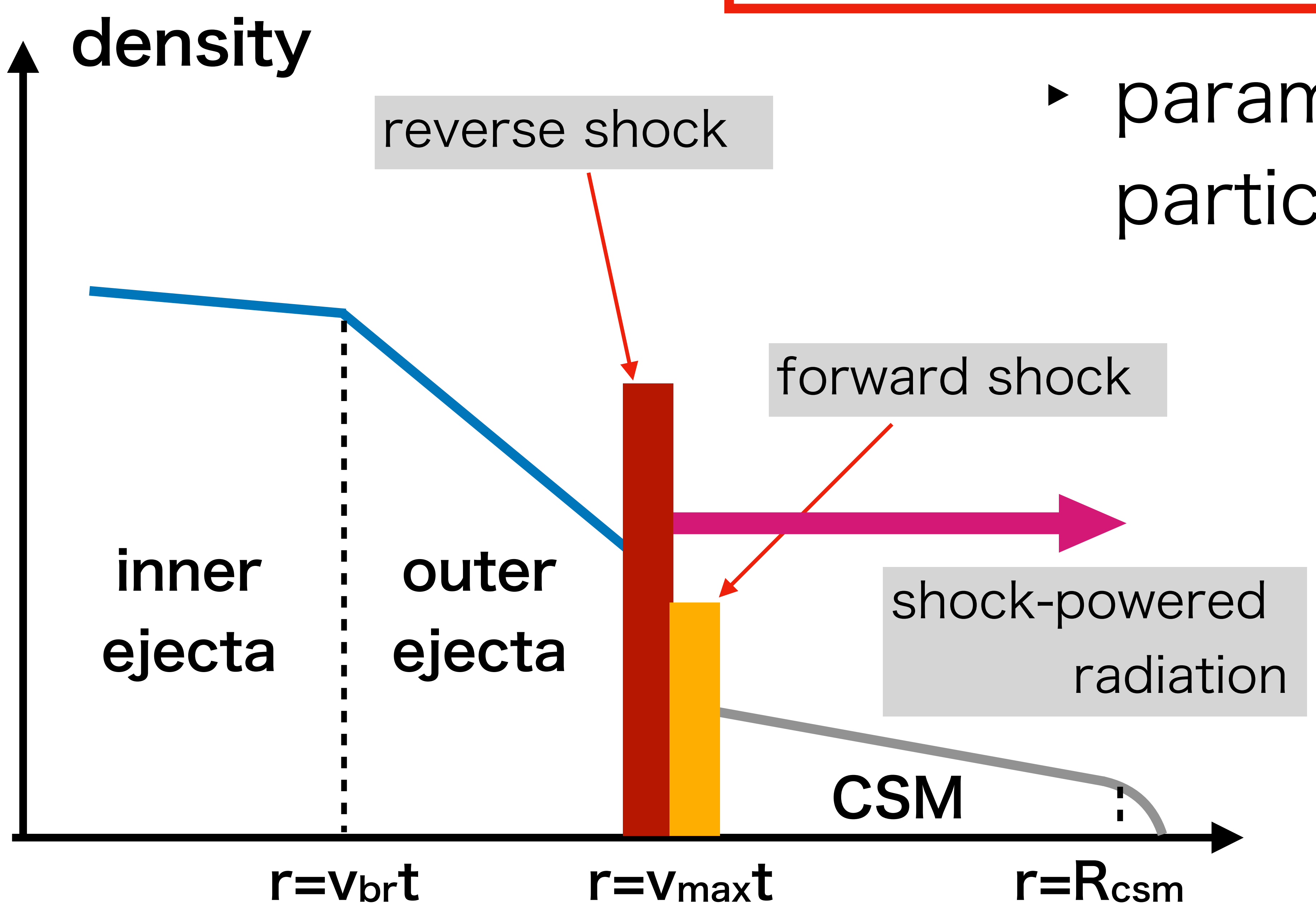
$$\xrightarrow{\text{thick}} E_{\rm opt}$$

$$\xrightarrow{\text{free-free}} E_{\rm X}$$

$$\xrightarrow{\text{MHD/plasma}} E_{\rm B}$$

$$\xrightarrow{\text{particle acc.}} E_{\rm ele}, E_{\rm CR}$$

- shock acceleration produces non-thermal electrons and cosmic-rays (CRs)
- non-thermal electrons in B-field emit synchrotron radiation
- In the presence of enough target protons, CRs produce gamma-ray emission and neutrino



- parameters of particle acceleration

$$E_{\rm B} = \epsilon_{\rm B} E_{\rm int,sh}$$

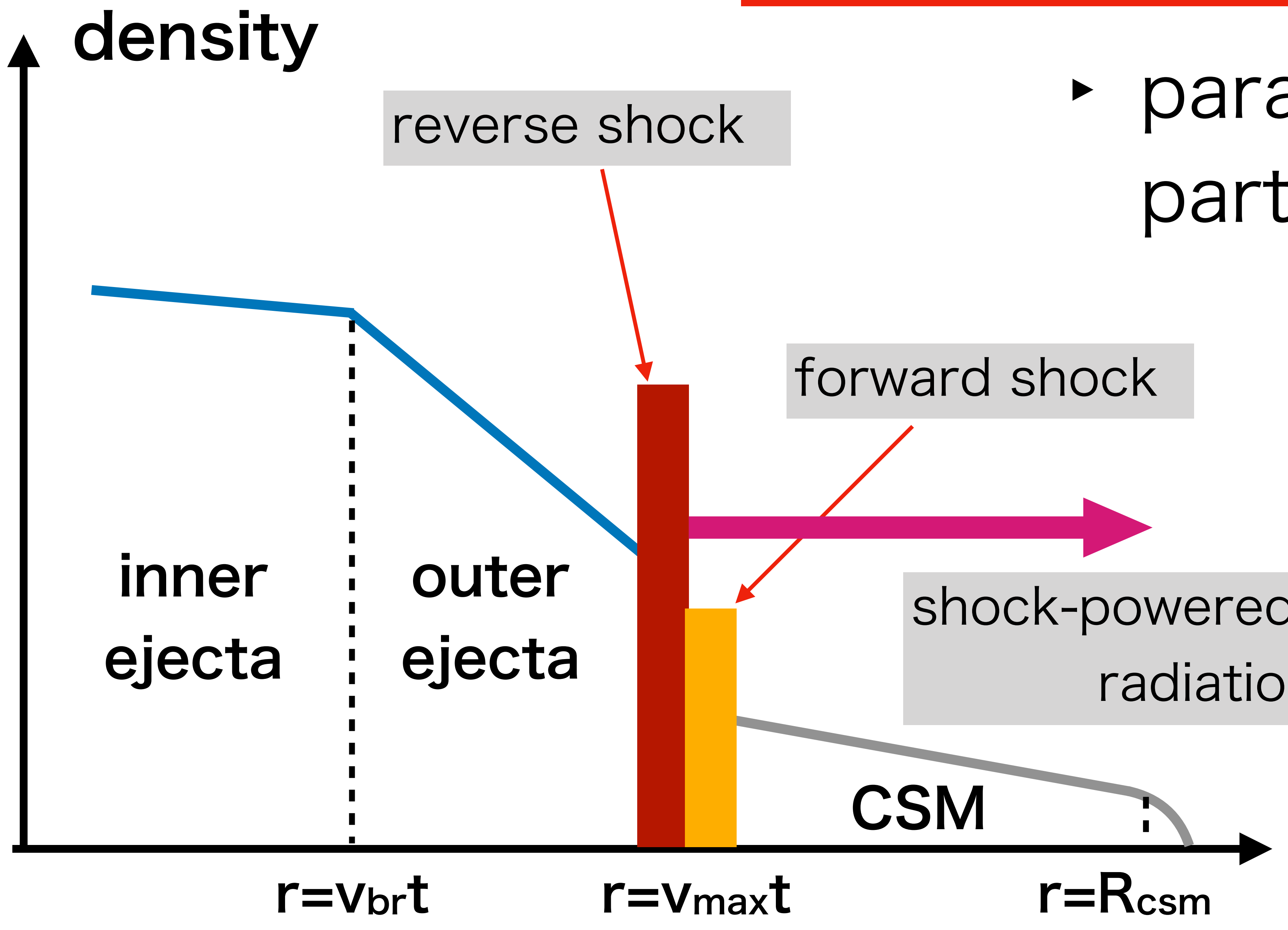
$$E_{\rm ele} = \epsilon_{\rm e} E_{\rm int,sh}$$

Shock-powered emission

$$E_{\rm kin} \xrightarrow{\text{shock}} E_{\rm int}$$

$$\xrightarrow{\text{thick}} E_{\rm opt}$$

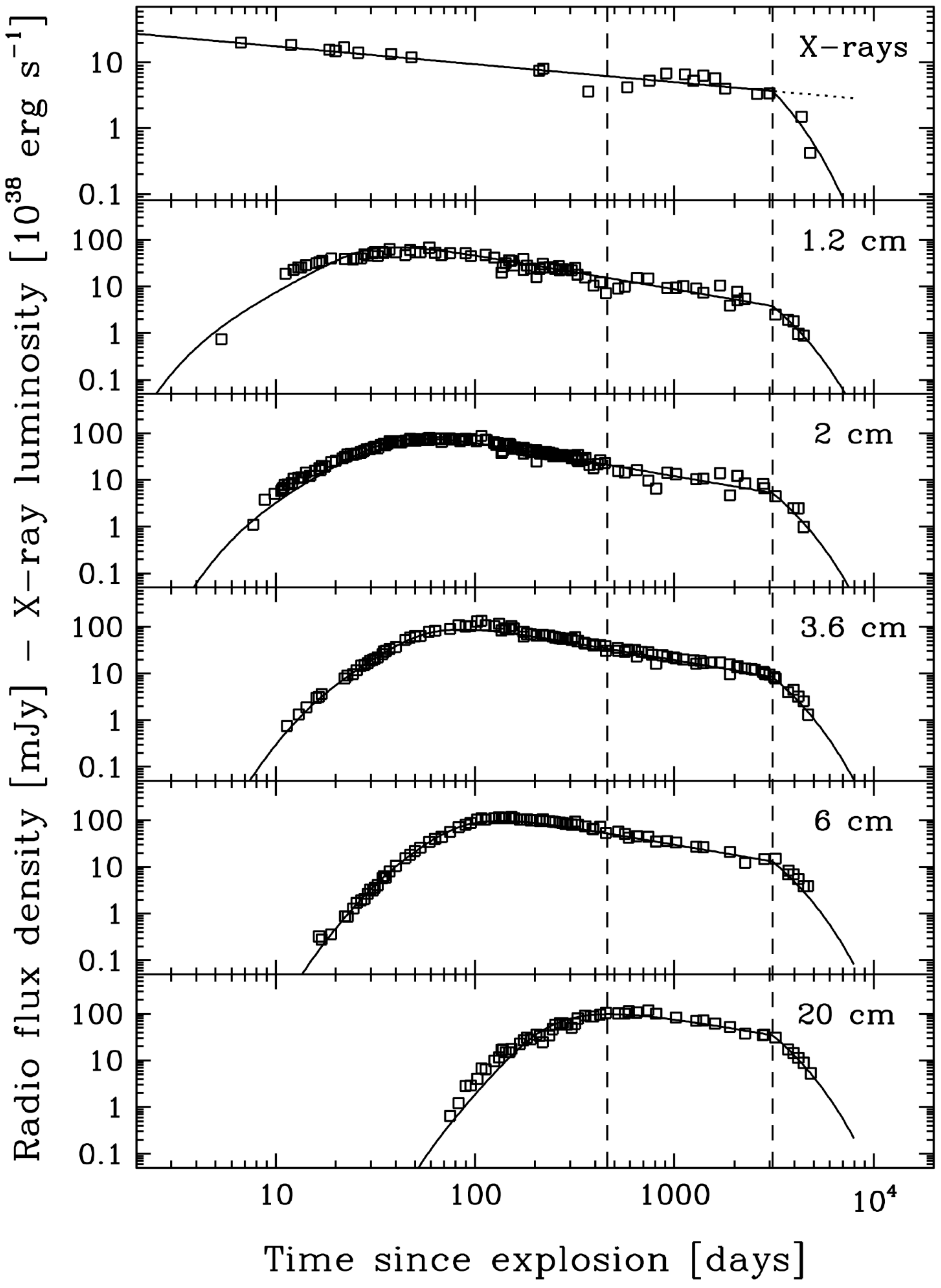
$$\boxed{\begin{array}{l} \xrightarrow{\text{free-free}} E_{\rm X} \\ \xrightarrow{\text{MHD/plasma}} E_{\rm B} \\ \xrightarrow{\text{particle acc.}} E_{\rm ele}, E_{\rm CR} \end{array}}$$



- parameters of particle acceleration

$$E_{\rm B} = \epsilon_{\rm B} E_{\rm int,sh}$$

$$E_{\rm ele} = \epsilon_{\rm e} E_{\rm int,sh}$$



X-ray and radio light curves of SN 1993J in M81 (Weiler+2007)

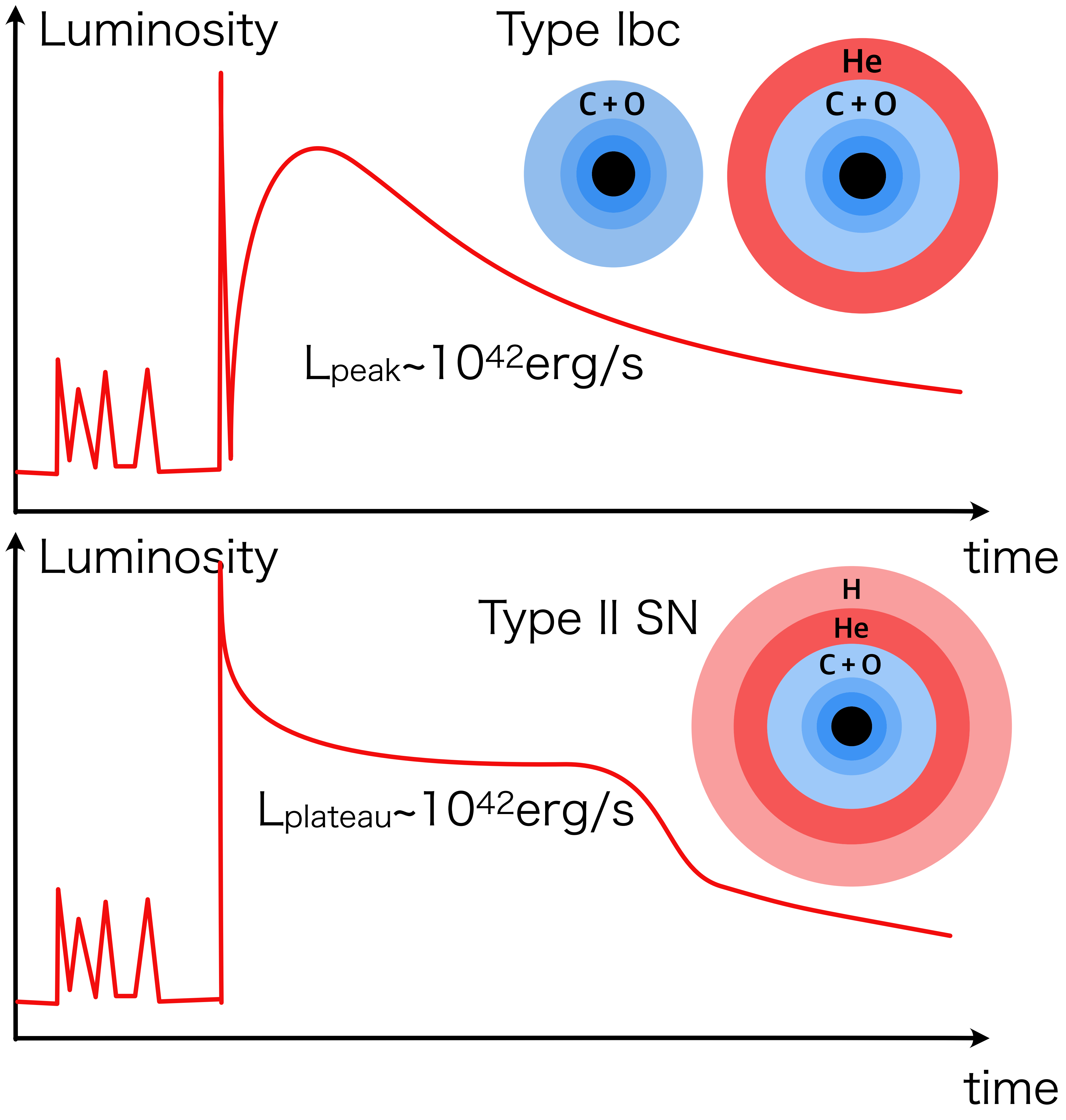
Supernova evolution

- In each phase, properties of exploding stars can be obtained through LCs and spectra (+ multi-λ obs.)

star/ejecta evolution | Research trend

- **pre-supernova image/activity**
  → progenitor properties/activities
- **SN shock breakout/cooling emission**
  → explosion dynamics, stellar radii
- **photospheric/plateau phase**
  → explosion dynamics, stellar mass
- **nebular phase**
  → stellar interior, nucleosynthesis

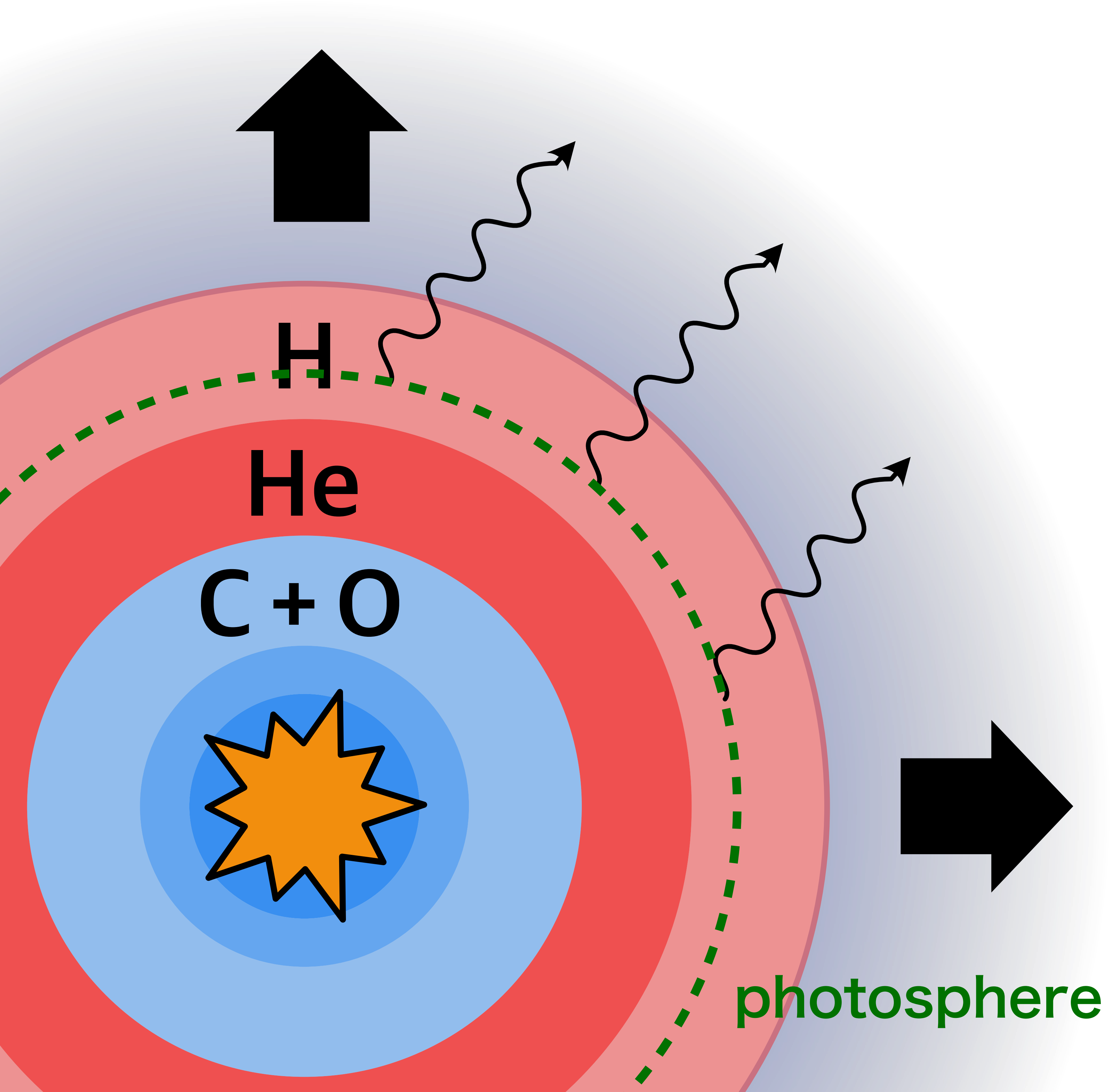
➡ SN remnant phase

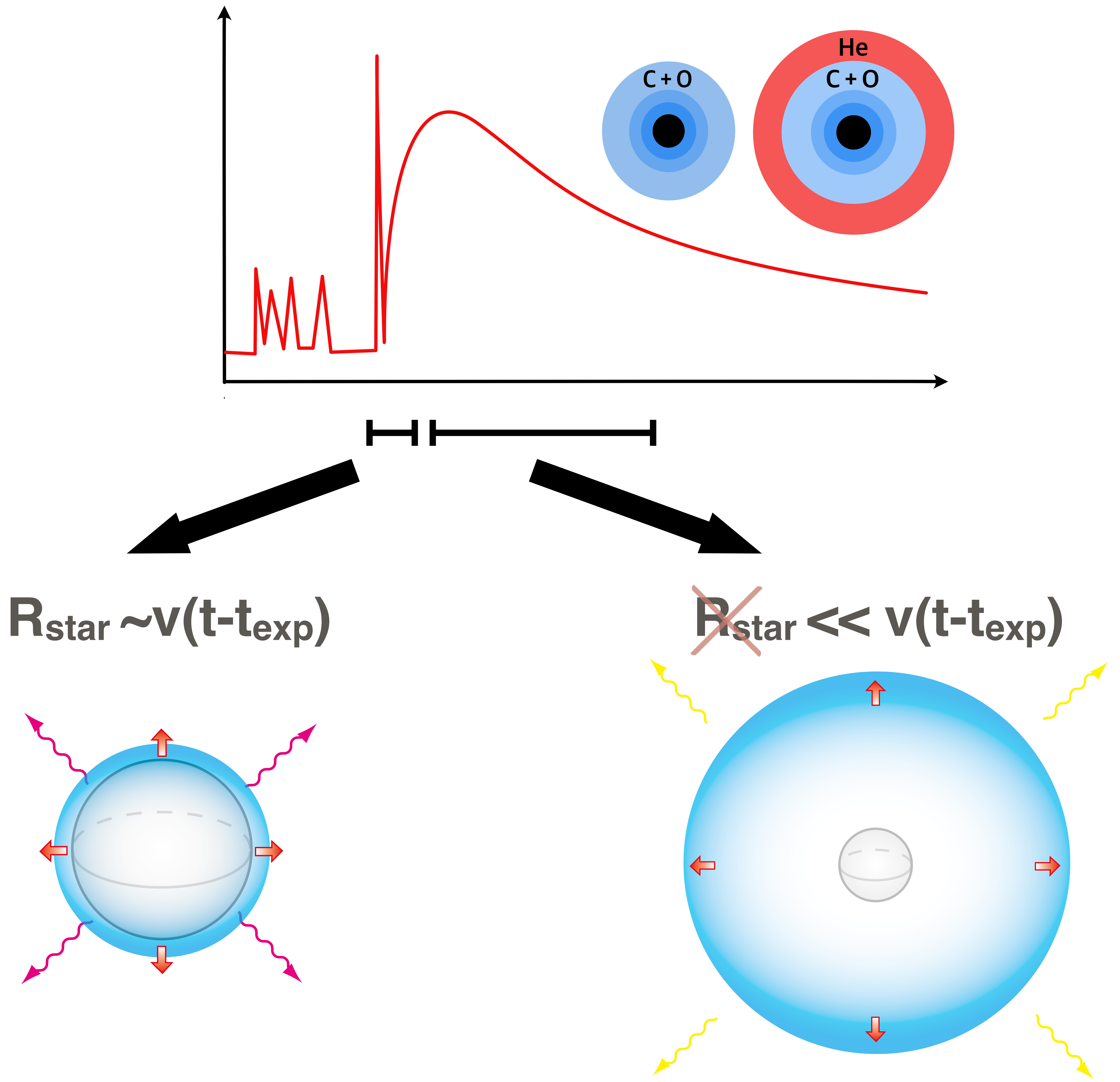


- Introduction
- Evolution of exploding massive stars
- Early emission and past/recent observations
- Progenitor and pre-supernova activities
- Summary

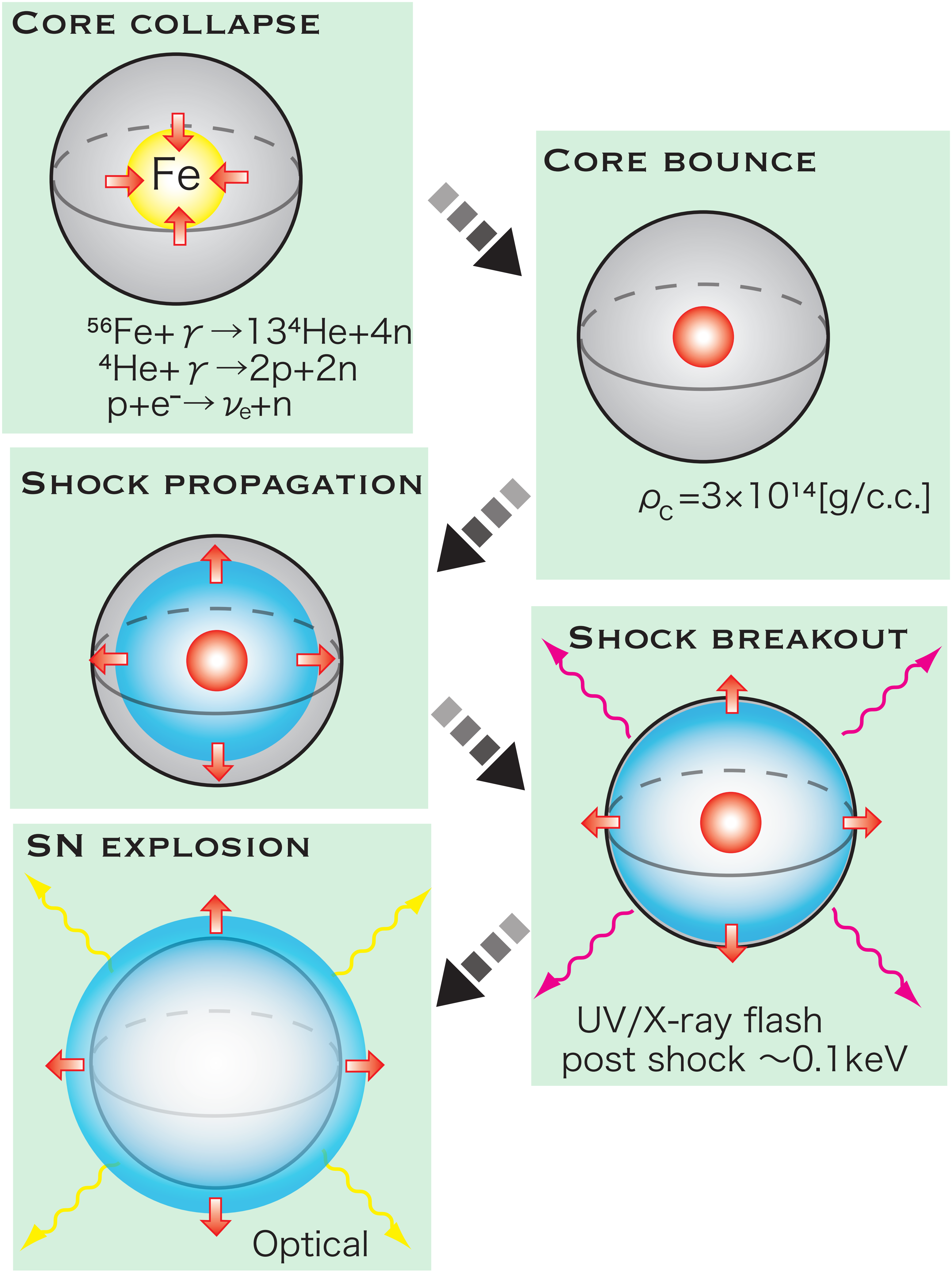
Early emission as a probe of stellar radius/environment

- So far, models have assumed a freely expanding (spherical) fireball, v=r/t
- But, R = R_{star} + v(t-t_{exp})

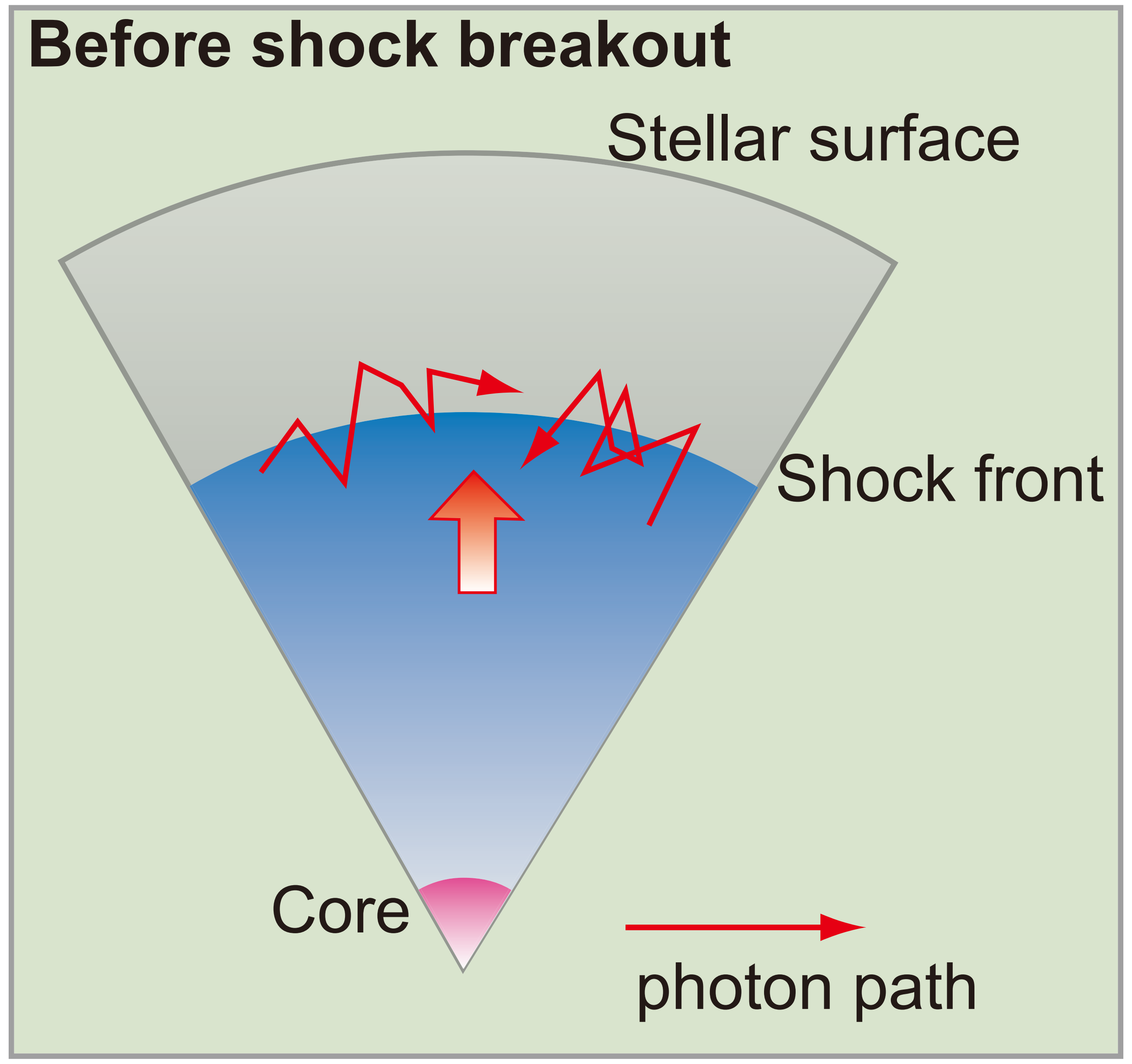


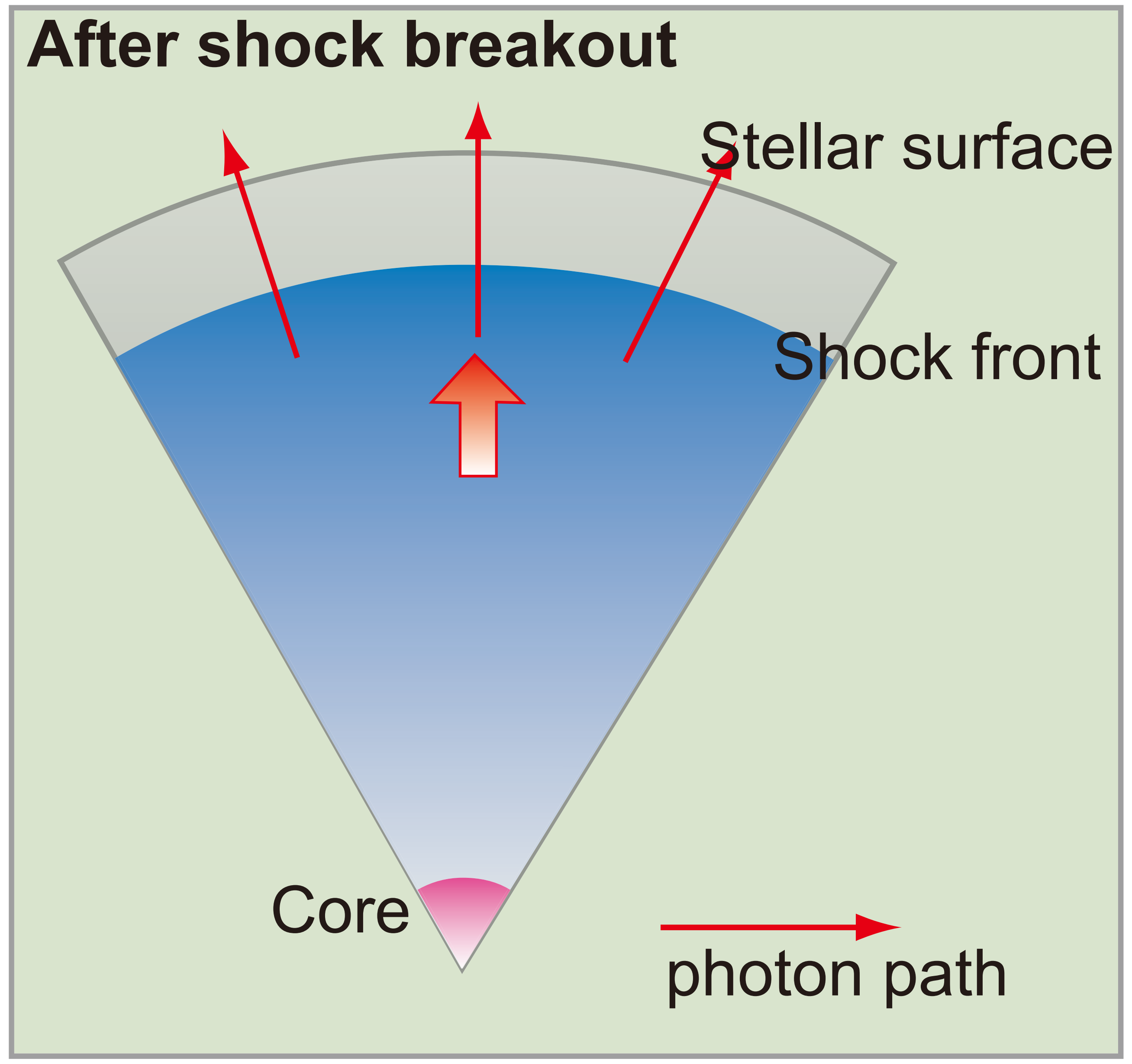


Shock breakout phase: first EM signal from SNe

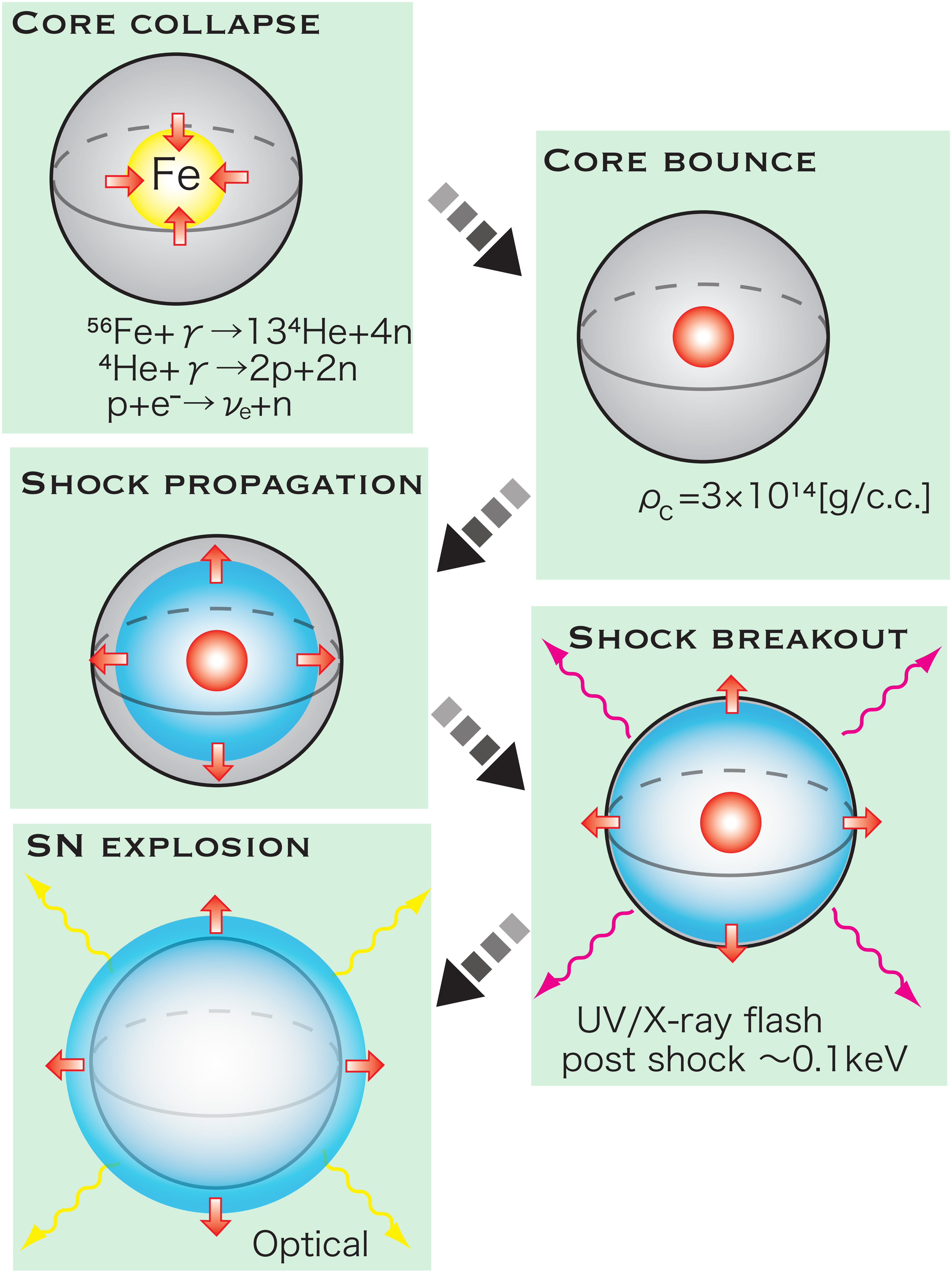


- shock propagation in stellar atmosphere
- shock velocity V_s vs photon diffusion c/τ
- $c/\tau > V_s \rightarrow$ photons start escaping
- EM obs. possible only after this phase

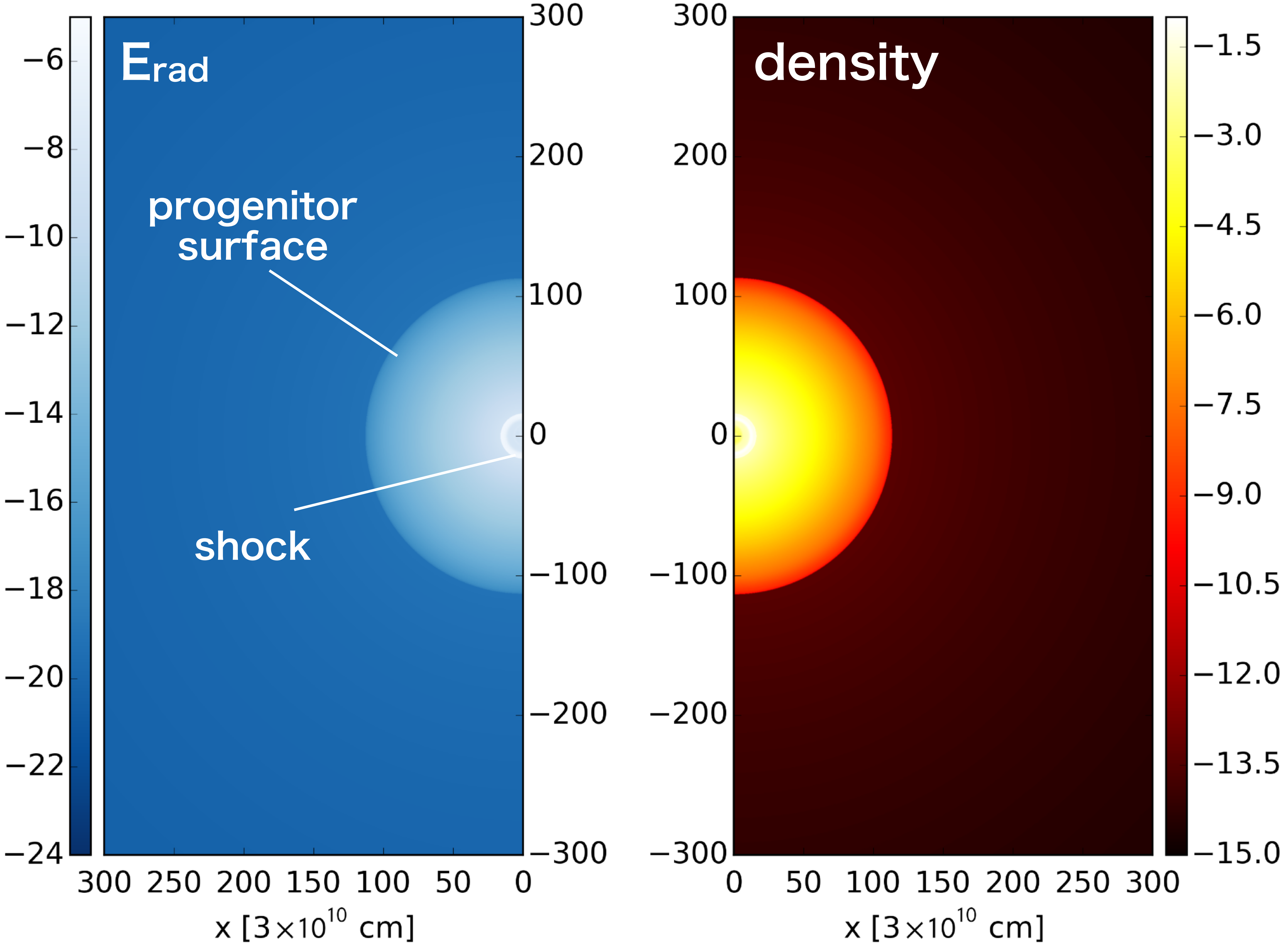




Shock breakout phase: first EM signal from SNe

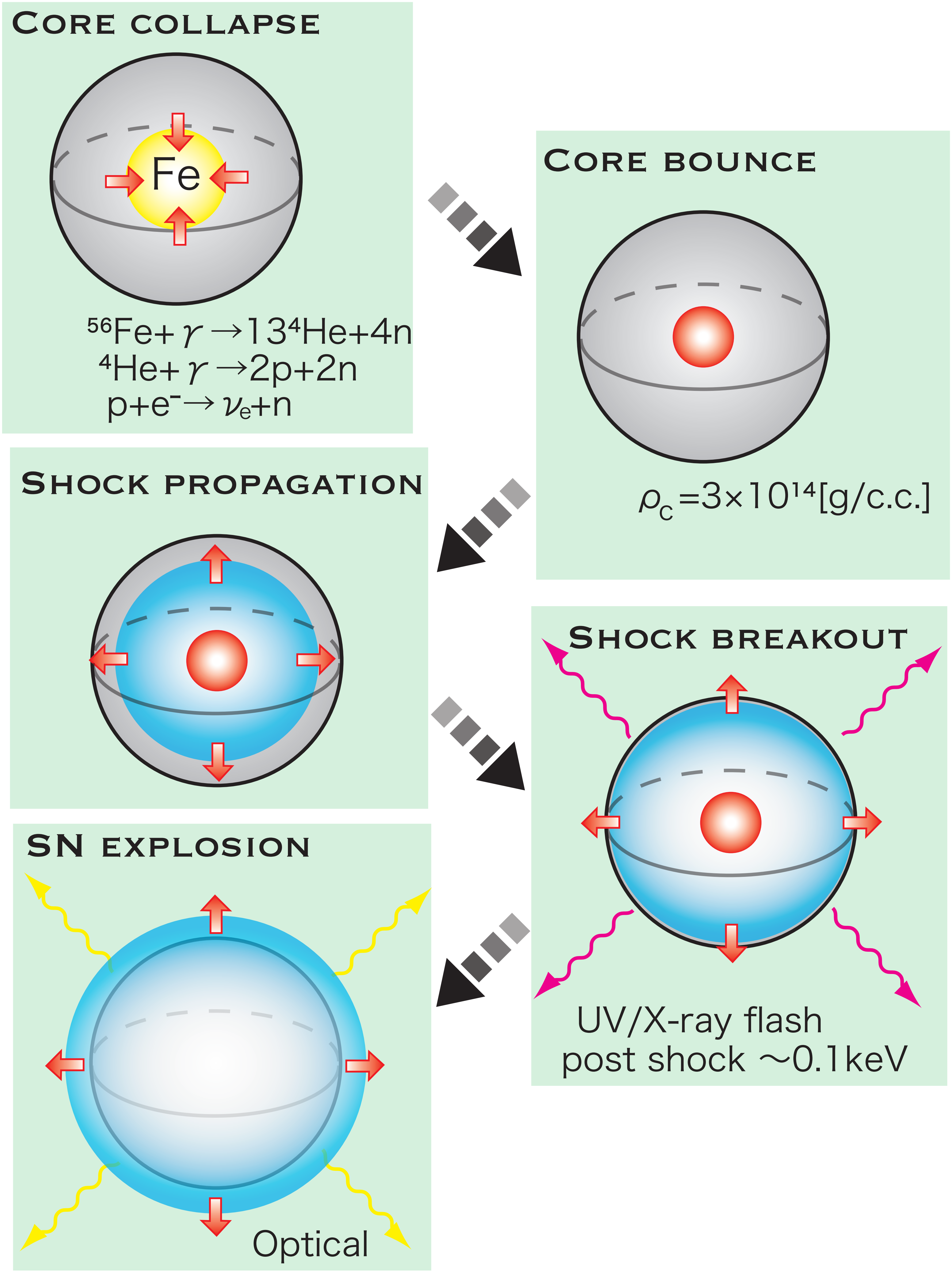


- SN 1987A progenitor: BSG with R_{star}=50R_{sun} M_{star}=14.6M_{sun}



AS, Maeda, & Shigeyama (2016)

Shock breakout phase: first EM signal from SNe



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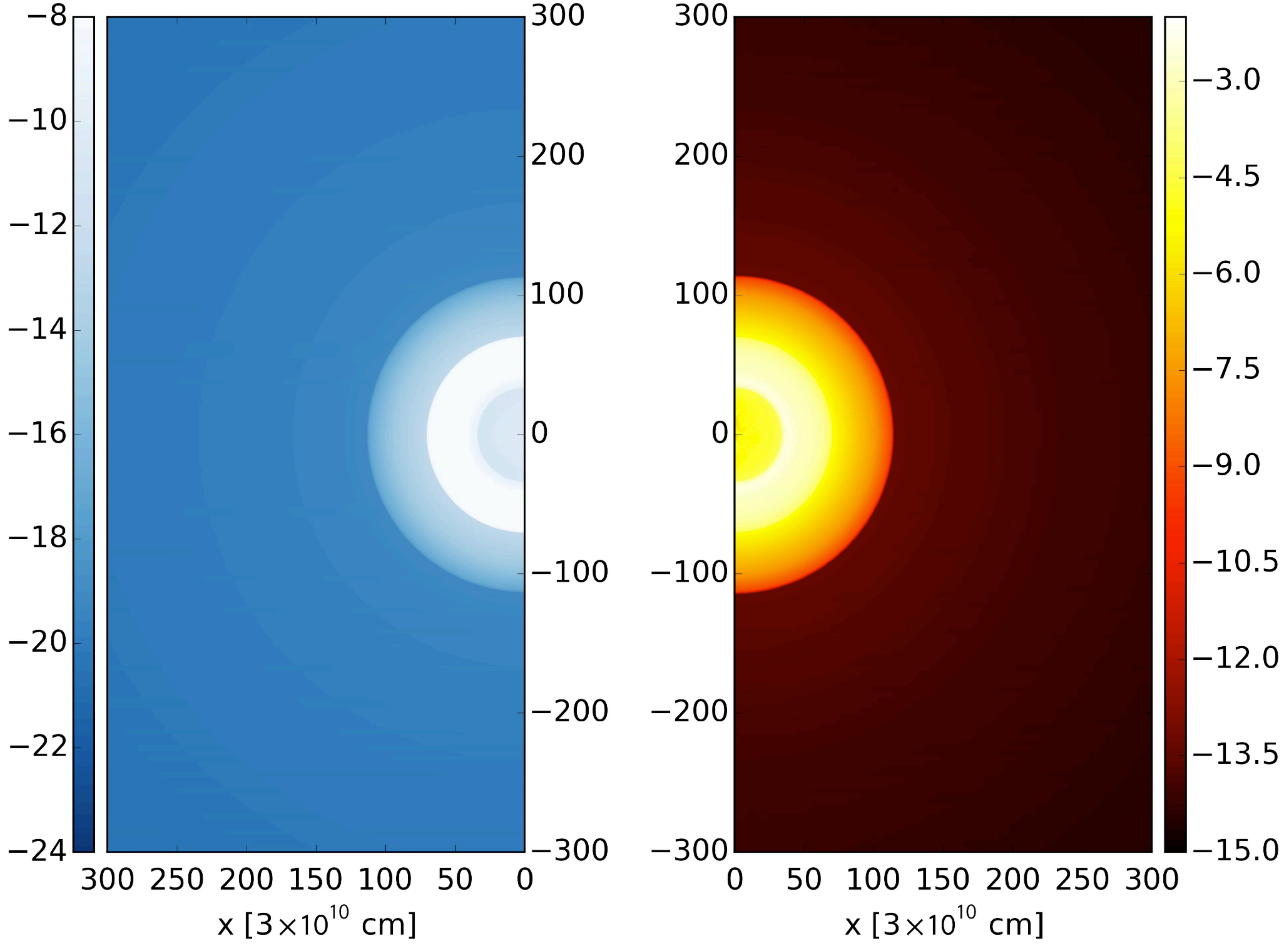
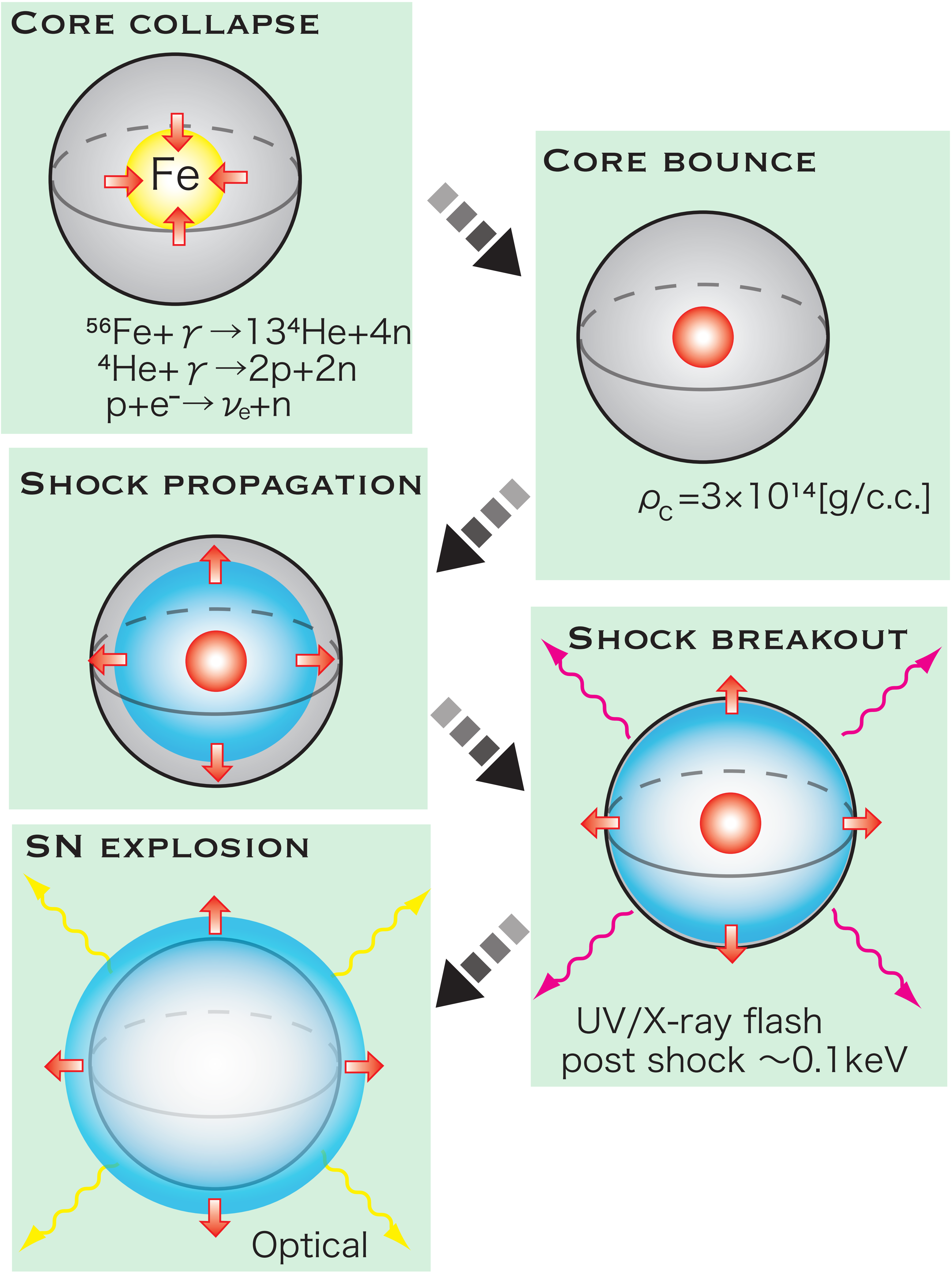


AS, Maeda, & Shigeyama (2016)

Shock breakout phase: first EM signal from SNe



- properties of shock breakout

post-shock temperature

$$T_{se} = 5.55 \times 10^5 \left(\frac{\kappa}{0.34\ \mathrm{cm^2\ g^{-1}}}\right)^{-0.10} \left(\frac{\rho_1}{\rho_*}\right)^{0.070} \times \left(\frac{E_{in}}{10^{51}\ \mathrm{ergs}}\right)^{0.20} \left(\frac{M_{ej}}{10\ M_\odot}\right)^{-0.052} \times \left(\frac{R_*}{500\ R_\odot}\right)^{-0.54} \mathrm{K} \quad \left(n = \frac{3}{2}\right),$$

$$T_{se} = 1.31 \times 10^6 \left(\frac{\kappa}{0.34\ \mathrm{cm^2\ g^{-1}}}\right)^{-0.14} \left(\frac{\rho_1}{\rho_*}\right)^{0.046} \times \left(\frac{E_{in}}{10^{51}\ \mathrm{ergs}}\right)^{0.18} \left(\frac{M_{ej}}{10\ M_\odot}\right)^{-0.068} \times \left(\frac{R_*}{50\ R_\odot}\right)^{-0.48} \mathrm{K} \quad (n = 3)\ .$$

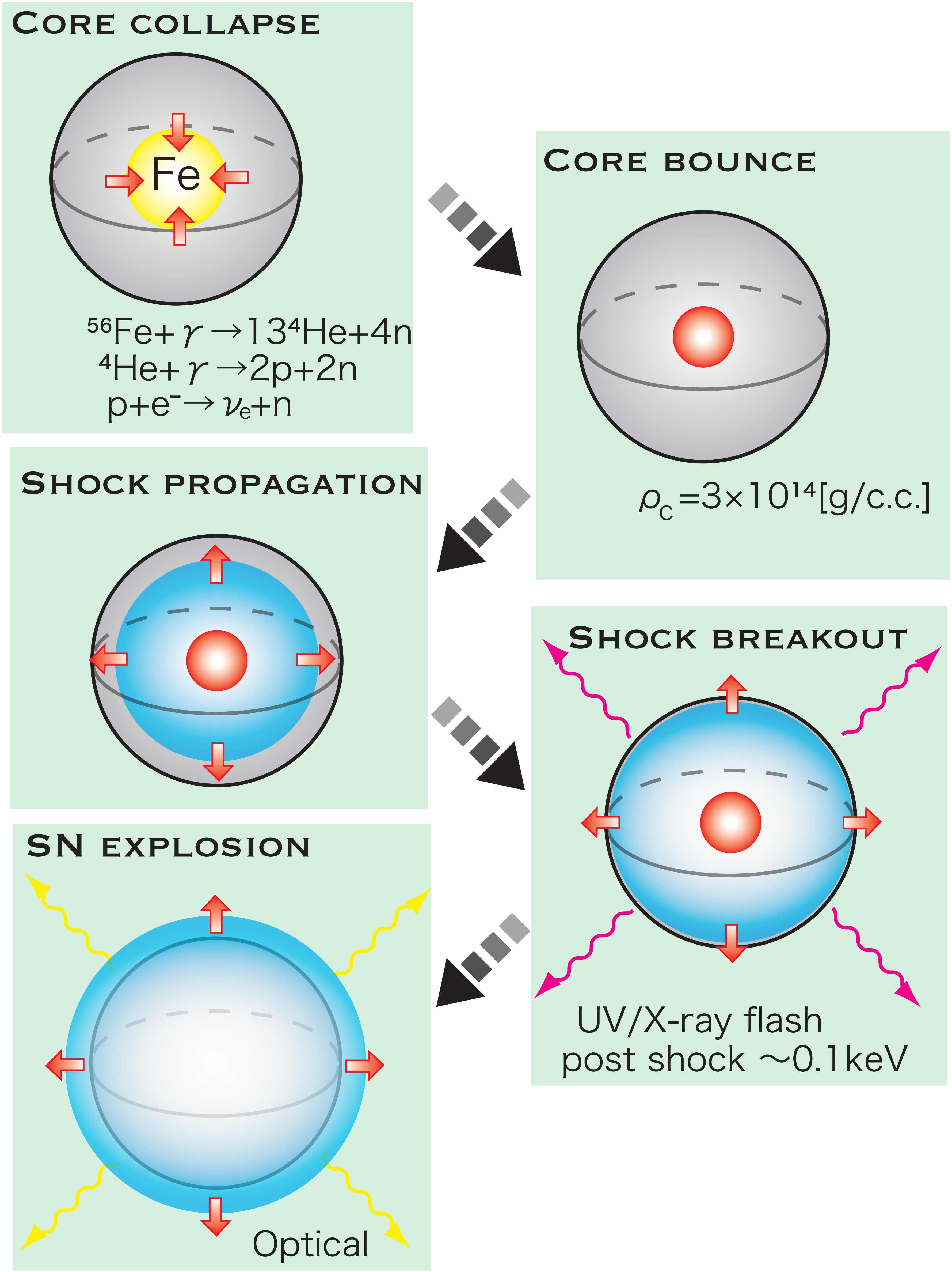
radiation energy

$$E_{se} = 1.7 \times 10^{48} \left(\frac{\kappa}{0.34\ \mathrm{cm^2\ g^{-1}}}\right)^{-0.87} \left(\frac{\rho_1}{\rho_*}\right)^{-0.086} \times \left(\frac{E_{in}}{10^{51}\ \mathrm{ergs}}\right)^{0.56} \left(\frac{M_{ej}}{10\ M_\odot}\right)^{-0.44} \times \left(\frac{R_*}{500\ R_\odot}\right)^{1.74} \mathrm{ergs} \quad \left(n = \frac{3}{2}\right),$$

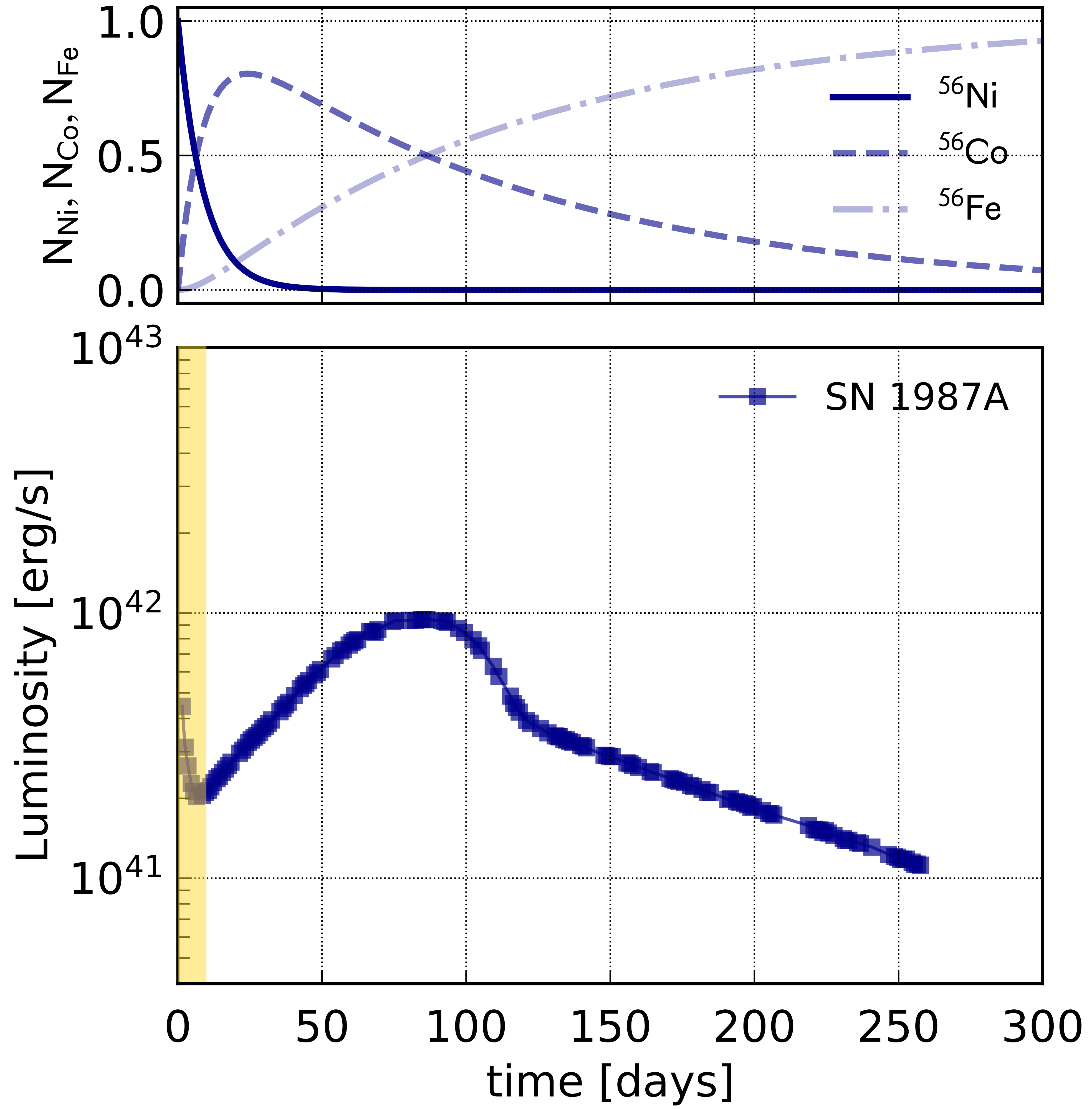
$$E_{se} = 7.6 \times 10^{46} \left(\frac{\kappa}{0.34\ \mathrm{cm^2\ g^{-1}}}\right)^{-0.84} \left(\frac{\rho_1}{\rho_*}\right)^{-0.054} \times \left(\frac{E_{in}}{10^{51}\ \mathrm{ergs}}\right)^{0.58} \left(\frac{M_{ej}}{10\ M_\odot}\right)^{-0.42} \times \left(\frac{R_*}{50\ R_\odot}\right)^{1.68} \mathrm{ergs} \quad (n = 3)\ .$$

Matzner&McKee (1999)

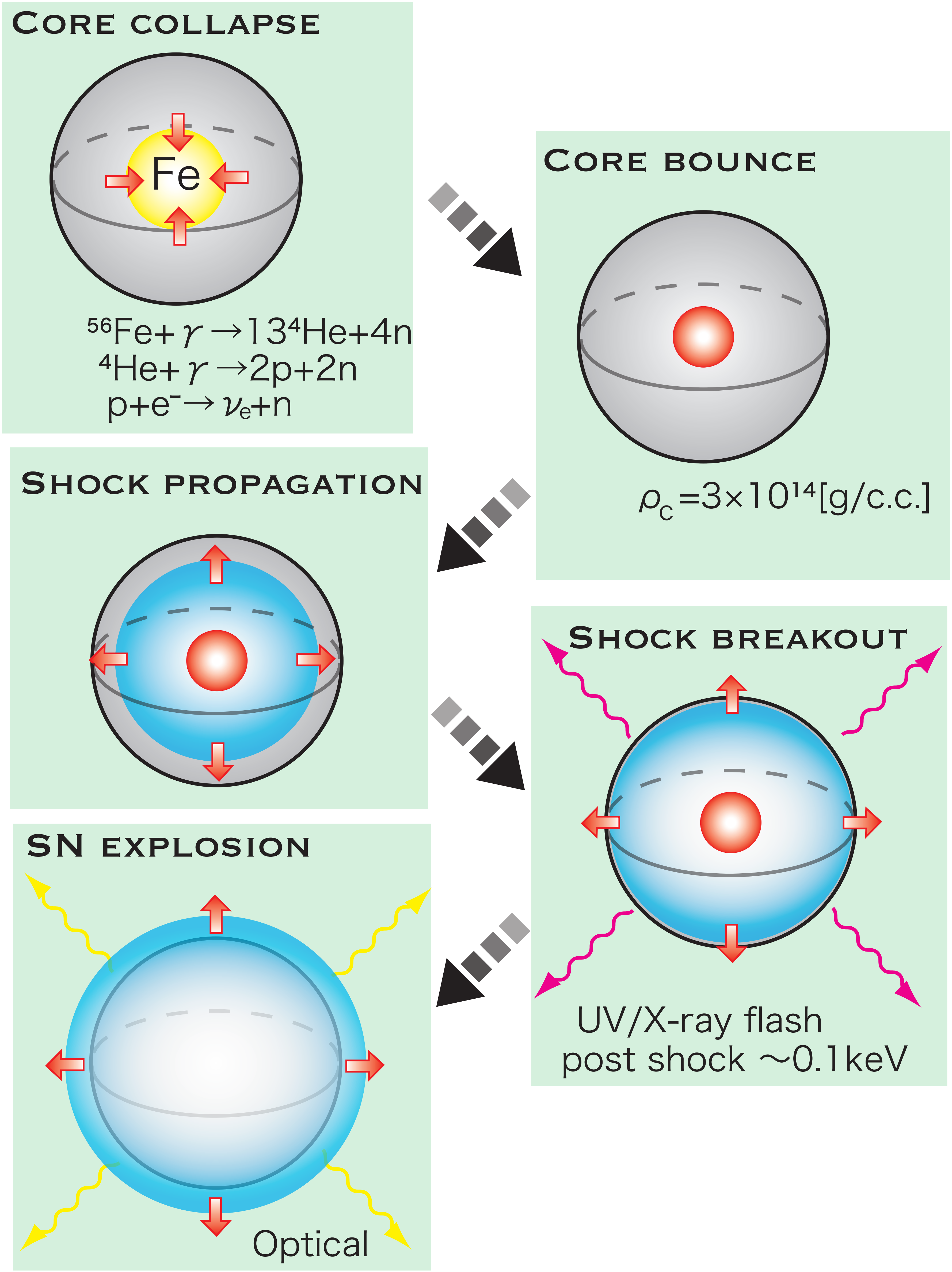
Early observations of CCSNe



- But, observations are challenging
- SN 1987A obs. : post-shock breakout emission



Early observations of CCSNe



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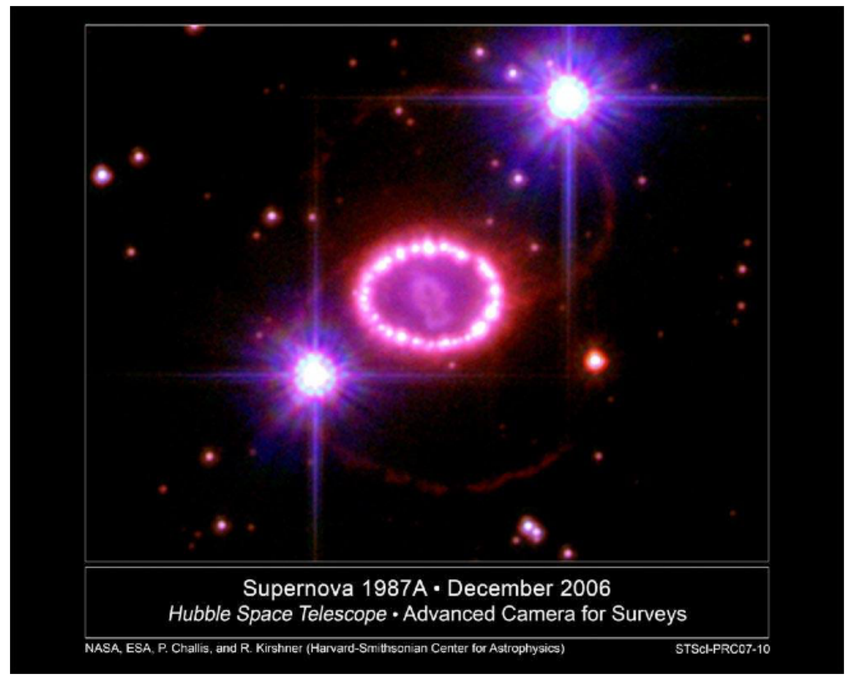
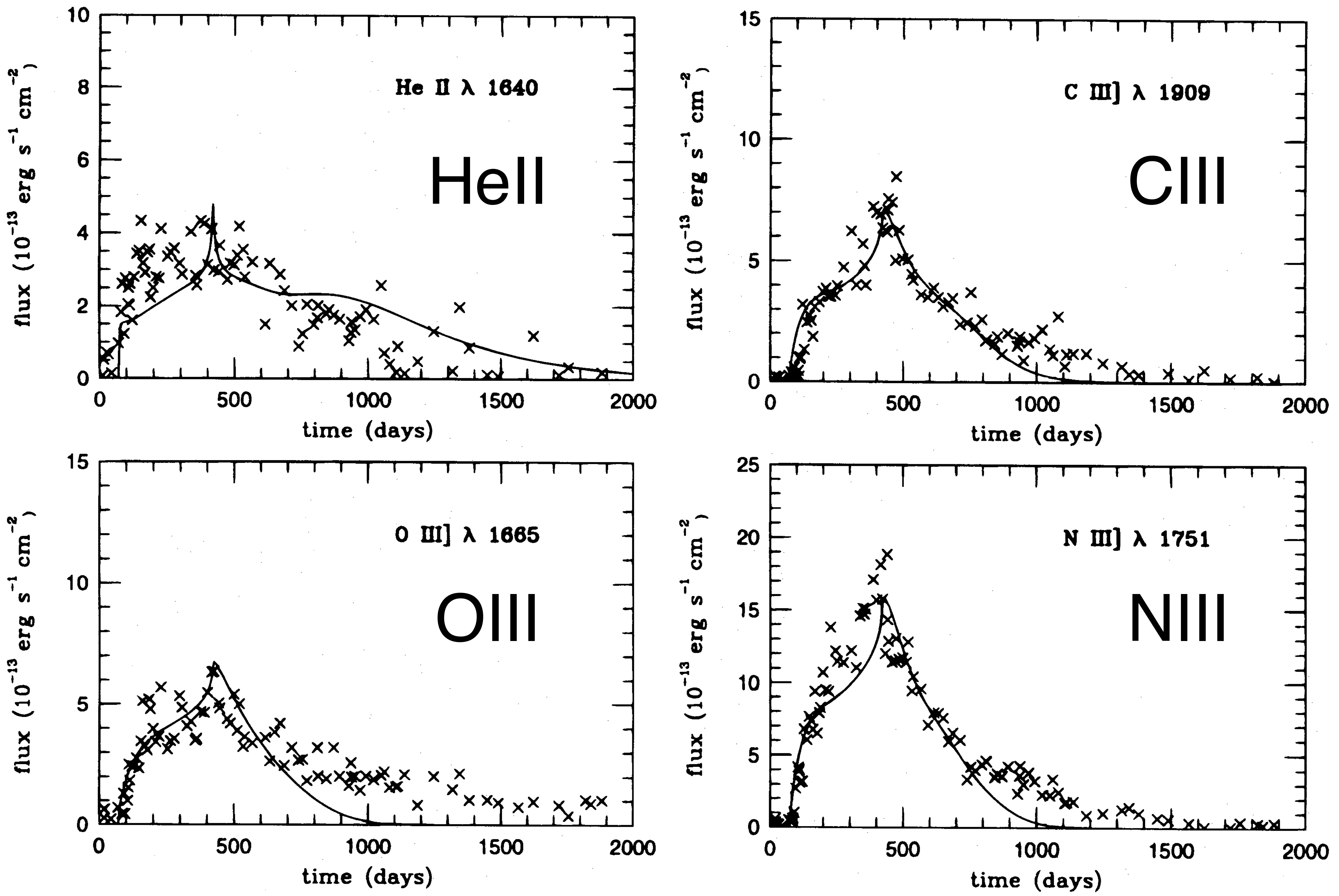
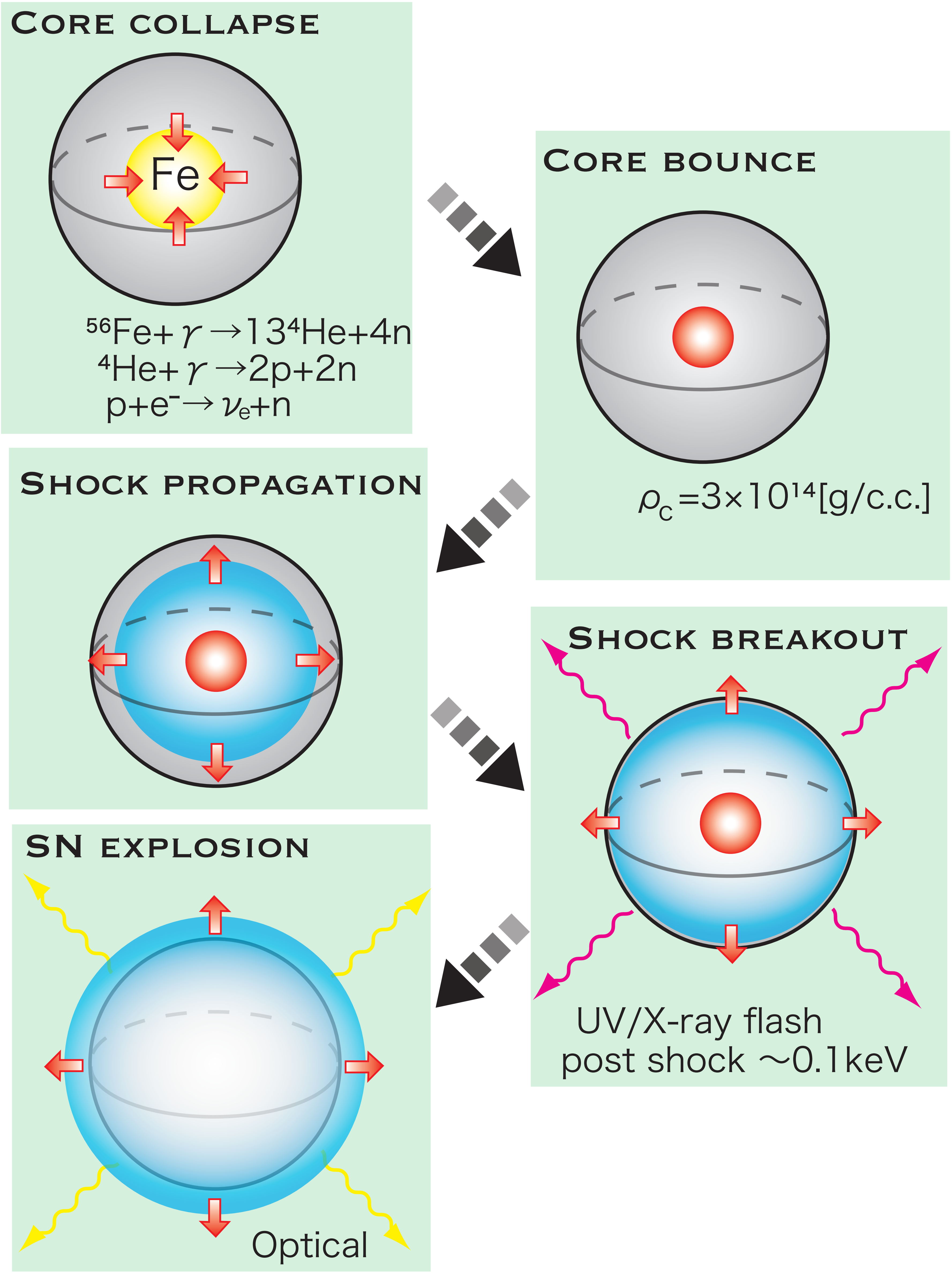
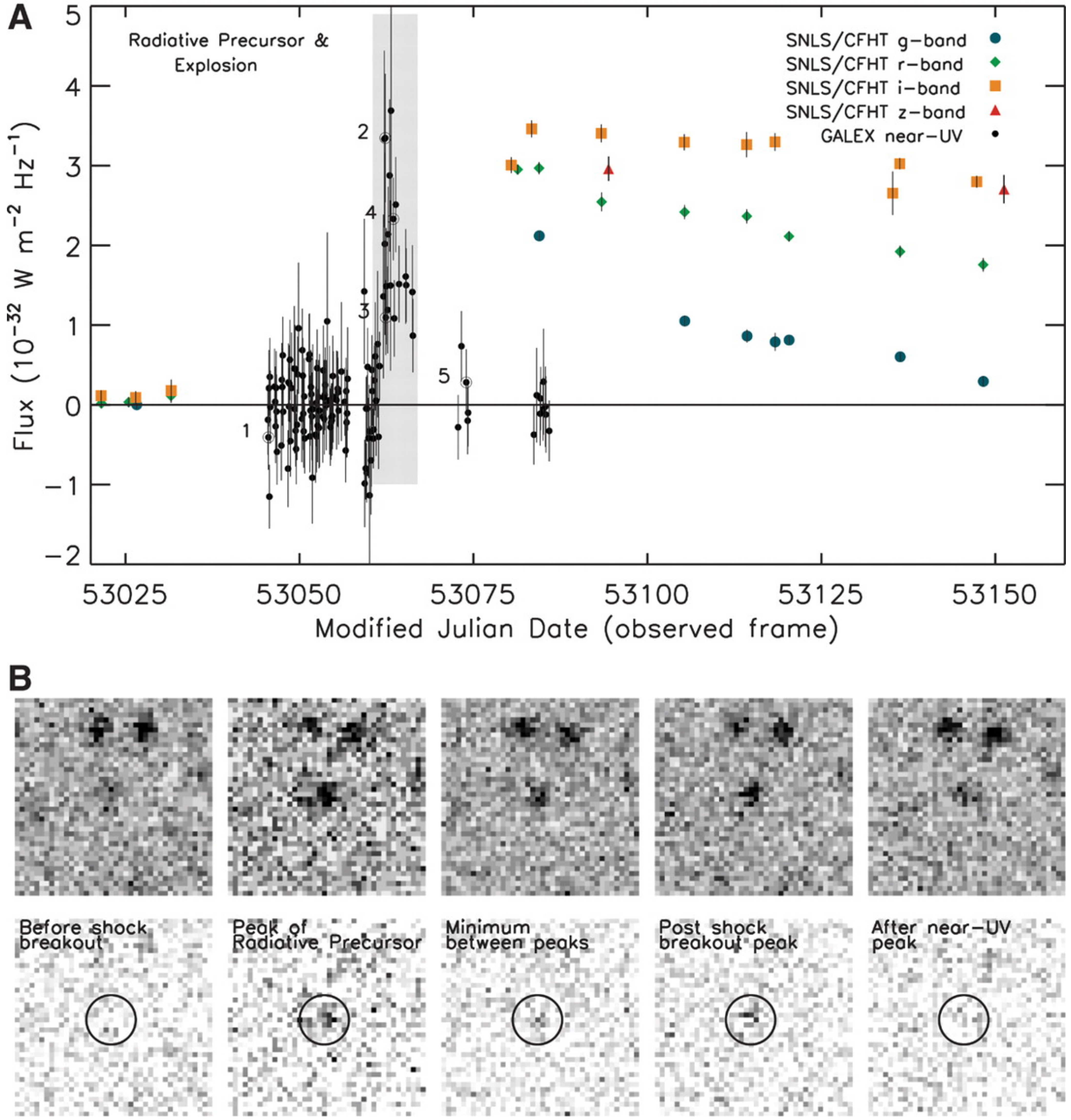


Narrow emission lines from SN 1987A
(Lundqvist&Fransson 1996)



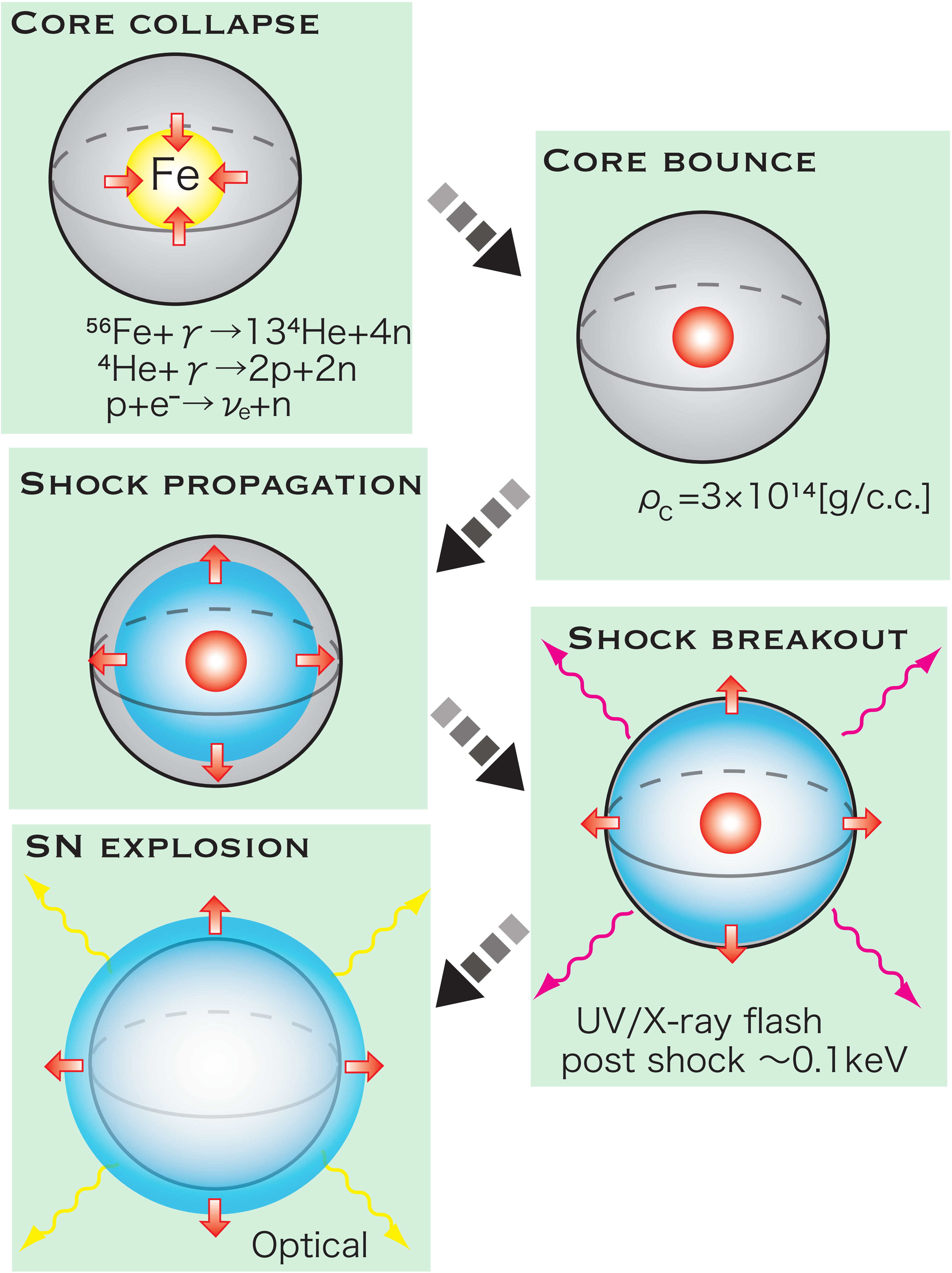
Early observations of CCSNe

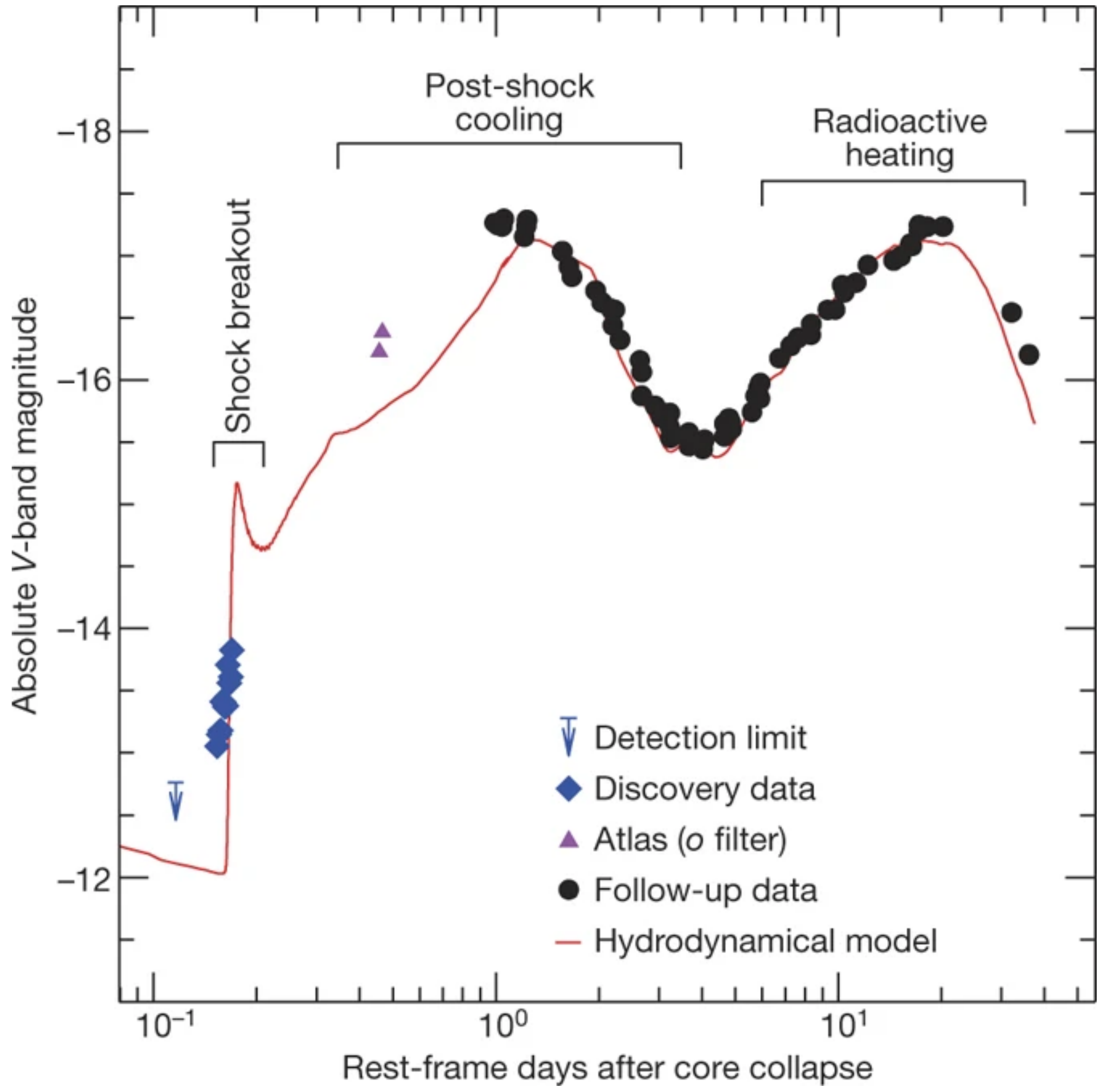




SN breakout emission observed by UV satellite GALEX
(Schwanski+2008)

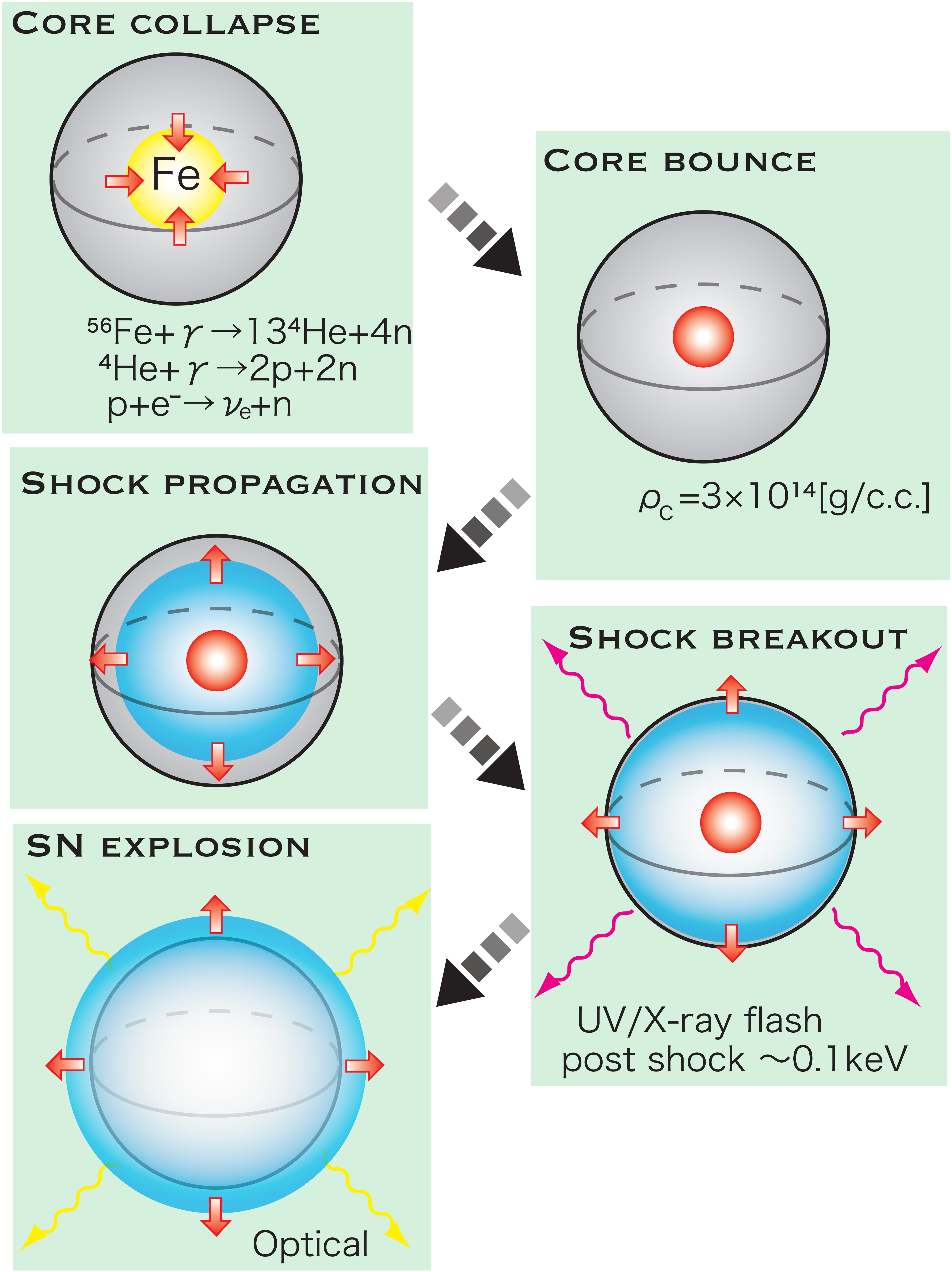
Early observations of CCSNe

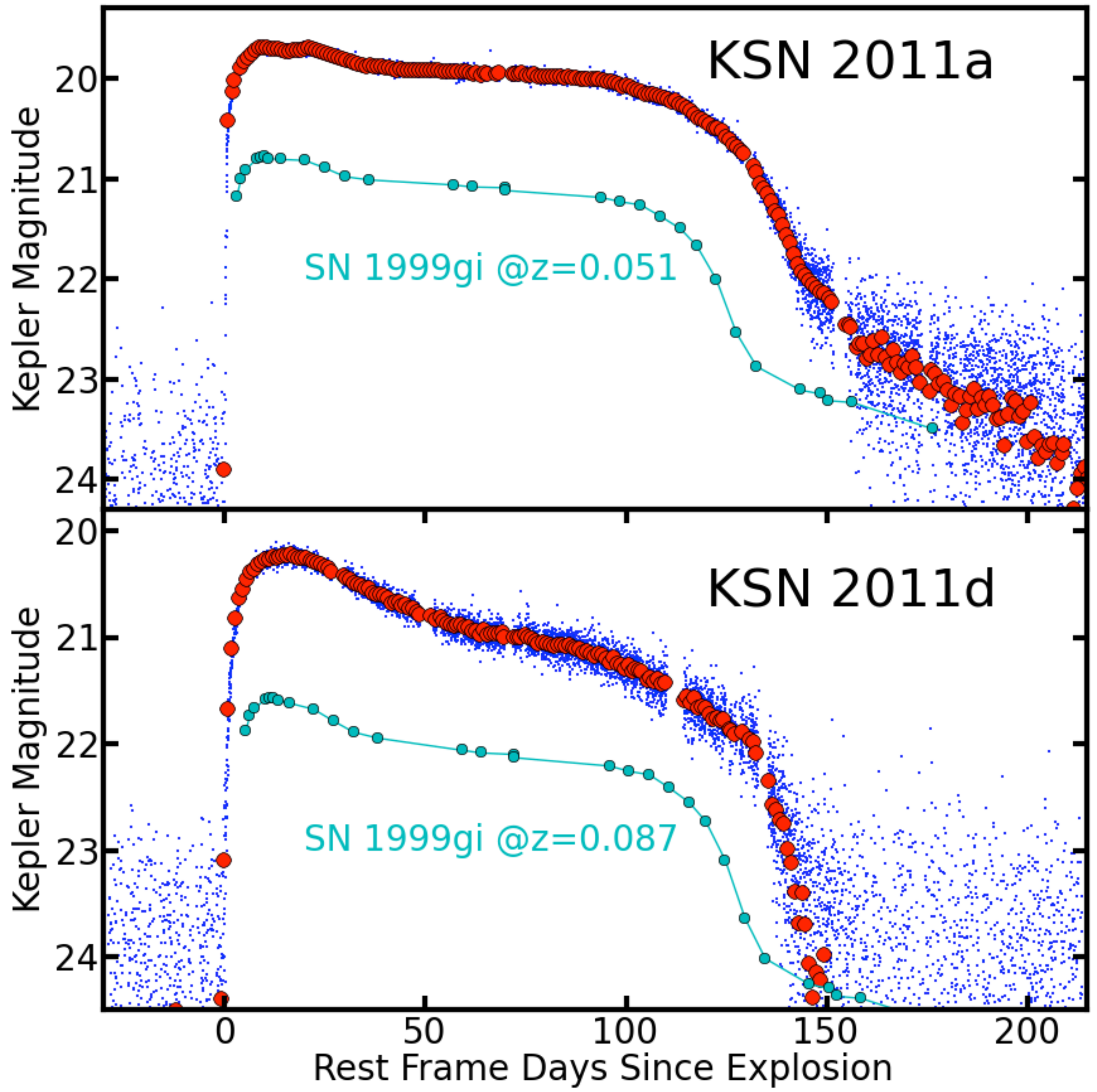


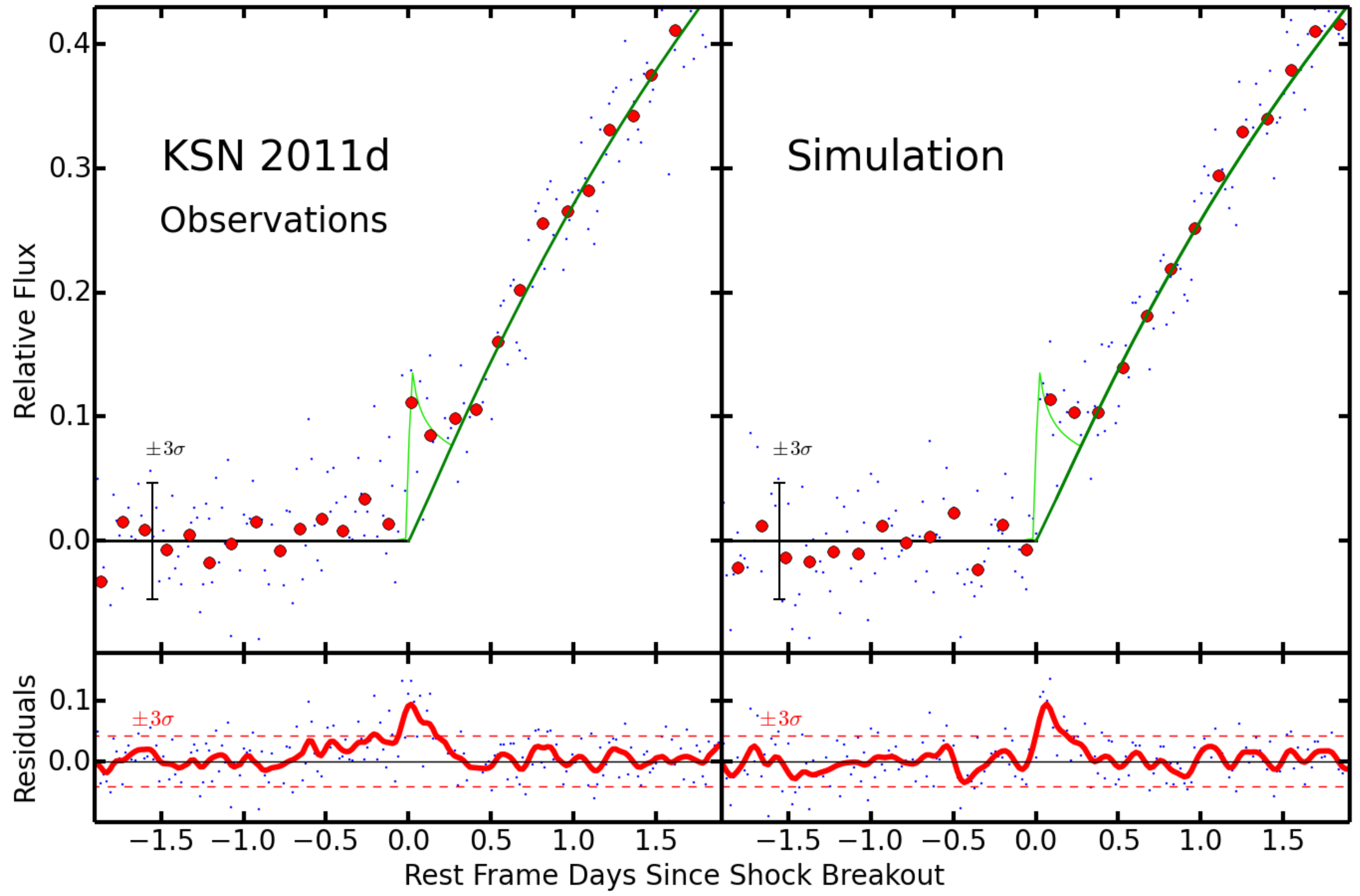


SN breakout emission in type IIb SN2016gkg
(Bersten+2018)

Early observations of CCSNe

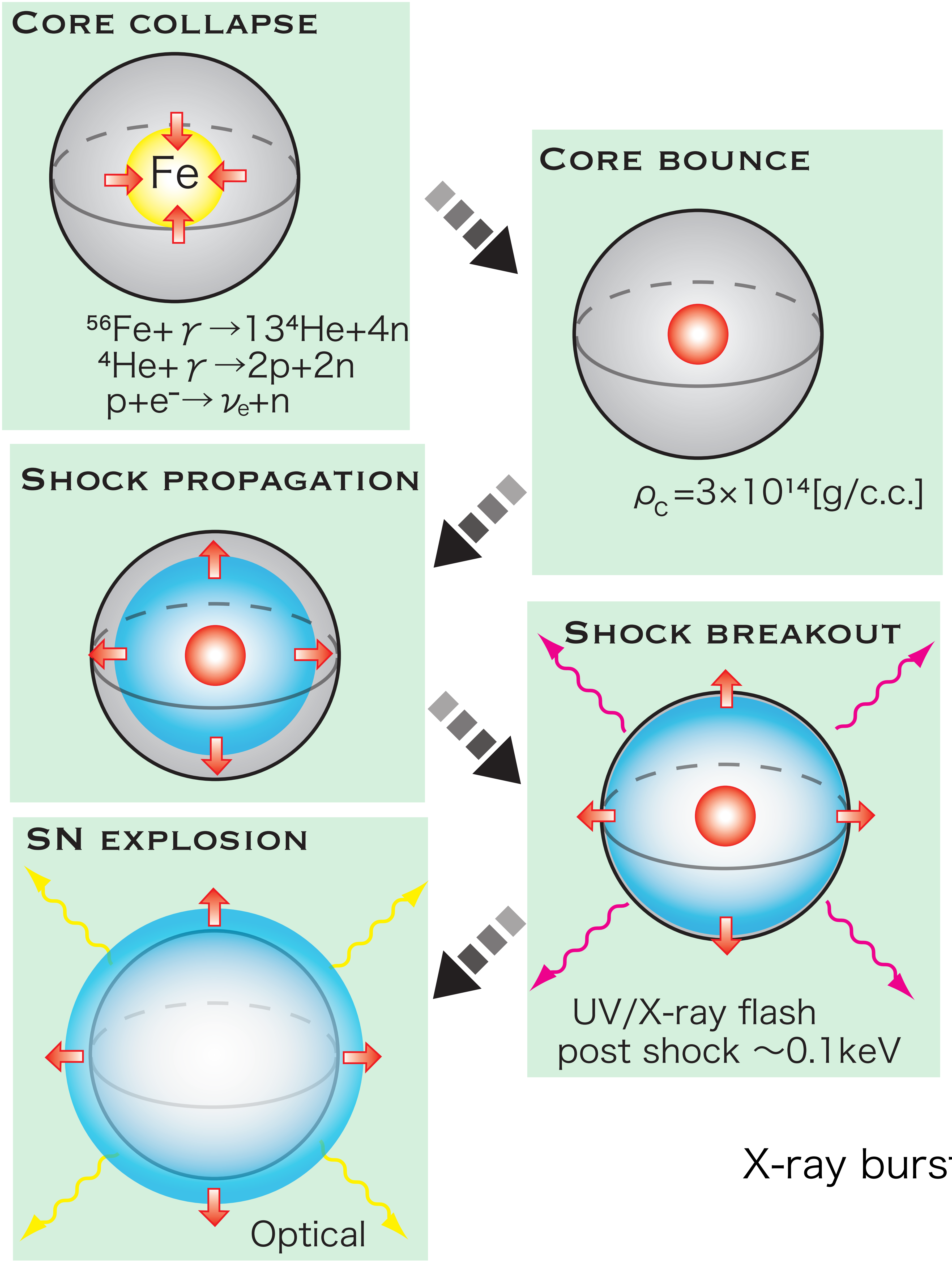


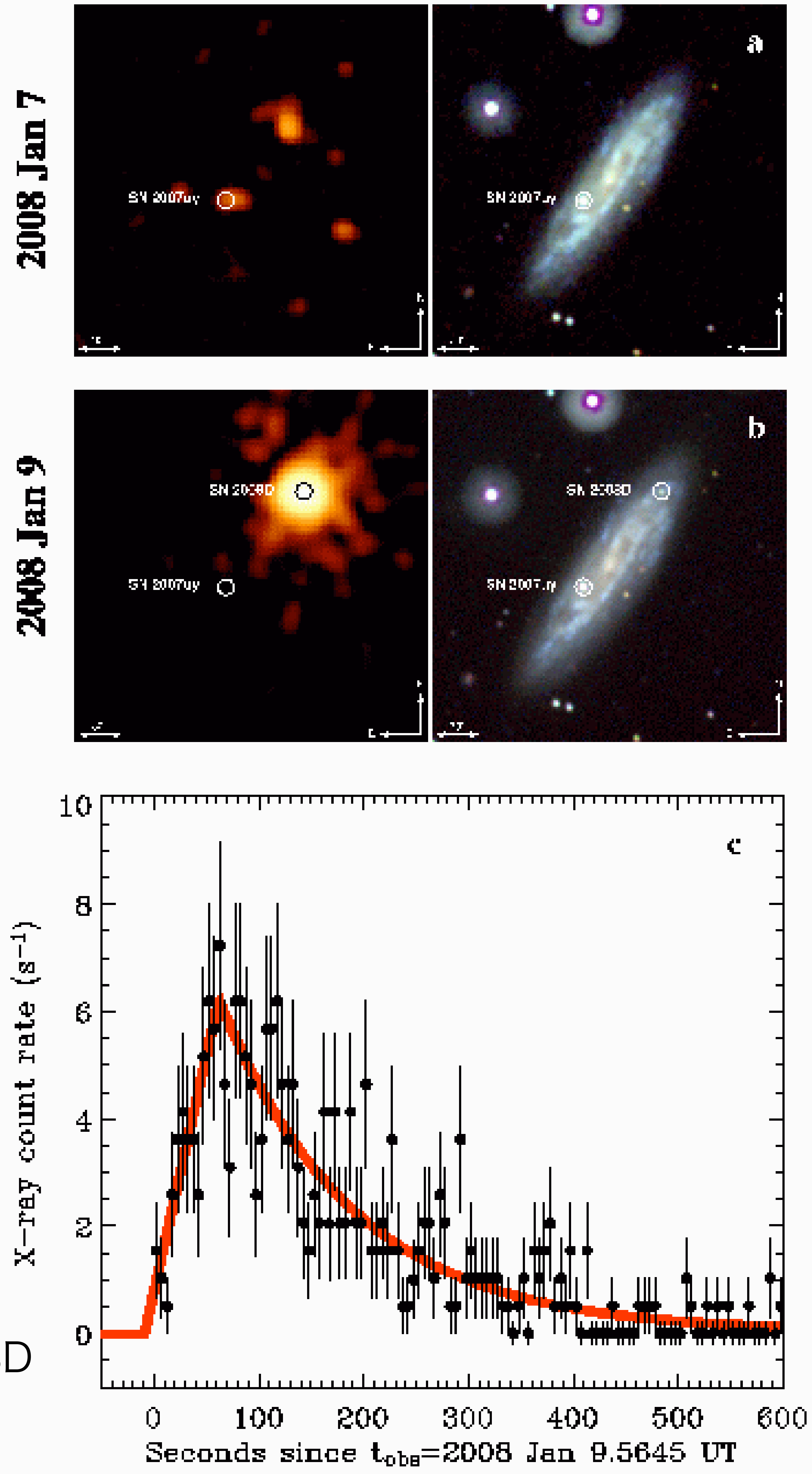




SN breakout emission?
in SNe observed by
Kepler satellite
(Garnavich+2019)

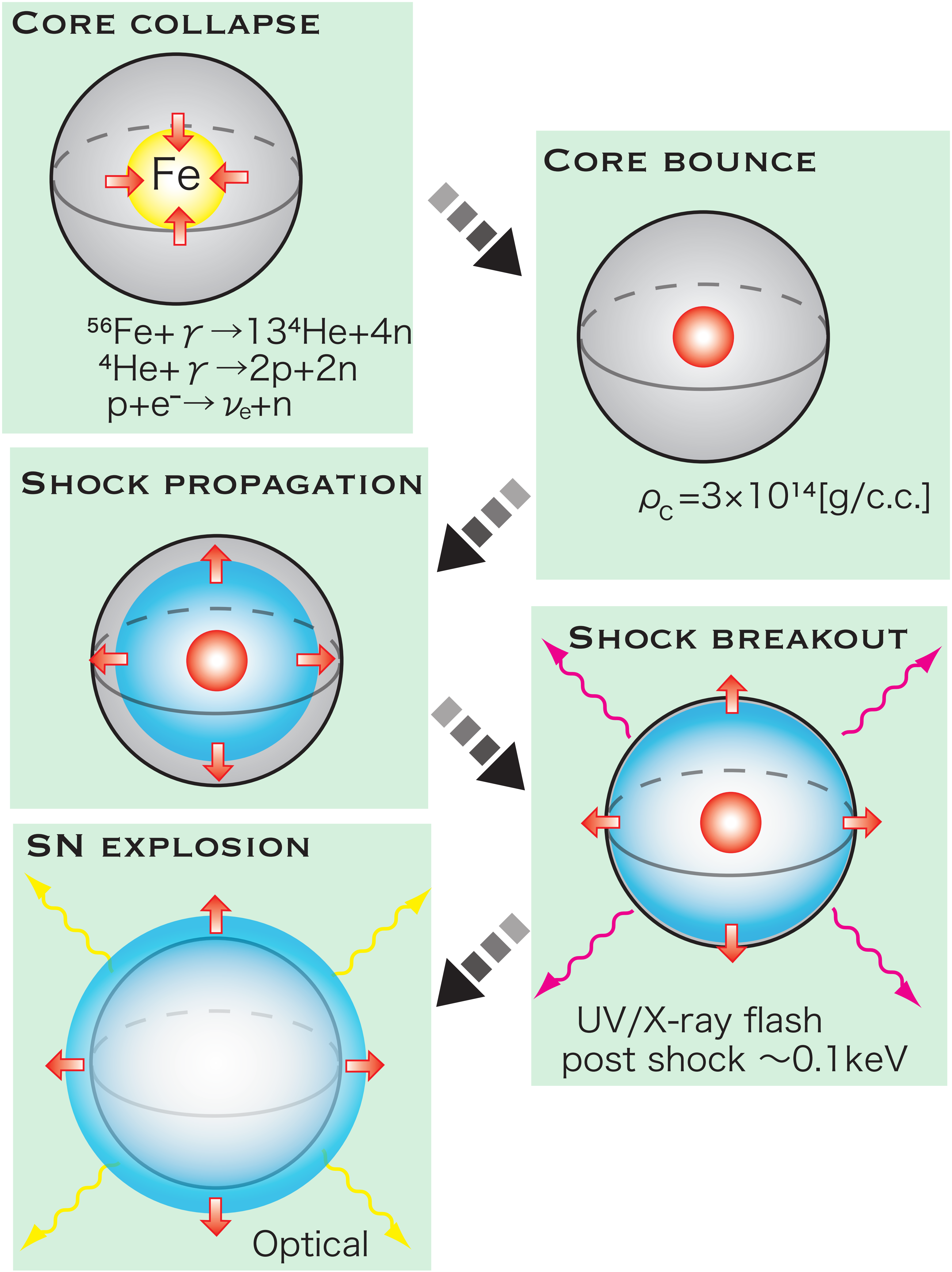
Early observations of CCSNe

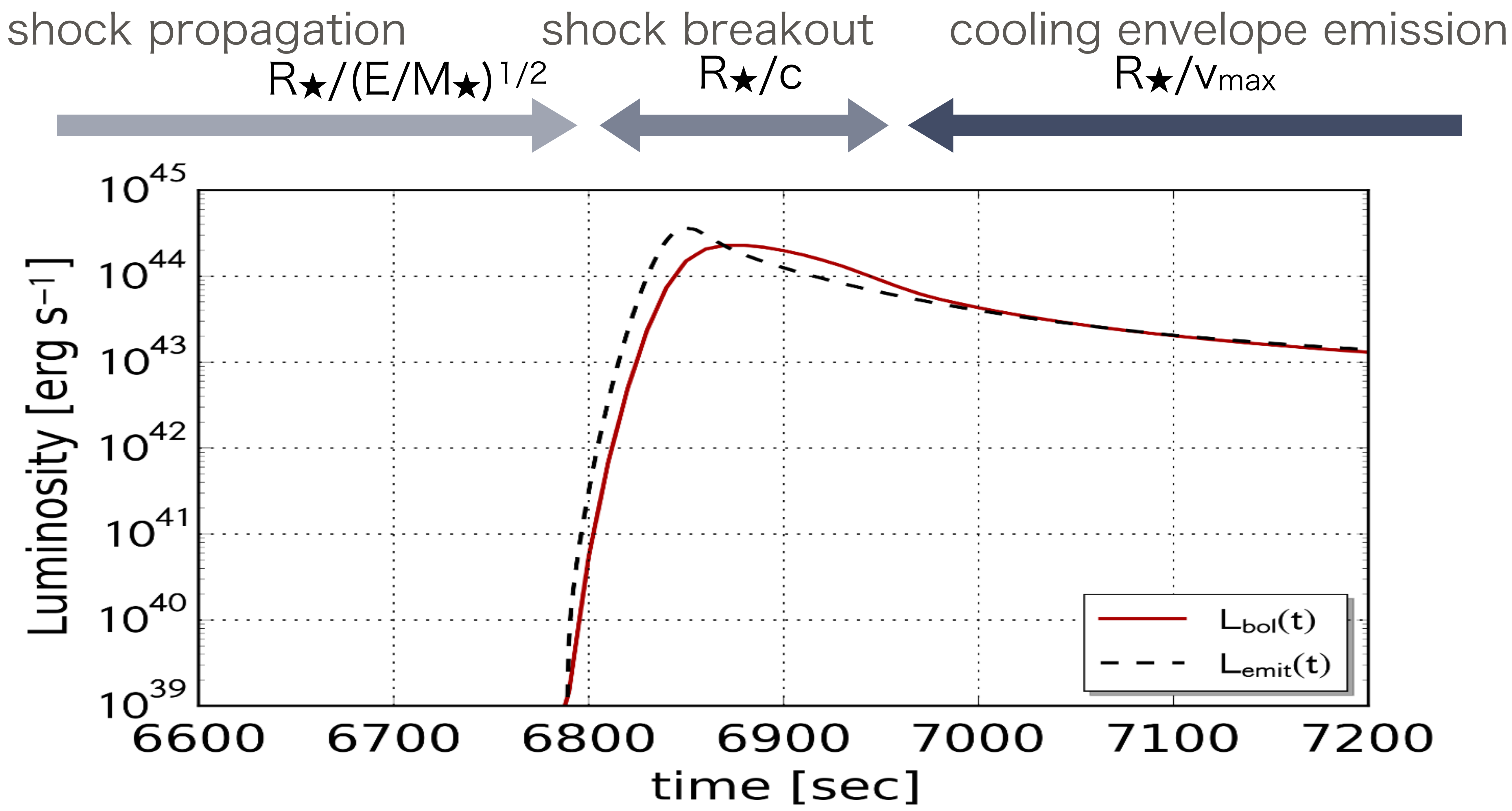




X-ray burst associated with the birth of SN 2008D (Soderberg+2009)

Shock breakout light curves





Characteristic time scales for $M_{presn}=10M_\odot$, $E_{exp}=10^{51}$ erg

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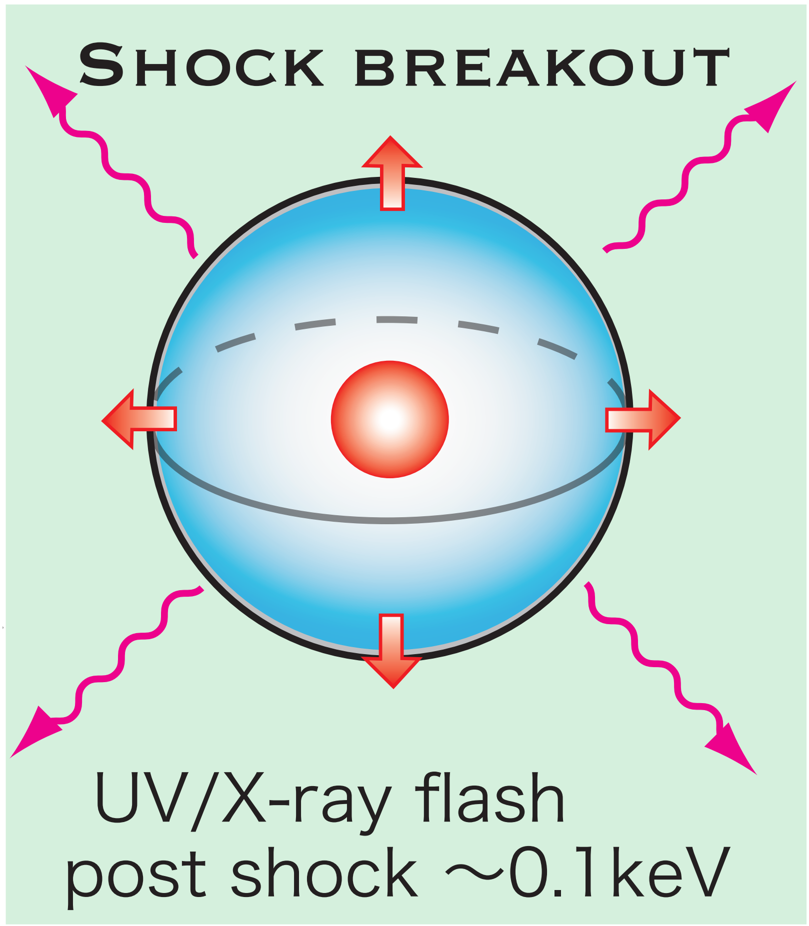
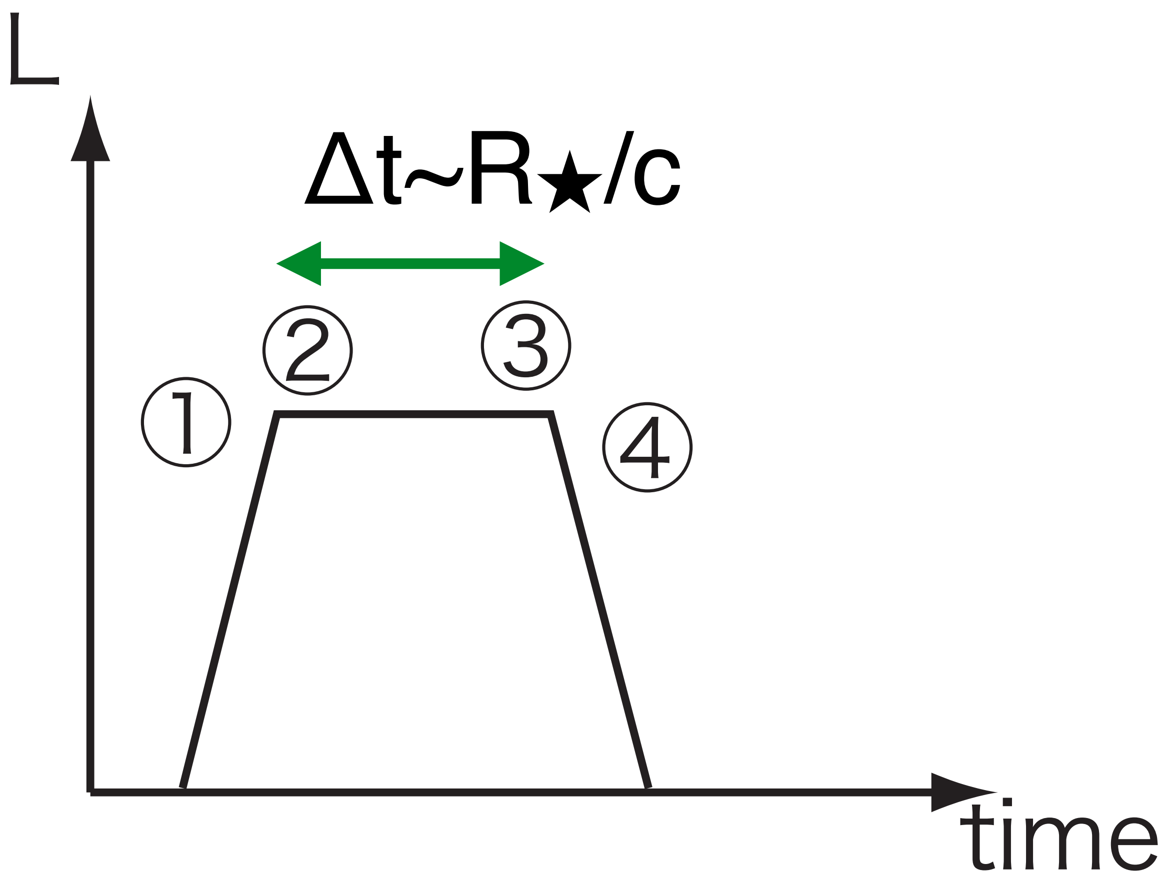
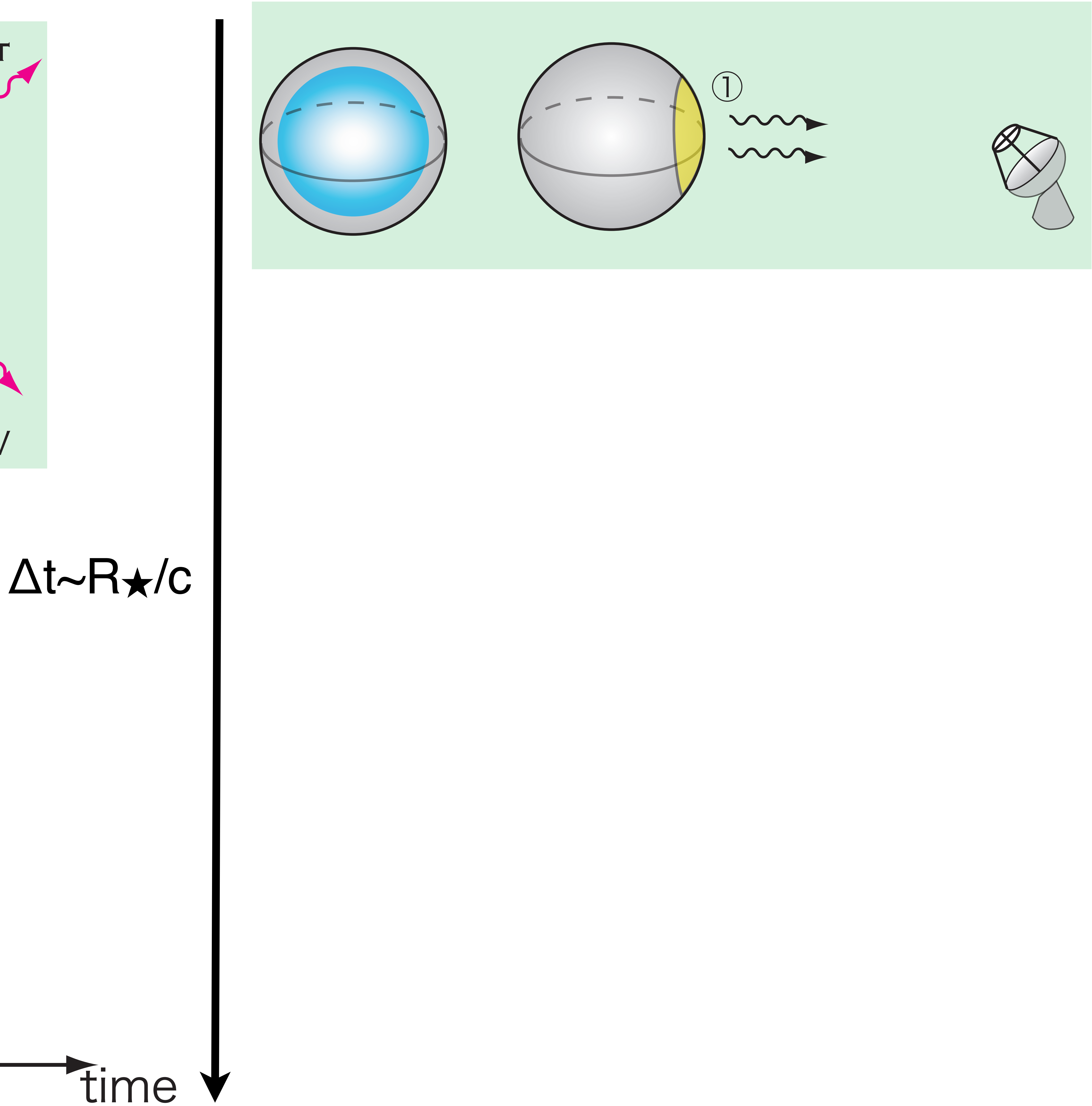
estimates based on Matzner & McKee (1999)

Shock breakout light curves

- In spherical explosion, shock breakout looks like an instantaneous "flash" of UV photons.
- post-shock temperature of several 0.01-0.1 keV
- light traveling time across the stellar radius governs the duration.







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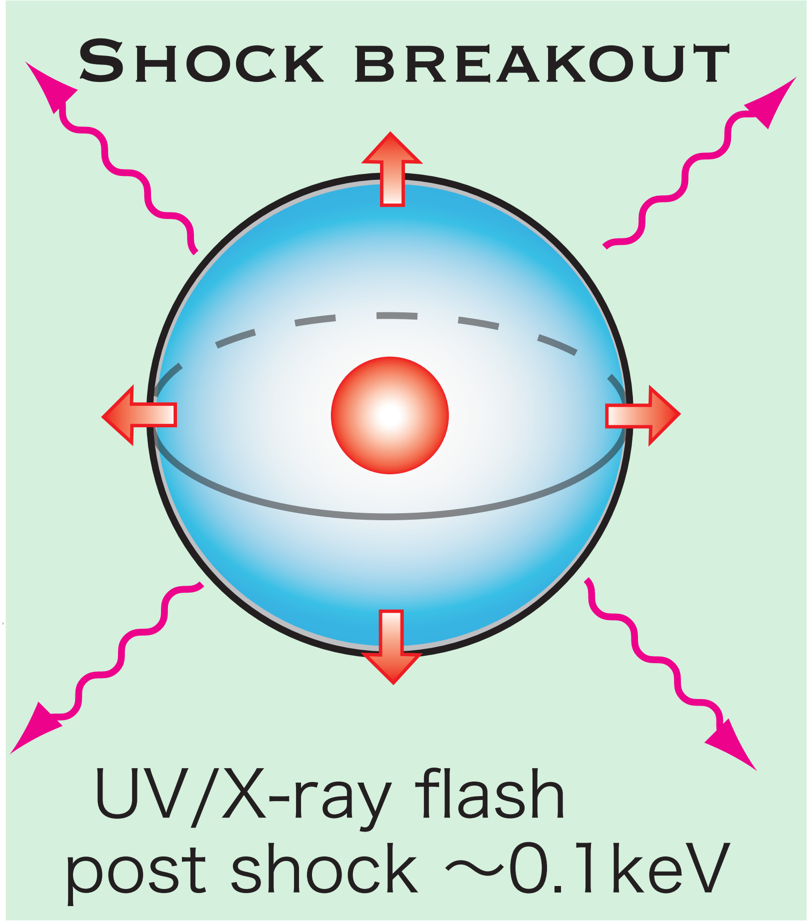

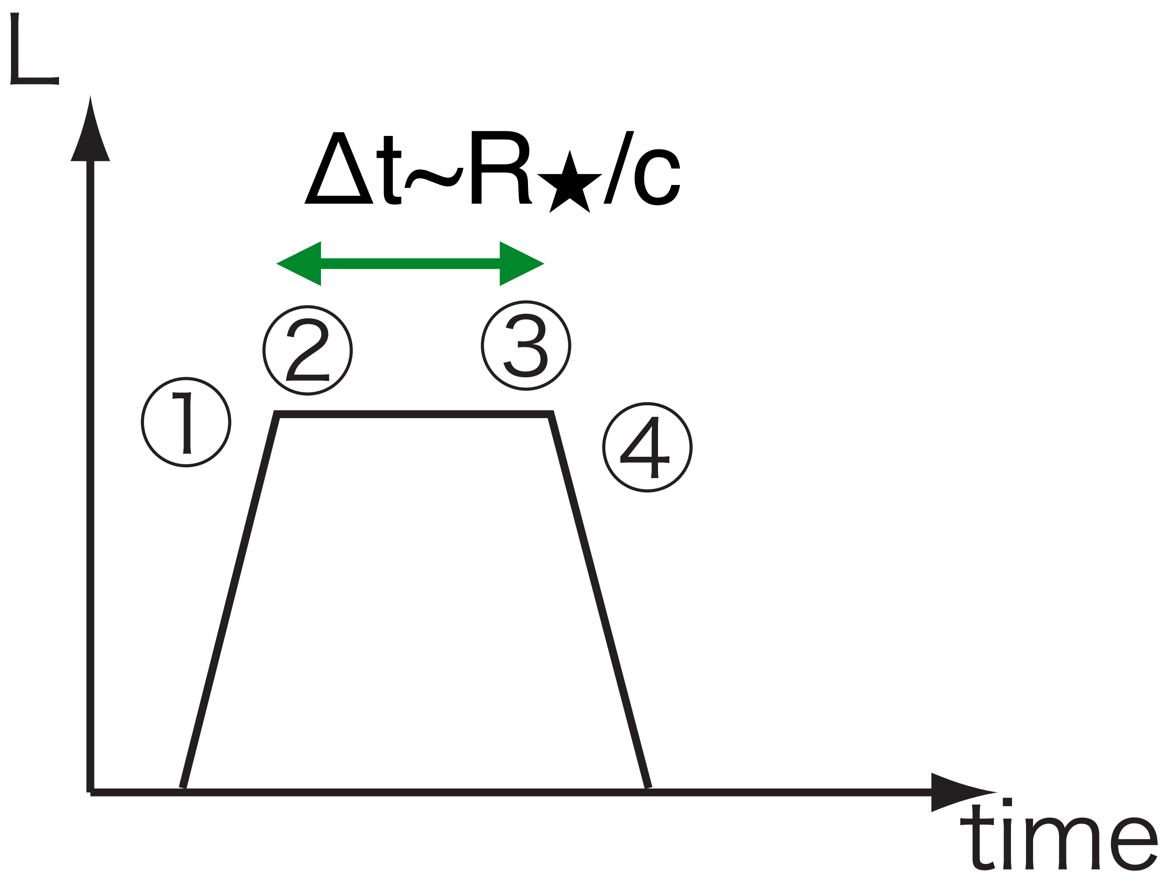

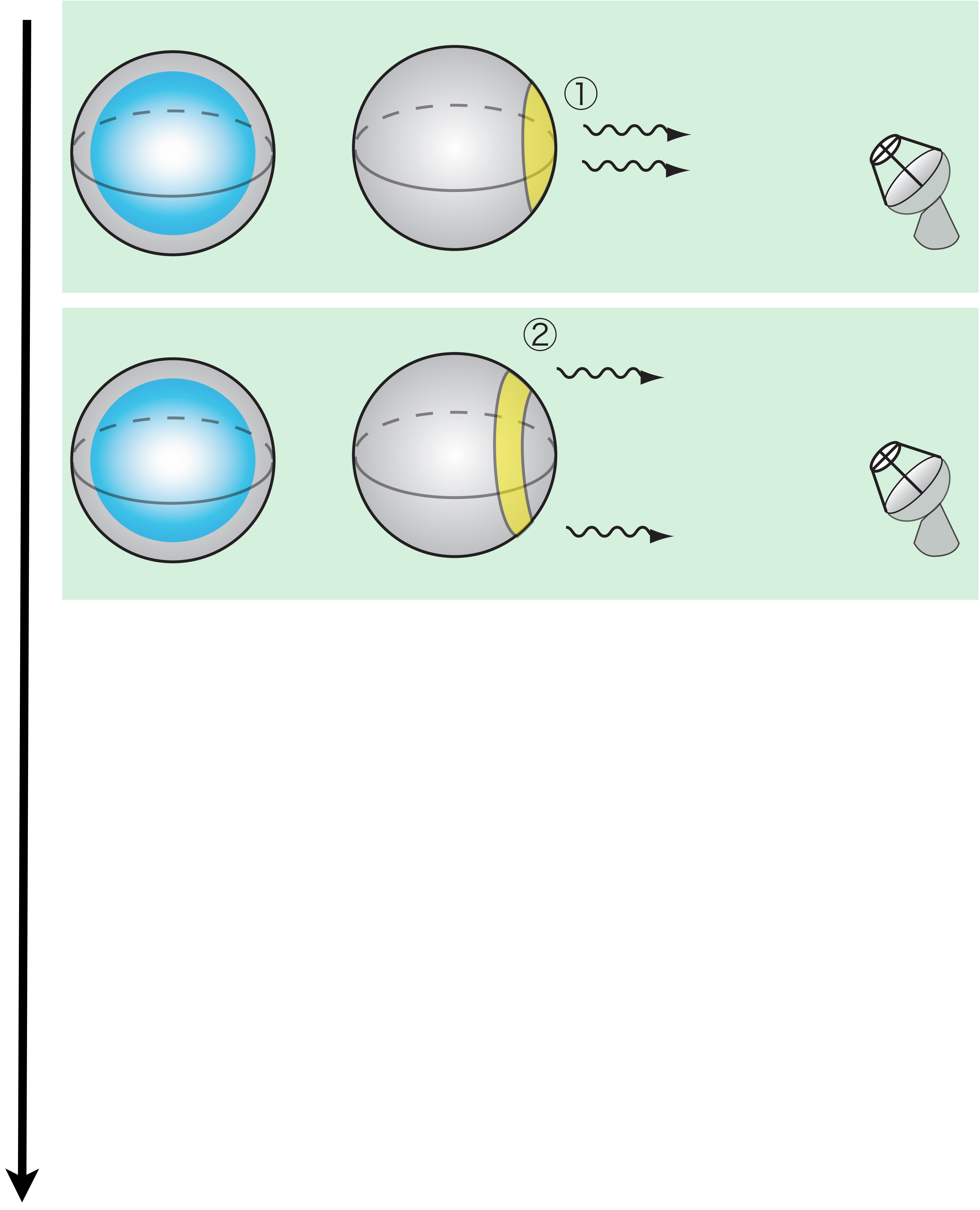

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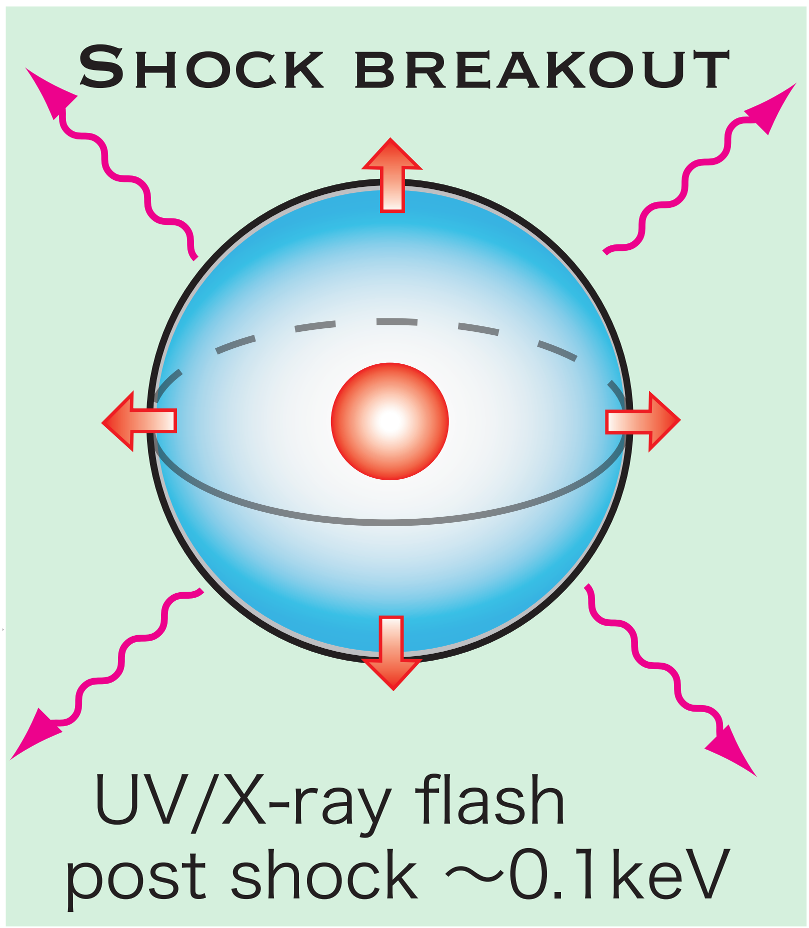

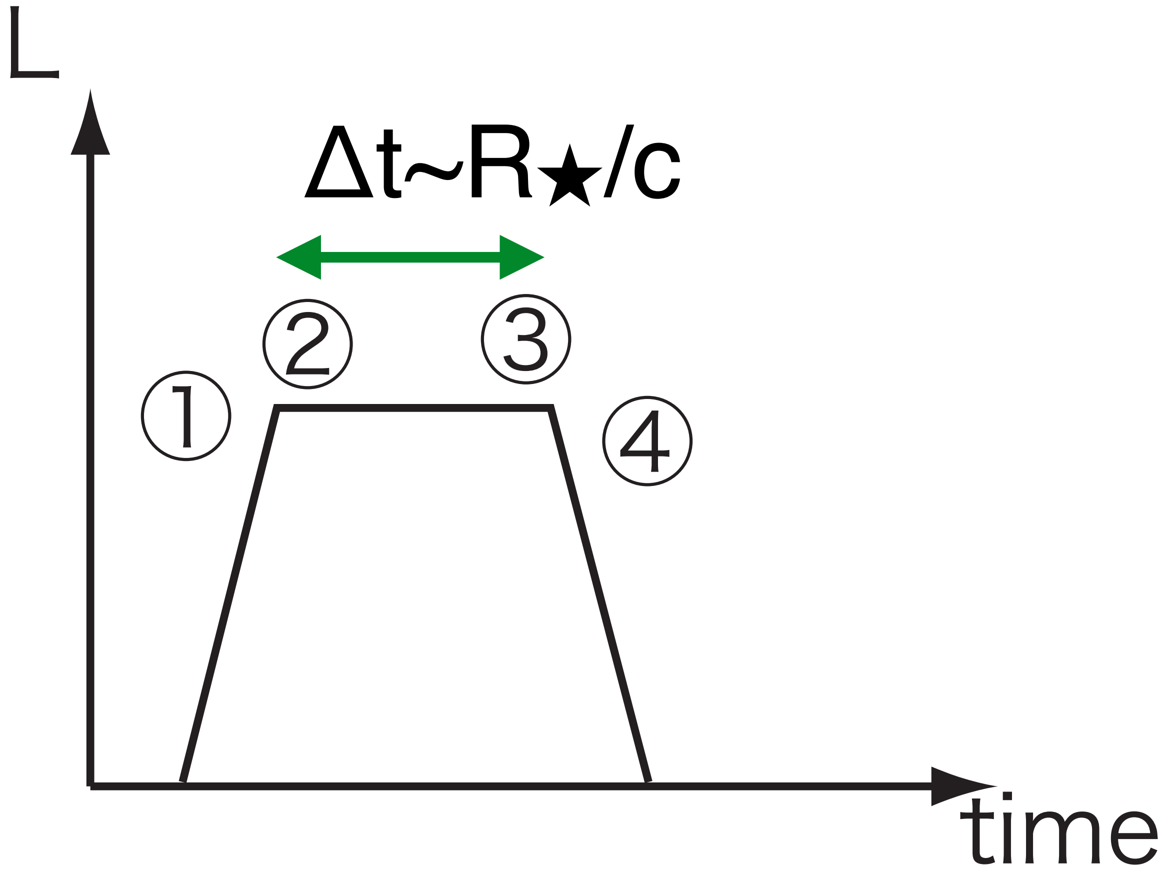

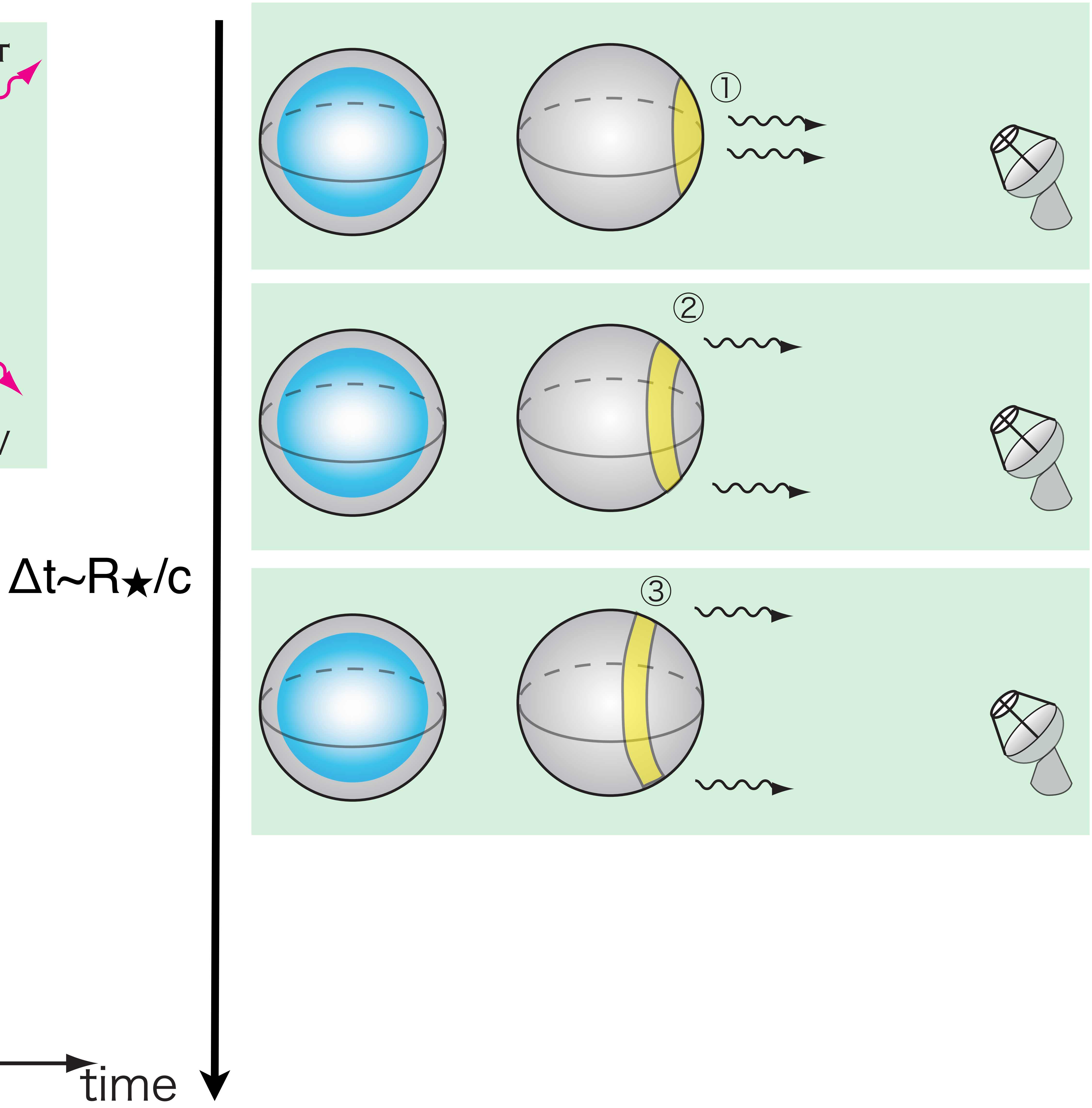

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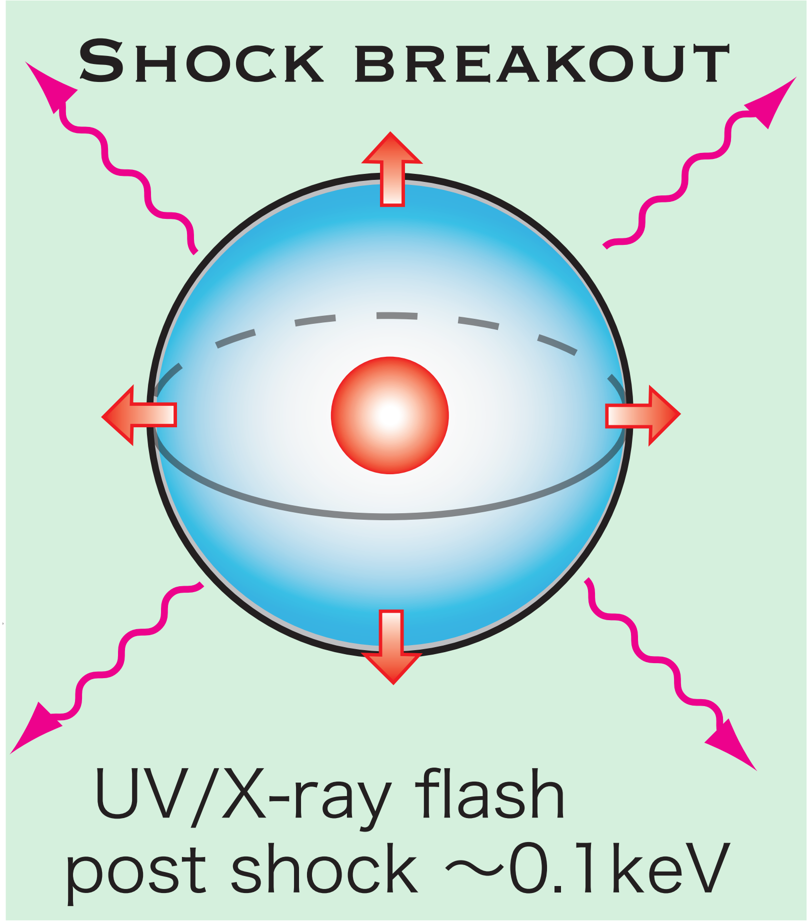
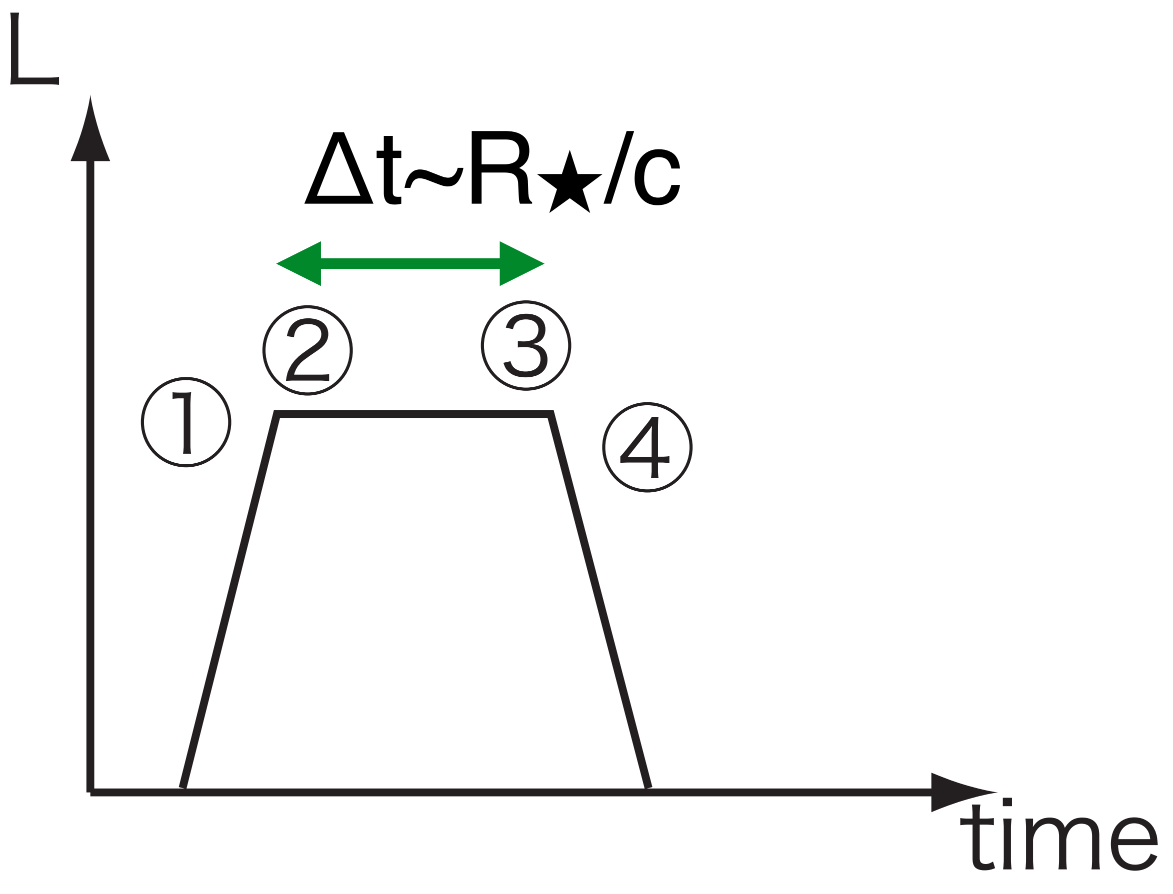
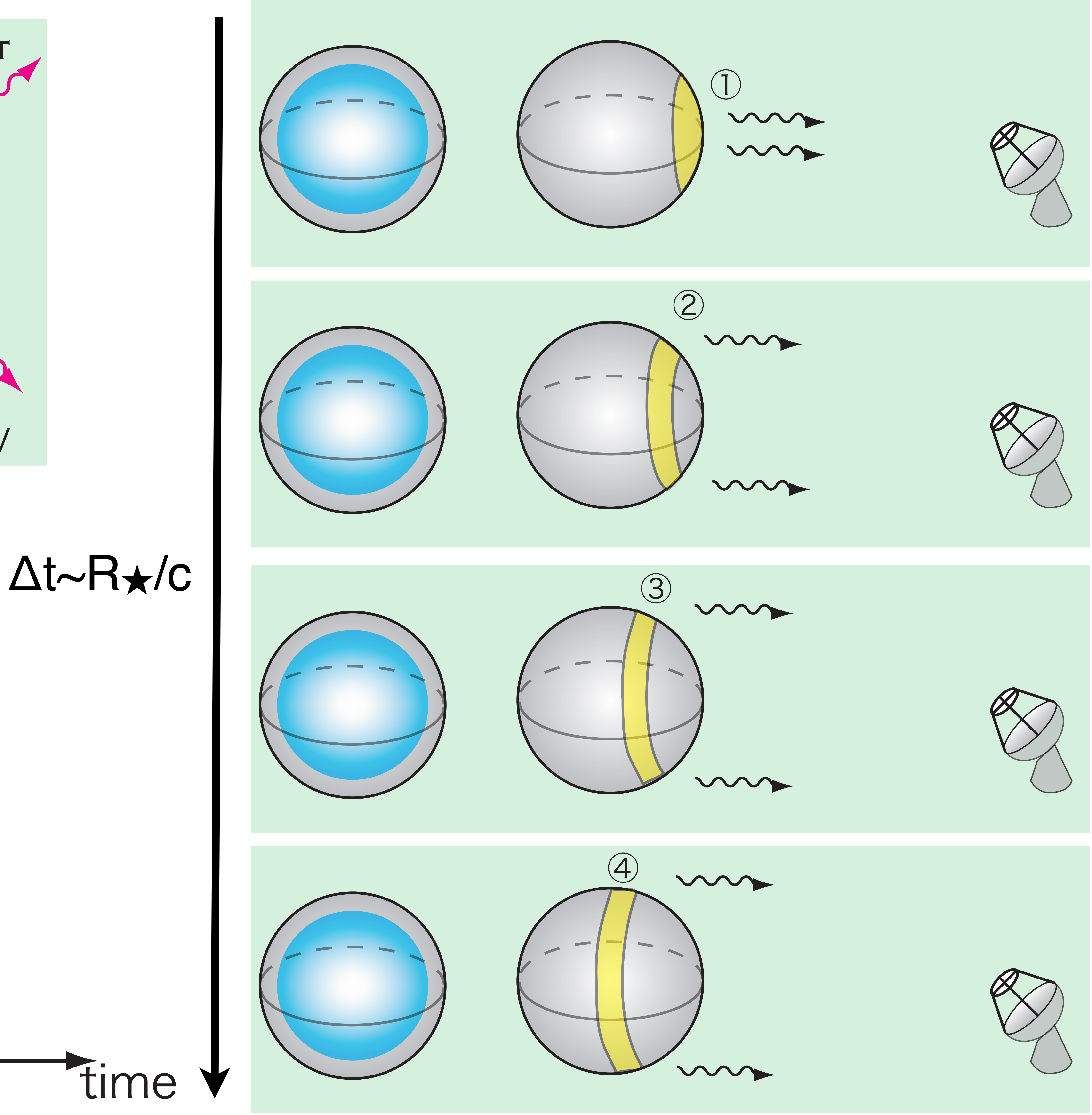
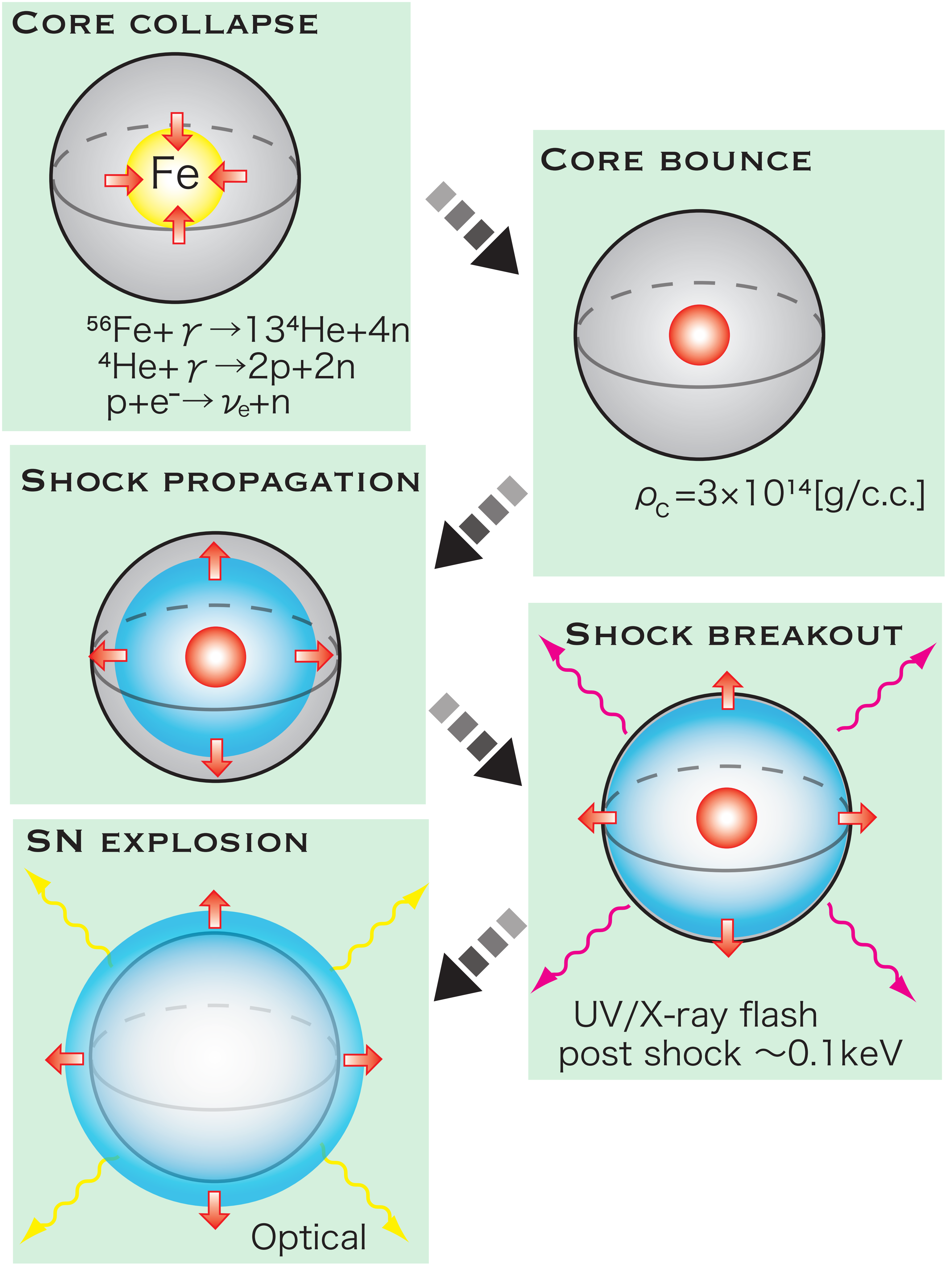






Shock cooling emission



- after the shock breakout, the expanding gas cools in adiabatic way (**cooling emission**)
- radiation-dominated ($\gamma=4/3$, $p\sim aT^4/3$)

radius x10

→ volume x10^3

$V \propto R^3$

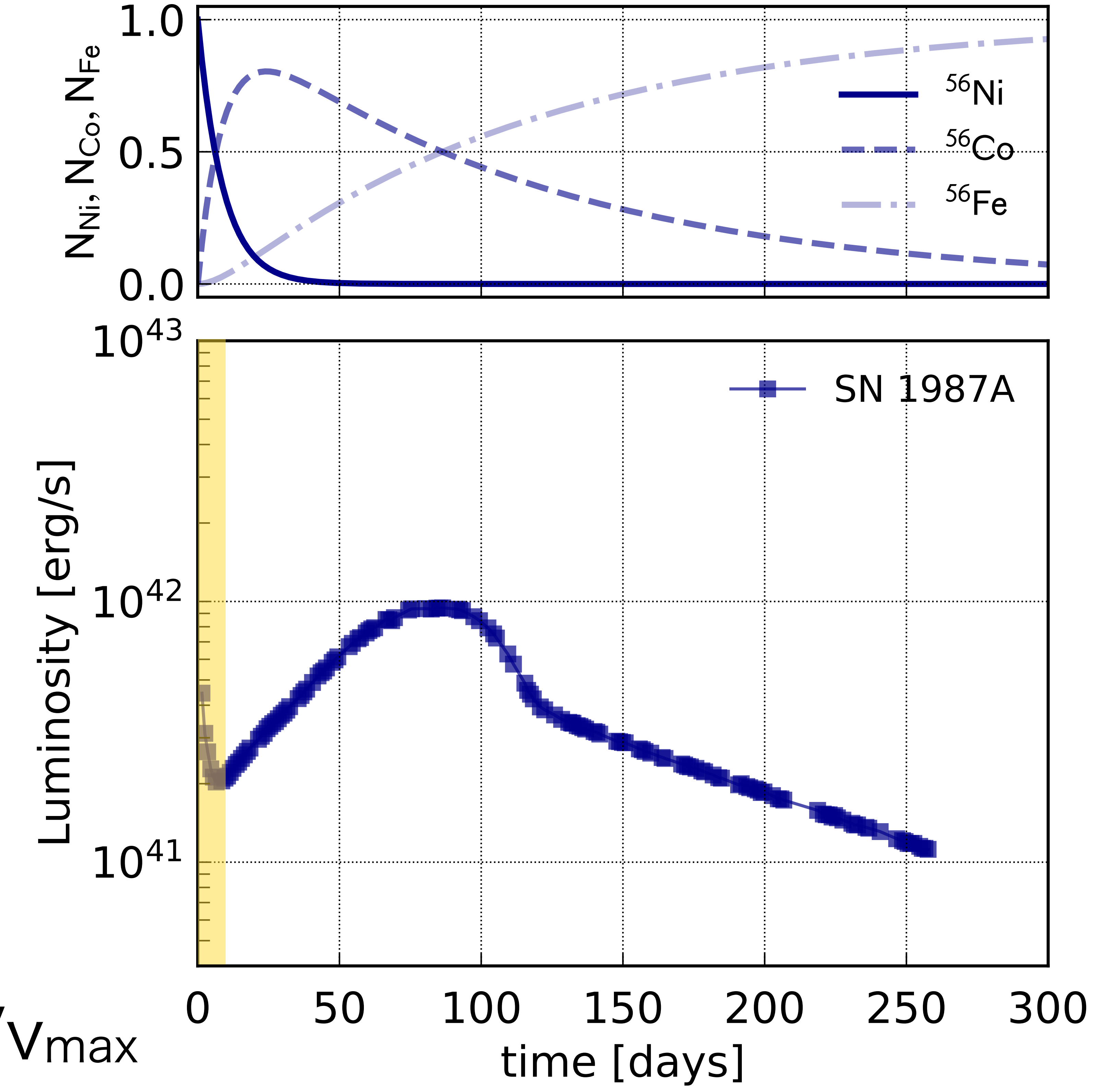
→ pressure x10^{-4}

$p \propto V^{-\gamma}$

→ temperature x10^{-1}.

$T \propto p^{1/4}$

cooling timescale $\propto R_{star}/v_{max}$



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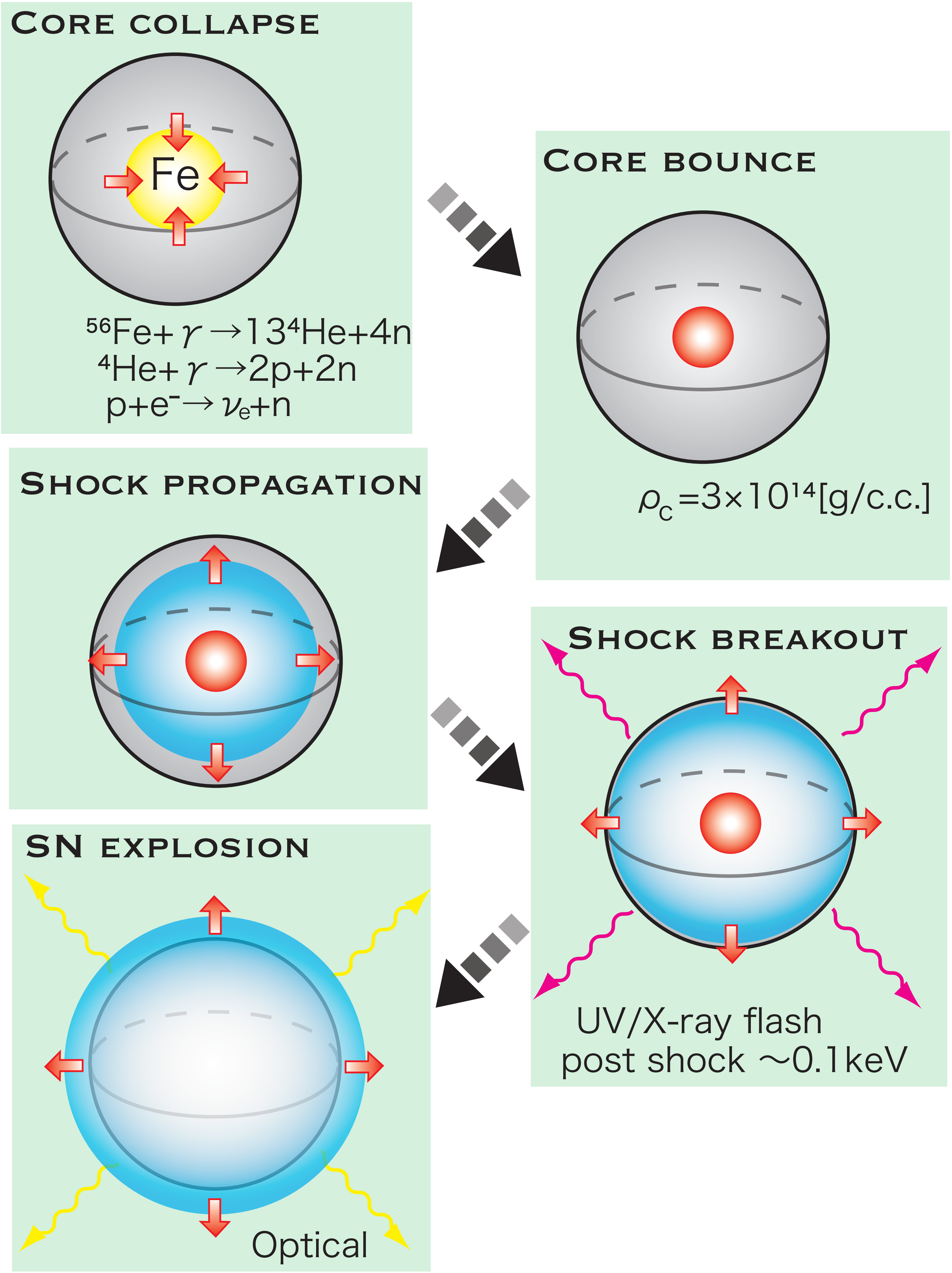

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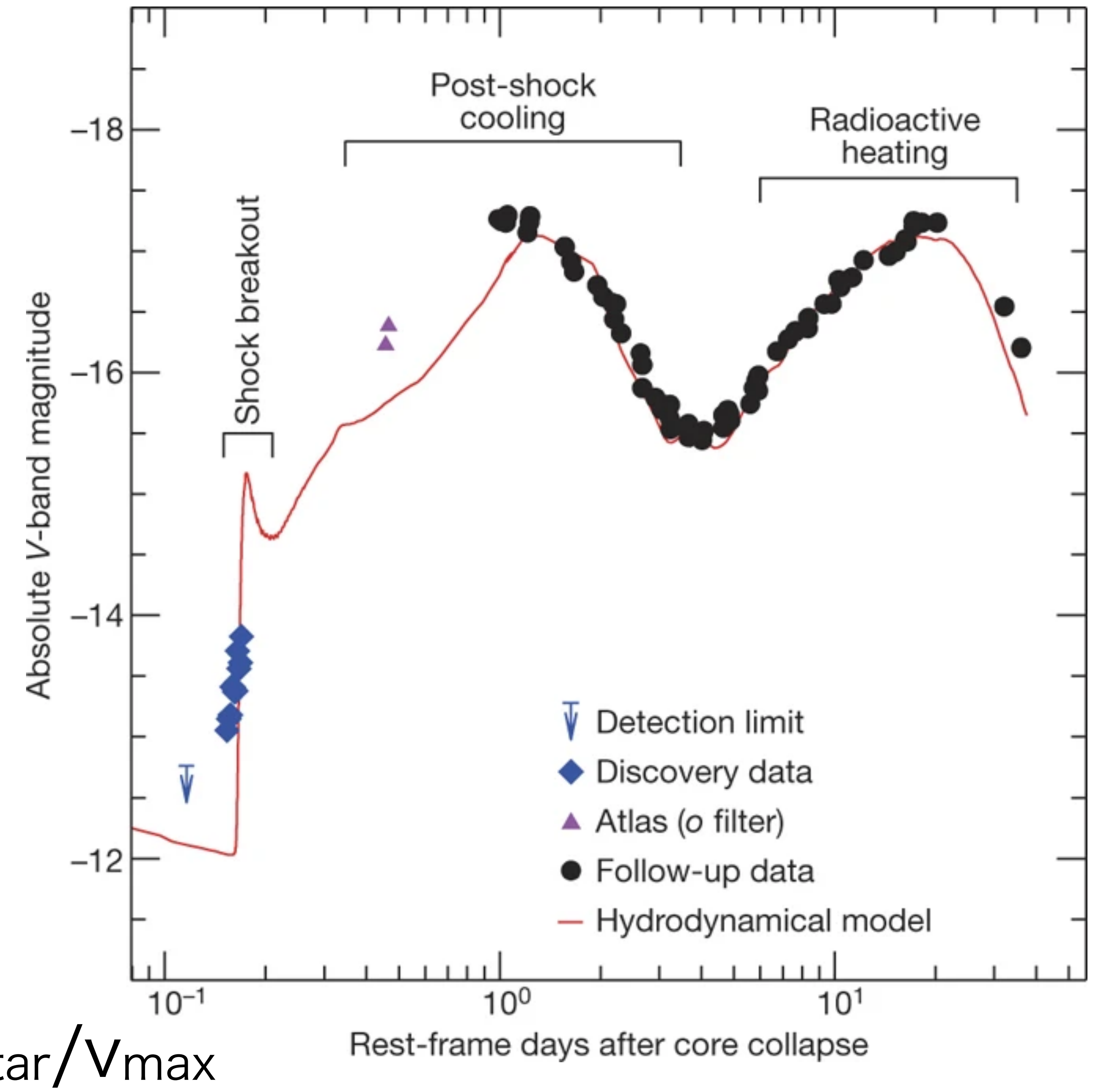

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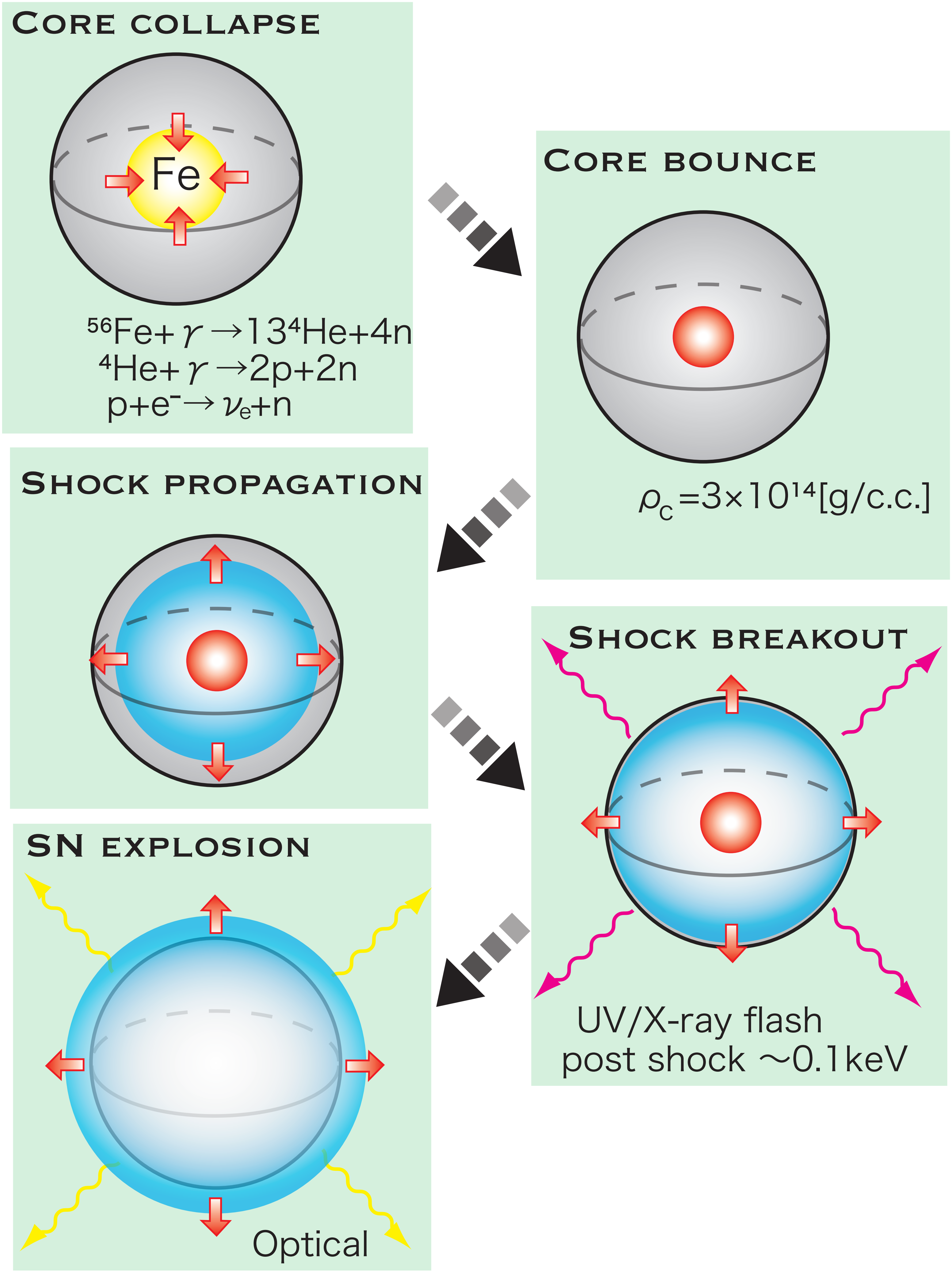
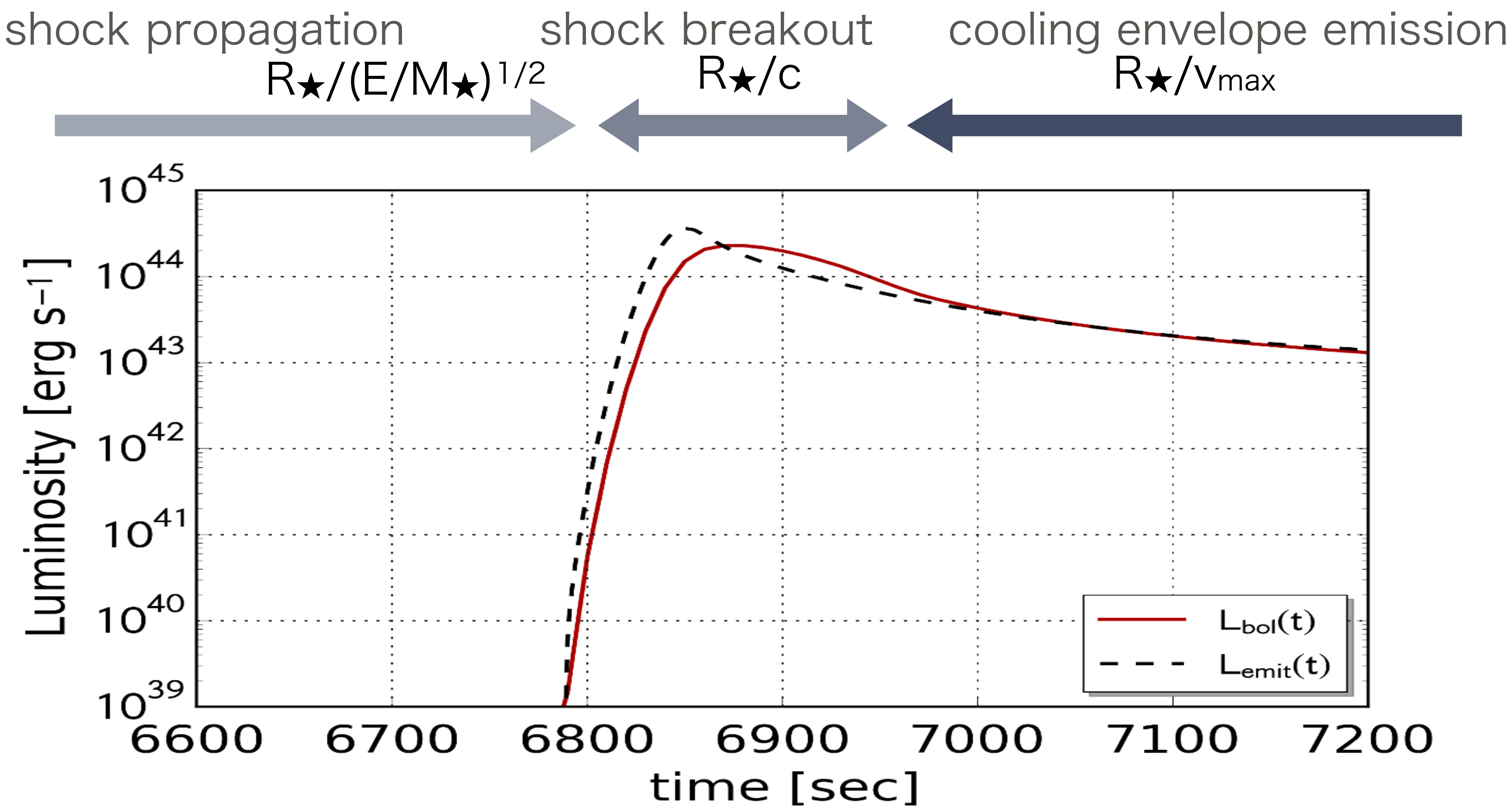
Shock breakout light curves





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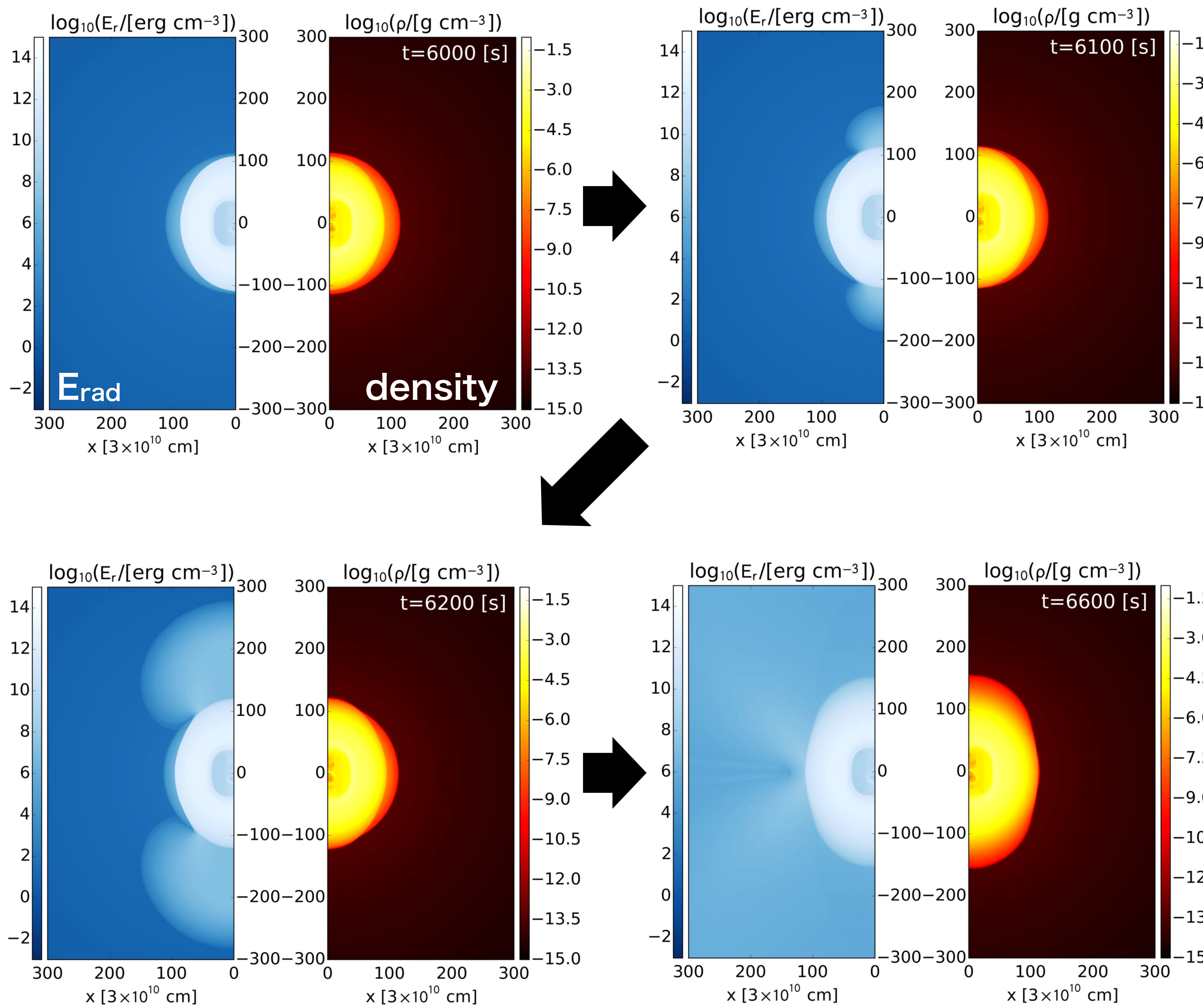
Shock breakout light curves

- aspherical shock?
- when the shock is aspherical, the shock breakout LCs can be quite different from the spherical case (**AS**&Shigeyama 2010)
- 2D RHD simulations for bipolar explosions of SN 1987A BSG progenitor (**AS**, Maeda, Shigeyama 2016)
- shock breakout light curve as <u>a probe of explosion geometry</u>



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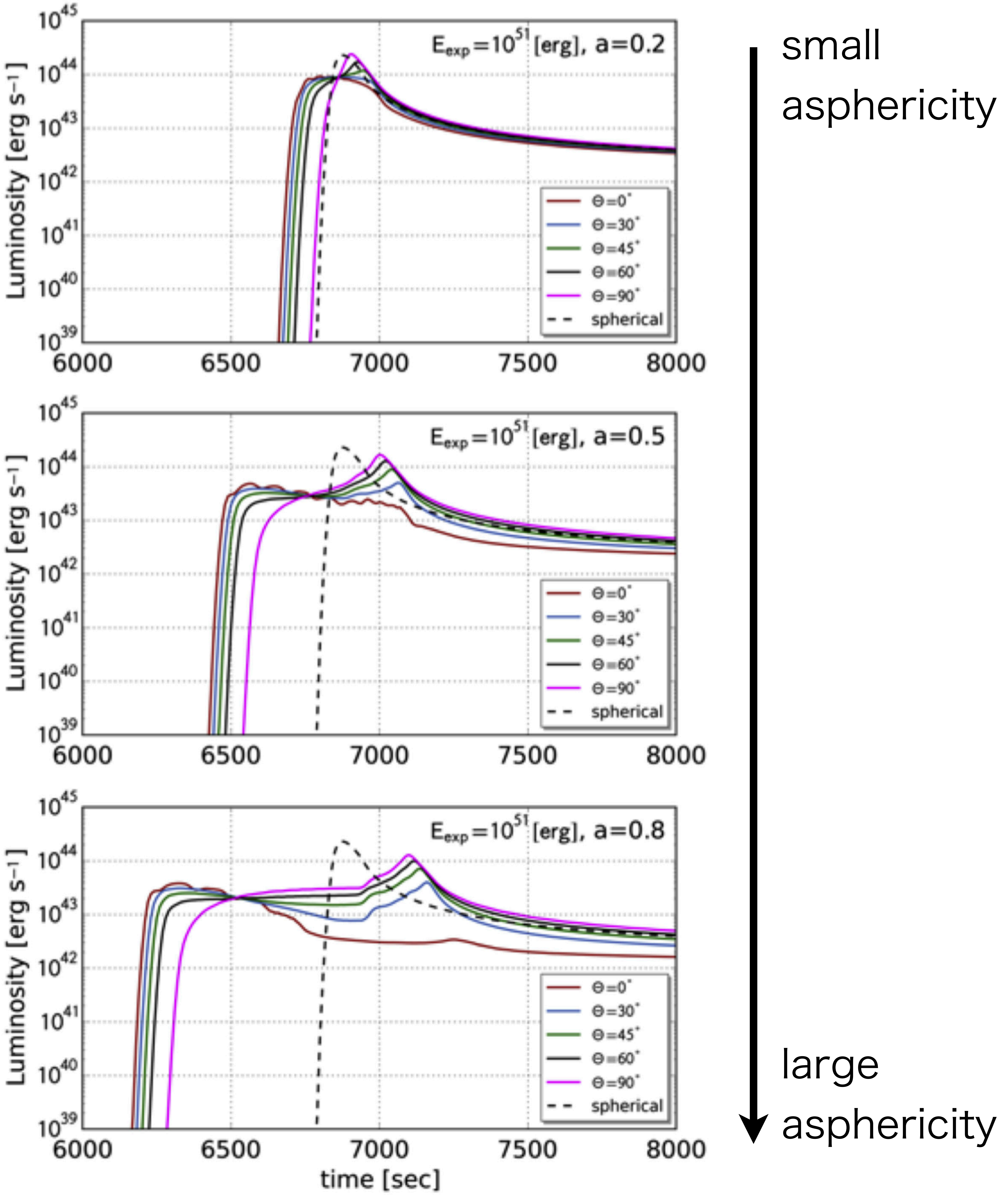
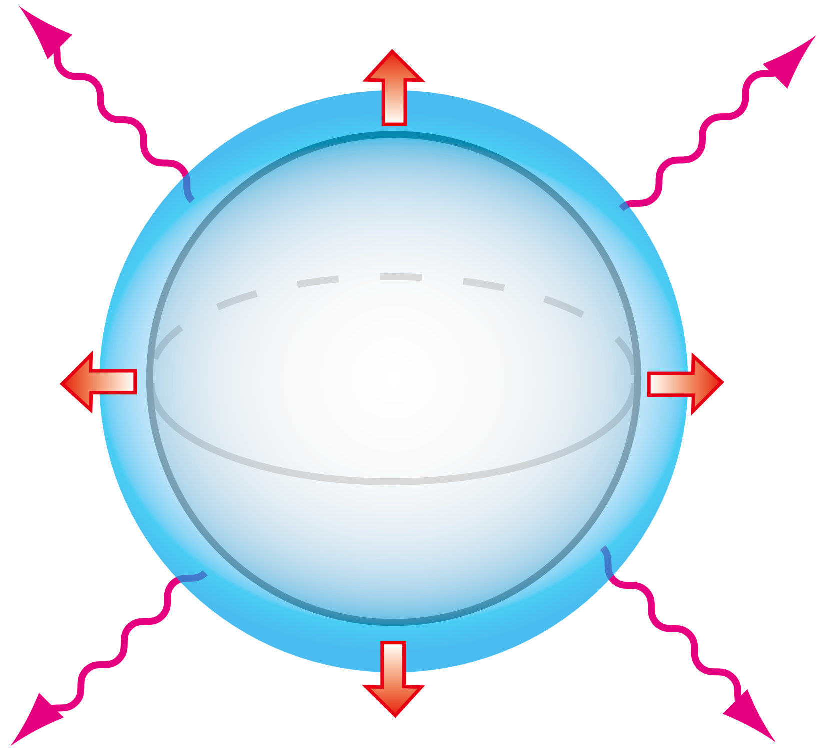


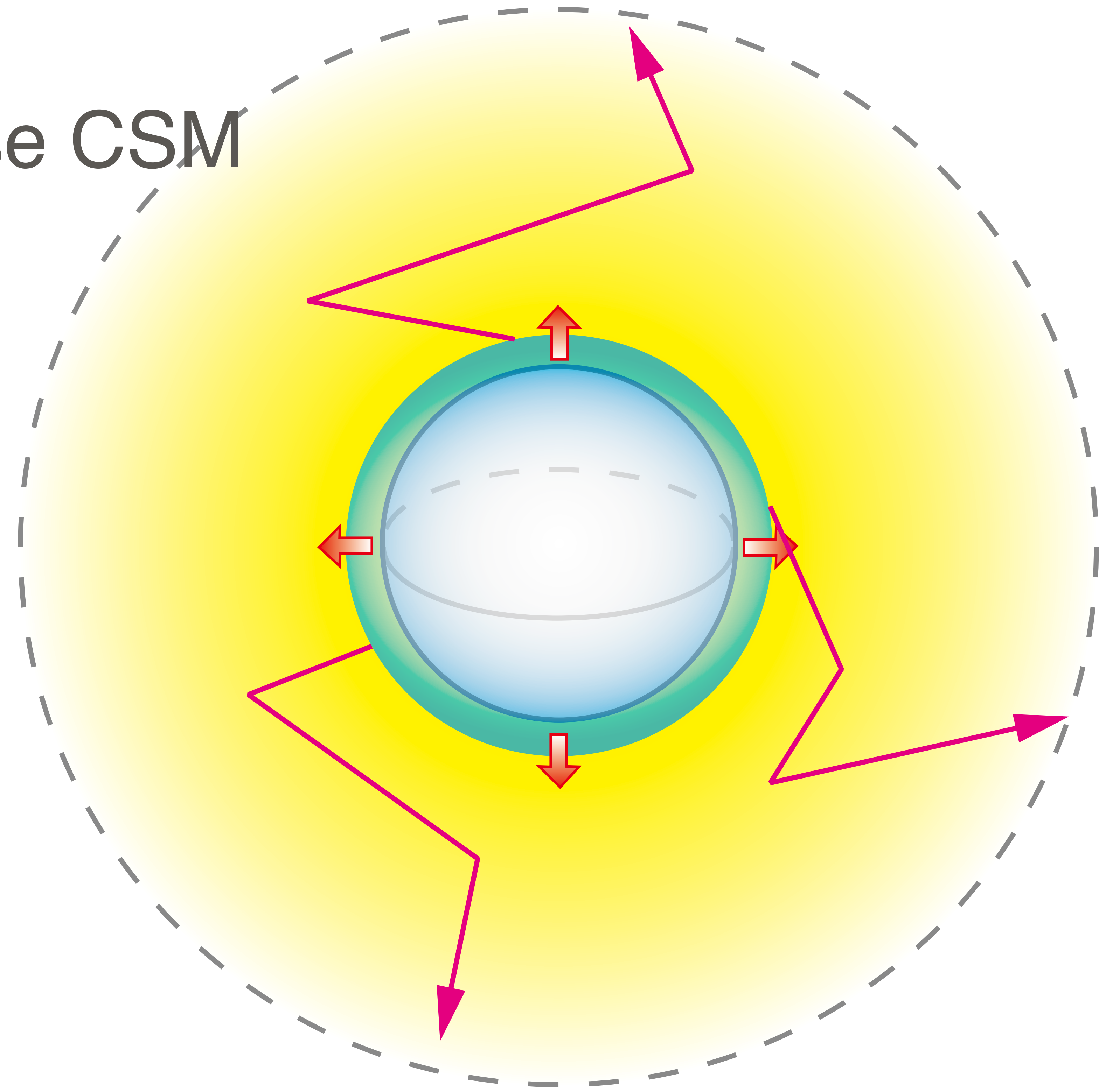
Shock breakout and circum-stellar materials

- Circum-stellar material/medium (CSM): gas surrounding the star
- SN 2013fs: “typical” type IIP SN
- early spectra (t<a few days) show “narrow” emission lines instead of “broad” P-Cygni profiles
- This indicates the presence of **dense/ massive CSM** surrounding the RSG progenitor, but only in the vicinity

without CSM



with dense CSM



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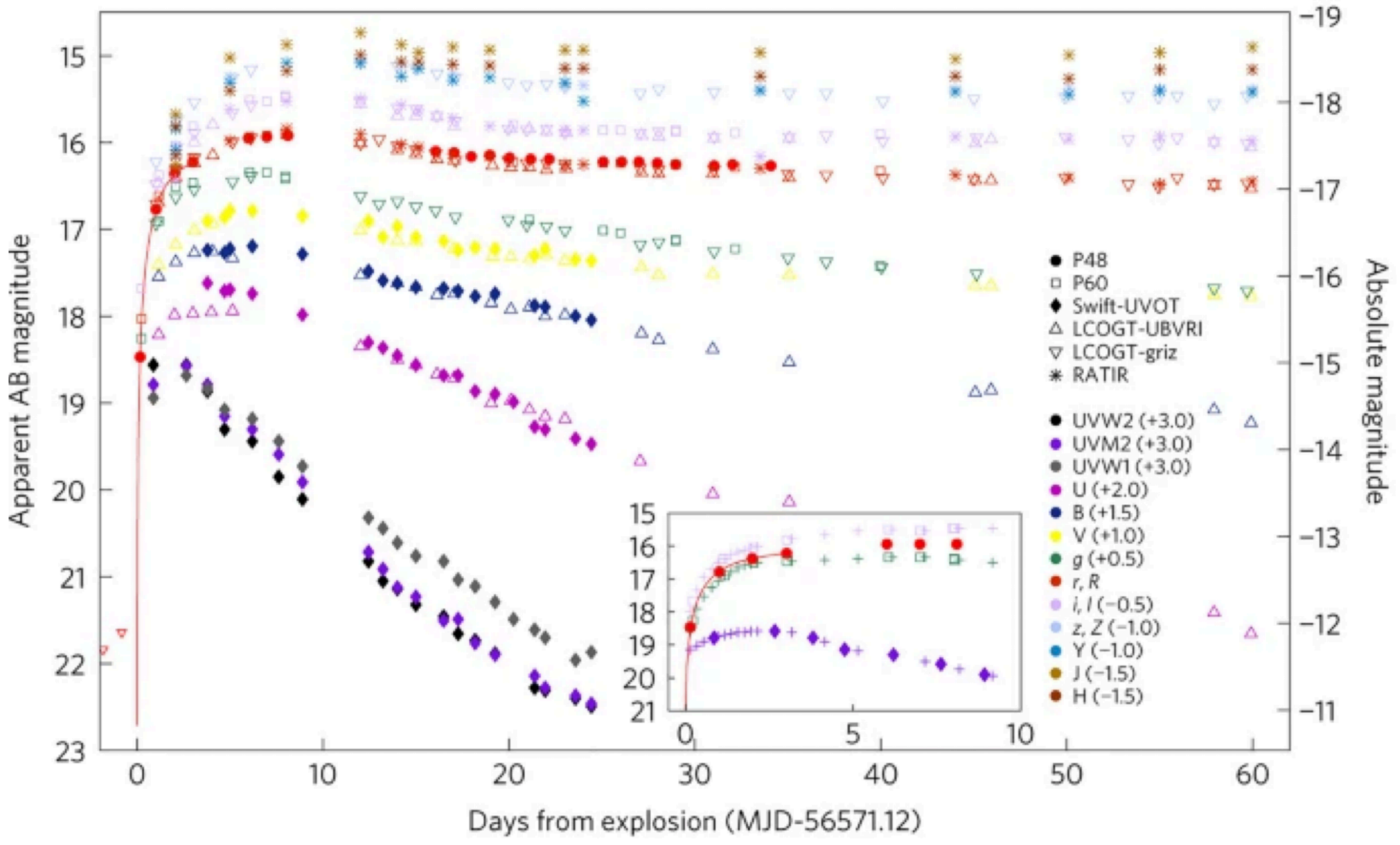

optical light curve and spectra of type IIP SN 2013fs (Yaron+2017)

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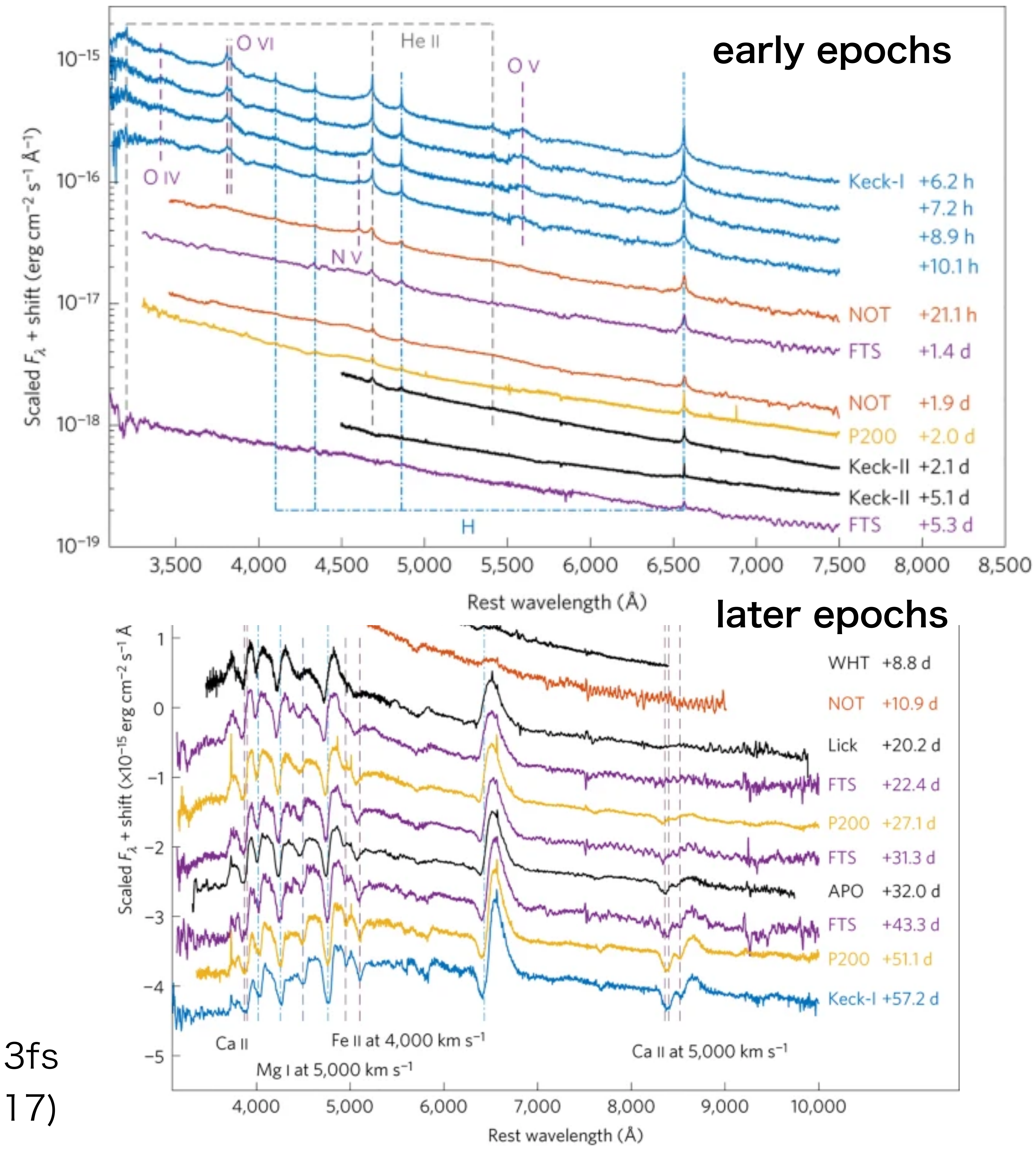

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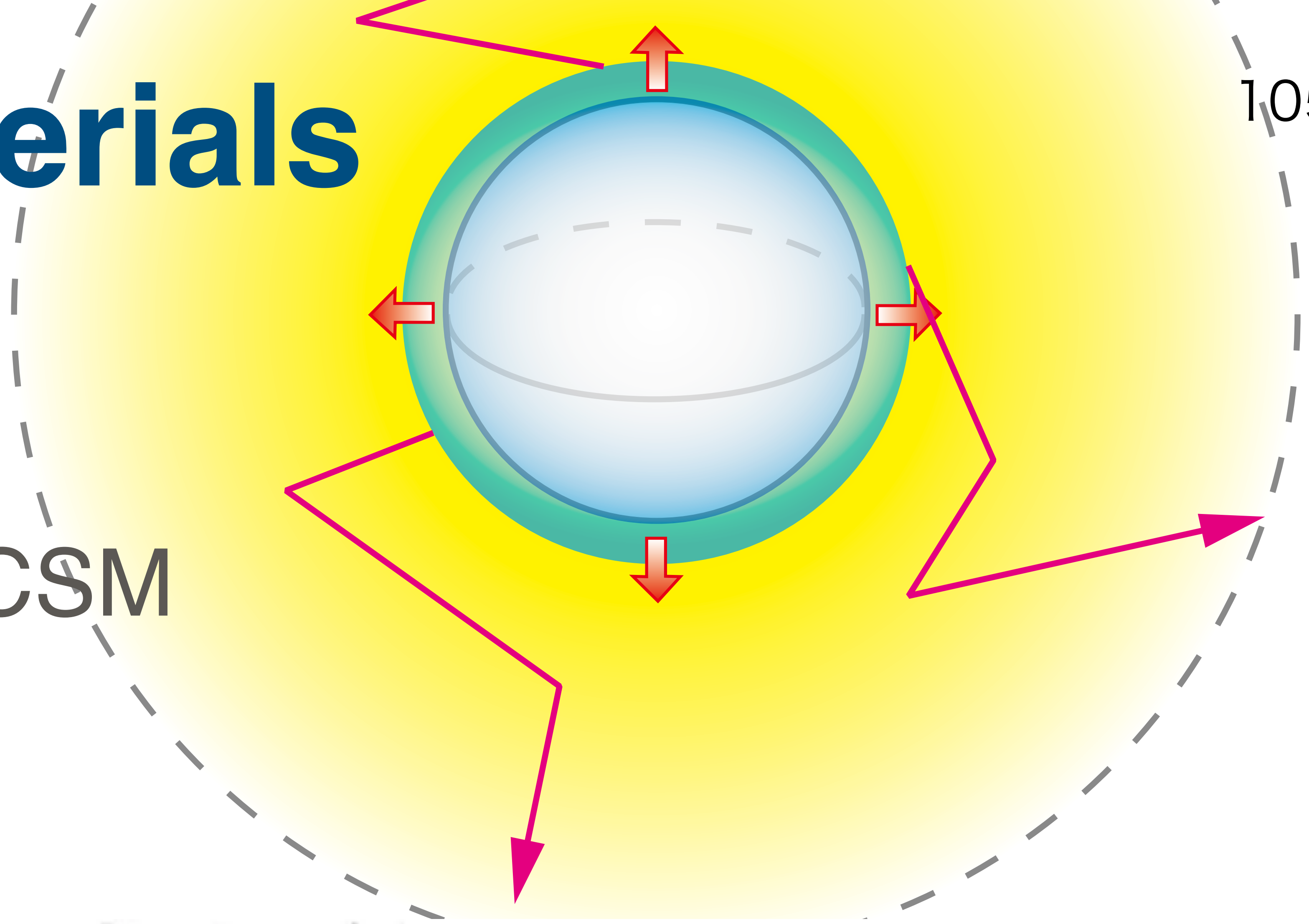

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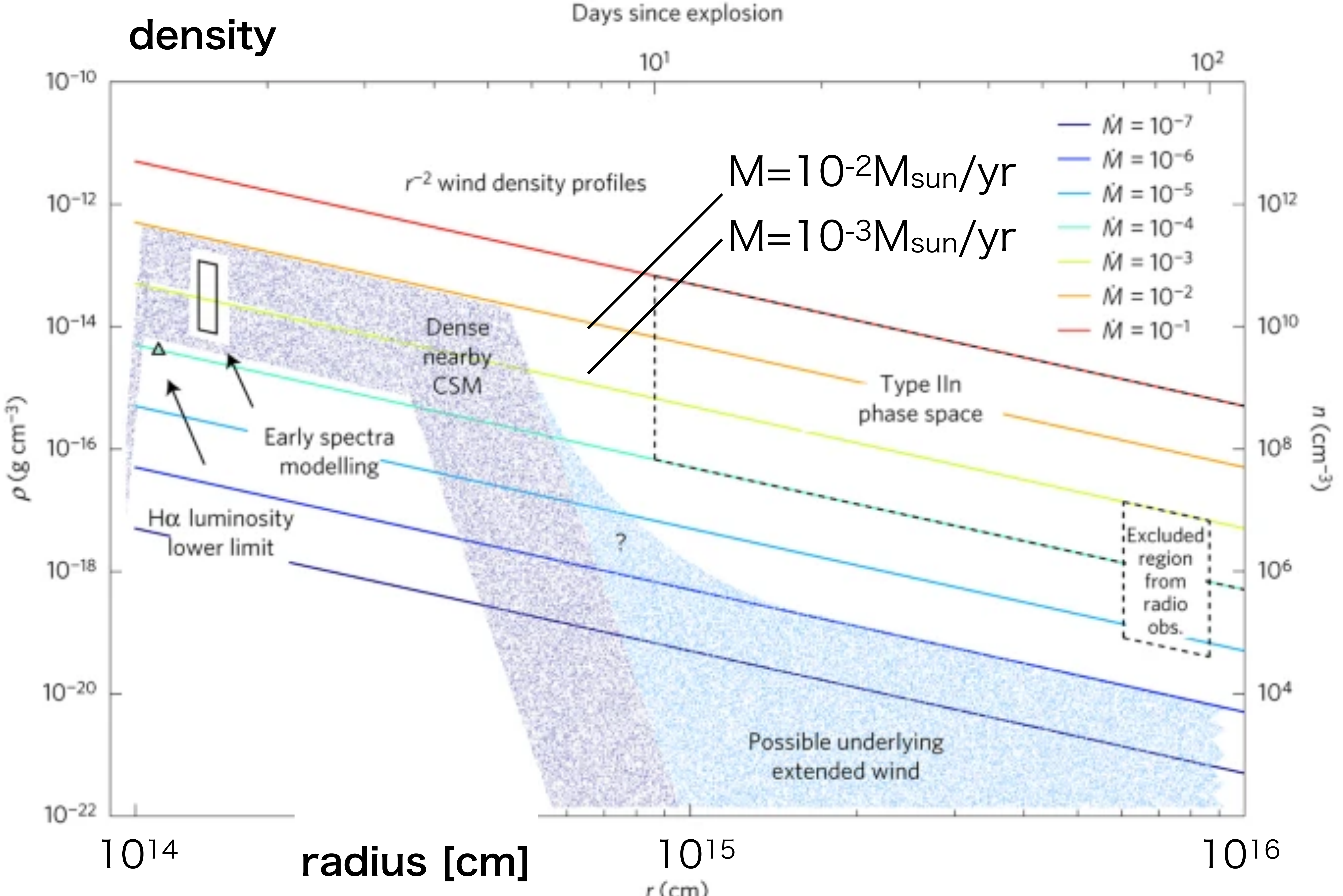

CSM density structure inferred from SN 2013fs (Yaron+2017)

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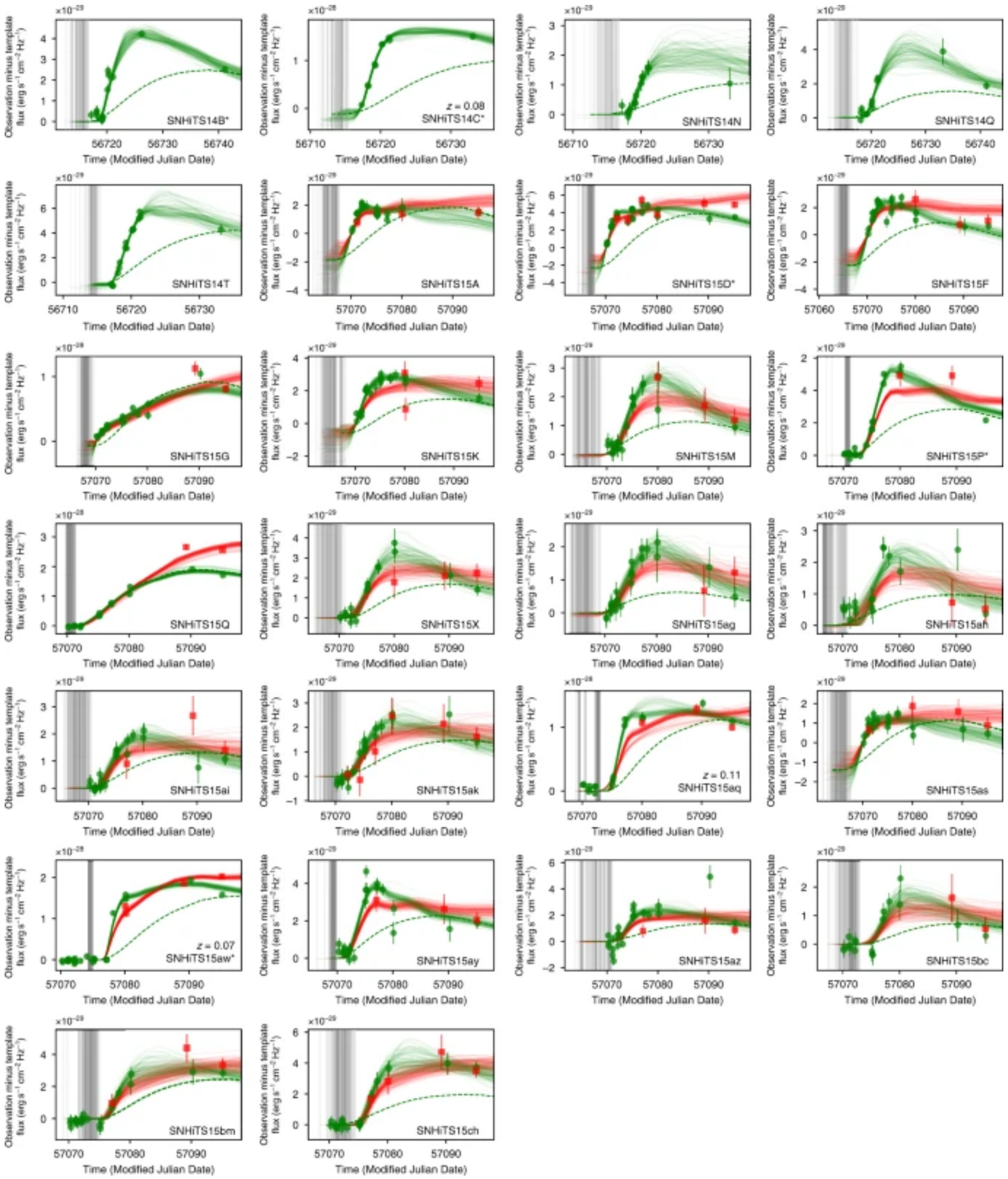
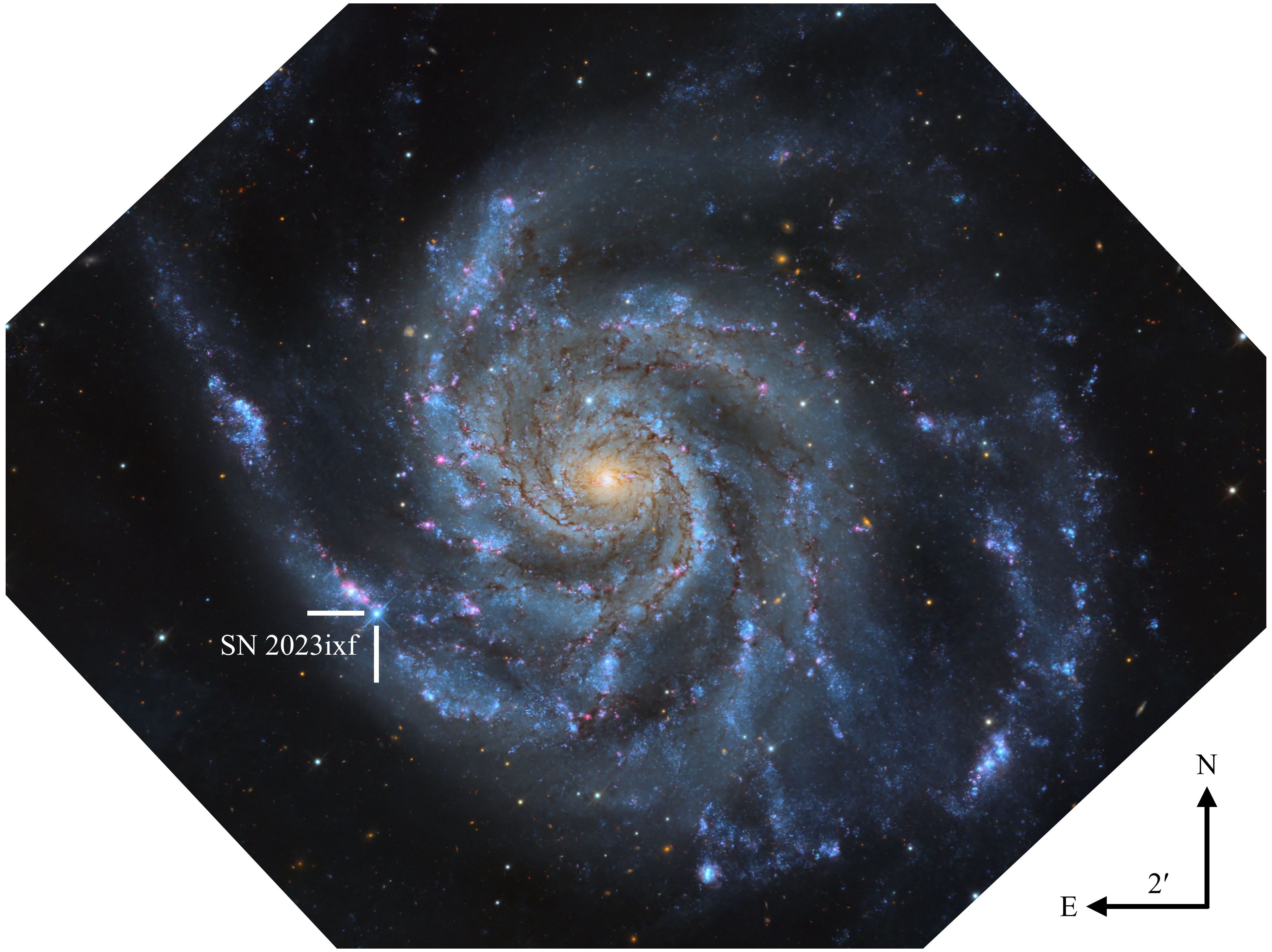
- confined CSM is more normal (>80%)?



Förster+2018, Nature Astronomy

Type-II SNe and SN 2023ixf in M101

- Type II SNe: an exploding RSG with massive H-rich envelope
- 1st report by K. Itagaki(2023/05/19/17:27 UTC)
- host galaxy M101: D=6.9Mpc, m-M=29.05 (Riess+ 2022)
- The nearest CCSN in the last 10 years: abundant data available (pre-explosion/ post-explosion, light curve, spectra, polarization)



star-forming galaxy M101 and SN 2023ixf (Hosseinzadeh+2023)

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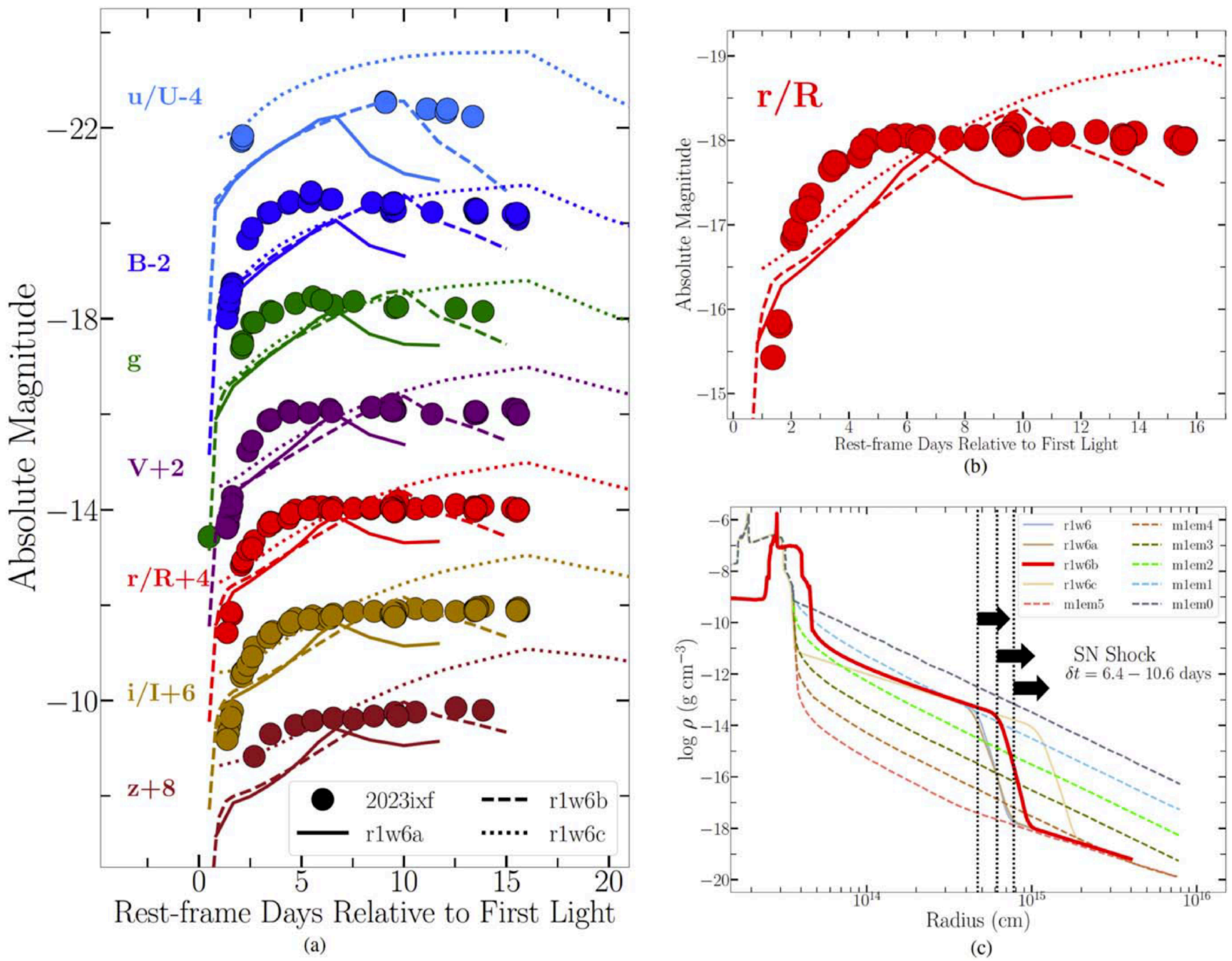
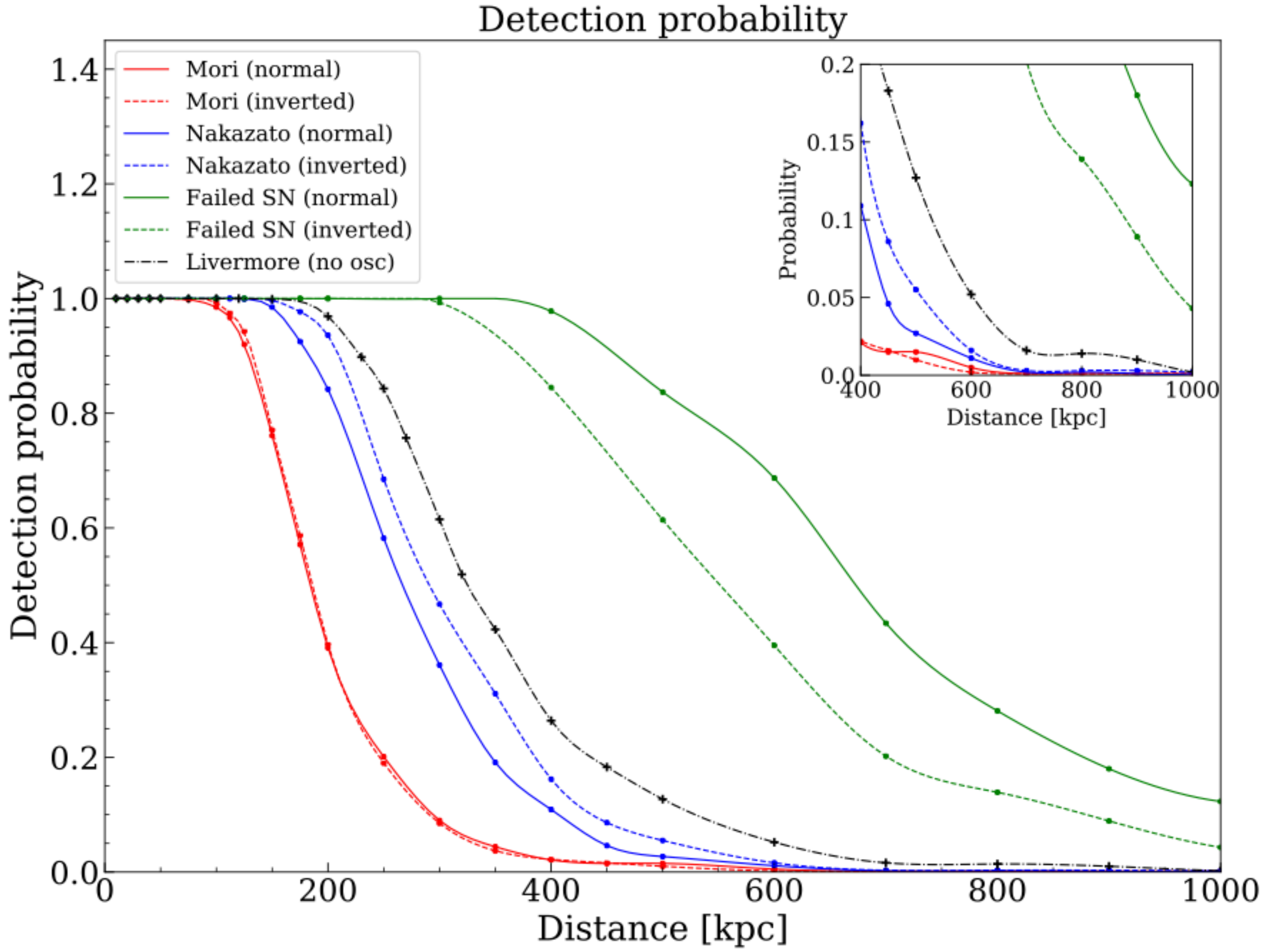


Early emission from SN 2023ixf (Jacobson-Galan+(2023))

Multi-messenger signals

- Type II SNe: an exploding RSG with massive H-rich envelope
- Despite the proximity, neutrino/GW detection is difficult…



Detection probability of SN neutrino (Mori+ 2022)

https://ui.adsabs.harvard.edu/abs/2022ApJ...938...35M/abstract

EM obs. and modelings of SN 2023ixf

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- enhanced mass-loss episodes in the last ~10 years: ~10^{-3}-$10^{-1}M_{sun}$/yr (or more) is needed for LC modeling (v_{wind}~50-100km/s)

  e.g. Hiramatsu+(2023), Martinez+(2024), Moriya+(2024),

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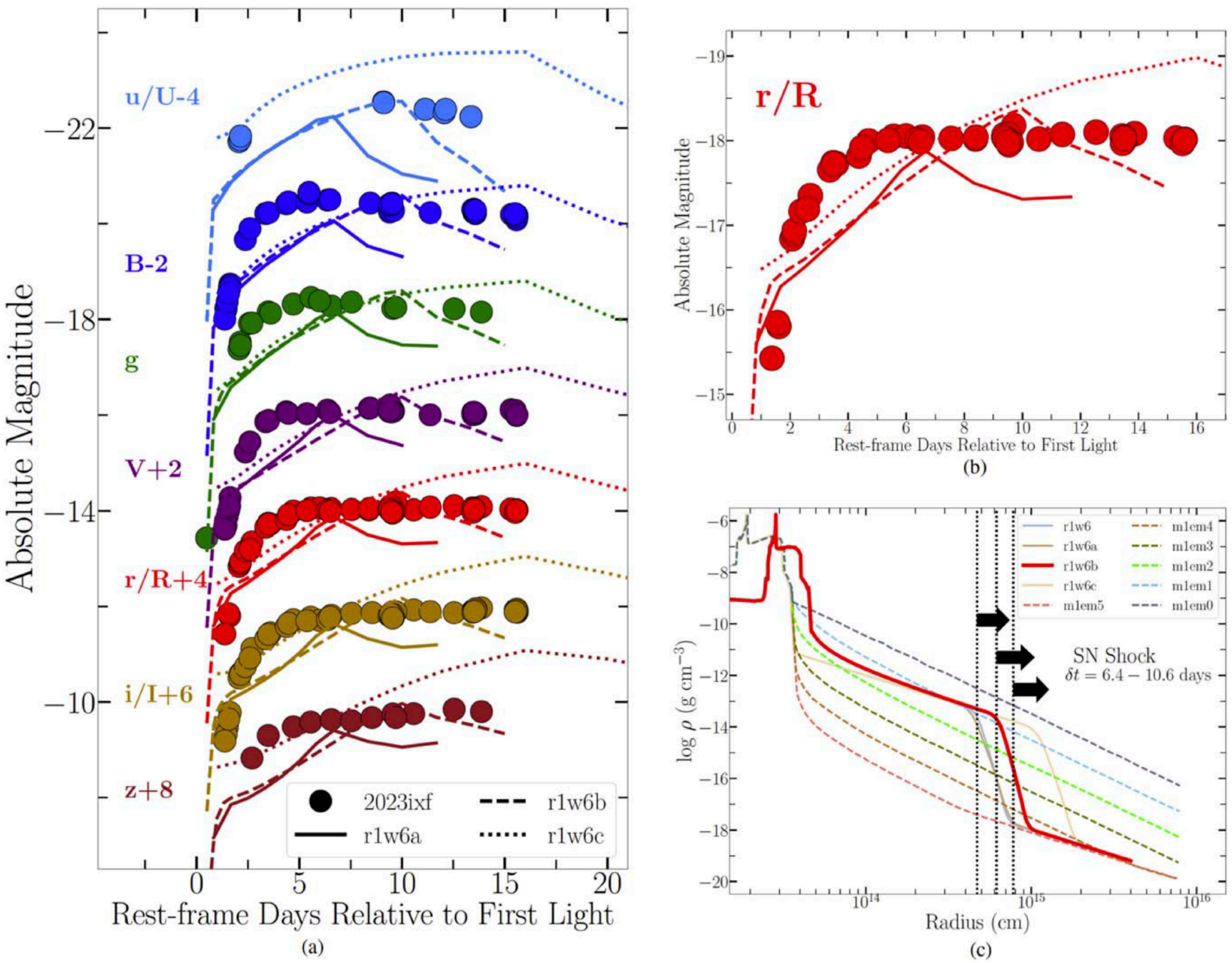

Early light curve of SN 2023ixf (Jacobson-Galan+(2023))

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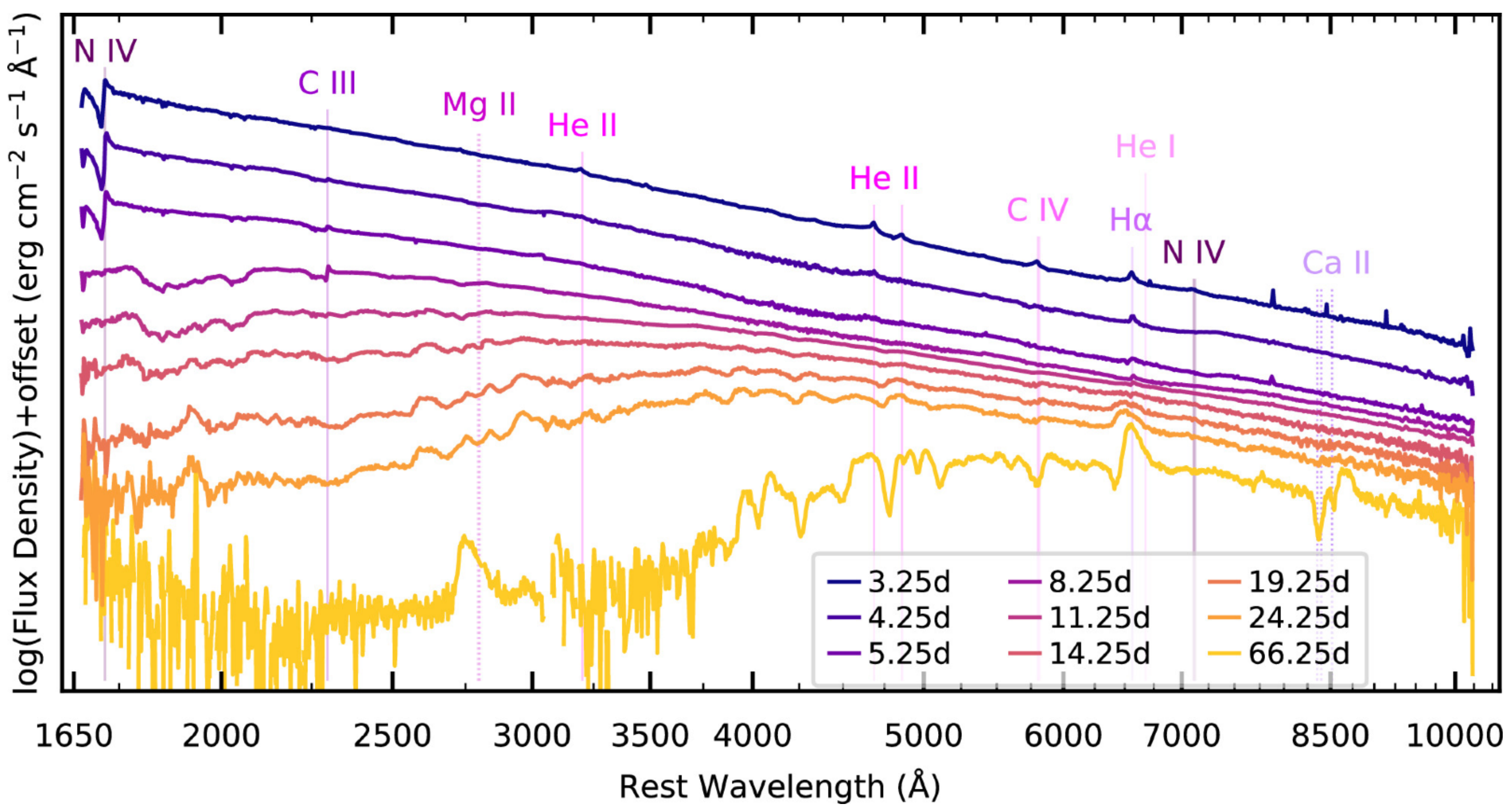
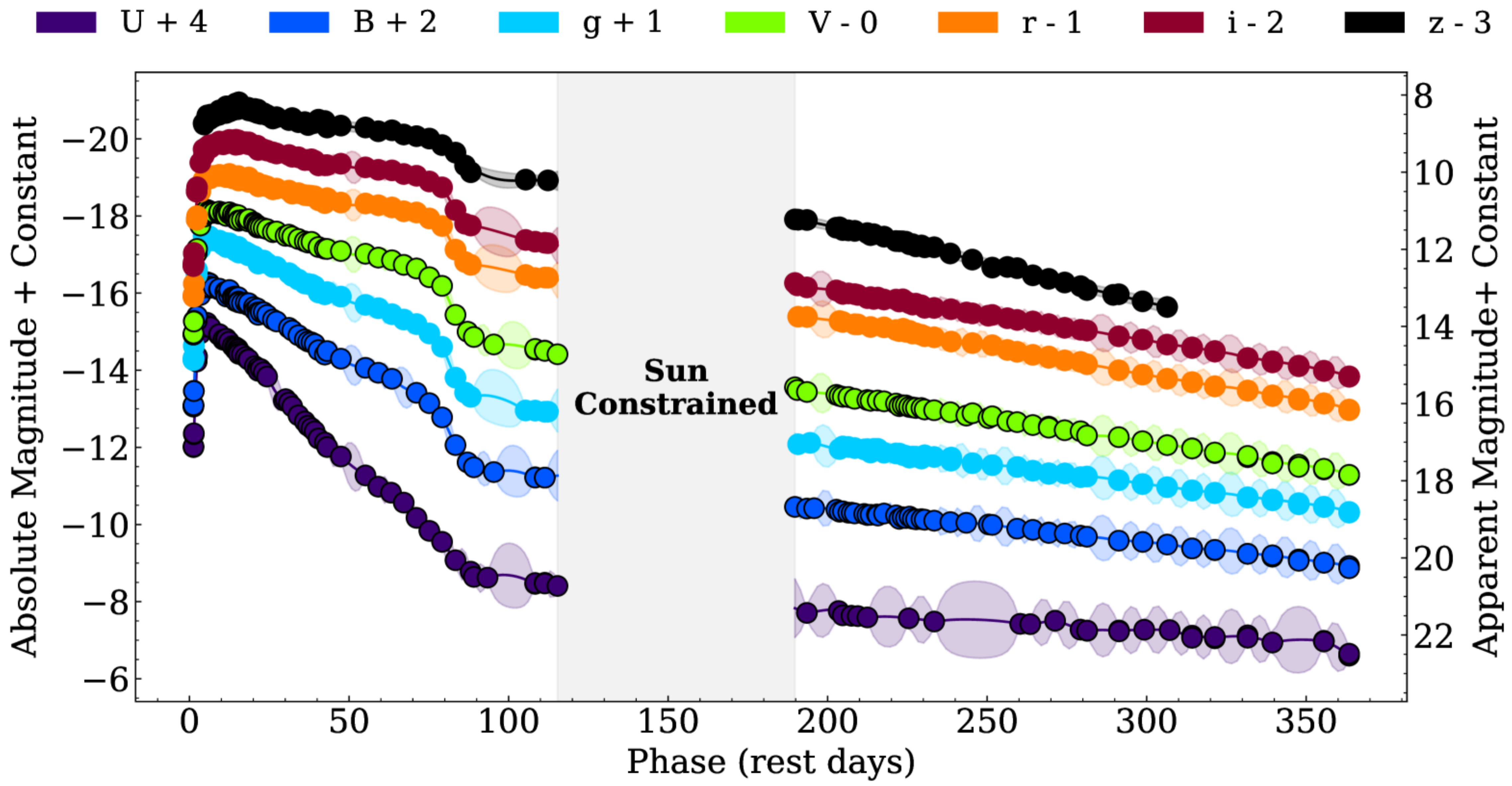
UV spectra of SN 2023ixf (Boestrom+2024)





Light curve of SN 2023ixf (Hsu+2024)

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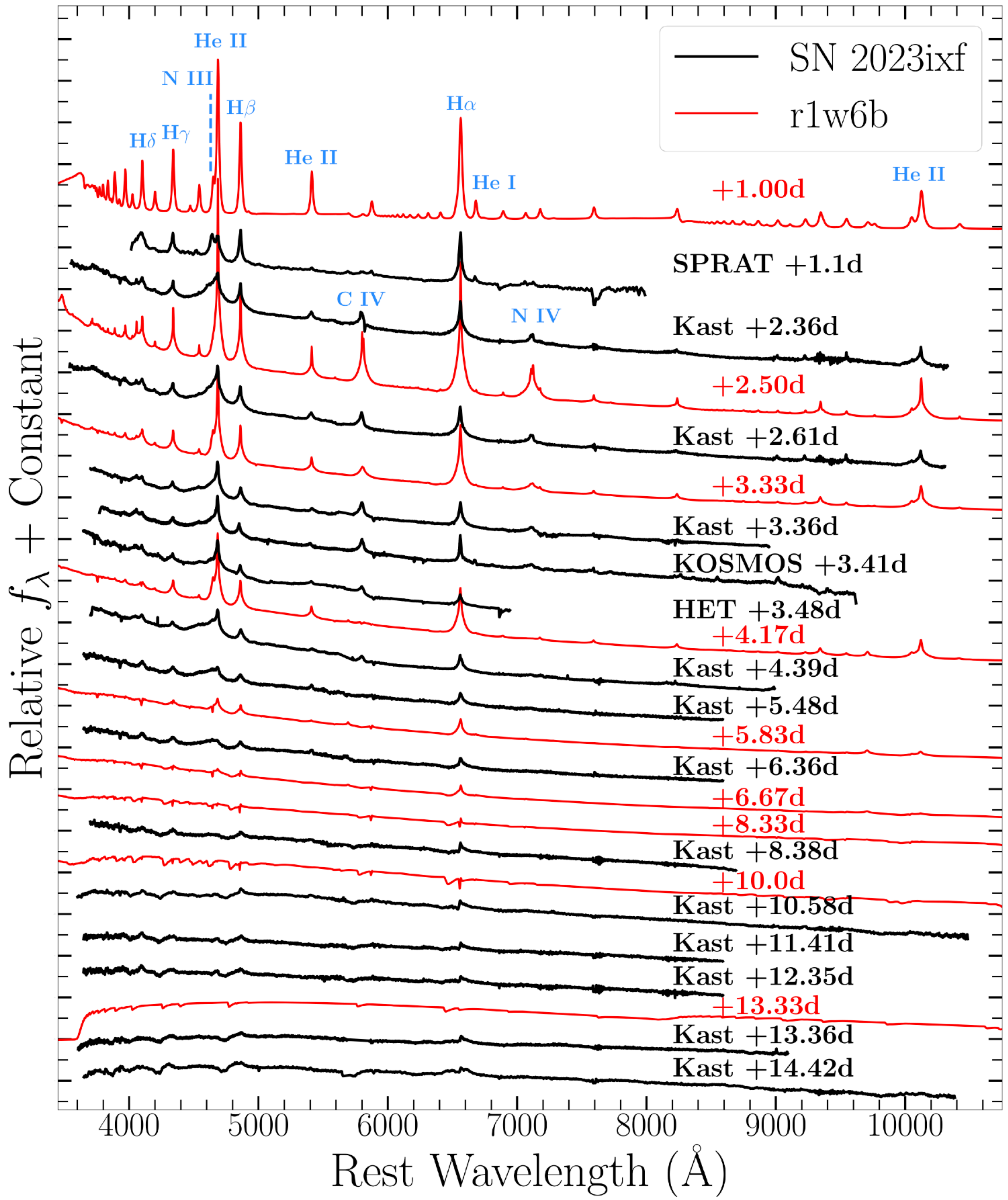

Early spectra of SN 2023ixf (Jacobson-Galan+(2023))

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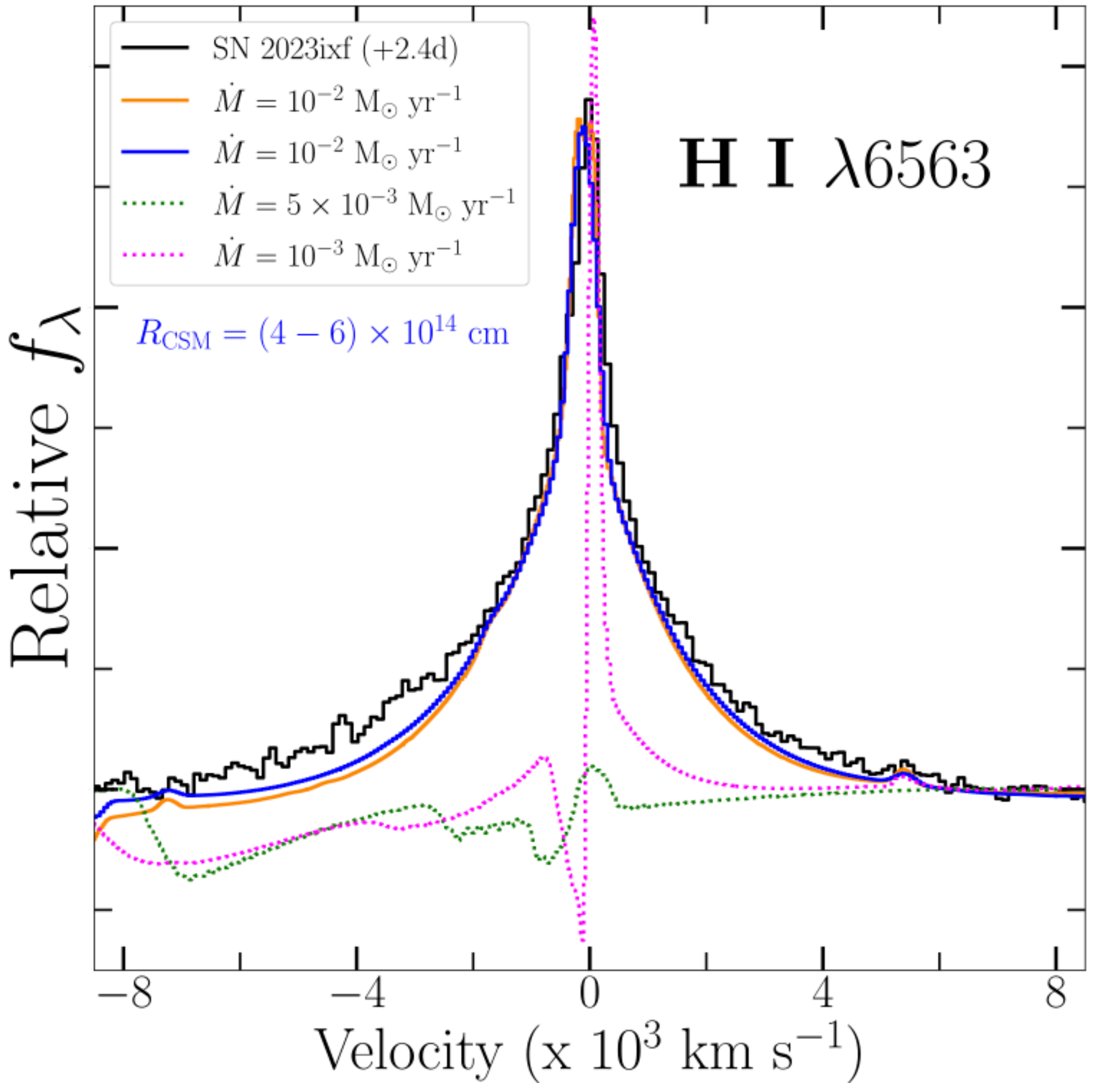
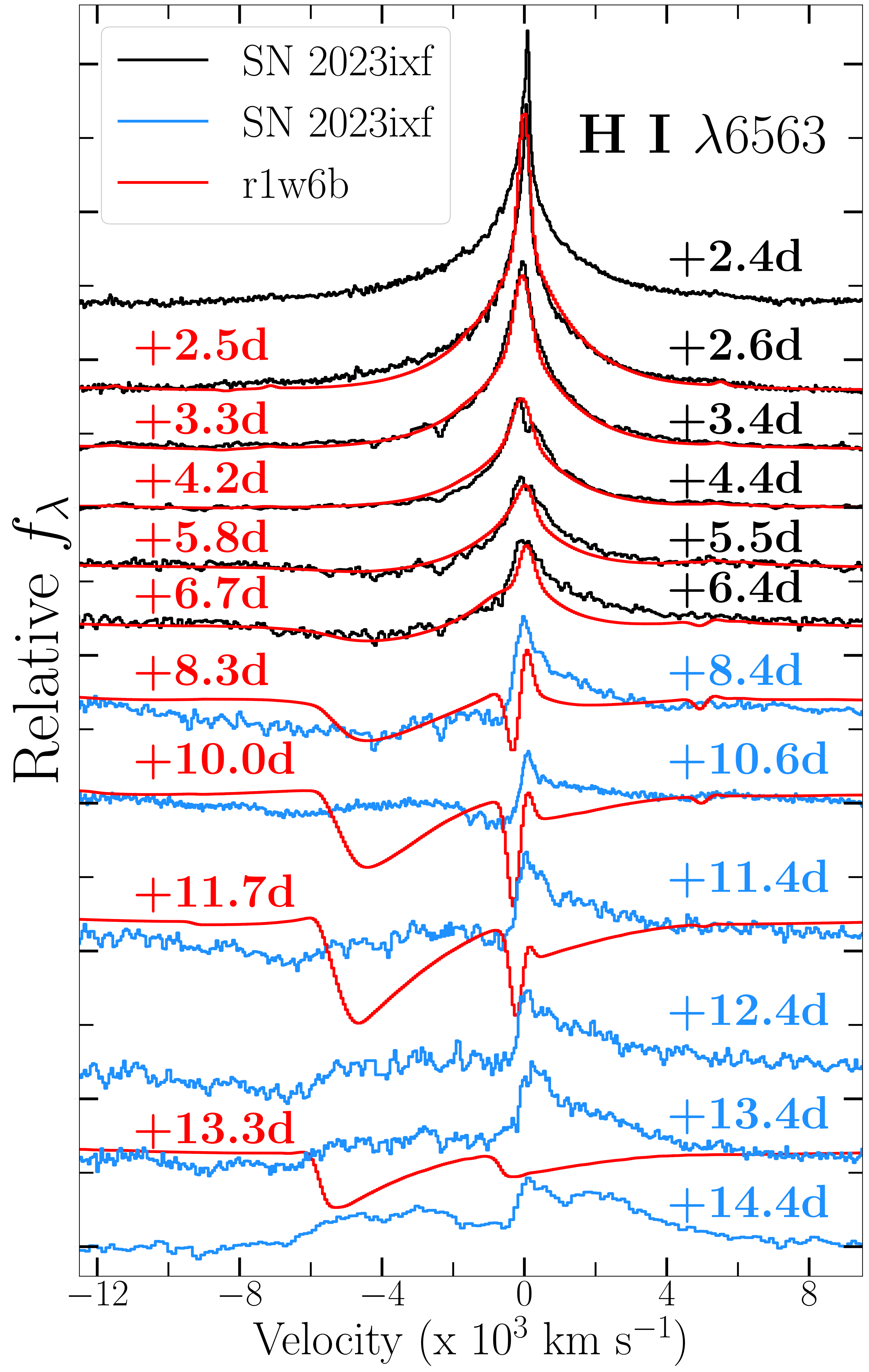
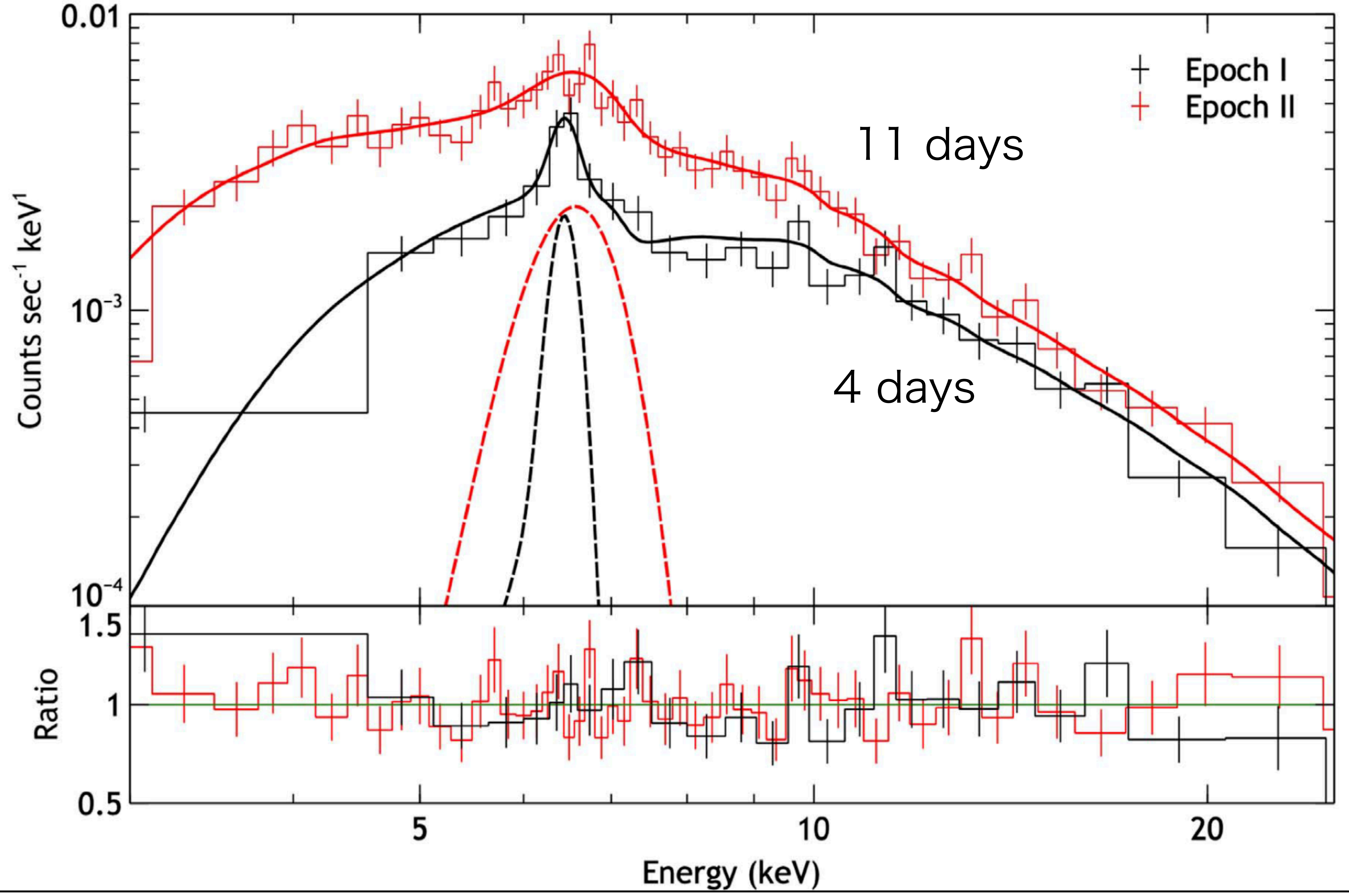




Early spectra of SN 2023ixf (Jacobson-Galan+(2023))

EM obs. and modelings of SN 2023ixf

- X-ray: free-free emission.
- possible Fe line detection
- evolution of column density N_H indicates a mass-loss rate of 2.5×10^{-4}[M_{sun}/yr] at 4 days
- inconsistent with optical data?



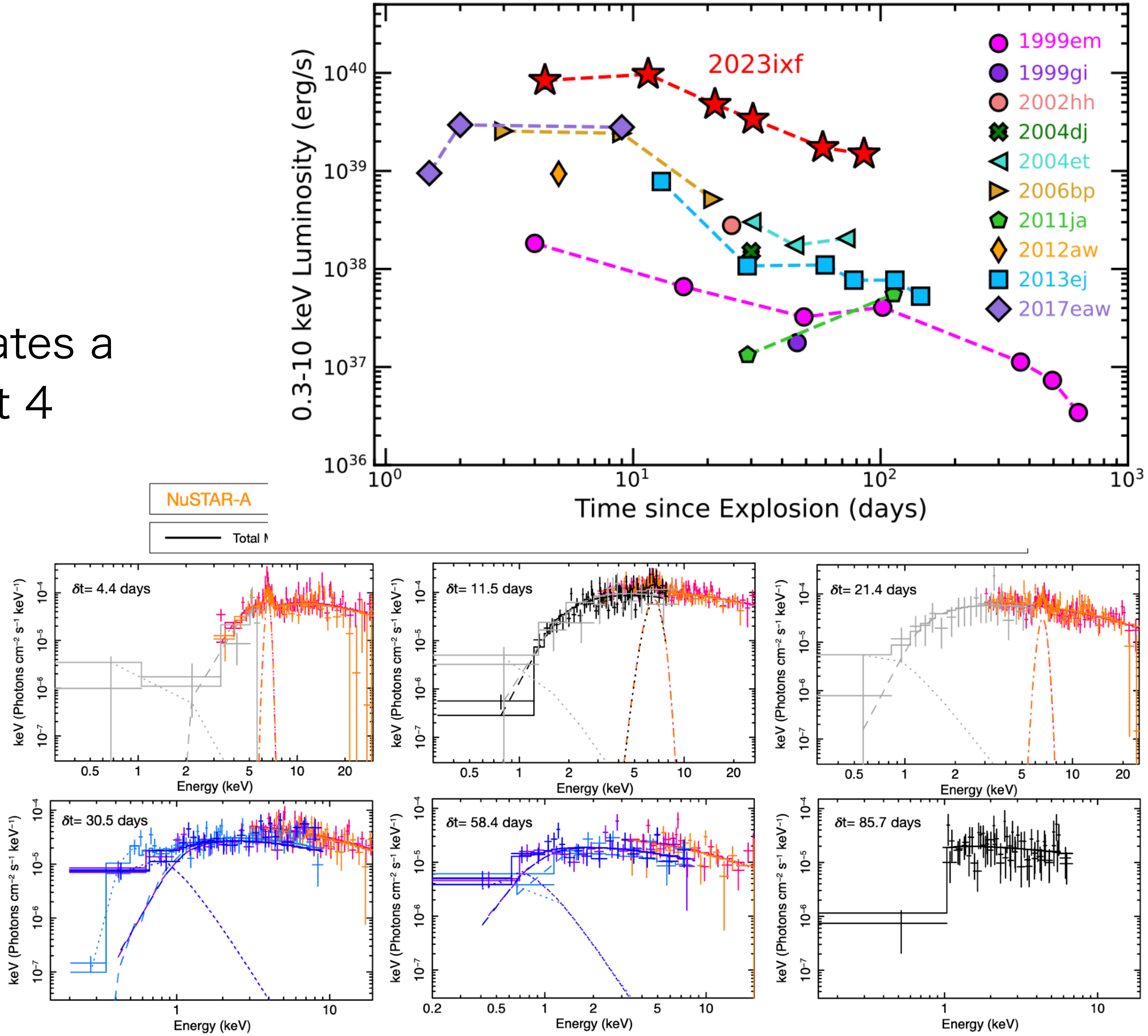
Epoch	N_{Hint}[a]	kT (keV)	Norm[b]	Line (keV)	Width (keV)	Norm[c]	Wstat/dof
Epoch I	26^{+5}_{-7}	>25	1.06 ± 0.13	6.45 ± 0.08	<0.2	6.6 ± 2	888/843
Epoch II	5.6 ± 2.7	34^{+22}_{-12}	$1.3^{+0.2}_{-0.1}$	6.57 ± 0.17	0.45 ± 0.2	14 ± 5	892/842

Epoch	EM (cm^{-3})	Flux 0.3–10 keV (erg cm^{-2} s^{-1})	Lum 0.3–10 keV (erg s^{-1})	Flux 10–79 keV (erg cm^{-2} s^{-1})	Lum 10–79 keV (erg s^{-1})
Epoch I	$6.0 \pm 0.7 \times 10^{62}$	$5.9 \pm 0.3 \times 10^{-13}$	$0.34 \pm 0.02 \times 10^{40}$	$3.4^{+0.2}_{-1.3} \times 10^{-12}$	$1.9^{+0.1}_{-0.7} \times 10^{40}$
Epoch I[a]	…	$1.7^{+0.7}_{-0.1} \times 10^{-12}$	$1.0^{+0.34}_{-0.05} \times 10^{40}$	$3.5^{+0.3}_{-1} \times 10^{-12}$	$2.0^{+0.2}_{-0.7} \times 10^{40}$
Epoch II	$7.5^{+0.9}_{-0.5} \times 10^{62}$	$1.44 \pm 0.08 \times 10^{-12}$	$0.82 \pm 0.05 \times 10^{40}$	$3.5 \pm 0.9 \times 10^{-12}$	$2 \pm 0.5 \times 10^{40}$
Epoch II[a]	…	$2.5 \pm 0.3 \times 10^{-12}$	$1.4 \pm 0.2 \times 10^{40}$	$3.5 \pm 0.9 \times 10^{-12}$	$2 \pm 0.5 \times 10^{40}$

NuSTAR X-ray spectra from SN 2023ixf (Grefenstette+ 2023)

EM obs. and modelings of SN 2023ixf

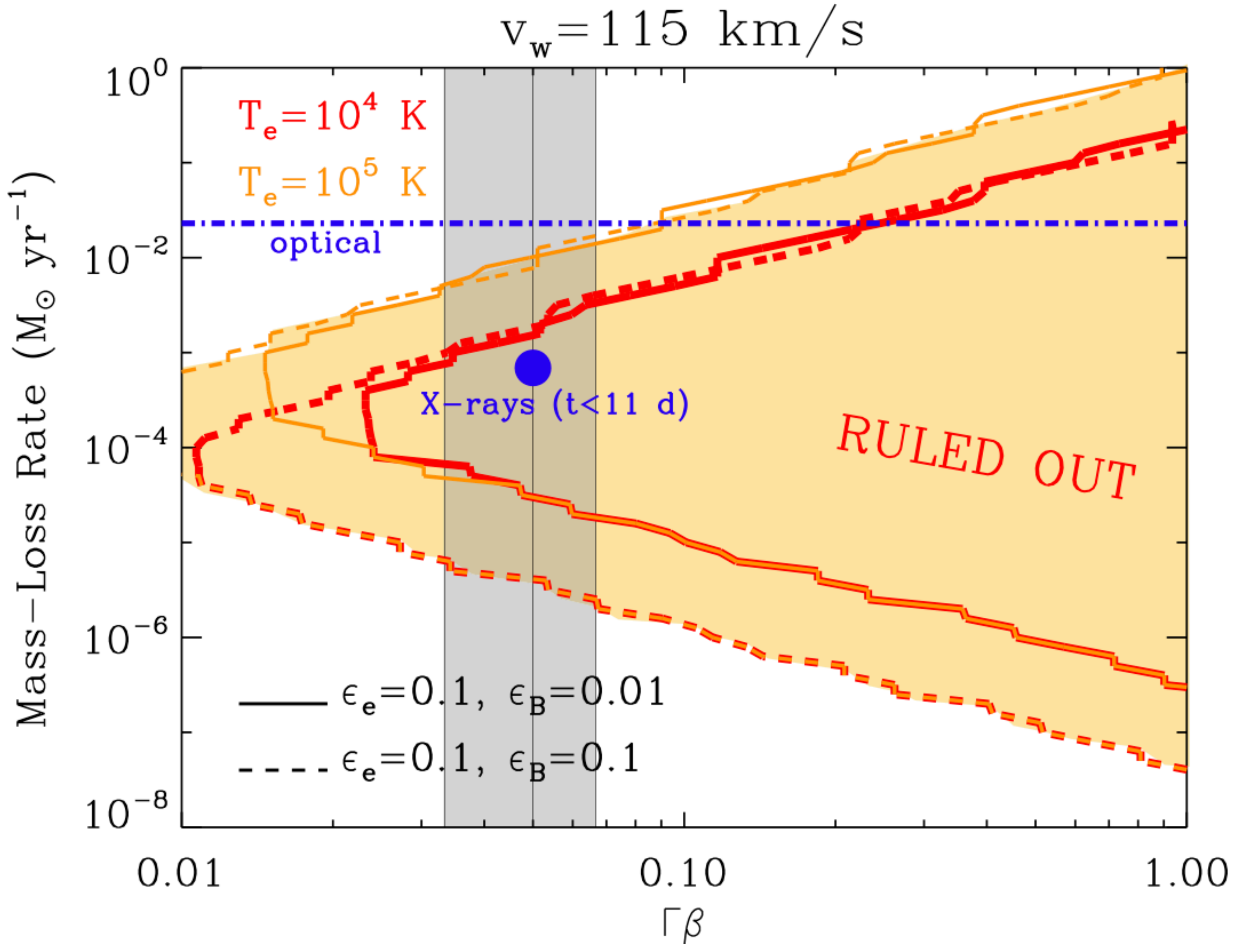
- X-ray: free-free emission.
- possible Fe line detection
- evolution of column density N_H indicates a mass-loss rate of 2.5×10^{-4}[M_{sun}/yr] at 4 days
- inconsistent with optical data?

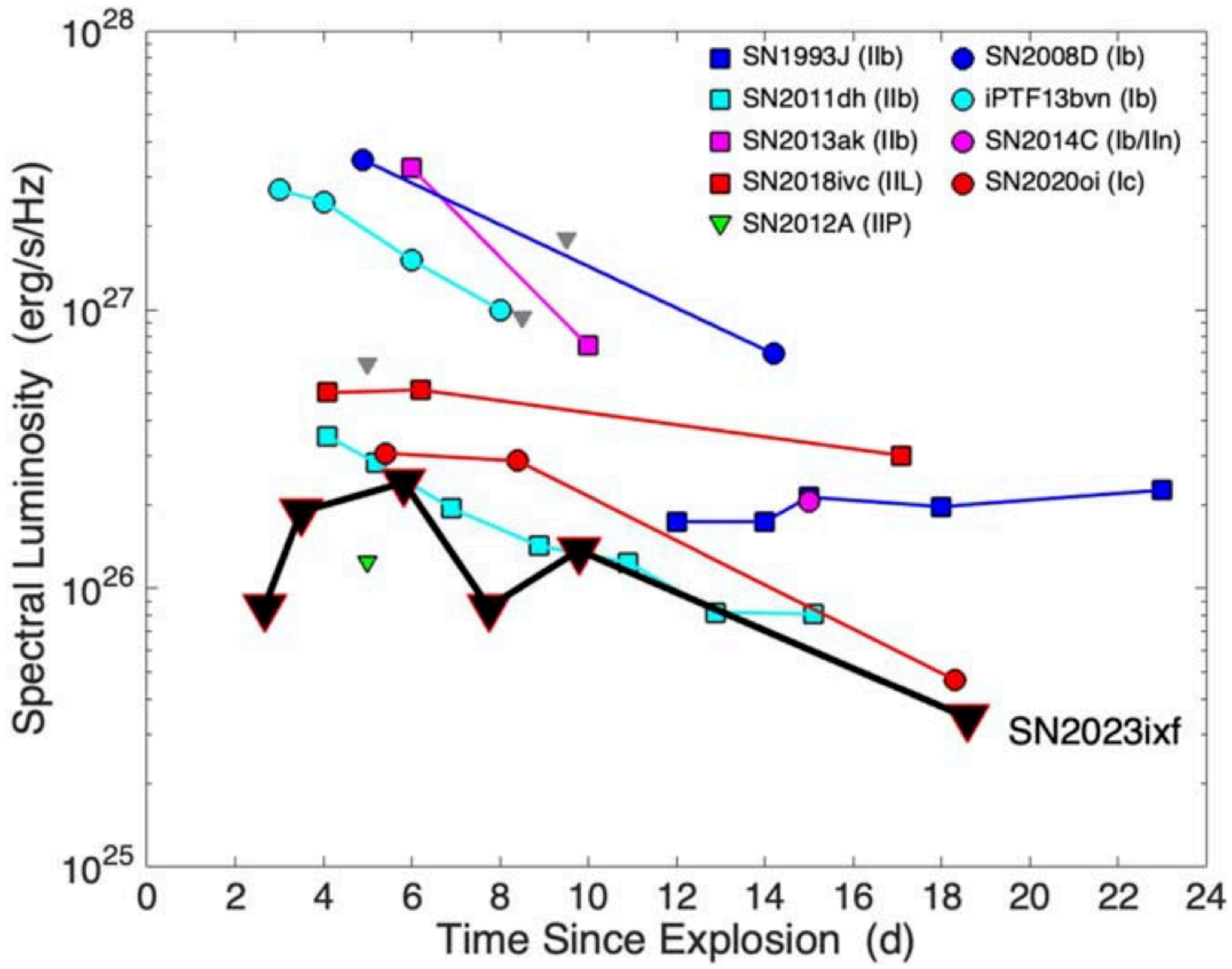


X-ray observations of SN 2023ixf (Nayana+ 2024)

EM obs. and modelings of SN 2023ixf

- radio: synchrotron emission
- early non-detection: optically thick or low density?



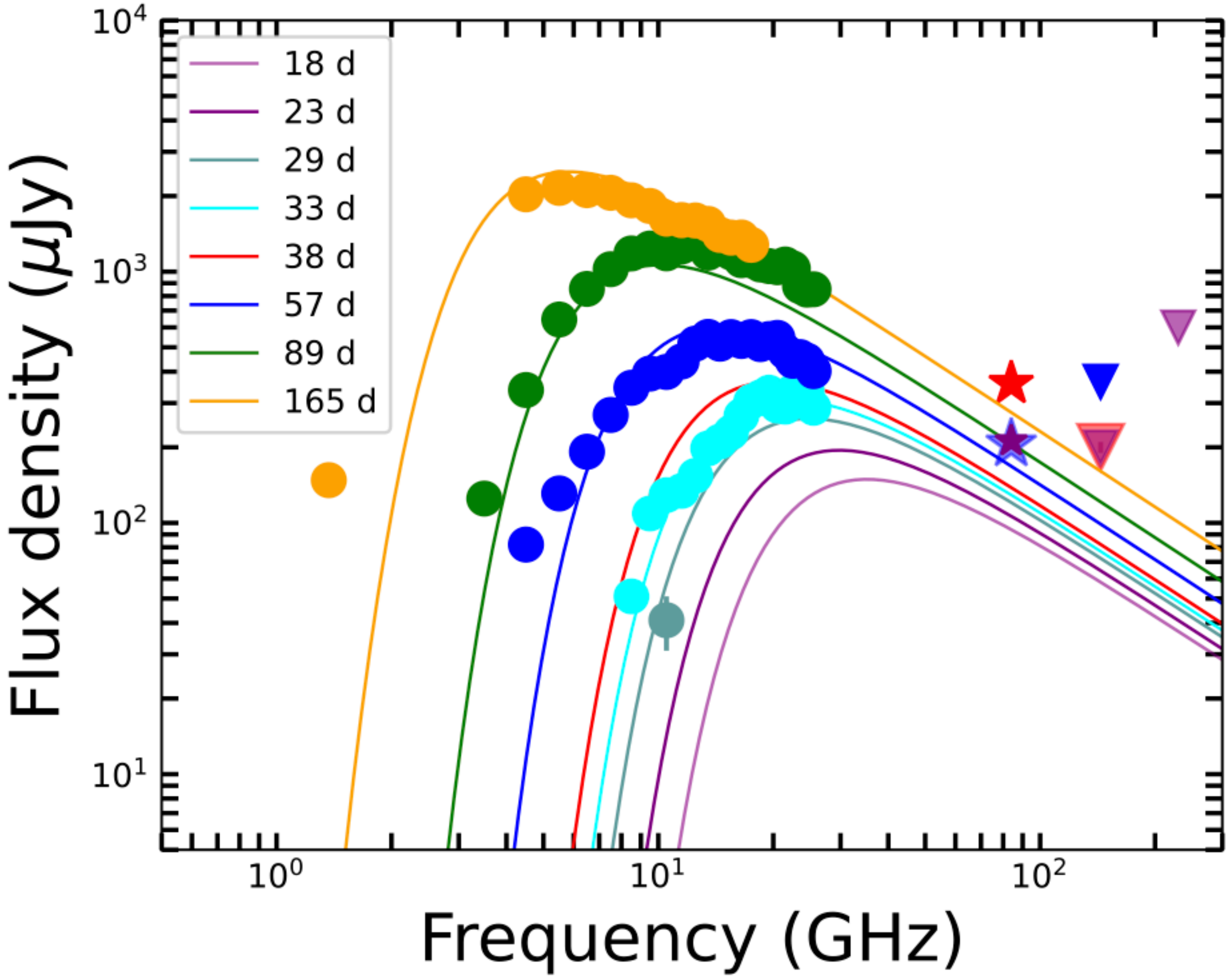


Early radio upper limits on SN 2023ixf (Burger+ 2023)

EM obs. and modelings of SN 2023ixf

- radio: synchrotron emission
- early non-detection: optically thick or low density?
- optically thick/thin at low/high frequency
- turn over frequency gives CSM density → estimate for mass-loss rate

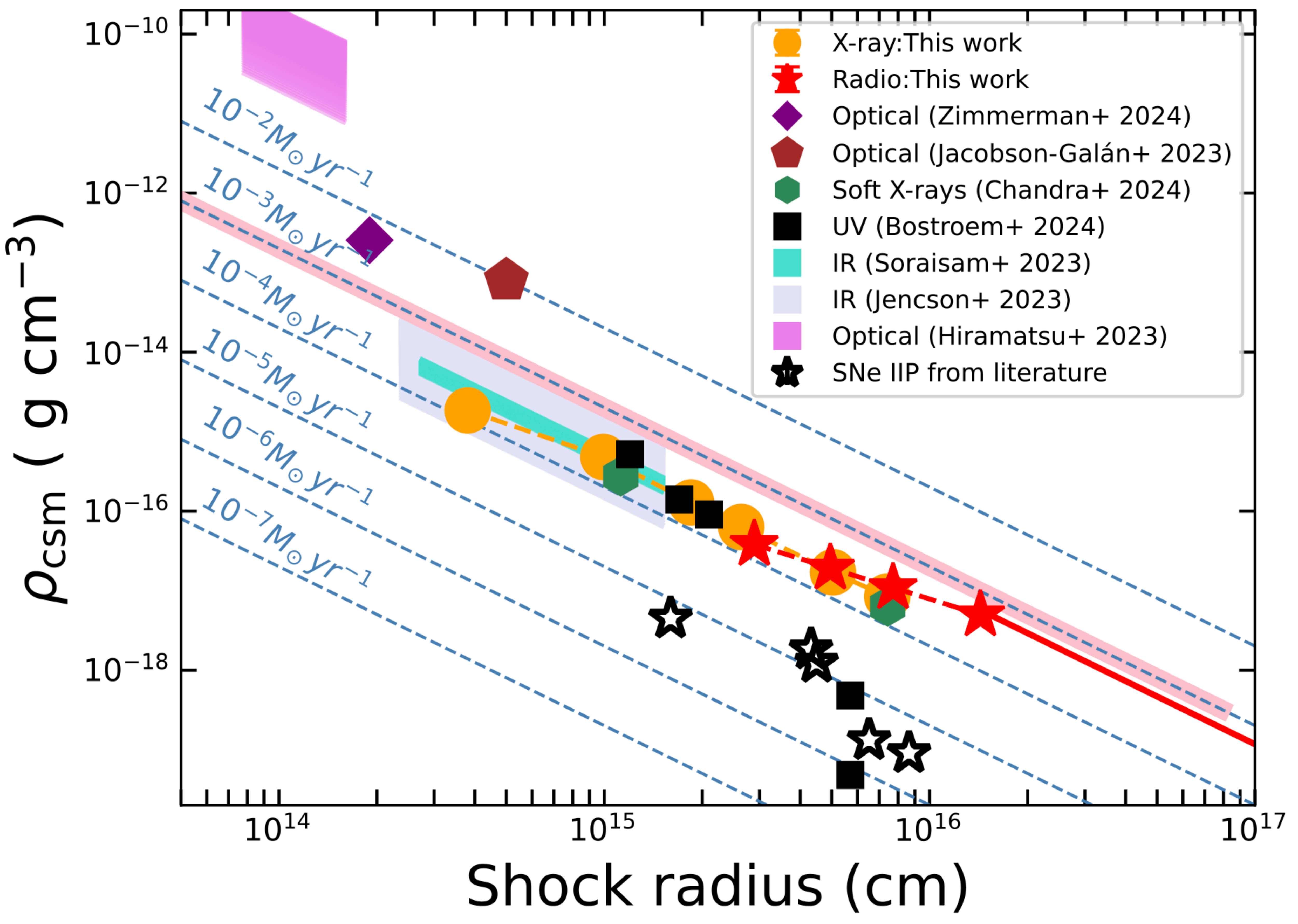
$$\rho = \frac{\dot{M}}{4\pi v_{\mathrm{w}} r^2}$$



Later radio detections of SN 2023ixf (Nayana+ 2023)

EM obs. and modelings of SN 2023ixf

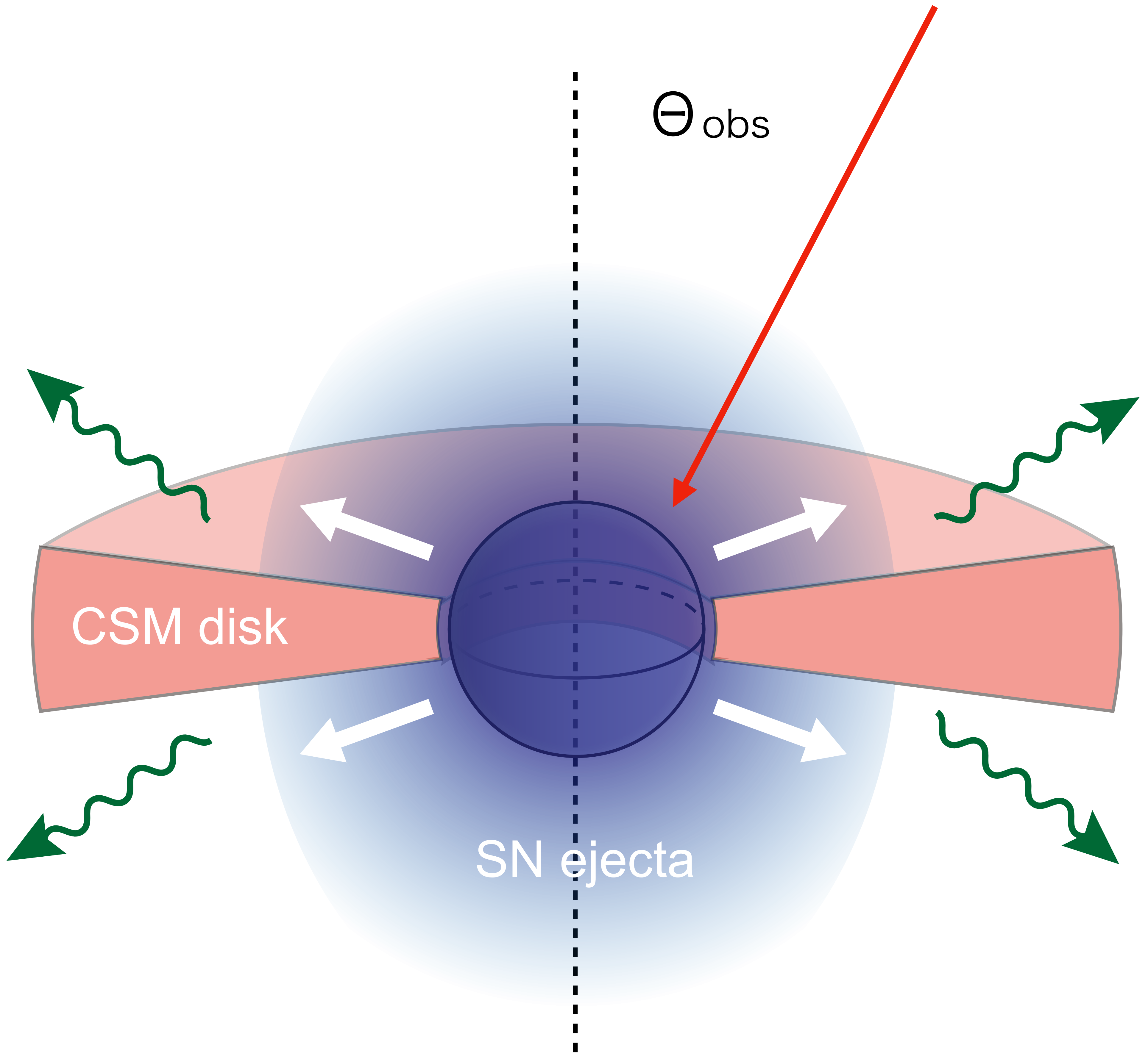
- inferred CSM density structure
- simultaneous optical and X-ray obs. suggest different CSM density
- X-rays cannot escape from dense CSM inferred from optical obs.
- spatially distinct emitting regions?
- CSM could be aspherical
- bipolar? disk-like? clumpy?



CSM structure inferred from SN 2023ixf (Nayana+ 2024)

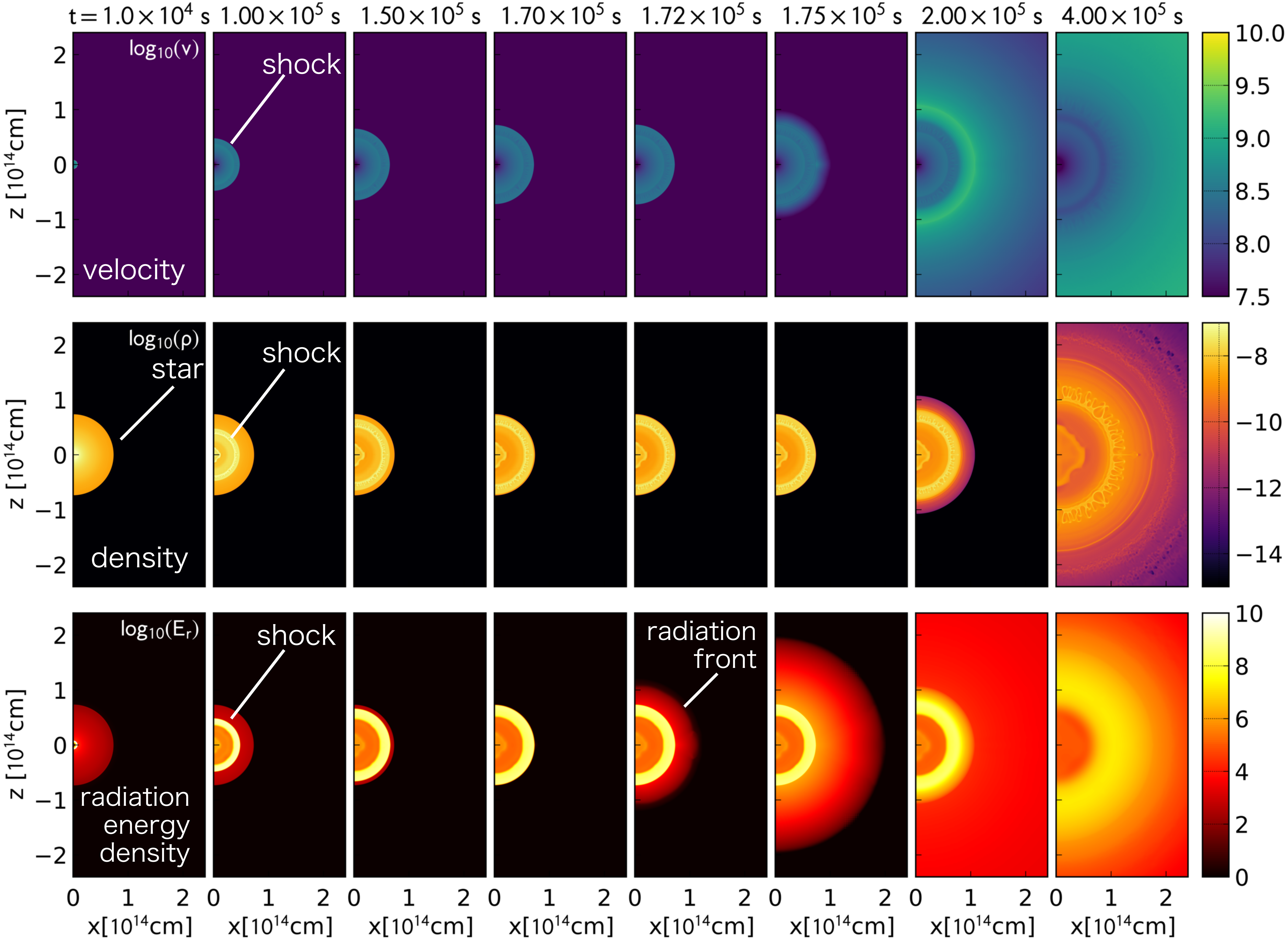
2D radiation-hydrodynamic simulations

- 2D rad-hydro simulation: similar simulation code as Suzuki+(2019)
- $18M_{sun}$ RSG ($Z=0.014$, $R_{presn}=1070R_{sun}$, $M_{presn}=12.6M_{sun}$), $M_{NS}=1.4M_{sun}$
- $E_{exp}=1.0\times10^{51}$erg, $M_{Ni}=0.05M_{sun}$
- $\rho\propto r^{-2}$ CSM with cut-off at $r=R_{csm}$
- 12 species: H,He,C,N,O,Ne,Mg,Si,S,Ar,Ca,Fe
- EoS: ideal gas with $\gamma=5/3$
- opacity: fitting formula(ρ,T, X_h, X_{he}) by Christy (1966) (for computational convenience)



No CSM model: shock breakout

- $18M_{sun}$ RSG ($M_{presn}=12.6M_{sun}$)
- $E_{exp}=10^{51}$erg
- No CSM



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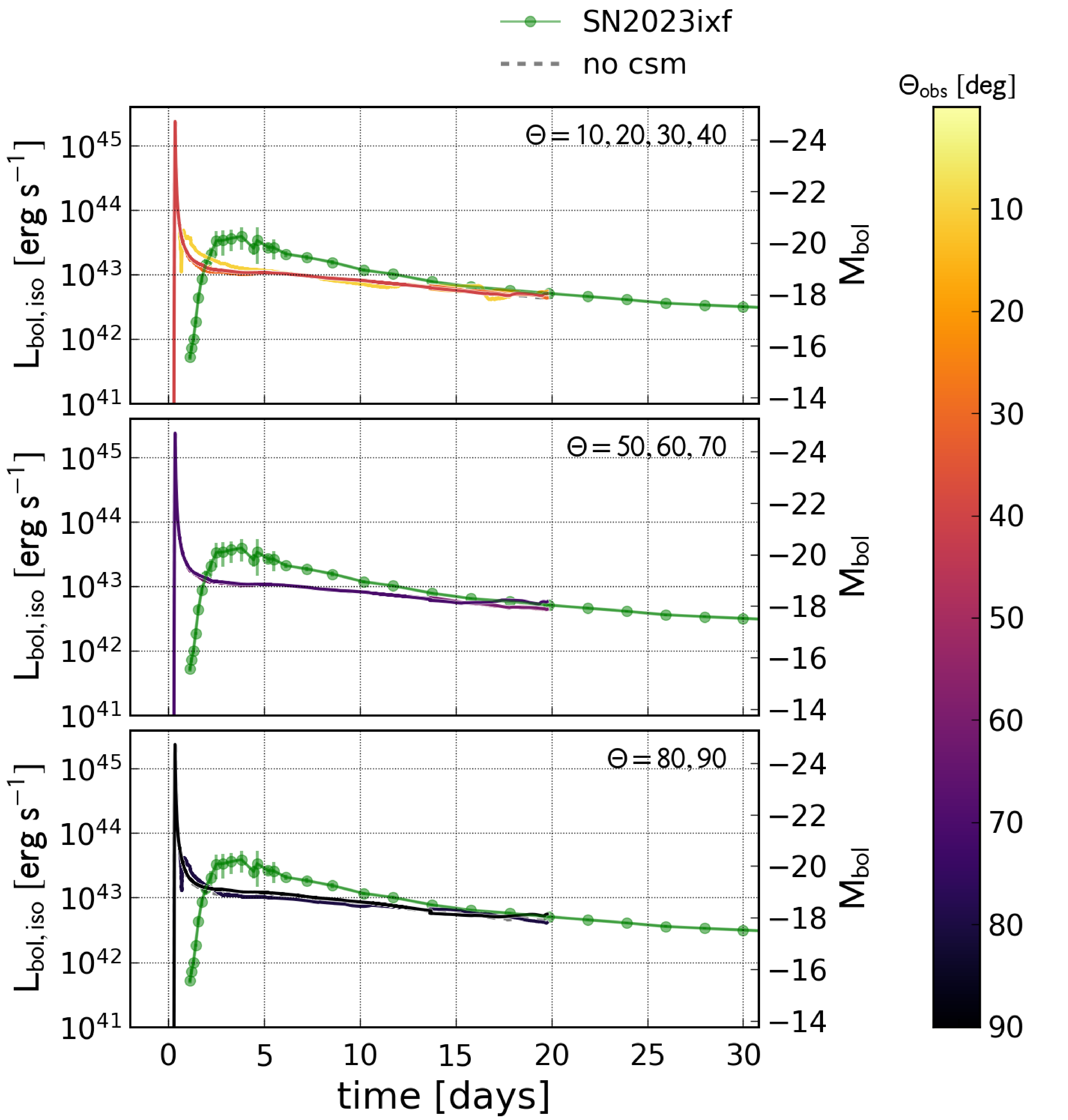
- **Shock breakout + cooling emission**
- monotonic decrease in the luminosity and temperature
- inconsistent with SN 2023ixf light curve
- but, maximum velocity exceeds 10,000km/s



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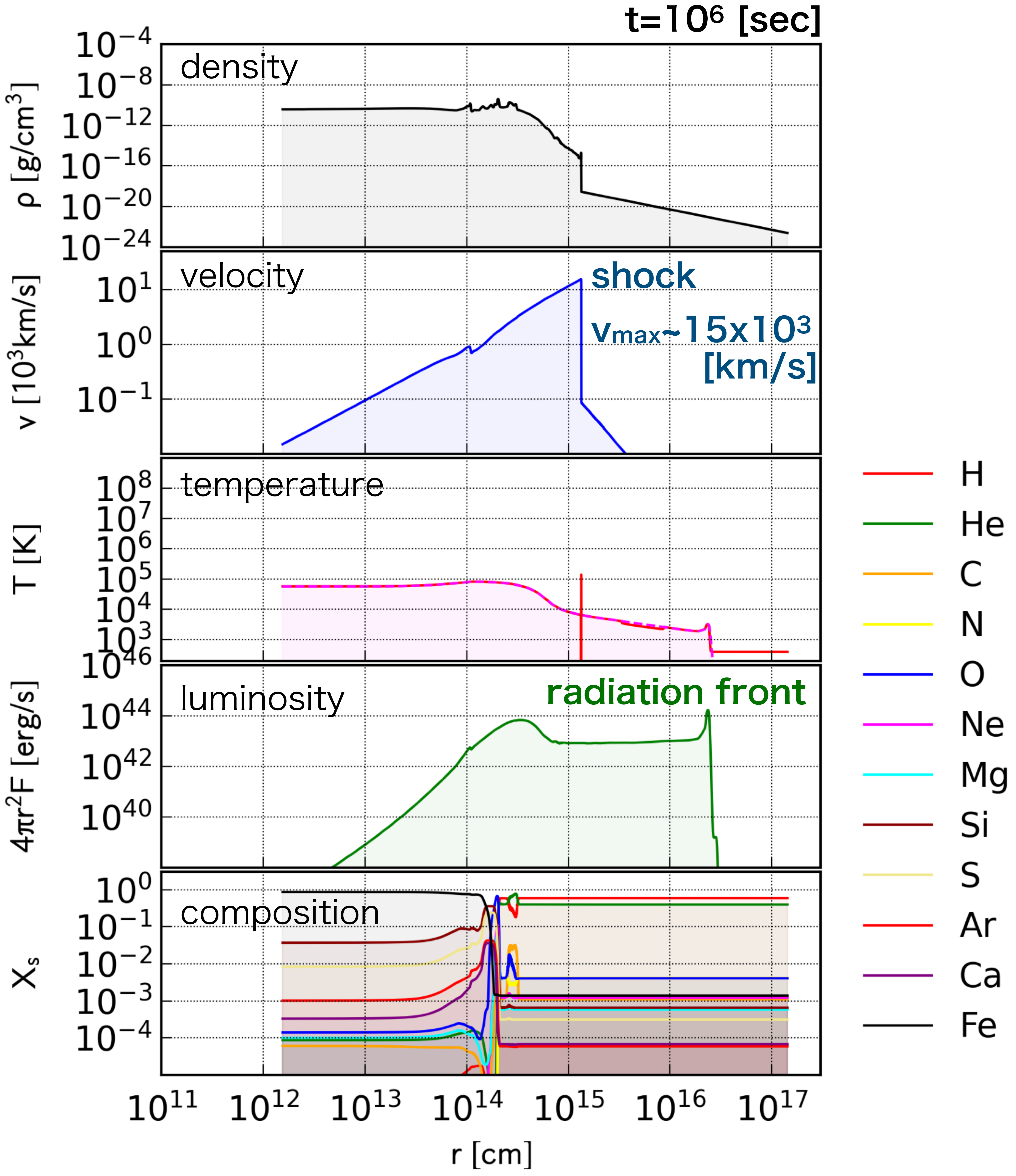
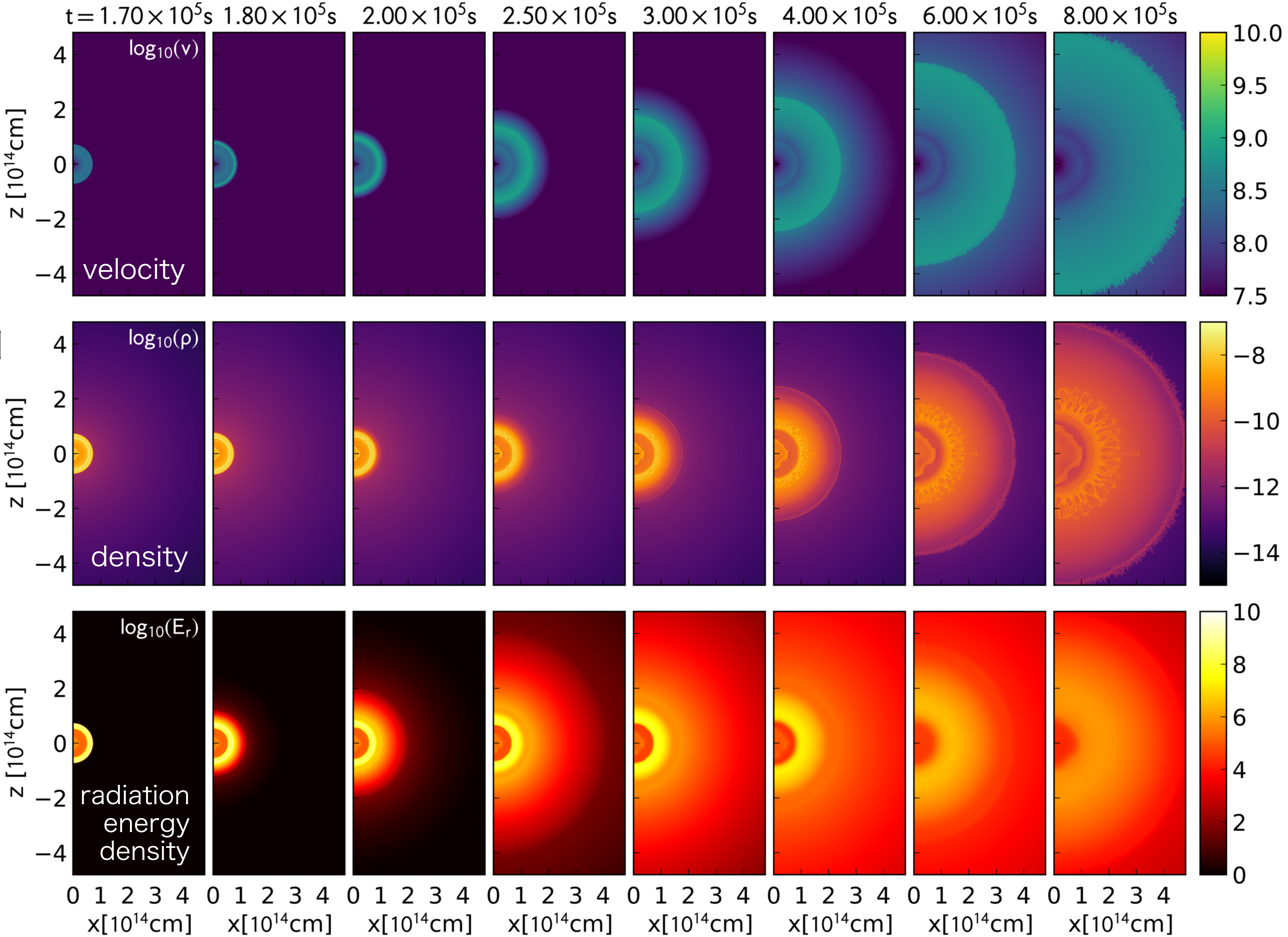


Spherical CSM model: delayed shock breakout

- 18M_{sun} RSG (M_{presn}=12.6M_{sun})
- E_{exp}=10^{51}erg
- 0.05M_{sun} spherical CSM
- R_{csm}=6x10^{14}cm



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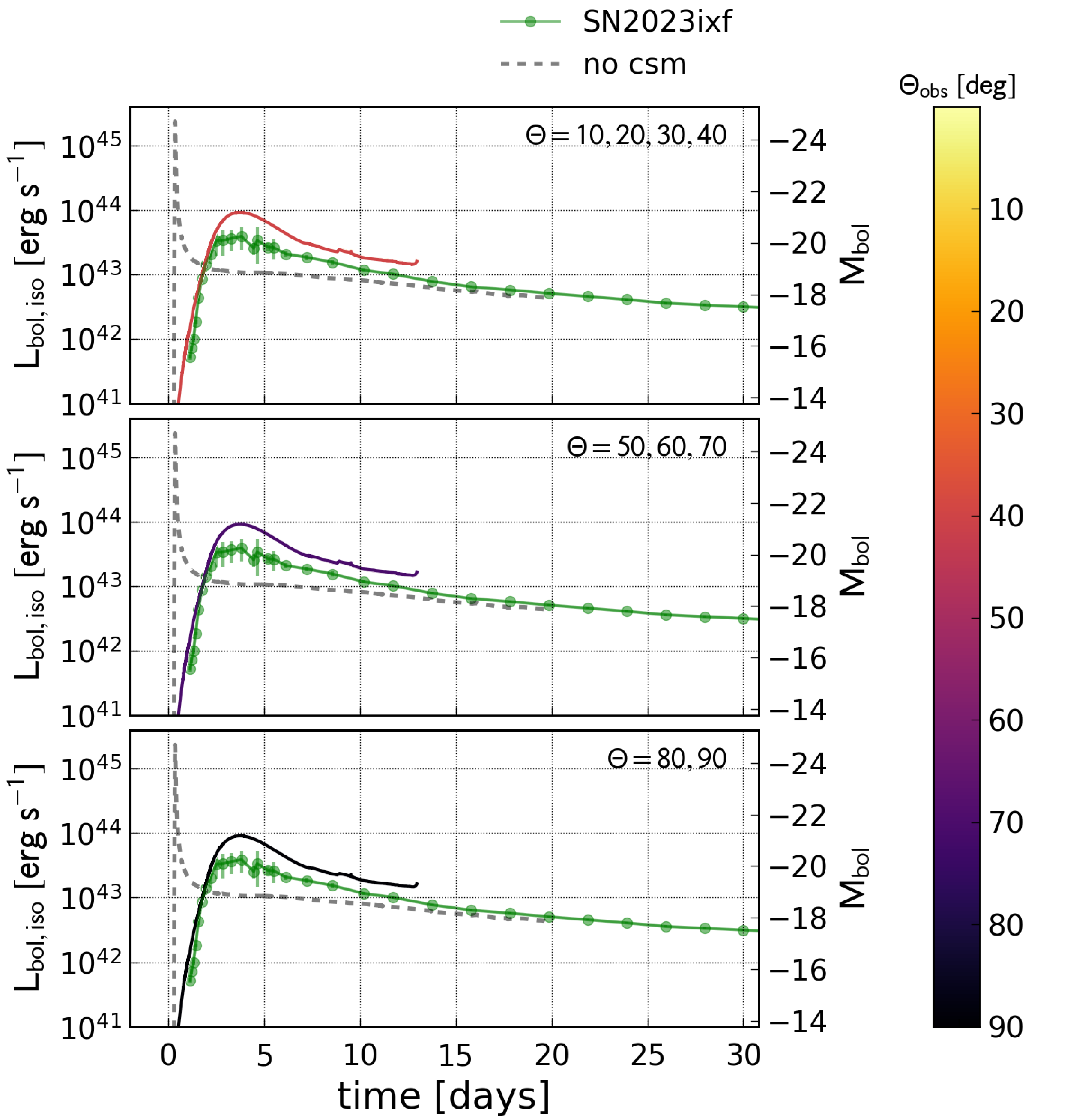
- **delayed shock breakout**
- luminosity peak is at ~3-4days
- LC evolution looks similar to observations
- but, maximum velocity is less than 7,000km/s



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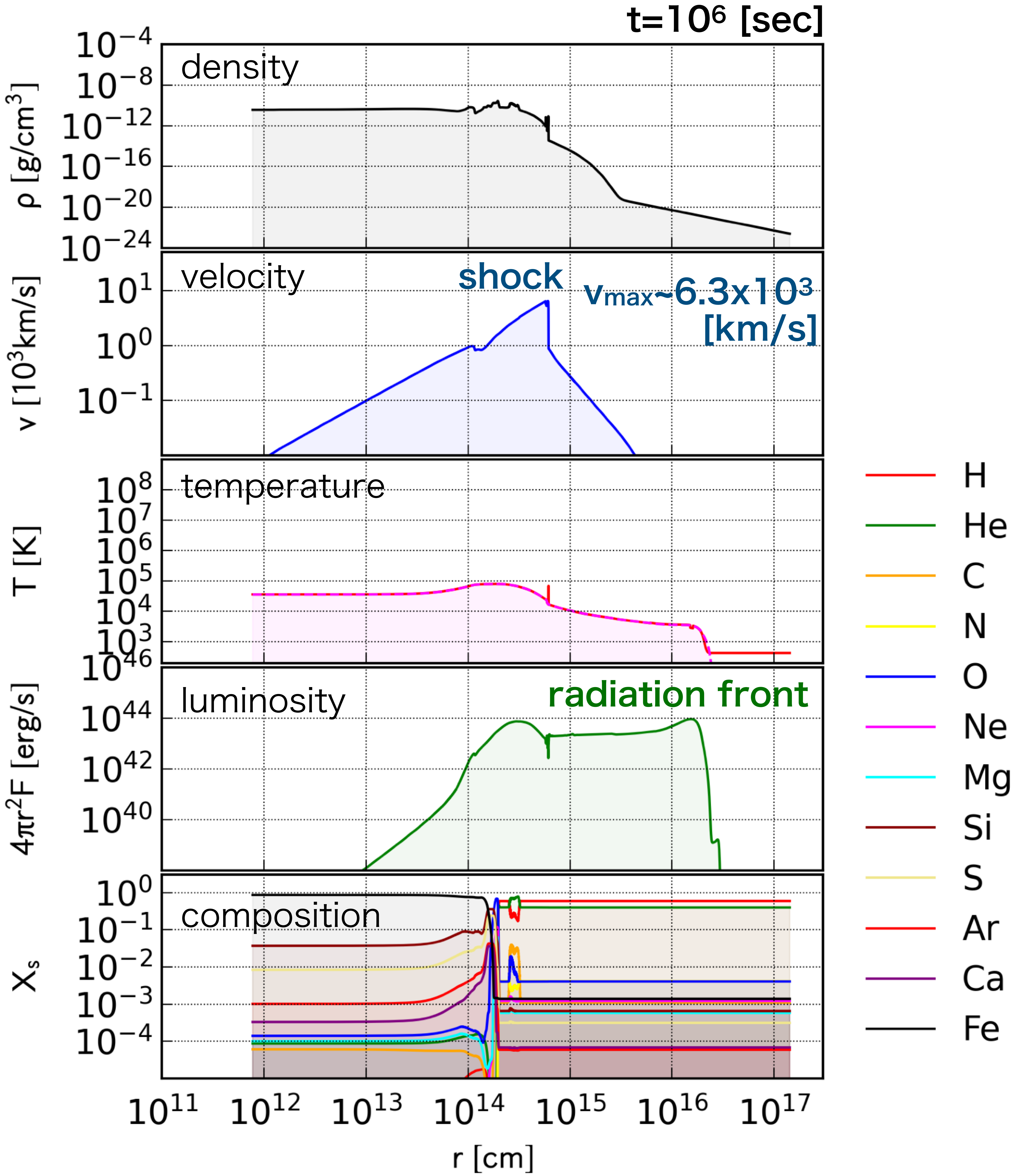
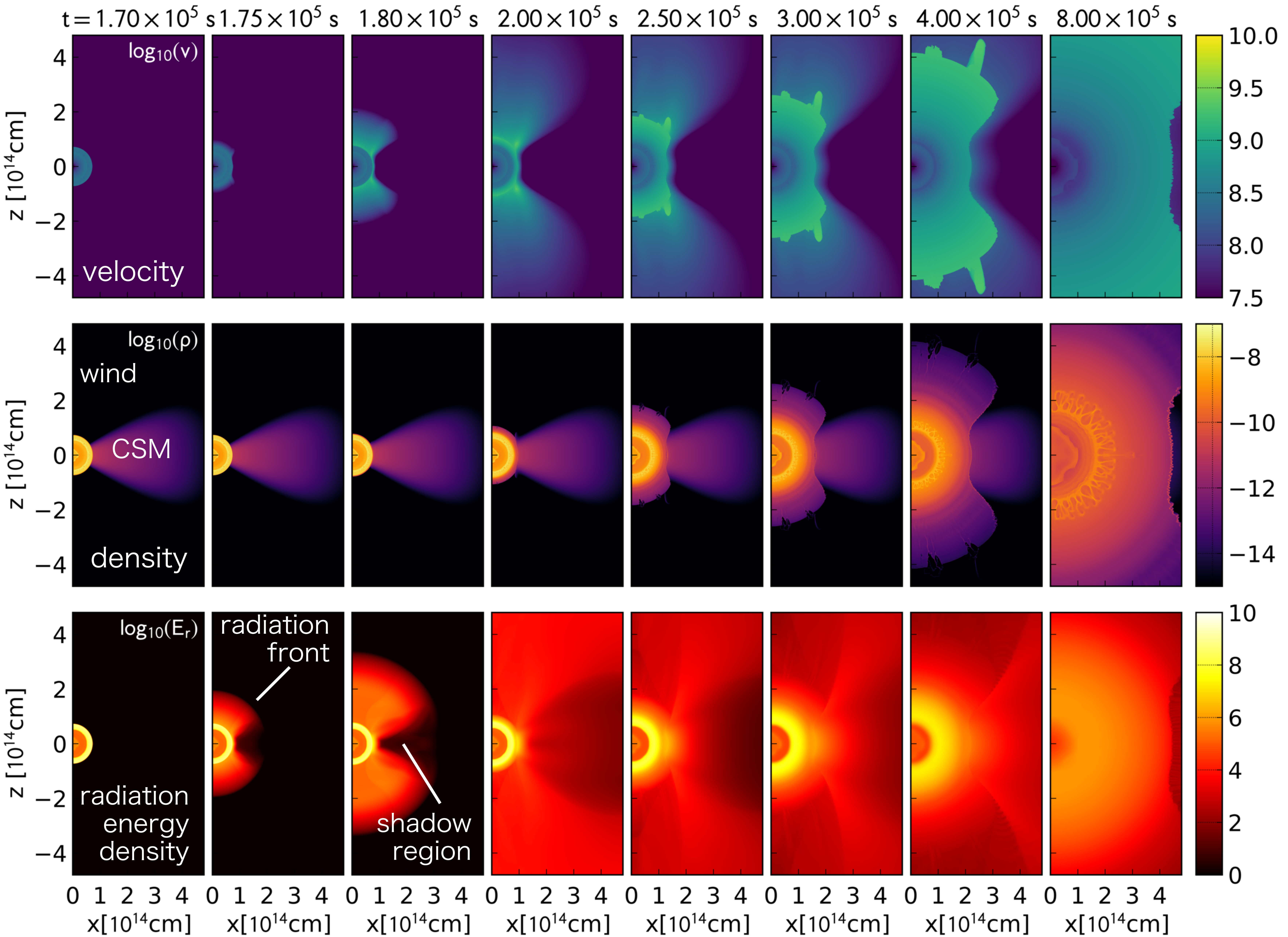


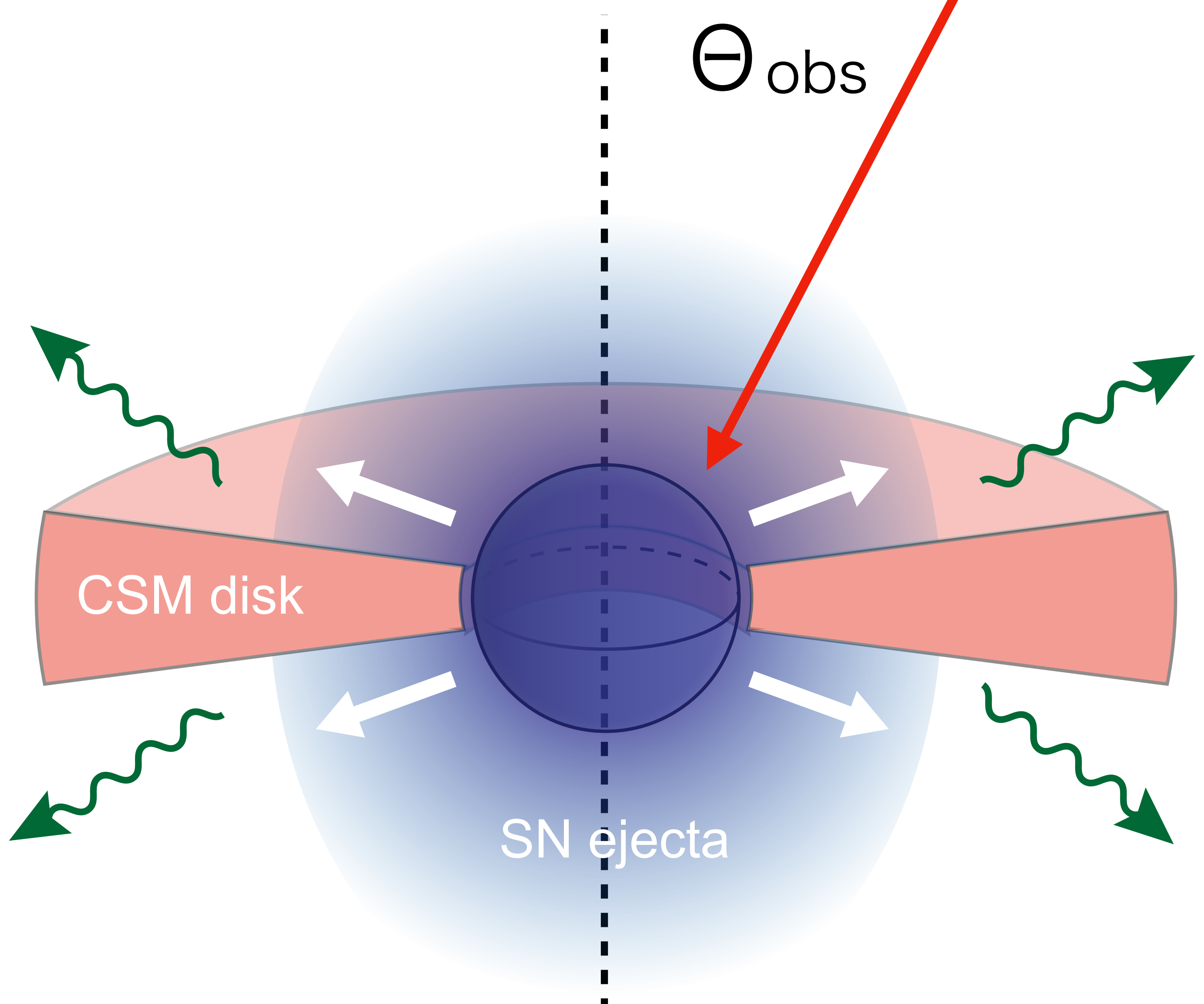
Disk-like CSM model: hybrid shock breakout

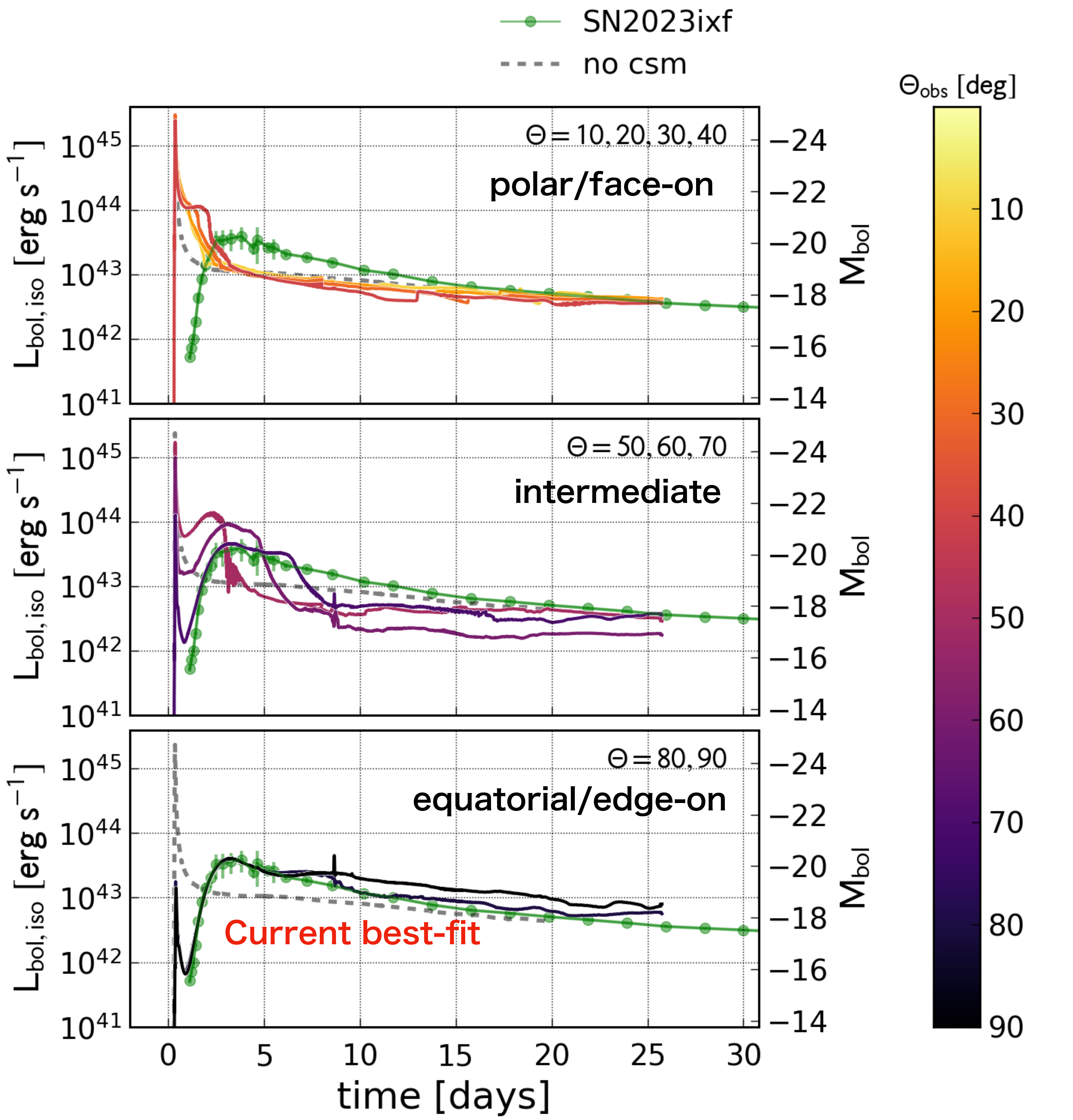
- $18M_{sun}$ RSG ($M_{presn}=12.6M_{sun}$)
- $E_{exp}=10^{51}$erg
- disk-like CSM with θ_{disk}=20deg
- $M_{csm,iso}=0.1M_{sun}$
- $R_{csm}=2\times10^{14}$cm



Disk-like CSM model: hybrid shock breakout

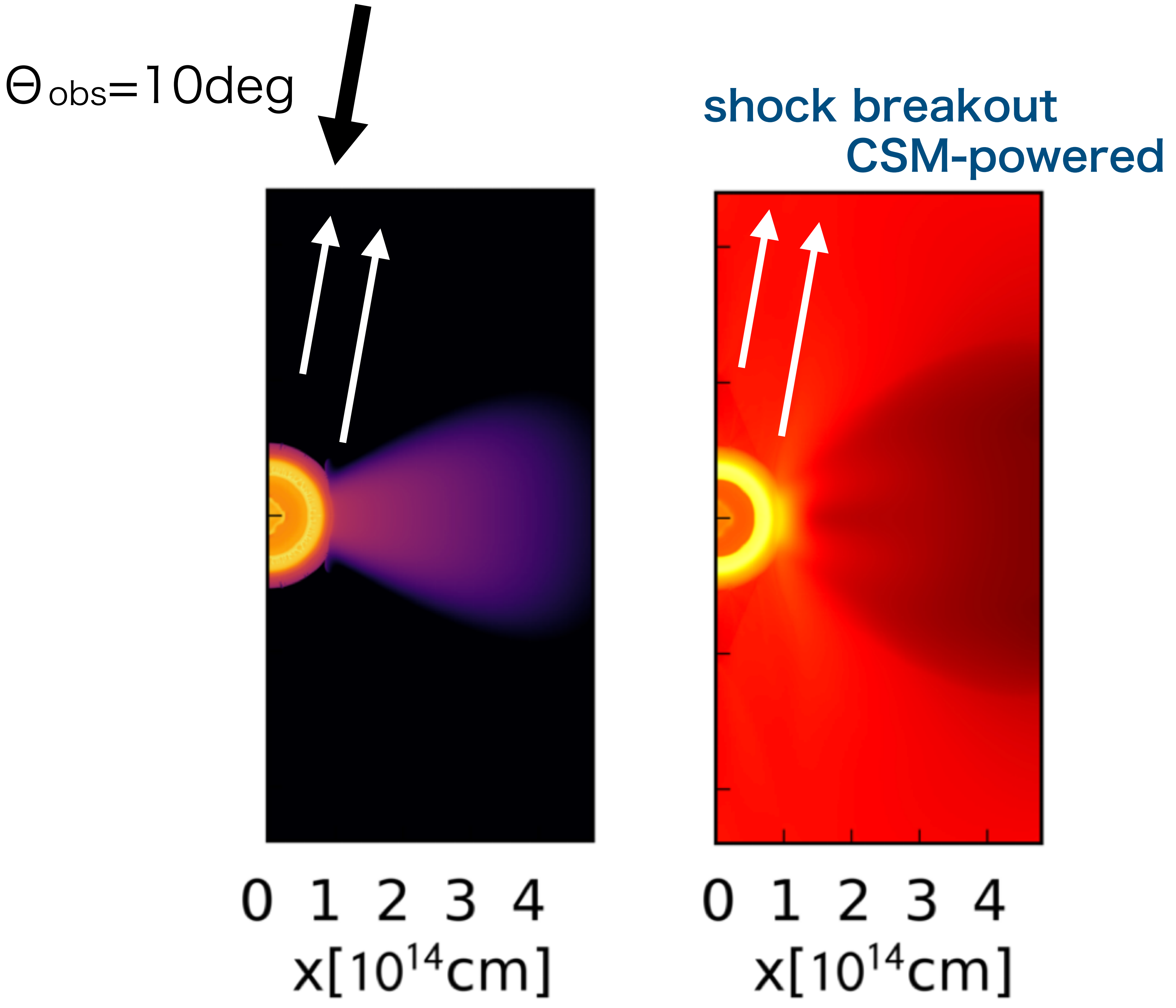
- LCs with viewing angles <40[deg]: shock breakout+ CSM-powered emission within a few days
- LCs with viewing angles of 80-90[deg] quite well explain the observed bolometric light curve.
- LCs with intermediate angles show more complex evolution

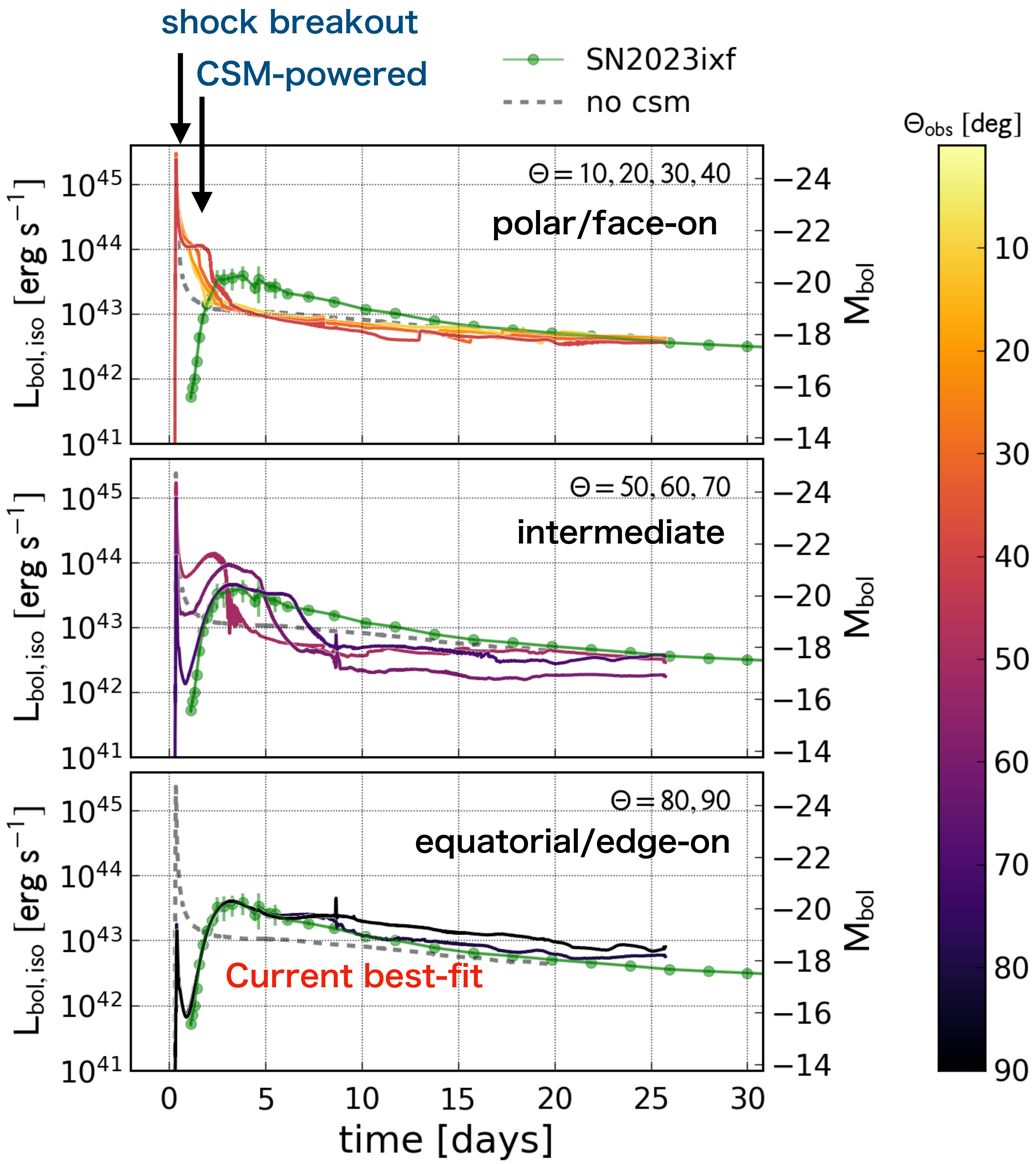




Disk-like CSM model: hybrid shock breakout

- Even around the symmetry axis, CSM-powered emission can be observed.
- Thermal photons initially diffuse up and down (smaller optical depth than equator)

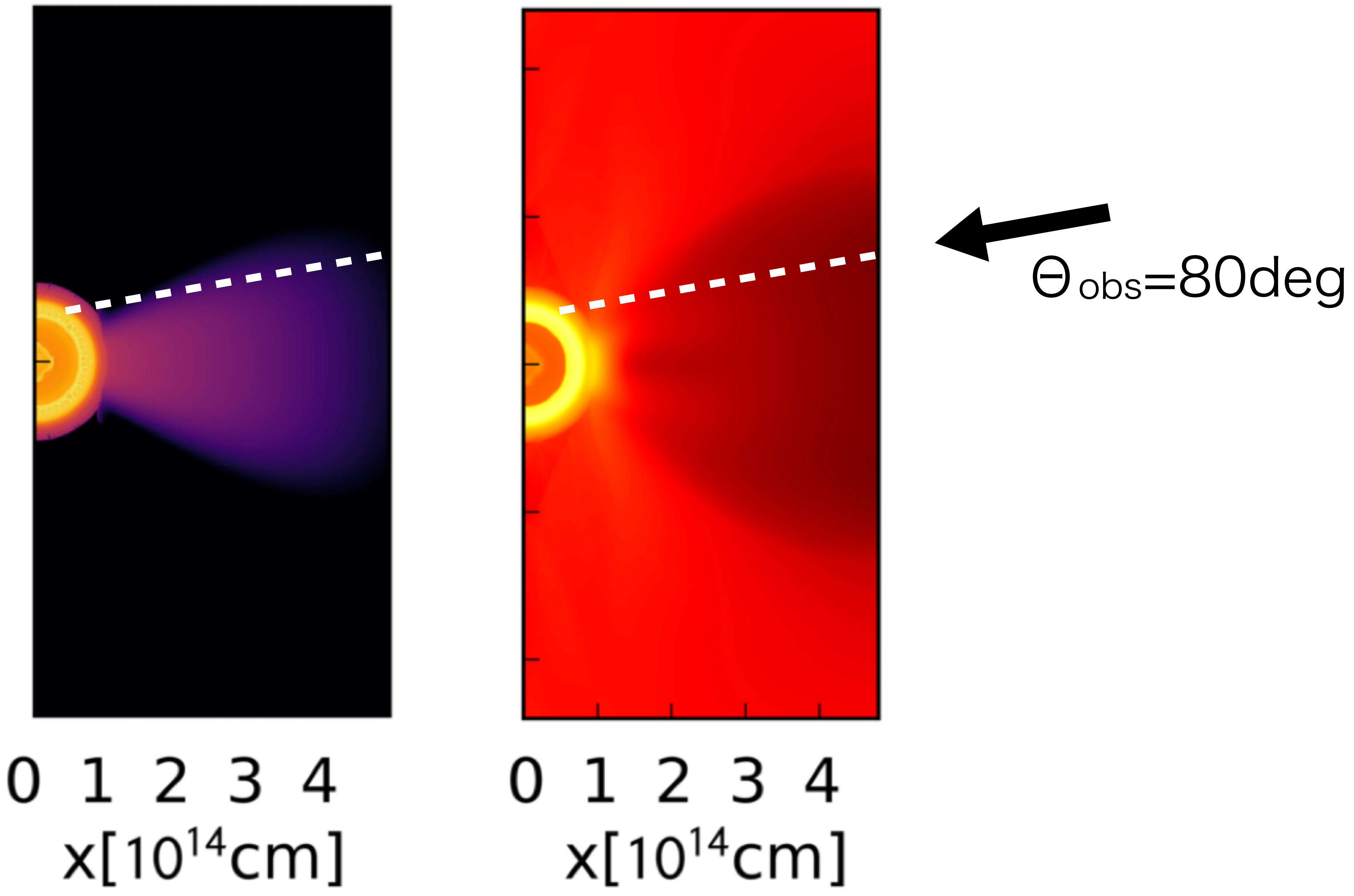




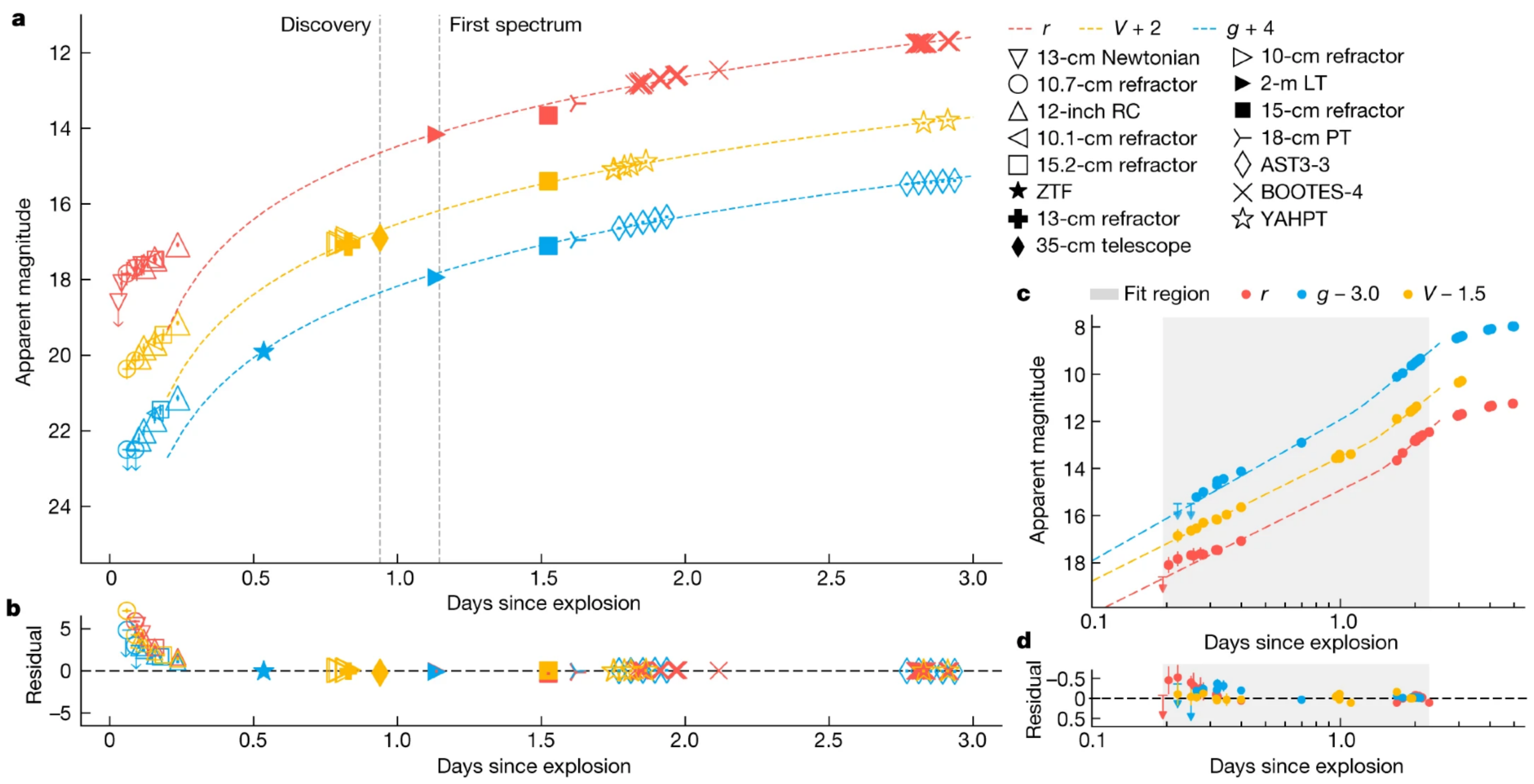
Disk-like CSM model: hybrid shock breakout

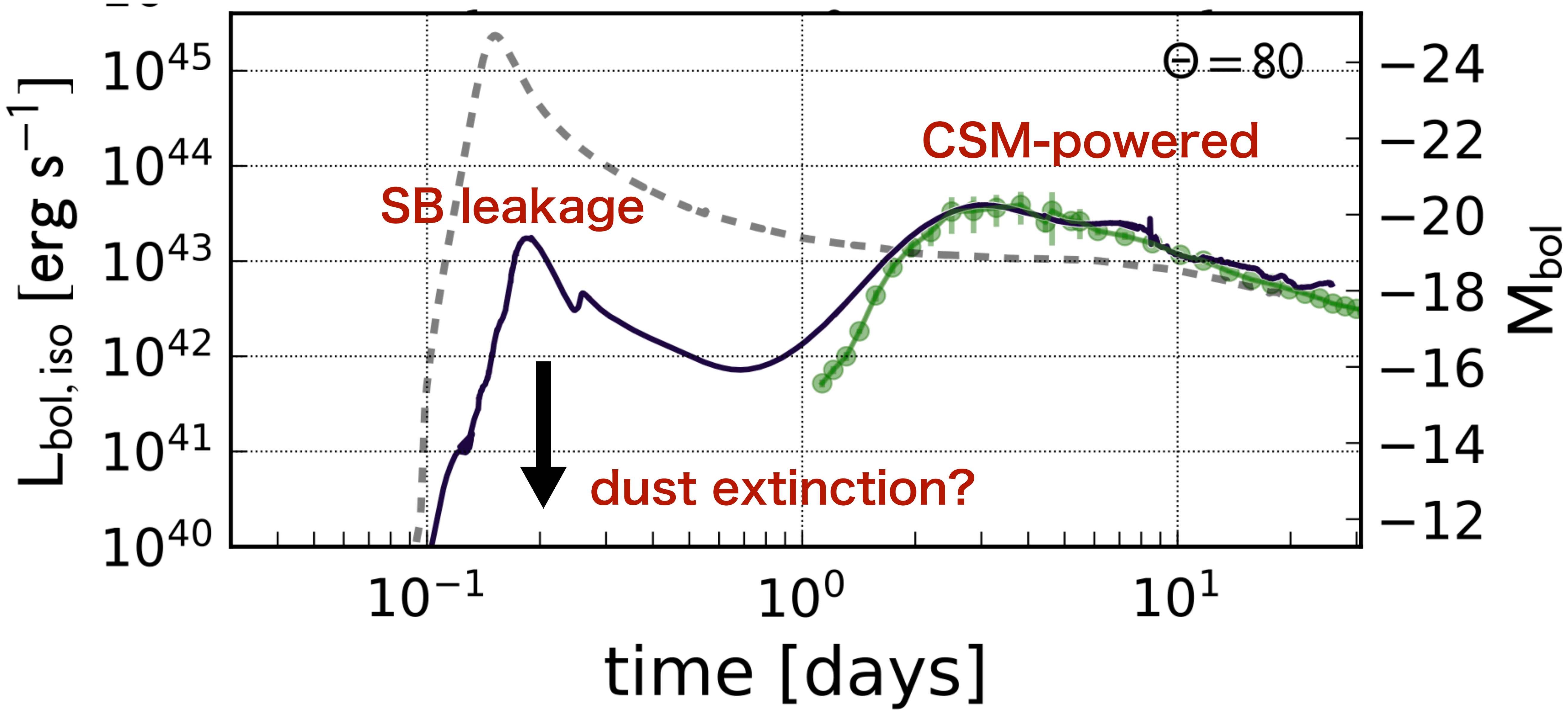
- SB emission is difficult to hide even through the equatorial plane
- dust extinction?

work still in progress!



Early multi-band light curve of SN 2023ixf (Li+2024)





Disk-like CSM model: hybrid shock breakout

- maximum velocity still exceeds 15,000 [km/s] along 50 [deg]
- 15,000xcos(30°)~13,000[km/s]

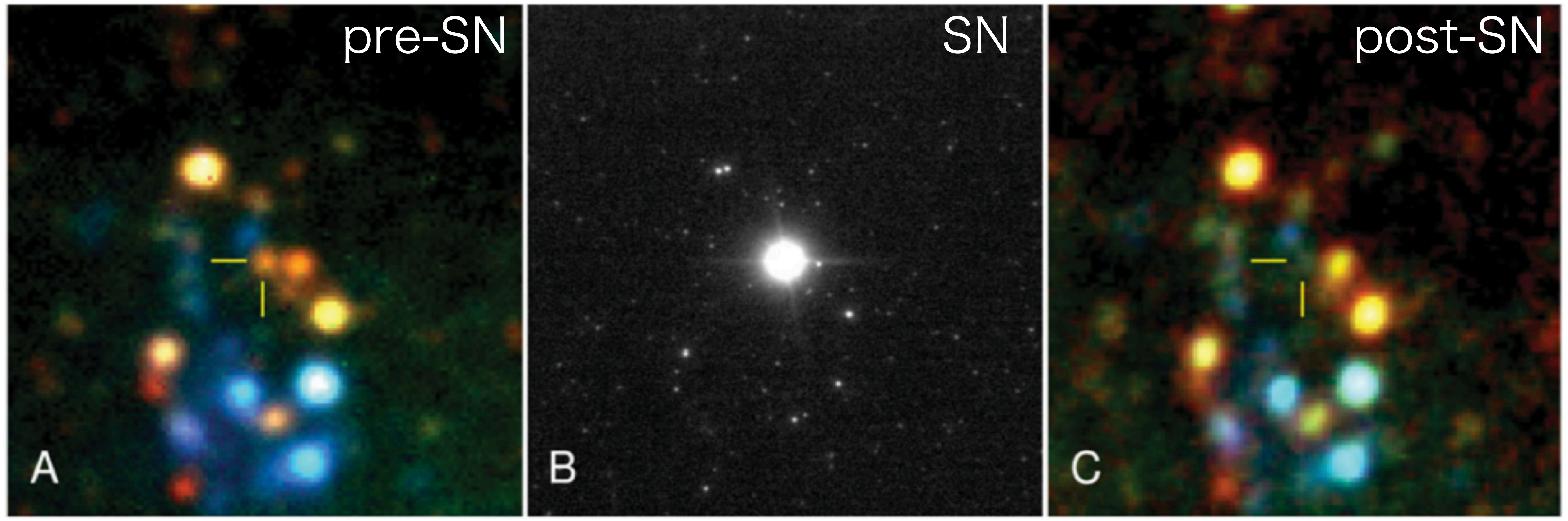
- Introduction
- Evolution of exploding massive stars
- Early emission and past/recent observations
- **Progenitor and pre-supernova activities**
- Summary

Pre-supernova image

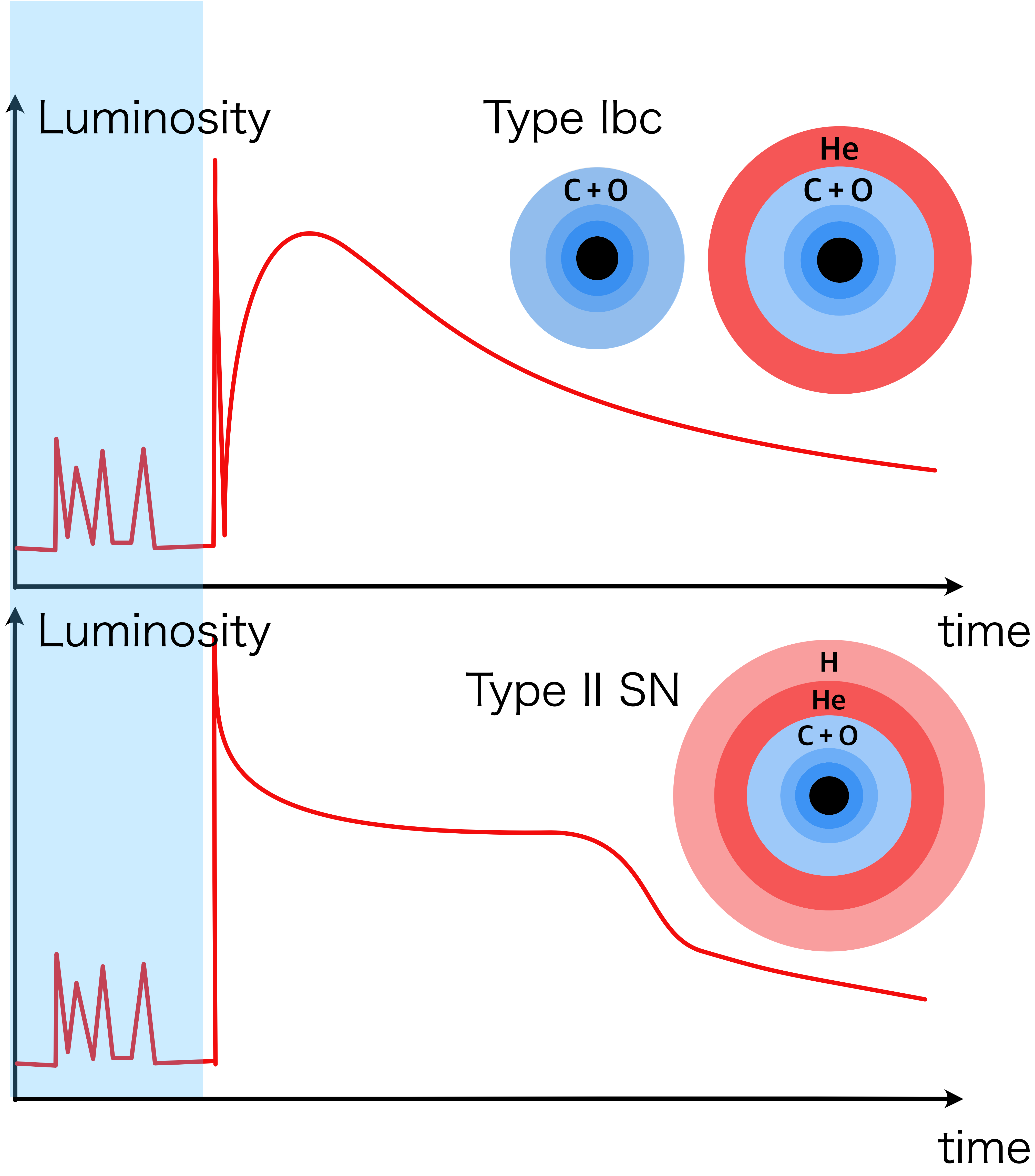
- **pre-supernova image**: check archival data(HST, etc) to see if the pre-explosion star is resolved.
  → progenitor luminosity function/mass distribution

- **pre-supernova activity**: check any possible variability/non-variability of the pre-explosion stars in previous transient surveys

Type IIP SN2008bkのpre-SN, SN, post-SN imageとspectrum (Smartt 2015)



Pre-supernova image
Pre-supernova activity



Pre-supernova image

- ~20-30 Type IIP SN progenitors
- ZAMS mass estimate from evolutionary tracks in HR diagram
- M_{low}~9.5M_{sun}, M_{high}~16.5M_{sun} for Salpeter IMF? (Smartt 2015)
- On the other hand, nearby star-forming galaxies host ~25M_{sun} RSGs…? (RSG problem)

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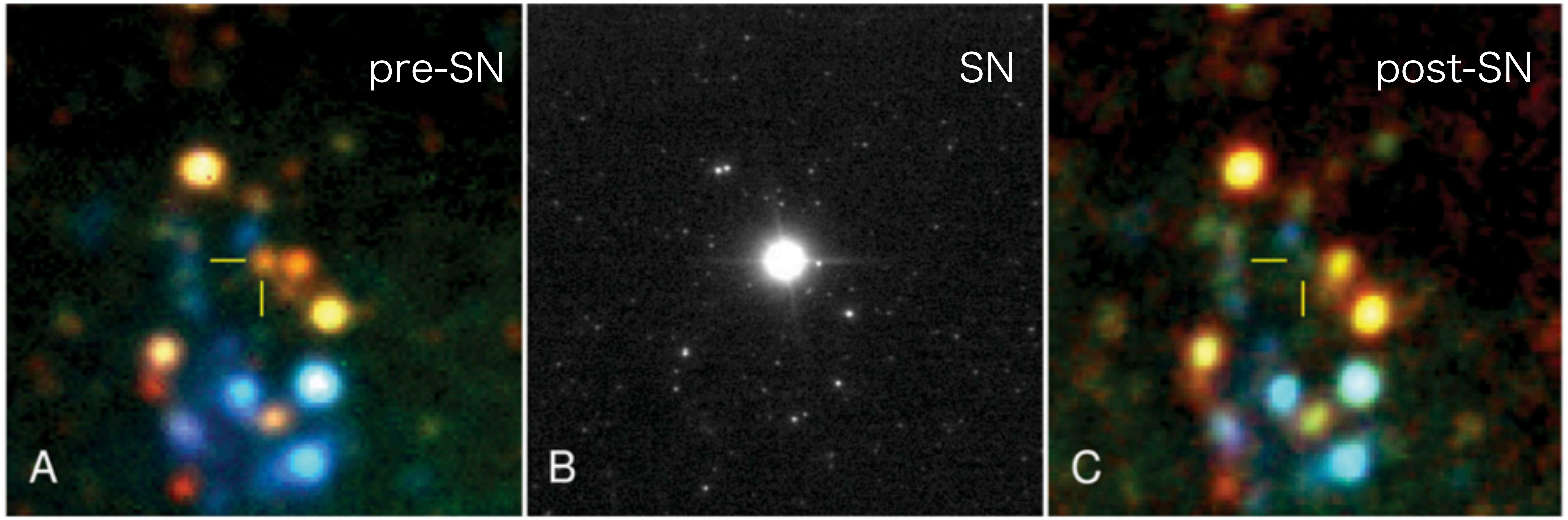

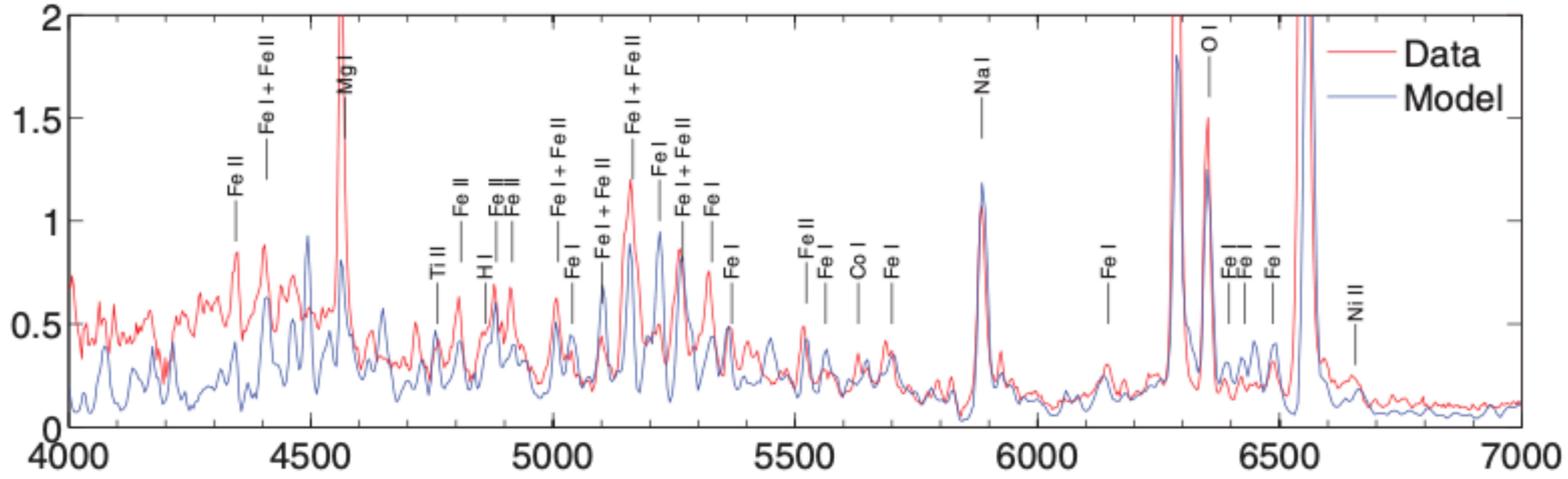

SN progenitors from pre-supernova images, Smartt (2015)

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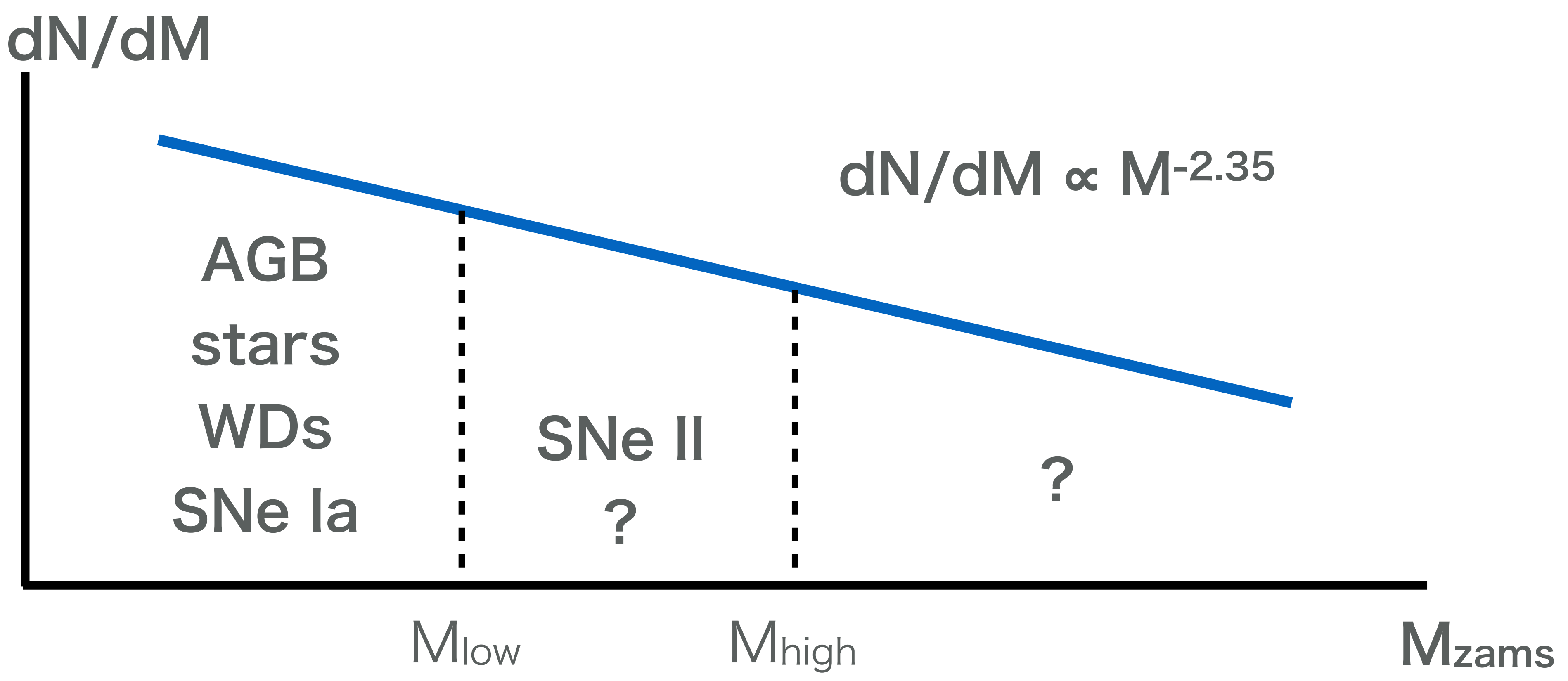

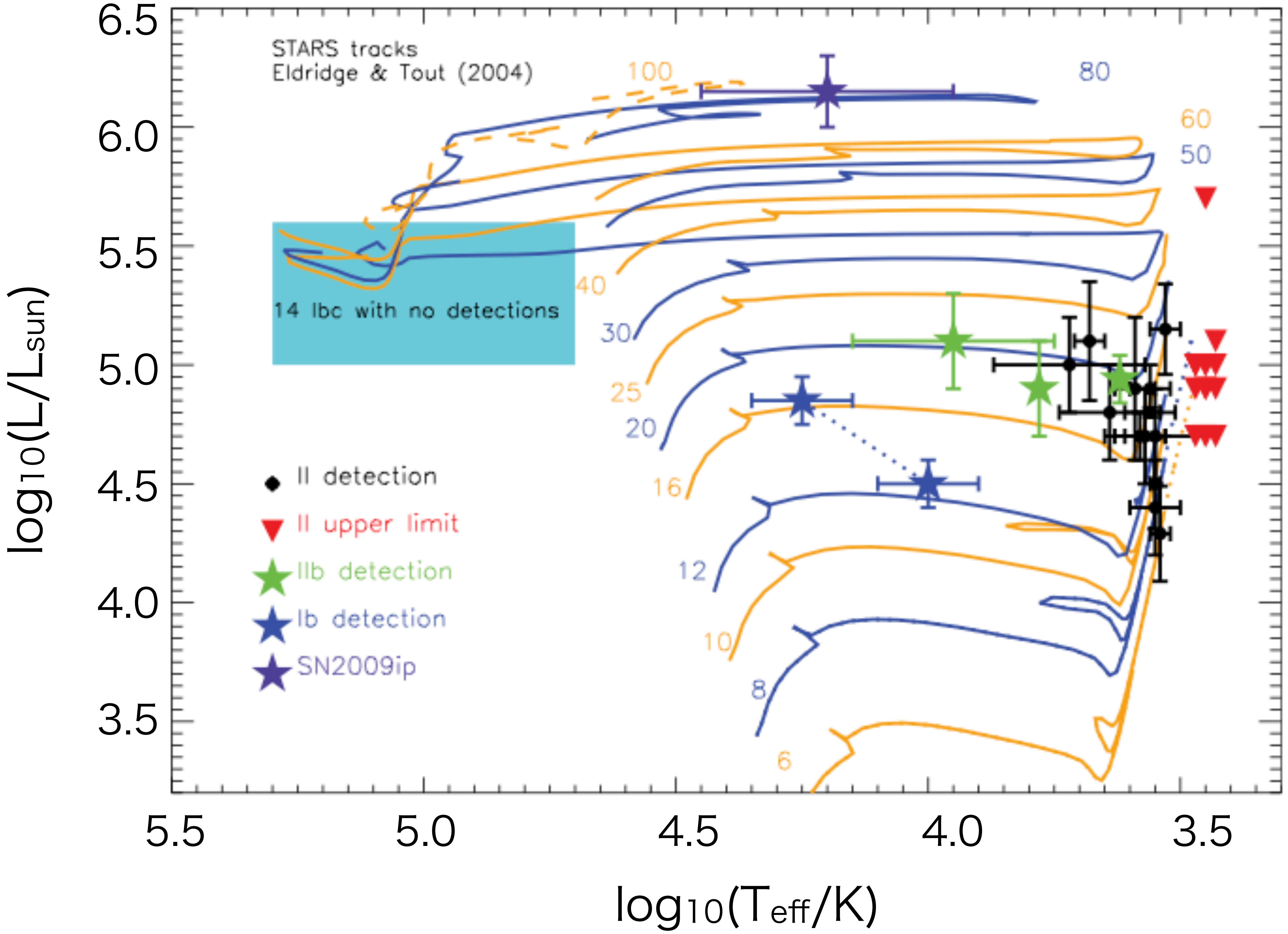

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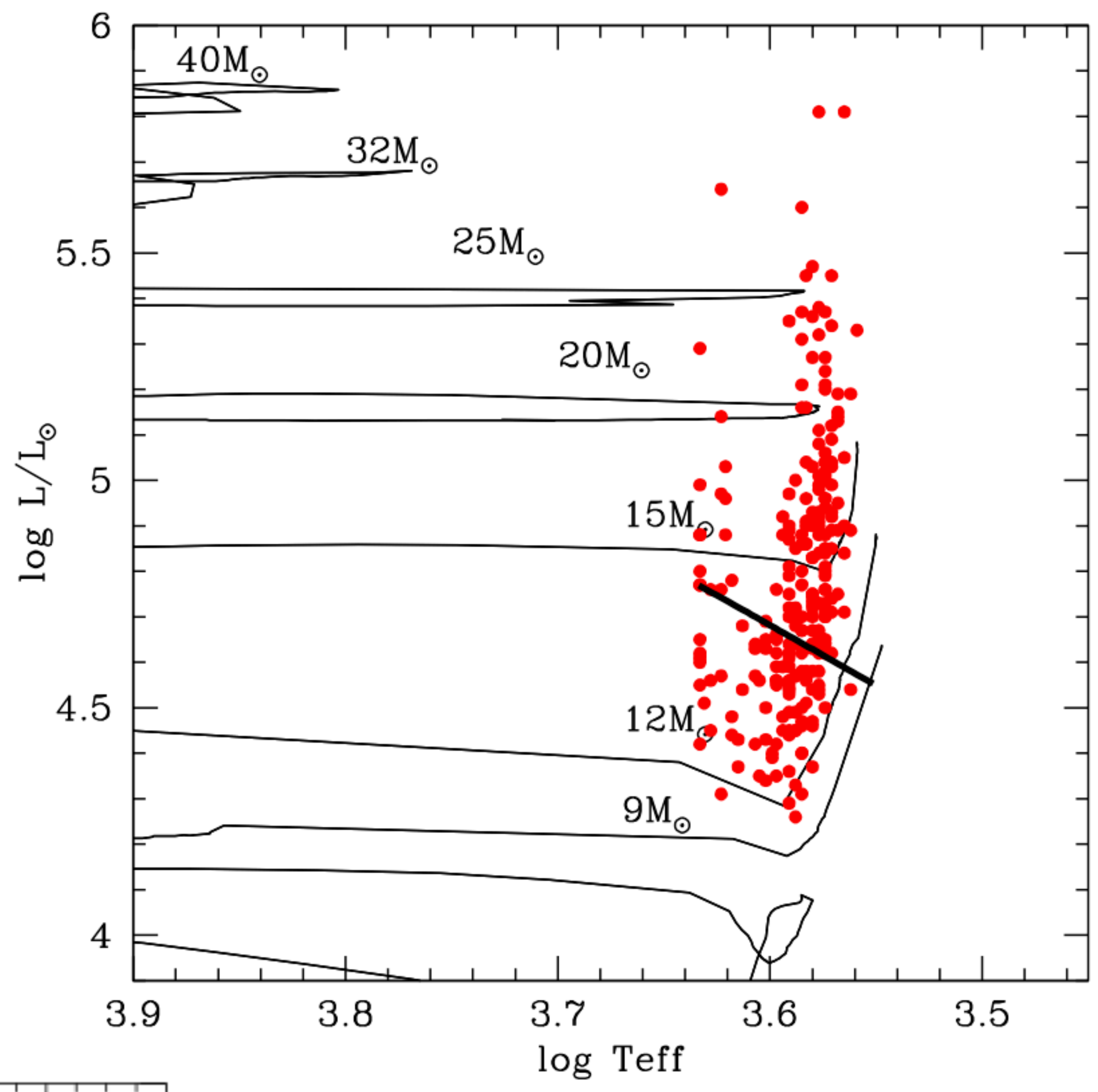
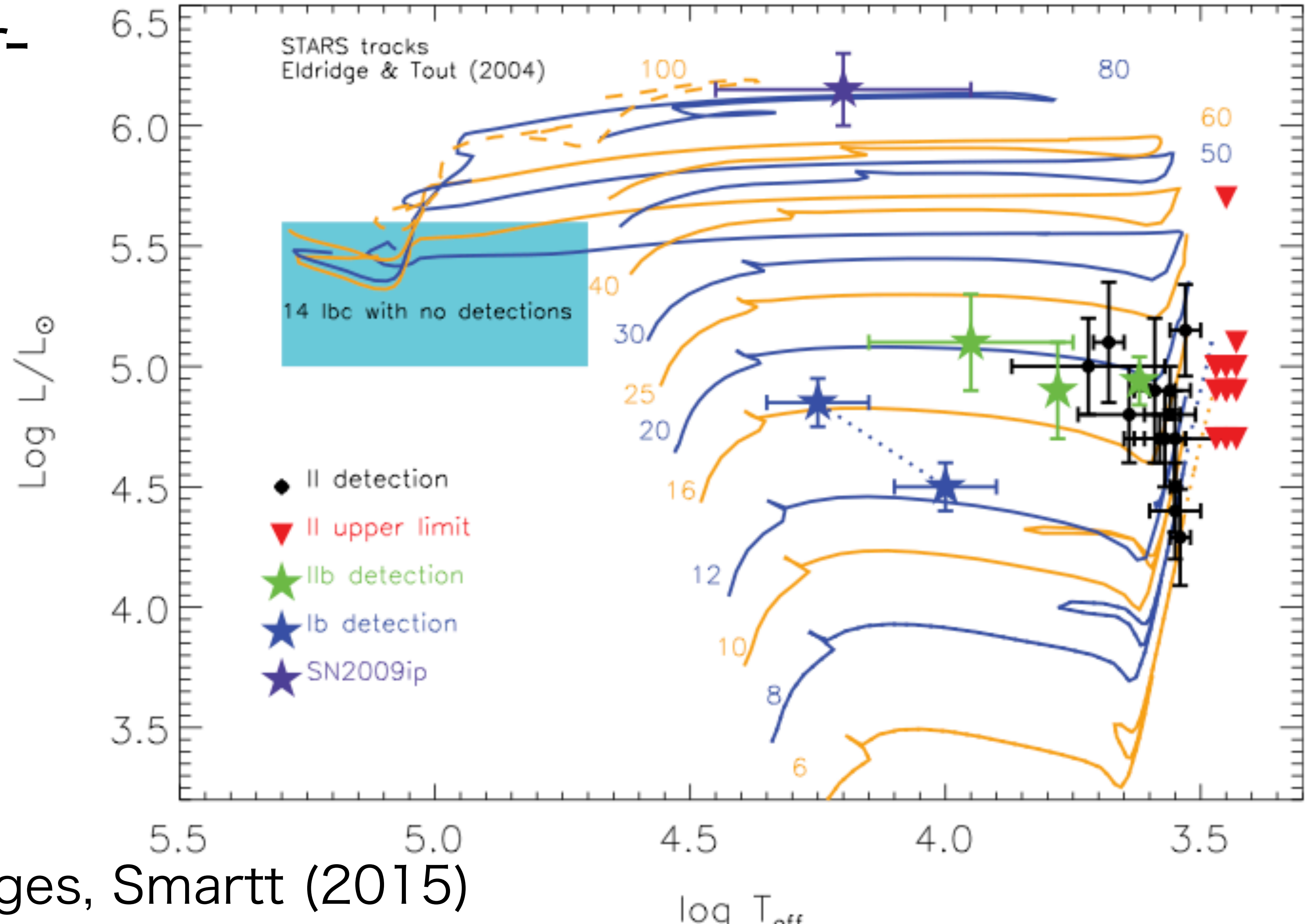
RSG population in M31, Neugent+(2020)





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Pre-supernova activity

- What is the mechanism of pre-SN mass-loss?
- wave-driven? binary interaction?
- there should be some activity in pre-SN stage (**SN precursor**)
- unbiased transient surveys gradually make it feasible to directly observe massive stars in their pre-SN stages
- future JWST detections are expected

SN 2009ip, Maruerhan+ (2013a)

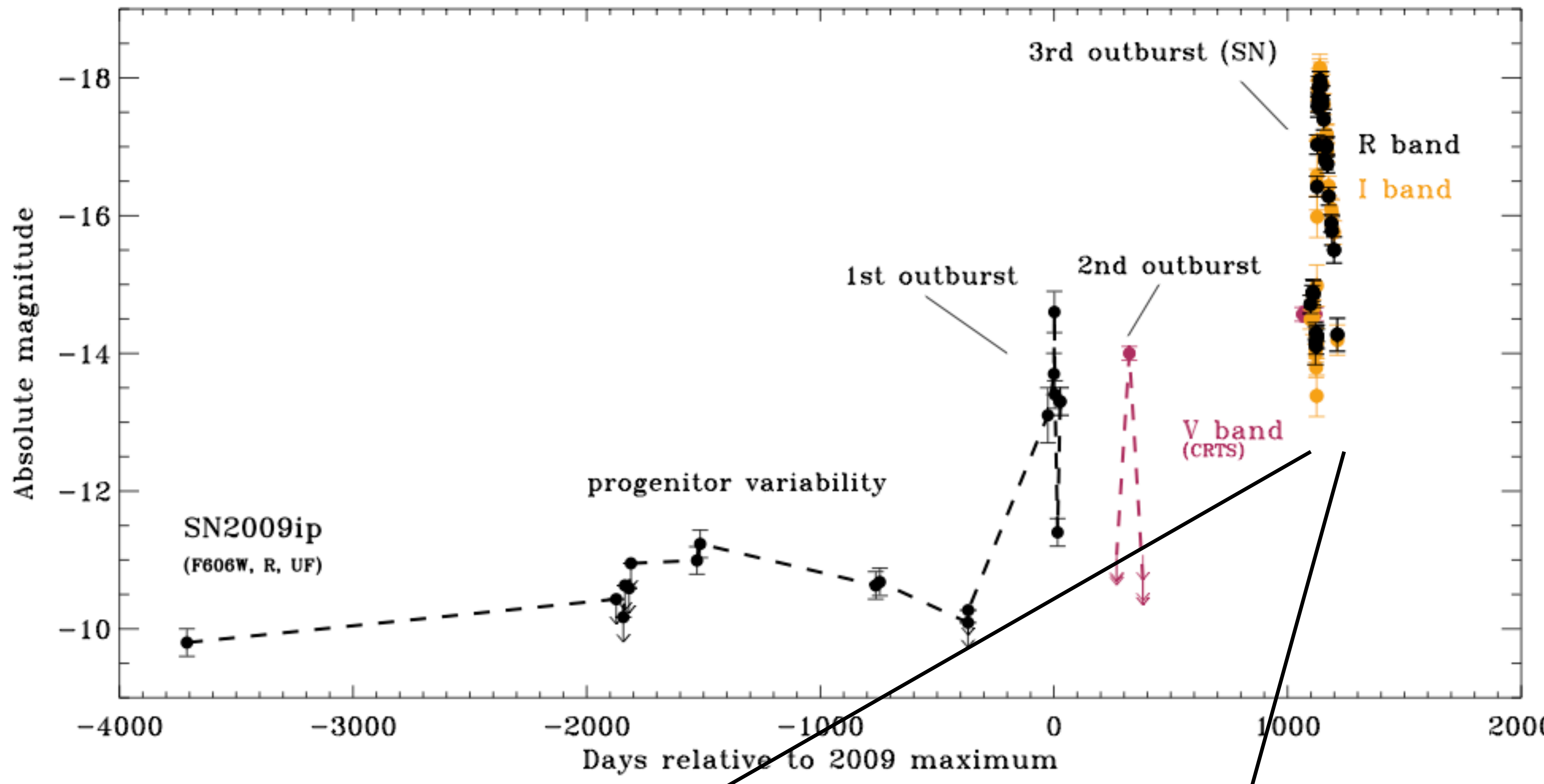
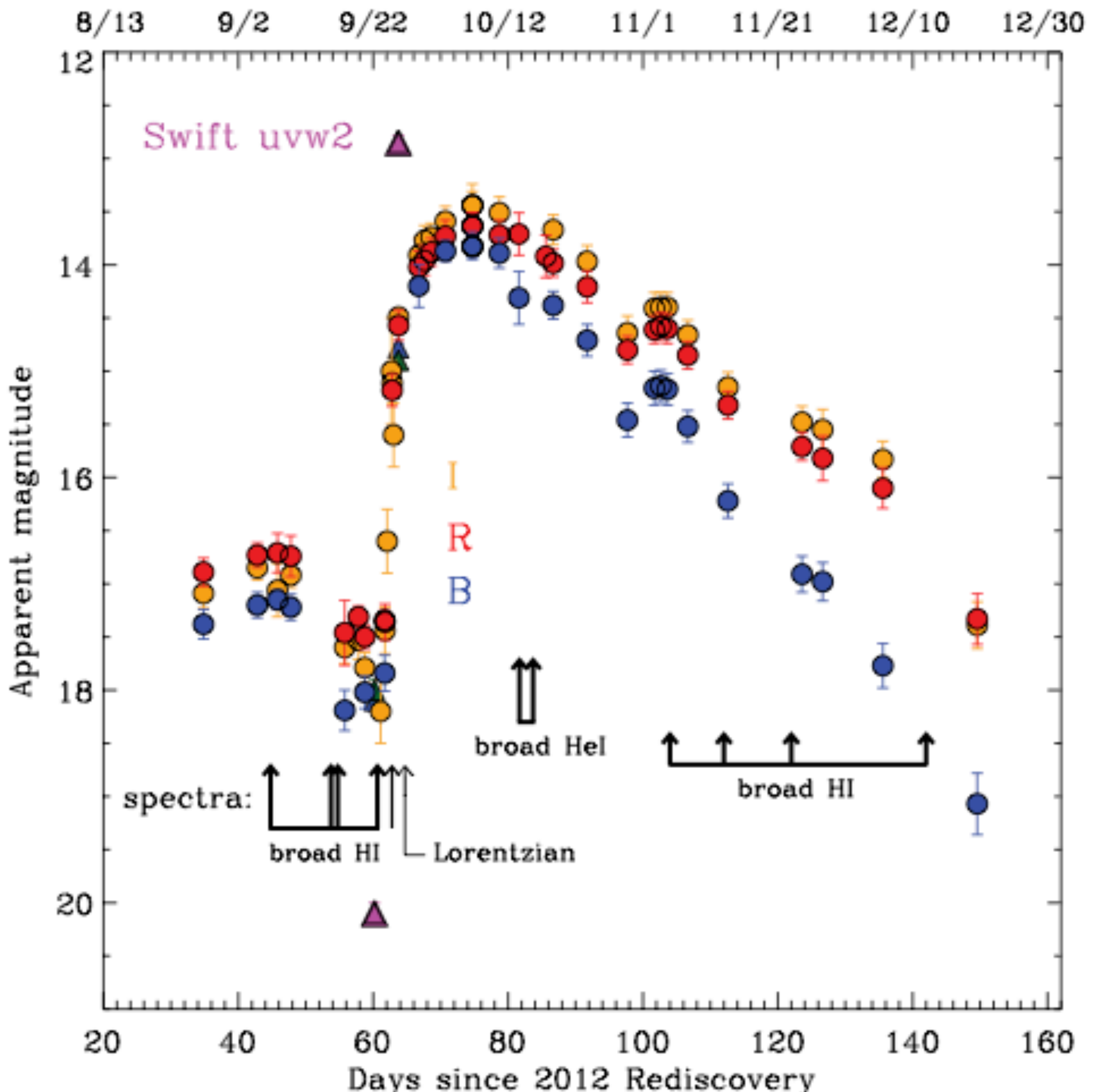


Figure 3. Absolute magnitude light curve of SN 2009ip, including archival *HST* data, and the ground-based *V*, *R*, *I* and unfiltered photometry (see Smith et al. 2010b).



Pre-supernova activity

H-rich SN 2020tlf, Jacobs-Galan+ (2022)

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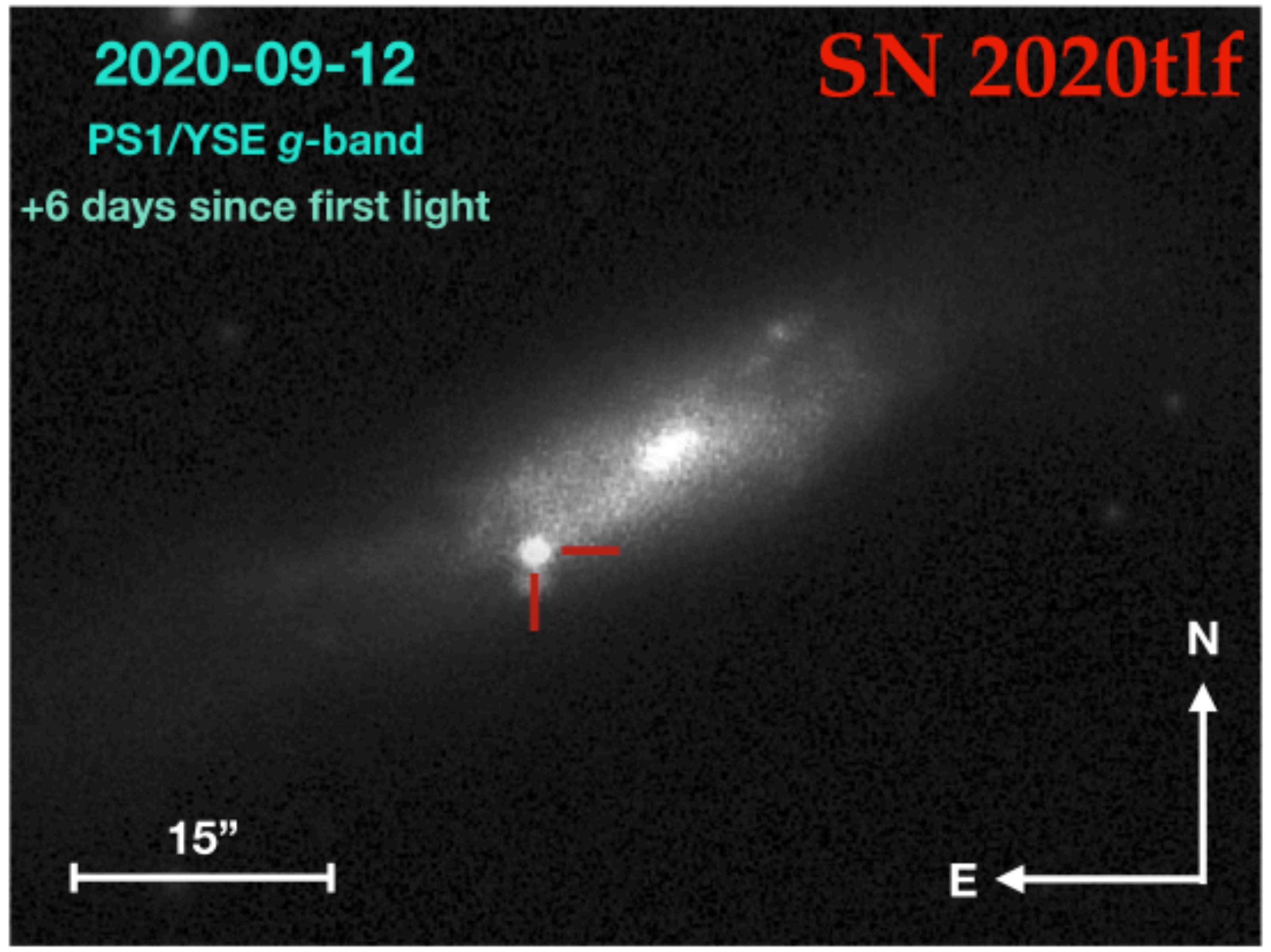

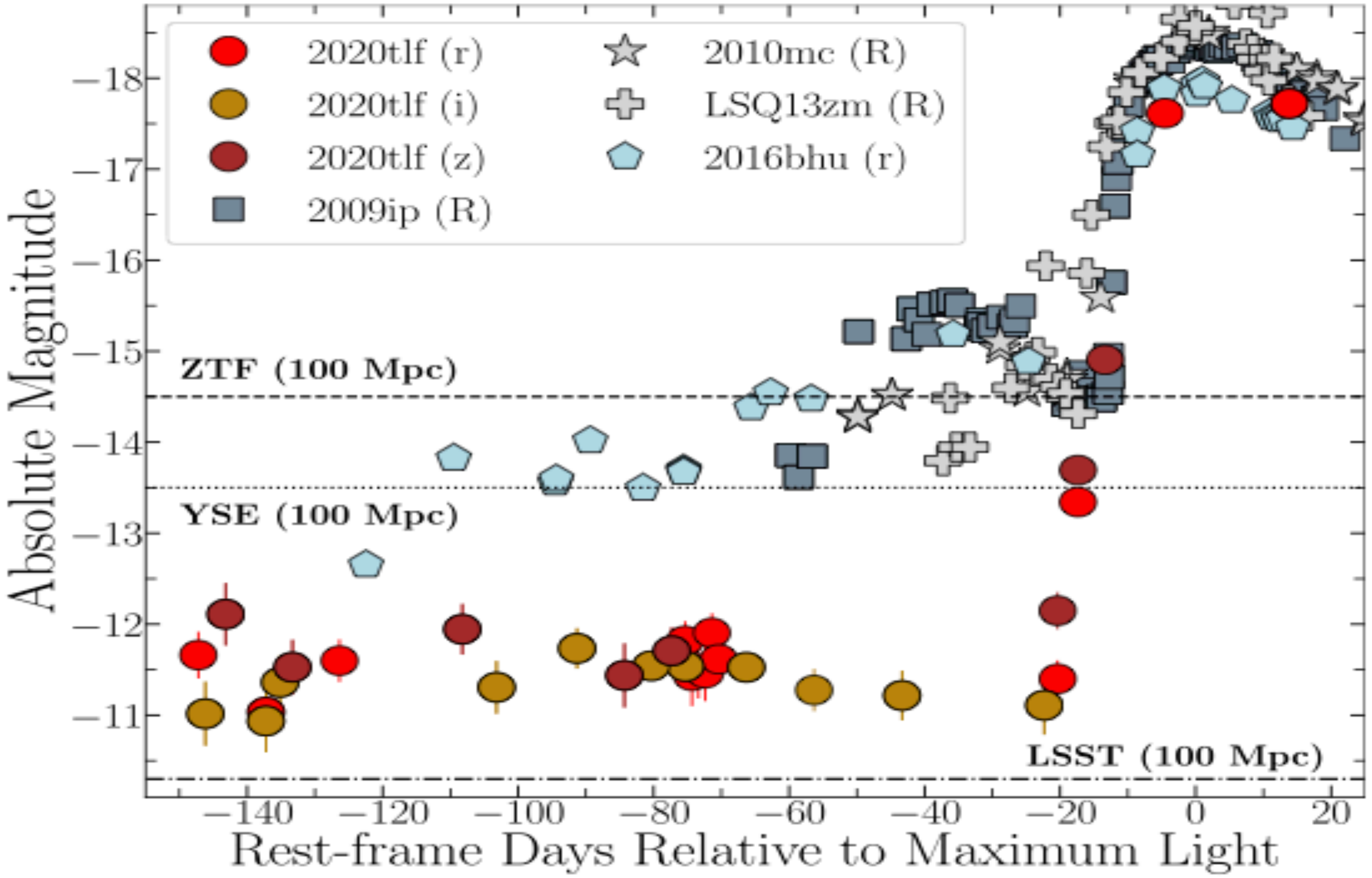

SN 2023ixf progenitor?

- Kilpatrick+: $\log_{10}(L/L_{sun})=4.74\pm0.07$, $T_{eff}=3920^{+200}_{-160}$K
- Jencson+: $\log_{10}(L/L_{sun})=5.1\pm0.2$, $T_{eff}=3500^{+800}_{-1400}$K (GRAMS)
- Niu+: $\log_{10}(L/L_{sun})=5.11$, $T_{eff}\sim3700$K (C-rich dust)
- Soraisam+: $\log_{10}(L/L_{sun})=5.2$-5.4 (P-L relation)
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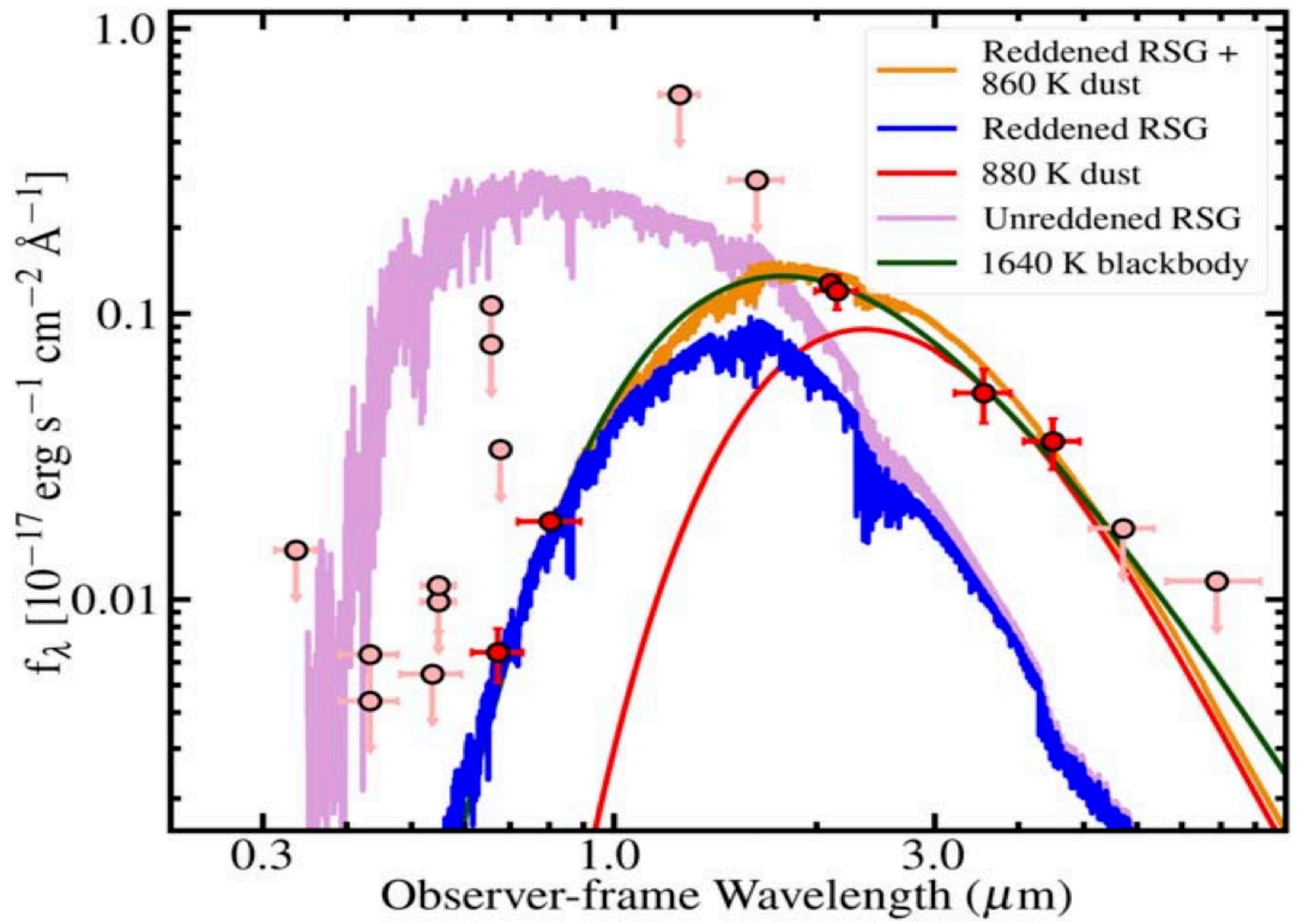
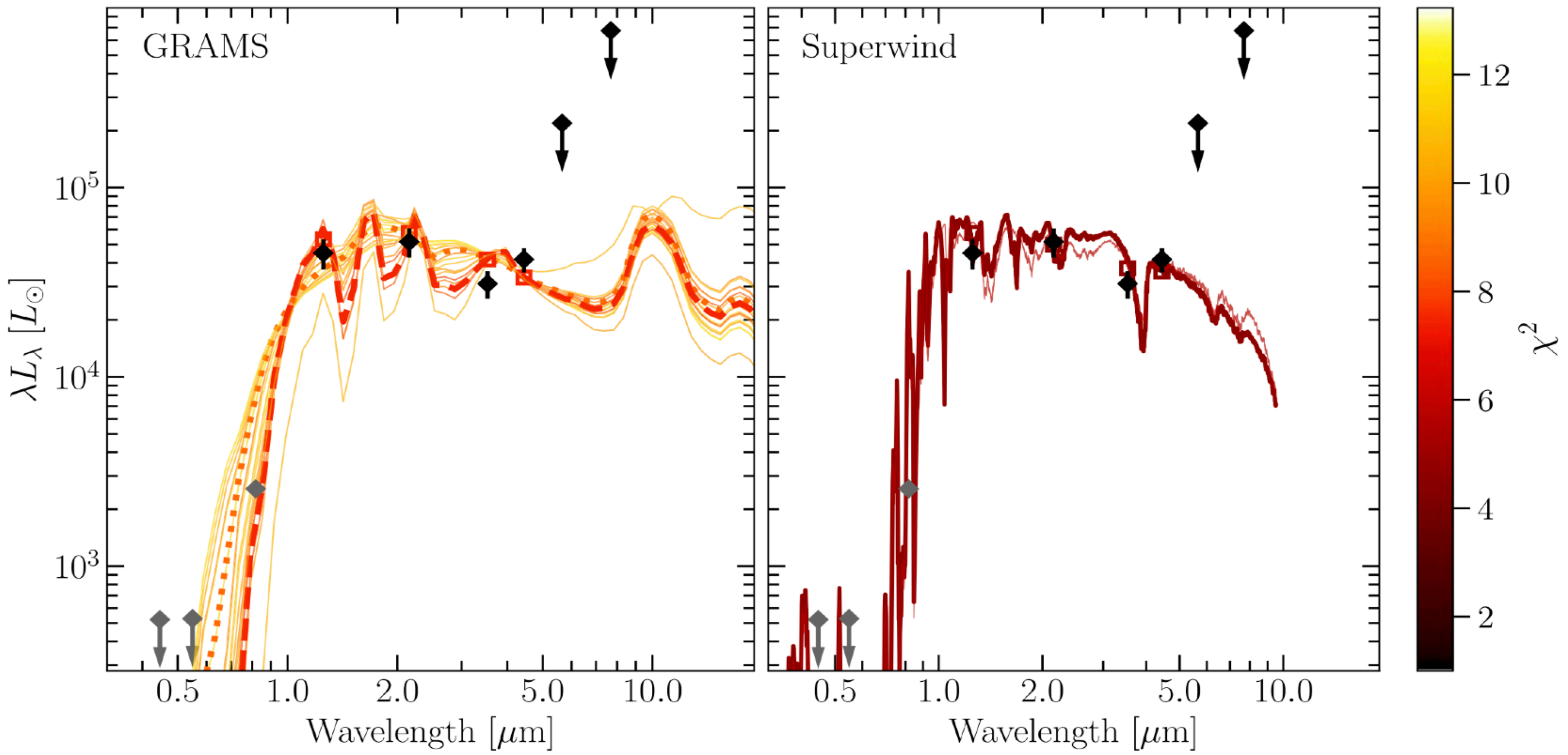
- Qin+: $\log10(L/L_{sun})=5.10\pm0.02\pm0.11$(osc.), $T_{eff}=3343\pm27$K

Kilpatrick+2023[138]

https://ui.adsabs.harvard.edu/abs/2023ApJ...952L..23K





Jencson+2023

https://ui.adsabs.harvard.edu/abs/2023ApJ...952L..30J/abstract

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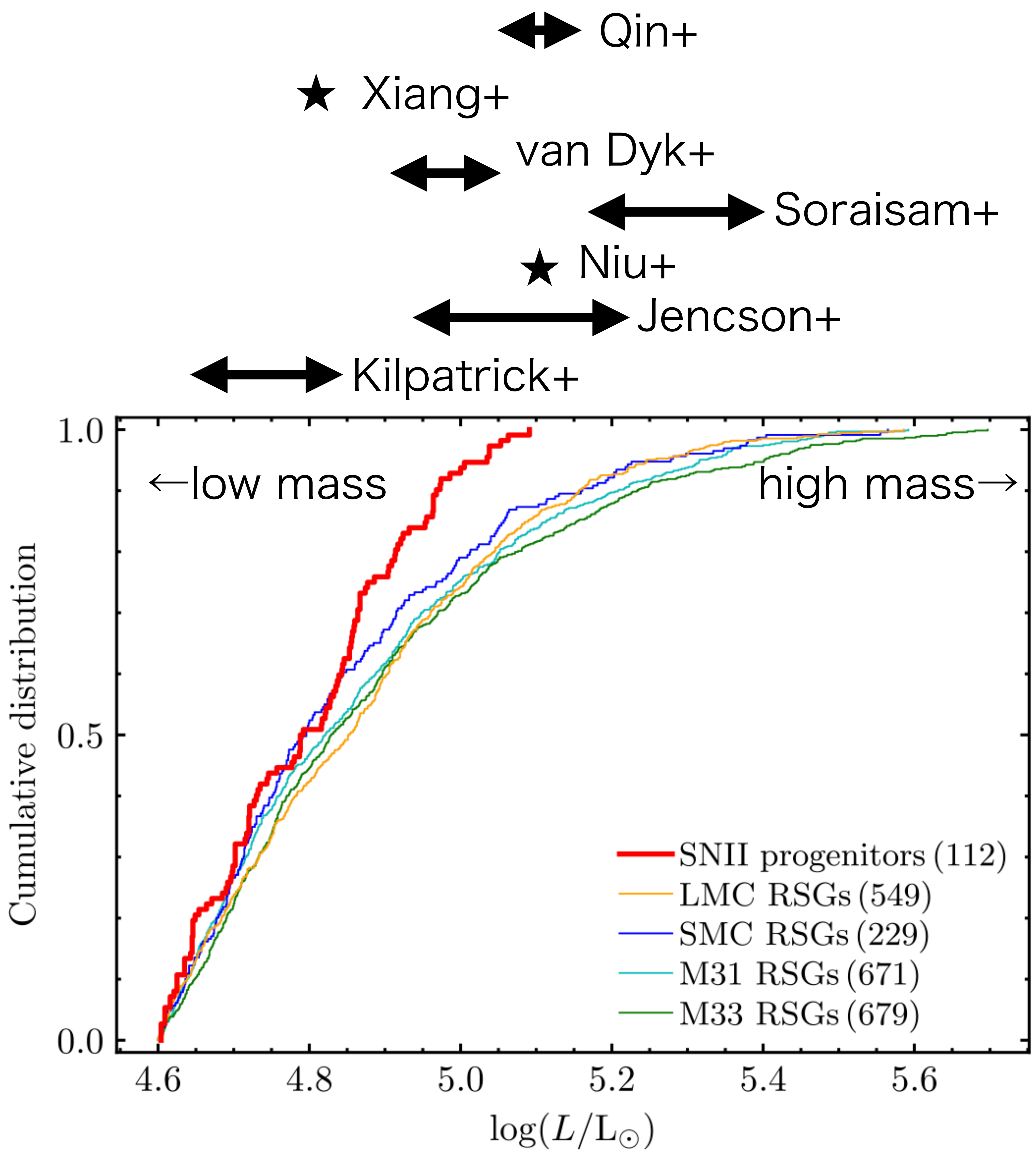

Progenitor or RSG luminosity

Rodriguez+2022, SN-IIP progenitor luminosity
https://ui.adsabs.harvard.edu/abs/2022MNRAS.515..897R/

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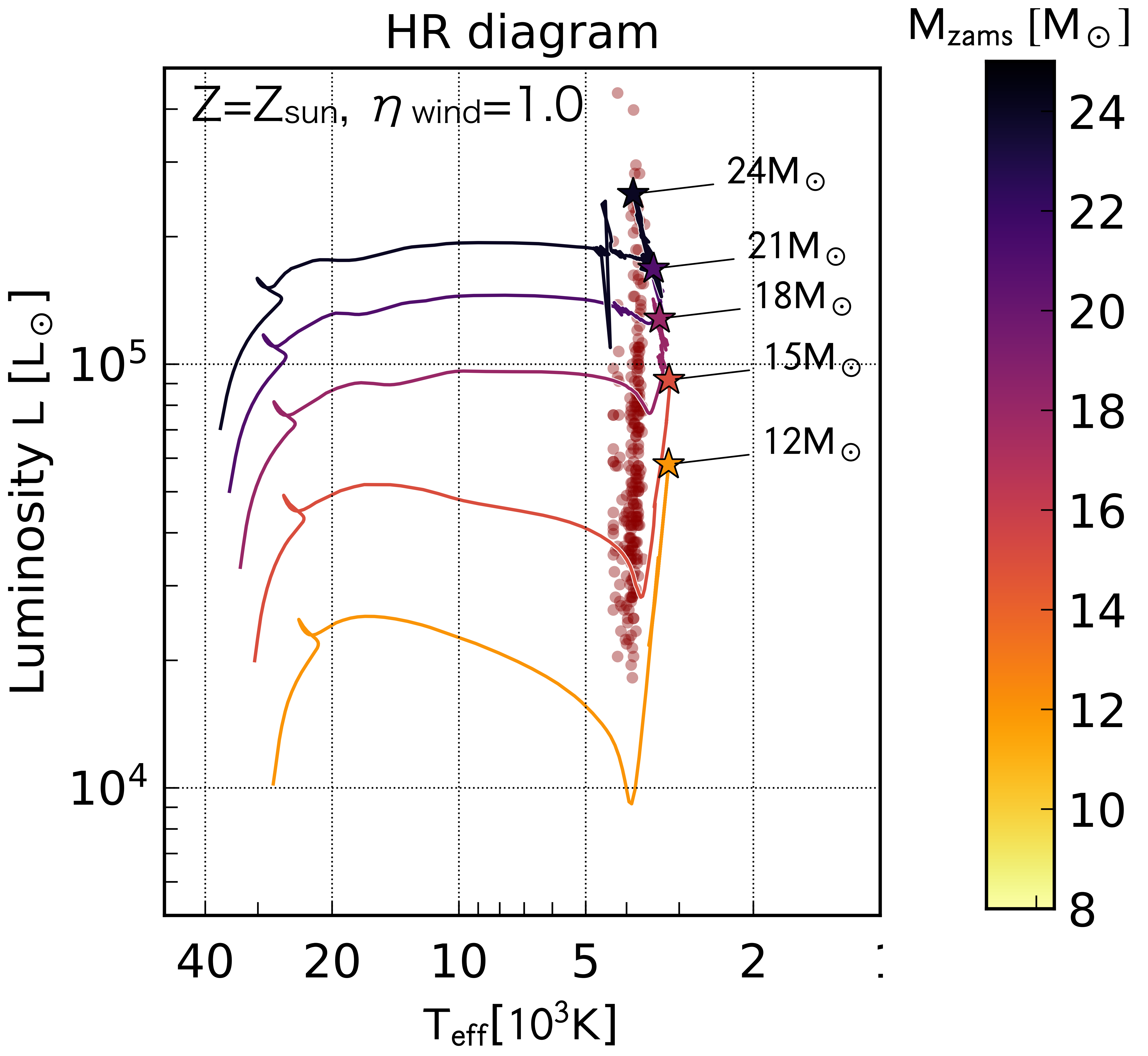
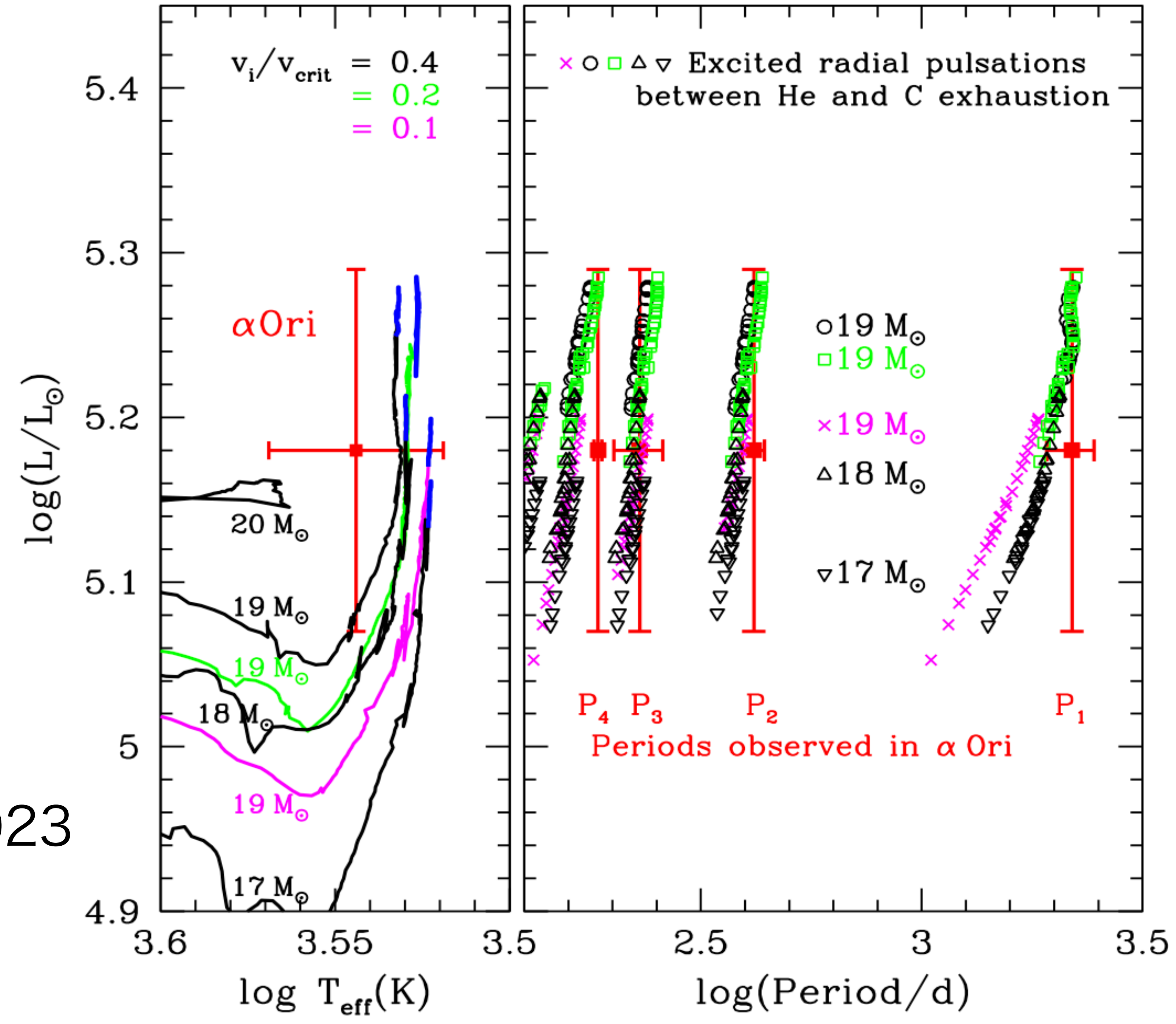


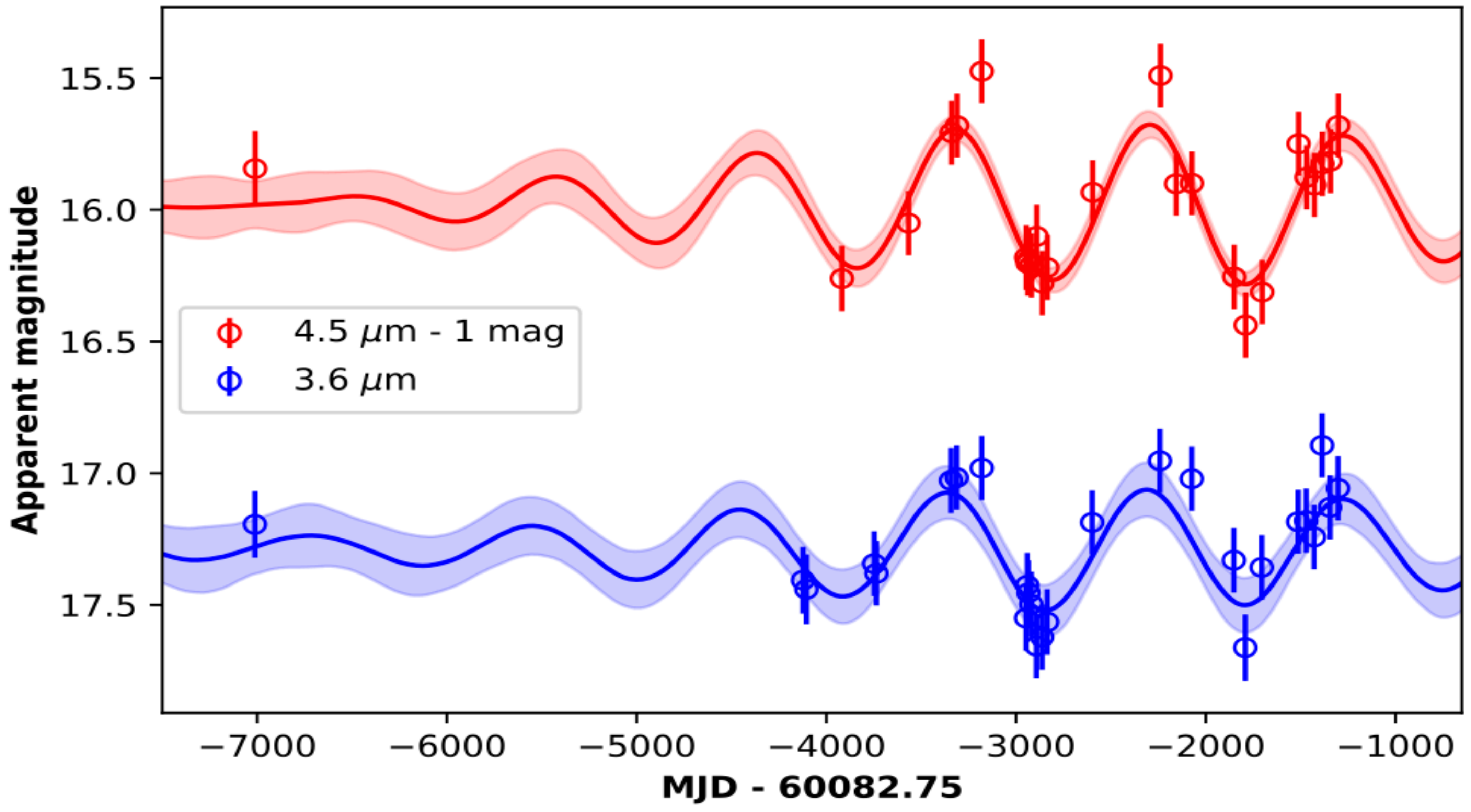
evolutionary tracks of M_{zams}=12-24M_{sun} stars and M31 RSGs(red circle)

SN 2023ixf progenitor?

- multi-epoch pre-SN photometry in infra-red (Spitzer space telescope)
- pulsation with P~1000days?
- massive RSGs are unstable to radial pulsation
- pulsation-driven mass-loss may play a role in RSG progenitor (Heger+1997, Yoon&Cantiello 2010)



Saio+2023



Soraisam+2023

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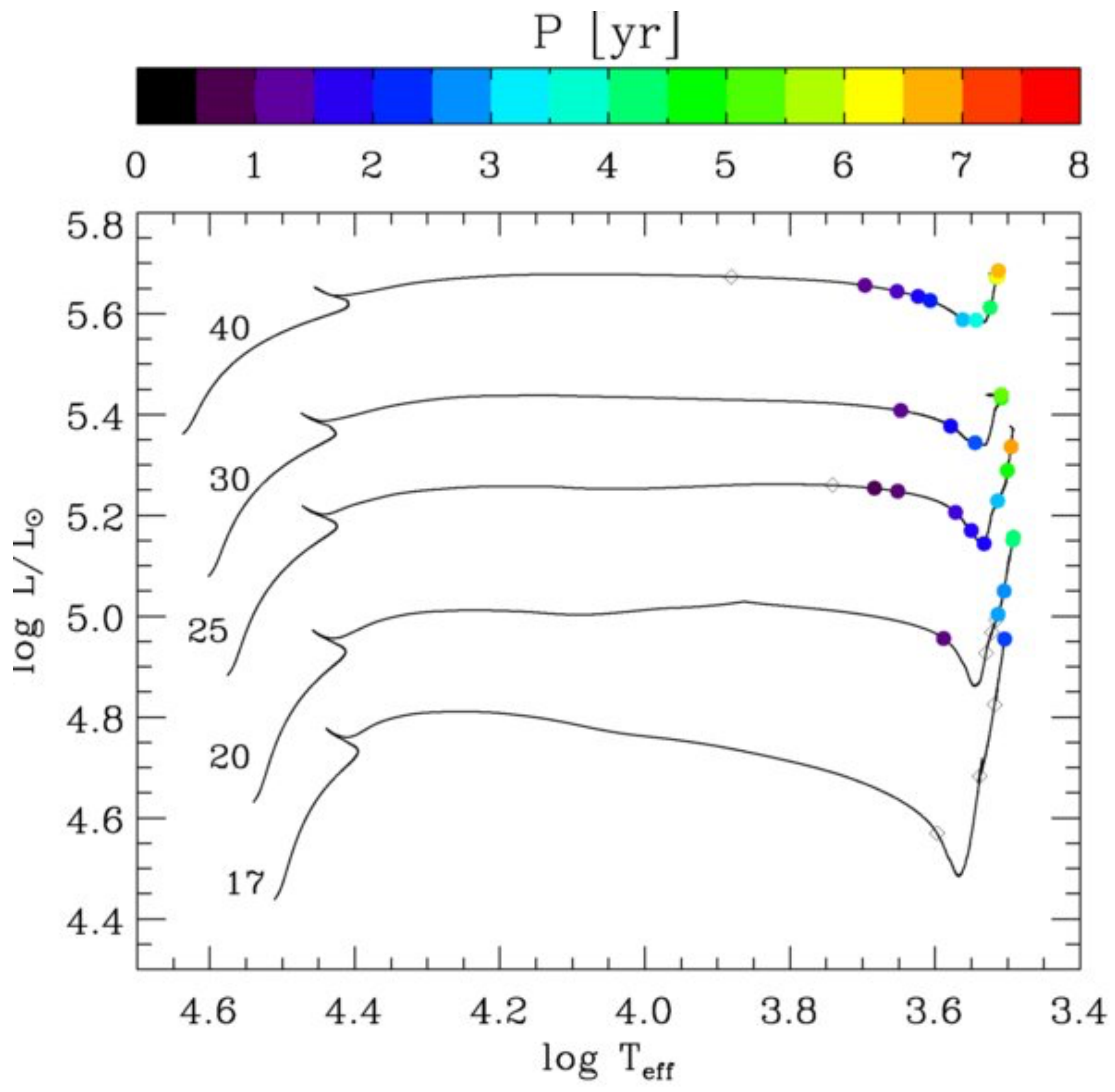
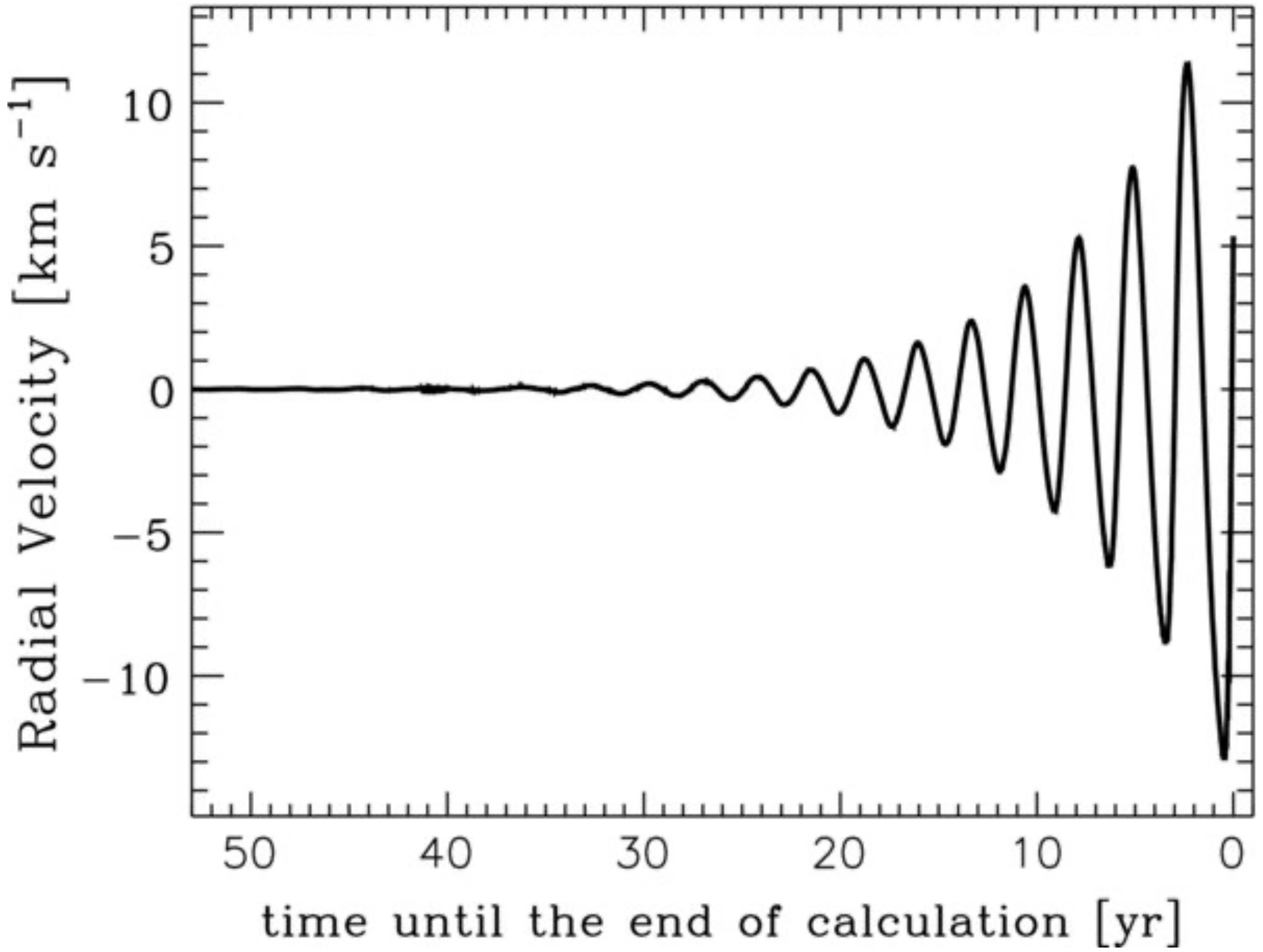
- pulsation with P~1000days?
- massive RSGs are unstable to radial pulsation
- pulsation-driven mass-loss may play a role in RSG progenitor (Heger+1997, Yoon&Cantiello 2010)



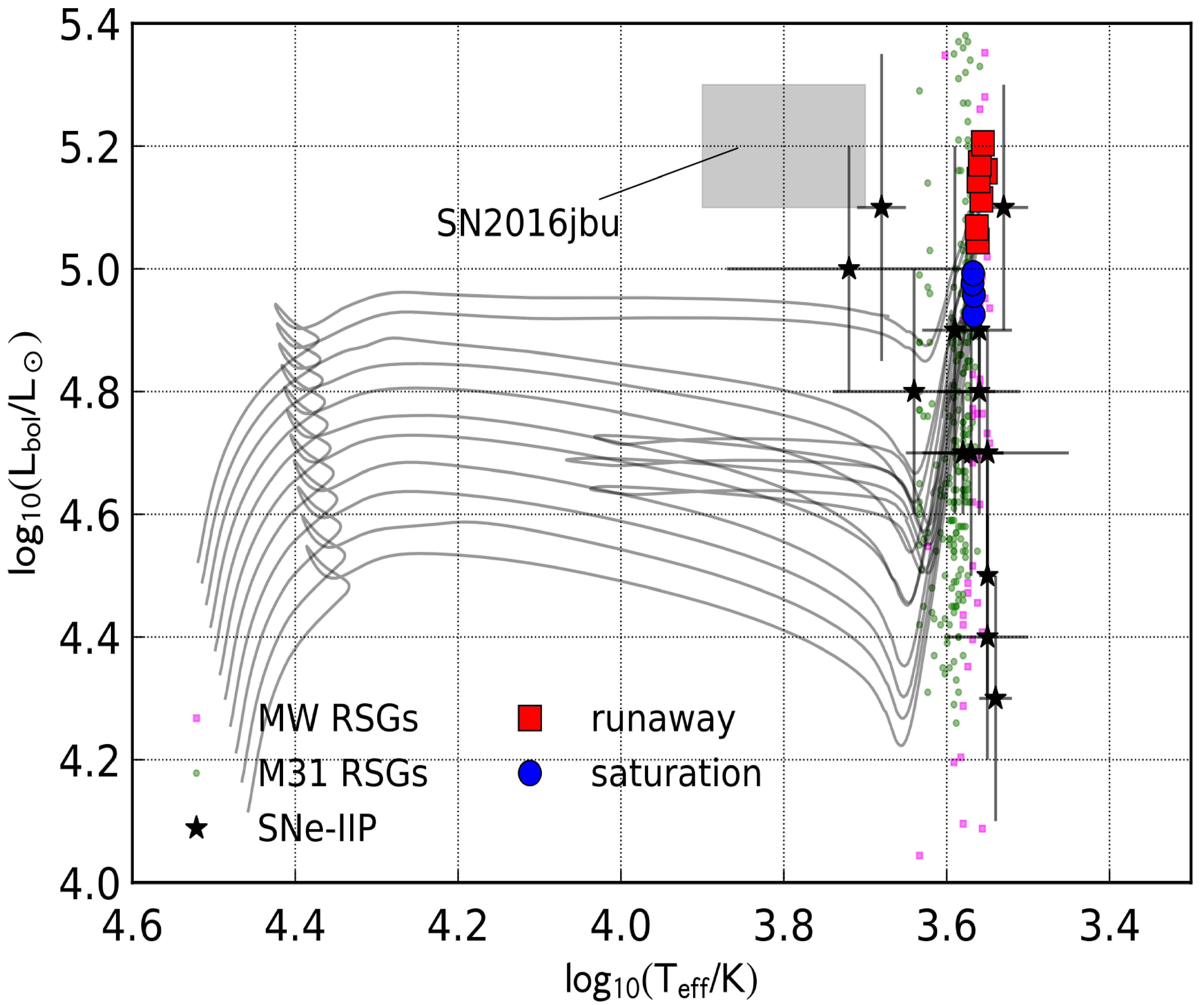
Yoon&Cantiello(2010)



RSG pulsation and instability

- open-source stellar evolution code MESA (Module for Experiments in Stellar Astrophysics)
- 13-18M_{sun} RSGs covering $L/L_{sun}=10^{4.9}$-$10^{5.2}$ at core-collapse.
- models are calibrate to reproduce HR diagram and period-luminosity relations of RSGs
- 11 models are computed until core-collapse

AS&Shigeyama (2025?)



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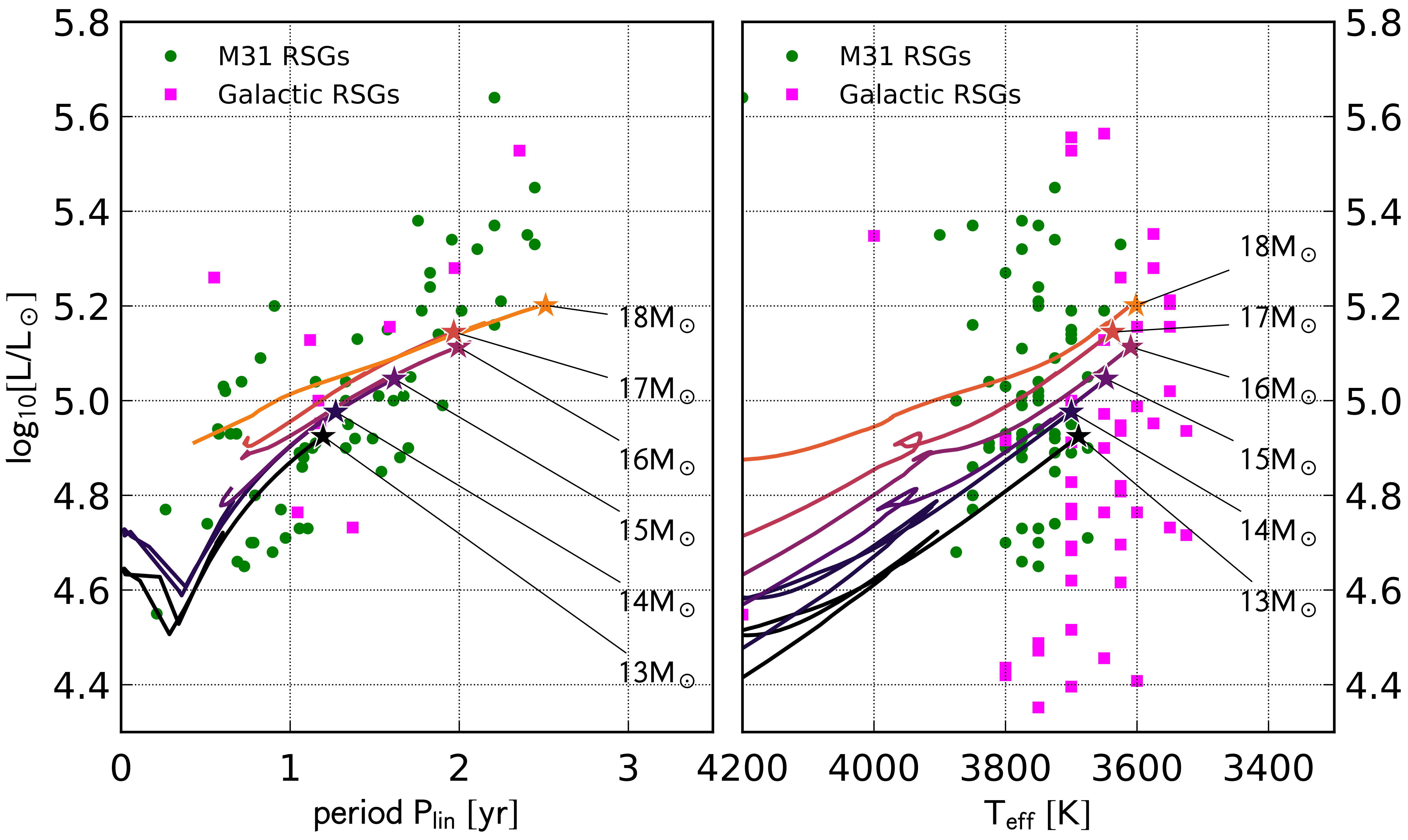

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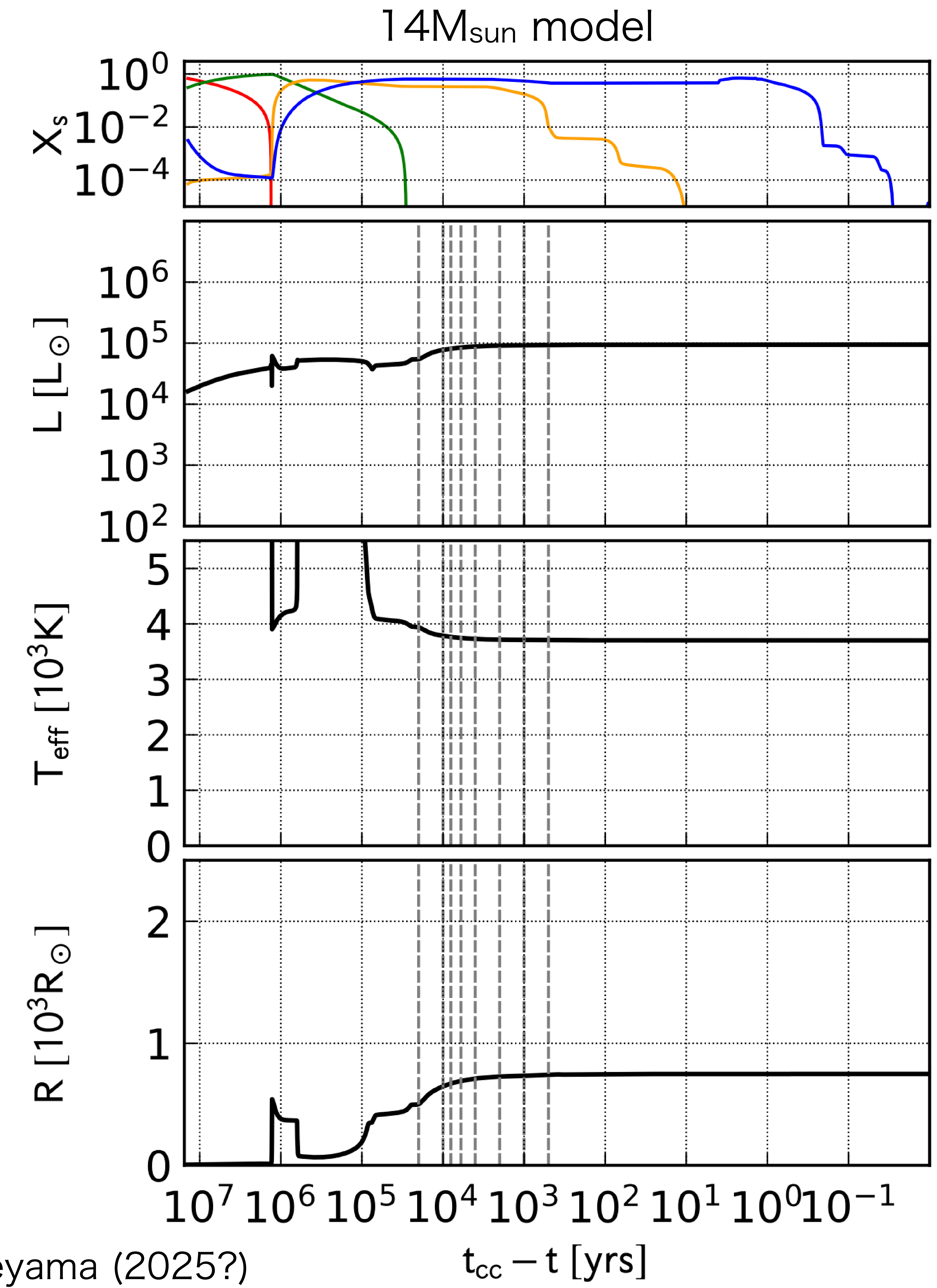
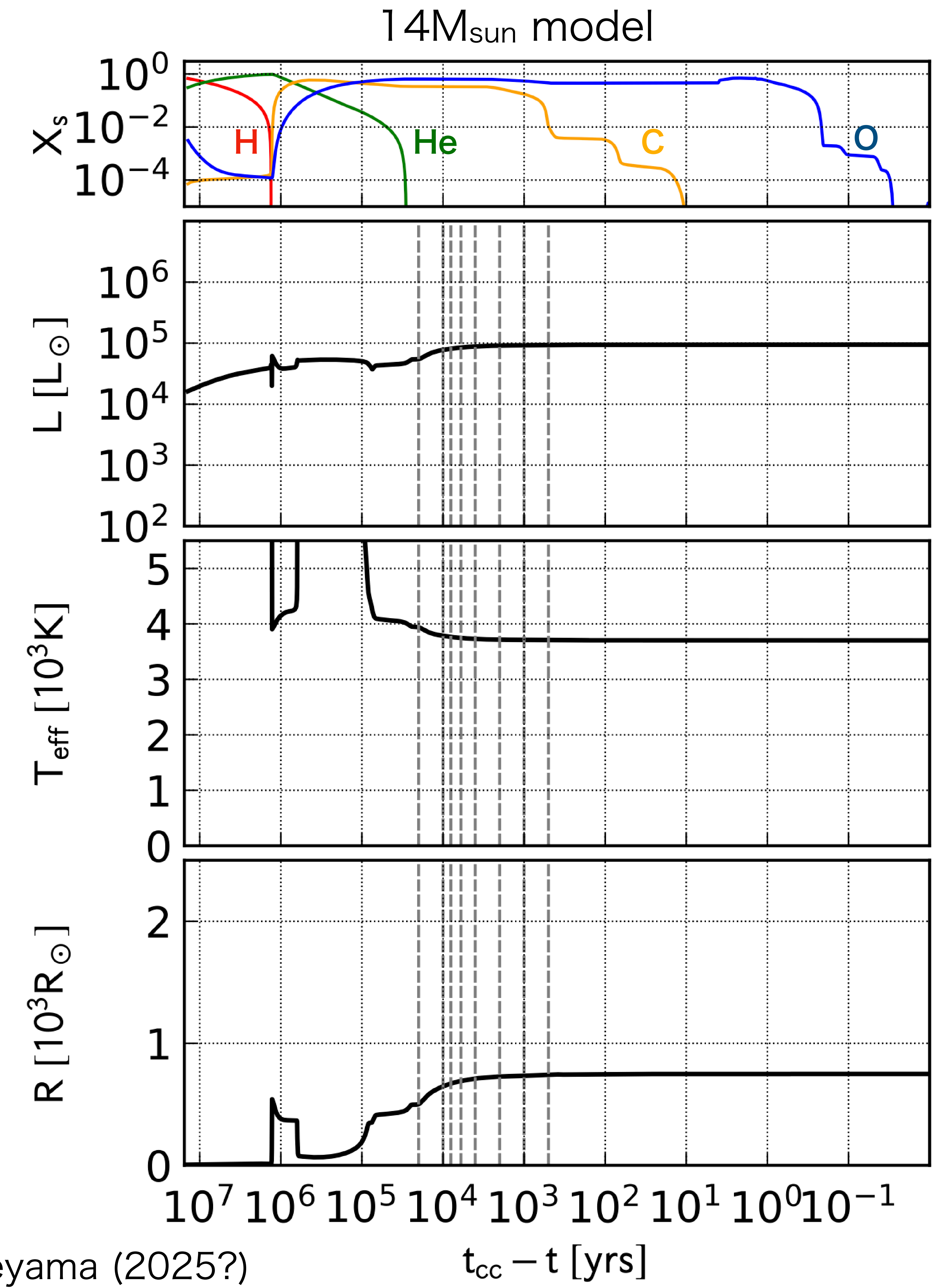


AS&Shigeyama (2025?)

RSG pulsation and instability

- We pickup 8 epochs ($t-t_{cc}$=20-0.5[kyr]) and restart simulations with much shorter time step Δt(=5x10^{-4} yr < 0.2 days)

M_{ini}=14M_{sun}	$t_{ini}-t_{cc}$ [10^3yr]	period [yr]
model1	20	0.59
model2	10	0.94
model3	8	1.02
model4	6	1.09
model5	4	1.15
model6	2	1.20
model7	1	1.20
model8	0.5	1.22



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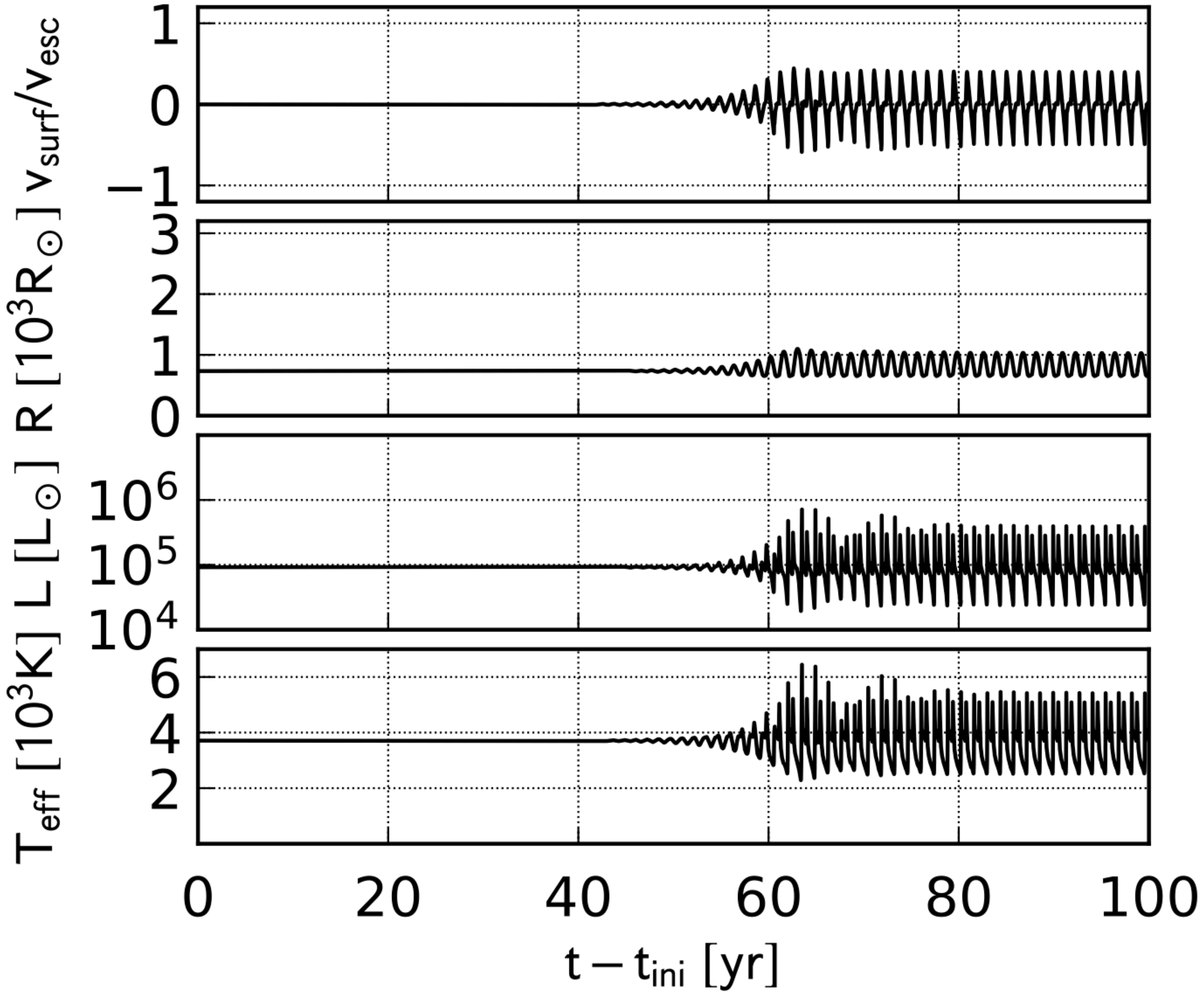
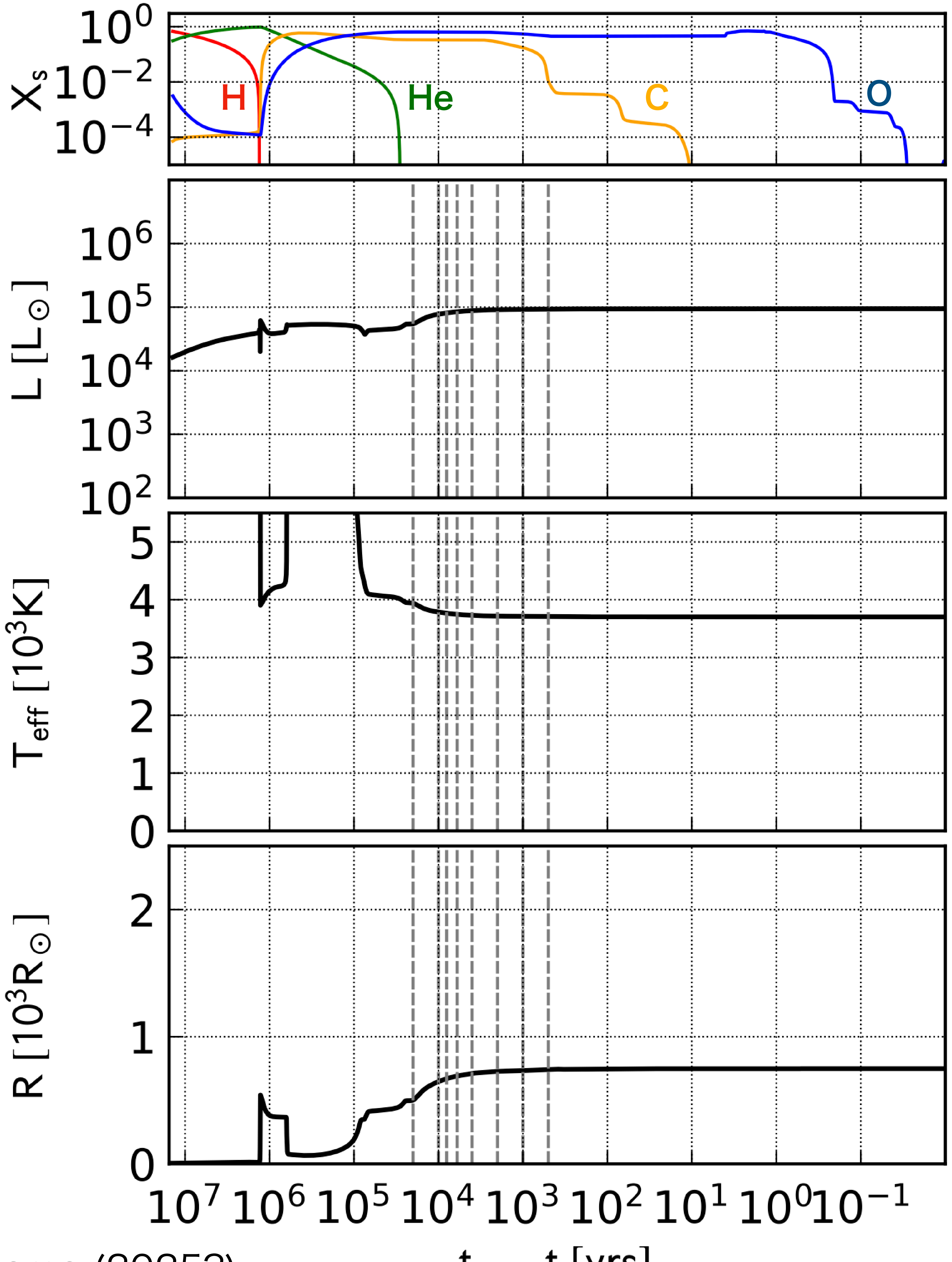
14.0Msun, epoch 7 (t_{cc}-t_{ini}= 10^3yr)



14Msun model



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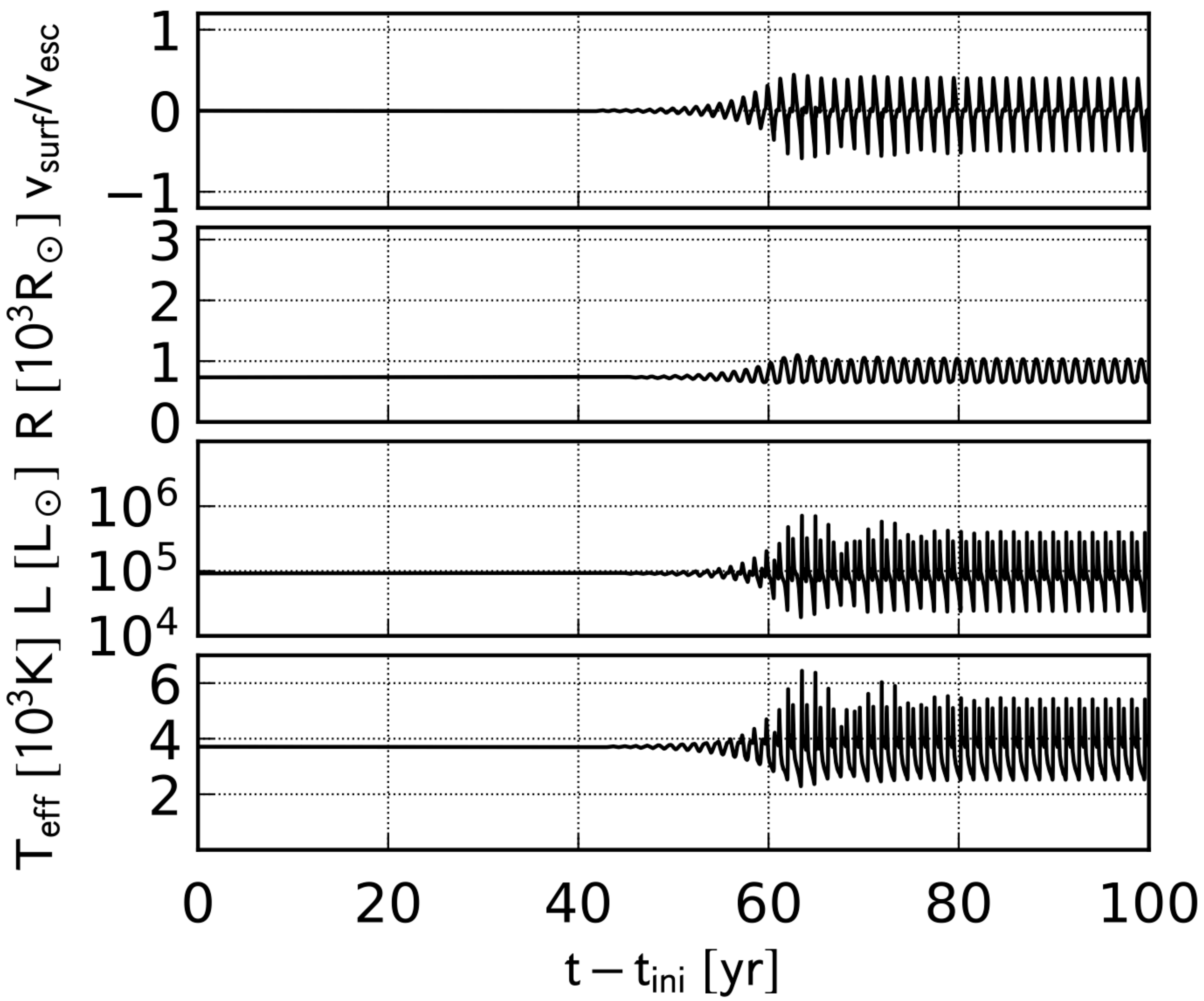

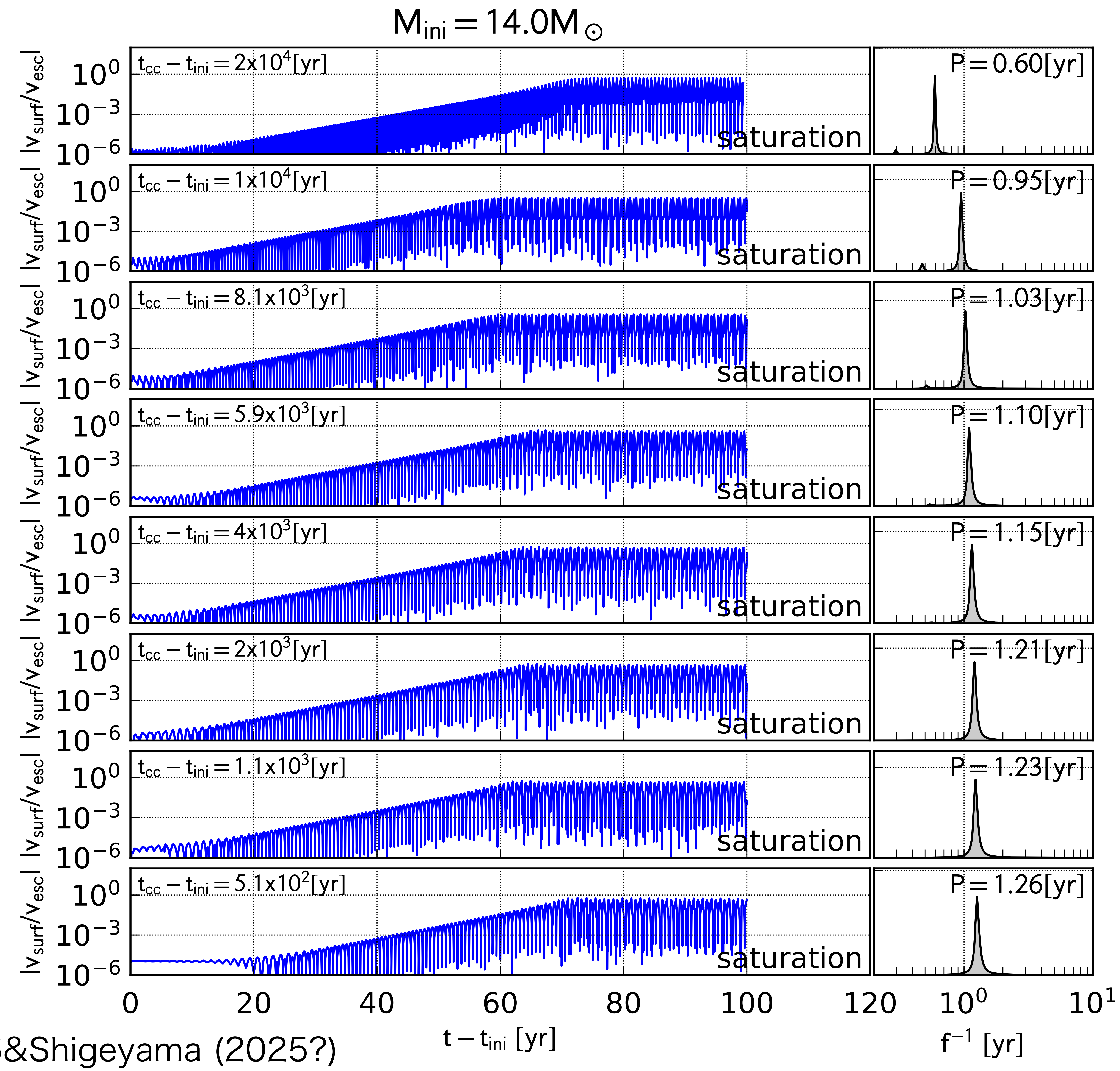

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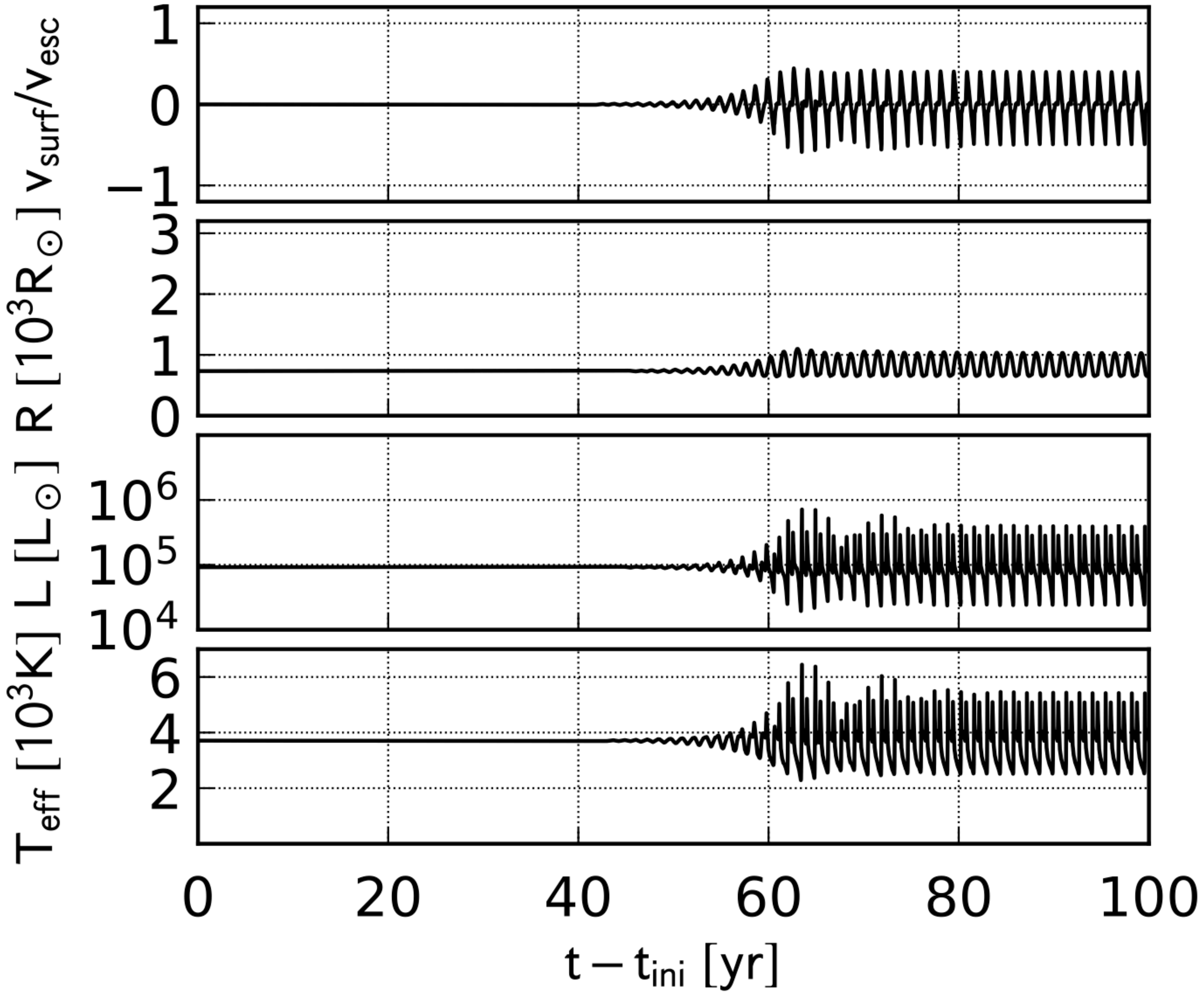
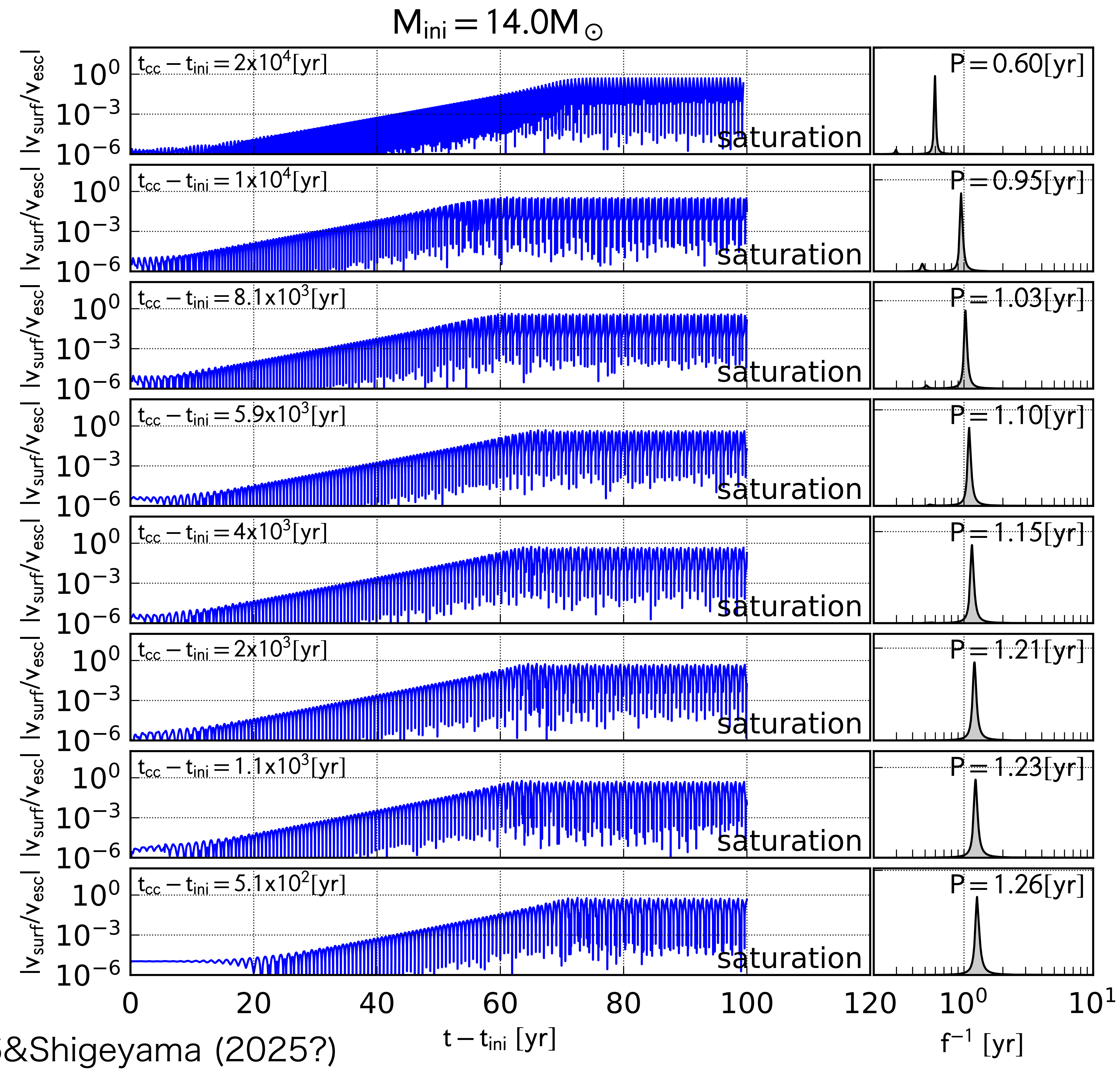


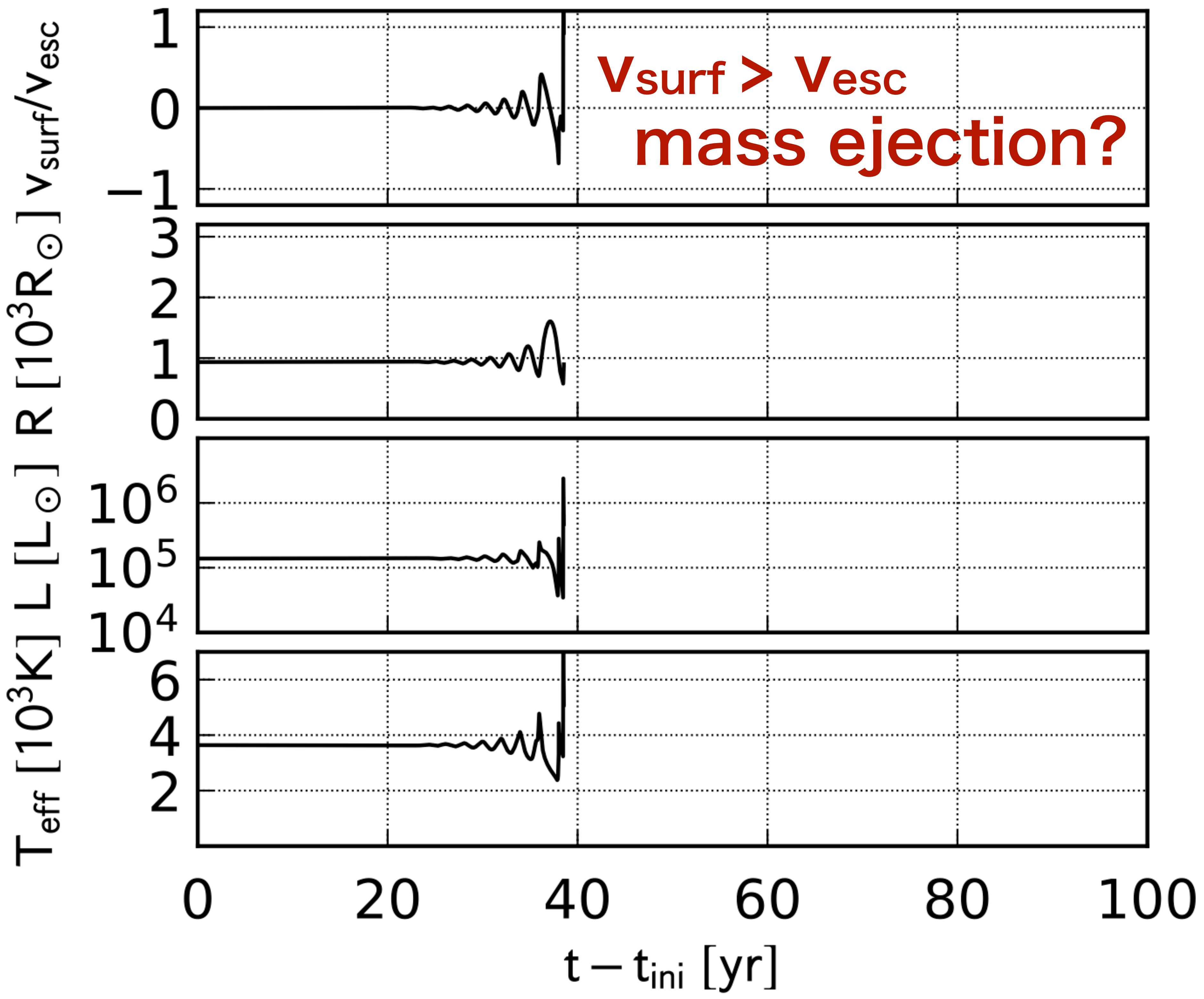


AS&Shigeyama (2025?)

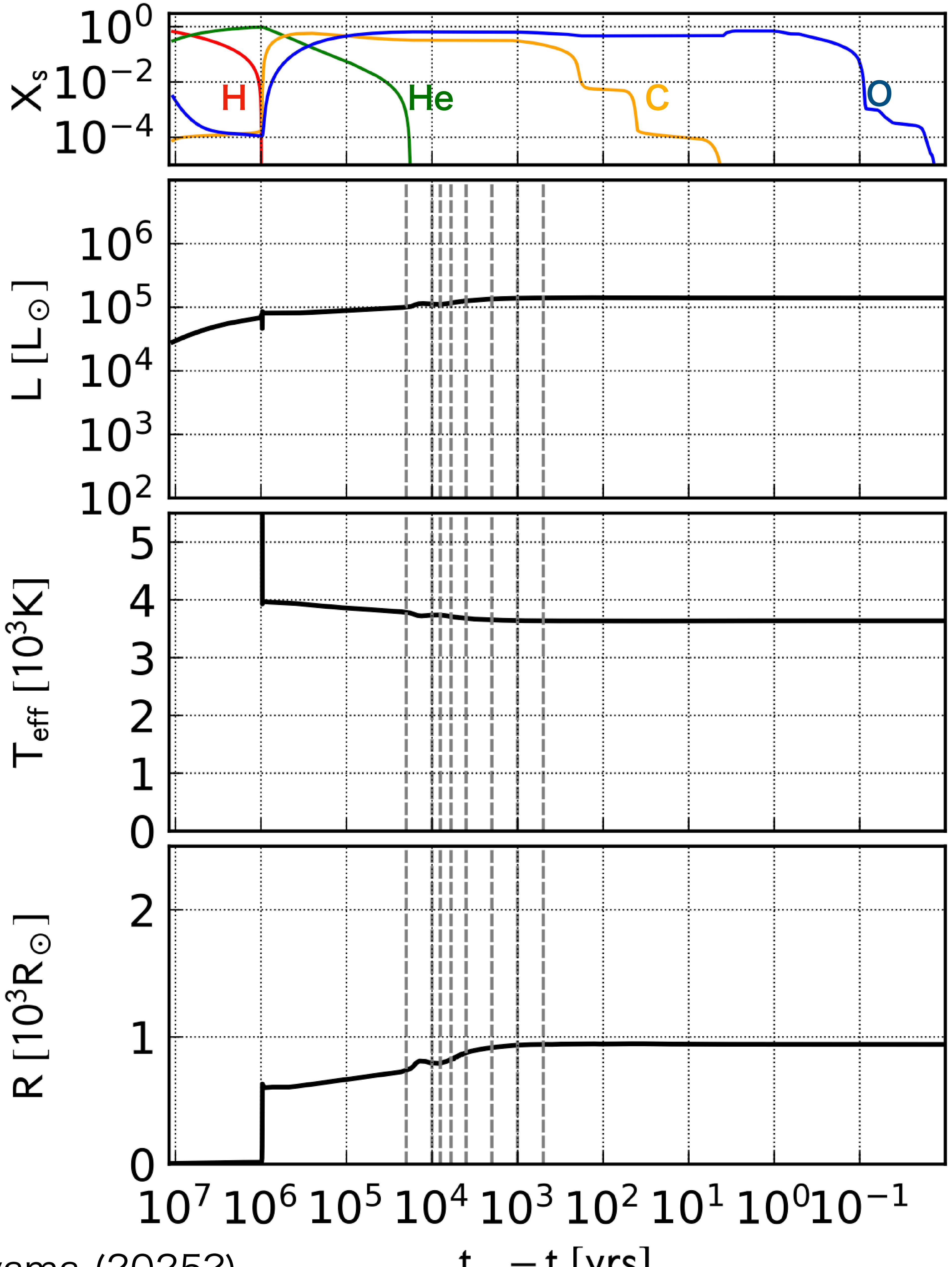
RSG pulsation and instability

- We pickup 8 epochs ($t-t_{cc}$=20-0.5[kyr]) and restart simulations with much shorter time step Δt(=5x10^{-4} yr < 0.2 days)

17.0Msun, epoch 7 (t_{cc}-t_{ini}= 10^{3}yr)



17Msun model



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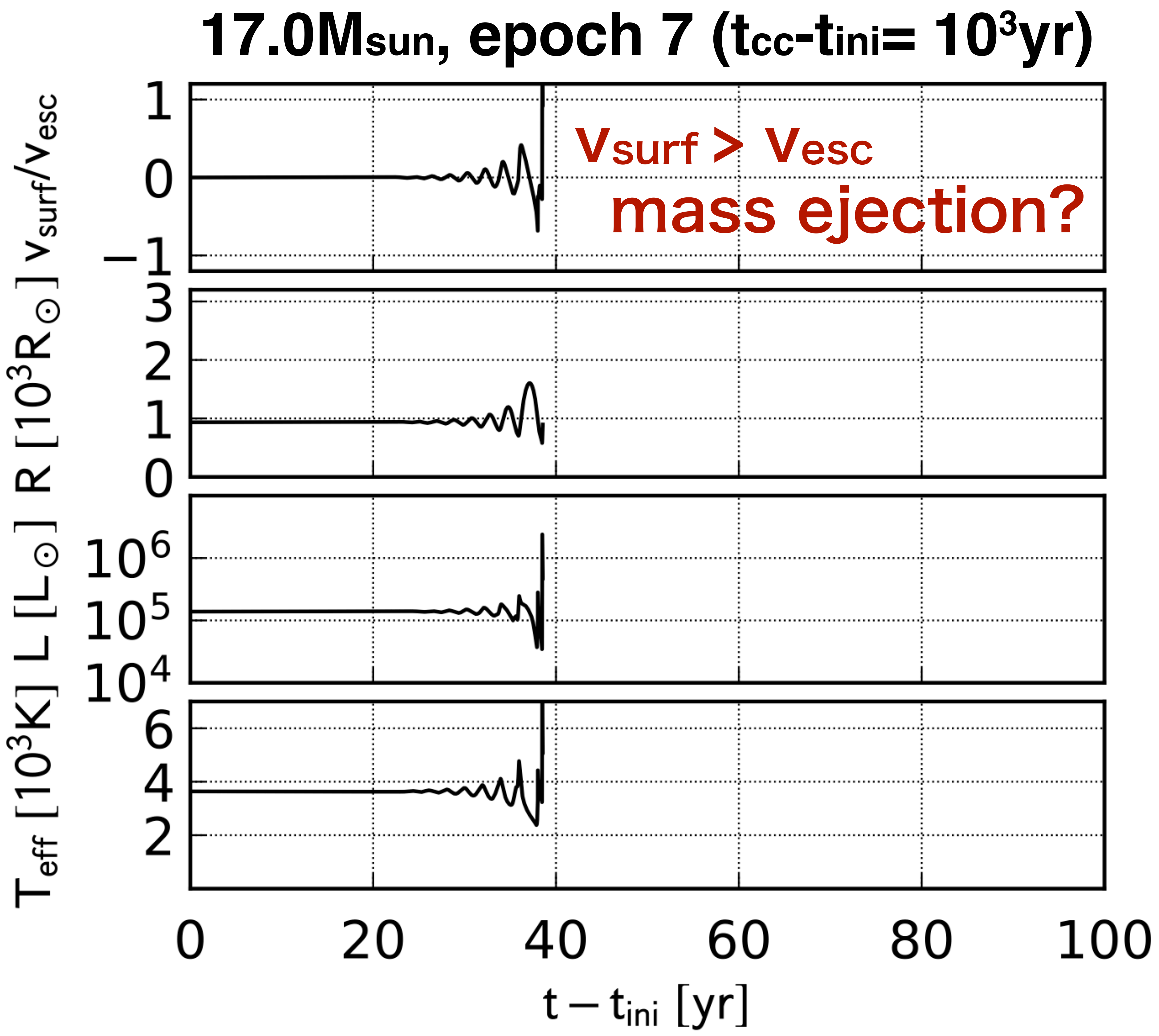
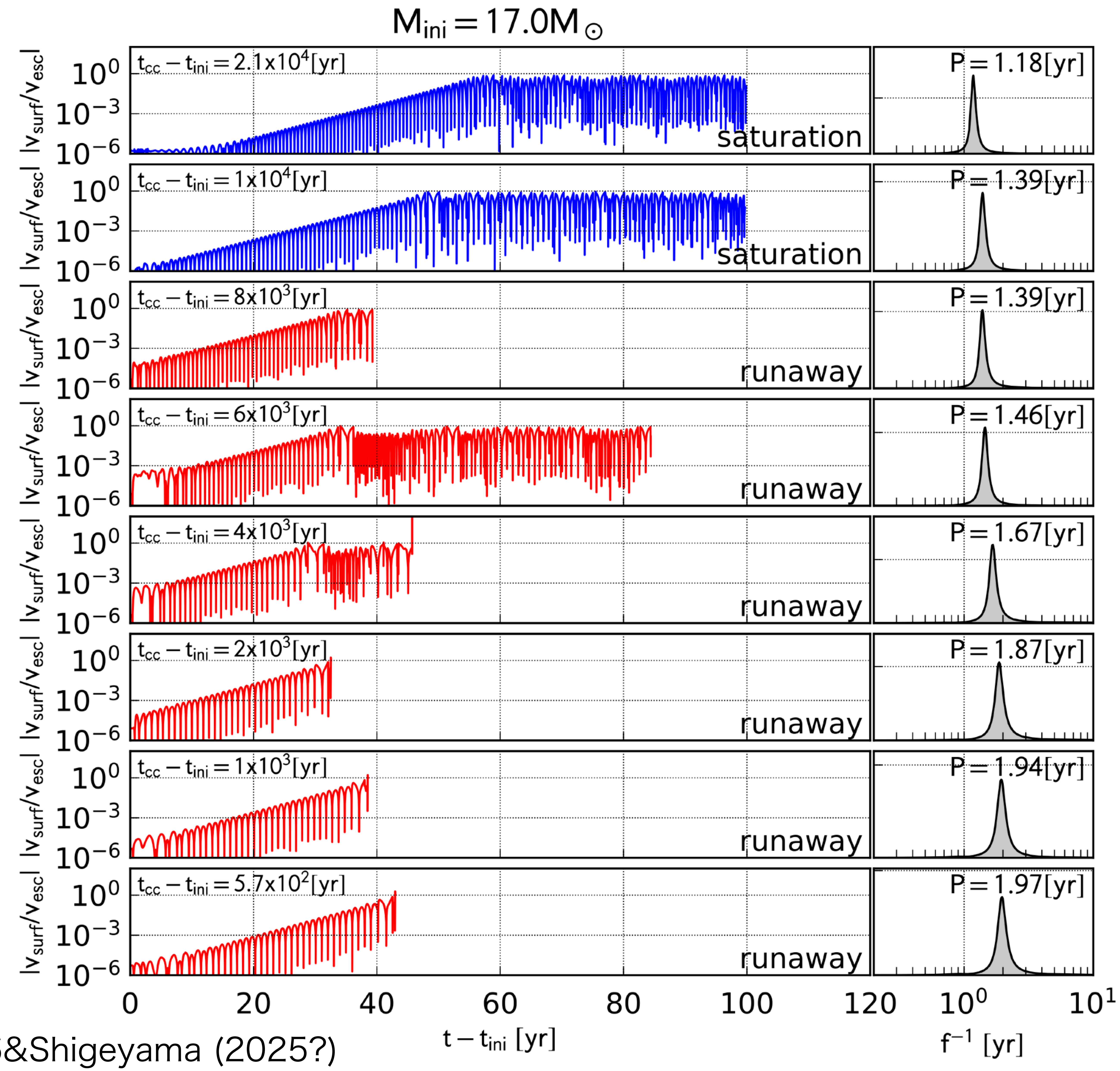


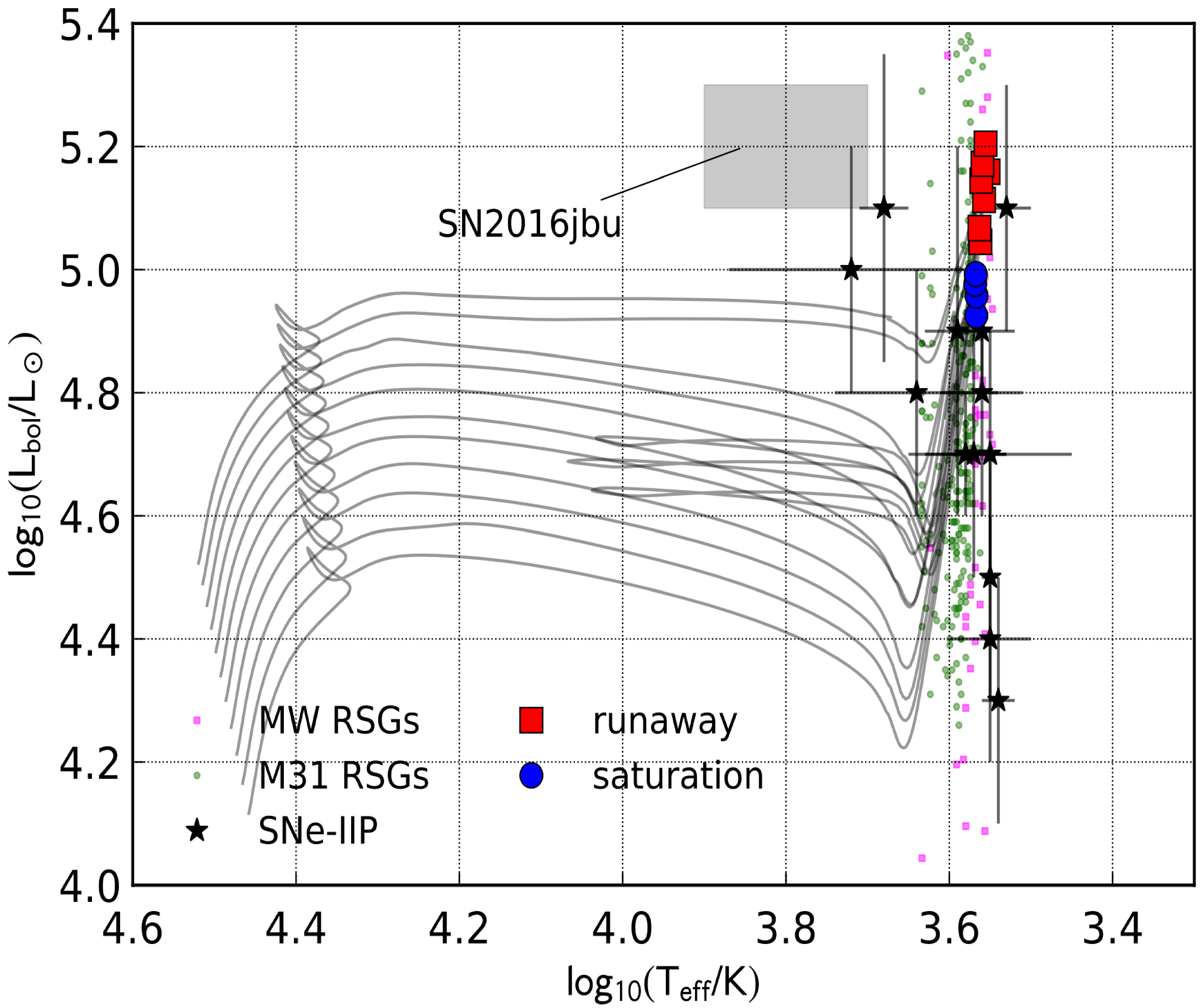


AS&Shigeyama (2025?)

RSG pulsation and instability

AS&Shigeyama (2025?)

- models with M_{ini} > $15M_{sun}$ suffer from radial pulsation runaway (v_{surf} > v_{esc})
- if we assume eruptive mass-loss for these stars, we do NOT expect normal type IIP SNe
- instead, we get type IIn SNe?
- also, observed as variable RSGs prior to core-collapse (SN precursor)



work still in progress!

- Introduction
- Evolution of exploding massive stars
- Early emission and past/recent observations
- Progenitor and pre-supernova activities
- Summary

Supernova evolution

- In each phase, properties of exploding stars can be obtained through LCs and spectra (+ multi-λ obs.)

star/ejecta evolution

Research trend

- **pre-supernova image/activity**
  → progenitor properties/activities
- **SN shock breakout/cooling emission**
  → explosion dynamics, stellar radii
- **photospheric/plateau phase**
  → explosion dynamics, stellar mass
- **nebular phase**
  → stellar interior, nucleosynthesis

➡ SN remnant phase