Supernova Shock Breakout

and related topics

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★ Introduction for SN shock breakout

★ Detected events, possible events

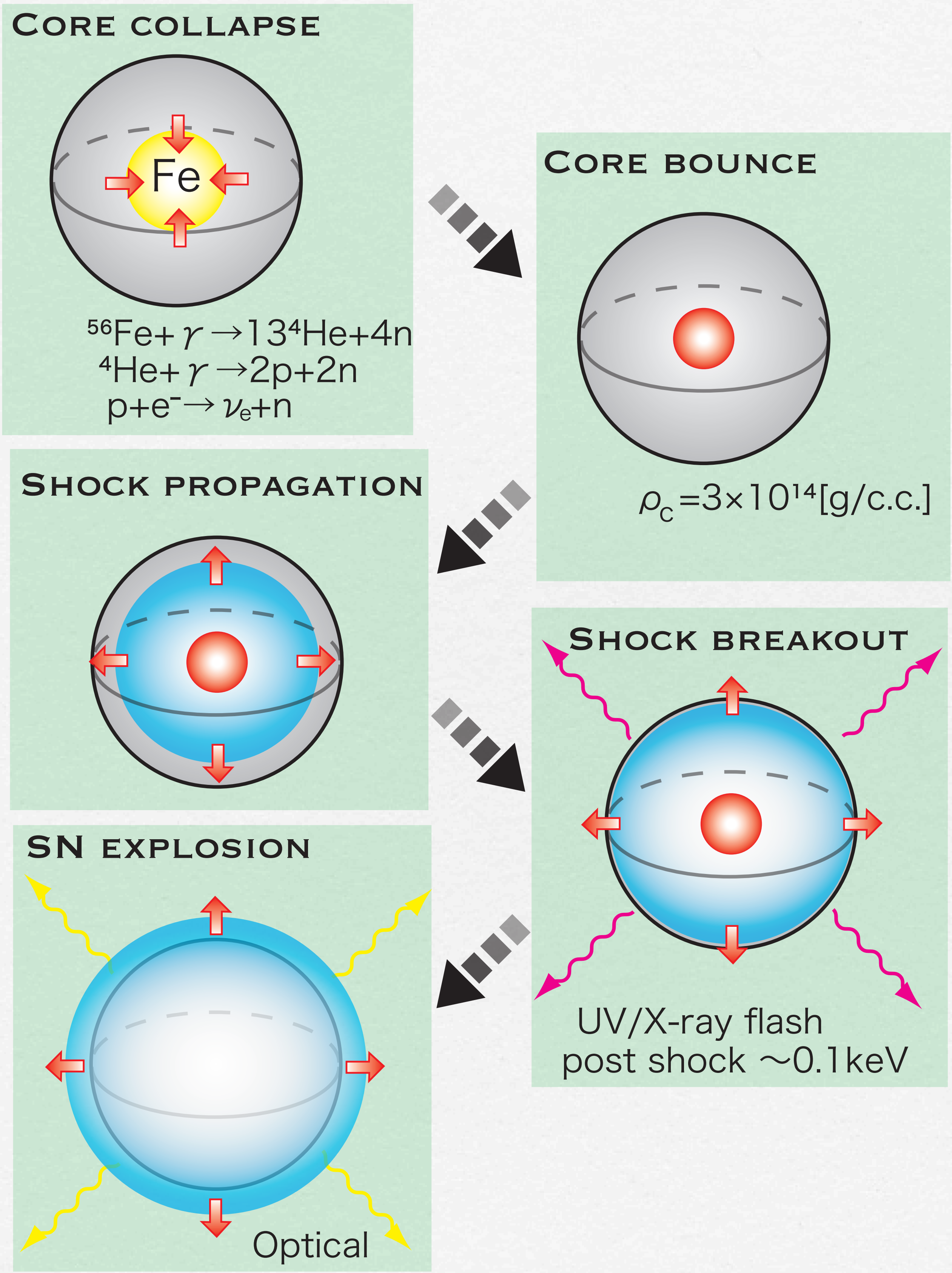
★ What can we learn from SN shock breakout

★ Our works

★ Summary

Core-collapse supernova

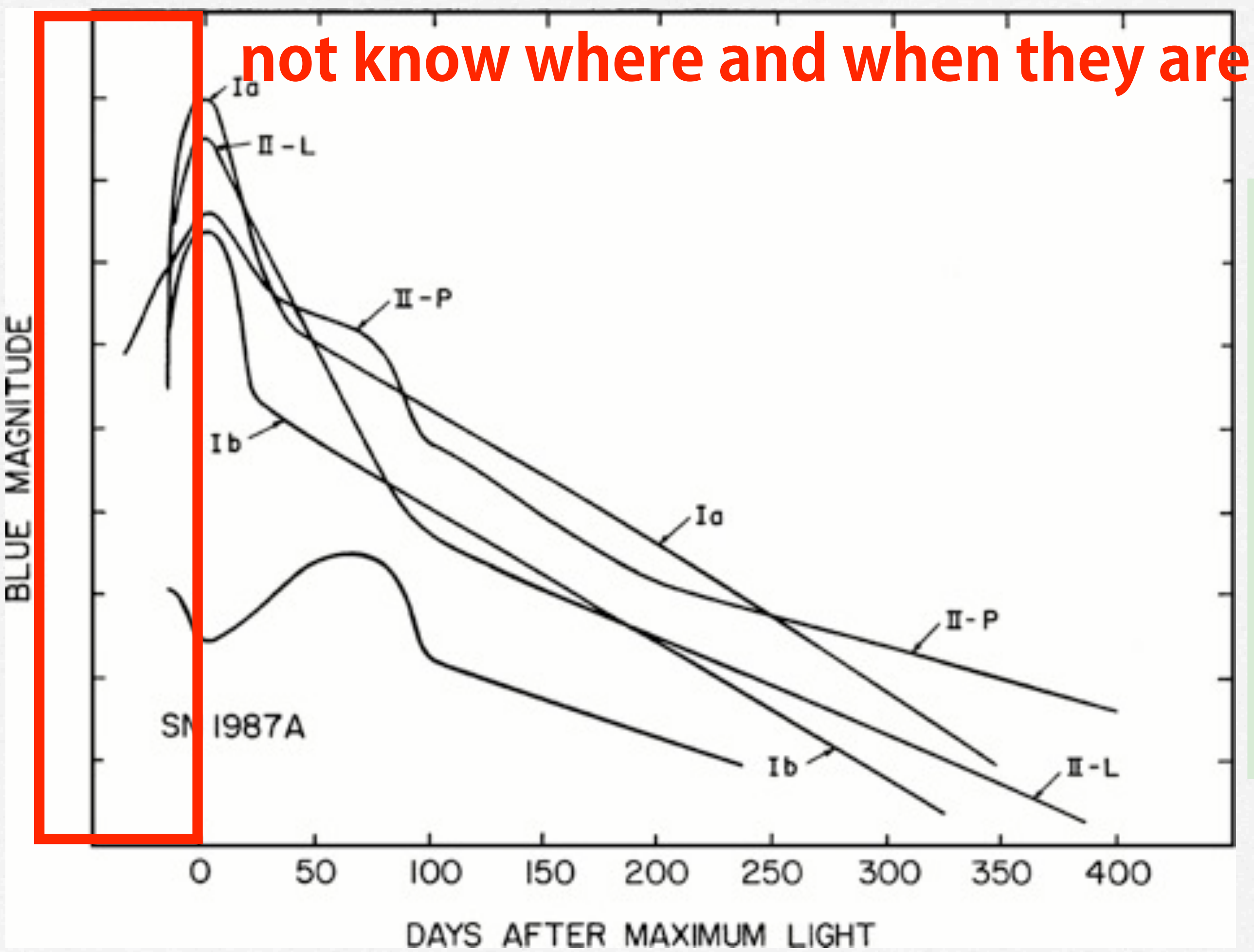
- ➡ collapse of Iron core
- ➡ core bounce
- ➡ shock formation and propagation in the star
- ➡ emerging from the surface
- ➡ expanding ejecta

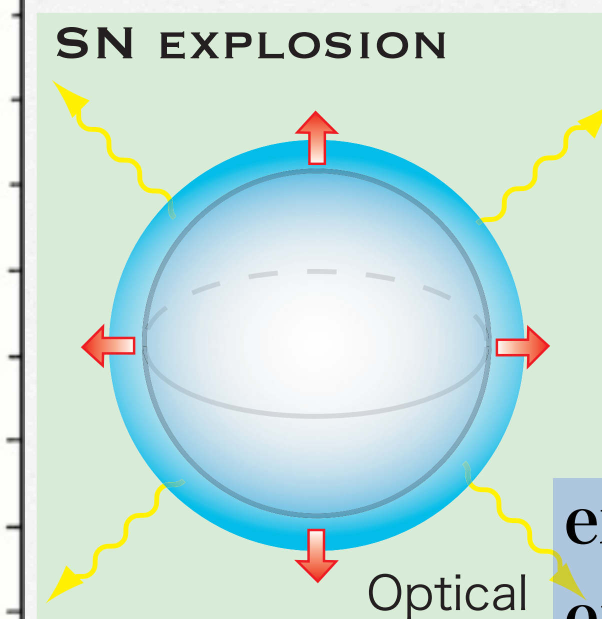


Observations of SNe

➡ Traditionally, optical observations probe the ejecta dynamics, abundance, etc

Early emission: we need to detect EM signals that we do not know where and when they are emitted





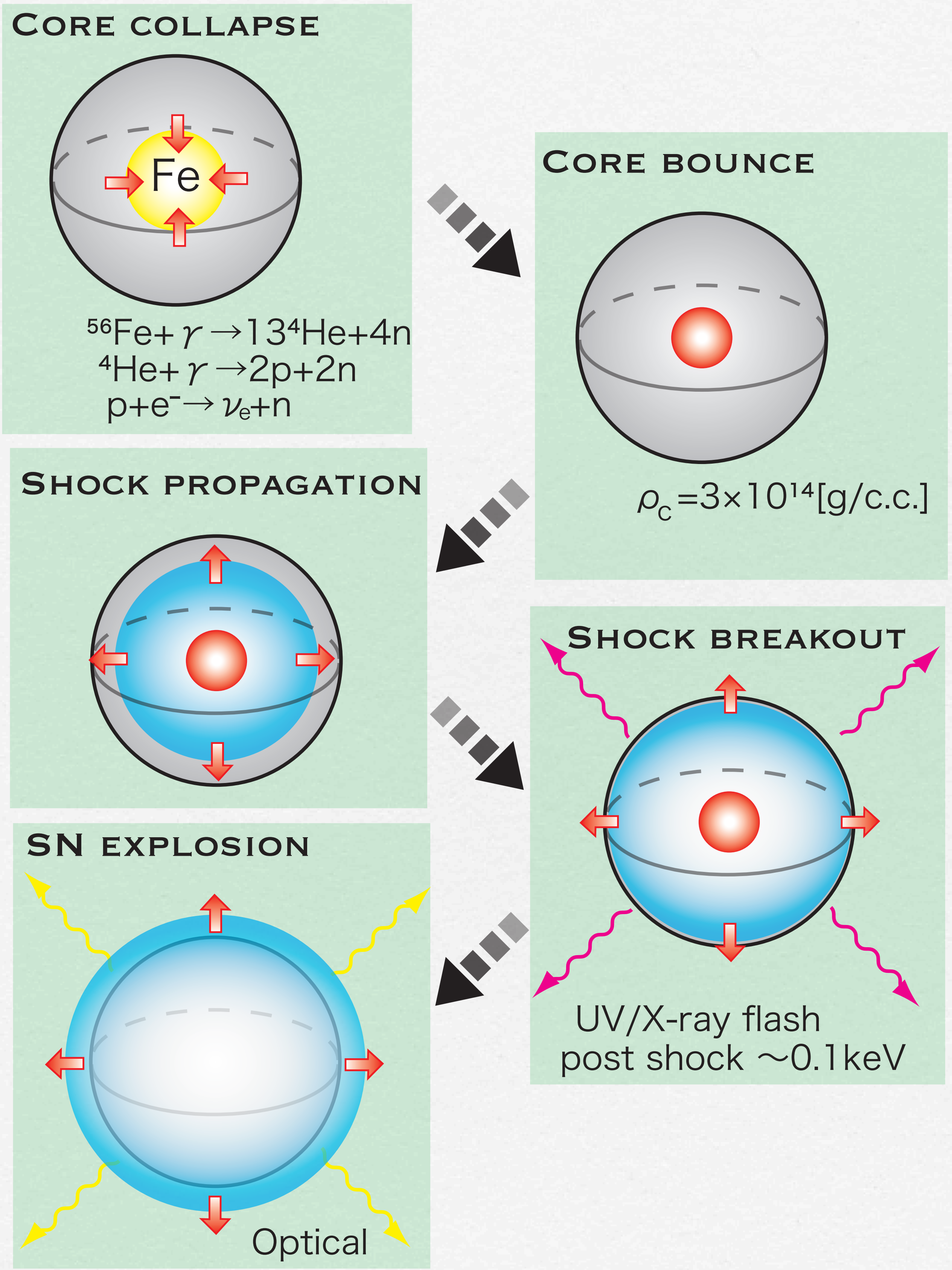
light curves
spectra
polarimetry

⇩

explosion energy
ejecta mass
chemical composition
explosion geometry

Core-collapse supernova

- ➡ collapse of Iron core
- ➡ core bounce
- ➡ shock formation and propagation in the star
- ➡ emerging from the surface **(SN shock breakout)**
- ➡ expanding ejecta



SN shock breakout

➡ UV/X-ray flash associated with the birth of an SN explosion

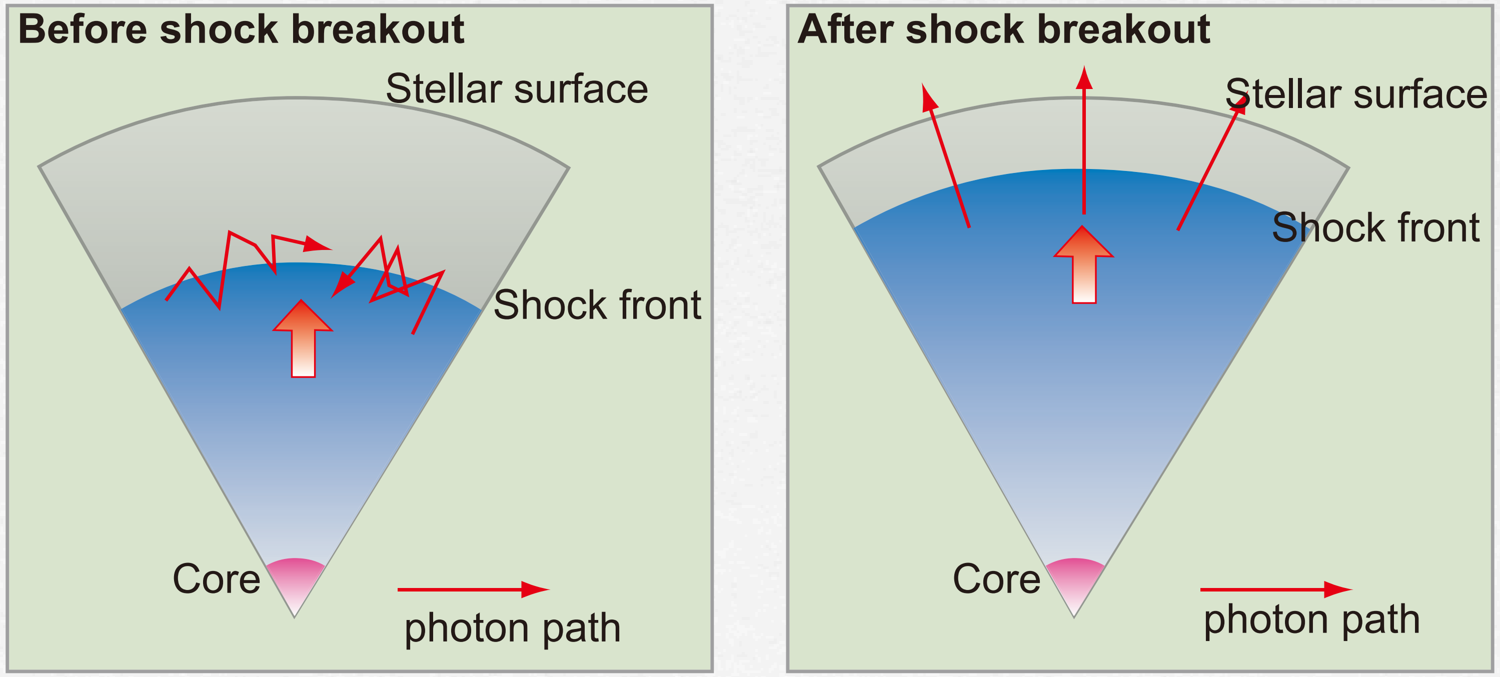
➡ It occurs when the strong shock having been generated at the iron core emerges from the stellar surface

➡ We can observe the SN through EM only after shock breakout

photon diffusion velocity $V_{diff}=c/\tau$

shock velocity V_s

breakout condition $c/\tau > V_s$



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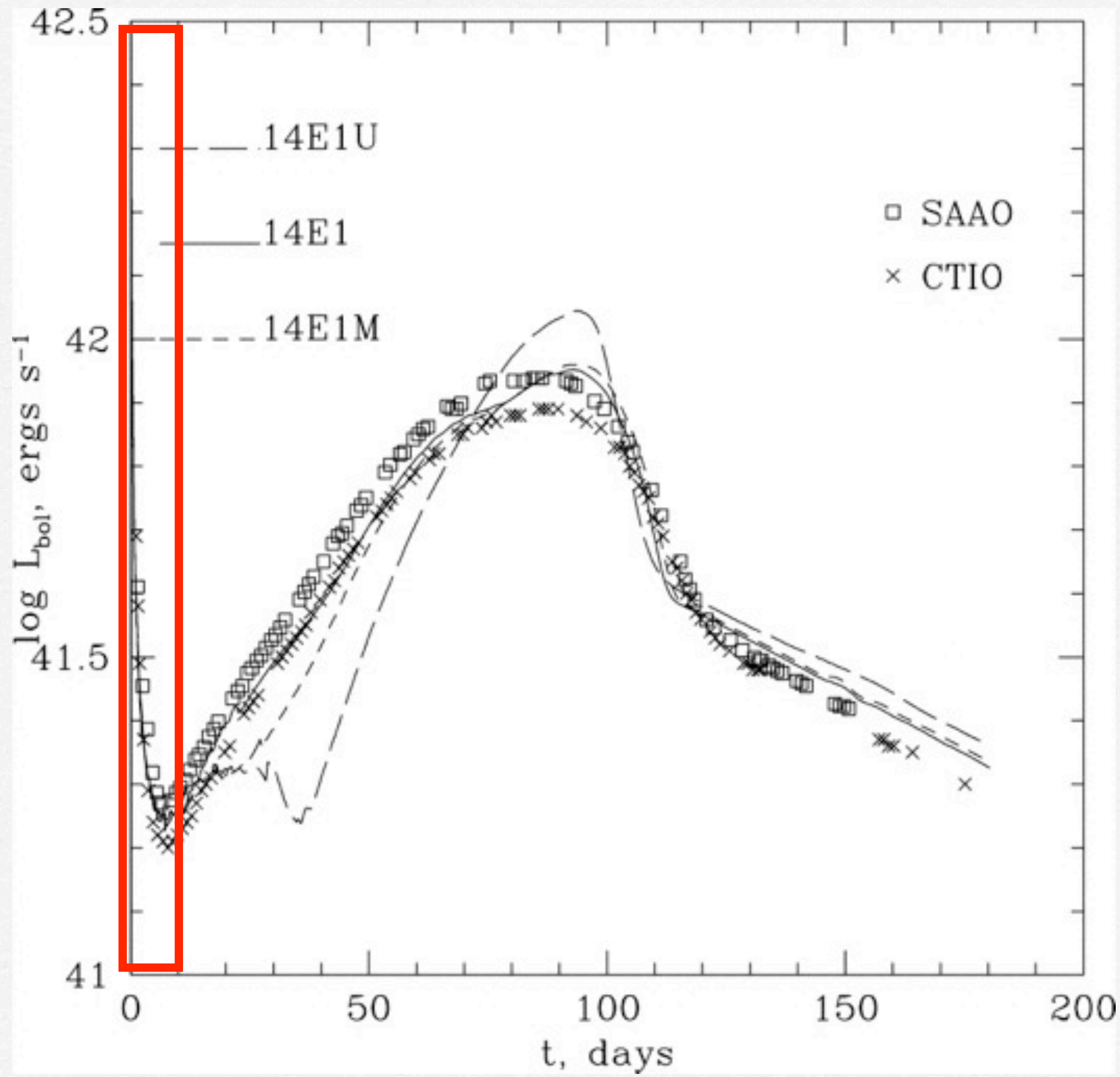
SN 1987A

Blinnikov+(2000)

- most famous SNe @ magellanic cloud
- type II-peculiar
- decay phase of the breakout emission
- recombination lines from ions with high excitation energy: gas photoionized by breakout emission(UV flash)



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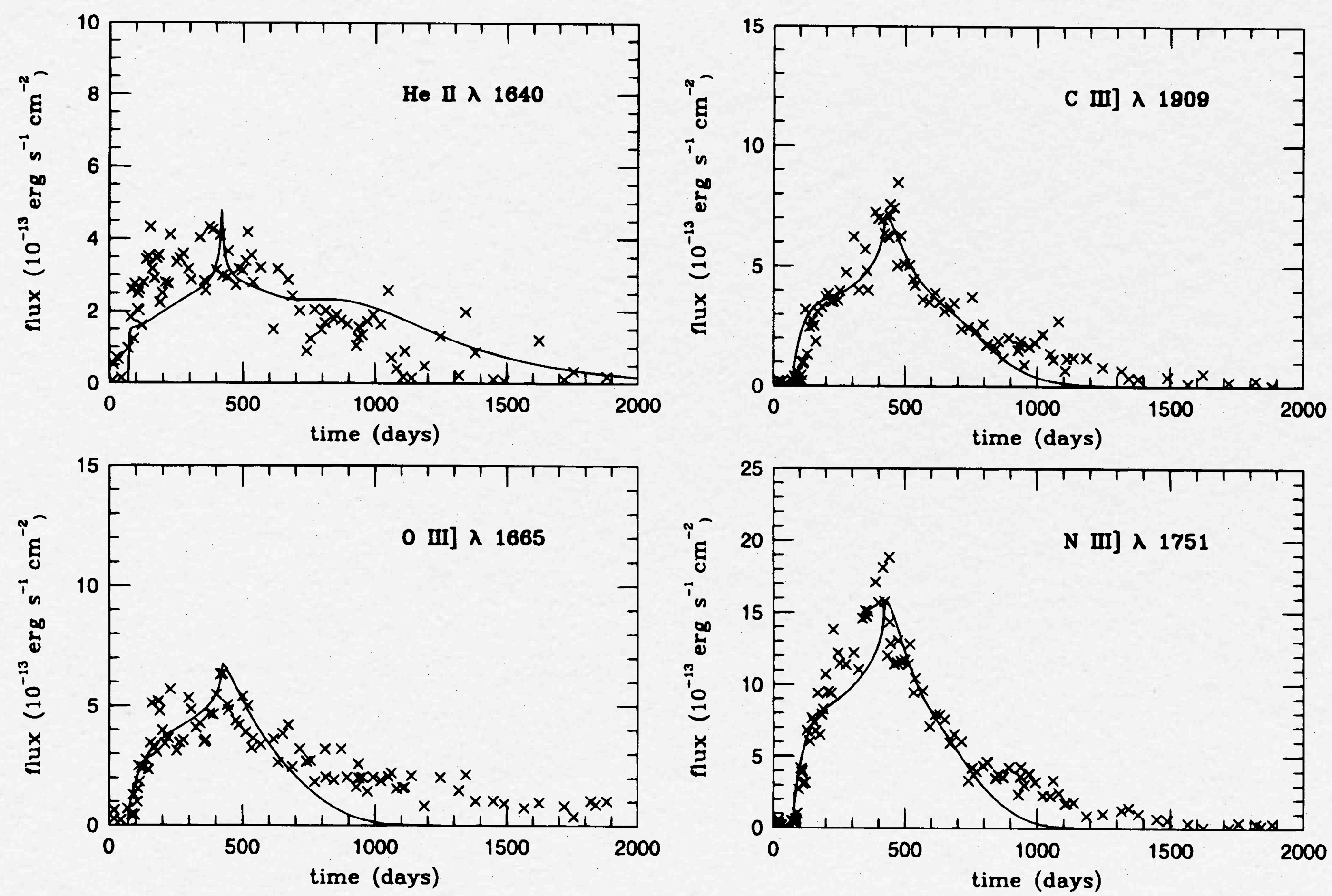
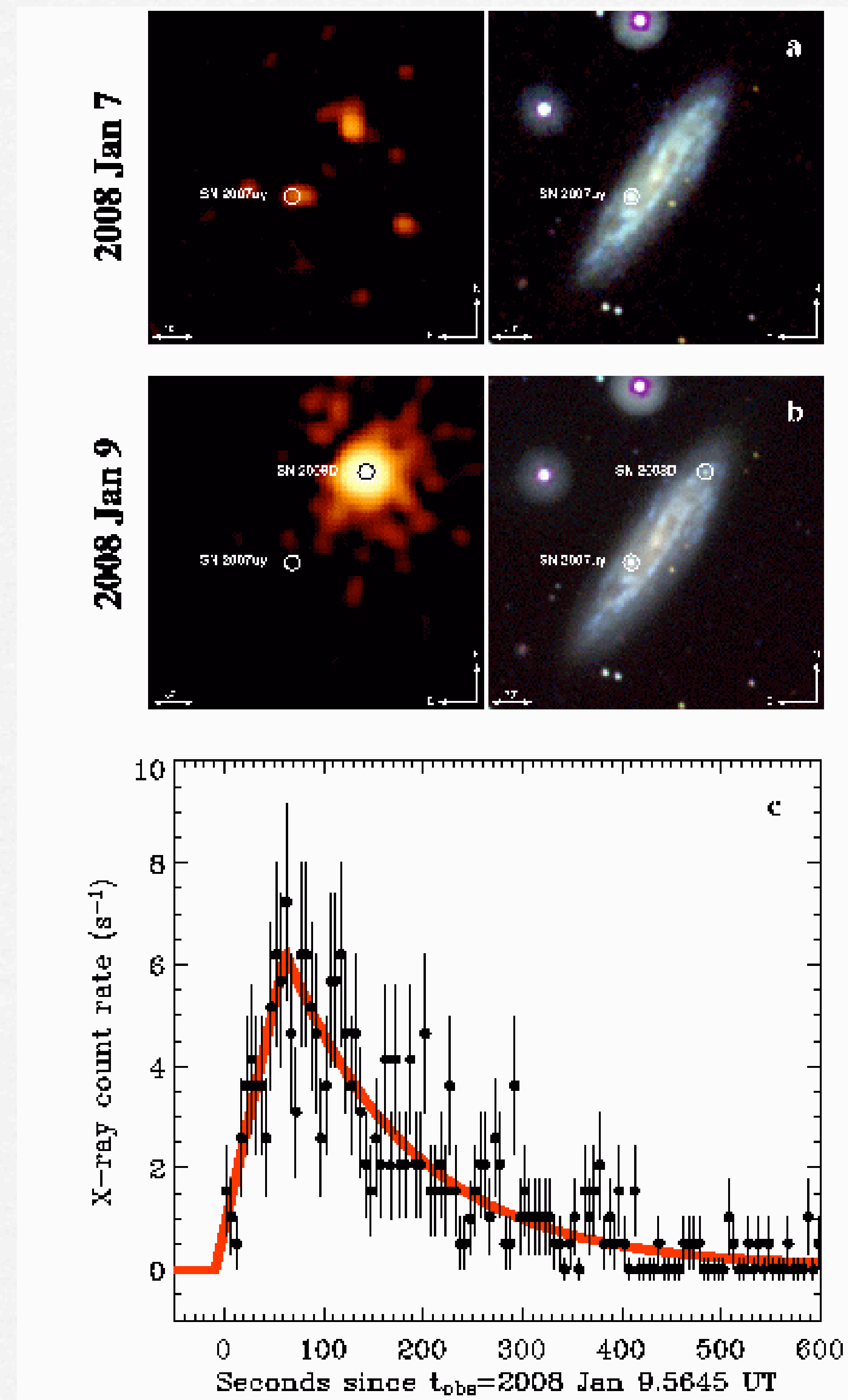
Lundqvist&Fransson(1996)



XRF 080109/SN 2008D

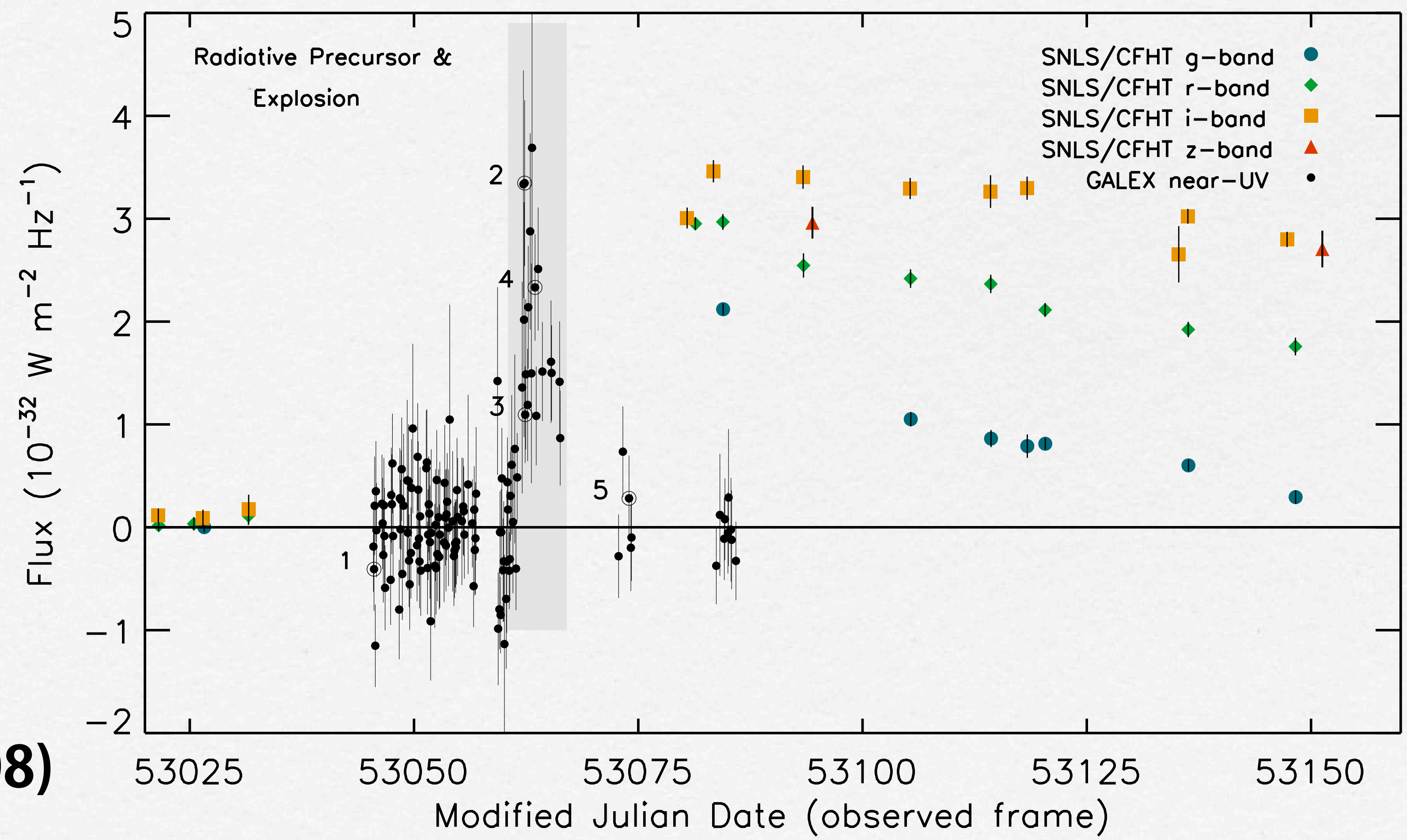
Soderberg+(2008)

- ➡ SN Ib @NGC2770 D=27Mpc
- ➡ Swift serendipitously observed an X-ray flash associated with the birth of the SN
- ➡ Lx~ a few × 10^{43} erg/s, duration~ 200-300 sec, Ex~10^{46} erg



SNLS-04D2DC

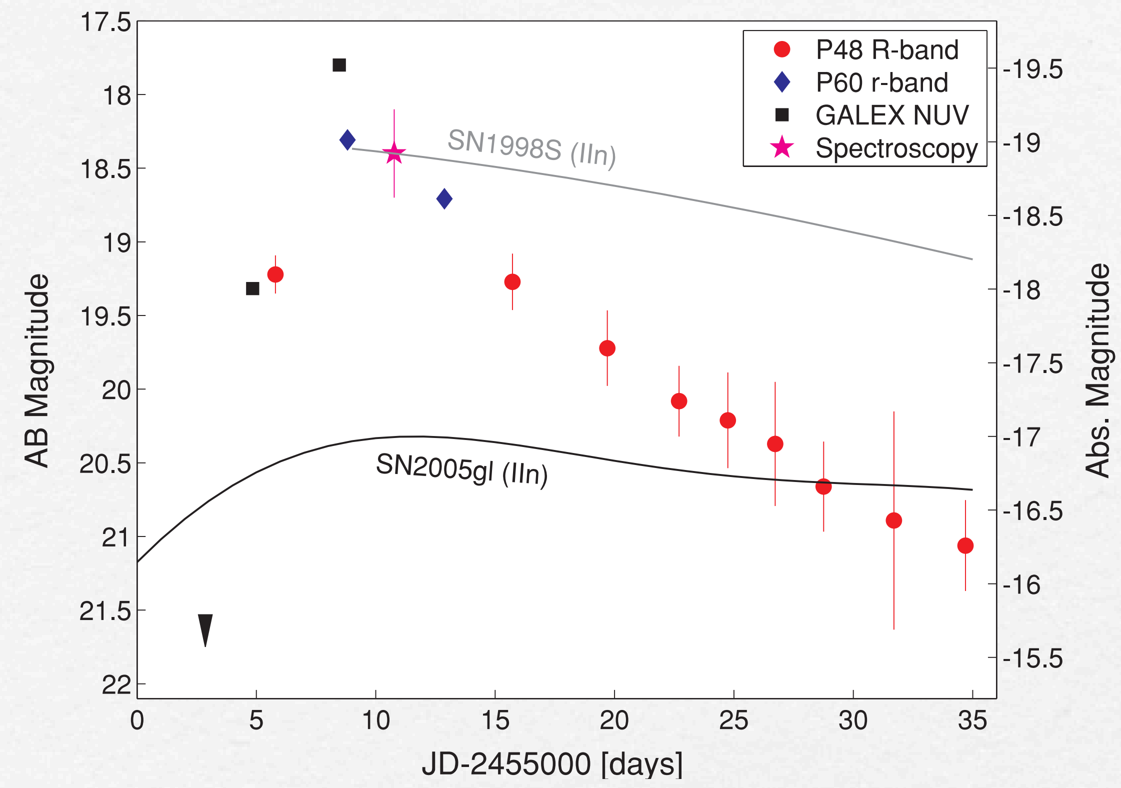
- Supernova Legacy Survey
- coincidence in time and position of an UV flash and a SN (@z=0.1854):
  GALEX satellite archival data

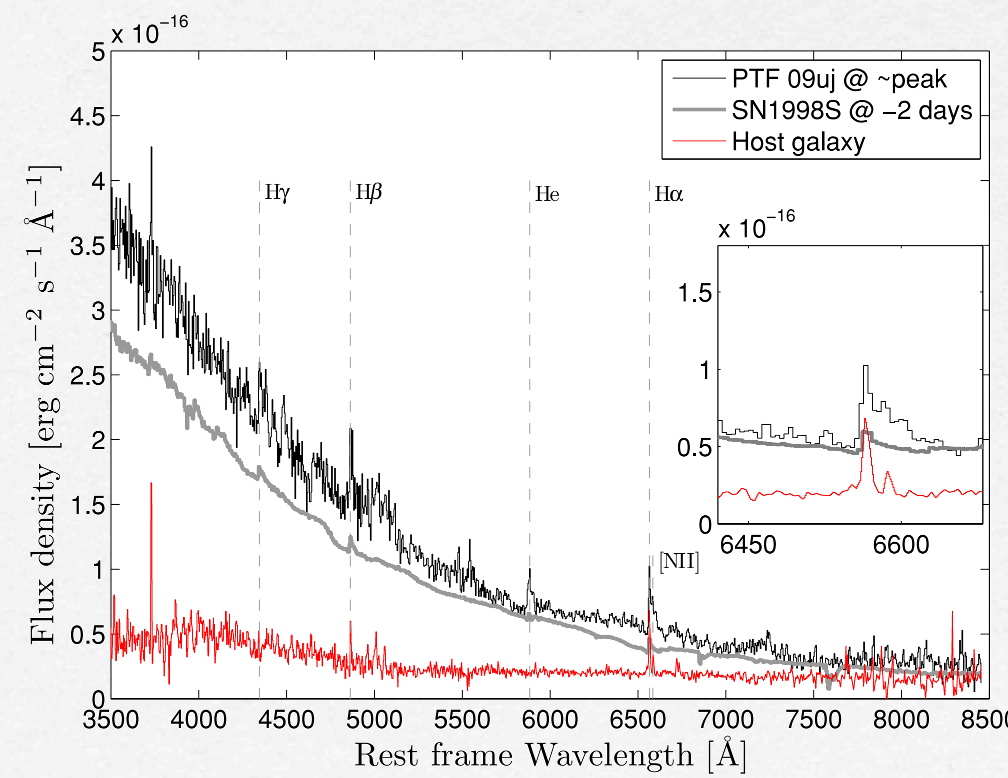


Schawinski+(2008)

PTF 09uj

- Palomar Transient Factory
- coincidence in time and position of an UV flash serendipitously observed by GALEX and the SN.
- UV emission for 2 weak. too long?
- spectrum: blue continuum, narrow Hα line

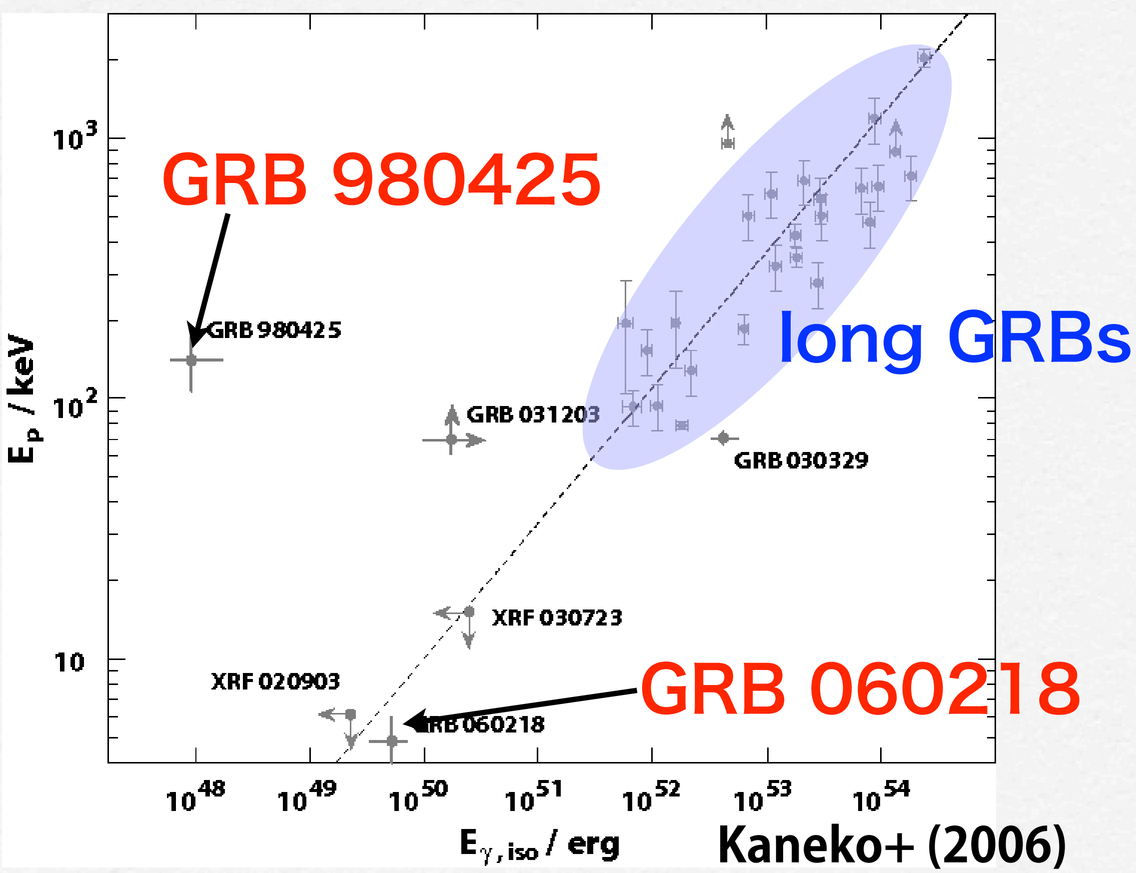




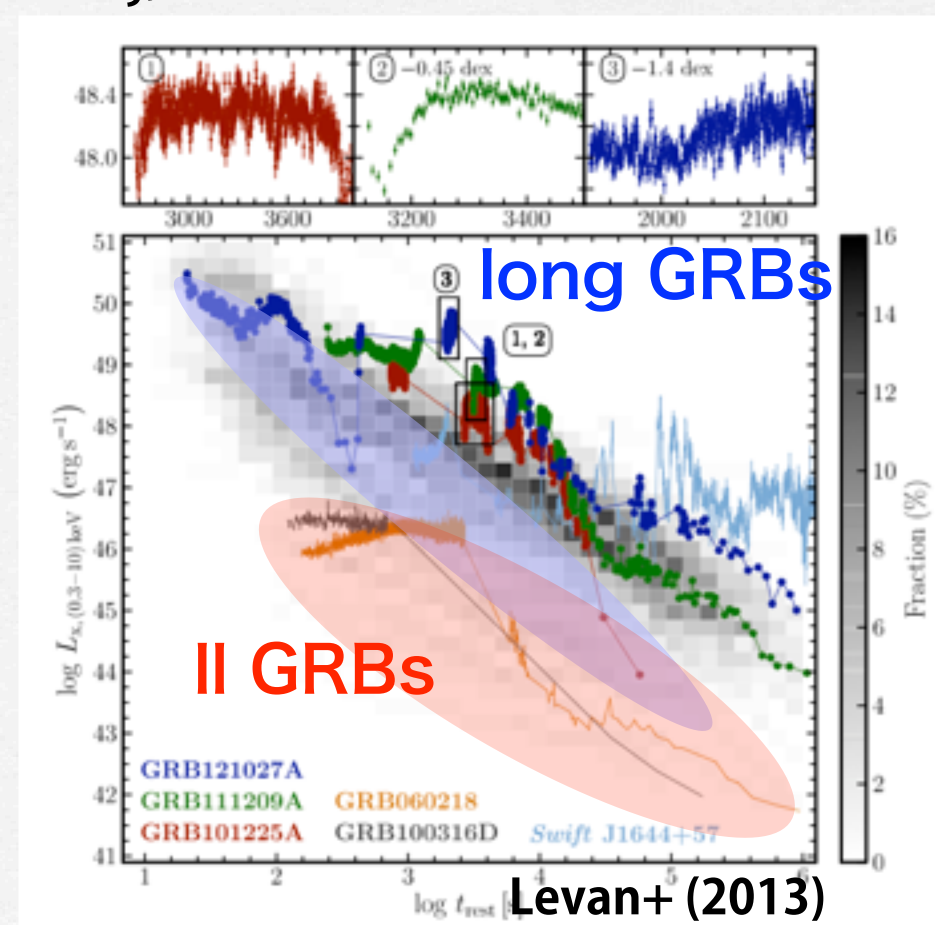
Ofek+(2010)

Other possible events: low-luminosity GRBs

- ➡ sub-energetic class of long GRBs: relativistic shock breakout?
- ➡ only nearby events are detected, but event rate is rather high
  e.g., 230^{+490}_{-190} Gpc^{-3} yr^{-1} (Soderberg+ 2006), 100-1800 Gpc^{-3} yr^{-1} (Guetta&Della Valle 2007)
- ➡ They accompany broad-lined Ic SNe
- ➡ Ex. GRB 980425/SN 1998bw, GRB 060218/SN 2006aj, GRB100316D/ SN2010bh



Kaneko+ (2006)



Levan+ (2013)

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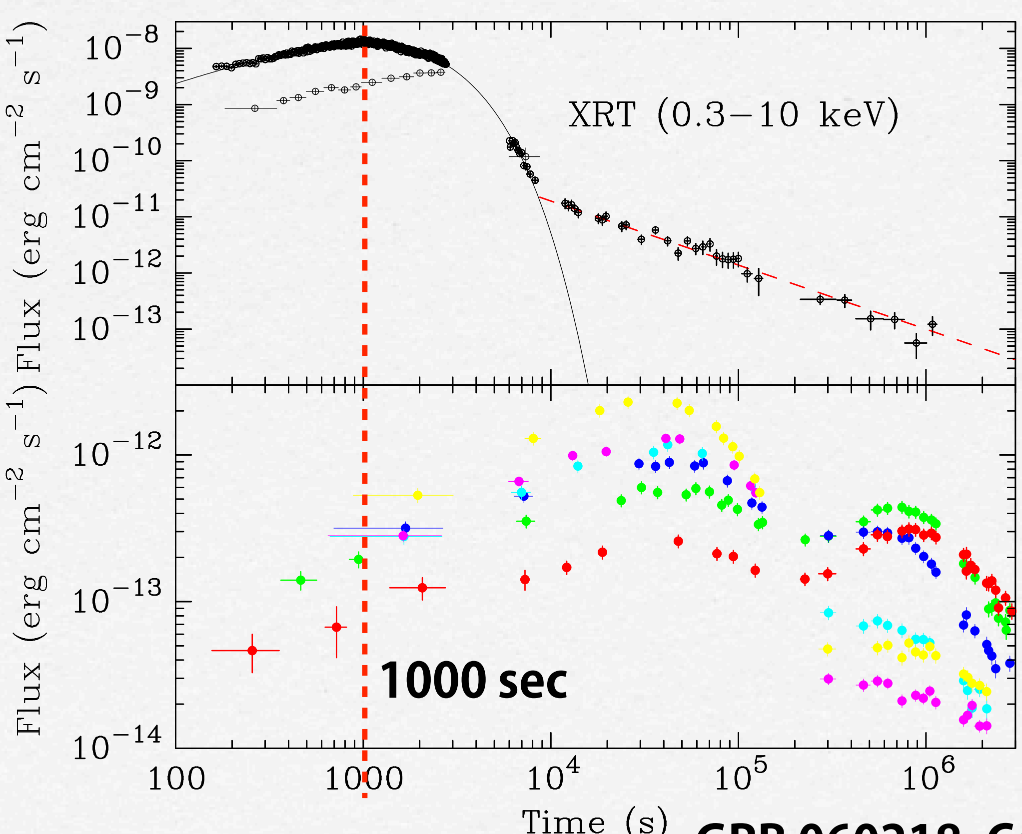
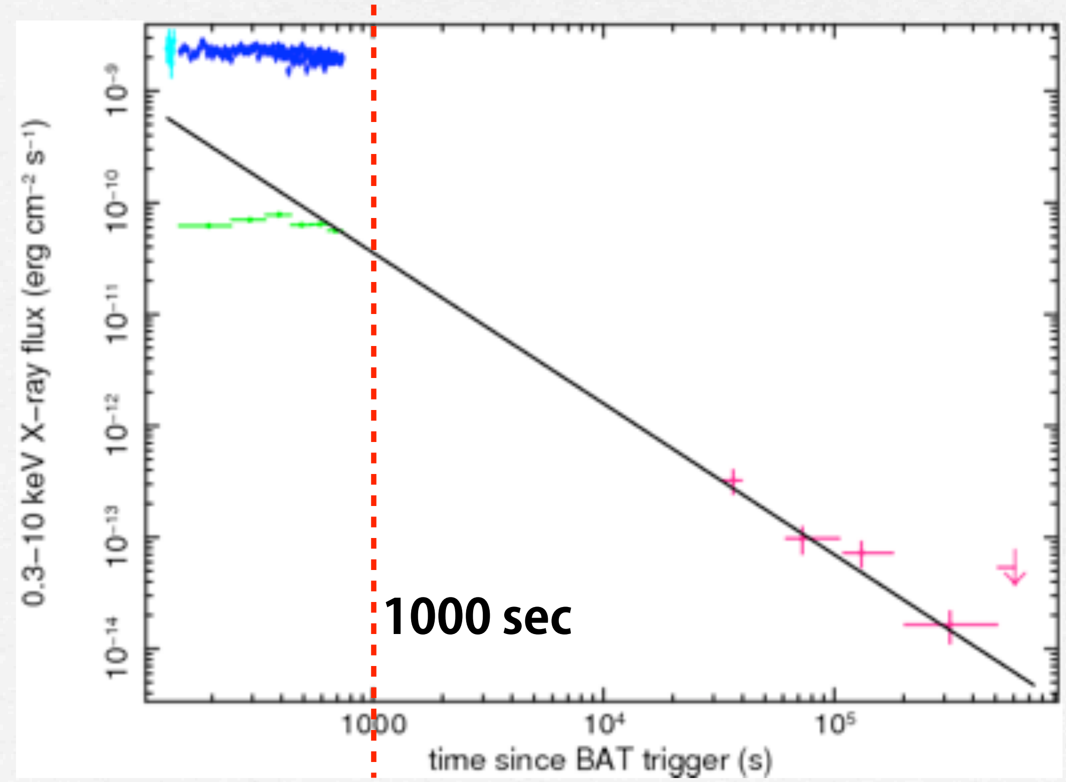


GRB 060218, Campana+ (2006)



GRB 100316D, Starling+ (2011)

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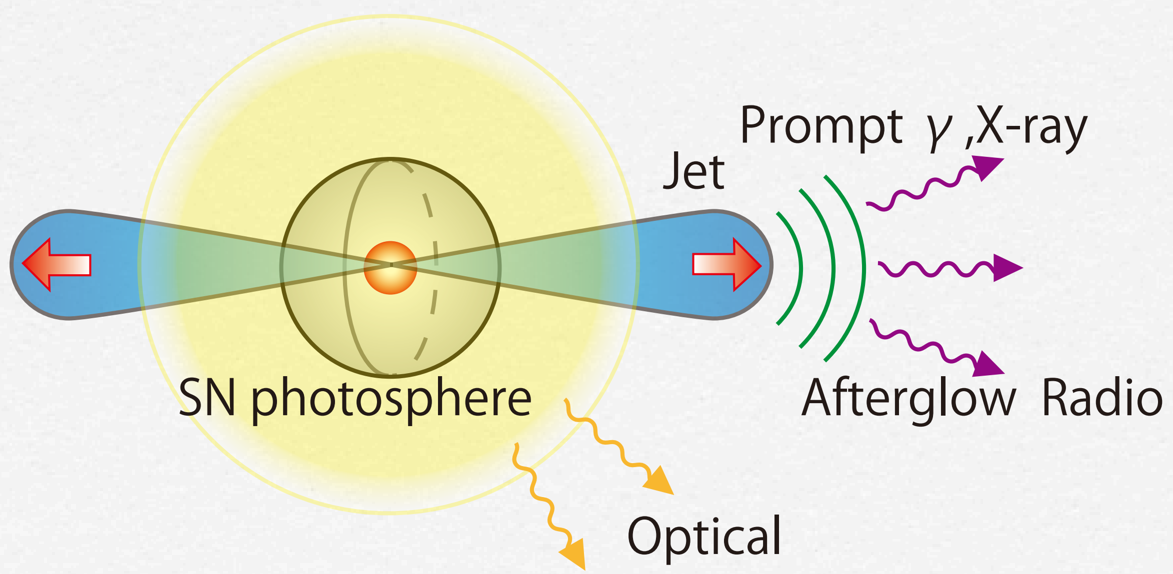
	Luminosity $L_{\gamma,iso}$	Isotropic energy E_{iso}	Duration T_{90}	peak energy E_p
GRB 980425 SN 1998bw	6×10^{46} erg/s	9×10^{47} erg	35 s	122 keV
GRB 060218 SN 2006aj	2×10^{46} erg/s	4×10^{49} erg	2100 s	4.7 keV
GRB 100316D SN 2010bh	5×10^{46} erg/s	6×10^{49} erg	1300 s	18 keV

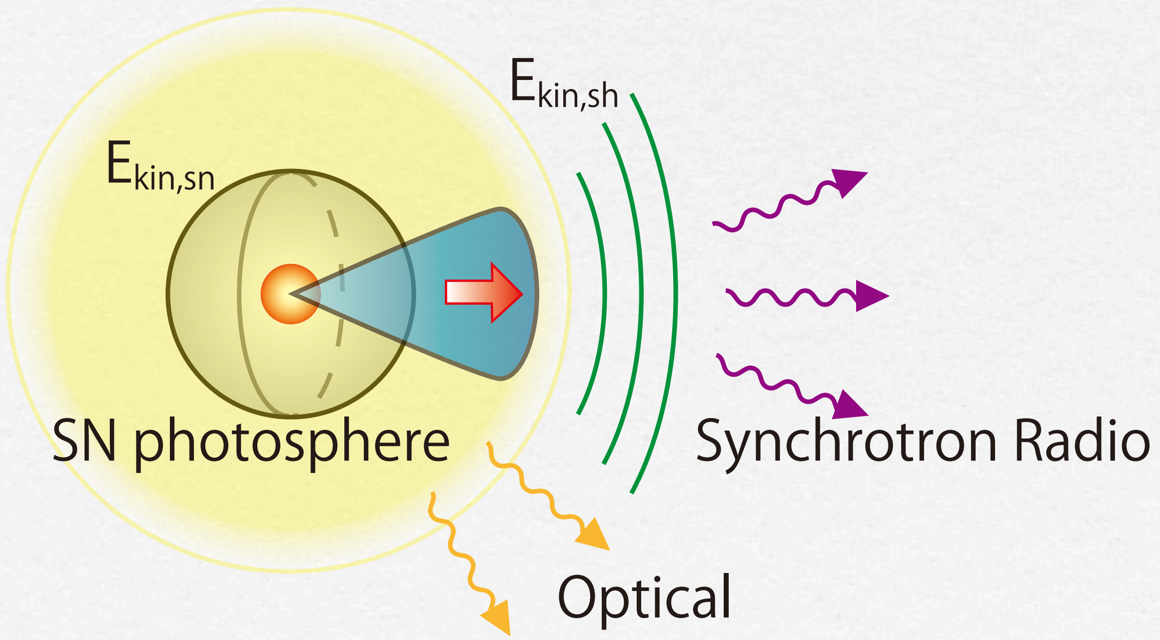
cf. Liso~10^{51} erg/s, Eiso~10^{52-53} erg for standard GRBs

from Hjorth (2011)

Other possible events: low-luminosity GRBs

- Their origin is still under debate....
- SN shock breakout emission from relativistic SNe (in a dense wind)?
  Campana+(2006), Waxman+(2007), Li(2007)
- Weak/Failed/Off axis-viewed jet? engine-activity?
  Pian+(2006), Soderberg+(2006), Toma+(2007)
- We need more events to constrain their origin, event rate, and so on





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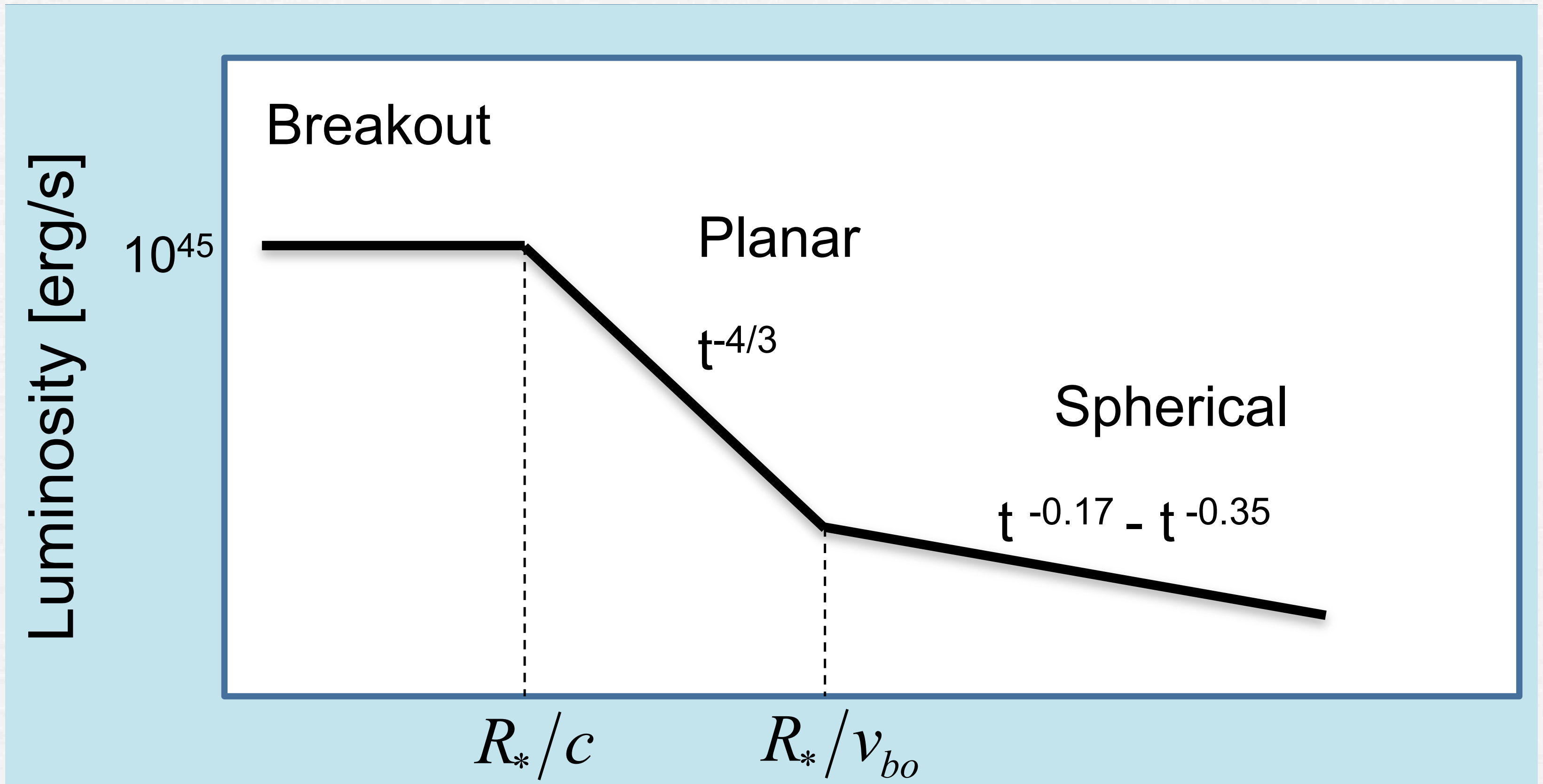
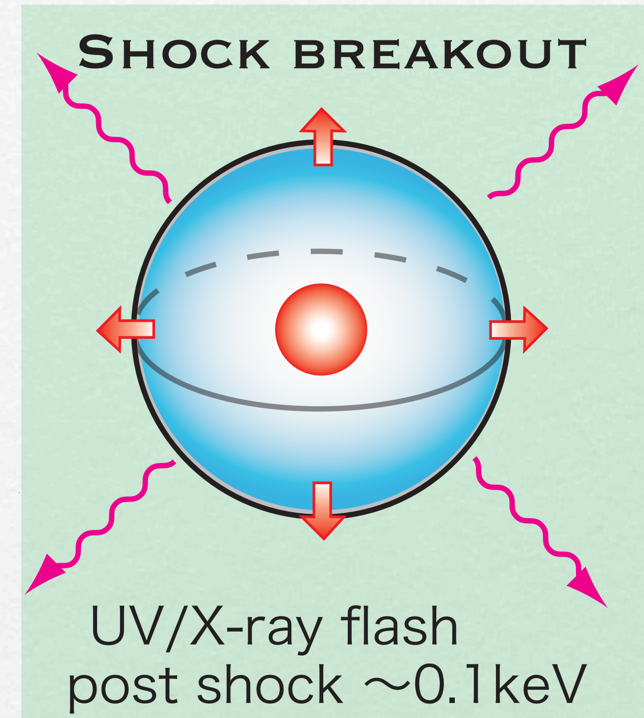
What can we learn from SN breakout?





light crossing time for stellar radius

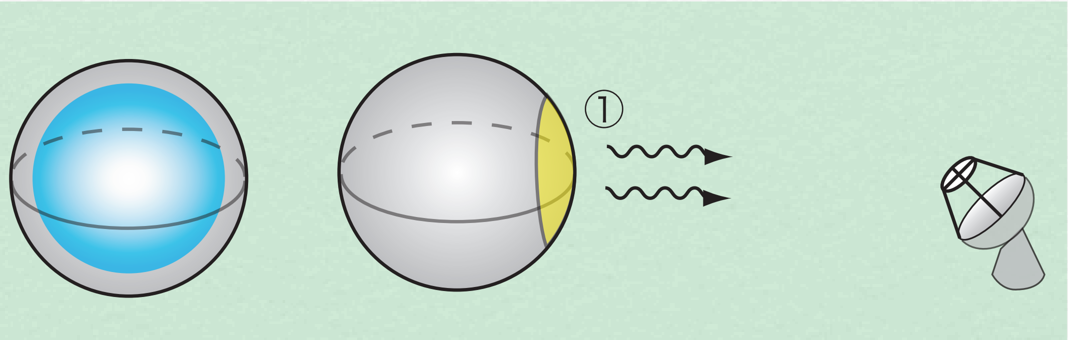
traveling time of ejecta for stellar radius

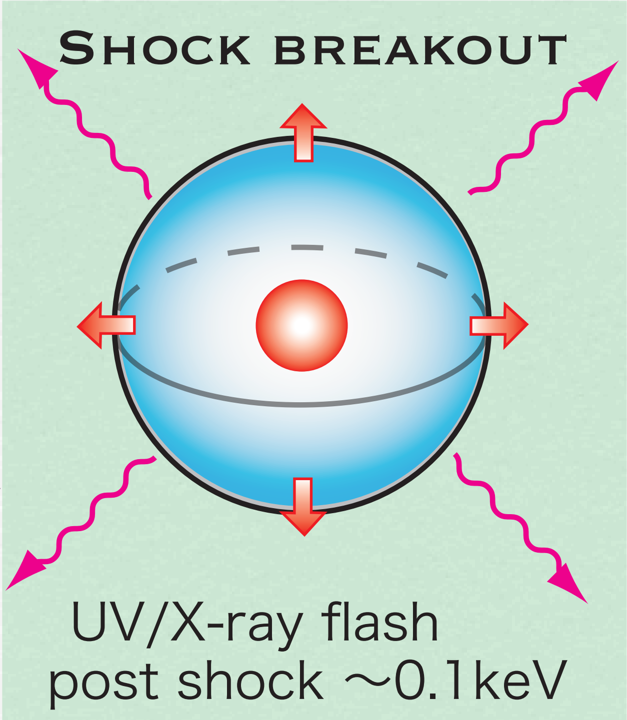
Nakar&Sari(2010)

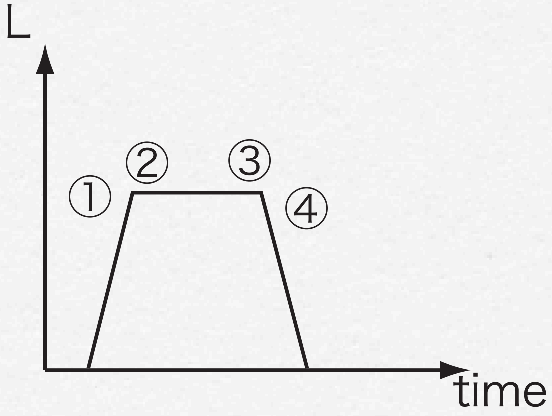
	R★	R★/c	R★/c
WR	~10^{11}cm	3 sec	10-20 sec
BSG	~3×10^{12}cm	100 sec	15 min
RSG	~3×10^{13}cm	15 min	2-3 hr

light curve of shock breakout: spherical case

➡ Shock breakout occurs at every point of the surface at the same time







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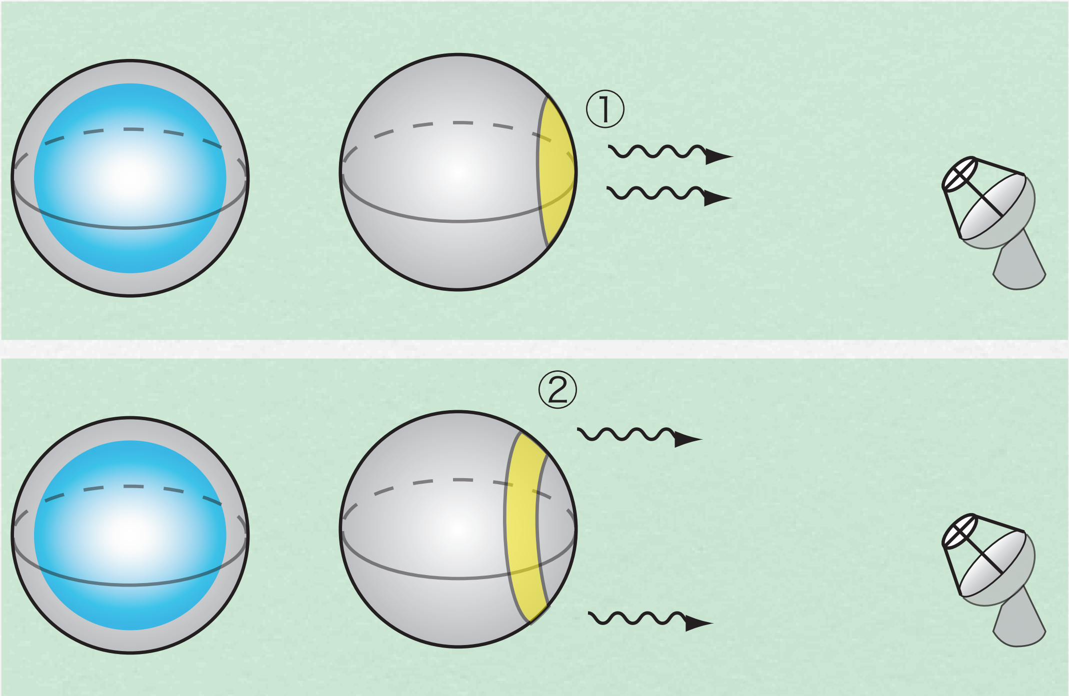

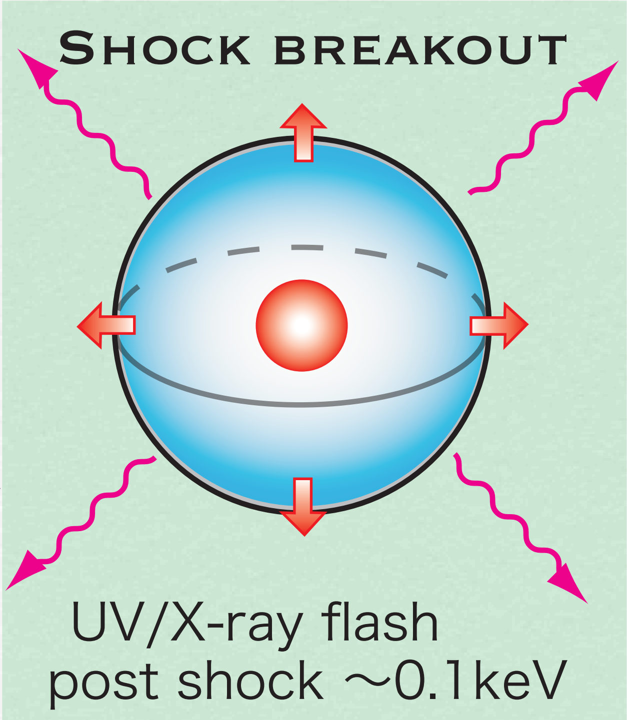

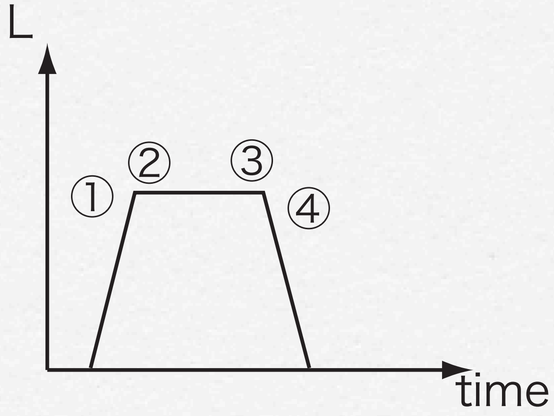

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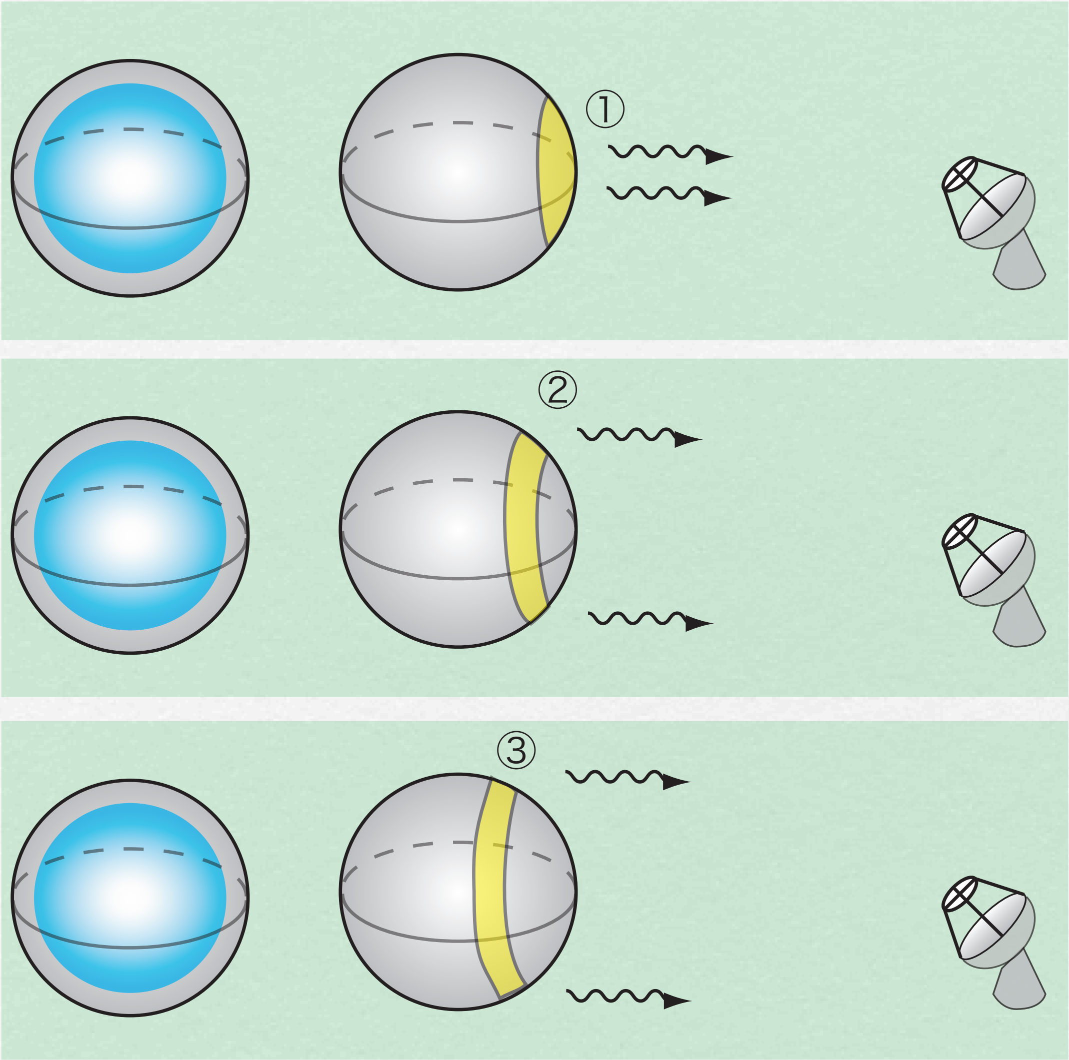

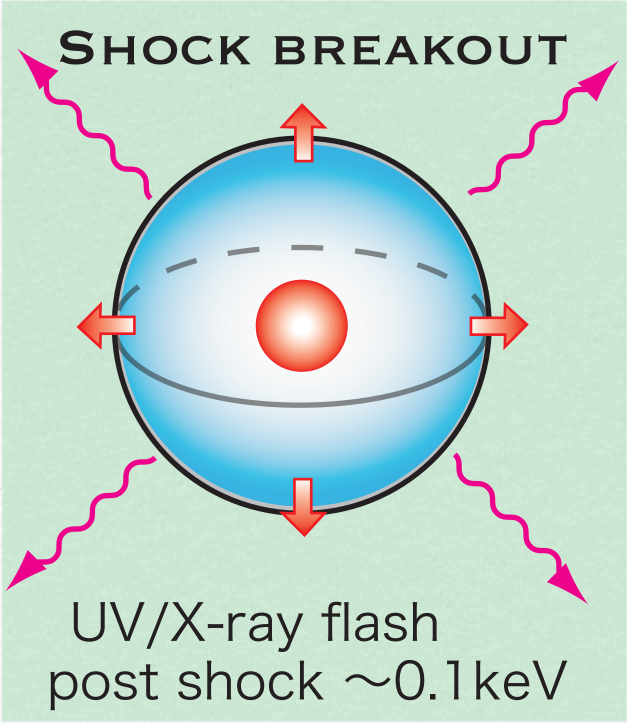

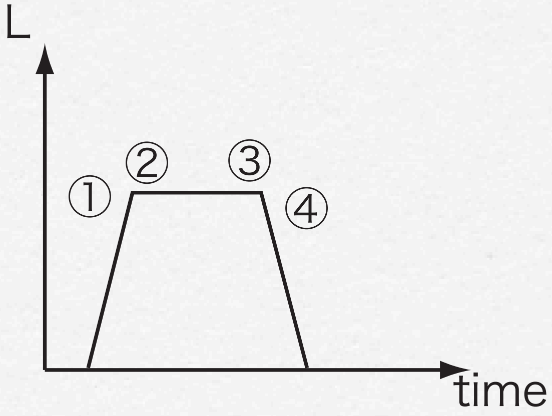

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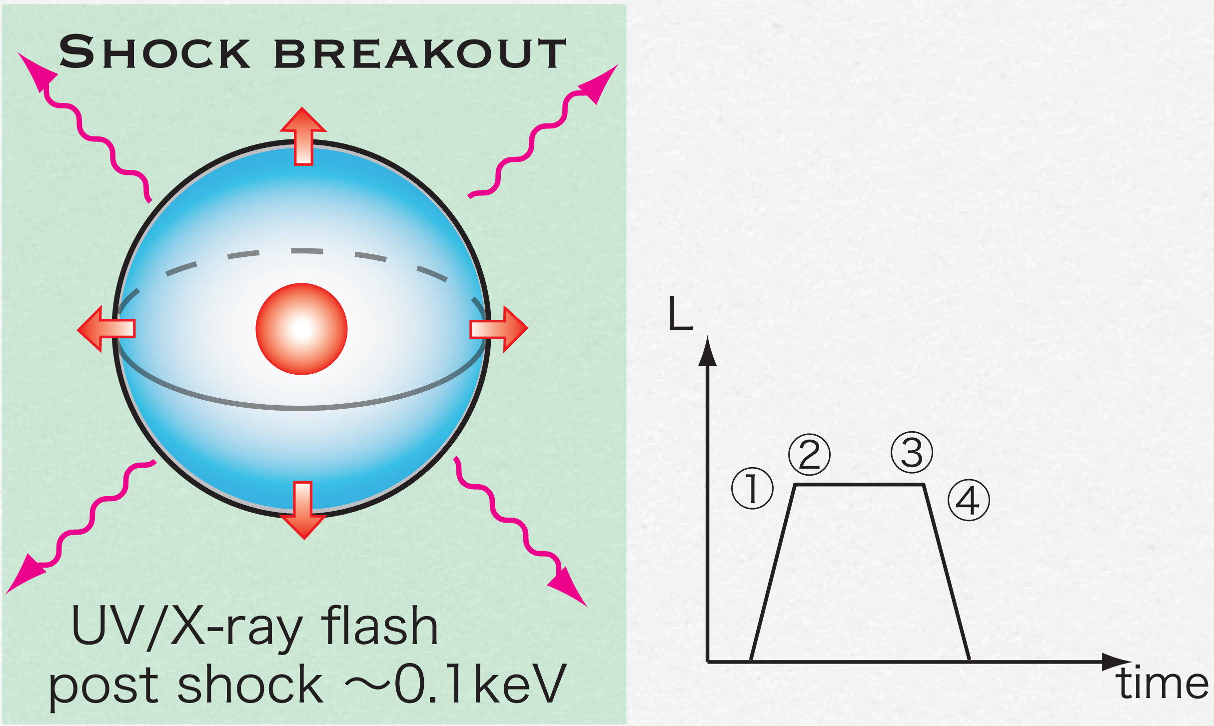

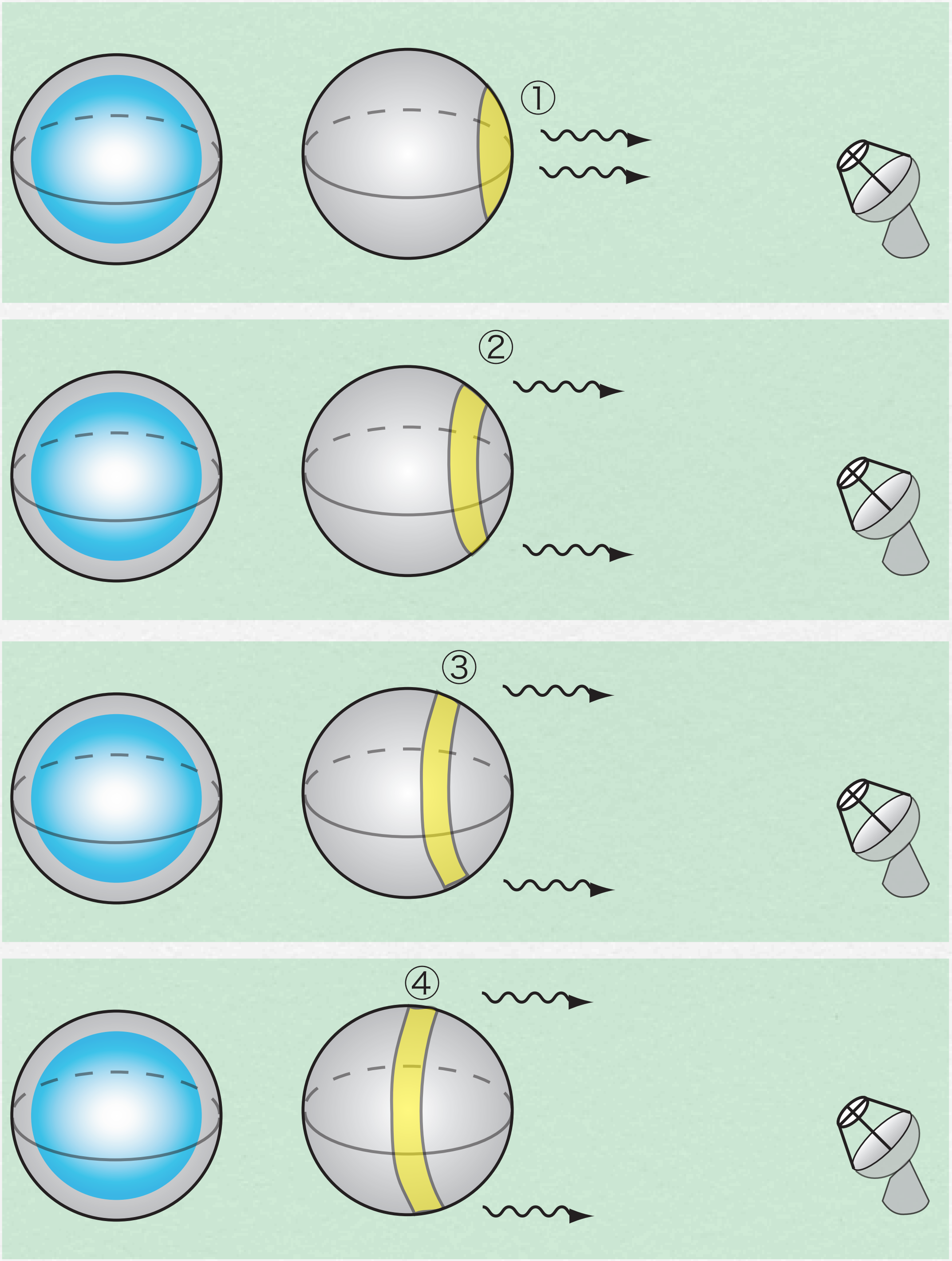

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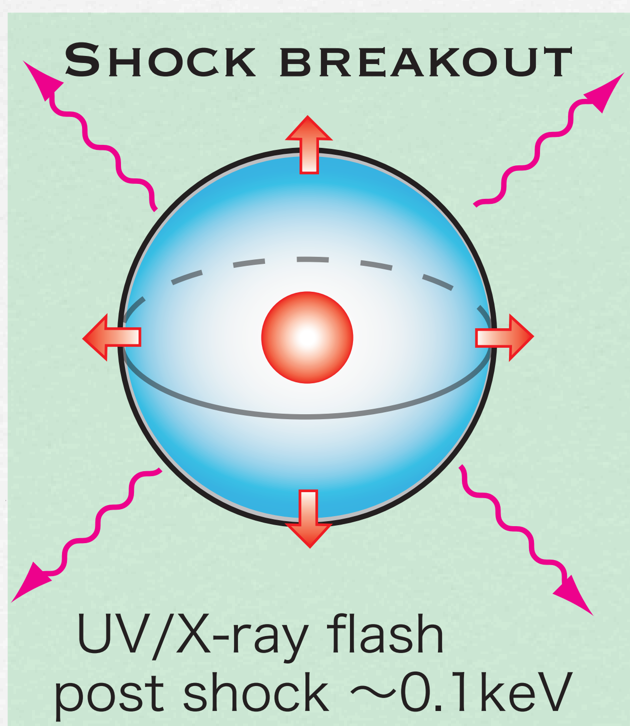
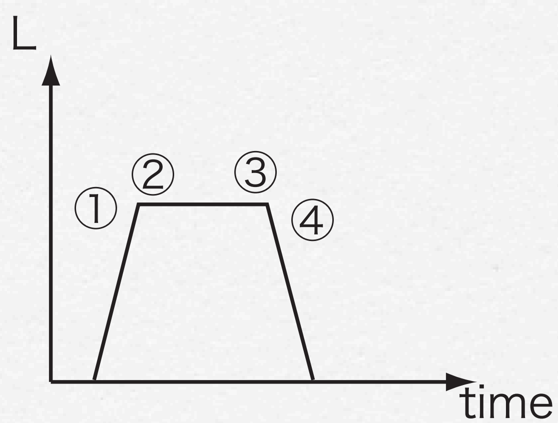
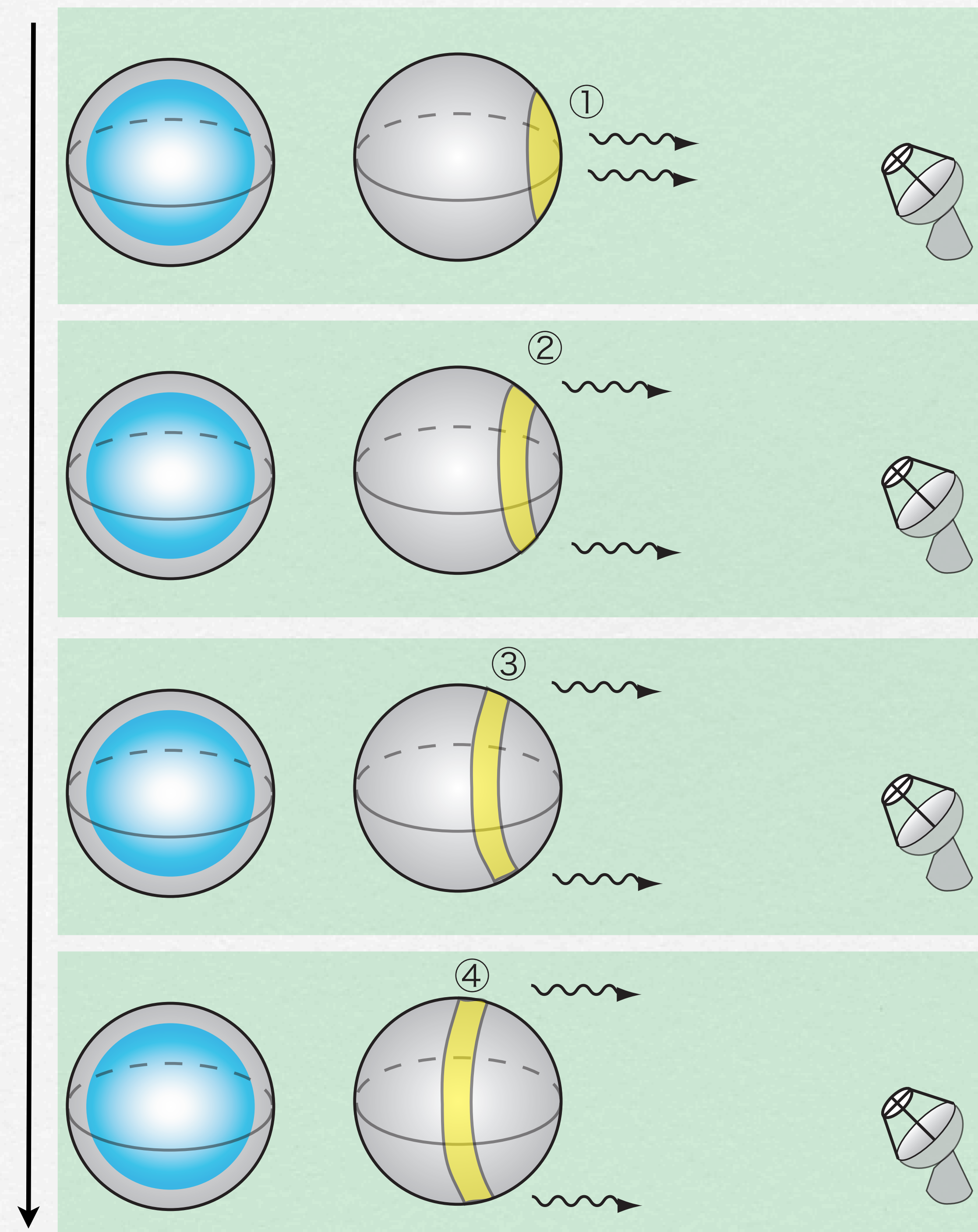
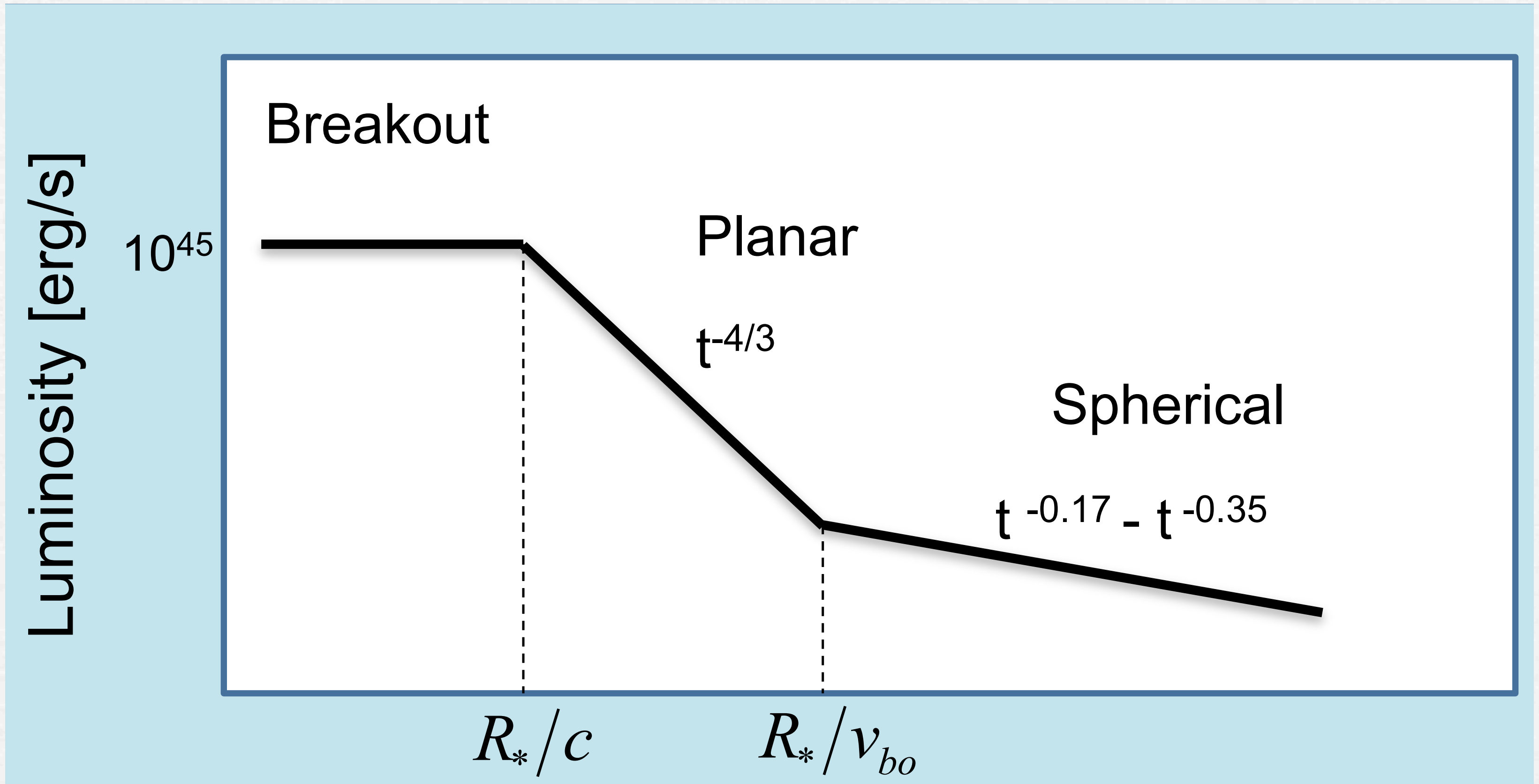




Δt~R★/c

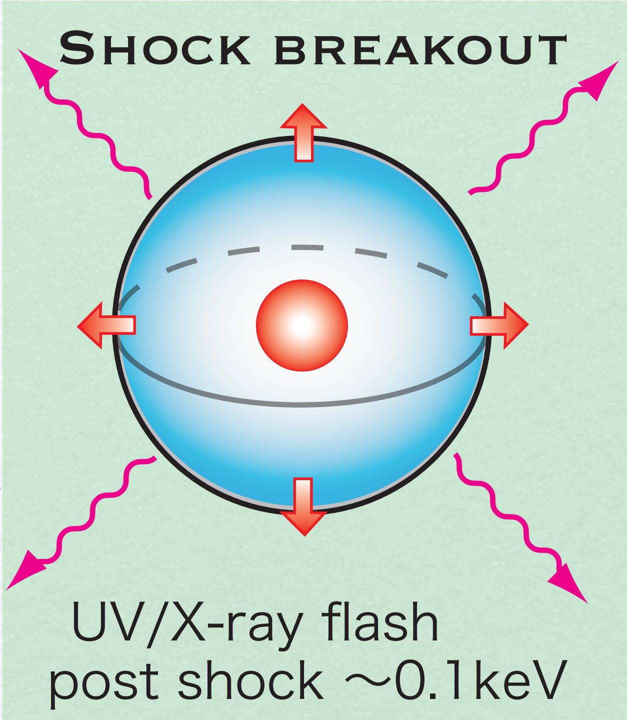


What can we learn from SN breakout?



light crossing time for stellar radius

traveling time of ejecta for stellar radius



Nakar&Sari(2010)

	$R_\star$	$R_\star/c$	$R_\star/v_{ej}$
WR	~10^{11}cm	3 sec	10-20 sec
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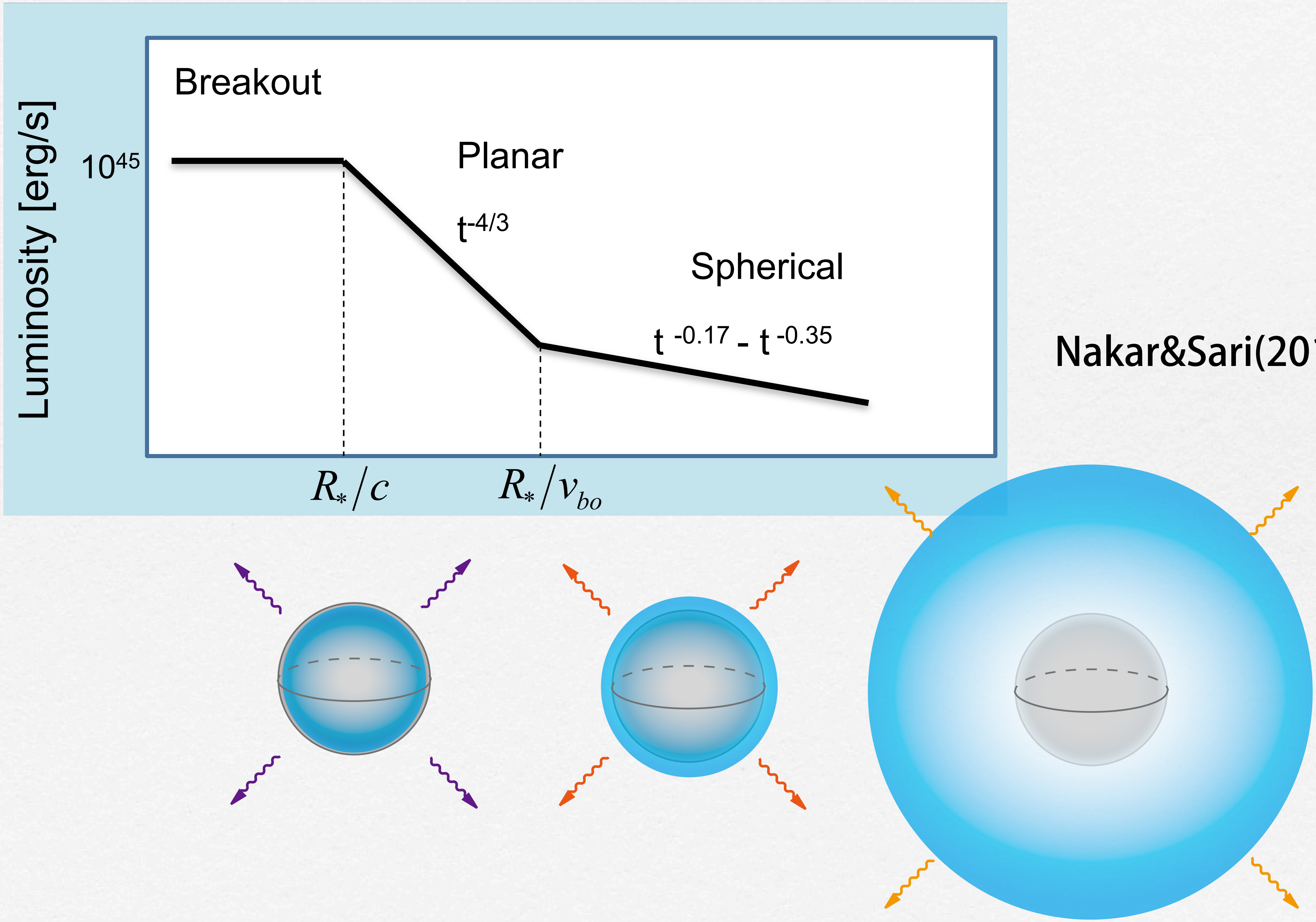
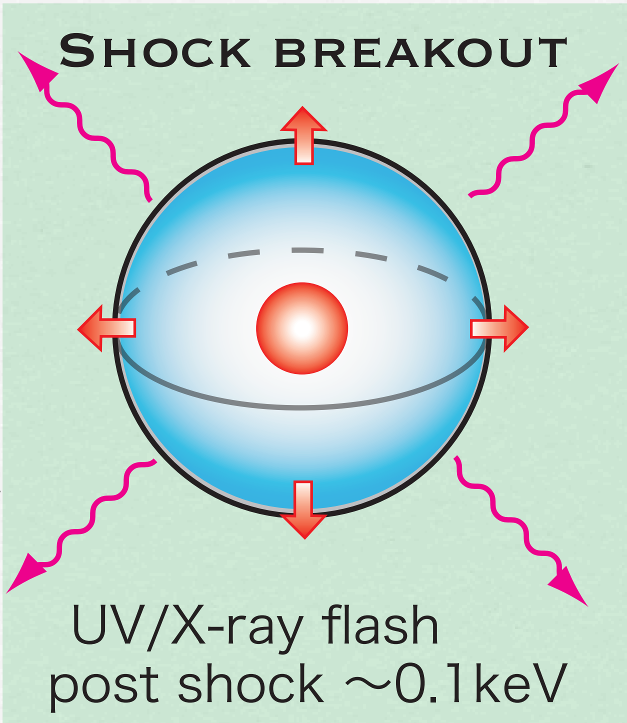


Nakar&Sari(2010)

What can we learn from SN breakout?

➡ large R→long duration ,low T, low v_{ej}

$E_{int}/R_{\star}^3 \sim aT^4$



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

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

$$t_{se} = 790 \left(\frac{\kappa}{0.34\ \mathrm{cm^2\ g^{-1}}}\right)^{-0.58} \left(\frac{\rho_1}{\rho_*}\right)^{-0.28} \times \left(\frac{E_{in}}{10^{51}\ \mathrm{ergs}}\right)^{-0.79} \left(\frac{M_{ej}}{10\ M_\odot}\right)^{0.21} \times \left(\frac{R_*}{500\ R_\odot}\right)^{2.16} \mathrm{s} \quad \left(n = \frac{3}{2}\right),$$

for RSG, Matzner&McKee(1999)

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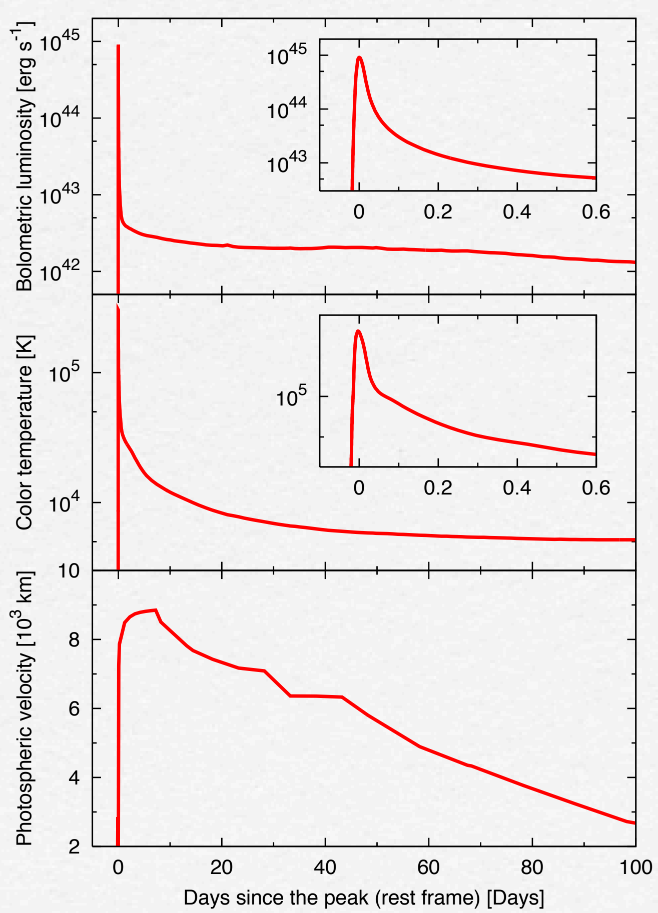

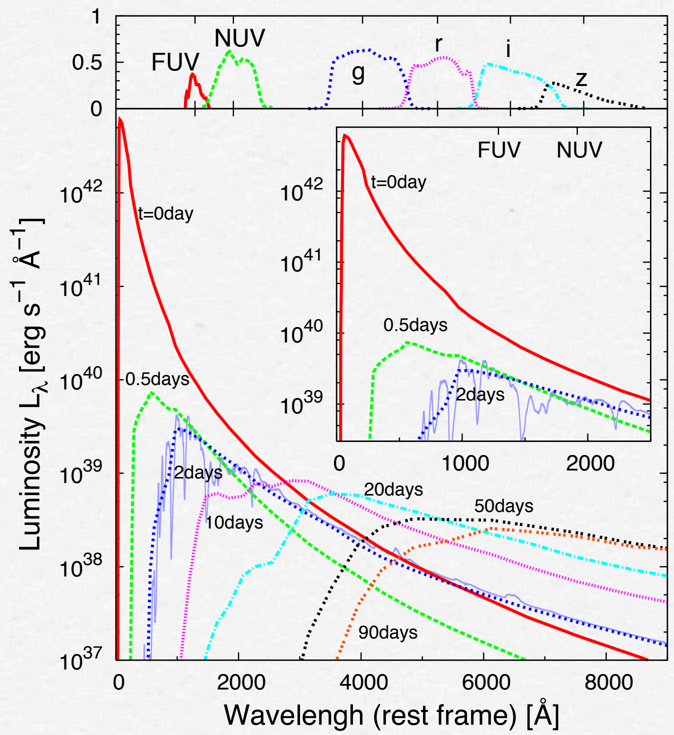

for RSG, Tominaga+(2009)

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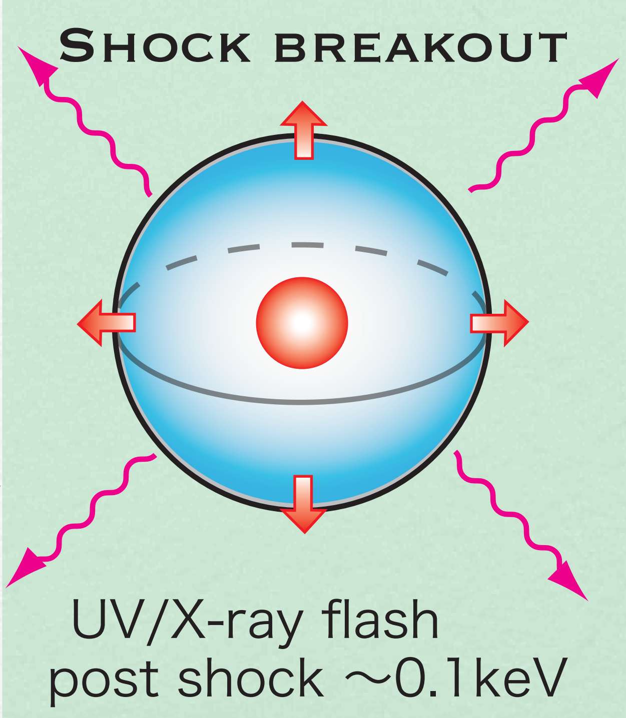
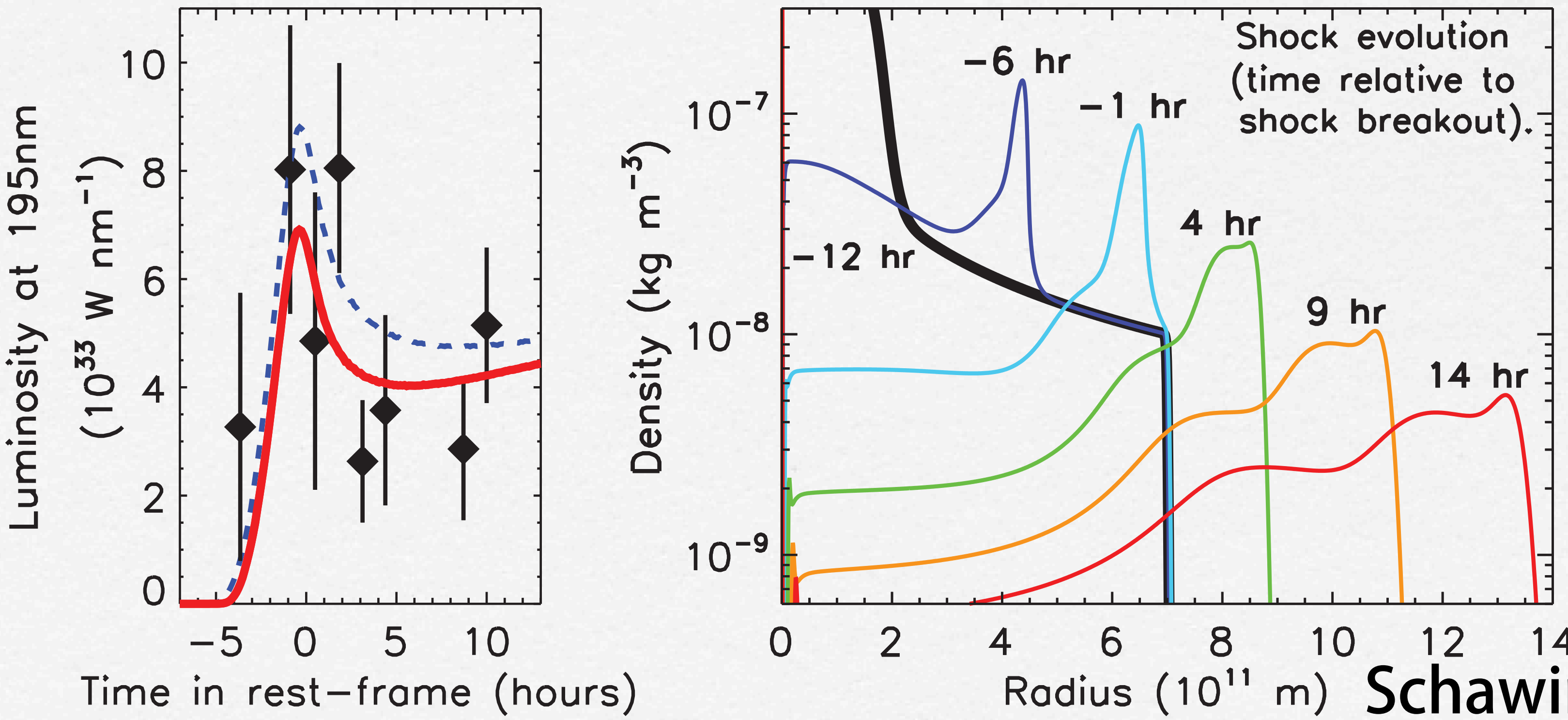


- SNLS-04D2DC
- light curve modeling tells us about the progenitor's radius
- Red giant with $R_\star \sim 1000 R_\odot$(Schawinski+2008), $800 R_\odot$(Tominaga+2009)



Schawinski+(2008)

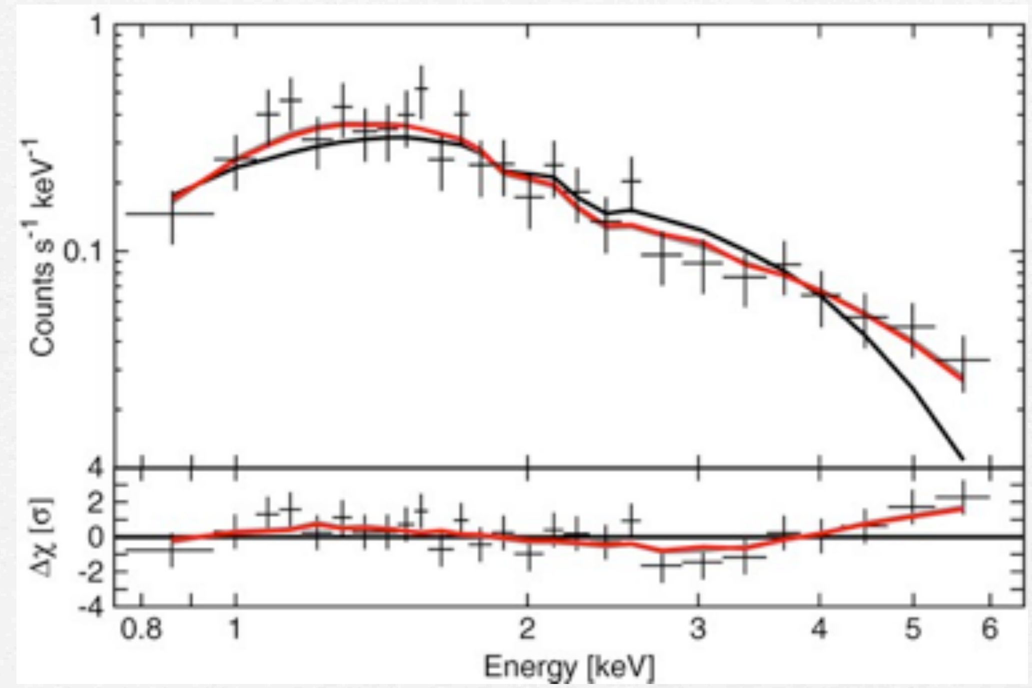
What can we learn from SN breakout?

- SN 2008D (an example of shock breakout detected in X-ray)
- spectrum is uncertain

  if pure BB, kT~0.7keV, $R_\star \sim 2 \times 10^{10}$cm

  if non-thermal, $\Gamma \sim 2$

  if thermal+non-thermal, kT~0.1keV → $R_\star \sim 10^{11}$cm
- duration 300 sec → $R_\star \sim 10^{13}$cm?
- photosphere in stellar wind?



Modjaz+(2009)

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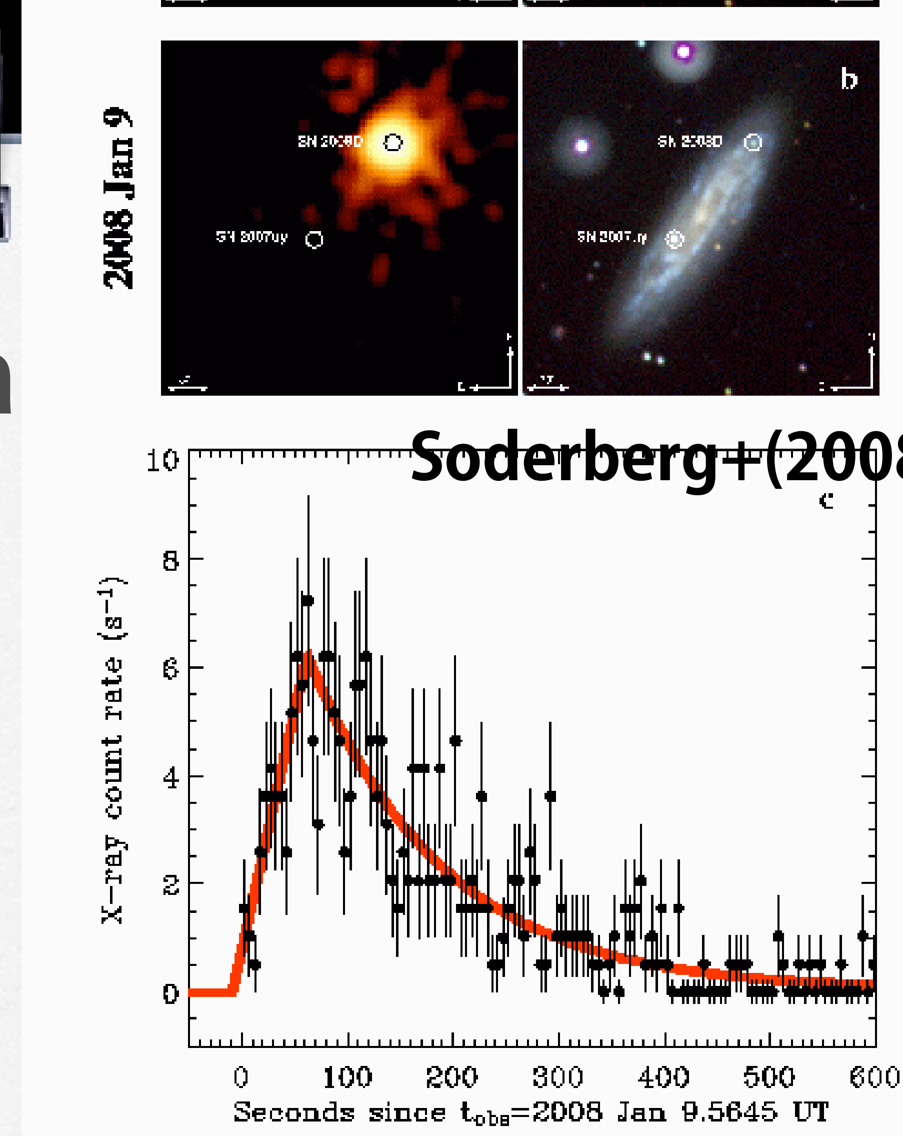

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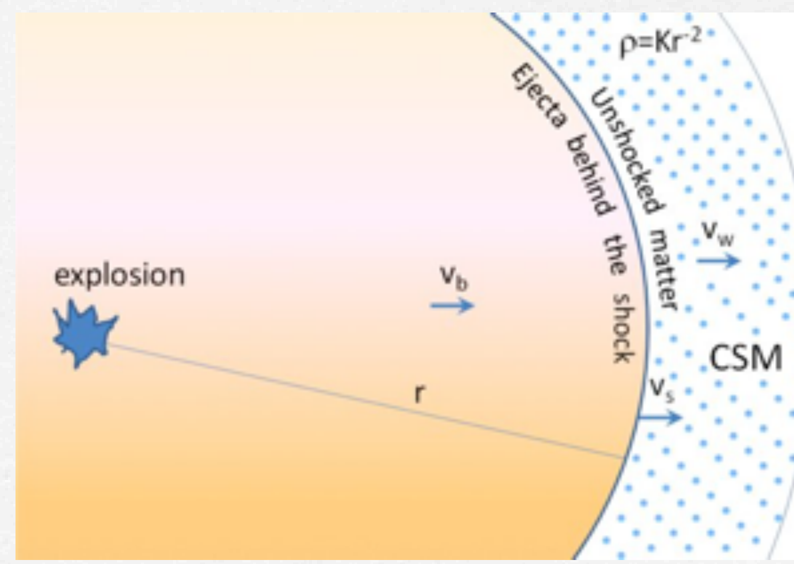

Ofek+(2011)

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Theoretical works on SN shock breakout

- ➡ **pioneering works:** Colgate (1974), Klein&Chevalier(1976), Falk (1978), Imshennik and Nadyozhin(1988), Matzner&McKee(1999)
- ➡ **steady shock structure:** Weaver(1976),Katz+(2010),Budnik+(2010)
- ➡ **analytical**: Naker&Sari(2010,2011),Rabinak&Waxman(2012),
- ➡ **1D RHD**: Ensmann&Burrows(1992), Tominaga+(2009), Sapir+(2011,2013)
- ➡ **multi-D HD**: Suzuki&Shigeyama(2010),Couch+(2011), Ro&Matzner(2013), Matzner+(2013)
- ➡ **wind breakout**: Arcavi+(2011), Chevalier&Irwin(2011), Moriya&Tominaga(2011), Ofek+(2011), Svirsky+(2012),
- ➡ **1D SR-RHD**: Tolstov+(2013)

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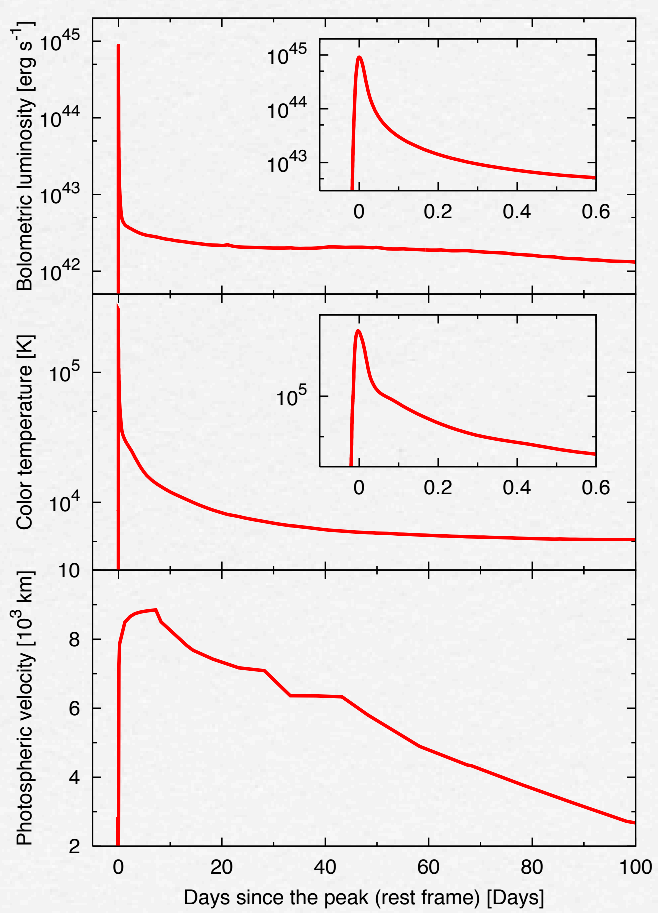
- ➡ **1D SR-RHD**: Tolstov+(2013)

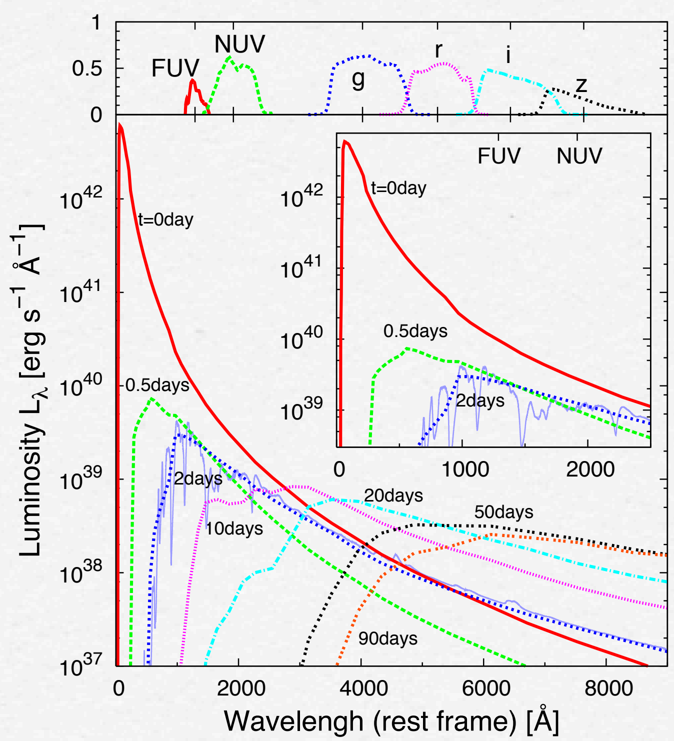
→ toward multi-D SR-RHD

Shock breakout from compact progenitor

➡ large R→large E ,long duration ,low T

compact star = high T, sub-relativistic velocity





for RSG, Tominaga+(2009)

$$T_{\rm se} = 5.55\times10^5\left(\frac{\kappa}{0.34\ {\rm cm^2\ g^{-1}}}\right)^{-0.10}\left(\frac{\rho_1}{\rho_*}\right)^{0.070}\times\left(\frac{E_{\rm in}}{10^{51}\ {\rm ergs}}\right)^{0.20}\left(\frac{M_{\rm ej}}{10\ M_\odot}\right)^{-0.052}\times\left(\frac{R_*}{500\ R_\odot}\right)^{-0.54}\ {\rm K}\quad\left(n=\frac{3}{2}\right),$$

$$E_{\rm se} = 1.7\times10^{48}\left(\frac{\kappa}{0.34\ {\rm cm^2\ g^{-1}}}\right)^{-0.87}\left(\frac{\rho_1}{\rho_*}\right)^{-0.086}\times\left(\frac{E_{\rm in}}{10^{51}\ {\rm ergs}}\right)^{0.56}\left(\frac{M_{\rm ej}}{10\ M_\odot}\right)^{-0.44}\times\left(\frac{R_*}{500\ R_\odot}\right)^{1.74}\ {\rm ergs}\quad\left(n=\frac{3}{2}\right),$$

$$t_{\rm se} = 790\left(\frac{\kappa}{0.34\ {\rm cm^2\ g^{-1}}}\right)^{-0.58}\left(\frac{\rho_1}{\rho_*}\right)^{-0.28}\times\left(\frac{E_{\rm in}}{10^{51}\ {\rm ergs}}\right)^{-0.79}\left(\frac{M_{\rm ej}}{10\ M_\odot}\right)^{0.21}\times\left(\frac{R_*}{500\ R_\odot}\right)^{2.16}\ {\rm s}\quad\left(n=\frac{3}{2}\right),$$

for RSG, Matzner&McKee(1999)

Shock breakout from compact progenitor

- ➡ It is known that the shock wave propagates their atmosphere at sub-relativistic speeds
- ➡ We need special relativistic radiation-hydrodynamics simulations
- ➡ I present results of our recent study on shock breakout simulations with SR-RHD code we developed

Matzner&McKee(1999)

$$v_{f\max} = 33{,}000\left(\frac{\kappa}{0.34\ \mathrm{cm^2\ g^{-1}}}\right)^{0.16}\left(\frac{\rho_1}{\rho_*}\right)^{-0.054} \times \left(\frac{E_{\mathrm{in}}}{10^{51}\ \mathrm{ergs}}\right)^{0.58}\left(\frac{M_{\mathrm{ej}}}{10\ M_\odot}\right)^{-0.42} \times \left(\frac{R_*}{50\ R_\odot}\right)^{-0.32}\ \mathrm{km\ s^{-1}} \quad (n=3)\ .$$

Radiation Hydrodynamics code

➡ Moment equations written in "mixed frame"

$$\frac{\partial I_\nu(t,\boldsymbol{x},\boldsymbol{l})}{\partial t} + (\boldsymbol{l}\cdot\nabla)I_\nu(t,\boldsymbol{x},\boldsymbol{l}) = \eta_\nu + \int g(\nu,\boldsymbol{l};\nu'\boldsymbol{l}')\rho\sigma_\nu I_{\nu'}(t,\boldsymbol{x},\boldsymbol{l}')d\nu' d\Omega' - \rho(\kappa_\nu+\sigma_\nu)I_\nu(t,\boldsymbol{x},\boldsymbol{l})$$

Transfer equation

$$E_{\rm r}(t,\boldsymbol{x}) = \int E_{{\rm r},\nu}(t,\boldsymbol{x})d\nu = \int I_\nu(t,\boldsymbol{x},\boldsymbol{l})d\nu d\Omega$$

$$F^i_{\rm r}(t,\boldsymbol{x}) = \int F^i_{{\rm r},\nu}(t,\boldsymbol{x})d\nu = \int l^i I_\nu(t,\boldsymbol{x},\boldsymbol{l})d\nu d\Omega$$

$$P^{ij}_{\rm r}(t,\boldsymbol{x}) = \int P^{ij}_{{\rm r},\nu}(t,\boldsymbol{x})d\nu = \int l^i l^j I_\nu(t,\boldsymbol{x},\boldsymbol{l})d\nu d\Omega$$

Moment equations

$$\frac{\partial E_{\rm r}}{\partial t} + \frac{\partial F^i_{\rm r}}{\partial x^i} = \rho_0\kappa_0(a_{\rm r}T^4_{g0} - E_{\rm r}) + \rho_0\kappa_0\beta_j F^j_{\rm r} - \rho_0\sigma_0\beta_j F^i_{\rm r}$$

$$\frac{\partial F^i_{\rm r}}{\partial t} + \frac{\partial P^{ij}_{\rm r}}{\partial x^j} = \rho_0\kappa_0 a_{\rm r}T^4_{g0}\beta^i + \rho_0\sigma_0 E_{\rm r}\beta^i - \rho_0(\kappa_0+\sigma_0)(F^i_{\rm r} - \beta_j P^{ij}_{\rm r})$$

M1 Closure relation

$$P^{ij}_{\rm r} = D^{ij}E_{\rm r}, \quad D^{ij} = \frac{1-\chi}{2}\delta^{ij} + \frac{3-\chi}{2}n^i n_j$$

$$n^i = \frac{F^i_{\rm r}}{\sqrt{F^i_{\rm r}F_{{\rm r},i}}}, \quad f^i = \frac{F^i_{\rm r}}{E_{\rm r}}, \quad \chi = \frac{3+4f^i f_i}{5+2\sqrt{4-3f^i f_i}}$$

Livermore (1984)

➡ advection term: HLL

➡ source term: implicit method

see, Takahashi+,Takahashi&Ohsuga(2013a,b)

Radiation Hydrodynamics code

➡ Moment eq

$$\frac{\partial I_\nu(t,\boldsymbol{x},\boldsymbol{l})}{\partial t} + (\boldsymbol{l}\cdot\nabla)I_\nu(t,$$

Transfer equa

$$\frac{\partial(\rho_0\Gamma)}{\partial t} + \frac{\partial(\rho_0\Gamma\beta^j)}{\partial x^j} = 0$$

$$\frac{\partial(\rho_0 h\Gamma^2\beta^i)}{\partial t} + \frac{\partial(\rho_0 h\Gamma^2\beta^i\beta^j + P\delta^{ij})}{\partial x^j} = G^i$$

$$\frac{\partial(\rho_0 h\Gamma^2 - P)}{\partial t} + \frac{\partial(\rho_0 h\Gamma^2\beta^i)}{\partial x^j} = G^0$$

EOS: ideal gas

Moment equations

$$\frac{\partial E_{\rm r}}{\partial t} + \frac{\partial F_{\rm r}^i}{\partial x^i} = \rho_0\kappa_0(a_{\rm r}T_{g0}^4 - E_{\rm r}) + \rho_0\kappa_0\beta_j F_{\rm r}^j - \rho_0\sigma_0\beta_j F_{\rm r}^i$$

$$\frac{\partial F_{\rm r}^i}{\partial t} + \frac{\partial P_{\rm r}^{ij}}{\partial x^j} = \rho_0\kappa_0 a_{\rm r}T_{g0}^4\beta^i + \rho_0\sigma_0 E_{\rm r}\beta^i - \rho_0(\kappa_0+\sigma_0)(F_{\rm r}^i - \beta_j P_{\rm r}^{ij})$$

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Livermore (1984)

➡ advection term: HLL

➡ source term: implicit method

see, Takahashi+,Takahashi&Ohsuga(2013a,b)

1D SR-RHD simulation

Model atmosphere

- ➡ Plane-parallel
- ➡ Polytropic : $P \propto \rho^{4/3}$ $\rightarrow$ Analytical expression of profiles
- ➡ mass M_*,radius R_*,luminosity L_* -> atmosphere model
- ➡ a compact star with $M_*=10M_\odot$,$R_*=1R_\odot$,$L_*=0.1L_{edd}$

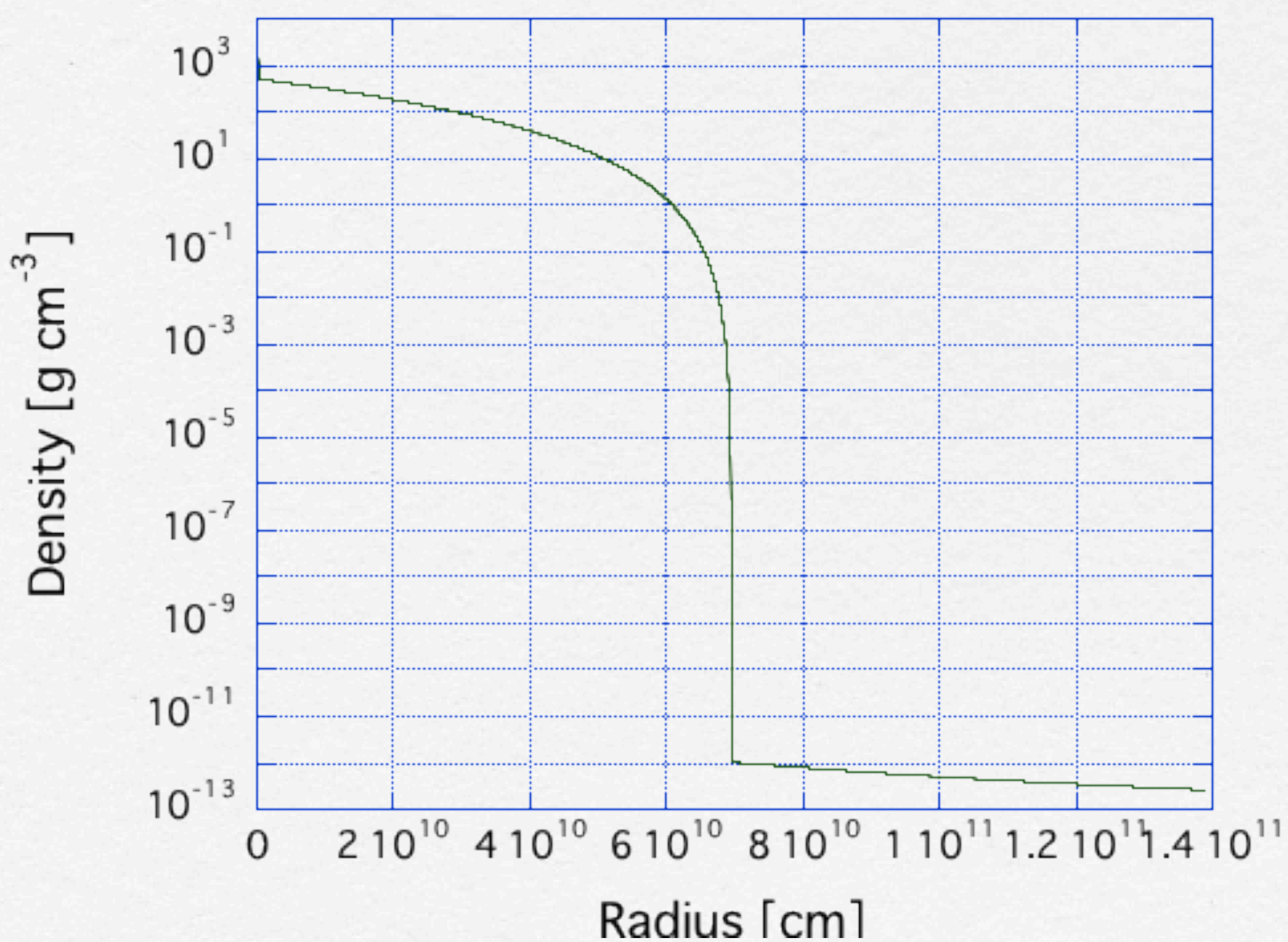
$$\rho = \frac{a}{192}\frac{\beta^4}{1-\beta}\left(\frac{\mu m_\mathrm{H}}{k_\mathrm{B}}\right)^4\left(\frac{GM_*}{R_*}\right)^3\left(1-\frac{r}{R_*}\right)^3$$

$$P_\mathrm{tot} = \frac{a}{768}\frac{\beta^4}{1-\beta}\left(\frac{\mu m_\mathrm{H}}{k_\mathrm{B}}\right)^4\left(\frac{GM_*}{R_*}\right)^4\left(1-\frac{r}{R_*}\right)^4$$

$$1-\beta = \frac{\kappa L_*}{4\pi c G M_*} = \frac{L_*}{L_\mathrm{edd}}$$

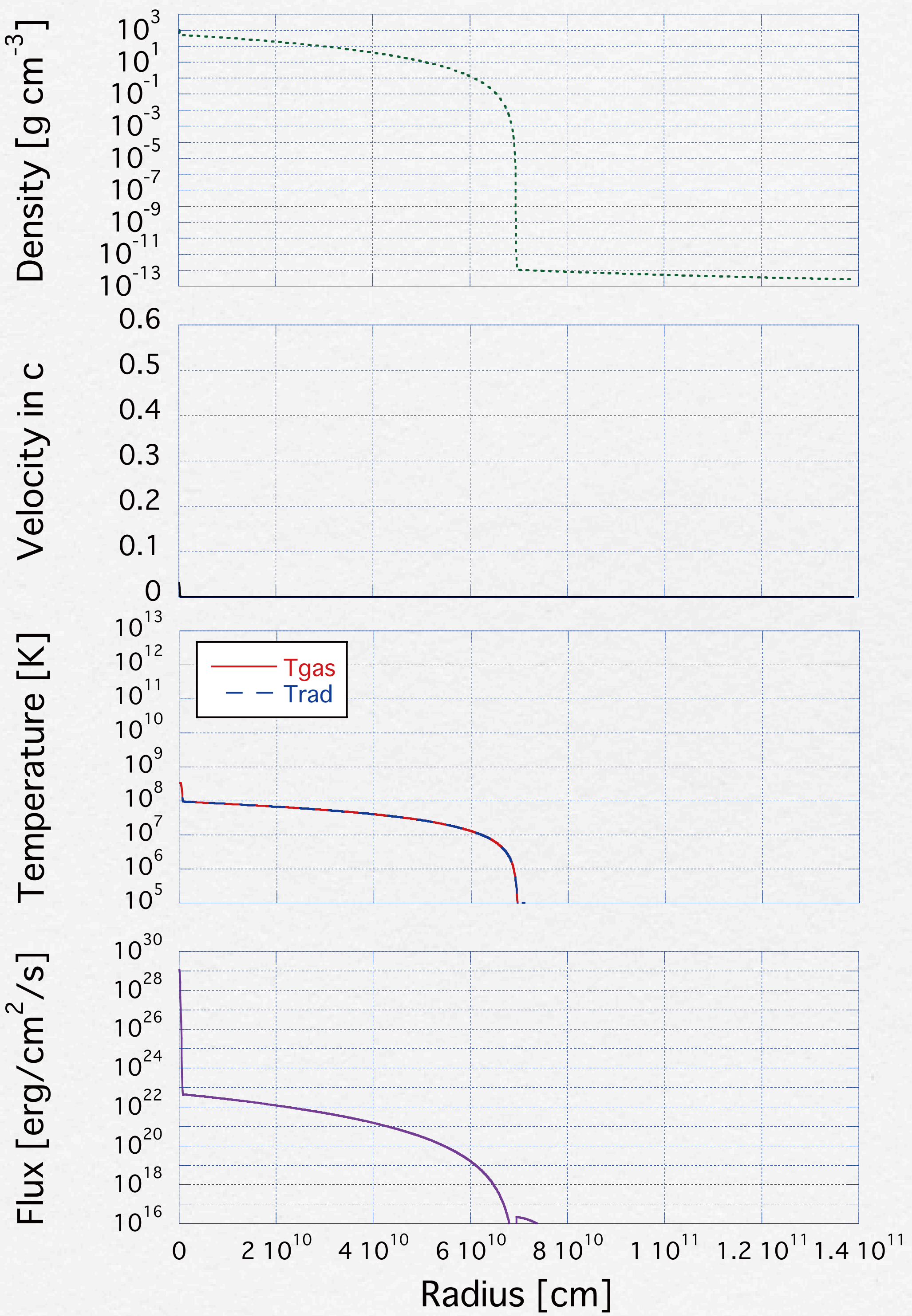
Shock injection

- ➡ mass M_*,radius R_*,luminosity L_*
- ➡ a compact star with $M_*=10M_\odot$,$R_*=1R_\odot$,$L_*=0.1L_{edd}$
- ➡ we inject a strong shock from the inner boundar
- ➡ $v_{in}=10^9$ cm/s



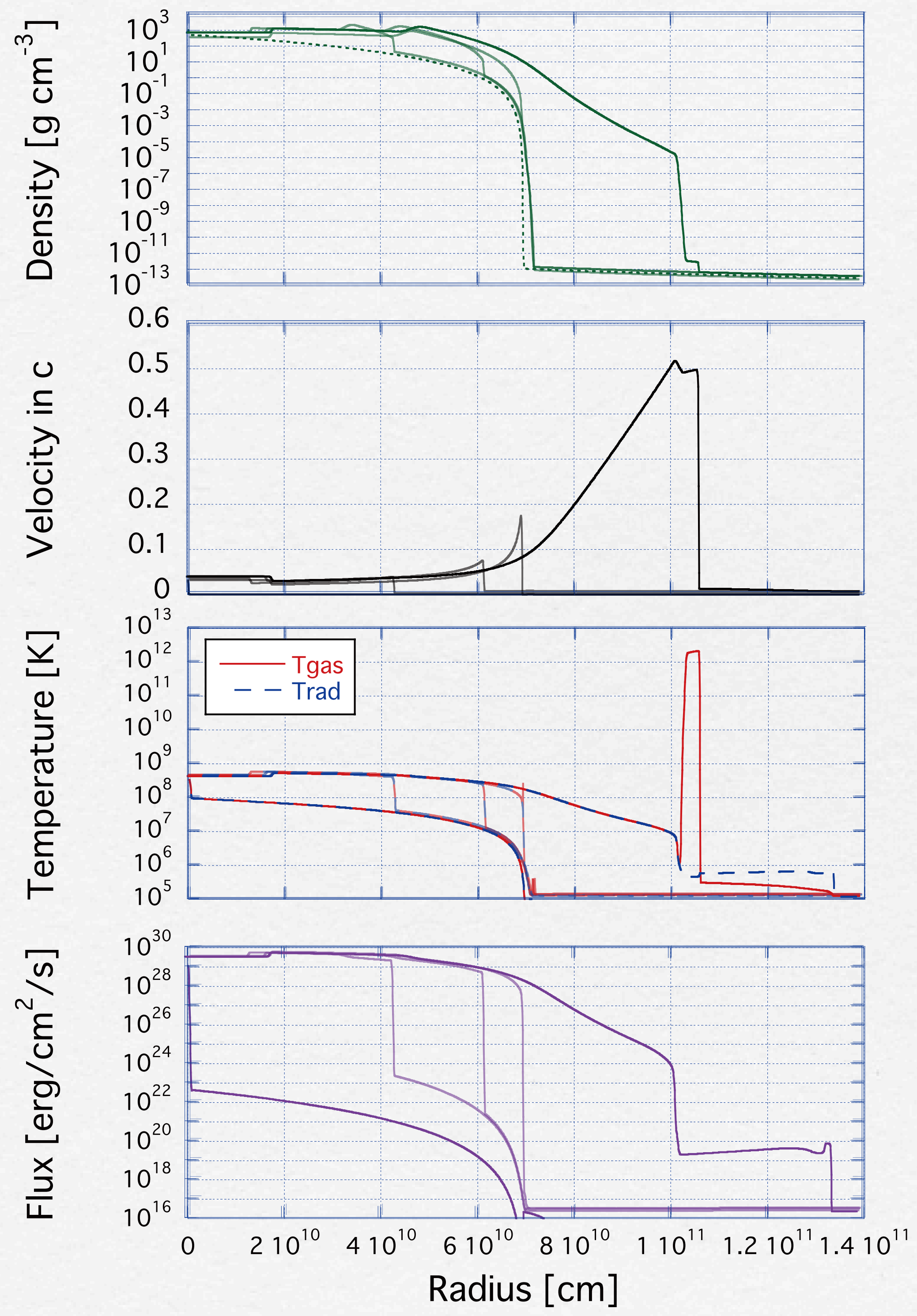
Results of 1D shock breakout

➡ initial setup



Results of 1D shock breakout

- ➡ initial setup
- ➡ strong shock propagates to the surface
- ➡ gas and radiation are strongly coupled with each other
- ➡ velocity reaches 0.1-0.2c before the breakout
- ➡ after the breakout,

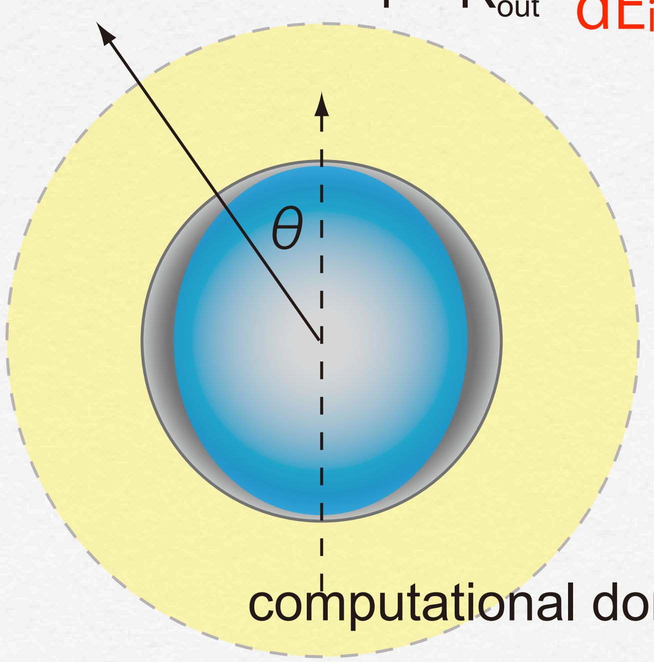


2D SR-RHD simulation

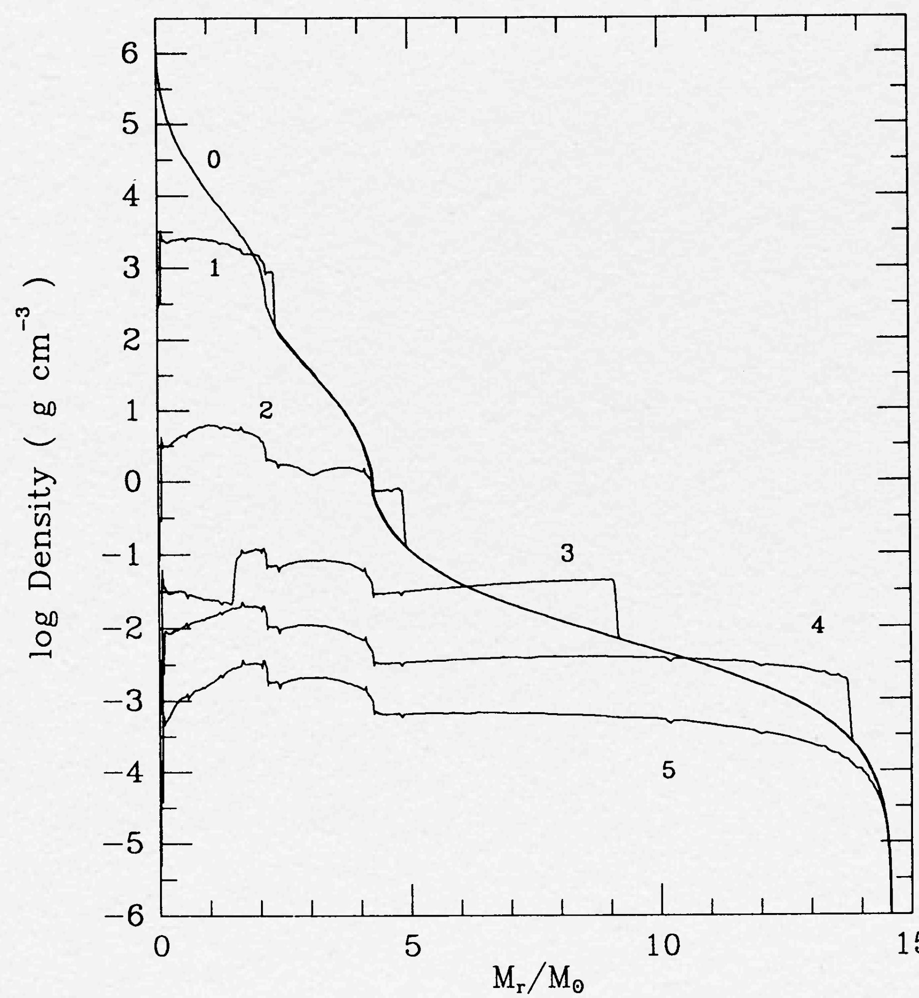
Shock breakout in 2D

- ➡ 2D RHD simulations
- ➡ 1987A progenitor: BSG with $R_\star=50R_\odot$, $M_\star=14.6M_\odot$
  (Nomoto&Hashimoto 1988, Shigeyama&Nomoto 1990)
- ➡ $3\times10^8\mathrm{cm}\leqq r\leqq 4R_\star$, $0\leqq\theta\leqq\pi$
- ➡ energy injection: $E_{exp}=10^{51}$[erg], $t_{exp}=0.1$[s]
- ➡ asphericity: parameter a

$dE_{int}/dt \propto E_{exp}/t_{exp}[1+a\cos(2\theta)]$

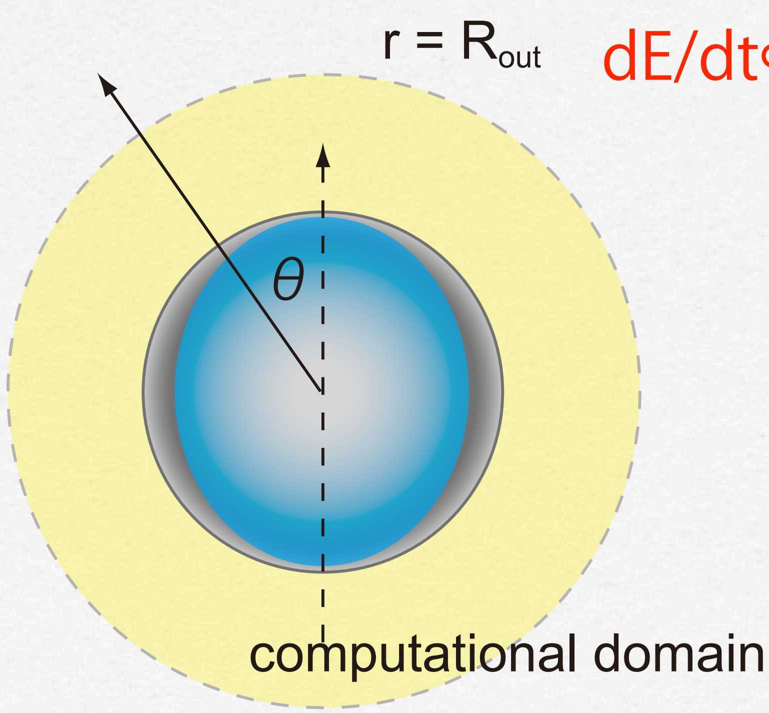


Shigeyama&Nomoto(1990)



Shock breakout in 2D

- ➡ 2D RHD simulations
- ➡ Absorption: free-free
- ➡ Scattering: e^- scattering $\kappa = 0.2(1+X)\ \mathrm{cm^2/g}$ with $X=0.565$



$dE/dt \propto E_{exp}/t_{exp}[1 + a\cos(2\theta)]$

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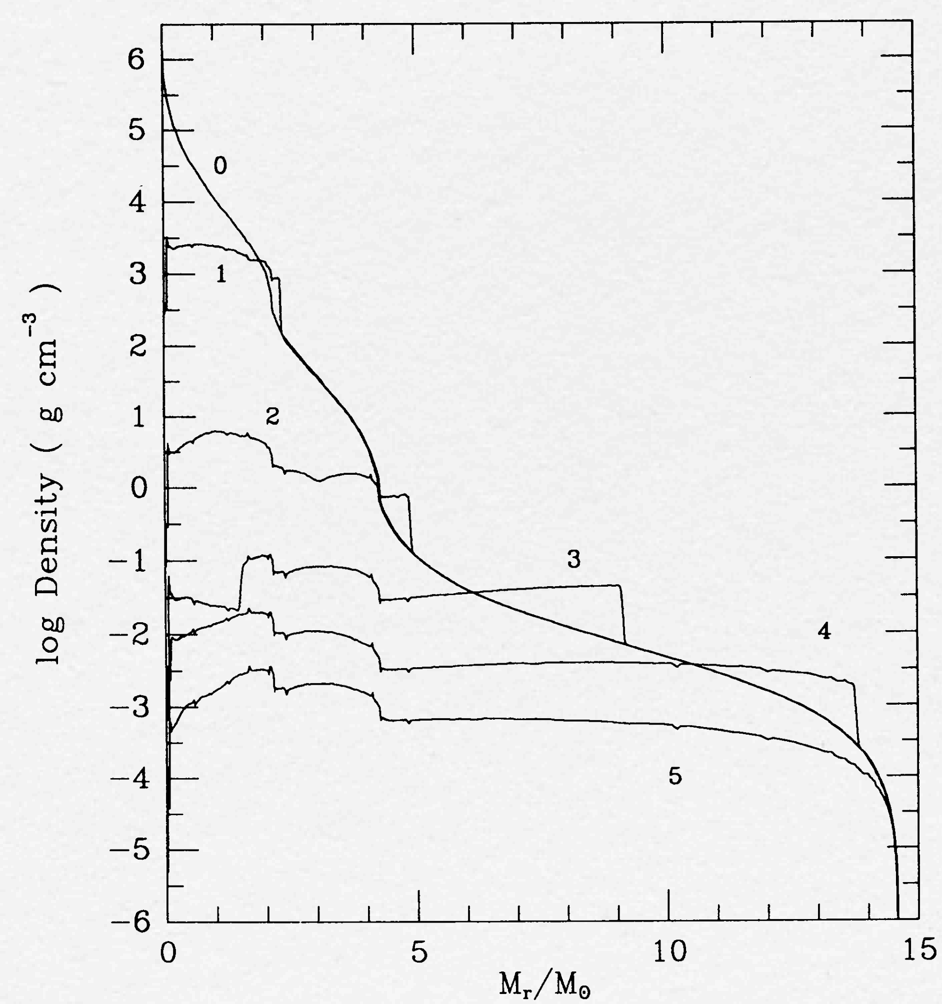
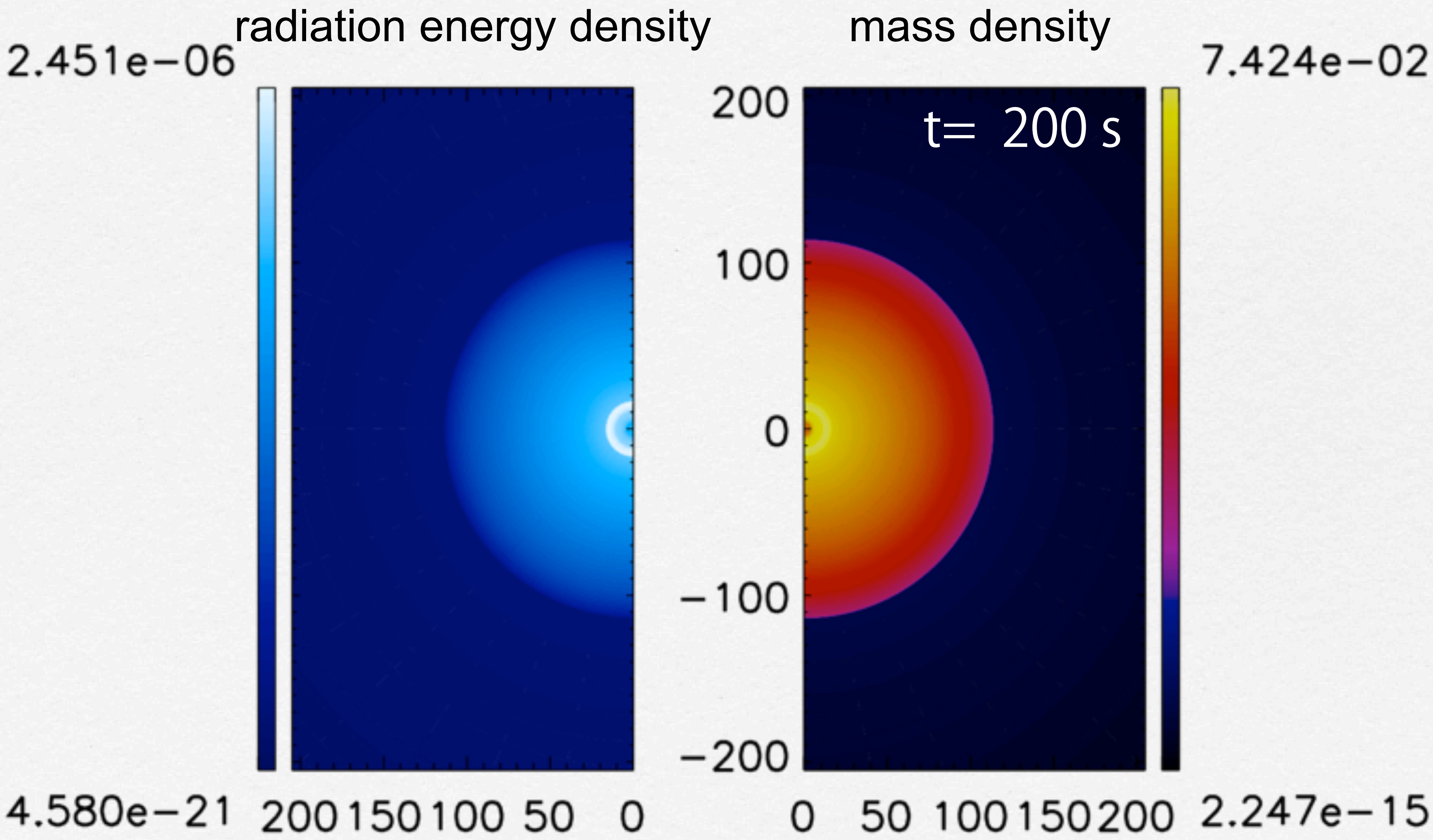


Shock breakout in 2D

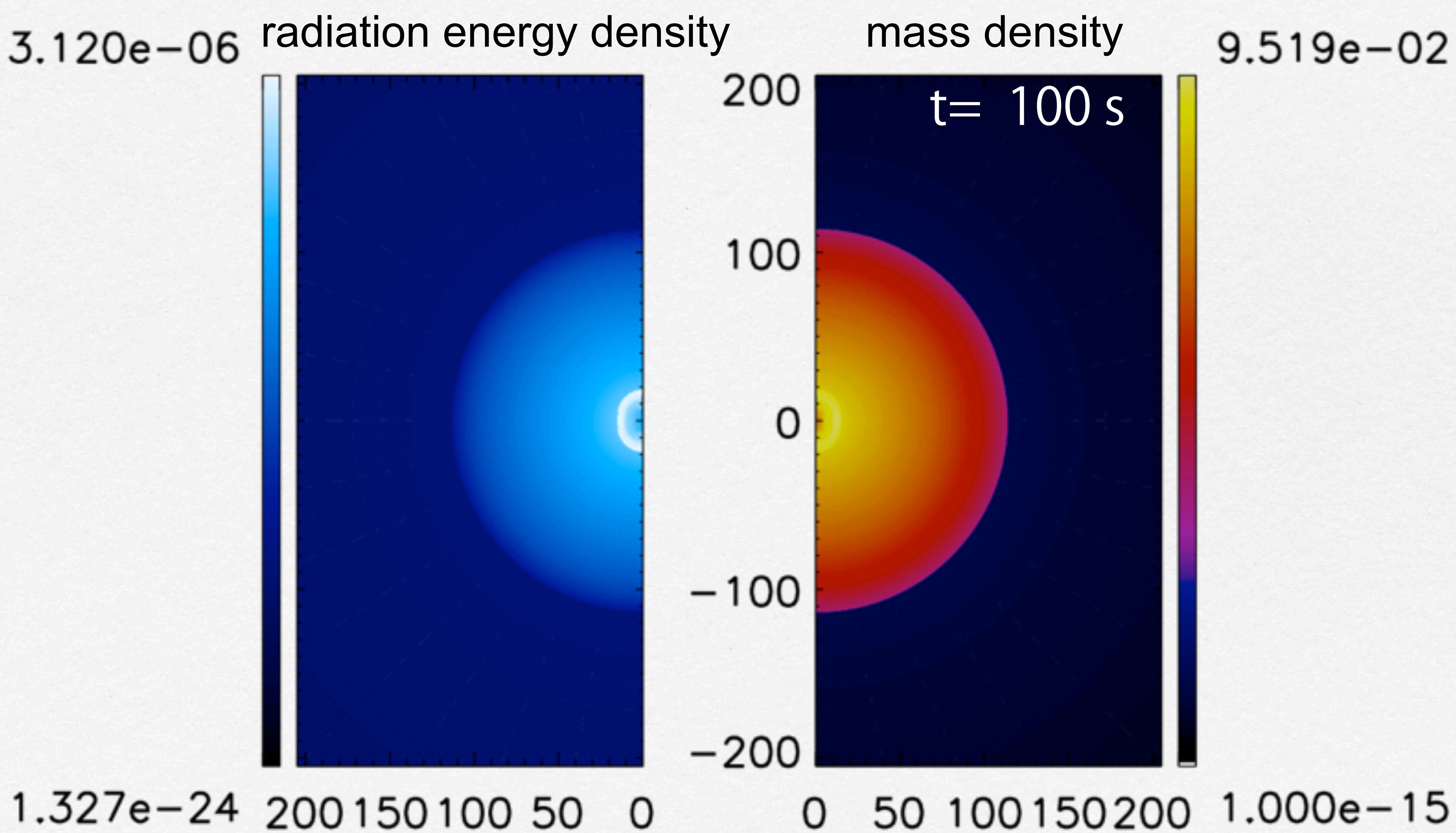
➡ 1987A progenitor: BSG

➡ spherical case: a=0 $dE/dt \propto E_{exp}/t_{exp}[1+a\cos(2\theta)]$



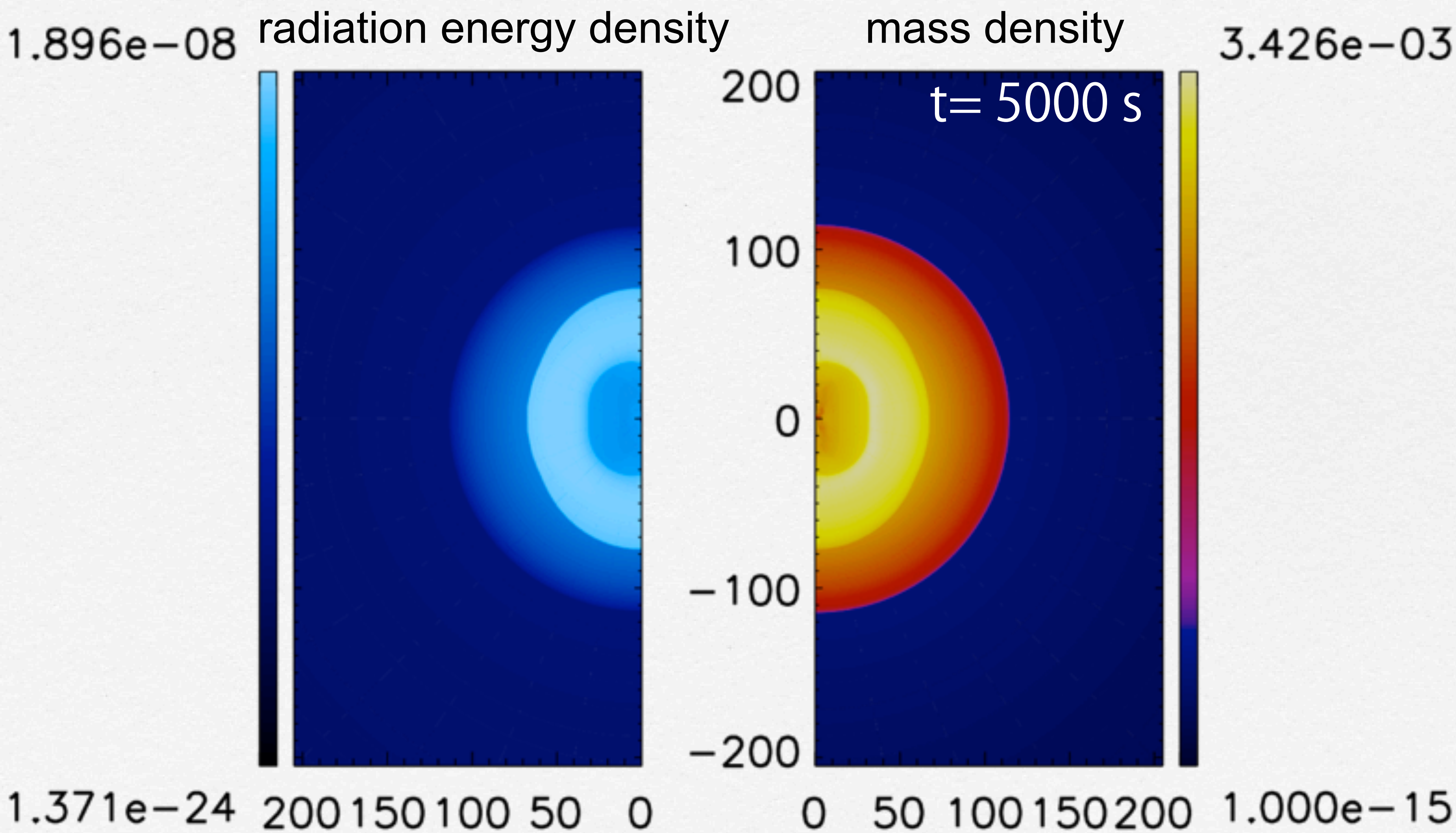
Shock breakout in 2D

- ➡ 1987A progenitor: BSG
- ➡ aspherical case: a=0.5 $dE/dt \propto E_{exp}/t_{exp}[1+a \cos(2\theta)]$



Shock breakout in 2D

- ➡ 1987A progenitor: BSG
- ➡ aspherical case: a=0.5 $dE/dt \propto E_{exp}/t_{exp}[1+a\cos(2\theta)]$

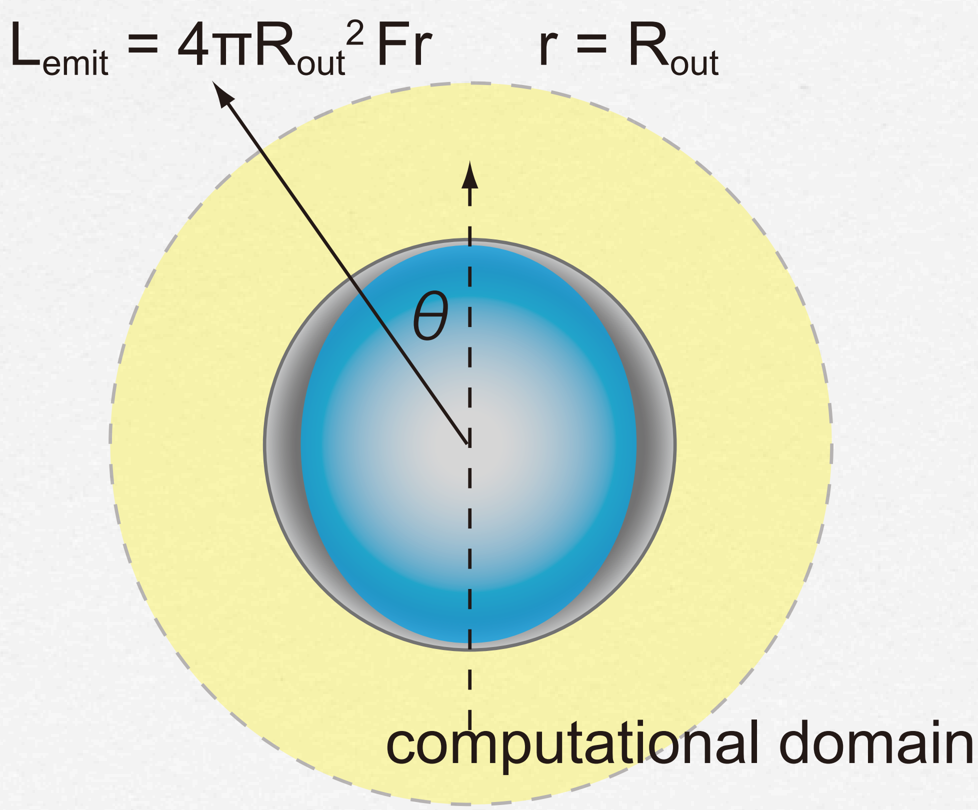


Shock breakout in 2D

➡ Light curve calculations

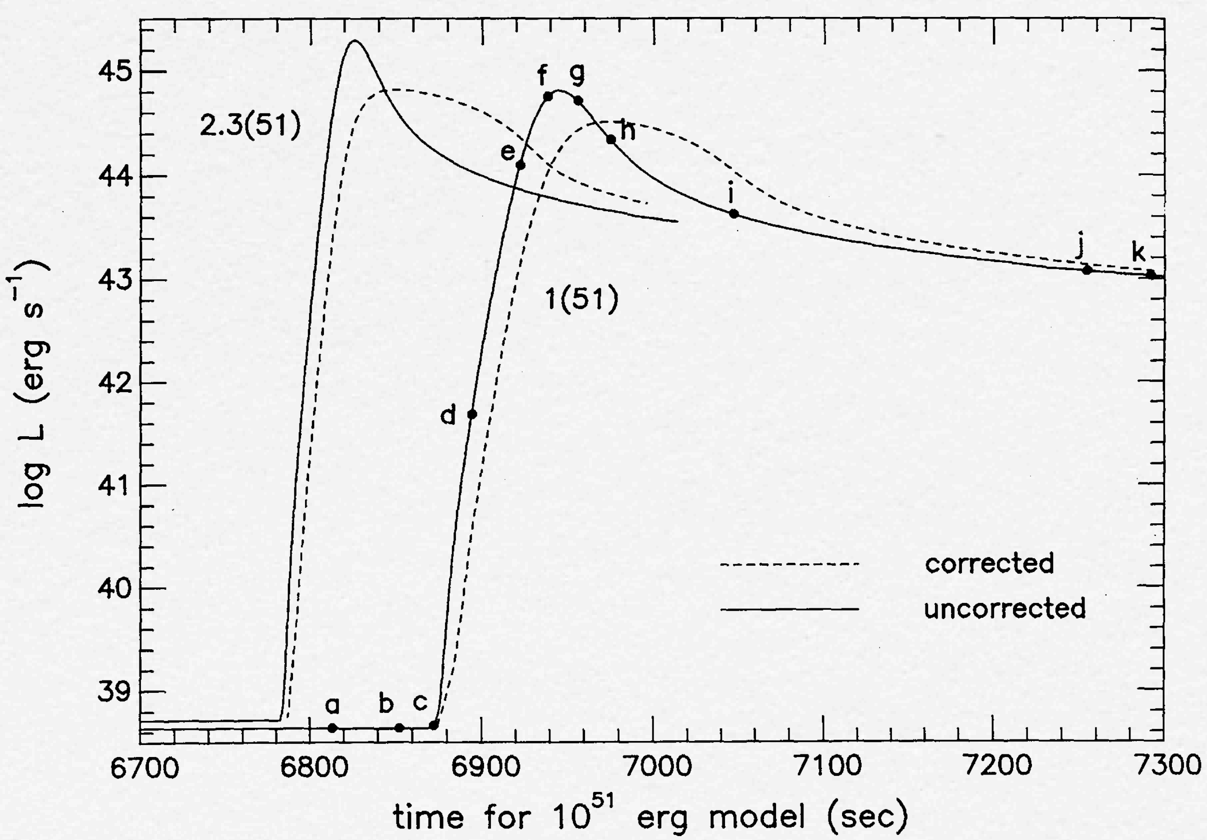
➡ spherical case: LC consistent with 1D RHD calculations by Shigeyama+(1988), Ensmann&Burrows(1992) for SN 1987A

➡ aspherical case: wide variety of light curves depending on the viewing angle



Shock breakout in 2D

- ➡ Light curve calculations
- ➡ spherical case: L_{emit} evolution consistent with 1D RHD calculations by Shigeyama+(1988), Ensmann&Burrows(1992) for SN 1987A
- ➡ aspherical case: wide variety of light curves depending on the viewing angle



Ensmann&Burrows(1992)

★ Introduction for SN shock breakout

★ Detected events, possible events

★ What can we learn from SN shock breakout

★ Our works

★ Summary

SN Shock breakout as a unique probe

- ➡ increasing number of detections
- ➡ LCs are characterized by $R_\star/c, R_\star/v_{ej}$,
- ➡ information on the progenitor radius, explosion energy,asphericity
- ➡ multi-D SR-RHD simulations are ongoing