Modeling of SNe I b/c Shock Breakouts: from XRO080109/SN2008D to the Future Surveys

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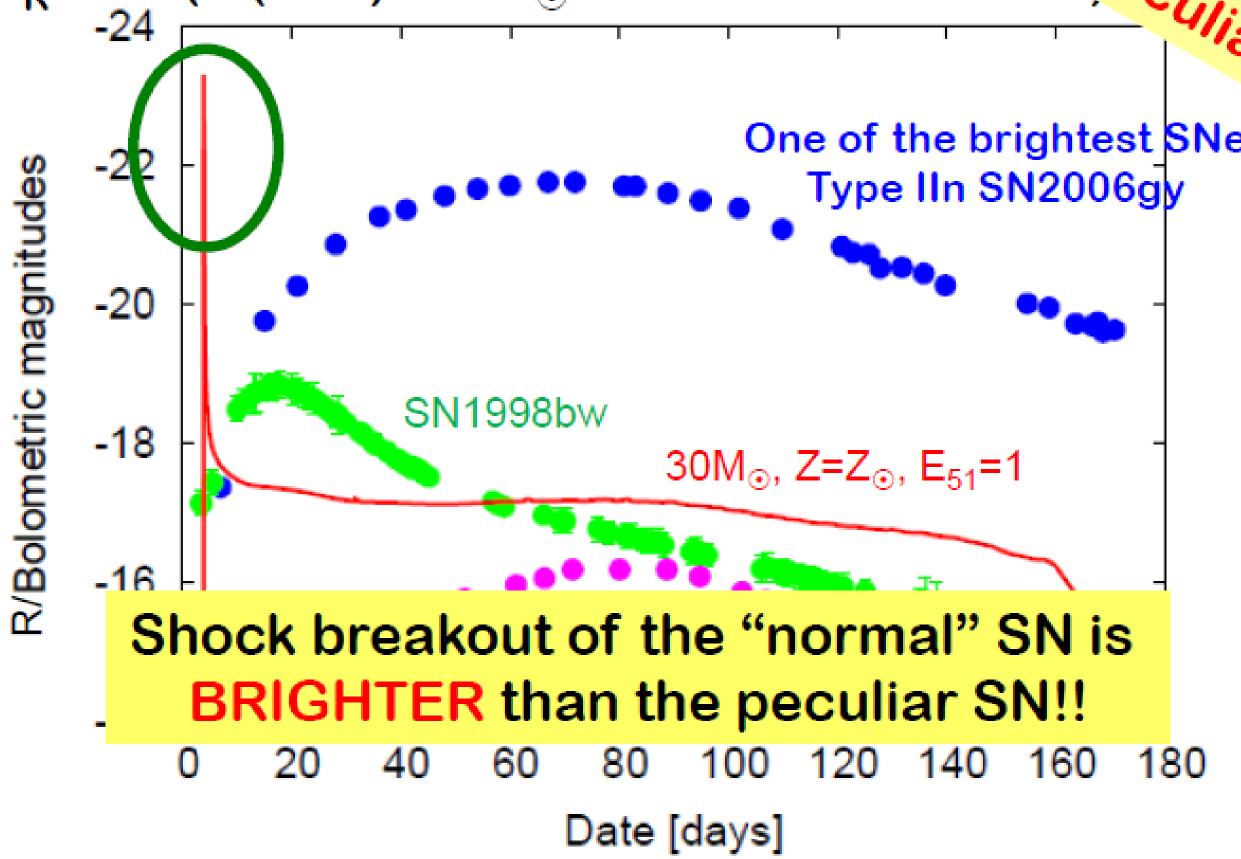
Supernova shock breakout (by N. Tominaga)

SN 2006gy (z=0.02: Smith + 08; Kawabata, …, 09)

– M_R~-22 ($M(^{56}Ni)$~$15M_\odot$ or CSM interactio

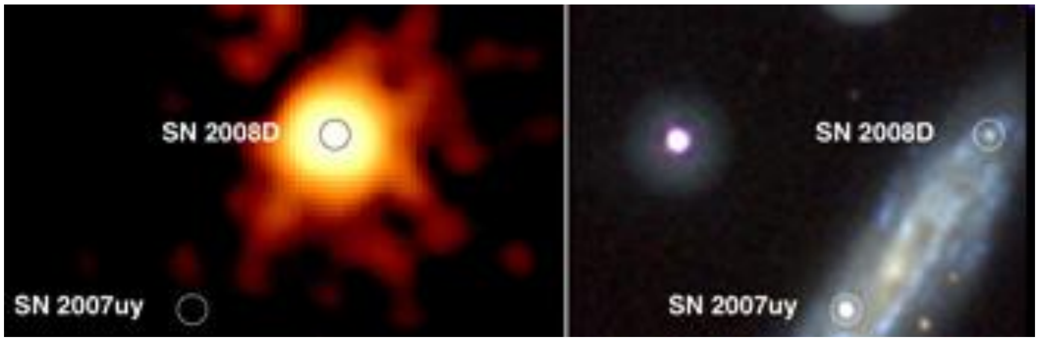
This is a "peculiar" SN.

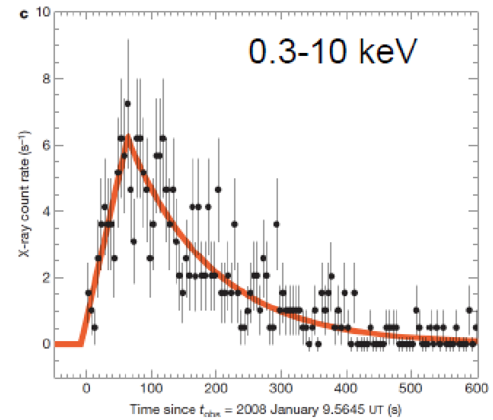


Shock breakout of the "normal" SN is **BRIGHTER** than the peculiar SN!!

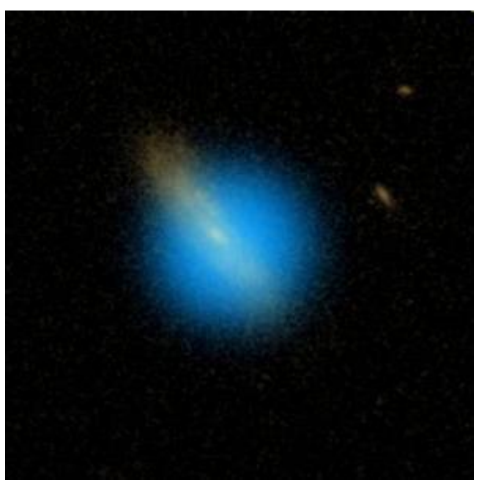
Supernova shock breakout (SB) observations

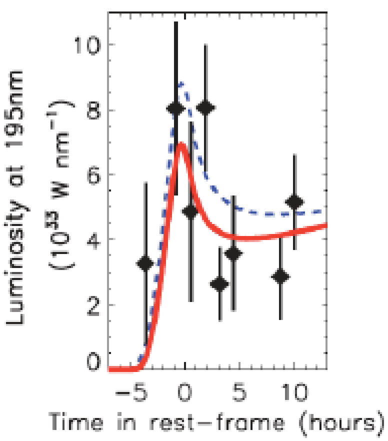
SN2008D, Type Ib/c, WR candidate progenitor, Swift





SNLS-04D2dc, Type II RSG progenitor, GALEX





Subaru/Hyper Supreme Camera (HSC)

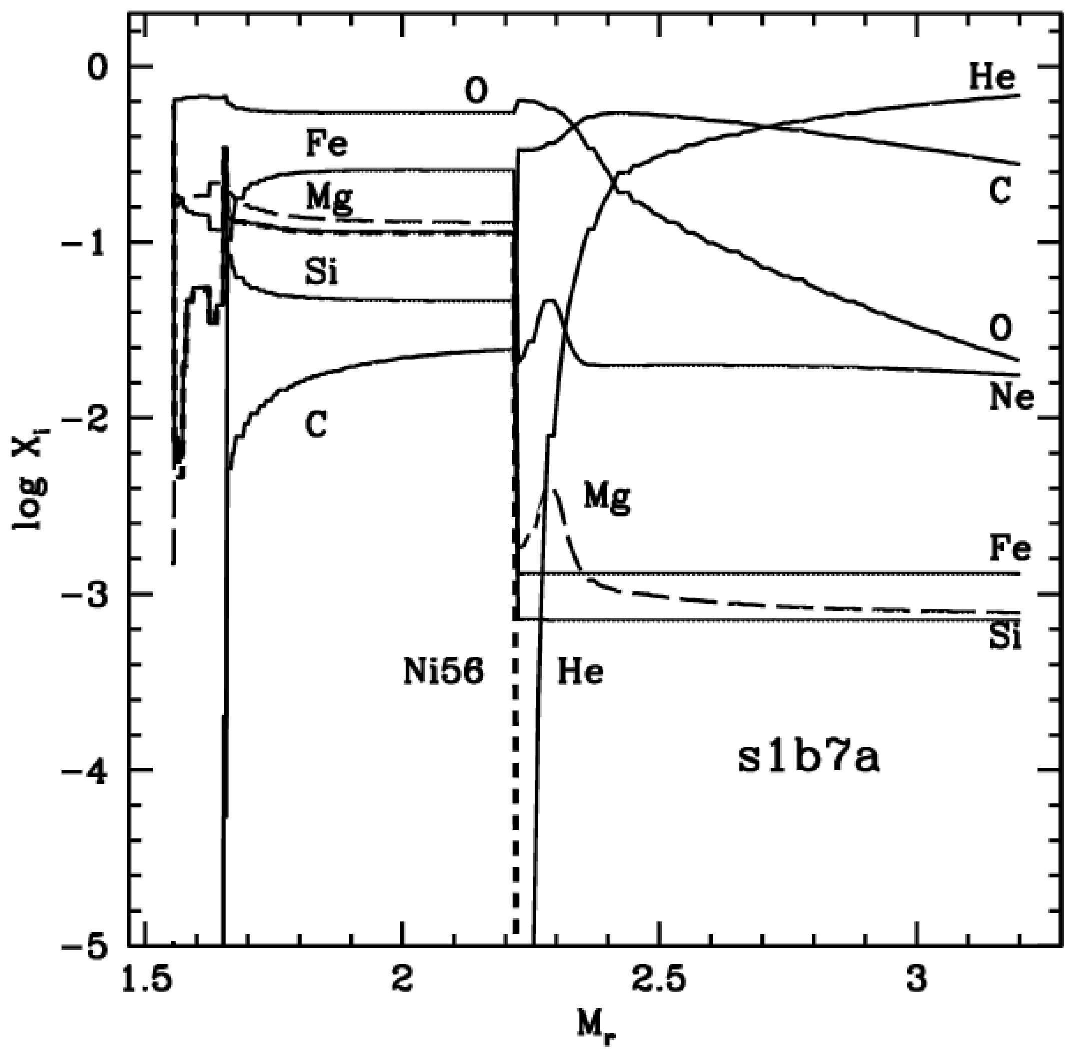
	Suprime-Cam	HSC
CCD Make and Model	Hamamatsu S10892-01	Hamamatsu S10892-02
Number of CCDs	10	104 + AG 4 + AF 8
Pixel	15 micron square (0.2 arc-sec)	15 micron square (0.17 arcsec)
Field of View	34 arcmin x 27 arcmin	90 arcmin daiameter
Conversion Factor	2.5-3.7 e/ADU	3.0 e/ADU
Readout noise	~ 10 e	TBD e
Readout time	18 sec	20 sec
Full well	150,000 e	150,000 e
Number of Filters	10	6
Filter Exchange Time	300 s	600 s (900 s while commissioning)

- **The detection of transients such as shock breakout of SNe is one of the most important missions of HSC**

Interpretation of early light curves and spectra – explanation of the nature of exploding stars.
From Swift , GALEX to Subaru/HSC, PTF, LOSS, CRTS, KWFC, Skymapper, DES, Pan-STARRS, LSST.
Theoretical models are in demand!

Ibc Presupernova Model

- Evolutionary calculation of helium star M = 10M $_\odot$ (Woosley et al., 1995)
- STELLA provides a shock velocity at breakout up to 0.5c (Blinnikov et al., 1998)
- M = 3.199 M $_\odot$
  R = $1.41 \cdot 10^{11}$ cm
  Z = 0.33, Z_{Fe} = 0.013
  M_{Ni} = 0.072 M $_\odot$



Numerical algorithms STELLA and RADA

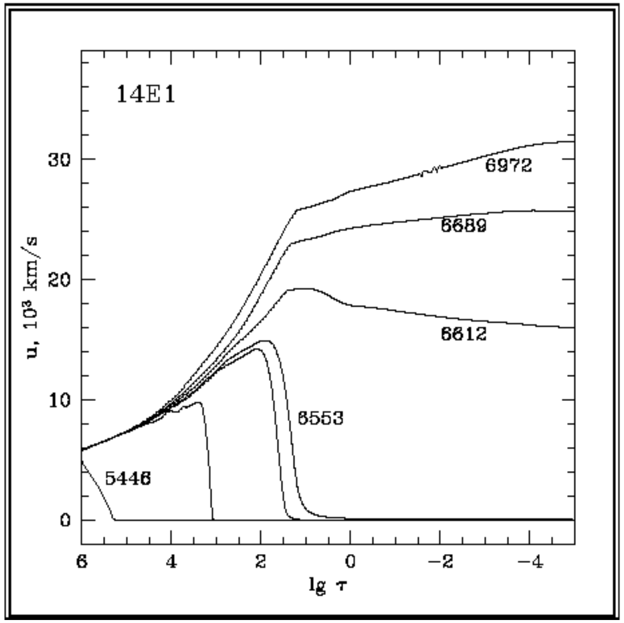
STELLA (STatic Eddington-factor Low-velocity Limit Approximation) (Blinnikov et al., 1998)

- 1D Lagrangian NR Hydro + Radiation Moments Equations, VEF closure, multigroup (100-300 groups)
- Opacity includes photoionization, free-free absorption, lines and electron scattering (Blandford, Payne 1981). Ionization – Saha's approximation
- STELLA was used in modeling of many SN light curves: SN 1987A, SN 1993J and many others (Blinnikov et al. 2006)
- STELLA shows good agreement with observations in case of SNLS-04D2dc. (Tominaga et al. 2009, 2011)

For Ib/c model STELLA is not accurate!

RADA (fully Relativistic rADiative transfer Approximation) (Tolstov, Blinnikov, 2003)

- 1D Relativistic Radiative Transfer in comoving frame (McCrea & Mitra 1936, Mihalas, 1980)
- Relativistic transformation of fluxes from the source to the observer



$t_{\delta R} = t_{diff}$:

$$\tau = \frac{\delta R}{l} \lesssim \frac{c}{D} \sim 10$$

l – photon mean free path
δR - the distance from the shock to the photosphere
D – shock front velocity

Comoving radiation transfer (Mihalas, 1980)

Transfer equation:

$$\frac{\gamma}{c}(1+\beta\mu_0)\frac{\partial I_0(\mu_0,\nu_0)}{\partial t}+\gamma(\mu_0+\beta)\frac{\partial I_0(\mu_0,\nu_0)}{\partial r}$$
$$+\gamma(1-\mu_0{}^2)\left[\frac{(1+\beta\mu_0)}{r}-\frac{\gamma^2}{c}(1+\beta\mu_0)\frac{\partial\beta}{\partial t}-\gamma^2(\mu_0+\beta)\frac{\partial\beta}{\partial r}\right]\frac{\partial I_0(\mu_0,\nu_0)}{\partial\mu_0}$$
$$-\gamma\left[\frac{\beta(1-\mu_0{}^2)}{r}+\frac{\gamma^2}{c}\mu_0(1+\beta\mu_0)\frac{\partial\beta}{\partial t}+\gamma^2\mu_0(\mu_0+\beta)\frac{\partial\beta}{\partial r}\right]\nu_0\frac{\partial I_0(\mu_0,\nu_0)}{\partial\nu_0}$$
$$+3\gamma\left[\frac{\beta(1-\mu_0{}^2)}{r}+\frac{\gamma^2\mu_0}{c}(1+\beta\mu_0)\frac{\partial\beta}{\partial t}+\gamma^2\mu_0(\mu_0+\beta)\frac{\partial\beta}{\partial r}\right]I_0(\mu_0,\nu_0)$$
$$=\eta_0(\nu_0)-\chi_0(\nu_0)I_0(\mu_0,\nu_0)\,.$$

Moments equation:

$$\frac{\gamma}{c}\left[\frac{\partial J_0(\nu_0)}{\partial t}+\beta\frac{\partial H_0(\nu_0)}{\partial t}\right]+\gamma\left[\frac{\partial H_0(\nu_0)}{\partial r}+\beta\frac{\partial J_0(\nu_0)}{\partial r}\right]$$
$$-\gamma\nu_0\left\{\frac{\beta}{r}\left[\frac{\partial J_0(\nu_0)}{\partial\nu_0}-\frac{\partial K_0(\nu_0)}{\partial\nu_0}\right]+\frac{\gamma^2}{c}\frac{\partial\beta}{\partial t}\left[\frac{\partial H_0(\nu_0)}{\partial\nu_0}+\beta\frac{\partial K_0(\nu_0)}{\partial\nu_0}\right]+\gamma^2\frac{\partial\beta}{\partial r}\left[\frac{\partial K_0(\nu_0)}{\partial\nu_0}+\beta\frac{\partial H_0(\nu_0)}{\partial\nu_0}\right]\right\}$$
$$+\gamma\left\{\frac{2}{r}[H_0(\nu_0)+\beta J_0(\nu_0)]+\frac{\gamma^2}{c}\frac{\partial\beta}{\partial t}[H_0(\nu_0)+\beta J_0(\nu_0)]+\gamma^2\frac{\partial\beta}{\partial r}[J_0(\nu_0)+\beta H_0(\nu_0)]\right\}$$
$$=\eta_0(\nu_0)-\chi_0(\nu_0)J_0(\nu_0)$$

$$\frac{\gamma}{c}\left[\frac{\partial H_0(\nu_0)}{\partial t}+\beta\frac{\partial K_0(\nu_0)}{\partial t}\right]+\gamma\left[\frac{\partial K_0(\nu_0)}{\partial r}+\beta\frac{\partial H_0(\nu_0)}{\partial r}\right]$$
$$-\gamma\nu_0\left\{\frac{\beta}{r}\left[\frac{\partial H_0(\nu_0)}{\partial\nu_0}-\frac{\partial N_0(\nu_0)}{\partial\nu_0}\right]+\frac{\gamma^2}{c}\frac{\partial\beta}{\partial t}\left[\frac{\partial K_0(\nu_0)}{\partial\nu_0}+\beta\frac{\partial N_0(\nu_0)}{\partial\nu_0}\right]+\gamma^2\frac{\partial\beta}{\partial r}\left[\frac{\partial N_0(\nu_0)}{\partial\nu_0}+\beta\frac{\partial K_0(\nu_0)}{\partial\nu_0}\right]\right\}$$
$$+\gamma\left\{\frac{1}{r}[3K_0(\nu_0)-J_0(\nu_0)+\beta H_0(\nu_0)+\beta N_0(\nu_0)]+\frac{\gamma^2}{c}\frac{\partial\beta}{\partial t}[J_0(\nu_0)+2\beta H_0(\nu_0)-\beta N_0(\nu_0)]\right.$$
$$\left.+\gamma^2\frac{\partial\beta}{\partial r}[2H_0(\nu_0)-N_0(\nu_0)+\beta J_0(\nu_0)]\right\}=-\chi_0(\nu_0)H_0(\nu_0)$$

SRRHD. Radiation-dominated mildly-relativistic shock wave

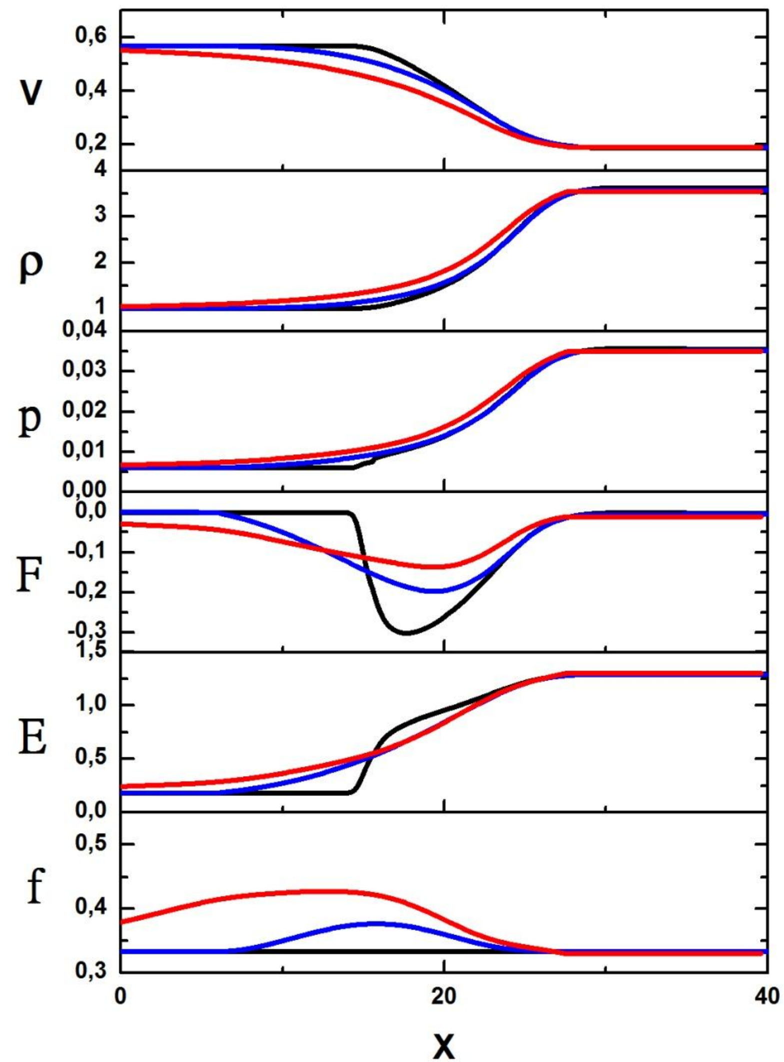
Semi-analytic relativistic hydro + Relativistic radiation transfer (no closure condition)

Shock tube configuration (Farris et al., 2008), $P_r/P_g \approx 10$

Γ	κ^a	Left state^c	Right State^c
5/3	0.08	$\rho_0 = 1.0$	$\rho_0 = 3.65$
		$P = 6.0 \times 10^{-3}$	$P = 3.59 \times 10^{-2}$
		$u^x = 0.69$	$u^x = 0.189$
		$E = 0.18$	$E = 1.30$

Closure condition: P = fE

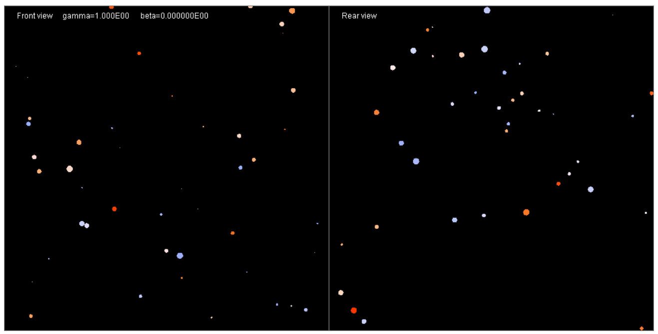
- Eddington approximation: f = 1/3
- M1-closure (Levermore, 1984) f = f(E,F) joins "optically thin" and "thick" cases
- **Photon Boltzmann equation**

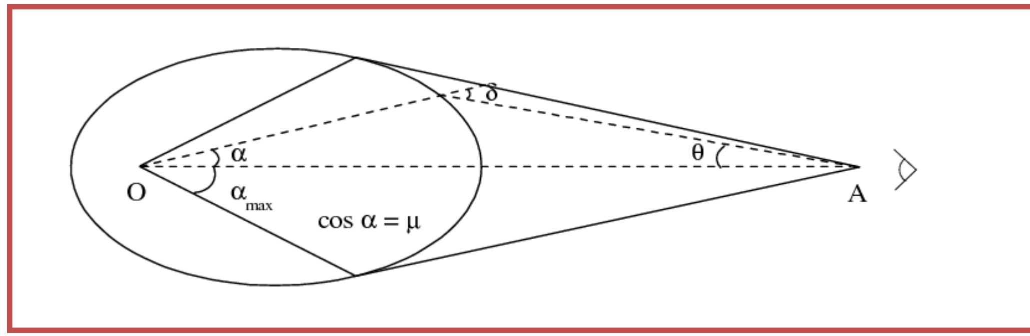


Transformation of fluxes from source to observer’s frame

Lorentz covariance, Doppler effect and aberration

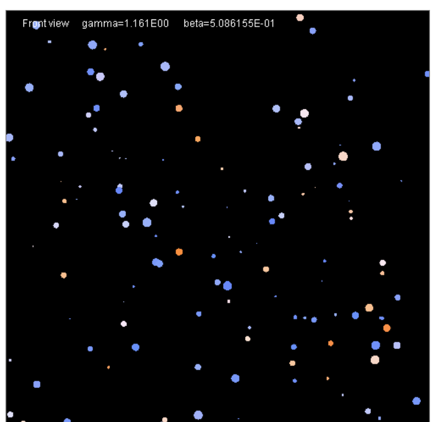
- Radiation flux increases
- Spectrum becomes harder
- The space shrinks towards the direction of motion



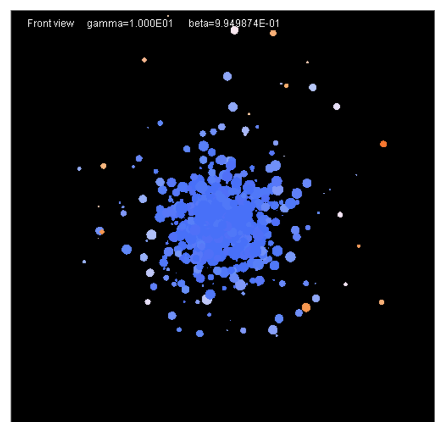


V = 0

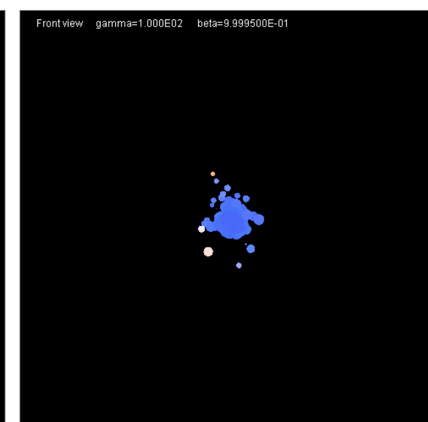
V = 0.5 c



Γ = 10



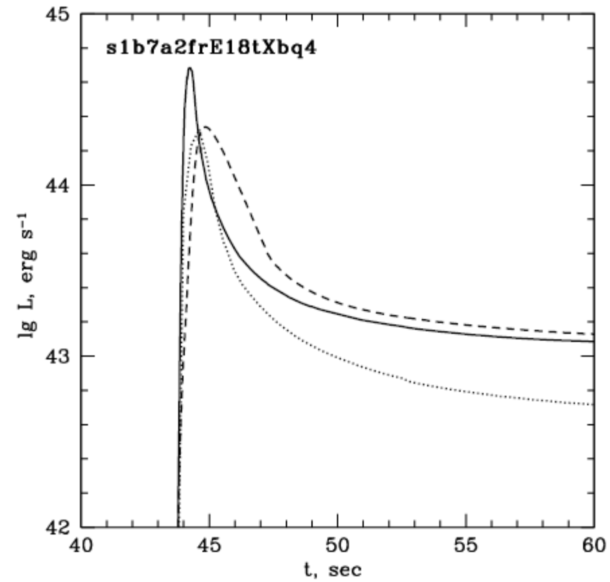
Γ = 100



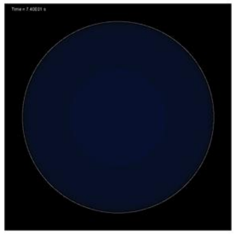
SN Ibc shock breakout modeling (Tolstov et al. 2013)

Explosion energy = 1.8 foe,
Shock velocity at shock breakout ≈ 0.5c

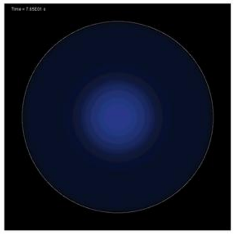
- Radiation Transfer – Short Characteristic Method (about 90% of calculation time)
- Radius x Angle x Energy = 350 * 100 * 200 = = 7 000 000 for 1 time step
- 200 steps of RADA , 10000 steps of STELLA, 3 days of calculation



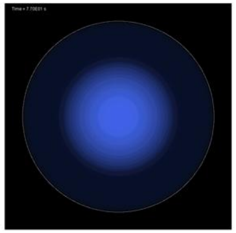
74 s



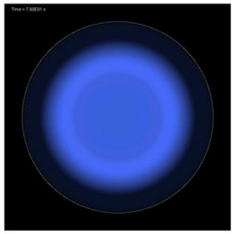
76.5 s



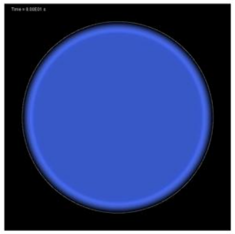
77 s



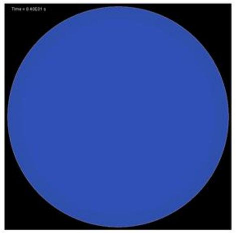
78 s

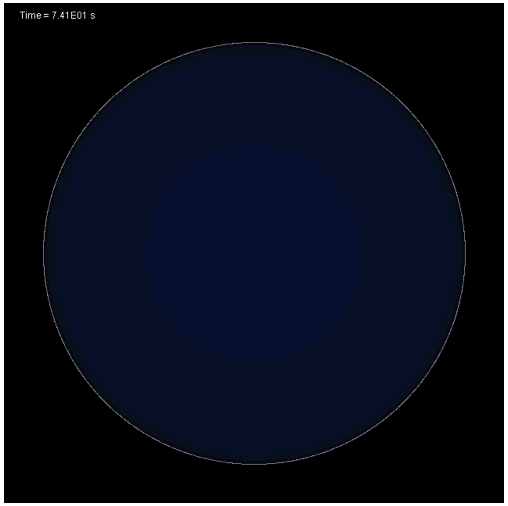


80 s

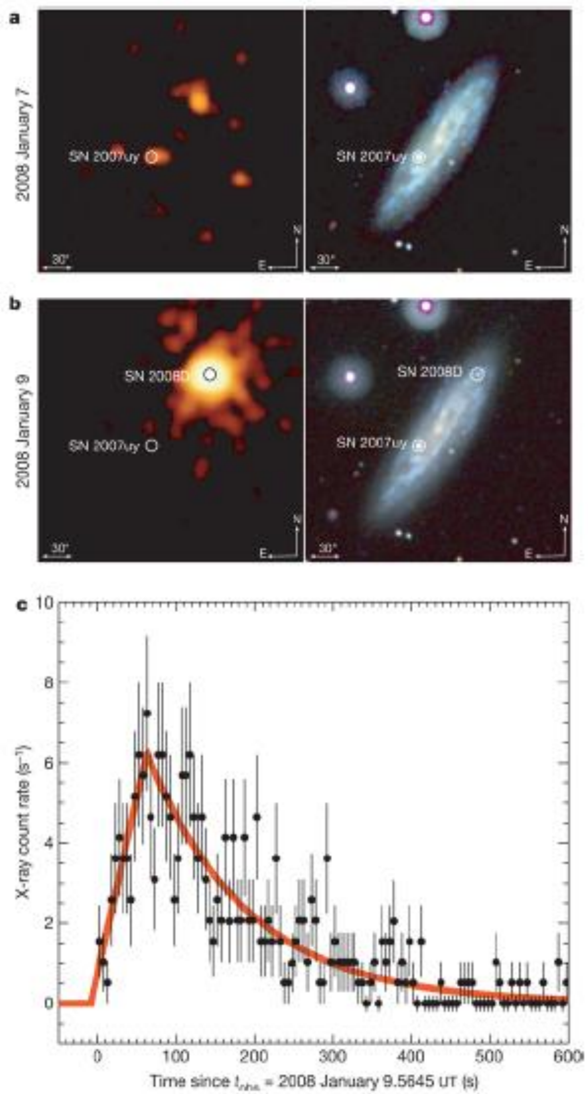


84 s



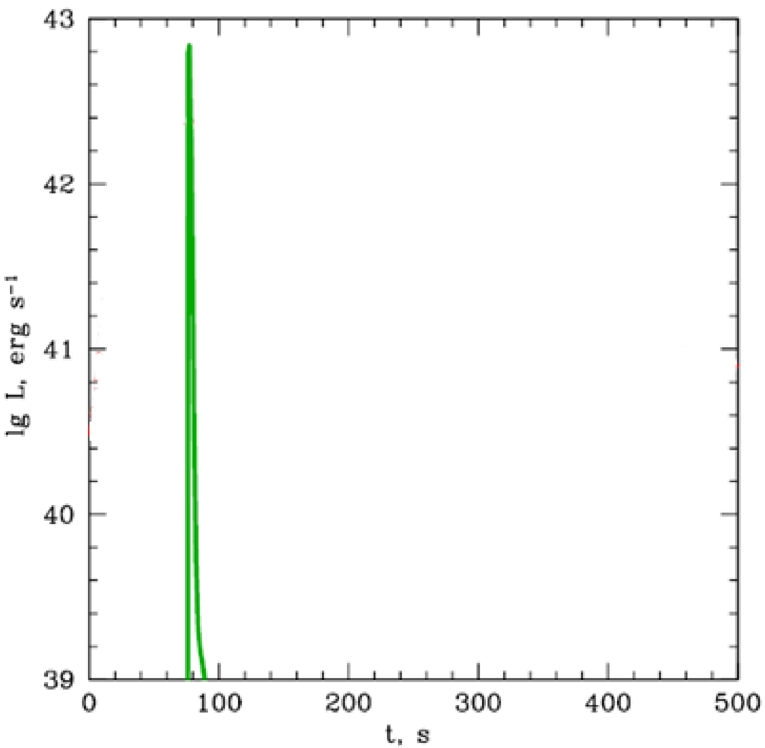


XRO080109/SN2008D in the Model of SNIb



How to explain the duration and spectrum of the outburst?

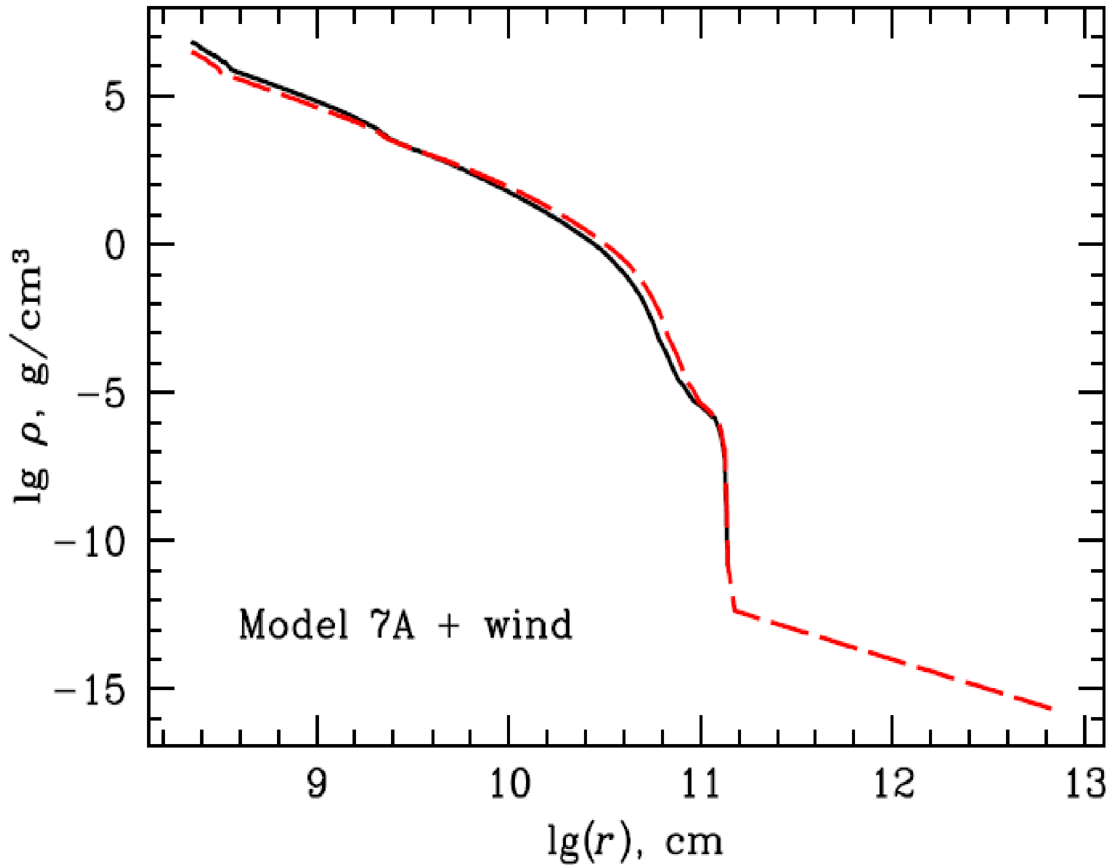
External medium is optically thin to affect the radiation (Chevalier, Roger A., Fransson, Claes, 2008, ApJ, 683L, 135C)



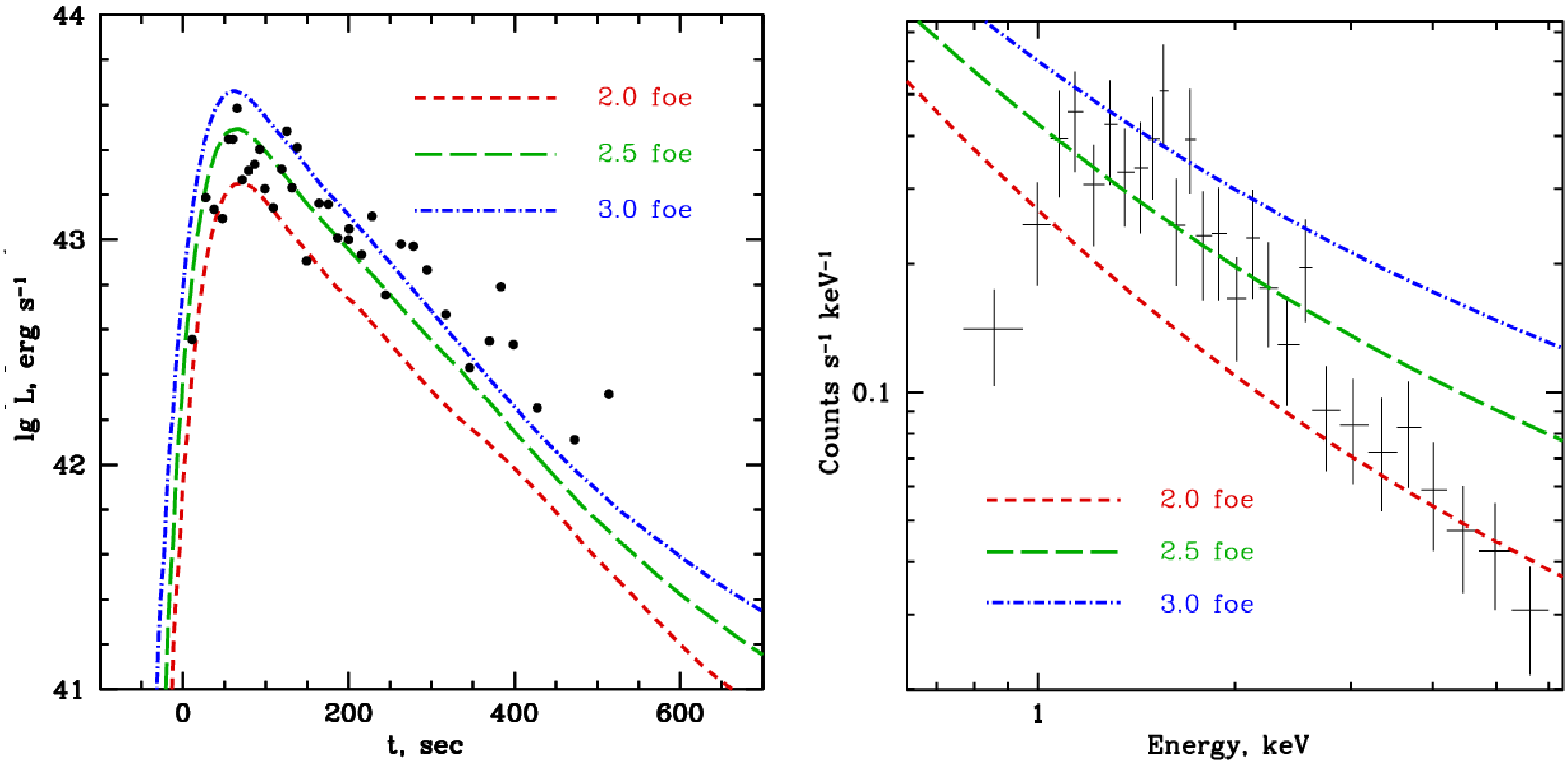
XRO080109/SN2008D in the Model of SNIb with the Stellar Wind

Can we explain the observational data by ‘natural’ model (WR star + wind)?

1. The growth of photosphere before the shock front
2. Changes in absorption/emission of the perturbed wind

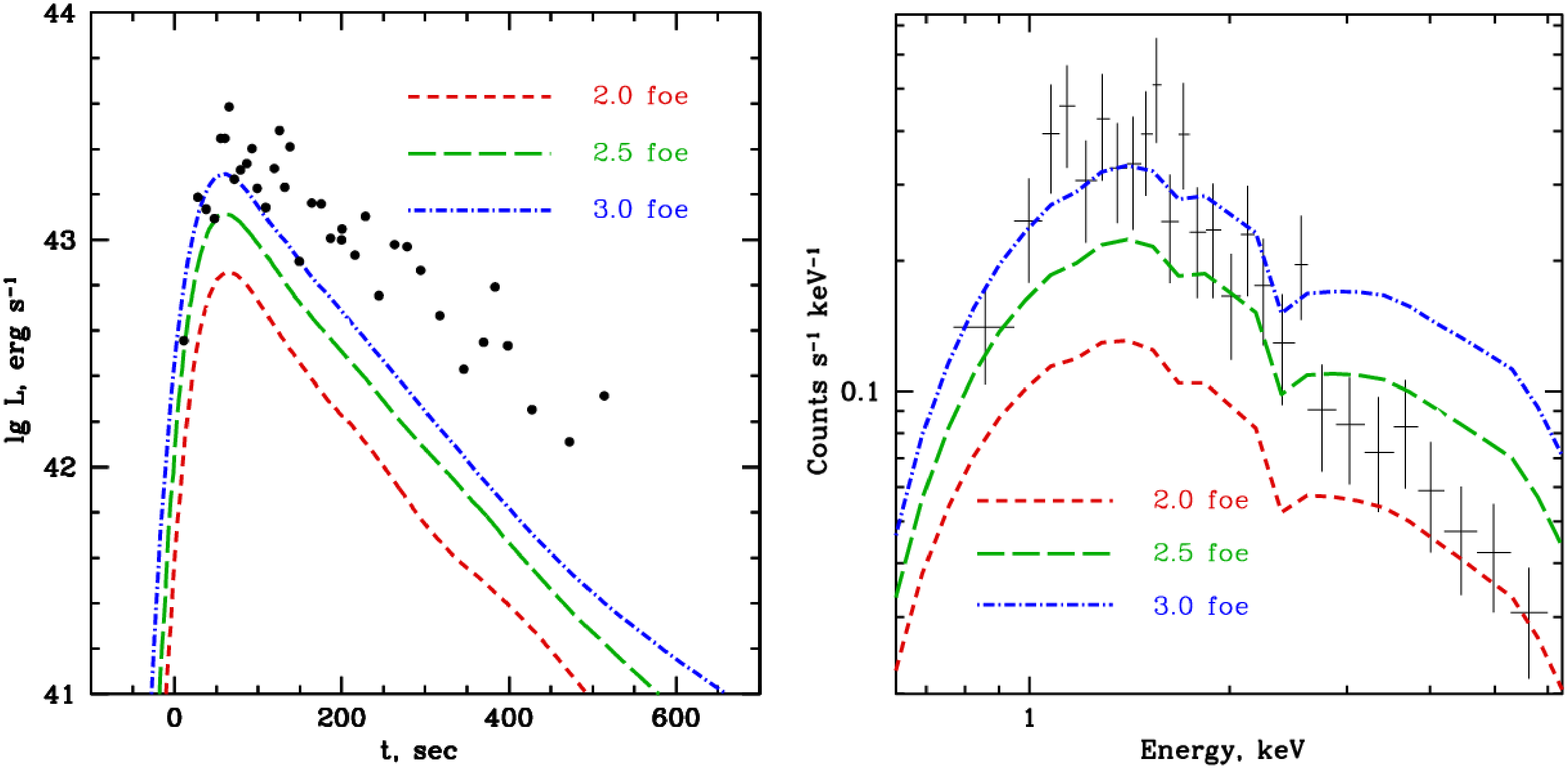


XRO080109/SN2008D Spectra and Light Curves



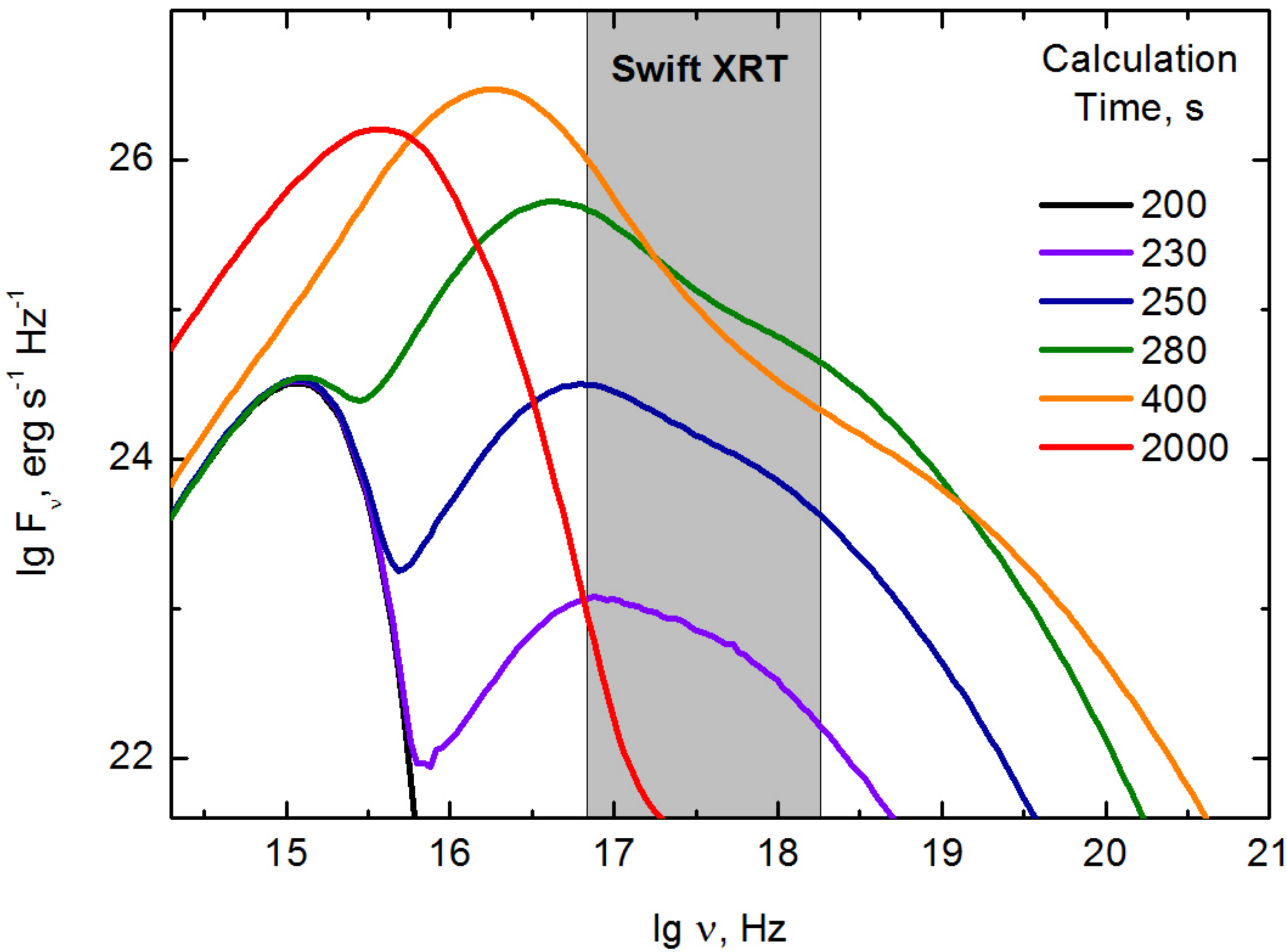
- **X-Ray light curves and spectra, averaged over the duration of the flash, of XRO 080109 in Swift/XRT band (0.3-10 keV) for 10A presupernova model**
- **No extinction**

XRO080109/SN2008D Spectra and Light Curves (extinction)



- **X-Ray light curves and spectra, averaged over the duration of the flash, of XRO 080109 in Swift/XRT band (0.3-10 keV) for 10A presupernova model**
- **N_H = 2 × 10^{21} cm^{-2}, XRT response**
- **E_K = 6±2.5 foe (Tanaka et al. 2009) in modeling of SN2008D light curve**

XRO 080109 Spectral Evolution



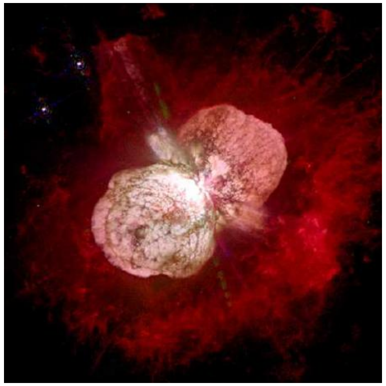
Objectives

- ***Analyses, prediction and interpretation of data of Subaru Hyper-Suprime Cam (HSC) using SB templates for SN type Ib/c***

  New serveys: Palomar Transient Factory (PTF), Lick Observatory Supernova Search (LOSS), Catalina Real-Time Transient Survey (CRTS), Kiso/Kiso Wide Field Camera (KWFC), Skymapper, Dark Energy Survey (DES), Pan-STARRS, Subaru/HSC, Large Synoptic Survey Telescope (LSST)

- Research and development of ***new and effective numerical methods*** for calculating the radiation of relativistic gas dynamics

- ***Numerical Improvements in SRRHD code***:
  - Relativistic radiation hydrodynamics in 1D
  - Relativistic radiation hydrodynamics in 2D-3D
  - Scattering processes and radiation mechanisms



SN Ibc Shock Breakout at High Redshift

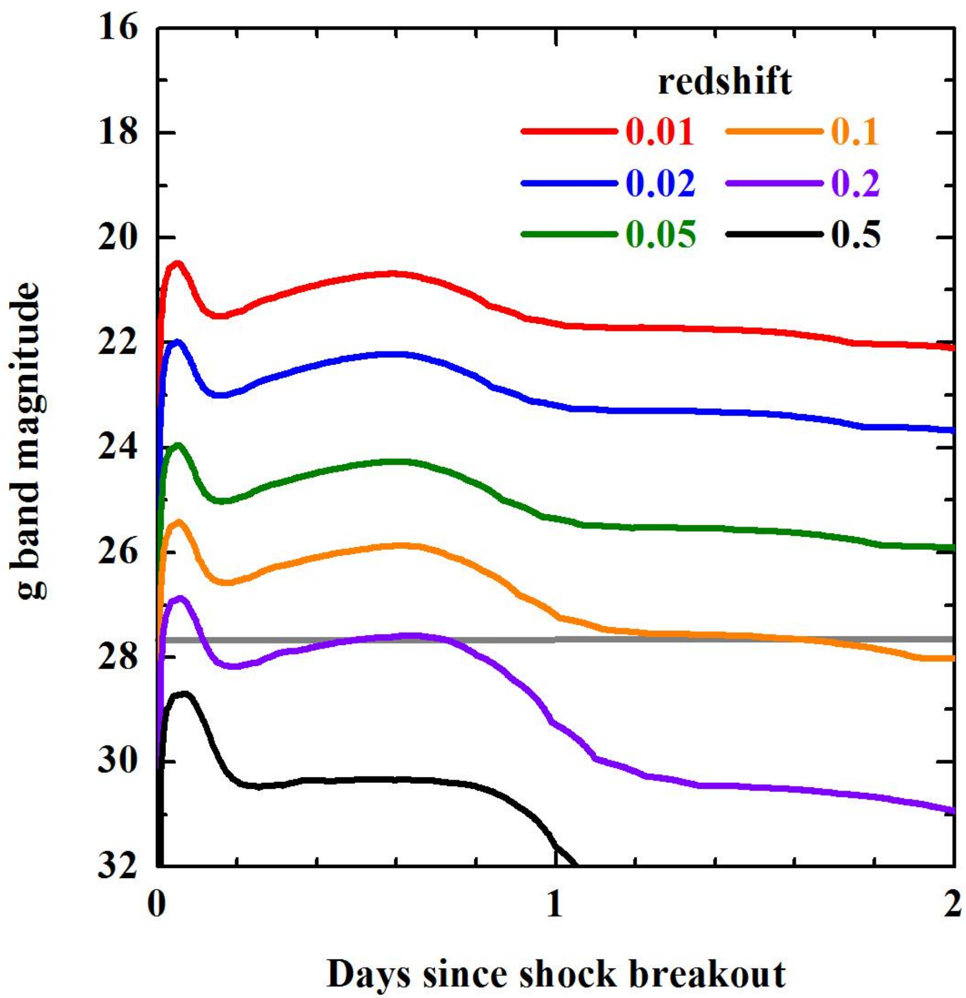
PRELIMINARY RESULTS

- **Cosmological parameters *(Komatsu et al. 2009):***
  $H0 = 70.5$ km s^{-1} Mpc^{-1}
  $k = 0$
  $\Omega_\lambda = 0.726$
  $\Omega_M = 0.274$

- **Dilated and redshifted multigroup LCs with the g bandpass of the Subaru/HSC**

- **The horizontal line − *5σ detection limit in the g-*band for the Subaru/*HSC 1 hr integration***

- **No extinction and no IGM absorption**



Conclusions

- **The phenomenon of XRO080109/SN2008D may well be explained qualitatively by the explosion of a conventional WR-star surrounded by a stellar wind. The explosion energy > 3 foe. Previous analytic estimations do not take into account the growth of the photosphere accurately**
- **SN2008D light curve must be modeled for the optimal model**
- **For the accurate consideration of mildy relativistic radiation dominated shock waves *it is necessary to solve radiation transfer equation (Eddington and M1 closure are not good approximations)***
- **Our numerical calculations provides us the opportunity to build robust templates for the analysis and interpretation of the SN Ibc observations that will be received by Subaru/Hyper-Suprime Cam (HSC) and a number of others surveys**

Thank you!

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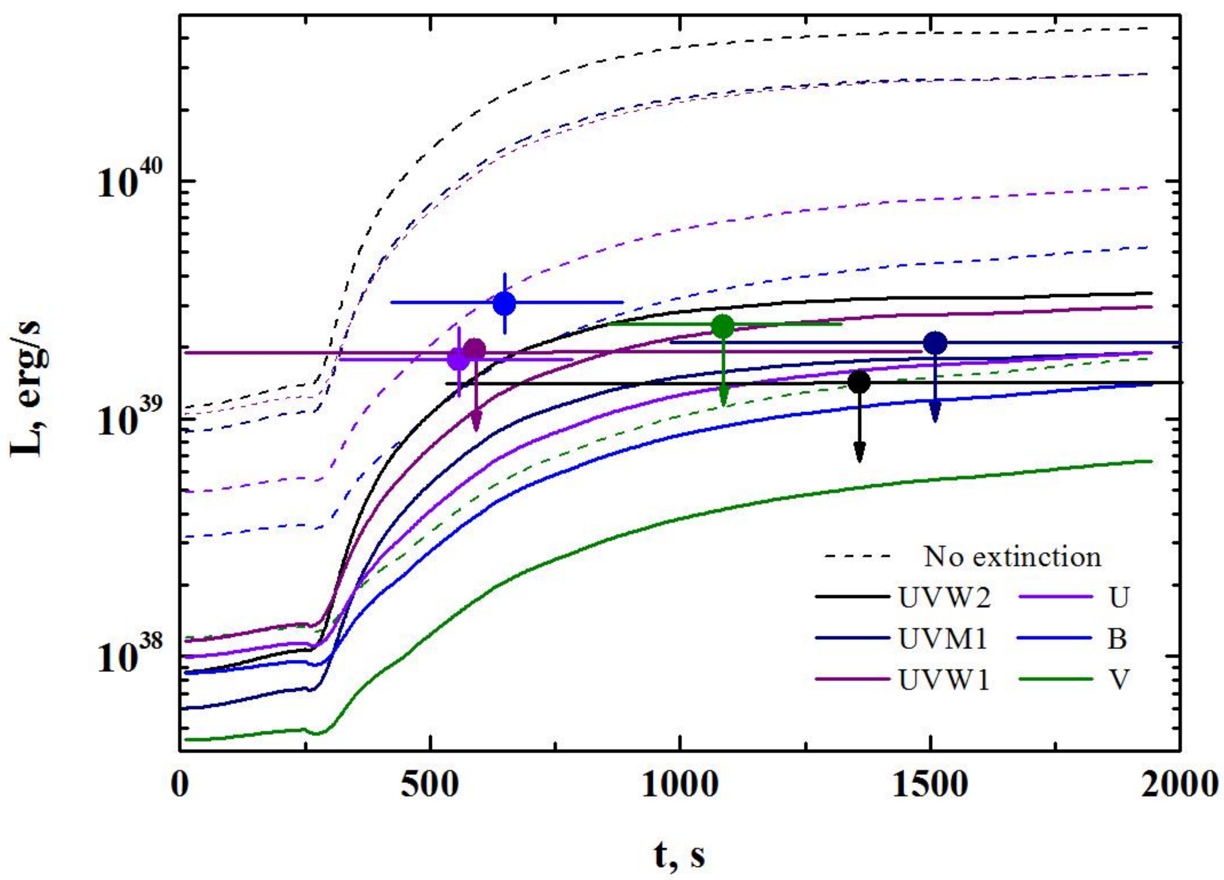
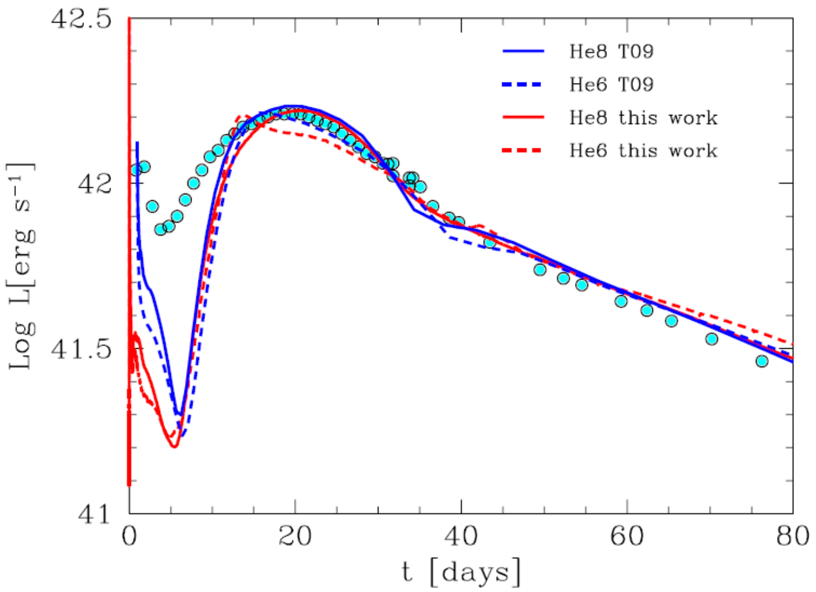
Additional Slides

Optical data

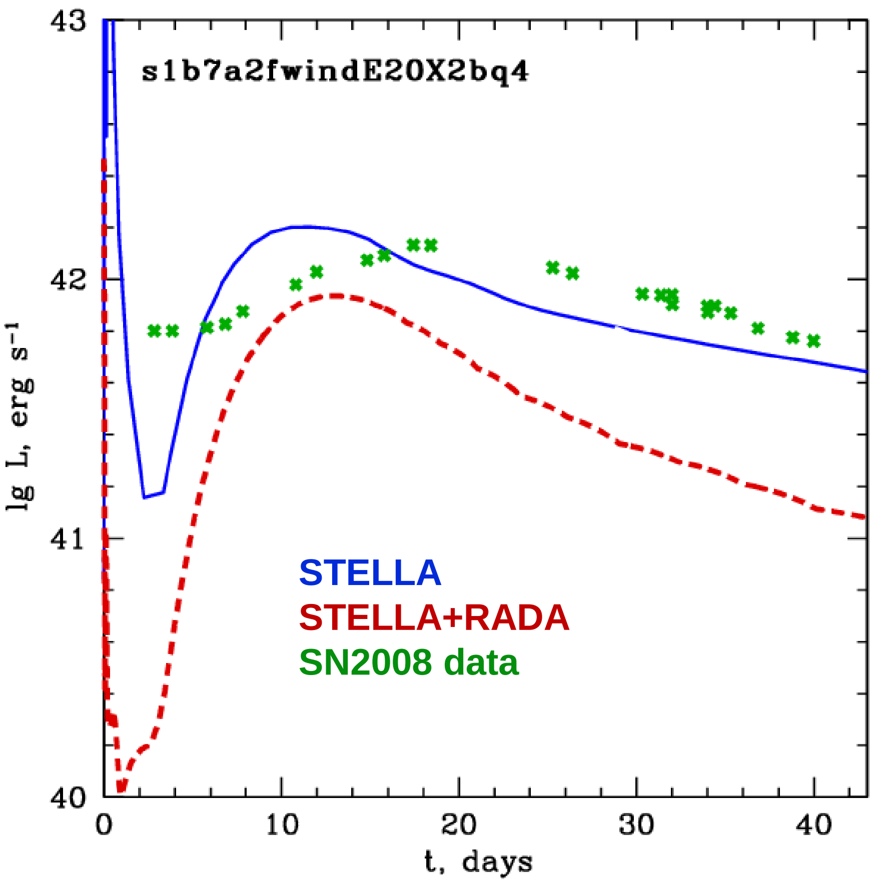
(Page K.L. et al. GCN Report 110.1 15 Jan 2008), E = 2.5 foe



SN2008D light curve modeling, E=2 foe



Tanaka M. et al., 2009, Bersten M. 2013



Density modulations of circumstellar medium
OR
Chemical composition of the progenitor
OR
Jet geometry