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Simulations of Supernova Light Curves and Spectra Using Multigroup Radiation Hydrodynamics

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- Shocks in supernovae. Supernova shock breakouts.

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- Development of algorithm for solving a problem of radiation transfer in fluids moving with high values of Lorentz factor
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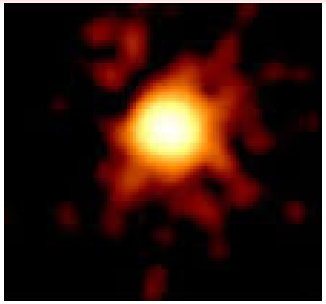
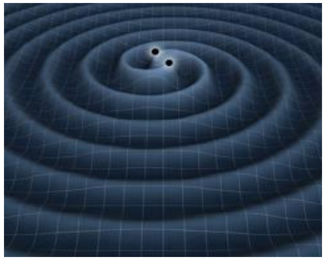
II. Supernova light curves and spectra modeling

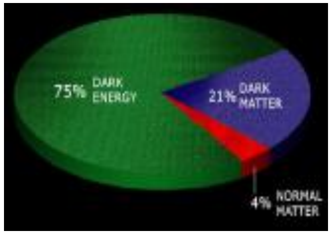
- Shock breakout model for type I b/c supernovae using multigroup radiation hydrodynamics
- The influence of relativistic and geometric effects of radiation propagation to the distant observer on light curves and spectra
- Numerical modeling in application for data analysis and interpretation of cosmic observations

Role of shock breakouts in astrophysics

- The most reliable predictions for SN outbursts in observations
- The theory of radiation hydrodynamics can be improved including the case of the ejecta moving with high value of Lorentz factor
- Stellar evolution problems resolution, e.g. unknown number of outbursts collapsing I b/c supernovae hard for detection.
- Better description of the connection of SNe with GRBs
- For nearby supernovae (in our galaxy), correlation with the detection of gravitational waves and neutrinos.
- Improvements of new direct measurements of distance in the Universe, aimed at studying the evolution of the dark energy.

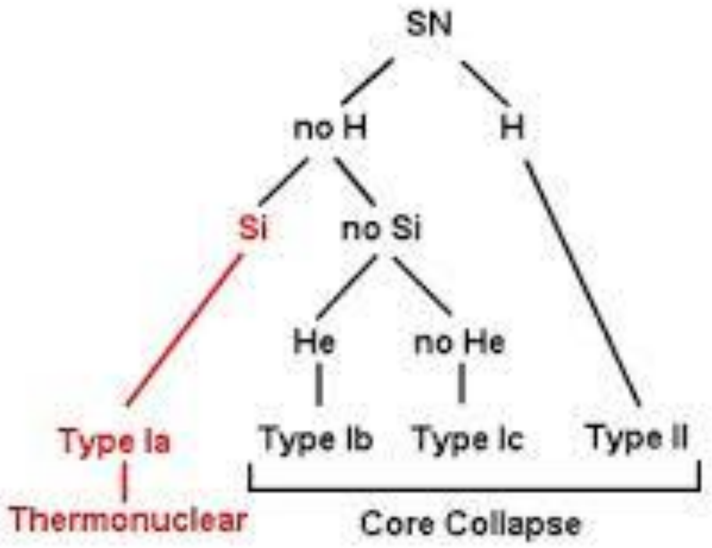






SN classification

Radioactive decays
^{56}Ni → ^{56}Co
(following D.K. Nadyozhin)


SN

no H

H

Si

no Si

He

no He

Type Ia

Type Ib

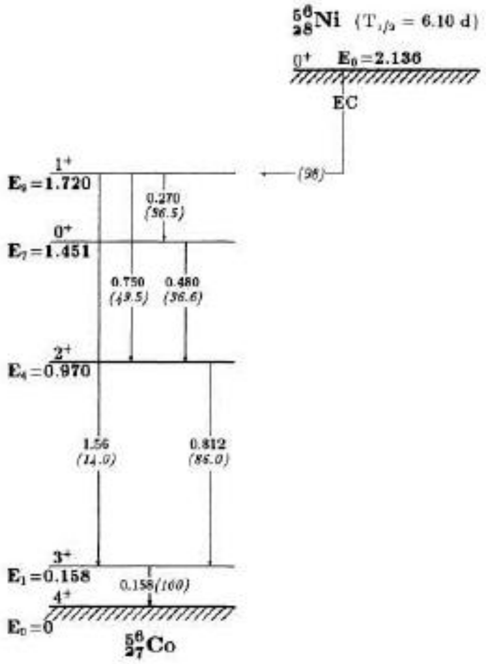
Type Ic

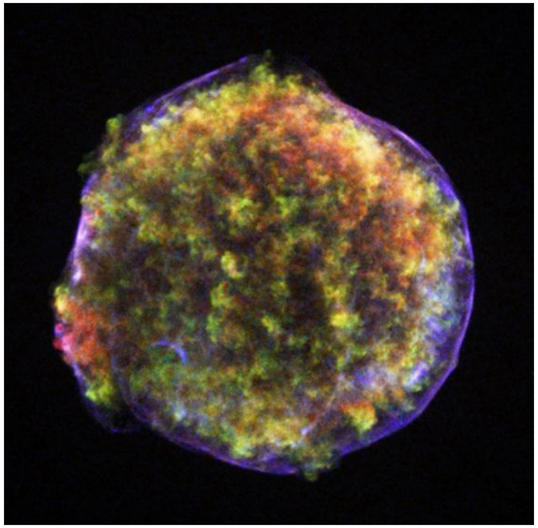
Type II

Thermonuclear

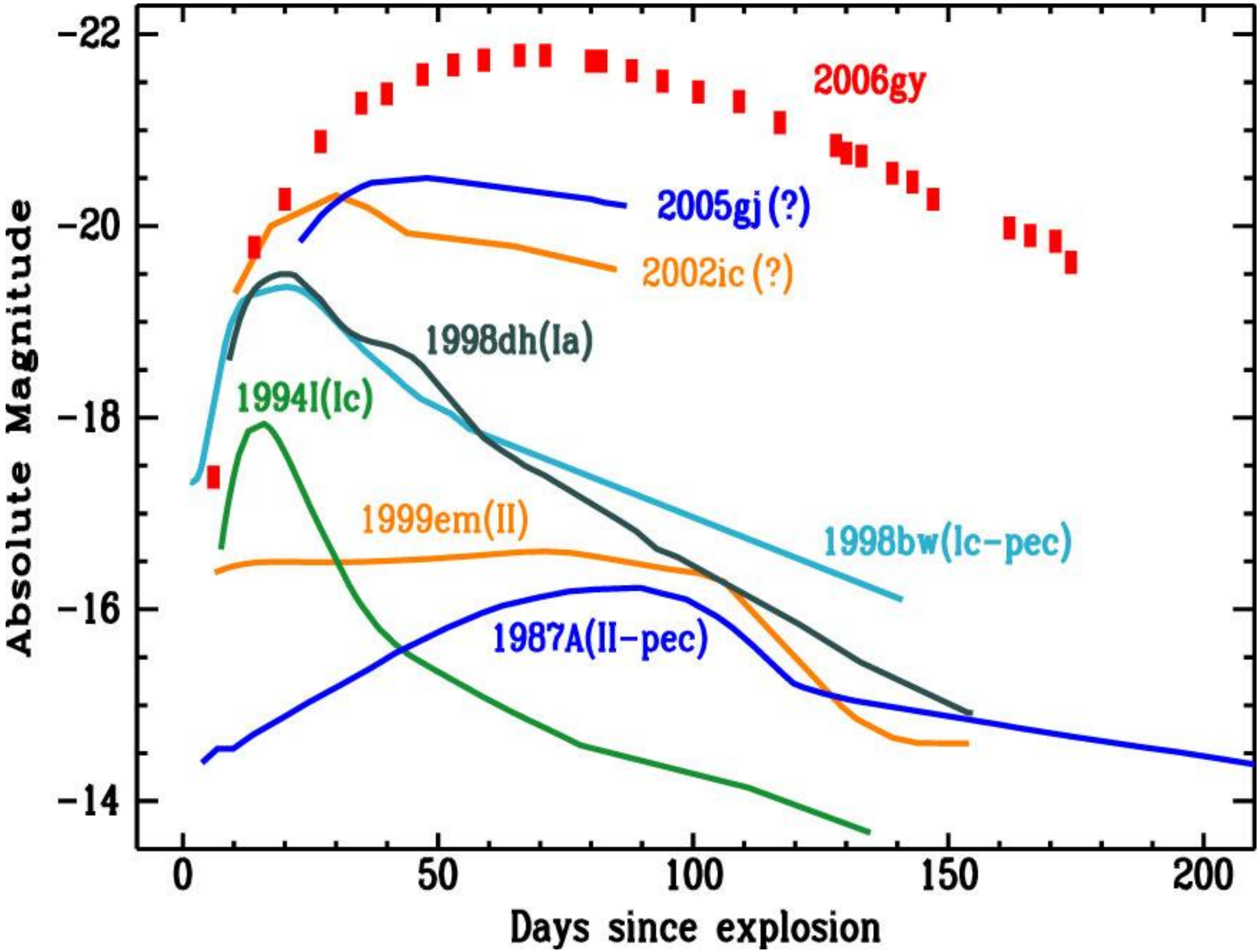
Core Collapse

The luminescence due to shock interacting with medium can last tens of thousand of years





Supernova light curves

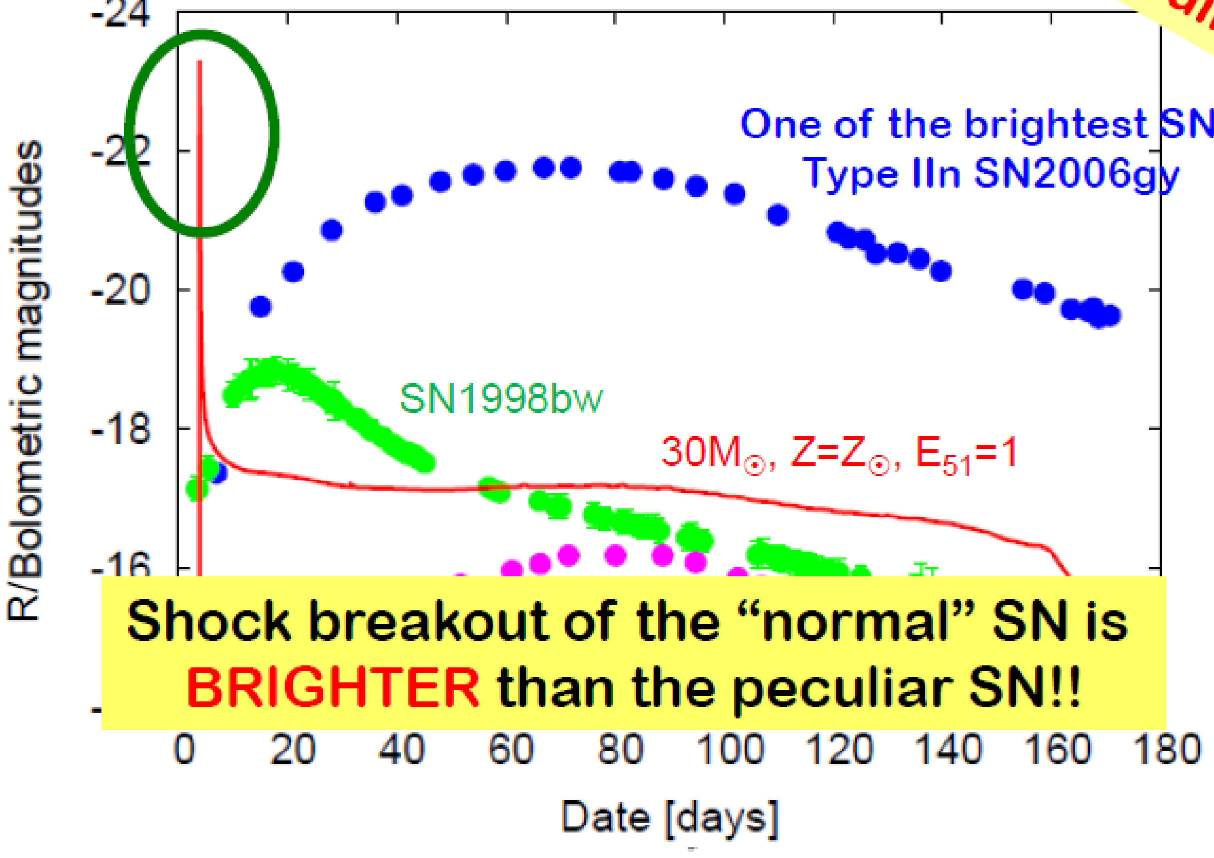


Supernova shock breakout (by N. Tominaga)

SN 2006gy (z=0.02: Smith + 08; Kawabata, ...,

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

This is a "peculiar" SN.

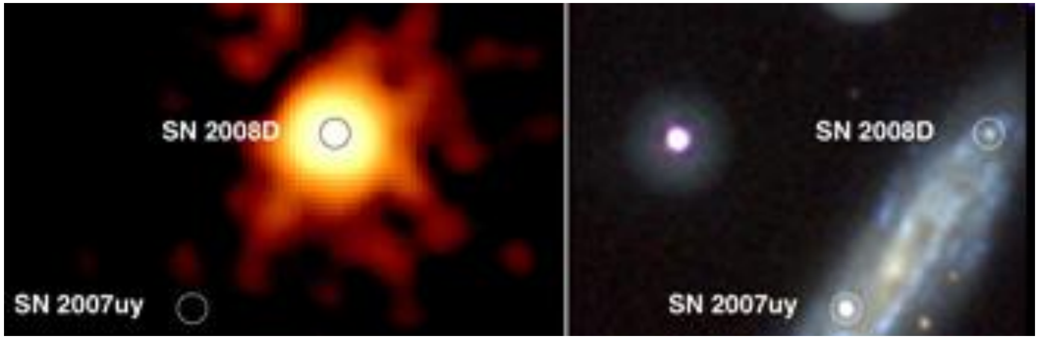


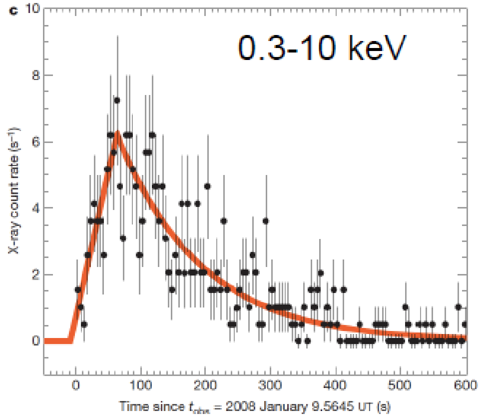
One of the brightest SNe
Type IIn SN2006gy

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

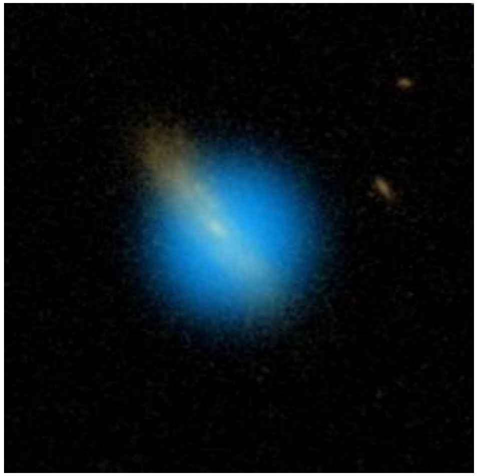
Supernova shock breakout (SB) observations

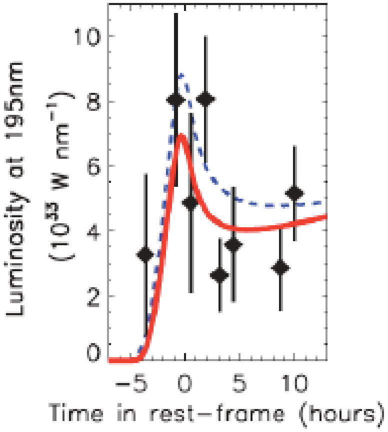
SN2008D, Type Ib/c, WR candidate progenitor, Swift





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.

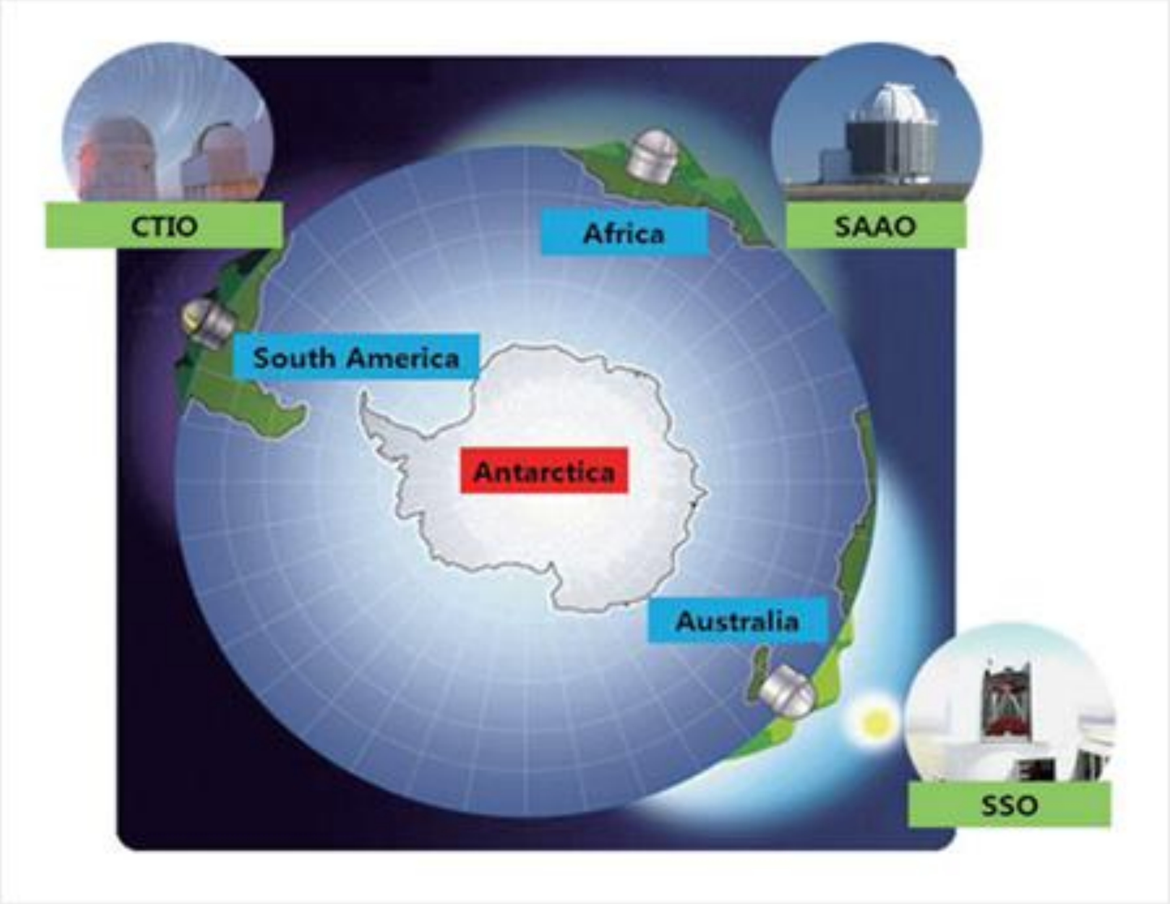
From Swift , GALEX to Subaru/HSC, PTF, LOSS, CRTS, KWFC, Skymapper, DES, Pan-STARRS, LSST, KMTNet

Theoretical models are in demand!

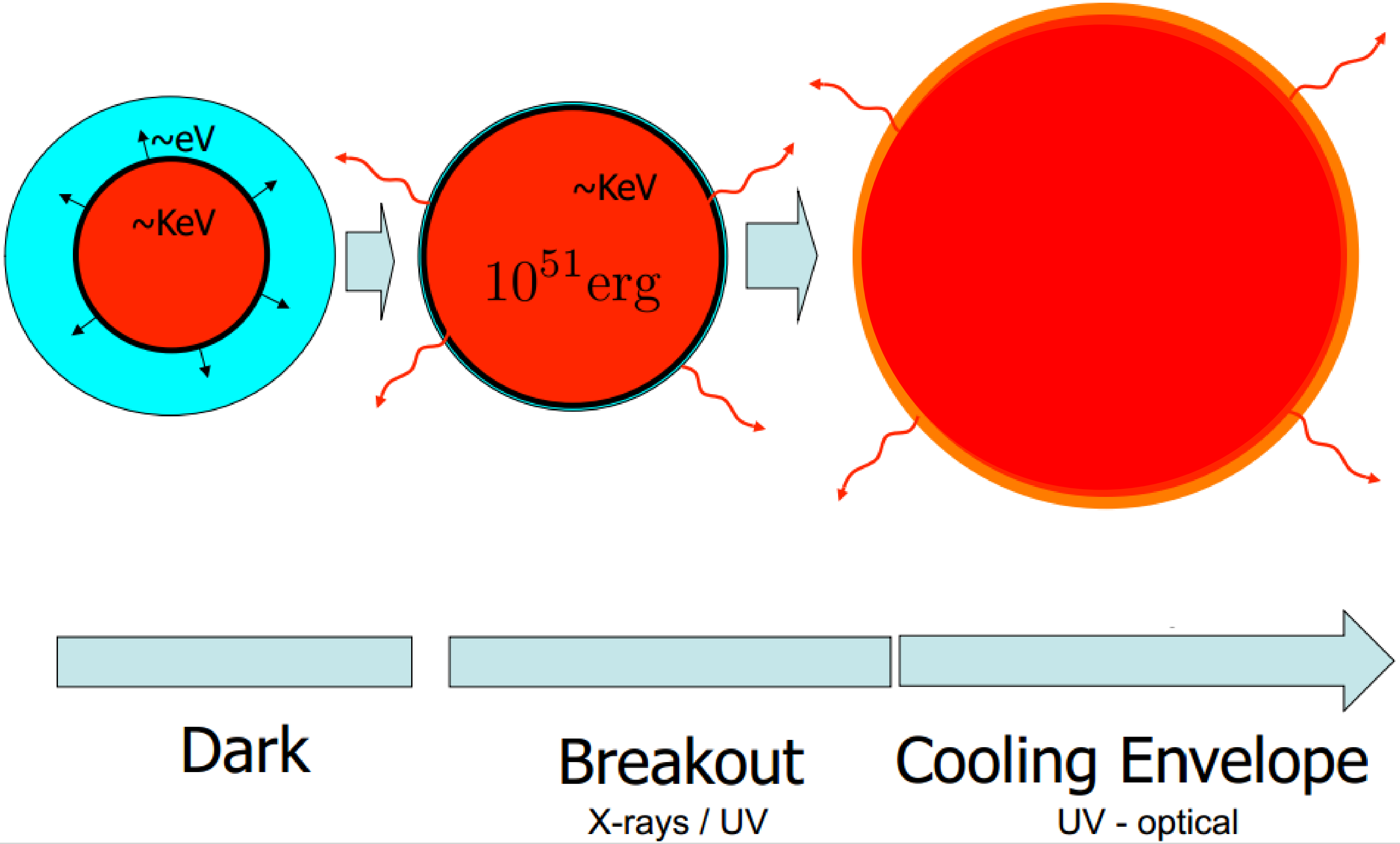
KMTNet (Korea Microlensing Telescope Network)

The KASI plans to build a network of wide-field photometric survey systems called Korea Microlensing Telescopes Network (KMTNet), funded by the government of Korea, in the southern hemisphere (Chile, South Africa, and Australia).

http://www.kasi.re.kr/english/project/KMTNet.aspx



Supernova shock breakout (by B. Katz)



SN Shock Breakout Summary

- The phenomenon of a supernova in most cases should start with a bright flash, caused by a shock wave emerging on the surface of the star after the phase of collapse or thermonuclear explosion in interiors.

- The detection of such outbursts associated with SN SBO can be used to obtain information about explosion properties and presupernova parameters.

- For an accurate treatment of the shock wave propagation near the surface of a presupernova it is necessary to perform numerical calculations.

- In some cases, e.g. in compact type Ib/c presupernovae, shock waves reach relativistic velocities. Then one has to include into consideration a number of relativistic effects.

Numerical simulation of relativistic radiation transfer

Numerical algorithms STELLA and RADA

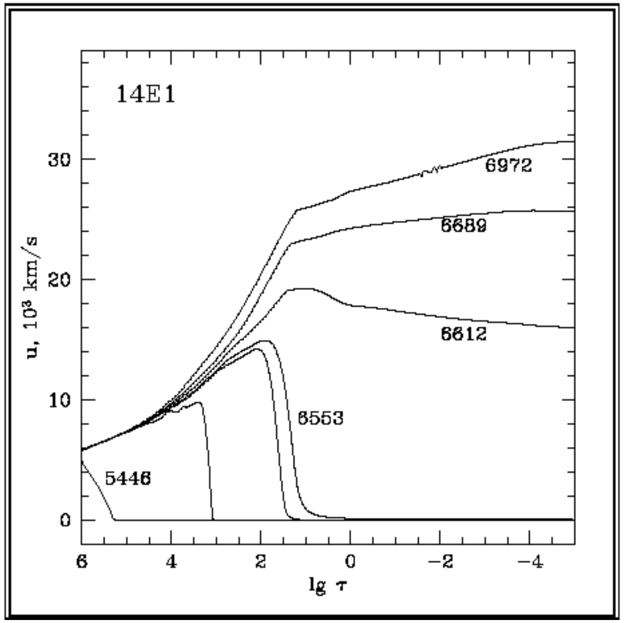
STELLA (STatic Eddington-factor Low-velocity Limit Approximation) (Blinnikov et al., 1998)

- 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
c – speed of light

Hydrodynamics

STELLA hydro equations:

$$\frac{\partial r}{\partial t} = u$$

$$\frac{\partial u}{\partial t} = -4\pi r^2 \frac{\partial (p+q)}{\partial m} - \frac{Gm}{r^2} + a_{\mathrm{r}}$$

$$\frac{\partial r}{\partial m} = \frac{1}{4\pi r^2 \rho} .$$

$$a_{\mathrm{r}} = \frac{4\pi}{c} \int_0^\infty (\chi_{\mathrm{a}} + \chi_{\mathrm{s}}) \frac{H_\nu}{\rho} d\nu$$

$$\left(\frac{\partial e}{\partial T}\right)_\rho \frac{\partial T}{\partial t} = \varepsilon + 4\pi \int_0^\infty \chi_{\mathrm{a}} \frac{J_\nu - B_\nu}{\rho} d\nu - \\ -4\pi \frac{\partial r^2 u}{\partial m} \left[T \left(\frac{\partial p}{\partial T}\right)_\rho + q \right]$$

$$\mathcal{K} = f_{\mathrm{Edd}} \mathcal{J}$$

Comoving radiation transfer (Mihalas, 1980)

Transfer equation:

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

Moments equation:

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

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

SRRHD. Non-relativistic strong shock

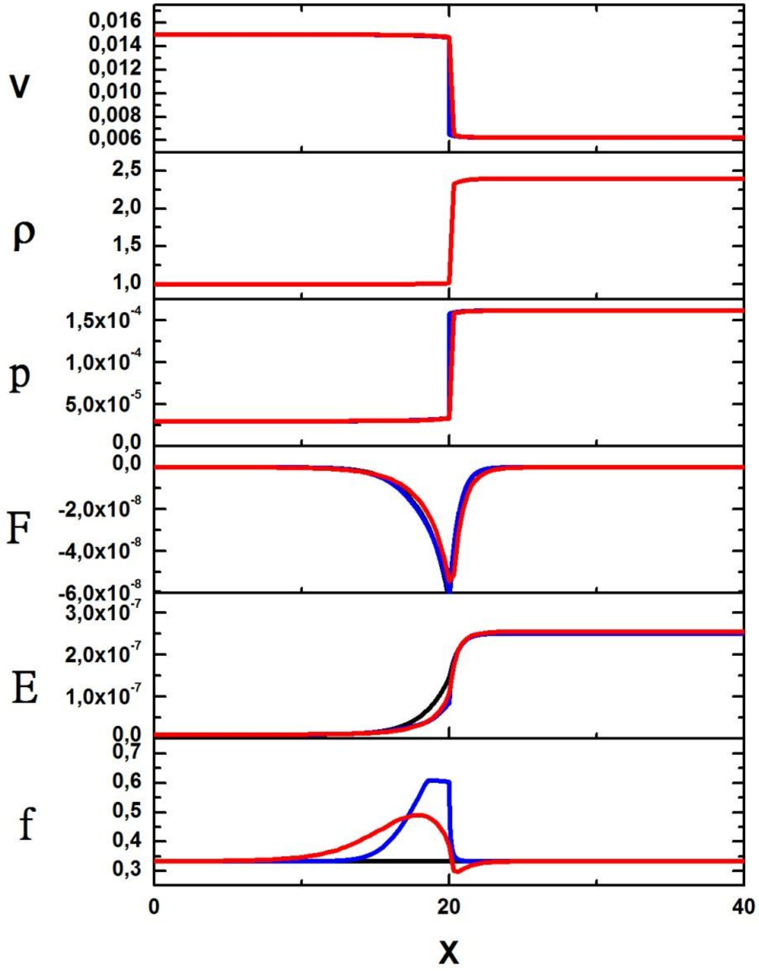
Semi-analytic relativistic hydro + Relativistic radiation transfer (no closure condition)

Shock tube configuration
(Farris et al., 2008), $P_r/P_g \approx 0.001$

Γ	κ^a	Left state^c	Right State^c
5/3	0.4	$\rho_0 = 1.0$ $P = 3.0 \times 10^{-5}$ $u^x = 0.015$ $E = 1.0 \times 10^{-8}$	$\rho_0 = 2.4$ $P = 1.61 \times 10^{-4}$ $u^x = 6.25 \times 10^{-3}$ $E = 2.51 \times 10^{-7}$

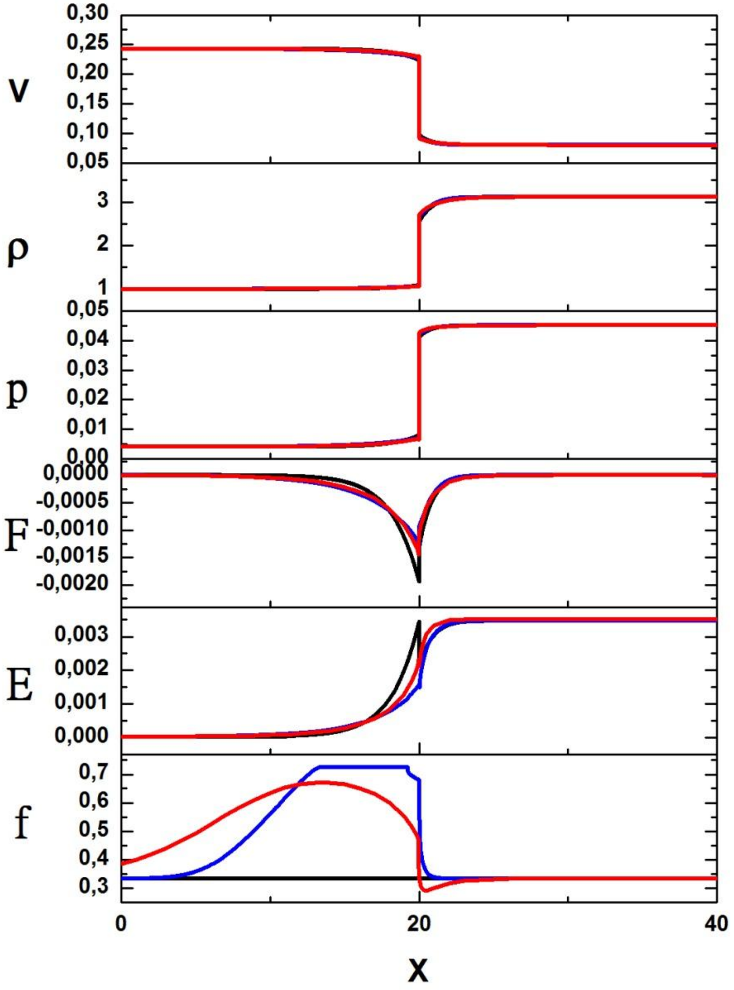
Closure condition: P = fE

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

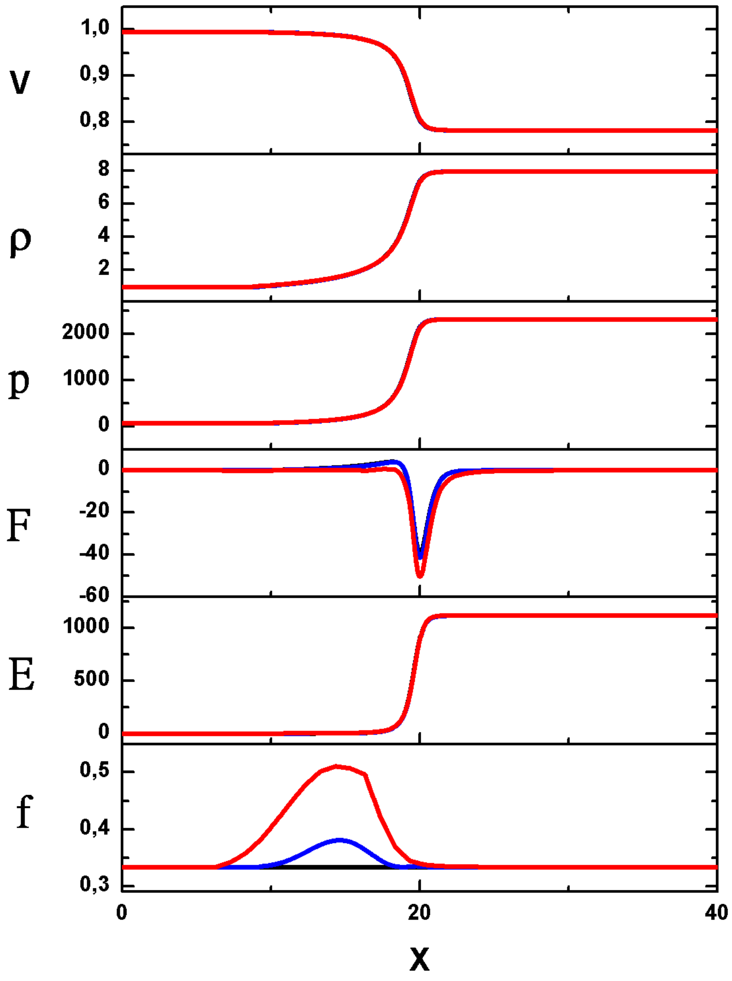


SRRHD. Strong shock and relativistic wave

- **Mildly Relativistic Strong Shock (Test 2)**



- **Relativistic Strong Shock (Test 3)**



SRRHD. Radiation-dominated mildly-relativistic shock wave

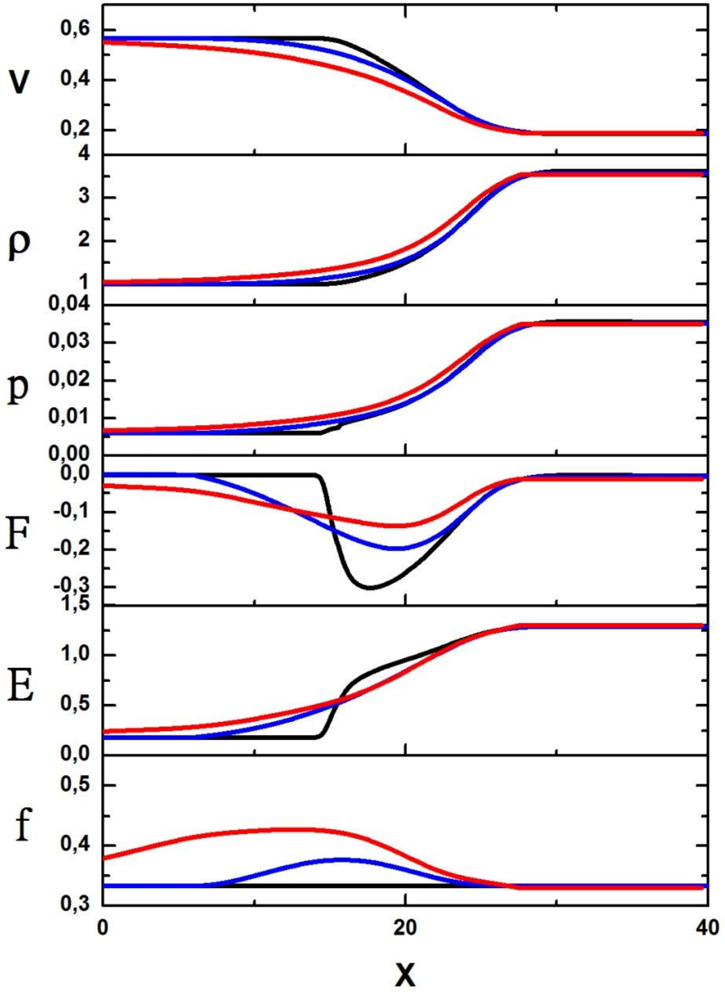
Semi-analytic relativistic hydro +
Relativistic radiation transfer
(no closure condition)

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	$\rho_0 = 1.0$ $P = 6.0 \times 10^{-3}$ $u^x = 0.69$ $E = 0.18$	$\rho_0 = 3.65$ $P = 3.59 \times 10^{-2}$ $u^x = 0.189$ $E = 1.30$

Closure condition: P = fE

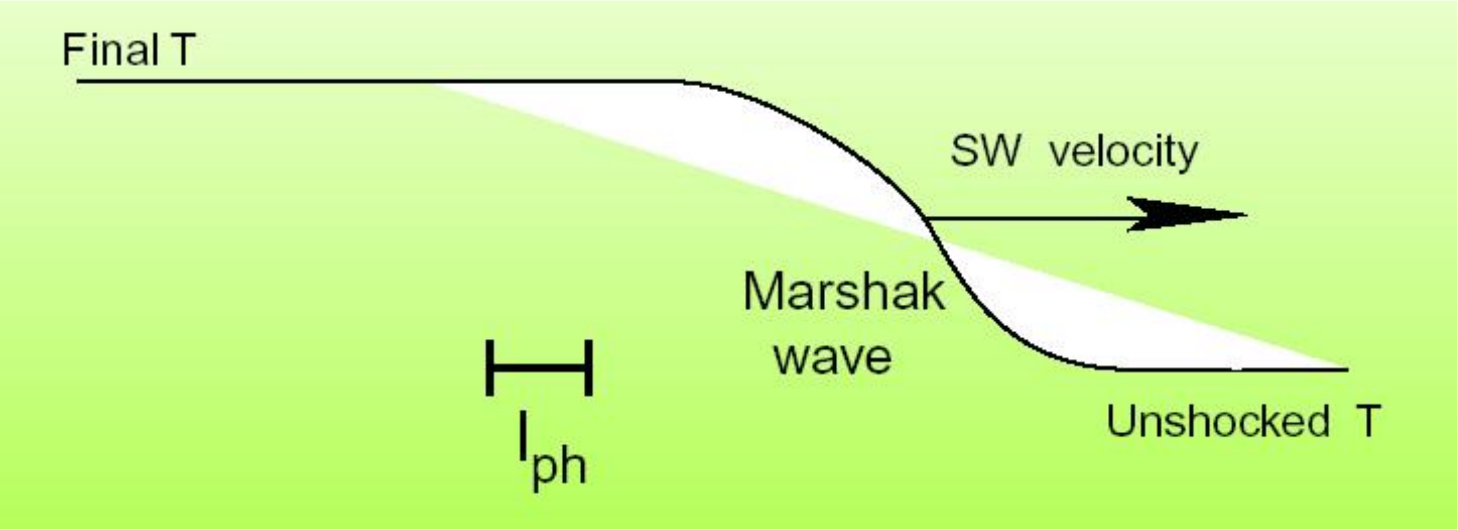
- Eddington approximation: f = 1/3
- M1-closure (Levermore, 1984)
  f = f(E,F) joins "optically thin" and "thick" cases
- **Photon Boltzmann equation**



Radiative shocks

Discontinuity disappears if radiation energy and pressure exceeds gas energy and pressure.
Theoretical estimations (Belokon, 1959, Imshennik, Morozov, 1964):

$$P_r / P_g \sim 8.5$$



Shock wave structure for strong shock

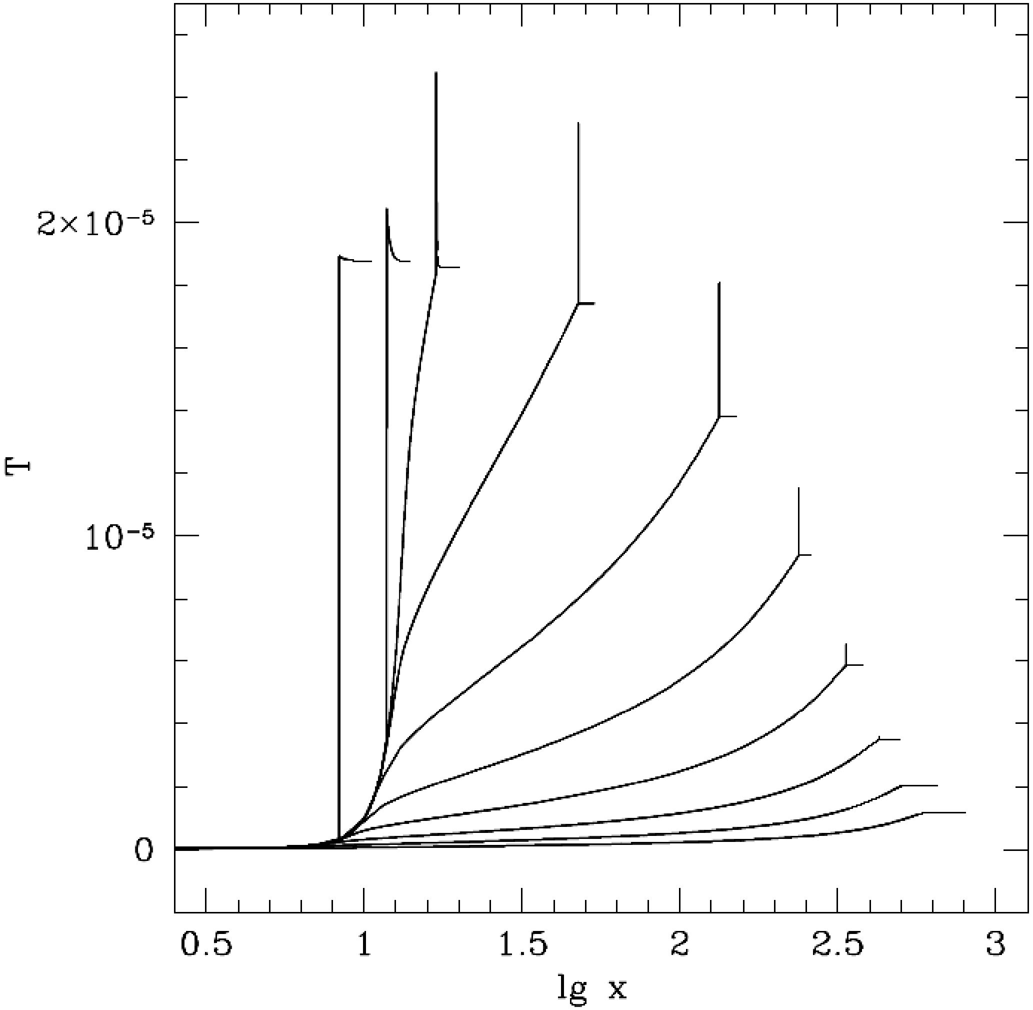
Closure condition: P = fE

- Eddington approximation: f = 1/3
- M1-closure
- **Photon Boltzmann equation**

$$P_r / P_g \sim 8.5$$

Diffusion approximation:

$$P_r / P_g \sim 4.65$$

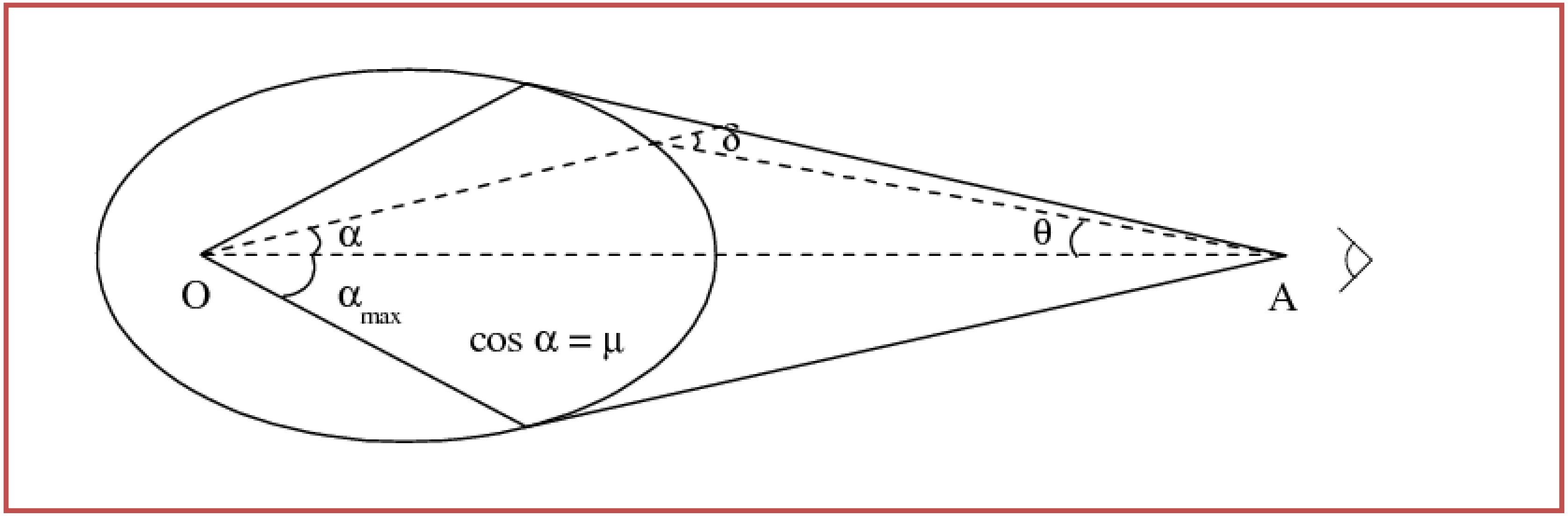


Transformation of fluxes from source to observer’s frame

Allowance of time delay, Doppler effect and aberration

Flux ***F*** in the point of observation – integral of intensity ***I*$_0$** over the surface:

$$F_\nu(t_{obs}) = 2\pi\int_{\mu_{min}}^{1} \mu p^2 I_0\left(R(\mu),\nu\left(\frac{\nu_0}{\nu}\right),\cos\delta_0(\cos\delta)\right)\left(\frac{\nu}{\nu_0}\right)^3 d\mu$$



Effects of Lorentz covariance

Transfer equation Lorentz covariance, Doppler effect and aberration:

$$I(\mu, \nu) = (\nu/\nu_0)^3 I_0(\mu_0, \nu_0) ,$$

$$\nu = \nu_0 \gamma (1 + \beta\mu_0) ,$$

$$\mu = \frac{\mu_0 + \beta}{1 + \beta\mu_0} ,$$

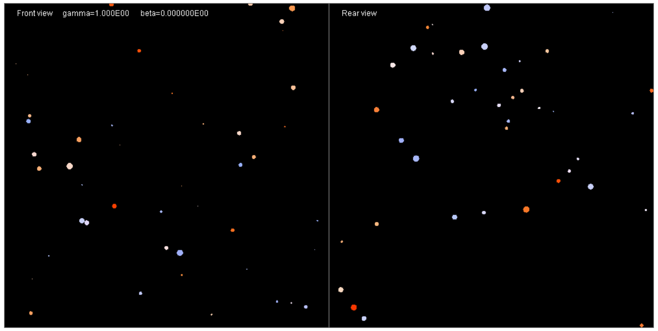
lead to the following visible effects in moving to radiation sources:

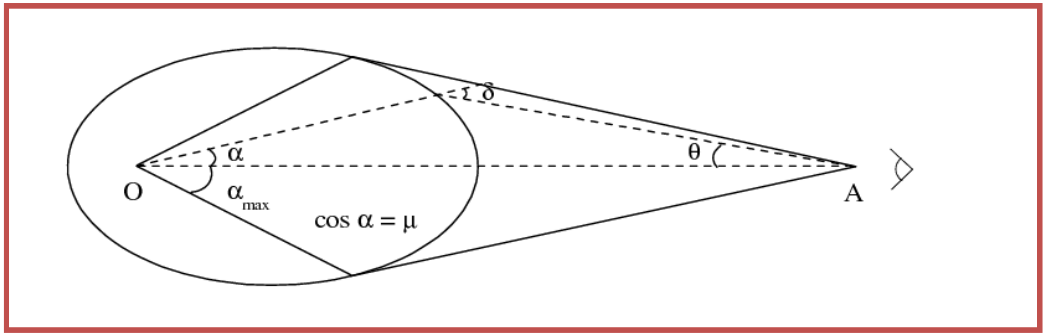
1. Radiation flux increases
2. Spectrum becomes harder
3. The space moves towards the direction of motion

Transformation of fluxes from source to observer’s frame

Lorentz covariance, Doppler effect and aberration

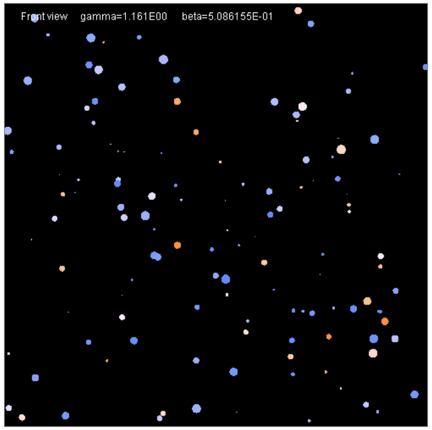
- Radiation flux increases
- Spectrum becomes harder
- The space shrinks towards the direction of motion



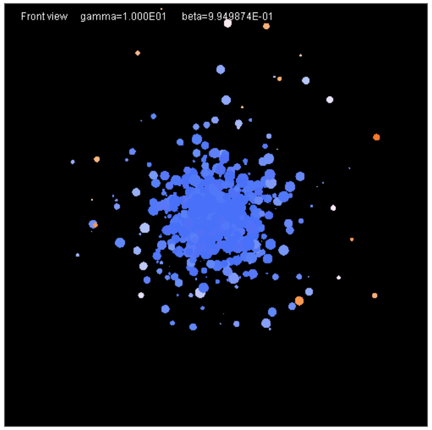


V = 0

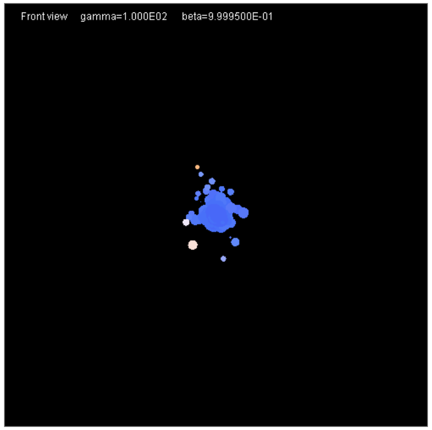
V = 0.5 c



Γ = 10



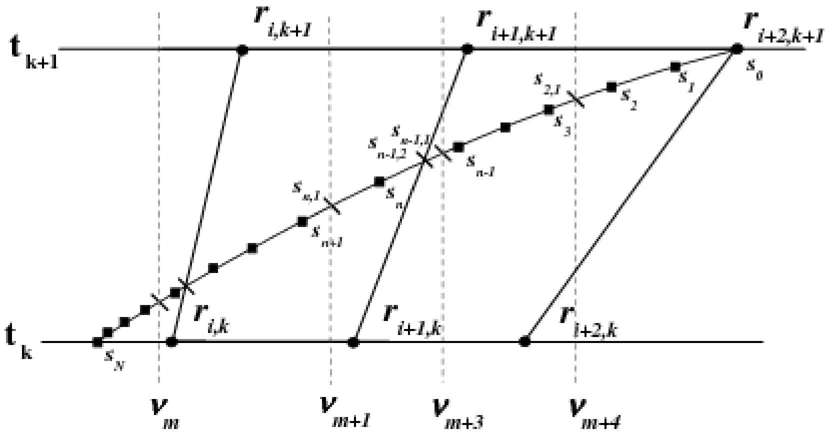
Γ = 100

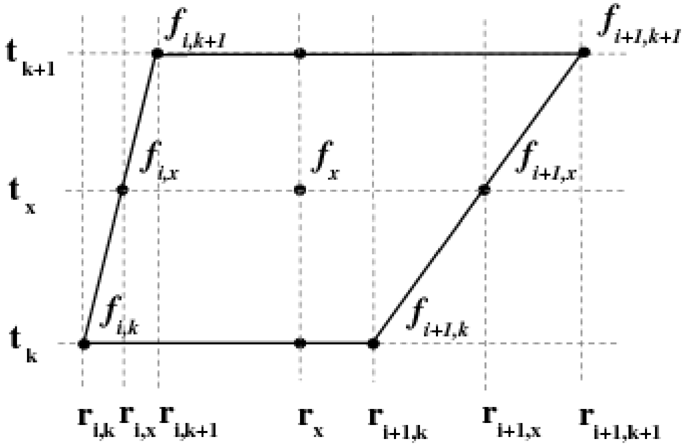


STELLA RADA Integration

Algorithm RADA turns on before shock breakout starts

STELLA uses Lagrangian grid over mass coordinate, RADA – short characteristics with physical quantities interpolation





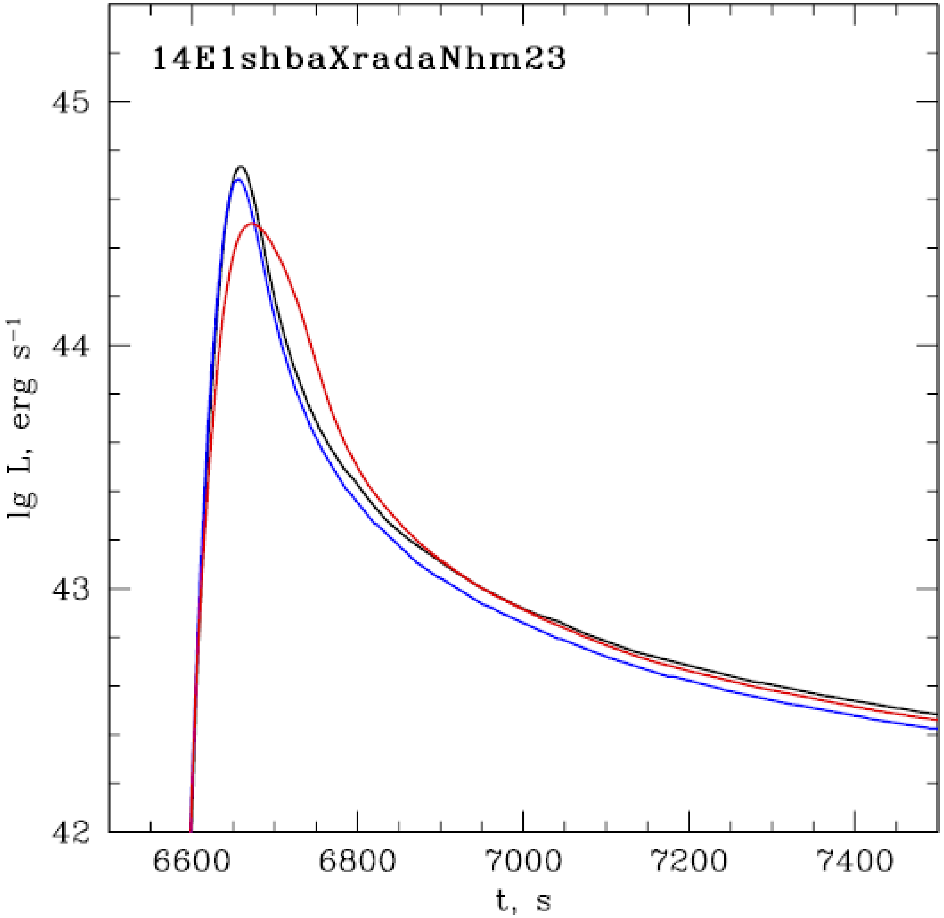
$$\frac{dI(s)}{s} = \eta + \tilde{\eta} s - \chi I(s) - \tilde{\chi} s I(s)$$

$$\eta_\nu = \alpha_\nu b_\nu + \sigma_\nu J$$

$$I(s) = I_0 - \frac{\tilde{\eta}}{\tilde{\chi}} e^{-\tau} + \frac{\tilde{\eta}}{\tilde{\chi}}\left(\eta - \chi \frac{\tilde{\eta}}{\tilde{\chi}}\right) e^{-\tau} \int_0^s e^{\tau(s')} ds', \qquad \tau = 0.5\,\tilde{\chi} s^2 + \chi s$$

I b/c Shock Breakout Simulations

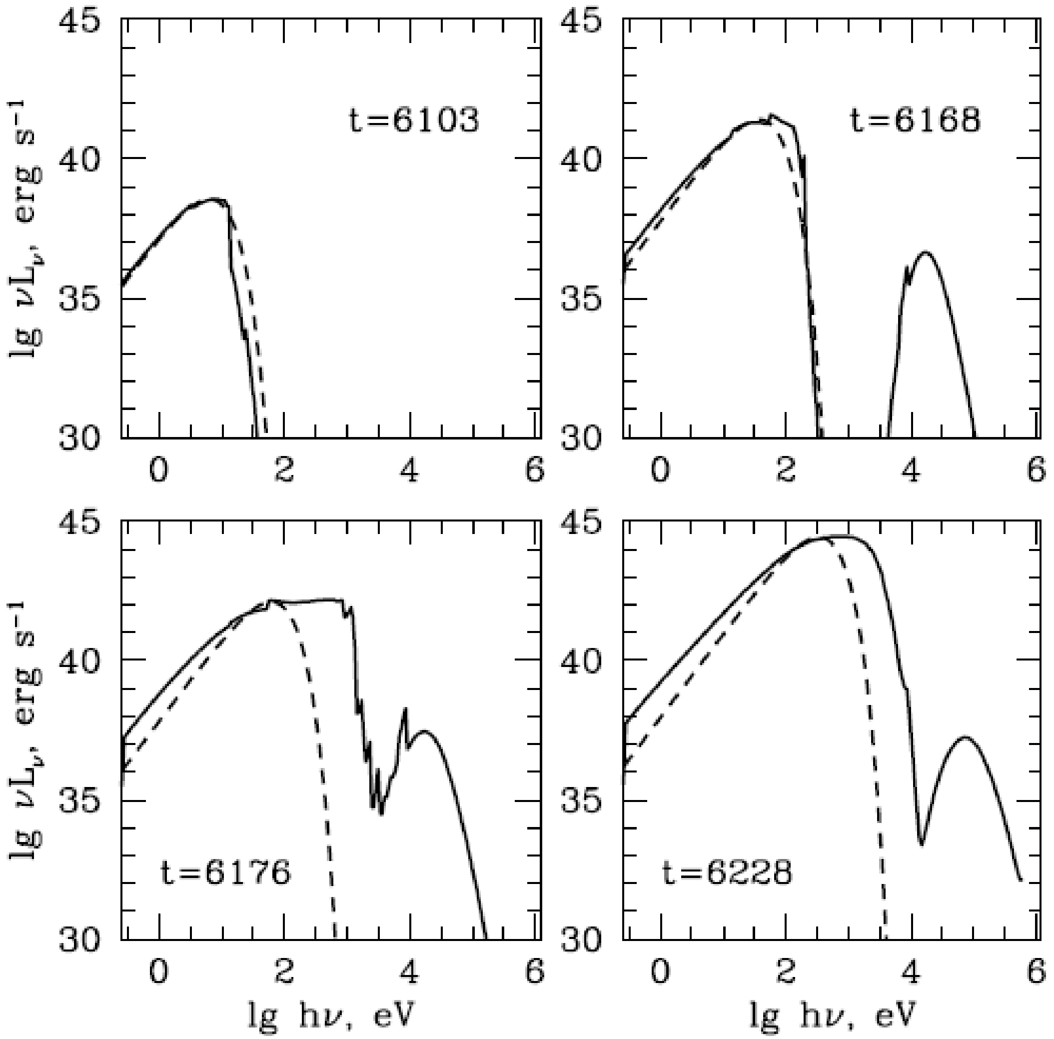
SN 1987A shock breakout



The **black** and **blue** lines represent, respectively, the **STELLA** and **RADA** calculations in the **comoving frame** of reference.

Red line - RADA calculations in **observer's frame** of reference taking into account radiation time delay.

SN 1987A shock breakout spectra

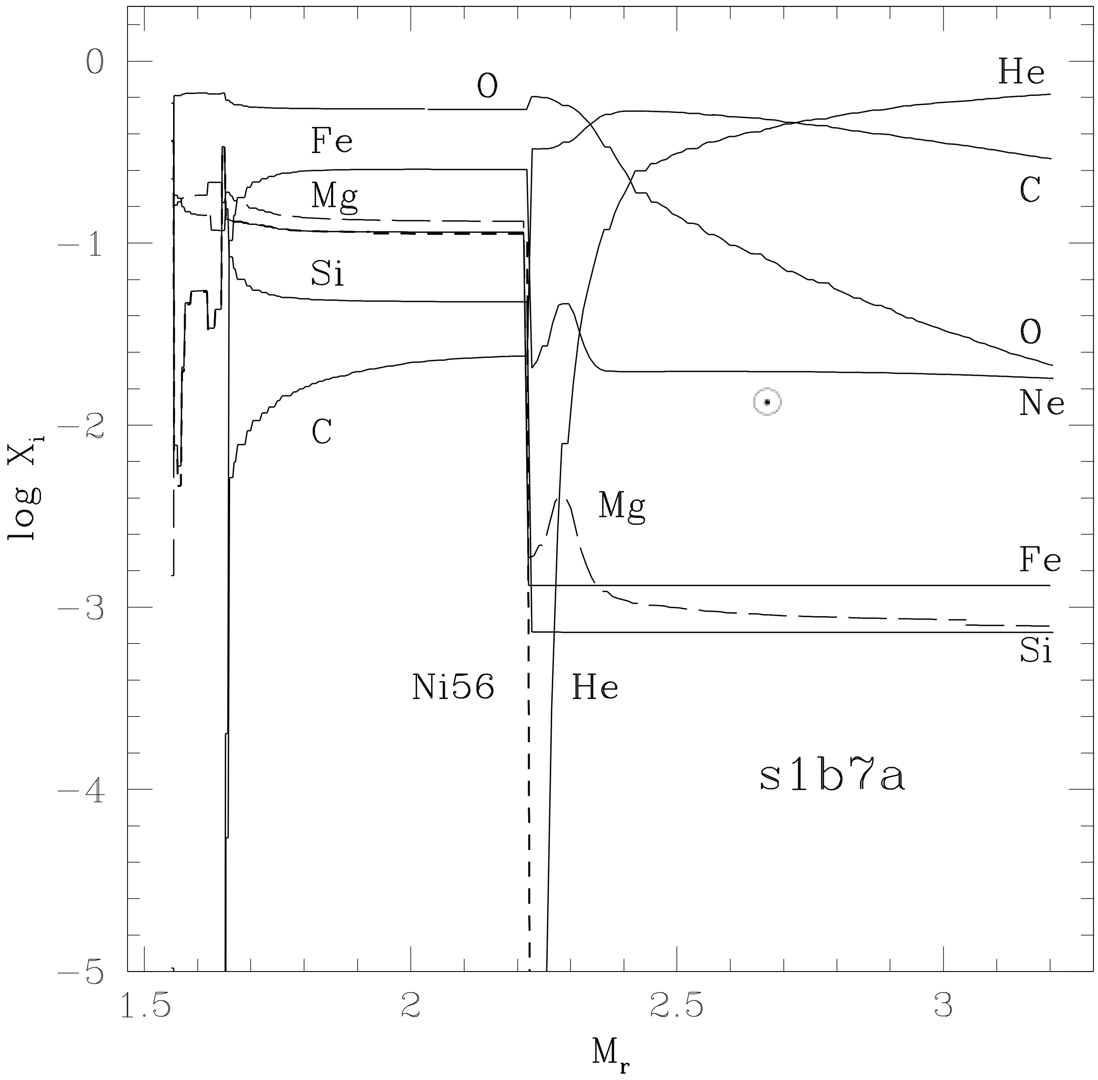


The hardest semi-relativistic model, the SN Ib/c model

- Evolutionary calculation of KEPLER program for a main sequence star (Woosley et al., 1995)
- STELLA provides a shock velocity at breakout up to 0.6c (Blinnikov, 1998)
- M = 3.199 M$_\odot$

  R = 1.41 10^{11} cm

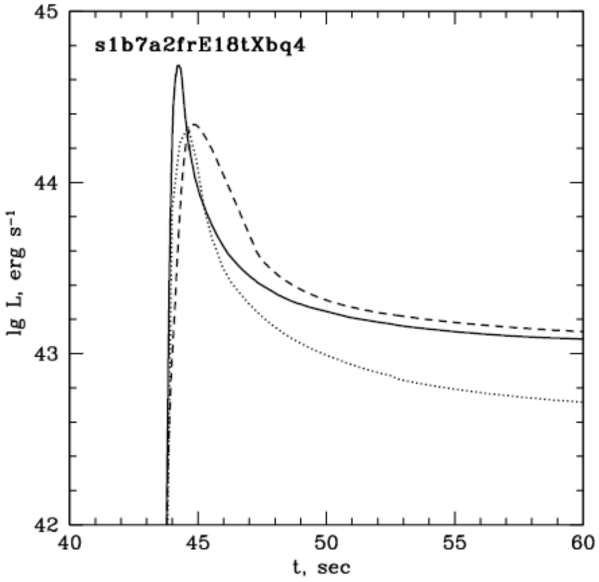
  E = 0.9 10^{51} erg



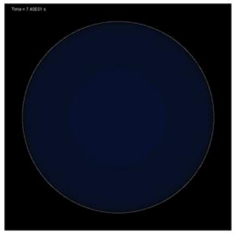
SN Ibc shock breakout modeling (Tolstov et al. 2013)

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

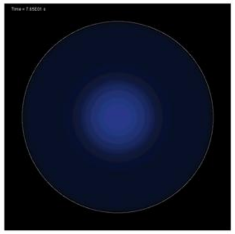
- Radiation Transfer – Short Characteristic Method (about 90% of calculation time)
- Radius x Angle x Energy = 350 * 100 * 200 = = 7 000 000 for 1 time step
- 200 steps of RADA , 10000 steps of STELLA, 3 days of calculation



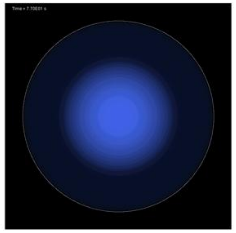
74 s



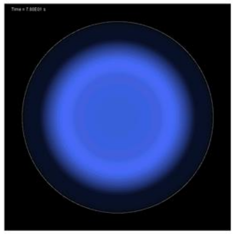
76.5 s



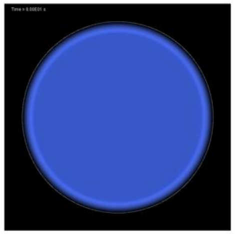
77 s



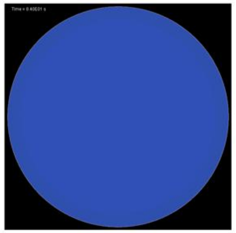
78 s

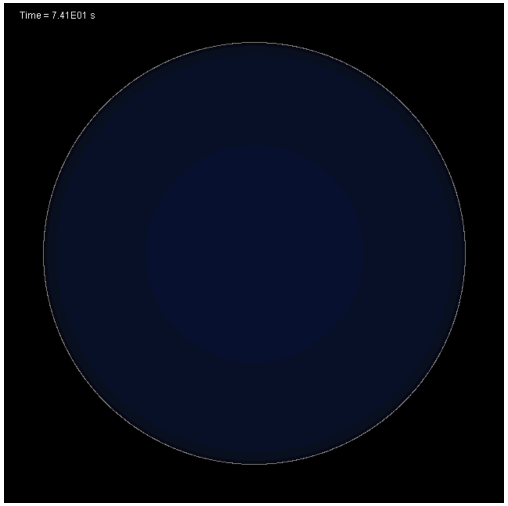


80 s



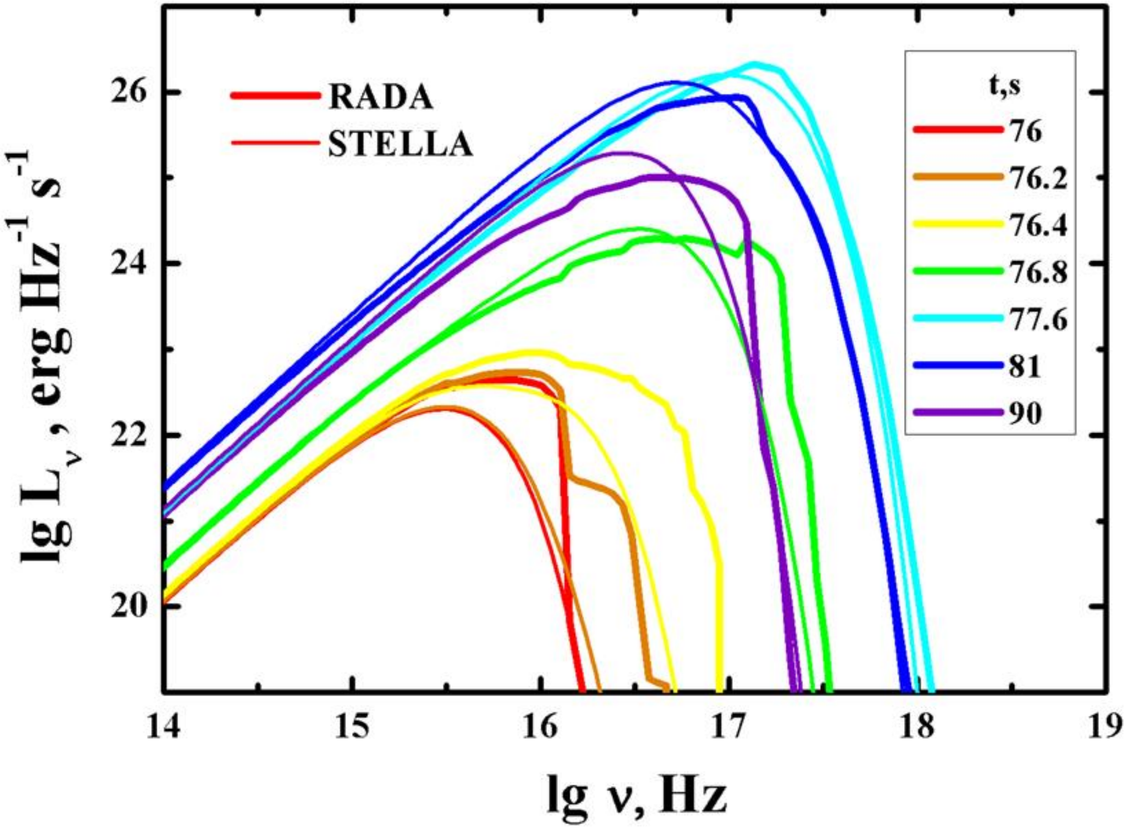
84 s





Spectra in observer's frame of reference

- Instantaneous spectra for various times at the epoch of SBO.



SN I b/c model light curves

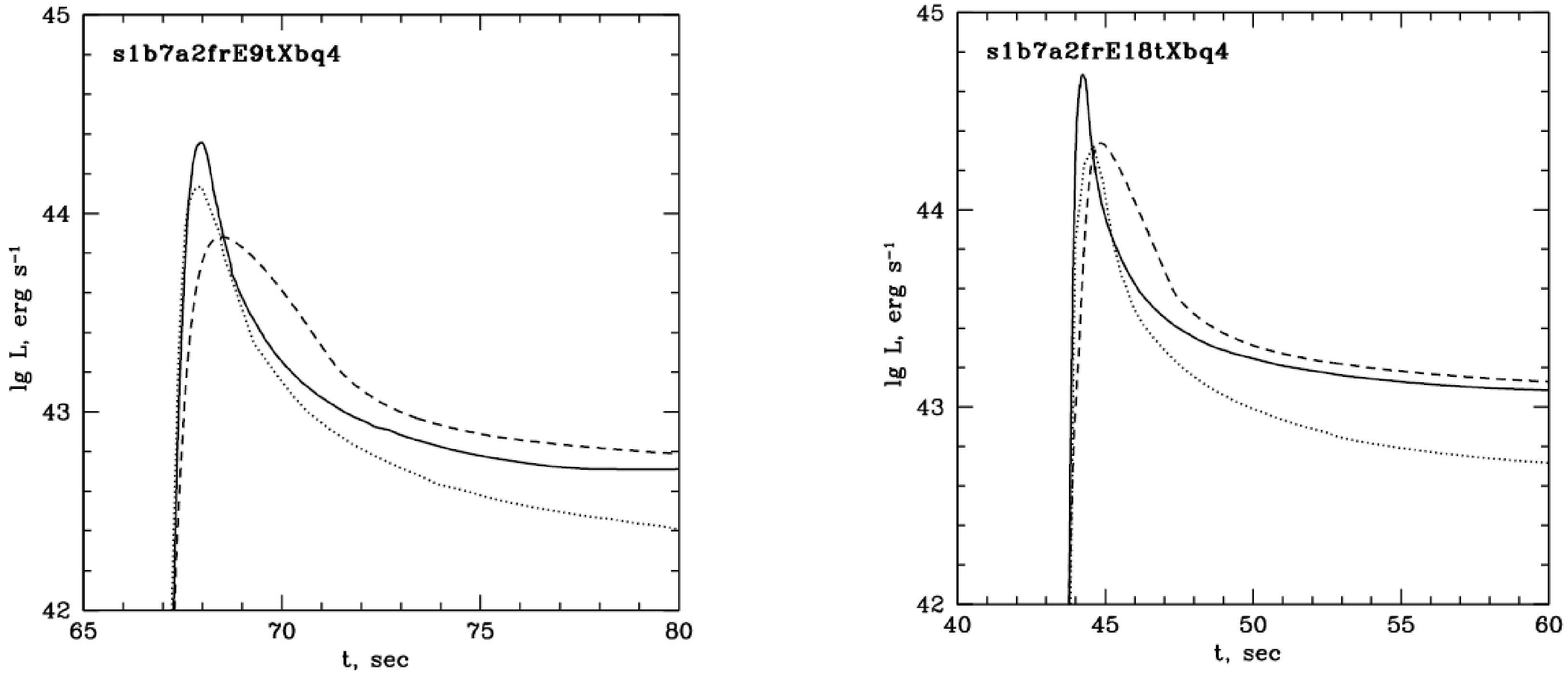
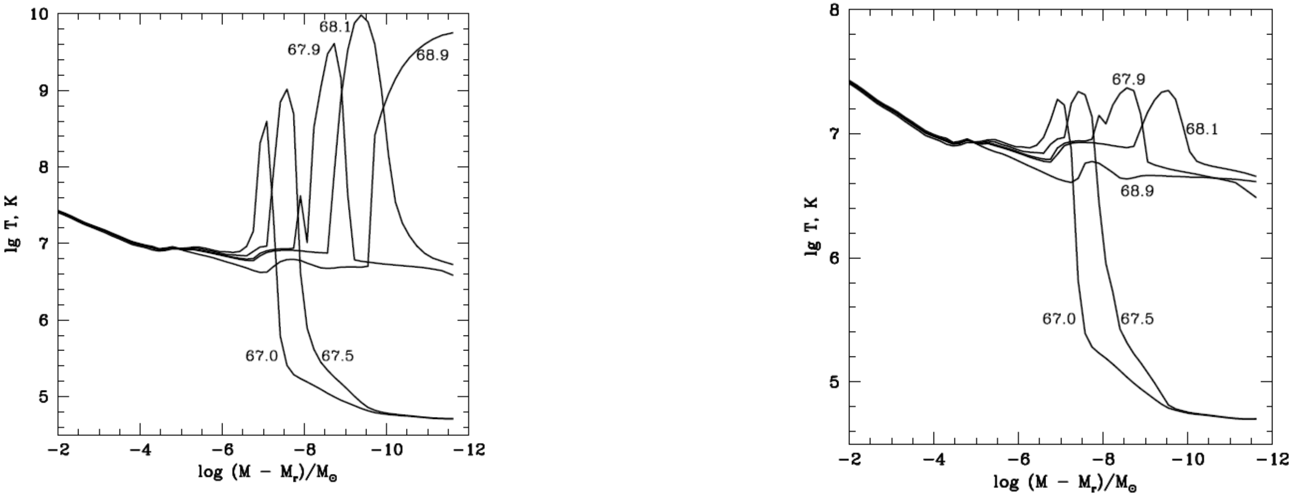


Figure 20. Comparison of the bolometric light curves at the epoch of shock breakout for a type Ib/c presupernova models: explosion energy $E = 9 \cdot 10^{50}$ erg, maximum matter velocity $v_{max} \approx 0.3c$ (top) and $E = 1.8 \cdot 10^{51}$ erg, $v_{max} \approx 0.5c$ (bottom). The solid and dotted lines represent, respectively, the STELLA and RADA calculations in comoving frame of reference. Dashed line represents RADA calculations in observer's frame of reference taking into account radiation time delay in the observer's frame of reference.

Scattering is important!

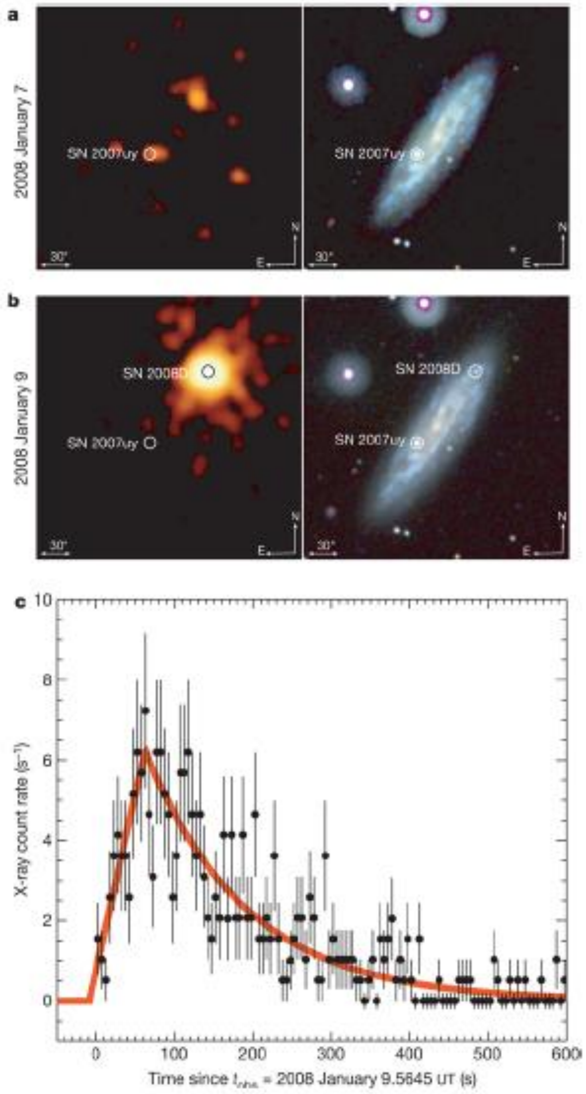
Like for the 14E1X2 version above we switched off the thermalization of photons at the first scattering and increase the number of frequency bins for the version **s1b7a2X**. The maximum temperature becomes enormous (~ 10^{10} K), but small admixture of true “gray” (i.e. frequency-independent) absorption, 10^{-6} of the Thomson scattering in an SN Ib progenitor, makes the temperature lower for several orders of magnitude (the version **s1b7a2Xm6**)



Matter temperature for the version s1b7a2X (left) and s1b7a2Xm6 (right) at shock breakout versus Lagrangian mass M_r measured from the surface. The time in seconds is given near the curves. The temperature peak is at an optical depth ~ 200; 50; 4; 1; 0 at times 67.0, 67.5, 67.9, 68.1, 68.9 s.

Modeling of XRO080109/SN2008D

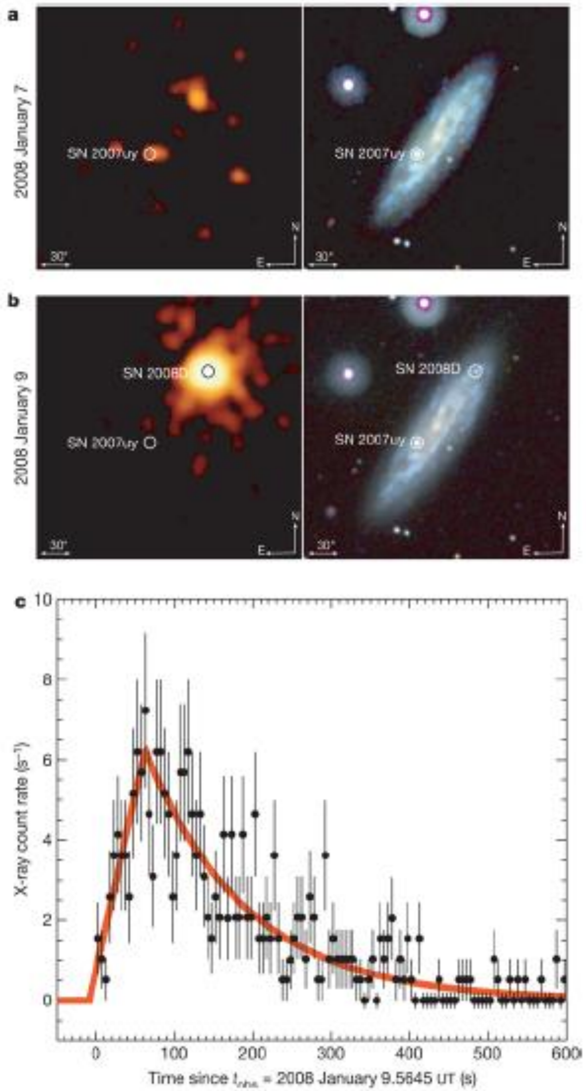
XRO080109/SN2008D



- On 2008 Jan 9 at 13:32:49 UT, we serendipitously discovered an extremely bright X-ray transient during a scheduled Swift X-ray Telescope (XRT) observation of the galaxy NGC 2770 (d = 27 Mpc). Previous XRT observations of the field just two days earlier revealed no pre-existing source at this location. The transient, hereafter designated as X-ray outburst (XRO) 080109, lasted about 400 s, and was coincident with one of the galaxy's spiral arms (Soderberg A. et al. Nature, Volume 453, Issue 7194, pp. 469-474 (2008))

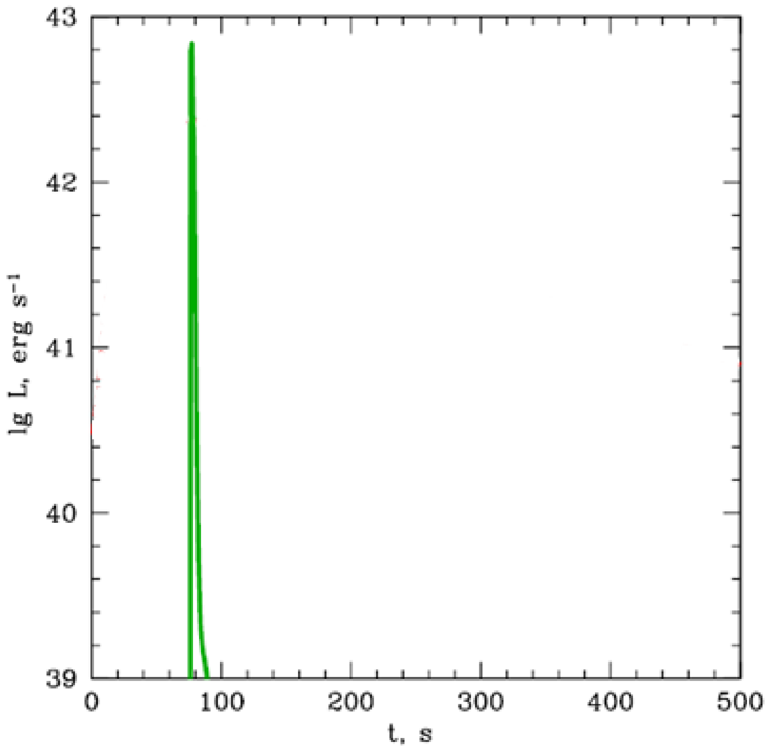
- Drawing on optical, UV, radio, and X-ray observations shows that the progenitor was compact ($R \approx 10^{11}$cm) and stripped of its outer Hydrogen envelope by a strong and steady stellar wind. These properties are consistent with those of Wolf-Rayet (WR) stars, the favored progenitors of Type Ibc SNe.

XRO080109/SN2008D in the Model of SNIb



How to explain the duration and spectrum of the outburst?

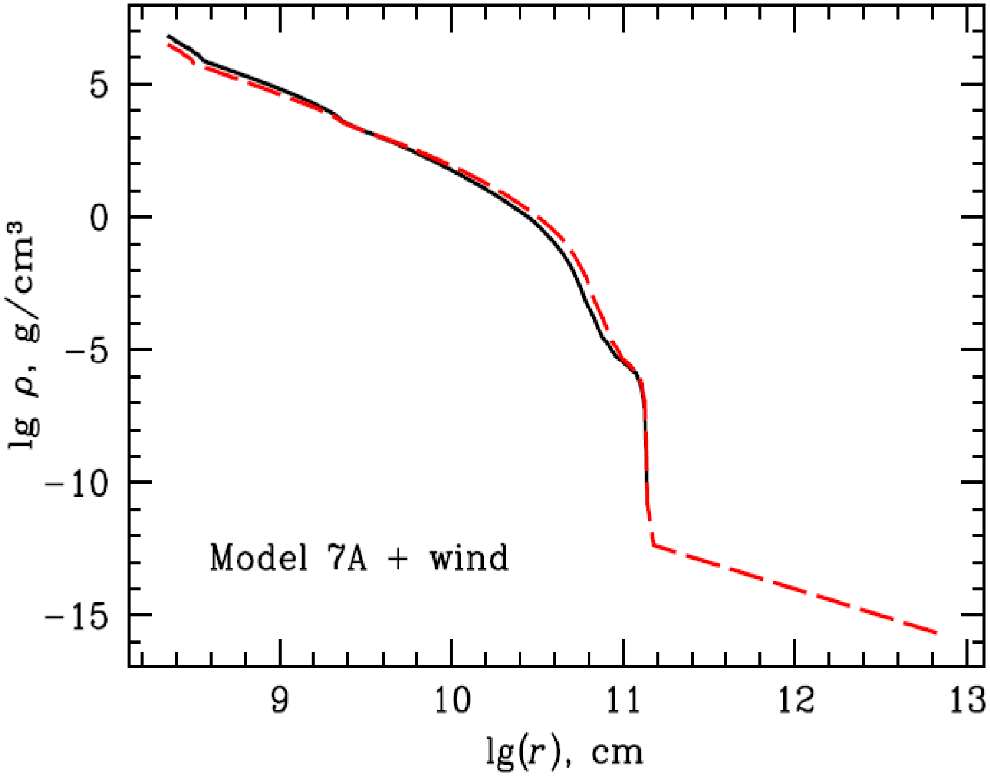
External medium is optically thin to affect the radiation (Chevalier, Roger A., Fransson, Claes, 2008, ApJ, 683L, 135C)



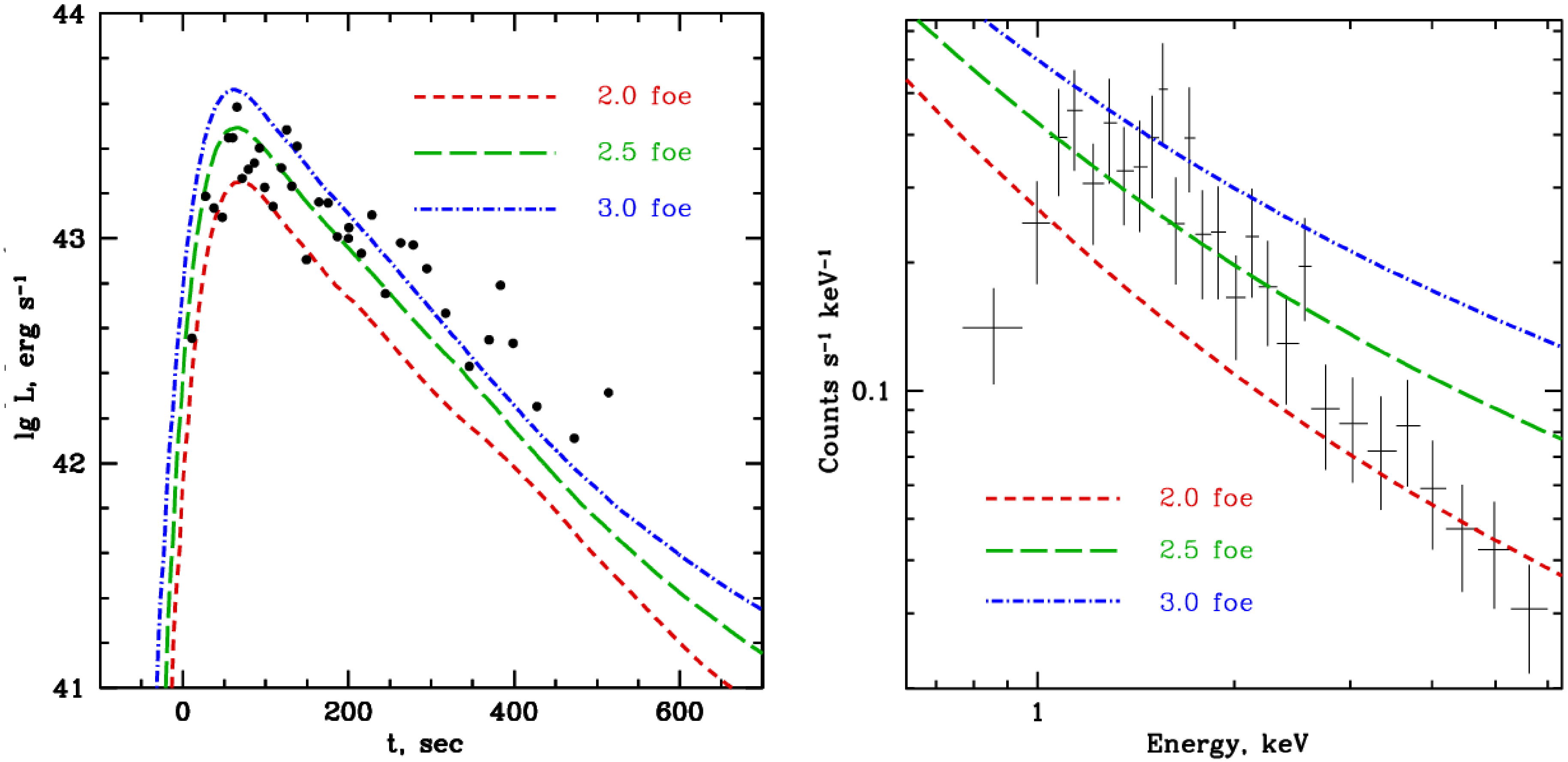
XRO080109/SN2008D in the Model of SNIb with the Stellar Wind

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

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

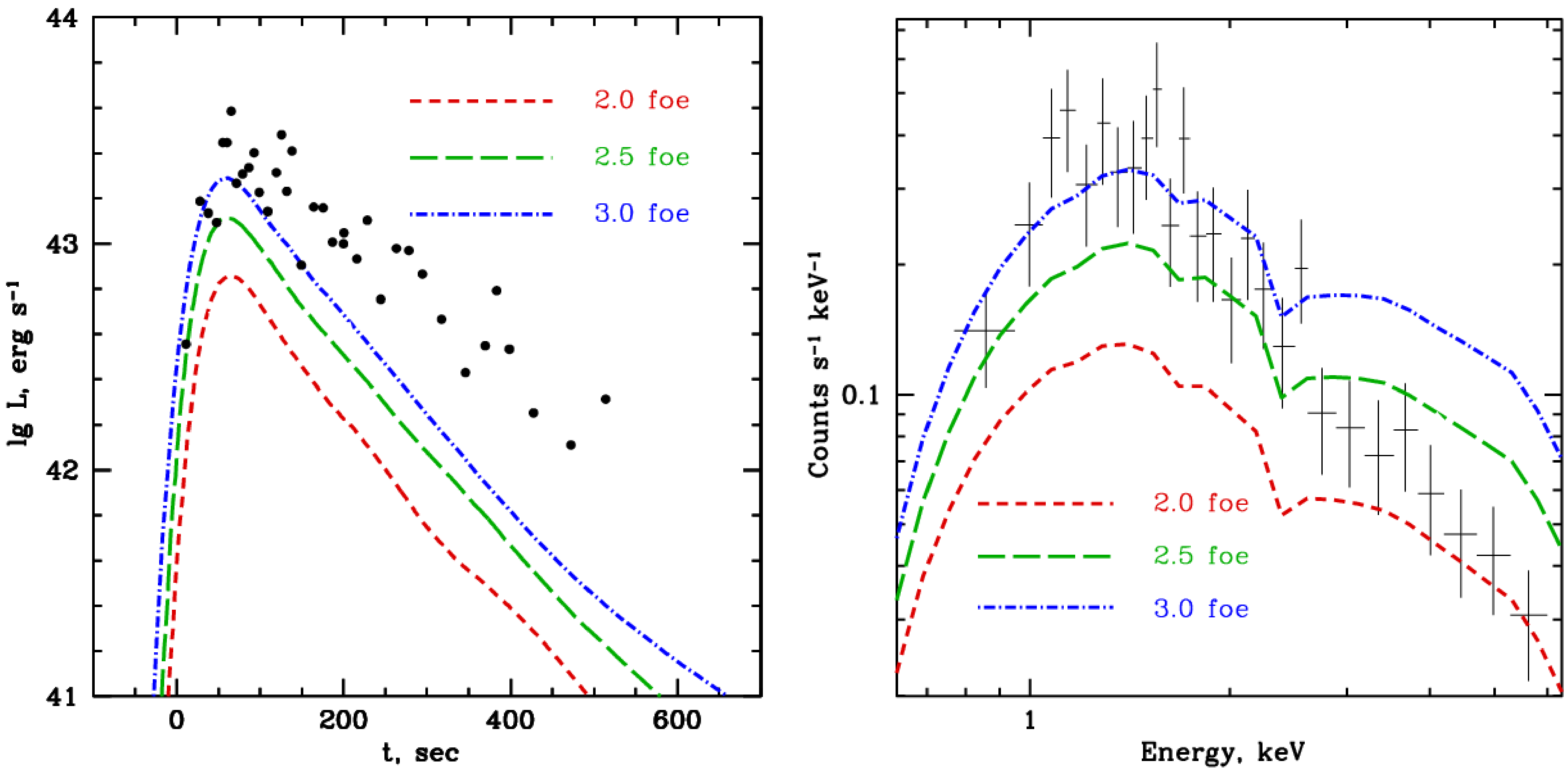


XRO080109/SN2008D Spectra and Light Curves



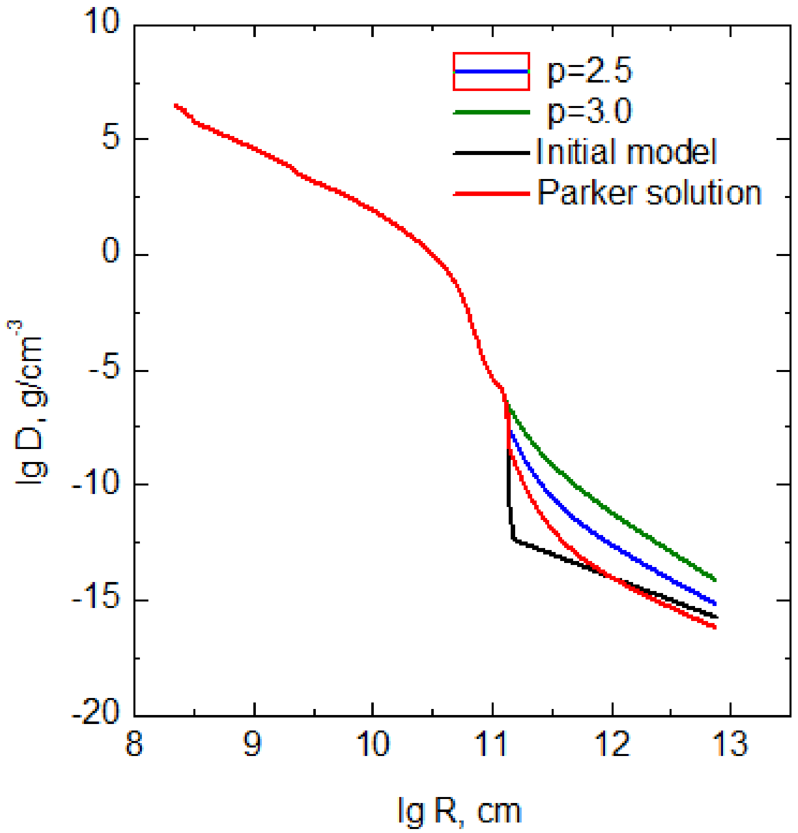
- **X-Ray light curves and spectra, averaged over the duration of the flash, of XRO 080109 in Swift/XRT band (0.3-10 keV) for 10A presupernova model**
- **No extinction**

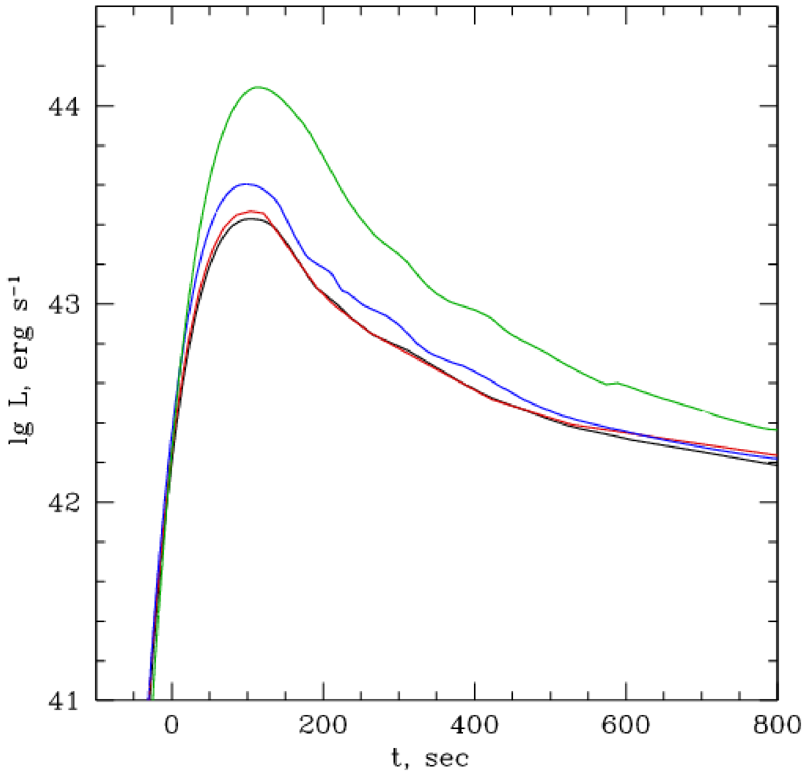
XRO080109/SN2008D Spectra and Light Curves (extinction)



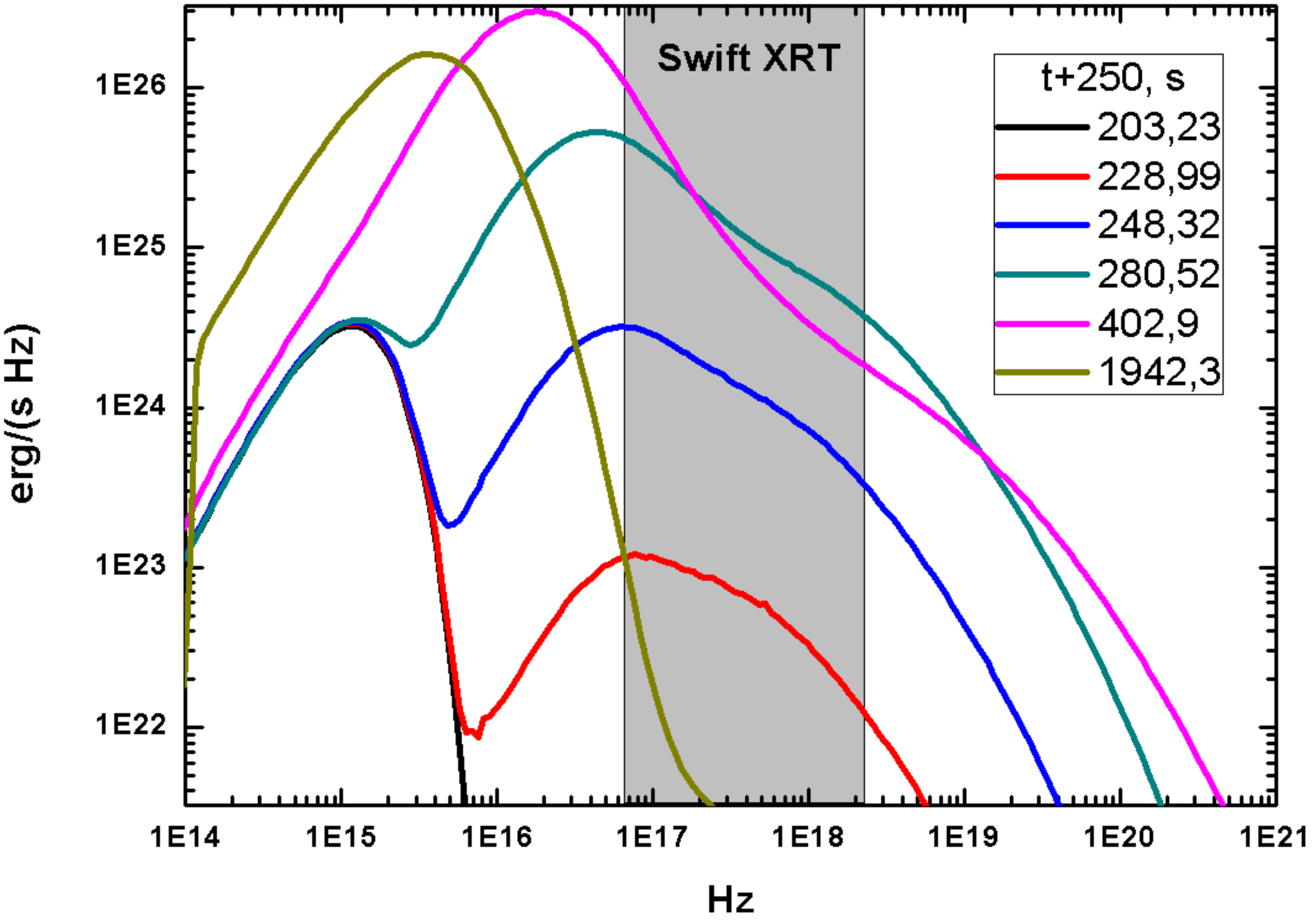
- X-Ray light curves and spectra, averaged over the duration of the flash, of XRO 080109 in Swift/XRT band (0.3-10 keV) for 10A presupernova model
- N_H = 2×10^{21} cm^{-2}, XRT response
- E_K = 6±2.5 foe (Tanaka et al. 2009) in modeling of SN2008D light curve

Ibc models. Variations of stellar wind parameters

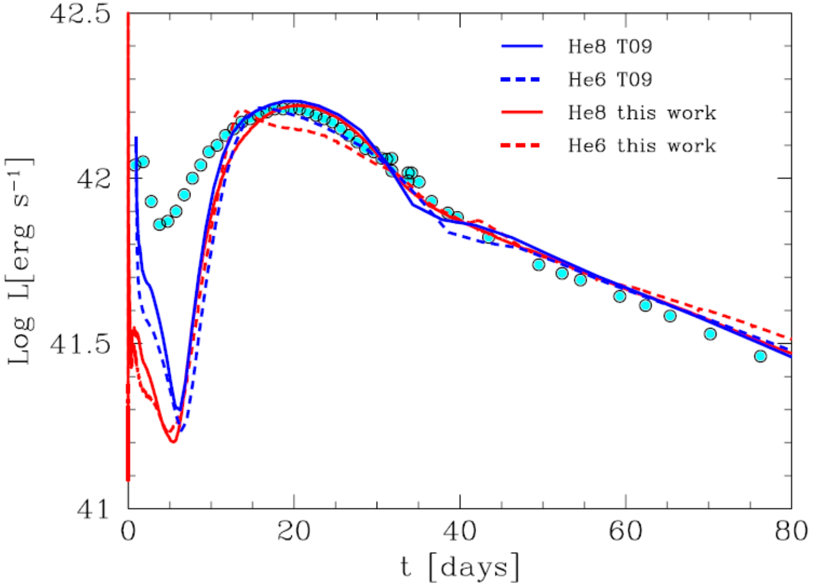




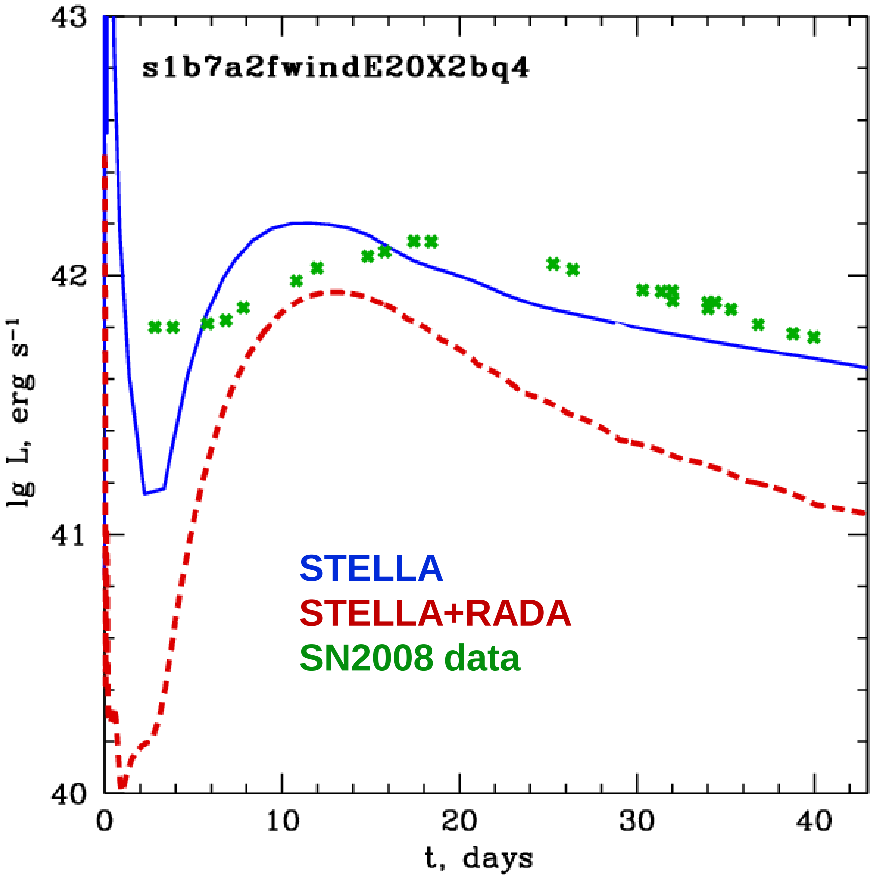
XRO080109 Spectrum Evolution



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

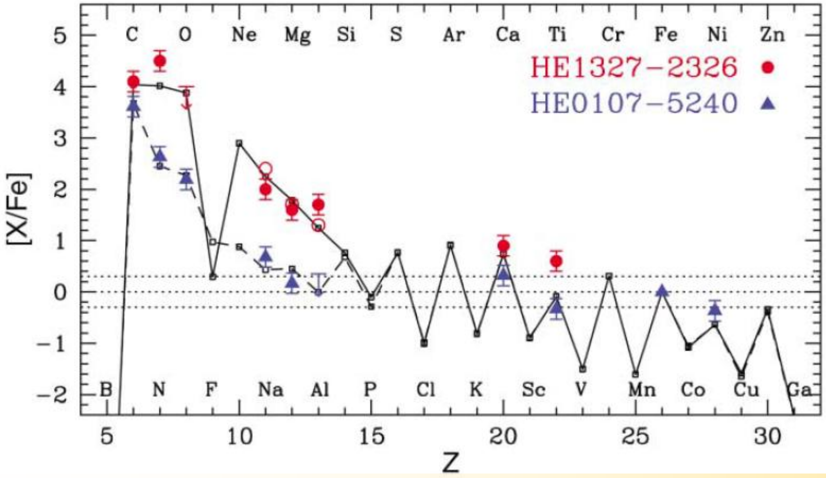
Jet geometry

Current projects and Future plans

IPMU: The First Stars (2014-2016)

- **400 million years after the Big Bang**
  Direct insight into the age of galaxy formation

- **Elemental abundance ratio in EMP stars (Iwamoto et al., 2003,2005)**



- Light curves and spectra of First Supernovae (including shock breakout)
- Chemical enrichment of the early Universe
- 2nd generation (low mass) extremely metal-poor (EMP) stars: abundance pattern and distribution (mixing)
- Abundance pattern of EMP stars provides constraints on Mass, Explosion energy of First supernovae
- Low 56Ni mass, low E faint supernovae
- Observational signature of First Supernovae (M, E, abundance) expected from first stars: no metal blue supergiant progenitor of First SNe

Understanding of the earliest star formation and the chemical enrichment history of the Universe!

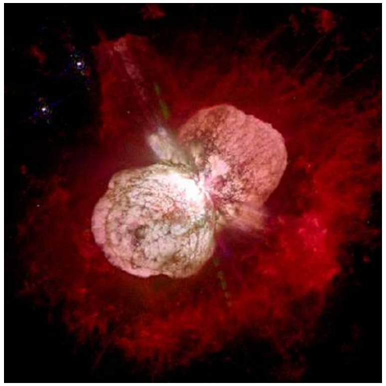
Objectives

- ***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), KMTNet

- 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



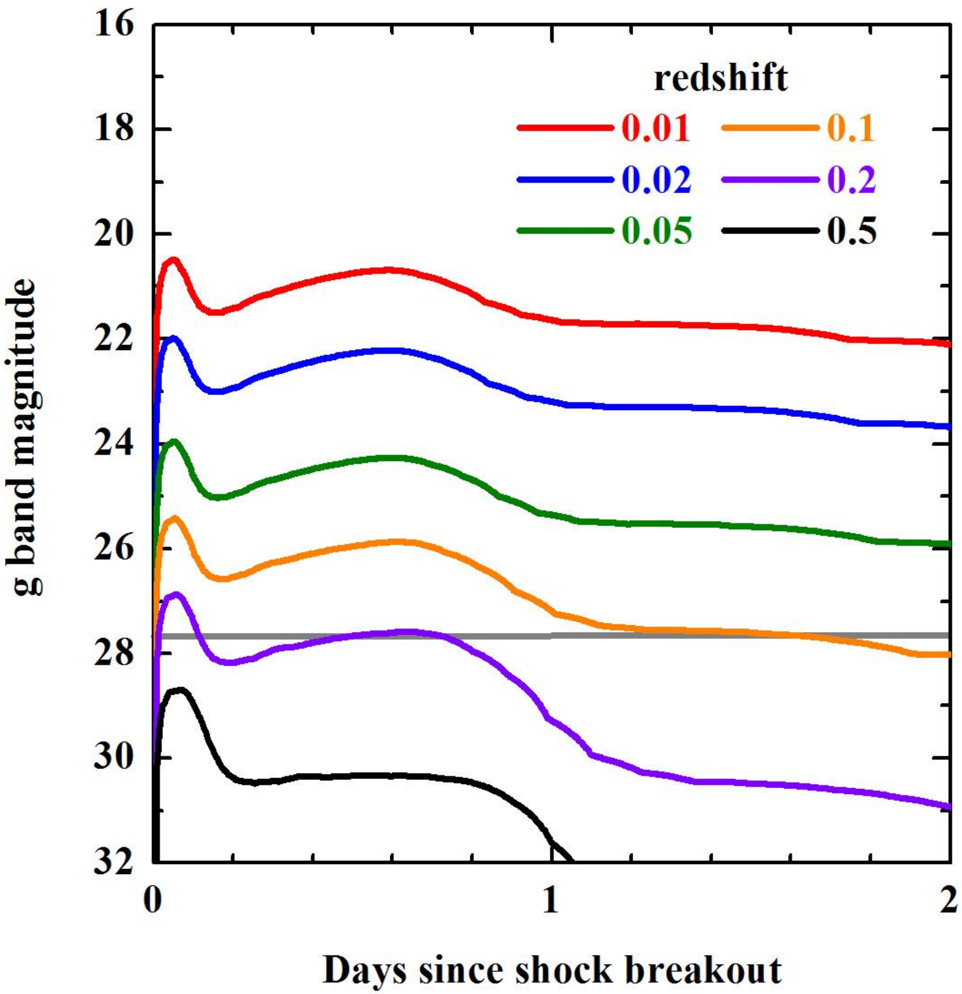
SN Ibc Shock Breakout at High Redshift

- **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**



Current status of Radiation Hydrodynamics calculations

RHD Technique\ Spacial Dim	1D	2D	3D
Single Energy (Relativistic code / Nonrelativistic code)	RRMHD Codes (Farris, Zanotti, Roedig, Sadowski, Takahashi) Edd Approx	Herant (1994)	SNSPH (Fryer 2006) , HARMRAD (McKinley 2013)
Multi Energy	STELLA (Blinnikov 1998, VEF), Hoflich, VEF (1993)	FLD by Burrows (1995)	RAGE (Frey 2013)
Multi Energy + Multi Angle	RADA (+ HD static) (Tolstov 2013)	ZEUS (Norman) Muller, Janka 2012 (GR, Neutrino 2D but “ray-by-ray-plus” (1D))	ZEUS, Code by Jiang et al. (2013) (VEF,LTE, no AV, only tests) Kuroda 2012 (GR, fEdd approx, low-res), Ott 2013 (GR) “ray-by-ray”, ATHENA (Davis, 2012)

Conclusions

- **Our numerical calculations provides us the opportunity to build templates for the analysis and interpretation of the SN observations**

- **The phenomenon of XRO080109/SN2008D may well be explained qualitatively by the explosion of a conventional WR-star surrounded by a stellar wind. SN2008D light curve must be modeled for the optimal model**

- **For the accurate consideration of not very strong radiation dominated shock waves *it is necessary to solve radiation transfer equation (Eddington and M1 closure are not good approximations)***

Thank you!

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Shock wave discontinuity

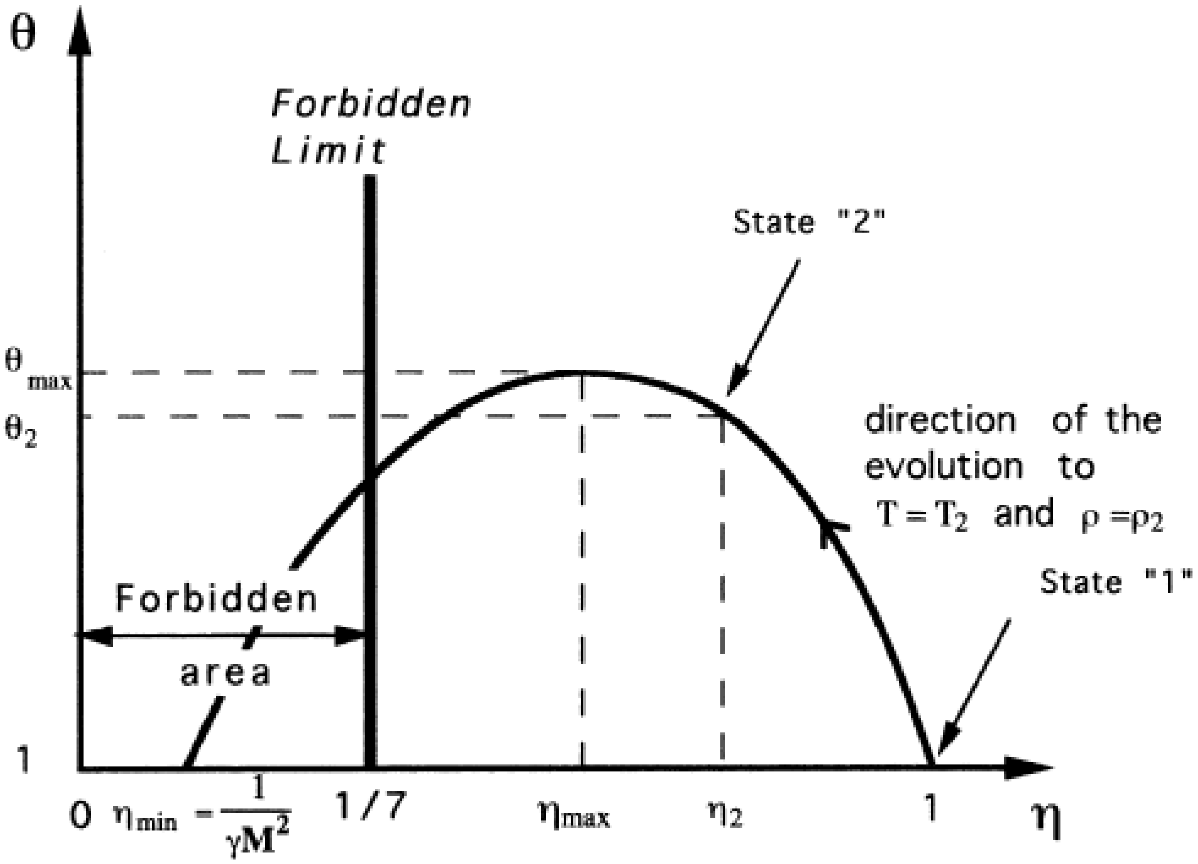

FIG. 6.—Curve $\theta = f(\eta)$ corresponding to eq. (12)