Light produced by shocks and shocks produced by light: Superluminous supernovae and GRB afterglows

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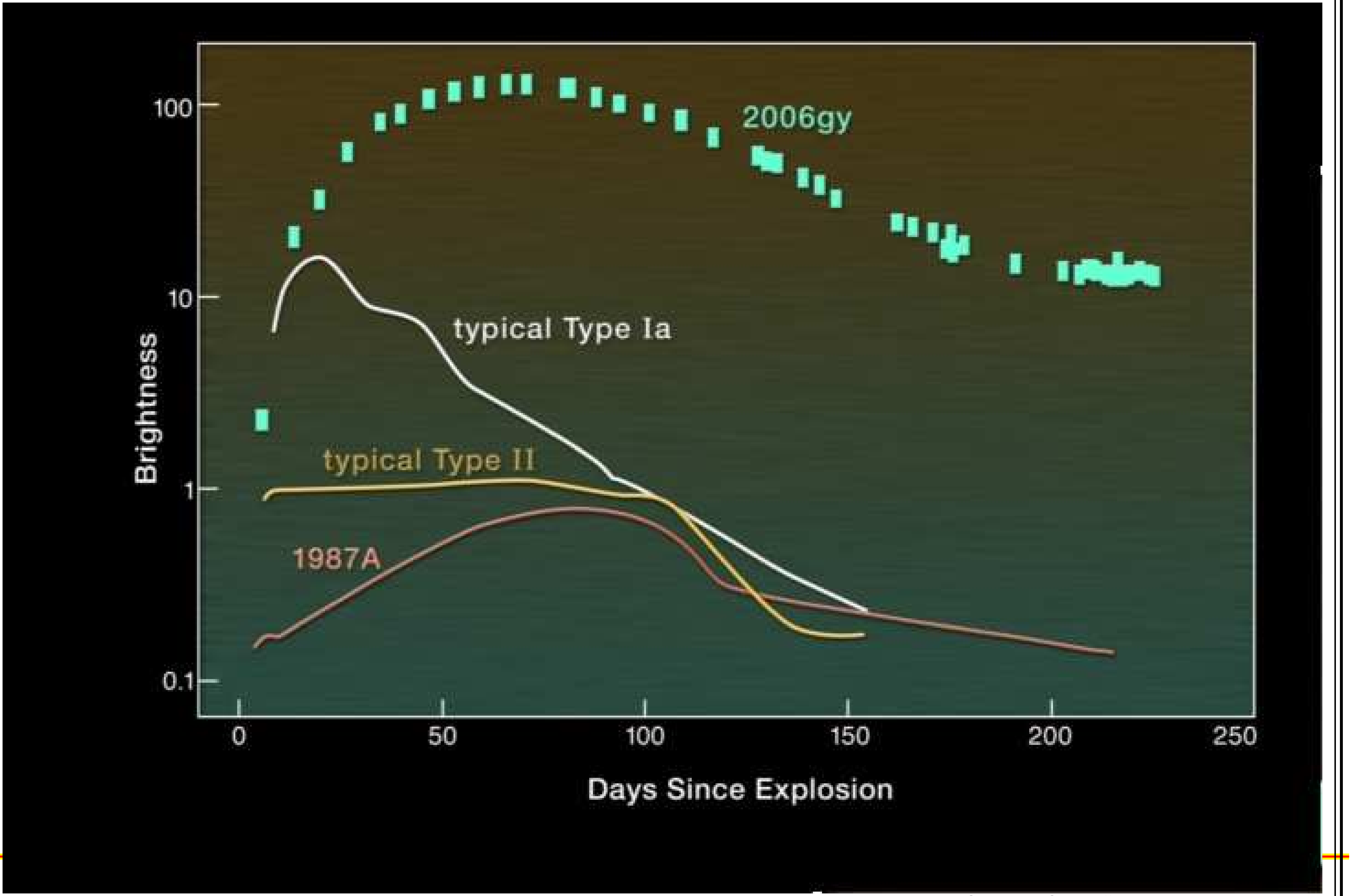
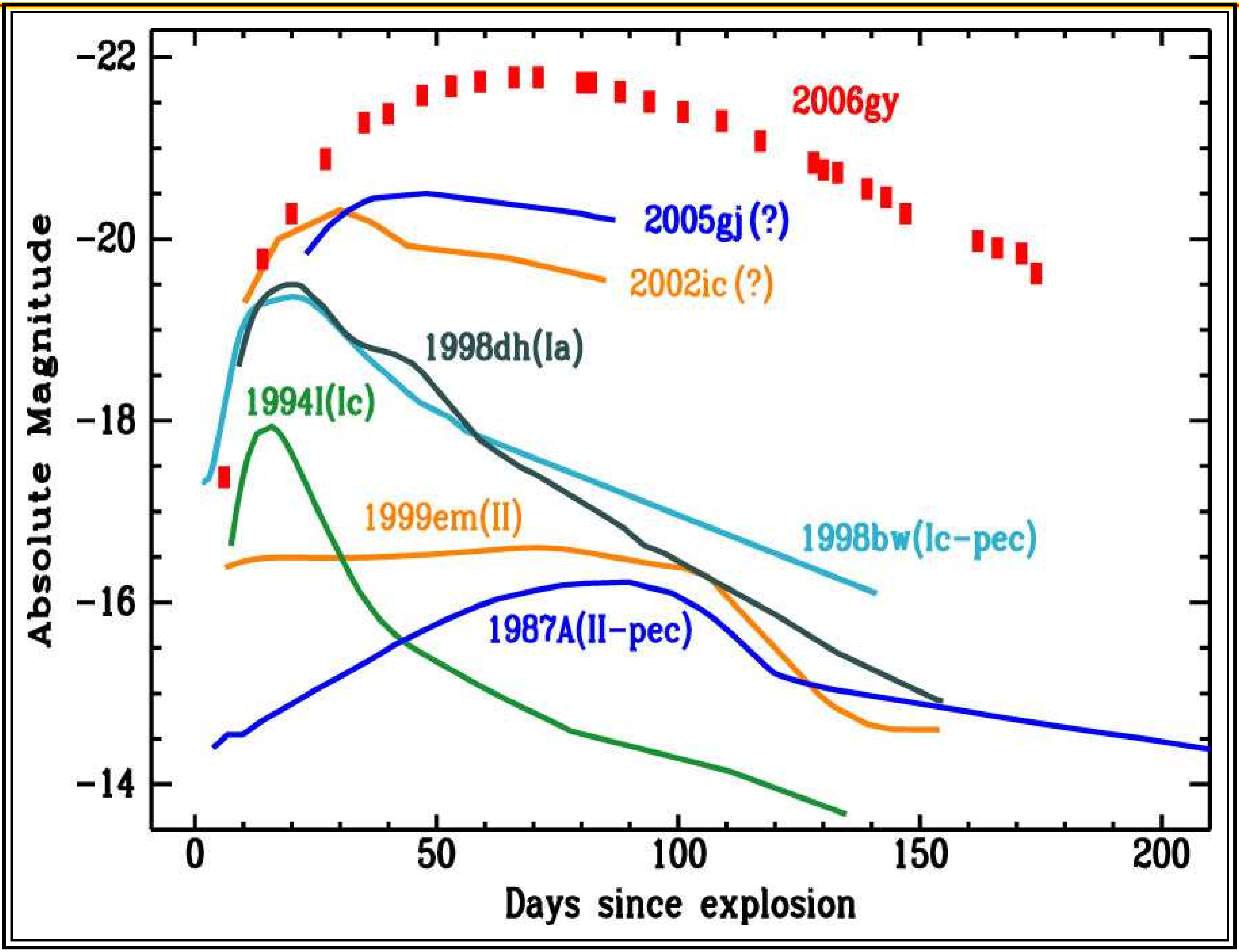
Partly based on arXiv:1009.4353 and MN 432 (2013) 2454

2006: Brightest. Supernova. Ever

by N.Smith

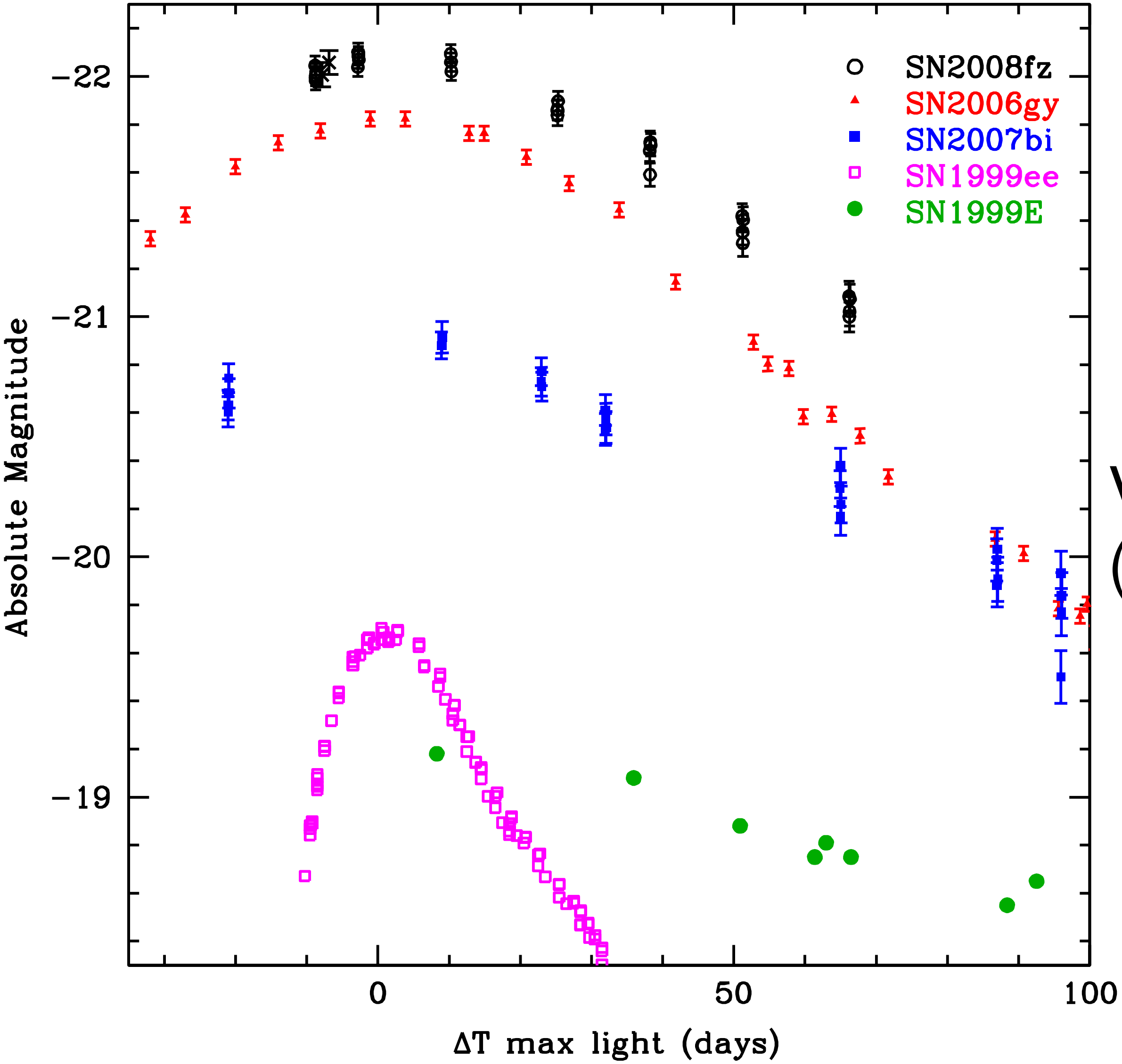


It was Most Luminous SN by 2006, but not now



Now we have many SN events which are more luminous.

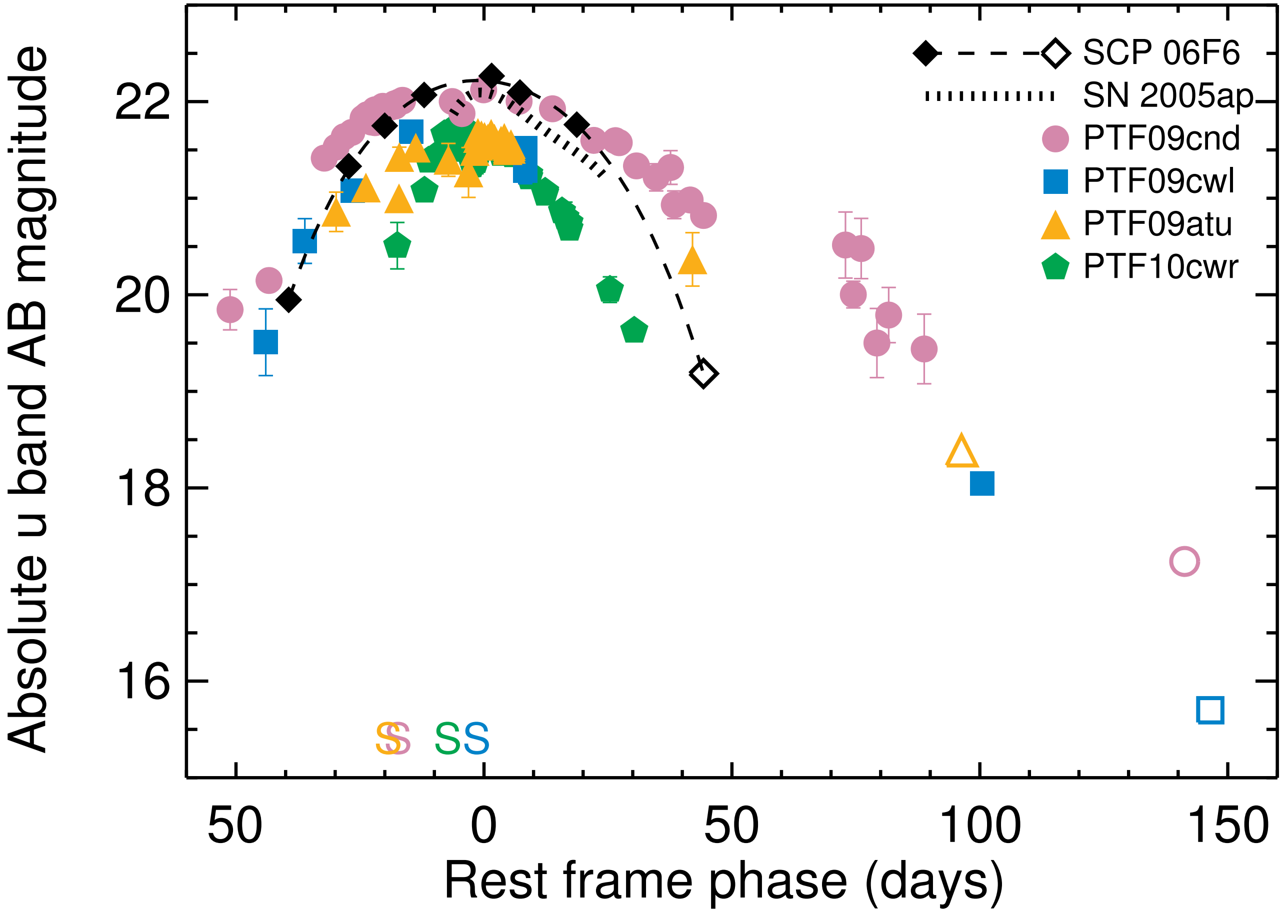
H-rich superluminous Type IIn SNe



V-band
(Drake et al. 2010)

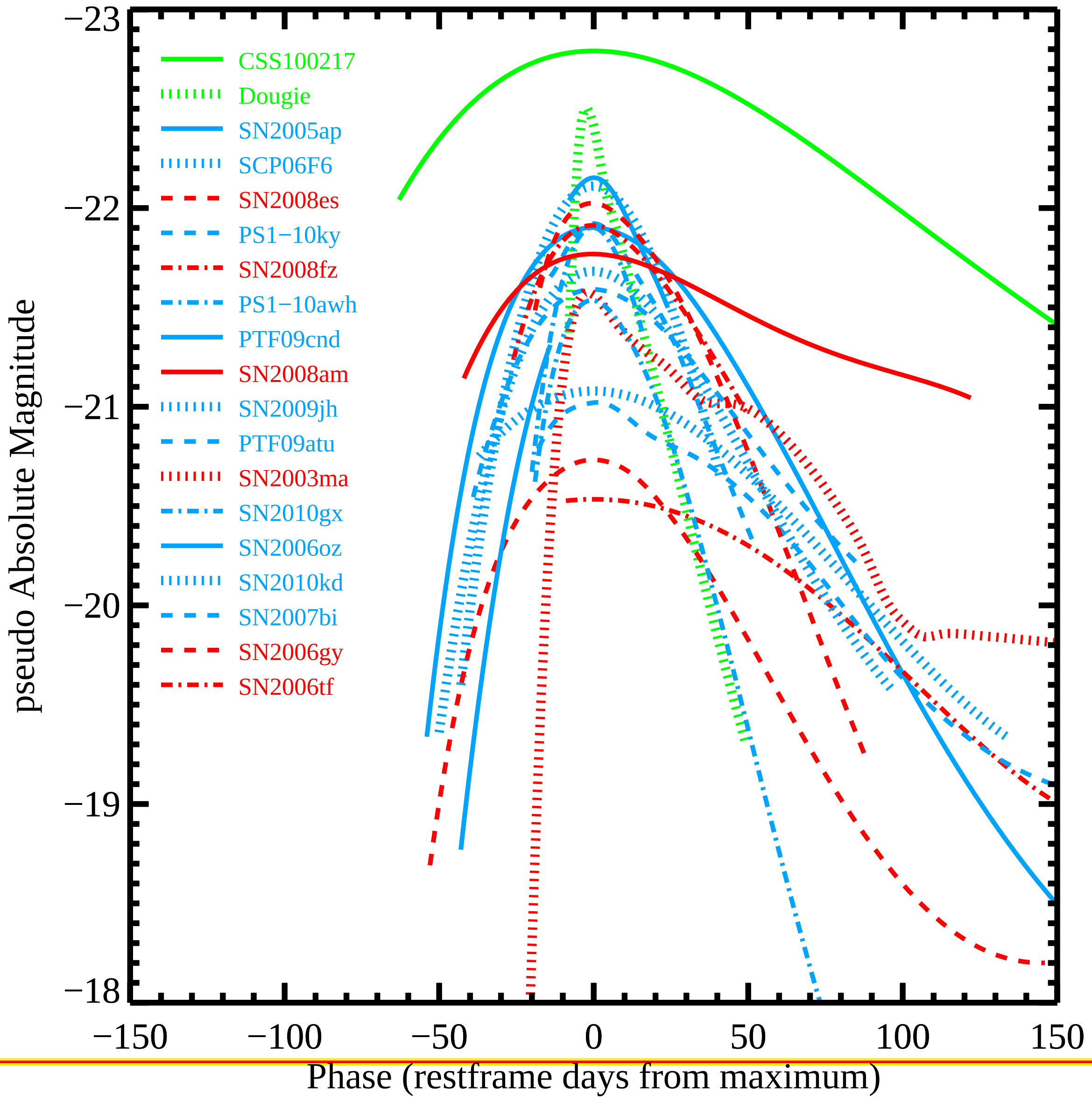
PTF: H-poor superluminous SNe

Quimby et al. 2011, –AB is plotted



SLSNe wide range

Quimby et al. 2013

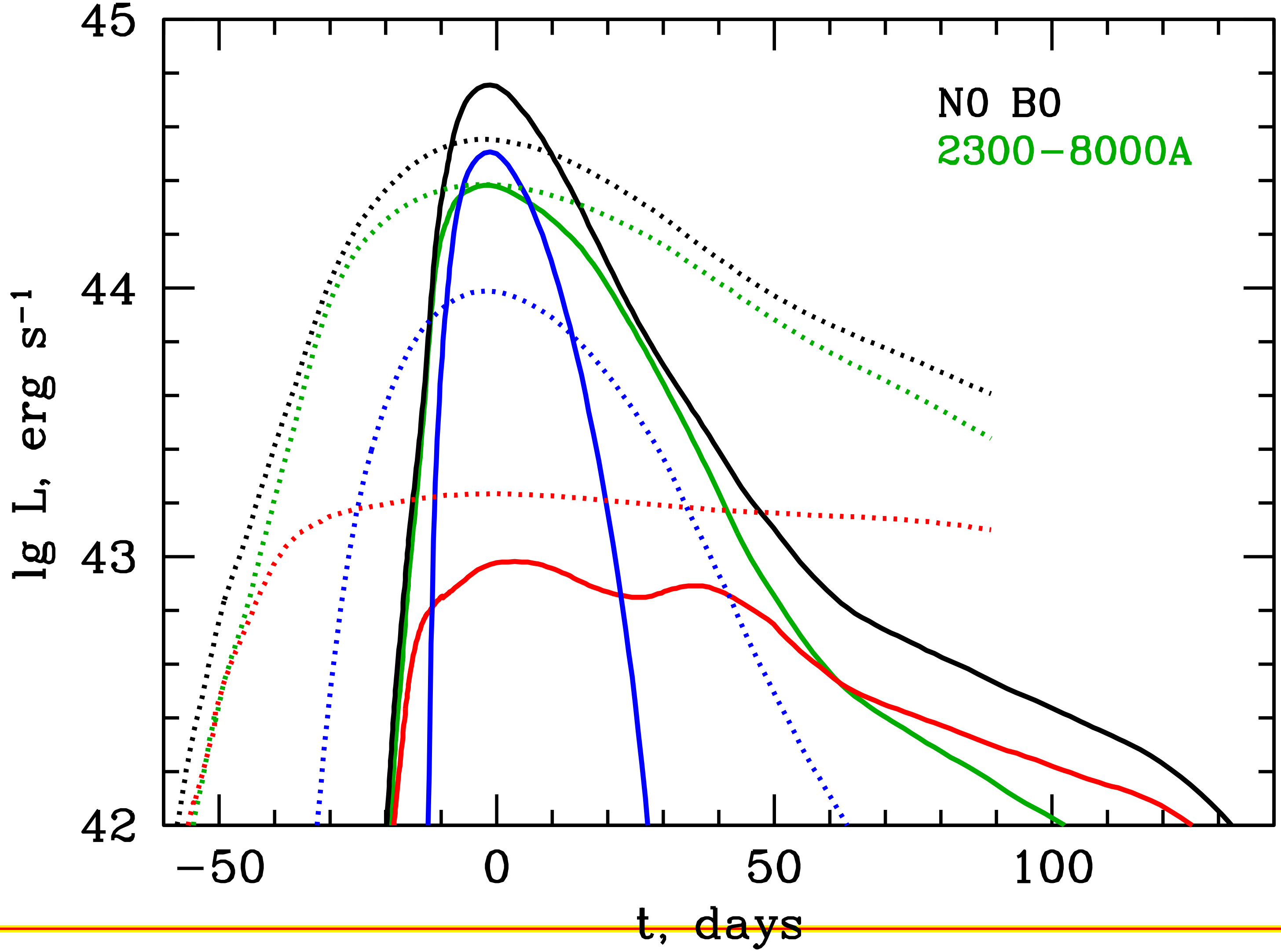


Models proposed for SLSNe

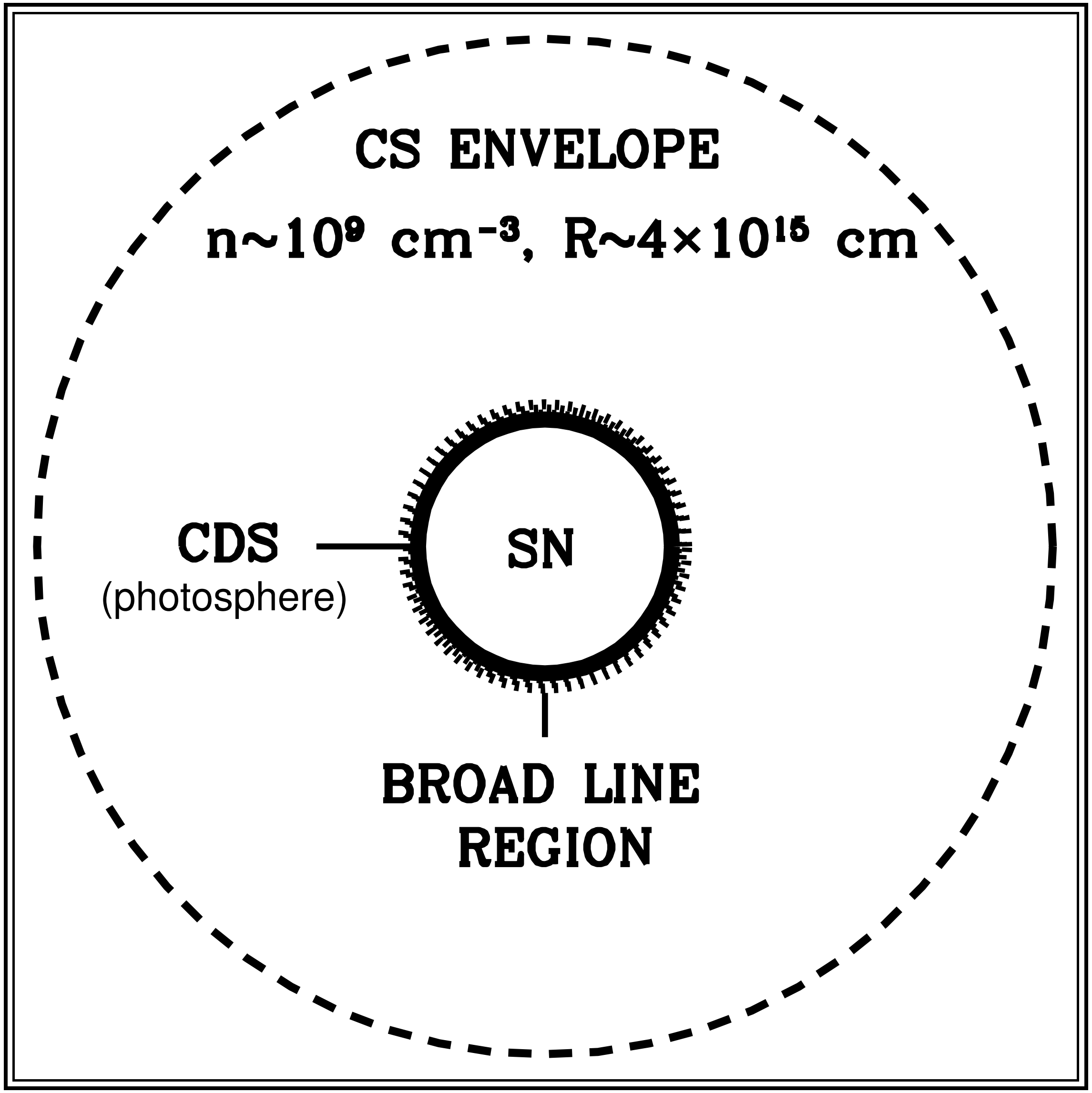
- Pair instability, PISN
- Magnetar pumping
- Shock interaction with CSM, e.g. Pulsational pair instability, PPISN

We’re able to reproduce the range

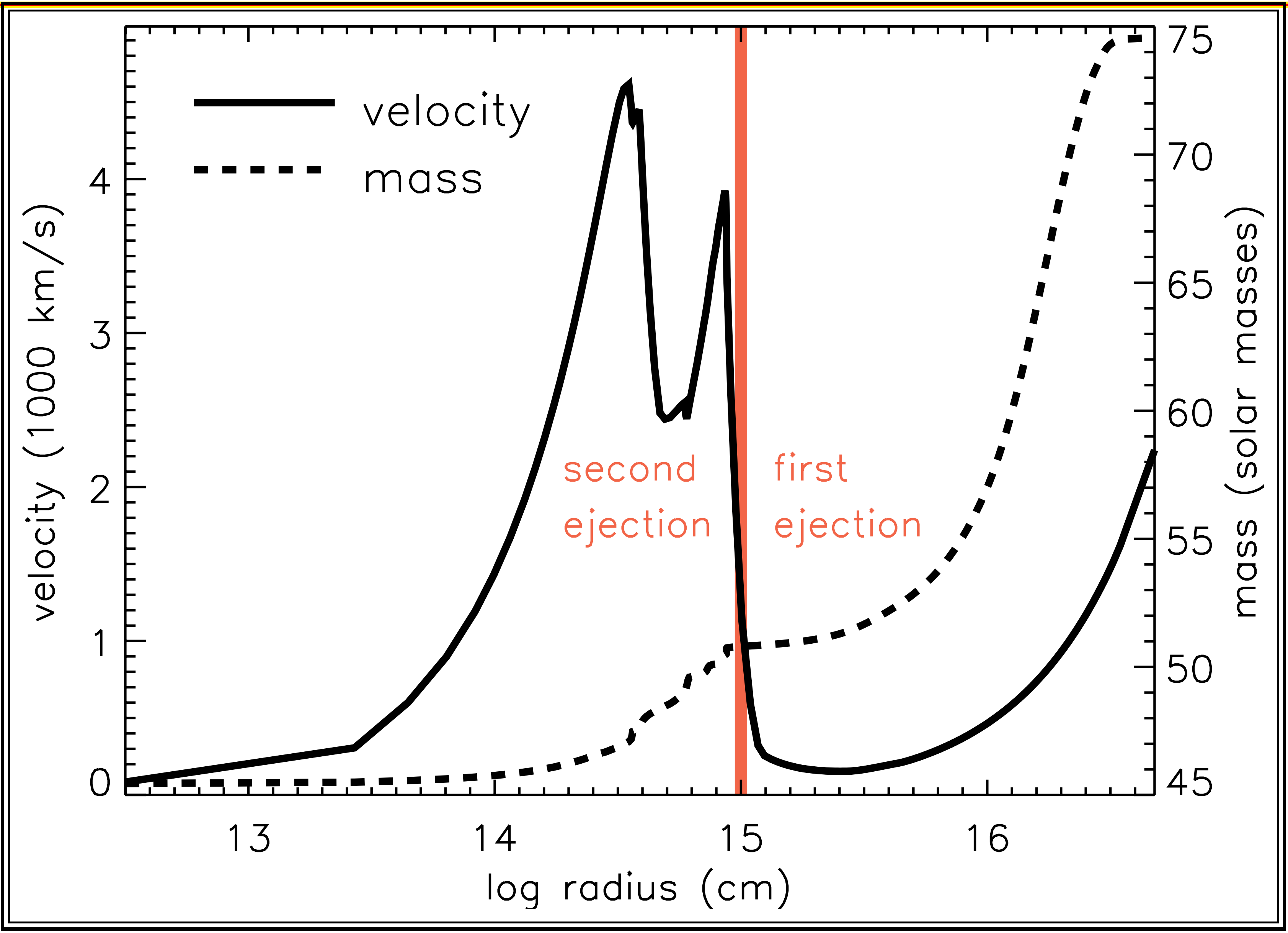
In one class of models with modest energy,
the latter option, which is the most economical in energy



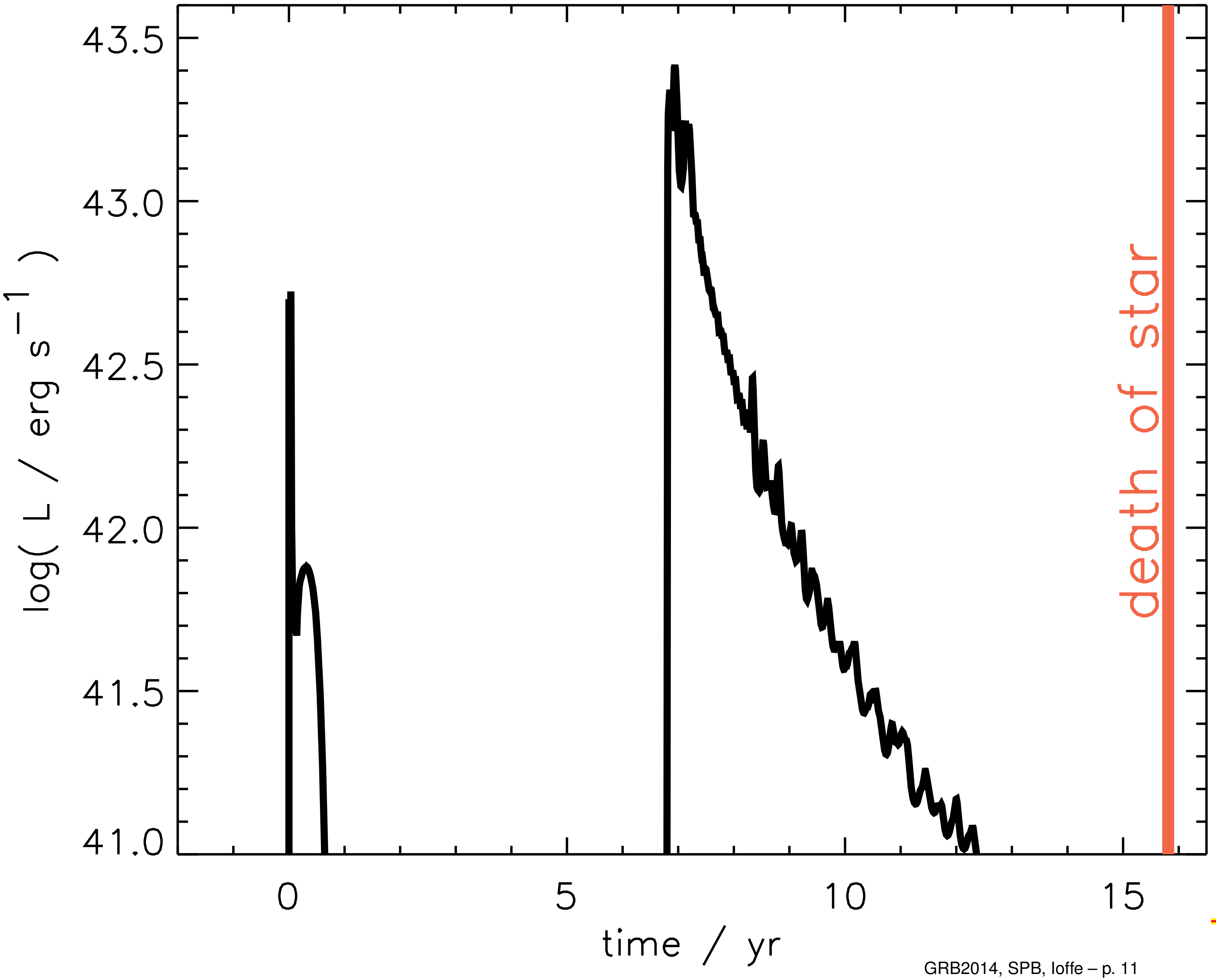
SN IIn structure, Chugai, SB ea’04



PPISN: Two mass ejections, Woosley+ 2007

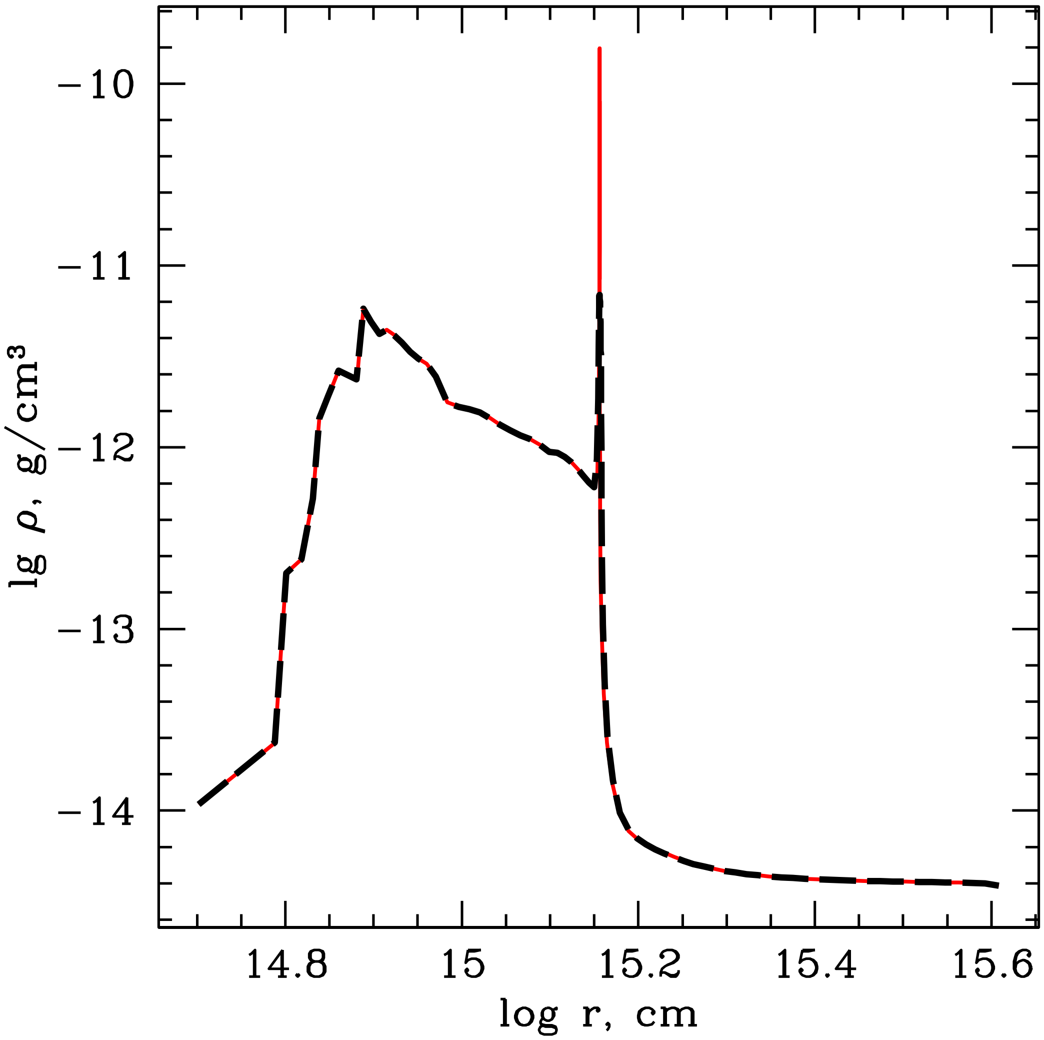


SN-repeaters, Woosley+ 2007



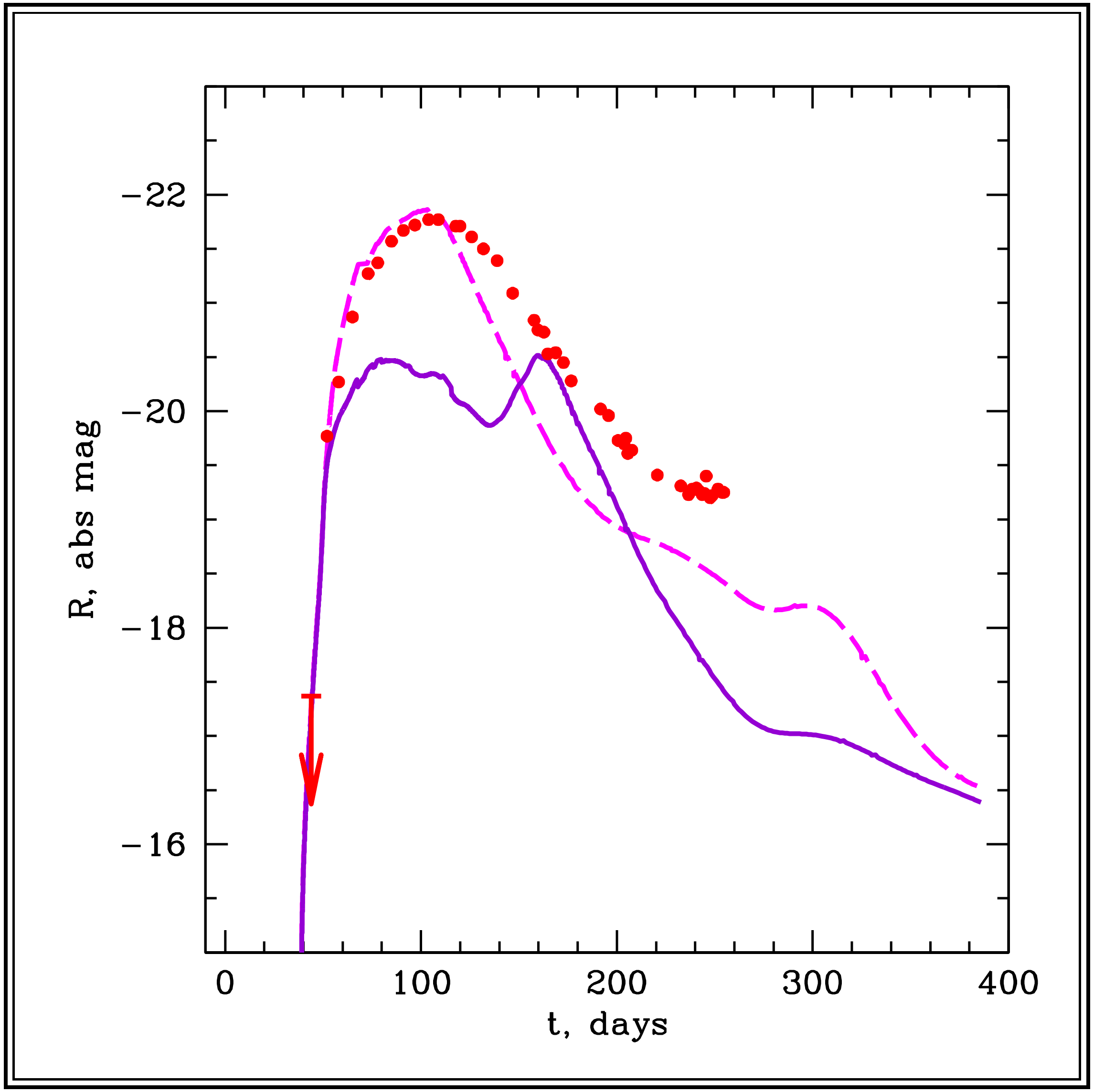
Shocks in SNe IIn

A long living shock: an example for SN1994w of type IIn. Density as a function of the radius r in two models at day 30. The structure tends to an isothermal shock wave.



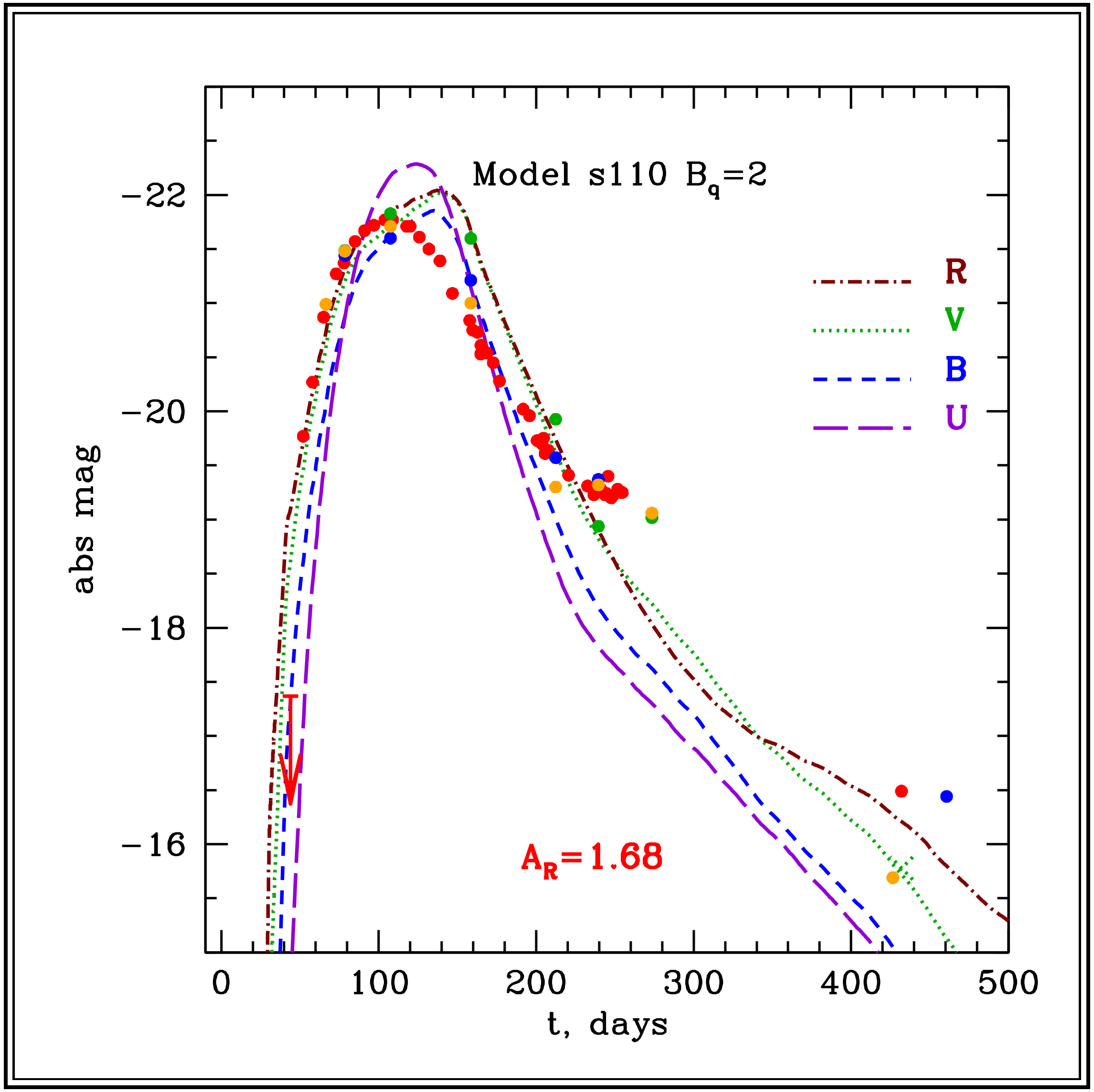
Light curve for SN2006gy

from Woosley, SB, Heger (2007)



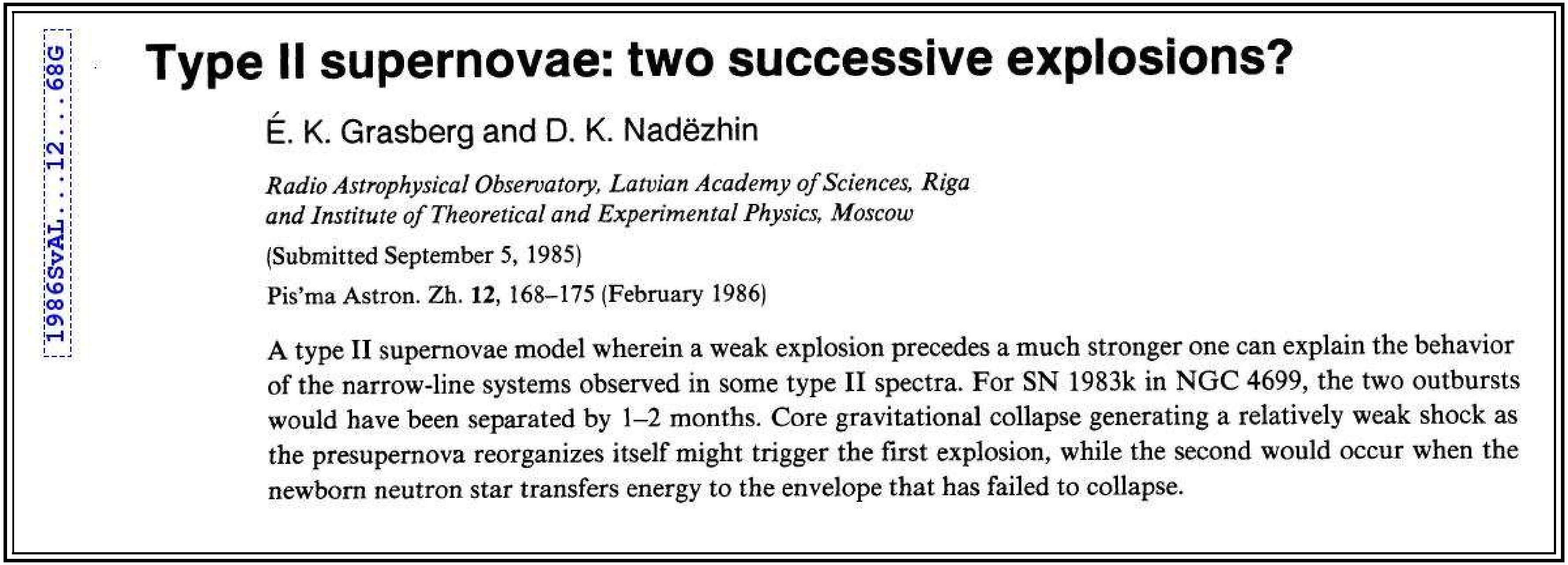
Stella: LCs for SN2006gy

new runs



Double explosion: old idea

Grasberg & Nadyozhin (1986)



Type II supernovae: two successive explosions?

É. K. Grasberg and D. K. Nadëzhin

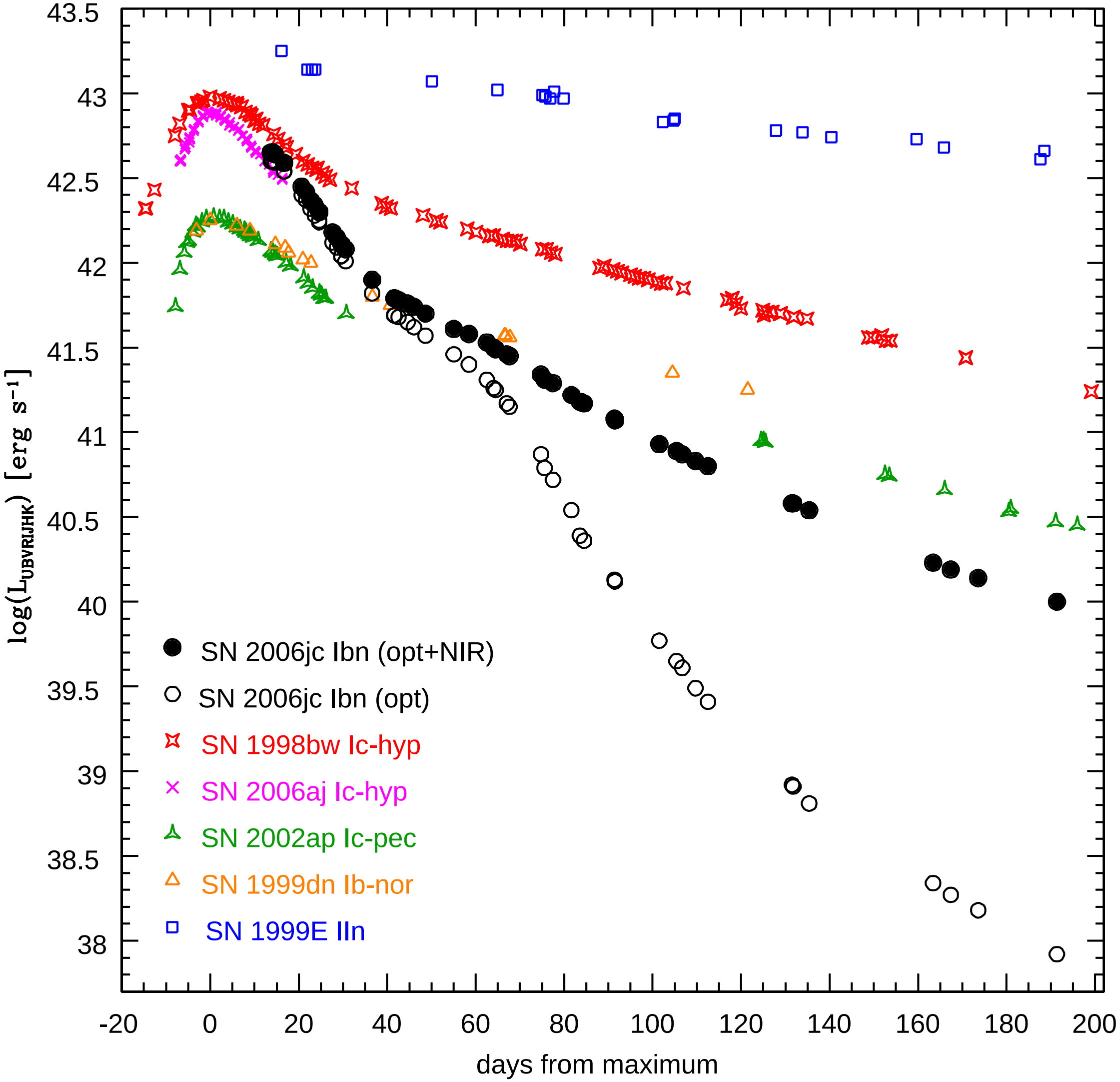
Radio Astrophysical Observatory, Latvian Academy of Sciences, Riga
and Institute of Theoretical and Experimental Physics, Moscow

(Submitted September 5, 1985)

Pis'ma Astron. Zh. **12**, 168–175 (February 1986)

A type II supernovae model wherein a weak explosion precedes a much stronger one can explain the behavior of the narrow-line systems observed in some type II spectra. For SN 1983k in NGC 4699, the two outbursts would have been separated by 1–2 months. Core gravitational collapse generating a relatively weak shock as the presupernova reorganizes itself might trigger the first explosion, while the second would occur when the newborn neutron star transfers energy to the envelope that has failed to collapse.

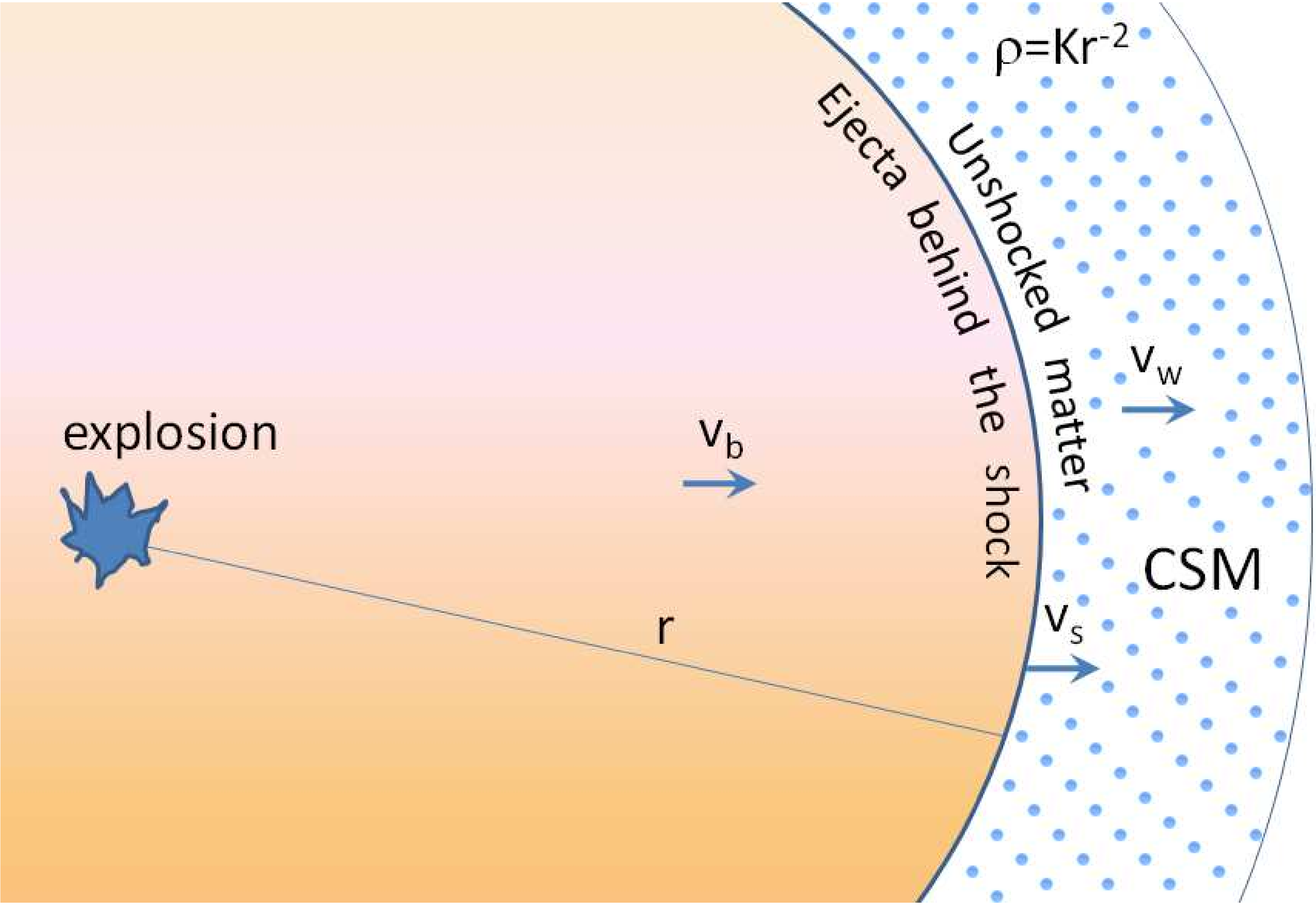
Very bright Type Ib SNe with narrow lines



Type Ibn, still rather weak compared to PTFs

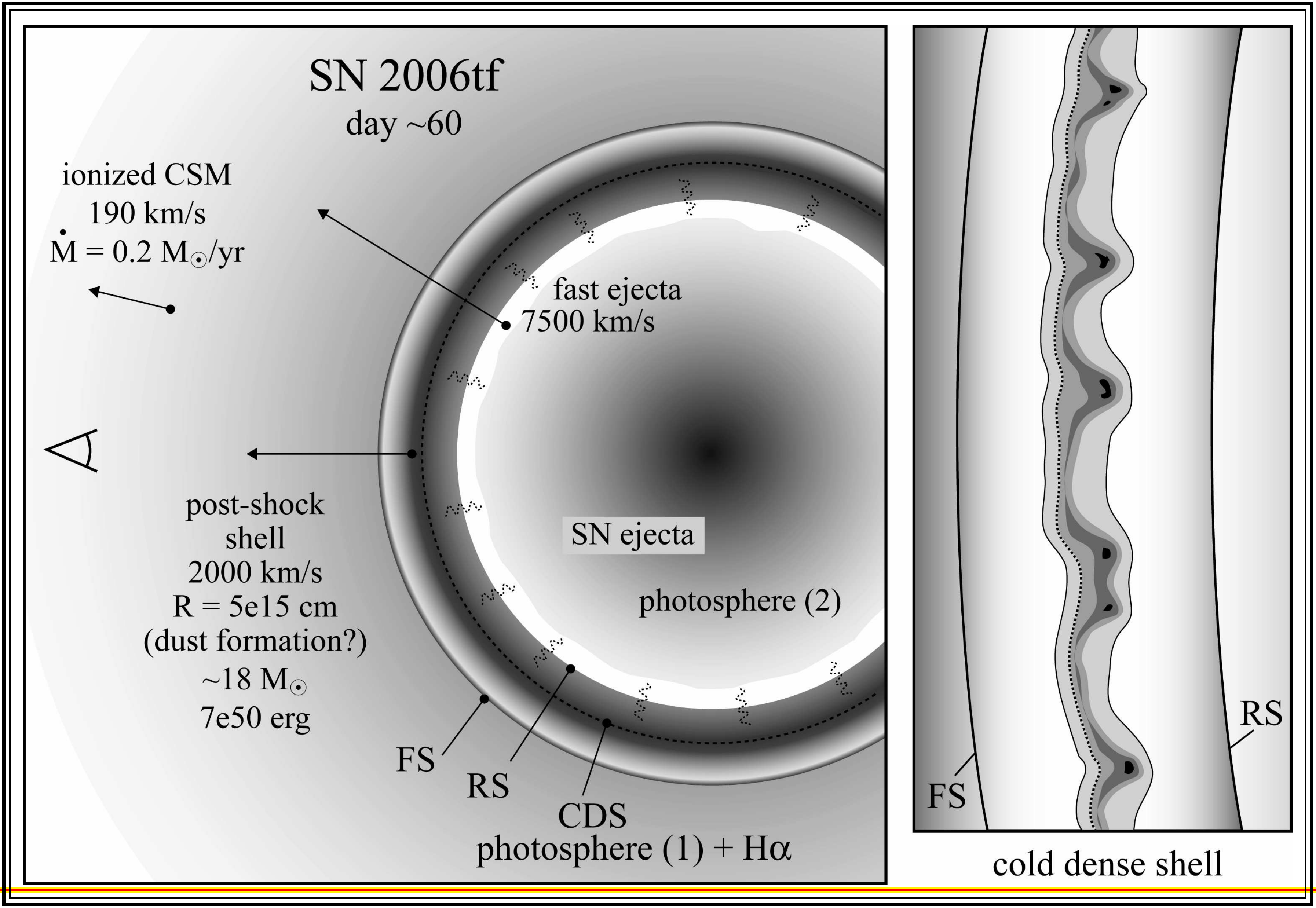
Quasi-bolometric (optical+NIR) (Pastorello et al. 2008)

Windy models for very luminous SNe

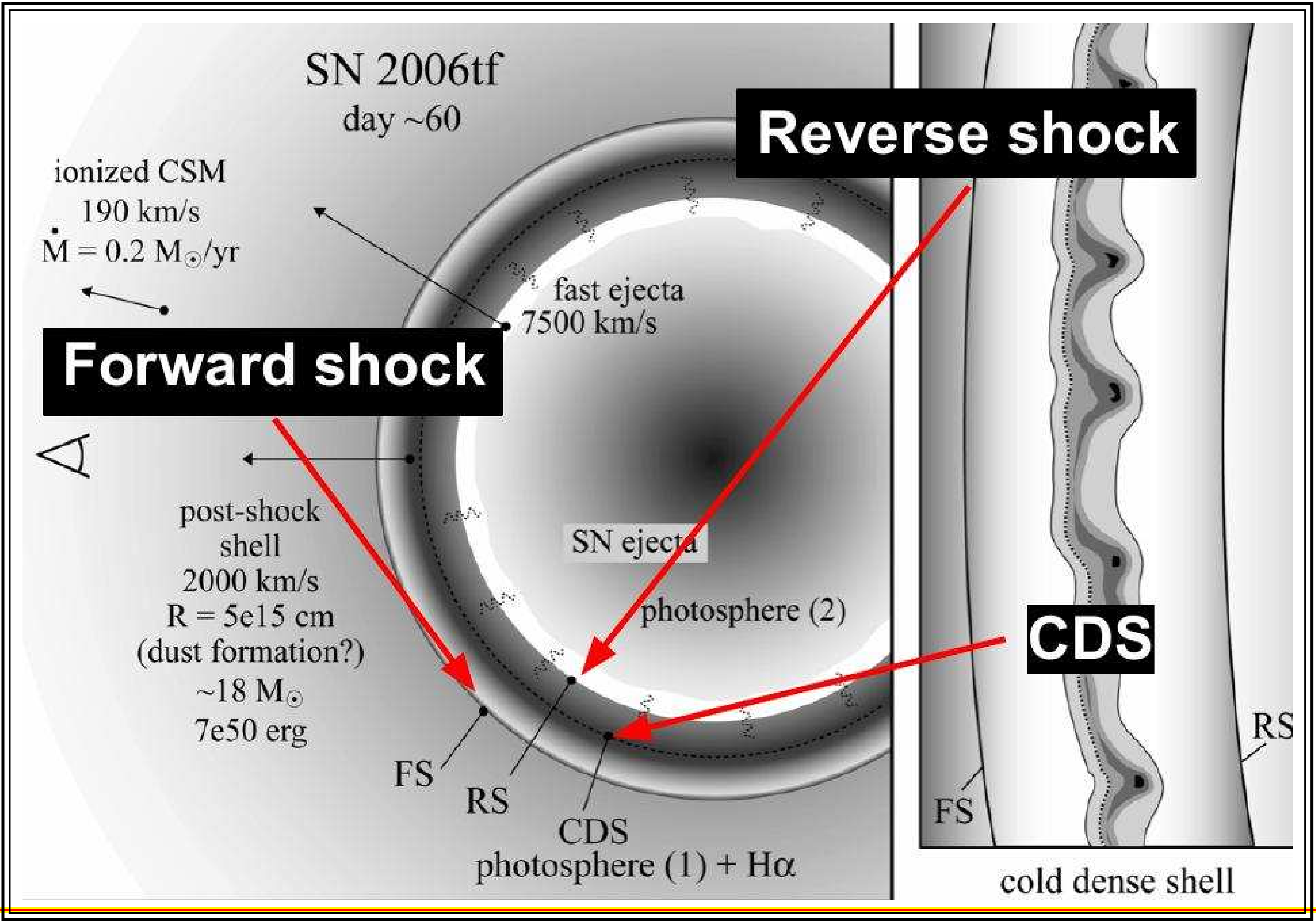


Ofek et al. 2010

Smith,Chornock ea cartoon, 06tf



Cold Dense Shell

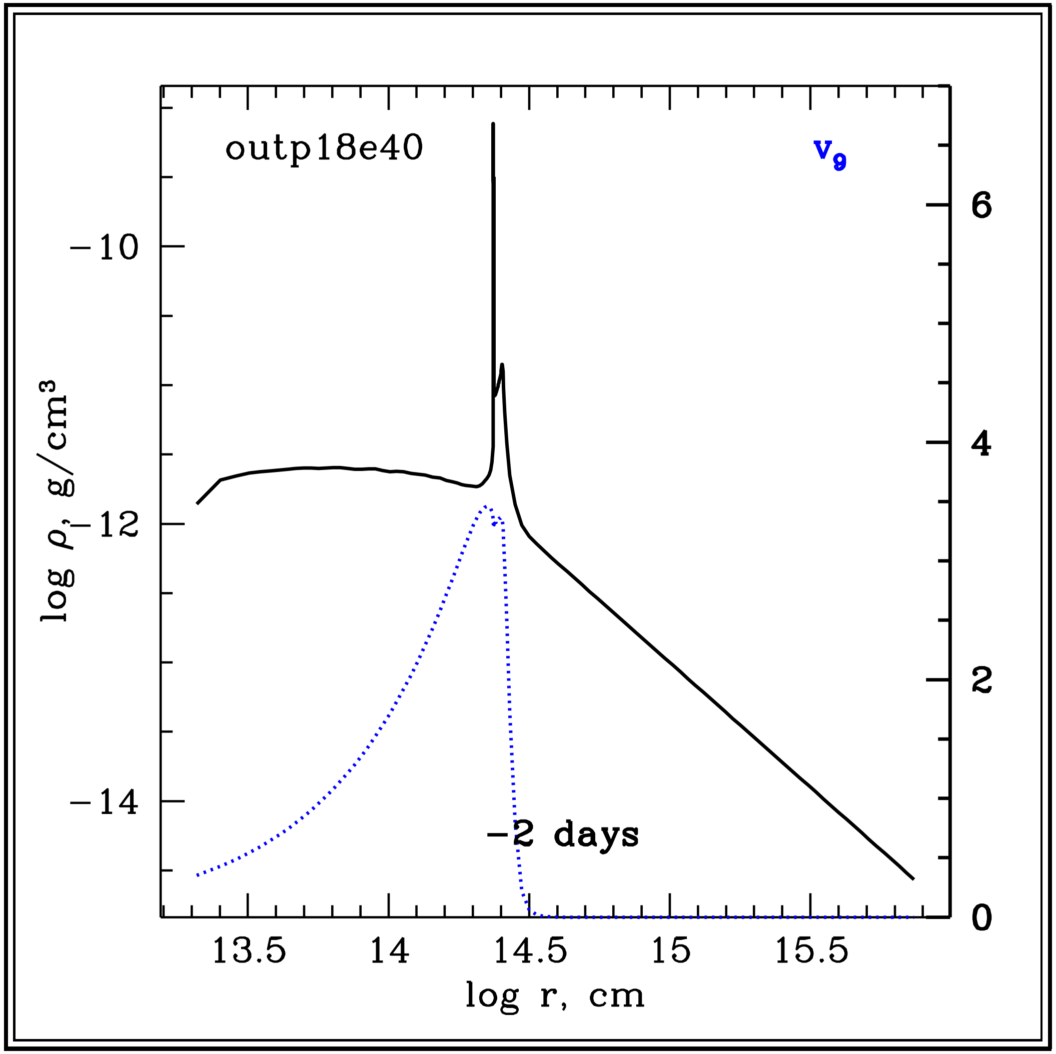


Modeling with the STELLA code

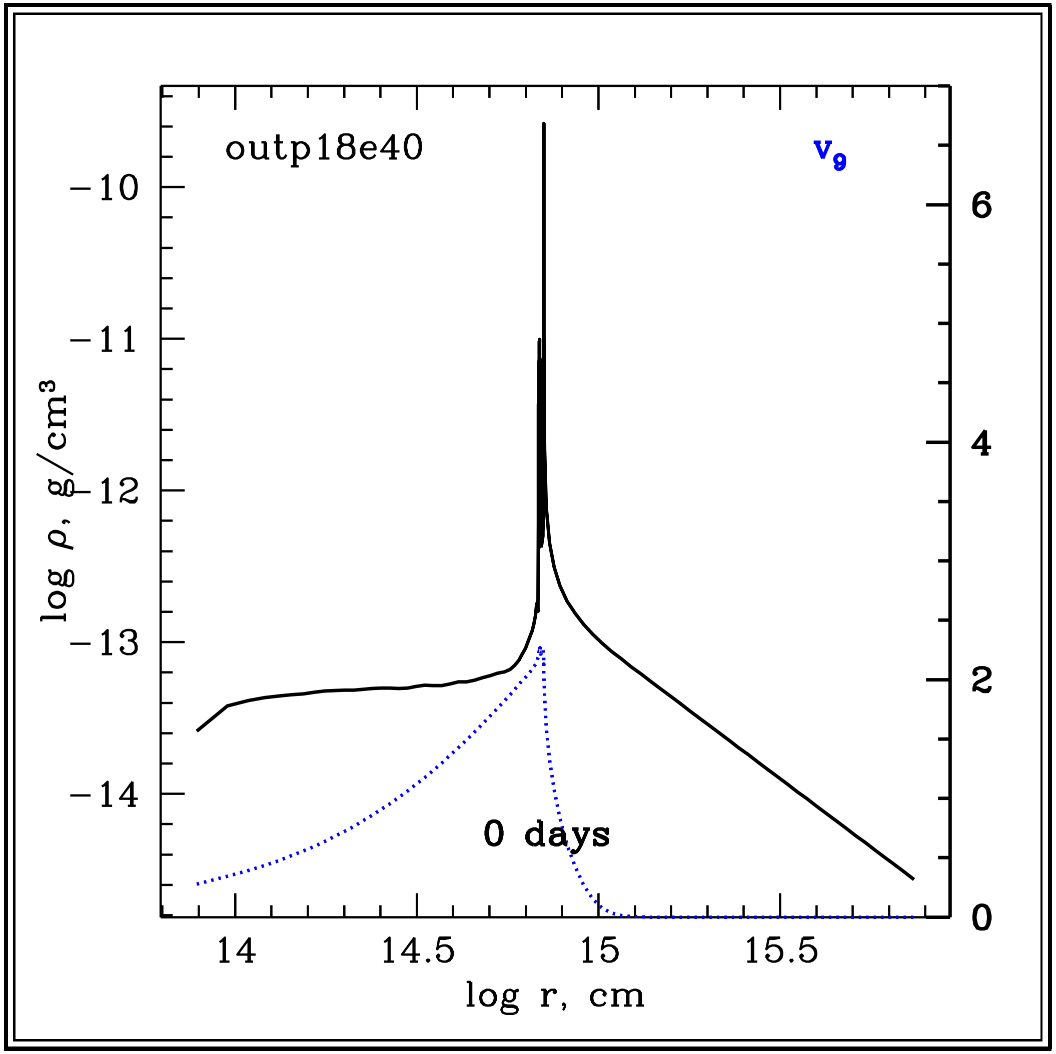
The STELLA code, originally developed for supernova light curve simulations, (*Blinnikov et al., 1998*)

- multigroup time dependent radiation hydrodynamics
- Non-relativistic ($O(v/c)$), spherically symmetric,
- Lagrangean coordinates, staggered mesh.
- Full implicit time-dependent predictor-corrector solver for stiff ODE systems, modified Gear method (*Brayton, Gustavson, Hatchel, 1972*), flexible dynamic step and error control.

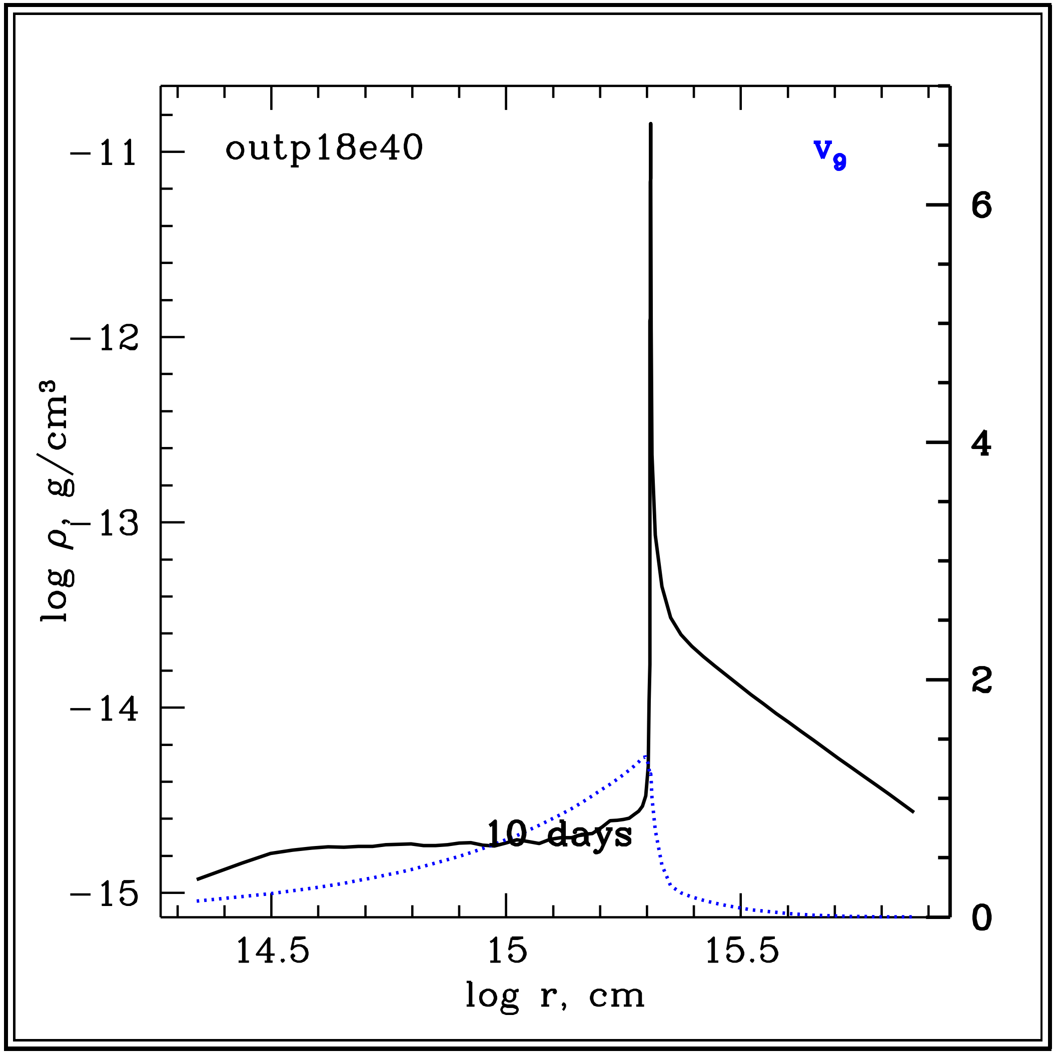
Long Living Dense shells-1 Sorokina et al.



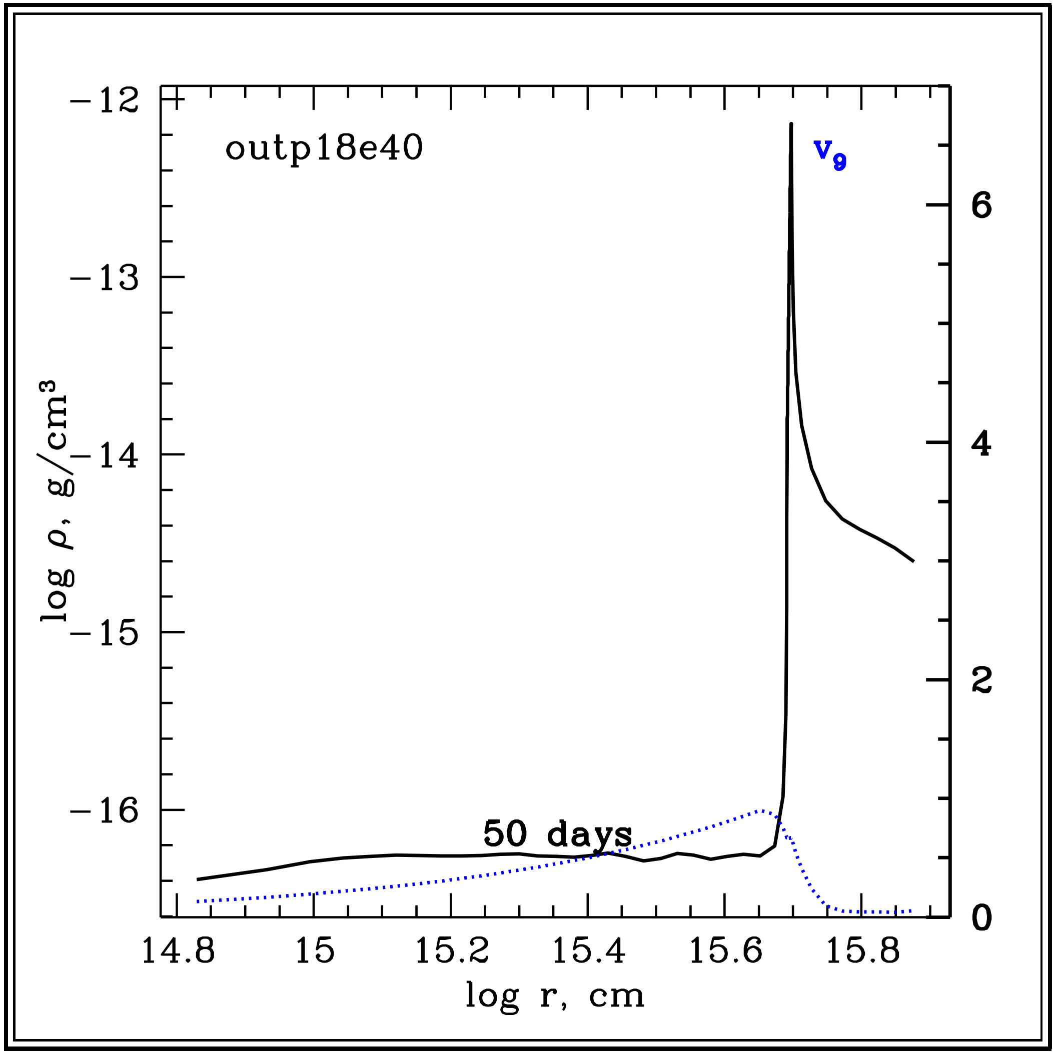
Long Living Dense shells-2 Sorokina et al.



Long Living Dense shells-3 Sorokina et al.



Long Living Dense shells-4 Sorokina et al.



Our synthetic models for type Ic SNe

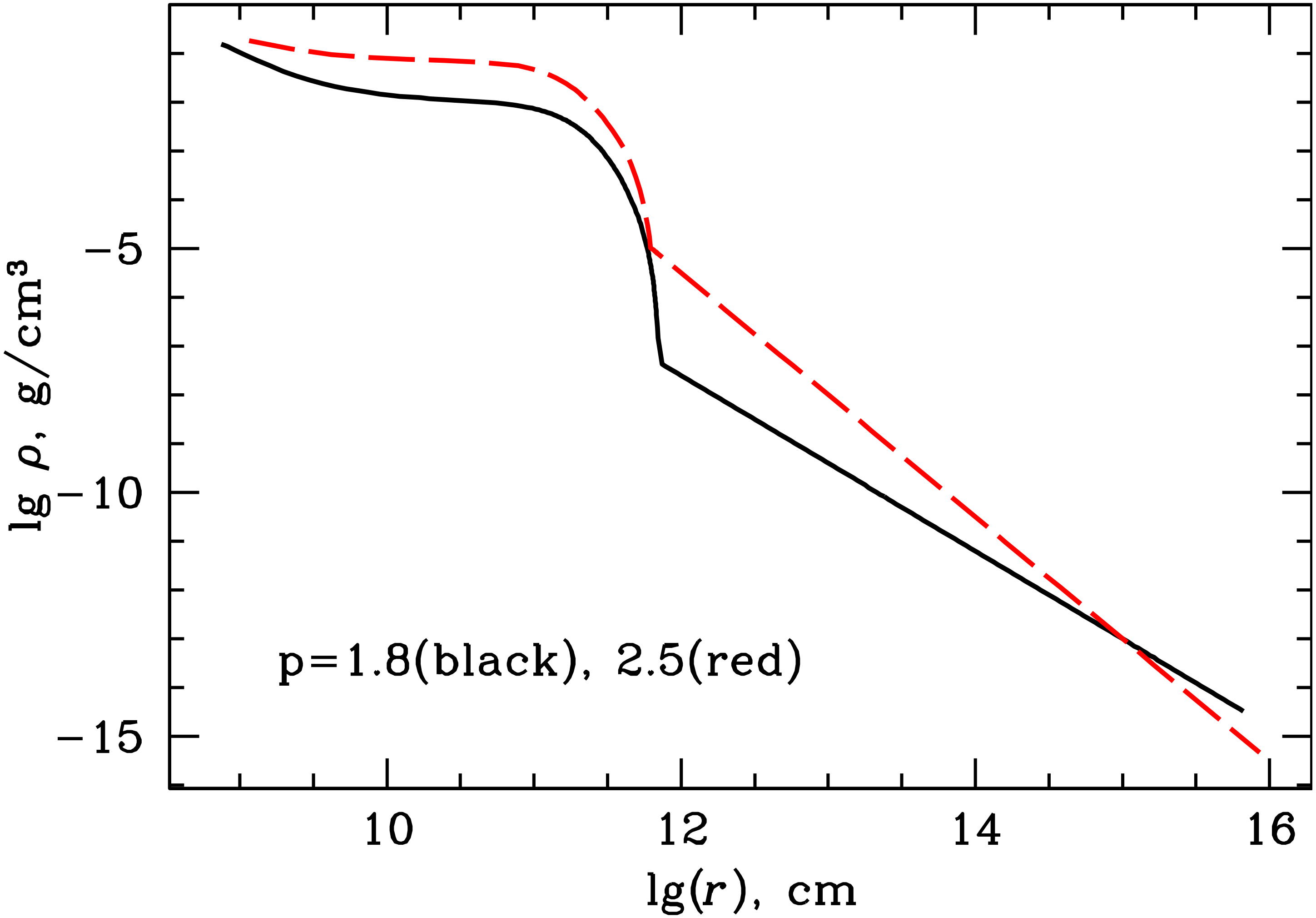
Ejecta: polytropic mass distribution;
Wind: $\rho \sim r^{-p}$

Composition: uniform for most of models (always uniform for the wind):
0.5 C + 0.5 O + 2% heavier elements of Solar abundance;
or 0.9 C + 0.1 O + 2% or more heavier elements;
or 0.1 C + 0.9 O + 2% or more heavier elements ;
or He + 2% Z or more
as a rule no ^{56}Ni – to check the influence of the pure shock

as a rule: velocity in the “wind”: $u = 0$, but some runs are done for high u

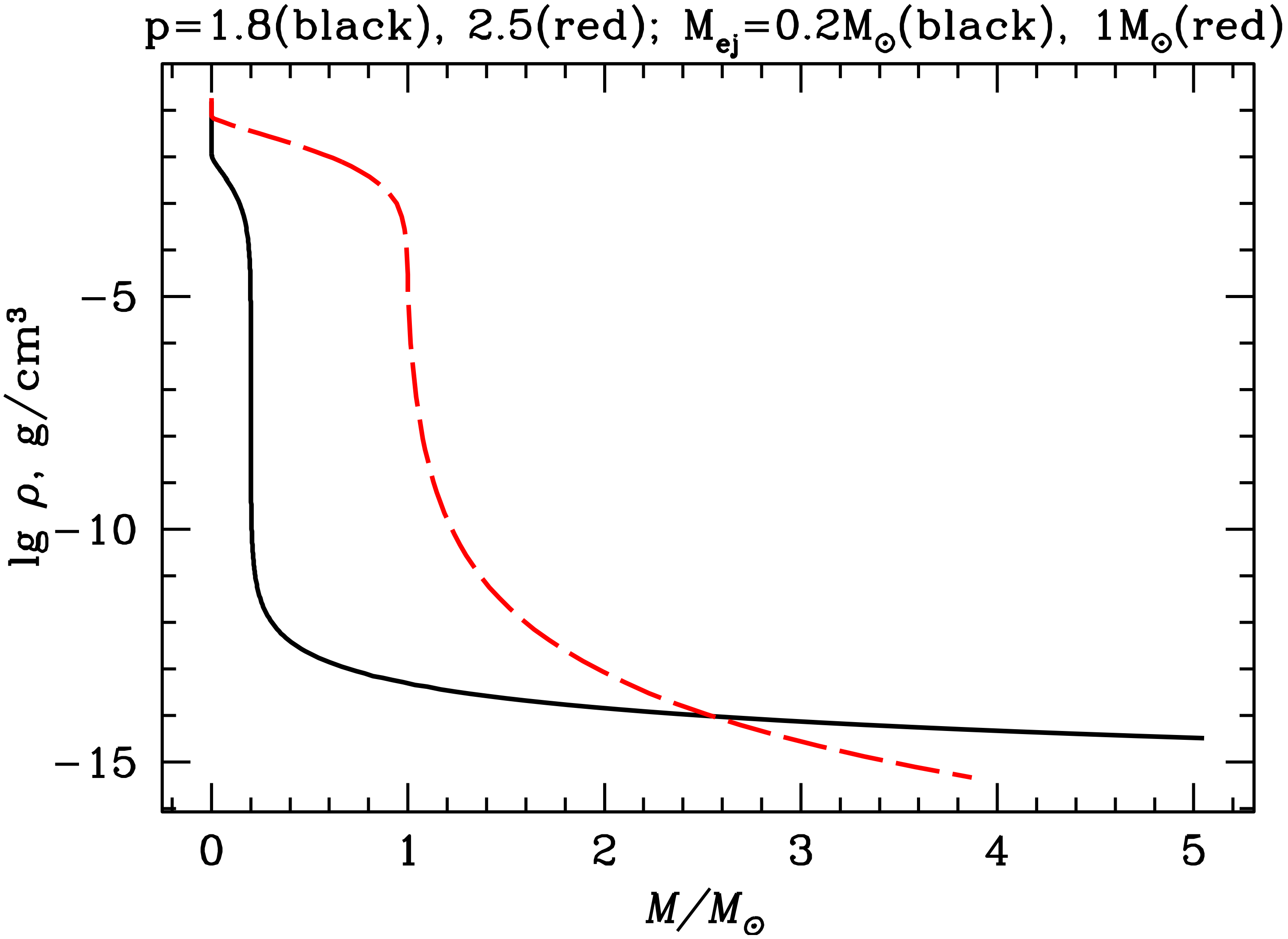
Initial models

Samples of the density distribution



Initial models

Samples of the density distribution



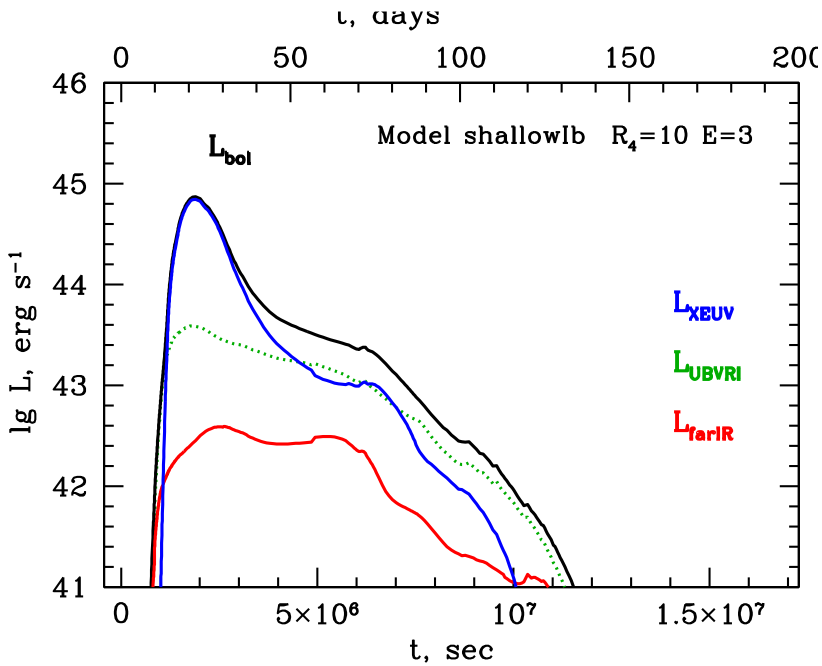
Windy models for type Ic SNe

all masses M and radii R are in solar units

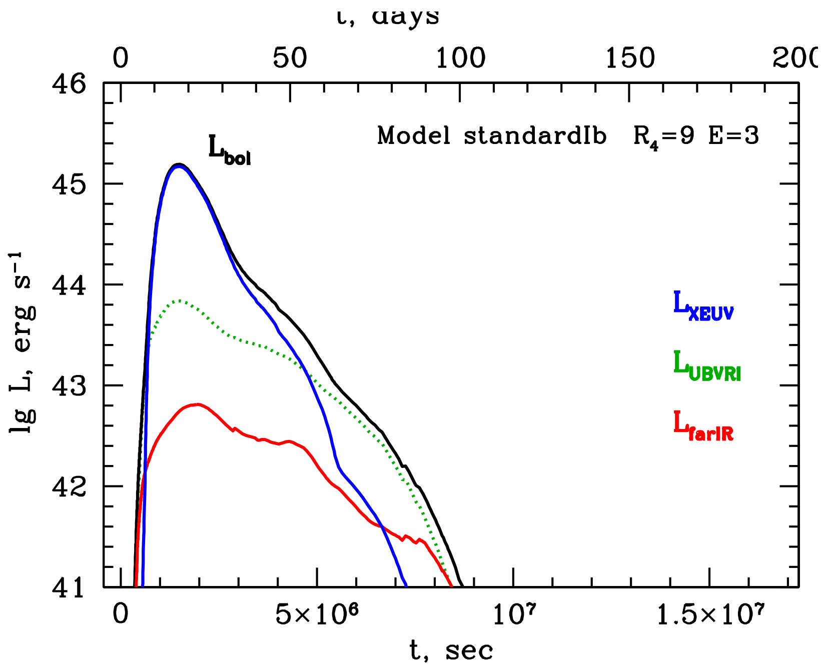
Model	$M_{\rm ej}$	$R_{\rm ej}$	$M_{\rm Ni}$	p	$M_{\rm w}$	$R_{\rm w}$	E, foe
`out6esa`	10	$9.1 \cdot 10^3$	0	0	4.15	10^5	1.5
`out7p3`	10	$6.3 \cdot 10^3$	0	3	3.3	10^5	1.5
`out8p3`	10	$5.7 \cdot 10^3$	0	3	6.8	10^5	1.5
`out9p3`	1.7	5	0	3	9.8	$1.2 \cdot 10^5$	1.5; 3
`out10p2`	2	10	0	2	4.5	$1.3 \cdot 10^5$	3
`out11p2`	10	$7.4 \cdot 10^3$	0	2	4	10^5	3
`out12p3`	2	9	0	3	0.45	$1.2 \cdot 10^5$	3
`out13p3`	2	9	0	3	0.52	$1.3 \cdot 10^6$	3
`out14p2`	1	10	0	2	4.5	$1.2 \cdot 10^5$	3
`out15p25`	1	9	0	2.5	2.9	$1.2 \cdot 10^5$	3

and others.....

Light curves for different wind structure

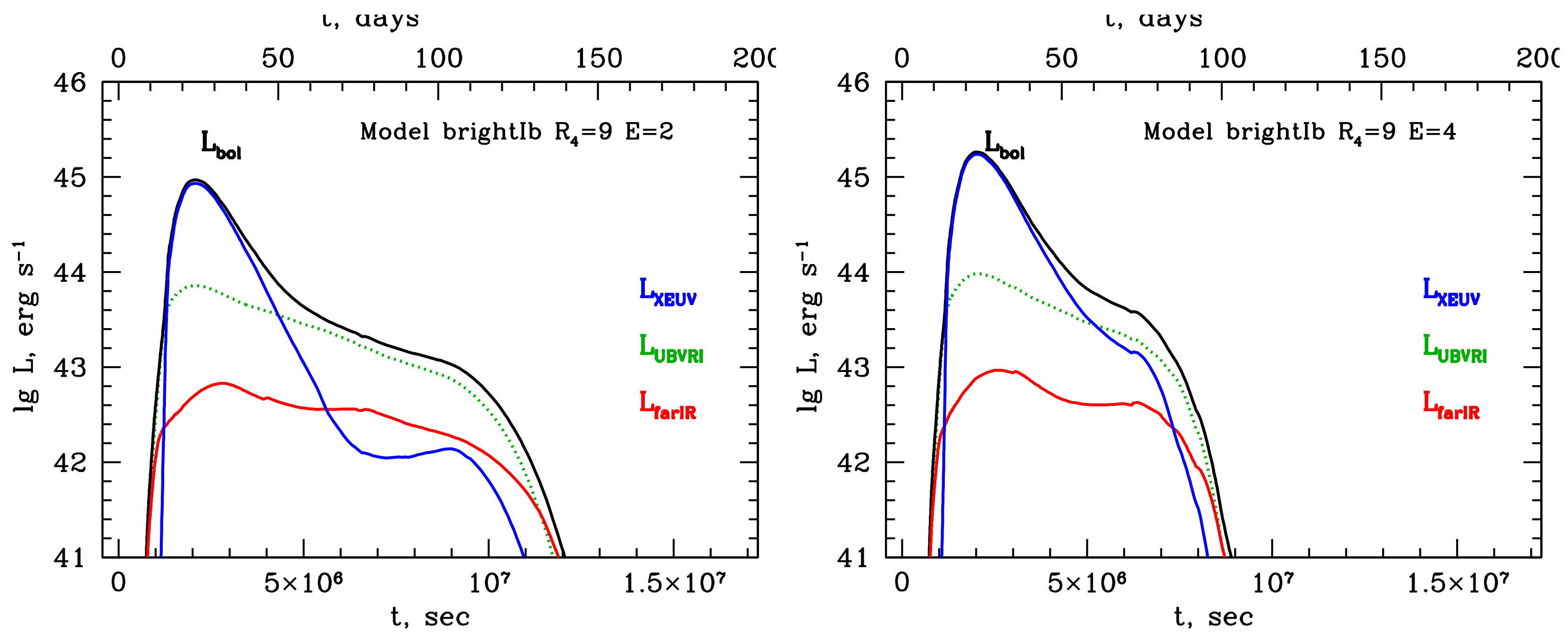


$$p = 2.5, M_w = 2.9M_\odot$$



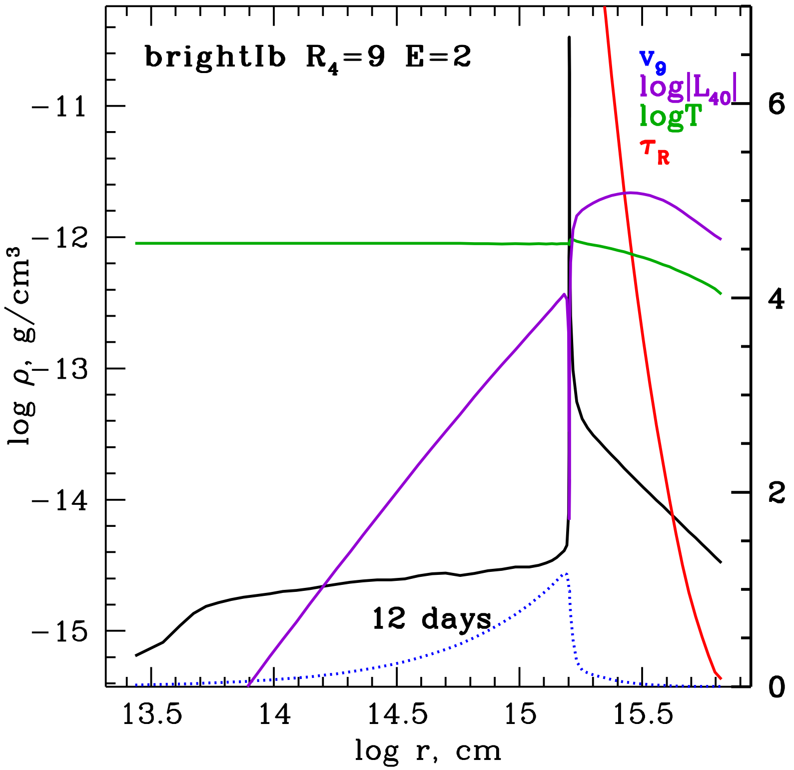
$$p = 2, M_w = 3.5M_\odot$$

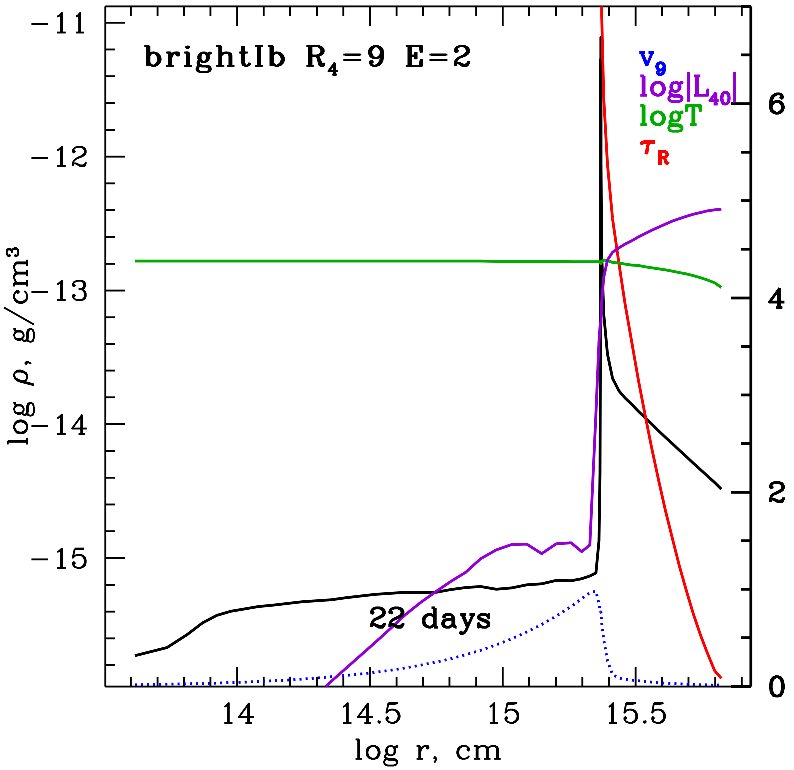
LCs for different explosion energies



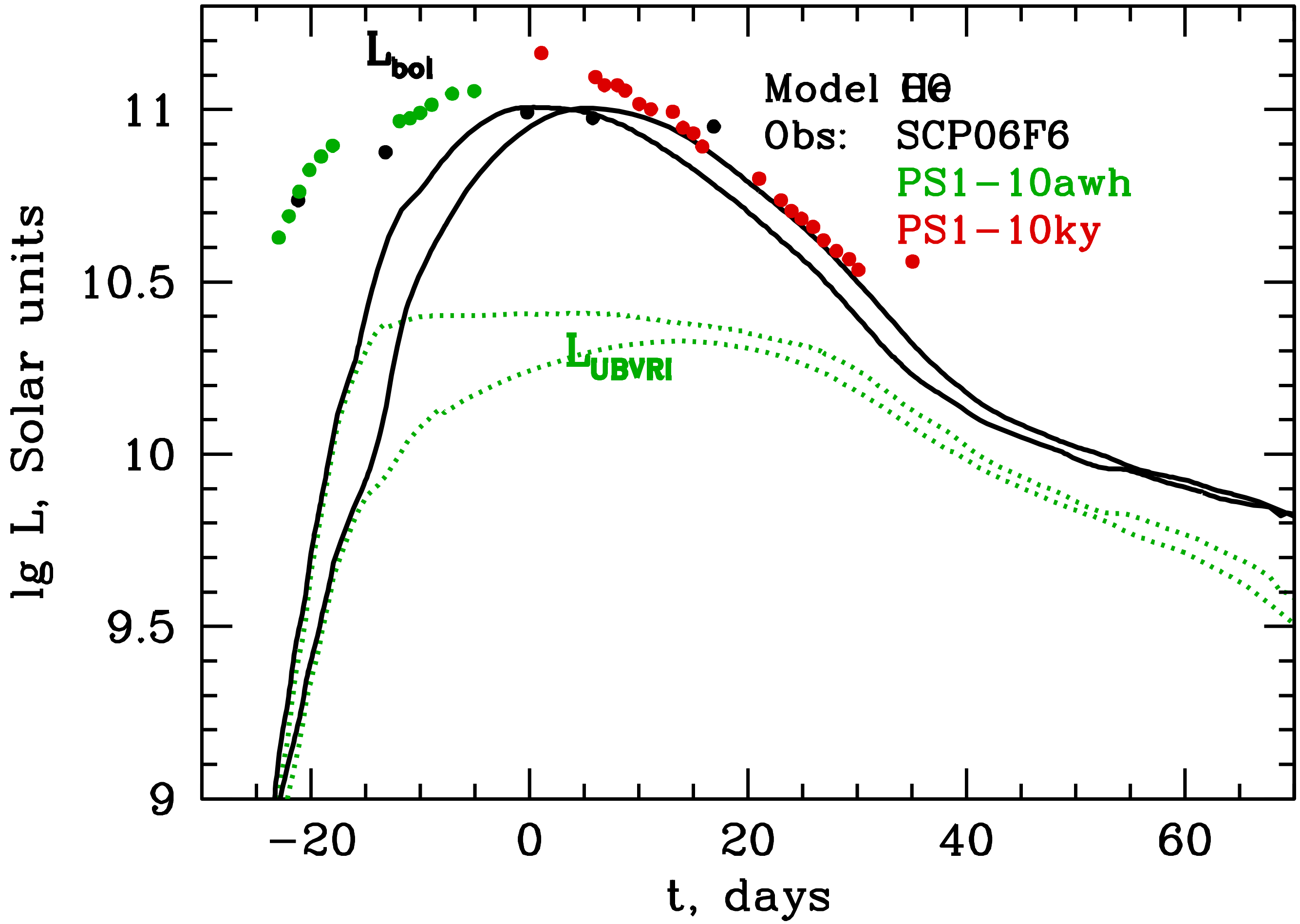
$$p = 1.8, M_w = 4.8 M_\odot$$

Evolution of model structure



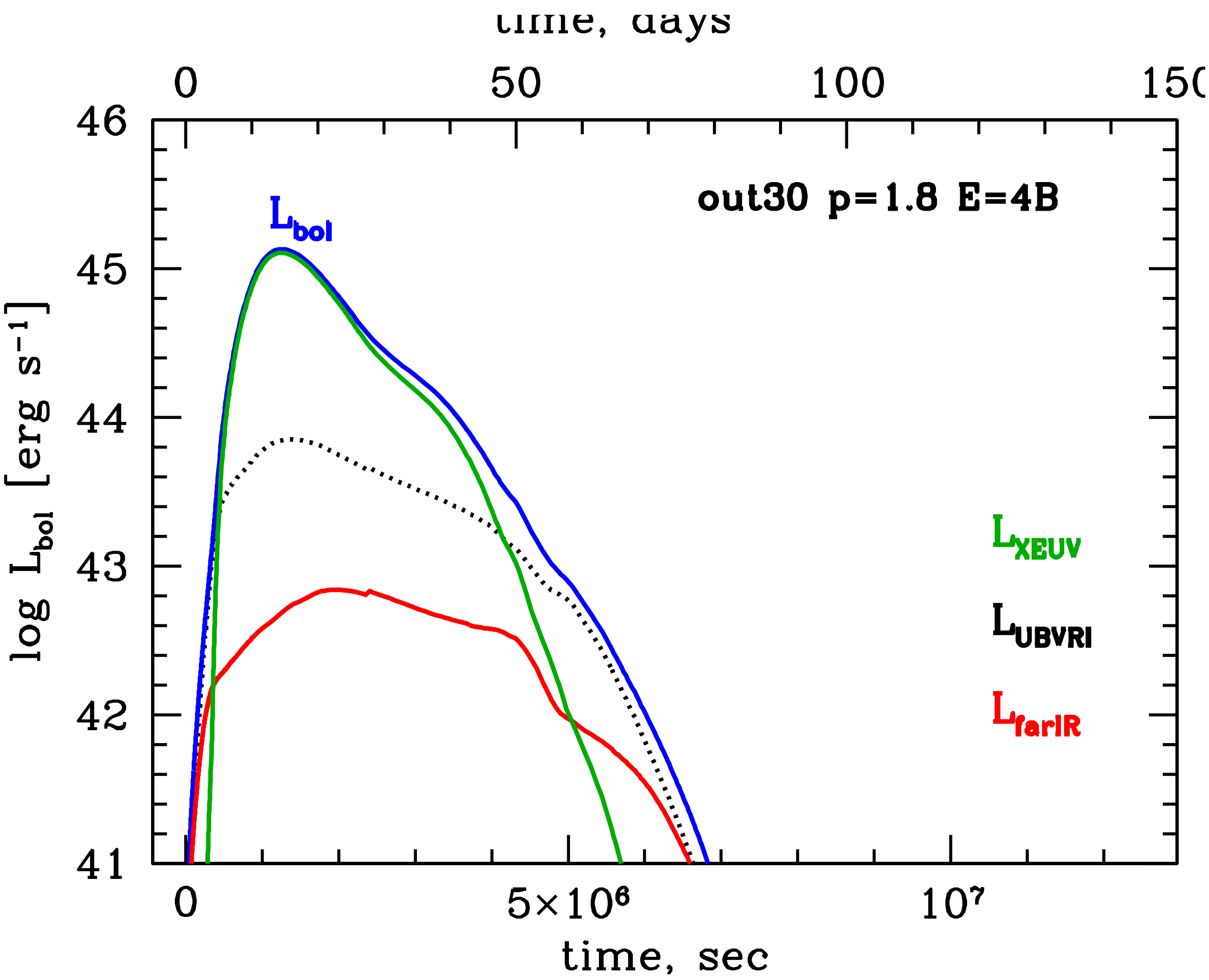


CO vs. He wind



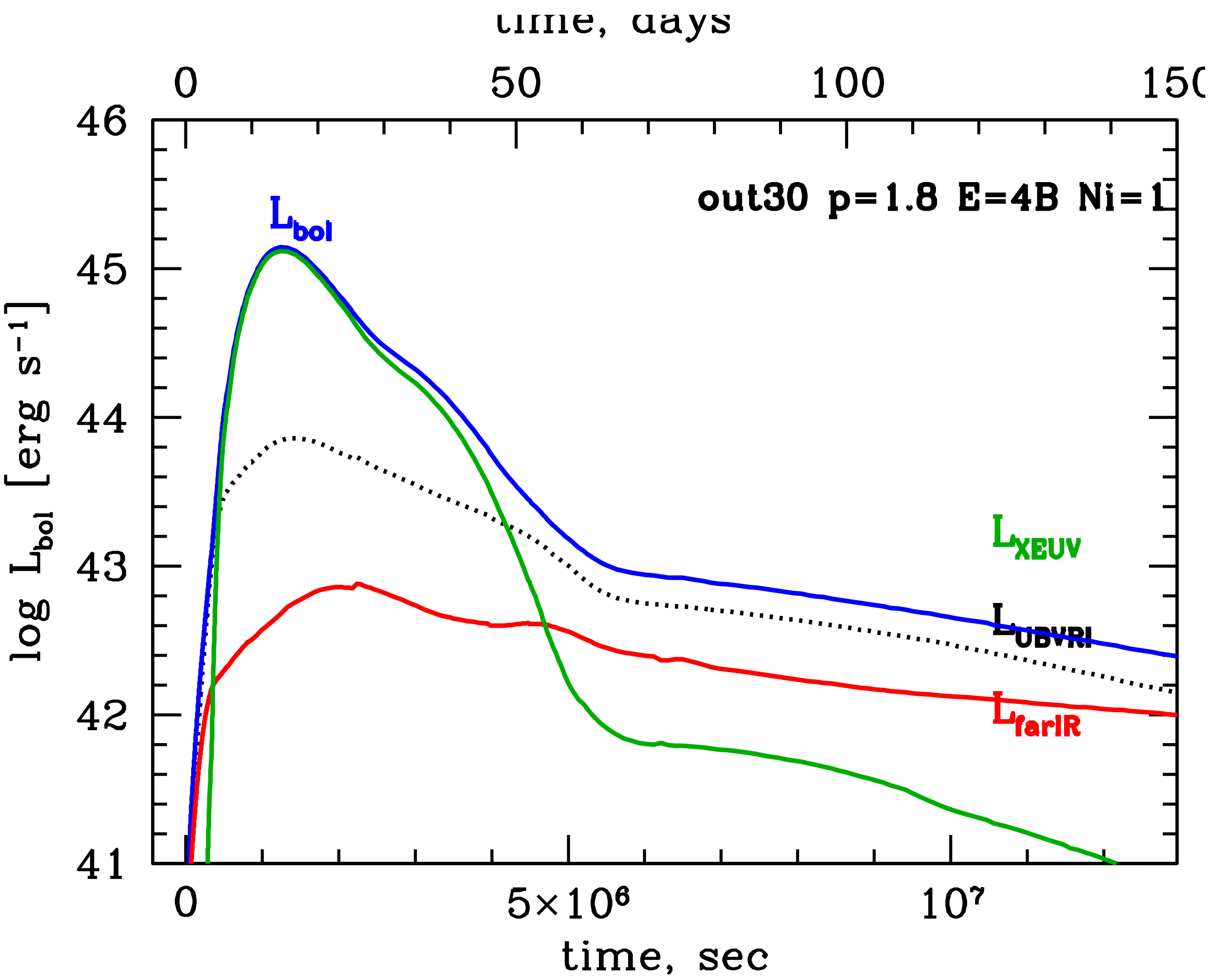
Model with He-wind is more symmetric around maximum light

^{56}Ni vs. Shock wave heating



no ^{56}Ni

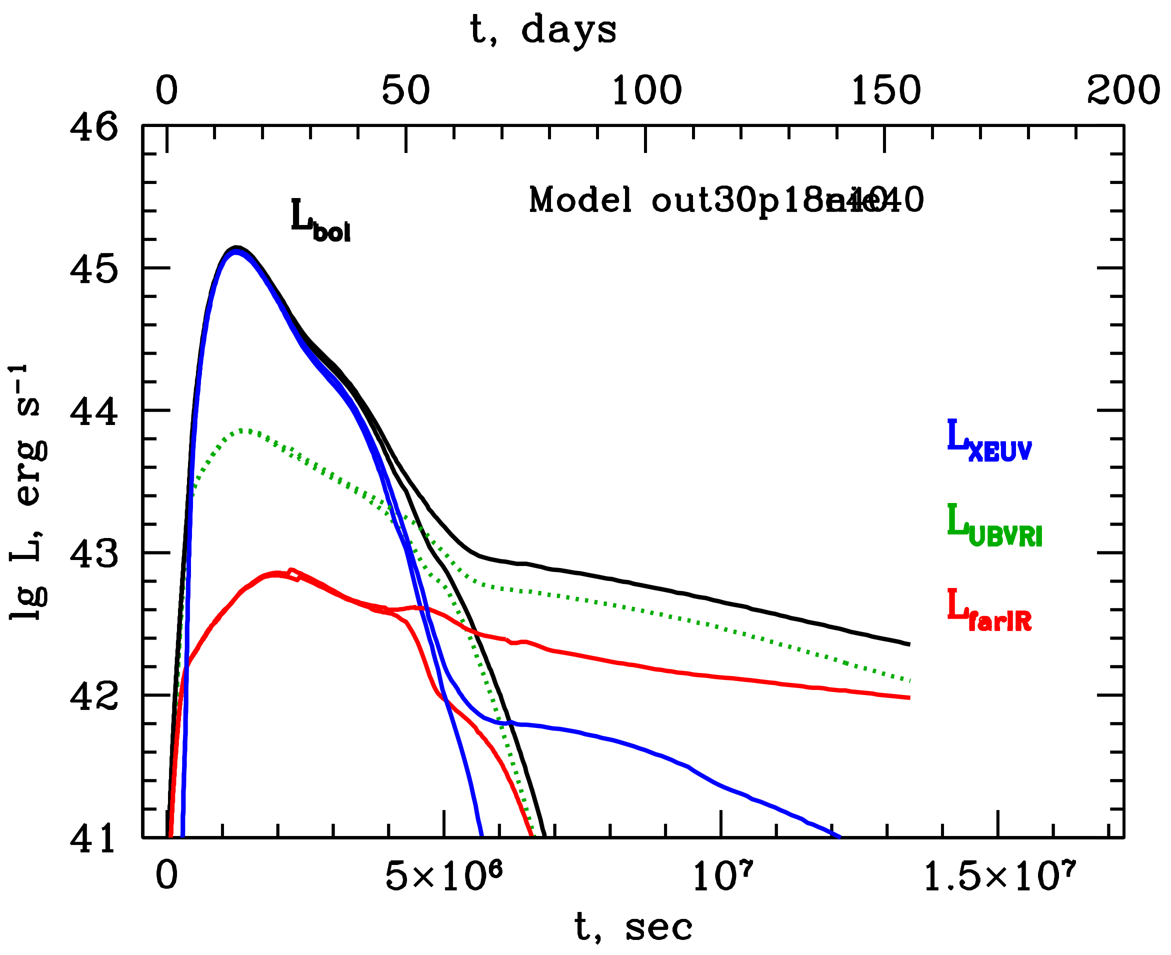
^{56}Ni vs. Shock wave heating



$M(^{56}\text{Ni}) = 1M_{\odot}$ in the ejecta

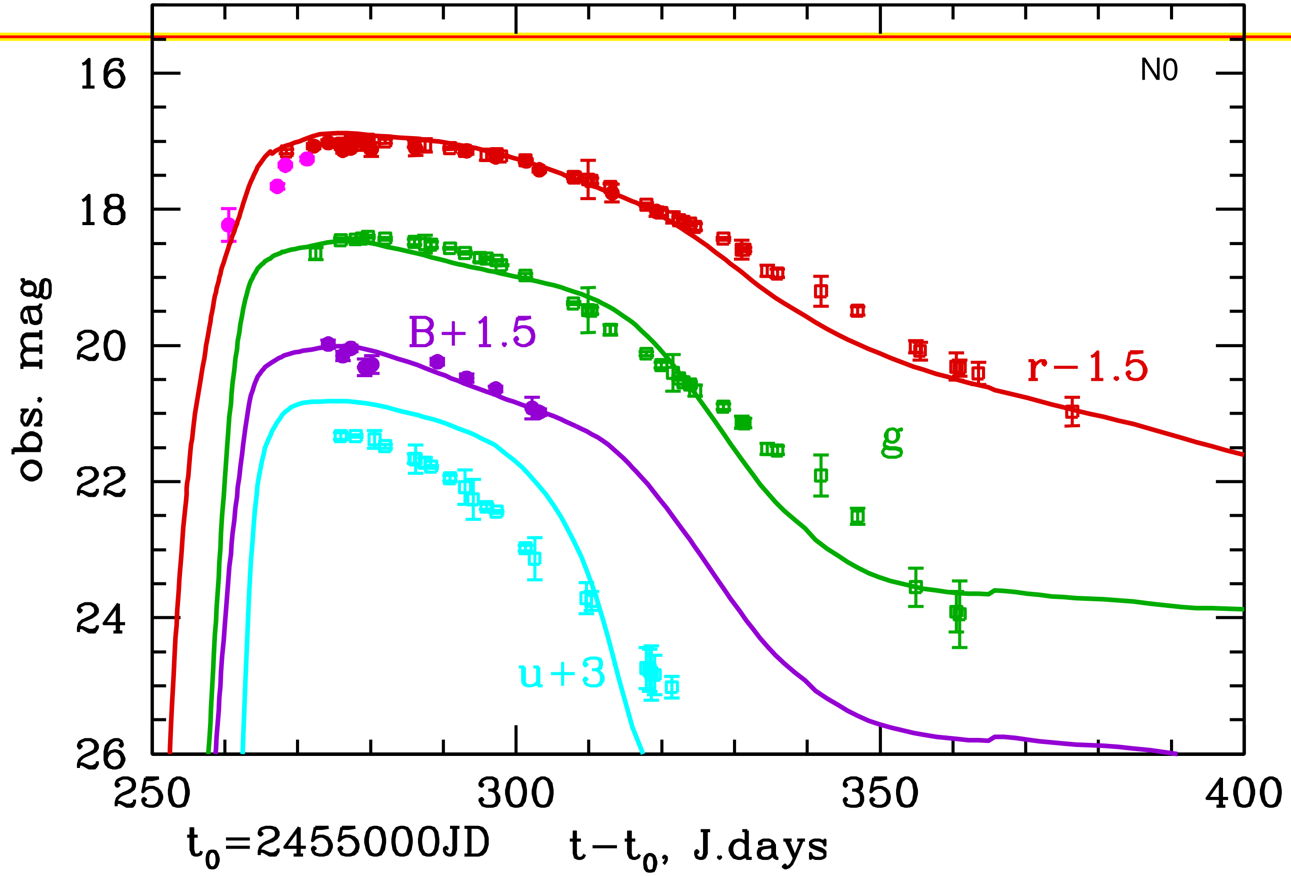
^{56}Ni vs. Shock wave heating

2 previous plots combined



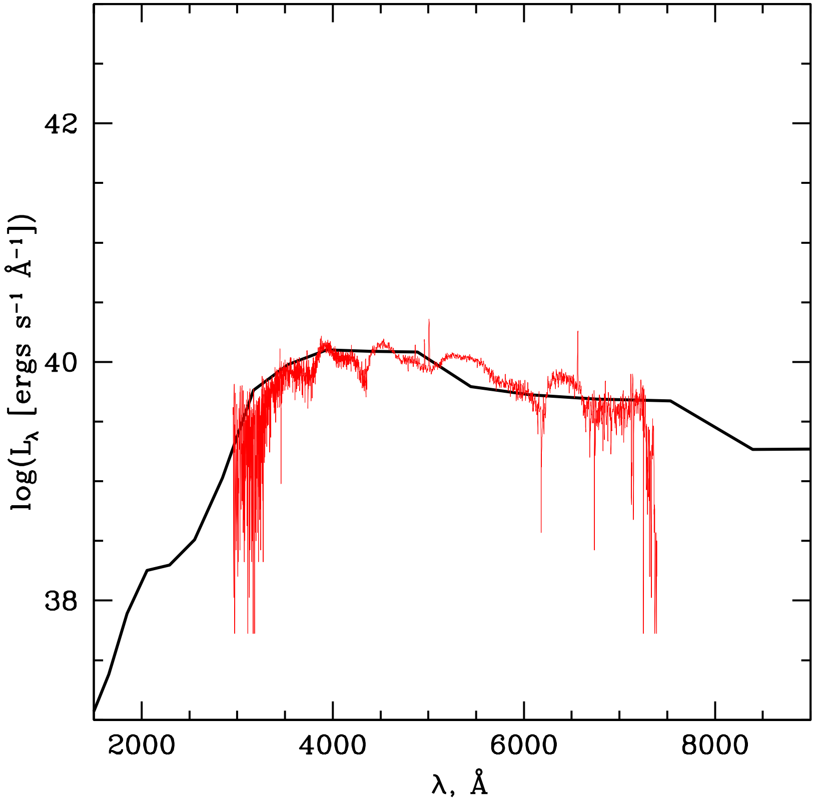
$M(^{56}\mathrm{Ni}) = 1 M_{\odot}$ added to the ejecta

Models for SN2010gx



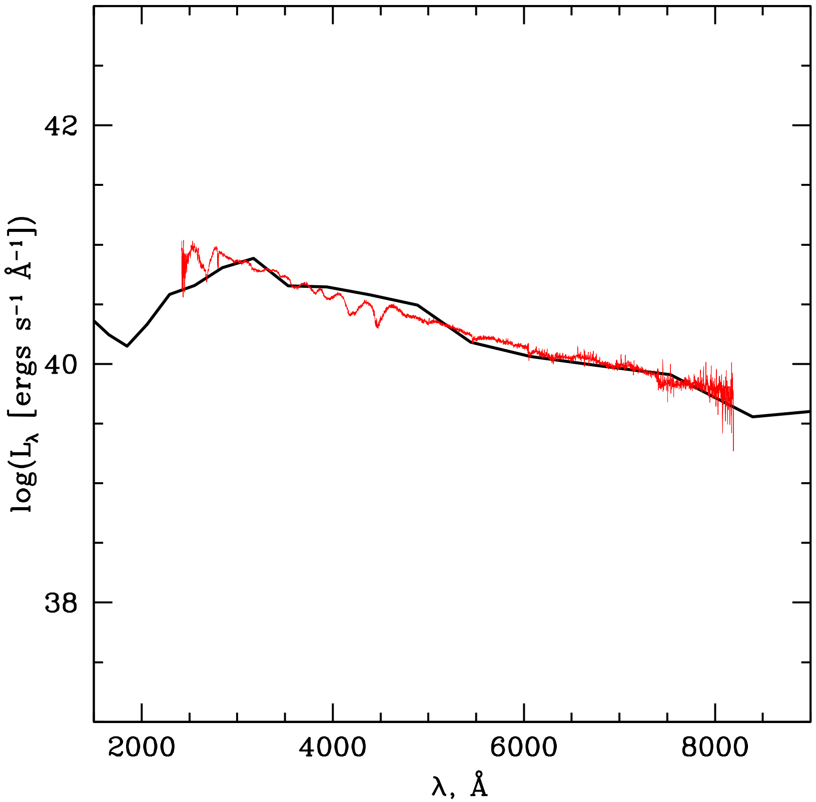
Synthetic light curves for the model N0, one of the best for SN 2010gx, in r, g, B, and u filters compared with Pan-STARRS and PTF observations. Pan-STARRS points are designated with open squares (u, g, and R bands), PTF points, with filled circles (B and r bands).

Spectra for SN2010gx



Rest frame observed (*red*) and modeled (*black*) spectra. Comparison of the observed spectrum of SN 2010gx at day $+27$ Quimby2013 with that of model N0 at day $+32$ after the maximum in *B*-band. The observed luminosities are in arbitrary units and can be shifted along *y*-axis for better fitting to the model.

Spectra for PTF09cnd



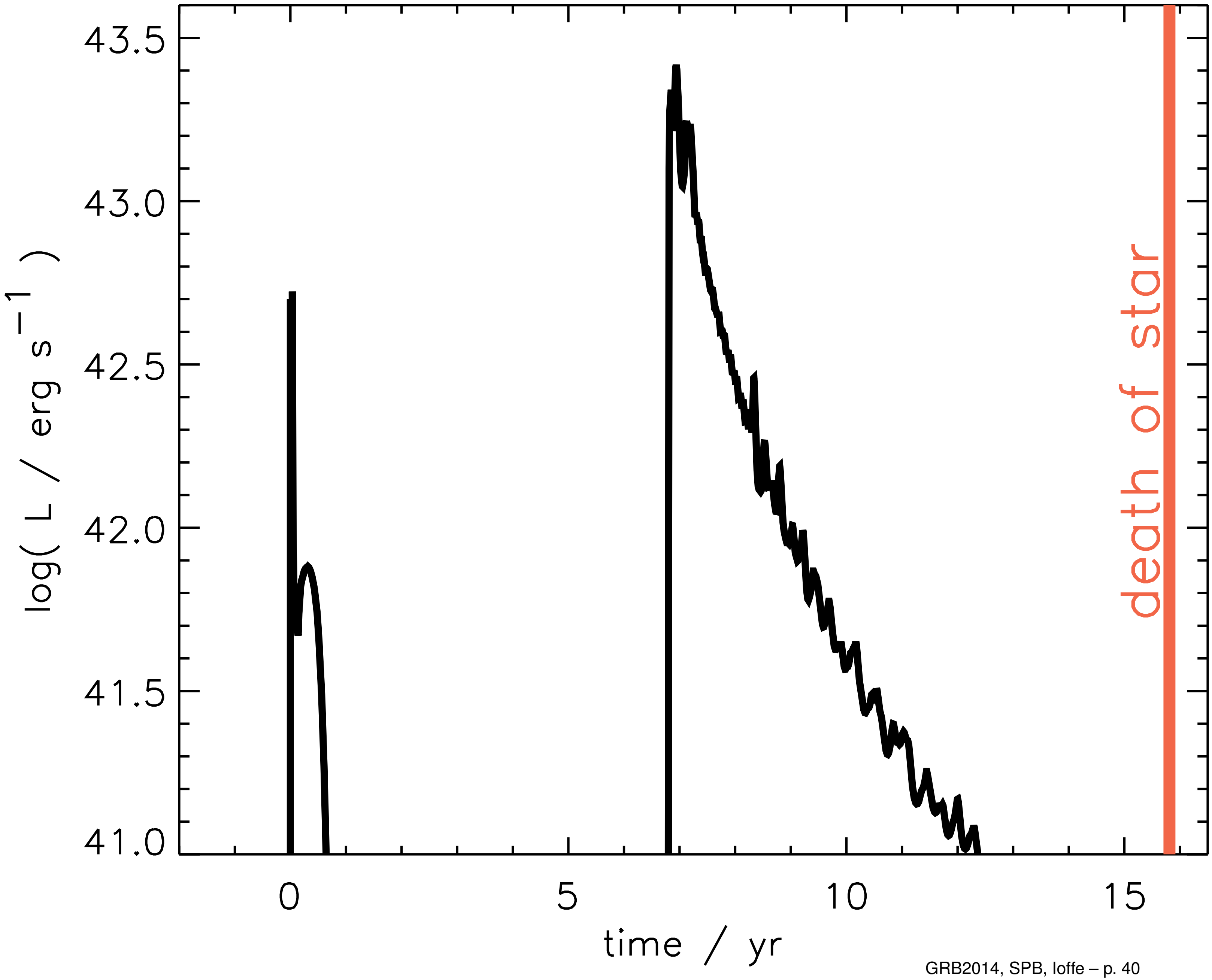
Rest frame observed (*red*) and modeled (*black*) spectra. Comparison of the observed spectrum of PTF09cnd at day -20 Quimby2013 with that of model B0 at day -20.

Now a GRB enters

We see that formation of a dense shell is a generic feature of SLSNe.

What happens if a GRB explodes inside that shell after the Supernova?

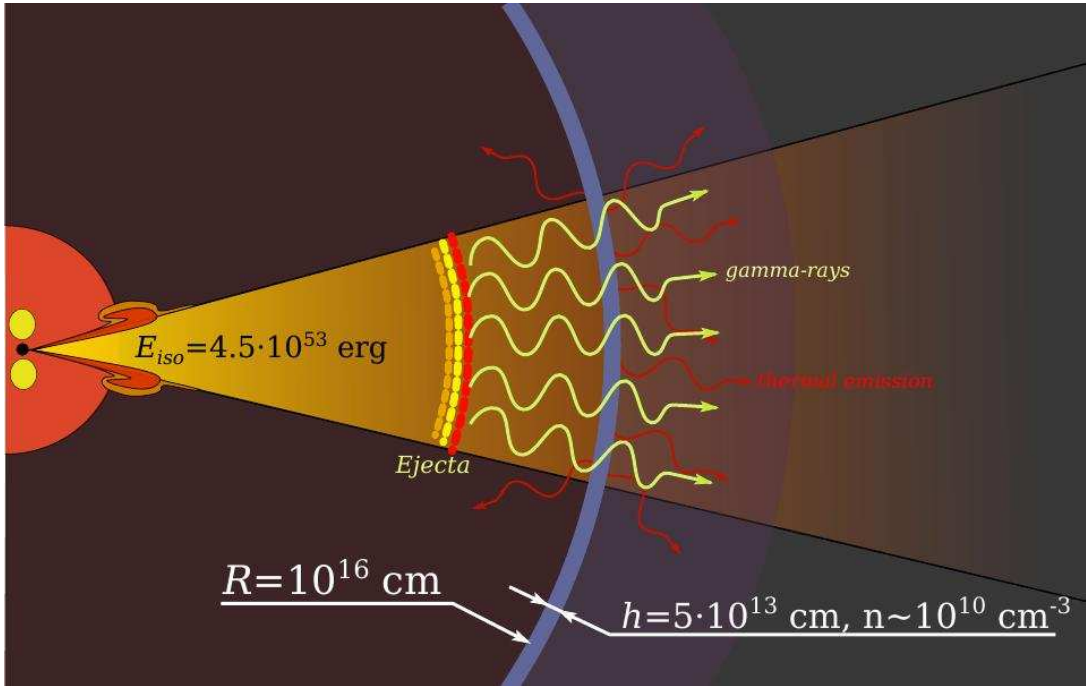
Woosley, SB, Heger 2007



A sketch of GRB-shell interaction

Badjin+ 2013:

A massive star → Pulsations or instabilities → 1-st ejection → 2-nd ejection, ejected masses collide and form structures (e.g. dense shells discussed above) → ... → $\circledast$ GRB, the shell is illuminated by prompt emission and then the relativistic ejecta run into it.



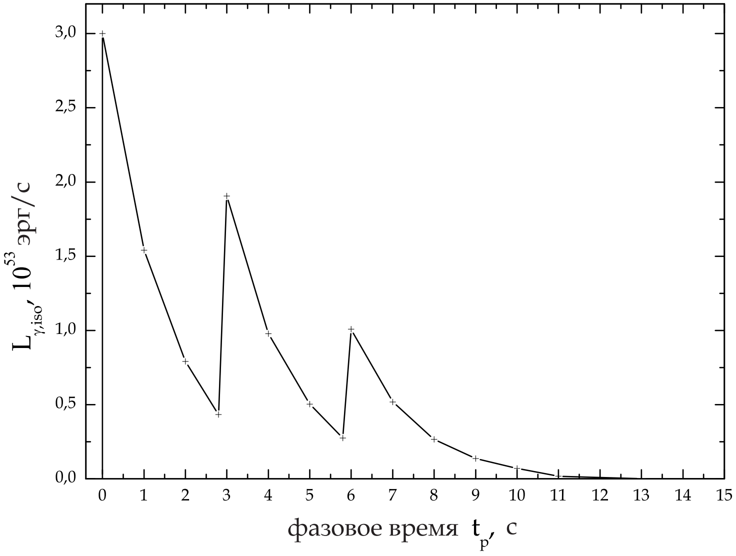
The shell $\sim 5M_{\odot}$ gains energy and should radiate it.

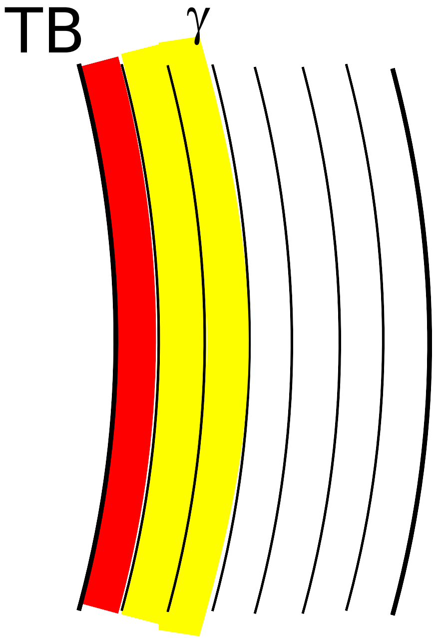
Initial Model

- Resembles *Woosley, Blinnikov & Heger (2007)* supernova shell. Abundances were taken from that paper.
- Thomson optical thickness not high: ($\tau_T \sim 1$)
- Various models have been simulated, but such a ‘wall’ displays the most pronounced features when illuminated by

Gamma-ray illumination of the shell

Fast Rise and Exponential Decay (FRED) pulses.
3 FRED pulses × 1.5 s, total duration 1 s, isotropic
$\boldsymbol{L_{\rm peak} = 3 \cdot 10^{53}}$ erg/s, broken power-law spectrum
(1 keV–30 MeV, $\boldsymbol{\alpha = 0.9, \quad \beta = 2.001, \quad E_0 = 300}$ keV),
100 energy bins. Assumed collimation $\boldsymbol{\theta_{\rm jet} = 10^\circ}$.





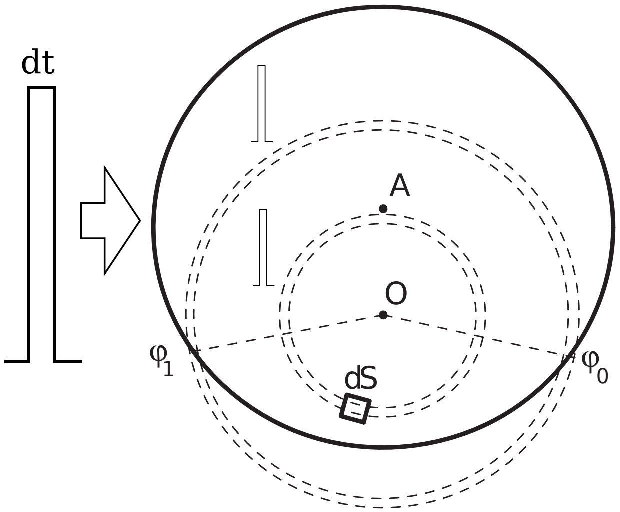
The impact of GRB Ejecta

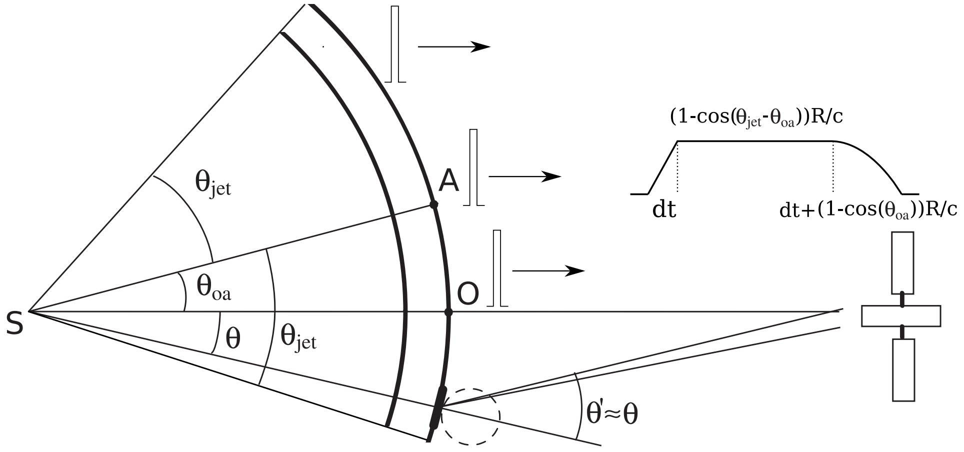
- Immediate deceleration $\frac{E_k}{c^2\Gamma} \leqslant M_{dec} < \frac{E_k}{c^2\Gamma^2} << M_{shell} \Rightarrow$ thermalization.
- Thermal energy $E_k = E_{iso,\gamma} = 4.5 \cdot 10^{53}$ erg is deposited into the innermost zone over $\delta R_z/c \approx 17$ s time scale. A 'Thermal Bomb' is triggered $\Delta t_{\gamma-ej} \sim \frac{R}{2c\Gamma^2} \approx 200$ s for $\Gamma = 30$.
- A clumpy structure is necessary to let the long term synchrotron afterglow to be emitted.

Thermal Emission Modeling

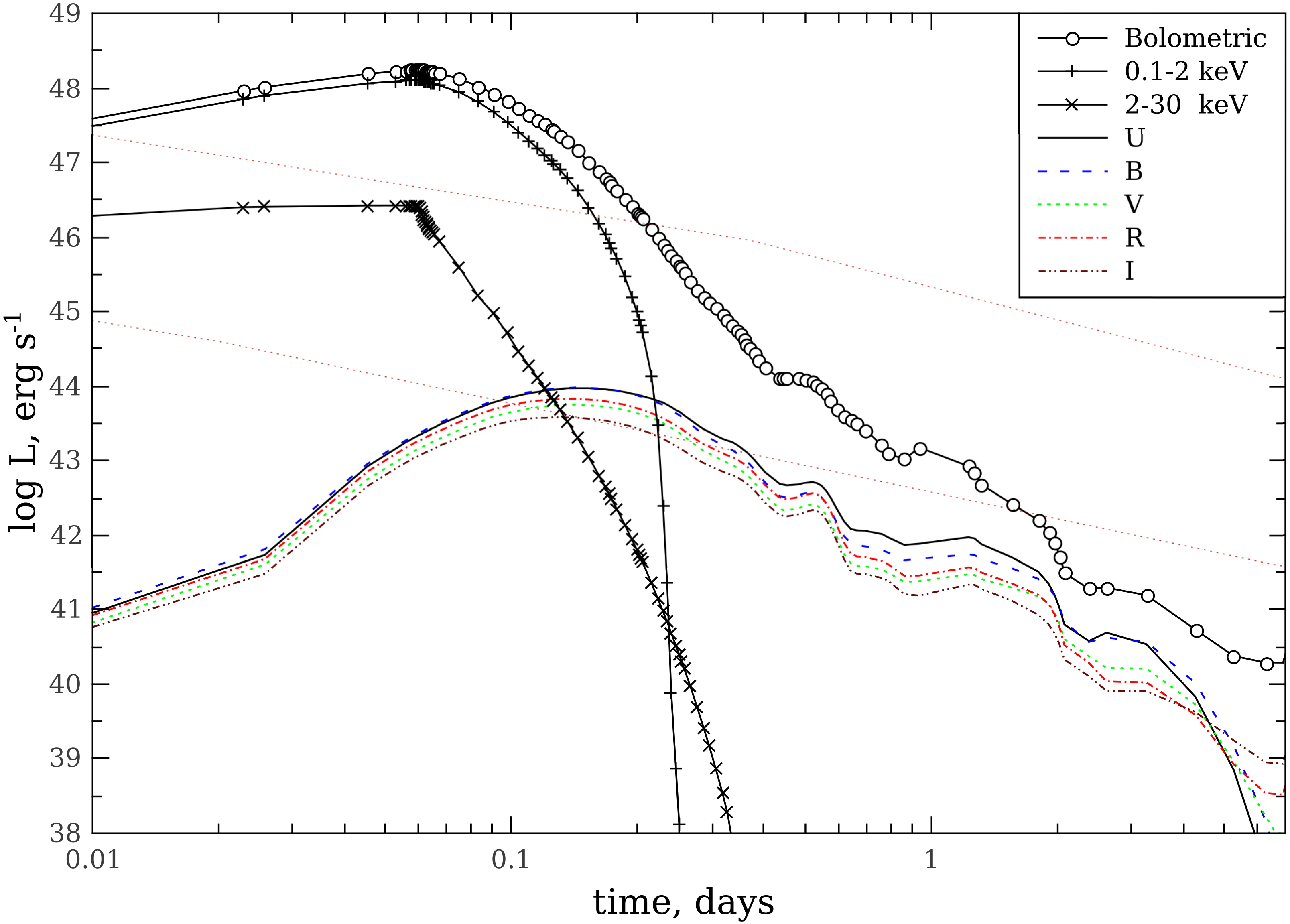
- $\boldsymbol{O(v/c)}$ aberration, Doppler shift, retardation; 120 groups from 50000 Å to 100 keV
- Source $\eta_\nu = \chi_{ab} b_\nu$, χ_{ab} – f-f, b-f, lots of b-b + expansion.
- Boundary conditions: $\mathcal{H}_\nu = h_E \mathcal{J}_\nu$, outer: >0; inner: <0. $P_{\mathrm{out}} = 0$.
- Light travel time correction: $L_{\nu,iso}(t_{obs}) = 8\pi^2 \int\limits_{\mu_{min}}^{1} \mu I_\nu(t'_{del},\mu) R^2_{out}(t'_{del}) \mathrm{d}\mu$, where

$$t'_{del} + \frac{R_{out}(t'_{del})}{c}(1-\mu) = t_{obs}$$

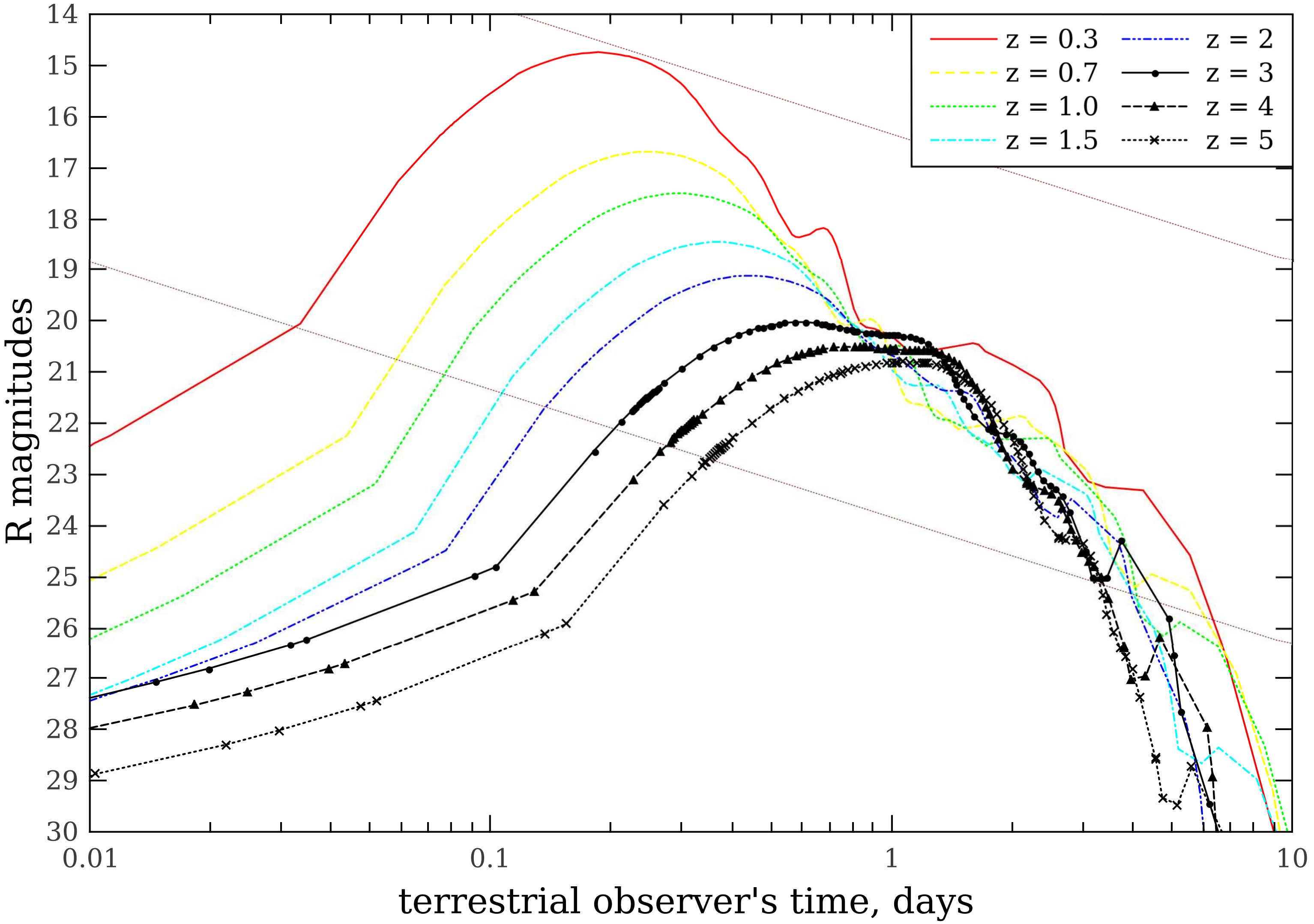




Luminosity, light curves

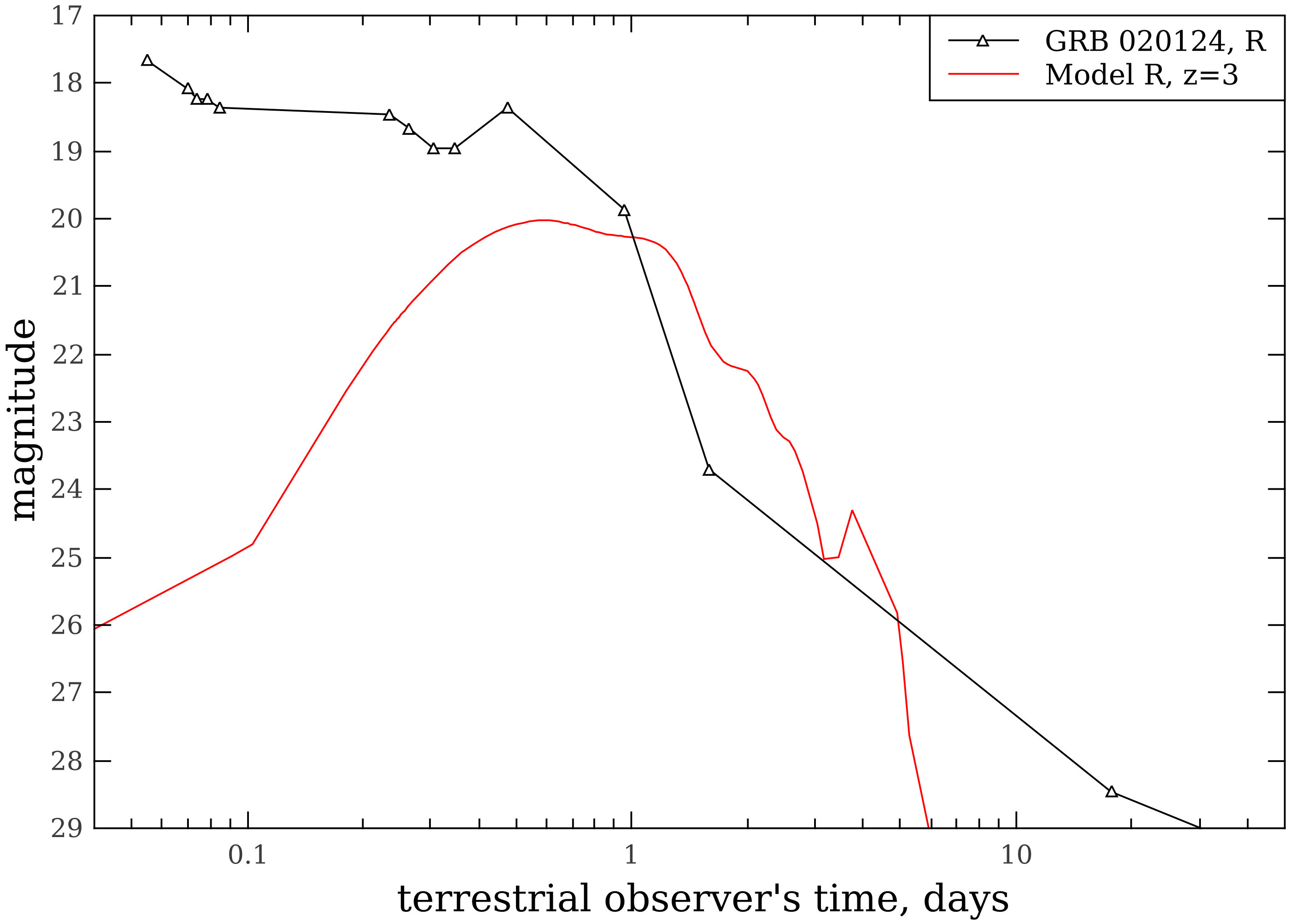


Stellar Magnitudes (Fluxes)



Optical Irregularity Model

GRB 021004, z≈3

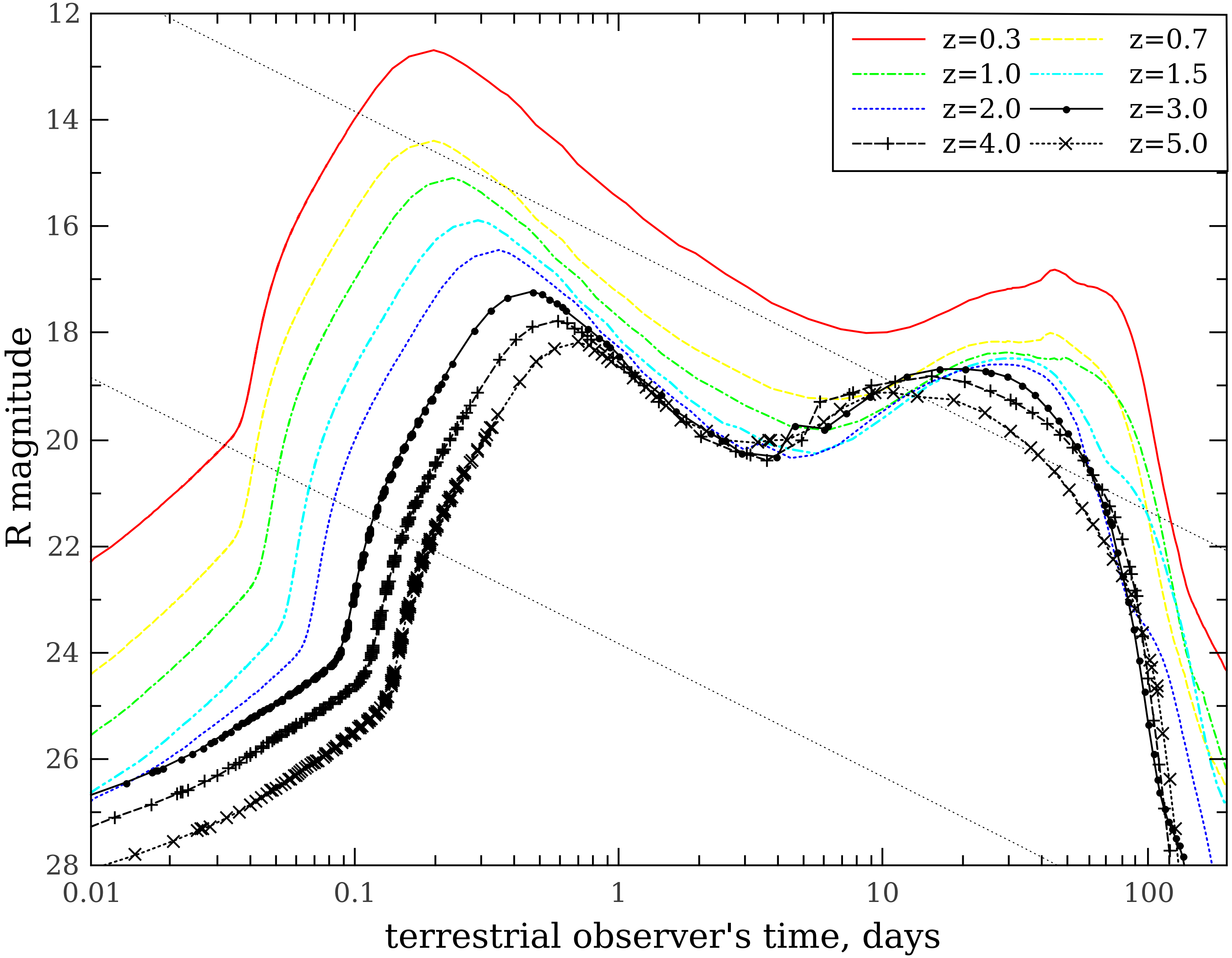


Quasi-Supernova = QSN

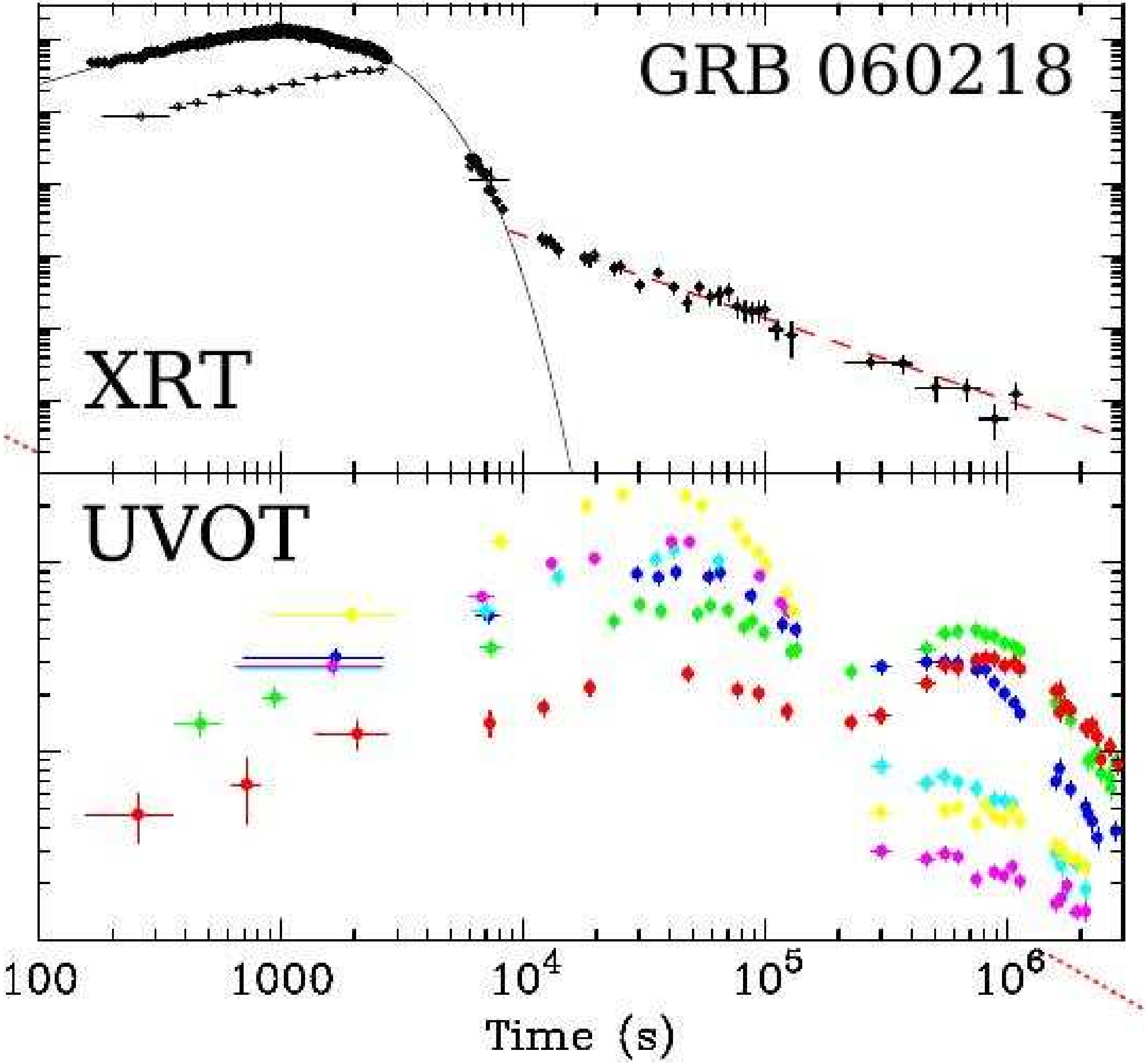
An extreme case: reflecting inner boundary, $\mathcal{H}_{\nu,in} = 0$.

- ► **Total peak luminosity** $\sim 10^{49}$ erg/s, X-rays unaffected ($\Rightarrow$ depend mostly on gamma-rays); in optics: **a bright flash** (like a shock breakout) $\rightarrow$ **a long bump/plateau**.
- ► **Expansion velocity** $\sim 6.5 \cdot 10^4$ km/s. A very energetic supernova.
- ► **Similar double-bumped** light curves for GRB 060218 (sn2006aj) (*Campana et al. 2006*). Also reported an X-ray blackbody component with a plateau of $\geqslant 3000$ s duraion.
- ► QSN – nonphysical in 1D, but illustrates **the importance of radiation** around an opacity jump (may be natural in 2D or 3D cases, near surfaces dividing hot and cold dense matter, e.g. jet channel walls).

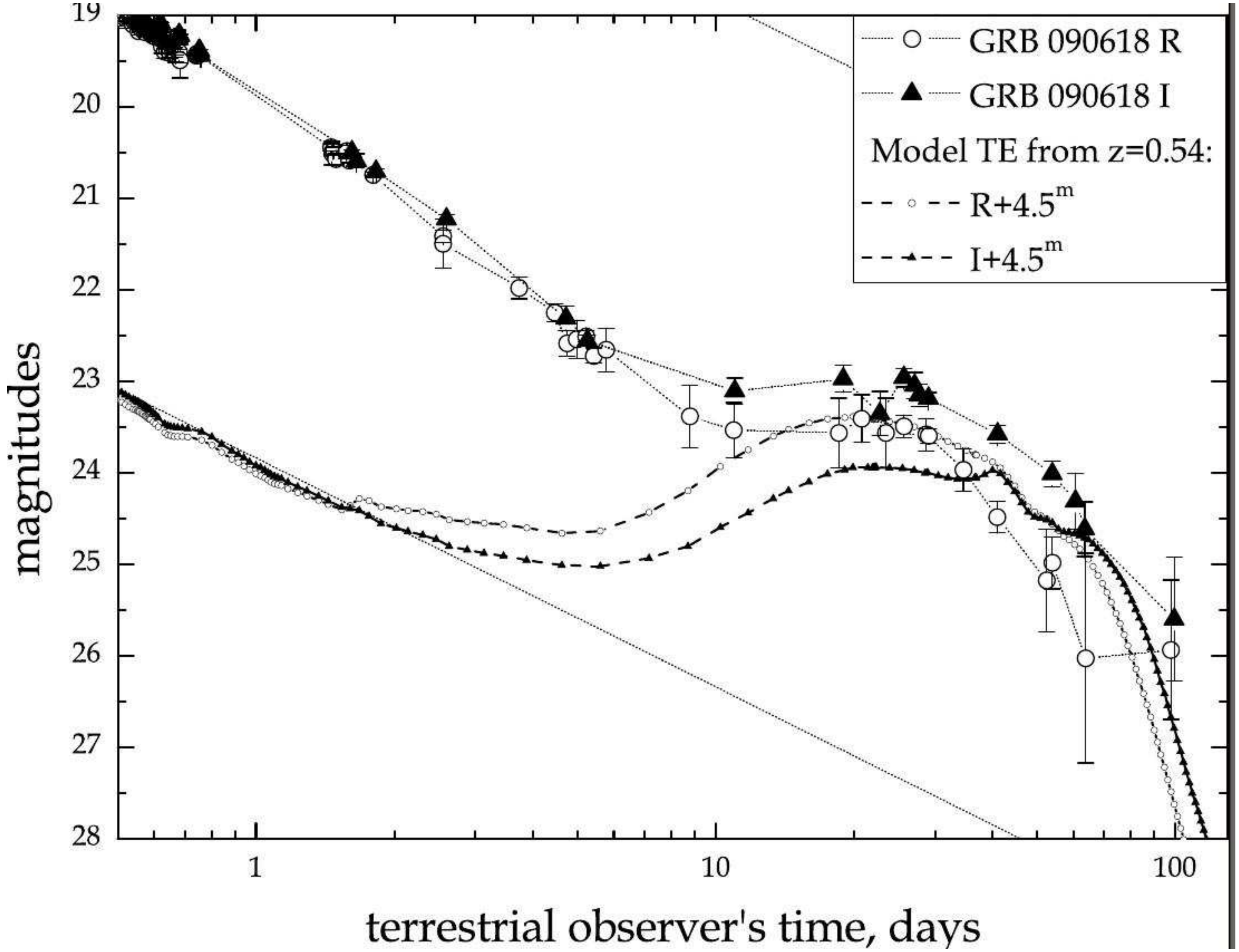
QSN


R magnitude
terrestrial observer's time, days
12
14
16
18
20
22
24
26
28
0.01
0.1
1
10
100
z=0.3
z=0.7
z=1.0
z=1.5
z=2.0
z=3.0
z=4.0
z=5.0

GRB 060218



QSN and GRB 060218



Quasi-Supernova

- **A curious consequence** for the GRB-SN connection and central engine theory:

since the SN-bump is allowed to originate in the environment (e.g. due to an explosion driven by radiation),

it removes the necessity for the central engine of the collimated ‘failed supernova’ outflow, to launch a widespread ‘successful’ one as well. The latter occurs outside.
A combination of ideas of the ‘failed supernova’ by Woosley, and ‘supranova’ by Vietri and Stella, emerges.

Conclusions SLSNe

- The shock wave which runs through rather dense matter surrounding an exploding star can produce enough light to explain very luminous SN events. No ^{56}Ni is needed in this case to explain the light curve near maximum light (some amount may be needed to explain light curve tails).
  We need the explosion energy of only 2-4 Bethe for the shell with $M = 3 - 6M_\odot$ and $R \lesssim 10^{16}$cm. Narrow lines are not necessarily produced!
  The brightness and the duration of the light curve maximum depend strongly on the mass, structure and on the explosion energy. The features of monochromatic light curves sometimes depend on chemical composition of the envelope.

Conclusions PreSNe

- Questions on the latest phases of star evolution arise:
  - Is it possible to form so big and dense envelopes? And how?
  - Time scale for such a formation
  - How far can the envelope extend?
  - Density and temperature profiles inside the envelope right before the explosion
- Question to observations: try to find traces of such shells for bright explosions.
  (There are spectral evidence of circumstellar shells for type IIn and Ibn SNe. Is it possible to find C–O envelopes as well?)

Conclusions TE in GRBs

- Massive structures of circumstellar matter ⇔ **detectable Thermal Emission**, plateaus, bumps, irregularities
- A possibility of off-center supernova-like explosions ⇒ **a way to explain the GRB-SN connection** without placing constraints on GRB central engine.
- An important role of radiation ⇒ a necessity in self-consistent relativistic multidimensional **Radiation** hydrodynamics codes.

Conclusions common

- Many technical problems in light curve calculations:
  - line opacities;
  - dimensionality: 3D is preferable, since the envelope can most probably be clumpy;
  - NLTE spectra