
Hyper-supernovae powered by radiative shocks

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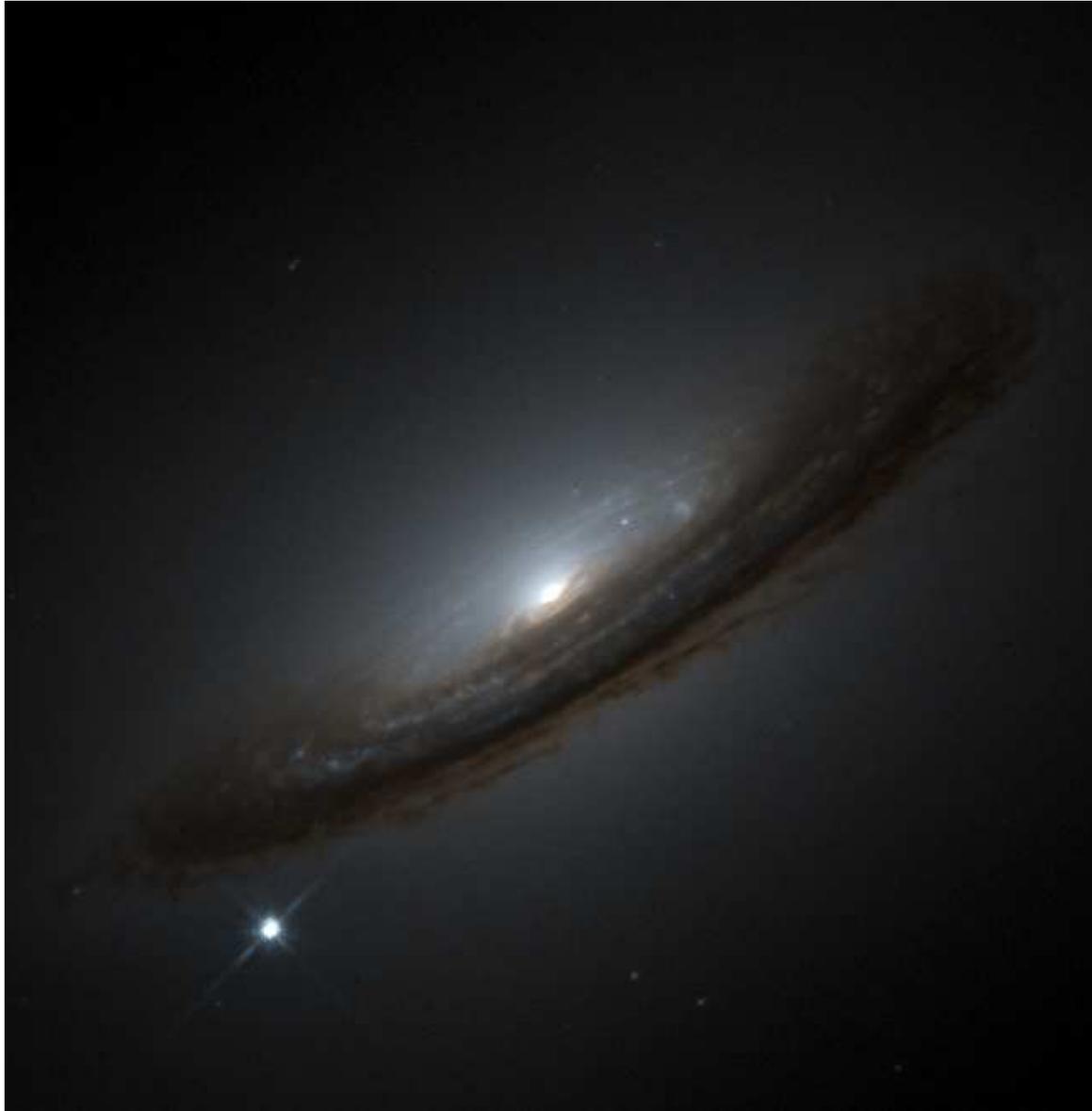


³ *work partly done at IPMU, Tokyo University, Kashiwa*



Supernova SN1994D in NGC4526

Shocks are not important for light in “Nobel prize” SNe Ia

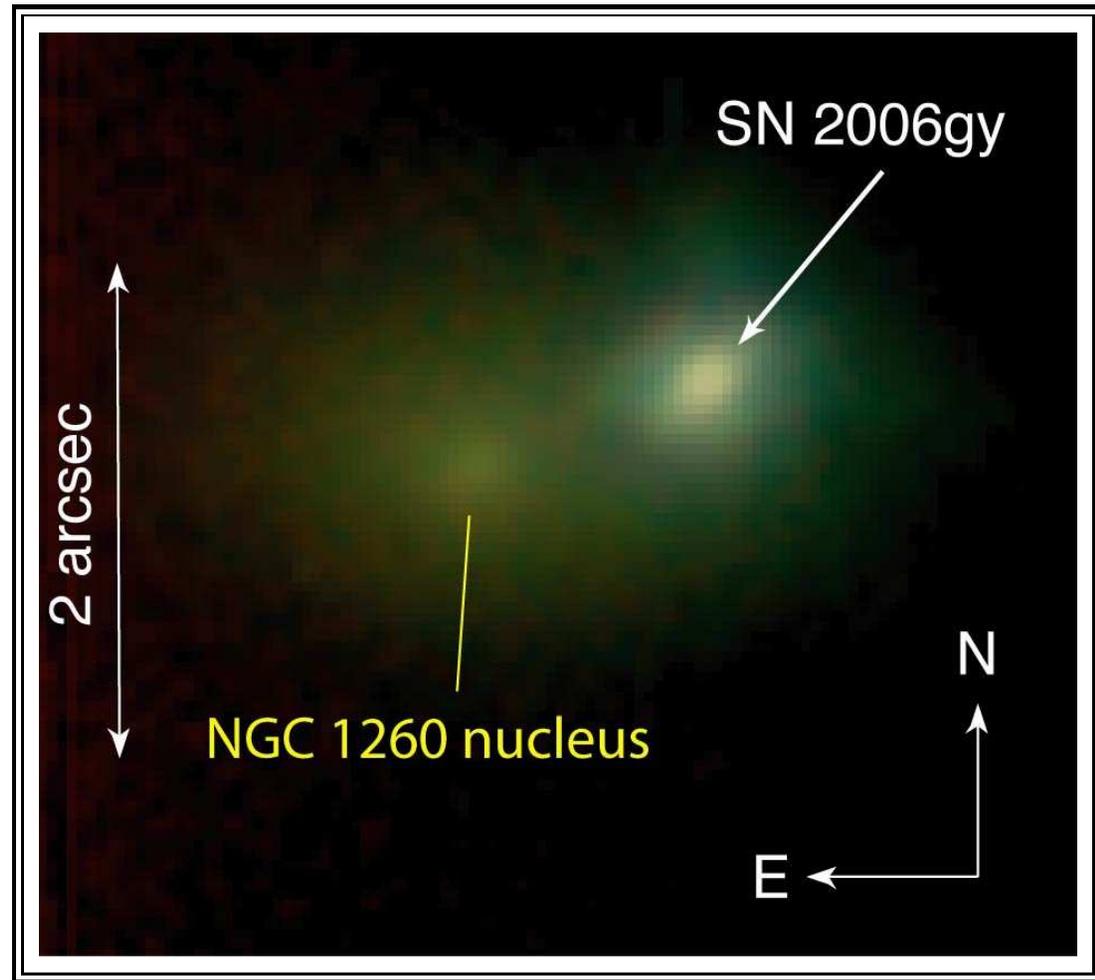


SN 2006gy

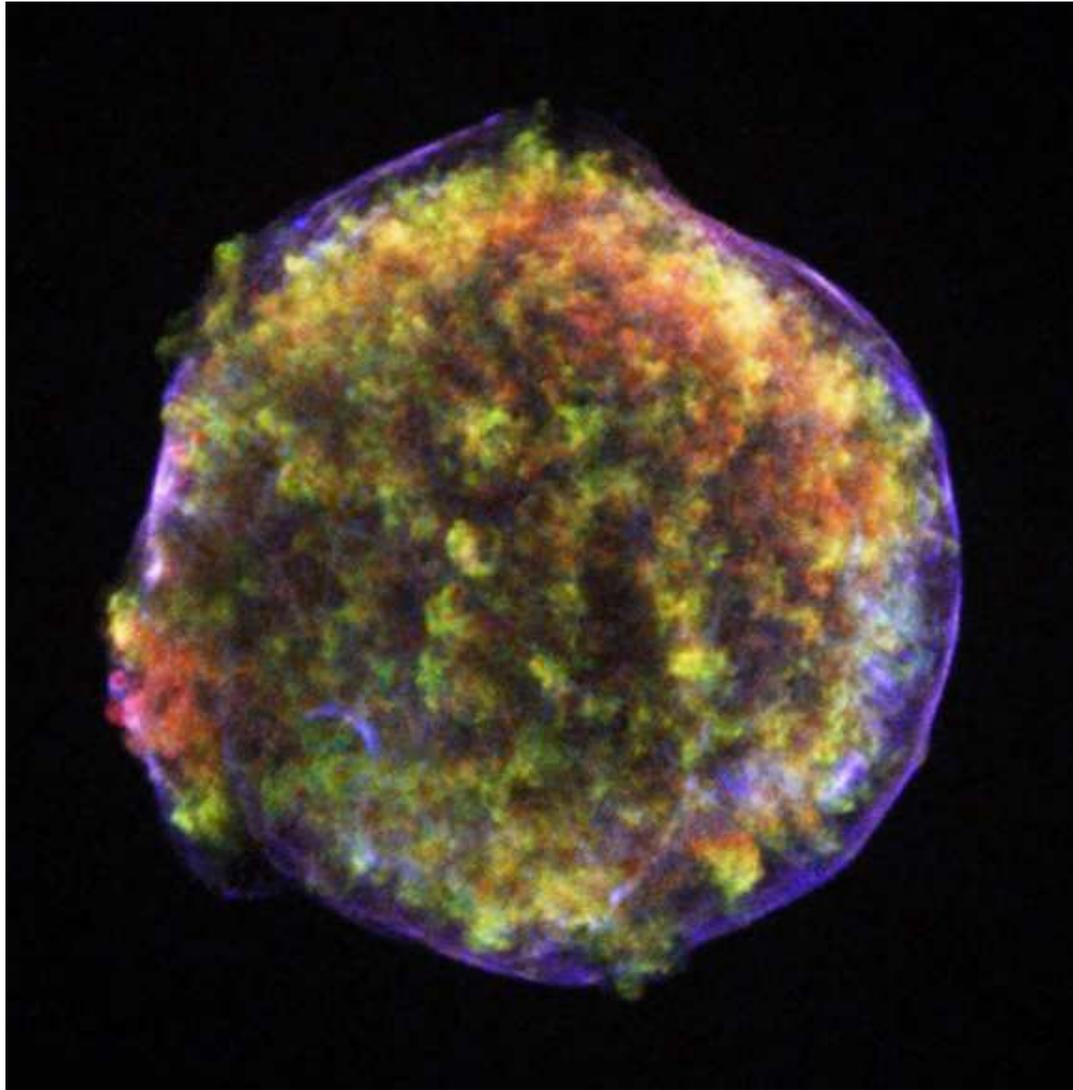
Ofek et al. 2007, ApJL

Smith et al. 2007, ApJ

Shocks are
vital for
explaining light
of those
superluminous
events for
many
months...



SNR Tycho in X-rays (Chandra)



...and thousands of years in SNRs

Supernovae: order of events

- Core collapse (CC) or explosion

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Supernovae: order of events

- Core collapse (CC) or explosion
- Neutrino/GW signal, accompanying signals
- Shock creation if any, propagation and entropy production inside a star
- Shock breakout (!)
- Diffusion of photons and cooling of ejecta
- But this produces ordinary, weak supernovae

Double explosion: an 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.

1986SVAL...12...68G

Another old idea (1984)

The first paper where merging
neutron stars we suggested as
extragalactic GRBs

1984SvAL...10..177B

Exploding neutron stars in close binaries

S. I. Blinnikov, I. D. Novikov, T. V. Perevodchikova, and A. G. Polnarev

*Institute of Theoretical and Experimental Physics, Moscow
and Institute for Space Research, USSR Academy of Sciences, Moscow*

(Submitted January 27, 1984)

Pis'ma Astron. Zh. 10, 422–428 (June 1984)

Not my subject today

First messengers of explosions

Neutrino?

First messengers of explosions

Neutrino?



Gravitational waves?

First messengers of explosions

Neutrino?



Gravitational waves?



Radio waves? At least in atmospheric explosions

First messengers of explosions

Neutrino?



Gravitational waves?



Radio waves? At least in atmospheric explosions

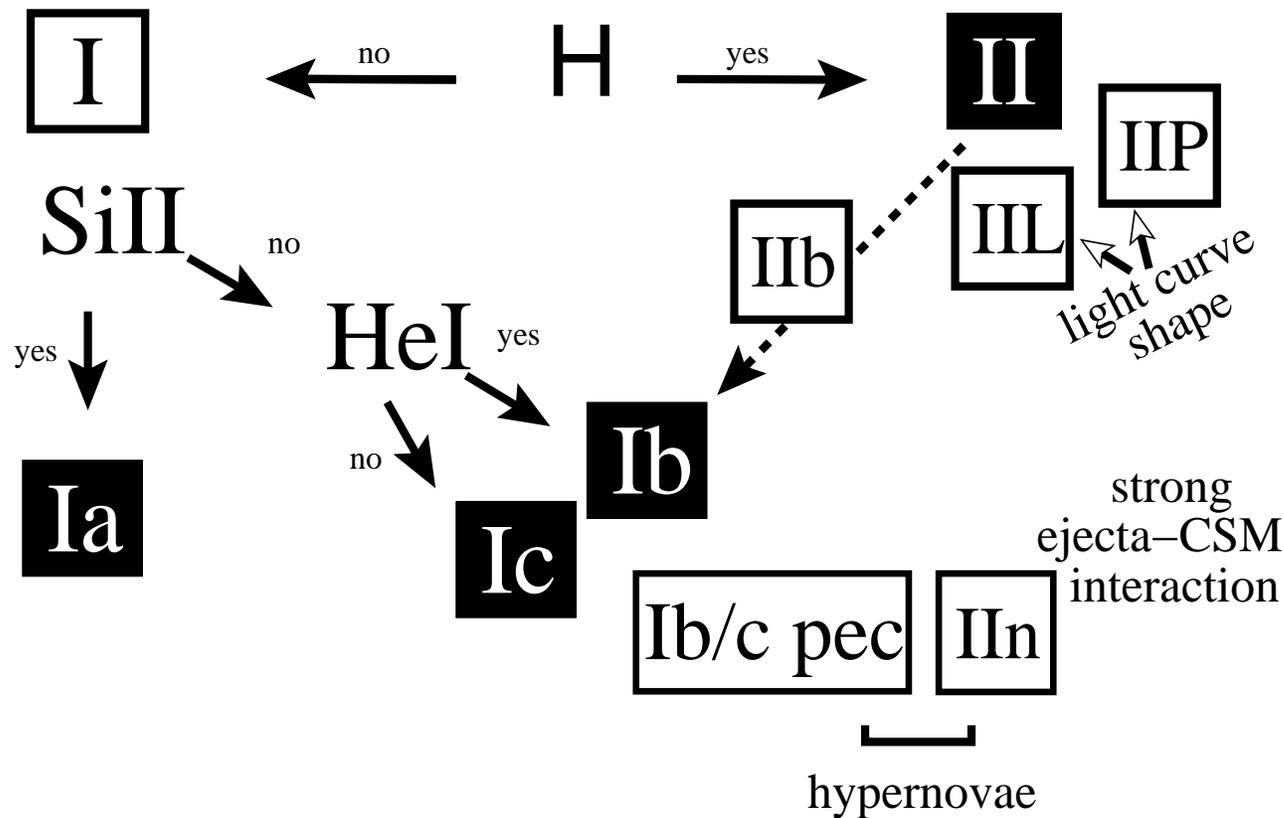


Shock breakout

SN classification

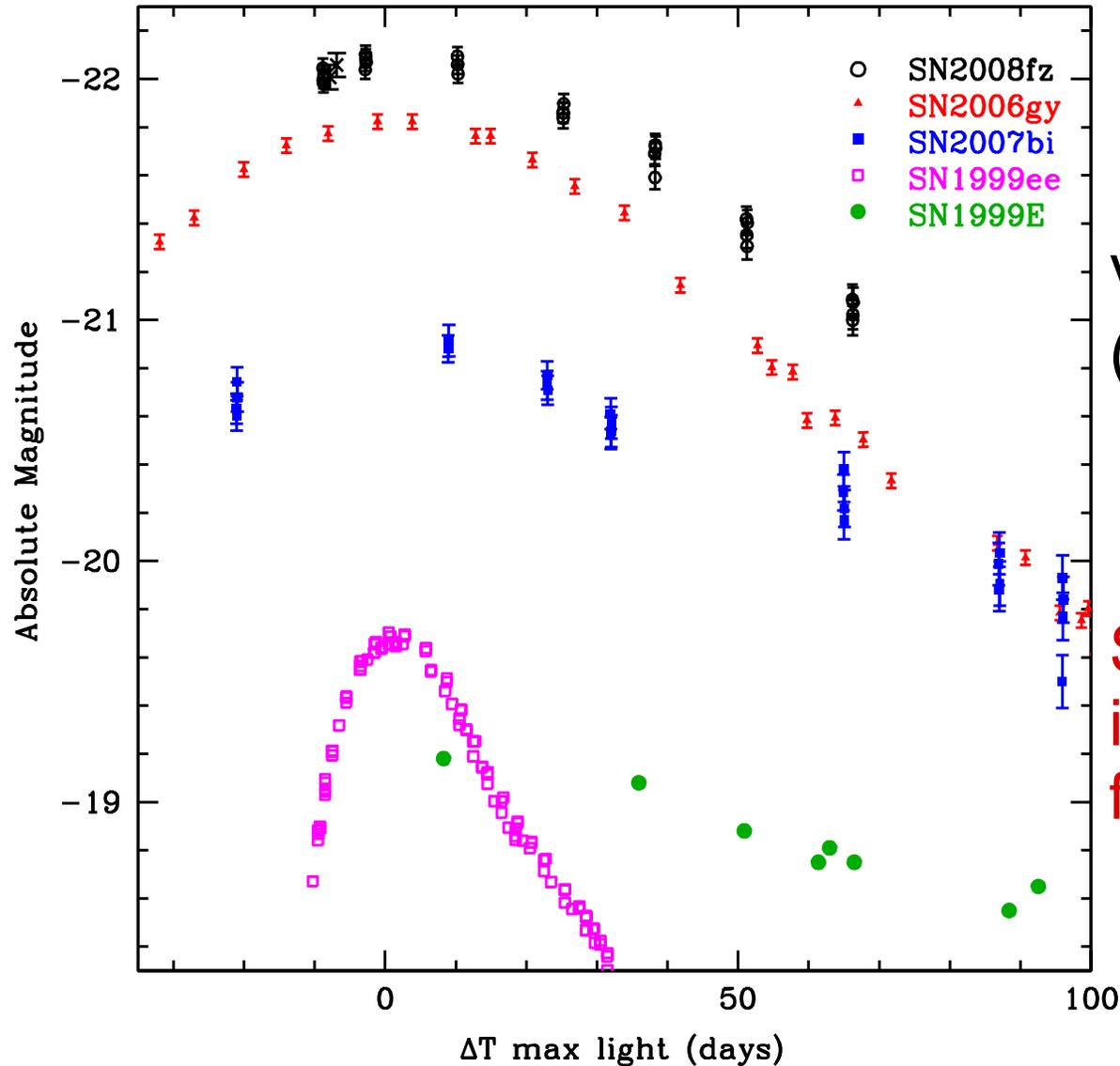
thermonuclear

core collapse



Turrato 2003

Extremely bright Type II In SNe

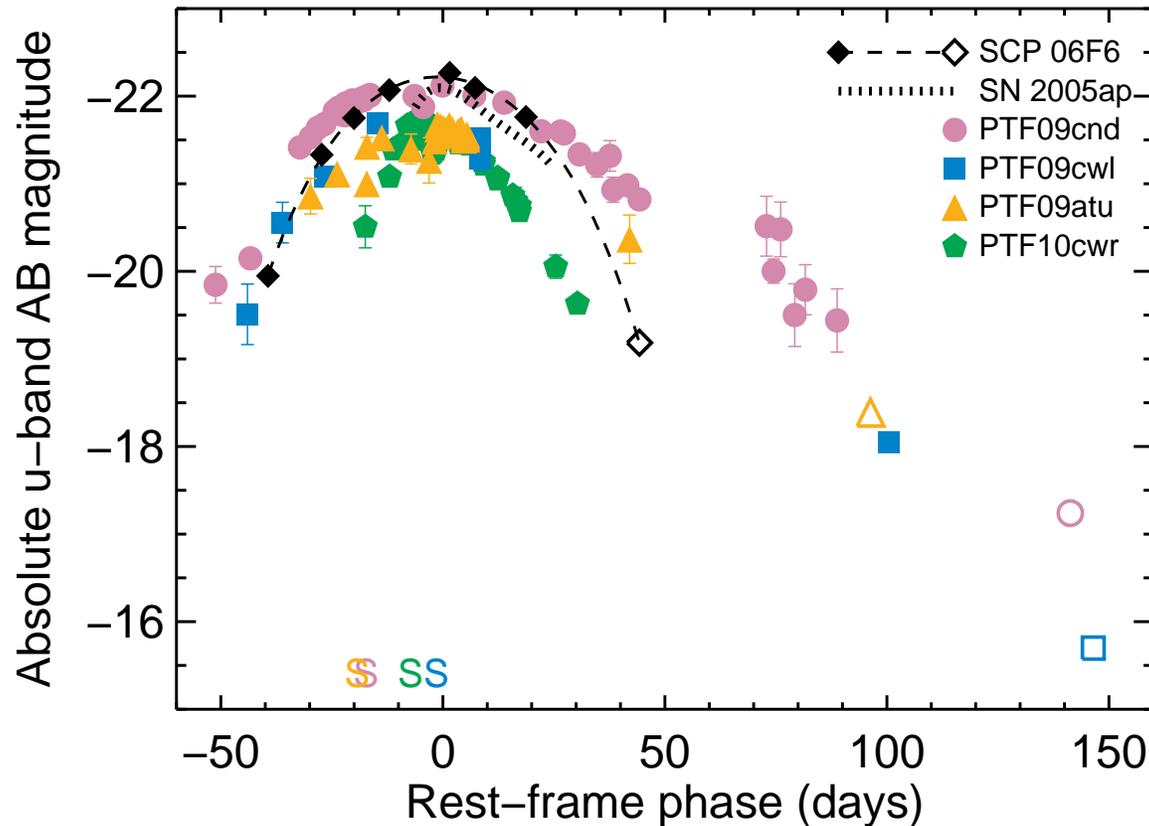


V-band
(Drake et al. 2010)

SN1987A and a typical SNIi below the frame!

H-poor superluminous SNe

Quimby et al. 2011



Still enigmatic. Most probably explained by a long living radiative shock. No better model is suggested

Relation to GRBs & Early Universe

- Some GRBs correlate with SNe (Hypernovae)
- Supeluminous SNe (SLSNe) can be probes of Early Universe (up to $z \sim 20 \div 30$ with JWST)
- Physics of radiating shocks can be studied in detail and may have relevance to the physics of GRBs and their afterglows

Radiative shocks

First, consider shock waves where the accompanying radiation (photons, and/or neutrinos) is trapped in the matter, contrary to SNRs.

see Zeldovich and Raizer (1966) “Physics of Shock Waves and High-Temperature Hydrodynamic Phenomena”

Important papers/books:

R.G.Sachs 1946

Ya.B.Zeldovich 1957, Yu.P.Raizer 1957

R.E.Marshak 1958

F.A.Baum, S.A.Kaplan, K.P.Stanjukovich 1958

H.K.Sen, A.W.Guess 1958

T.Kogure, T.Osaki 1961, N.Ohyama 1963

V.S.Imshennik, Yu.Morozov 1962 – 1975, also a book 1981

I.A.Klimishin+ 1959 – ... also a book 1984

S.Narita 1973, T.A.Weaver 1976

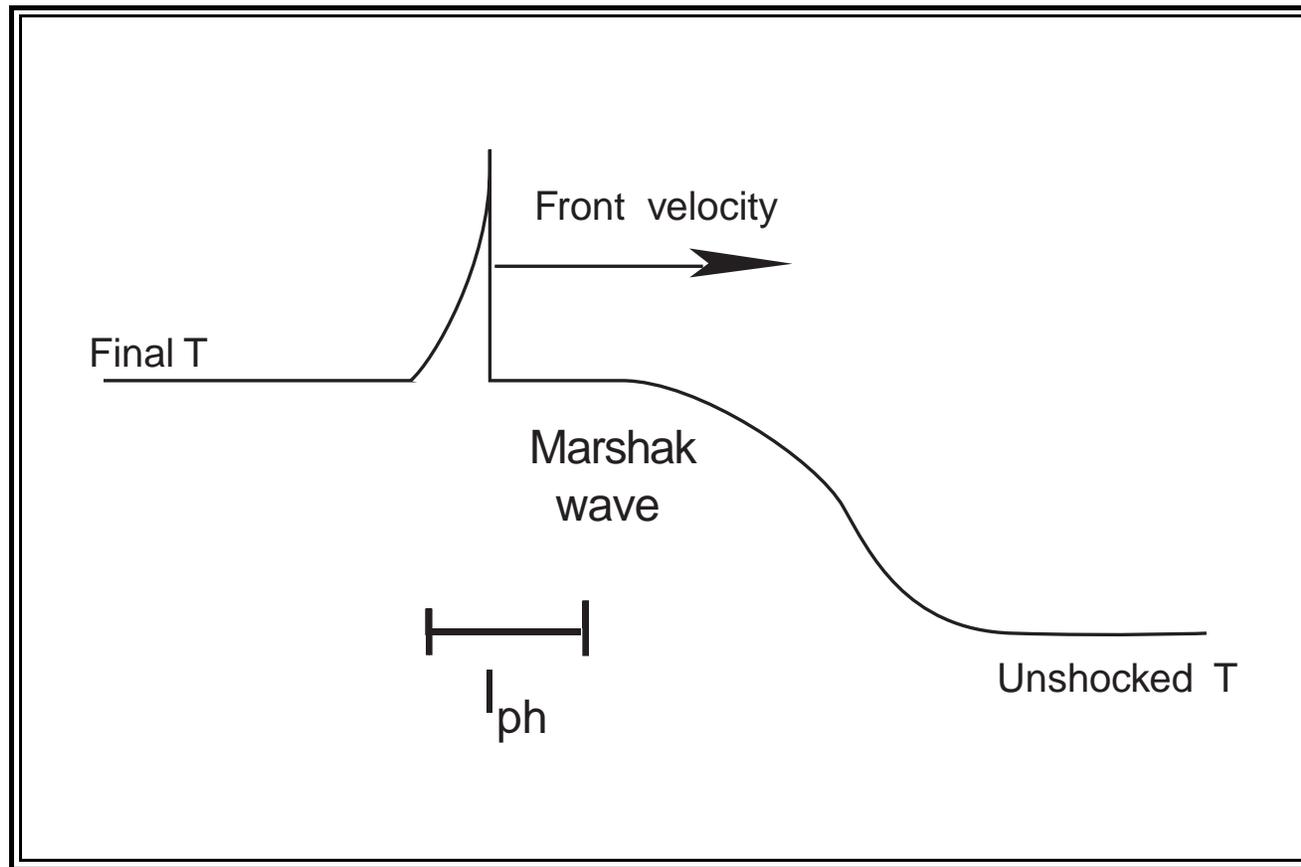
Zeldovich shock classification

Radiative shock waves are divided into four classes in order of increasing strength:

- 1) Subcritical Shocks
- 2) Critical Shocks
- 3) Supercritical Shocks
- 4) Radiation Dominated Shocks

Supercritical Shock Waves

The principal transport of energy is carried out by radiation through the leading Marshak wave. Almost all of the compression occurs as matter crosses the shock front.



Radiation Dominated Shocks

In extremely strong shocks the radiation pressure and energy density exceed the kinetic pressure and energy of the gas. At this point we basically have a shock in a photon gas and the photon gas (with $\gamma = 4/3$) dominates the situation.

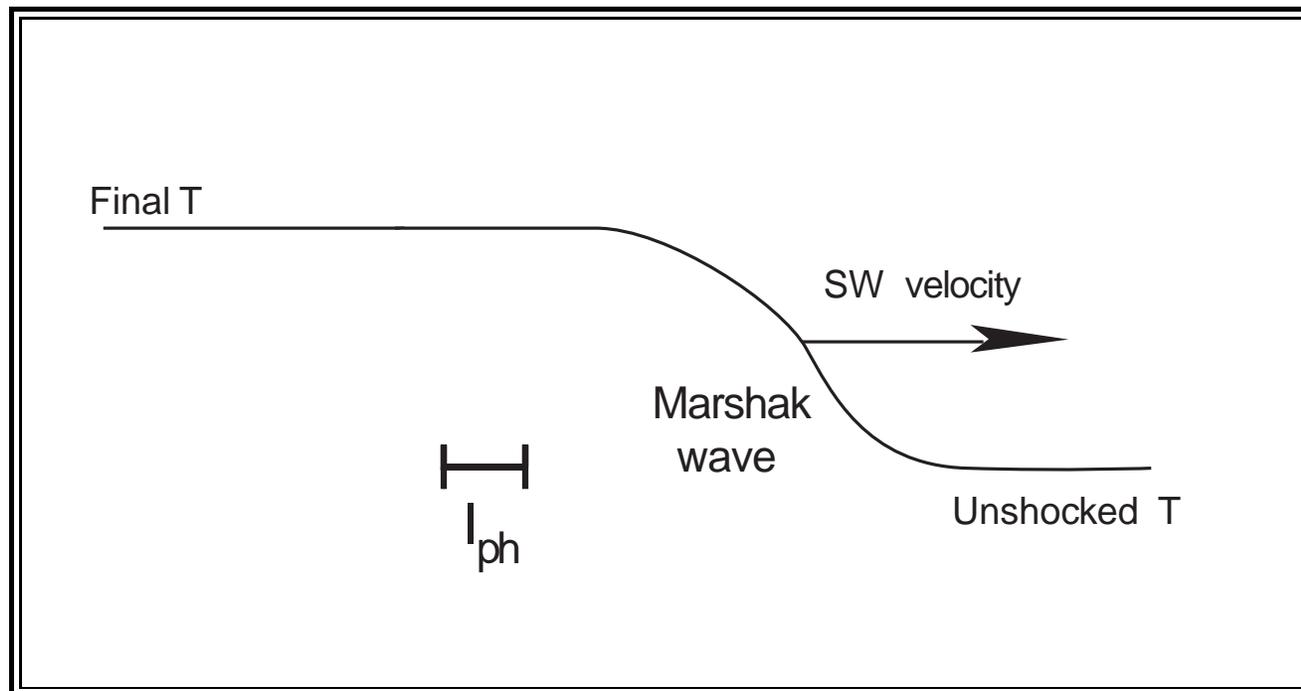
The maximum shock compression is thus:

$$\frac{\gamma + 1}{\gamma - 1} = \frac{4/3 + 1}{4/3 - 1} = 7 .$$

But this is true only for an adiabatic shock. For radiative (almost isothermal) shocks the compression may be orders of magnitude higher

Viscous jump disappears

In **radiation dominated shocks** the preheating effect becomes so large that one of the most typical features of classical shock waves, namely, the **viscous jump** in pressure and density at the hydrodynamic shock front – diminishes and completely **disappears** in a sufficiently strong shock.



No jump for large P_r/P_g

In the equilibrium diffusion approximation the jump disappears when the ratio between radiation pressure and gas pressure is $P_r/P_g \simeq 4.4$ - (S.Z.Belen'kii – unpublished report, V.A.Belokon' 1959) . **Agrees with Weaver and Chapline.**

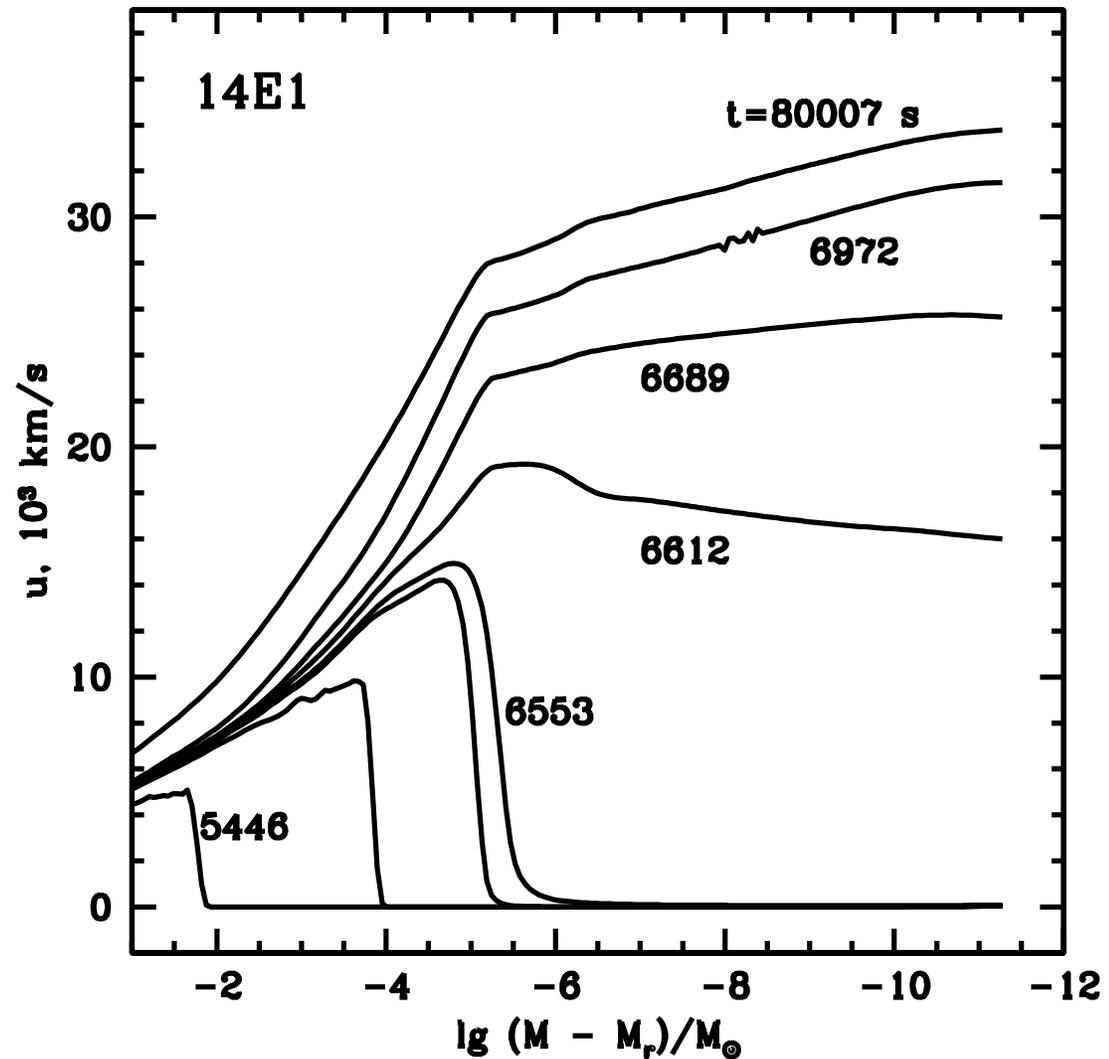
In **radiation dominated shocks** not only the preheating effect is important. The **momentum transfer** from photons to electrons (and hence to ions, via the electric field) is very large. This also destroys the viscous jump in pressure and density at the hydrodynamic shock front.

Imshennik, Morozov (1964) have found with accurate account of photon transfer (**but without account of scattering**) that this happens when $P_r/P_g \simeq 8.5$.

In the shocks with non-thermal relativistic particles, trapped by magnetic field (cosmic rays) a similar transition is possible - the viscous jump can disappear and the shock is mediated then by cosmic rays (see, e.g. Malkov & Drury; Bulanov & Sokolov; etc.).

Shocks inside SNe, e.g., SN 1987A

velocity vs
mass from
surface, time
in seconds
is given



Shocks: entropy source for SN II

A shock inside the star remains in **adiabatic phase** while optical depth,

$$\tau \equiv \frac{\delta R}{\ell} > \frac{c}{D},$$

where ℓ is photon mean free path and δR is the distance from the shock to the photosphere (Ohyama N. 1963, also Imshennik V.S., Morozov Yu.I. 1964)

When

$$\tau = \frac{\delta R}{\ell} \lesssim \frac{c}{D},$$

the burst of photon luminosity begins:

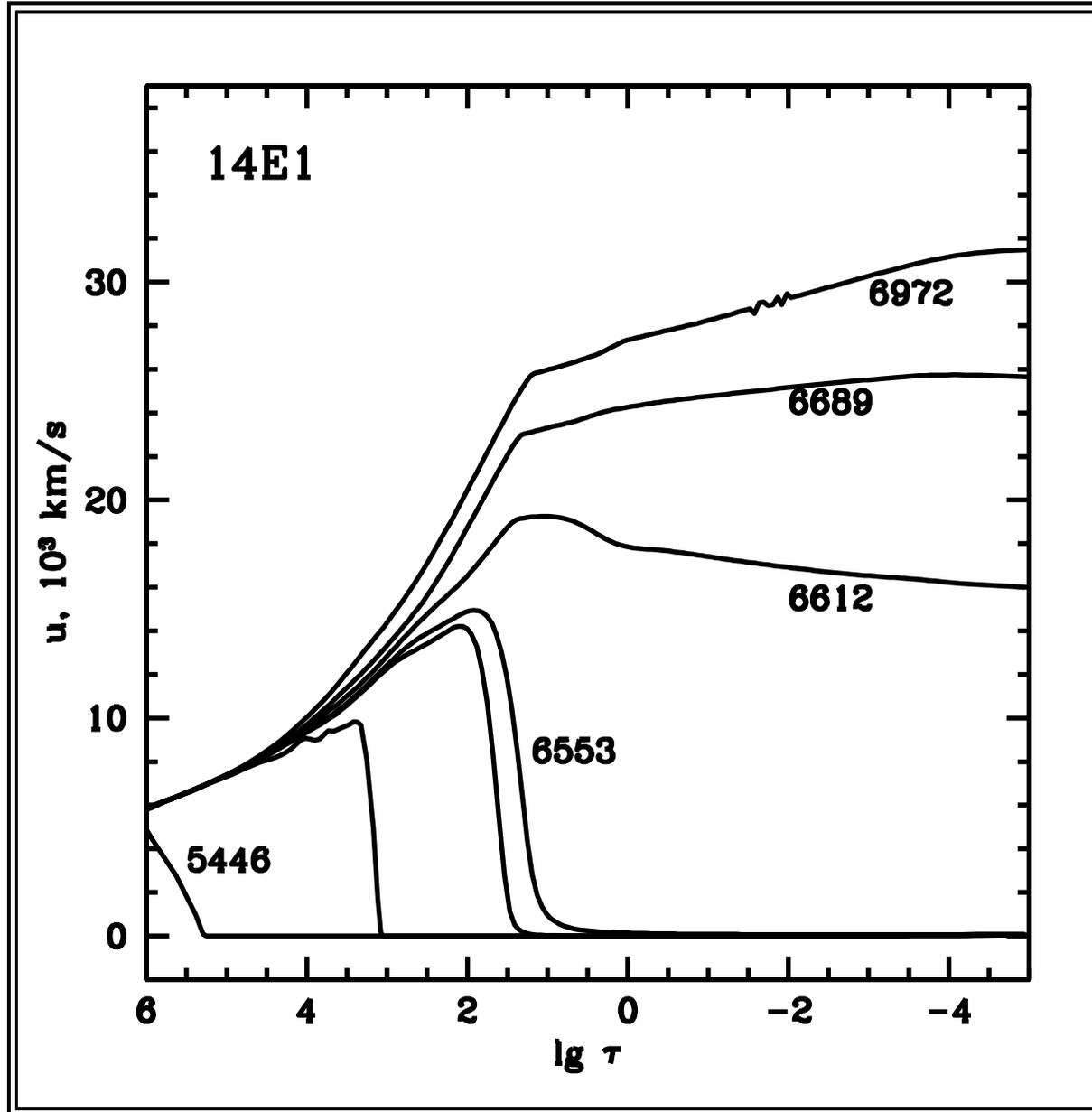
shock break-out .

End of shock acceleration

The termination of the shock acceleration process is clearly observed in computations.

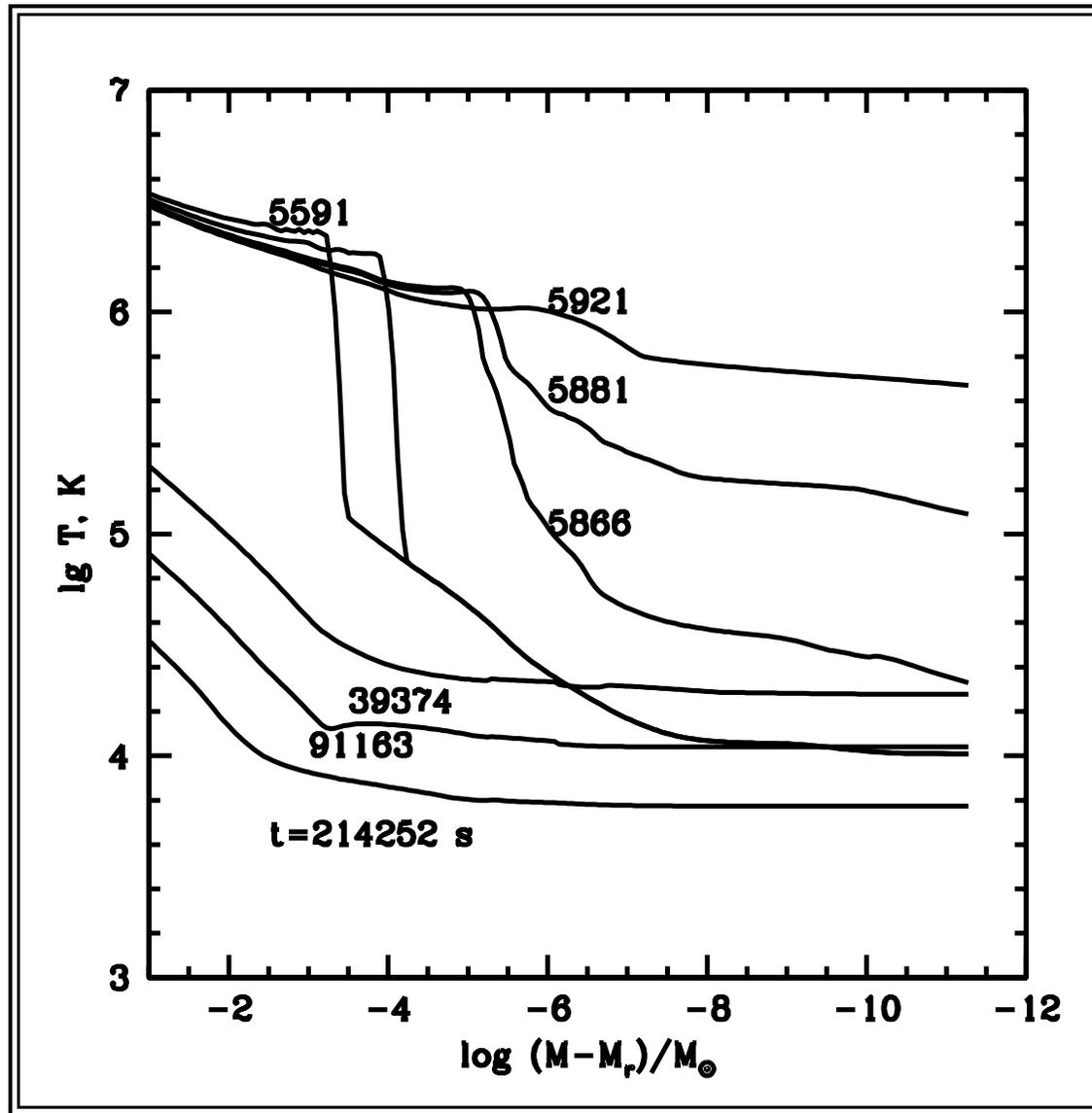
Next figure shows the profiles of **velocity** as a function of **optical depth** τ (Blinnikov 1999). Just at $\tau \sim c/D \sim 10$, as predicted, the photons start 'running-out' from behind the shock front. These photons slightly accelerate the outer layers, however, the cumulation of energy on the small mass is already not efficient due to strong radiative losses.

Velocity – optical depth



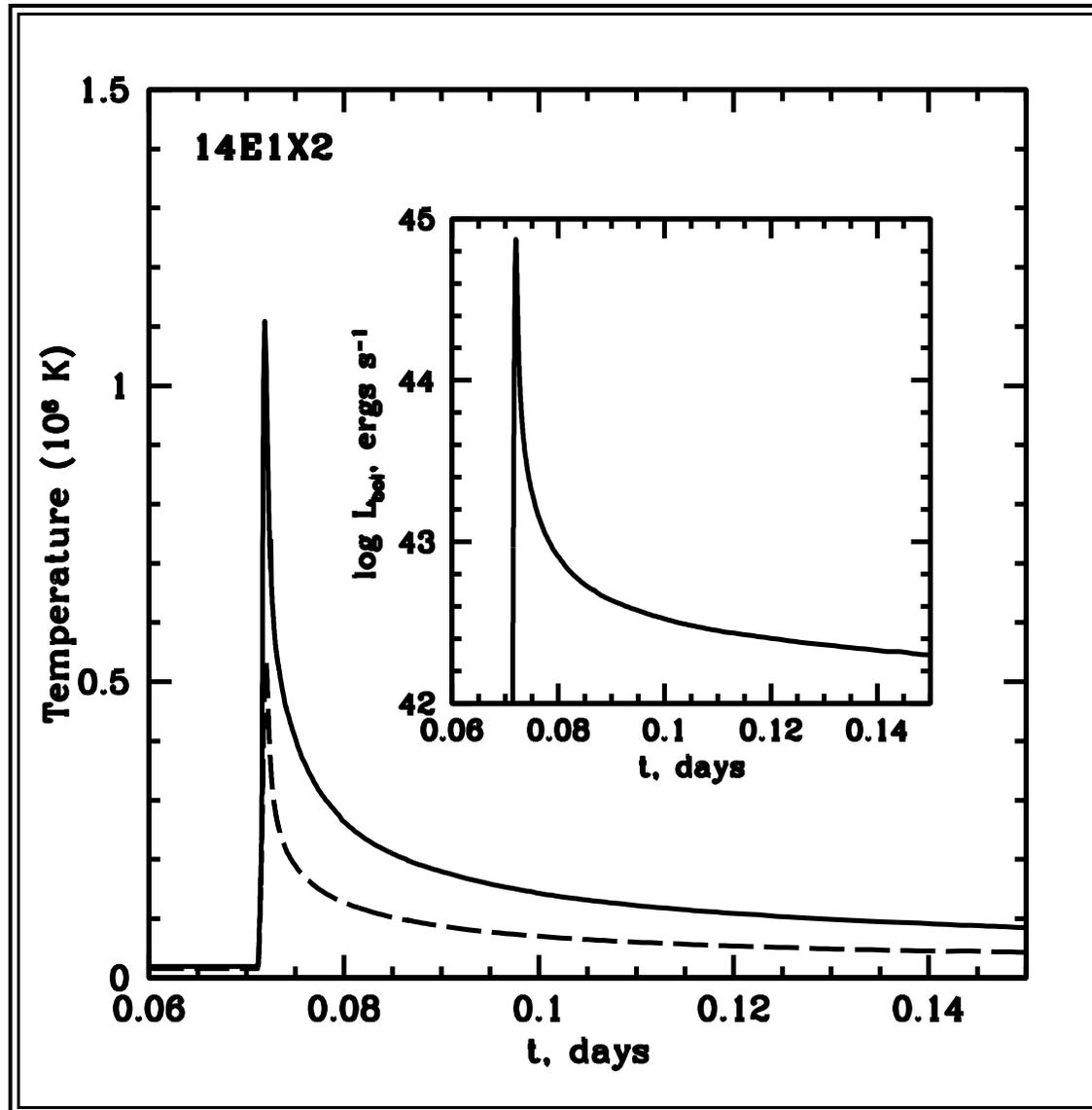
Shock $T(m)$ in SN 1987A

Normal opacity



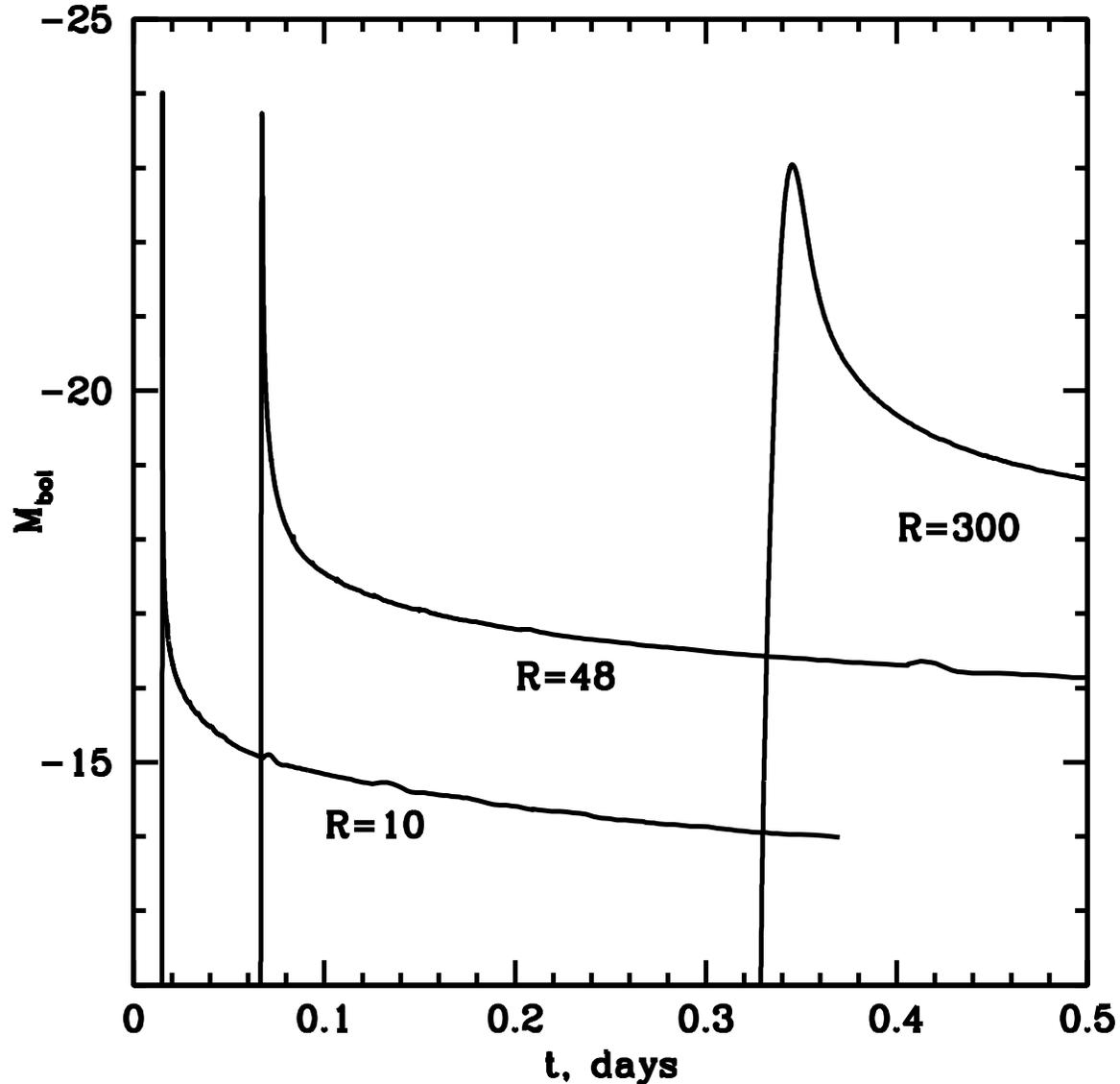
SN87A Luminosity and T_{obs}

$$N_f = 200, \lambda_{\text{min}} = 0.01$$

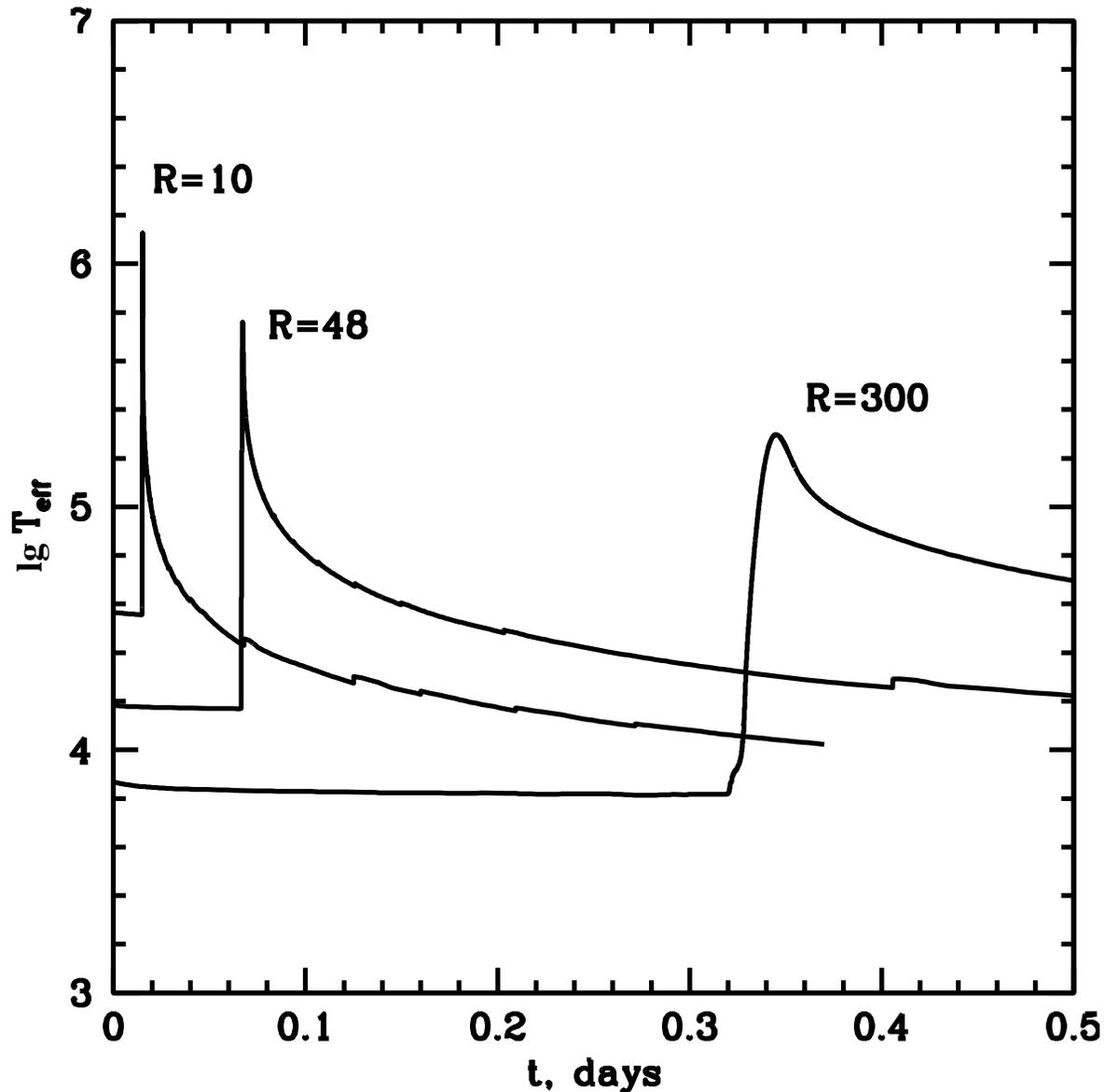


Shock Luminosity in SNe II

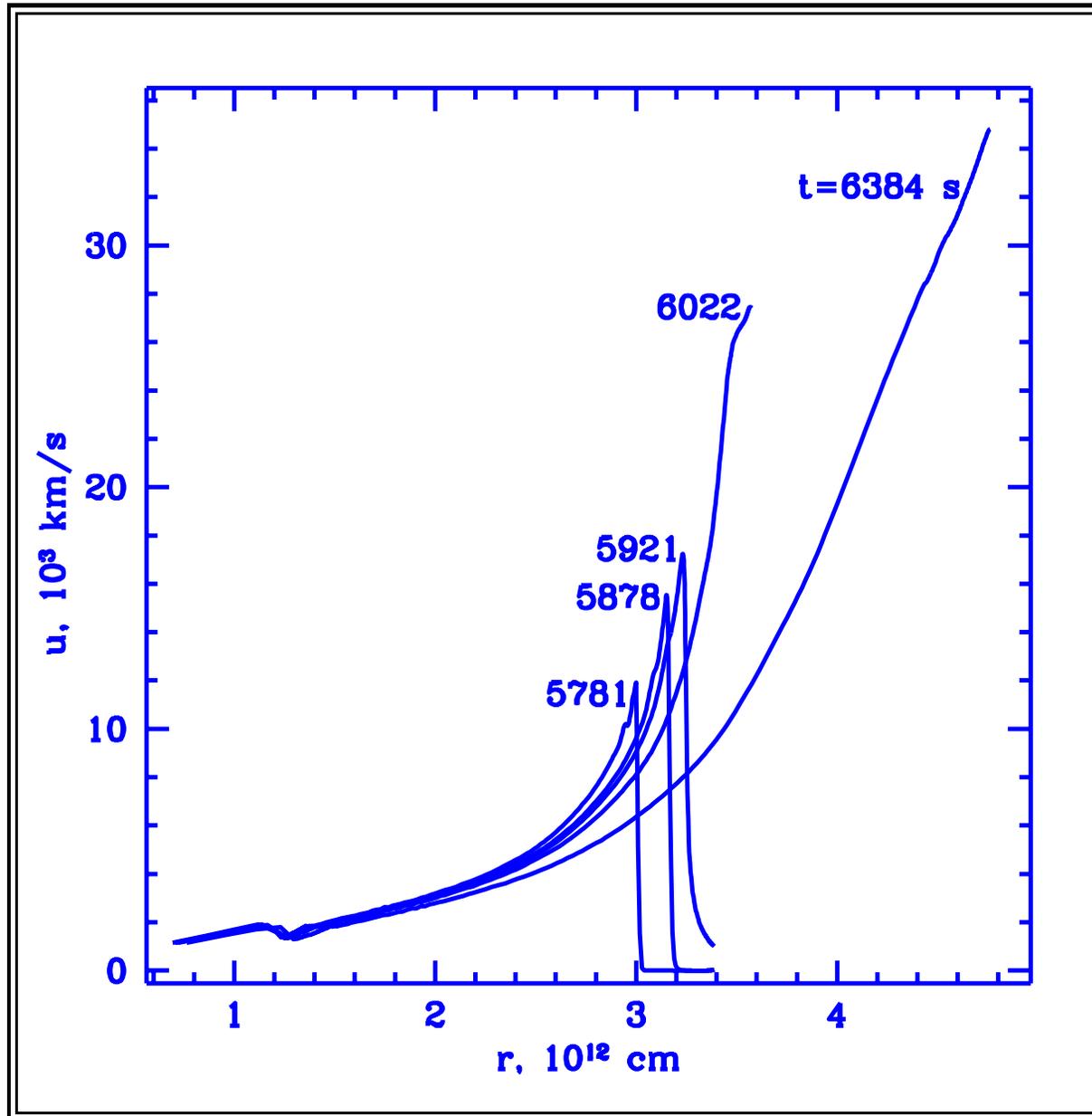
Shocks:
Different
radii at
shock-
breakout
epoch



Effective Temperature in SN II

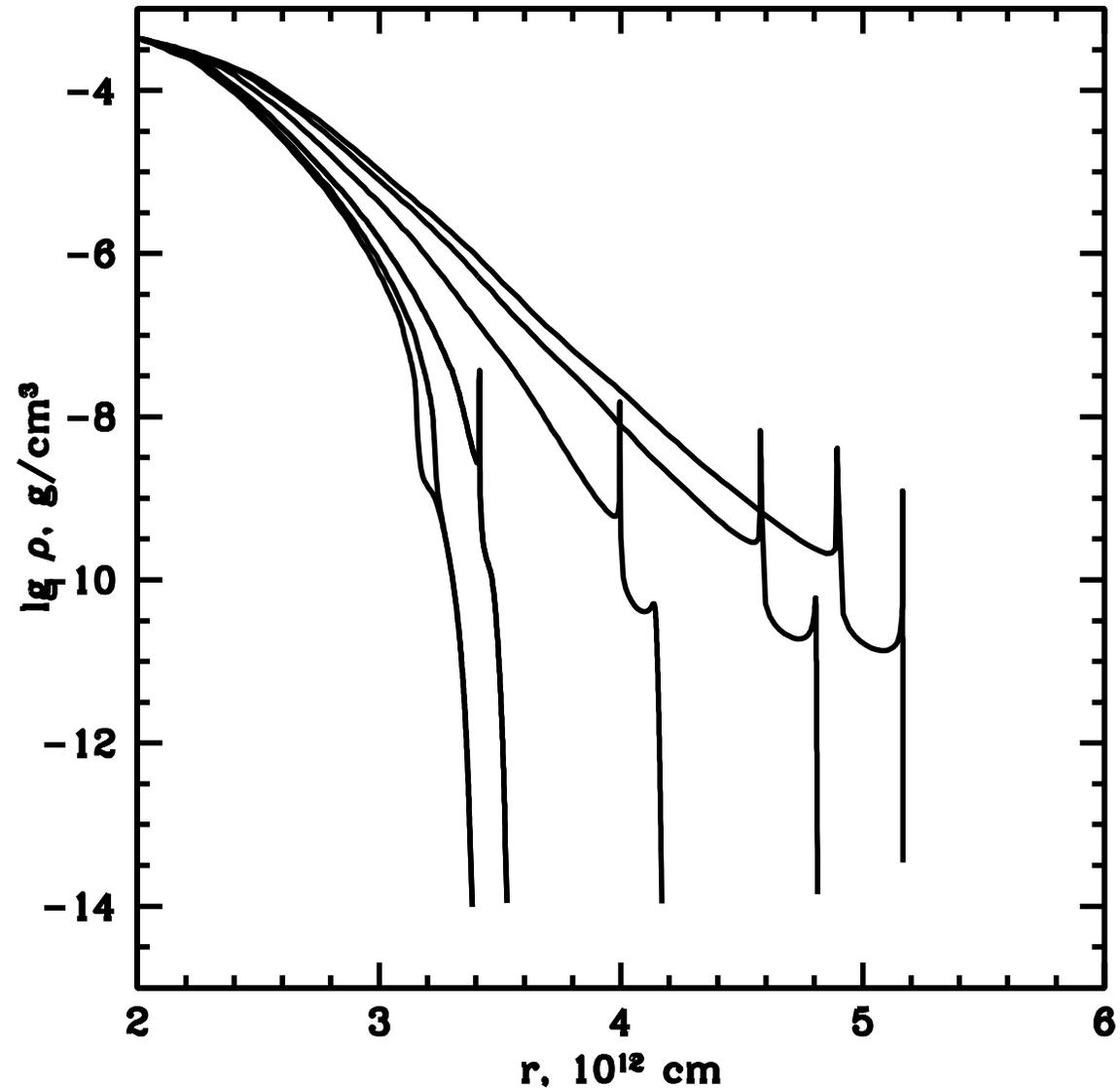


Velocity, Eulerian

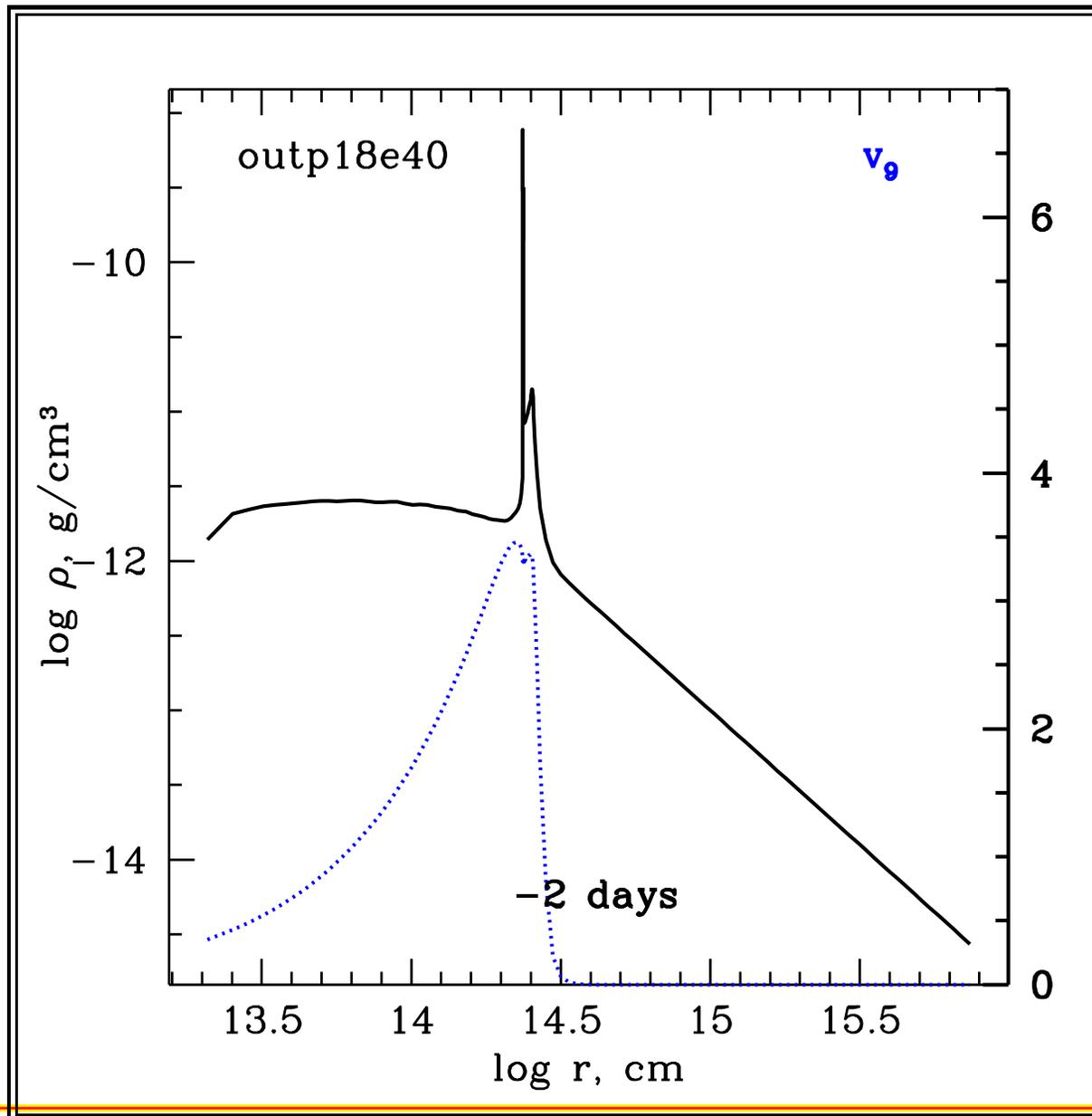


Density as a function of radius

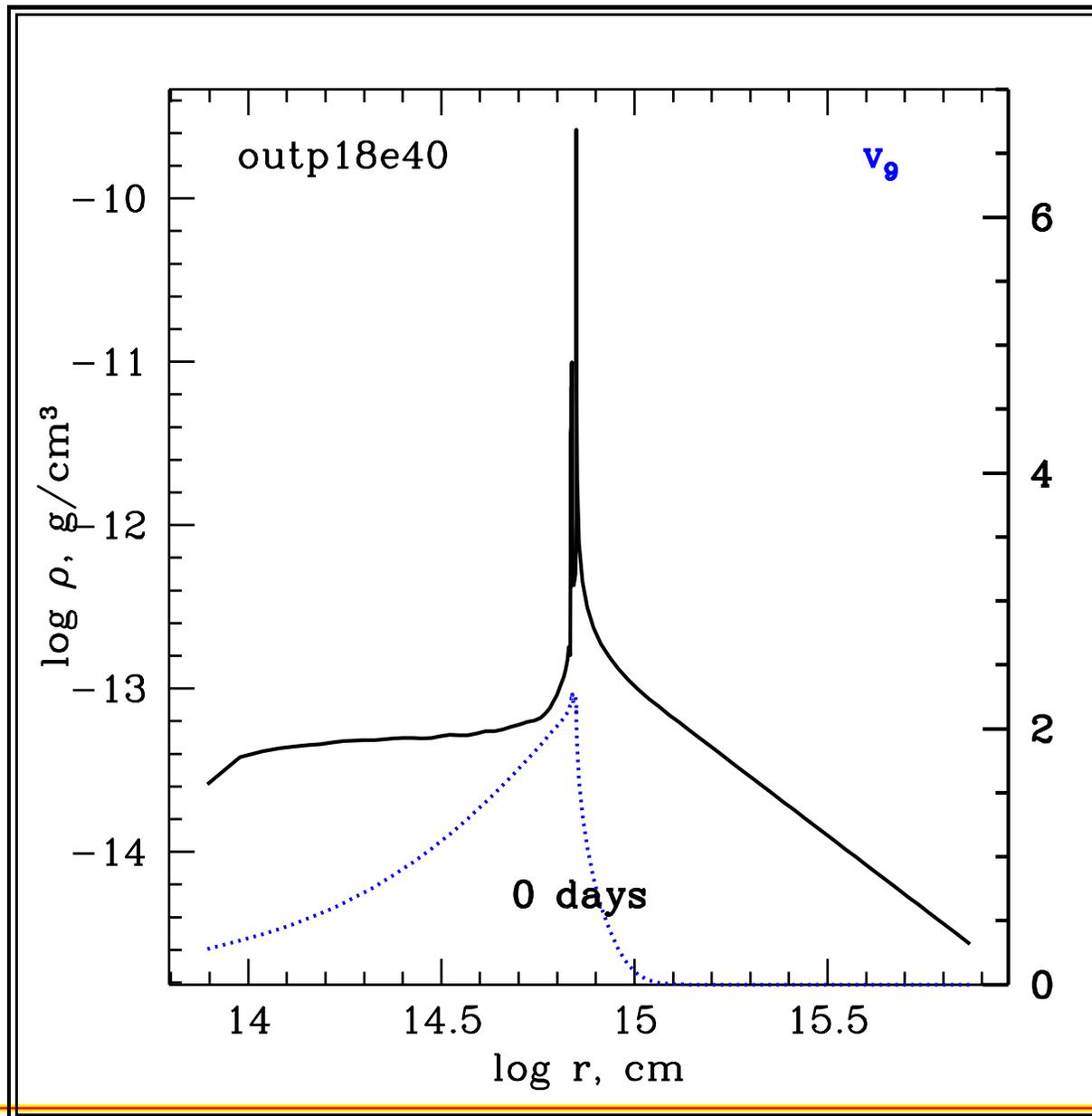
Due to inefficient acceleration a density peak is formed in outer layers.



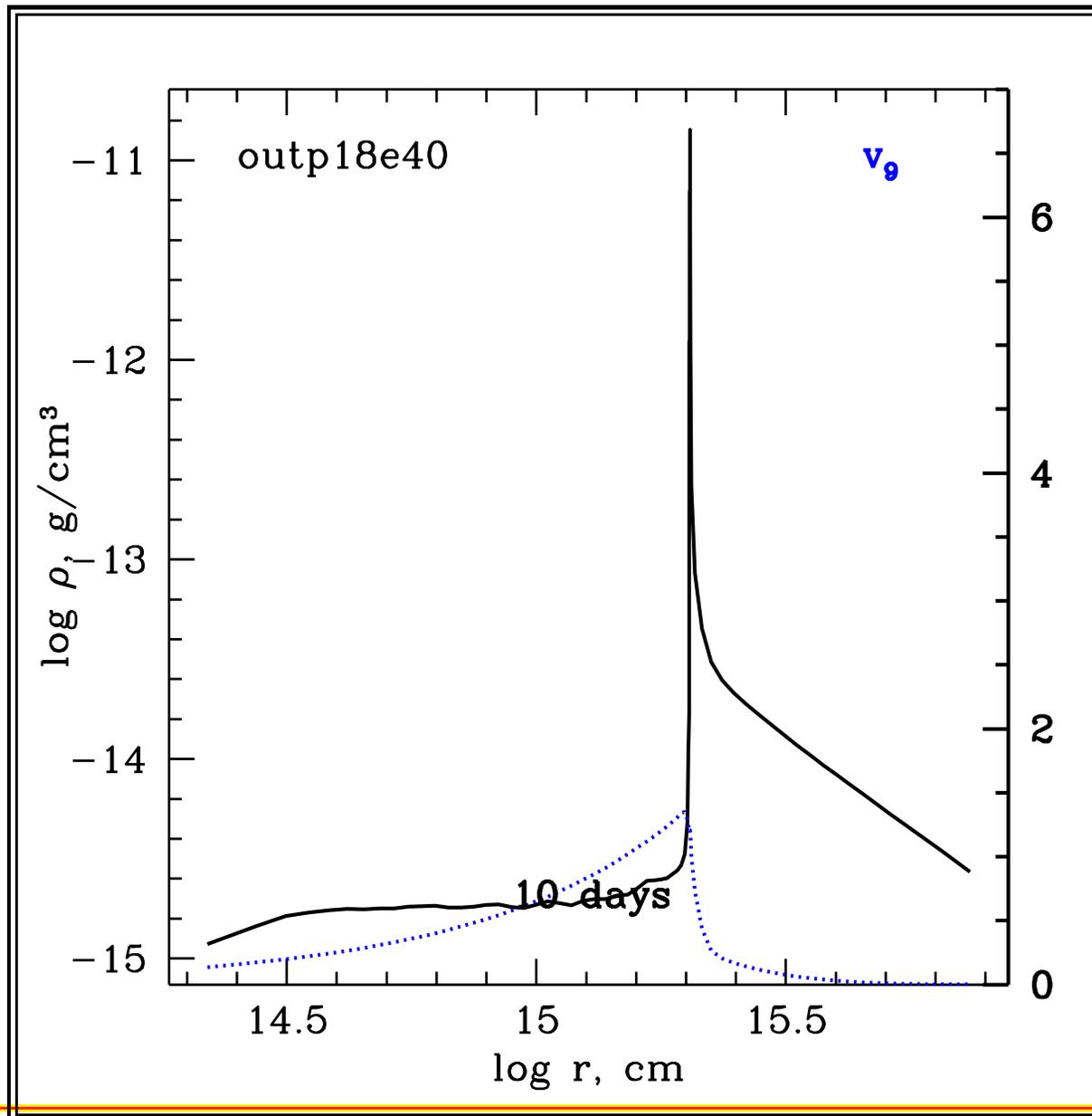
Long Living Dense shells-1



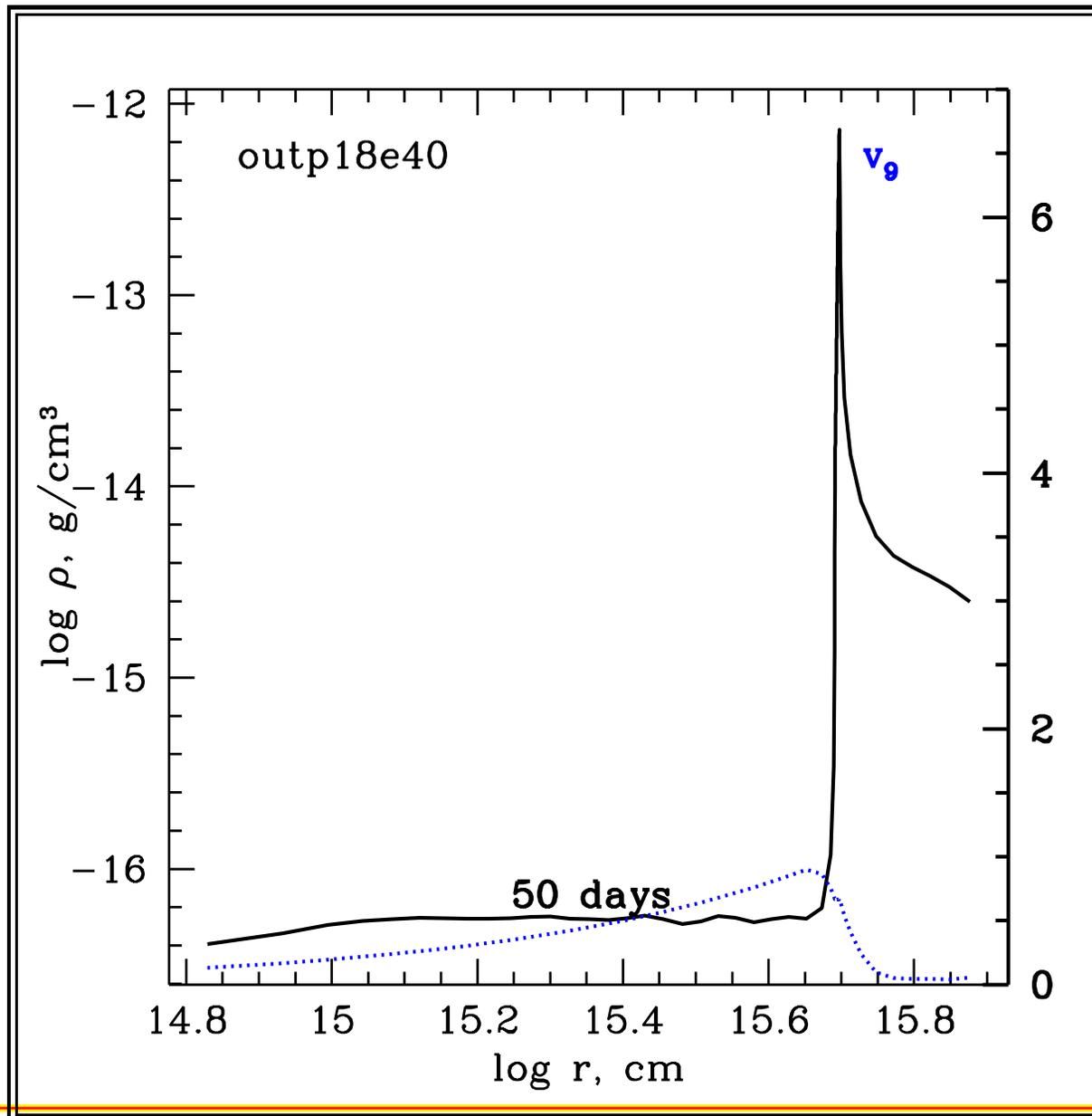
Long Living Dense shells-2



Long Living Dense shells-3



Long Living Dense shells-4



How to compute radiative shocks?

Comoving frame transfer For arbitrary Lorentz-factor γ (with $\beta = u/c$) Eq. (95.9) in (Mihalas & Mihalas 1984):

$$\begin{aligned} & \frac{\gamma}{c}(1 + \beta\mu) \frac{\partial I(\mu, \nu)}{\partial t} + \gamma(\mu + \beta) \frac{\partial I(\mu, \nu)}{\partial r} + \\ & + \gamma(1 - \mu^2) \left[\frac{(1 + \beta\mu)}{r} - \frac{\gamma^2}{c}(1 + \beta\mu) \frac{\partial \beta}{\partial t} - \gamma^2(\mu + \beta) \frac{\partial \beta}{\partial r} \right] \frac{\partial I(\mu, \nu)}{\partial \mu} - \\ & - \gamma \left[\frac{\beta(1 - \mu^2)}{r} + \frac{\gamma^2}{c}(1 + \beta\mu) \frac{\partial \beta}{\partial t} + \gamma^2 \mu(\mu + \beta) \frac{\partial \beta}{\partial r} \right] \nu \frac{\partial I(\mu, \nu)}{\partial \nu} + \\ & + 3\gamma \left[\frac{\beta(1 - \mu^2)}{r} + \frac{\gamma^2 \mu}{c}(1 + \beta\mu) \frac{\partial \beta}{\partial t} + \gamma^2 \mu(\mu + \beta) \frac{\partial \beta}{\partial r} \right] I(\mu, \nu) = \\ & = \eta(\nu) - \chi(\nu)I(\mu, \nu) . \end{aligned} \quad (1)$$

Here η - emission coefficient, χ - extinction coefficient

STELLA vs RADA for SNIB/c

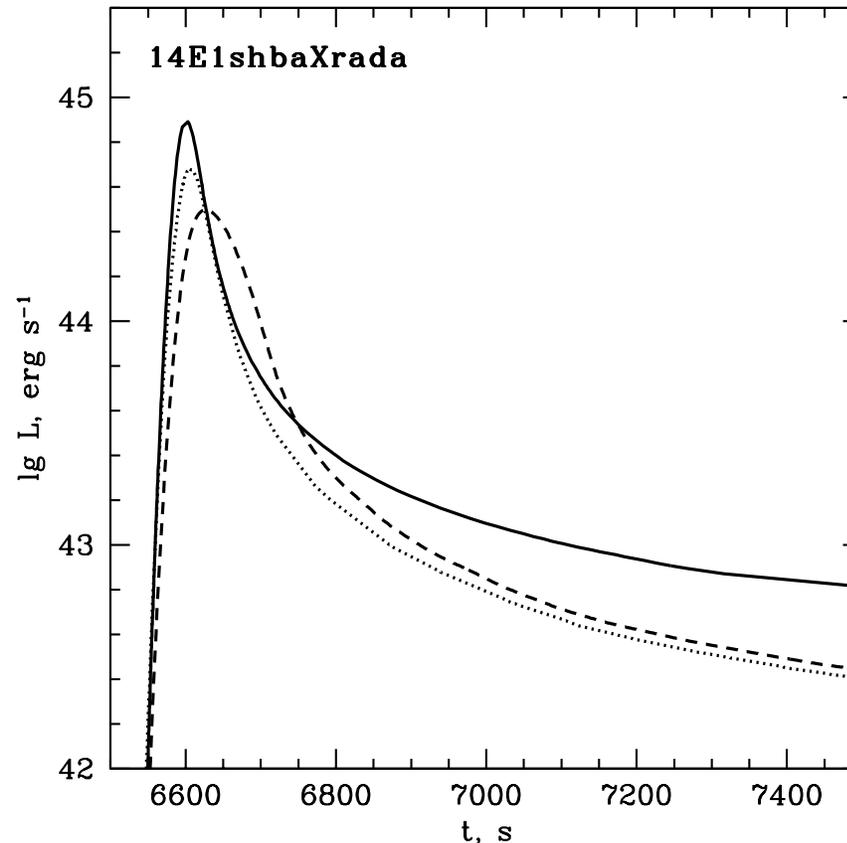
We used two algorithms: STELLA
and RADA

Two radiation hydro codes

Static Eddington-factor Low-velocity Limit Approximation

STELLA (solid) vs RADA (dotted) for SN1987A

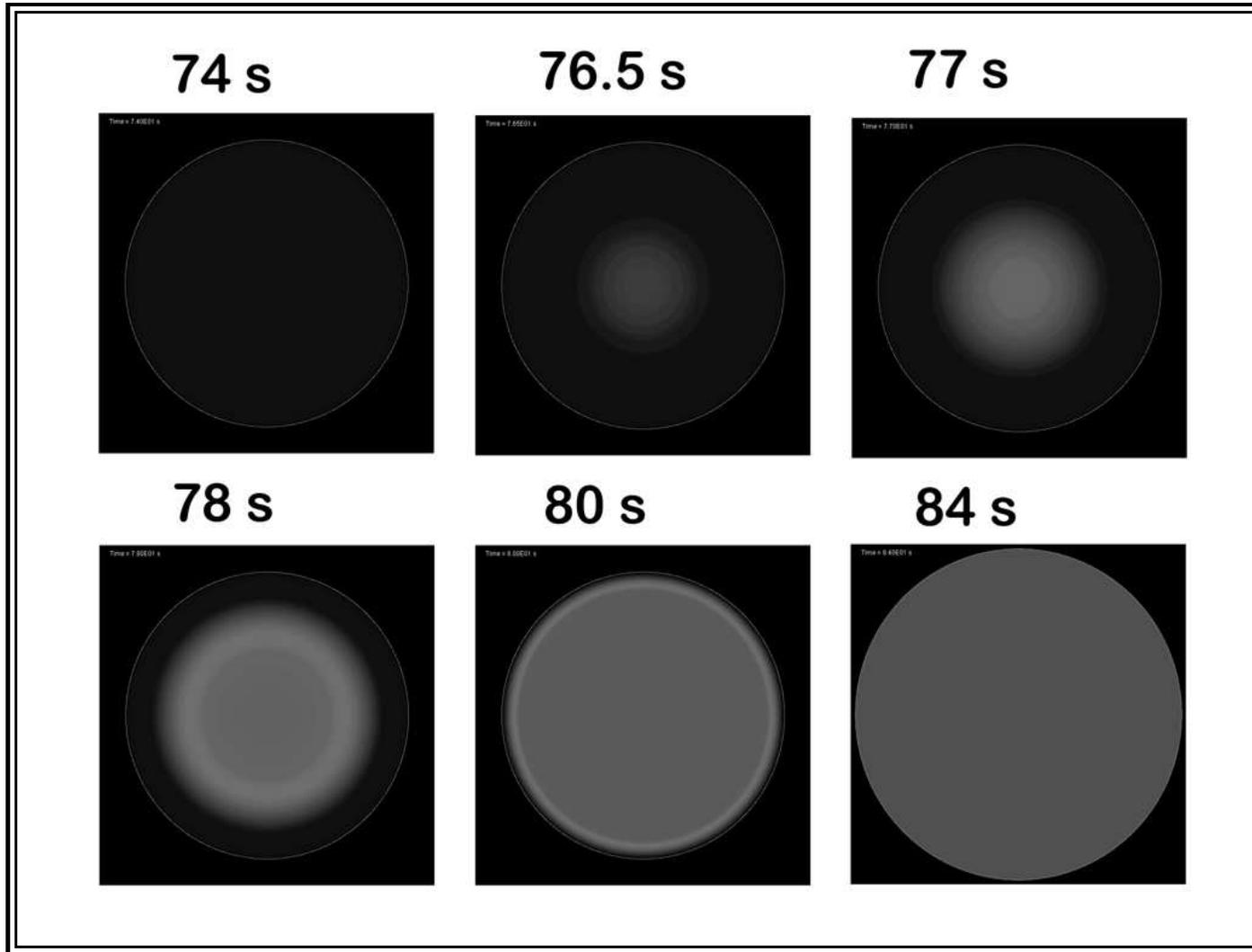
A.Tolstov: RADA – fully Relativistic rADiation transfer Approximation



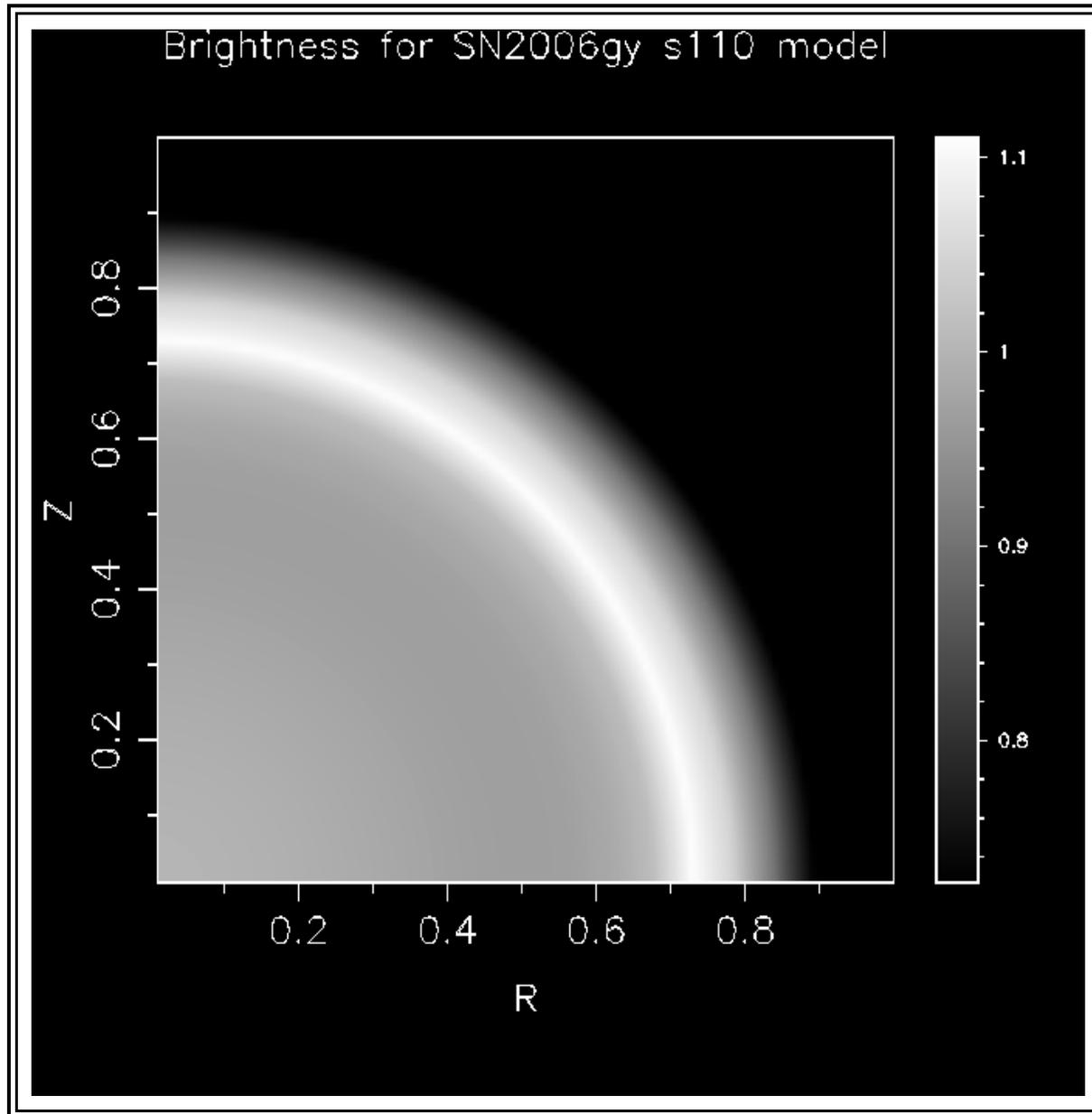
Dashed line represents RADA results in observer's frame with light-travel-time correction.

Flash at I_b shock breakout

Notice rings due to light-travel time delay:



'Visible' disk of SN 2006gy



What is T of matter and radiation?

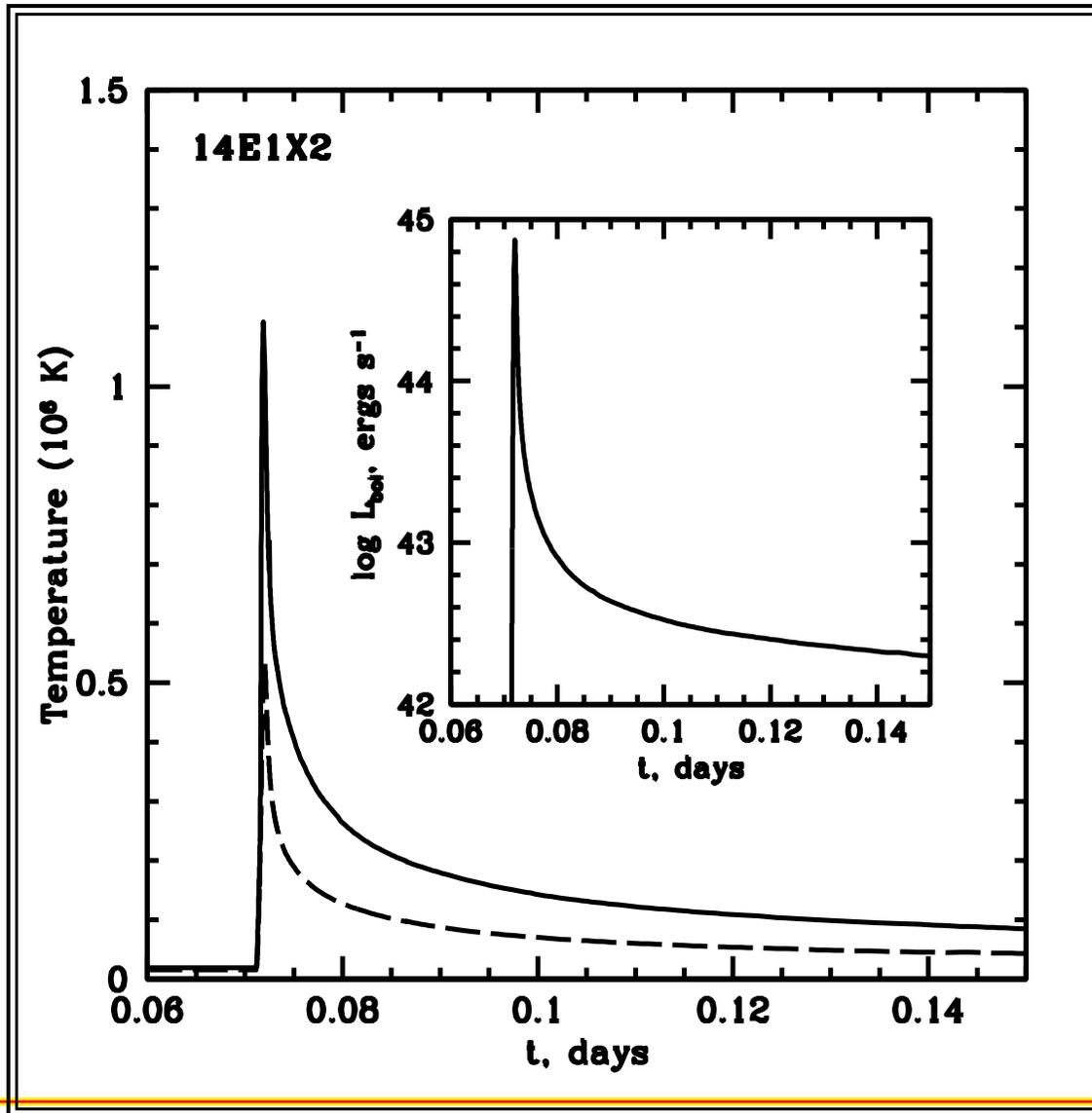
It is a Very Important Question.

Old simulations predicted a very hard X-ray spectrum for large stars like Red Supergiants and SN 1987A at shock-breakout.

We predict (with STELLA and RADA) rather soft spectra. Numerically this was already studied by Weaver (1976) but for higher density. **He never gets those high T shocks.** His work is virtually ignored by the SN community. **He was criticized for assuming equilibrium diffusion, but he had reasons.**

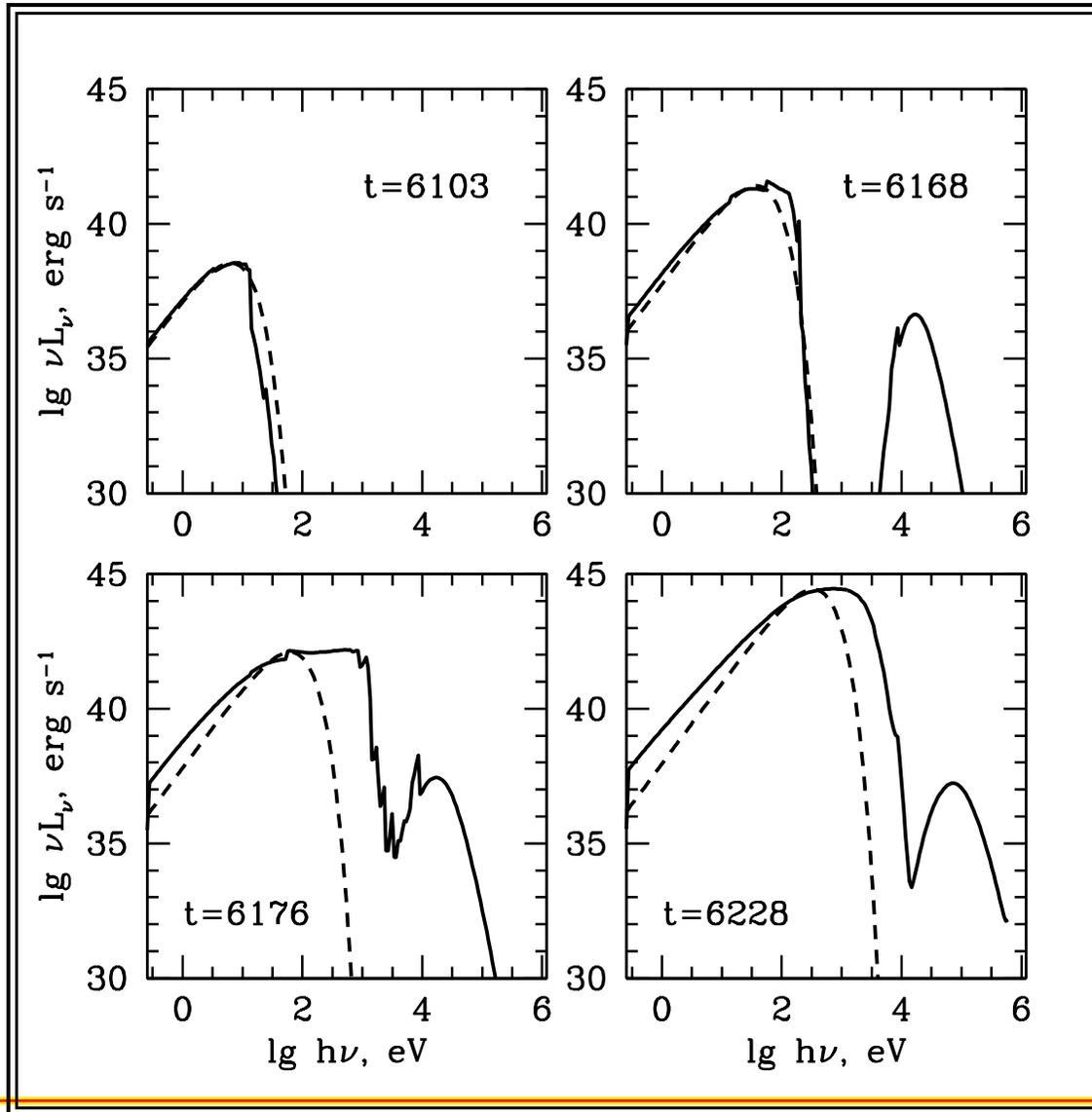
Luminosity and T : "X2" run

$$N_f = 200, \lambda_{\min} = 0.01$$



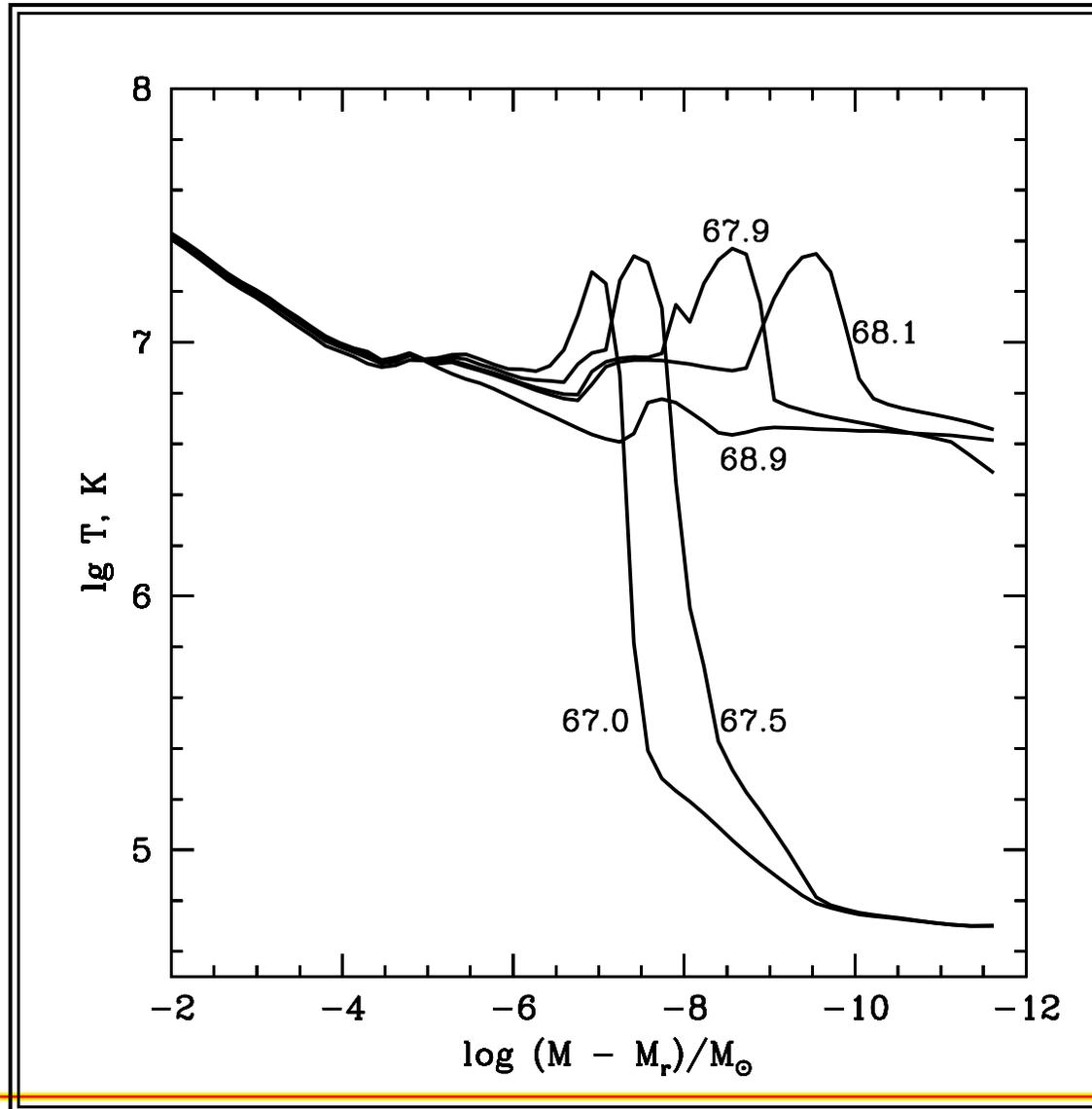
Now spectra νF_ν : "X2" run

$$N_f = 200, \lambda_{\min} = 0.01$$



Weak absorption $\alpha = 10^{-6}\sigma$ changes T

$N_f = 200, \lambda_{\min} = 0.001$; Peak T at $\tau \sim 200, 50, 4, 0.5$



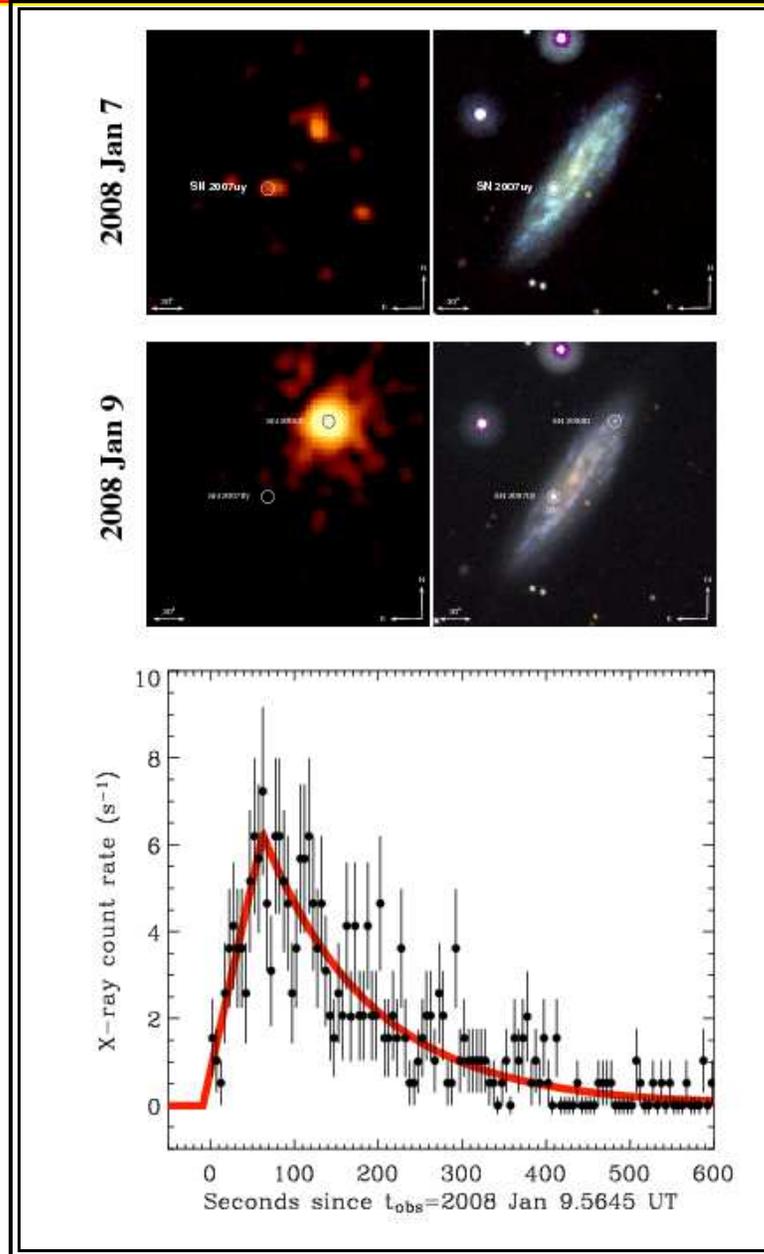
Direct observations of shock-breakouts

SN factory NGC2770

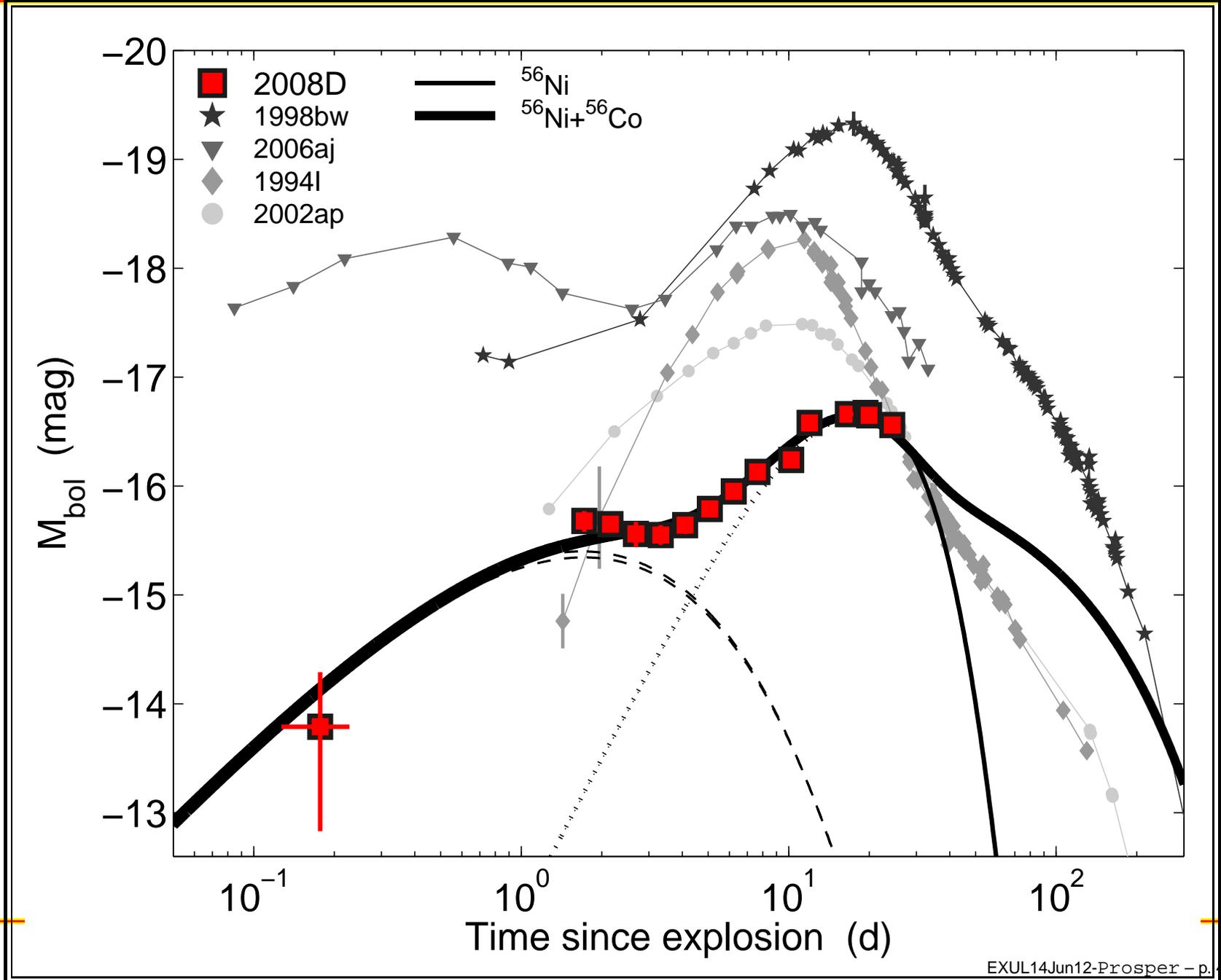
SN2008D shock-breakout caught by A.Soderberg et al.; LC
Modjaz et al. (2008); image 12 Jan 2008



XRT 080109/SN 2008D



SN 2008D and other SNIb/c



XRF080109, no shock breakout?

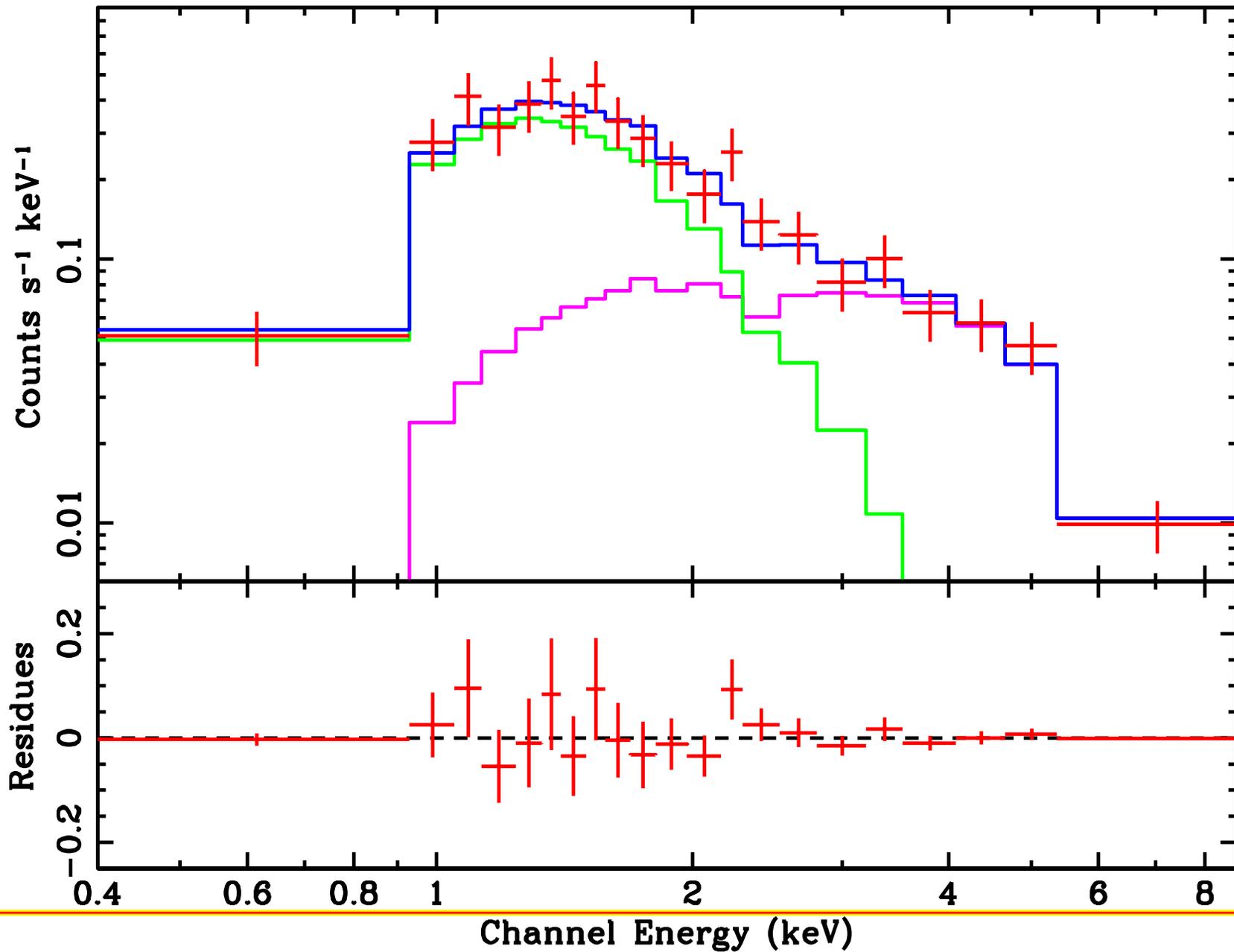
Li-Xin Li MNRAS 388(2008)603

A Two-temperature black-body
spectrum

Claims R_{ph} too small.

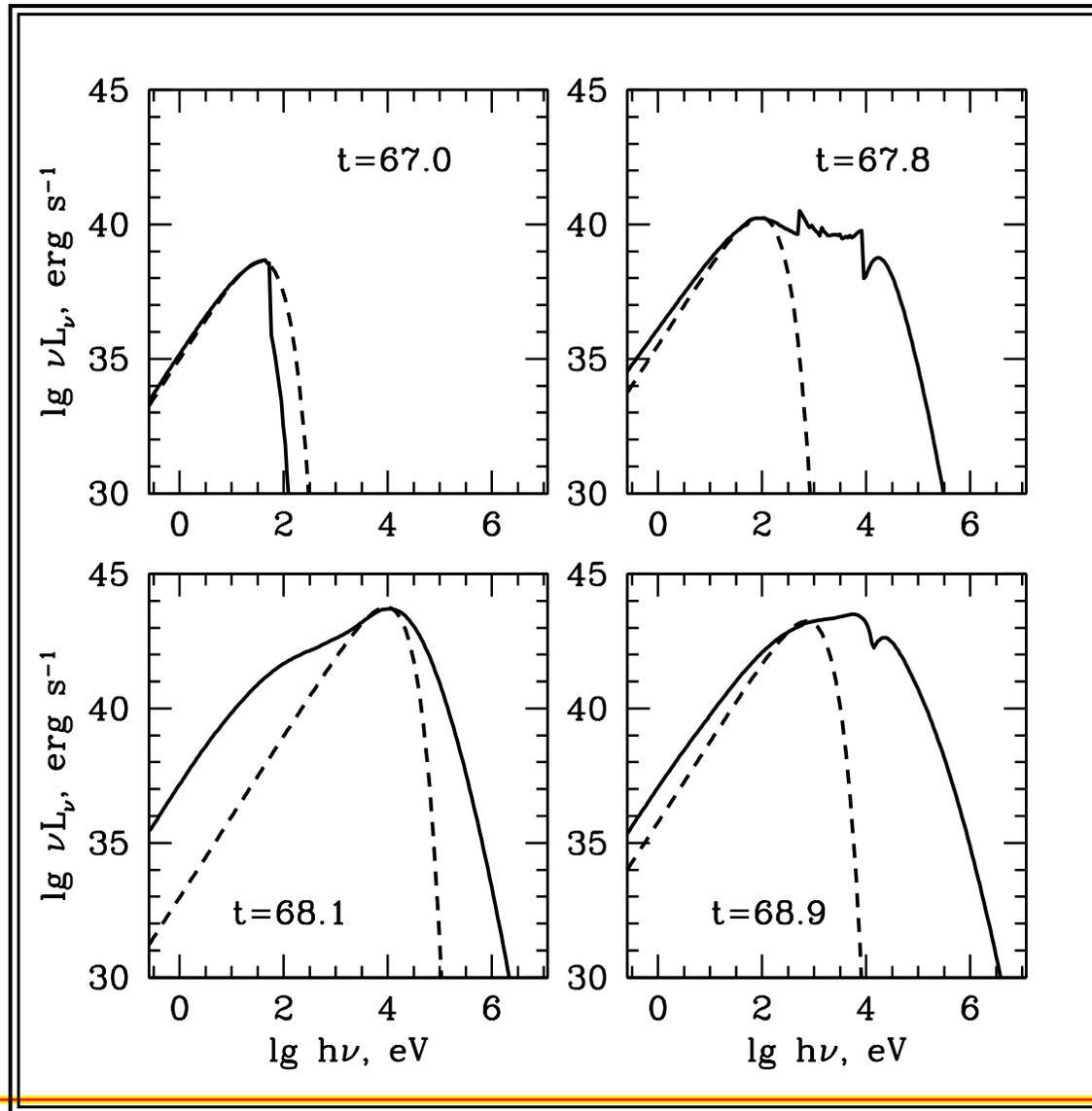
Actually, No Problem!

Two-temperature spectrum



Spectra νF_ν , s1b7a $\alpha = 10^{-6} \sigma$ run

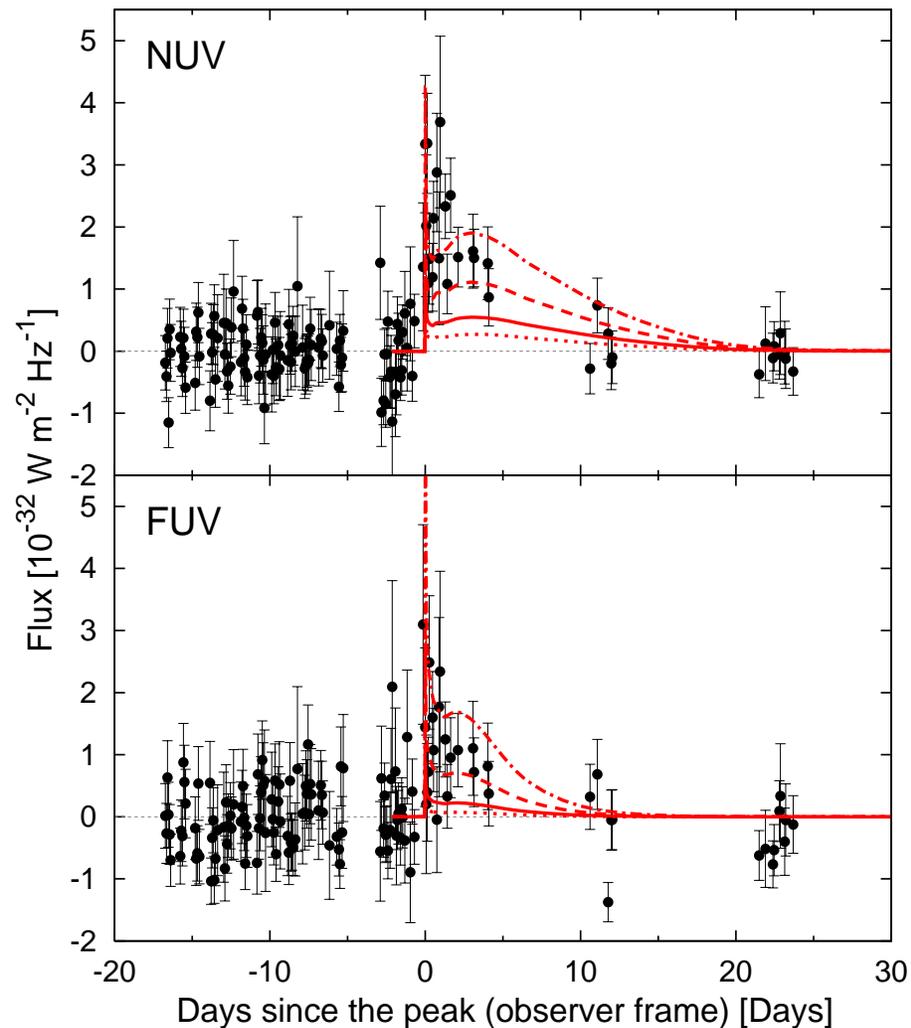
$$N_f = 200, \lambda_{\min} = 0.001$$



SN II shocks observed

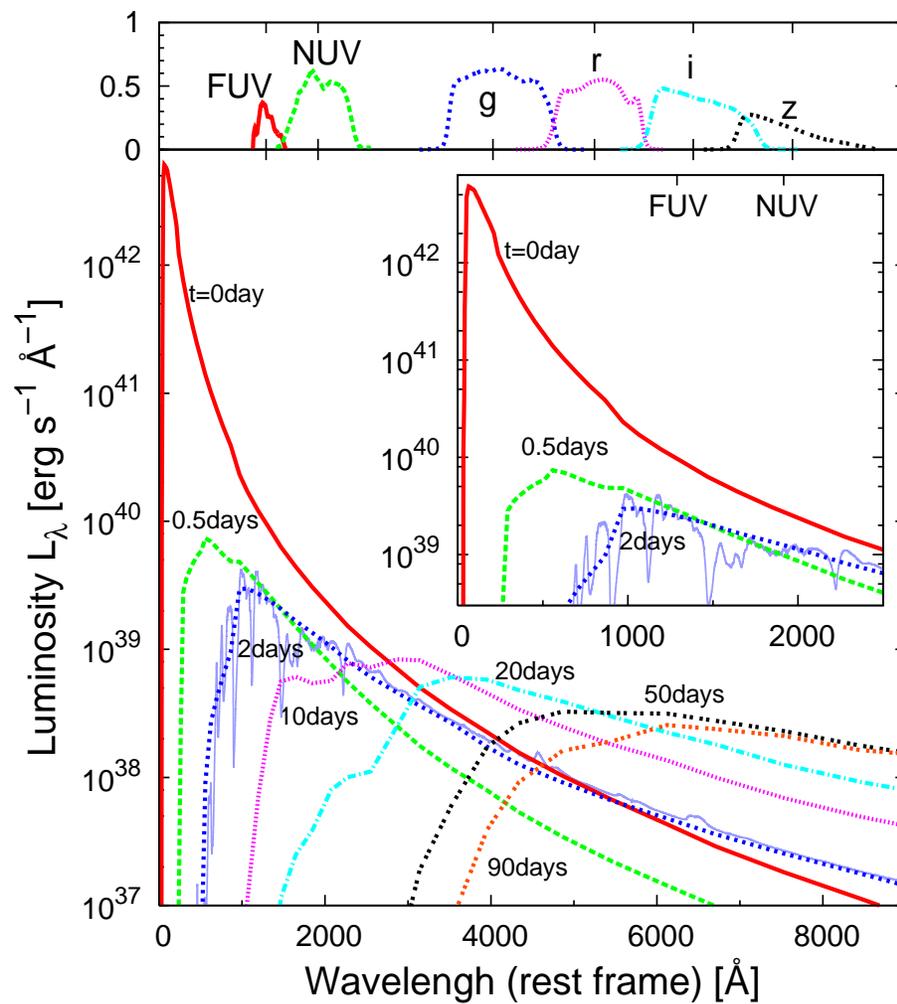
Observations Gezari ea'08, Schawinski ea'08, simulations Tominaga ea'09

Observed flash and STELLA



SN II shock spectrum

Observed spectrum and STELLA



Circumstellar matter

The main puzzle for XRF080109-SN2008D is its long duration (for a compact preSN Ib/c).

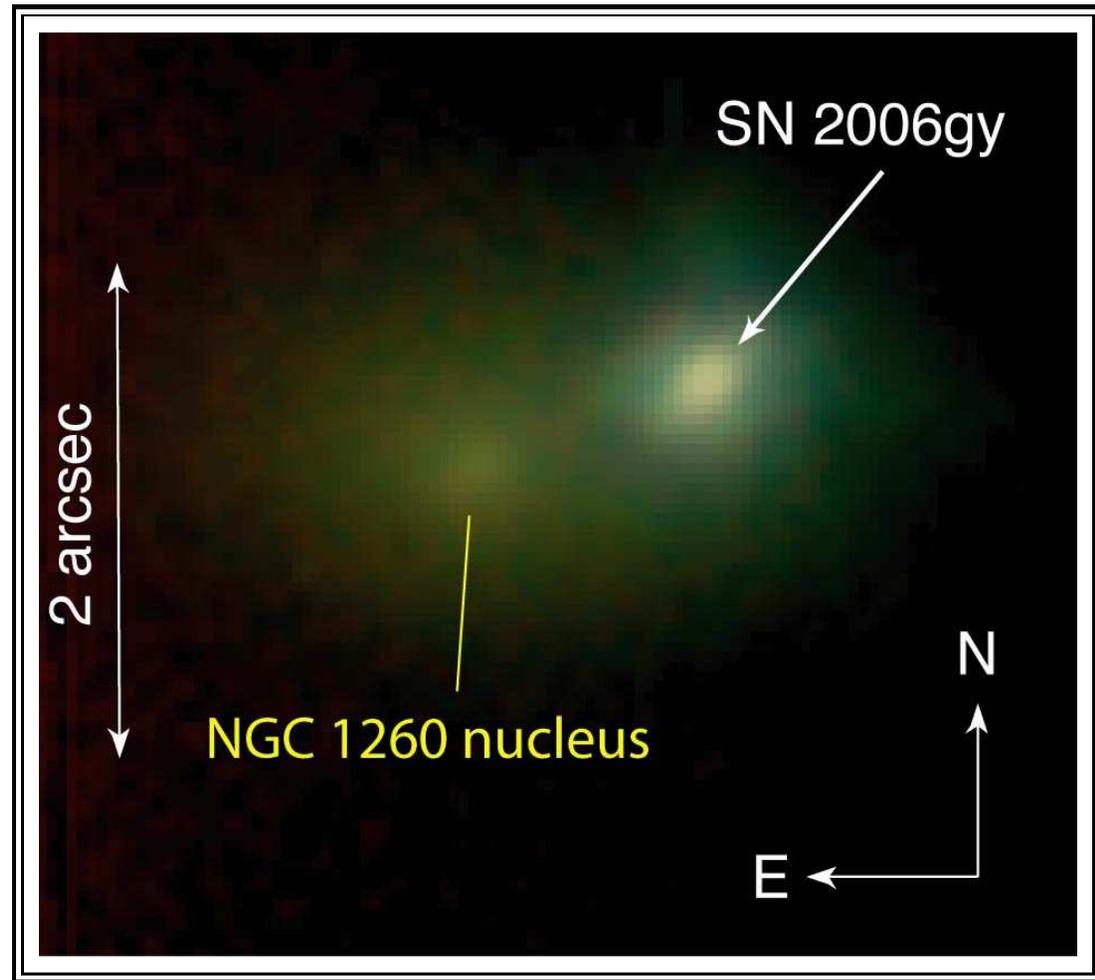
Explained by a rather dense wind, a circumstellar cloud.

This may be a general feature for some of the **Most Luminous Supernovae** on much larger and longer scale.

SN 2006gy

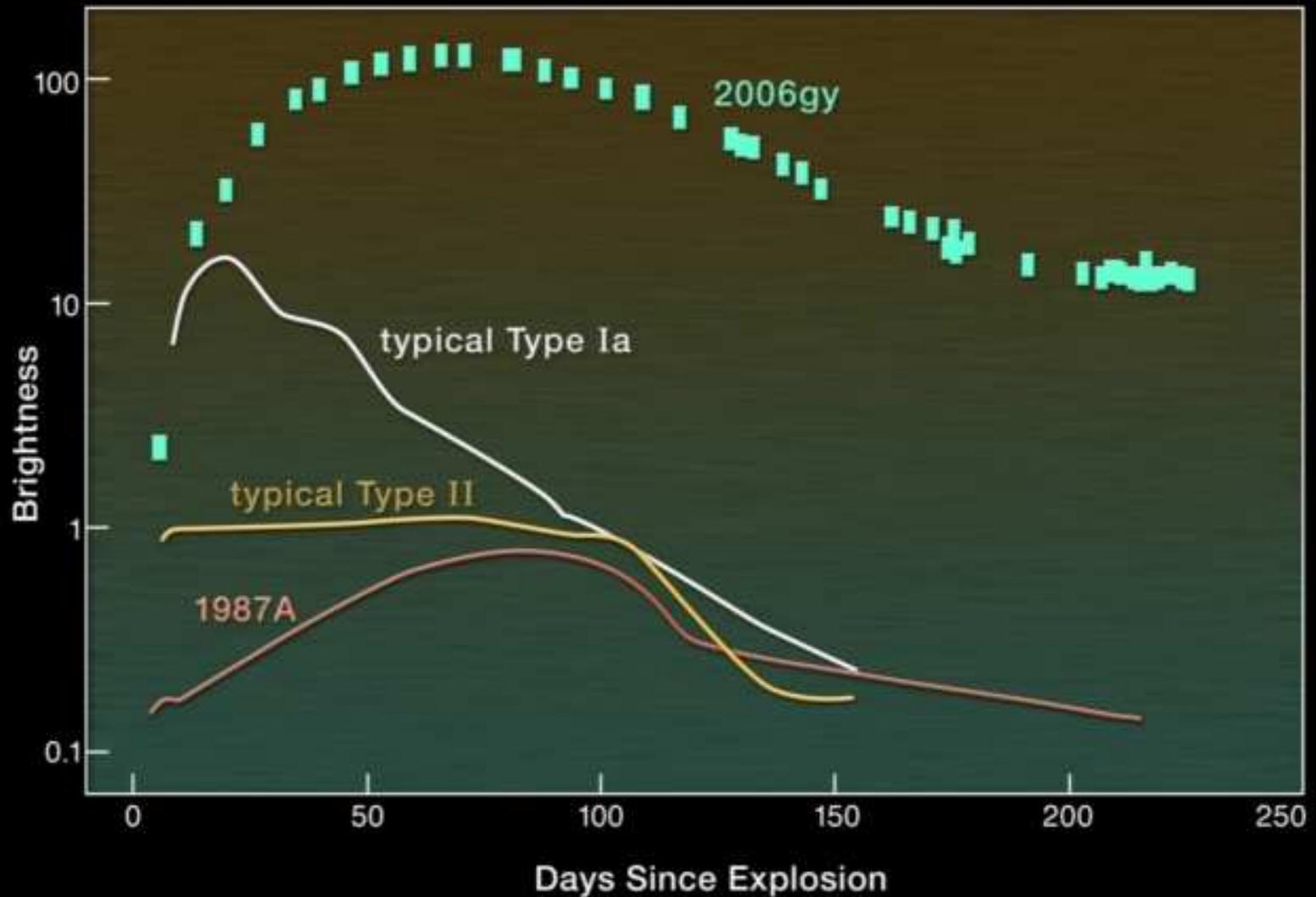
Ofek et al.
2007, ApJL,
astro-
ph/0612408)

Smith et al.
2007, Sep. 10
ApJ, astro-
ph/0612617)

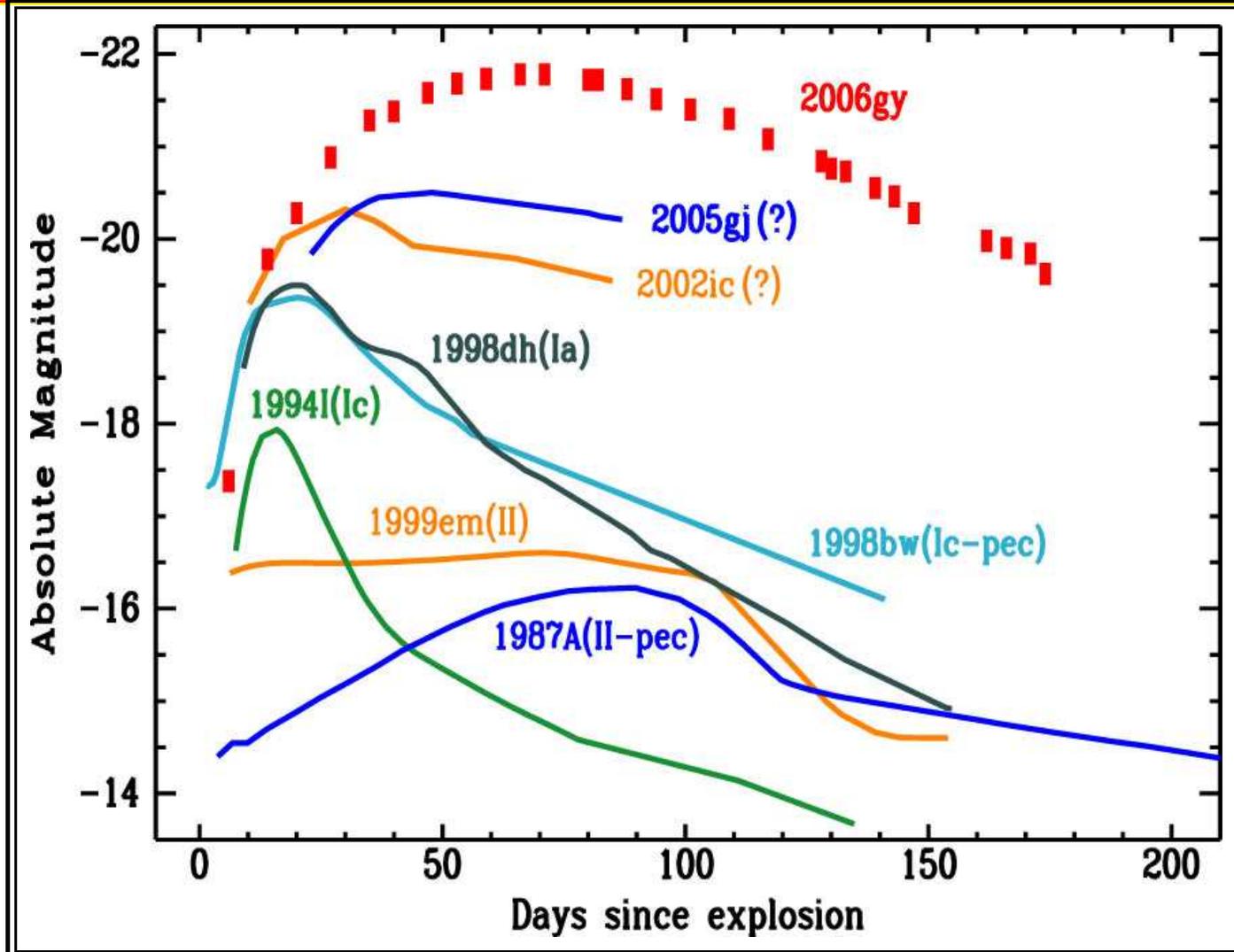


Brightest. Supernova. Ever

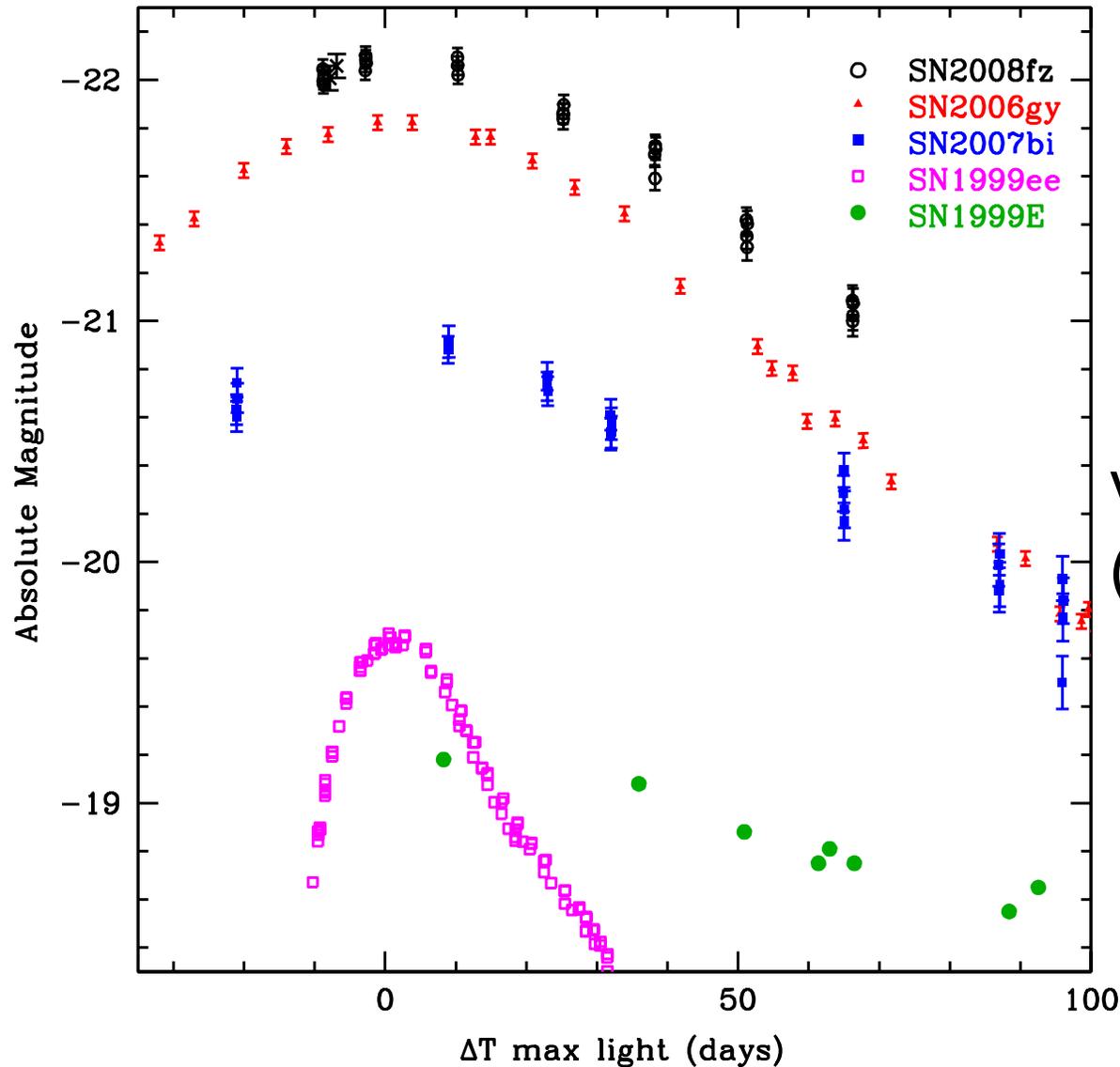
by N.Smith



It was Most Luminous SN ever



Extremely bright Type IIIn SNe



V-band
(Drake et al. 2010)

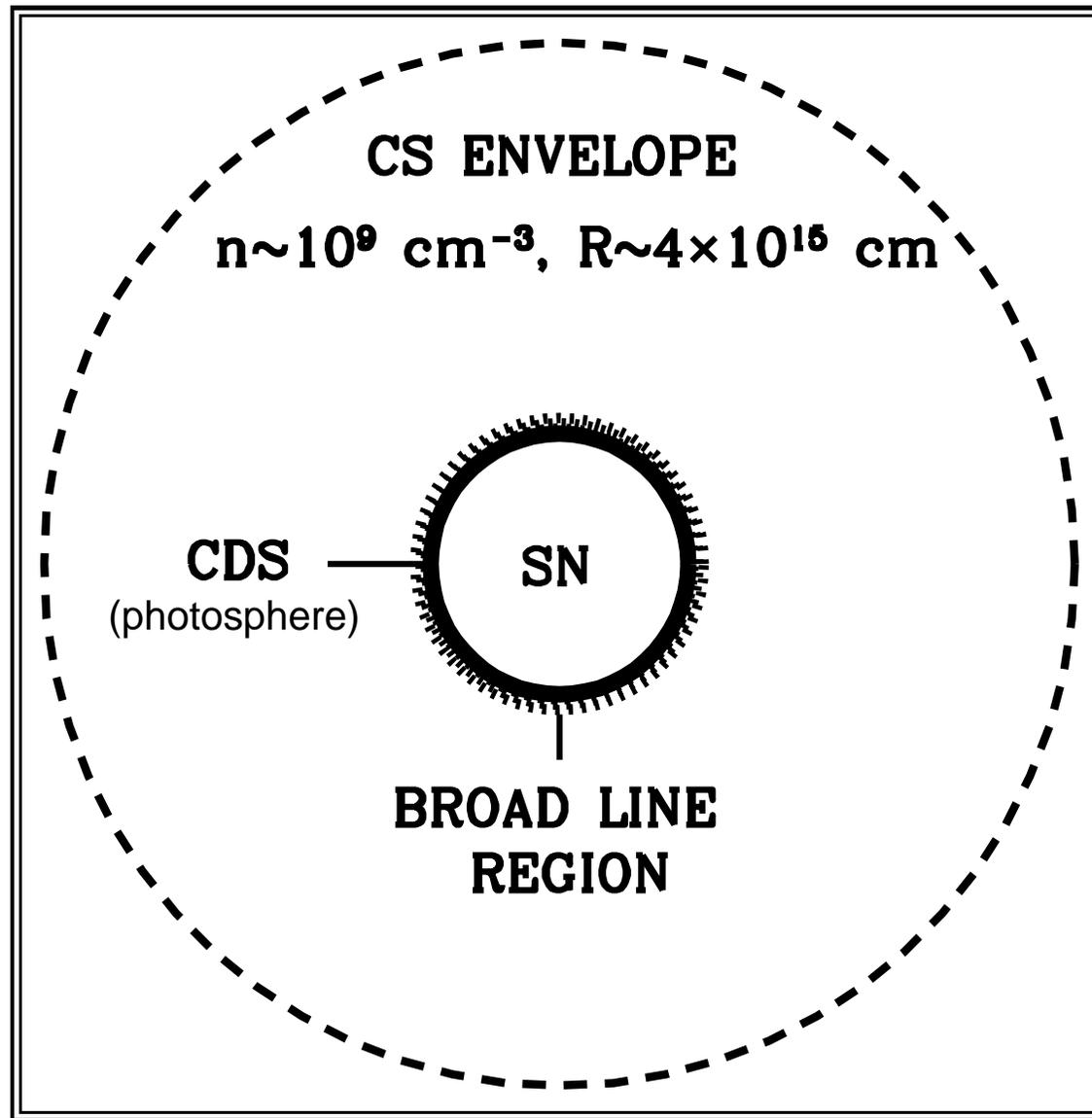
Luminous SN: too many photons?

Now we know a few other SNe with peak luminosity even higher than SN 2006gy.

Total light 10^{51} ergs: 2 orders of mag higher than normal core collapsing SN and 1 order more than brightest thermonuclear SN

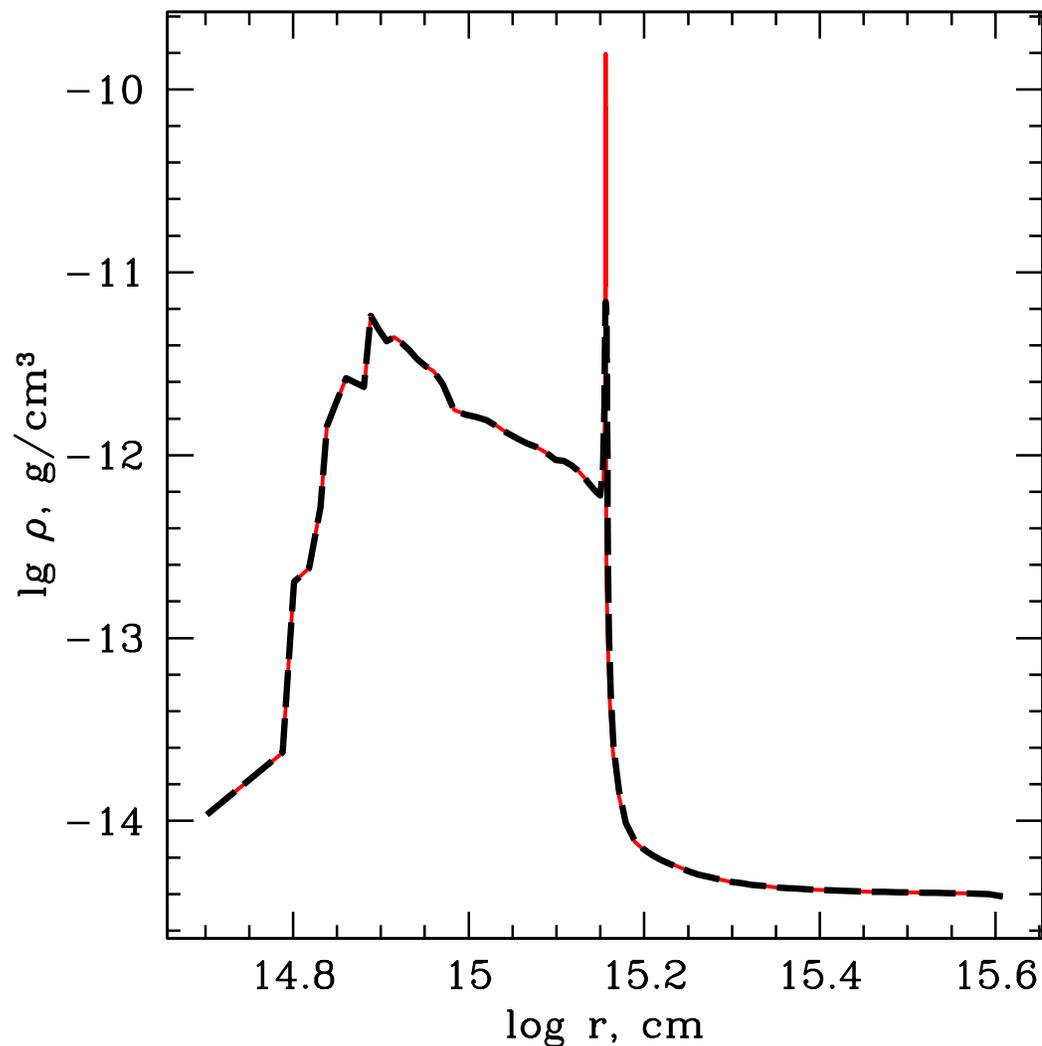
To explain this light we inevitably involve long-living radiative shocks.

SN IIn structure, Chugai, SB ea'04



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.

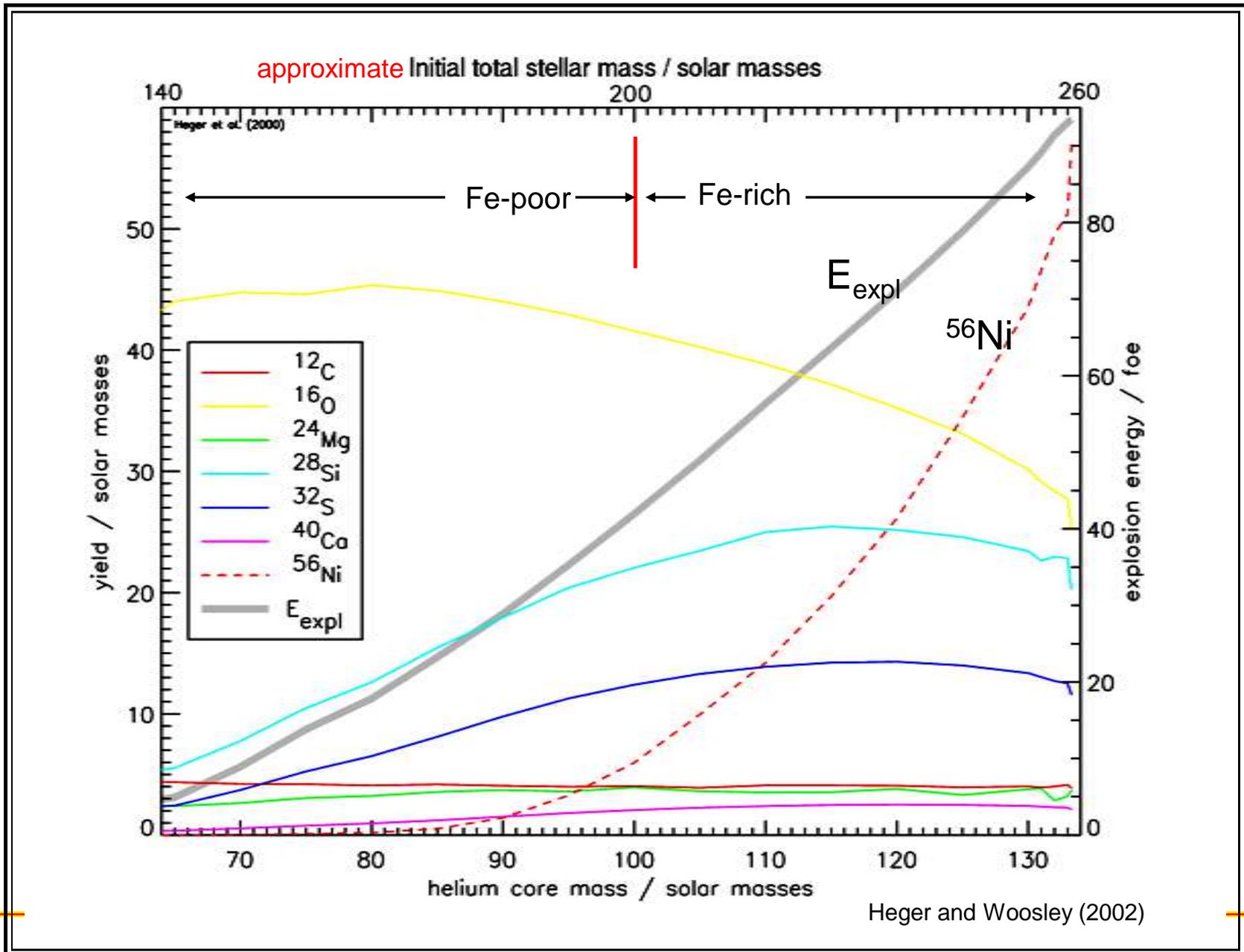


Four kinds of deaths

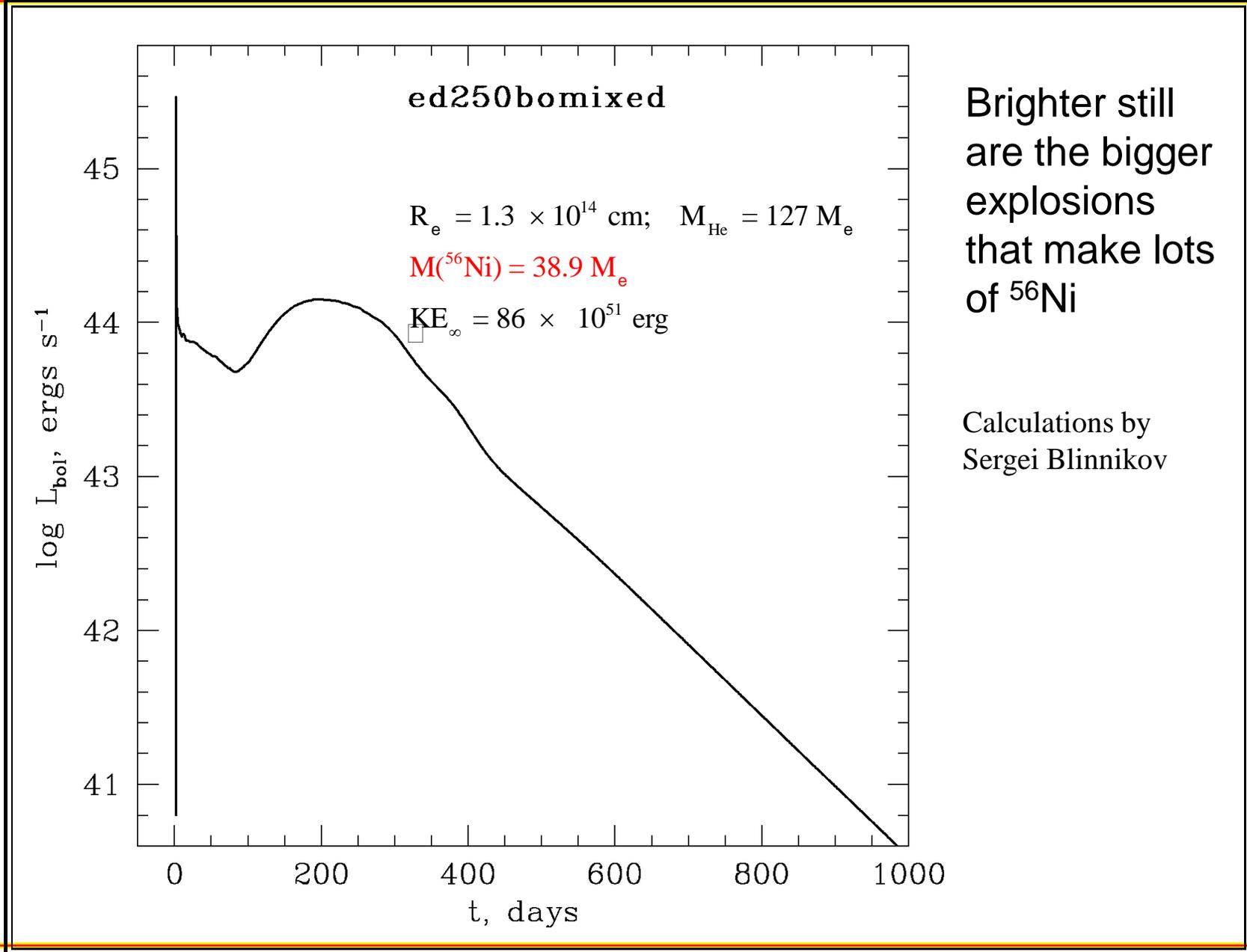
With some uncertainty about exact demarcations, one can delineate four kinds of deaths for non-rotating helium stars. (For rotation decrease main sequence mass 10 - 20%)

He Core	Main Seq. Mass	Supernova Mechanism
$2 \leq M \leq 40$	$10 \leq M \leq 95$	Fe core collapse to neutron star or a black hole
$40 \leq M \leq 60$	$95 \leq M \leq 130$	Pulsational pair instability followed by Fe core collapse
$60 \leq M \leq 137$	$130 \leq M \leq 260$	Pair instability supernova
$M \geq 137$	$M \geq 260$	Black hole. Possible GRB

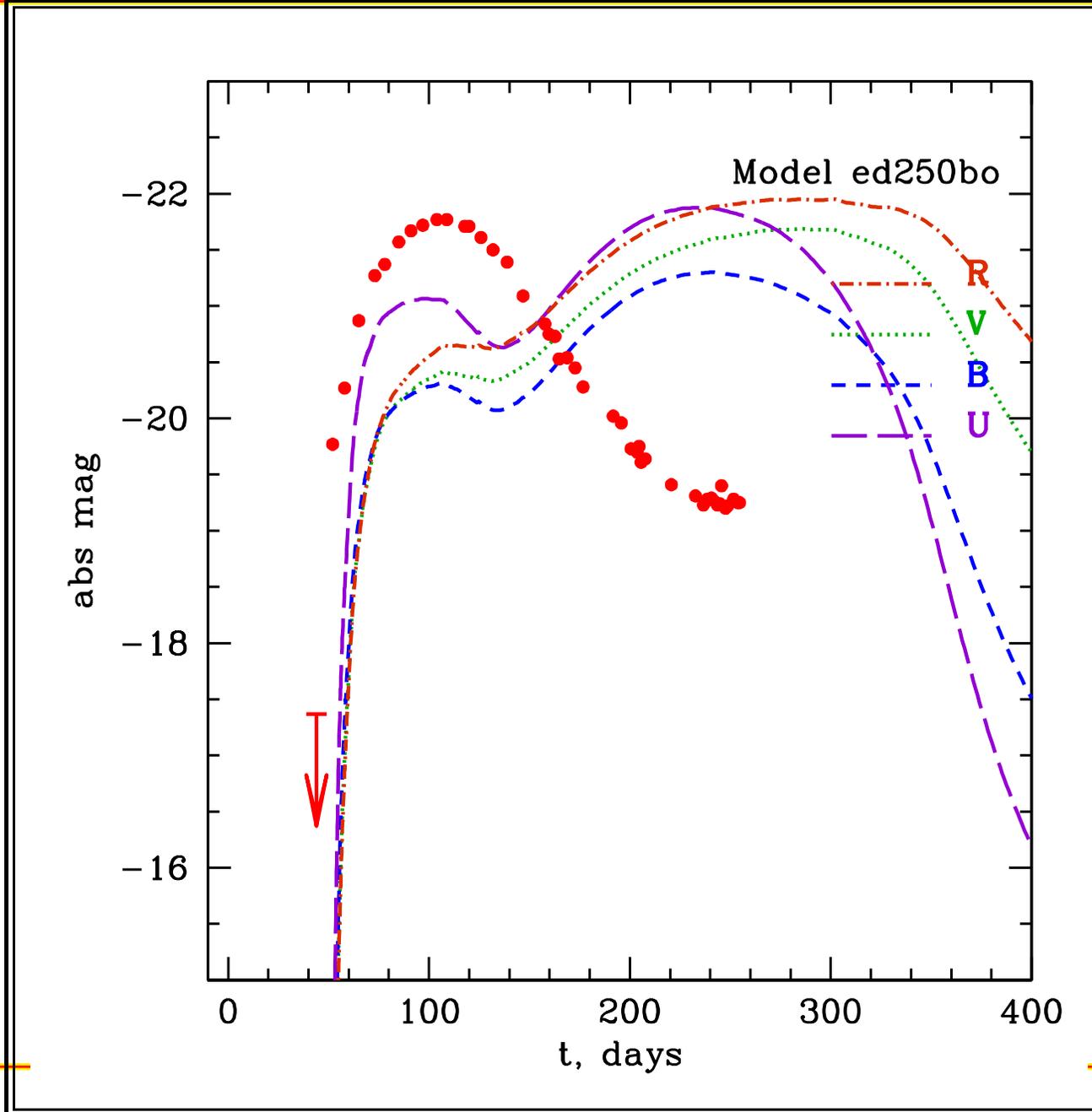
Very Massive Stars



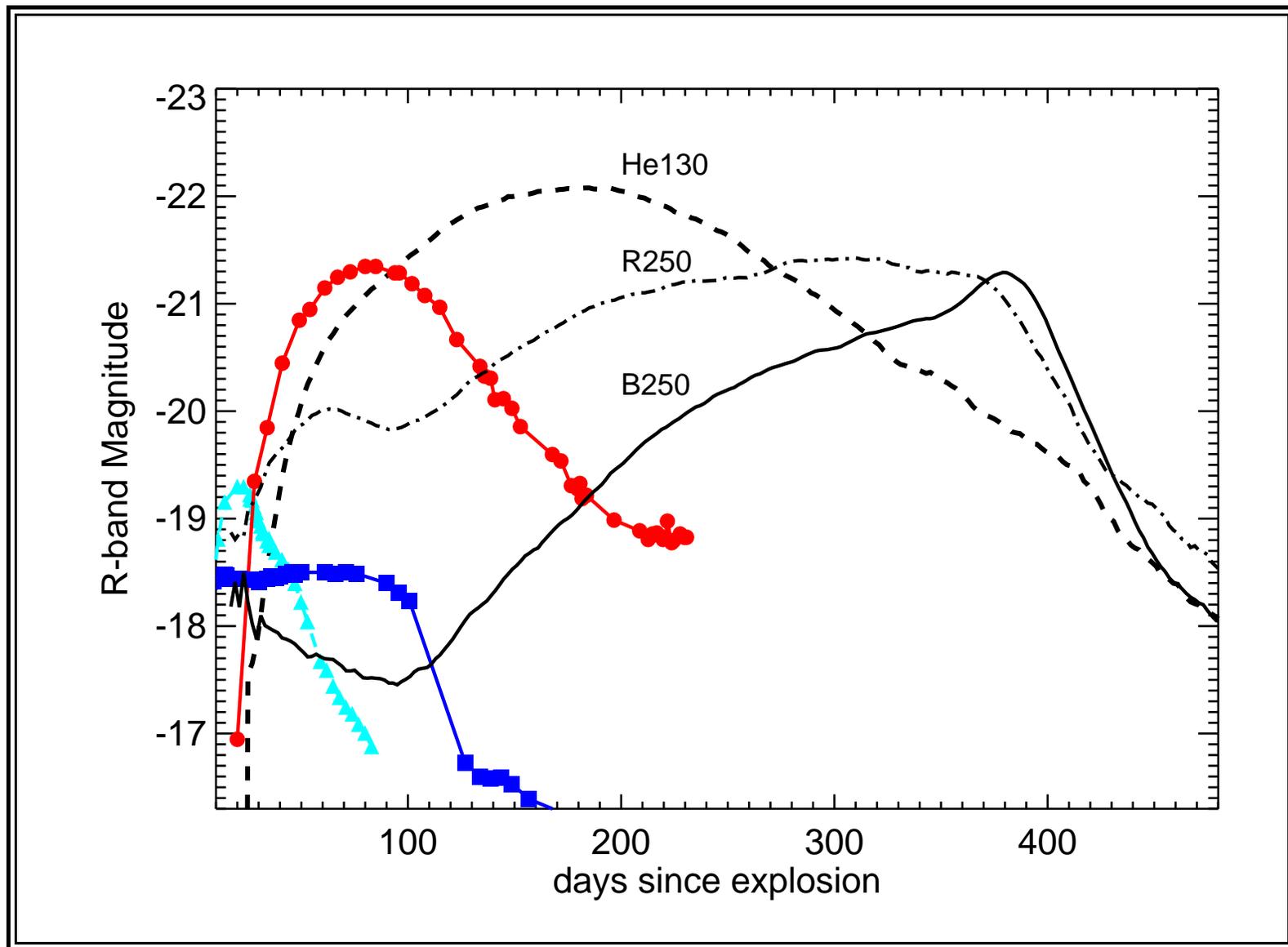
Bolometric for ed250 (2001)



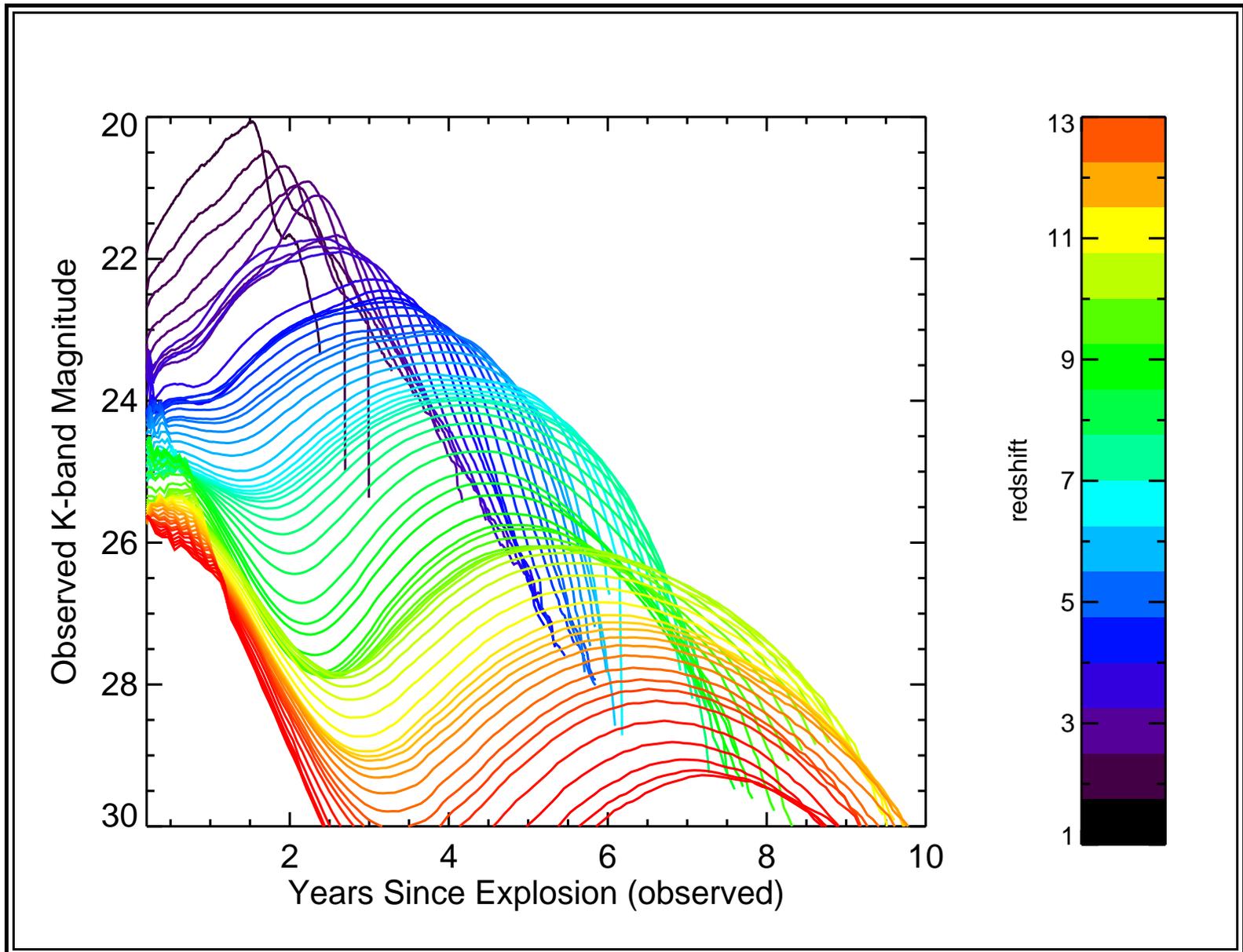
UBVR for ed250 and SN06gy



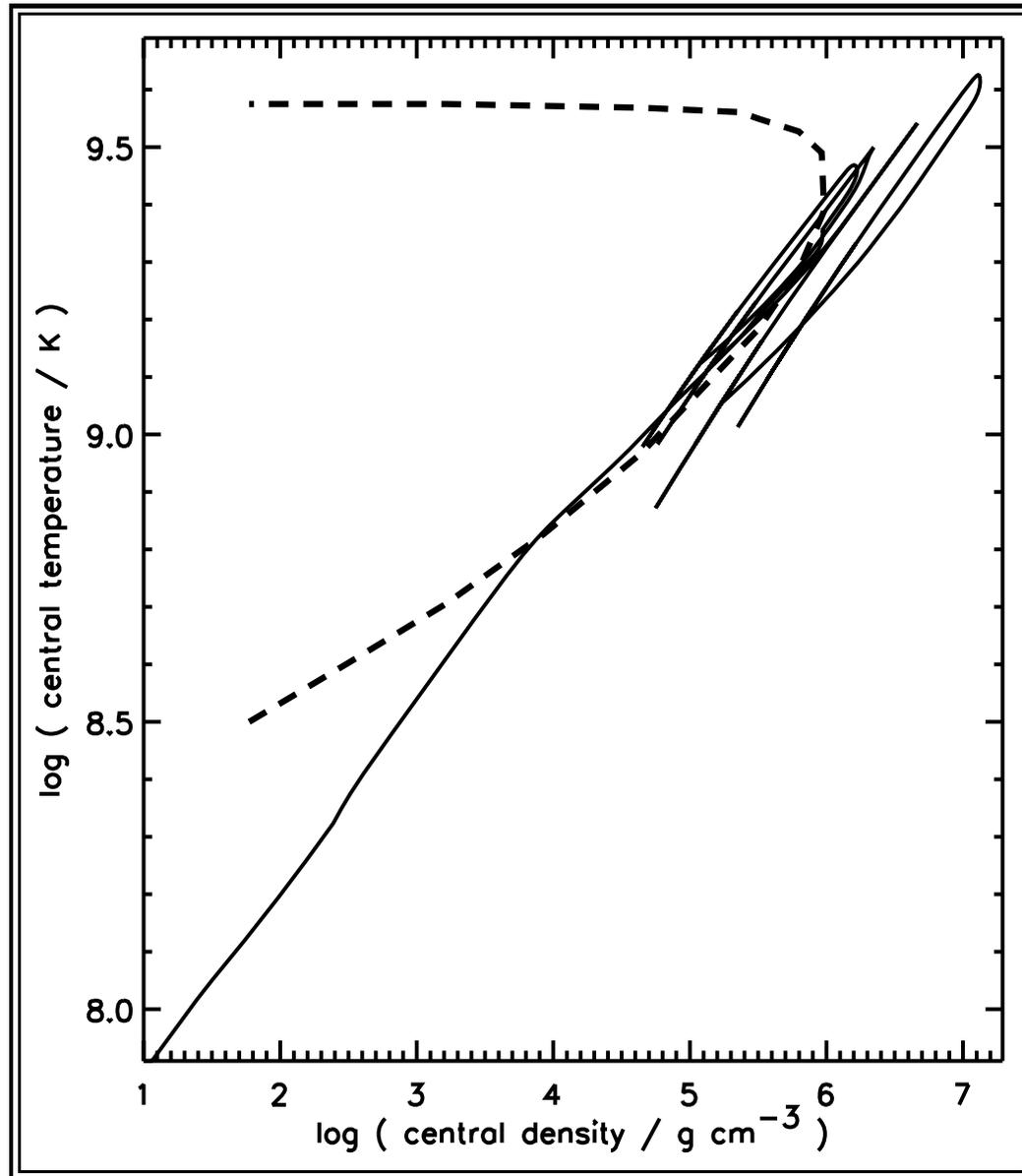
Kasen, Woosley, Heger 2011



Visibility at large z

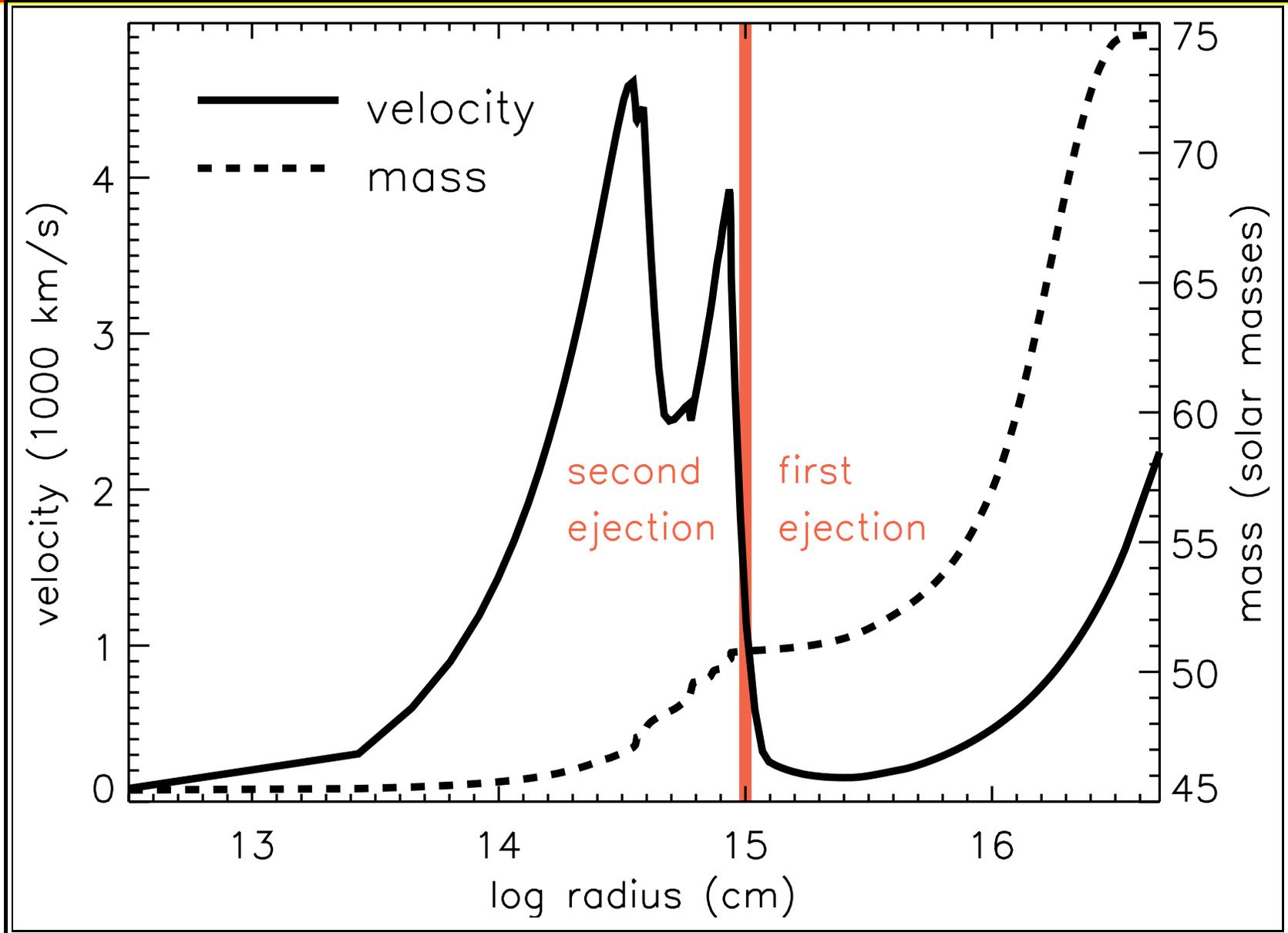


Woosley, Blinnikov, Heger, s103

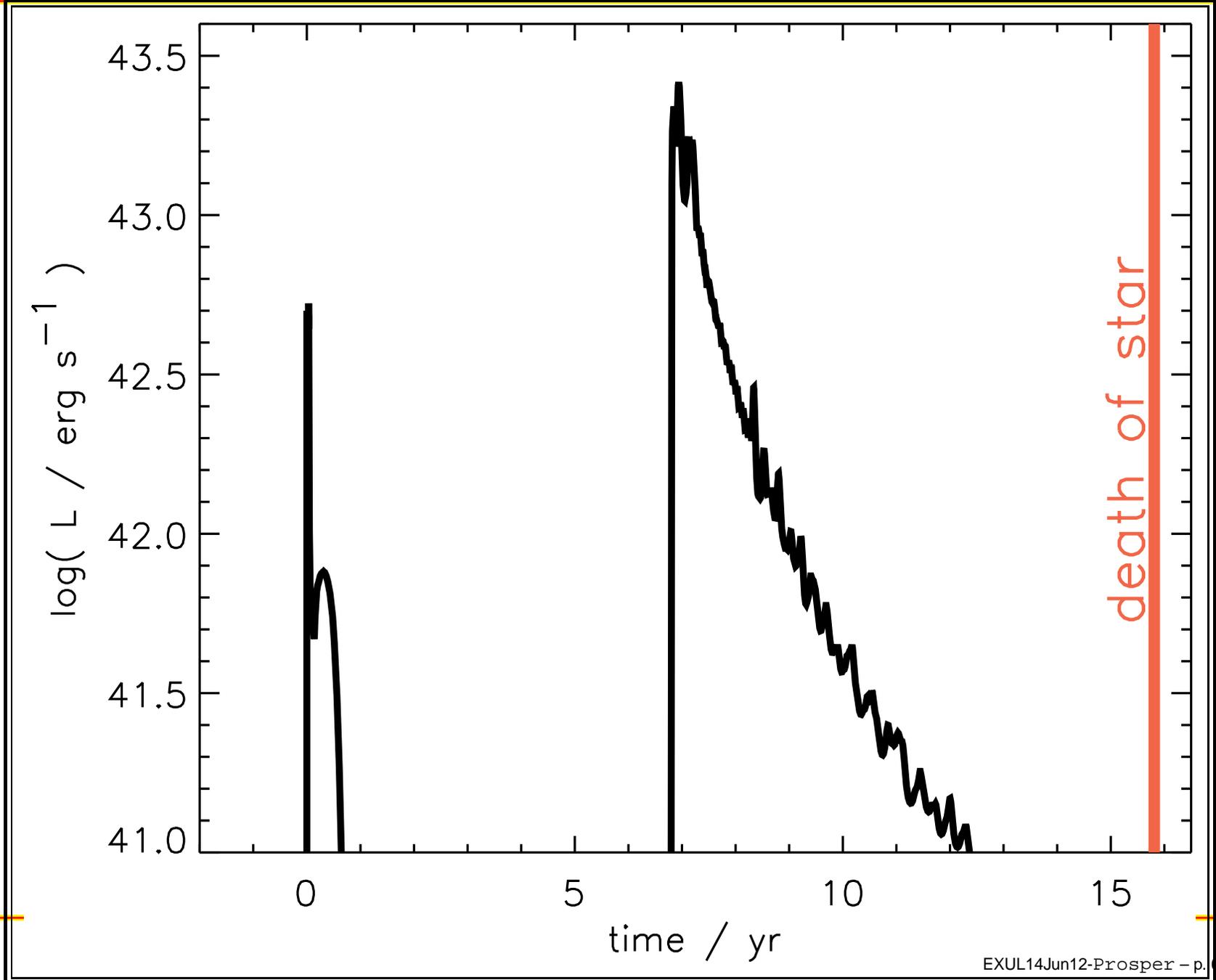


Pulsational pair instability may give the Most Luminous Supernovae.

Two mass ejections



SN-repeaters



Several ejections are possible

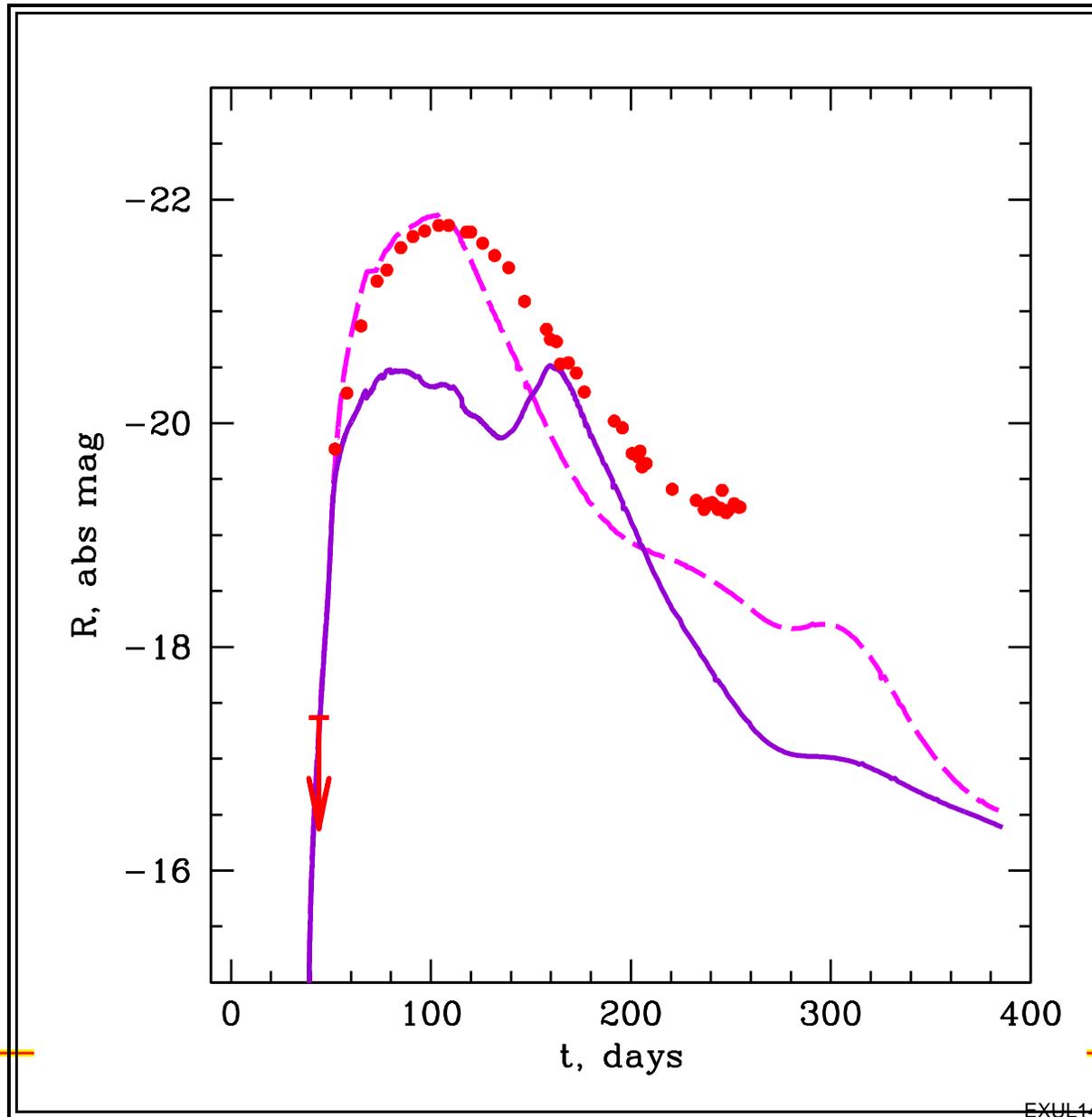
He Mass (M_{\odot})	Pulse	KE_1 (10^{50} erg)	ΔM (M_{\odot})	T_c (10^9 K)	ρ_c (10^5 g cm $^{-3}$)	interval (sec)
48	1	0.048	0.11	1.48	1.68	7.34(5)
	2	0.92	0.57	1.57	2.02	4.31(5)
	3	2.20	1.19	1.31	1.34	2.77(6)
	4	3.09	1.64	1.38	3.00	2.02(6)
	5	4.41	1.84	1.32	3.40	8.33(6)
	6	3.02	2.42	1.86	28.6	7.43(5)

52	1	0.85	1.13	1.01	0.40	6.32(7)
	2	1.46	0.94	1.57	5.02	4.58(5)
	3	4.27	1.90	1.16	2.74	8.10(6)
	4	7.29	3.12	1.09	2.68	9.56(7)

58	1	13.3	9.39	0.24	0.0072	1.24(11)
	2	4.00	2.39	1.46	6.08	2.10(6)
	3	7.78	3.06	1.07	3.31	1.61(8)

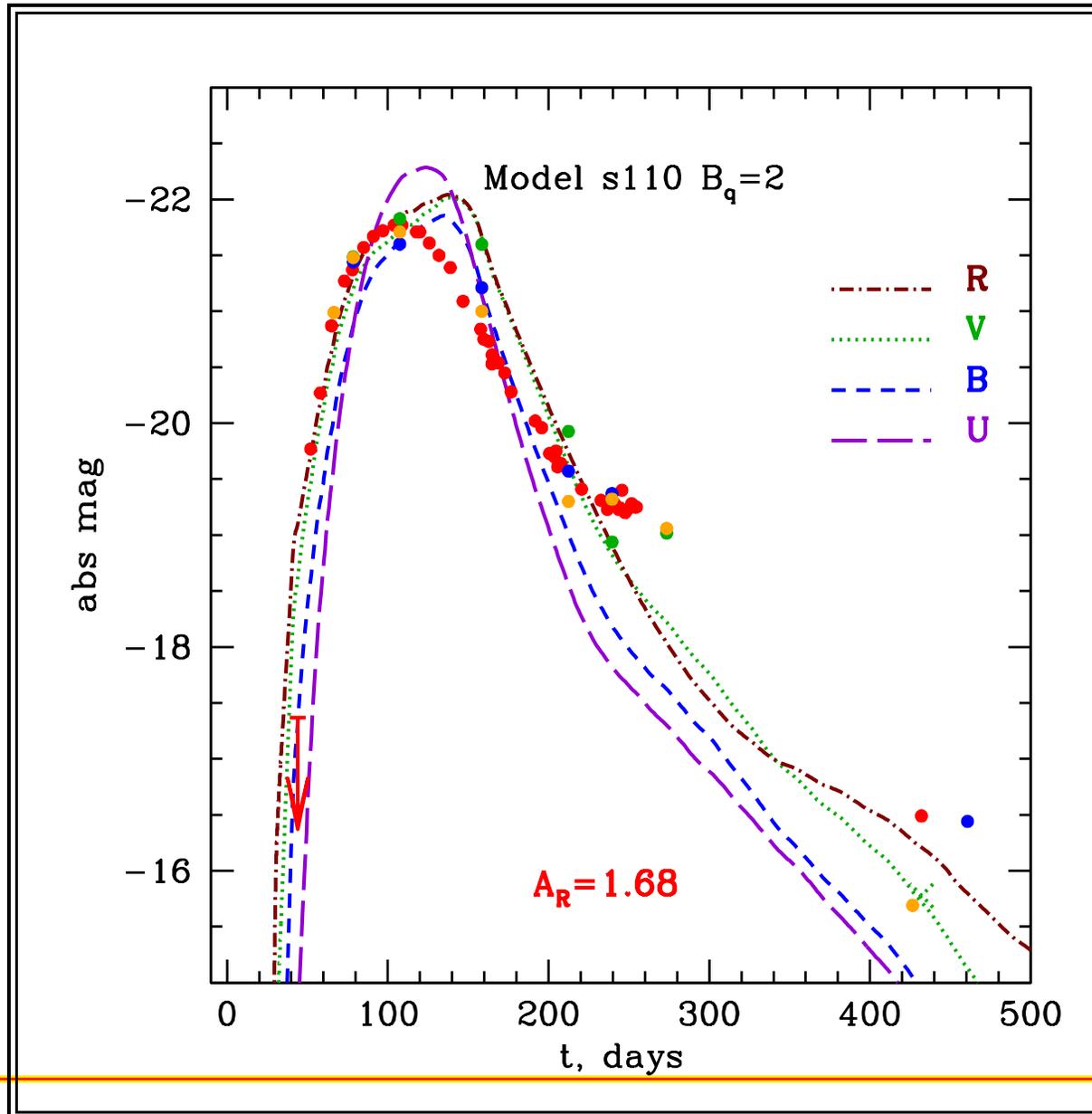
Light curve for SN2006gy

from Woosley, SB, Heger (2007)

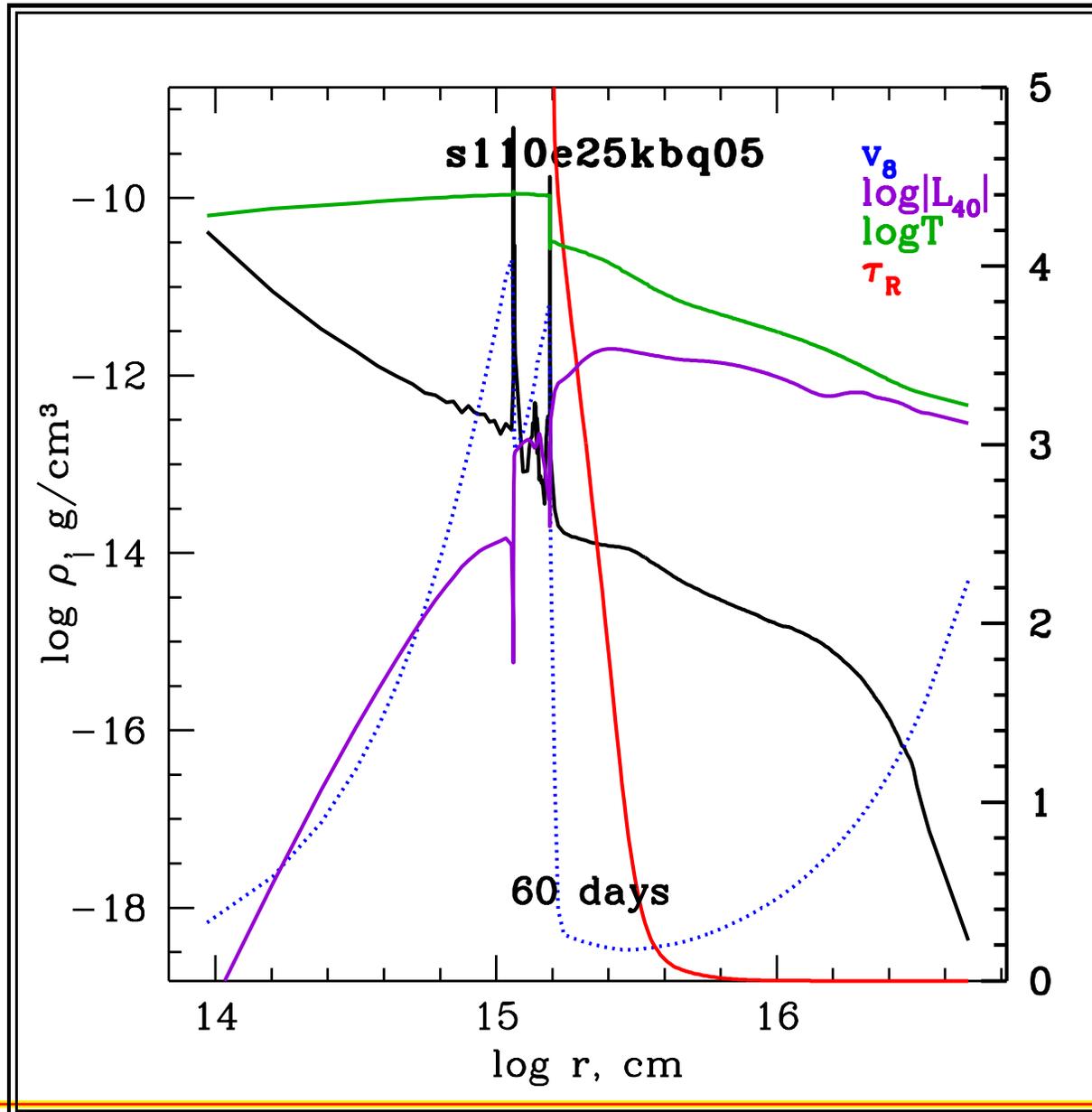


Stella: LCs for SN2006gy

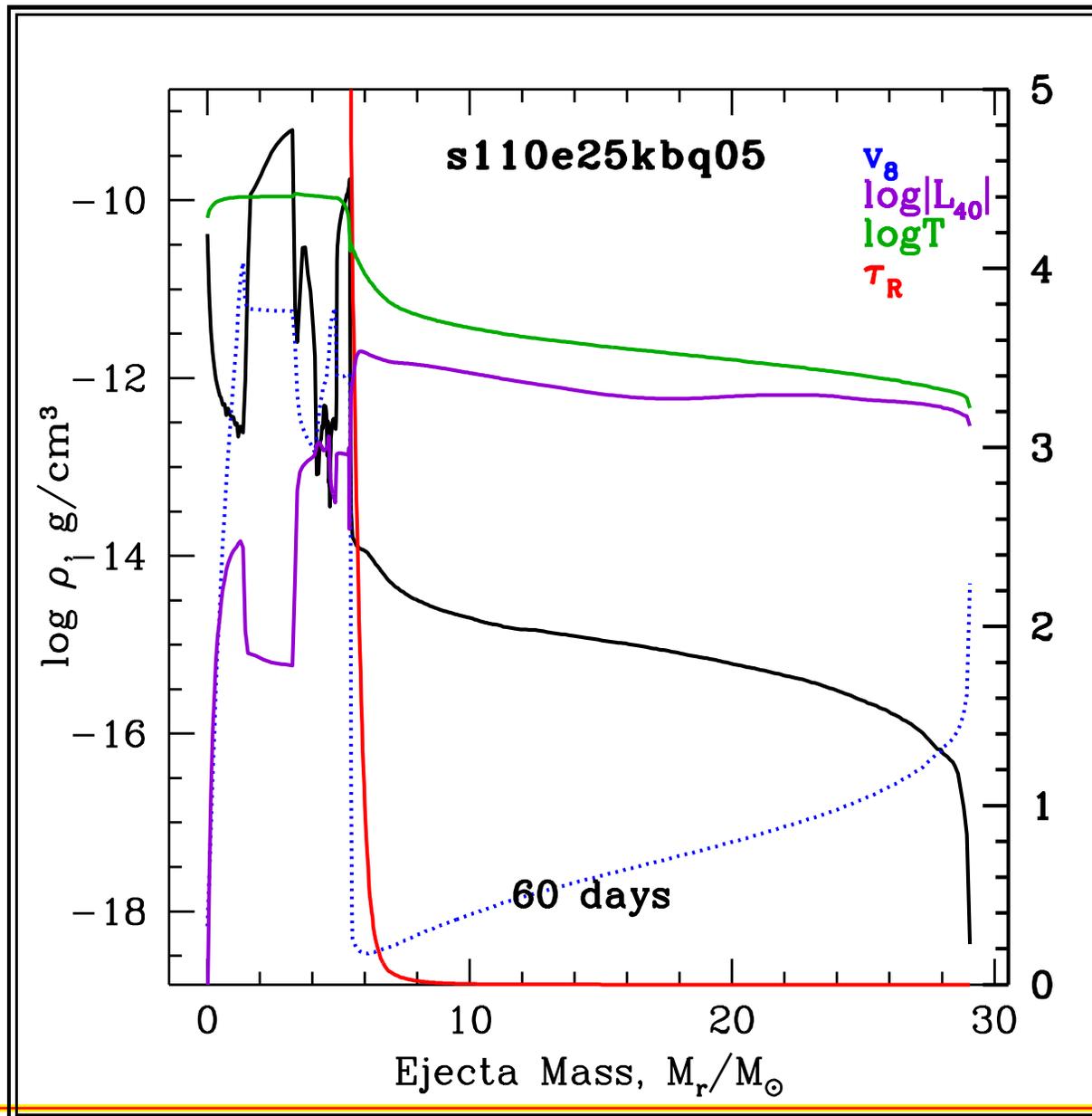
new runs



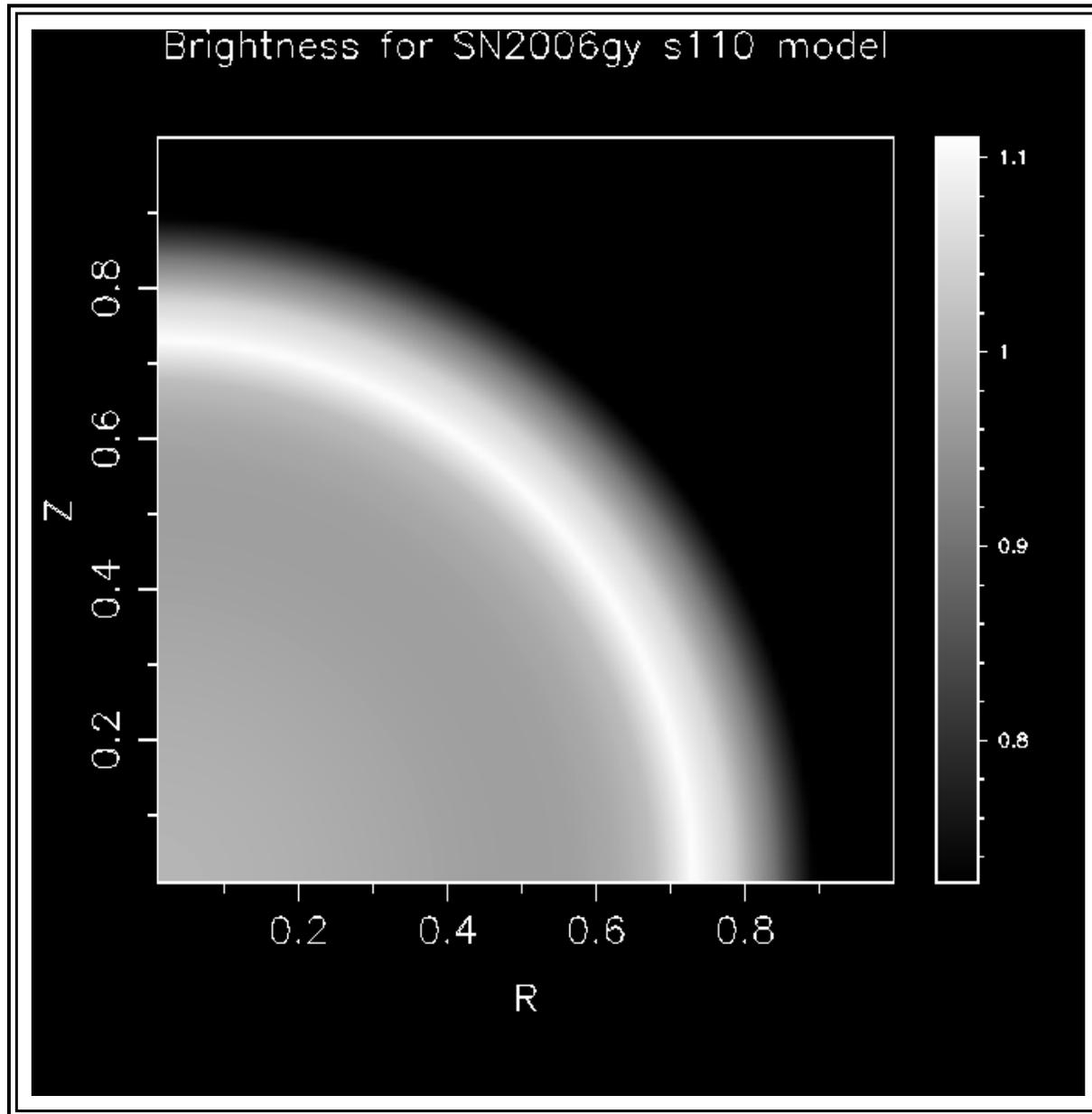
Hydro structure 60 d



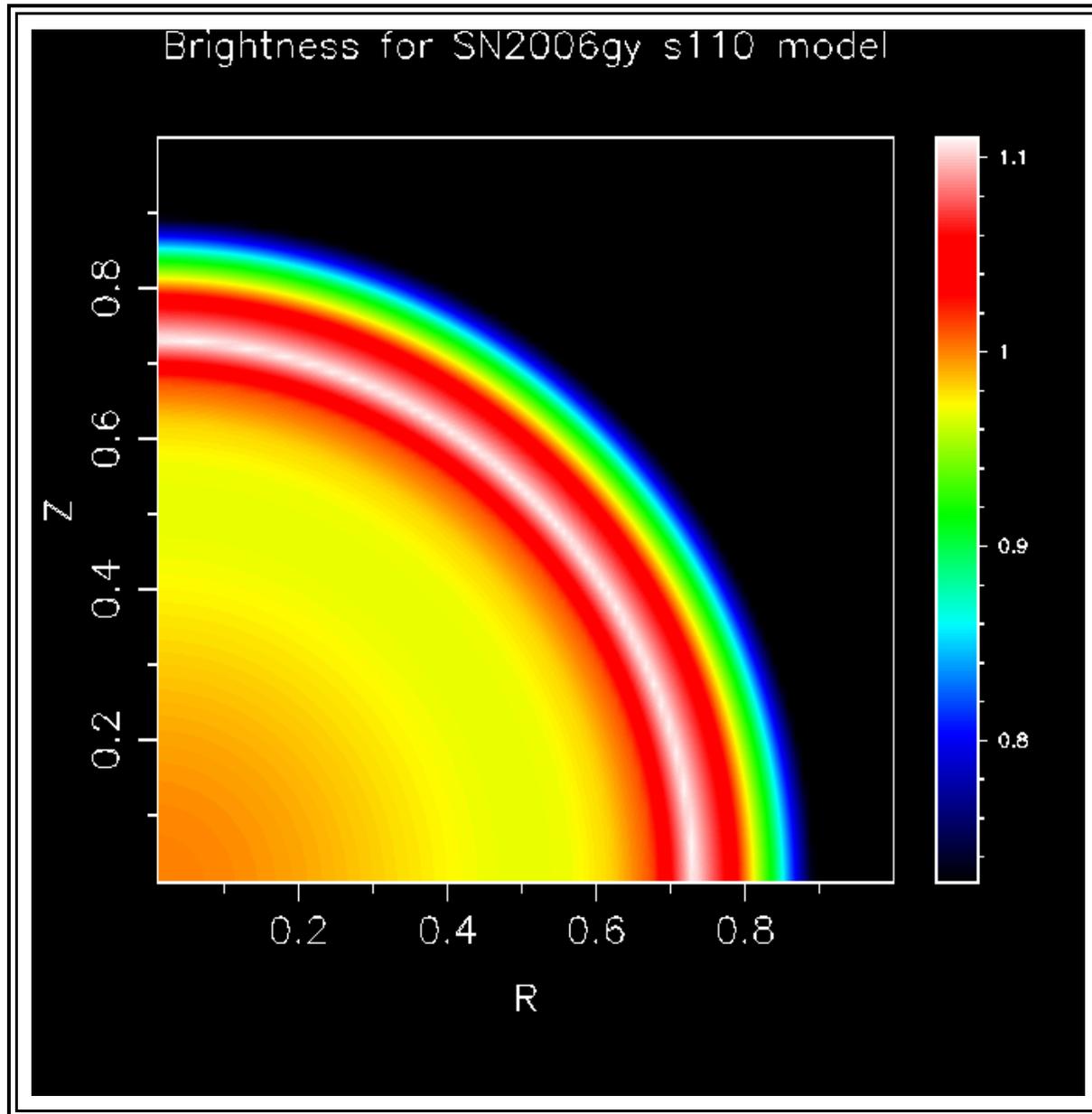
60 d, mass coordinate



'Visible' disk of SN 2006gy



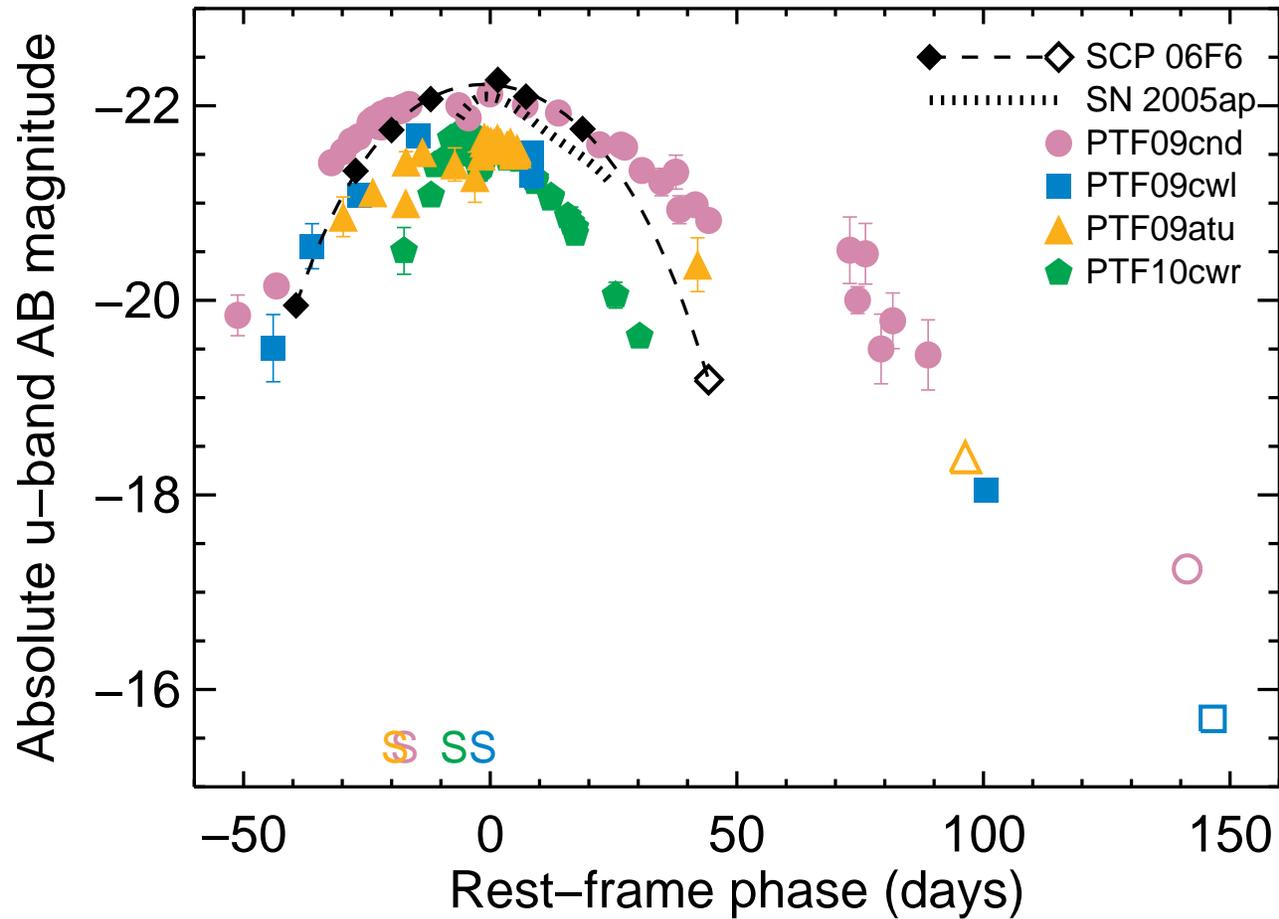
'Visible' disk of SN 2006gy c



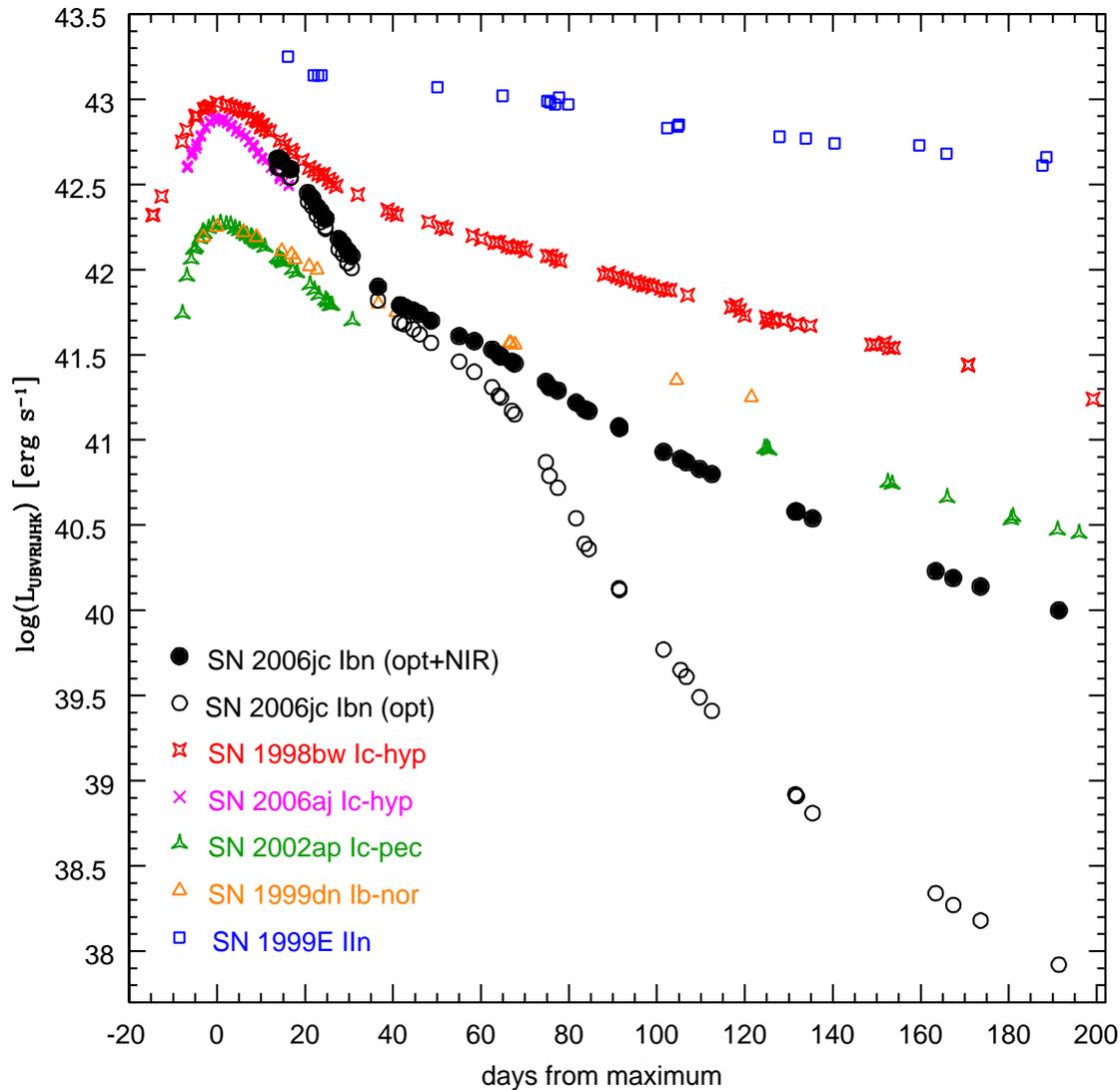
Next is partly based on arXiv:1009.4353 and inspired by
Chris Fryer's work on shocks in C/O winds

H-poor superluminous SNe

Quimby et al. 2011



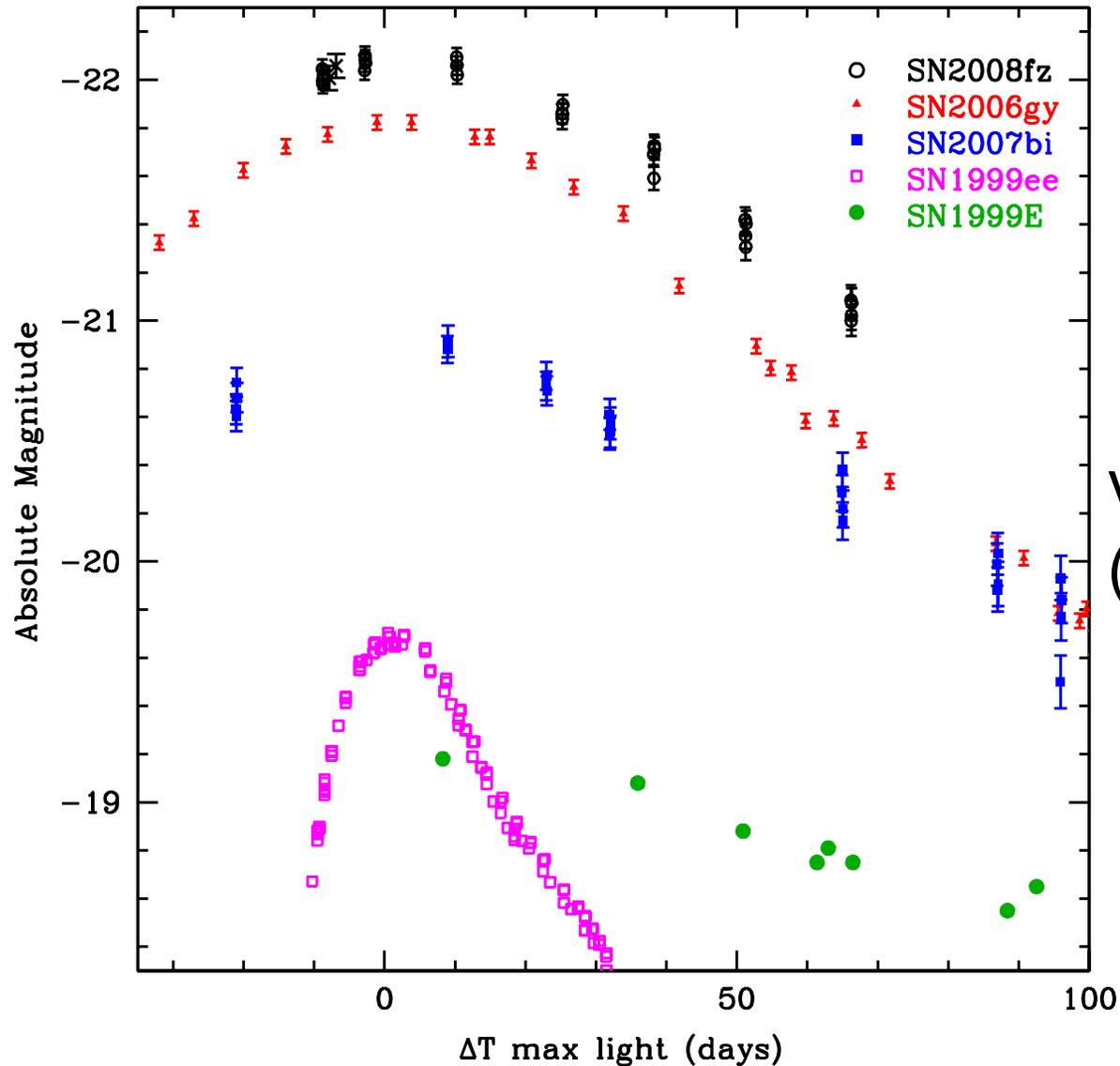
Very bright Type Ib SNe with narrow lines



Type I_{bn}, still rather weak compared to PTFs
notice SN1999E of type I_{ln}

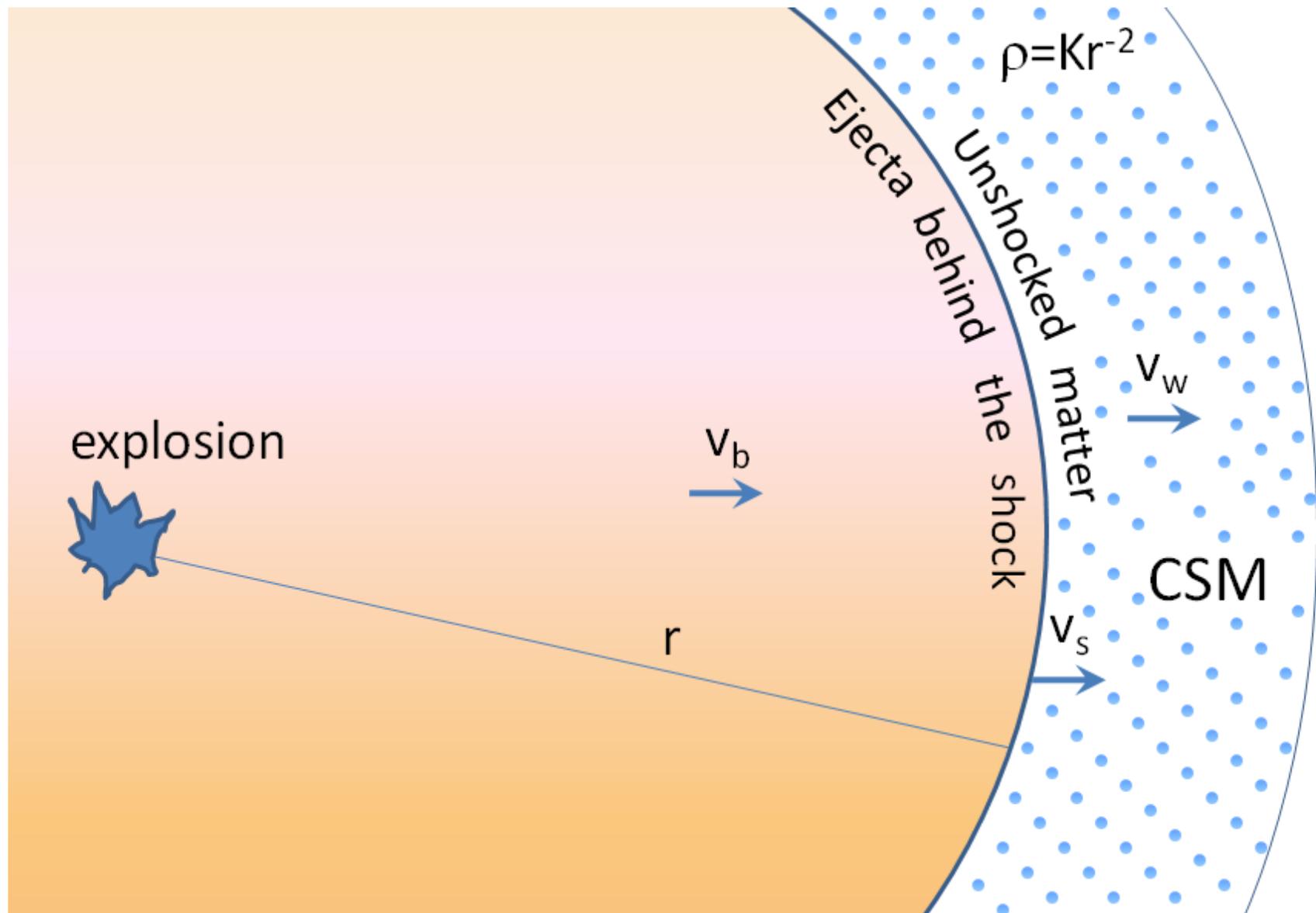
Quasi-bolometric (optical+NIR)
(Pastorello et al. 2008)

Compare SN1999E with brighter SNeIa



V-band
(Drake et al. 2010)

Windy models for core collapse SNe



Ofek et al. 2010

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;

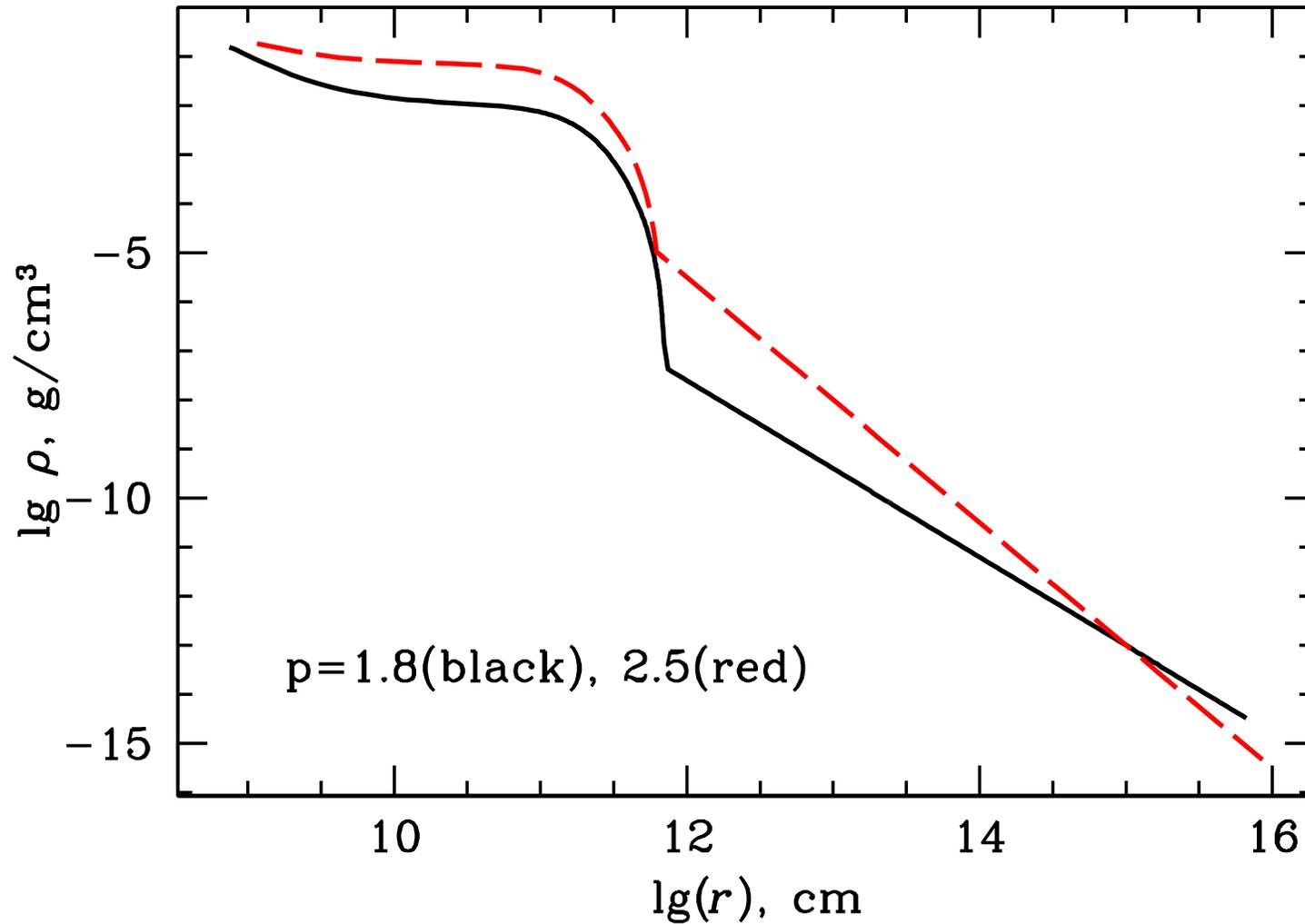
OR He + 2% Z

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

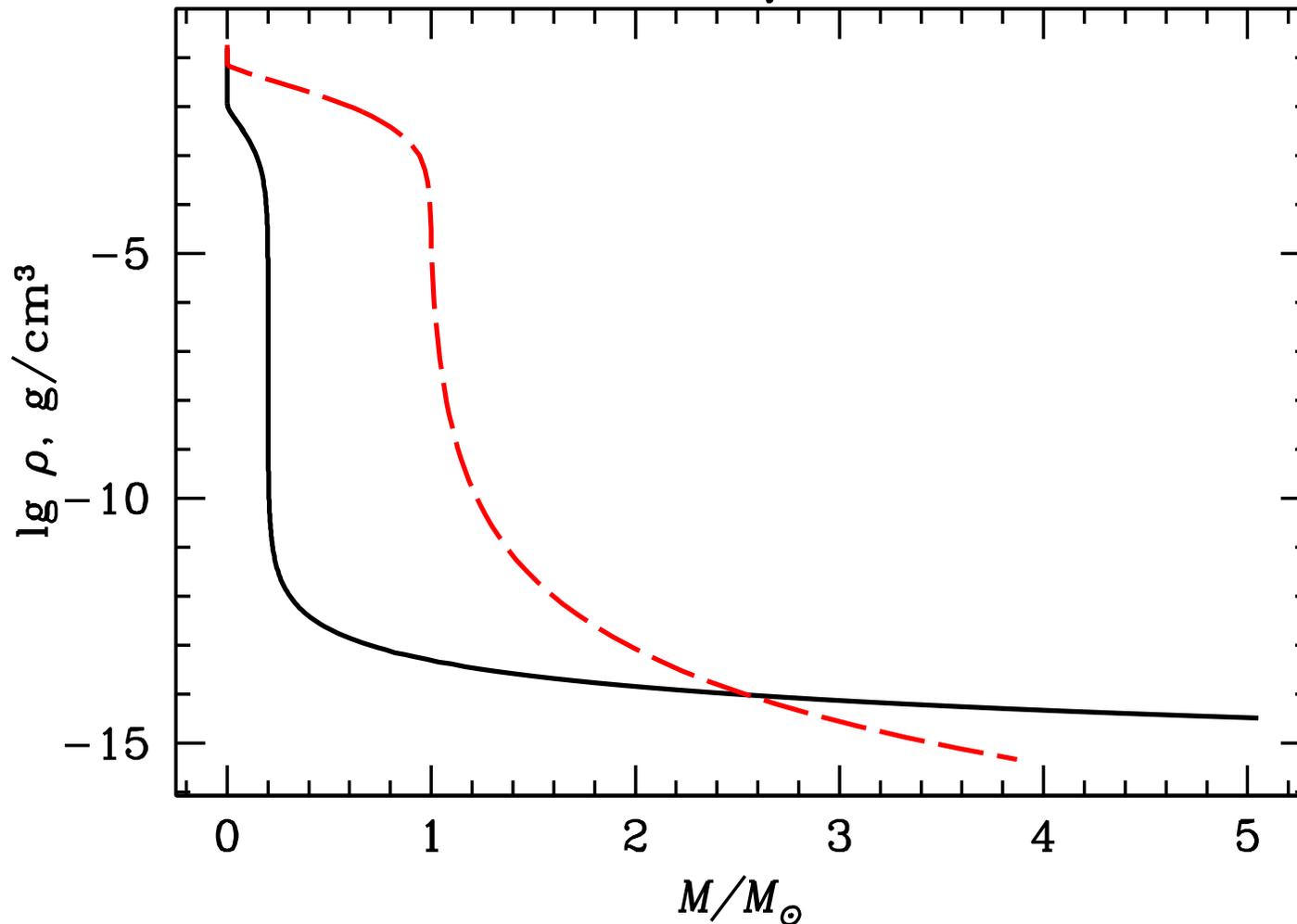
Samples of the density distribution



Initial models

Samples of the density distribution

$p=1.8$ (black), 2.5 (red); $M_{ej}=0.2M_{\odot}$ (black), $1M_{\odot}$ (red)



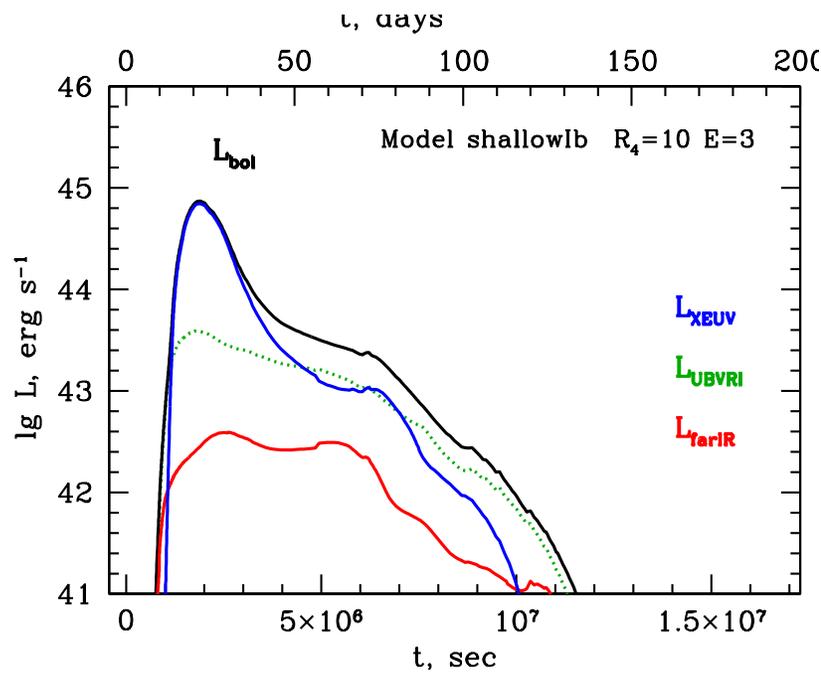
Windy models for type Ic SNe

all masses M and radii R are in solar units

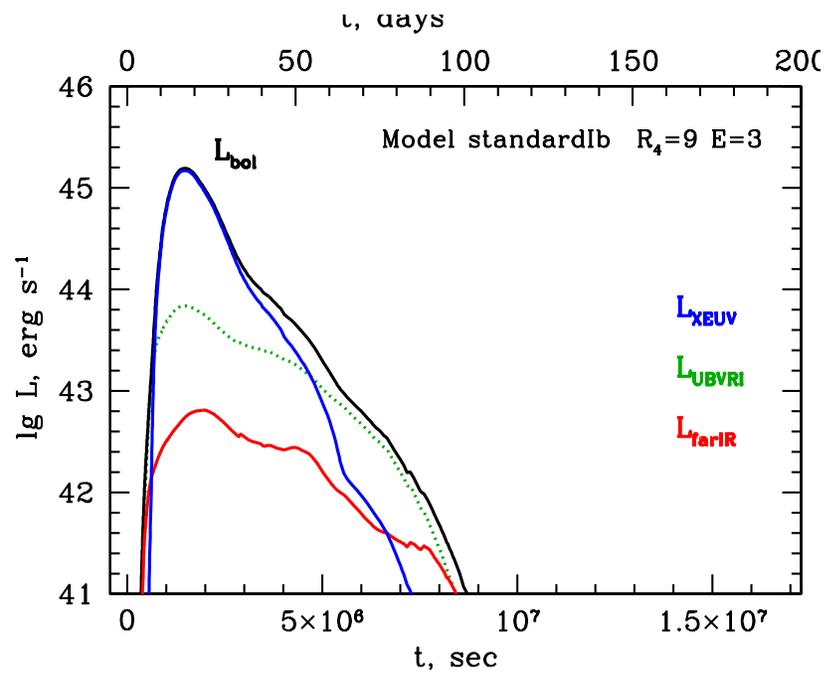
Model	M_{ej}	R_{ej}	M_{Ni}	p	M_{w}	R_{w}	E , foe
out6esa	10	$9.1 \cdot 10^3$	0	0	4.15	10^5	1.5
out7p3	10	$6.3 \cdot 10^3$	0	3	3.3	10^5	1.5
out8p3	10	$5.7 \cdot 10^3$	0	3	6.8	10^5	1.5
out9p3	1.7	5	0	3	9.8	$1.2 \cdot 10^5$	1.5; 3
out10p2	2	10	0	2	4.5	$1.3 \cdot 10^5$	3
out11p2	10	$7.4 \cdot 10^3$	0	2	4	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

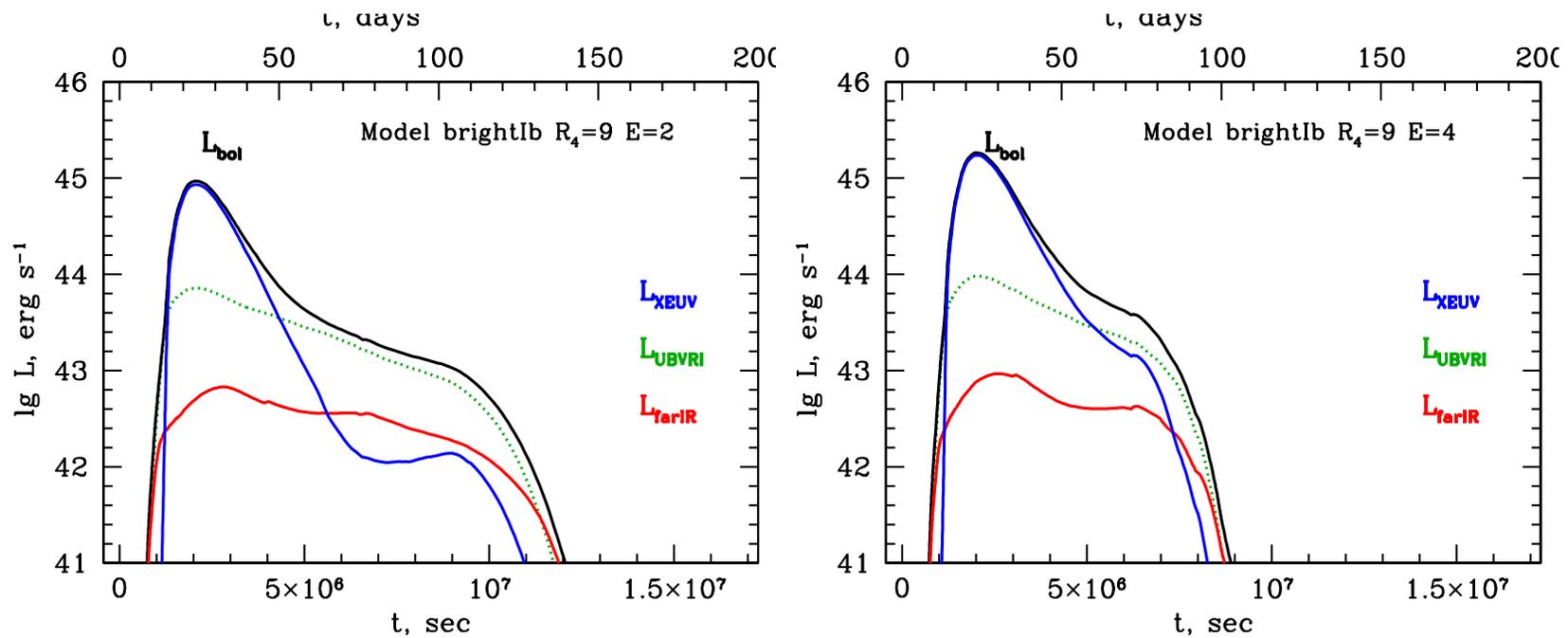


$$p = 2.5, M_w = 2.9M_{\odot}$$



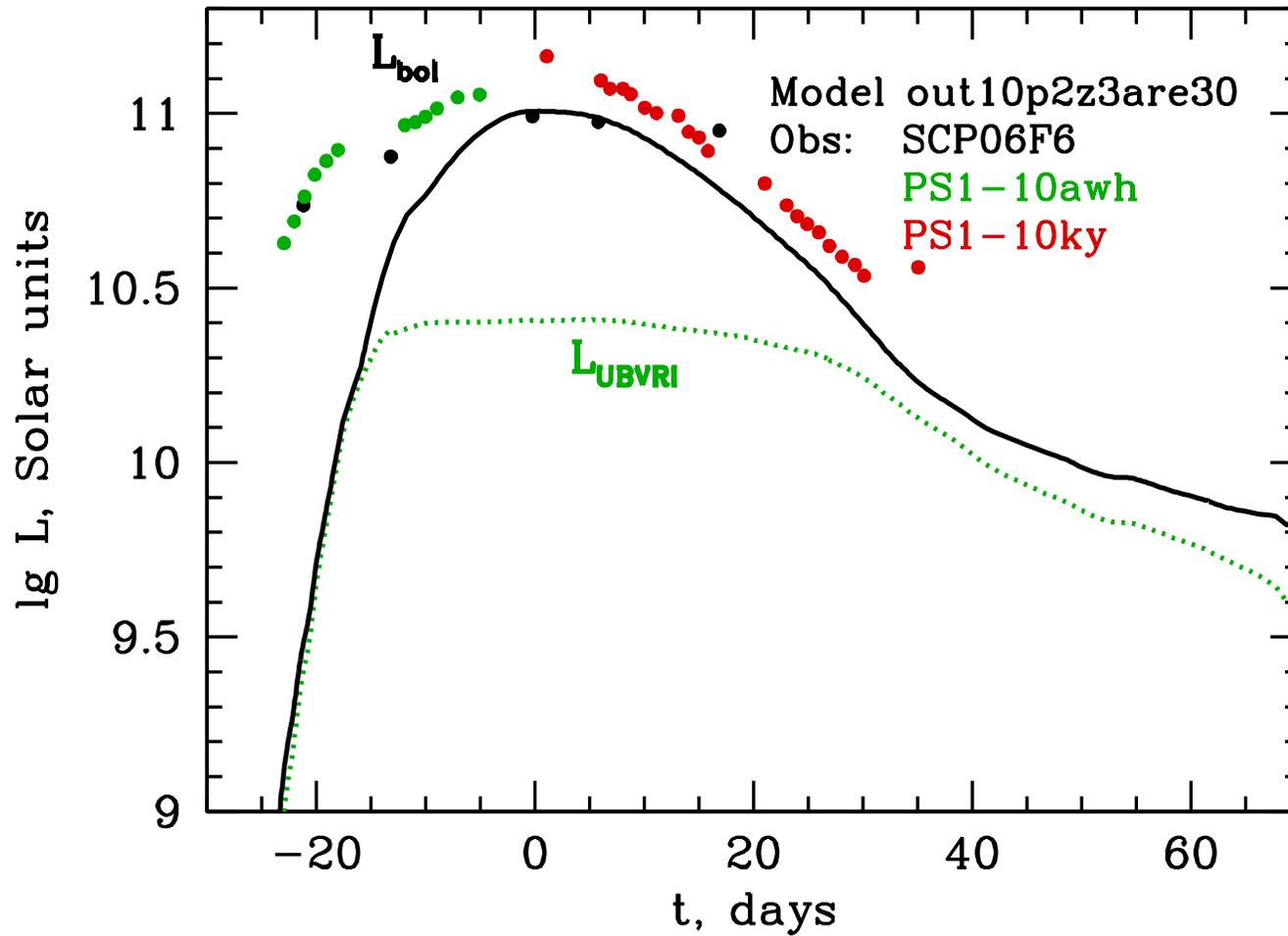
$$p = 2, M_w = 3.5M_{\odot}$$

LCs for different explosion energies



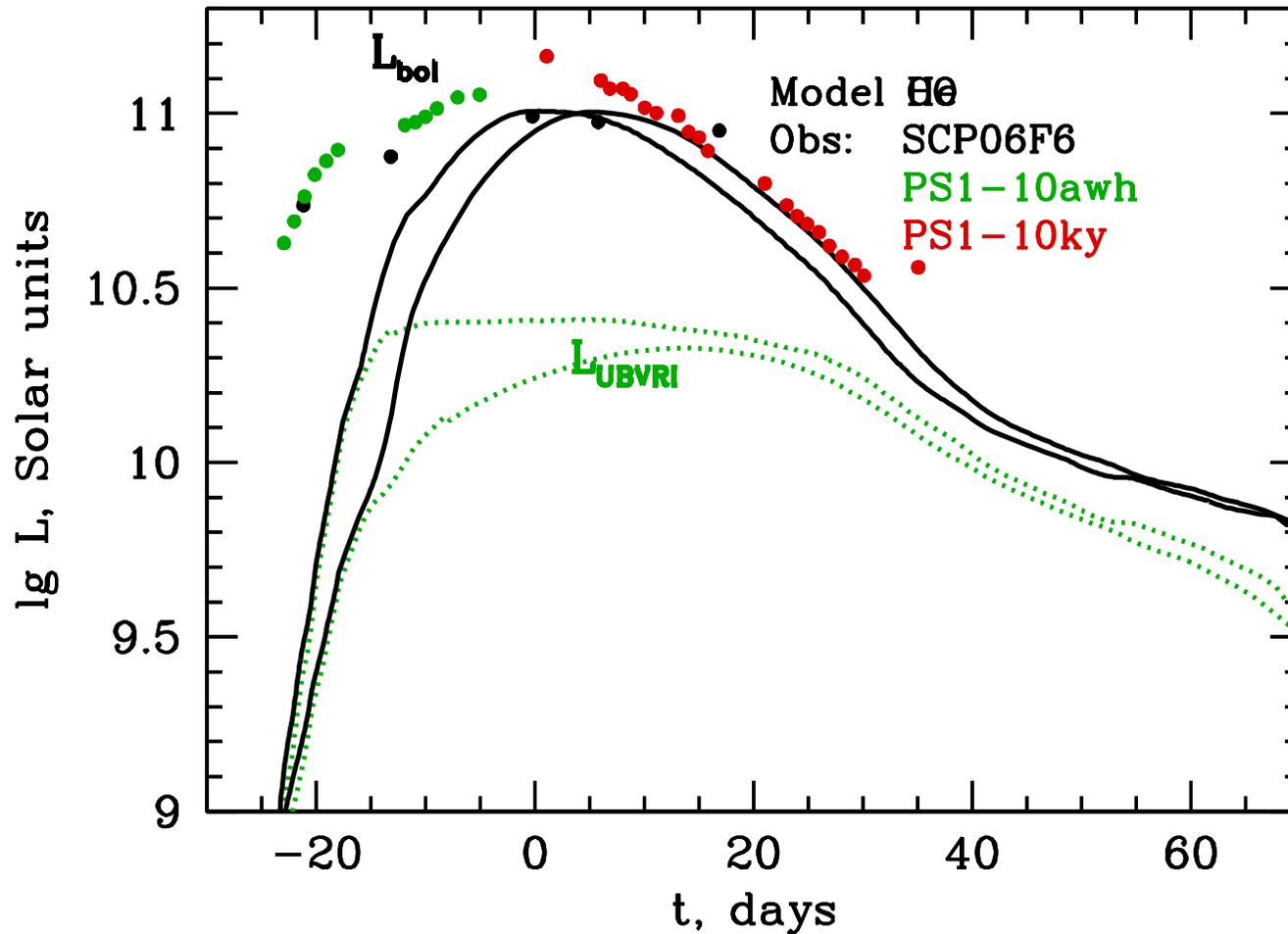
$$p = 1.8, M_w = 4.8M_\odot$$

CO vs. He wind



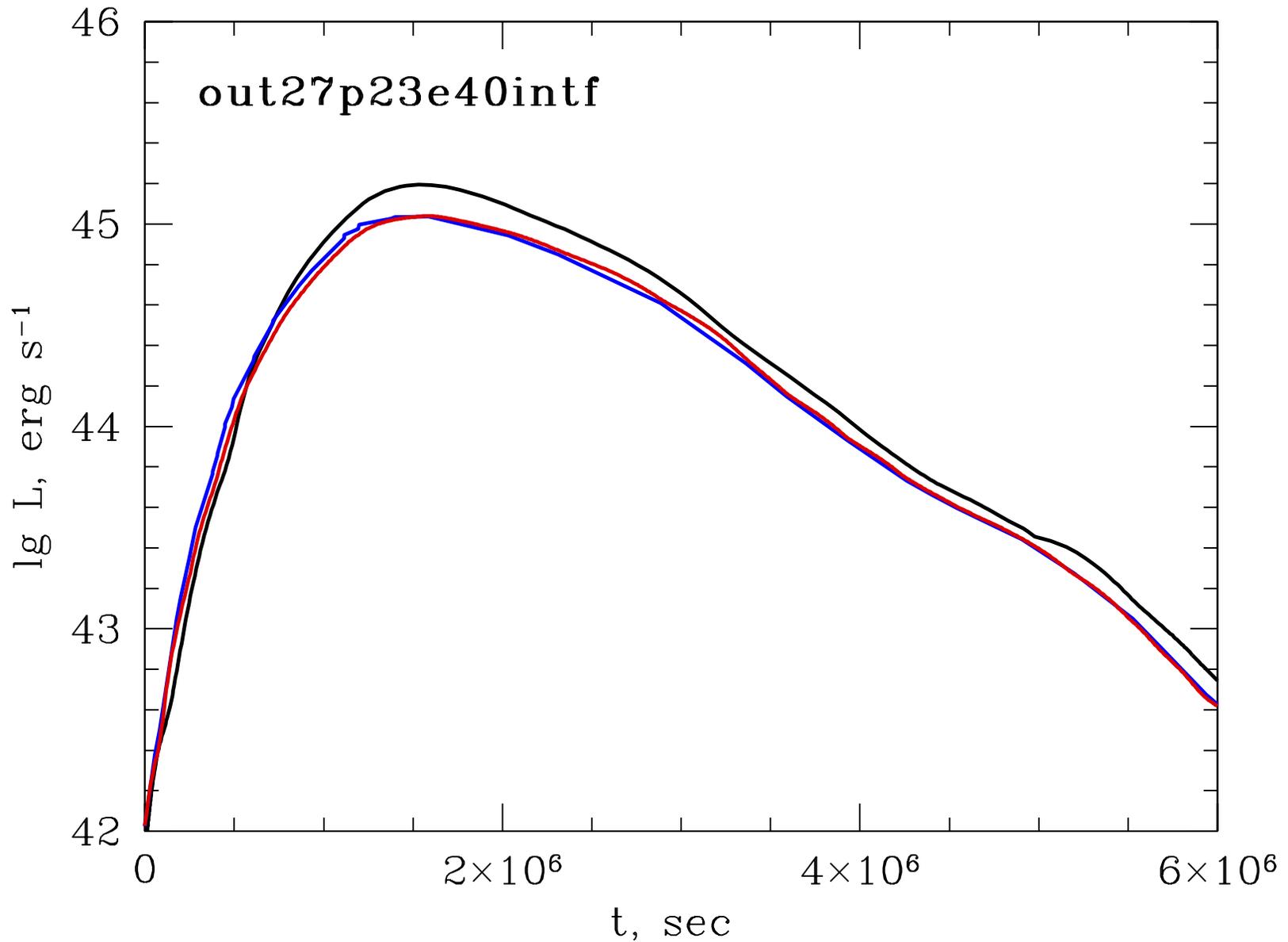
CO wind

CO vs. He wind

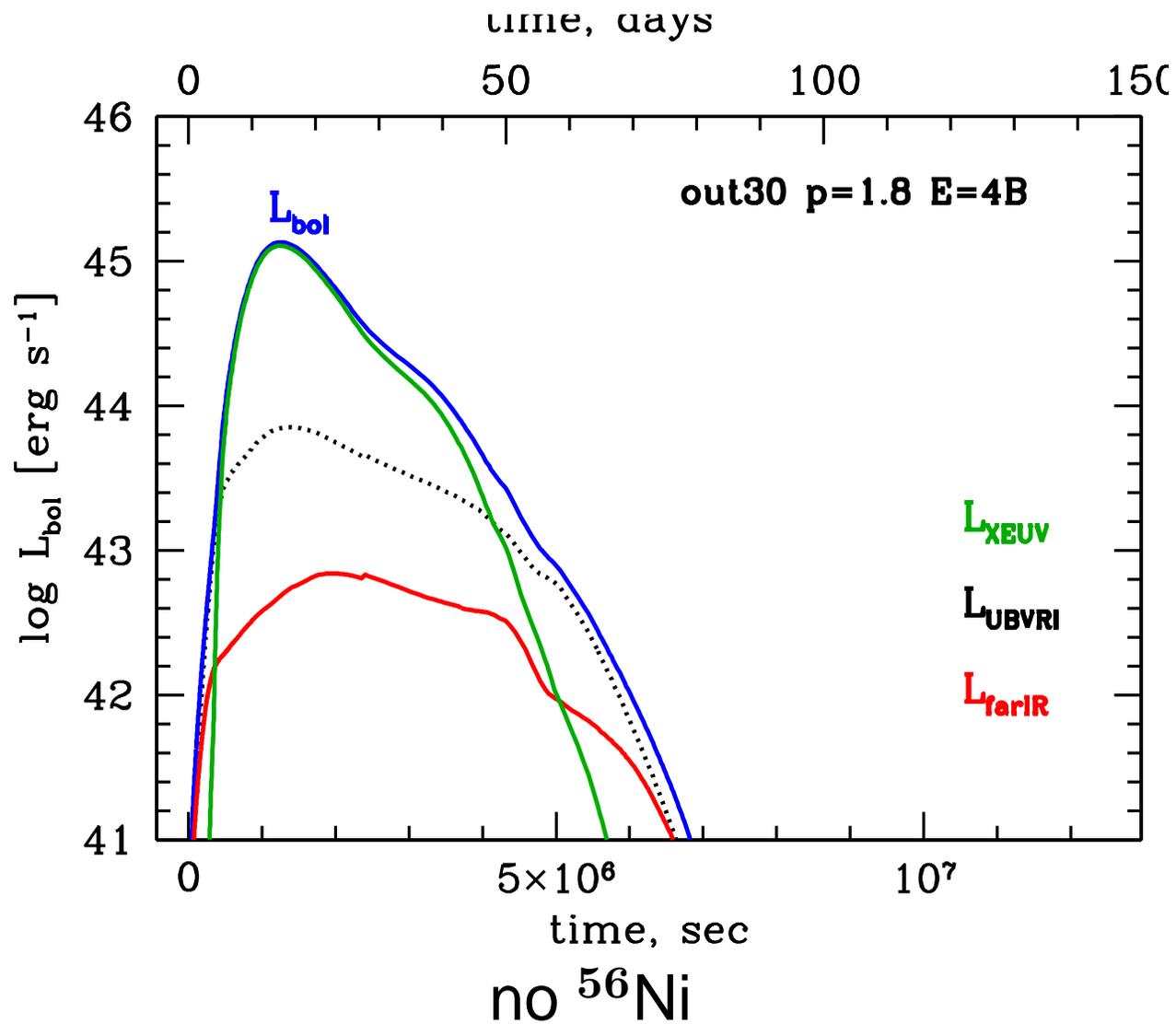


Model with He-wind is more symmetric around maximum light

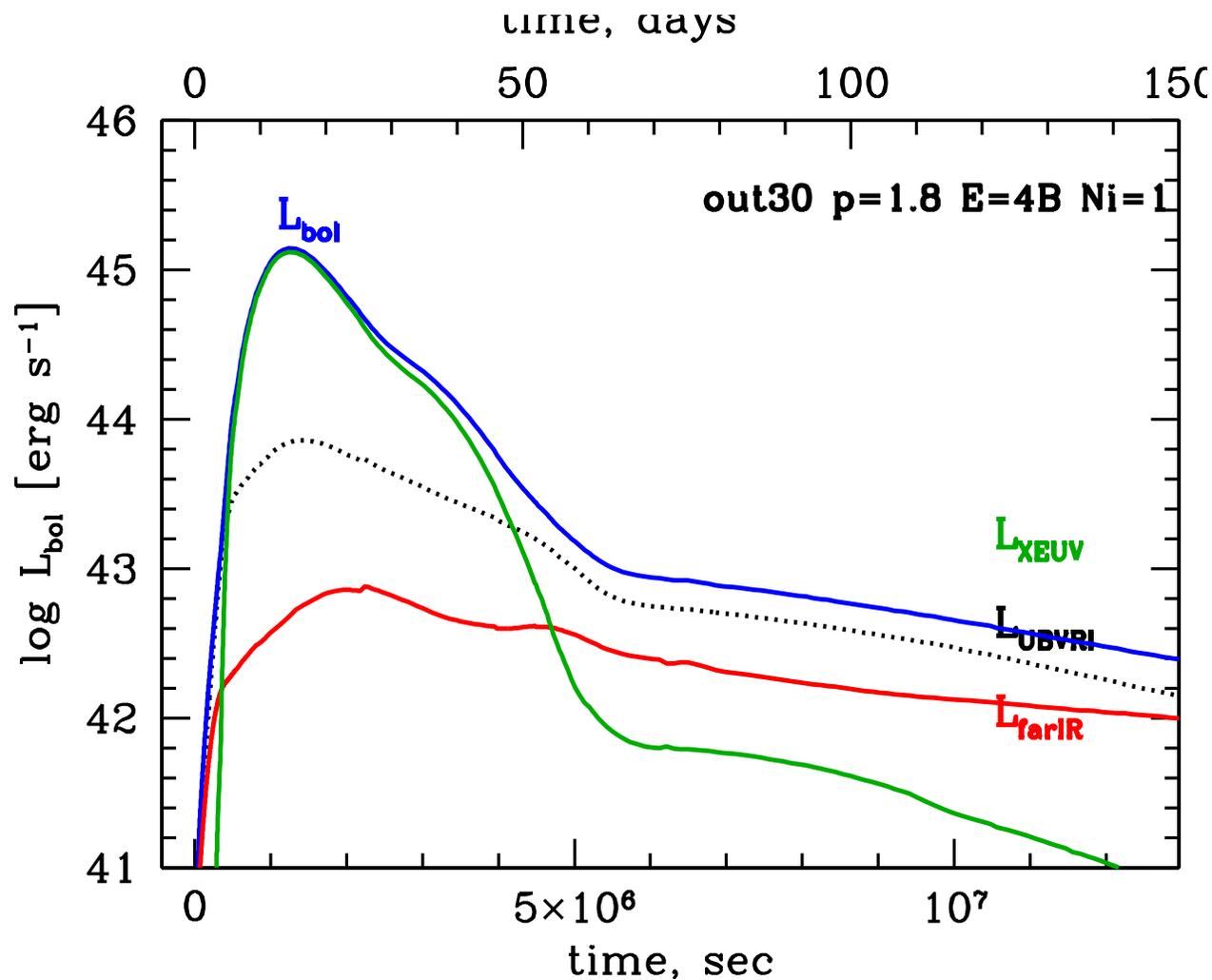
STELLA vs. RADA (colored)



^{56}Ni vs. Shock wave heating



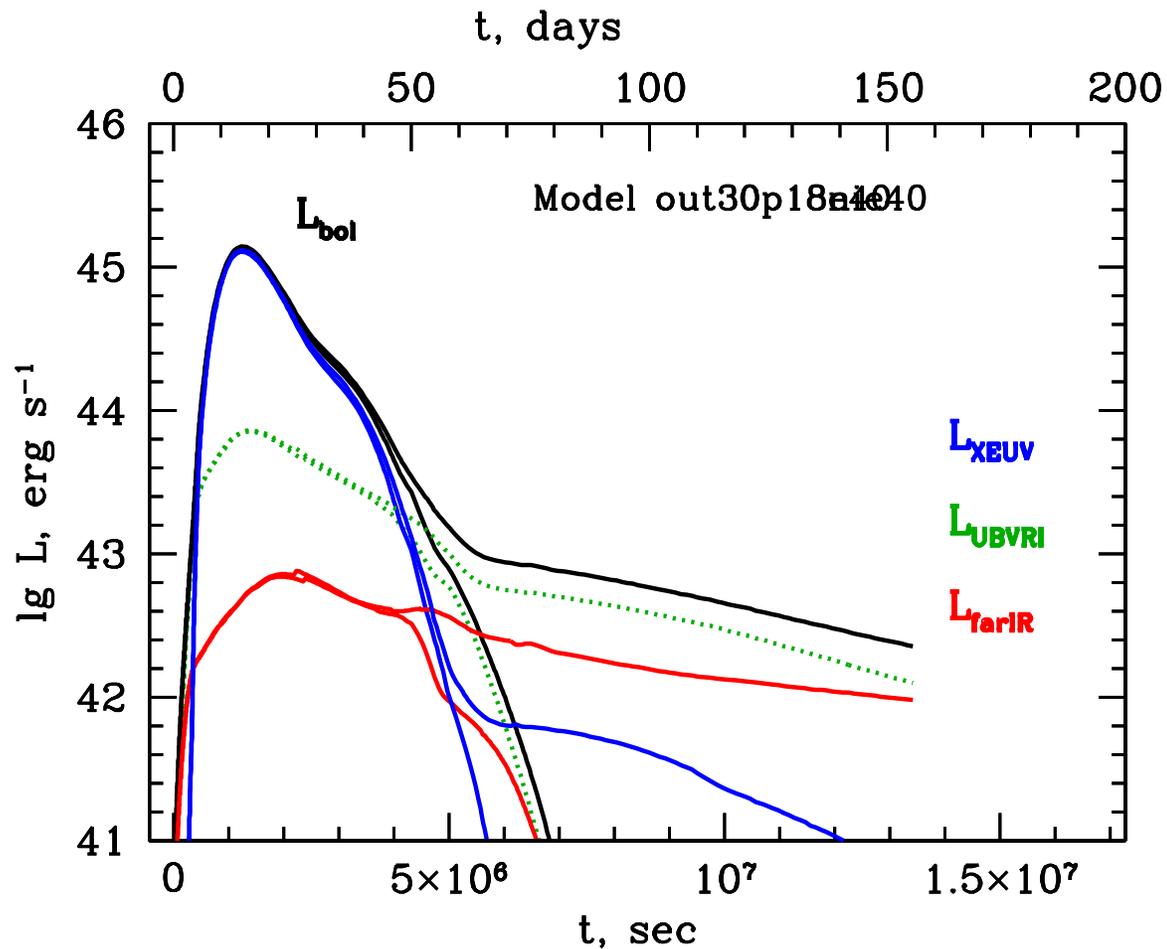
^{56}Ni vs. Shock wave heating



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

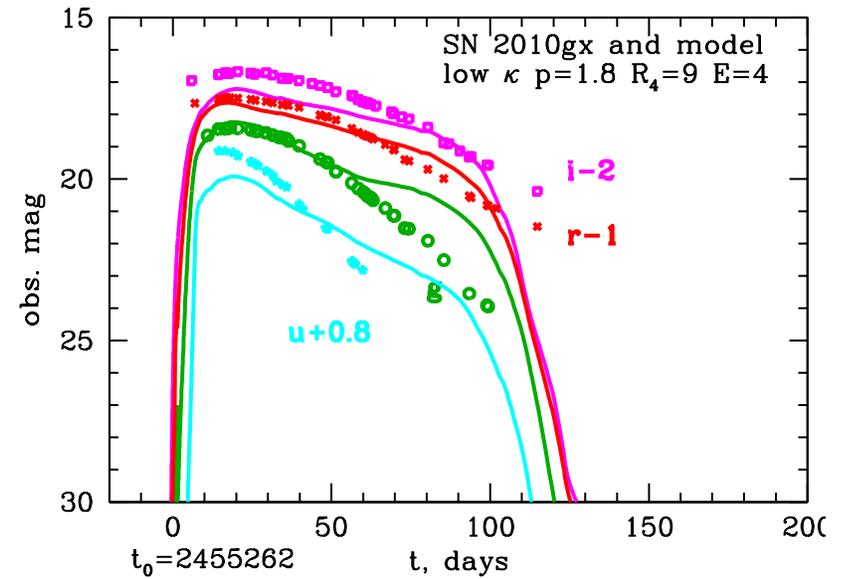
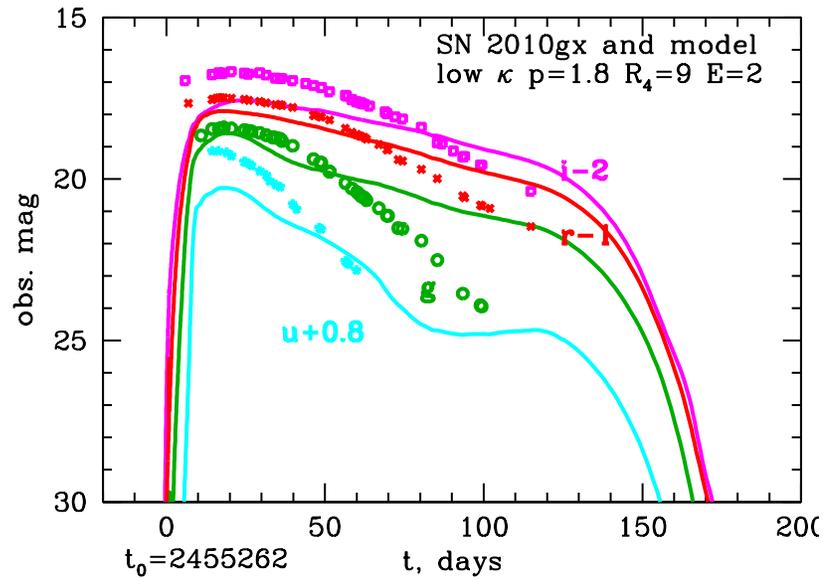
⁵⁶Ni vs. Shock wave heating

2 previous plots combined



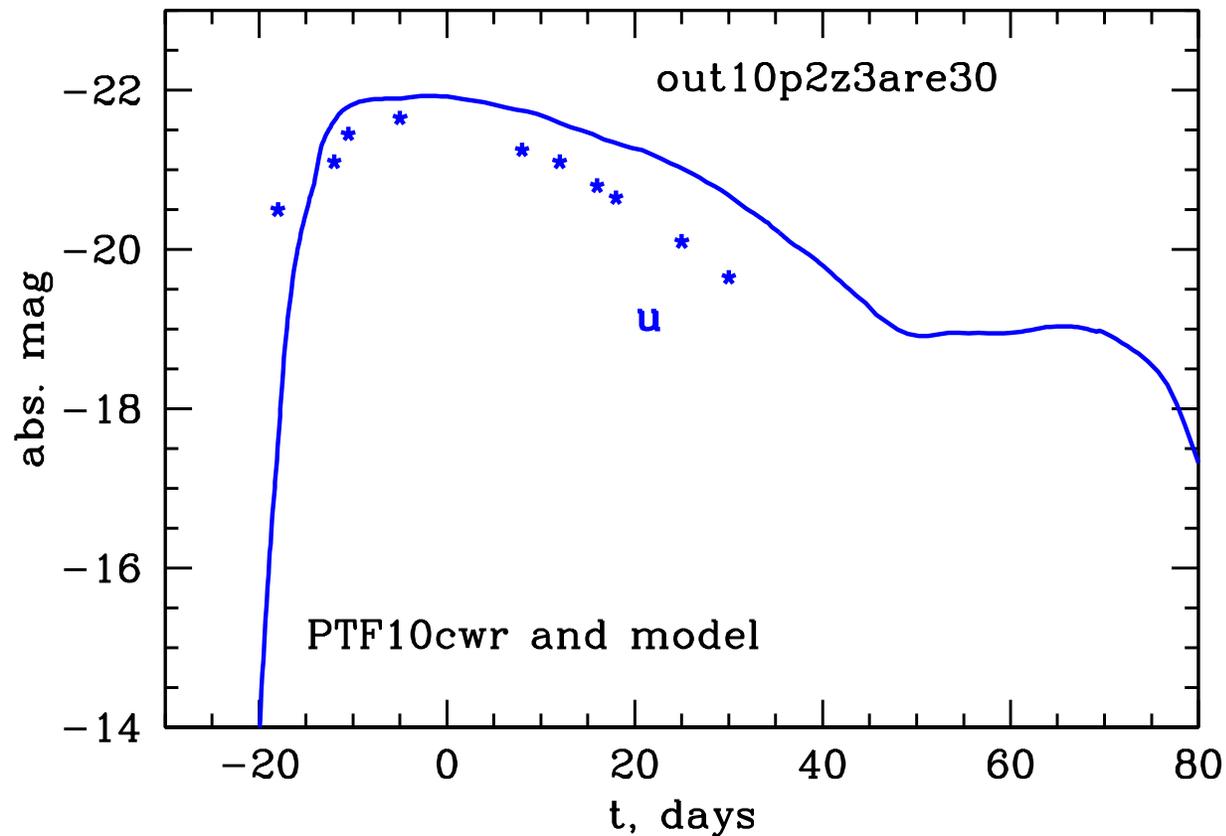
$M(^{56}\text{Ni}) = 1M_{\odot}$ added to the ejecta

Models for SN2010gx



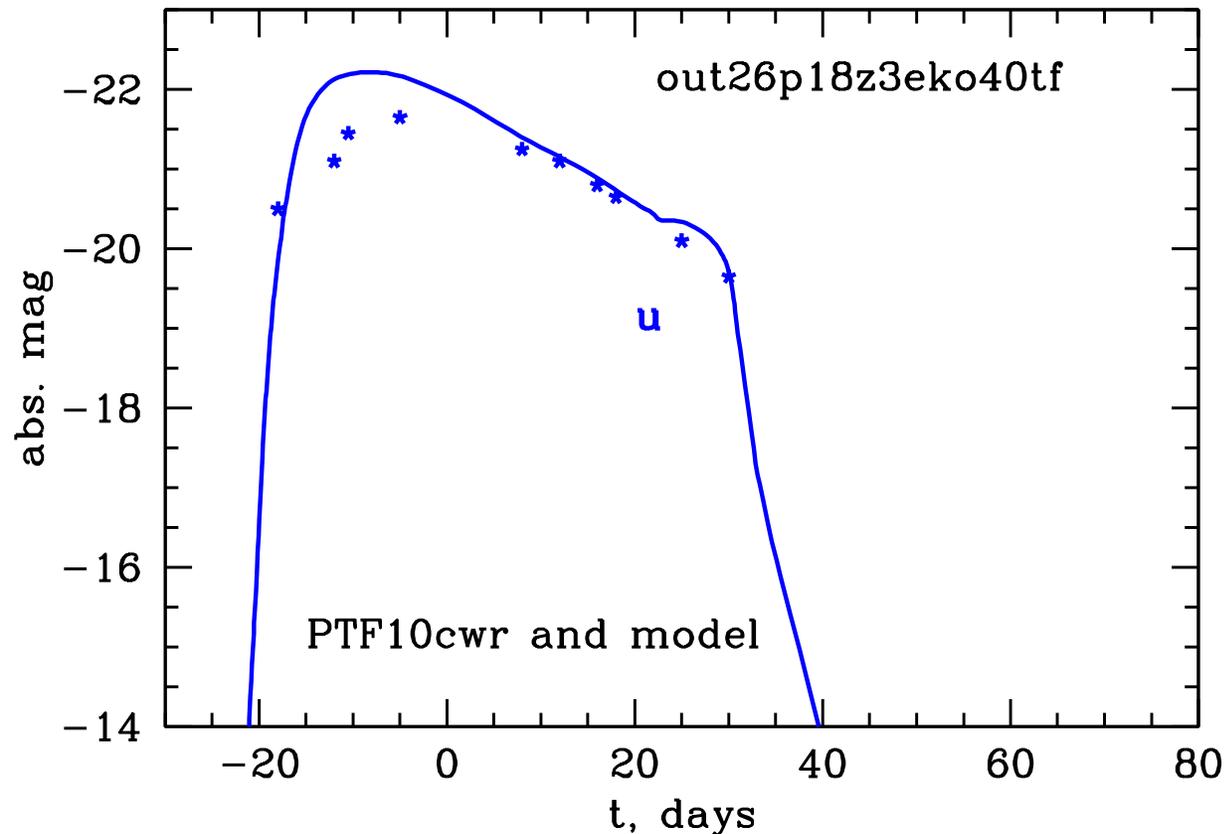
PTF10cwr=SN2010gx absolute u

$$\rho_w \propto r^{-2}, \quad E = 3 \text{ Bethe}$$



PTF10cwr=SN2010gx, double explosion

Fast moving “wind” $\rho_w \propto r^{-1.8}$, $E = 2 + 2$ Bethe



Basics for Cosmography

Photometric distance:

$$d_{\text{ph}}^2 = \frac{L(\text{emitted, ergs/s})}{4\pi F(\text{observed, ergs/s/cm}^2)}$$

Dependence on redshift z

$$d_{\text{ph}}(z)(\Omega_m, \Omega_{DE}, w(z)) | \text{theory}$$

is determined by cosmology. Comparison with the

$$d_{\text{ph}}(z)(\text{observed})$$

allows one to find $\Omega_m, \Omega_{DE}, w(z)$, etc.

Expanding Photosphere Method (EPM)

Cf. Baade(1926)-Wesselink(1946) method for Cepheids .
Measuring color and flux at two different times, t_1 and t_2 ,
one finds the ratio of the star's radii, R_2/R_1 (or from
interferometry).

Using weak lines which are believed to be formed near the
photosphere one can measure the photospheric speed v_{ph} .

Then $\int_{t_1}^{t_2} v_{\text{ph}} dt$ would give $\Delta R_{\text{ph}} = R_2 - R_1$.

Knowing R_2/R_1 and $R_2 - R_1$, it is easy to solve for the radii.
The ratio of fluxes gives

$$\frac{d^2}{R^2} = \frac{F_\nu(\text{emitted})}{F_\nu(\text{observed})} ,$$

hence the distance d .

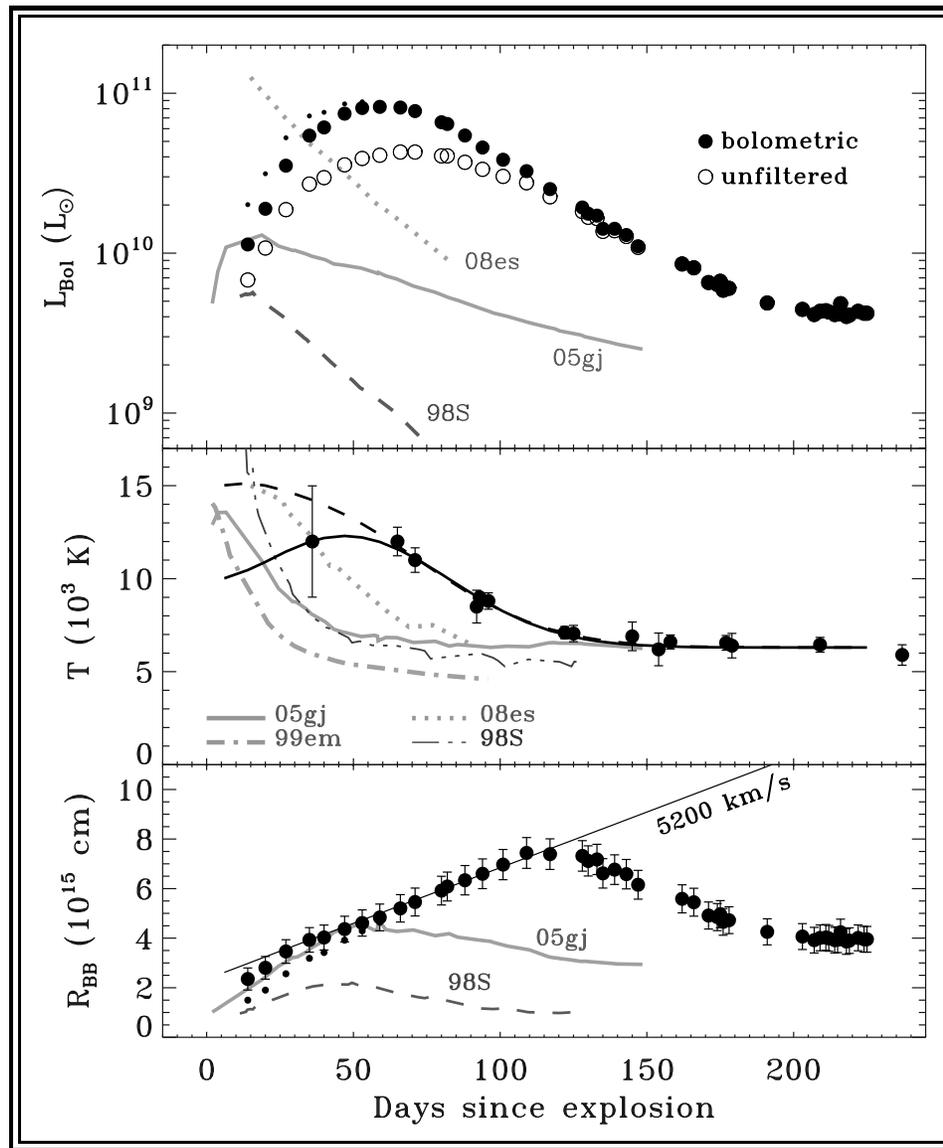
Distance from EPM

Now the distance d to the supernova is

$$d = R_{\text{ph}} \sqrt{\frac{F_{\nu}(\text{model})}{F_{\nu}(\text{observed})}}$$

if a reliable model flux $F_{\nu}(\text{model})$ at the SN photosphere is compared with the detected flux $F_{\nu}(\text{observed})$.

Observed $R(t)$ of SN2006gy



New DSM for SNe IIn

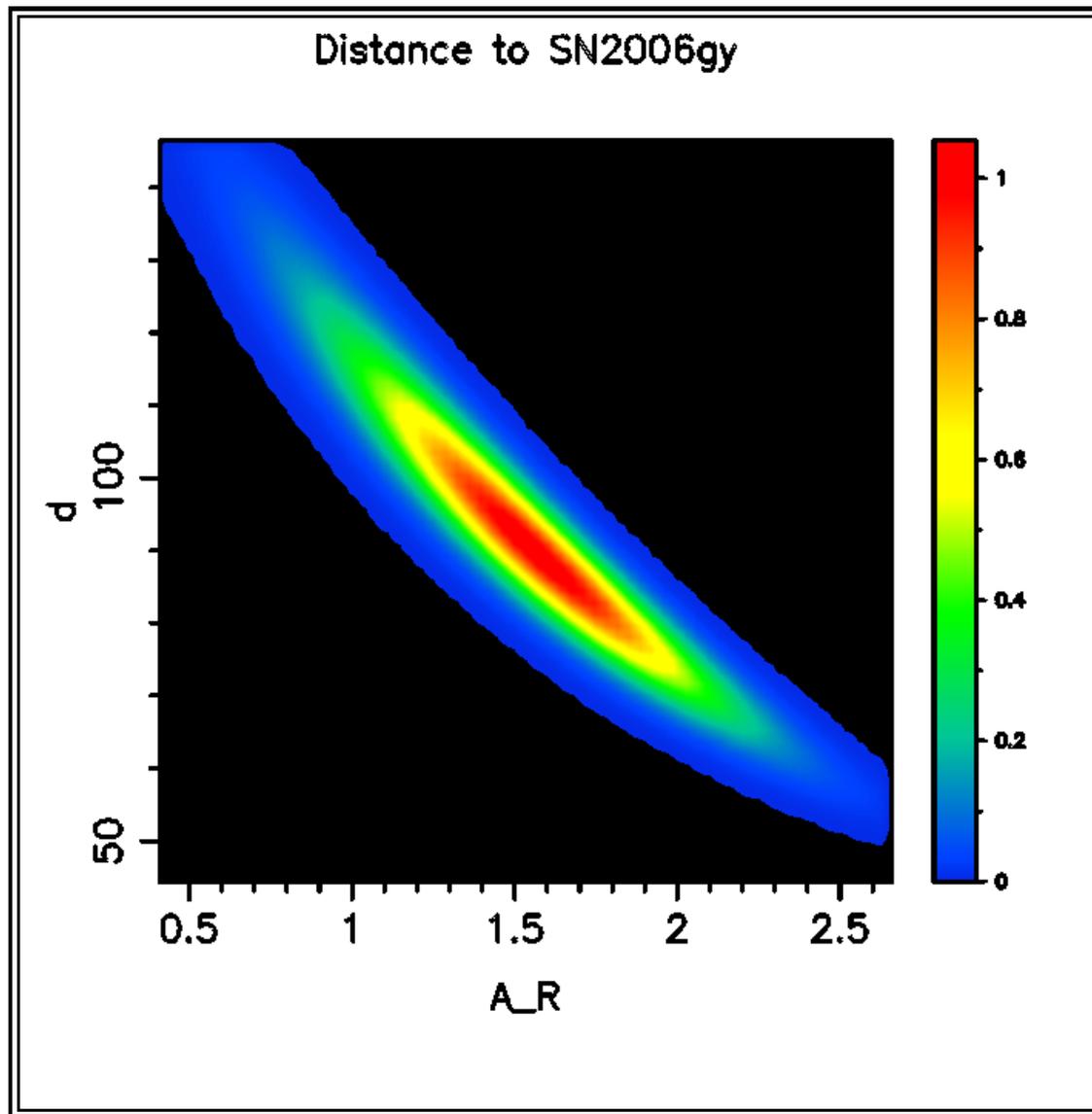
- Measure **narrow line** components to estimate the properties of CS envelope (may be done **crudely**).
- Measure **wide line** components to find the photospheric speed v_{ph} (**as accurately as possible**).
- Build a best fitting **model** for broad band photometry and the speed v_{ph} .

New DSM for SNe IIn

- Although the “Hubble”-law $v = r/t$ is not applicable, v_{ph} now measures **true** velocity of the photospheric radius (not only the matter flow speed, as in type II-P).
- Now the original Baade’s idea works for measuring the **radius by integrating v_{ph}** (of course, with due account of scattering, limb darkening etc in a time-dependent SEAM). This must be used when iterating the best fitting model.
- The observed flux then gives the **distance**.

MC probable d to SN 2006gy

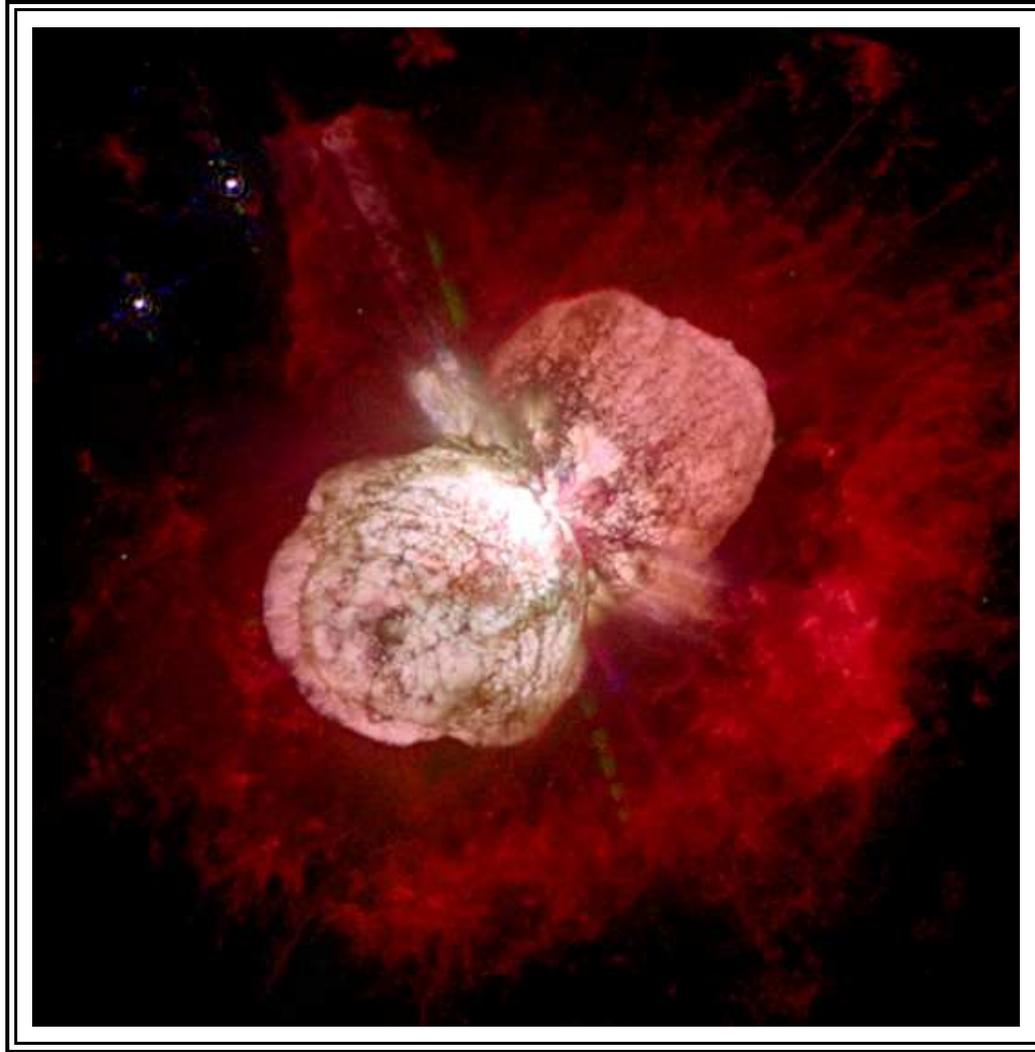
for $T = 9 \times 10^3$ K at day 80



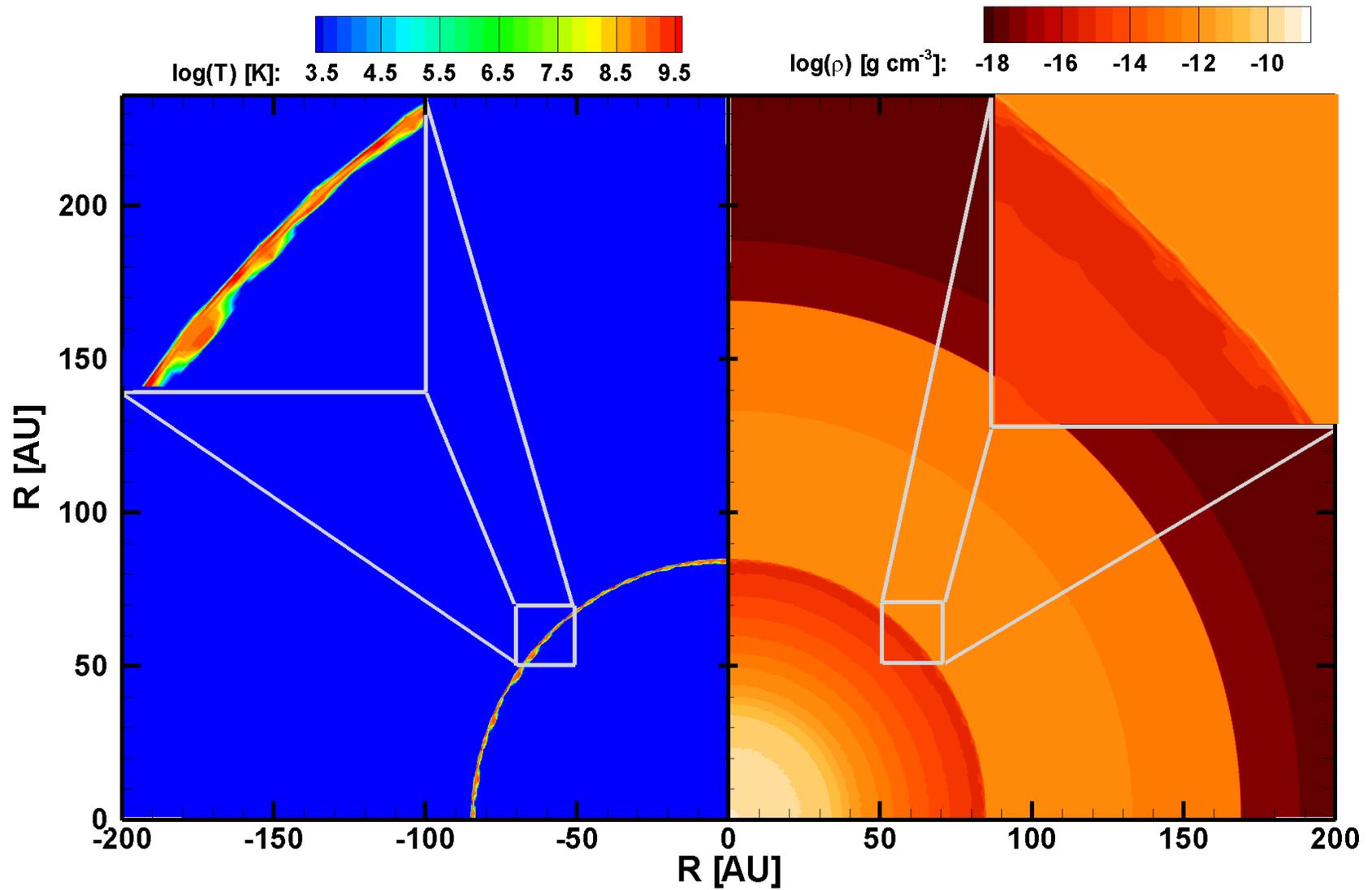
$$H_0 \approx 78 \pm 15 \text{ km/s/Mpc}$$

η Carinae: Multi-D is a must

for next steps in theoretical modeling

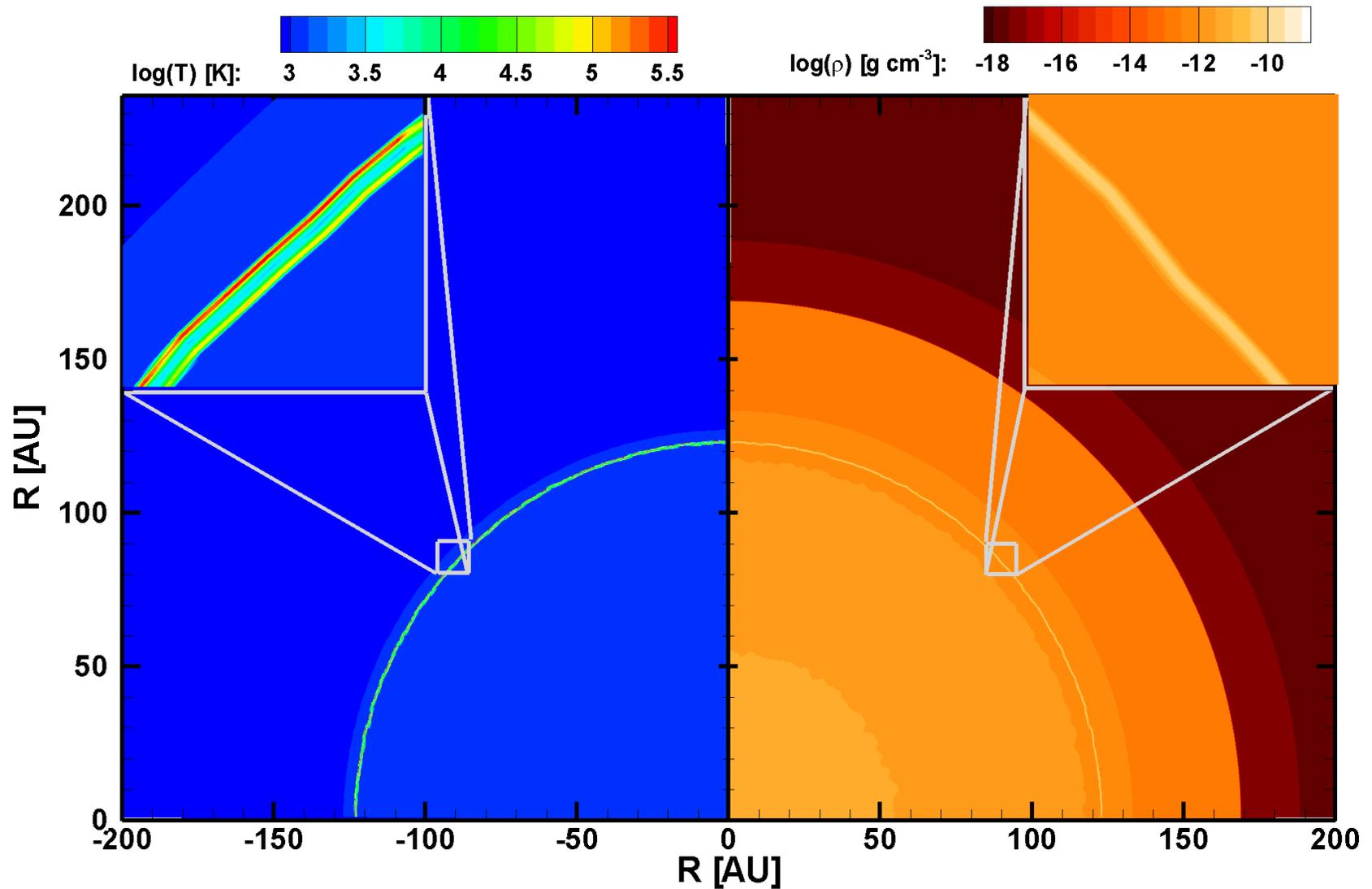


A. J. van Marle et al. MN 2010



23 days

A. J. van Marle et al. MN 2010



87 days

Summary on SN IIn in cosmology

- Radiating shocks are most probable sources of light in most luminous supernovae of type IIn like SN2006gy
- Most luminous SN IIn events may be observed at high z [for years due to $(1 + z)$] and may be useful as direct, **primary**, distance indicators in cosmology
- The new DSM is based on original Baade idea which really works now

Conclusions-1

- 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 $R \lesssim 10^{16}\text{cm}$. **NARROW LINES MAY NOT BE PRODUCED!**

Conclusions-2

- 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 II_n and Ib_n SNe. Is it possible to find C–O envelopes as well?)

Conclusions-3

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

Acknowledgements

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