New applications of type II Supernovae for extragalactic distance determinations

S.Blinnikov, based on paper with P.Baklanov, M.Potashov, in submission to MN

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ITEP, MPA, IPMU, SAI

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SNe in Cosmography

- Problems with SN Ia in cosmography

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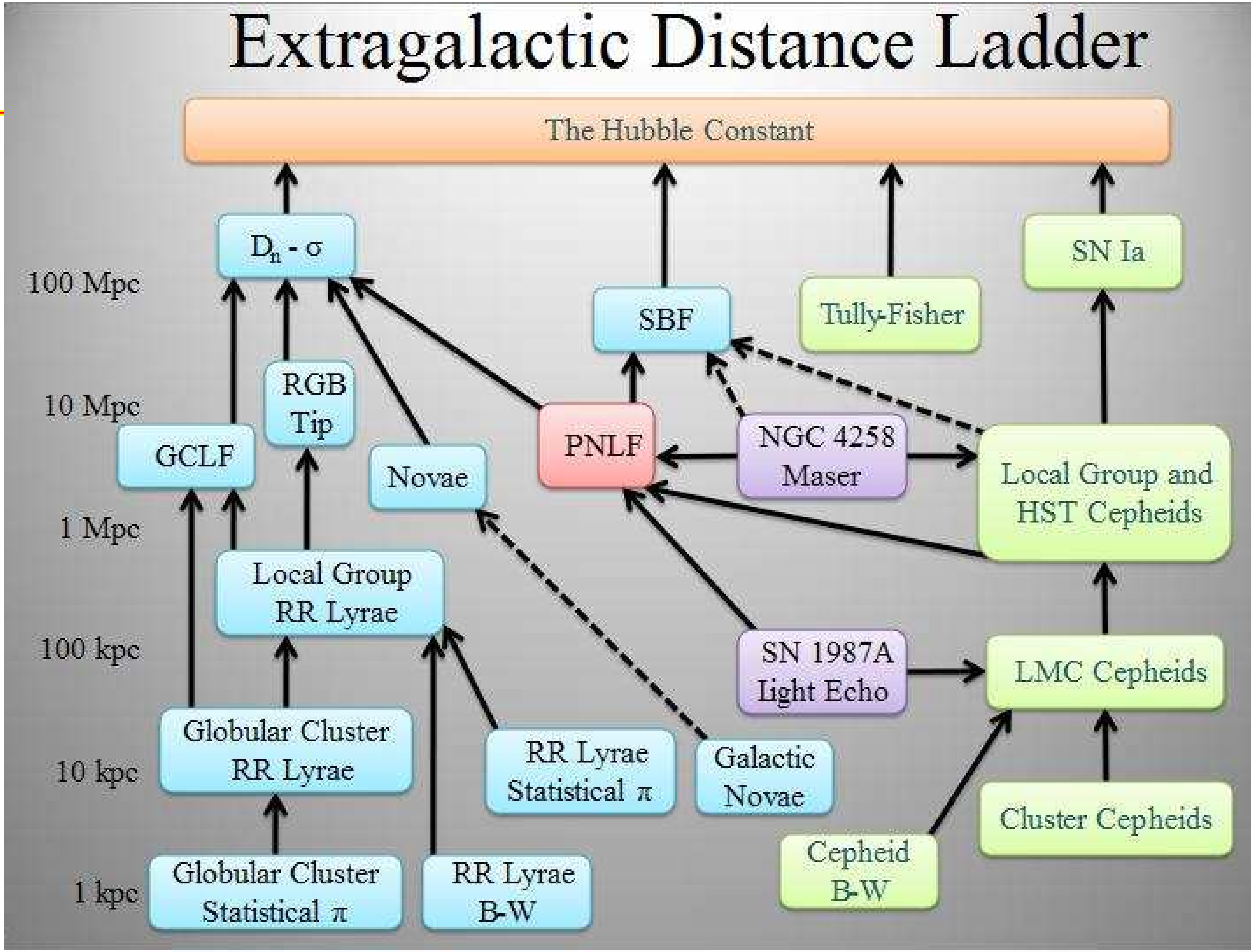
- Problems with SN Ia in cosmography
- Old direct Expanding Photosphere Method (EPM) for SNe II– advantages and problems
- A novel approach – most luminous SNe II: what is being done

The Cosmological Distance Ladder

Next few slides from various web-sites.
See e.g.
www.astr.ua.edu/keel/galaxies/distance.html


Extragalactic Distance Ladder
The Hubble Constant
D_n - σ
SBF
Tully-Fisher
SN Ia
100 Mpc
10 Mpc
1 Mpc
100 kpc
10 kpc
1 kpc
RGB Tip
GCLF
Novae
PNLF
NGC 4258 Maser
Local Group and HST Cepheids
Local Group RR Lyrae
SN 1987A Light Echo
LMC Cepheids
Globular Cluster RR Lyrae
RR Lyrae Statistical π
Galactic Novae
Cluster Cepheids
Cepheid B-W
Globular Cluster Statistical π
RR Lyrae B-W

Primary vs. Secondary Distance Indicators

Primary indicators are calibrated based on observations in our Galaxy

Secondary indicators rely on primary indicators to calibrate distances

- Trigonometric Parallax
- Converging Point
- Main Sequence Fitting
- Spectroscopic Parallax
- Cepheids, Baade-Wesselink (BW)
- Novae

- Tully-Fisher relation
- Fundamental plane
- Supernovae
- Globular Clusters
- Surface Brightness fluctuations
- Planetary Nebulae luminosity function

Toward an EG Distance Scale

Using Type-II Supernovae

Supernovae are among the most luminous phenomena in the universe, and may probe cosmological models. Type Ia supernova are currently the most favored secondary distance indicators. Although they are not uniform in luminosity, they are standardized based on statistical correlations found for nearby events.

Type II supernovae are interesting because there are ways to make them primary distance indicators.

Basics for Cosmography

Photometric distance:

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

Dependence on redshift z

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

is determined by cosmology. Comparison with the

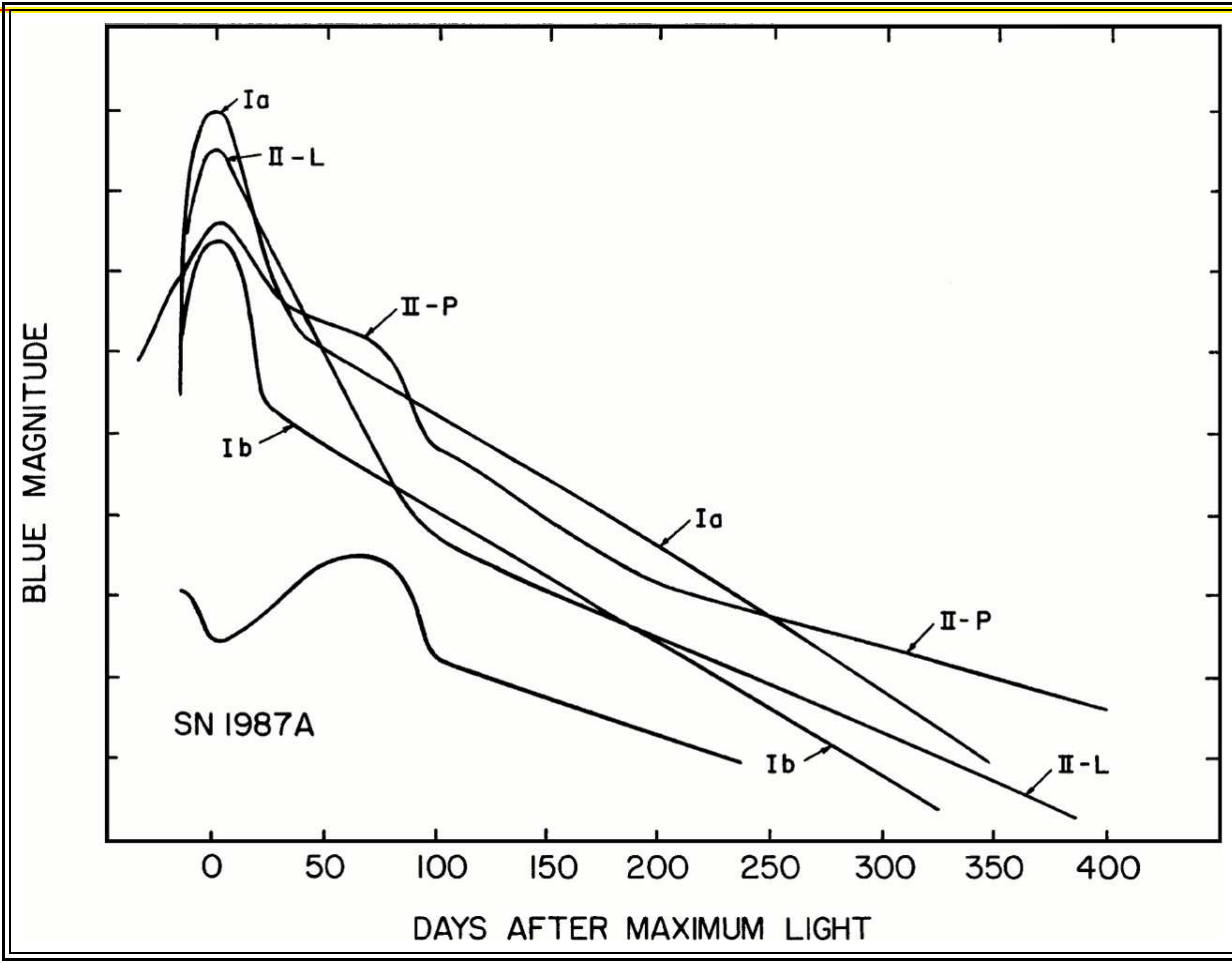
$$d_{\rm ph}(z)(\text{observed})$$

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

Thus, L is crucial

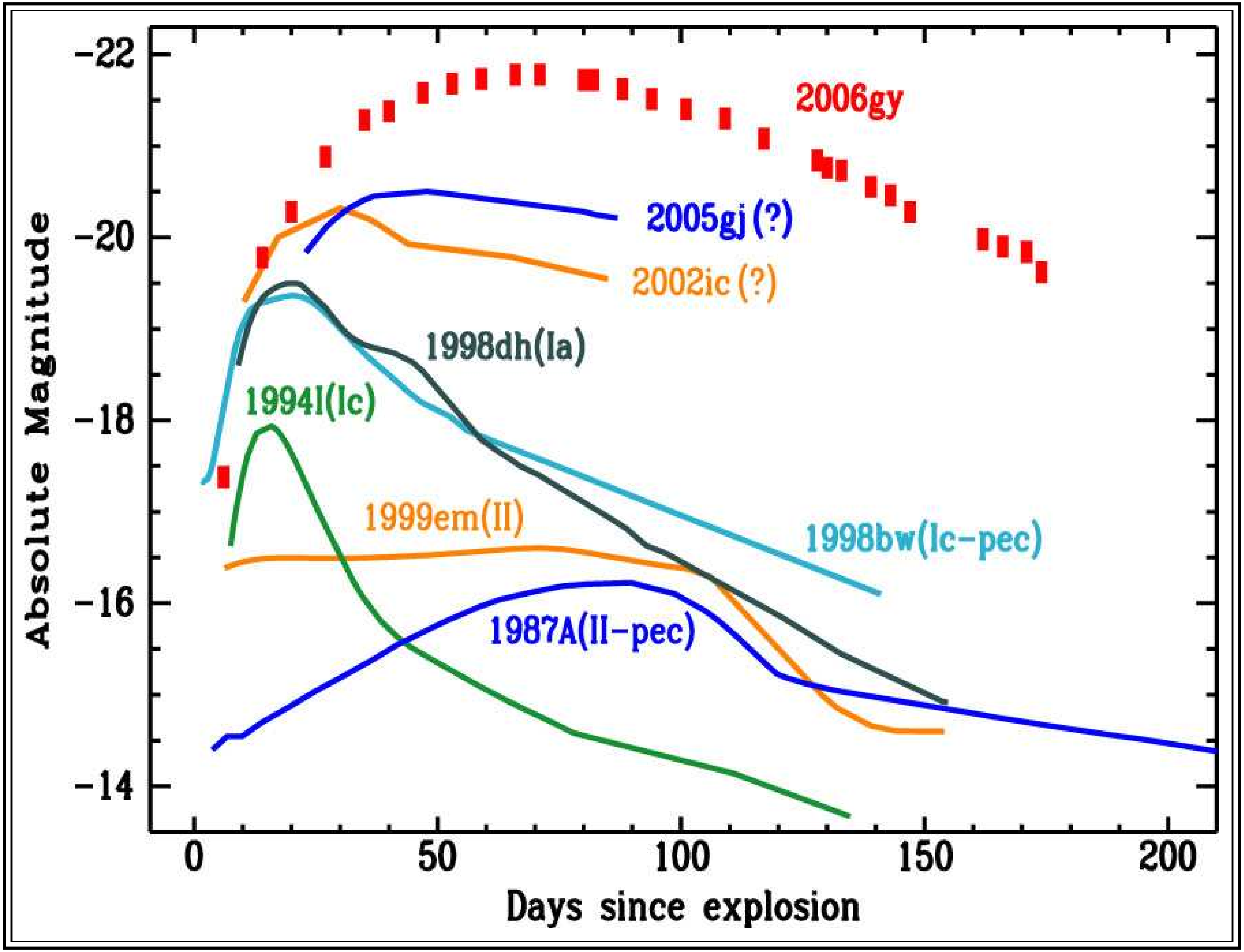
SNe are interesting to cosmology due to their brightness.
To understand possible systematic effects when using them one has to understand their physics.

SN Light Curves

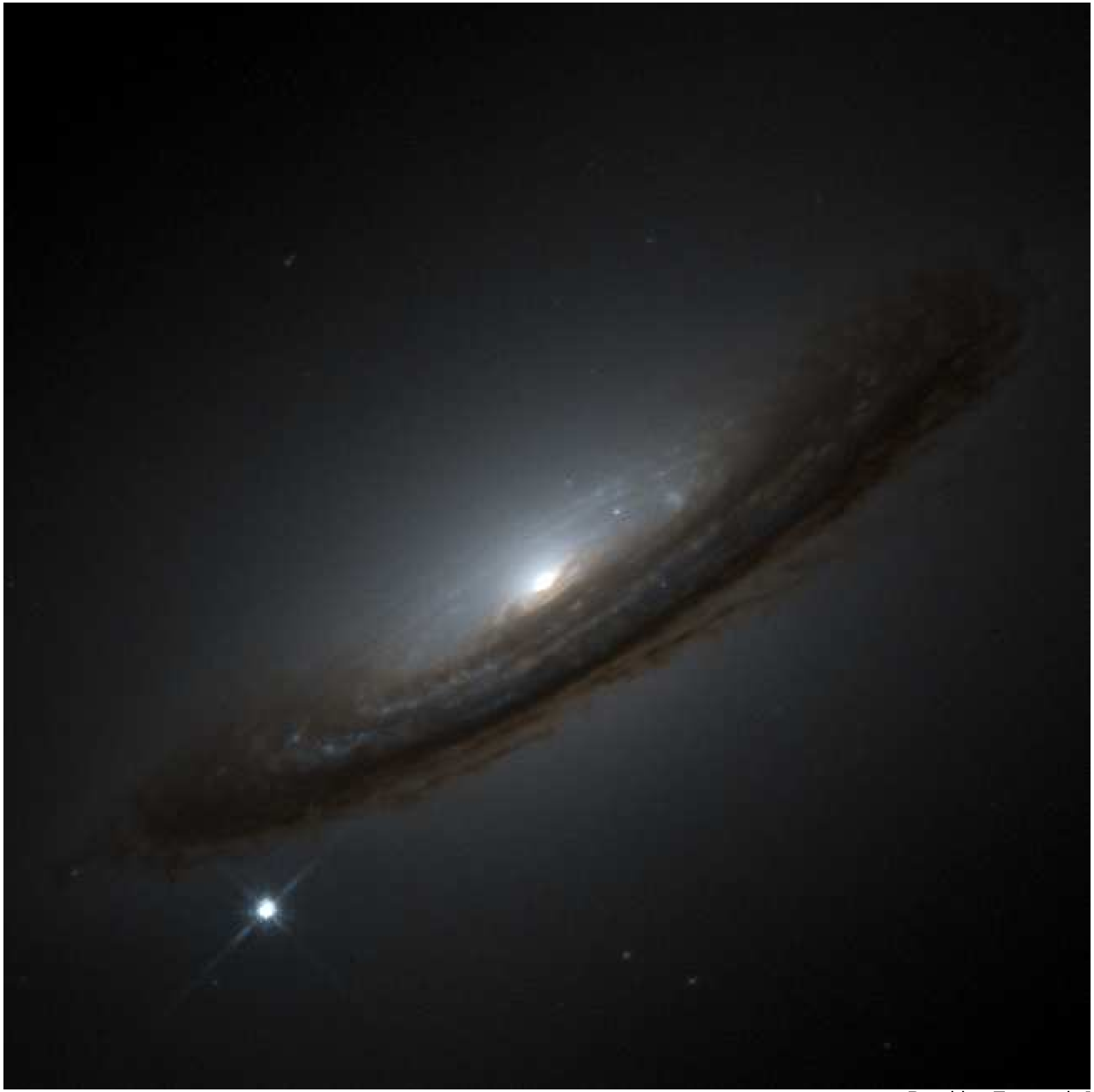


Most Luminous SNe

N.Smith ea'07

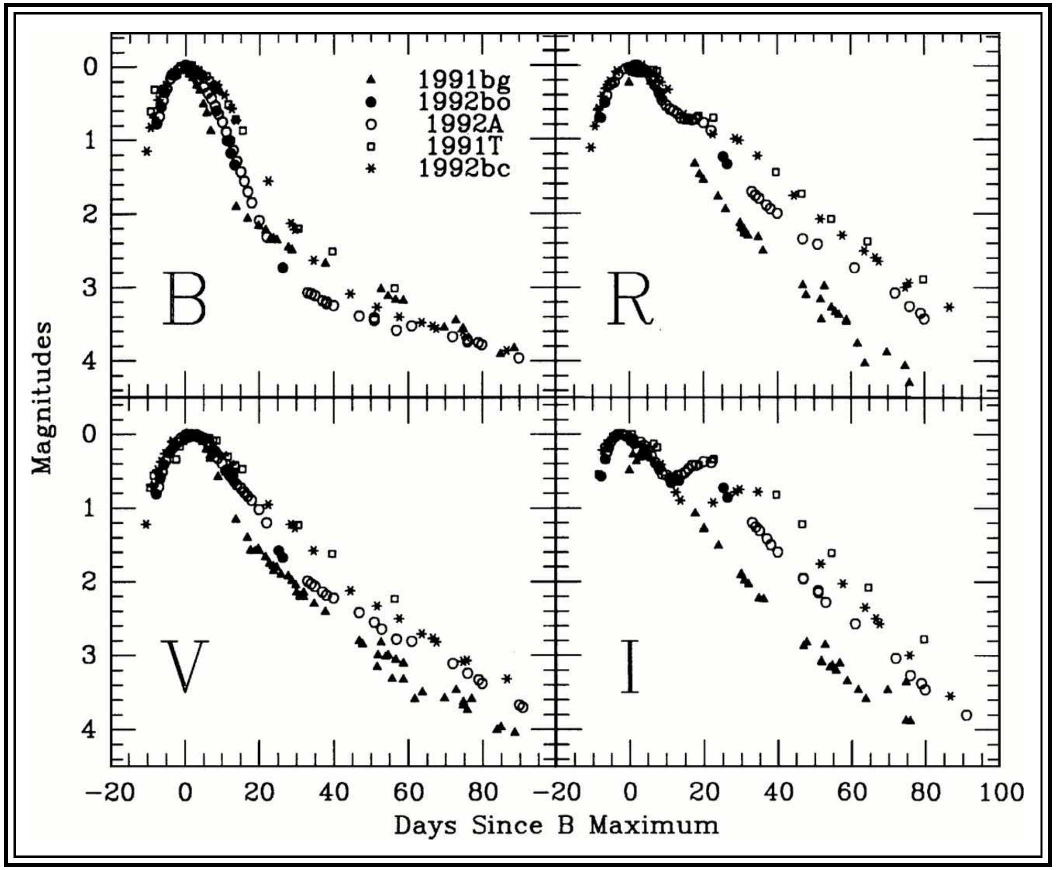


Type Ia SN1994D in NGC4526



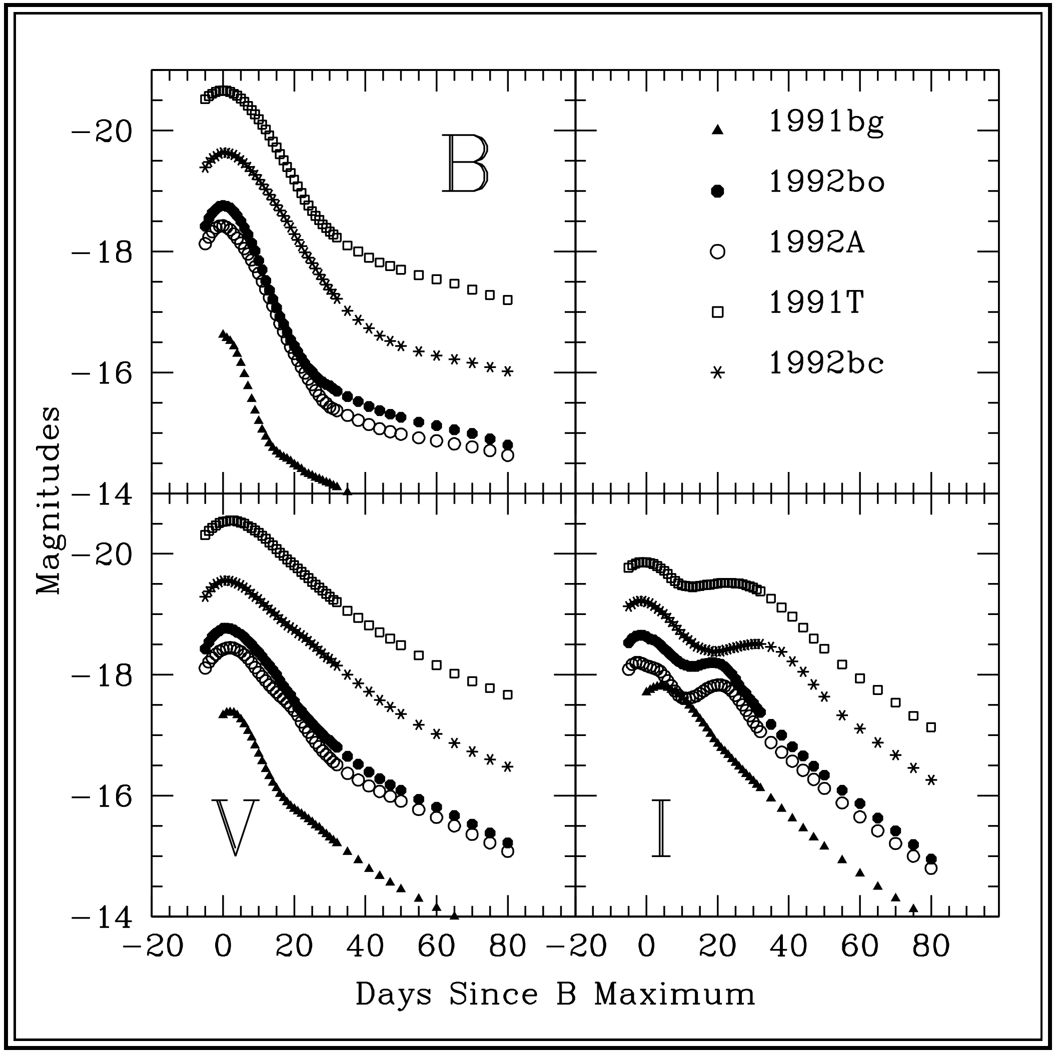
SN Ia Light Curves

N.Suntzeff (1996)



– seem to be alike, but not standard candles!

SN Ia LC Diversity

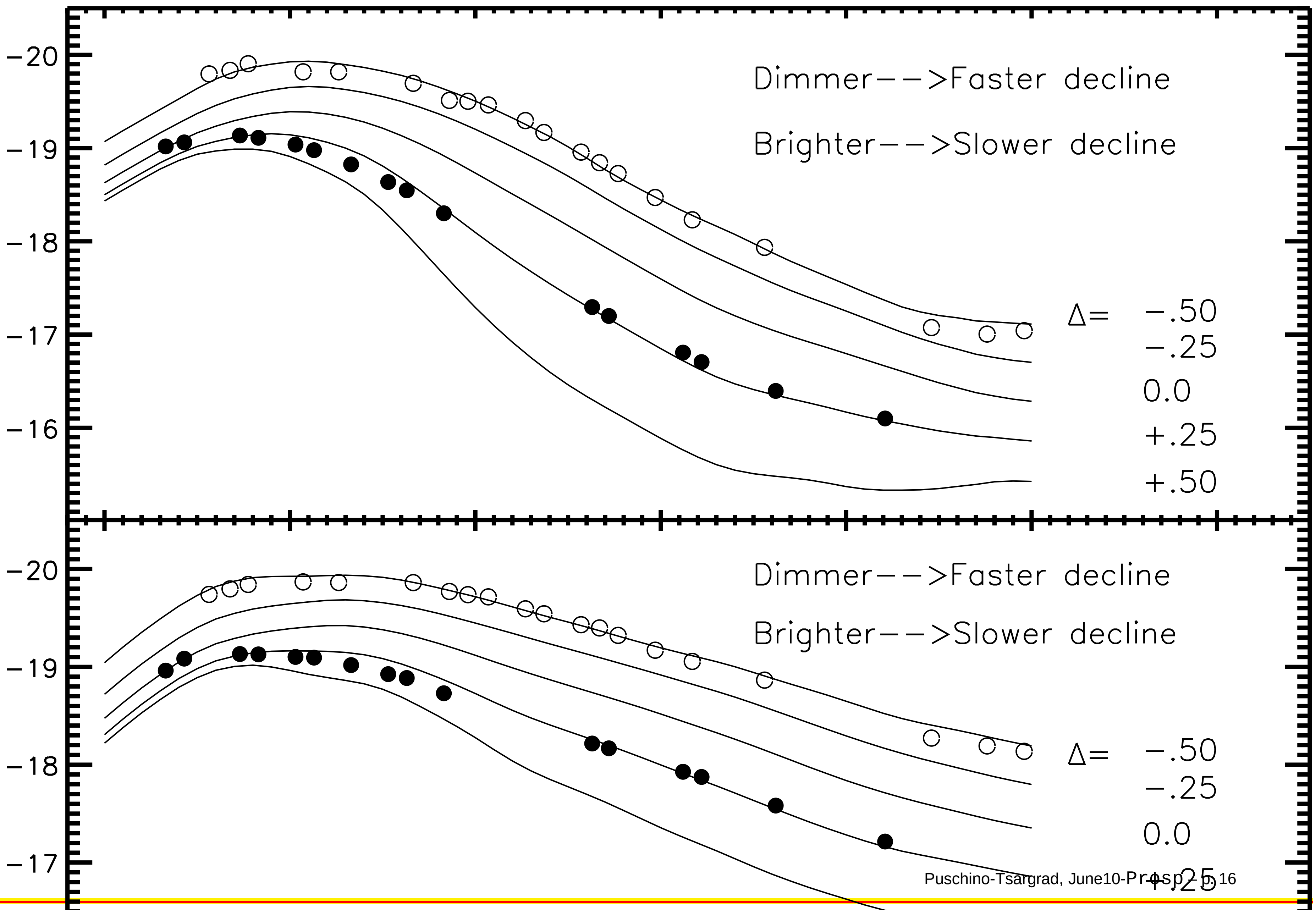


The same set of SN Ia in *BVI* filters but now the absolute luminosities are given

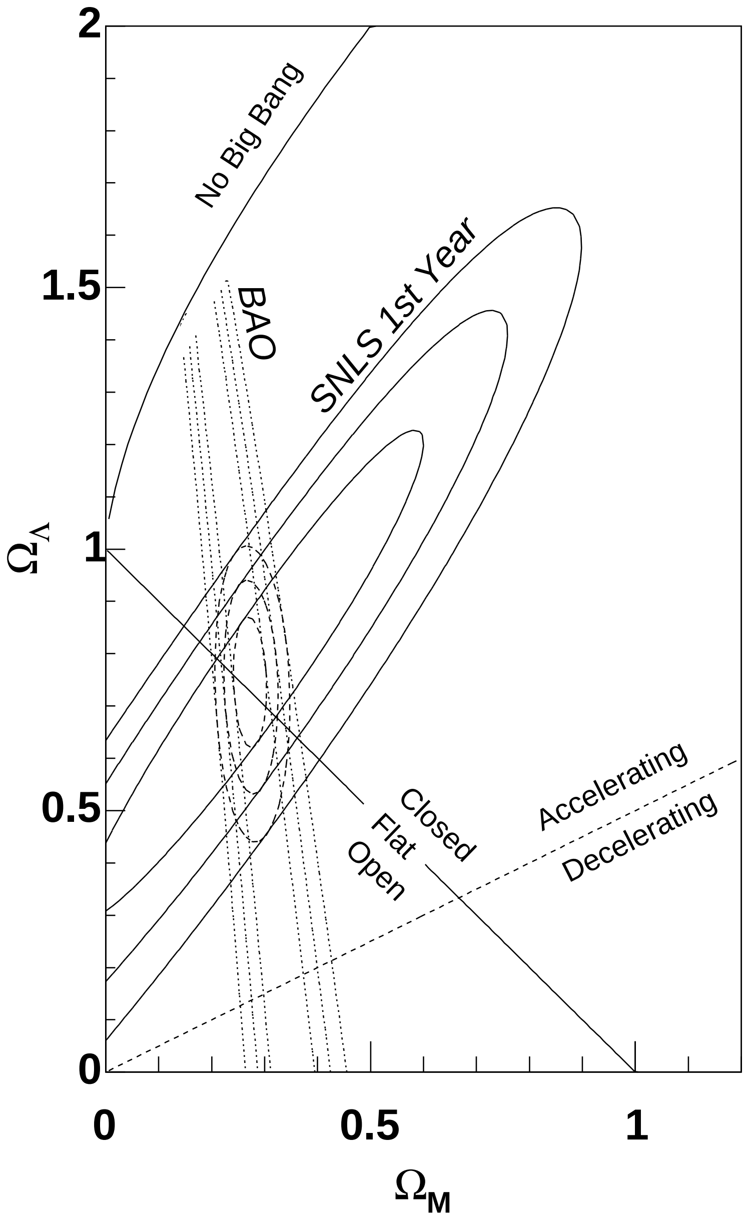
Type Ia diversity history

The luminosity L is derived from the peak luminosity – decline rate relation:
Yu.P. Pskovskii, Astron. Zh. **54**, 1188 (1977)
Luminosity-decline rate also (1967, 1984) – see the history in M.Phillips (Padua, 2004).
M.M. Phillips, ApJL **413**, L105 (1993)
— PP-relation, or WLR (Width-Luminosity-Relation), or BDR (Brightness-Decline-Rate)
(an example is $B - \Delta m_{15}$ correlation).

More luminous are slower



$(\Omega_m, \Omega_\Lambda)$ cosmology, SNLS



68.3%, 95.5% and 99.7% confidence levels for the SNLS Hubble diagram (solid contours), the SDSS baryon acoustic oscillations (Eisenstein et al. 2005, dotted lines), and the joint confidence contours (dashed lines). (Astier et al., 2006).

Systematics and z-dependence

- Intergalactic extinction

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- Intergalactic extinction
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- Relative role of different preSN Ia (e.g. SD vs. DD) with the age of Universe
- Misclassification of SNe

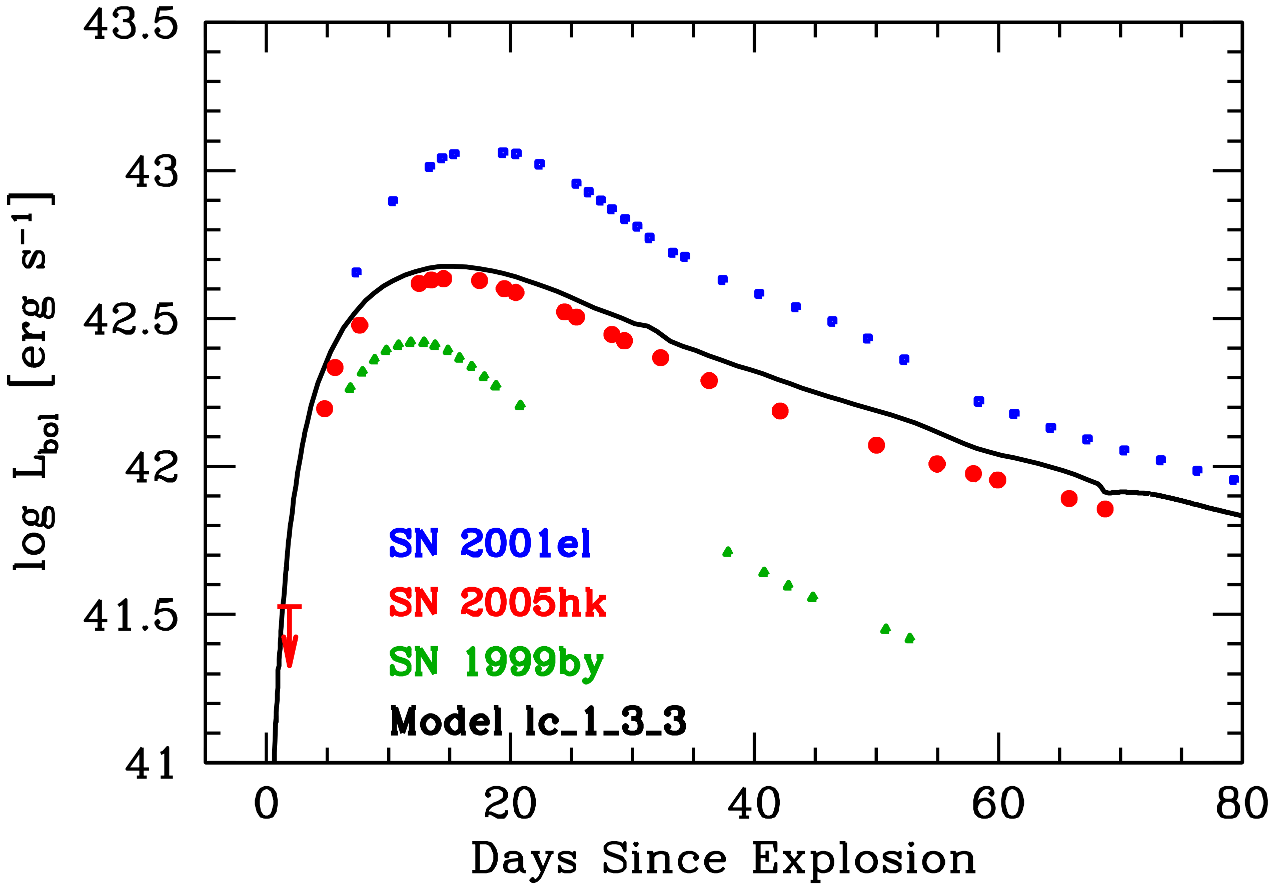
Admixture of Ia subtype events

The case of peculiar SN 2002cx: Weak, but slow! High ionization near maximum

See e.g. W.Li et al., 2003, astro-ph/0301428, $m - M = 35.09 \pm 0.3$

Many new of this subtype are discovered, e.g. SN 2005hk, see our paper M.Phillips et al. (2007)

SN 2005hk vs an MPA model



SN 2003fg: a super-Chandra-mass S

Howell et al. 2006 have reported the discovery of SN Ia SN 2003fg (SNLS-03D3bb): very likely a super-Chandrasekhar-mass SN Ia perhaps with a mass $\sim 2\,M_{\odot}$. Their work is the first strong evidence that has been presented for a super-Chandrasekhar SN Ia.

Scalzo et al., 2010

There may be a population of SNe Ia with a distribution of masses greater than M_{Ch}, with different explosion physics that interferes with luminosity standardization. The relative rate of such events among SNe Ia in general may also depend on redshift, and they need not be common to produce significant biases in reconstructions of the dark energy equation of state.

Other super-Chandra-mass SN Ia ?

At least four examples of overluminous SN Ia explosions with progenitor mass probably exceeding $M_{\rm Ch}$.
The first was SN 2003fg Howell ea'06;
then SN 2006gz Hicken ea'07,
SN 2007if Yuan ea'07,
and SN 2009dc Tanaka ea'09, Yamanaka ea'09, Silverman ea'10
were discovered later as events similar to SN 2003fg.

The main evidence for a very massive progenitor was the extremely high luminosity, hence unusually large ^{56}Ni synthesis.

Another interpretation Hillebrandt et al., 2007.

Anyway, a problem with standardization of I a.

SNe Ia vs. SNe II

SNe Ia are more luminous (on average) than SNe II. But the duration of maximum light is much longer for SNe II. Some SN II compete with most luminous type Ia's.

The physics of SNe Ia emission is more complicated: no true photosphere, more deviations from LTE.

Type II SNe show a rich variety of light curves and they clearly are not the 'standard candles'. But hydrogen provides for a real photosphere for a couple of months in many classical "plateau" light curve events.

The hydrogen envelope makes SNe II light much less dependent on details of the explosion mechanism.

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 $v_{\rm ph}$.

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

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.

Questions to BW assumptions

Alexei Rastorguev will discuss Baade-Wesselink for Cepheids in detail tomorrow at Sternberg.

I point out only one basic assumption, questioned already by Charles Whitney in his paper
The Radii of δ Cephei and η Aquilae. II.
1955ApJ...122..385W

“However, the Wesselink method assumes that
(a)equal color means equal surface brightness and
(b) surface displacements may be derived from the radial-velocity-curve.
The present agreement between the photometric and Wesselink analyses substantiates, but does not prove, the validity of these assumptions.”

Problems with BW

The assumption $v_{\rm ph} = dR_{\rm ph}/dt$ does not work (as a rule) in exploding stars! Velocity of matter at the photosphere is not at all $dR_{\rm ph}/dt$. The $v_{\rm ph}$ and $dR_{\rm ph}/dt$ may even have different signs!

BW applied for Novae:
McLaughlin 1936AJ.....45..145M – distances measured
Beer 1937MNRAS..97..231B – problems pointed out, but not clarified

BW for SNe:
Mustel 1972SvA....15..527M

Modern Baade-Wesselink Cepheids and problems:

Nardetto et al. 2009

Pedicelli ea arXiv:1003.3854

Kirshner & Kwan, 1974

The main idea of EPM for SNe is different from BW!
(Kirshner & Kwan were the first?)

Using weak lines one can measure the matter velocity on photospheric level, $v_{\rm ph}$, and then find,

$$R_{\rm ph} = v_{\rm ph}(t - t_0) \; .$$

This is based on the assumption of free expansion,

$$v = r/t \propto r \; ,$$

– like a Hubble law. Velocity is not assumed to be $dR_{\rm ph}/dt$.

Distance from EPM

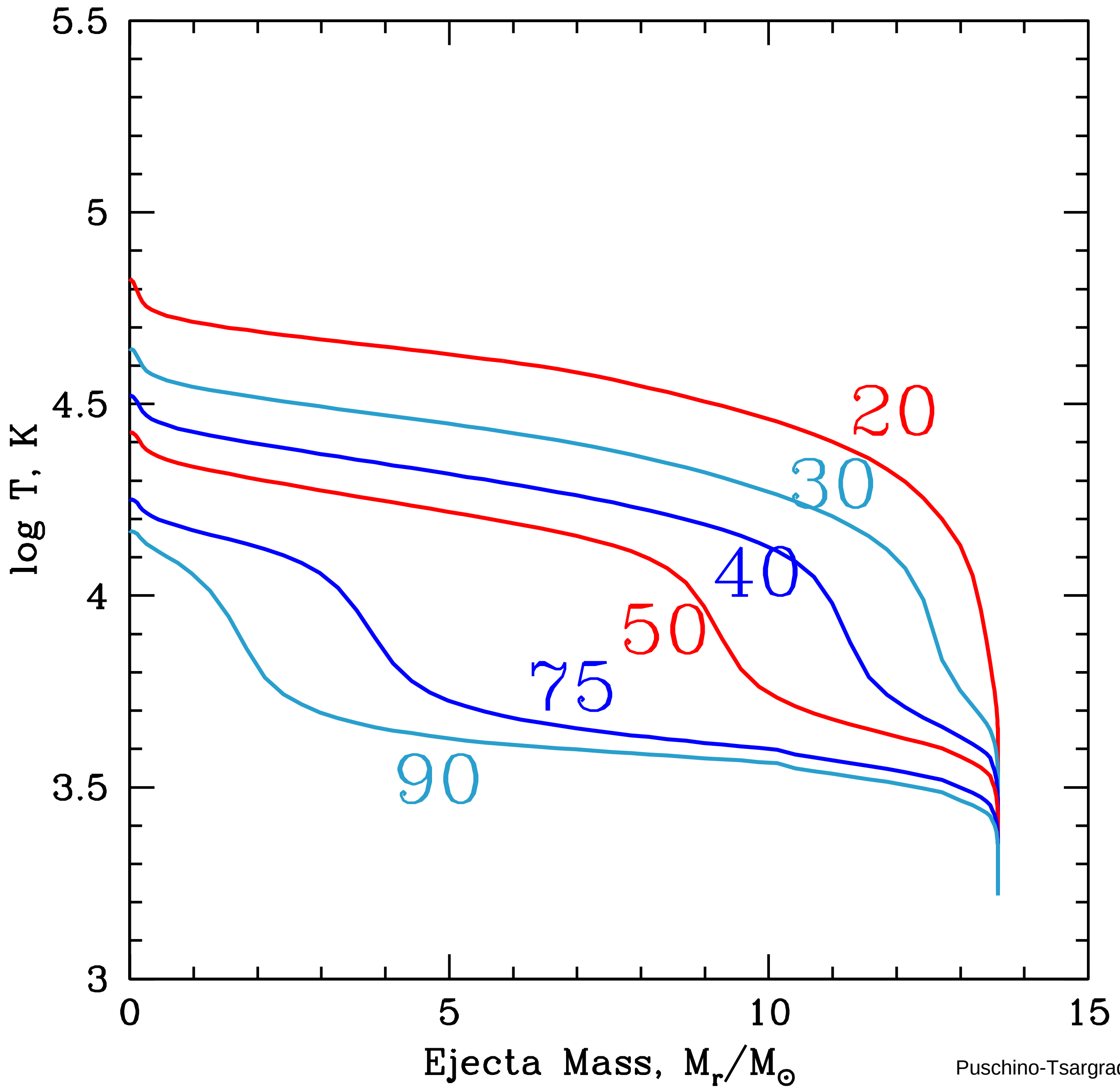
Now the distance d to the supernova is

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

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

Formation of LC plateau - T

Recombination front moving inside in M_r

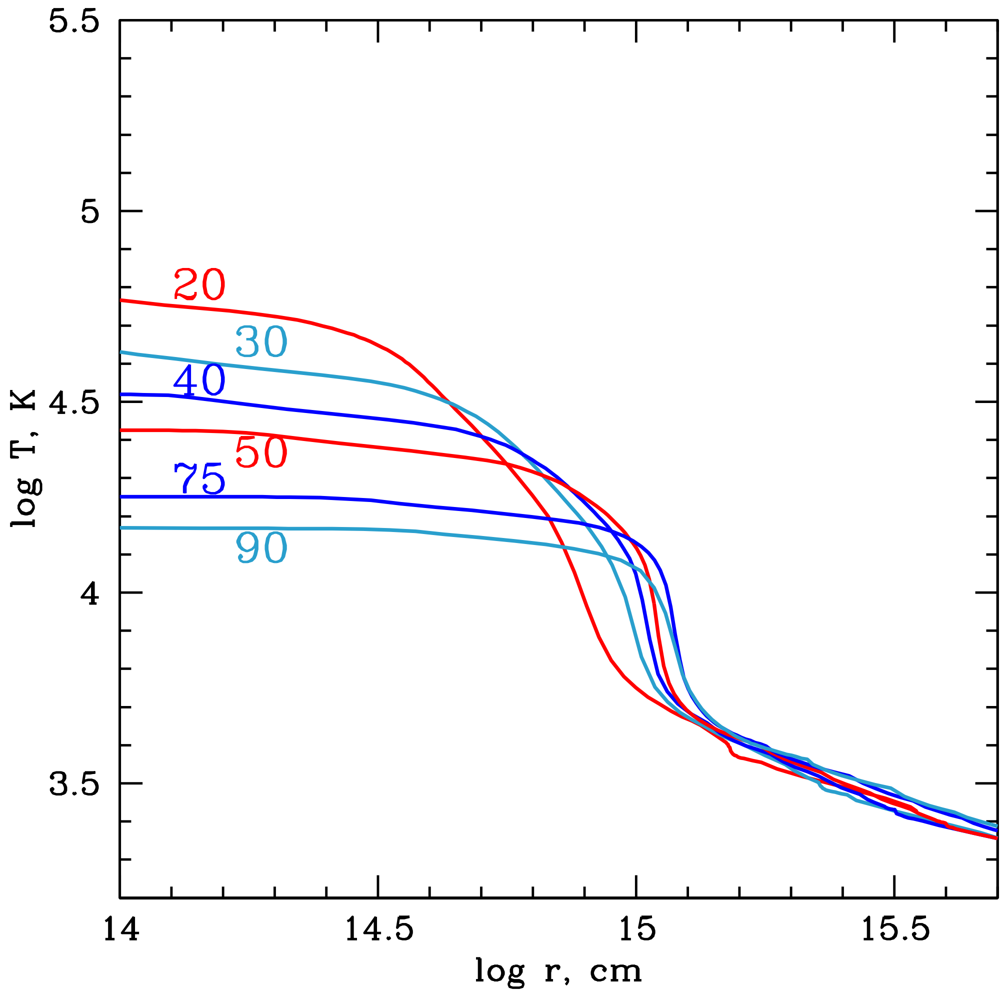


Type IIP photosphere

almost at rest - not much expanding in R and later contracting in R

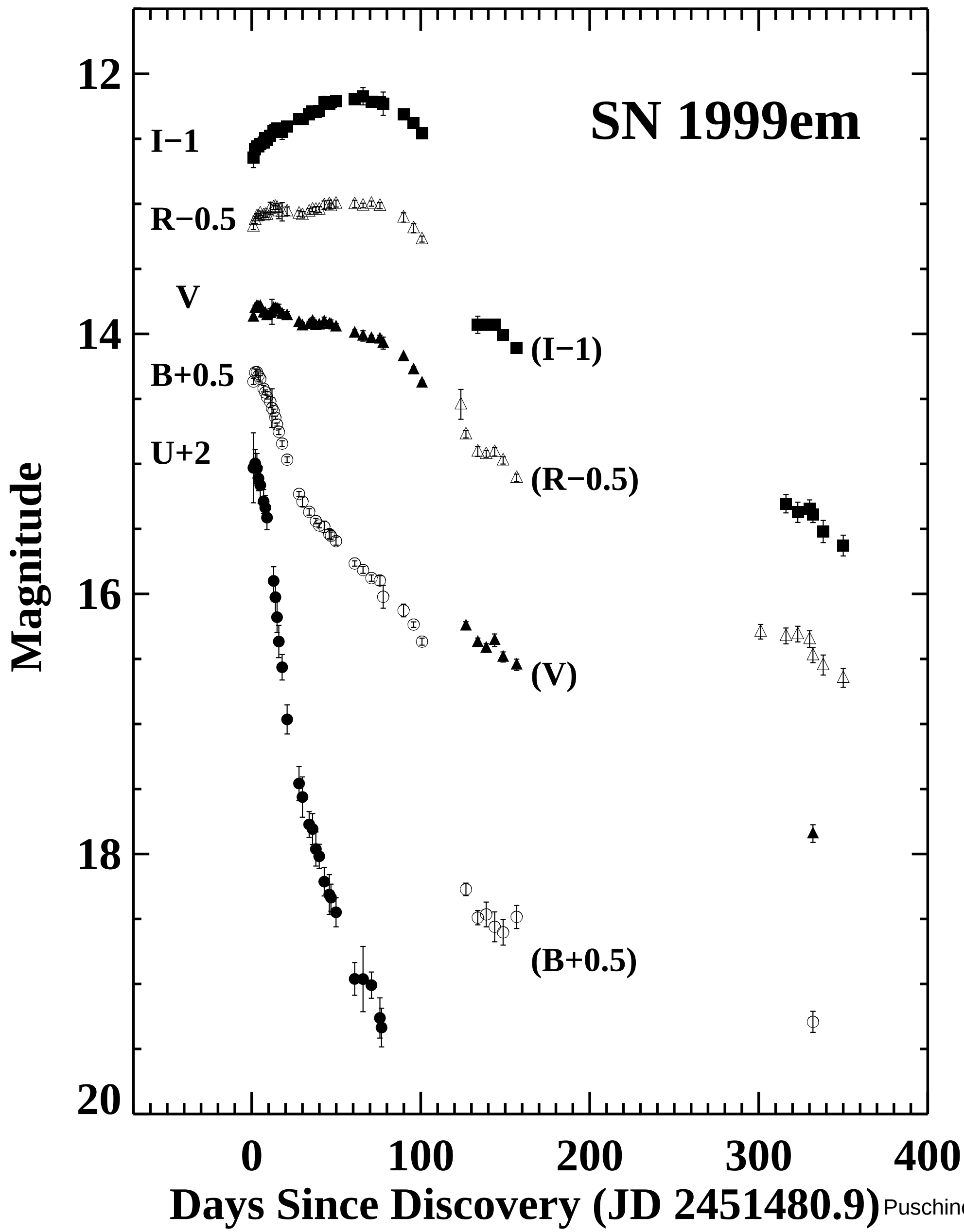
So, "CPM" (contracting photosphere method) can work as well.

Baklanov, Blinnikov, Pavlyuk (2005)



SN 1999em Leonard et al.(2002)

Detailed models are needed to reproduce observa- tions...
And to apply EPM!

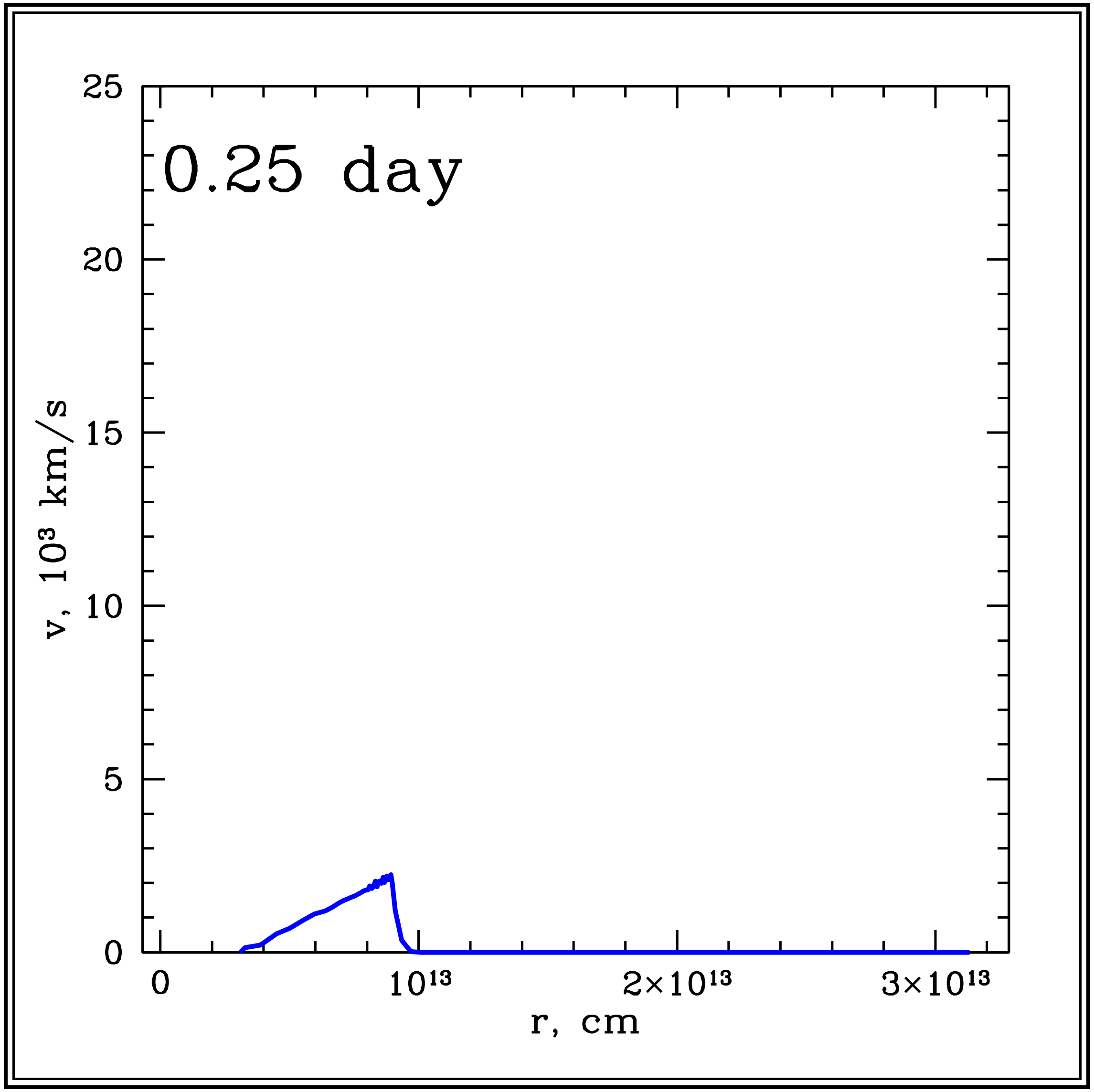


Hubble-law in SNe

Transition to free expansion called a “coasting” stage by D.Arnett –

STELLA for SN 1999em, Baklanov et al. (2005)

$$v = v(r)$$



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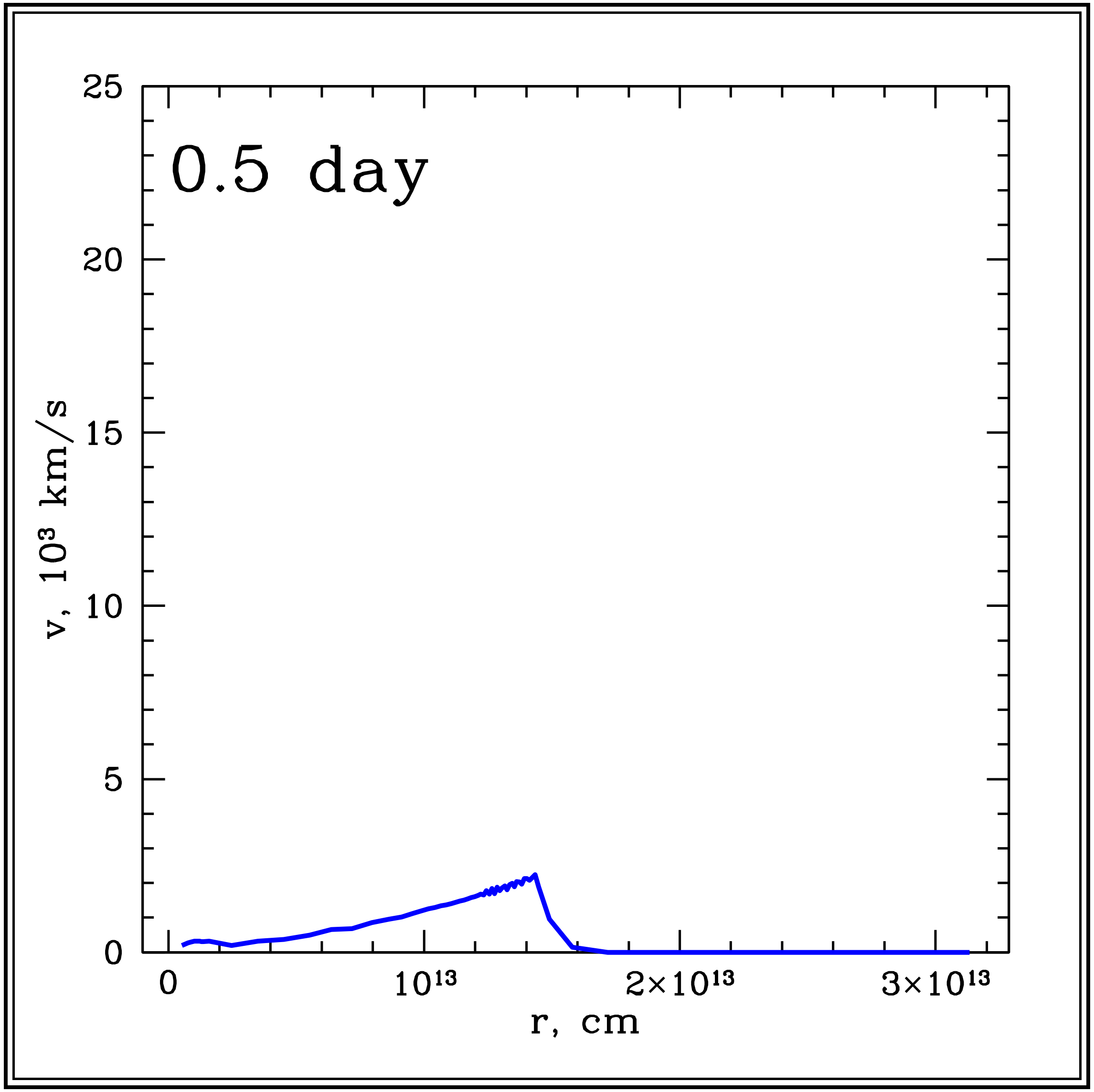

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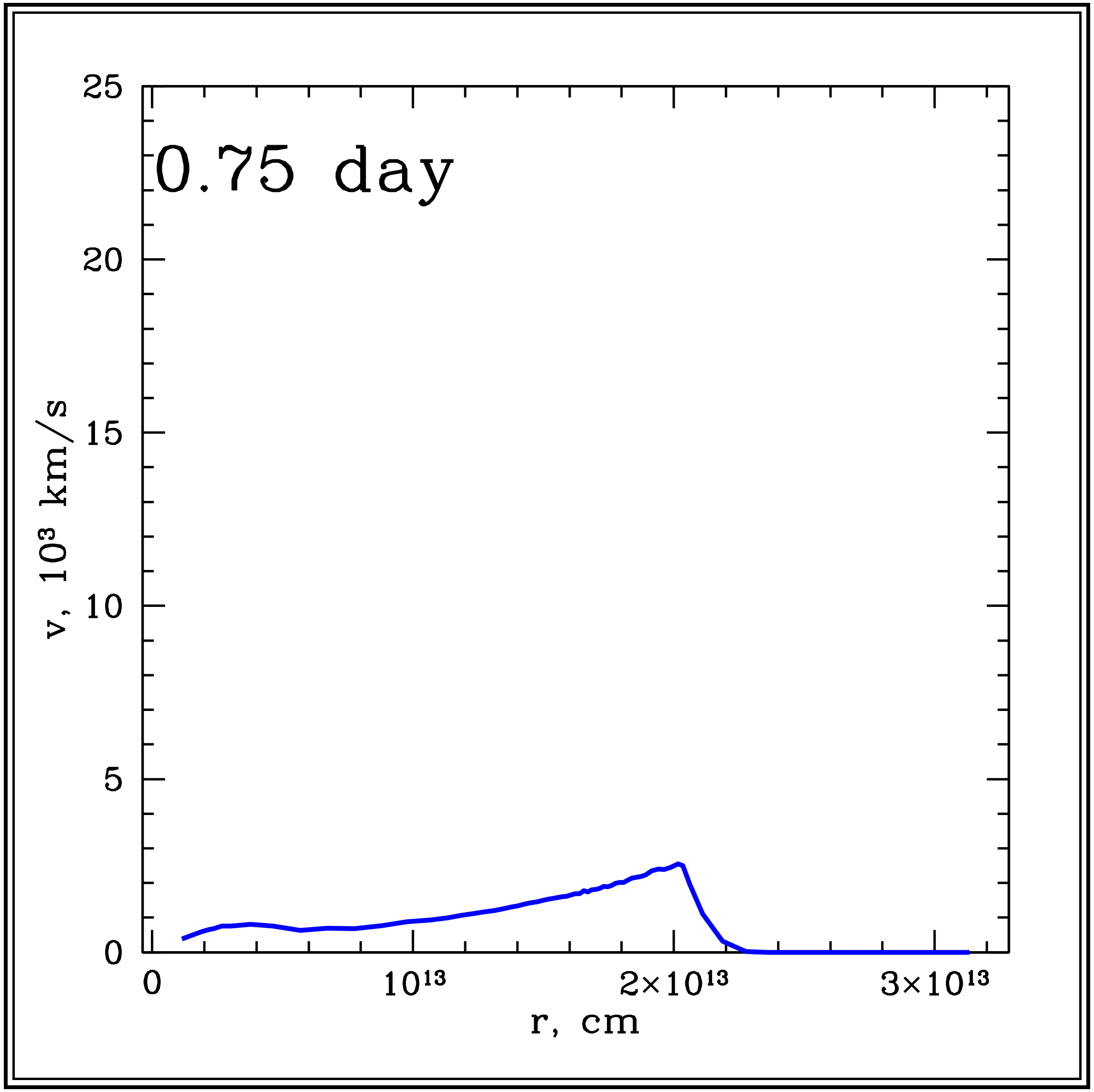

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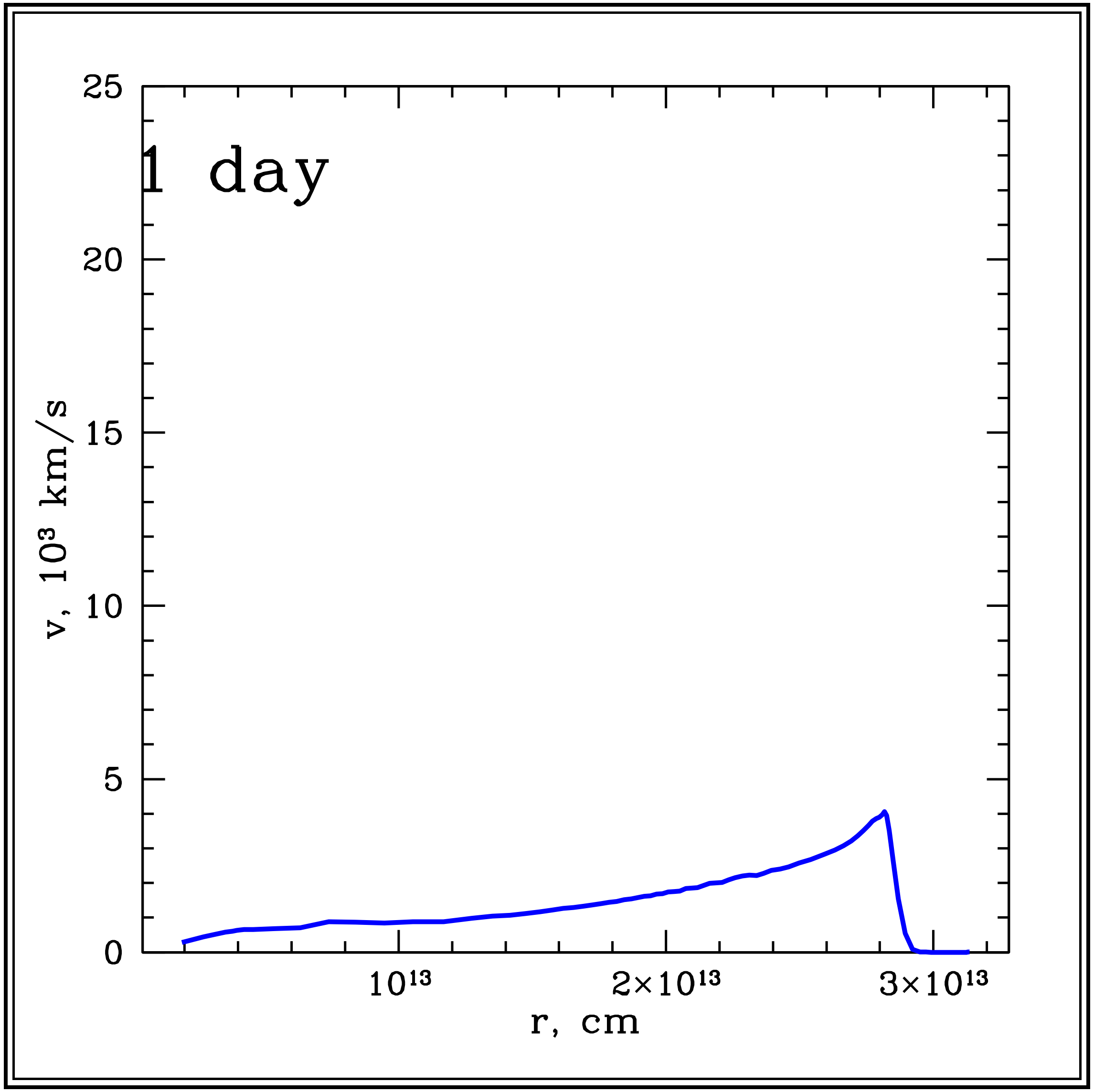

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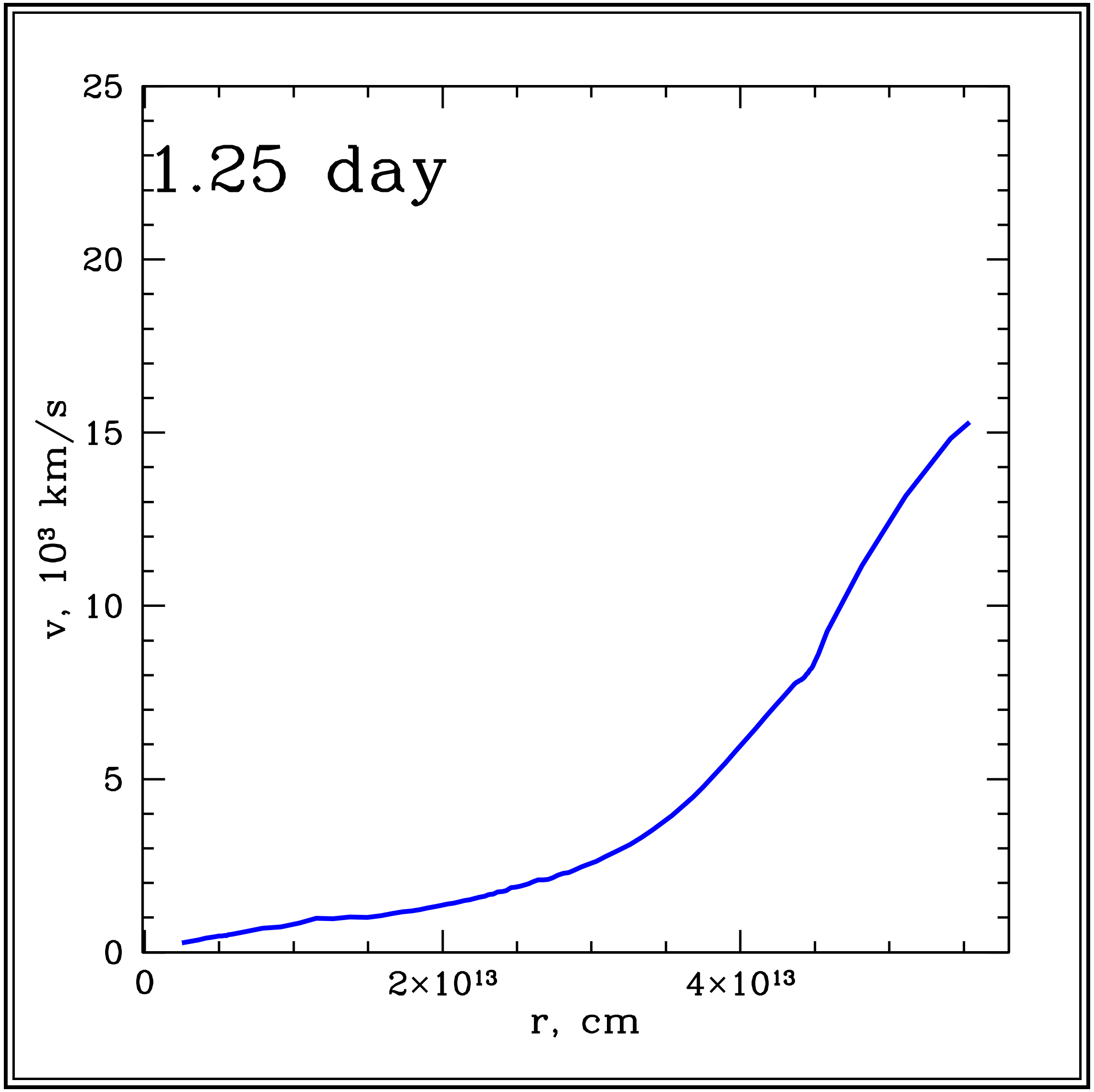
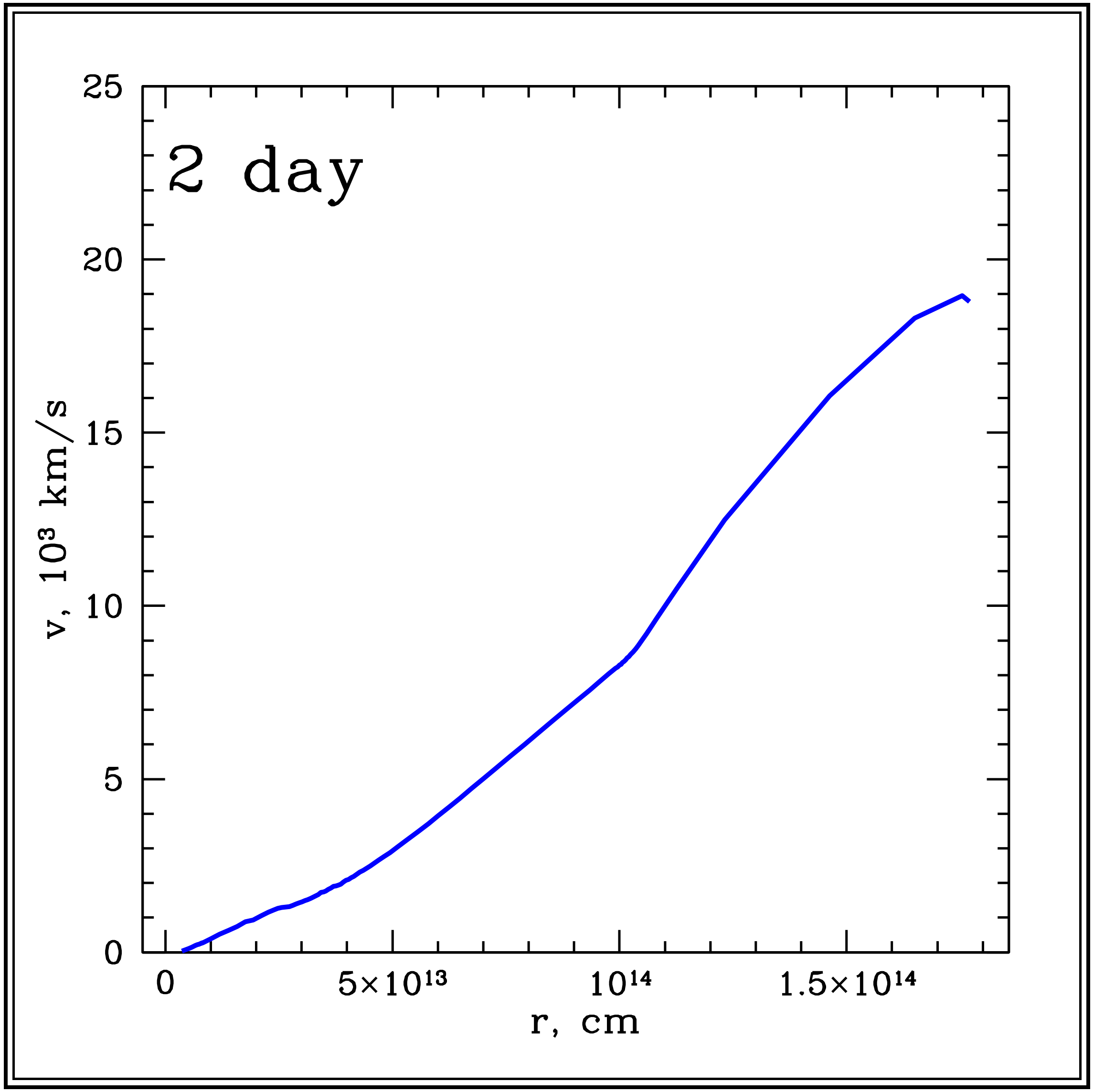


$v = v(r)$



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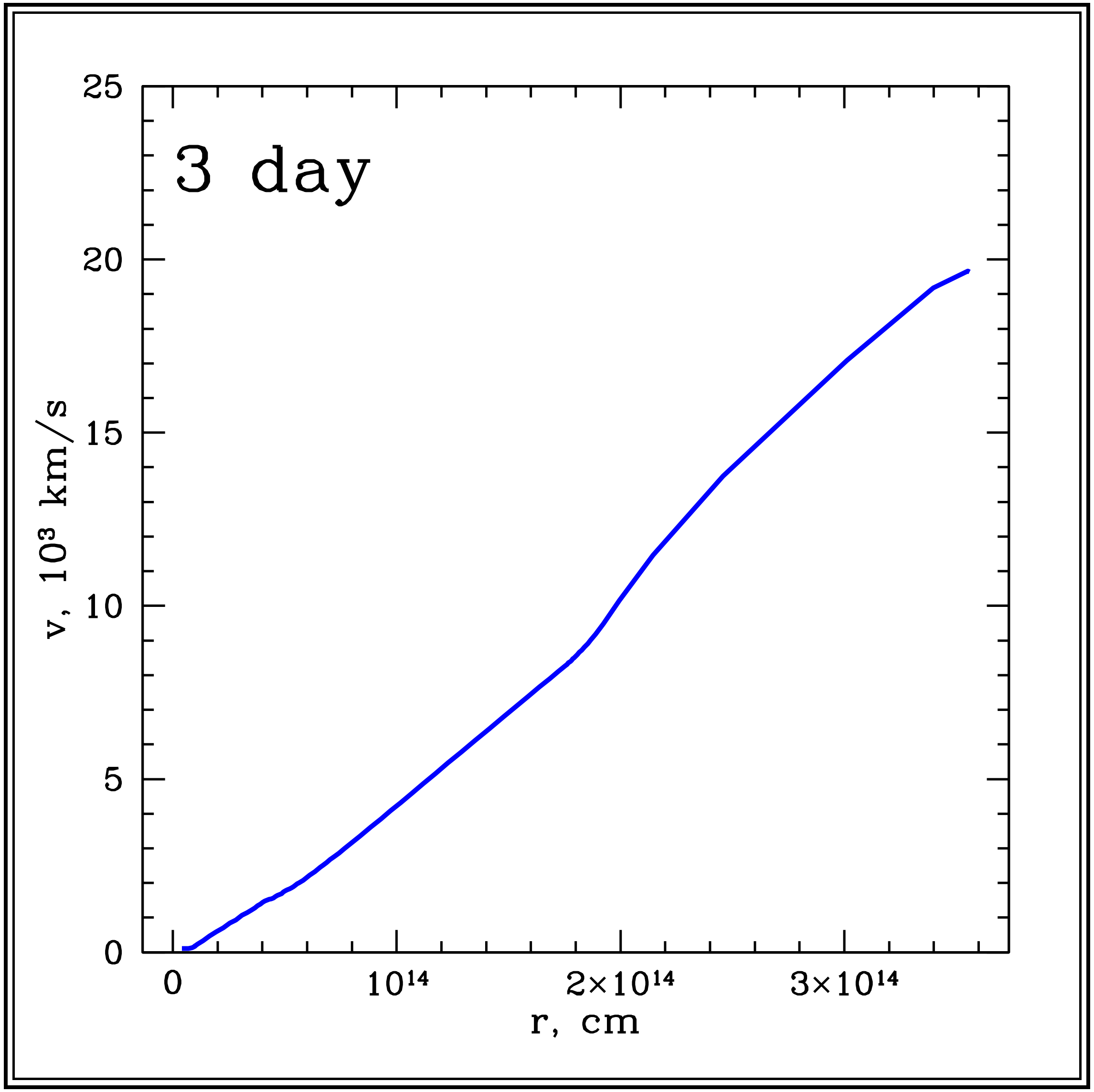

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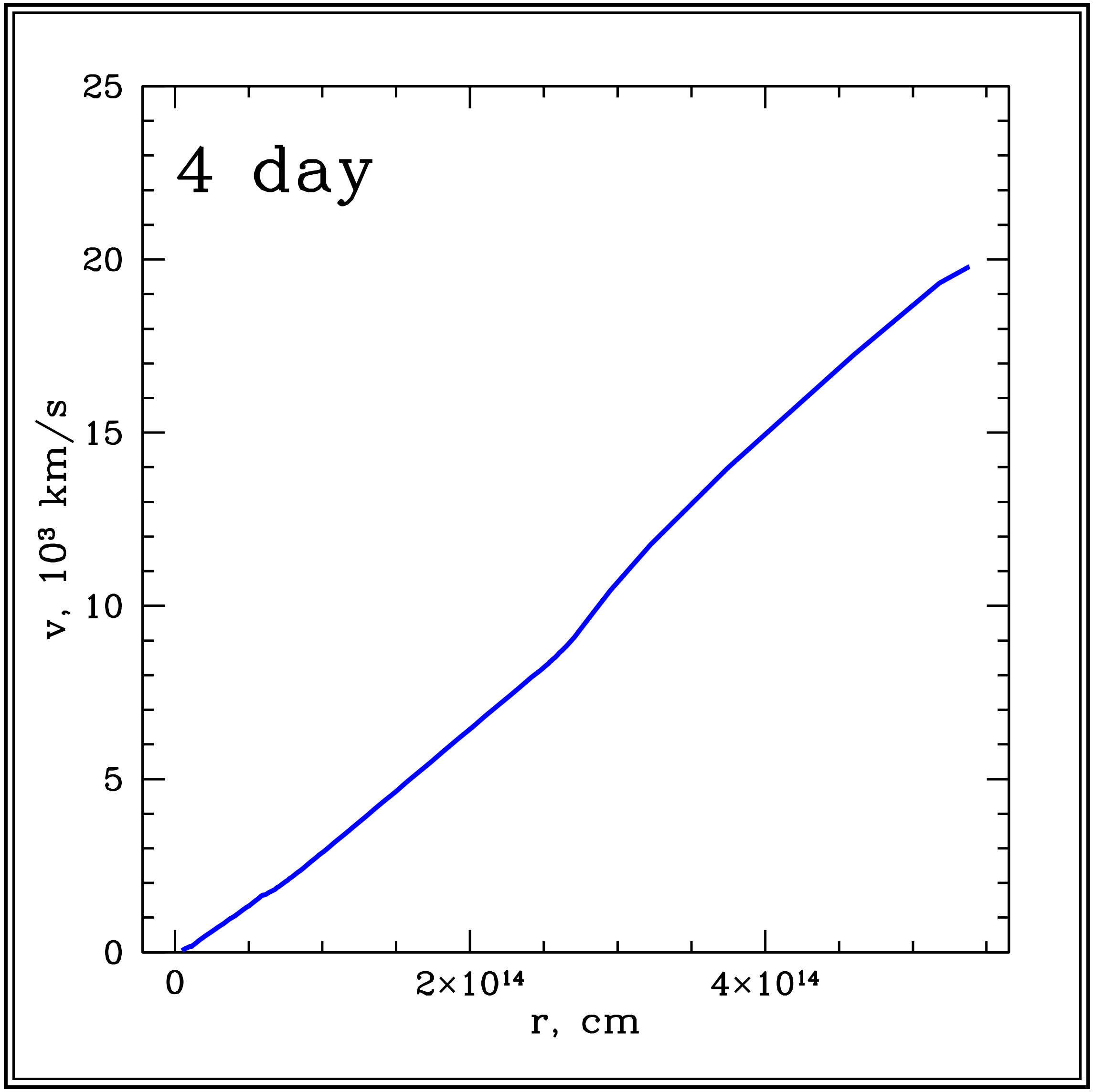

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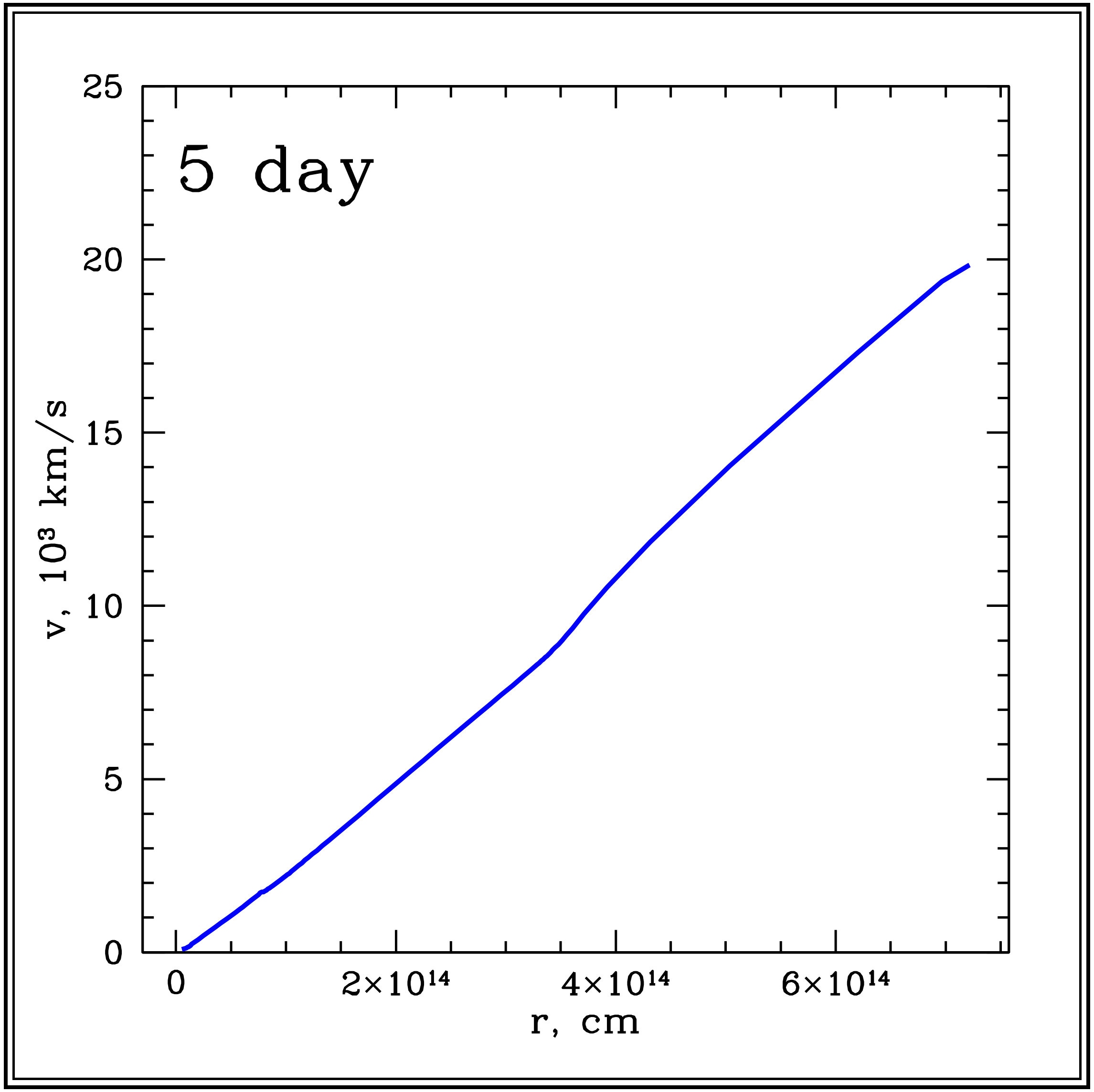

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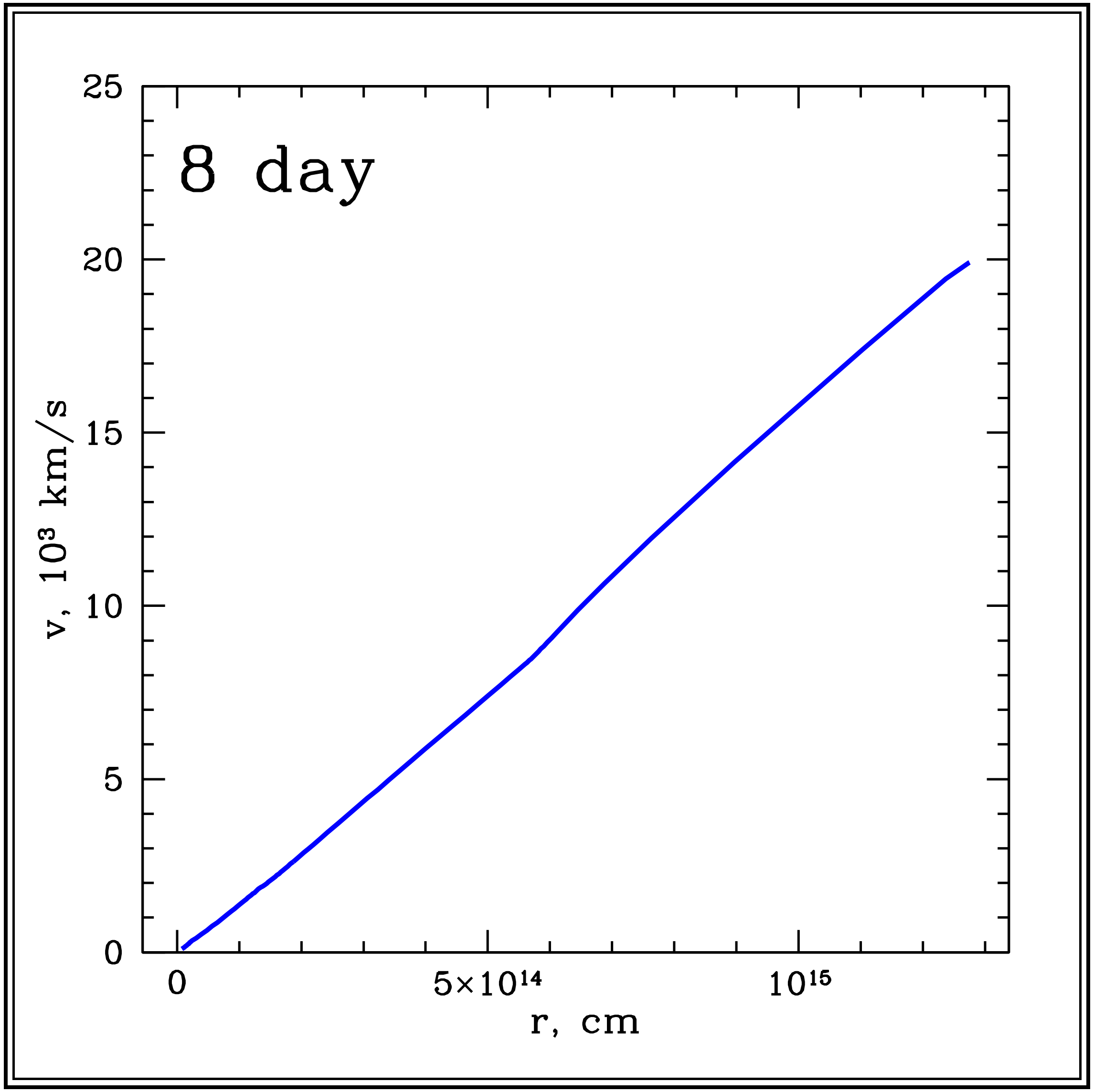
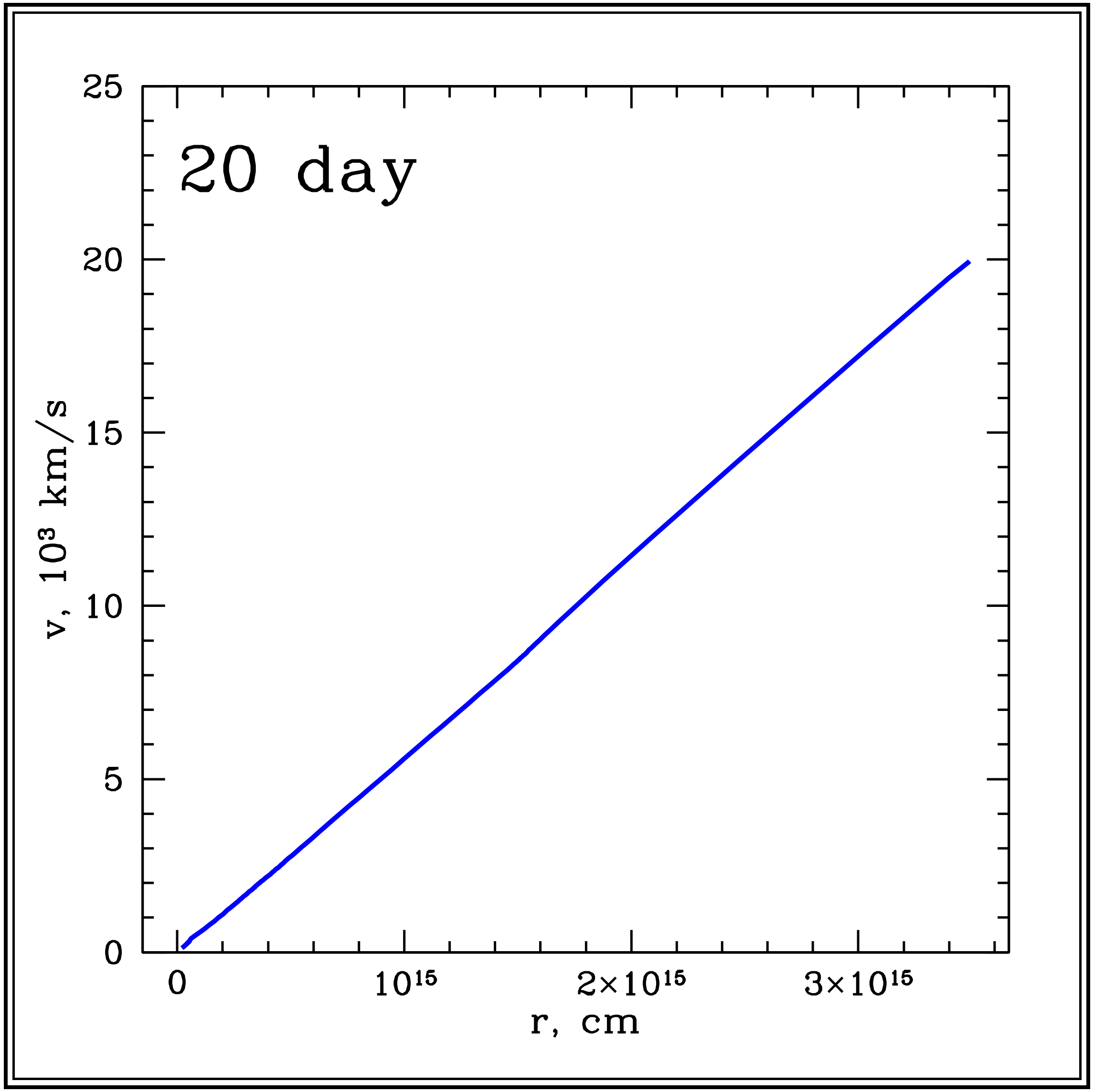
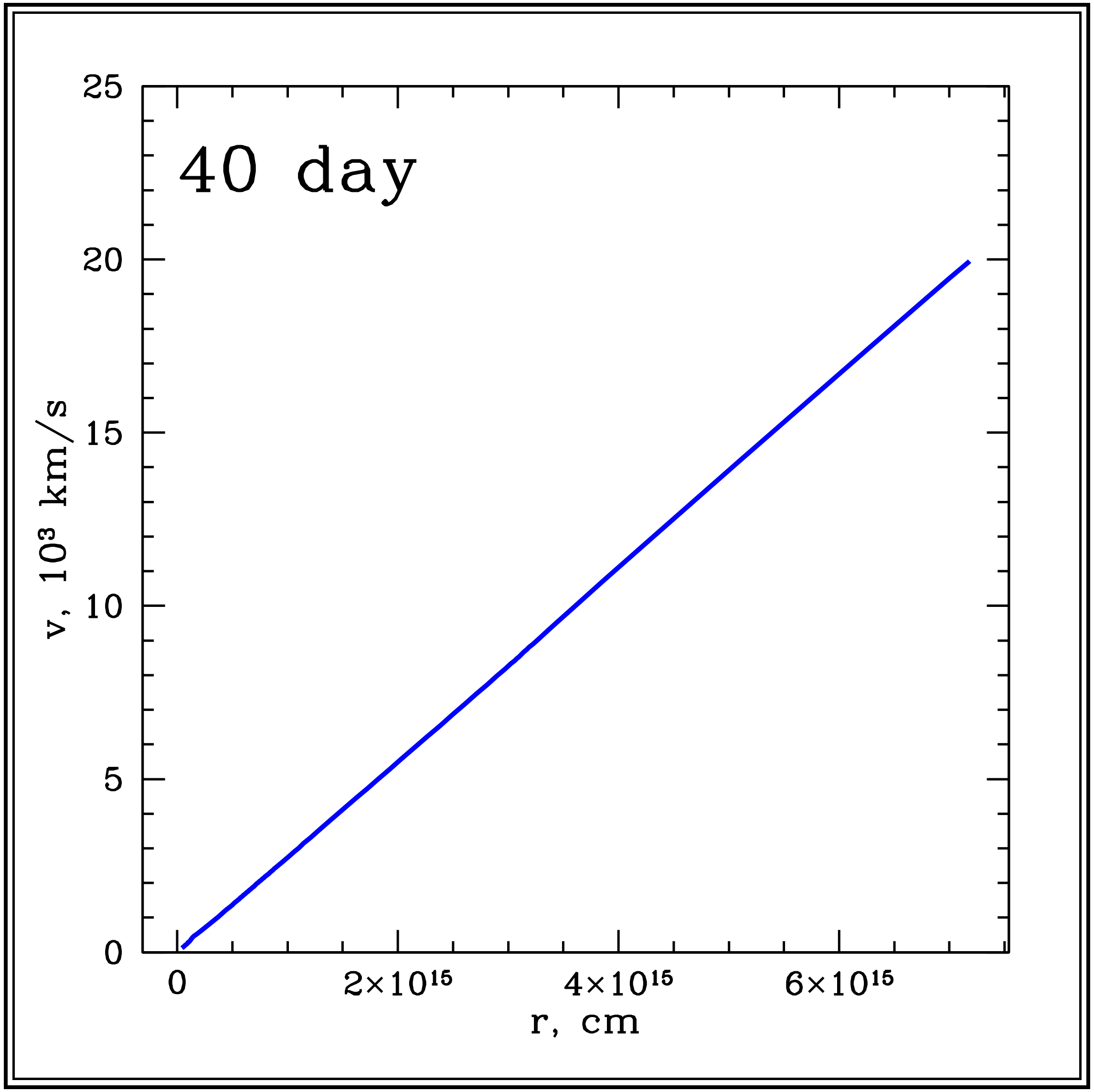


$v = v(r)$

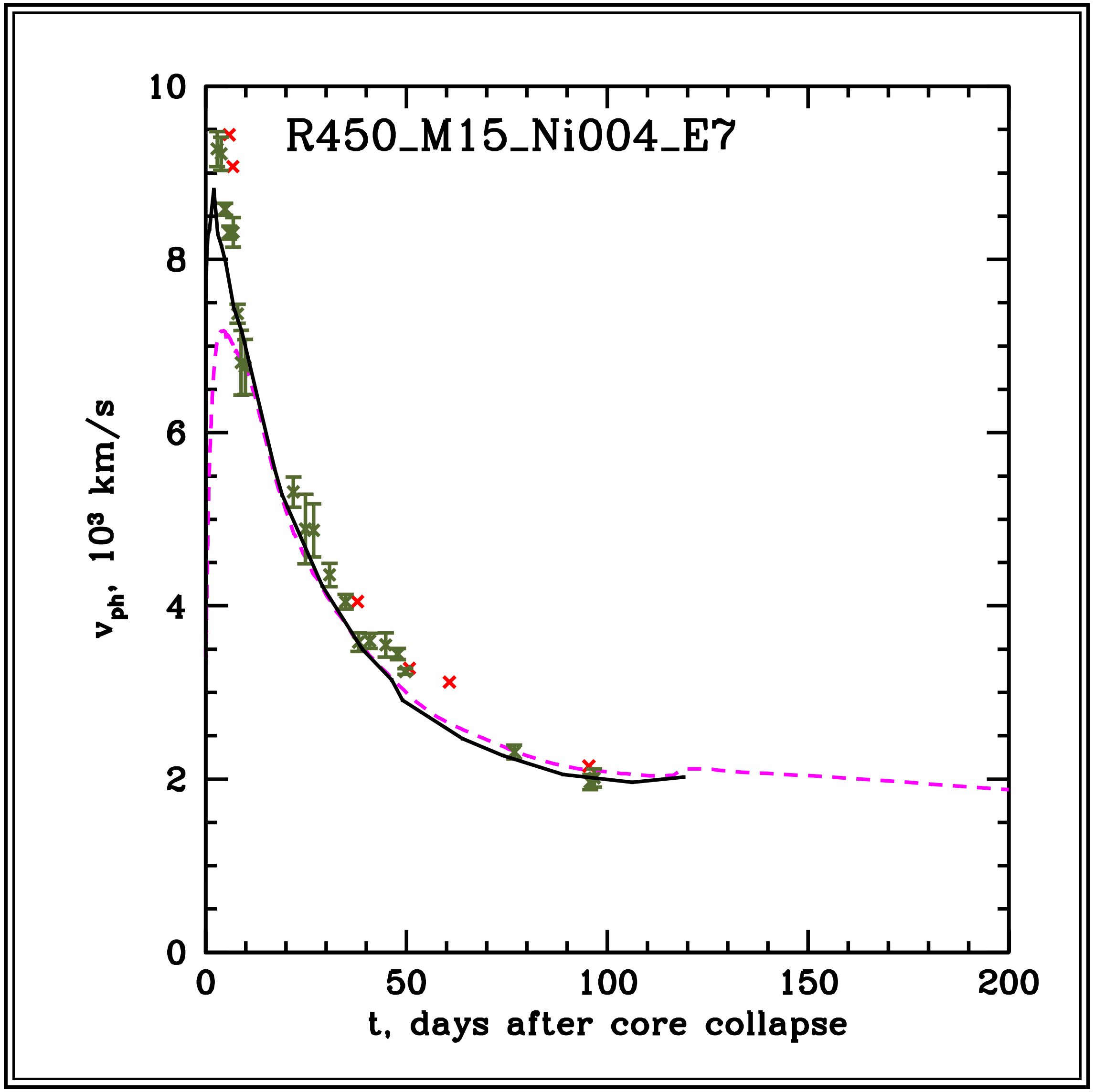


20 day
v, 10^3 km/s
25
20
15
10
5
0
0
10^{15}
2×10^{15}
3×10^{15}
r, cm

$$v = v(r)$$



$v_{\rm ph}$ for the last model



SEAM vs. EPM

Actually, using $F_\nu(\mathrm{model})$ is equivalent to the Spectral-fitting expanding atmosphere method (SEAM) (Baron et al.)
Original EPM is based on a simplified black-body assumption

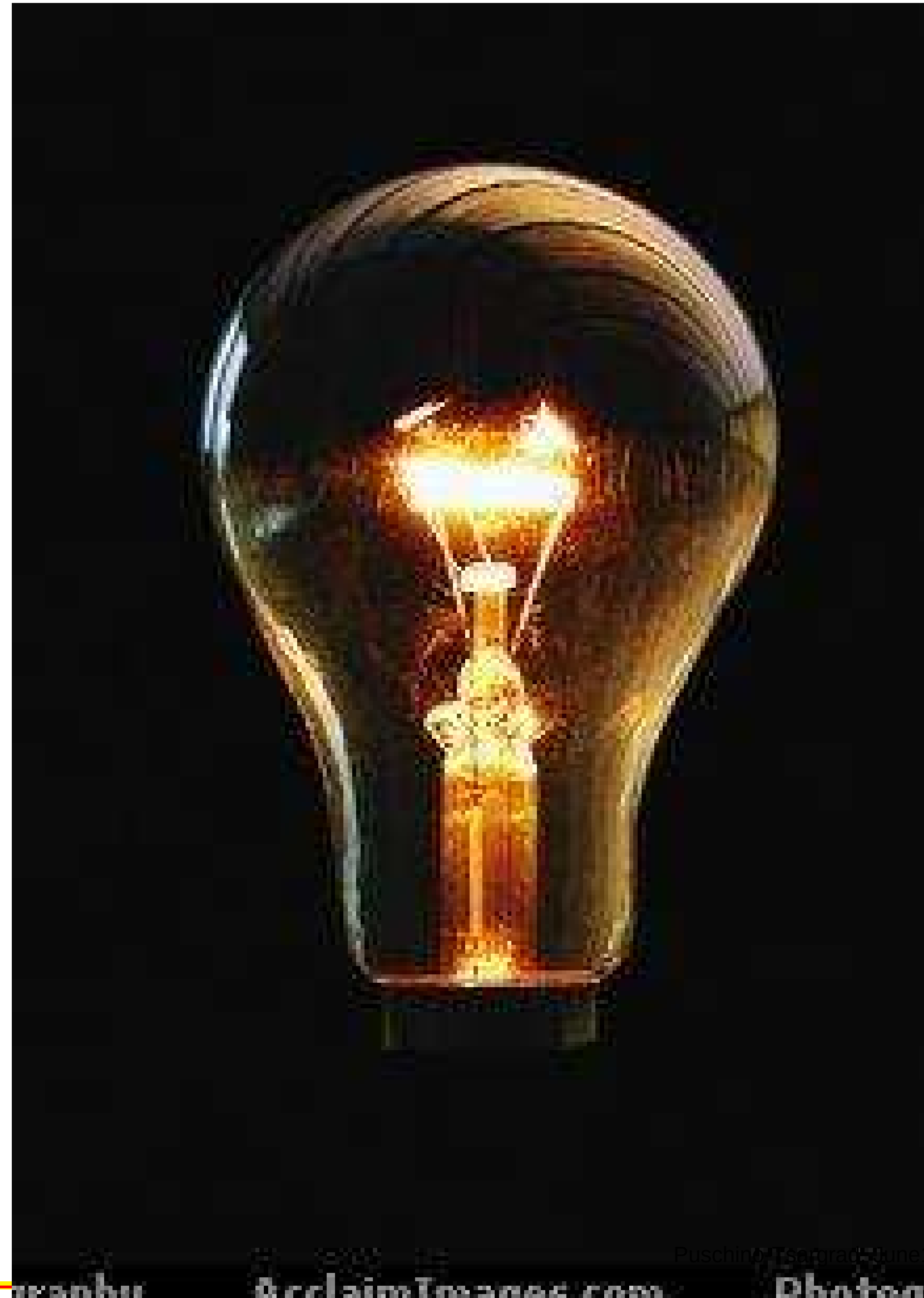
$$F_\nu = \pi B_\nu(T_c)$$

and a correction (dilution) factor ζ:

$$d = \zeta R_{\mathrm{ph}} \sqrt{\frac{\pi B_\nu(T_c)}{F_\nu(\mathrm{observed})}}$$

Dilution factor in EPM

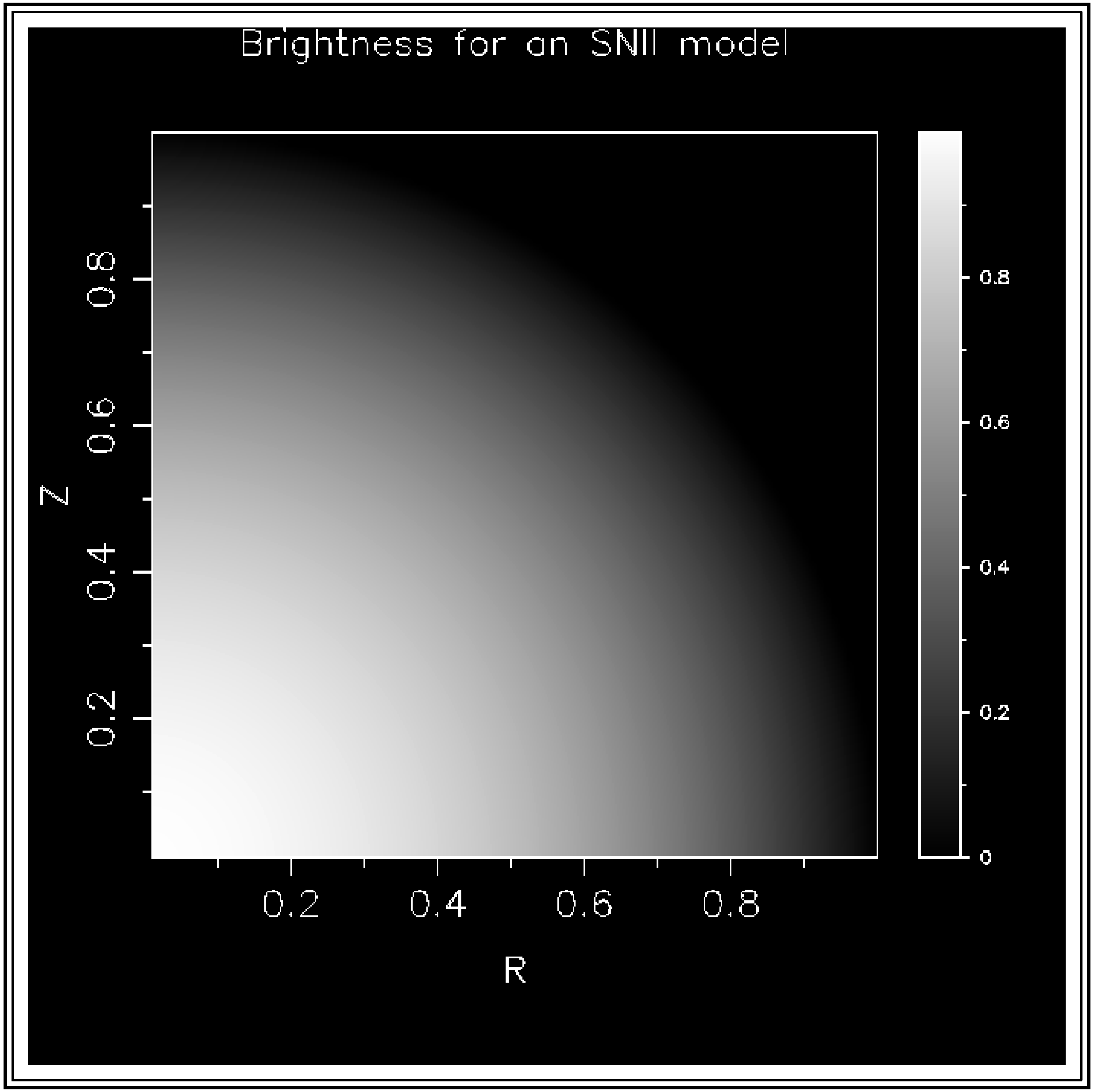
A black-body with $T \sim 3 \times 10^3$ K. Small emitting surface $\Longrightarrow$ high brightness $I_\nu = B_\nu(T)$.



Dilution analogy: frosted glass

Here the same black-body with $T \sim 3 \times 10^3$ K. Larger scattering surface $\Longrightarrow$ lower brightness $I_\nu = \zeta^2 B_\nu(T)$, here $\zeta < 1$.

‘Visible’ disk of SN IIP



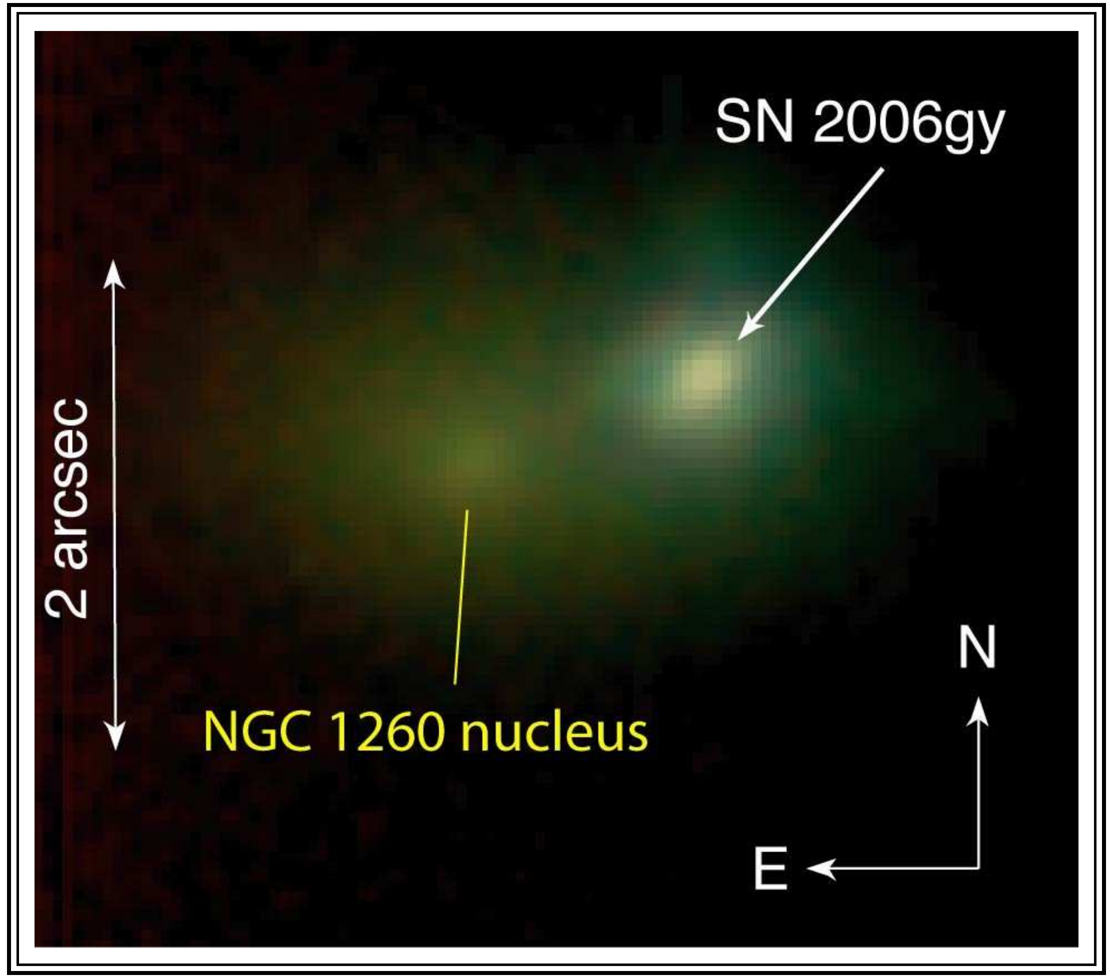
Great Success of EPM

B.Schmidt et al.(1994), R.Eastman et al.(1996) found $H_0 = 73 \pm 6$ based on EPM for a set of SNe II.

Very Luminous SN 2006gy

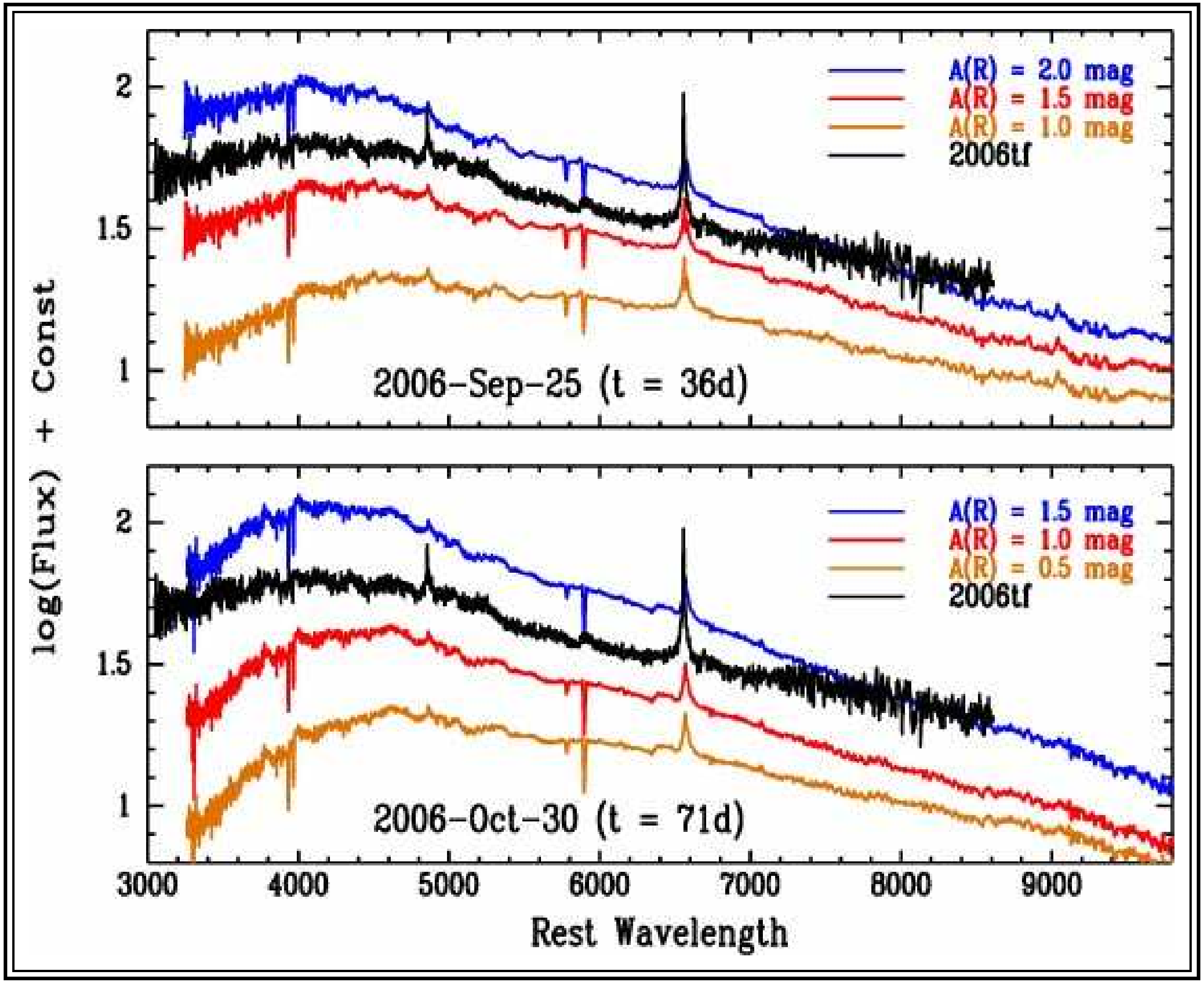
Ofek et al. 2007, ApJL, astro-ph/0612408)

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

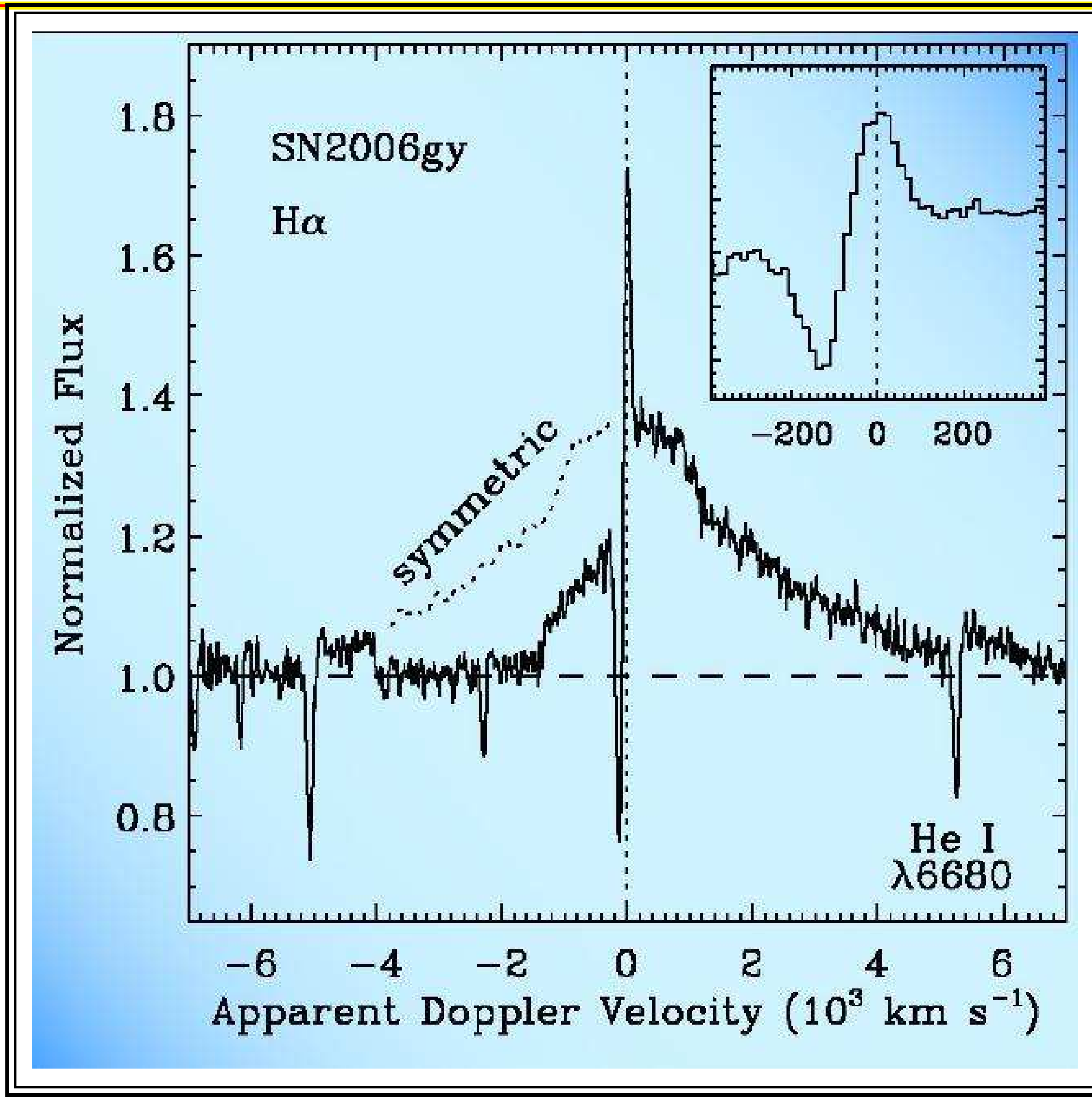


Smith et al. SN 2006gy spectra

Narrow lines: SNIIn

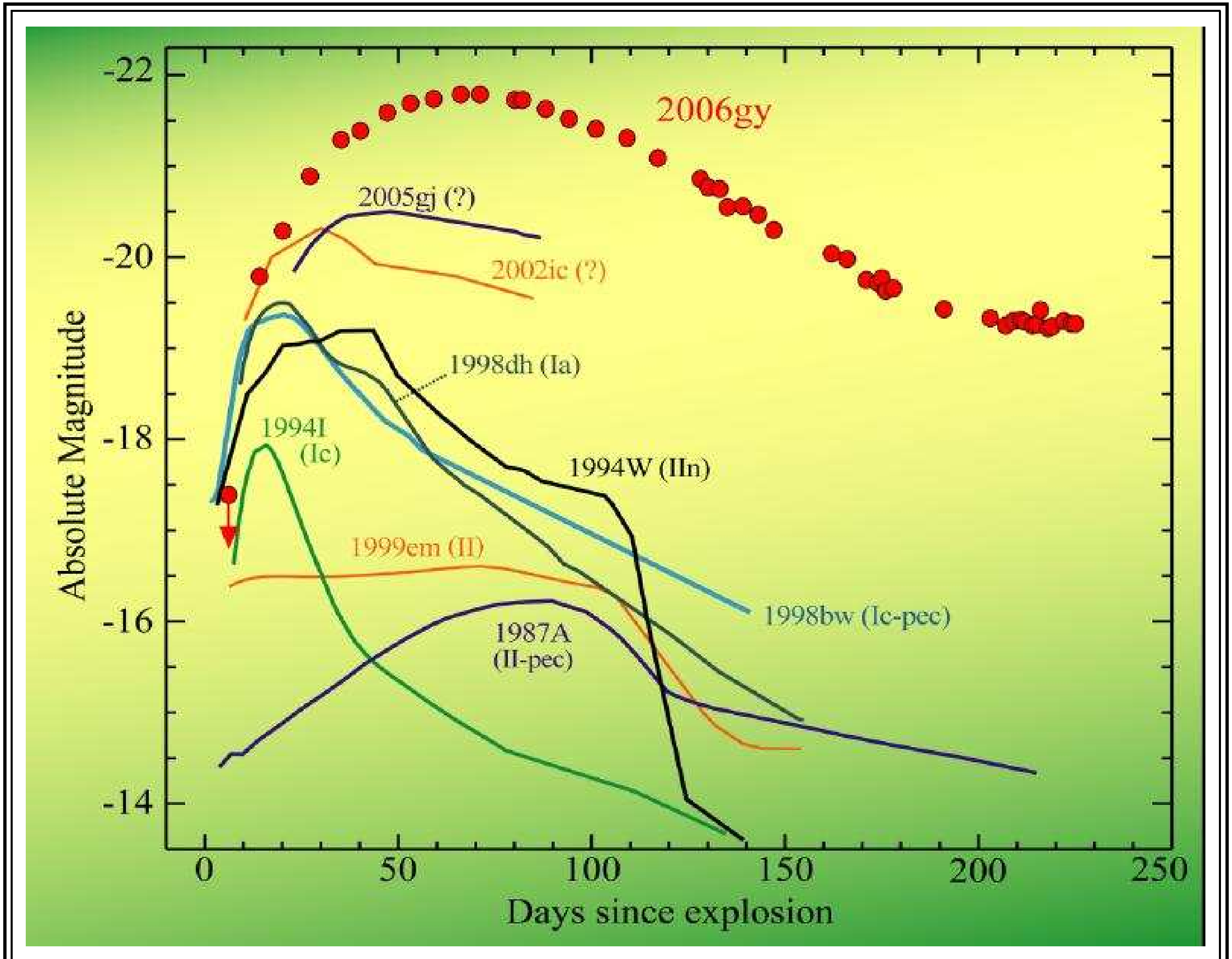


Smith et al. SN 2006gy, H_α profile

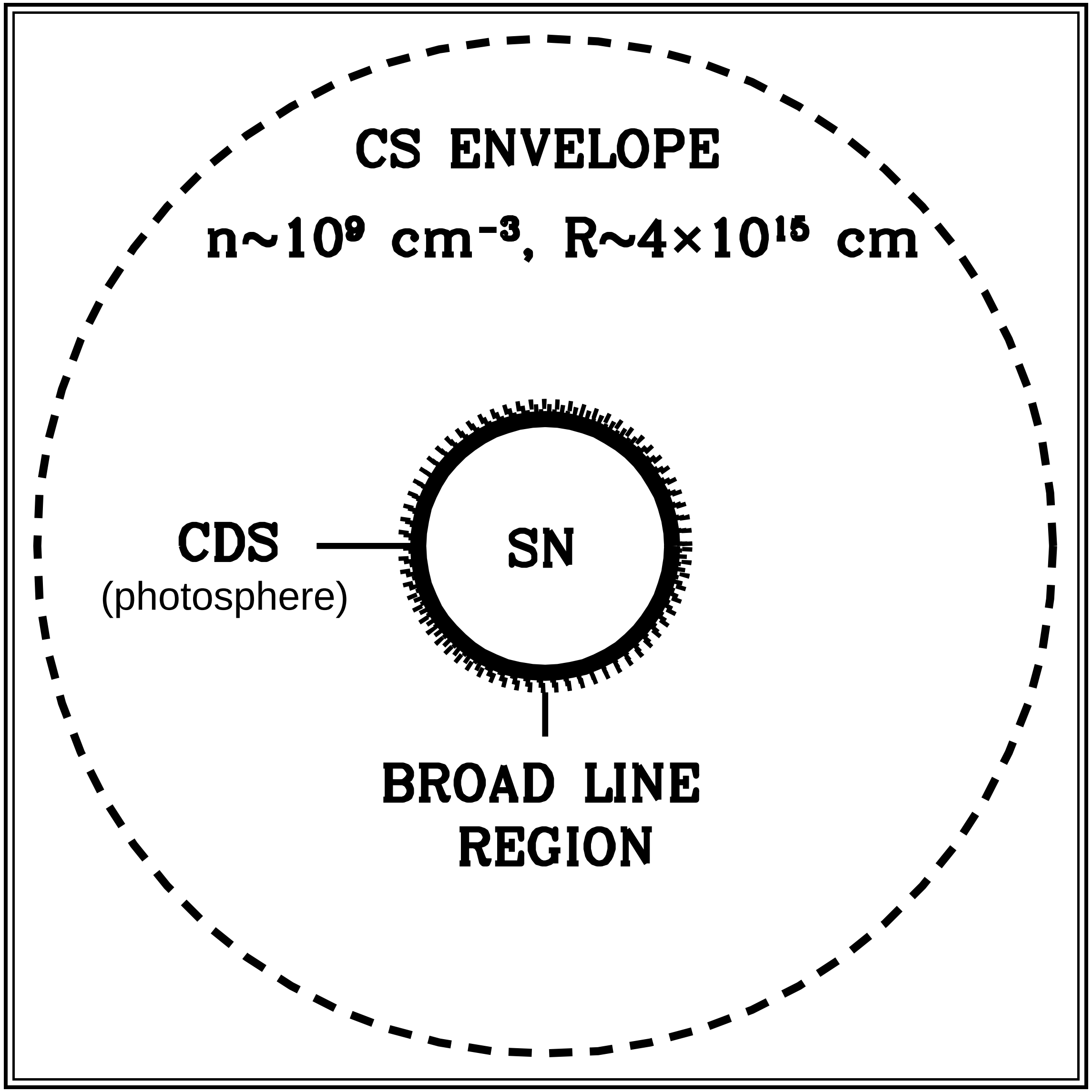


Narrow component ~ 200 km/s, wide ~ 5000 km/s.

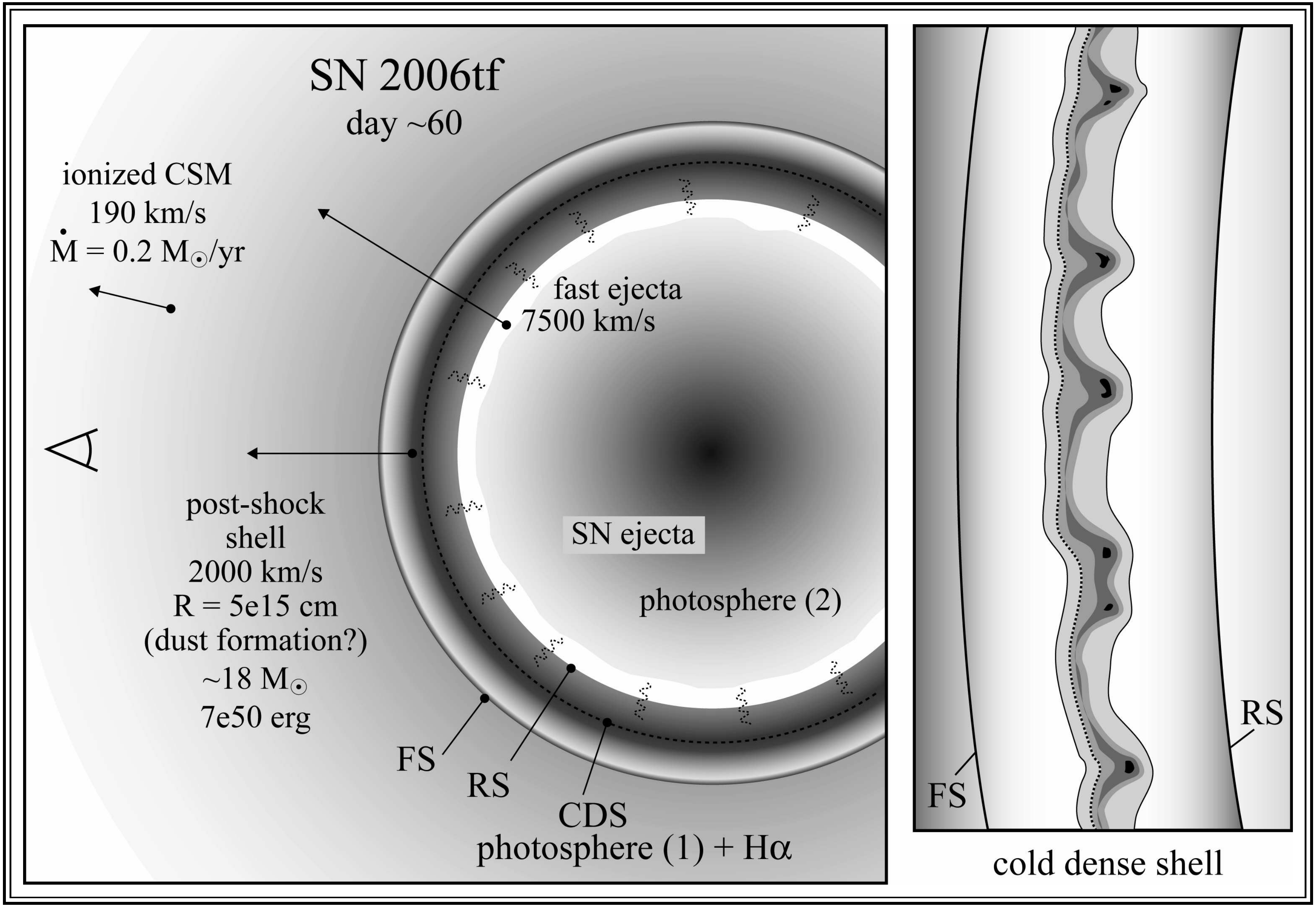
Another LC set with SN IIn



SN IIn structure, Chugai, SB ea'04

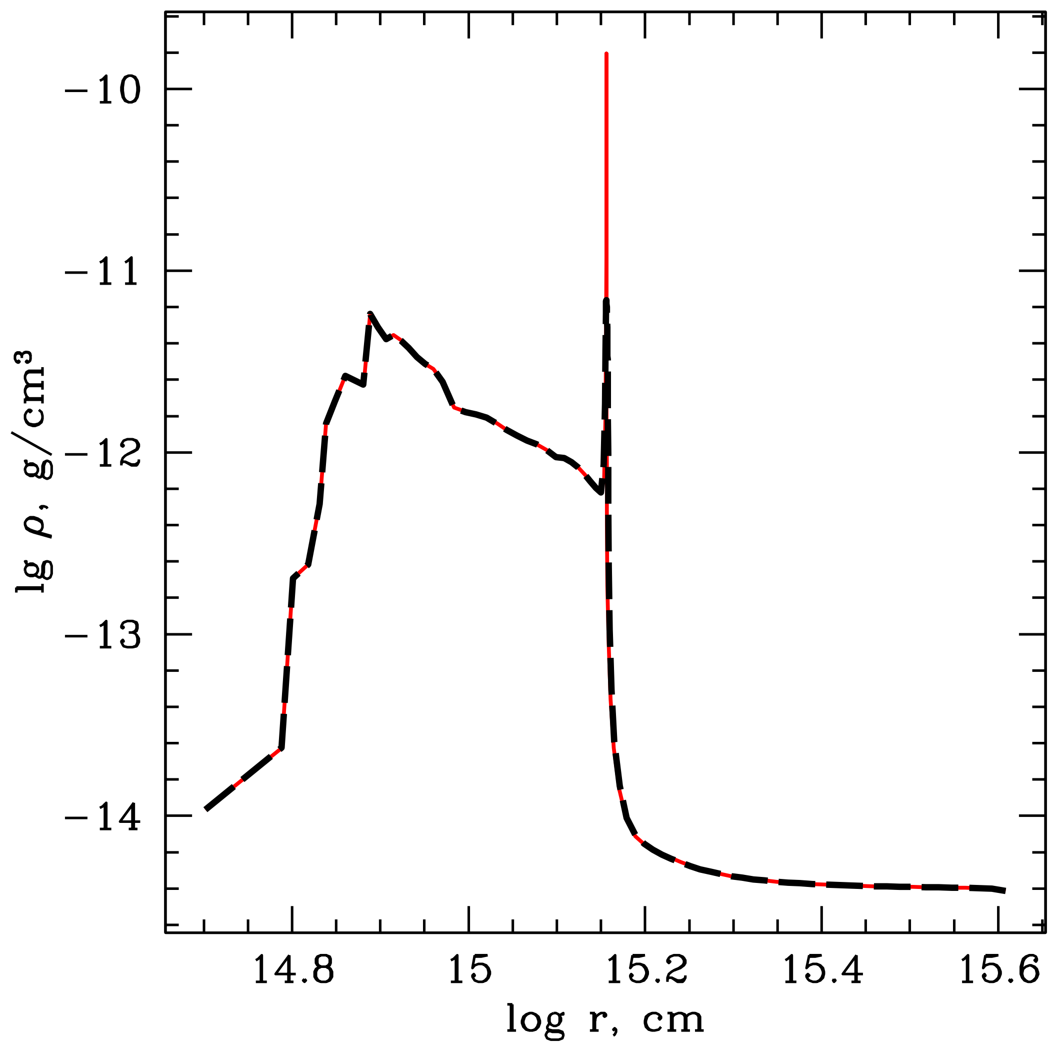


Smith,Chornock ea cartoon, 06tf

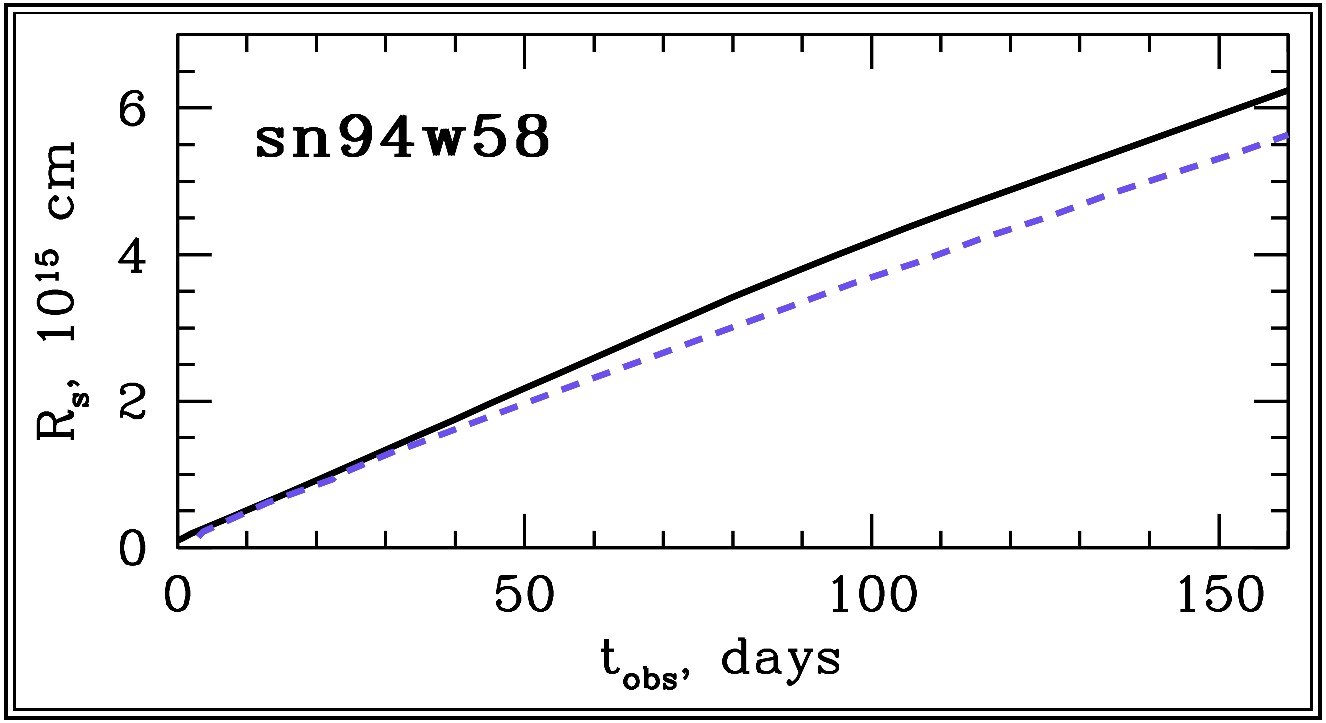


Shocks in SNe IIn

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.



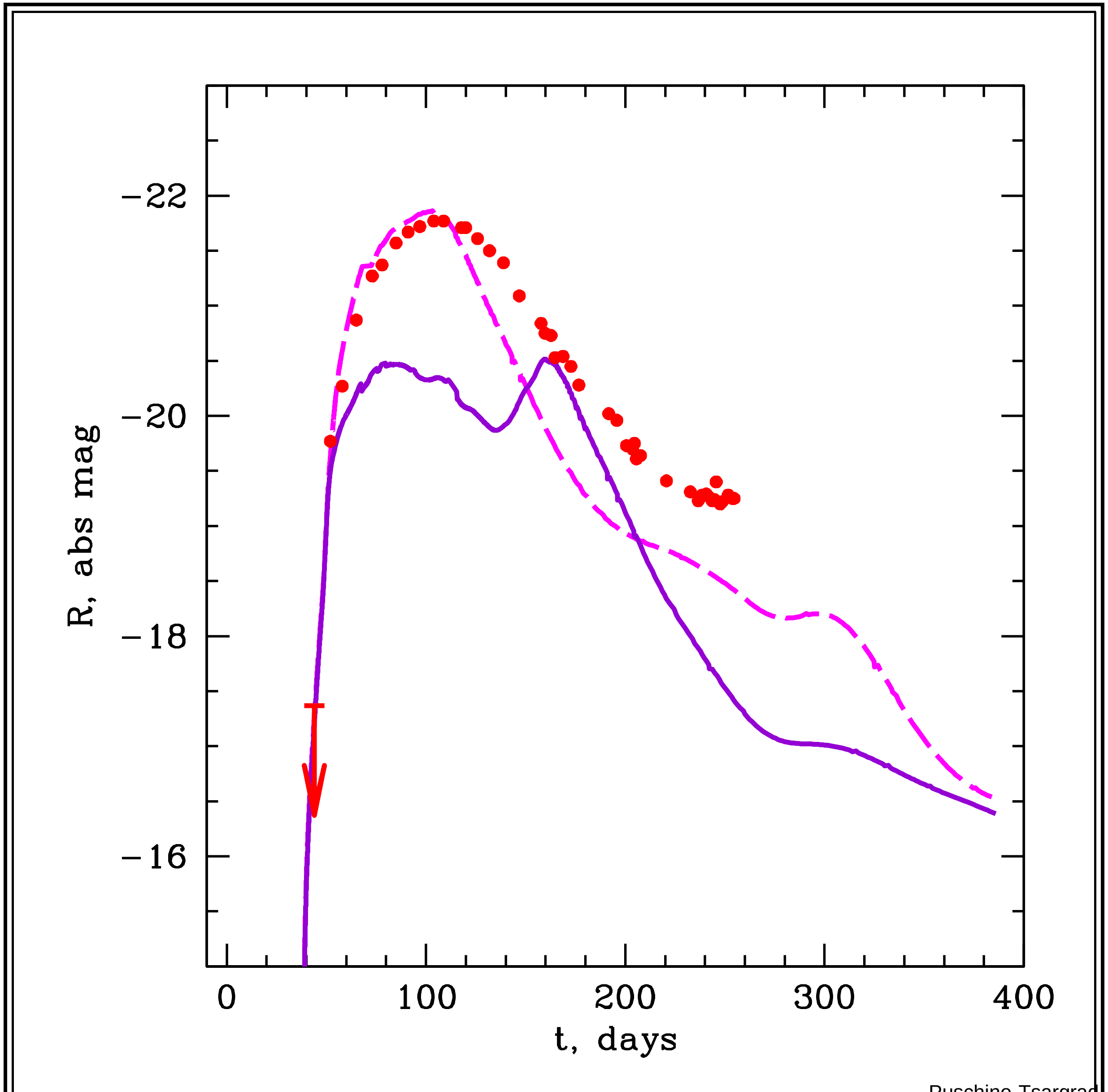
Compare $R(t)$ from the two models



Broken line is from spectra, solid – from hydro LC model.

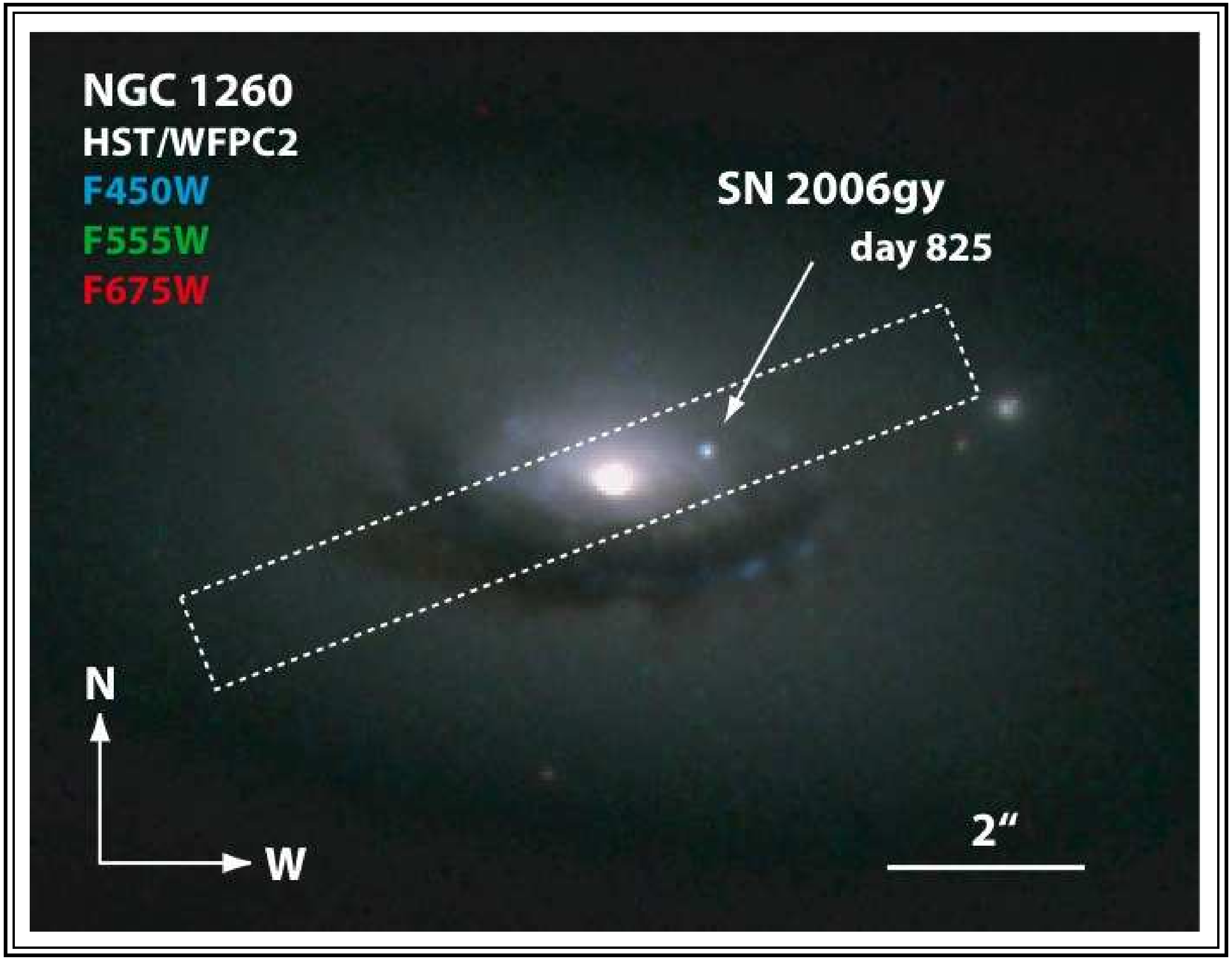
Stella: LCs for SN2006gy

from Woosley, SB, Heger (2007)

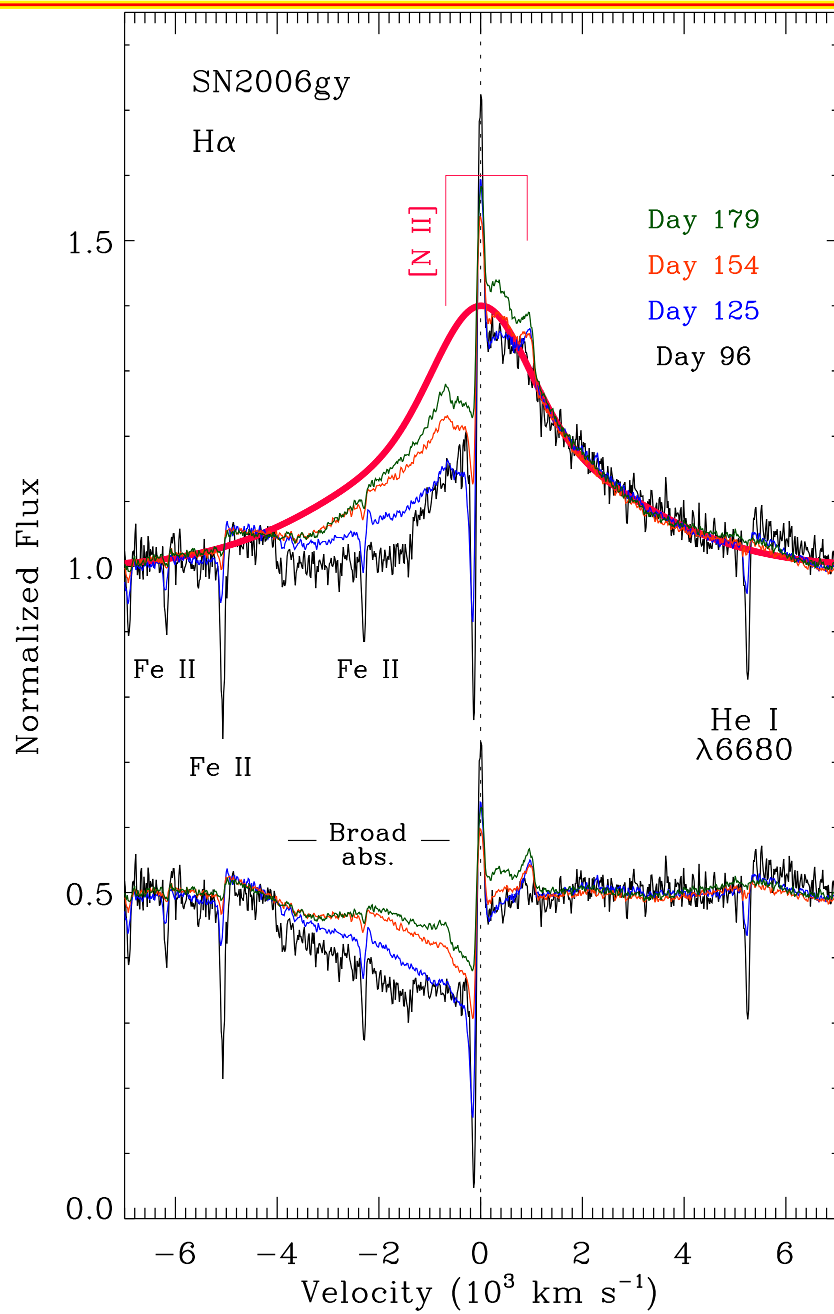


New data, on SN2006gy

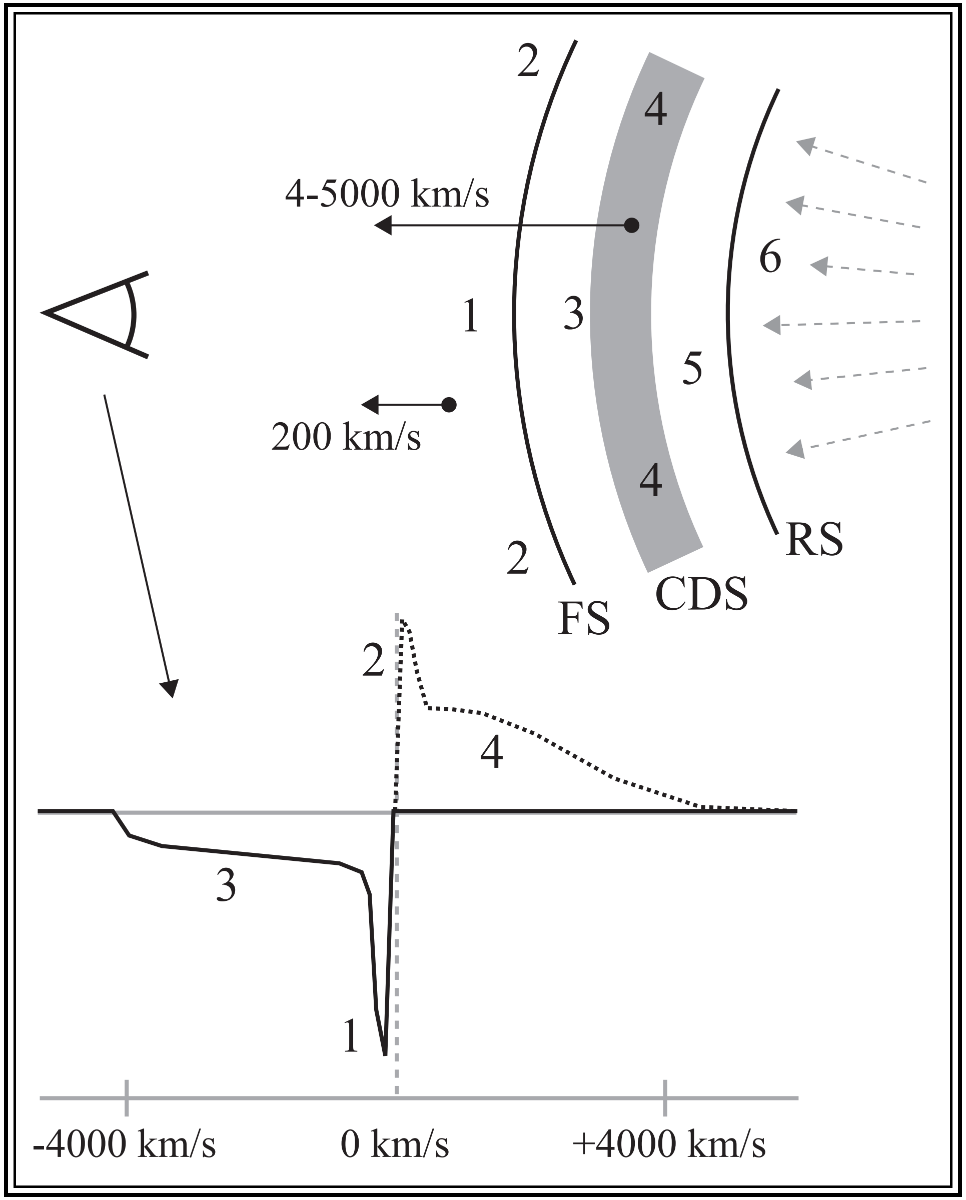
N.Smith et al., arXiv:0906.2200



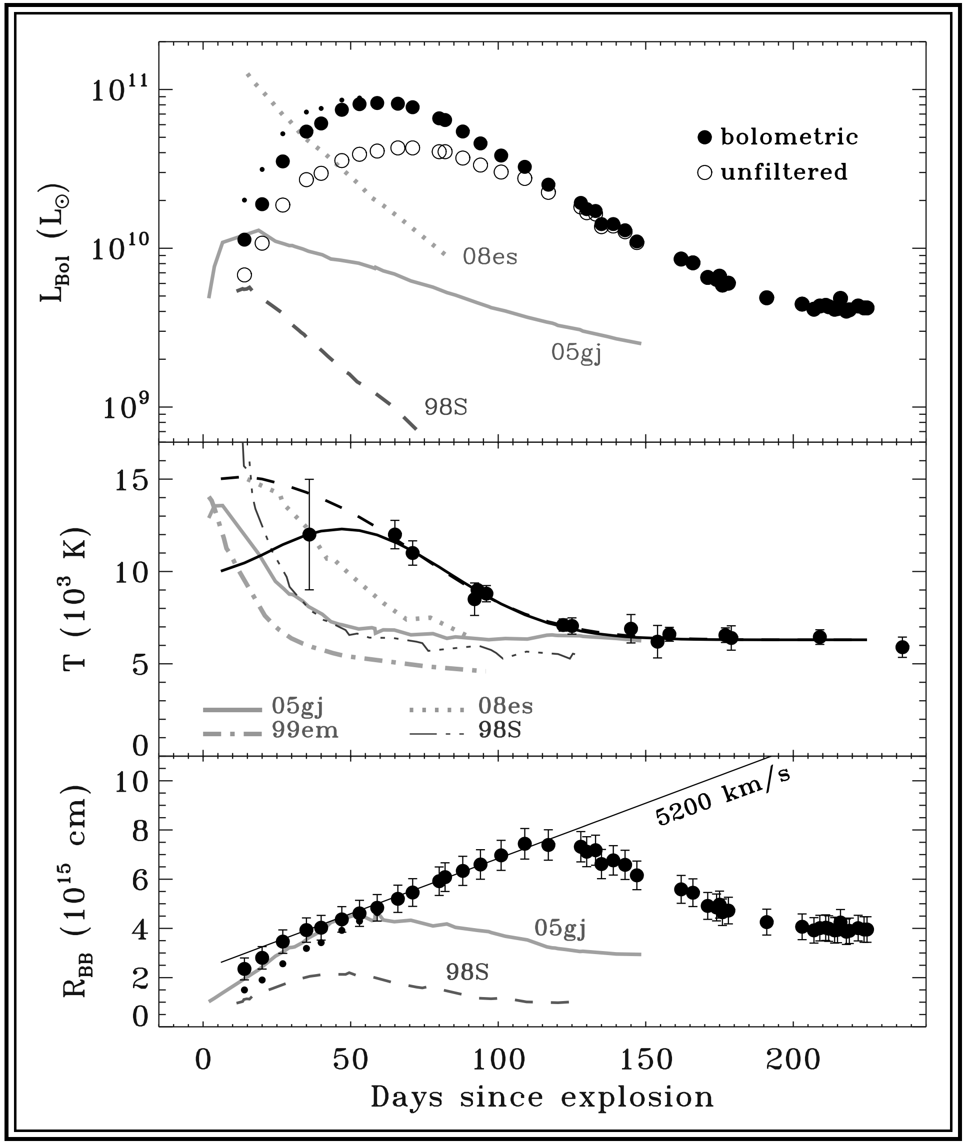
Observed lines of SN2006gy



Cartoon of line formation



Observed $R(t)$ of SN2006gy

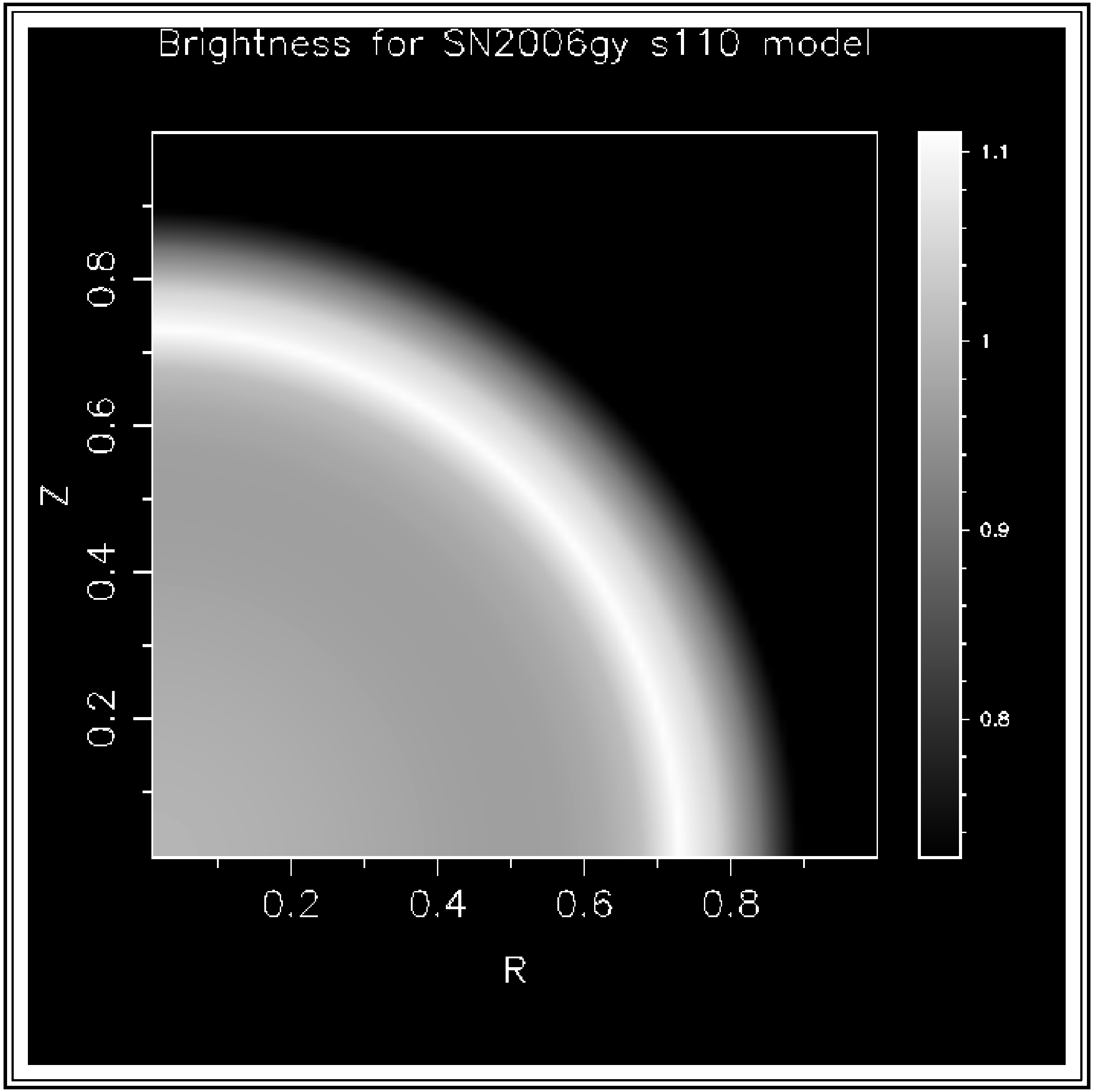


Decreasing $R_{\rm BB}$?

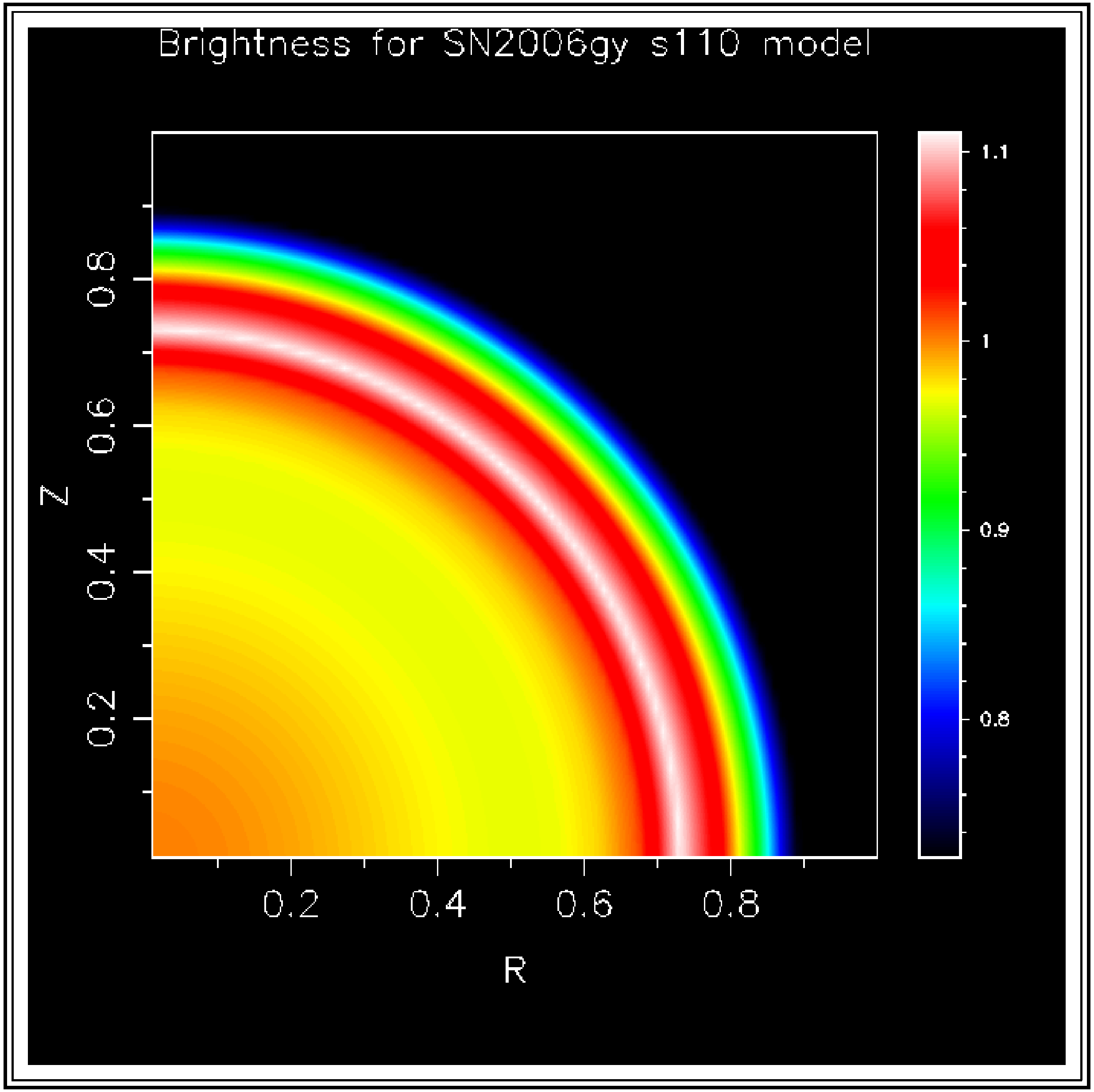
Some claim (e.g., Dessart et al.) that decrease of $R_{\rm BB}$ is an argument against the Dense Shell model, where $R_{\rm sh}$ grows.

In reality — $R_{\rm BB}$ measures not the shell radius but a surface of shining surface. Cf. Smith,Chornock ea'08 paper on SN 2006tf.

‘Visible’ disk of SN 2006gy



‘Visible’ disk of SN 2006gy c



Free expansion of ejecta???

Both EPM and SEAM rely on the “Hubble”-law

$$v = \frac{r}{t}.$$

This is violated on early stages in SN II-P and for months in the most luminous type II – SNe IIn.
Even if the free expansion obtains, both EPM and SEAM require crafting a good SN hydro-model.
But we are able to model SNe IIn in detail, so a new version of EPM/SEAM emerges: DSM – Dense Shell Method

New DSM for SNe IIn

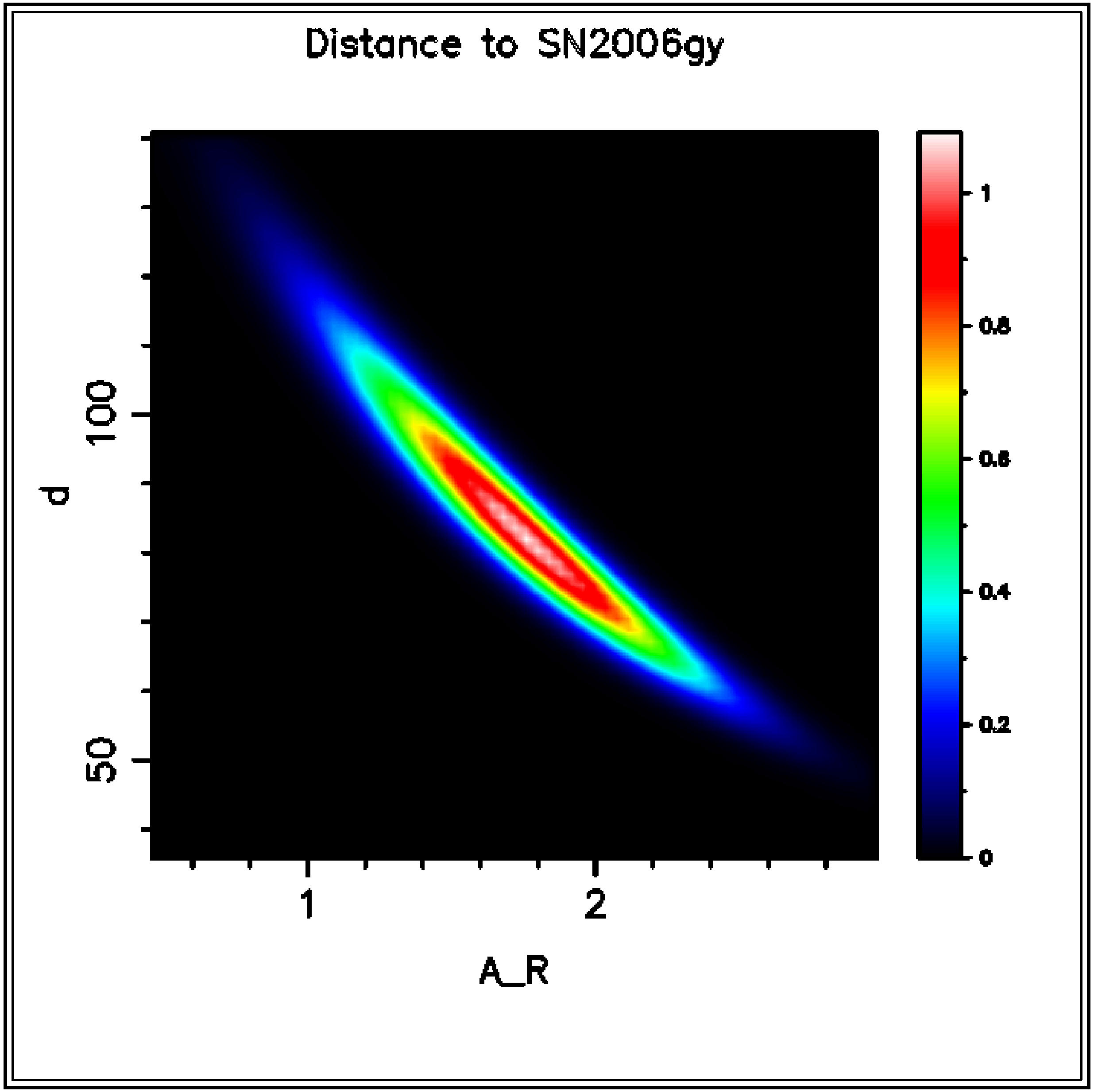
- Measure narrow line components to estimate the properties of CS envelope (may be done crudely).
- Measure wide line components to find the photospheric speed $v_{\rm ph}$ (as accurately as possible).
- Build a best fitting model for broad band photometry and the speed $v_{\rm ph}$.

New DSM for SNe IIn

- Although the "Hubble"-law $v = r/t$ is not applicable, $v_{\rm ph}$ 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 $v_{\rm ph}$ (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



Conclusions

- Baade-Wesselink (BW) method has numerous problems, because velocity of matter at $R_{\rm ph}$ is not at all $dR_{\rm ph}/dt$
- EPM is based not on BW, but on Kirshner-Kwan (KK) idea
- Radiating shocks are most probable sources of light in most luminous THERMONUCLEAR 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