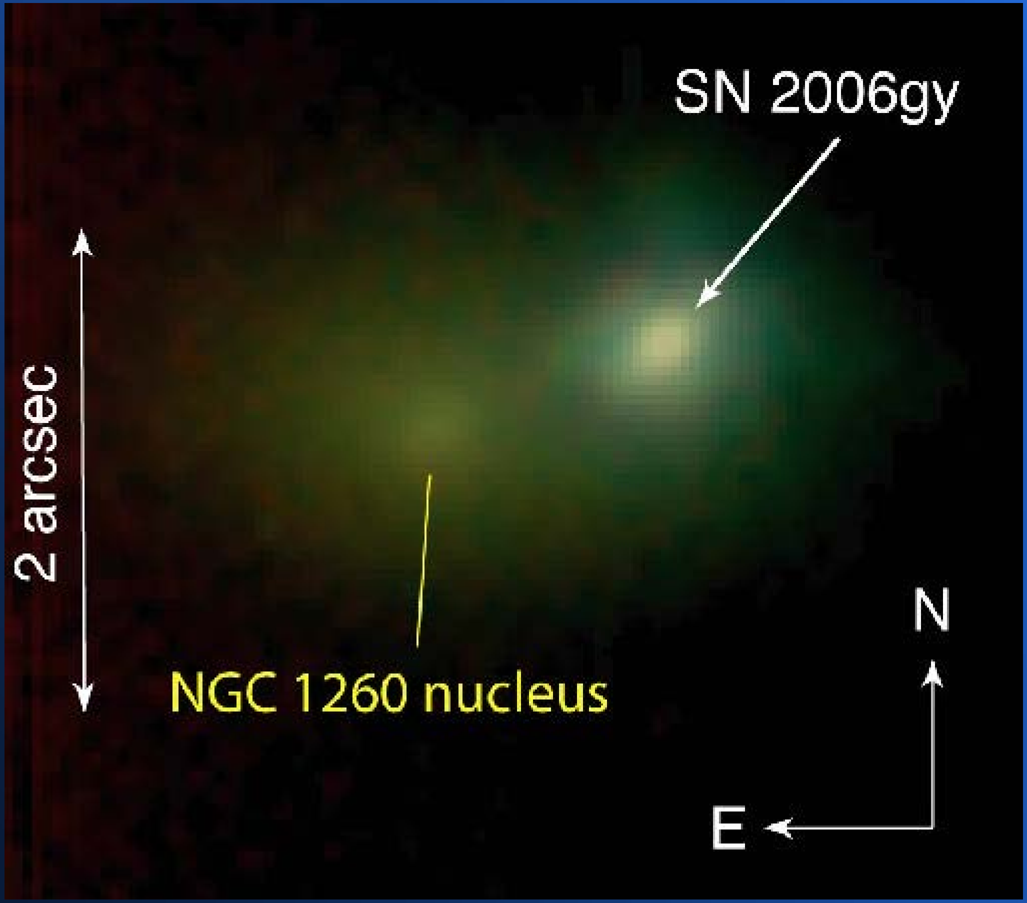
Building a cosmological distance scale based on type IIn supernovae



Sergei Blinnikov (ITEP)

Sources

- Work on SN light curves with E.Sorokina, P.Baklanov, M.Potashov, A.Tolstov, A.Dolgov, K.Nomoto, N.Tominaga, M.Tanaka, T.Moriya, Y.Kamiya
- Observations of SN2006gy, SN2009ip
- Theory of SNIIn (Nadyozhin,Grasberg,Chugai, Woosley,Heger...)
- ArXiv.org: Blinnikov e'a 1207.6914 (JETPL), Potashov e'a 1212.6893 (MNRAS, accepted)

Nobel prize in physics 2011

Prize motivation: "for the discovery of the accelerating expansion of the Universe through observations of distant supernovae"

Neither acceleration, nor the expansion itself of the Universe are directly observable!

This is hard because decades of accurate observations are about 10^{-9} of the age of the Universe. Accuracy of observations of distances and angles in large scale is orders of magnitude worse.

Basics for Cosmography

Photometric distance:

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

Dependence on redshift z

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

is determined by cosmology. Comparison with the

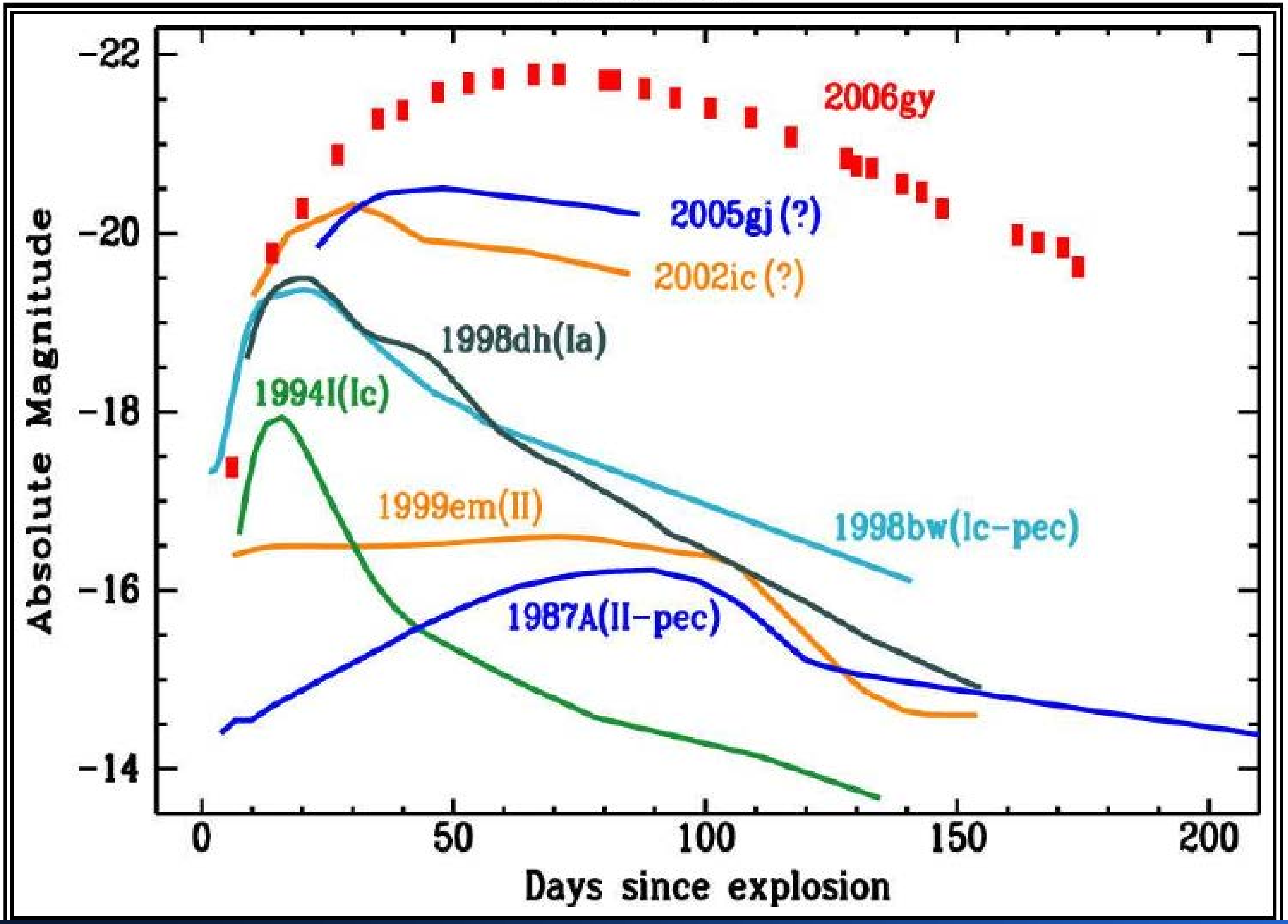
$$d_{\mathrm{ph}}(z)(\text{observed})$$

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

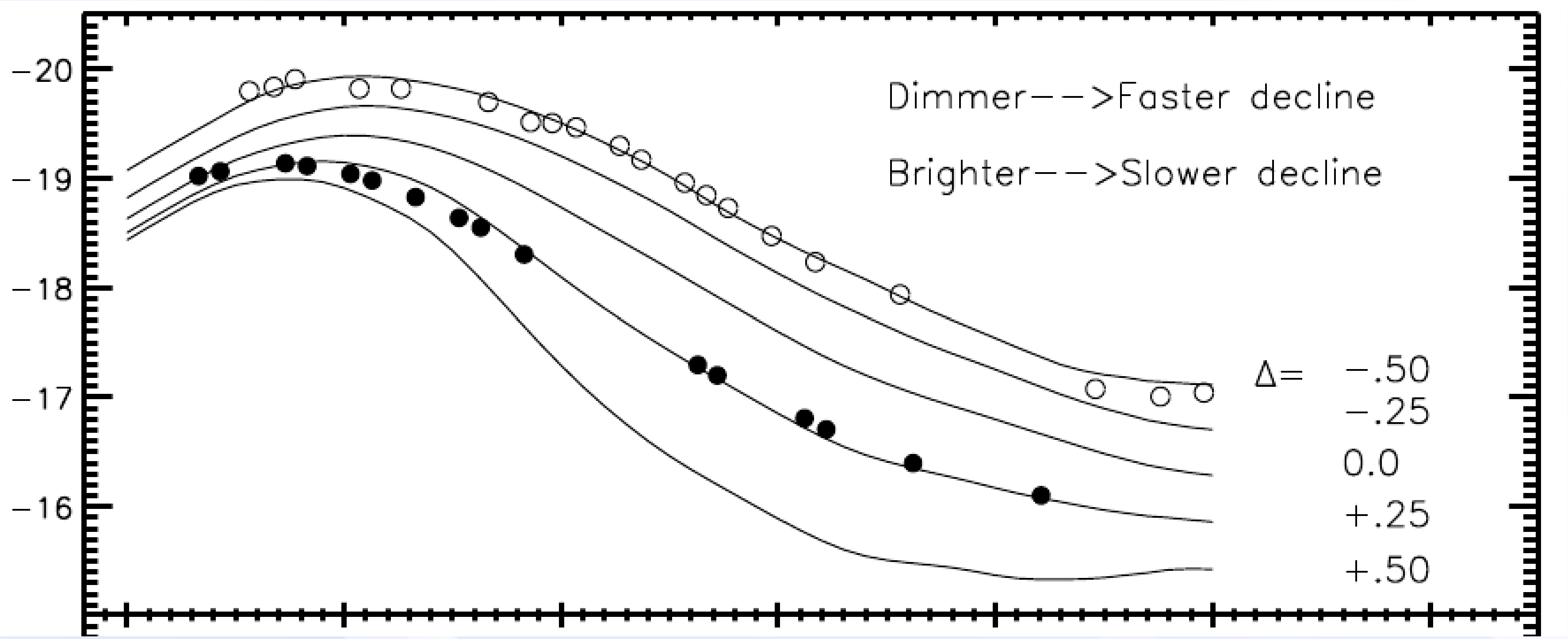
Thus, *L* is crucial

Most Luminous SNe

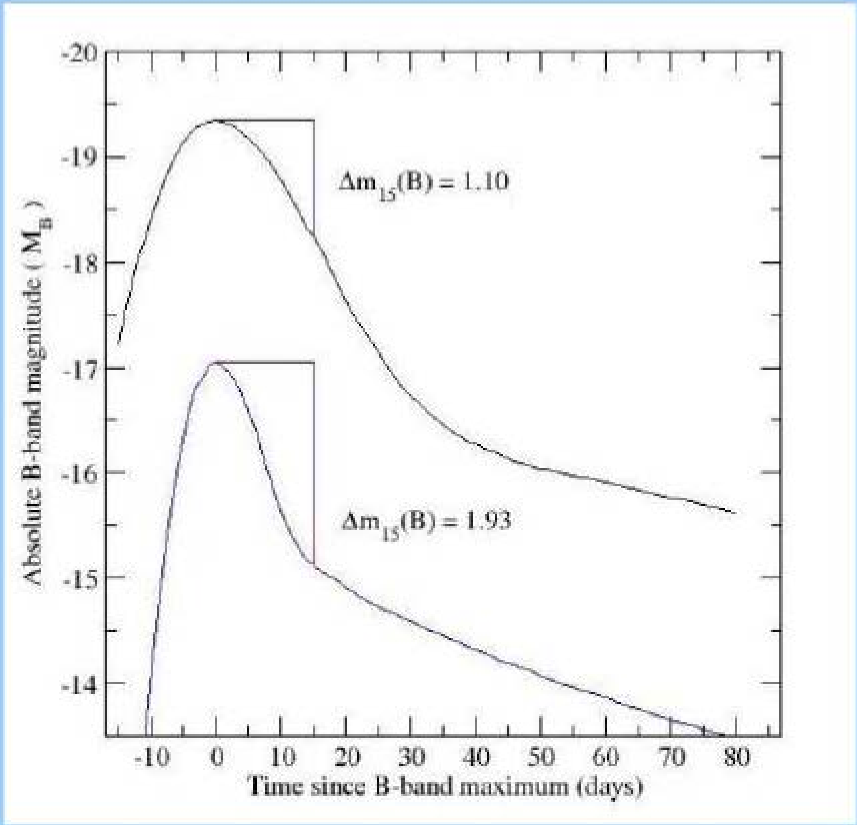
N.Smith ea'07



SNe Ia: More luminous are slower

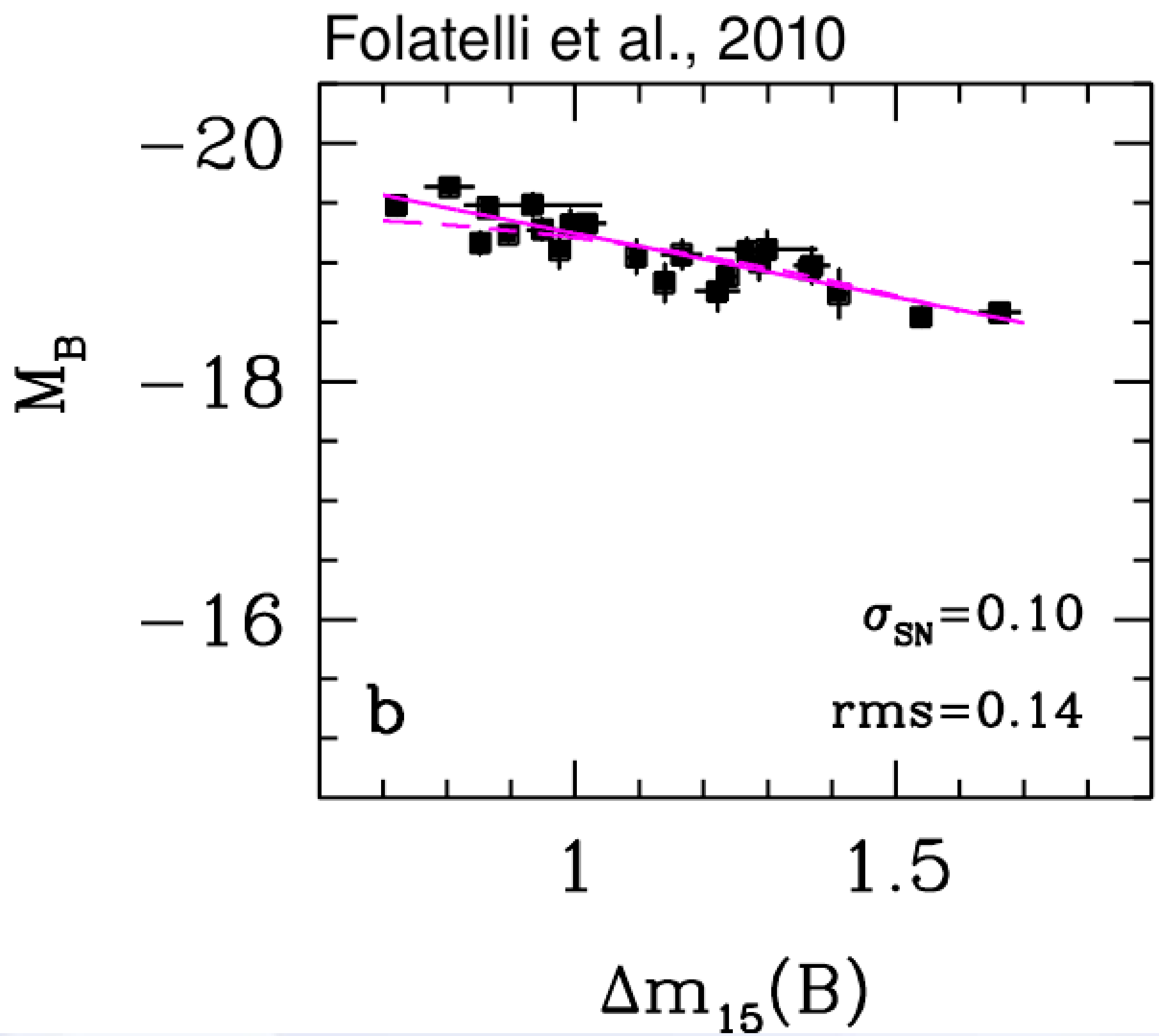


Peak Power – decline rate relation



For Type Ia supernovae we define the "decline rate" as the number of magnitudes the object gets dimmer in the first 15 days after maximum light in the blue. Fast decliners are fainter objects.

PP relation from Carnegi project



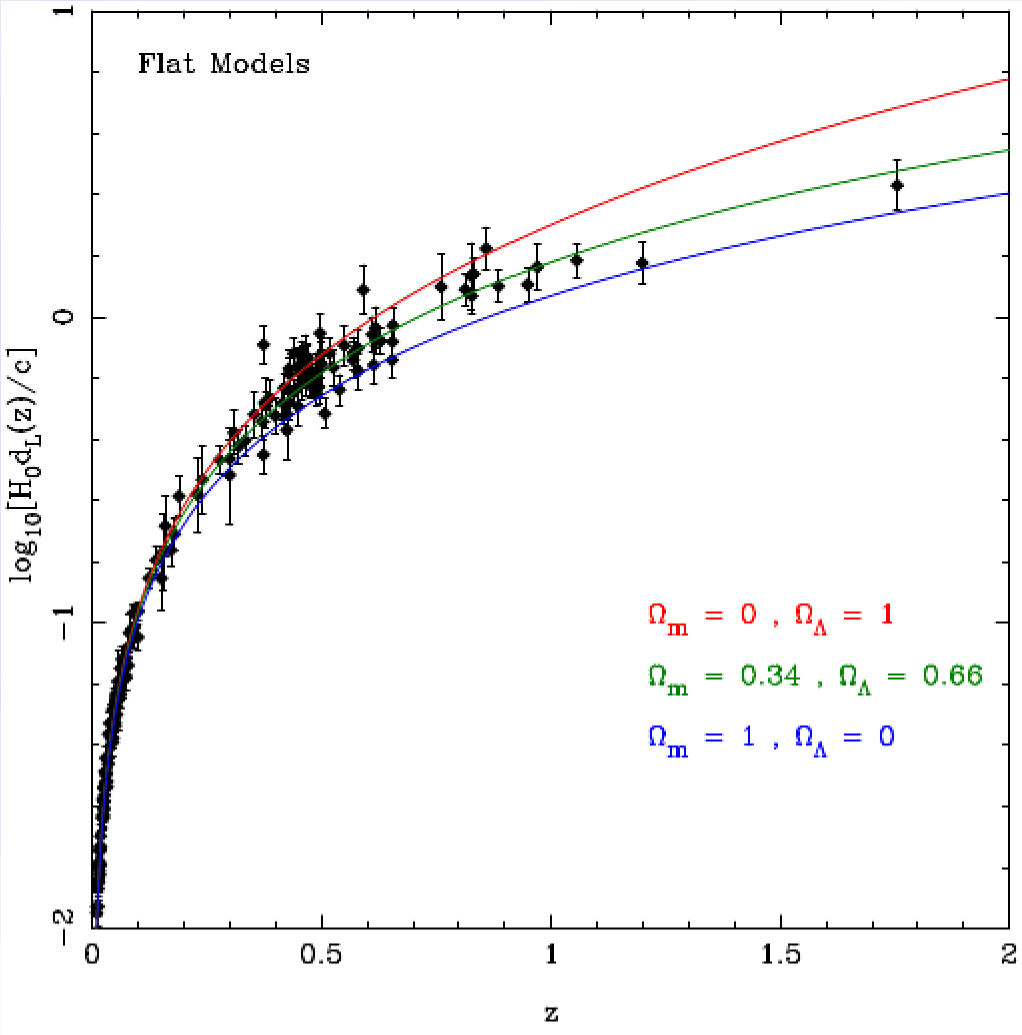
Now, take a formula for fits $d_{\rm ph}(z)$

$$d_{\rm ph} = \frac{c}{H_0}(1+z)\frac{1}{\sqrt{\Omega_k}}\times$$

$$\sinh\left\{\sqrt{\Omega_k}\int\limits_0^z \left[\Omega_{\rm M}(1+\bar{z})^3 + \Omega_\Lambda + \Omega_k(1+\bar{z})^2\right]^{-1/2} {\rm d}\bar{z}\right\}.$$

Here $\Omega_k = 1 - \Omega_{\rm M} - \Omega_\Lambda$, and for $\Omega_k < 0$: $\sinh \to \sin$. For $\Omega_k = 0$ the limit $\Omega_k \to 0$ is easily taken, so $\sinh$ disappears from the expression for $d_{\rm ph}$, and only the integral is left.

and plot it changing parameters



Systematics and z-dependence

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

Direct distance indicators are needed!

Primary vs. Secondary Distance Indicators

Primary indicators are calibrated based on observations in our Galaxy

- Trig. Parallax
- Converging Point
- Main Sequence Fitting
- Spectroscopic Parallax
- Cepheids BW: Baade-Wesselink
- Novae

Secondary indicators rely on primary indicators to calibrate distances

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

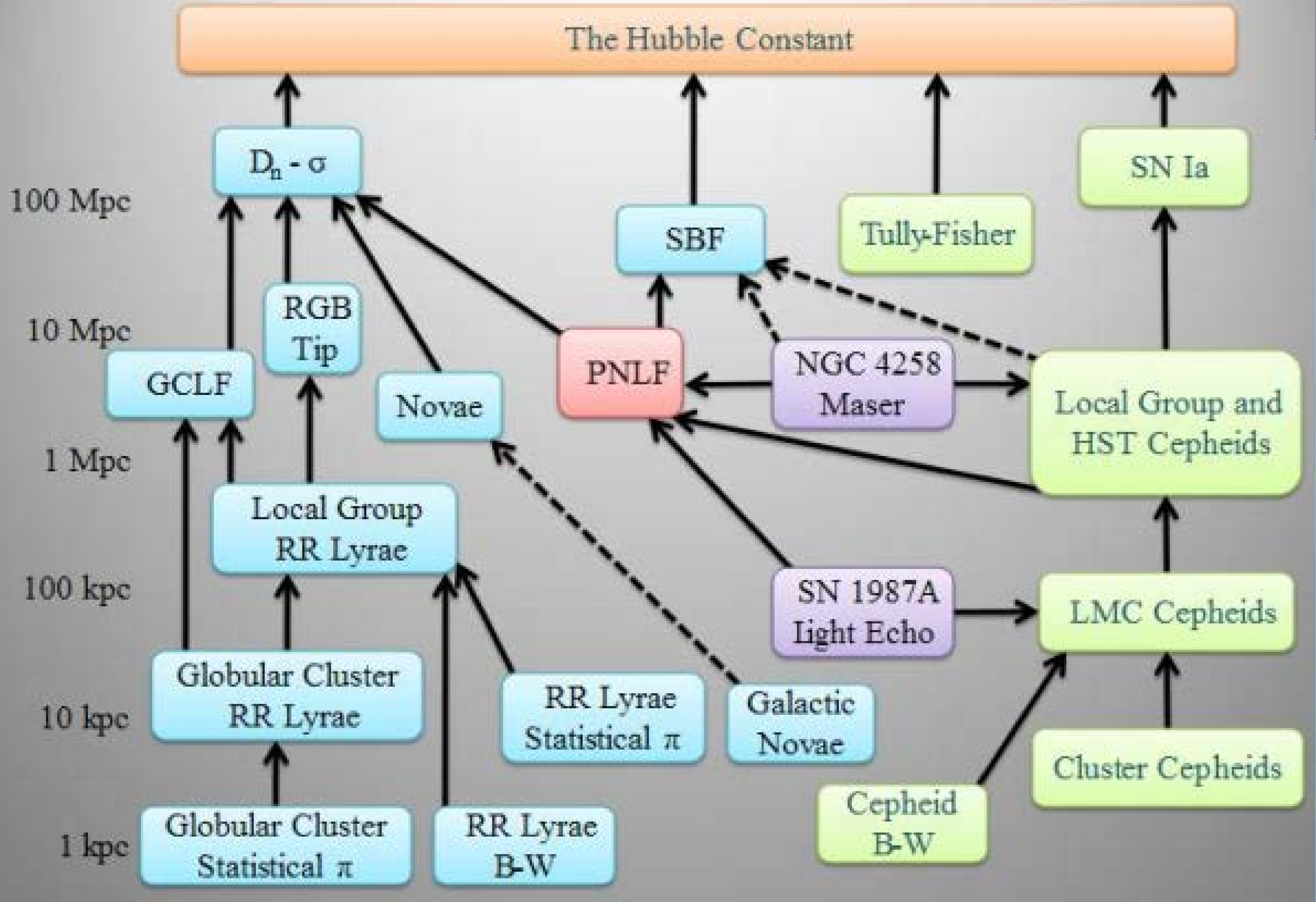
Toward an EG Distance Scale

Using Supernovae

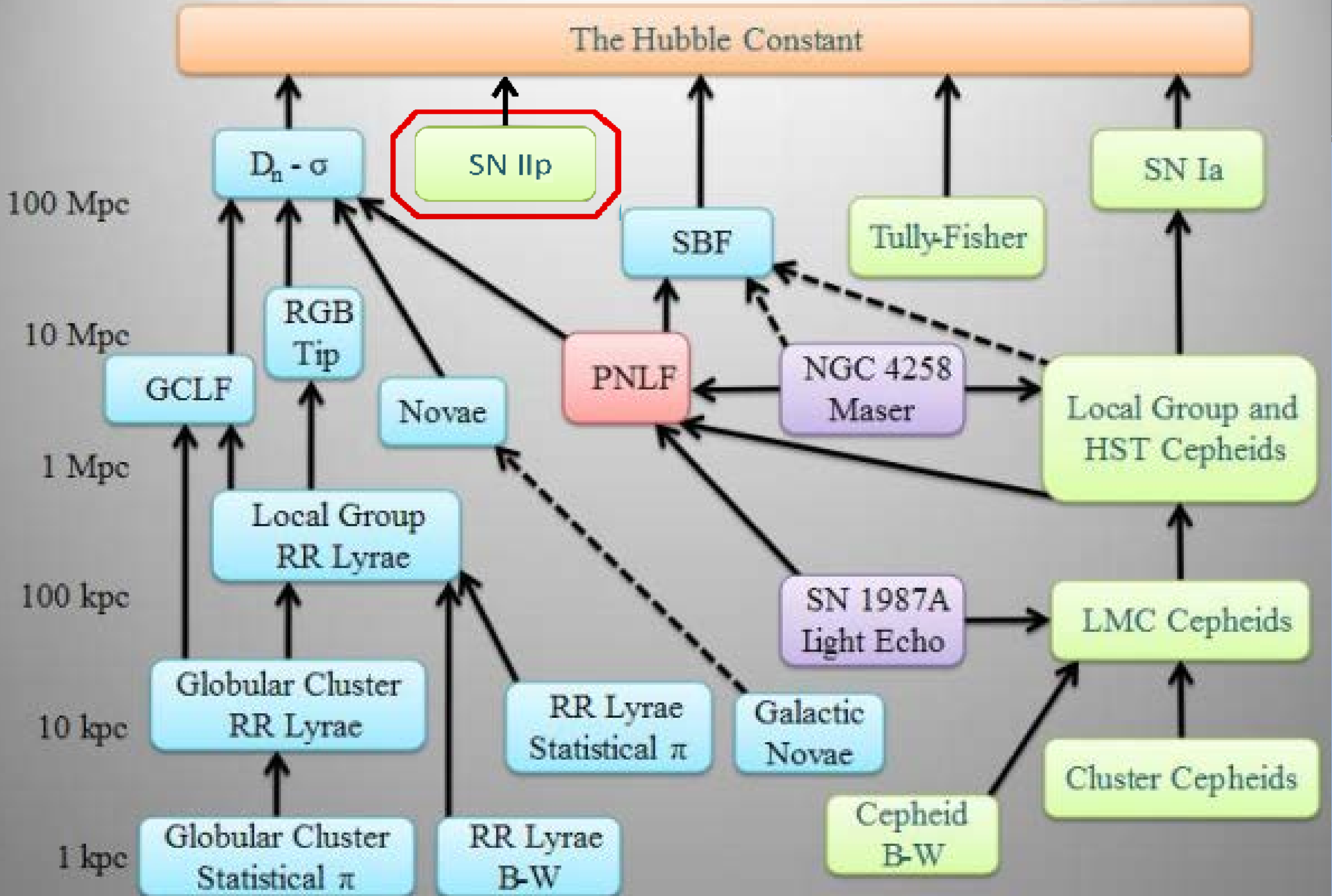
Supernovae are among the most luminous phenomena in the universe, and may probe cosmological models. Type Ia supernova are currently the most favored secondary distance indicators. Although they are not uniform in luminosity, they are standardized based on statistical correlations found for nearby events.

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

Extragalactic Distance Ladder



Extragalactic Distance Ladder



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.

Problems with BW

But this idea does not work (as a rule)!
Velocity of matter at the photosphere is not at all $dR_{\rm ph}/dt$. The $v_{\rm ph}$ and $\dot{R}_{\rm ph}$ may even have different signs!

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 or SEAM

SEAM = Spectral-fitting Expanding Atmosphere Method.

The distance *D* to the supernova is

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

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

EPM

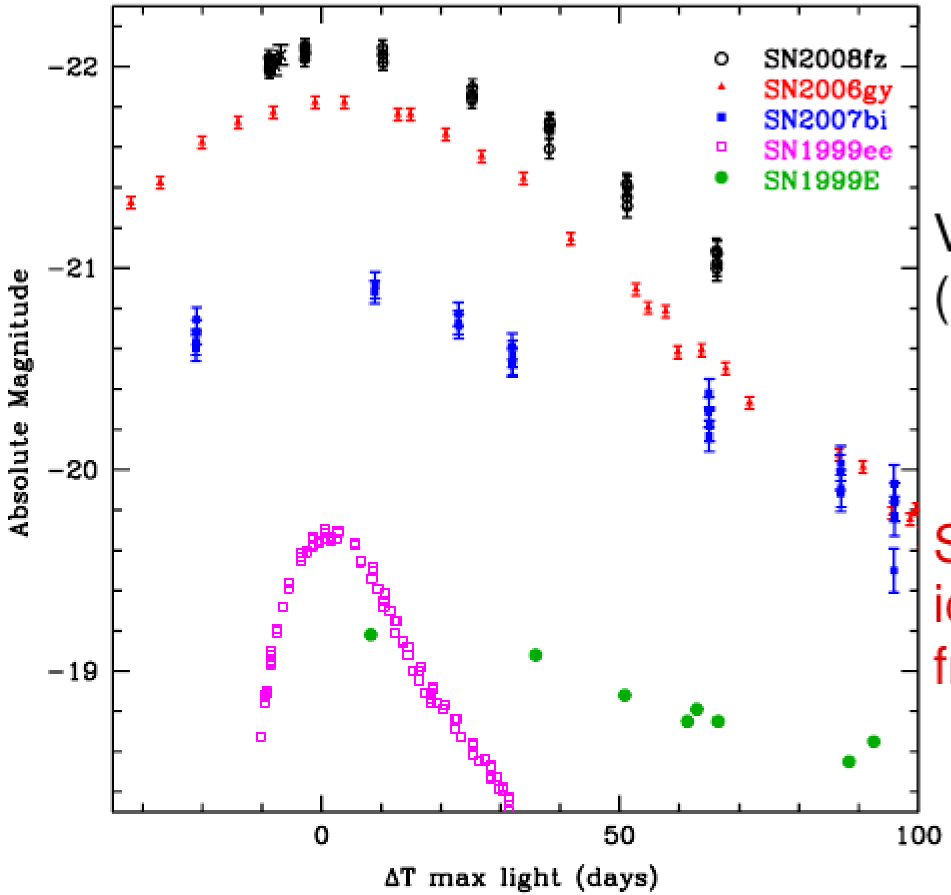
In practice usually $F_\nu(model) = \pi B_\nu(T_c)$

and, with some correction factors,

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

Corrections are needed for dilution and limb effects in brightness, ζ, and projection factor, relating true and spectral profile velocities, *p*.

Extremely bright Type IIn SNe



V-band
(Drake et al. 2010)

SN1987A and a typical SNII below the frame!

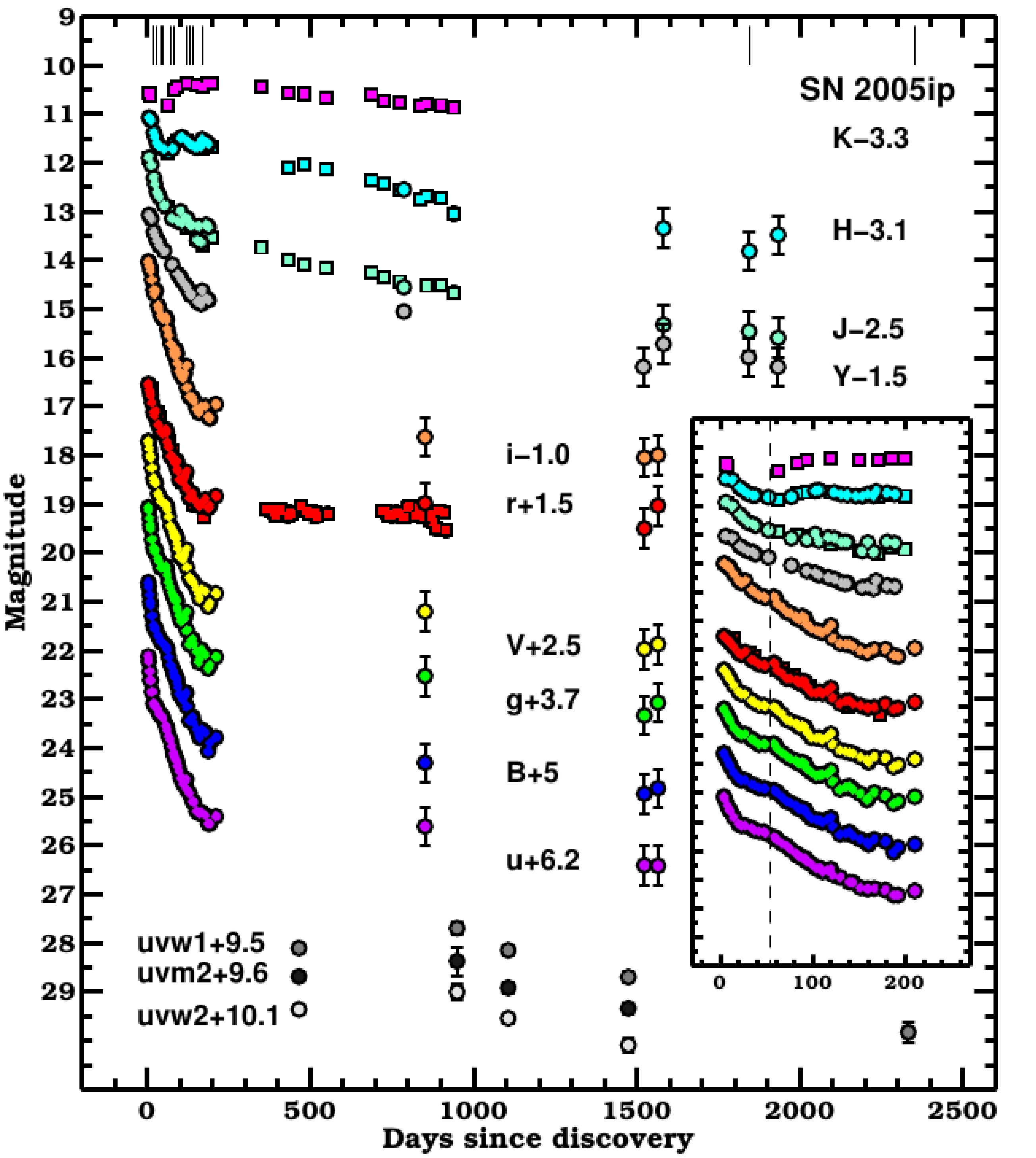
Free expansion of ejecta???

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

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

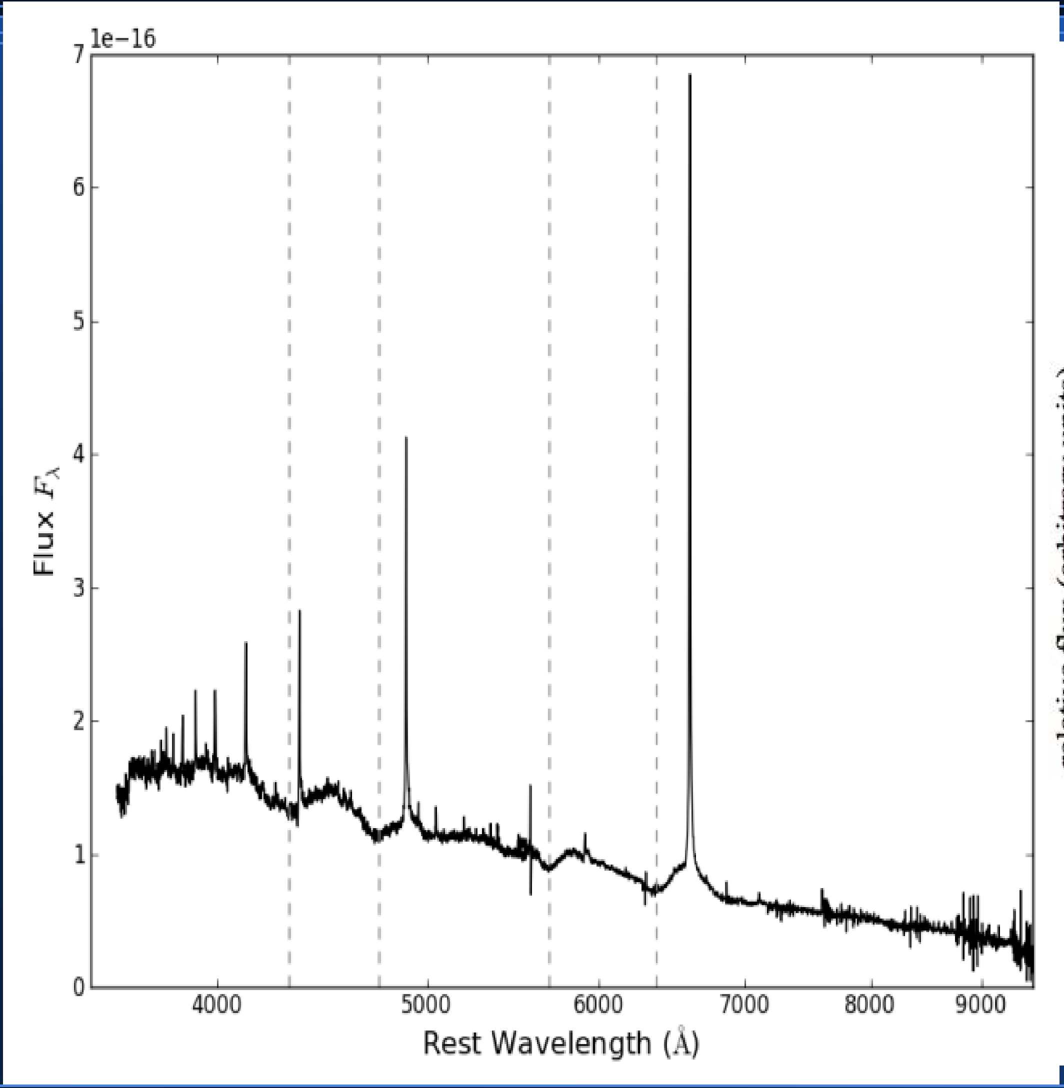
This is violated on early stages in SN II-P and for months in the most luminous type II – SNe IIn.
Even if the free expansion obtains, both EPM and SEAM require crafting a good SN hydro-model.
But we are able to model SNe IIn in detail, so a new version of EPM/SEAM emerges: DSM – Dense Shell Method

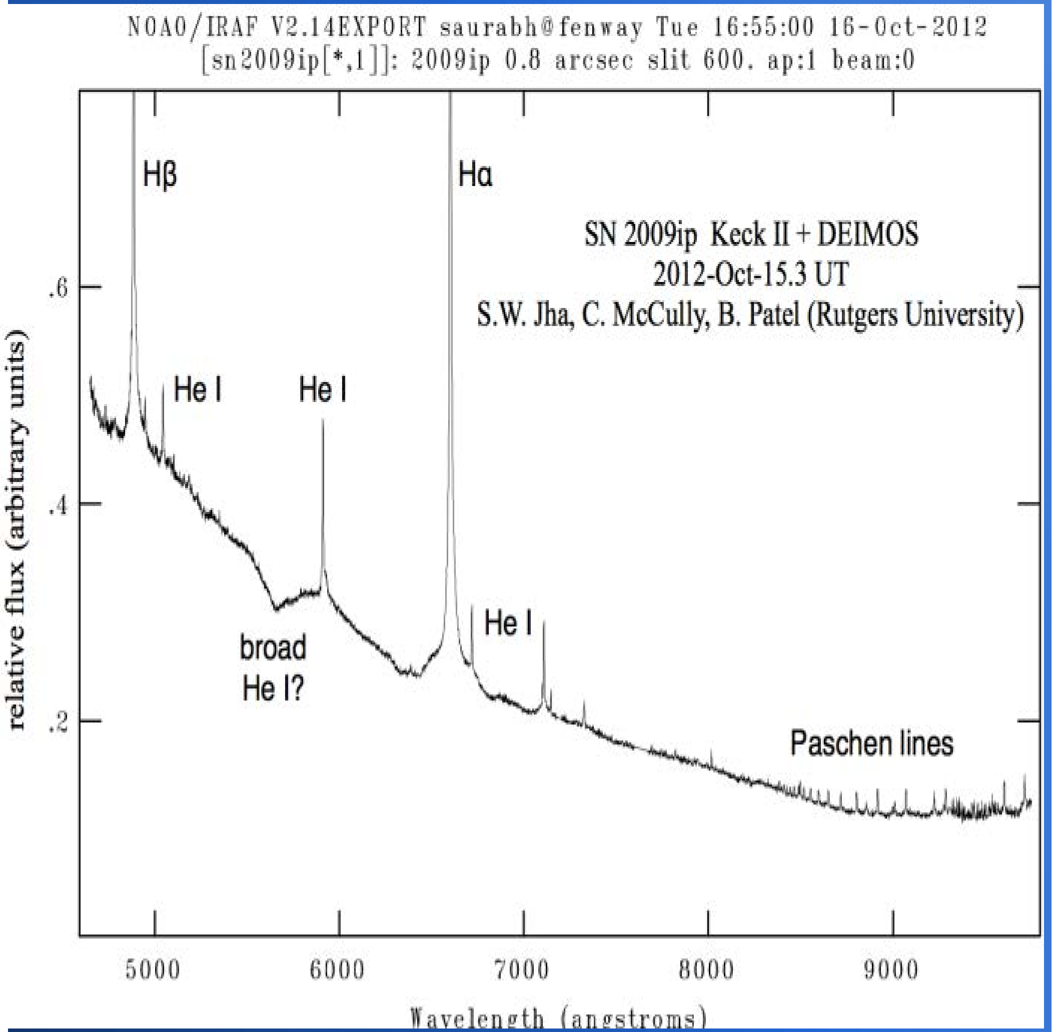
SNIIn LCs



- May be very long, but for us now only the rising part is interesting (not always discovered).
- Figure from Stritzinger et al. ApJ (2012)

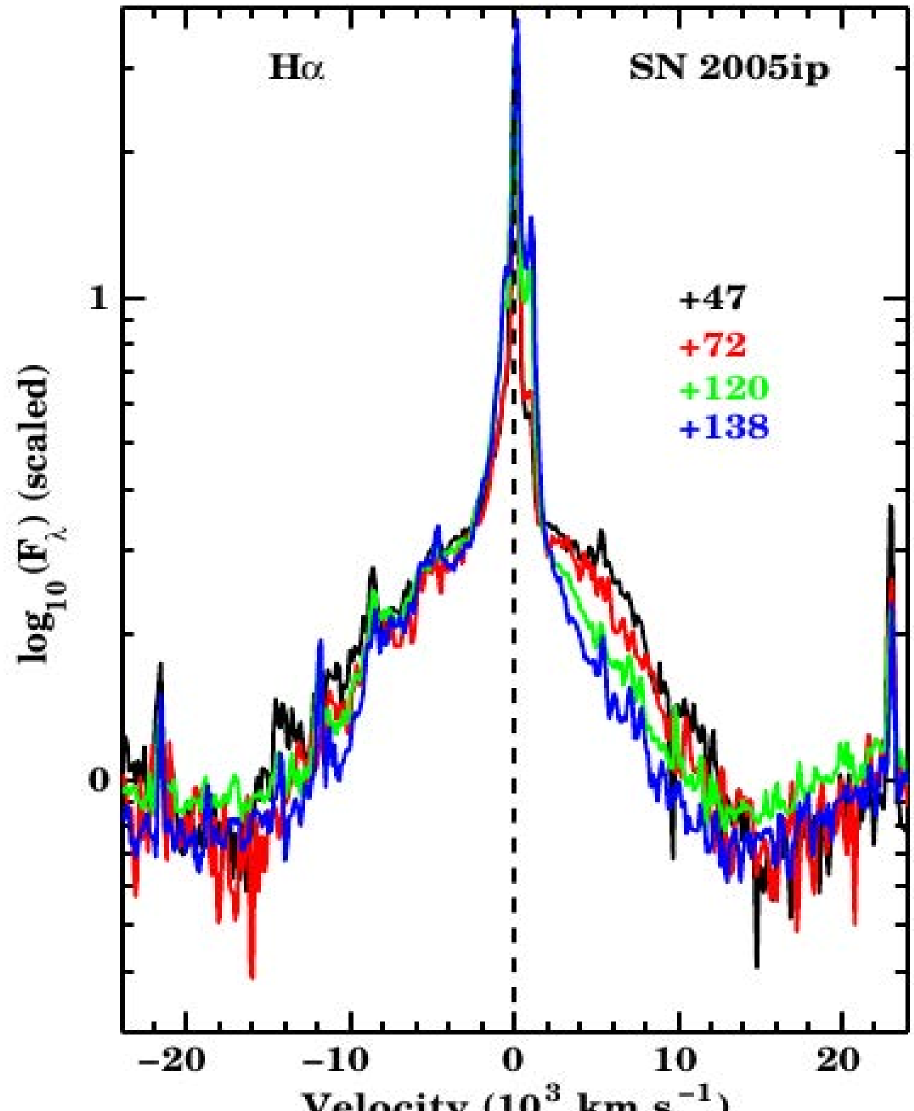
SN2009ip: high quality spectra



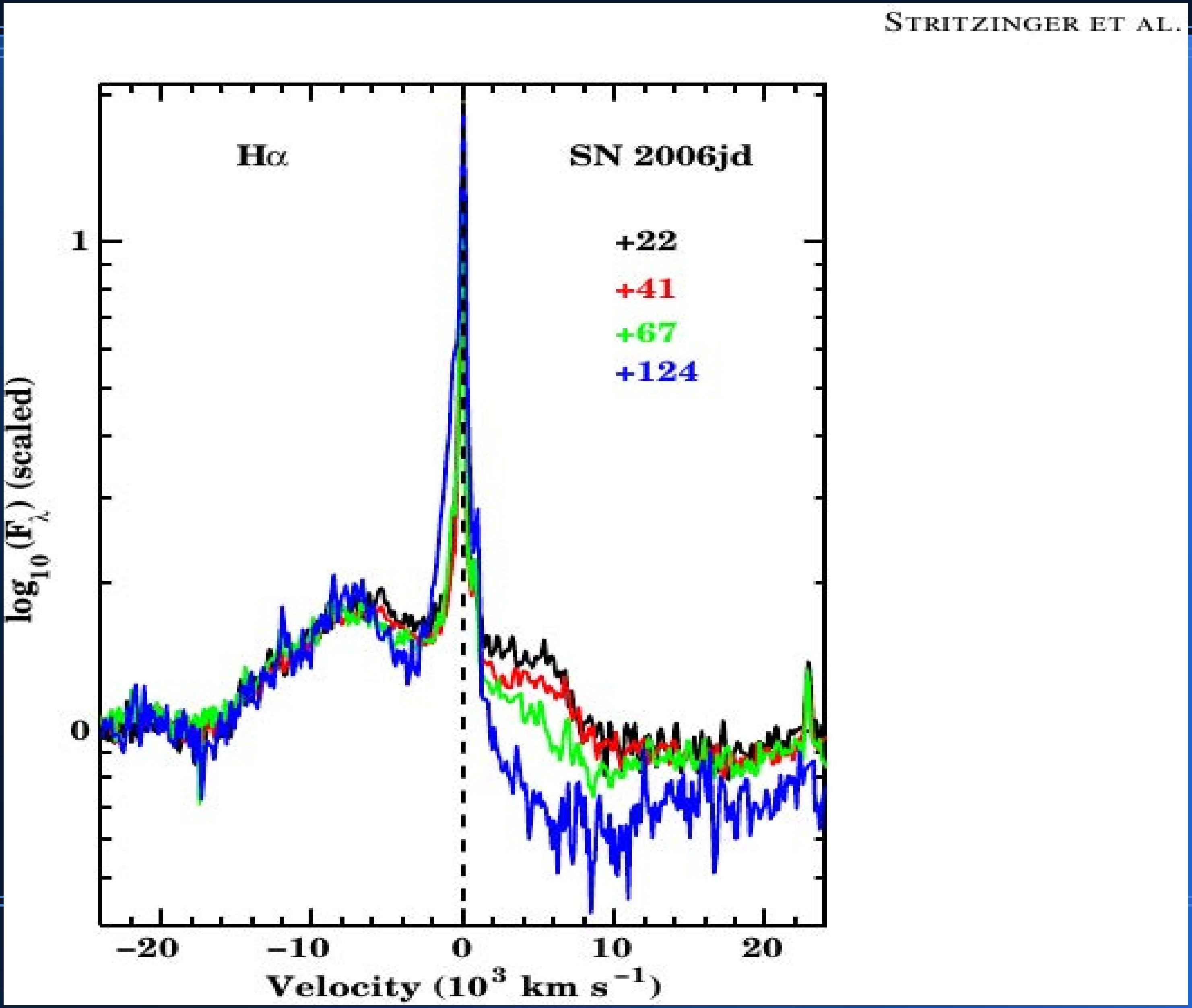


Narrow/wide lines in SNeIIn

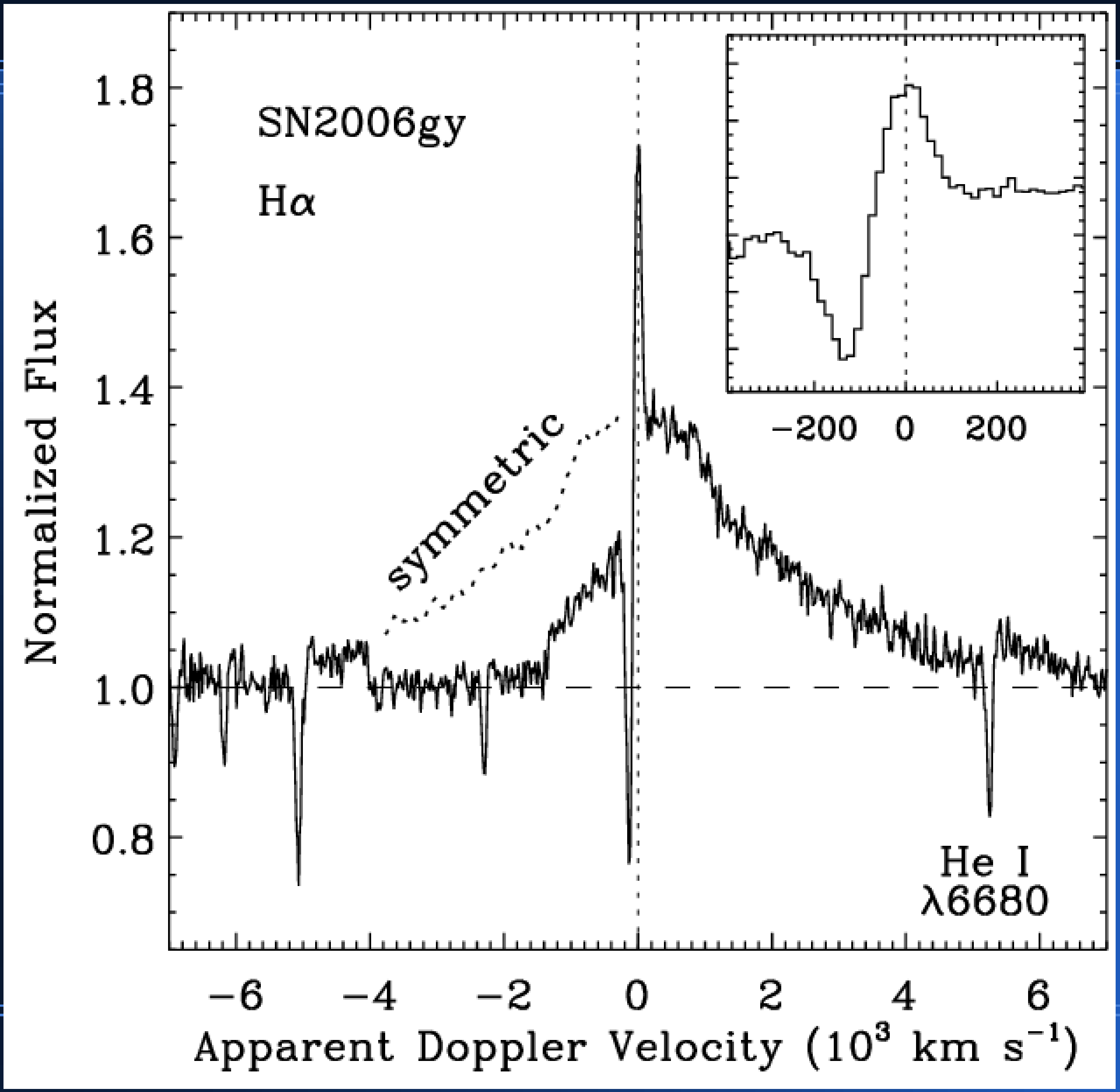
The Astrophysical Journal, 756:173 (19pp), 2012 September 10



Red suppression in wide lines



Blue suppression in wide lines



Double explosion: old idea

Grasberg & Nadyozhin (1986)

Type II supernovae: two successive explosions?

É. K. Grasberg and D. K. Nadëzhin

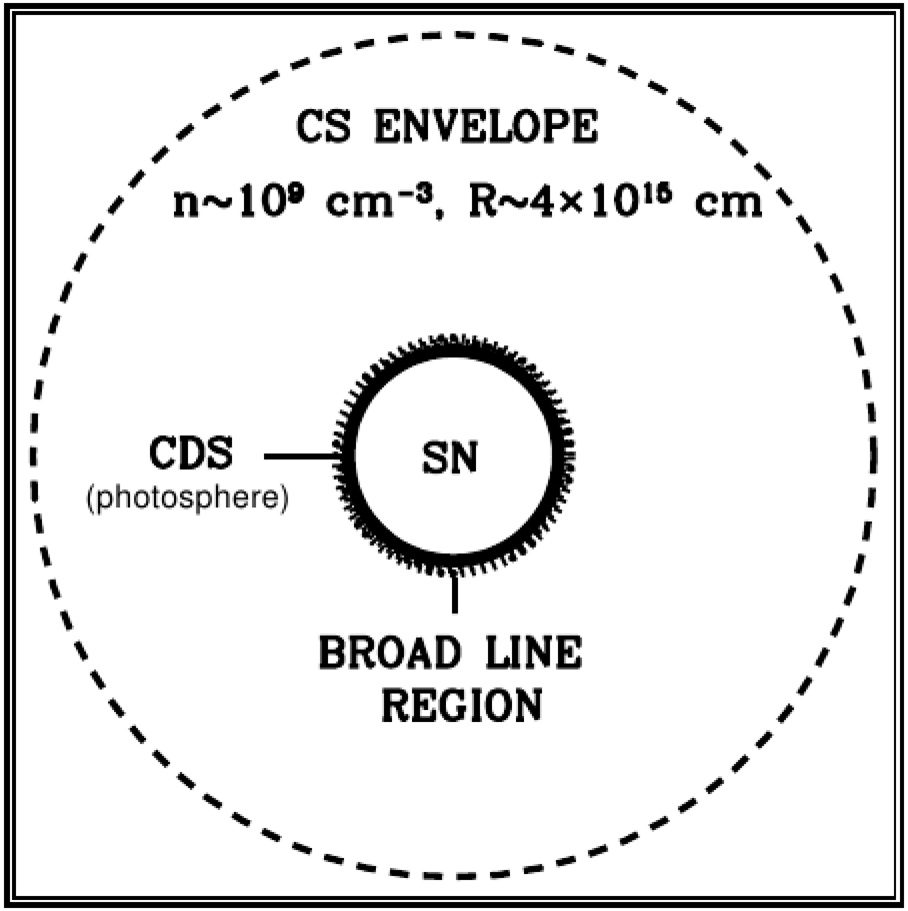
Radio Astrophysical Observatory, Latvian Academy of Sciences, Riga
and Institute of Theoretical and Experimental Physics, Moscow

(Submitted September 5, 1985)

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

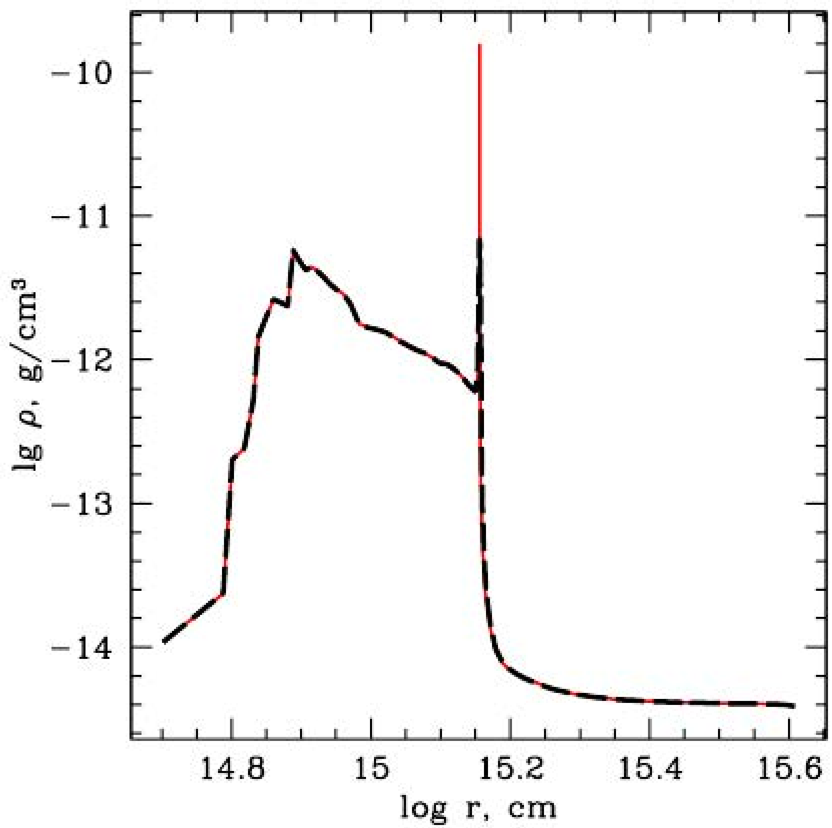
A type II supernovae model wherein a weak explosion precedes a much stronger one can explain the behavior of the narrow-line systems observed in some type II spectra. For SN 1983k in NGC 4699, the two outbursts would have been separated by 1–2 months. Core gravitational collapse generating a relatively 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.

SN IIn structure, Chugai, SB ea’04

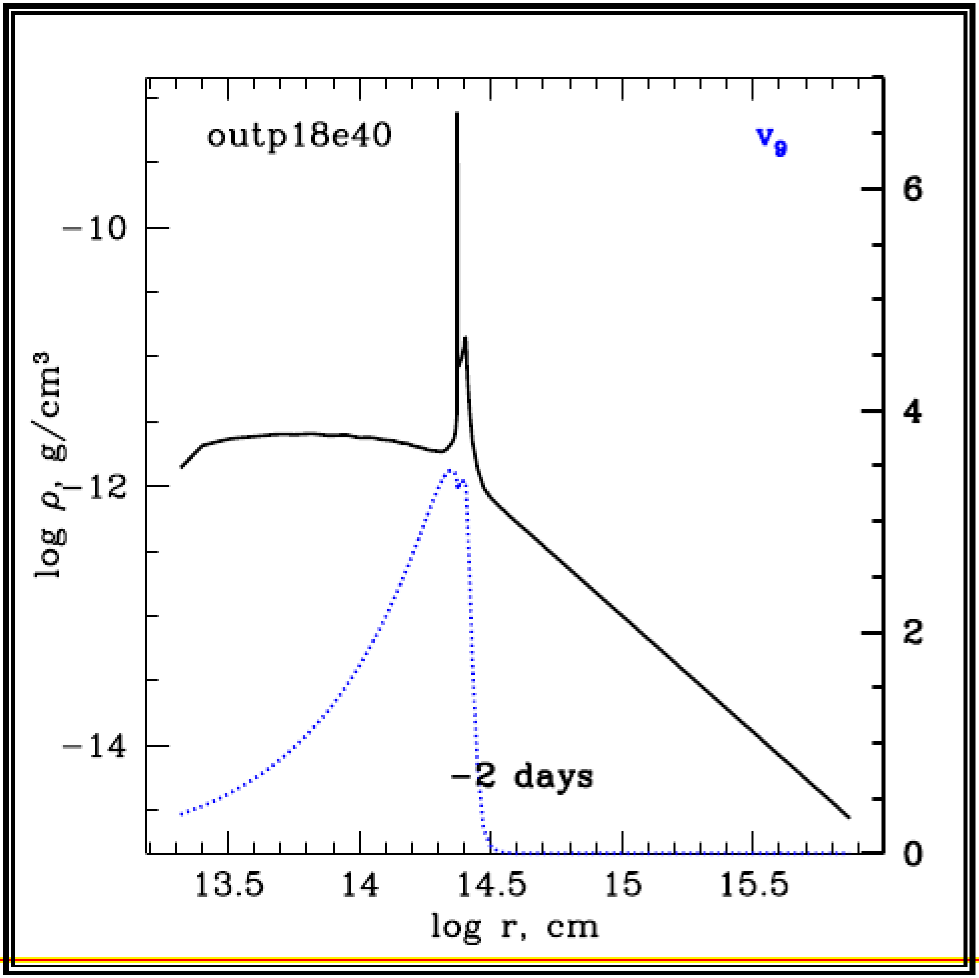


Shocks in SNe IIn

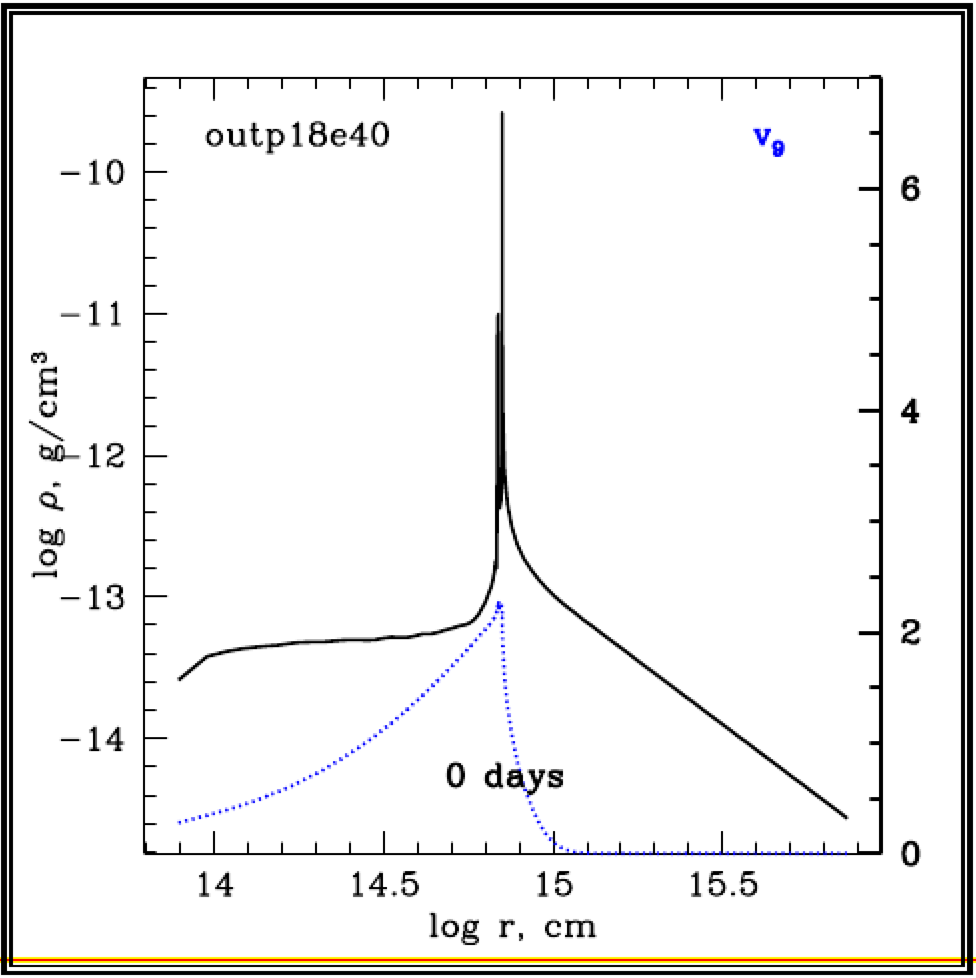
A long living shock: an example for SN1994w of type IIn. Density as a function of the radius r in two models at day 30. The structure tends to an isothermal shock wave.



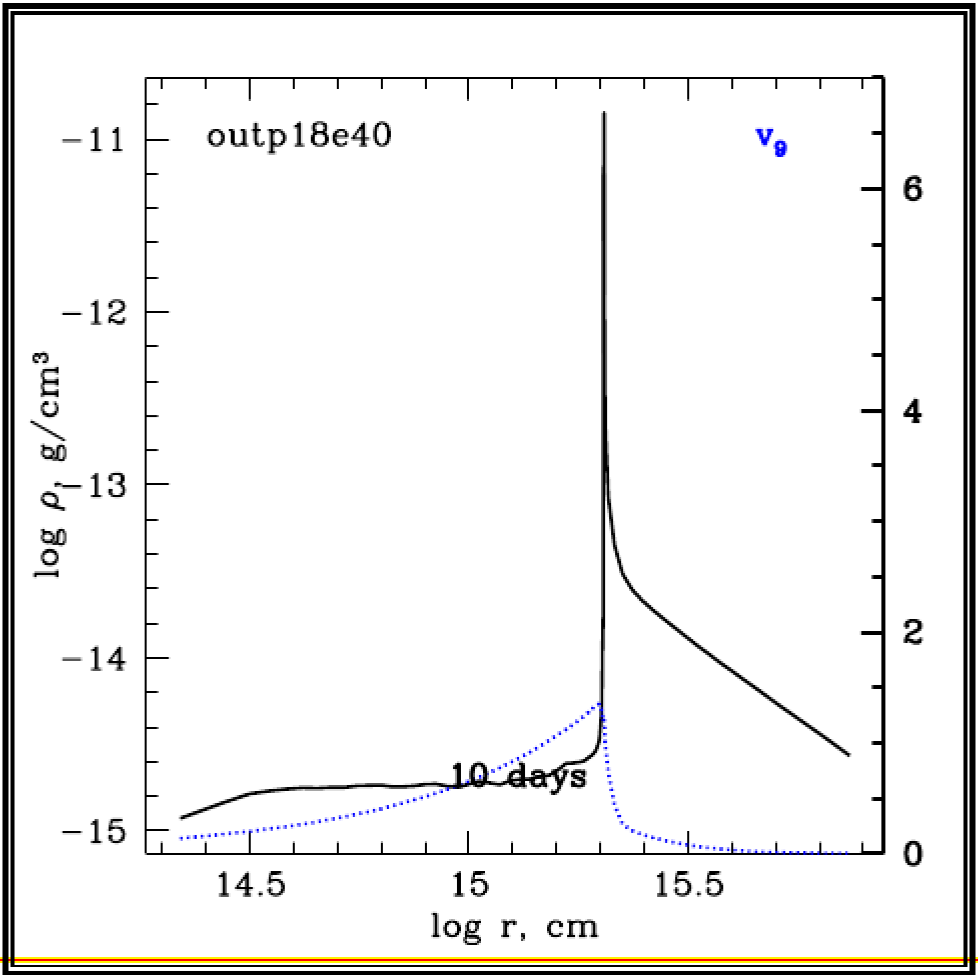
Long Living Dense shells-1



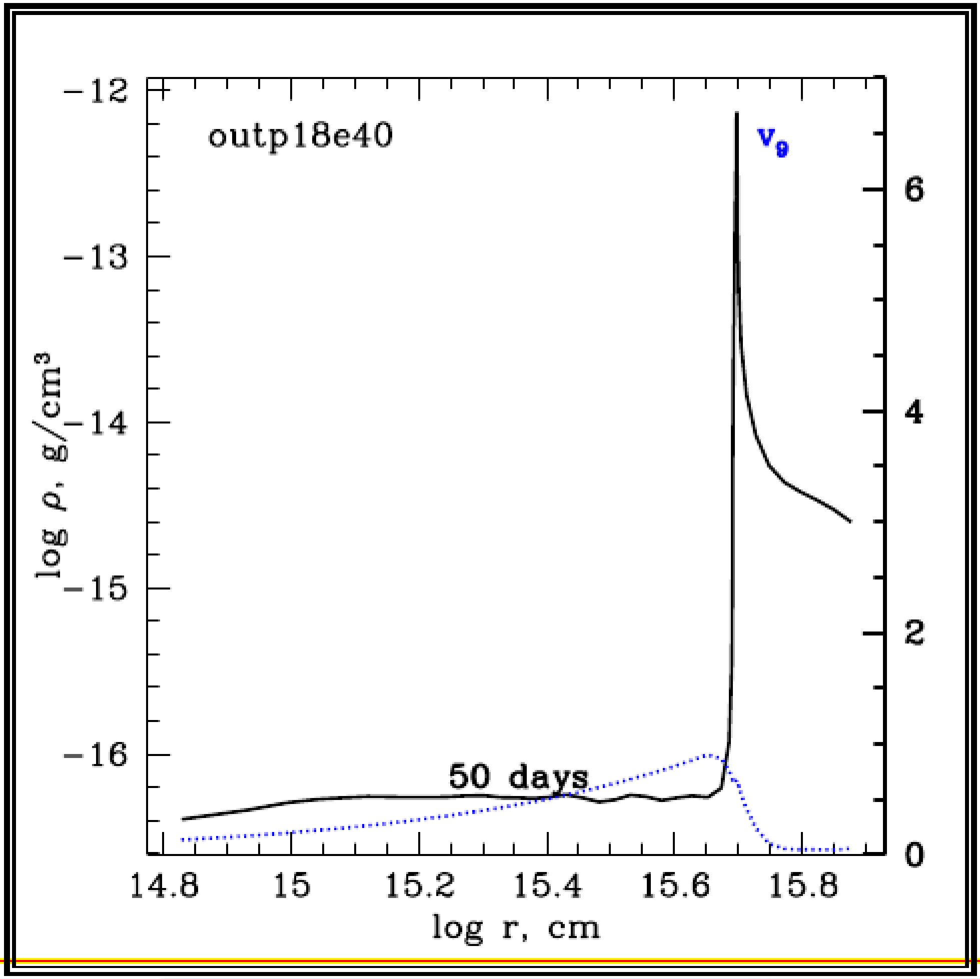
Long Living Dense shells-2



Long Living Dense shells-3



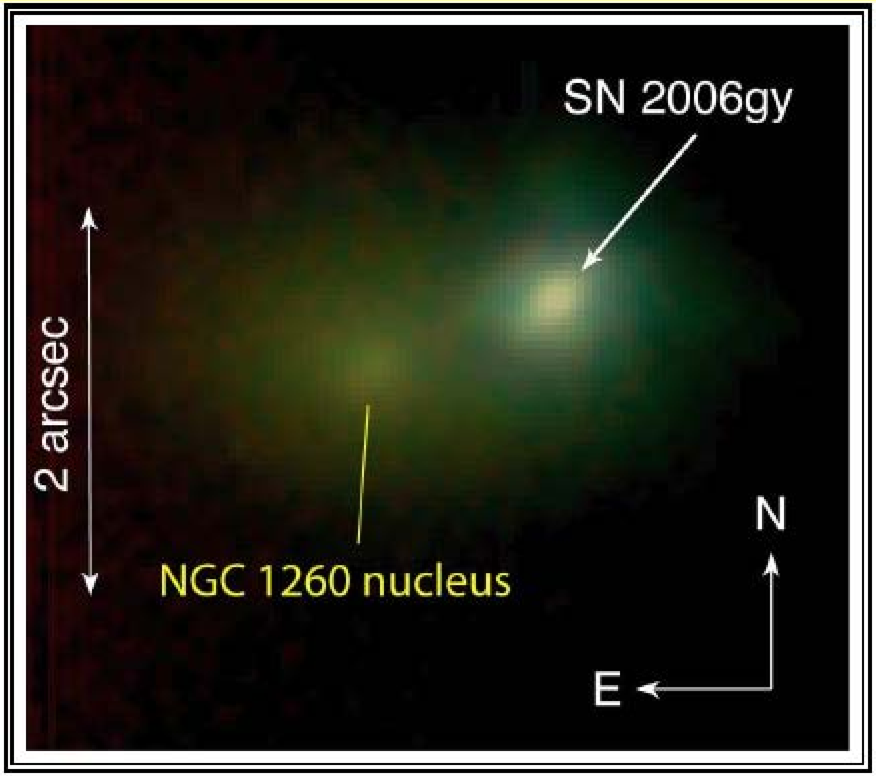
Long Living Dense shells-4



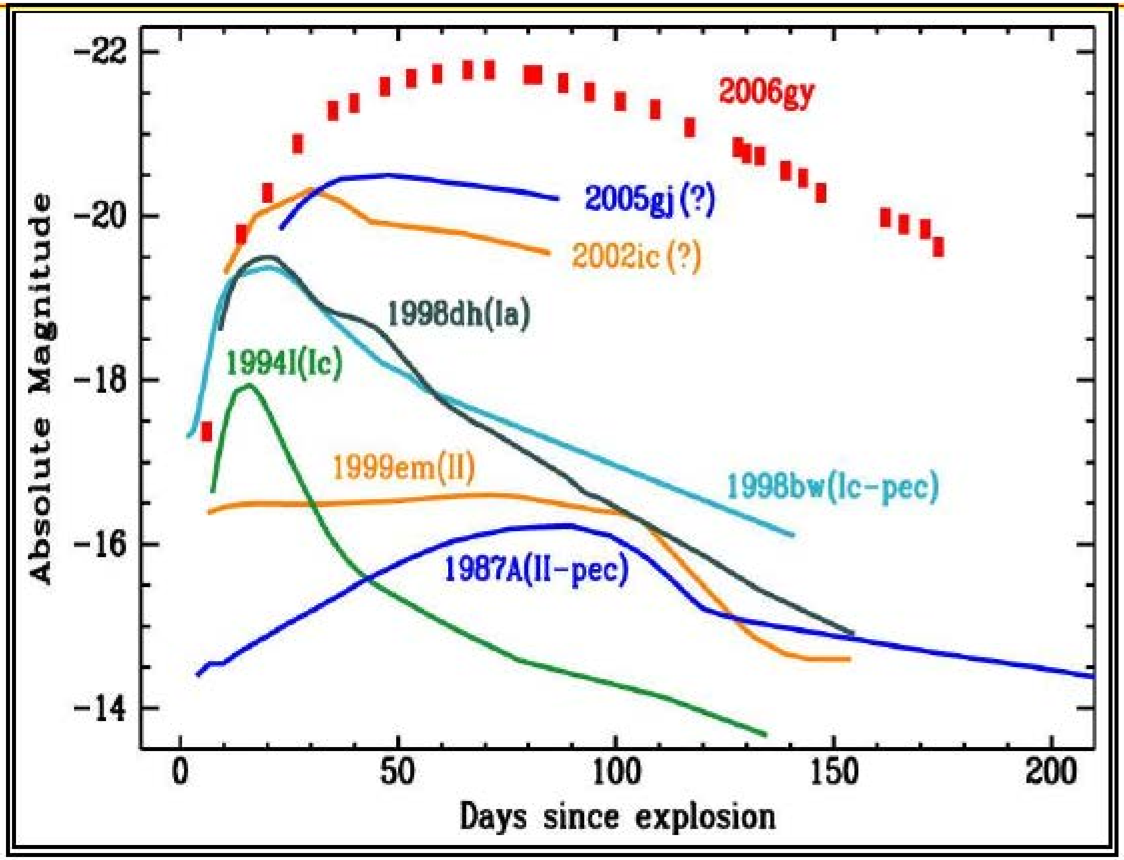
SN 2006gy

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

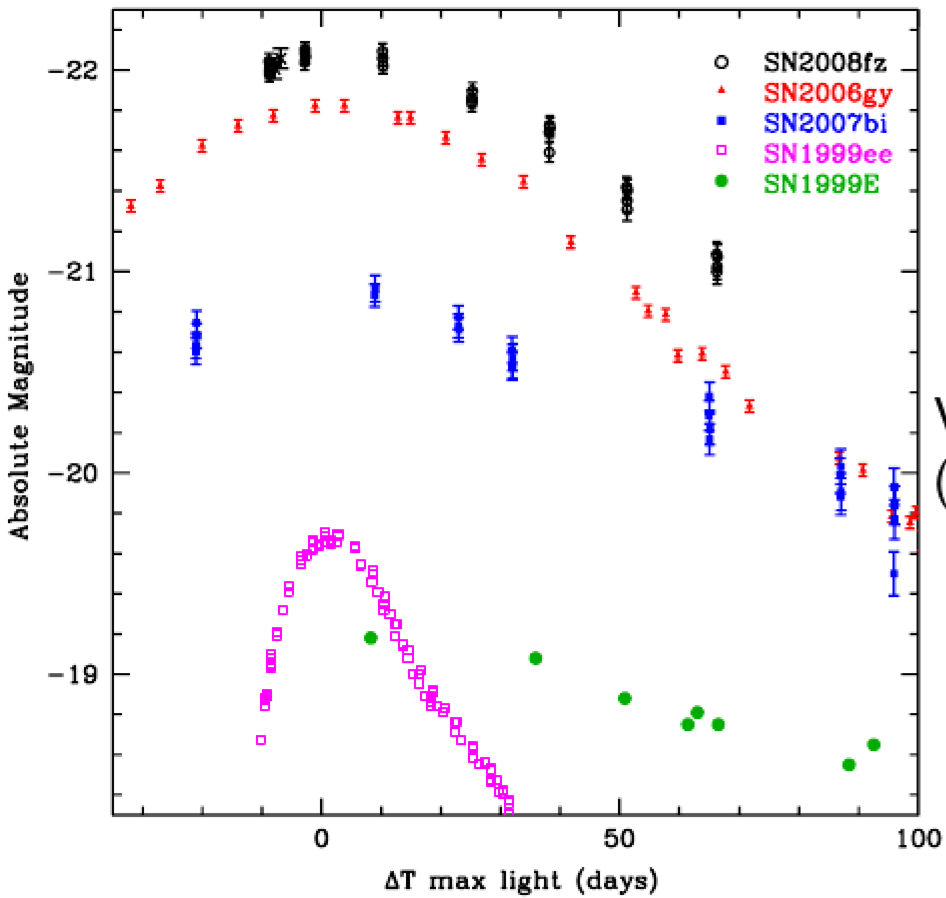
Smith et al. 2007, Sep. 10 ApJ, astro-ph/0612617)



It was Most Luminous SN ever



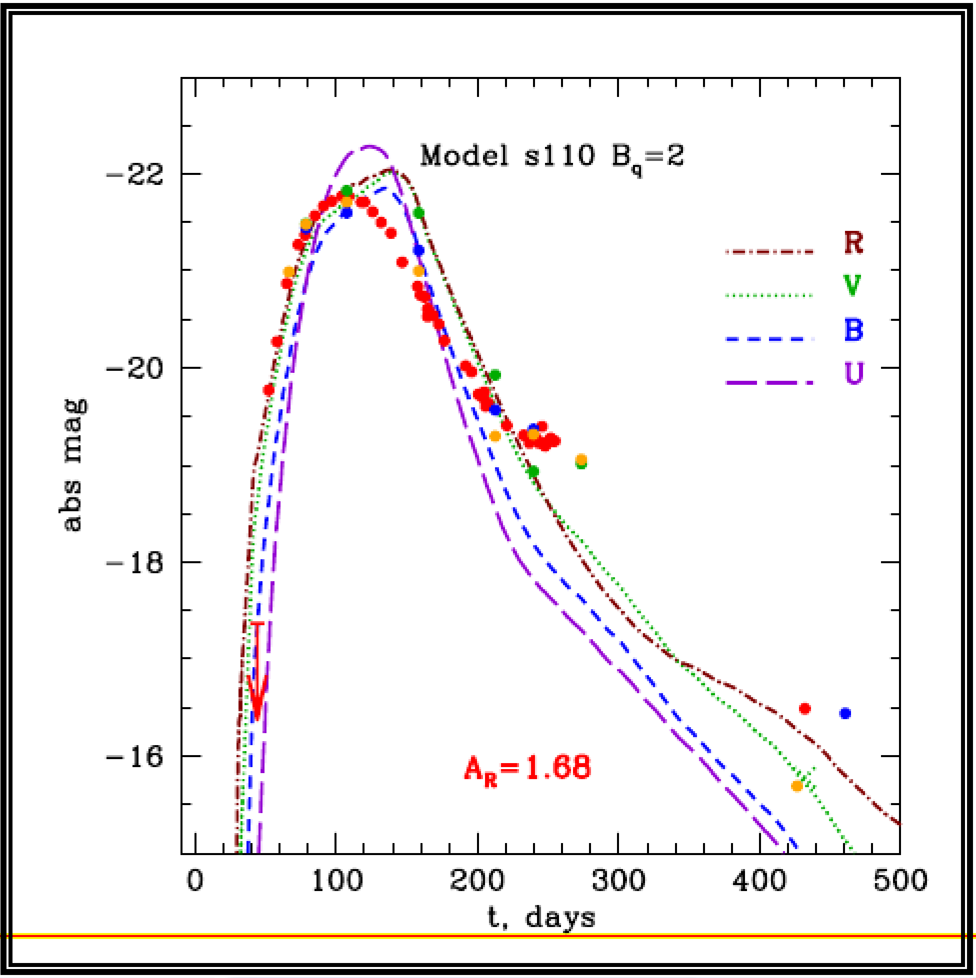
Extremely bright Type IIn SNe



V-band
(Drake et al. 2010)

Stella: LCs for SN2006gy

new runs



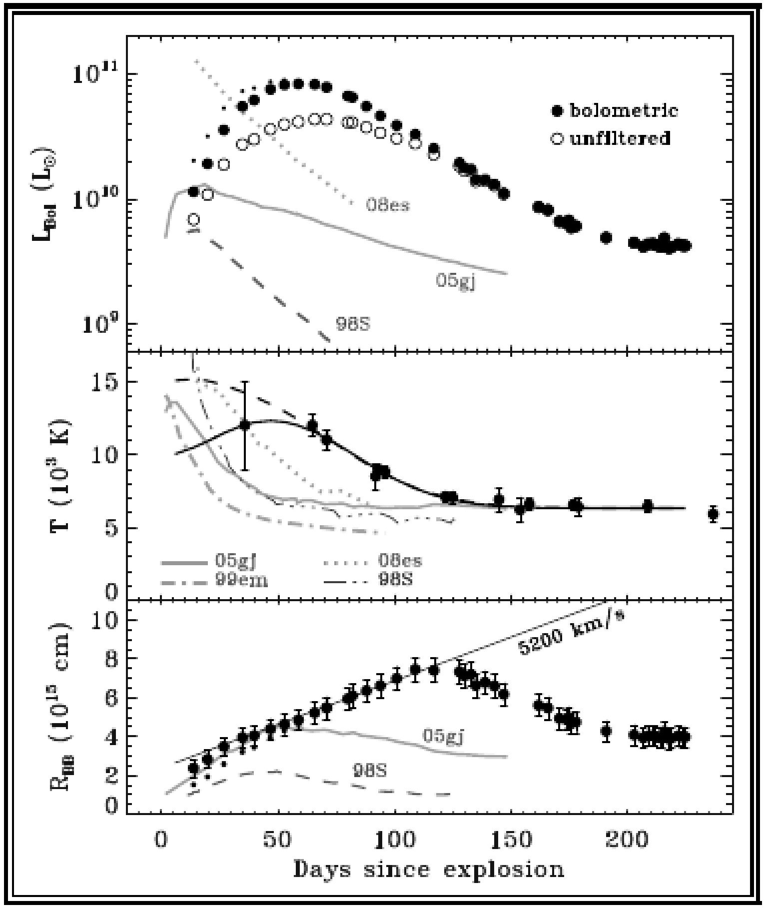
How to work in practice

Assume the observations are frequent enough to determine the variation of the photosphere radius according to the relation $dR_{\rm ph} = v_{\rm ph} dt$ for several time moments t_i with dt being the time interval between the measurements. Let $\Delta R_i \equiv \int_{t_0}^{t_i} v_{\rm ph} dt$ be the increase of the radius during a large time interval from the initial moment up to i-th time moment. We denote the initial radius (unknown to us) as R_0, and $R_i \equiv R_0 + \Delta R_i$ for $i = 1, 2, 3, \ldots$. Then

$$\zeta_{\nu i}^2 (R_0 + \Delta R_i)^2 \pi B_\nu(T_{c\nu i}) = 10^{0.4 A_\nu} D^2 F_{\nu i} \tag{1}$$

To find the distance D we need to know A_ν from the astronomical observations, or we can try to get it from the equation (1) written for different spectral filters.

Observed $R(t)$ of SN2006gy



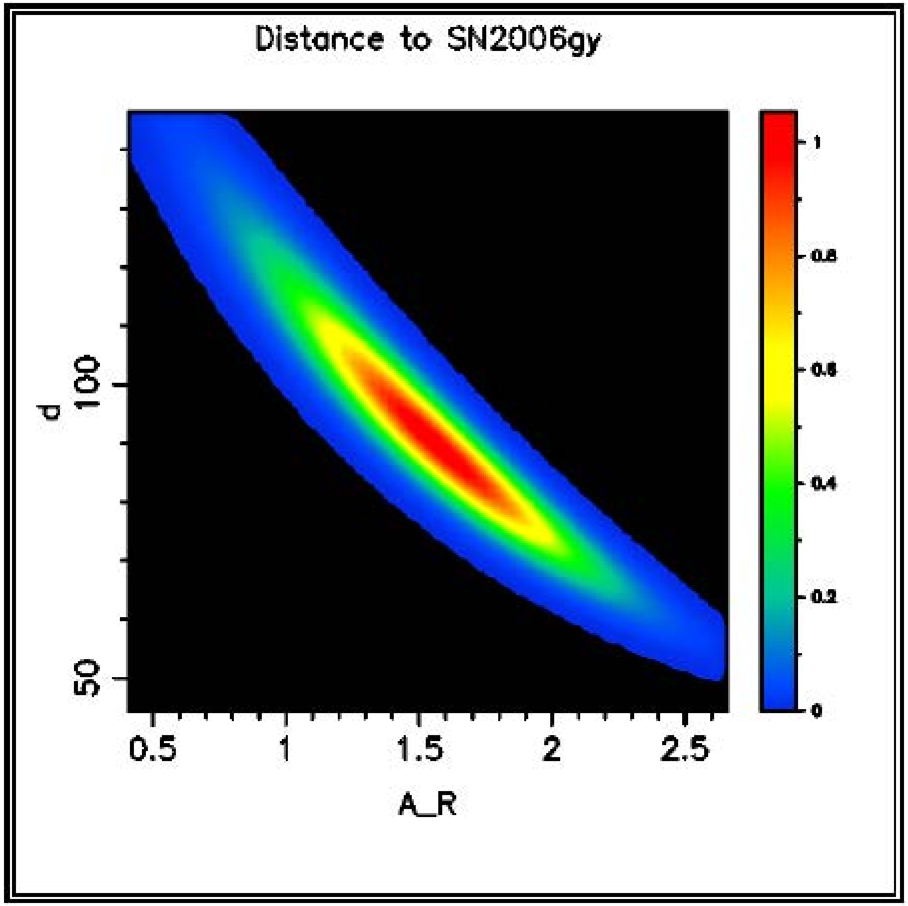
Observations of SN2006gy

time, d	$T, 10^3$ K	err.(T)	m_R	err.(m_R)
36.03	12	3	14.72	.03
40.95	12	.8	14.62	.03
47.97	12	.8	14.42	.03
59.92	12	.8	14.27	.03
71.0,	11	.7	14.22	.03
82.92	9	.8	14.28	.03
94.88	8.8	.4	14.49	.03

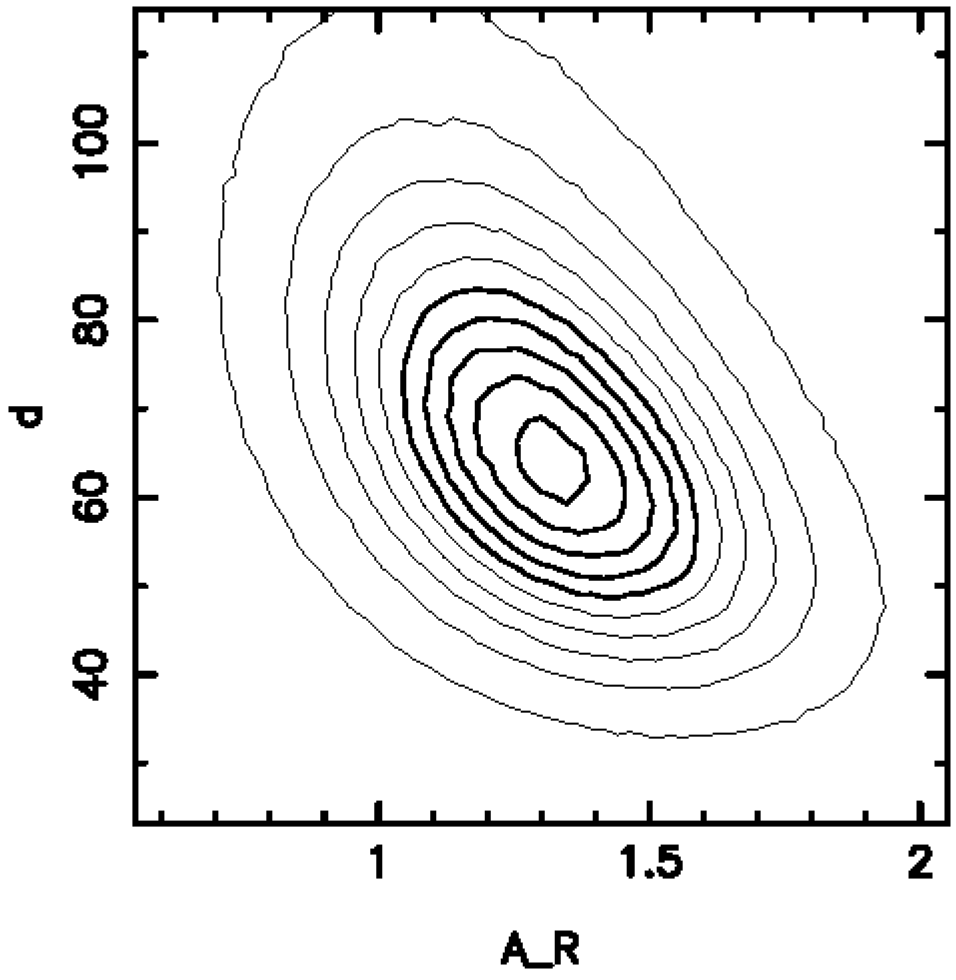
We have adopted *v* = 5200 +/- 320 km/s from Smith e'a 2010 and A_R=1.3 +/- 0.25 mag following Agnoletto e'a 2009.

MC probable d to SN 2006gy

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



More accurate MC for 6 observed points



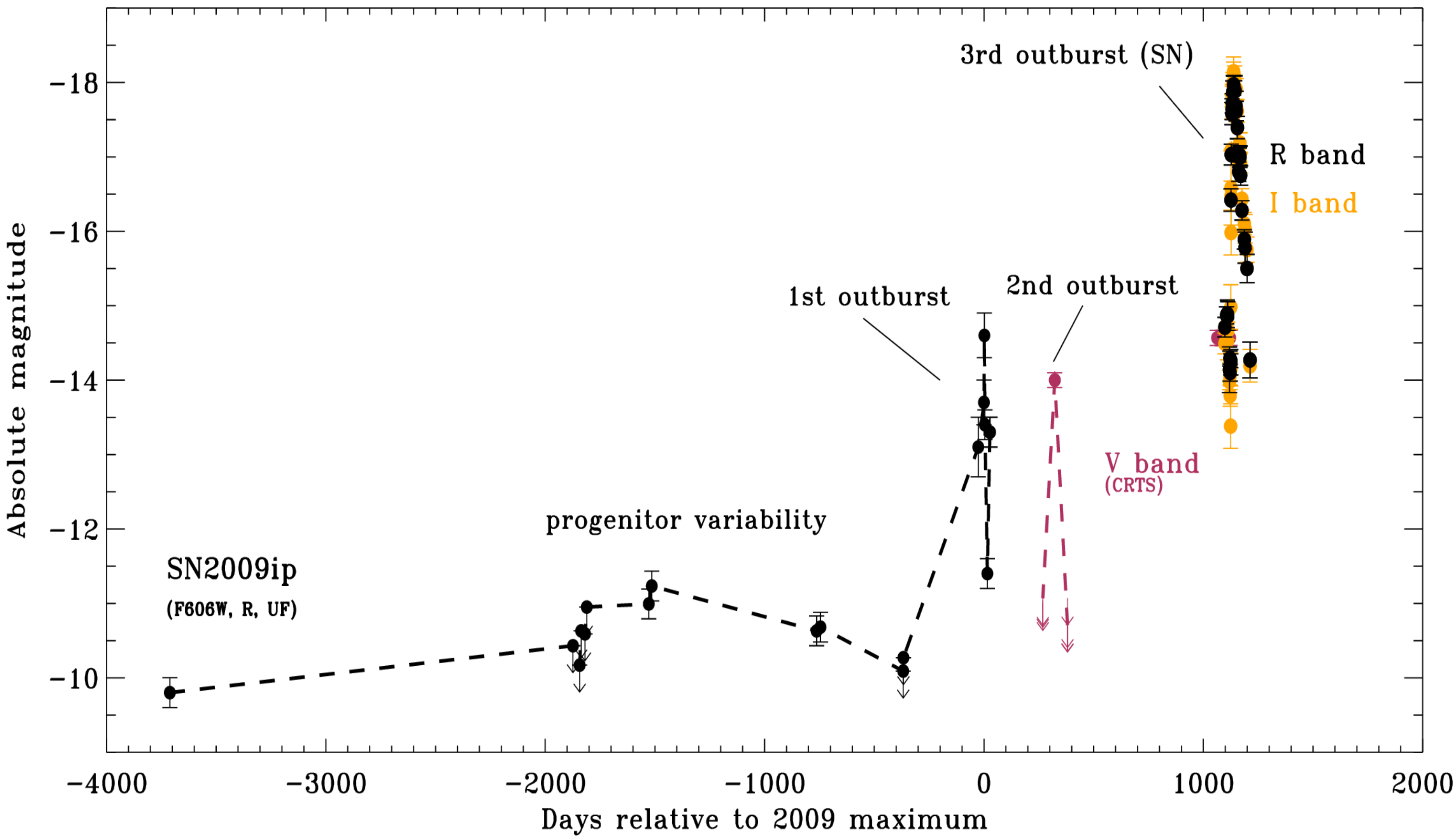
This gives

median D = 68.2 Mpc with 68% confidence interval (-15,+19) Mpc

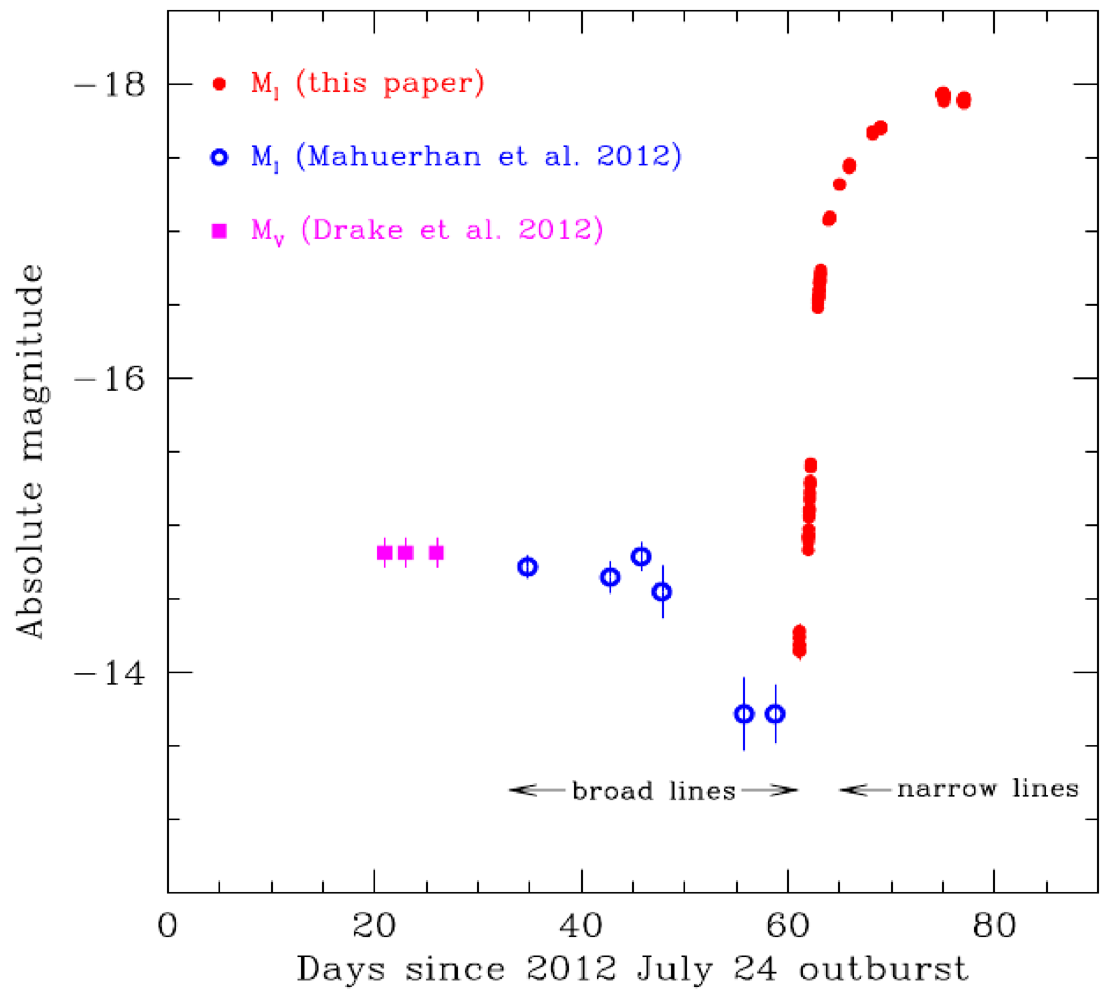
and H_0 = 79 (-17,+23) km/s/Mpc.

The error is large due to uncertainty in reddening, so we take another example.

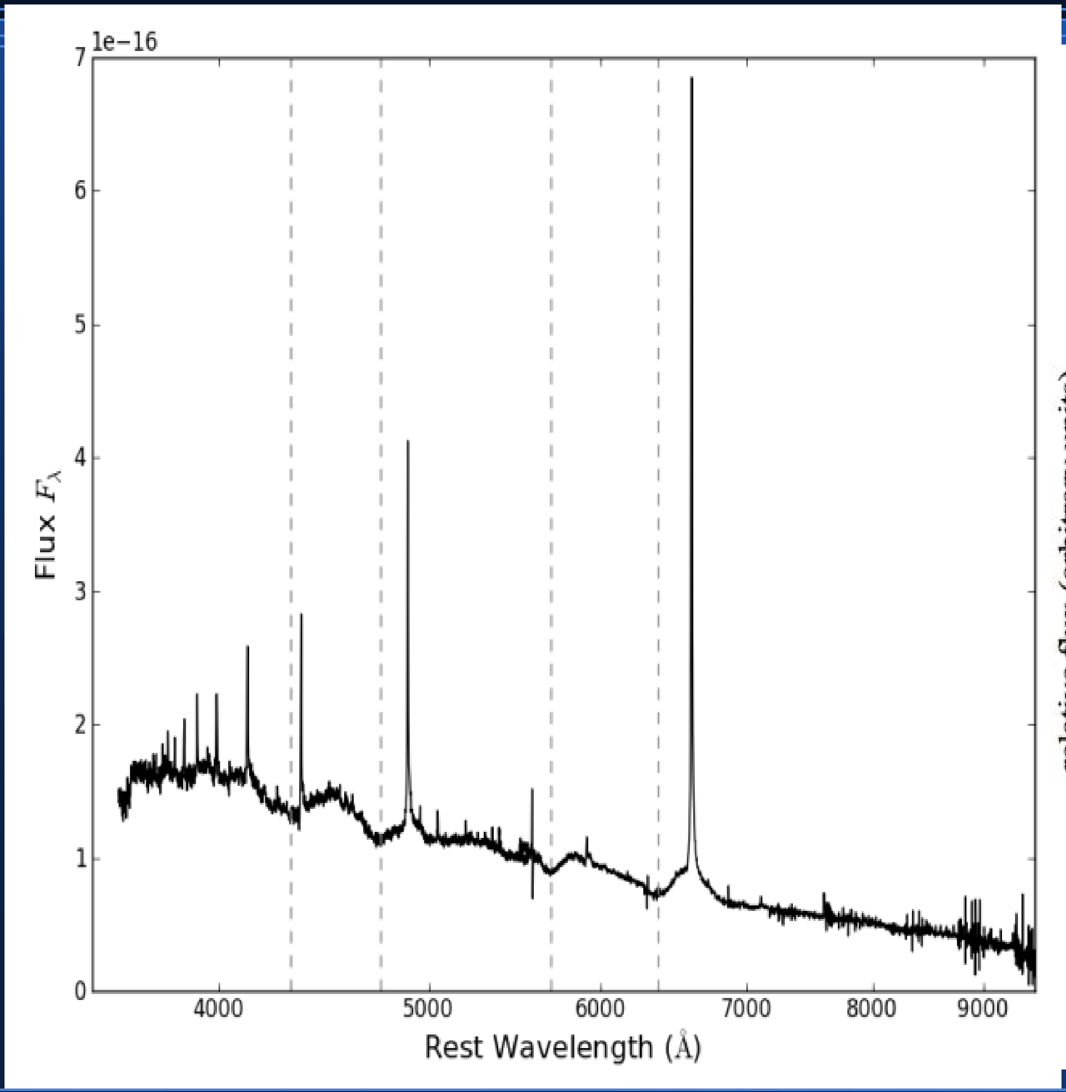
Light curve of SN2009ip

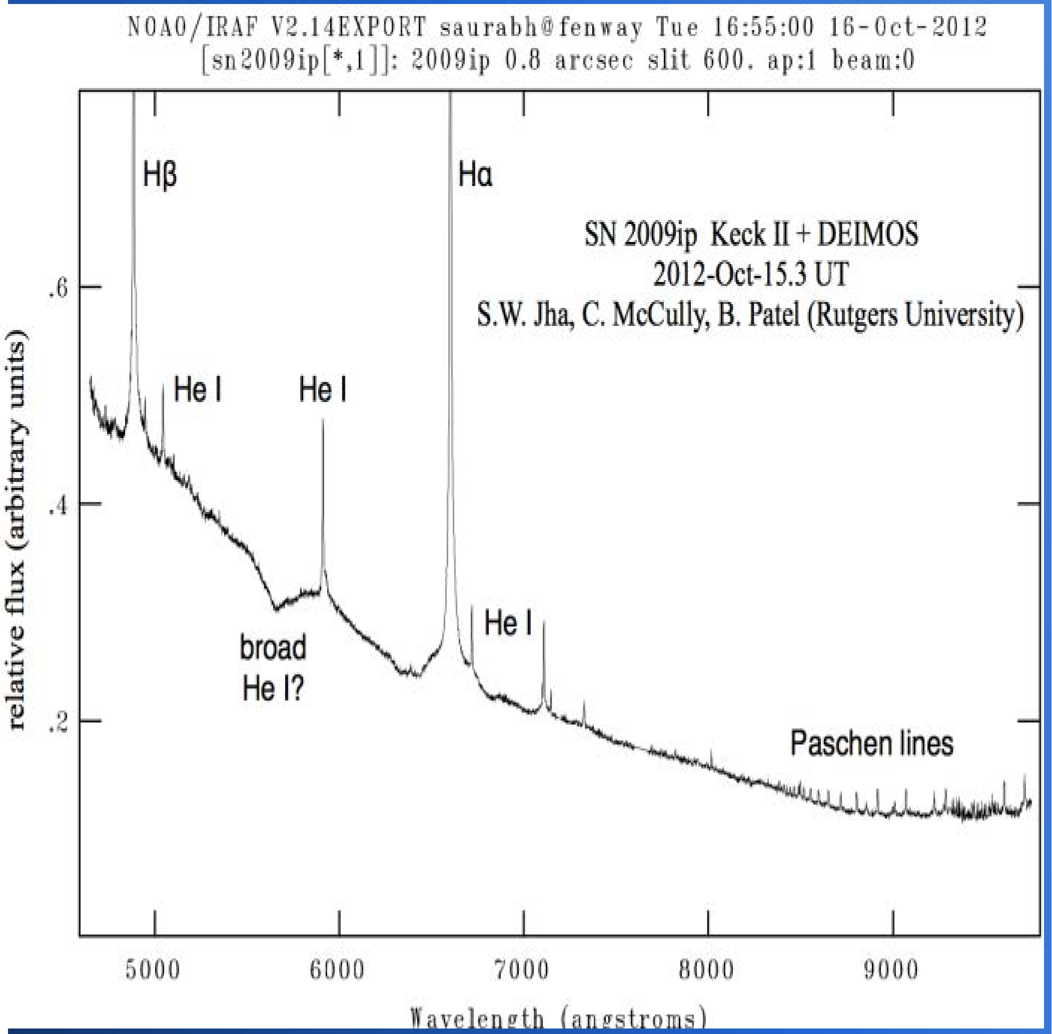


Prieto e'a, arXive:1210.3347

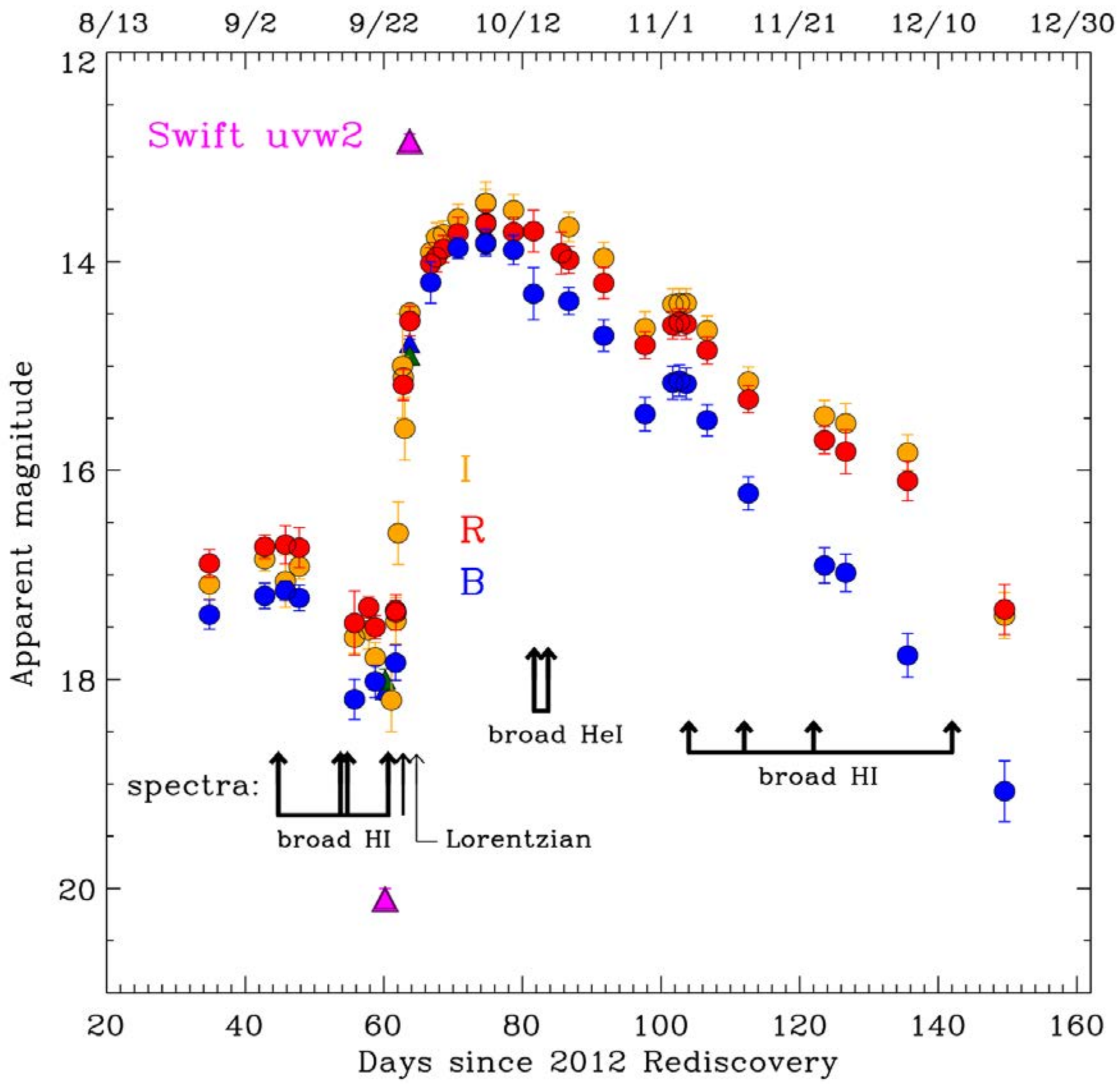


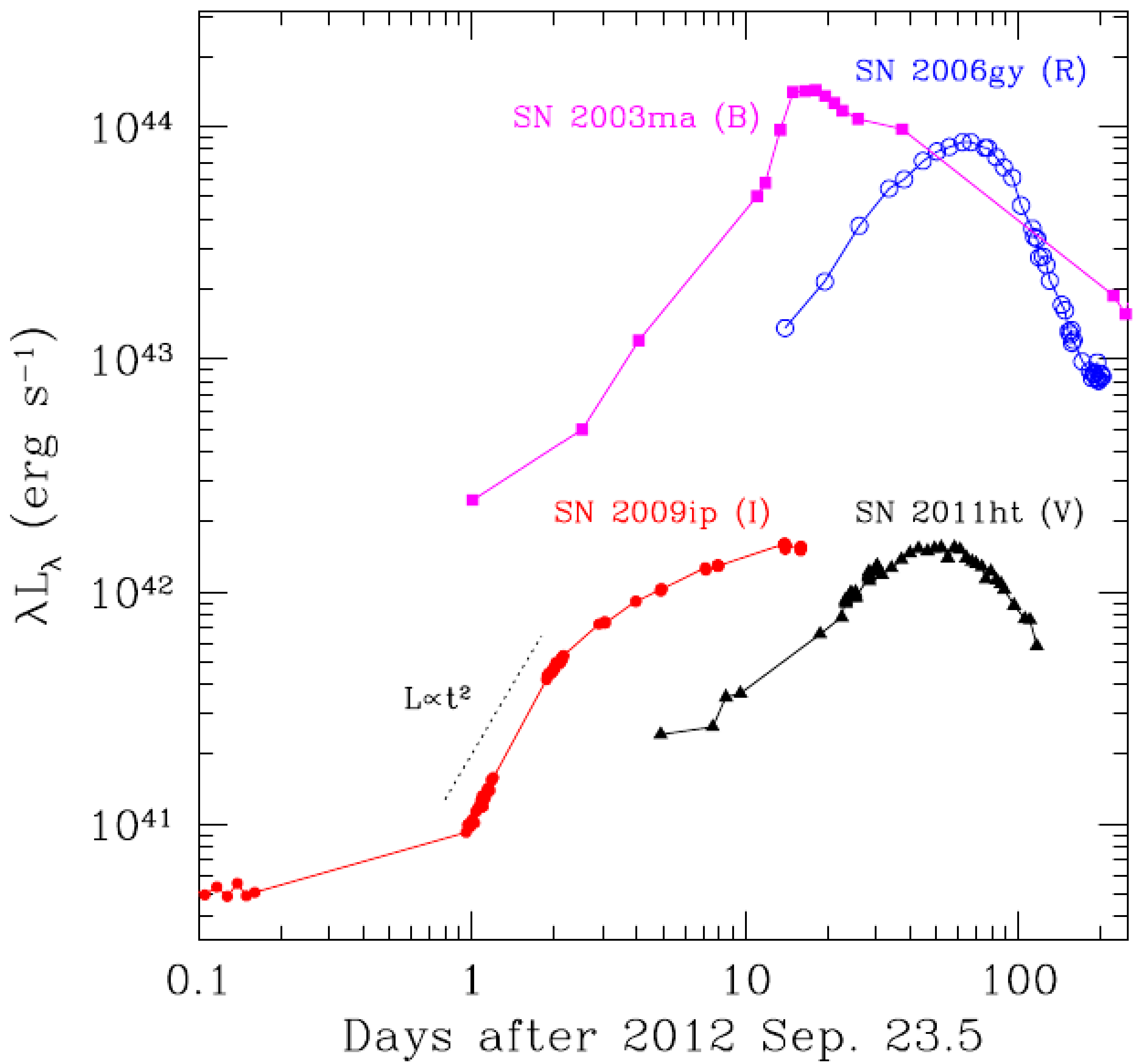
SN2009ip: narrow and wide lines





Mauerhan et al., arXiv:1209.6320v4

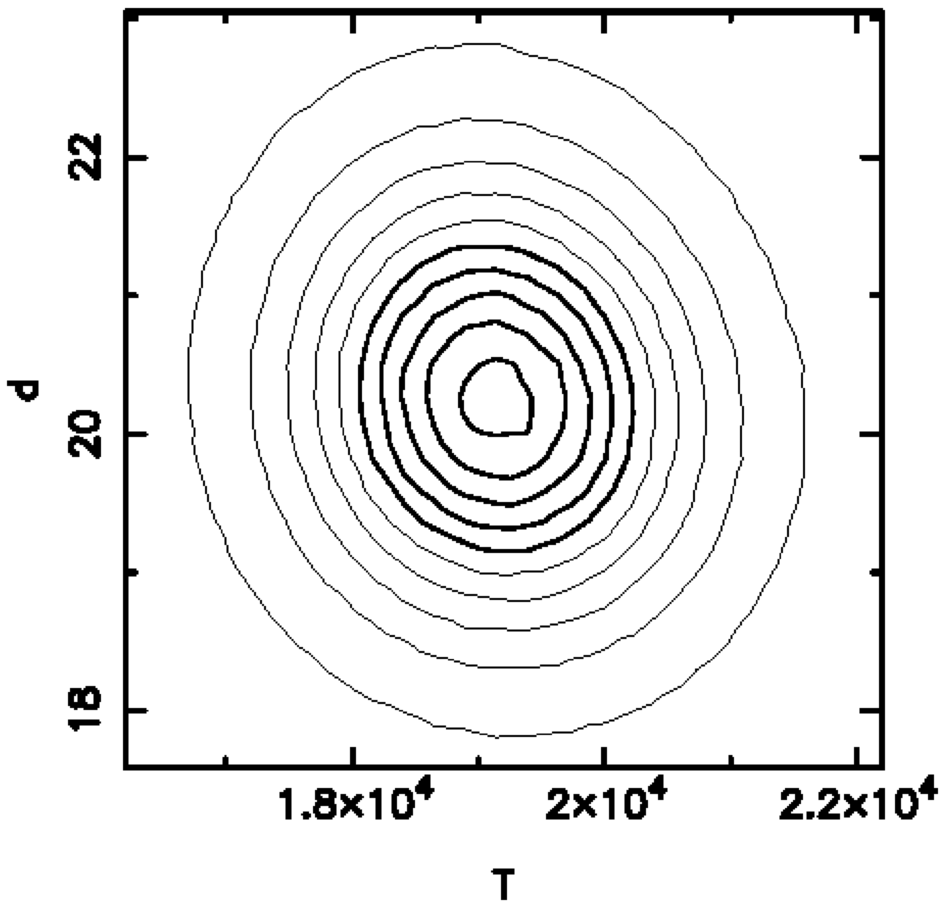



SN 2006gy (R)
SN 2003ma (B)
SN 2009ip (I)
SN 2011ht (V)
L∝t²
10^{44}
10^{43}
10^{42}
10^{41}
λL_λ (erg s^{-1})
0.1
1
10
100
Days after 2012 Sep. 23.5

We have used a short 2-day period after September 24, for which the velocity of the shell can be determined. During this period the luminosity is proportional to the square of time, which corresponds to the constant expansion velocity and the color temperature of the photosphere.
We took the first 36 points in R-band listed in the table in `http://www.astro.princeton.edu/~jprieto/sn09ip/photR.dat` from Prieto web page. These points correspond to the days that are most interesting for us.

To estimate the expansion velocity v of the shell we have used the data obtained from the H_α absorption component. During the epoch of a sudden increase in the luminosity of the SN 2009ip ($\sim$ 23-24 September) Pastorello2012 and Mauerhan2012 indicate values $v \approx 13000$ km/s and ≈ 13800 km/s, respectively. We have taken the matter velocity to be equal to $v \approx 13400$ km/s.
We have adopted the extinction of $A_R = 0.051$ mag following Mauerhan e'a (2012).

Slice of MC for SN2009ip



Results for SN2009ip

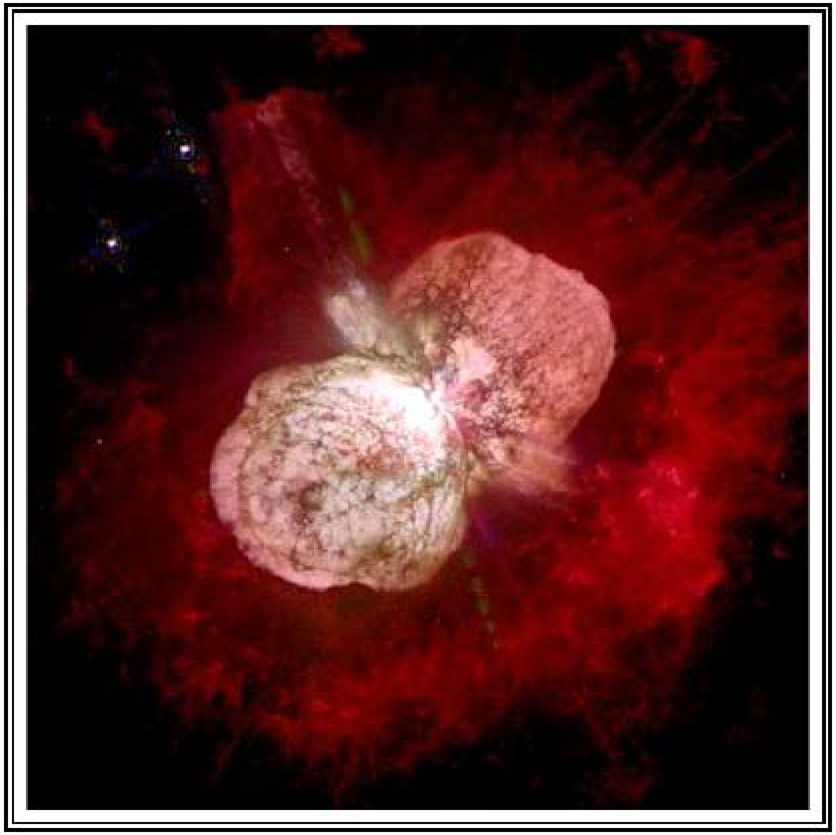
Taking the temperature of the first (Prieto e'a 2012) estimate as $T \approx 14500$ K and the relative errors in v and T equal to 5% we have obtained the median distance $D \approx 16.1$ Mpc with a 68% confidence interval ± 0.6 Mpc.
Taking the temperature of the second (Prieto e'a 2012) estimate as $T \approx 19200$ K and the relative error in v and T equal to 5% we have obtained the distance $D \approx 20.1$ Mpc with a 68% confidence interval ± 0.8 Mpc.
If we increase the relative errors of v and T by factor 2 again, we can find the distance $D \approx 19.9$ Mpc with a 68% confidence interval $(-1.4, +1.5)$ Mpc.

Uncertainties and systematics

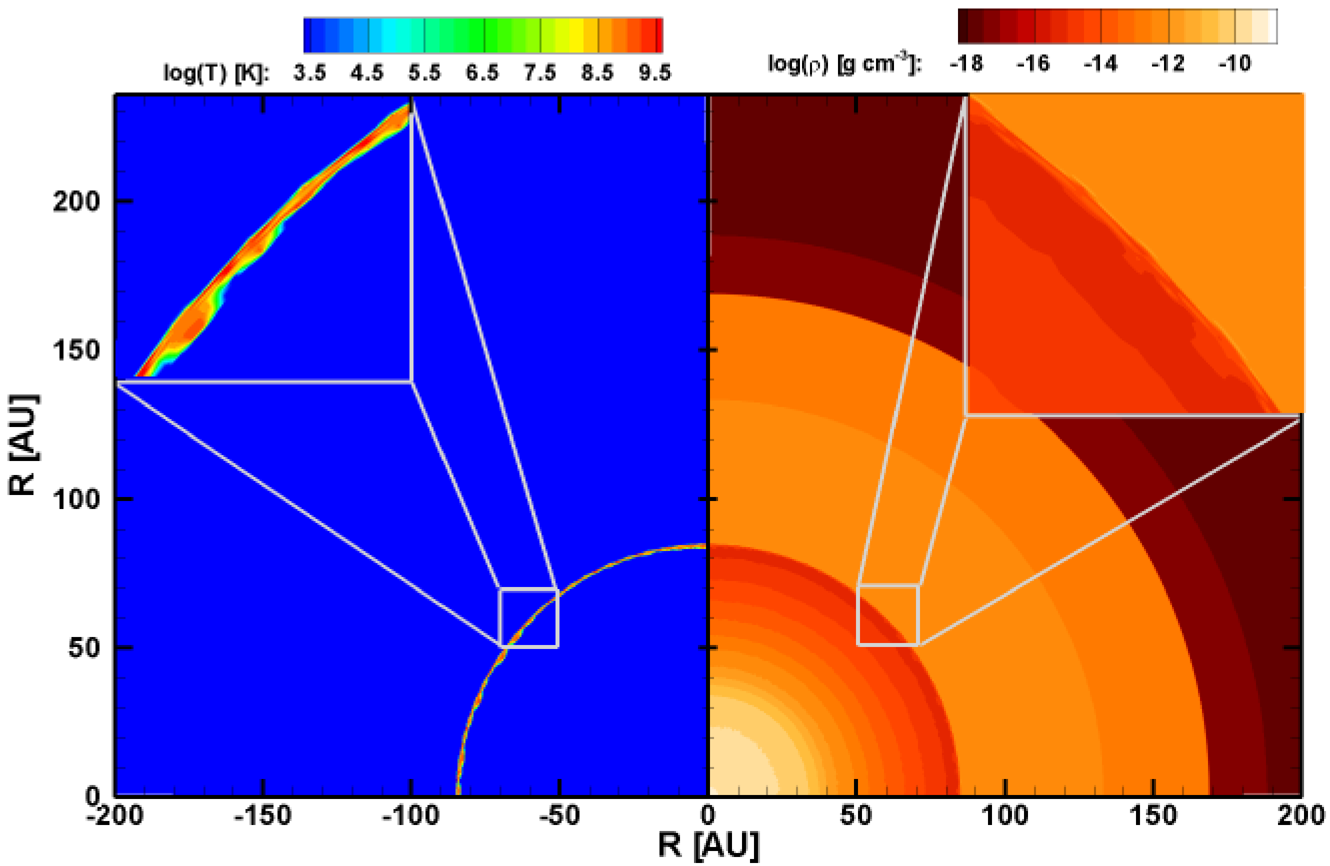
- Reddening
- Location of the dense shell below photosphere
- Then it is important to accurately model scattering (Luc Dessart e'a)
- Non-sphericity (jet-like models are suggested for SN2009ip)

η Carinae: Multi-D is a must

for next steps in theoretical modeling

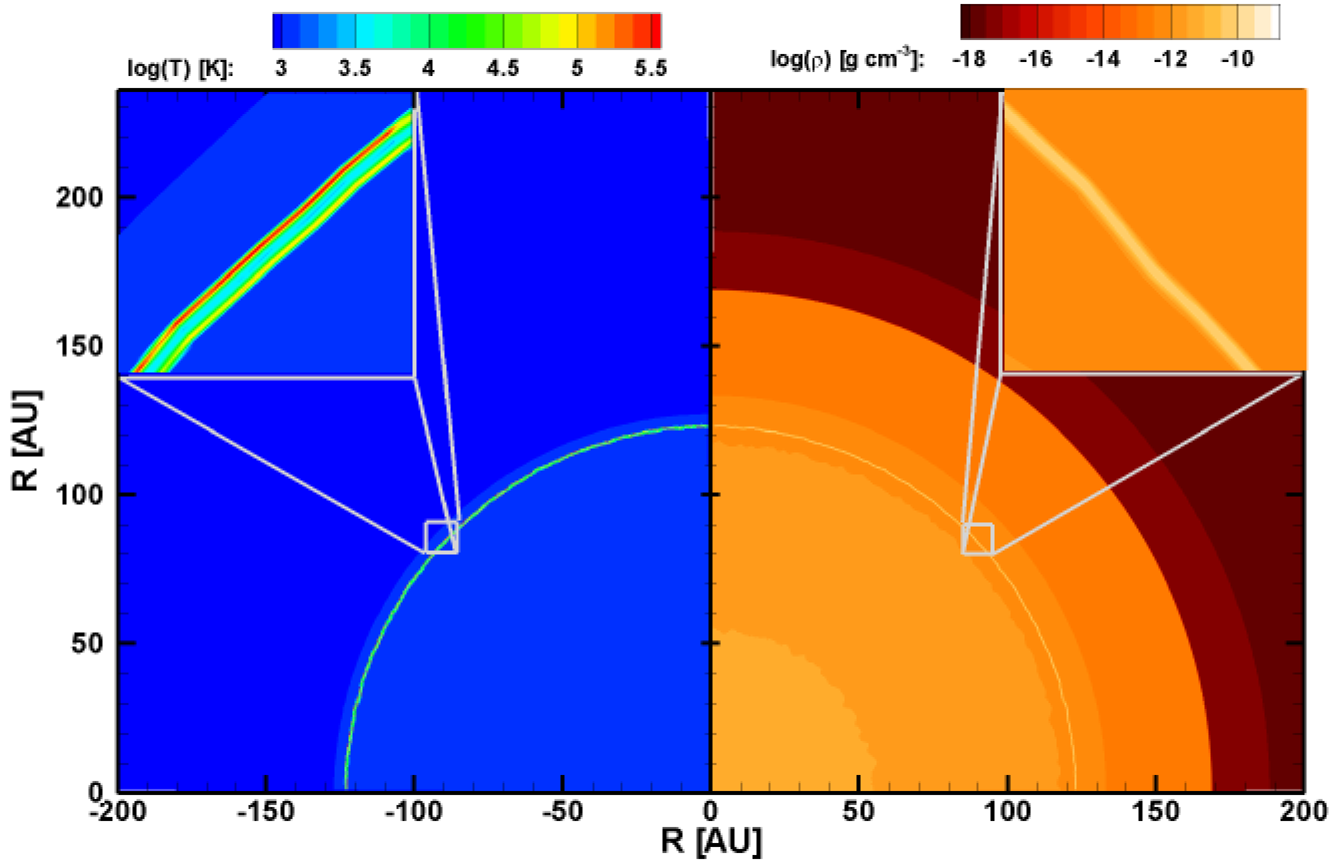


A. J. van Marle et al. MN 2010



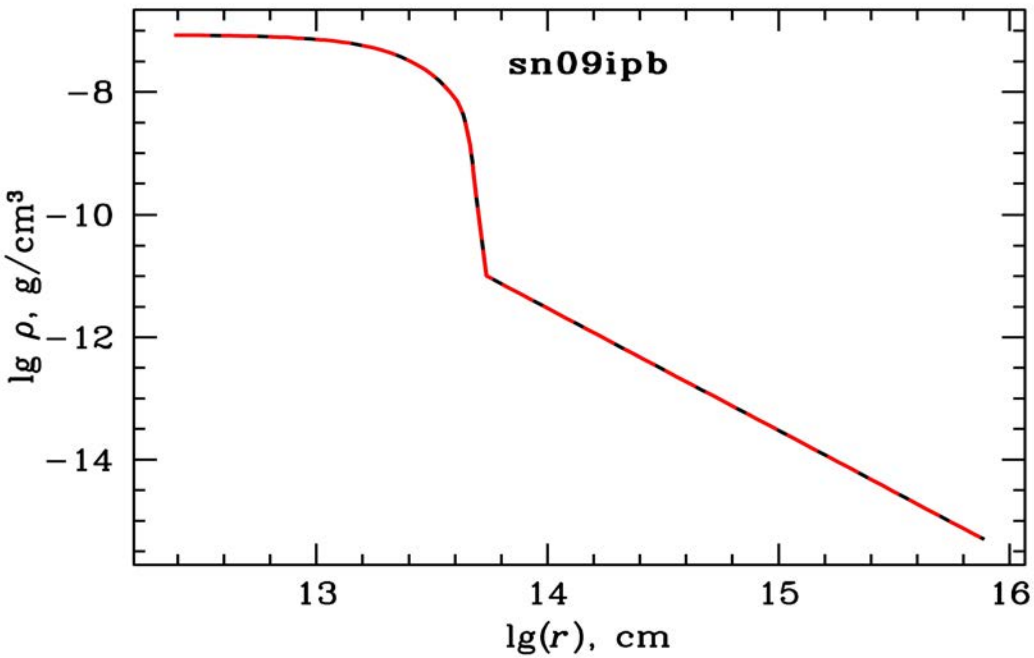
23 days

A. J. van Marle et al. MN 2010



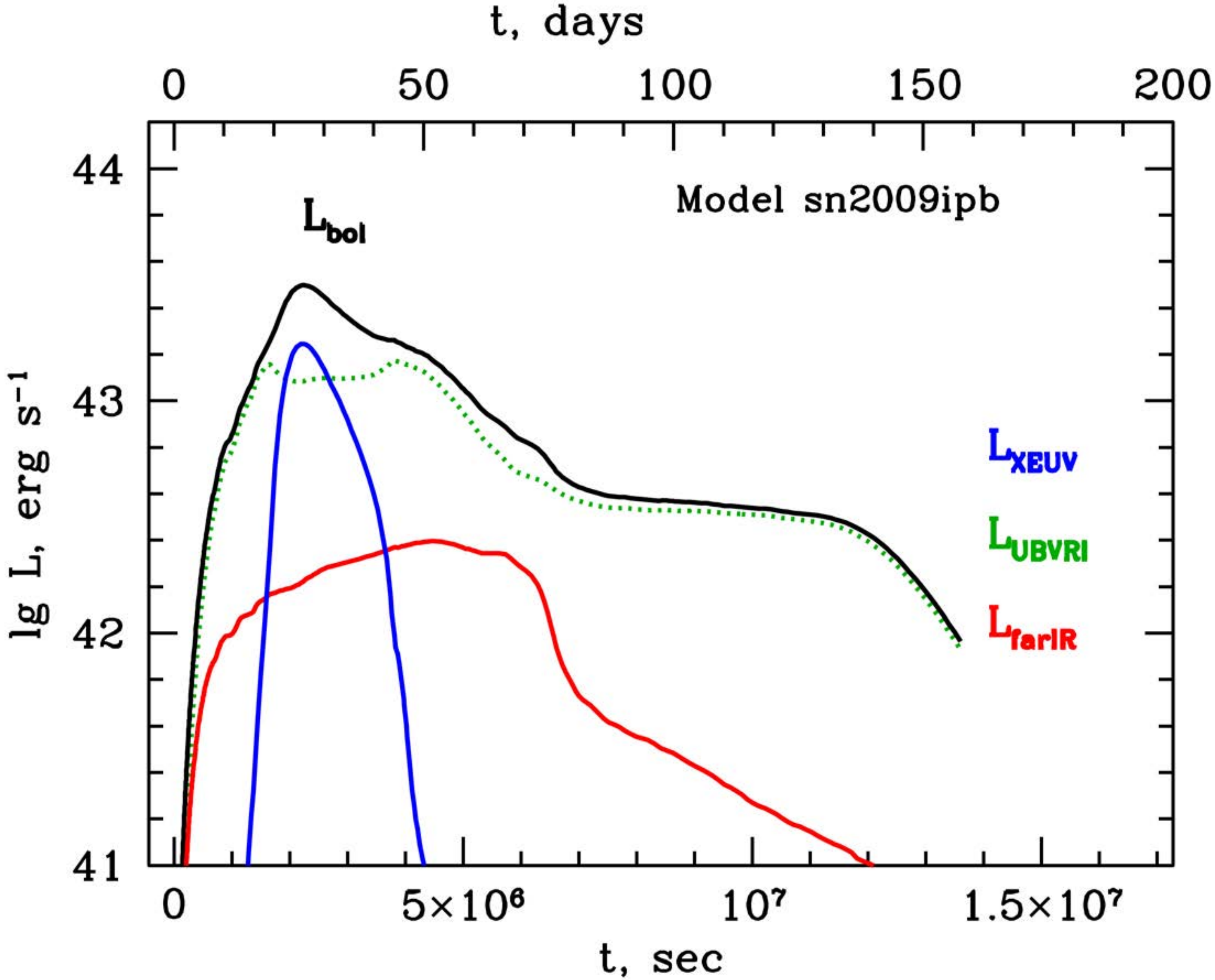
87 days

Models for SN2009ip

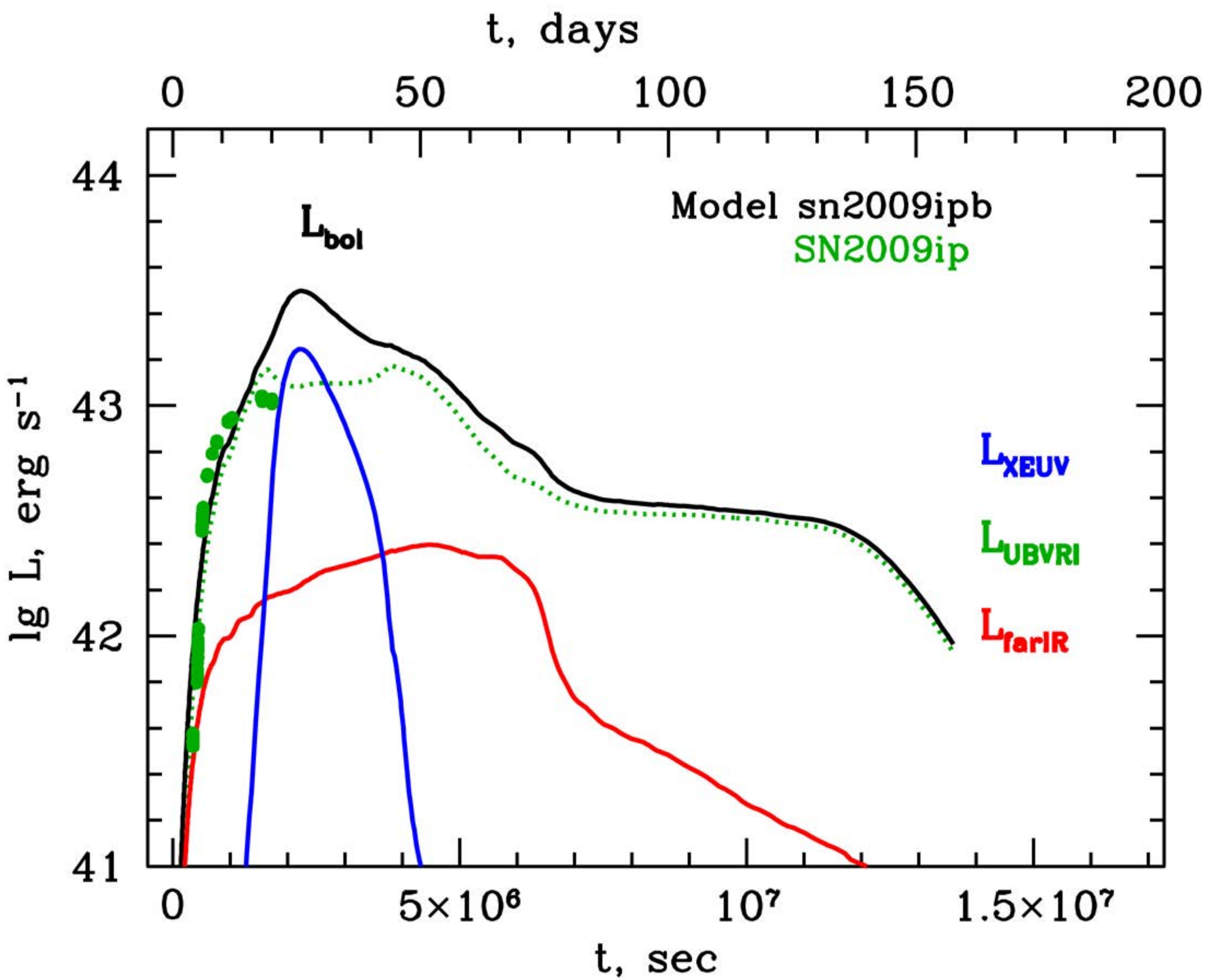


- $M_{ej} = 3.4\ M_{\odot}$
- $R_{ej} = 700\ R_{\odot}$
- $M_{wind} \sim 1.3\ M_{\odot}$
- $\rho_{wind} \propto r^{-2}$
-
- $E \sim 1$ foe $=1$ Bethe
-

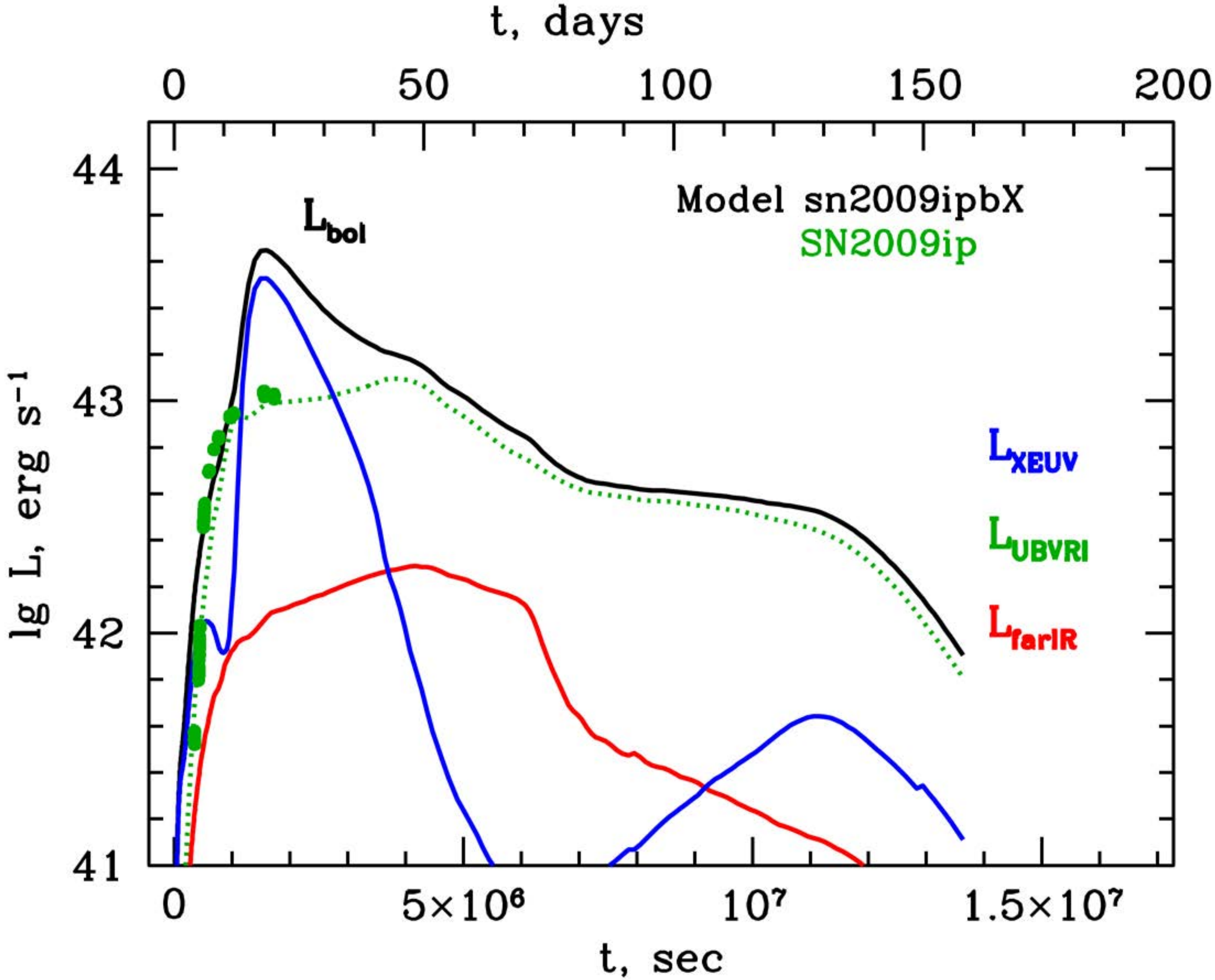
Bolometric LCs for SN2009ip



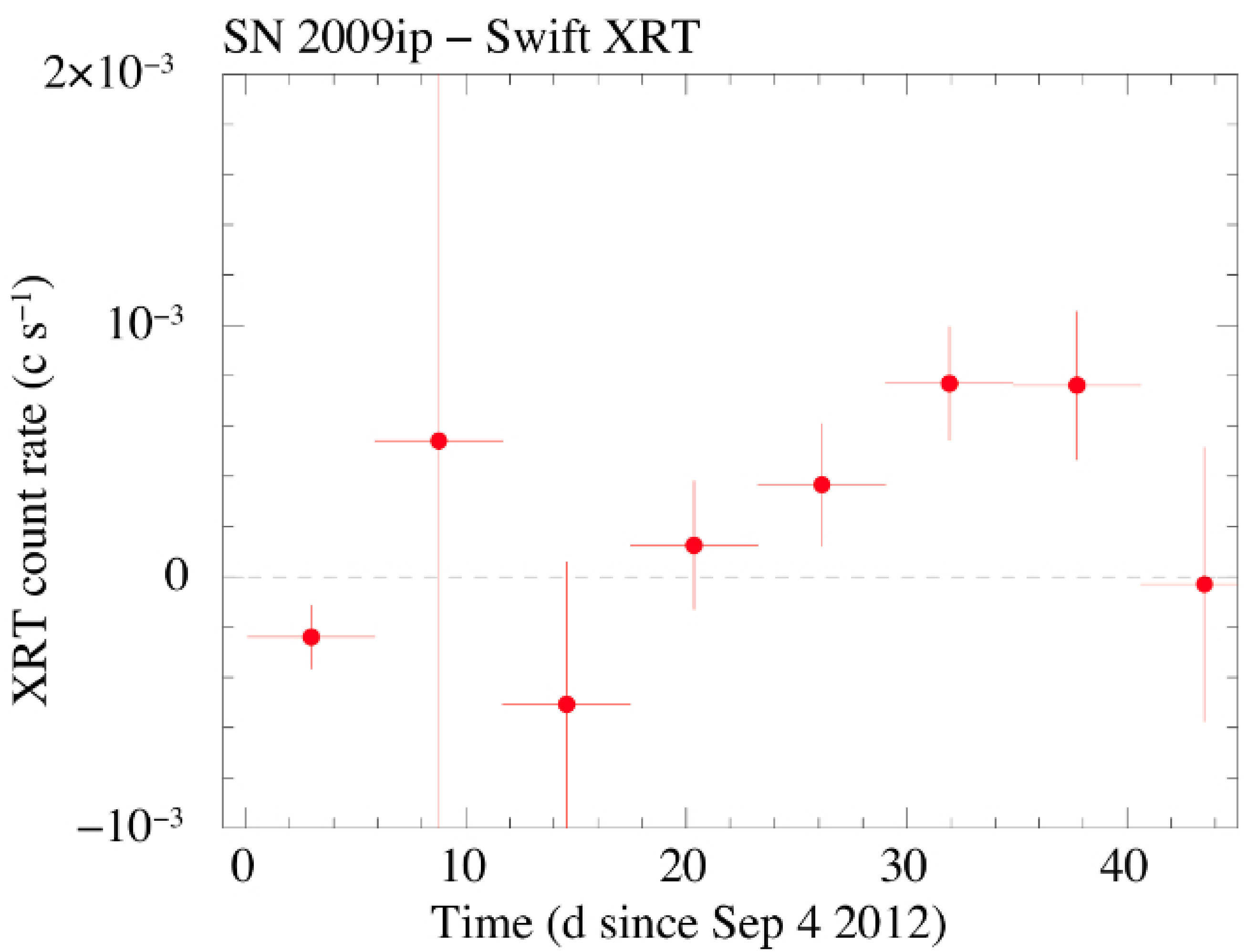
SN2009ip observations Prieto e'a



The same model, another opacity



X-ray observed by SWIFT

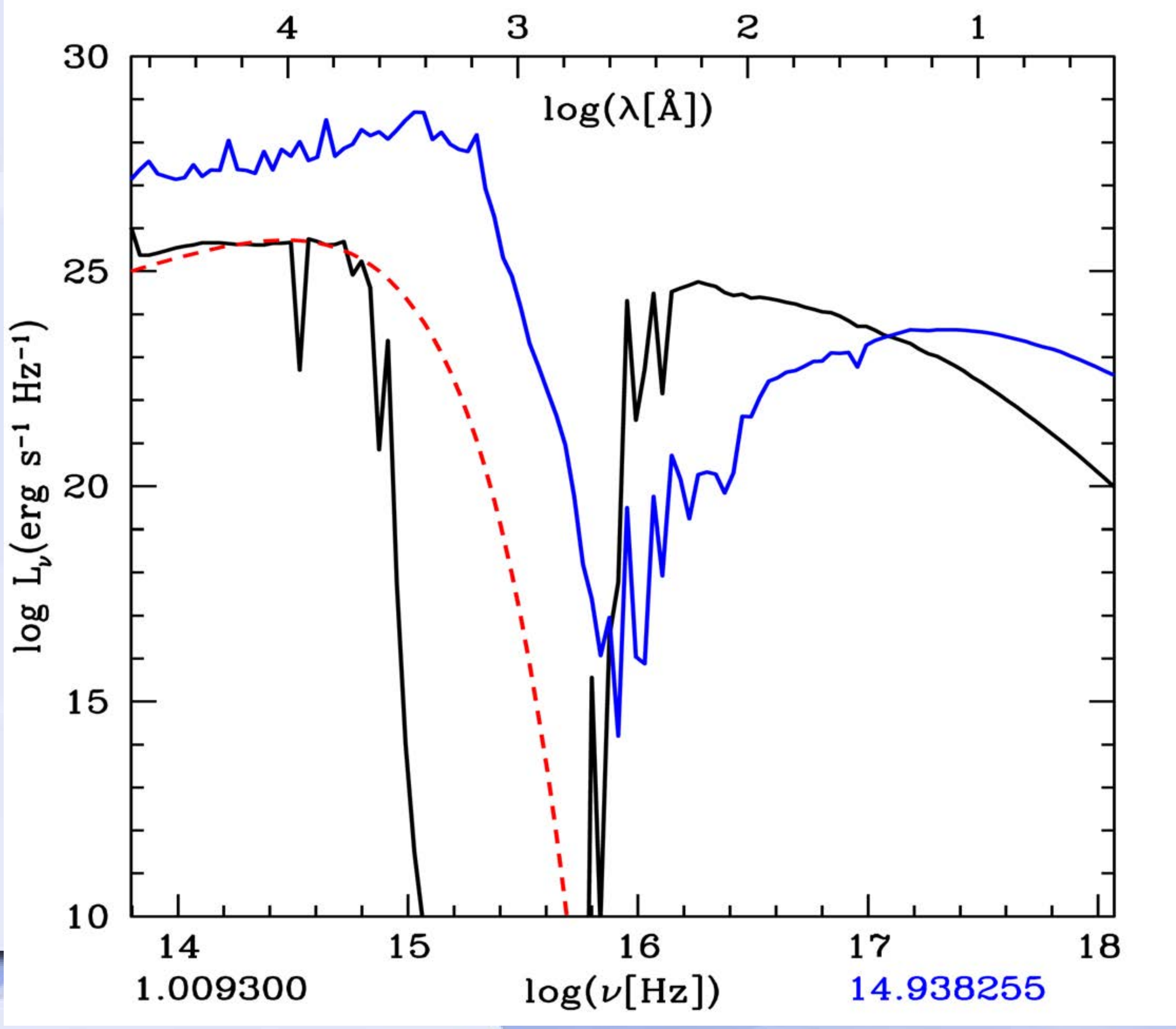


Swift/XRT back-ground subtracted light curve.

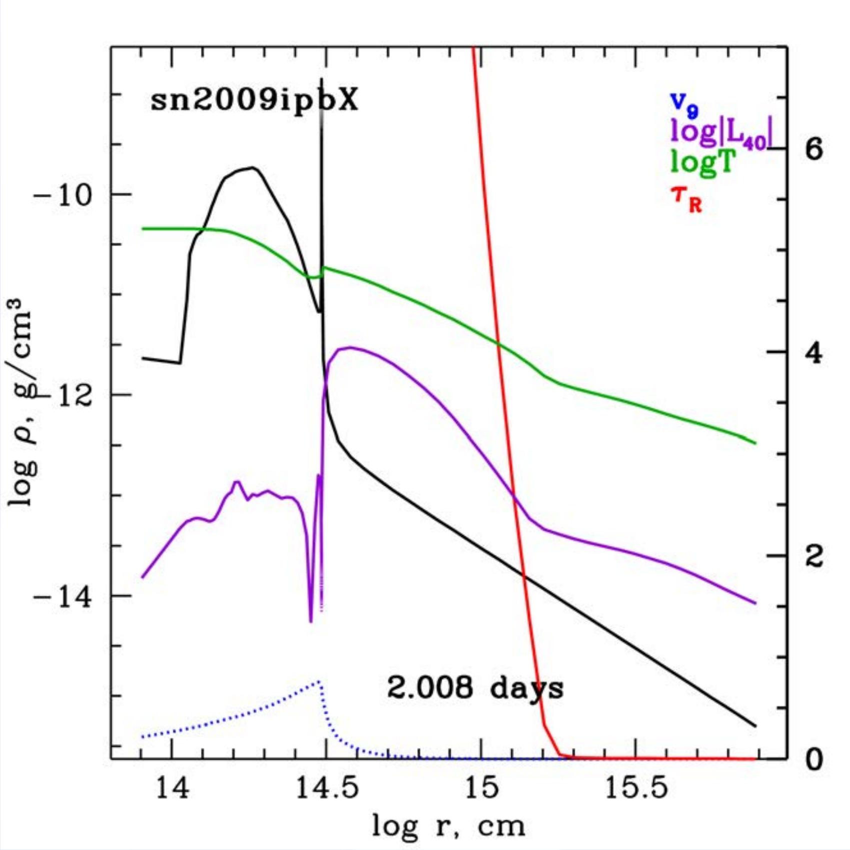
The light curve is in the 0.3-10 keV energy band

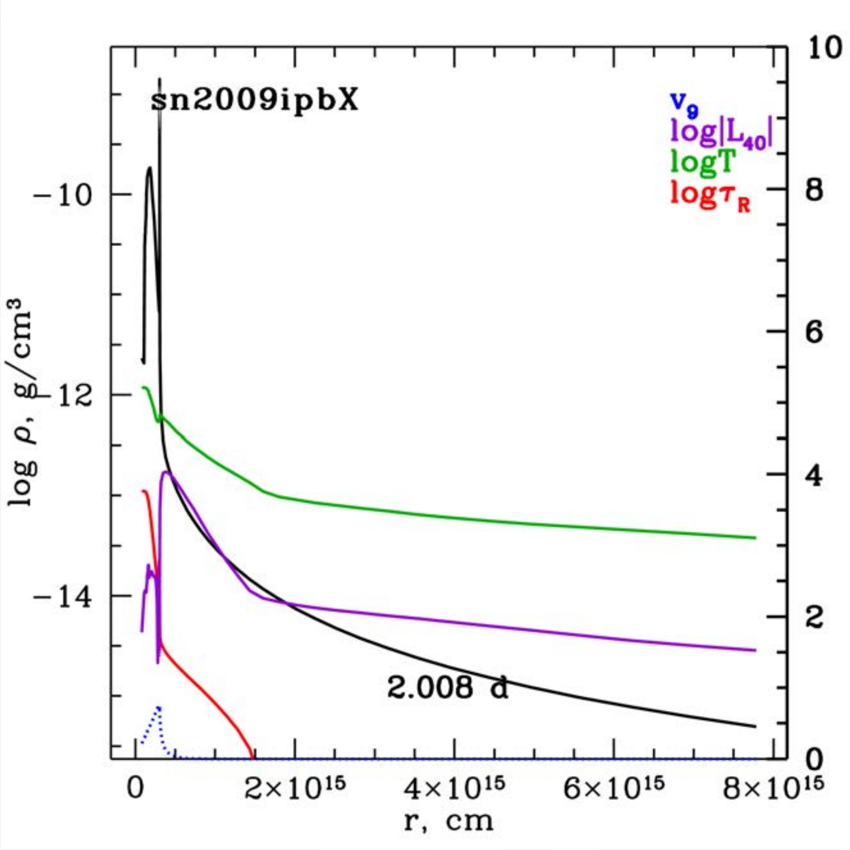
Peak luminosity L~4d39 erg/sec (at the distance of 24 Mpc)

Model predictions (preliminary)

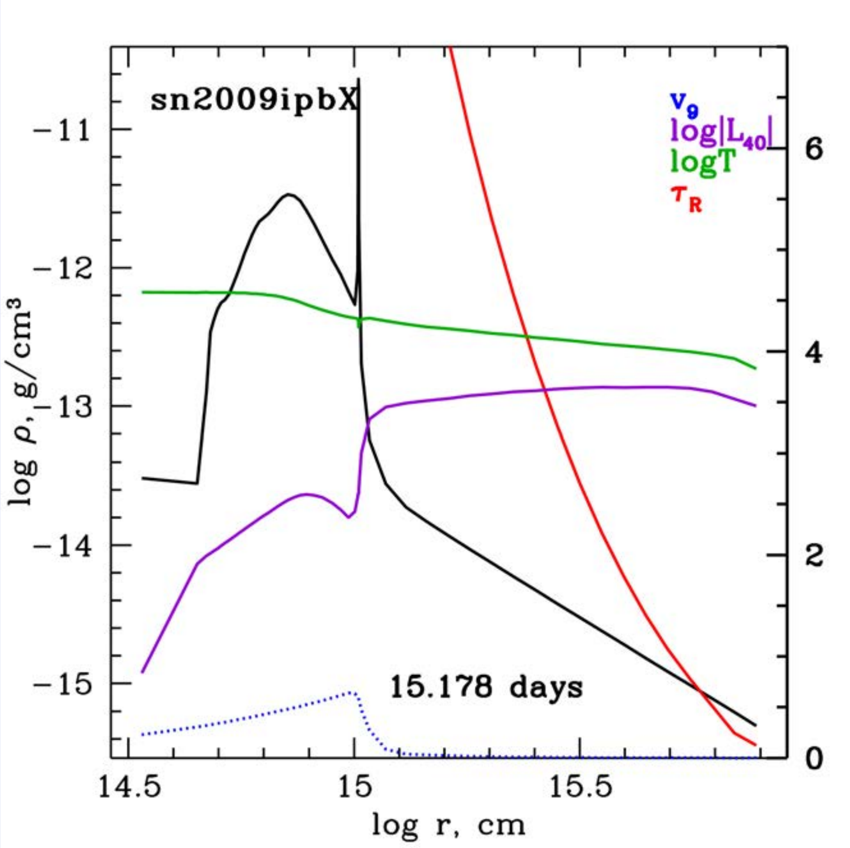


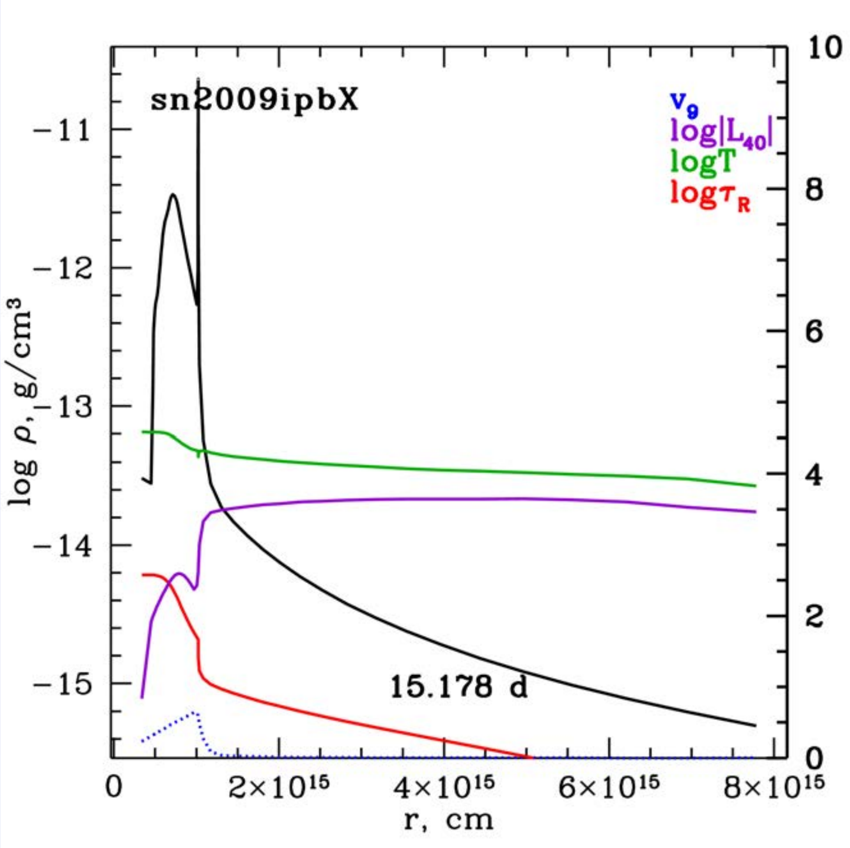
Model hydro-profiles @ 2 d





Model hydro-profiles @ 15 d





Models are far from perfect yet