Comparing Hydrodynamic Models with Observations of Type II Plateau Supernovae

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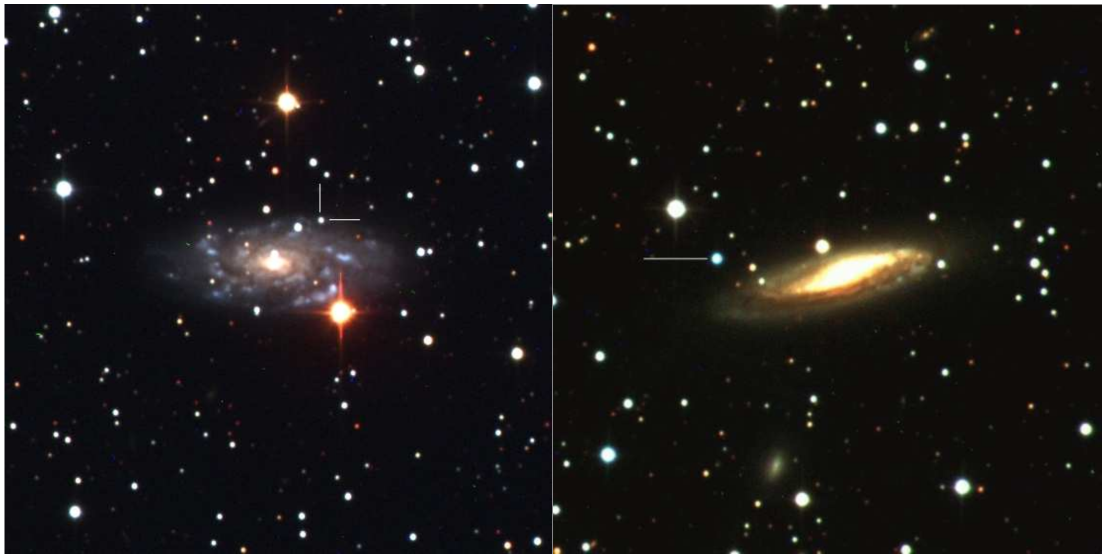
Outline

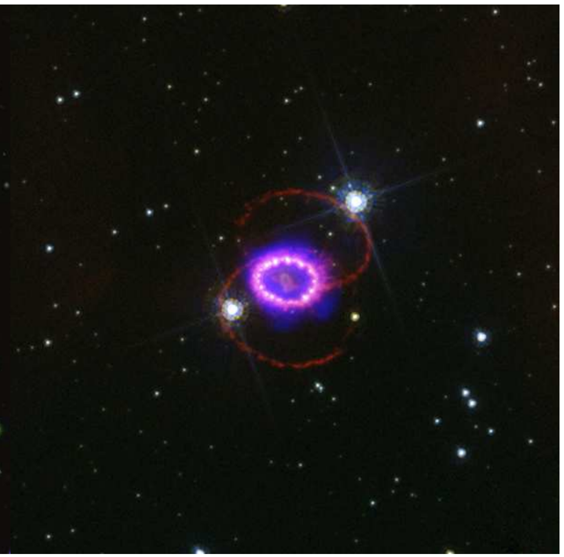
- Introduction
- Hydrodynamical Code
- Data Sample: Bolometric Corrections
- Analysis of our Sample of SNe II-P

Supernovae

- Kinetic energy: $\sim 10^{51}$ erg $=$ 1 foe $=$ 1 B
- Radiated energy: 1-10$\%$ E_k during weeks/months ($\sim 10^{10} L_\odot$)
- Velocities: $v_{\rm exp} \sim 10^4$ km s^{-1} $\Rightarrow \sim 10^5$ $R_\odot$ (few weeks)
- Temperature: $\sim T_\odot \Rightarrow R = (L/L_\odot)^{1/2}$ $R_\odot \sim 10^5$ $R_\odot$ (few weeks)

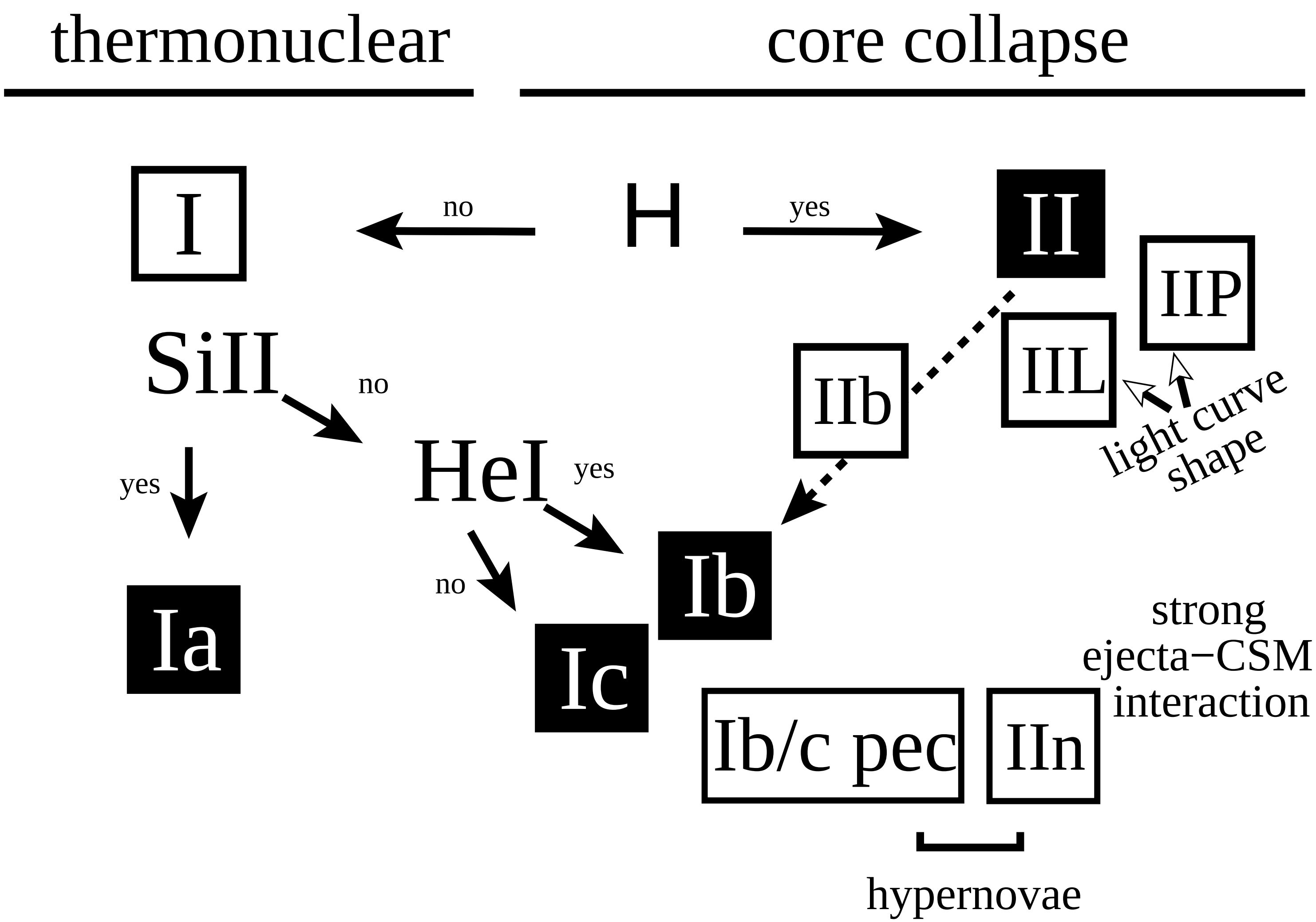


CSP supernovae



SN 1987A

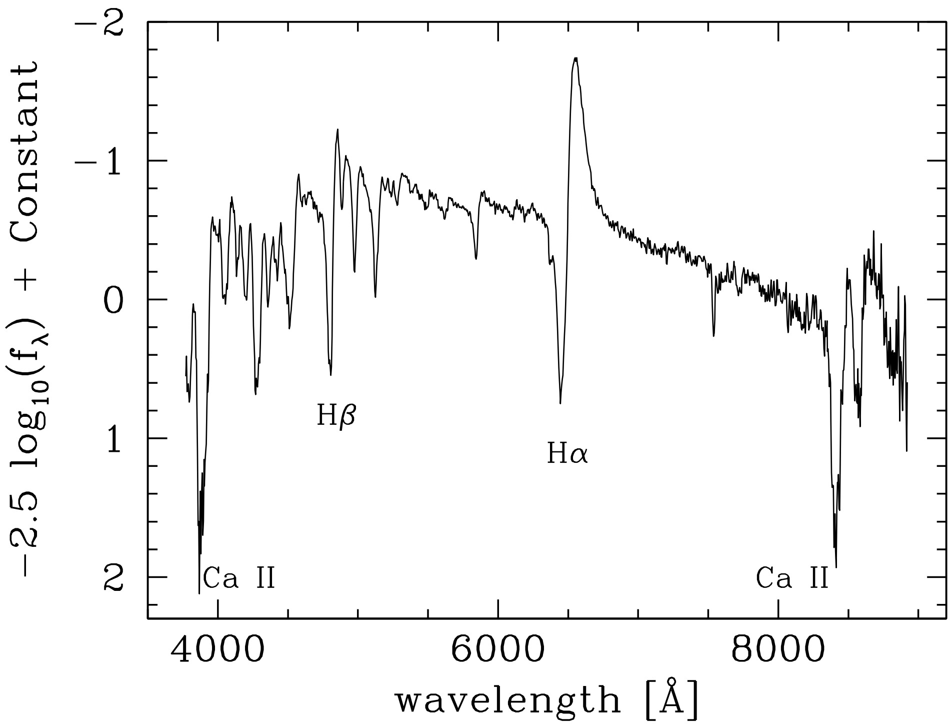
Supernova Classification

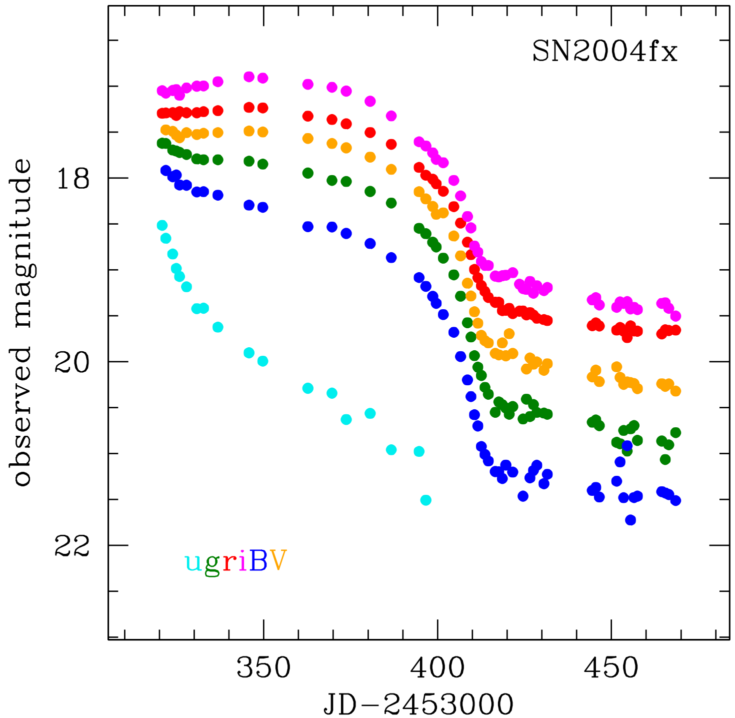


Turatto (2003)

Type II-P Supernovae

- Spectroscopy: prominent P-Cygni Balmer lines
- Photometry: long plateau phase (L $\sim$ const. for $\sim$100 days)
- Spectropolarimetry: explosion approximately spherical
- Most common type of SN (59% of CCSNe)





Courtesy CSP

Type II-P Supernovae

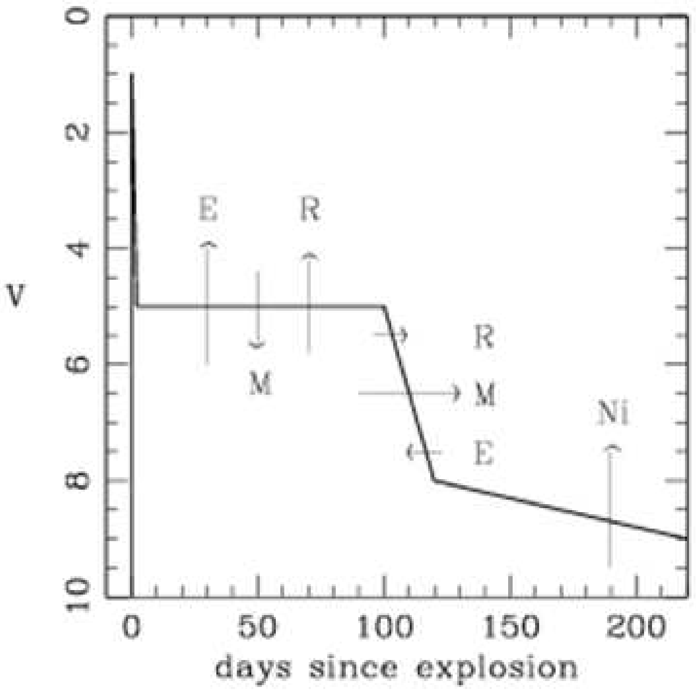
- Good distance indicators
  - Expanding photospheric method (EPM)
  - Spectral fitting expanding atmosphere method (SEAM)
  - Standard candle method (SCM)
- Connection with final stages of stellar evolution

$$\Downarrow$$

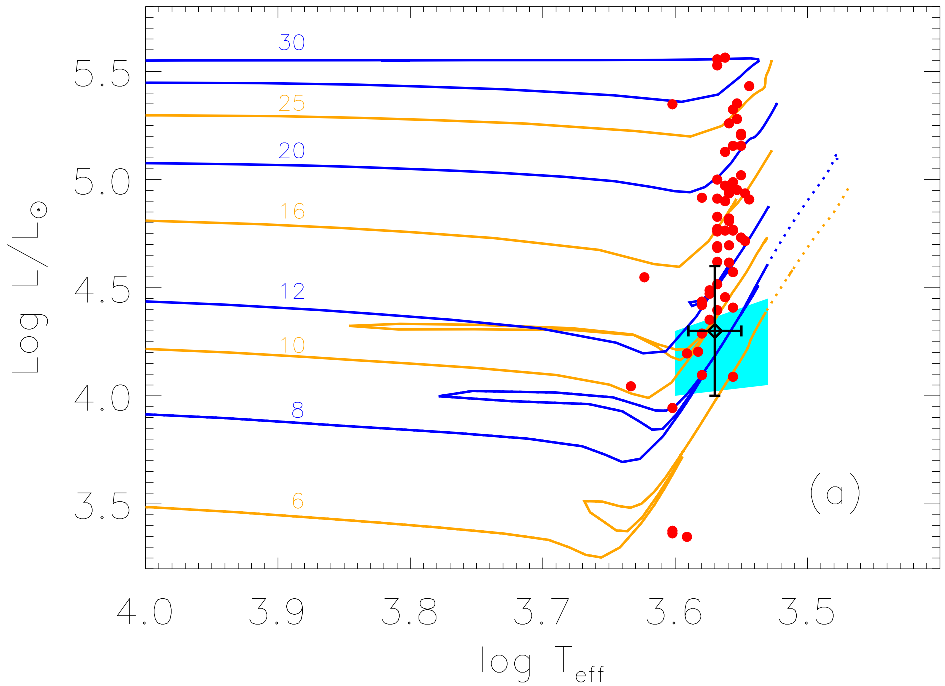
Physical properties of the progenitor

SN II-P Progenitors

- Wide range of plateau luminosity (L_p), plateau durations (Δt_p) and expansion velocities (v_p)$\Longrightarrow$ Different progenitors properties
- Light curve **+** spectral modelling $\Longrightarrow$ $M_{\rm ej}$, R , $E_{\rm exp}$ and $M_{\rm Ni}$
- Pre-supernova imaging **+** stellar evolution models $\Longrightarrow$ $M_{\rm ZAMS}$



Litvinova & Nadezhin 1983



Smartt et al. 2009

Type II-P Supernovae

- Good distance indicators: EPM, SEAM and SCM
- Connection with final stages of stellar evolution

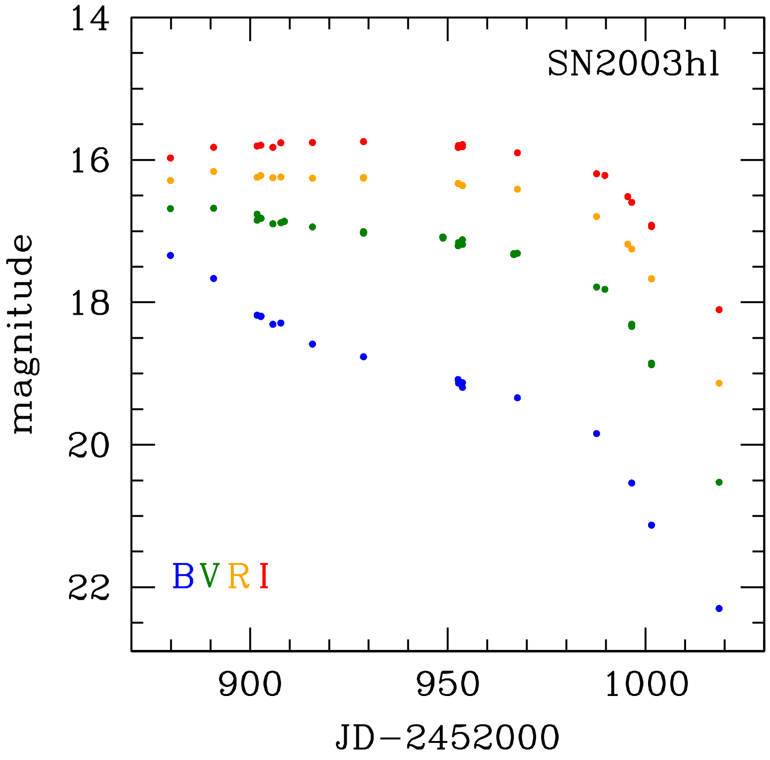
  Physical properties of the progenitor:

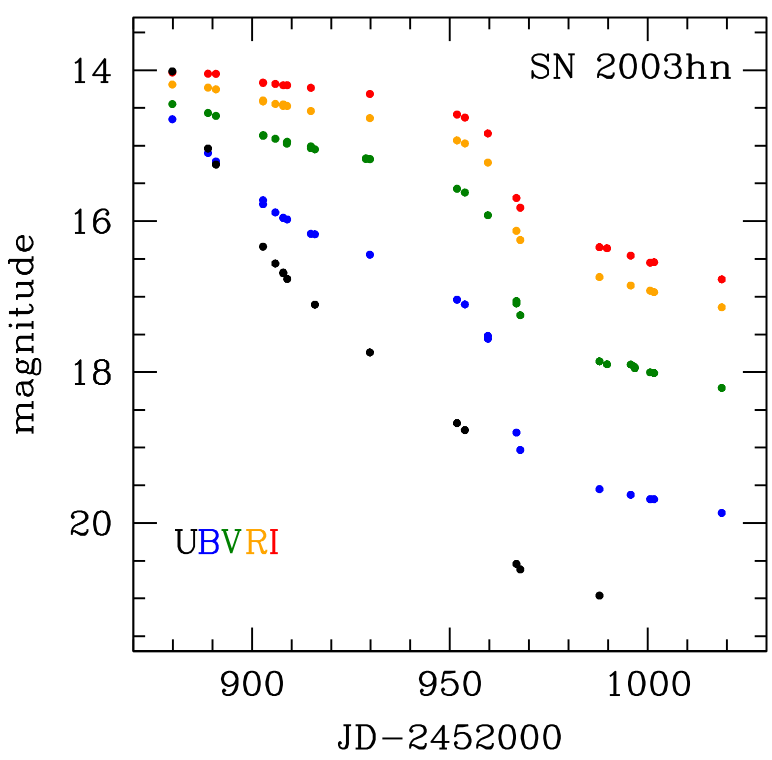
  - Red supergiant structure with H-rich envelope (Van Dyk et al. 2003)
  - Stellar evolution: $M_{\rm ZAMS}$: 8 – 25 $M_\odot$ (Heger et al. 2007)
  - Pre-SN imaging: $M_{\rm ZAMS}$: 8 – 17 $M_\odot$ (Smartt et al. 2009)
  - Hydrodynamical modelling favors high mass range (Utrobin & Chugai 2008)

- Availability of a large of SN II-P

Sample of SNe II-P

- $\sim$30 nearby SNe II-P: Calán/Tololo, SOIRS and CATS (1986-2003)
- High-quality, well-sampled $BVRI$ light curves and spectra
- The CSP is providing even more objects ($\sim$ 80 SNe II-P)





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  - Pre-SN imaging: $M_{\rm ZAMS}$: 8 – 17 $M_\odot$ (Smartt et al. 2009)
  - Hydrodynamical modelling favors high mass range (Utrobin & Chugai 2008)
- Availability of a large data of SN II-P
- Development of our own code to compare with our database of SNe II-P

Code

- Theoretical model of LC $\Longrightarrow$ numerical integration of the hydrodynamic equations $+$ radiative transfer

  Assumptions:

  - Spherically symmetric explosion $\Longrightarrow$ One-dimensional code
  - Diffusion approximation with flux-limited prescription
  - Computation of shock wave using an *artificial viscosity* term
  - Explosion simulated by a sudden release of energy near the core
  - Energy released by radioactive decay

Equations

$$V = \frac{4\pi}{3}\frac{\partial r^3}{\partial m}$$ $\Longrightarrow$ Mass conservation

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

$$\frac{\partial u}{\partial t} = -4\pi r^2 \frac{\partial}{\partial m}(P + q) - \frac{Gm}{r^2}$$ $\Longrightarrow$ Momentum conservation

$$\frac{\partial E}{\partial t} = \epsilon_{\mathrm{Ni}} - \frac{\partial L}{\partial m} - (P + q)\frac{\partial V}{\partial t}$$ $\Longrightarrow$ Energy conservation

$$L = -(4\pi r^2)^2 \frac{\lambda ac}{3\kappa}\frac{\partial T^4}{\partial m}$$ $\Longrightarrow$ Radiative energy transport

$+$

Initial and boundary conditions, and constituent equations

Code

- Method of finite differences: space-time grid
- Explicit scheme for the hydrodynamics ($\Delta t \leq \ t_{\mathrm{Courant}}$) and implicit for the temperature
- Gamma-ray deposition from ^{56}Ni–^{56}Co–^{56}Fe decay
  - transfer equation in grey approximation: $\frac{dI}{d\tau} = -I + S$
  - arbitrary spherically symetric distribution of ^{56}Ni
  - $\frac{dE}{dm} = \kappa_\gamma \int I d\Omega$; $\ \kappa_\gamma = 0.03$ cm^2 g^{-1}

Initial models

- Polytropic models: single and double
- Evolutionary calculations

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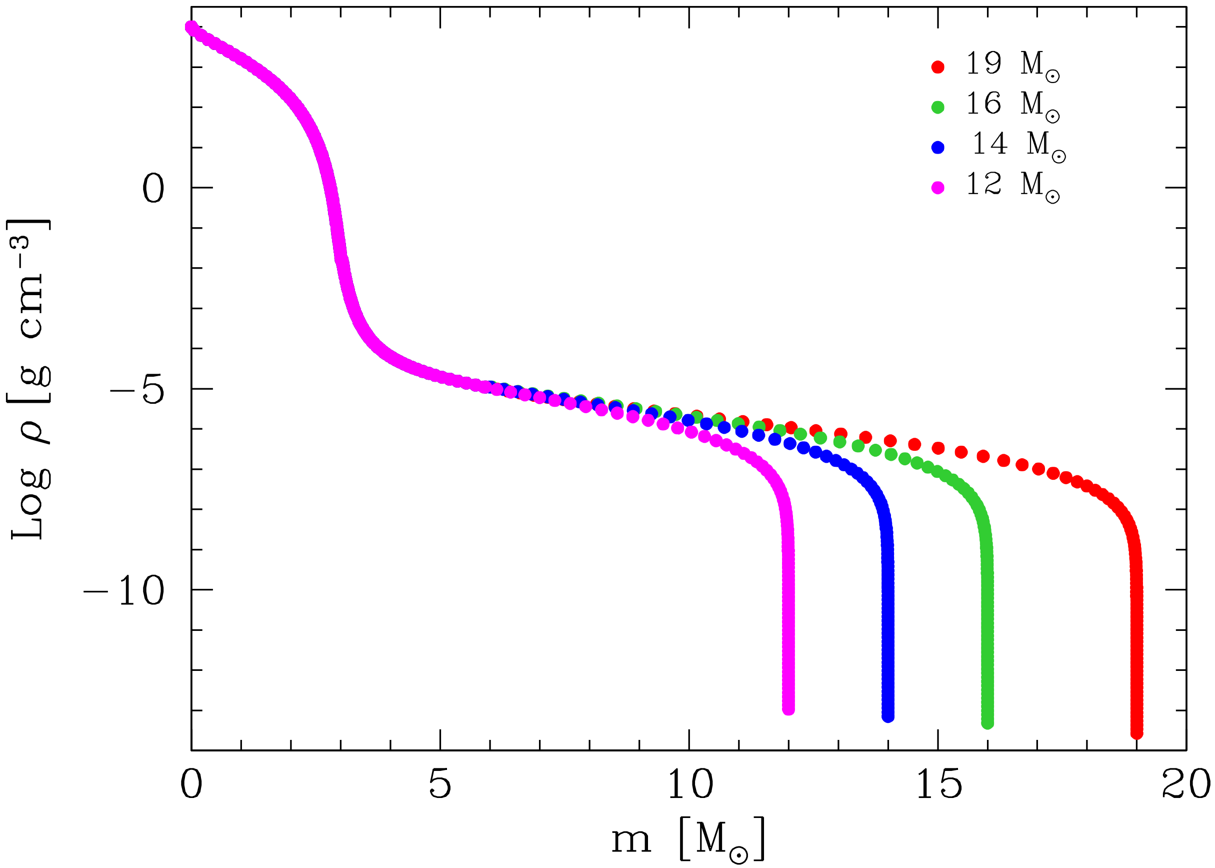
- Polytropic models: single and double
- Evolutionary calculations

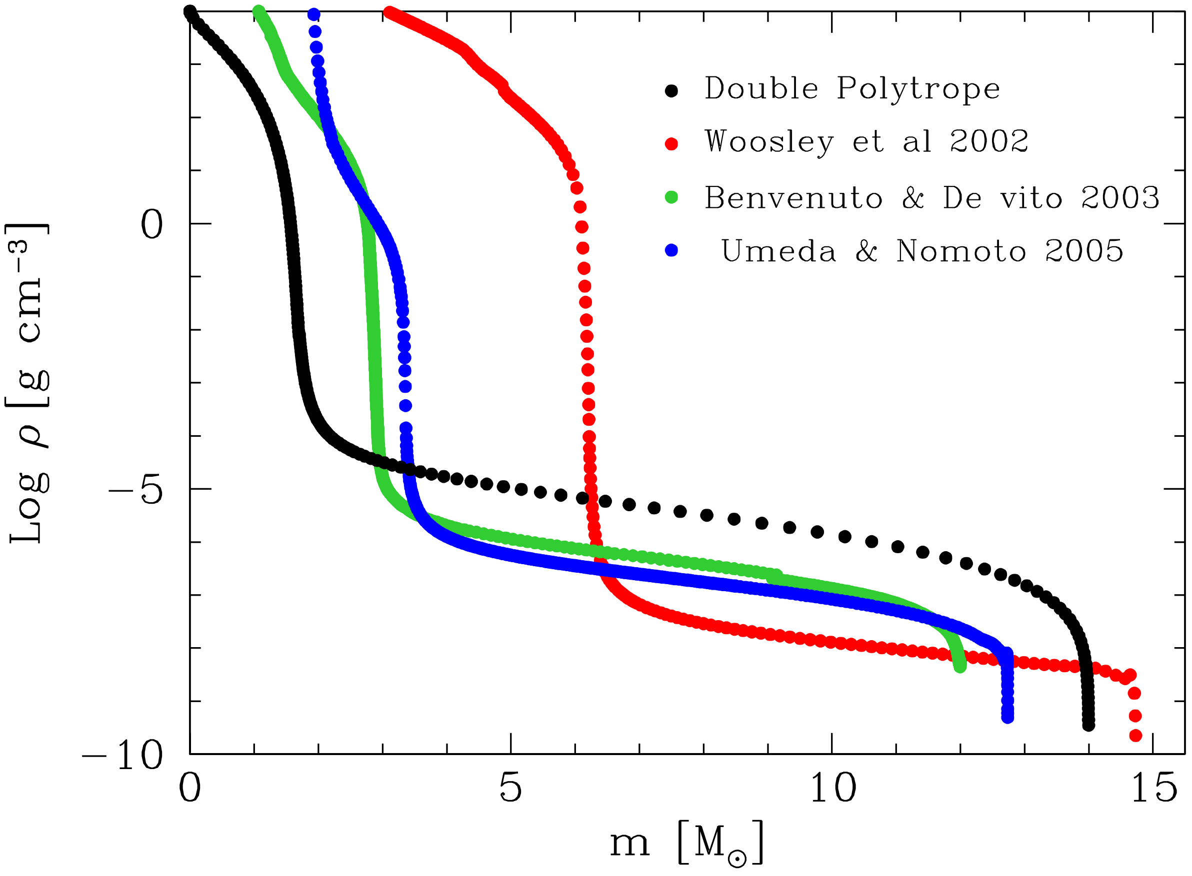
Double Polytrope



Initial models

- Polytropic models: single and double
- Evolutionary calculations

Evolutionary models

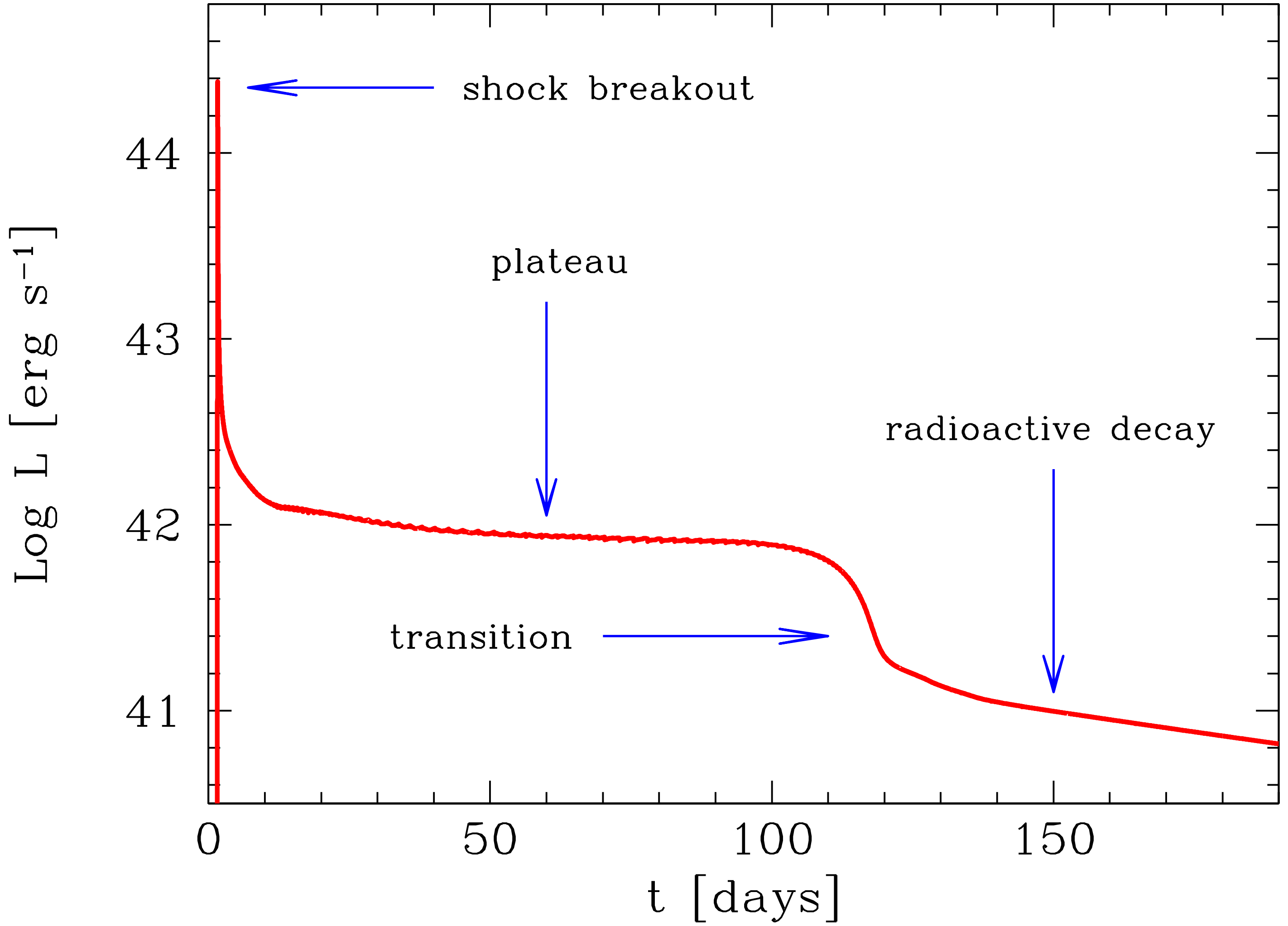


RESULTS

Theoretical Bolometric LC

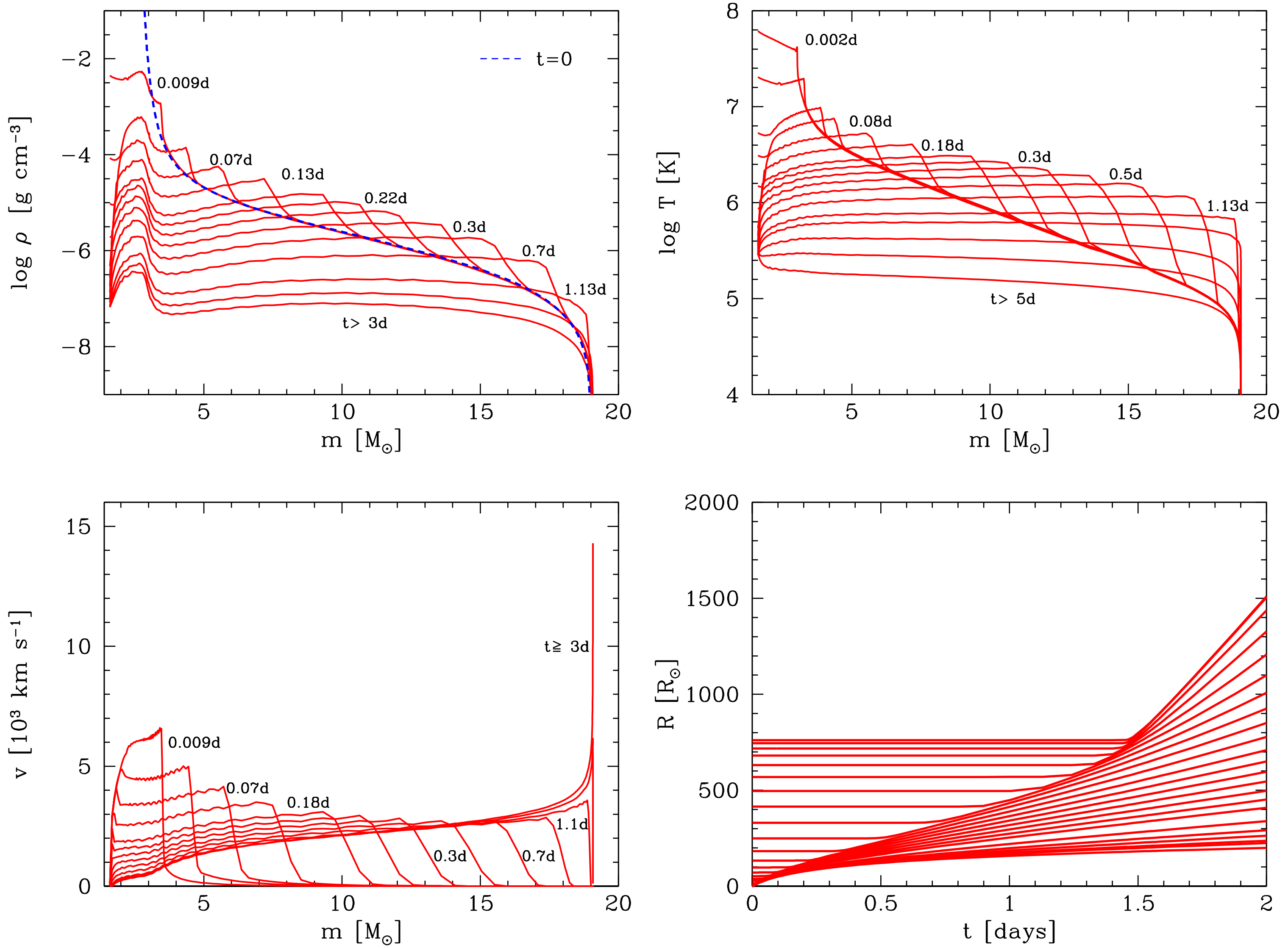
- Model with $E = 1.3$ foes, $R_0 = 800\ R_\odot$, $M_0 = 19\ M_\odot$

Evolutionary phases



Before breakout

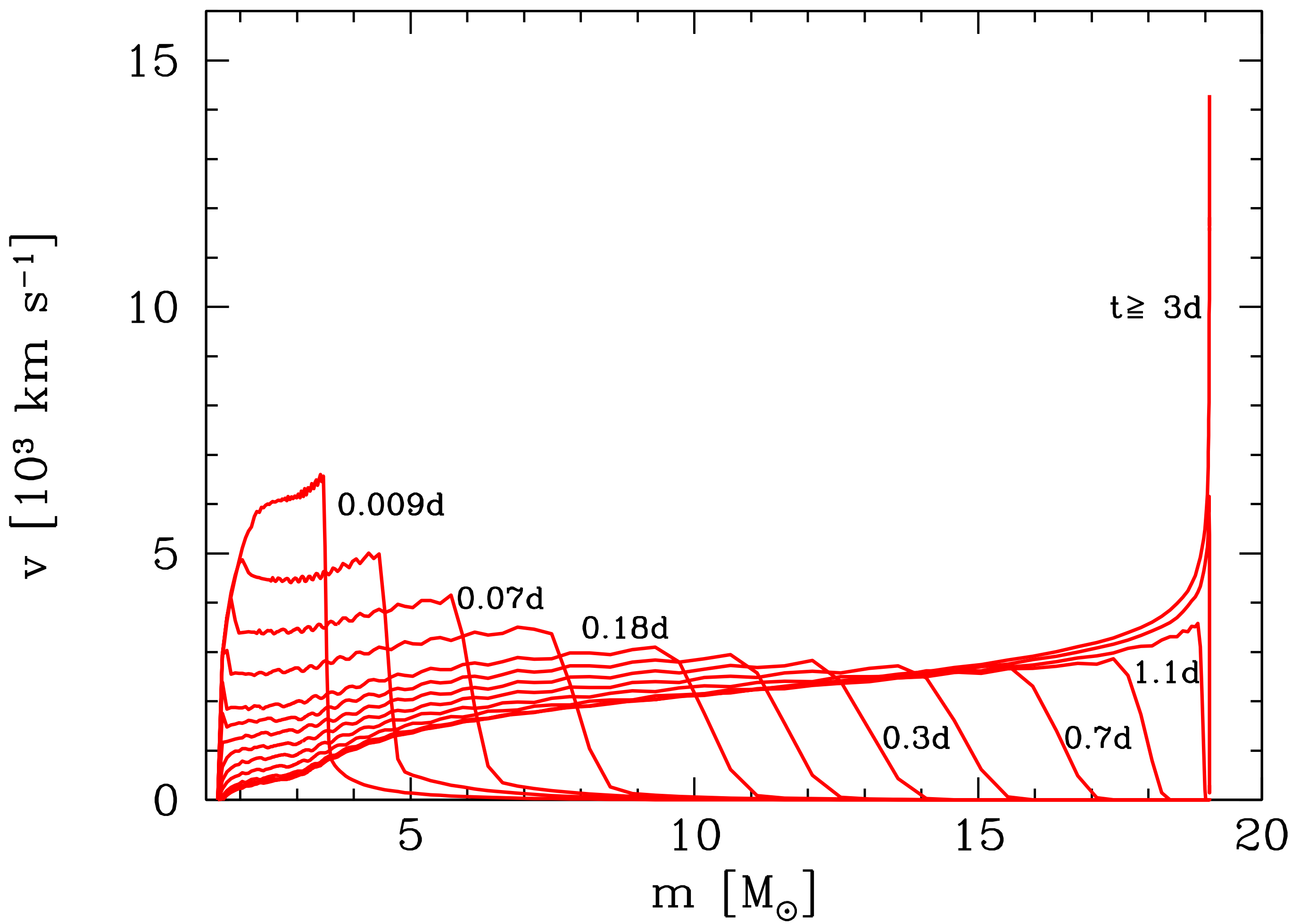
- Model with $E = 1.3$ foes, $R_0 = 800\ R_\odot$, $M_0 = 19\ M_\odot$



Before breakout

- Model with $E = 1.3$ foes, $R_0 = 800\ R_\odot$, $M_0 = 19\ M_\odot$

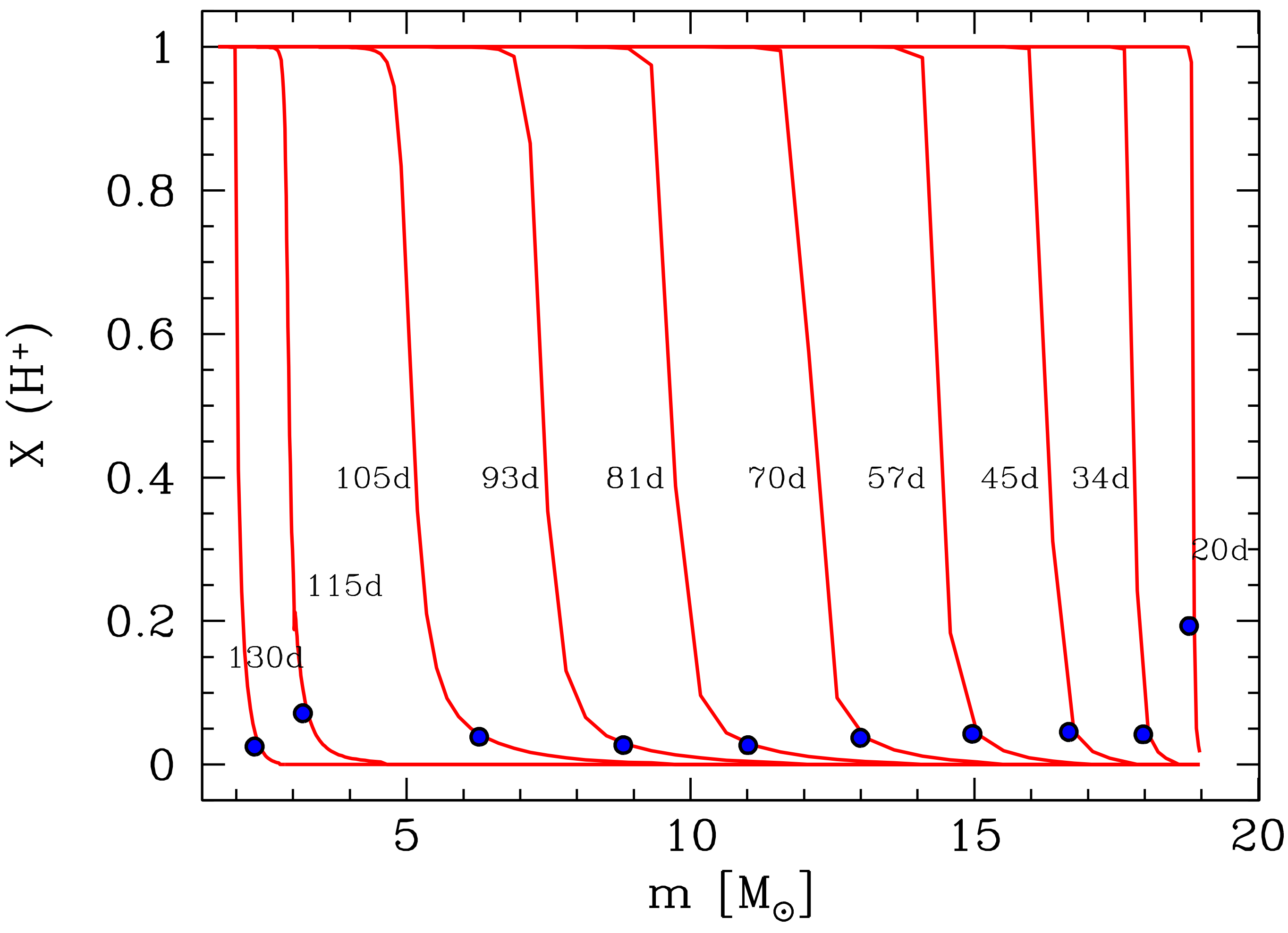
Velocity profiles at different times



After breakout

- Model with $E = 1.3$ foes, $R_0 = 800\ R_\odot$, $M_0 = 19\ M_\odot$

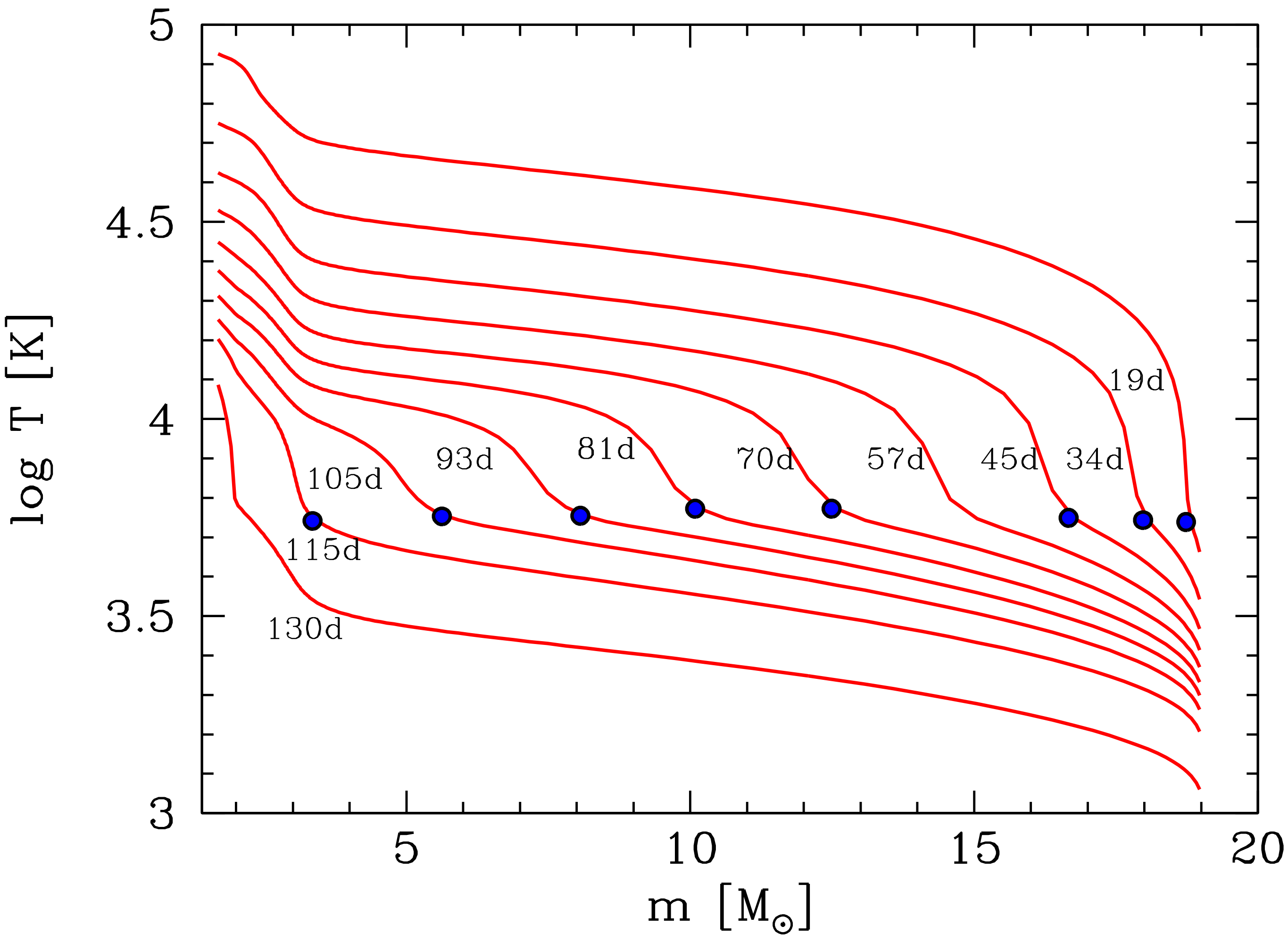
Profiles of the fraction of ionized Hydrogen



After breakout

- Model with $E = 1.3$ foes, $R_0 = 800\ R_\odot$, $M_0 = 19\ M_\odot$

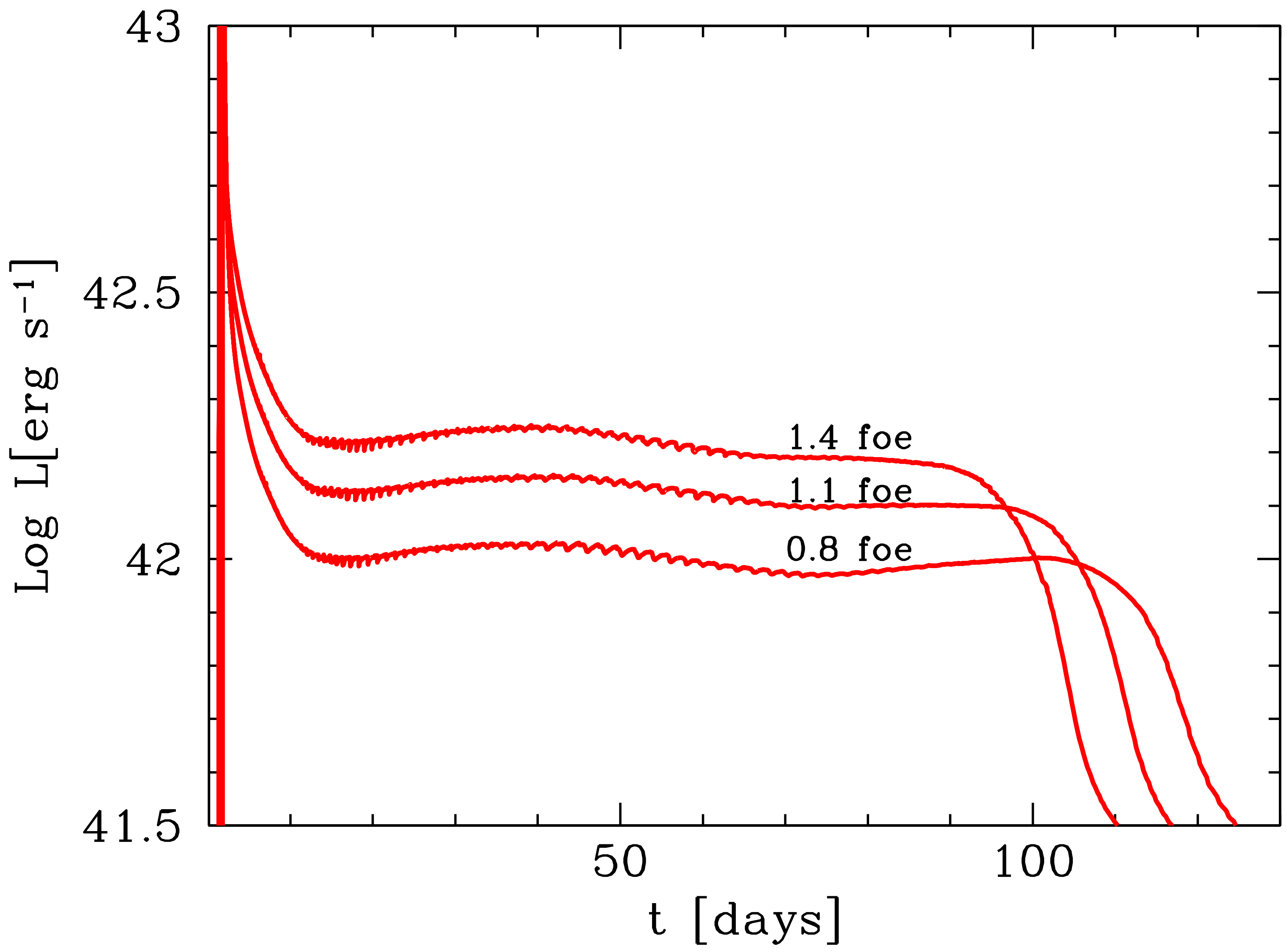
Temperature profiles



Variation of Parameters

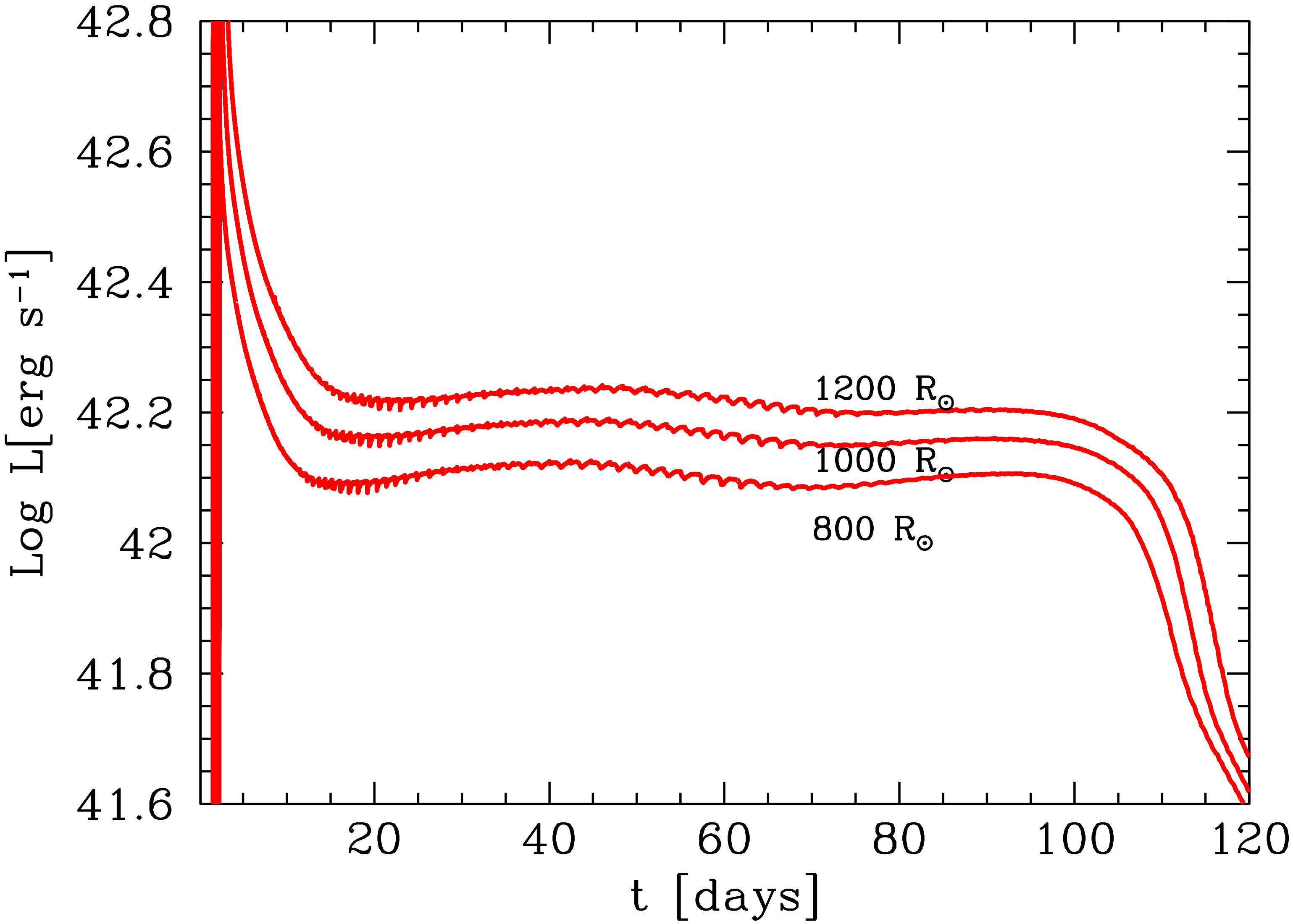
Variation of Parameters

Light curves for different energies



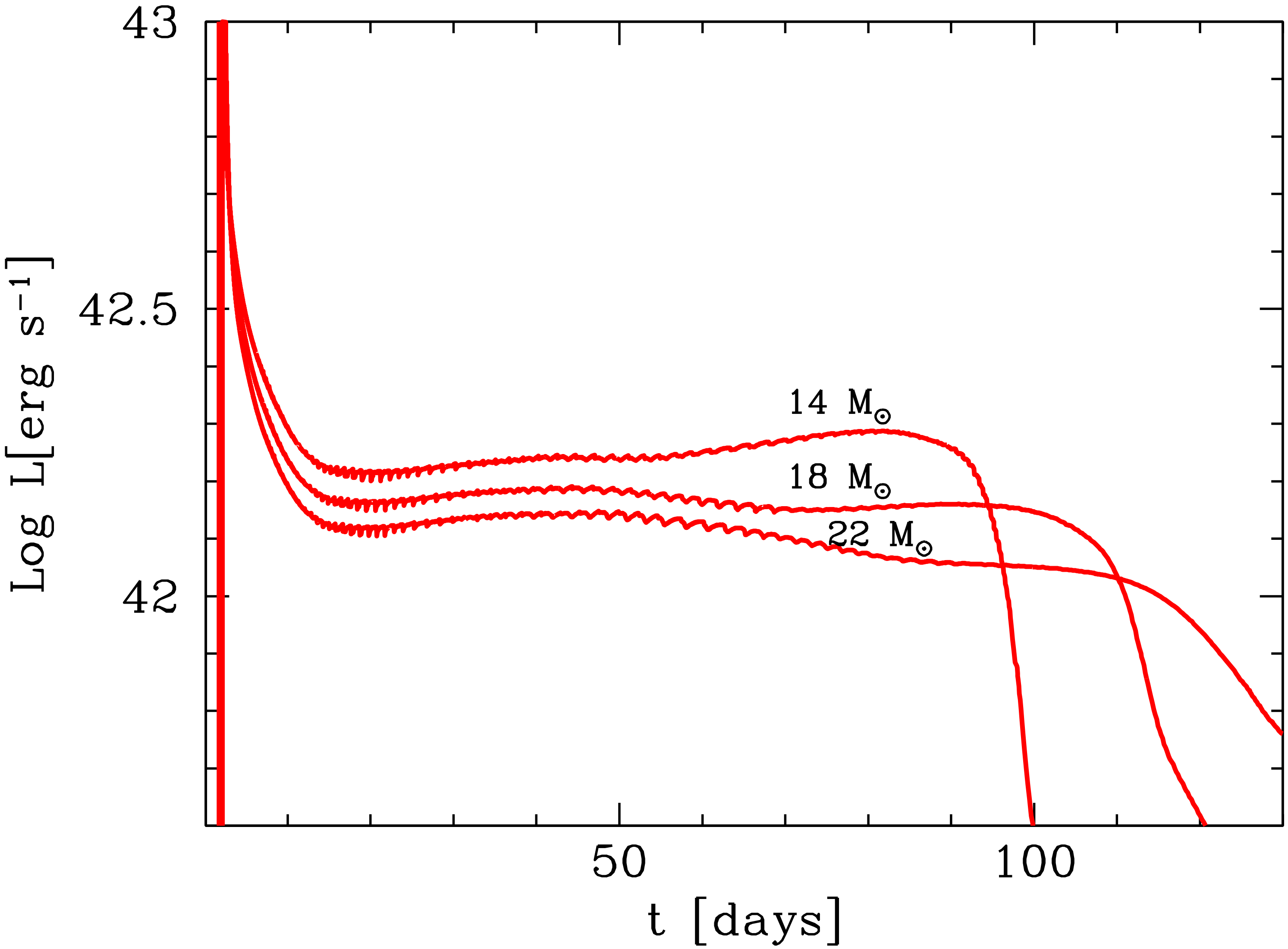
Variation of Parameters

Light curves for different radii



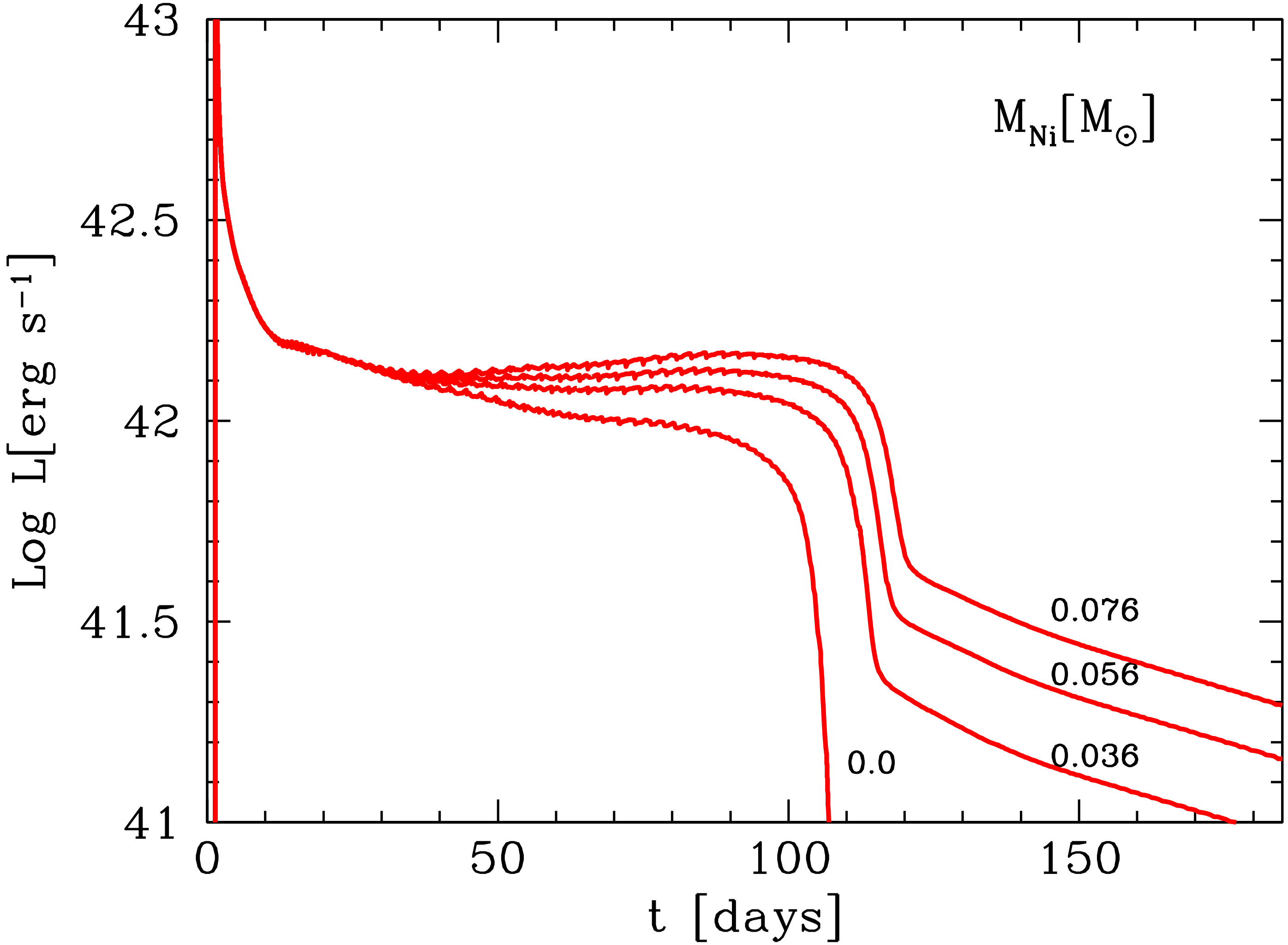
Variation of Parameters

Light curves for different masses



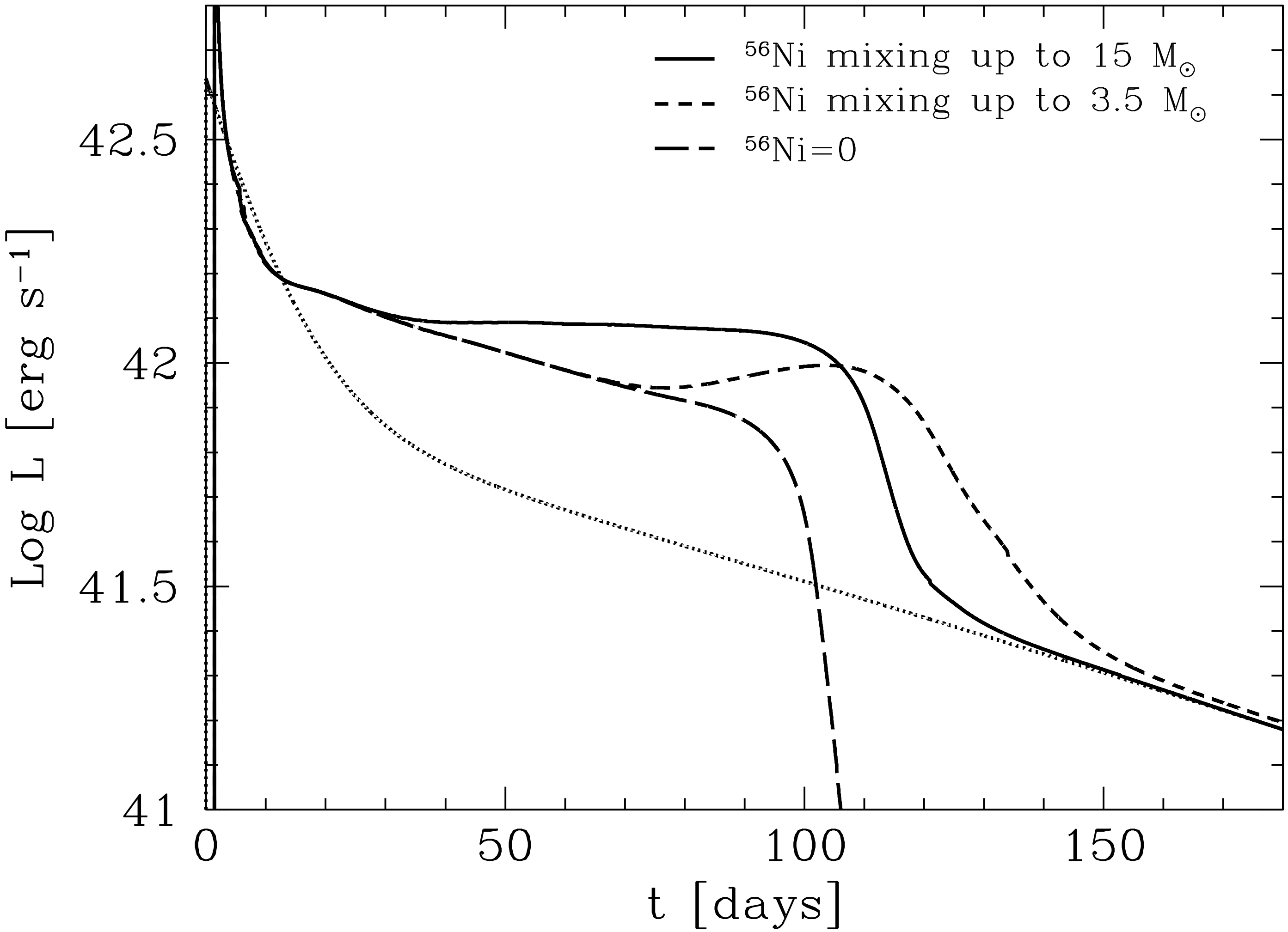
Variation of Parameters

Light curves for different ^{56}Ni mass



Variation of Parameters

Light curves for different ^{56}Ni distribution

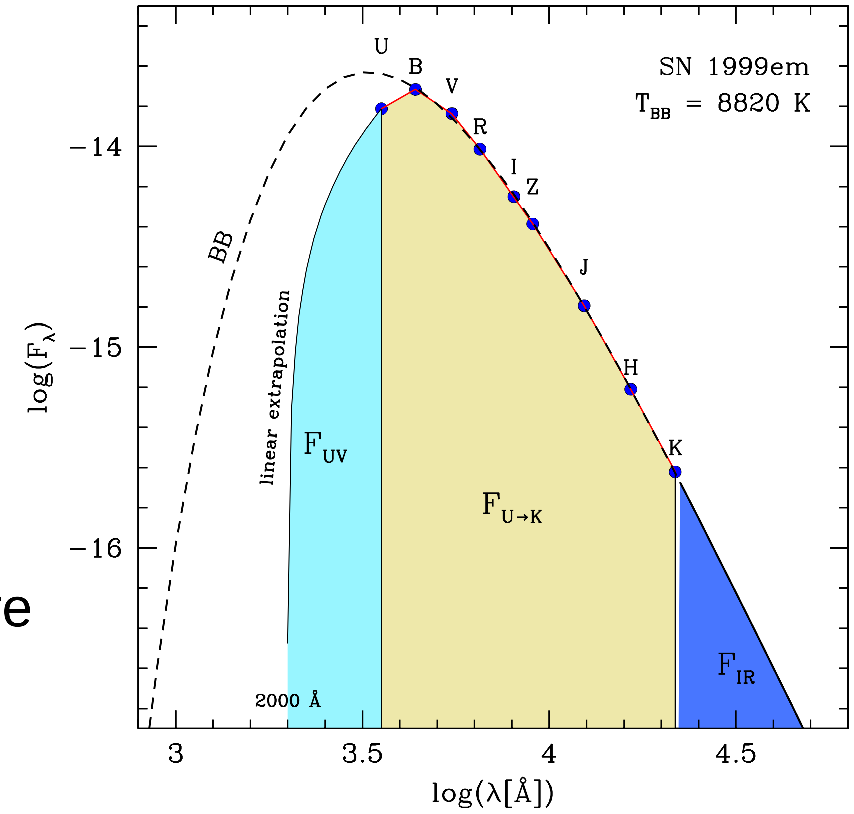


DATA SAMPLE

Bolometric Correction

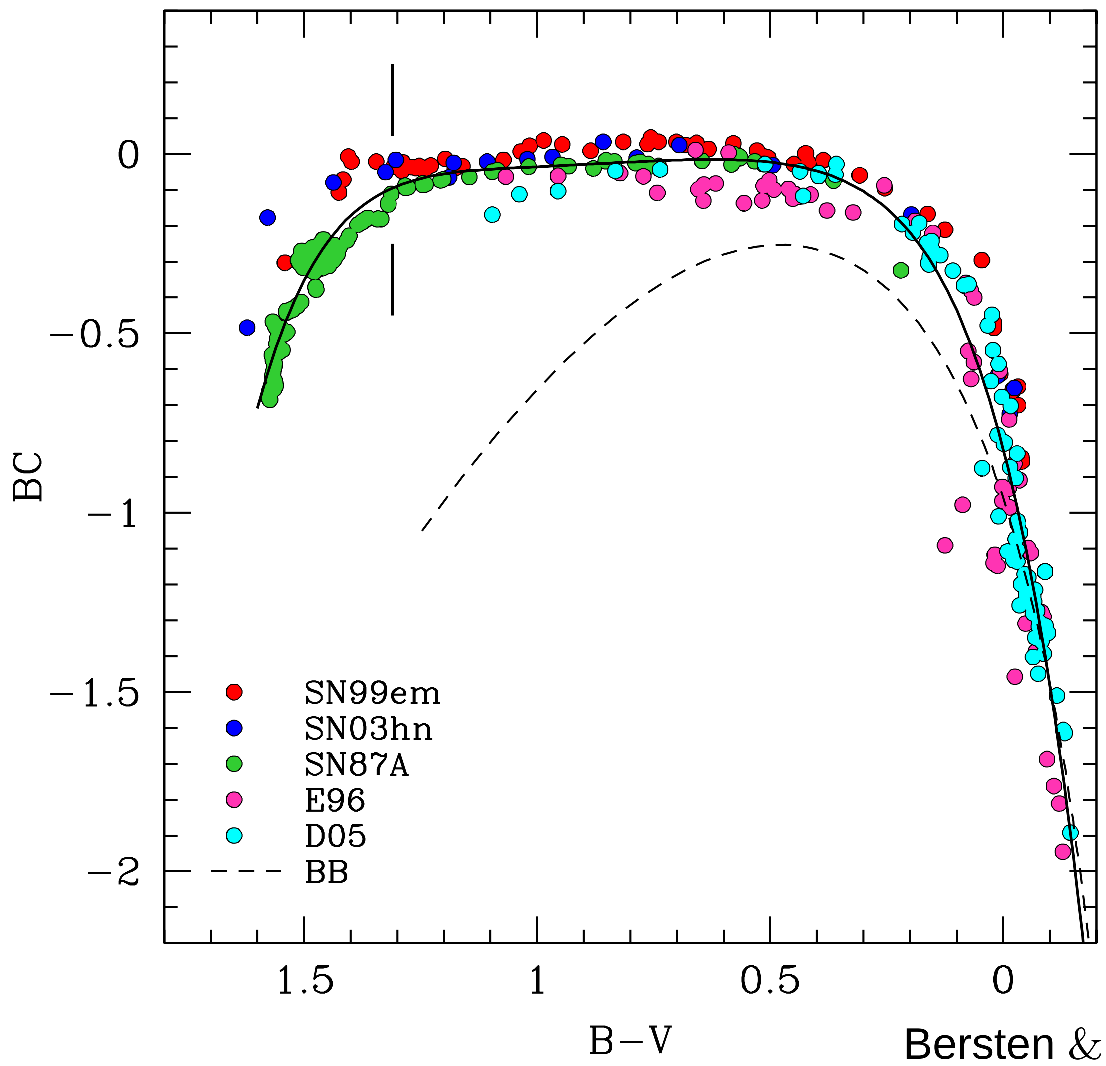
Bolometric Correction

- Three well-observed supernovae: SN 1987A, SN 1999em, and SN 2003hn
- Integration of all the available broadband data
- Estimation of the missing flux in UV and IR: blackbody (BB) fit
- Calculation of BC for two atmosphere models: Eastman et al. (1996) and Dessart & Hillier (2005)



Bolometric Correction

$$BC = m_{bol} - [V - A_V], \quad rms = 0.11 \text{ mag}$$



Bersten & Hamuy (2009)

Sample of SNe II-P

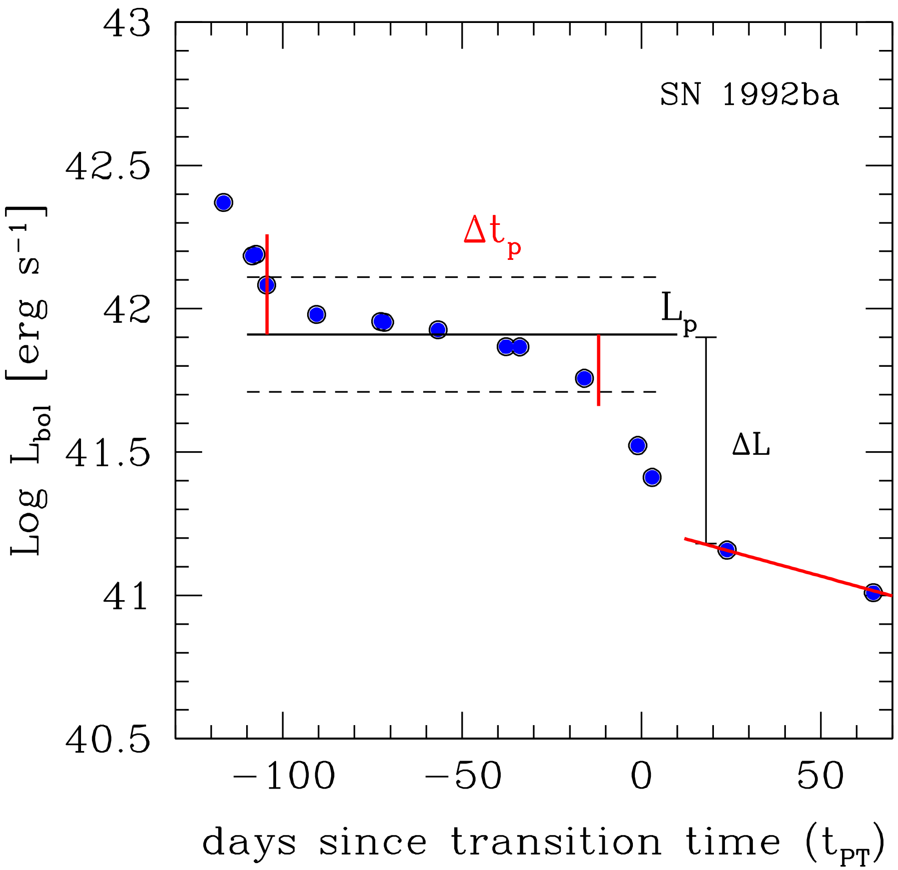
- Calculation of bolometric LCs for our sample of SNe II-P

  $\log L[\mathrm{erg\,s^{-1}}] = -0.4\,[BC(color) + V - A_{total}(V) - 11.64] + \log(4\,\pi D^2)$

- Olivares et. al (2010): D, $A_{host}(V)$

Sample of SNe II-P

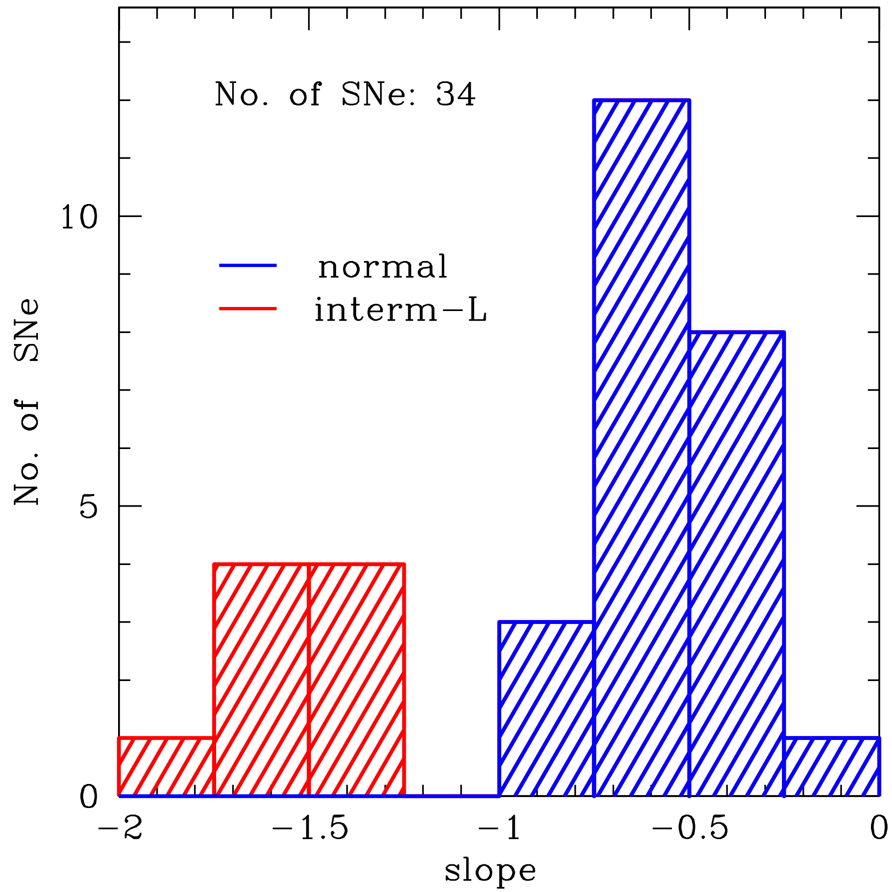
- Calculation of bolometric LCs for our sample of SNe II-P
- Estimation of parameters to characterize the LCs:
  - L_p: plateau luminosity
  - Δt_p: plateau duration
  - Δ log L: luminosity drop
  - $M_{\rm Ni}$: ^{56}Ni mass



- Analysis of observed parameters

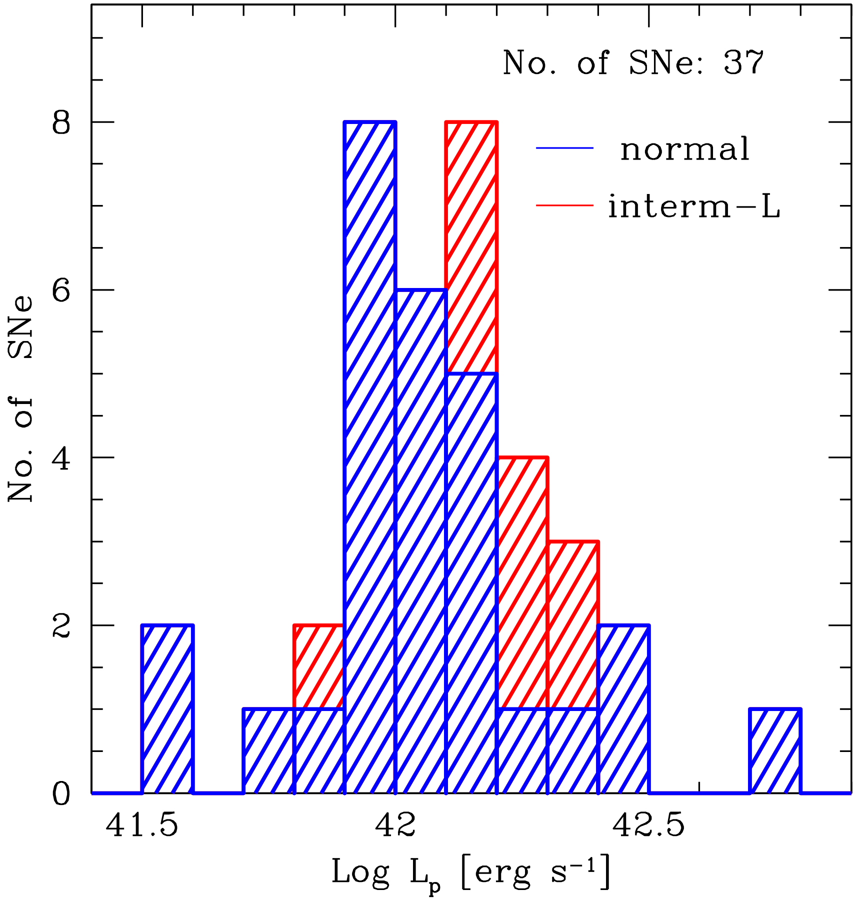
Slope during Plateau

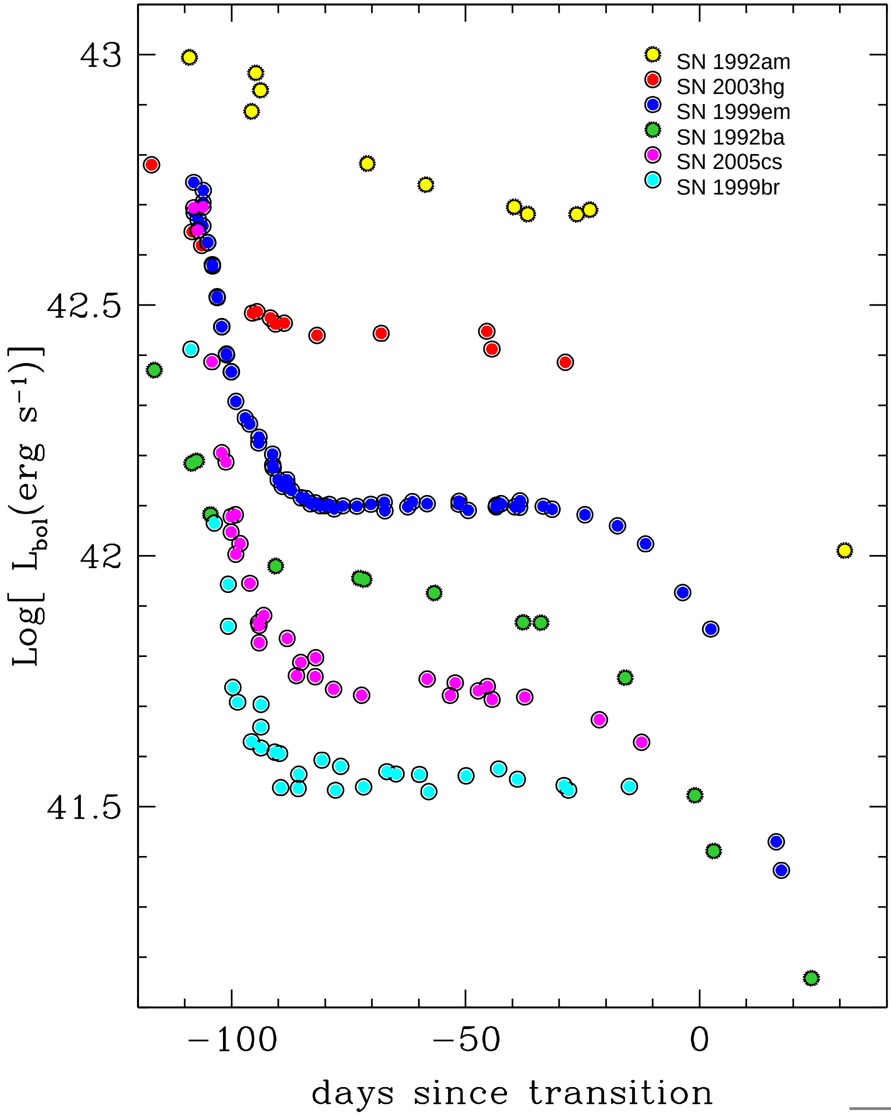
- Bi-modal tendency
- slope > -1 mag/100 d $\longrightarrow$ "normal plateau"
- slope < -1.25 mag/100 d $\longrightarrow$ "intermediate-plateau"



Bolometric Luminosity Range

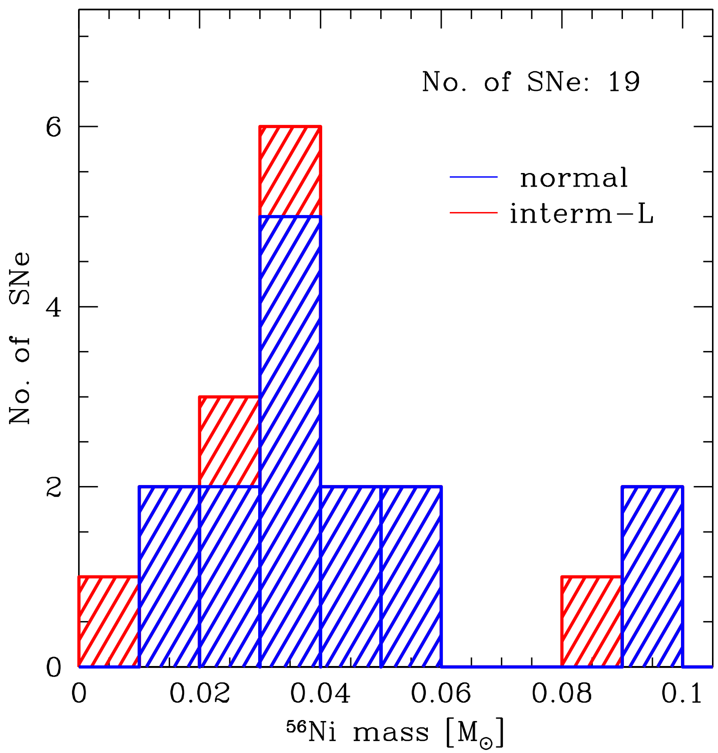
- Weighted average $\langle L_p \rangle = 1.26 \times 10^{42}$ erg s^{-1}
- Range of 1.15 dex in L_p

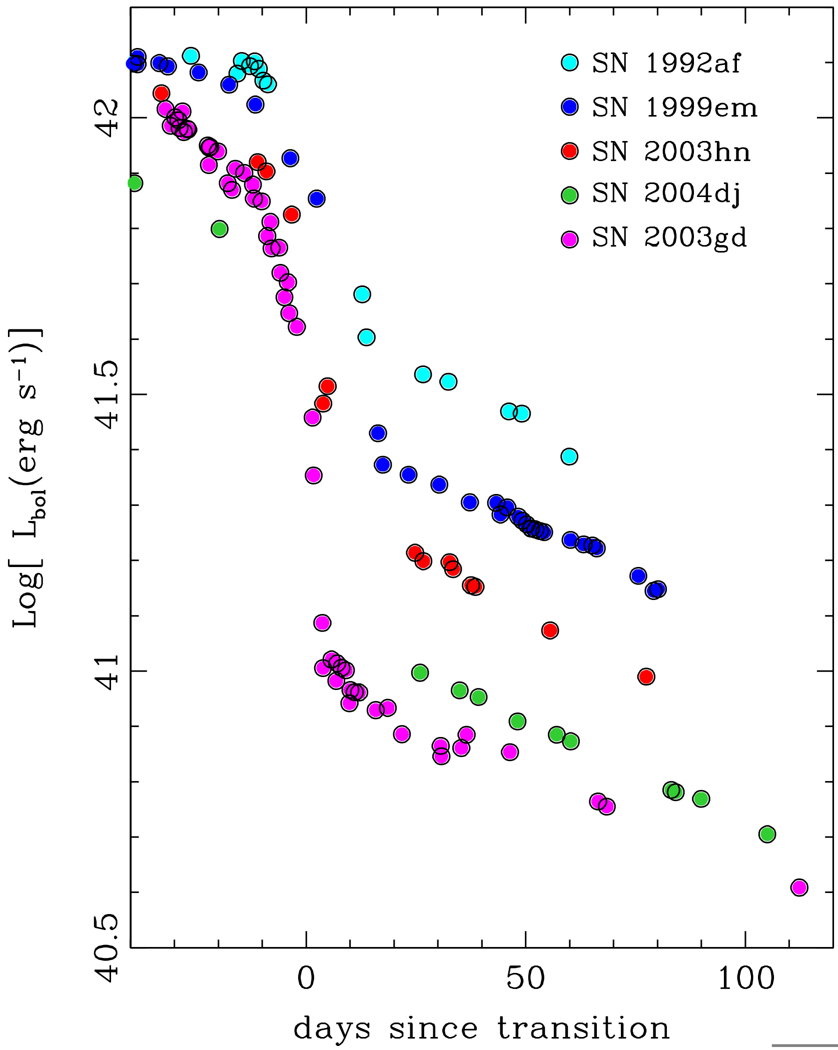




^{56}Ni mass

- $M_{\rm Ni}$ sensitive to adopted explosion time
- Assumed local deposition of gamma rays
- Weighted average $\langle M_{\rm Ni} \rangle = 0.024 M_\odot$
- $M_{\rm Ni} < 0.1 M_\odot$,
  except for SN 1992am ($M_{\rm Ni} > 0.26 M_\odot$)





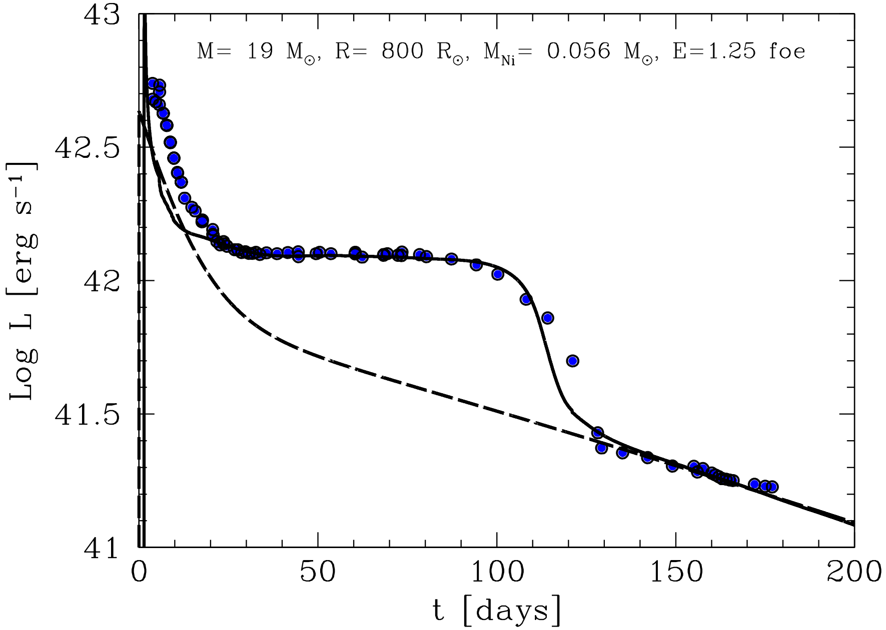
Model vs. Observation

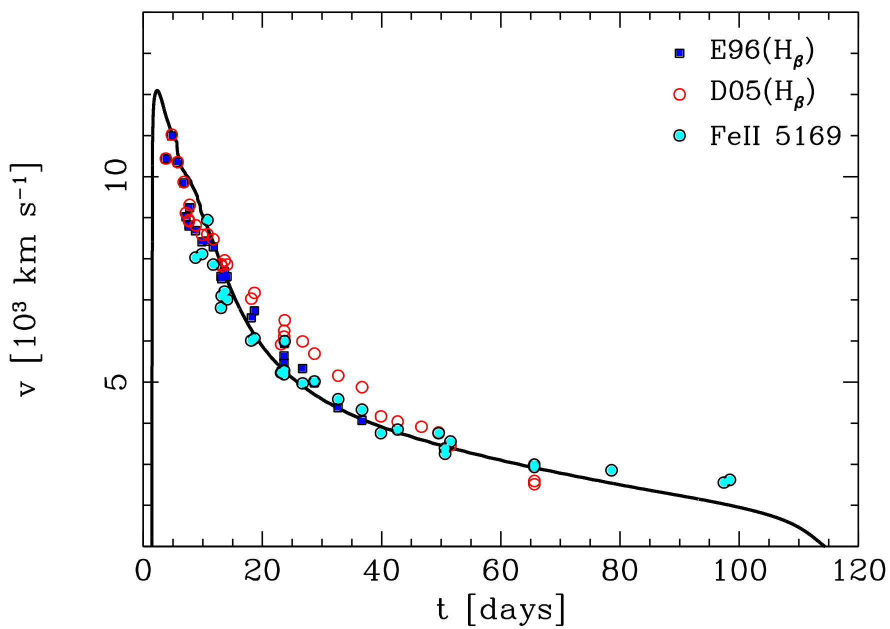
Hydro-Model of SN 1999em

- Proto-type SN II-P
- One of the best-oberved SNe II-P
- Determination of physical parameters (M_0,R_0, E and $M_{\rm Ni}$) by comparing
  - bolometric light curve
  - photospheric velocity evolution

Hydro-Model of SN 1999em

- Extended ^{56}Ni mixing
- Very good agreement with observations
- Physical parameters similar to previous hydrodynamical studies
  (Baklanov et al. 2005; Utrobin 2007)
- Low-mass models are not favored





Bersten, Benvenuto & Hamuy, ApJ in press

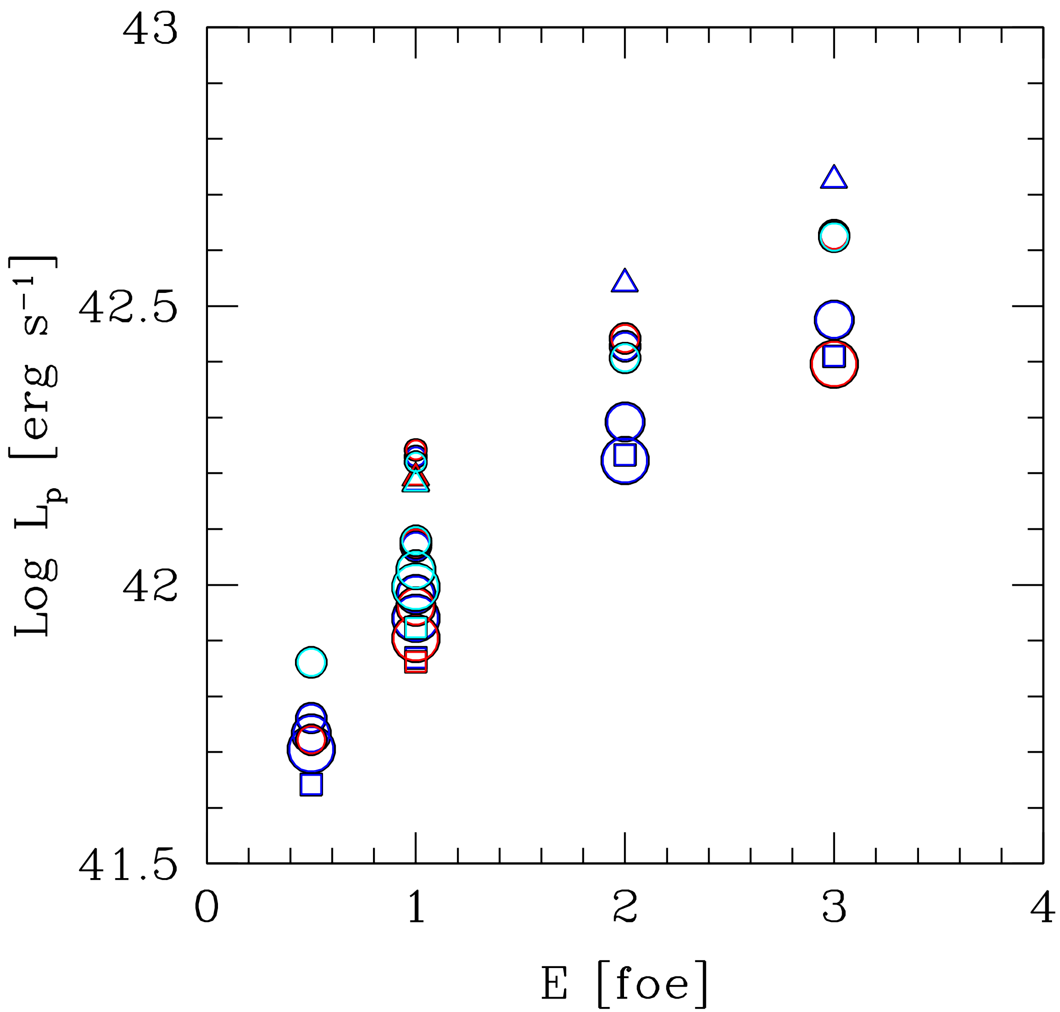
Grid of Hydrodynamical Models

- Set of 46 hydrodynamical models:
  - $M_0 =$ 10, 15, 20 and 25 $M_\odot$
  - $E =$ 0.5, 1, 2 and 3 foe
  - $R_0 =$ 500, 1000, and 1500 $R_\odot$
  - $M_{\rm Ni} =$ 0.02, 0.04 and 0.07 $M_\odot$
- For each model: L_p, Δt_p ,ΔL, M_{Ni} and v_{-30} are measured consistently with observations
  - Dependence of observable parameters on physical quantities
  - Study of correlations between observable parameters

Model dependences

- Symbols: size proportional to M_0, shape indicates different R_0 and colors related with M_{Ni} (fixed mixing)

Plateau luminosity



- Strong correlation with explosion energy
- ~0.4 dex of dispersion mainly related to M_0 and R_0
- $M_{\rm Ni}$ (fixed mixing) is not very influential

Model dependences

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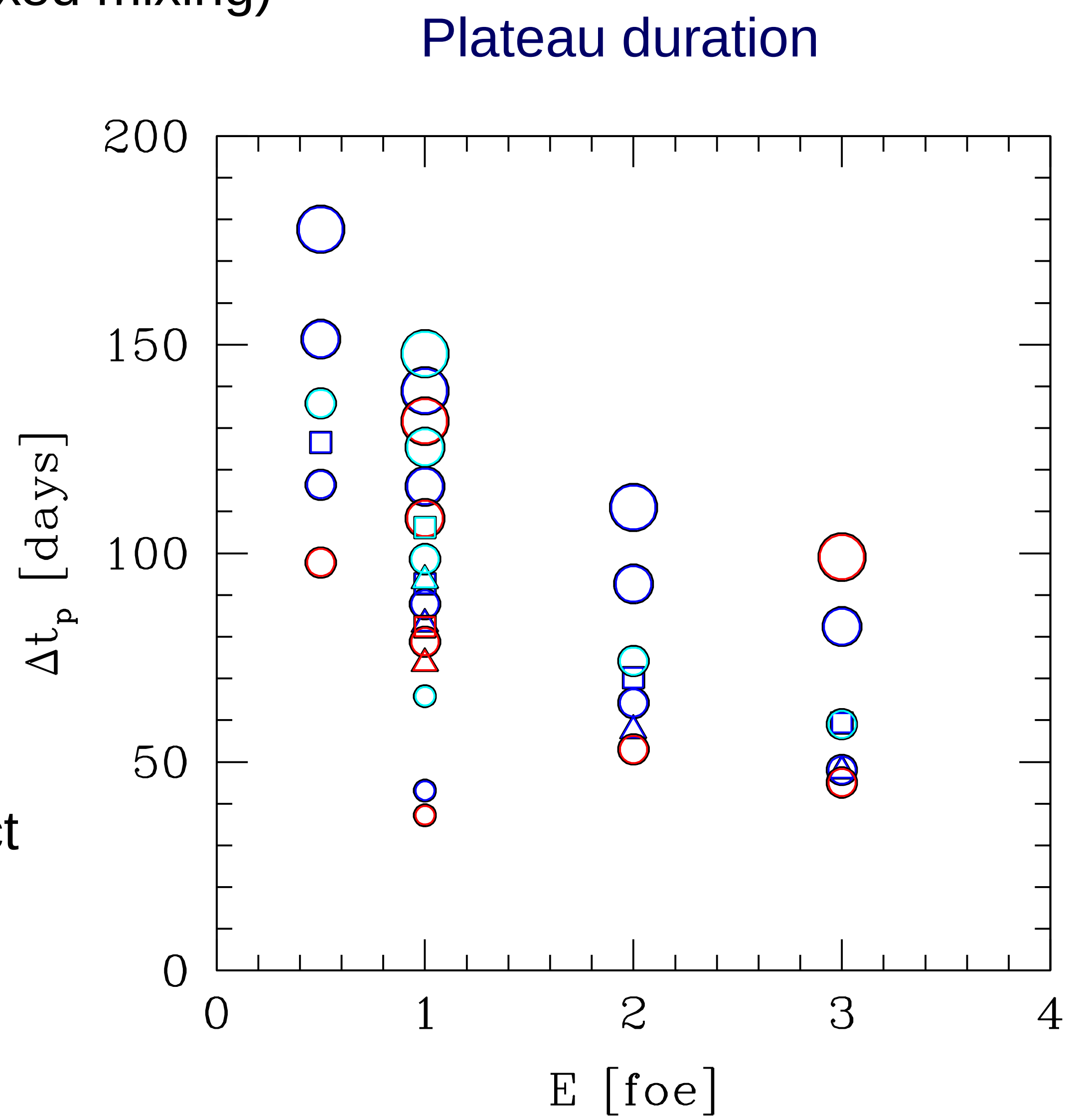


- Weaker correlation with explosion energy
- M_0 seems the most important factor but M_{Ni} also produces an effect
- R_0 produces a minor effect

Observed and Modeled Correlations

- The Standard Candle Method (SCM):
  - Correlation between luminosity and expansion velocity during the plateau phase found by Hamuy & Pinto (2002)
  - Detailed study of this correlation for our sample of SNe II-P given by Olivares et. al (2010) leading to a precision of 13% in distance
  - Study of this correlation using our hydrodynamical models

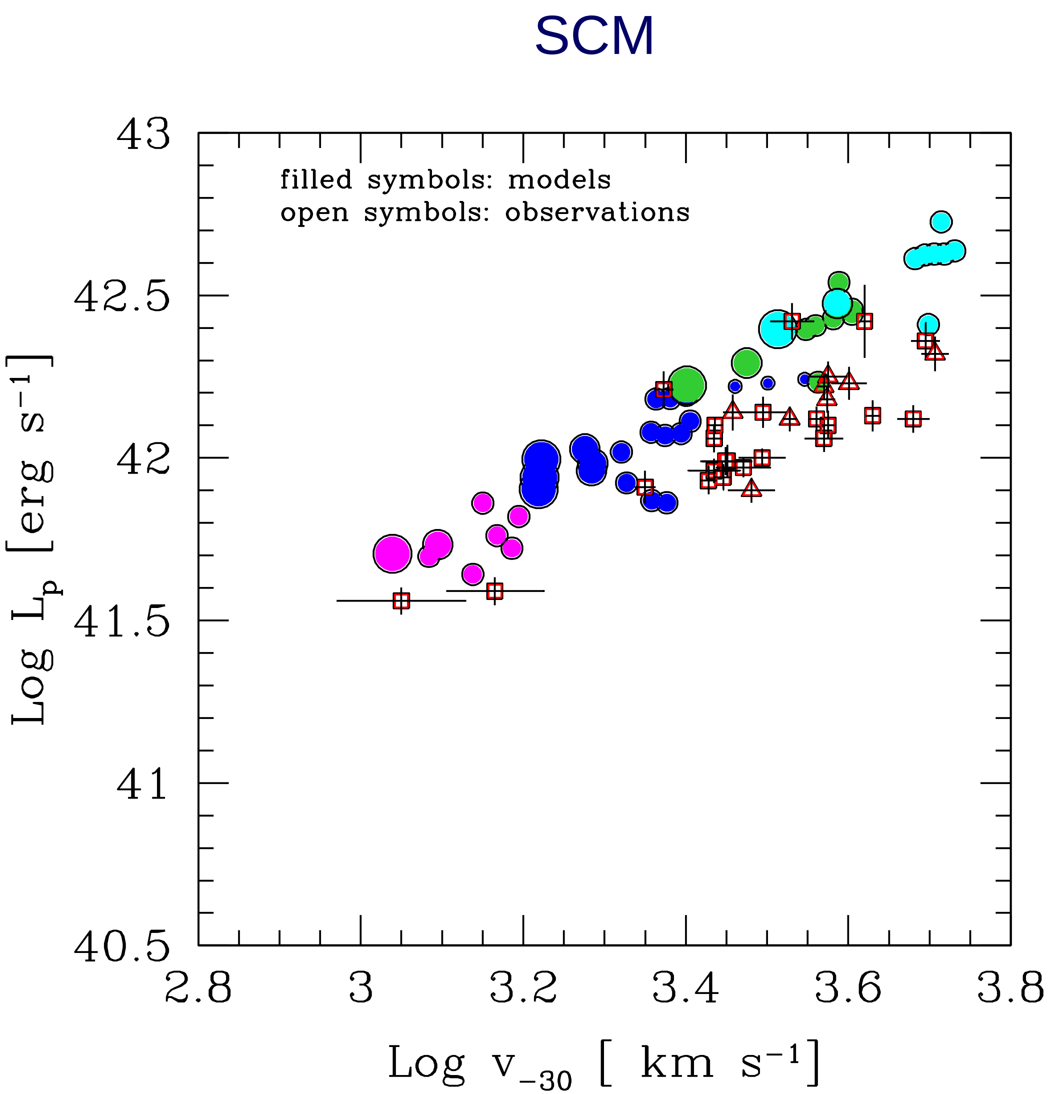
Observed and Modeled Correlations

- Symbol Colors: different explosion energies (E)

- Models reproduce very well the obverved trend

- E is the main driver

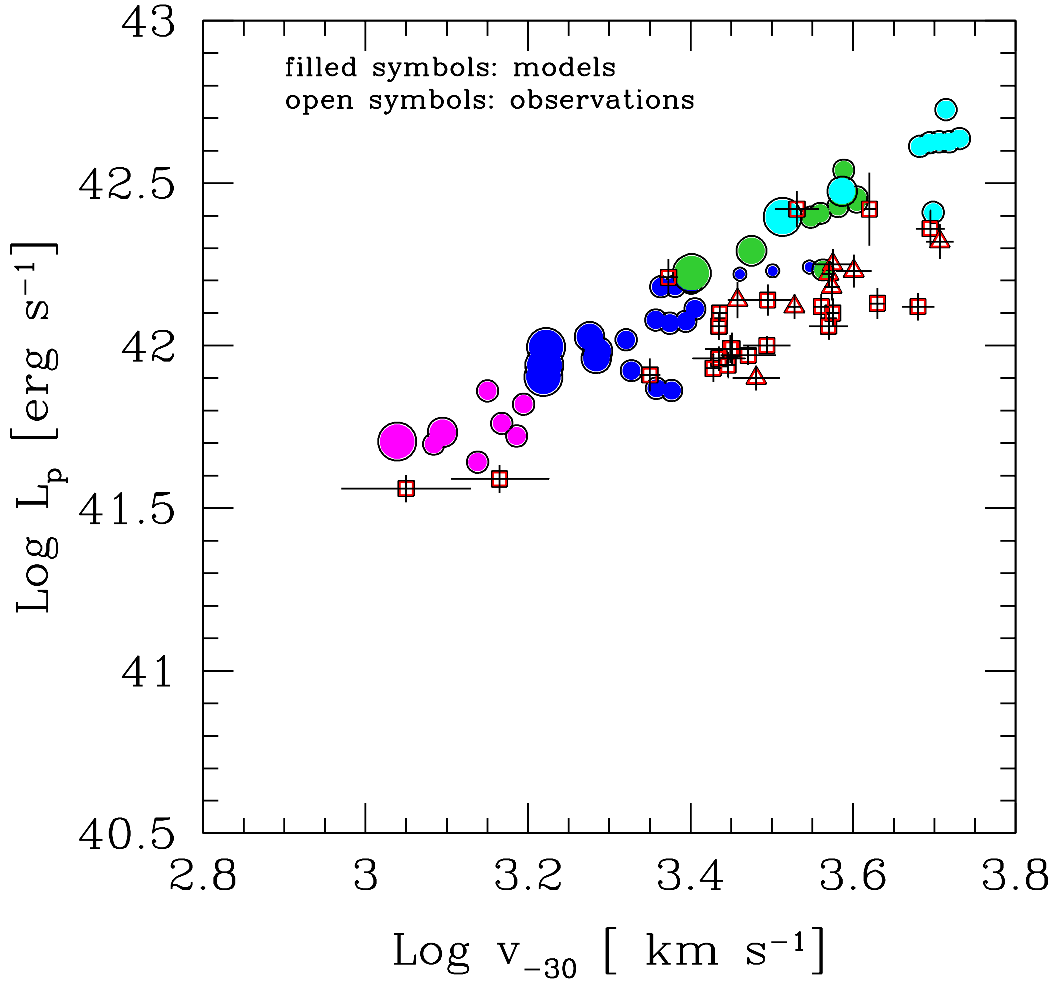
- Shift between models and observations



Observed and Modeled Correlations

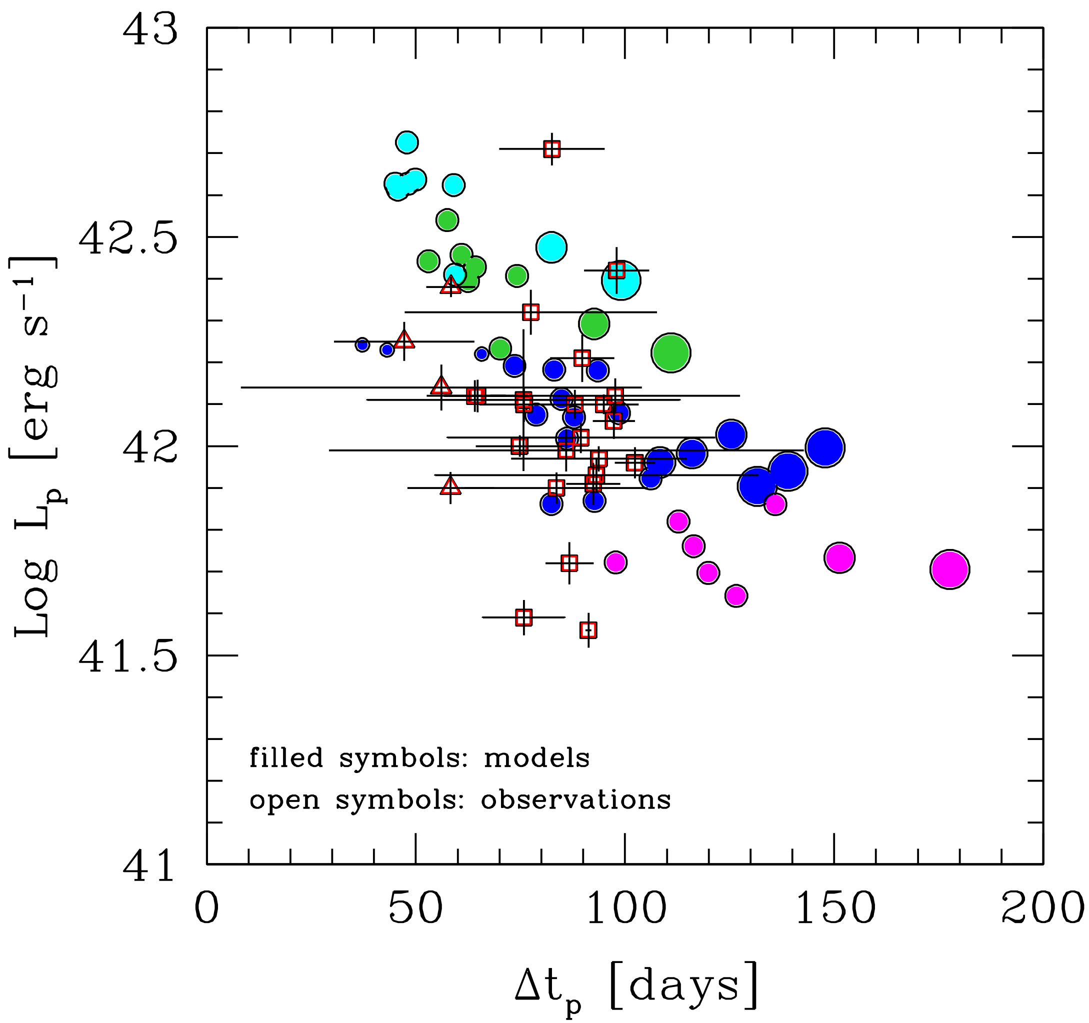
- Symbol Colors: different explosion energies (E)
- Shift between models and observations:
  - Adopted H_0
  - Extinction correction
  - Measurement inconsistencies
  - High-mass models

SCM



Observed and Modeled Correlations

- Symbol Colors: different explosion energies (E)
- Models show slight correlation previously noted by Kasen & Woosley (2009)
- Observations show no correlation
- Lowest E and high M are not favored



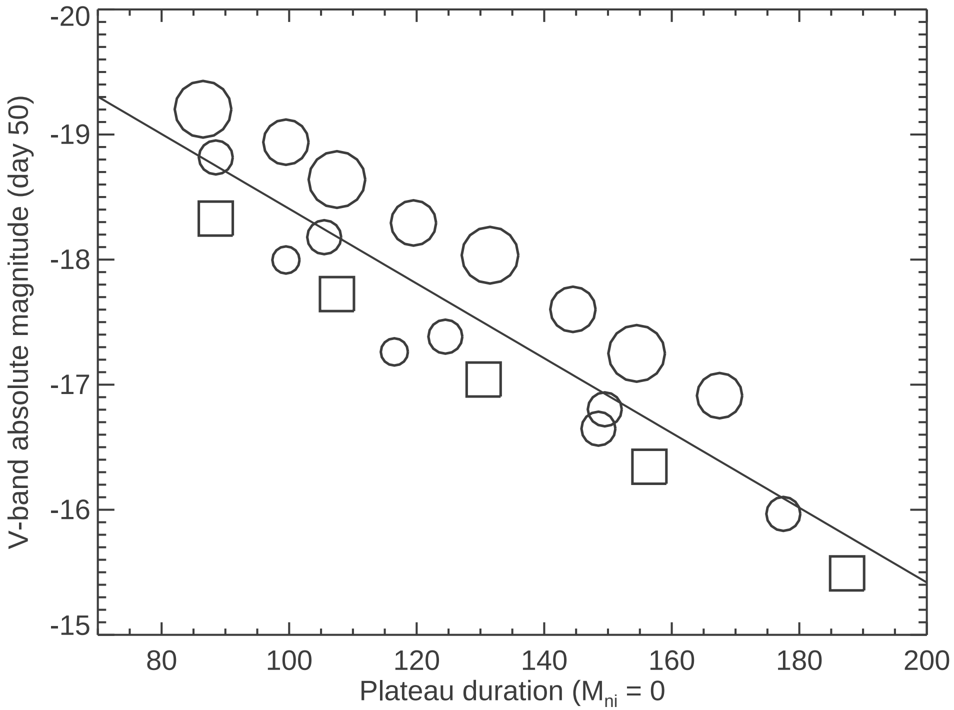
Kasen & Woosley 2009

- Grid hydro Models using pre-SN models from stellar evolutionary calculations: E=0.5-4 foe, M= 10.9-15.8 $M_\odot$ and R= 625-1349 $R_\odot$

- Strong correlation

$$M_{V,50} = -18.4 - 0.03[t_{p,0} - 100]$$

- Correction by ^{56}Ni mass is needed



$$t_p = t_{p,0} \times \left(1 + 0.35 M_{ni} E_{51}^{-1/2} R_0^{-1} M_{ej}^{1/2}\right)^{1/6}$$

Observed and Modeled Correlations

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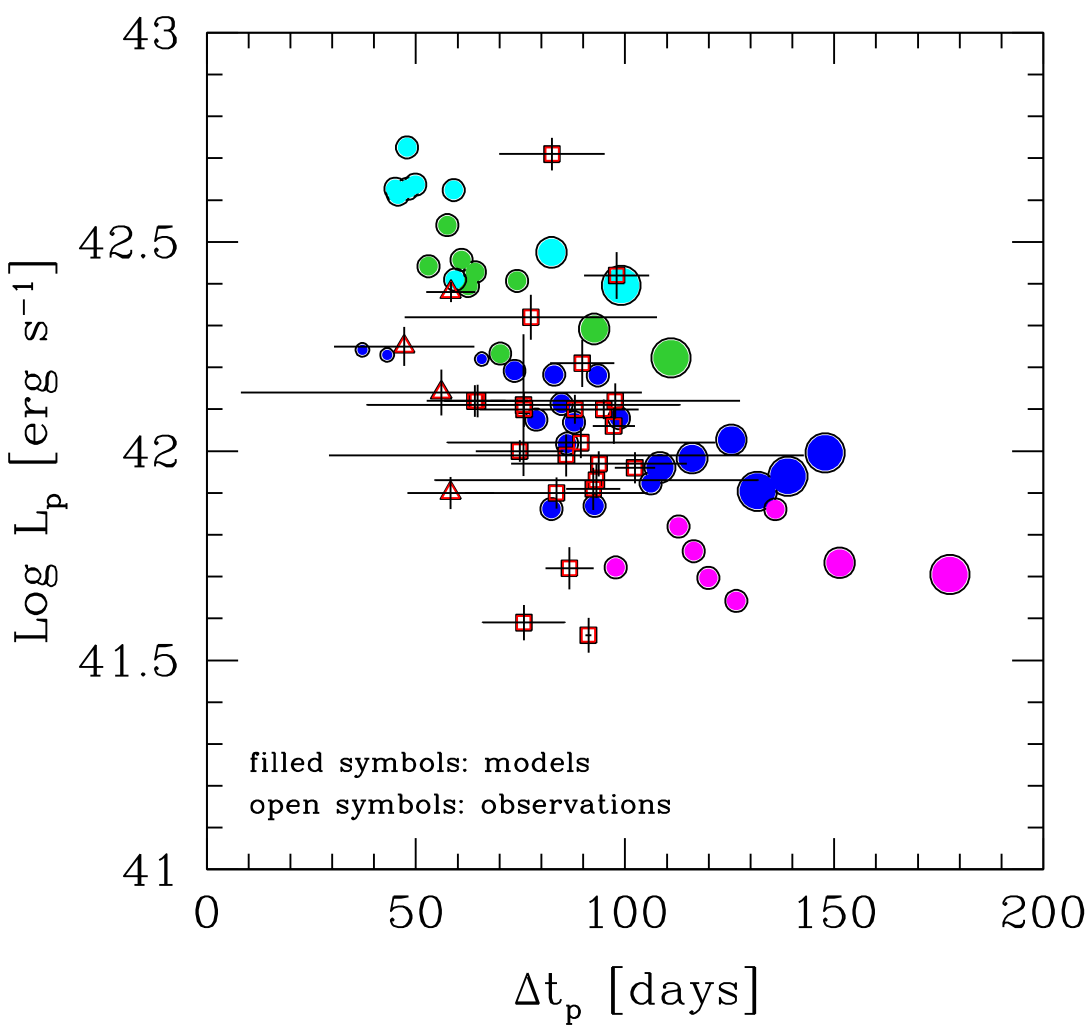
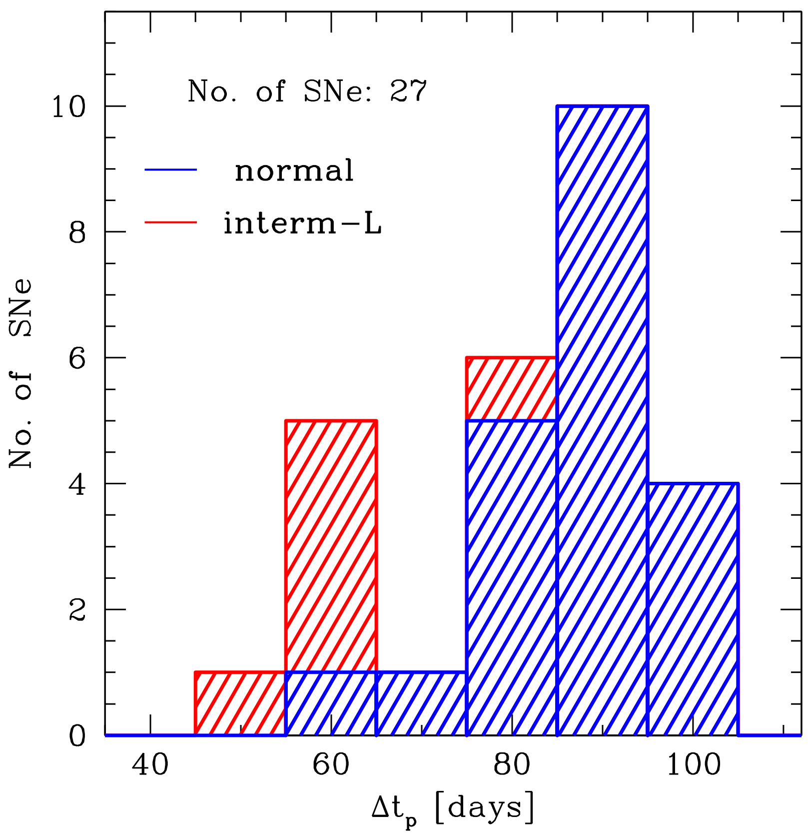


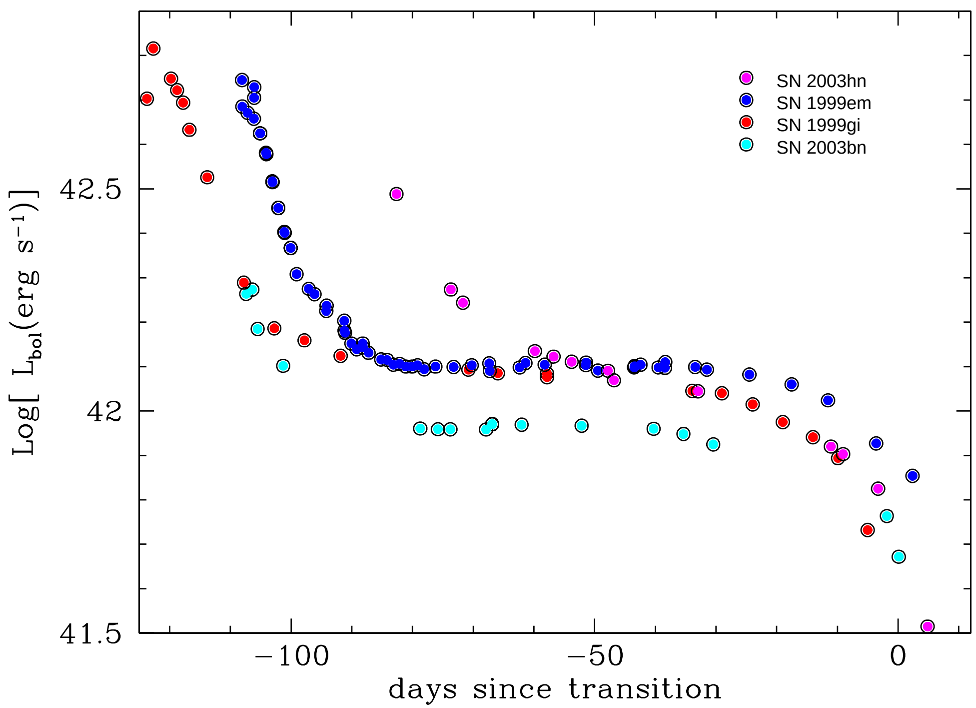
Summary

- We implemented a robust method to estimate BC from BVI photometry for SNe II-P with typical scatter of $\sim$0.1 mag
- We studied SN 1999em in detail obtaining a very good agreement with observations when extended mixing of ^{56}Ni is used
- We calculated a set of observable parameters (L_p, Δt_p, ΔL and $M_{\rm Ni}$) for our data sample and for a grid of hydrodynamical models:
  - Parameter distribution:
    - Bi-modal tendency of the slope during plateau
    - 1.15-dex range in plateau luminosities
    - $M_{\rm Ni} < 0.1 M_\odot$, except for SN 1992am with $M_{\rm Ni} > 0.26 M_\odot$
  - Dependence on physical quantities (E, R_0, M_0 and $M_{\rm Ni}$)
  - Correlations using models and observations
    - Models confirm the SCM relation
    - Lowest E and high M are not favored

Plateau Lengths

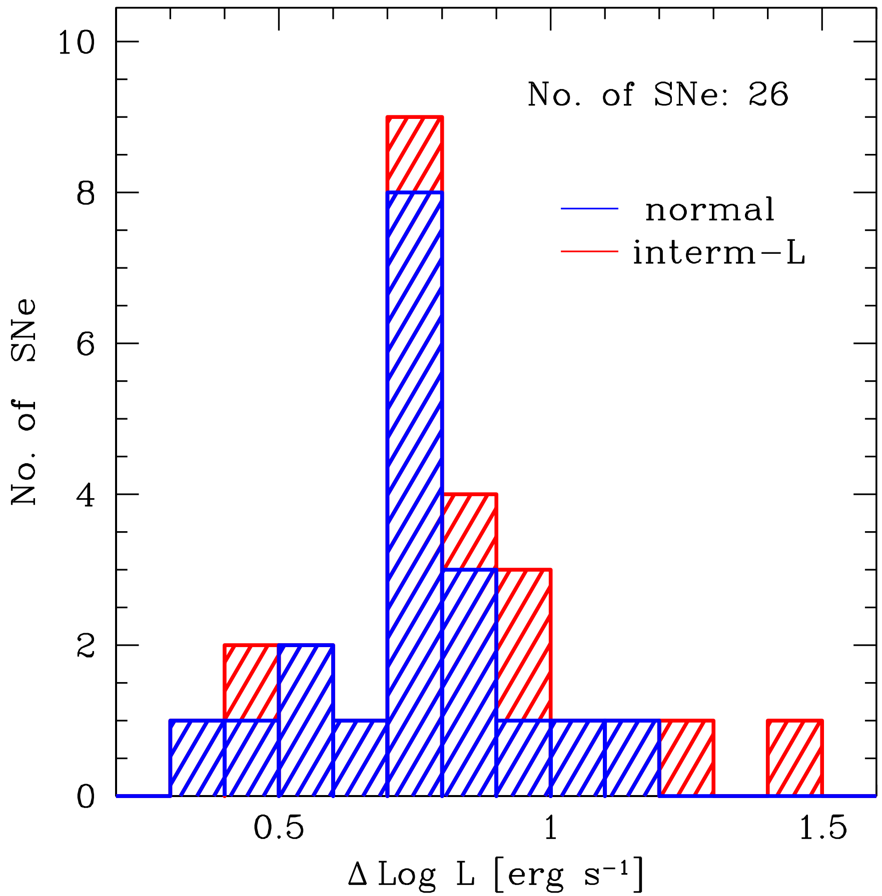
- Weighted average $\langle \Delta t_p \rangle = 90.47$ days
- Most SNe with $\langle \Delta t_p \rangle$ between 75 and 105 days
- Bi-modal trend in the distribution (secondary peak at $\sim$60 days)

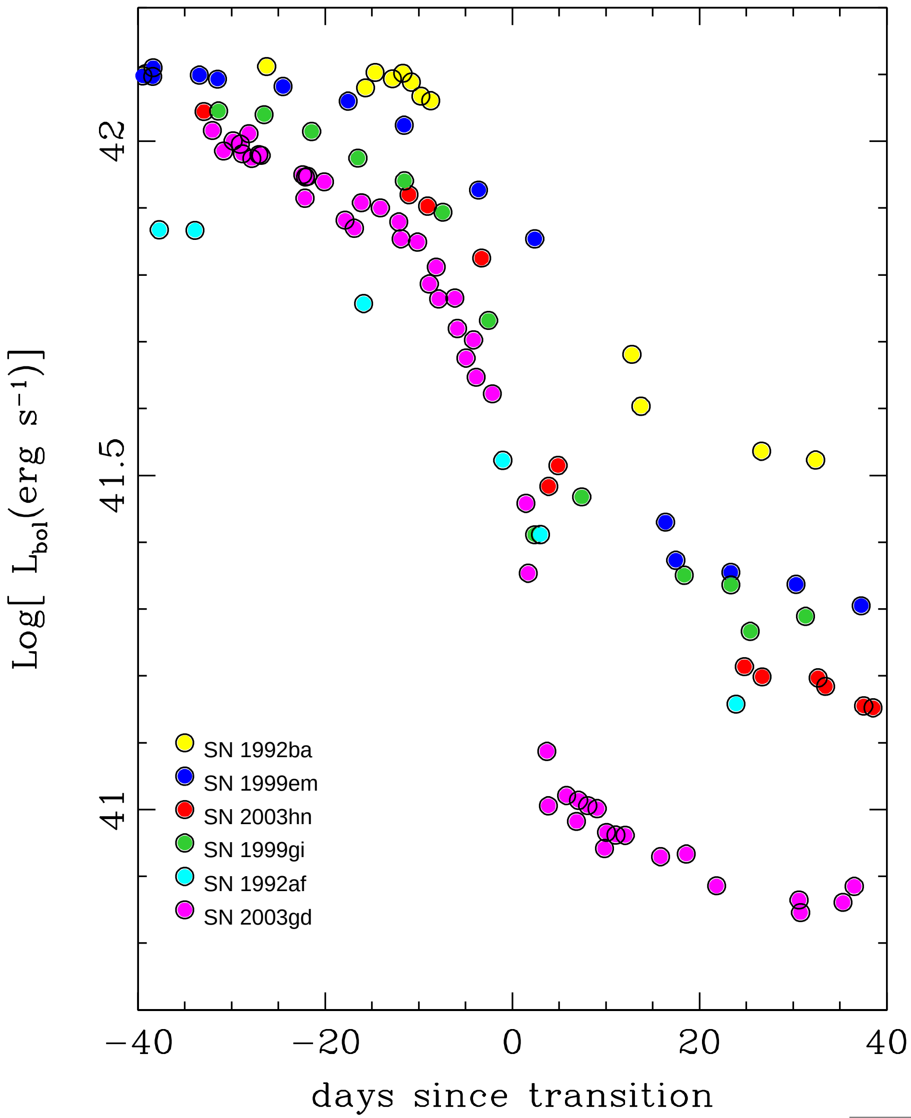




Luminosity drop: Δ log L

- Weighted average $\langle \Delta \log L \rangle = 0.783$ dex
- Range of $0.35–1.46$ dex in Δ log L

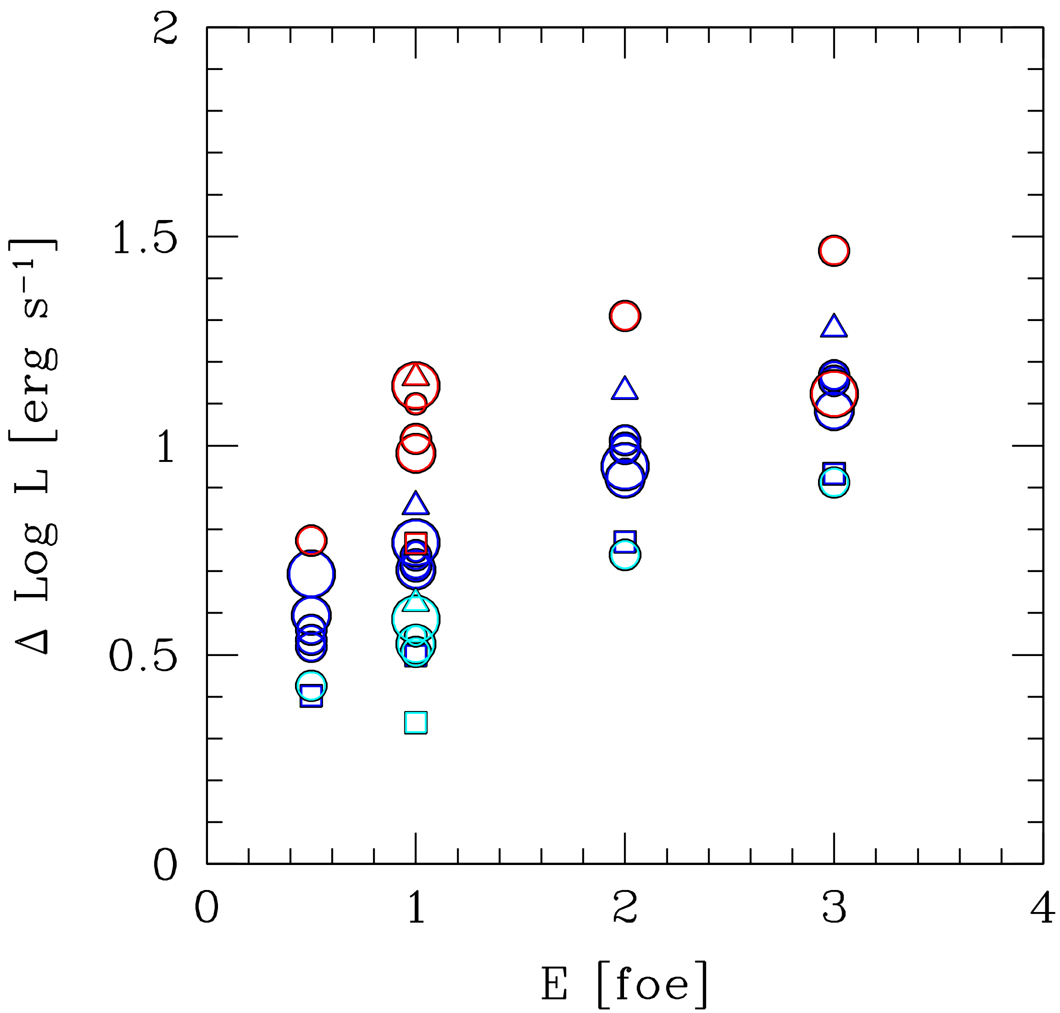




Model dependences

- Symbols: size proportional to M_0, shape indicates different R_0 and colors related with M_{Ni} (fixed mixing)

Luminosity drop

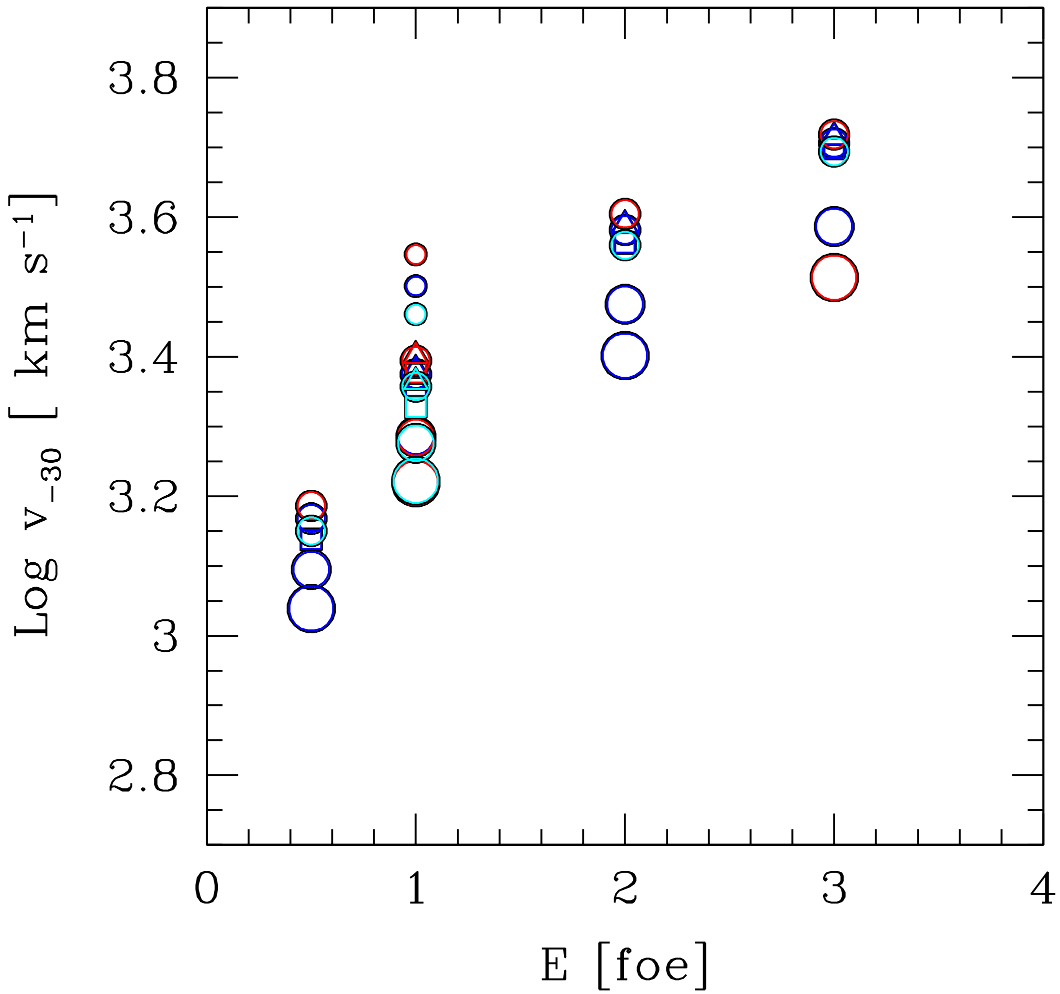


- Some dependence on explosion energy
- Strong correlation with $M_{\rm Ni}$
- Some dependence on R_0 but not on M_0

Model dependences

- Symbols: size proportional to M_0, shape indicates different R_0 and colors related with M_{Ni} (fixed mixing)

Expansion velocity



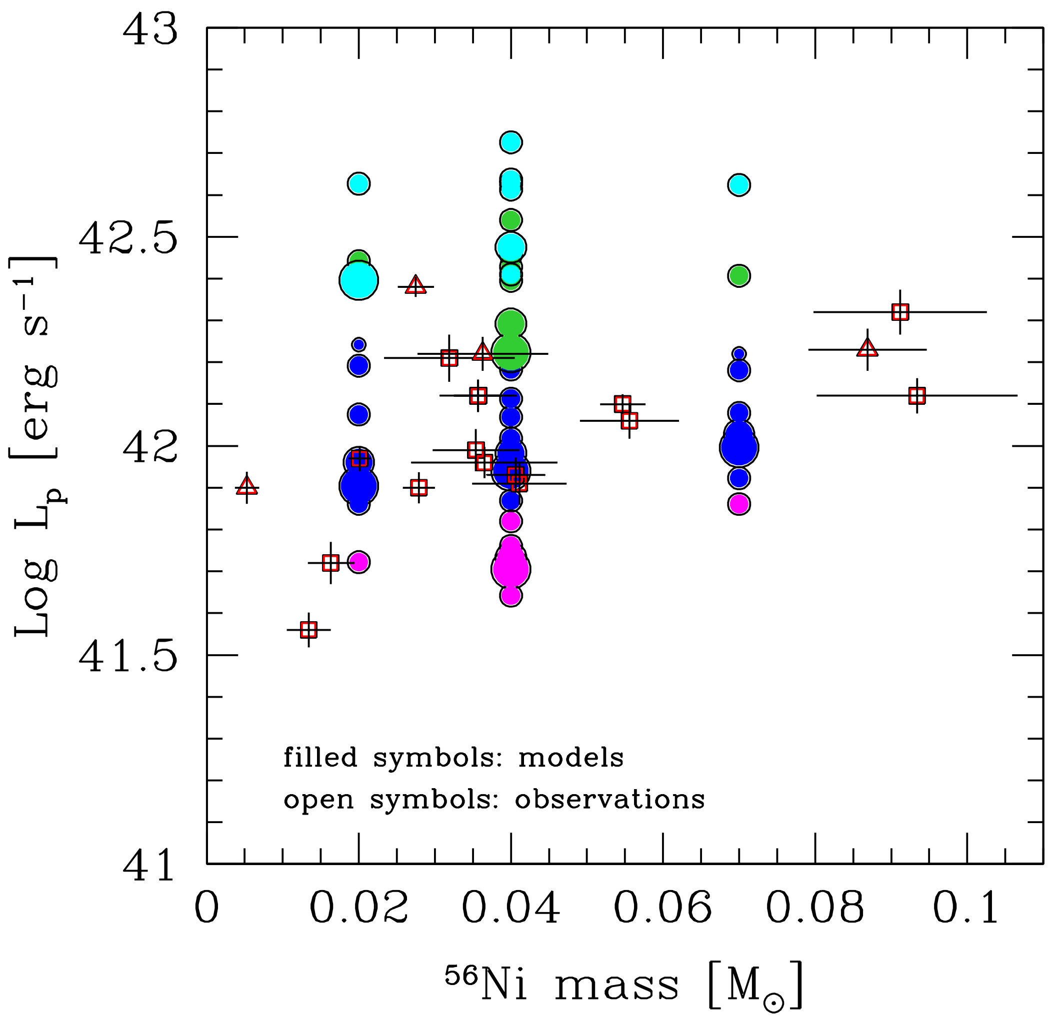
- Strong correlation with explosion energy
- M_0 is the main driver of the dispersion
- Slight dependence on $M_{\rm Ni}$ but not on R_0

Observed and Modeled Correlations

- Symbol Colors: different explosion energies (E)

- No correlation

- Ni mass affects tail luminosity but not the plateau



Comparison with STELLA Code

- STELLA code (Blinnikov et al. 1998):
  - implicit hydrodynamics + multi-group radiative transfer
  - includes the effect of the line opacities
- STELLA calculations by N. Tominaga