SUPERNOVAE
PhD Course 2013, SISSA

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III. Evolution of the ejecta

Physics of the expanding, shocked envelope

Physics of the expanding envelope: analytic model of the early evolution of the light curve (Arnett 1996)

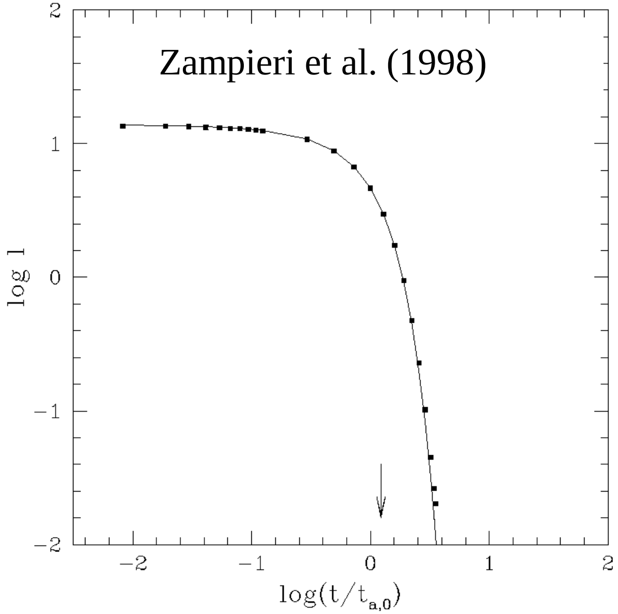
Energy conservation for the expanding SN envelope

$$d\varepsilon/dt + p\,d(1/\rho)/dt = Q - dL/dm$$

tdyn = R/V_0
tdiff = R^2/(lambda c)

Basic assumptions:
- homologous expansion: $R=V_0*t$
- uniform density ρ

Early evolution of the expanding envelope after shock breakout
- Massive, hot envelope, completely ionized and in LTE
- T decreases because of expansion and diffusion



Solution obtained by separation of variables (Q=0)

$$\mathbf{L=L_0\ exp(-t/t_{diff}-t^2/2t_{dyn}t_{diff})}$$

$$\mathbf{L_0=0.5\ \beta c\ (E_{expl}/M)R_0/\kappa}$$

- **L** initially constant (decrease in T compensated by increase in R and photon mean free path)
- For fixed $\mathbf{E_{expl}}$ less massive stars are brighter
- Large (tenous) stars brighter than small (dense) stars (suffer less adiabatic degradation of thermal energy)

Physics of the expanding envelope: different physical stages

Energy conservation for the expanding SN envelope

$$d\varepsilon/dt + p\,d(1/\rho)/dt = Q - dL/dm$$

<u>Basic assumptions</u>:
- homologous expansion: $R=V_0*t$
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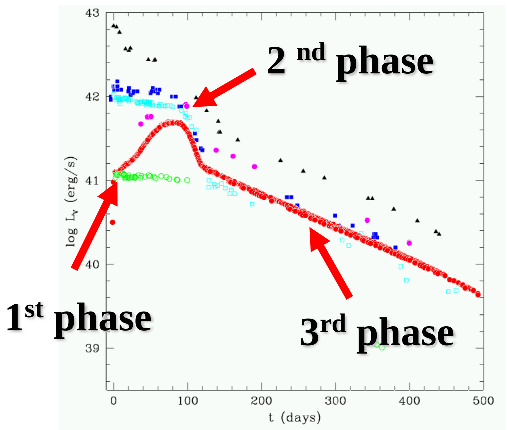


1st phase
- Envelope hot, completely ionized and in LTE
- T decreases because of expansion and diffusion

2nd phase
- Formation of a recombination front
- Envelope divided in 2 regions, below and above the wavefront

3rd phase
- Ejecta transparent to optical photons
- Only radioactive decay energy input

Physics of the expanding envelope: different physical stages

1st phase

$$T^4(t,r) = T_0^4 \left(\frac{R_0}{R}\right)^4 \psi(x)\phi(t)$$

$$L_{tot} = -(4\pi c a T_0^4)/(3\kappa\rho_0)[x^2 d\psi/dx]_{x=1} R_0 \phi(t)$$

2nd phase

$$T^4(t,r) = T_0^4 \left(\frac{R_0}{R}\right)^4 \psi(y)\phi(t)$$

$$\phi(t) = \frac{3}{4}\kappa\rho_0 R_0 \left(\frac{T_{eff}}{T_0}\right)^4 \left(-y^2\frac{d\psi}{dy}\right)^{-1}_{y=1} \left(\frac{R}{R_0}\right)^2 x_i$$

$$L = -(4\pi c a T_0^4)/(3\kappa\rho_0)[y^2 d\psi/dy]_{y=1} R_0 x_i \phi(t)$$

$$L_{r_i} = L + 4\pi r_i^2 v_i (a T_{eff}^4/2 + \rho Q_{ion})$$

$$L_{tot} = L_{r_i} + 4\pi\rho_0 R_0^3 X_{Ni} f(t) \int_{x_i}^1 x^2 \psi(x) dx$$

3rd phase

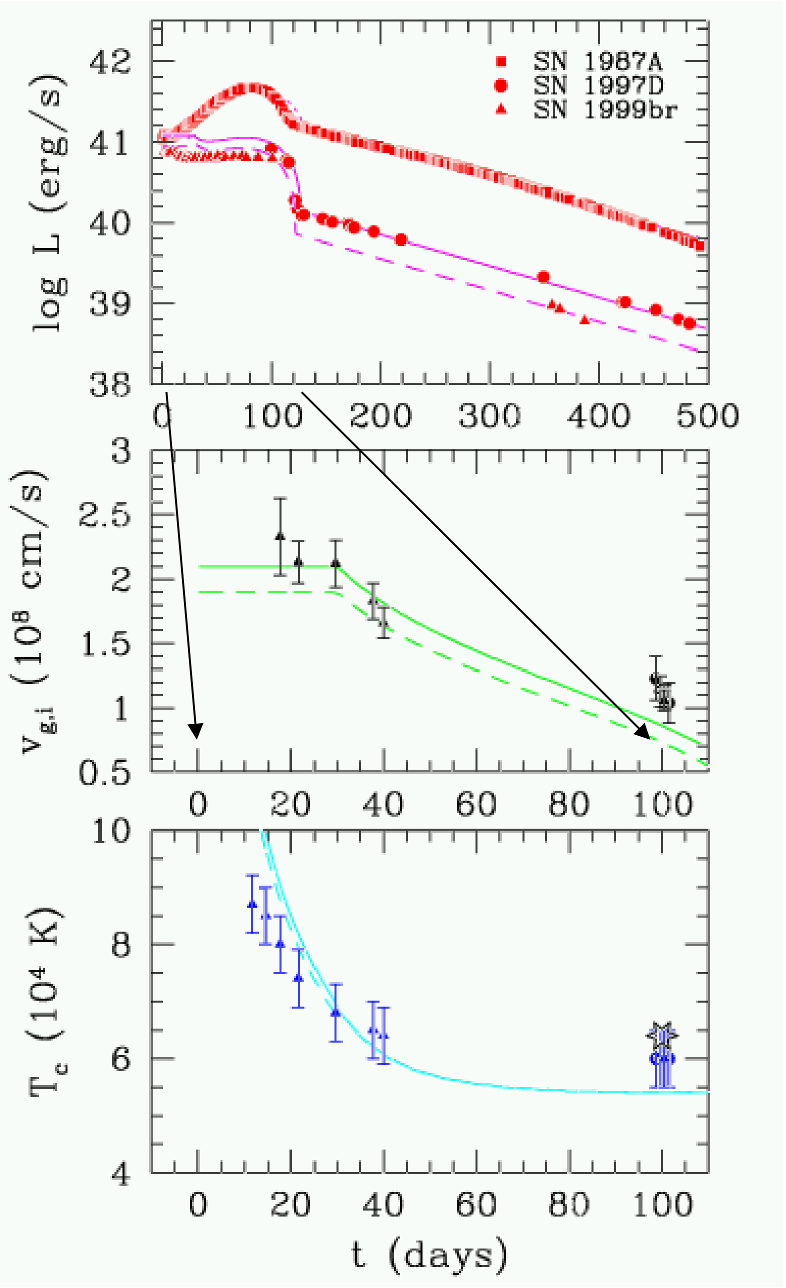
$$f(t) = [3.9\times 10^{10} e^{-t/\tau_{Ni}} + 7.2\times 10^9 \times (e^{-t/\tau_{Co}} - e^{-t/\tau_{Ni}})] \quad \mathrm{erg\ g^{-1}\ s^{-1}}$$

$$L_{tot} = 4\pi\rho_0 R_0^3 X_{Ni} f(t) \int_0^1 x^2 \psi(x) dx$$

L_{tot} = Mni f(t)
Mni = $4\pi\rho_0 R_0^3 \int x^2$ psi(x) dx

Assuming complete gamma-ray trapping, from the late time LC → Mni

$x=r/R$, $x_i=r_i/R$, $y=x/x_i$



Zampieri et al. (2003)

Physics of the expanding envelope:
Full radiation-hydrodynamics calculation

(Relativistic) radiation hydrodynamic equations of the expanding ejecta in spherically symmetry (Zampieri et al. 1996, 1998; Balberg et al. 2000; Pumo and Zampieri 2011)

LANL TOPS opacities and ionization fractions (Magee et al. 1995), extended at T< 5.8×10^3 K) using the tables of Alexander & Ferguson (1994)

Q → Energy (per unit mass and time) released by the decays of all the radioactive isotopes. A fraction $(1-\exp(-\tau_\gamma))$ of gamma rays is absorbed locally and the rest escapes. $f^+(t)$ → e^+ channel

Other radiation-hydro calculations by e.g. Blinnikov et al. 1998; Iwamoto et al. 2000; Chieffi et al. 2003; Young 2004; Kasen & Woosley 2009; Bersten et al. 2011

$$\epsilon_{,t} + a k_P (B - w_0) + p \left(\frac{1}{\rho}\right)_{,t} = Q \quad \text{energy eq.,} \qquad (1)$$

$$(w_0)_{,t} - a k_P \rho (B - w_0) + w_0 \left[\frac{4}{3}\left(\frac{b_{,t}}{b} + 2\frac{r_{,t}}{r}\right) + f\left(\frac{b_{,t}}{b} - \frac{r_{,t}}{r}\right)\right] + \frac{1}{abr^2}(w_1 a^2 r^2)_{,\mu} = 0 \quad \text{zero-th moment eq.,} \qquad (2)$$

$$(w_1)_{,t} + a k_R \rho w_1 + 2w_1\left(\frac{b_{,t}}{b} + \frac{r_{,t}}{r}\right) + a\left[\frac{1}{3a^4 b}(w_0 a^4)_{,\mu} + \frac{1}{3br^3}(f w_0 a r^3)_{,\mu}\right] = 0 \quad \text{first moment eq.,} \qquad (3)$$

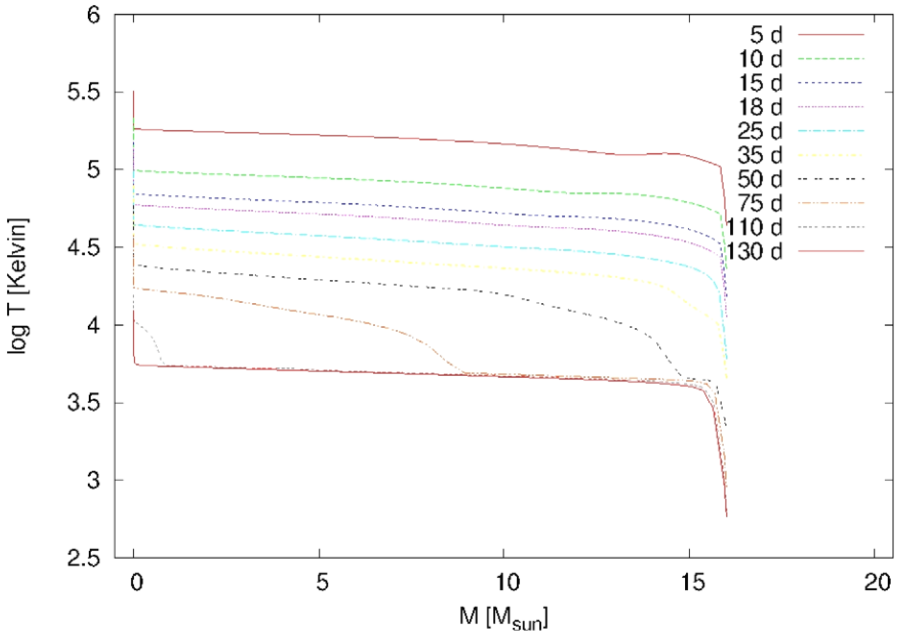
$$Q = \sum X \psi \left[f(t)\,(1-\exp(-\tau_\gamma)) + f^+(t)\right]$$

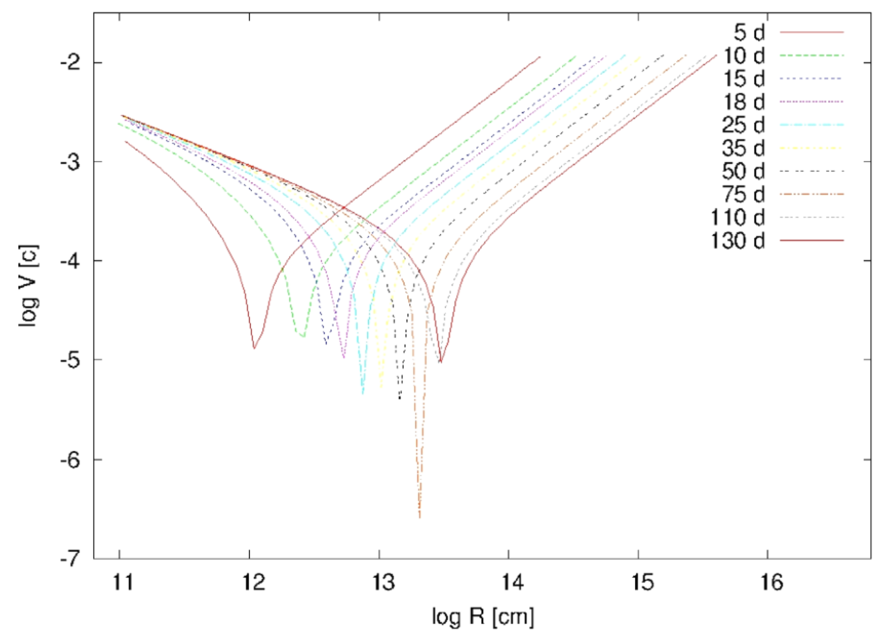
$$f(t) = \varepsilon_\gamma \exp(-t/\tau) \qquad f^+(t) = \varepsilon_{e+}$$

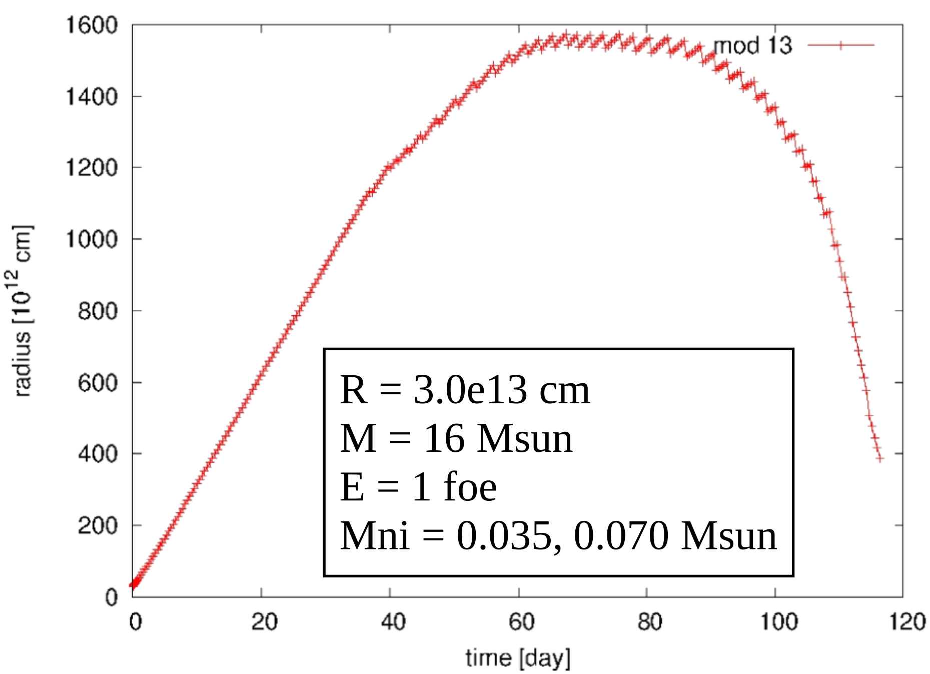
Isotope	ε_γ [erg g^{-1} s^{-1}]	ε_{e+} [erg g^{-1}s^{-1}]	τ [days]
^{56}Ni	3.90×10^{10}	0	8.8
^{56}Co	6.40×10^{9}	2.24×10^{8}	111.3
^{57}Co	6.81×10^{8}	0	391.0
^{44}Ti	2.06×10^{8}	6.54×10^{7}	3.28×10^{4}

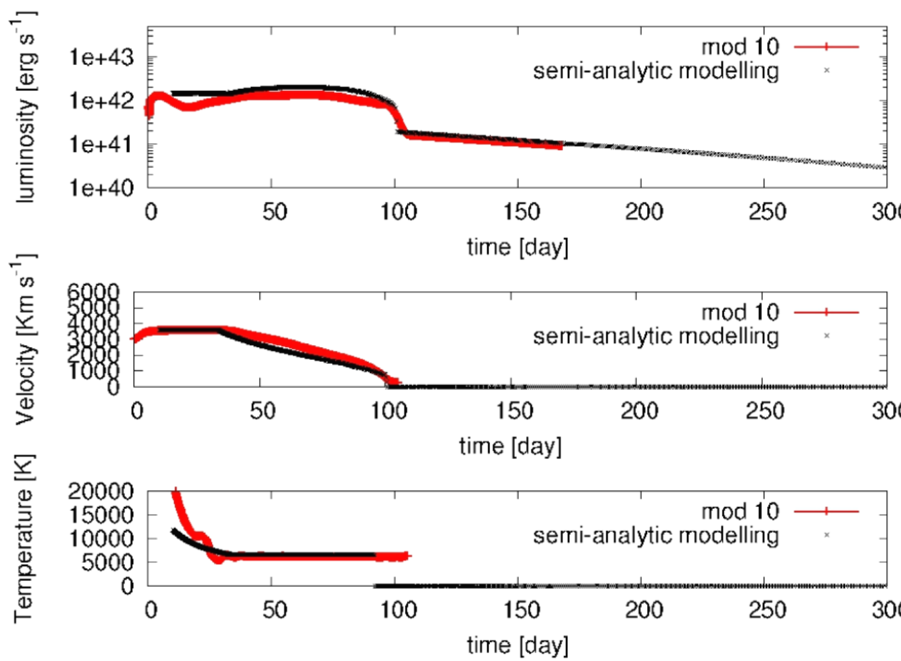
NOTE. — Data taken from Woosley, Pinto, & Hartmann (1989) and Shigeyama & Nomoto (1990).

Type II SN light curves and evolution of photospheric velocity and temperature

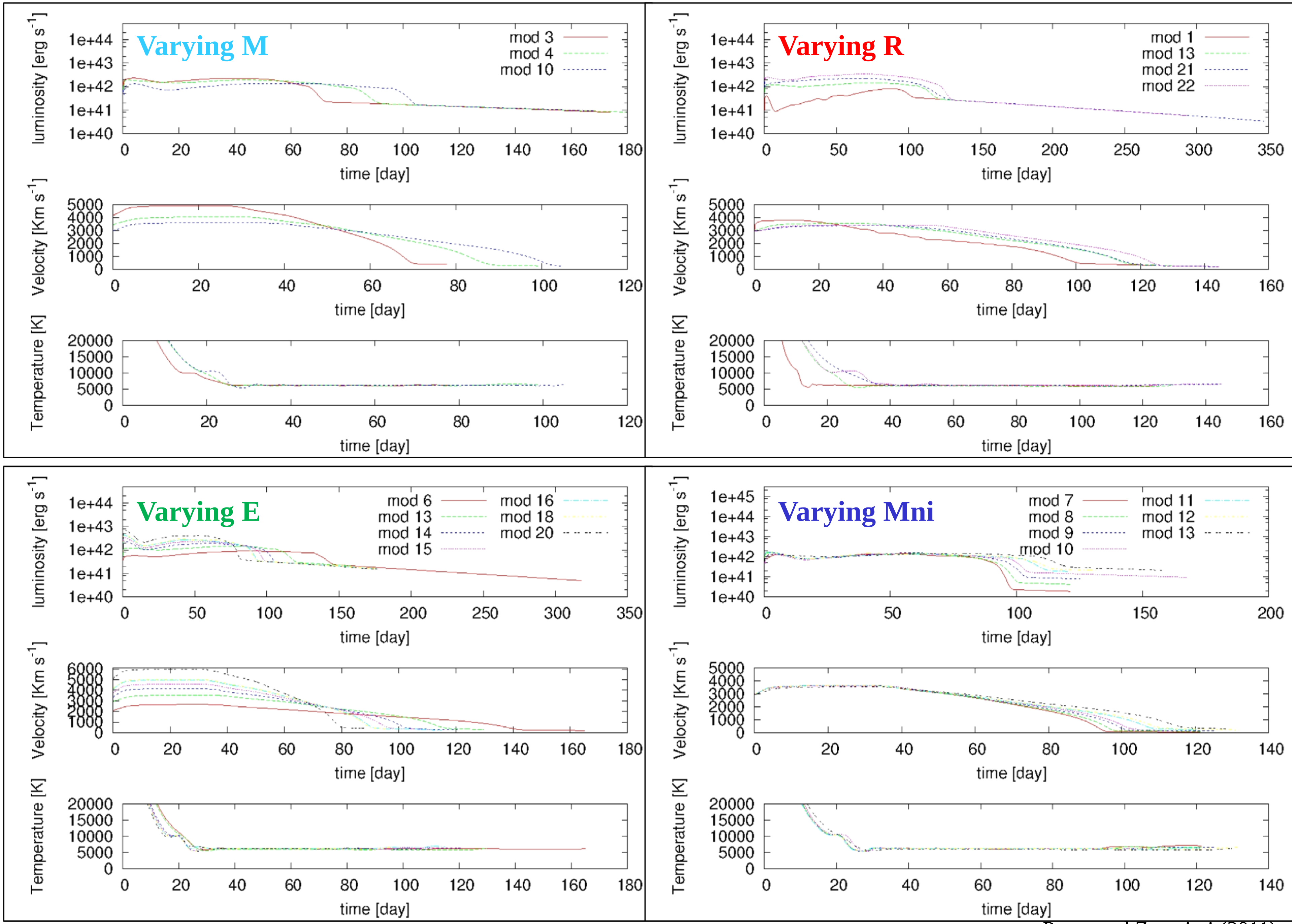








Pumo and Zampieri (2011)



Pumo and Zampieri (2011)

Type I SN light curves

Physics of the expanding envelope: radioactive heating and small initial radius

Energy conservation for the expanding SN envelope

$$d\varepsilon/dt + p\,d(1/\rho)/dt = Q - dL/dm$$

<u>Basic assumptions</u>:

- homologous expansion: $R=V_0*t$
- uniform density ρ
- small initial radius: $R_0 \rightarrow 0$

Solution obtained by separation of variables (Arnett 1982)

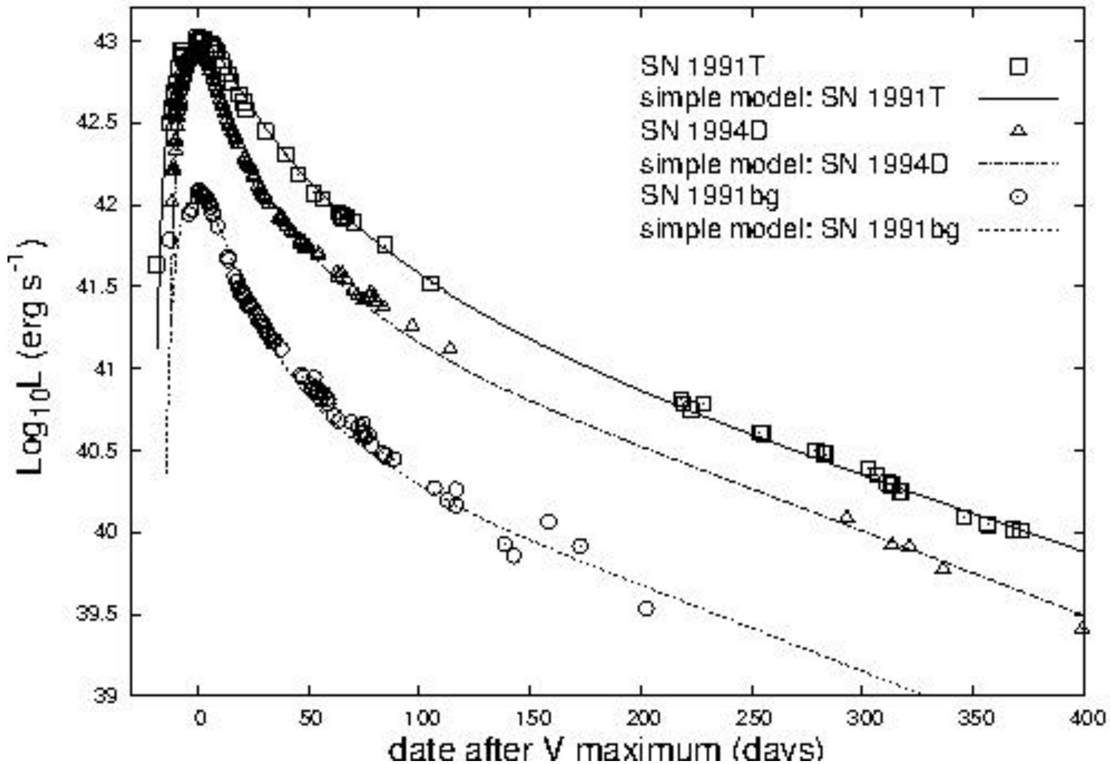
$$Q = \psi(r)\, f(t)$$

$$\mathbf{L} = \varepsilon_\gamma\, \boldsymbol{Mni\ Lambda(t,y)}$$

$$\boldsymbol{dL/dt=0 \rightarrow Lmax} = \varepsilon_\gamma\, \boldsymbol{Mni\ exp(-t_{max}/\tau_{ni})}$$

- At maximum light the diffusion luminosity equals the radioactive energy input
- Assuming a similar rise time to maximum, ***Lmax*** depends mostly on the amount of Ni in the ejecta
- Can be used to estimate ***Mni***. Assuming *tmax = 19* days (Stritzinger et al. 2005):

Lmax = 2.0e43 (Mni/Msun) erg/s

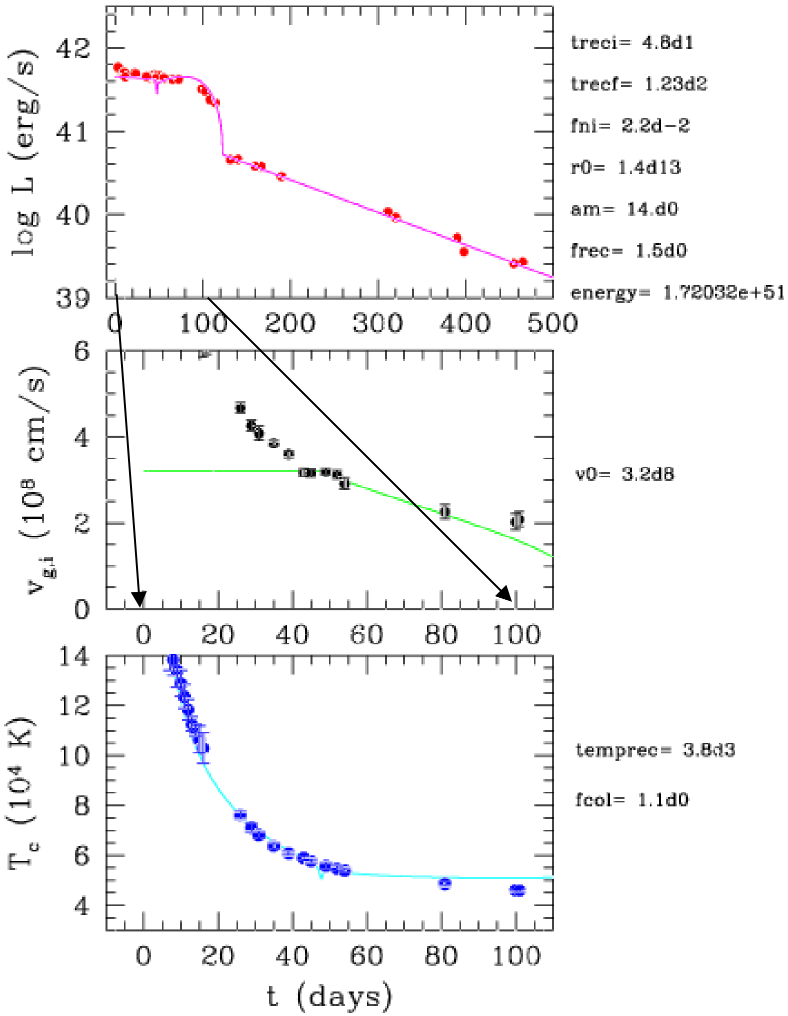


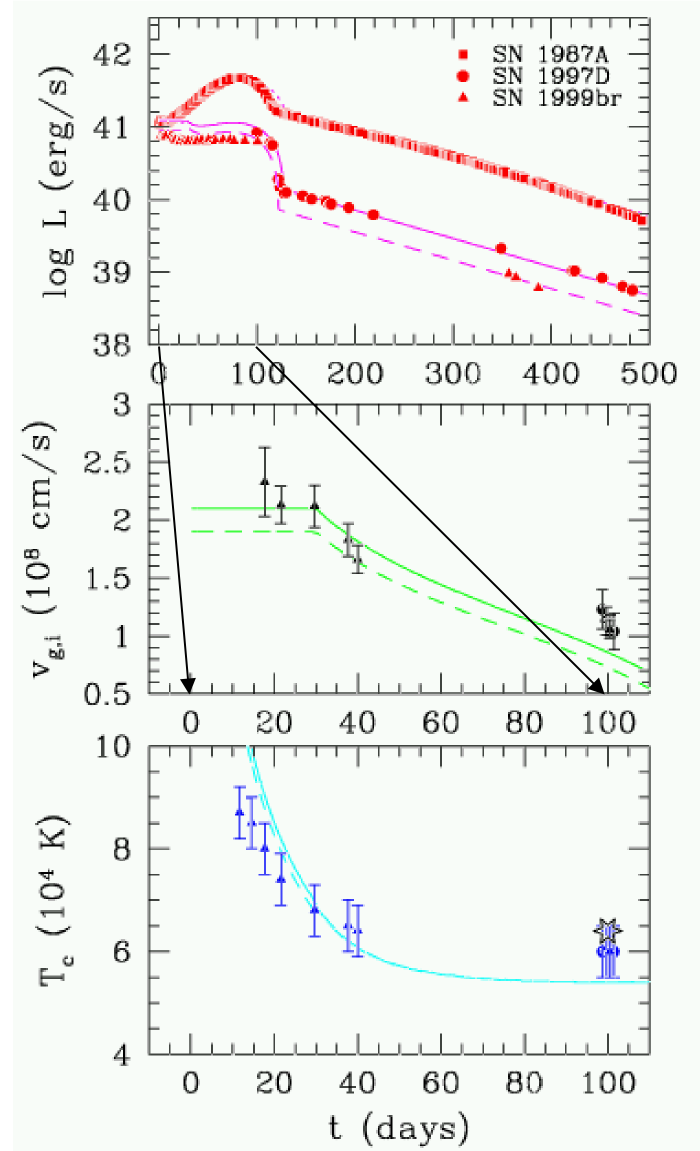
Valenti et al. (2008)

Light curve fitting and ejecta parameters estimation

Simultaneous 'fit' of

- UBVRI luminosity
- Velocity of metal (Sc II) lines (velocity of the gas at the wavefront/photosphere)
- Continuum temperature (Planckian fit)





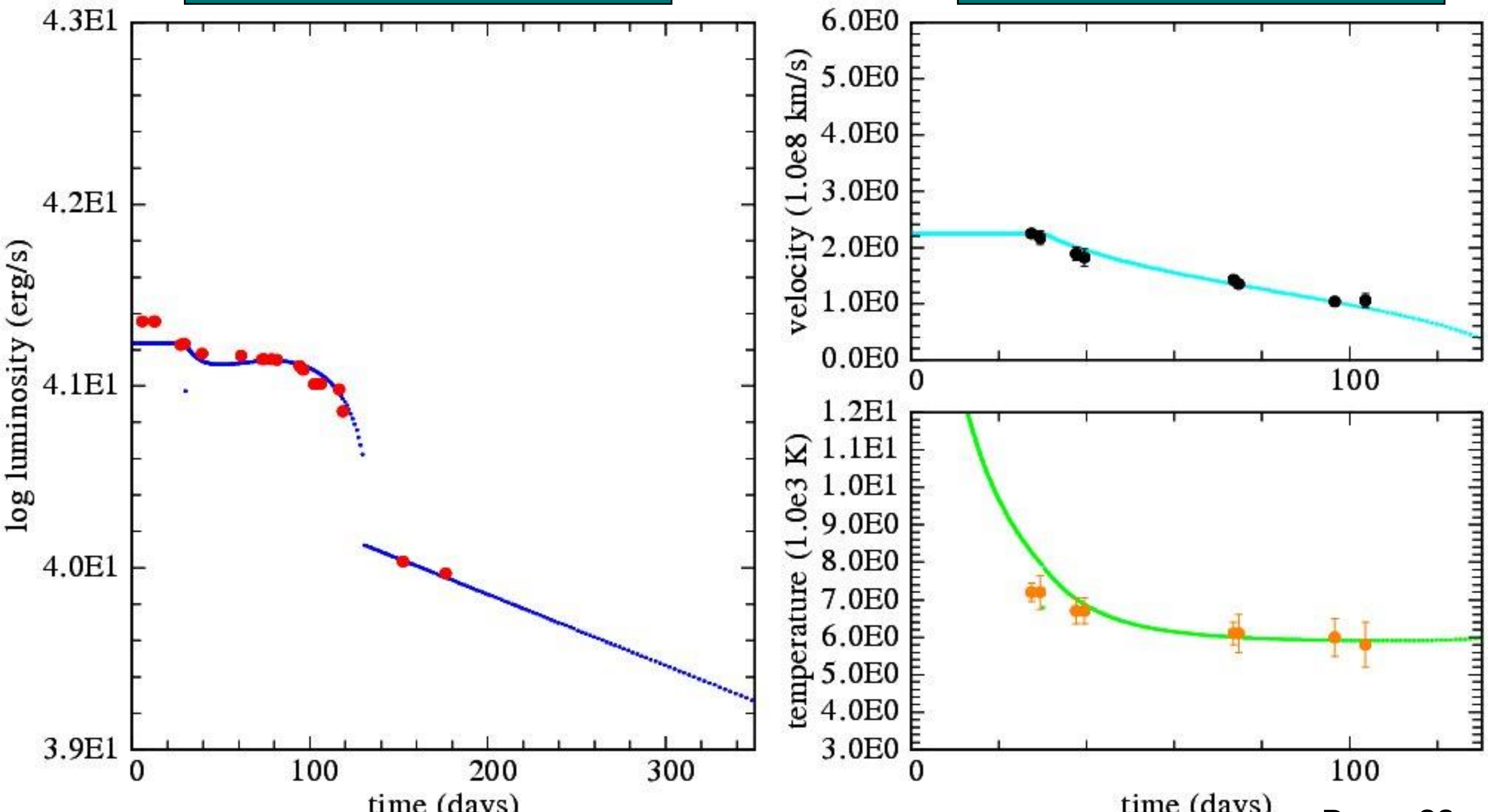
Zampieri et al. (2003)

Modelling the light curve, temperature and velocity: SN 2003Z

$R_0 = (\mathbf{1.1}^{+0.2}_{-0.2}) \times 10^{13}$ cm
$M = \mathbf{22}^{+2}_{-2}\, M_\odot$
$V_0 = \mathbf{2200}^{+300}_{-300}$ km/s

SN 2003z

E=**1.3** foe
$t_{plateau}$ = **130** days
M_{Ni} = **0.006** $M_\odot$



Modeling SNe

More accurate modelling of the SN ejecta involves:

1) 2D and 3D hydrodynamic calculations (e.g. Maeda et al. 2002)

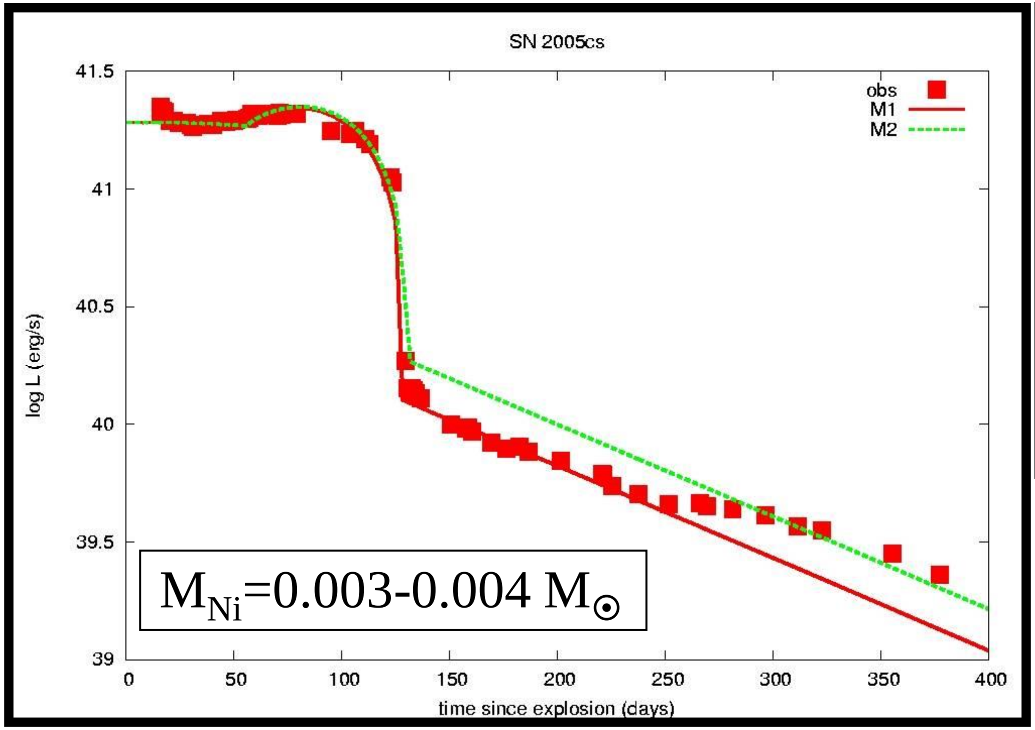
2) Realistic initial conditions (e.g. Woosley and Weaver 1995; Chieffi and Limongi 2004; Limongi and Chieffi 2010)

3) Frequency-dependent radiative transfer and spectral synthesis calculations, with detailed treatment of line blanketing and departures from LTE (e.g. Stehle et al. 2005; Dessart and Hillier 2011, 2012)

4) Joining all of the above

Faint core-collapse SNe, progenitor detections and Ni yields

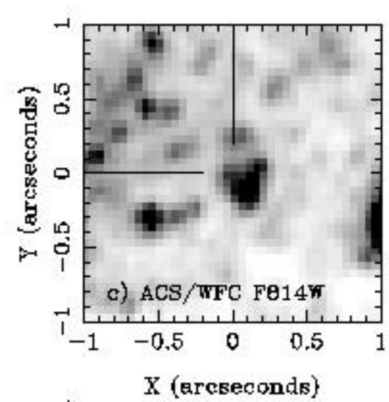
SN 2005cs: a faint core-collapse SN with progenitor detection



R_0 Initial radius of the ejecta	V_0 Outermost ejecta velocity	M Ejected mass
5-7x10^{12} cm	1500-1700 km/s	8-14 $M_\odot$

Pastorello et al. (2005)

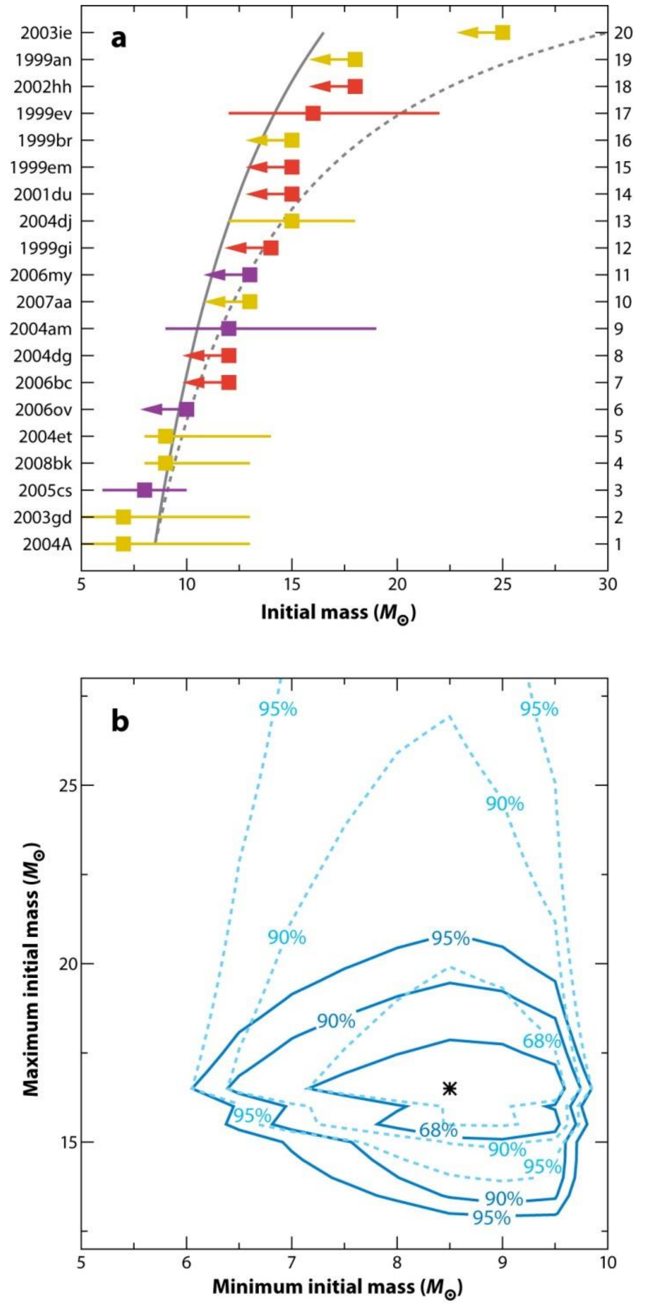
Detection of progenitor on HST pre-explosion images (Maund et al. 2005; Smartt et al. 2008):
M_*= 6-12 $M_\odot$



Maund et al. (2005)

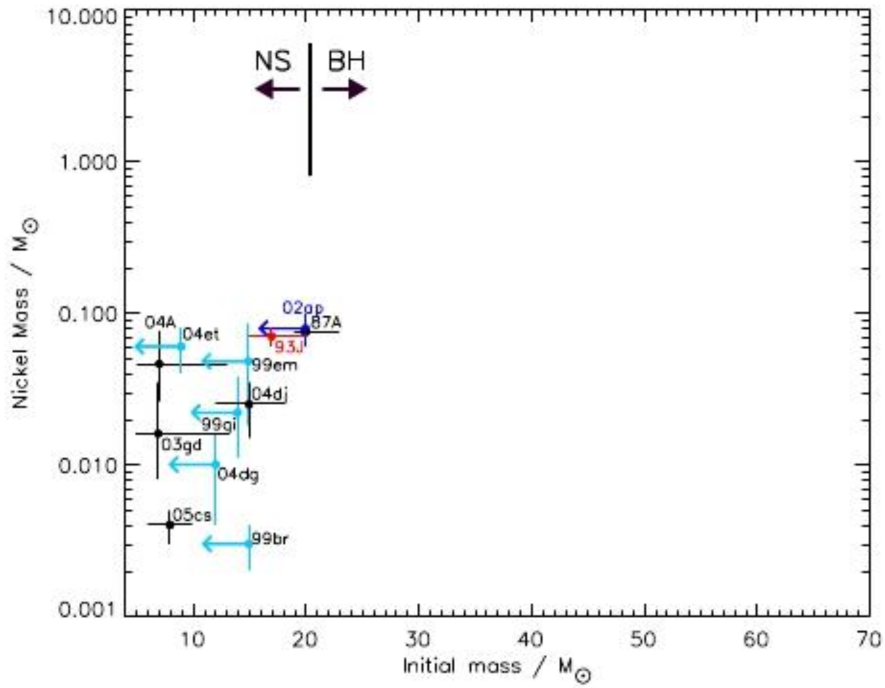
Progenitor detections and Type II SNe

- A 10.5 yr, volume limited search for SN progenitors (Smartt et al. 2008, 2009ab)
- Most progenitors are red supergiants and have *M = 7-20 Msun*
- What is the fate of progenitors with *M > 20 Msun?*



Smartt SJ. 2009.
Annu. Rev. Astron. Astrophys. 47:63–106

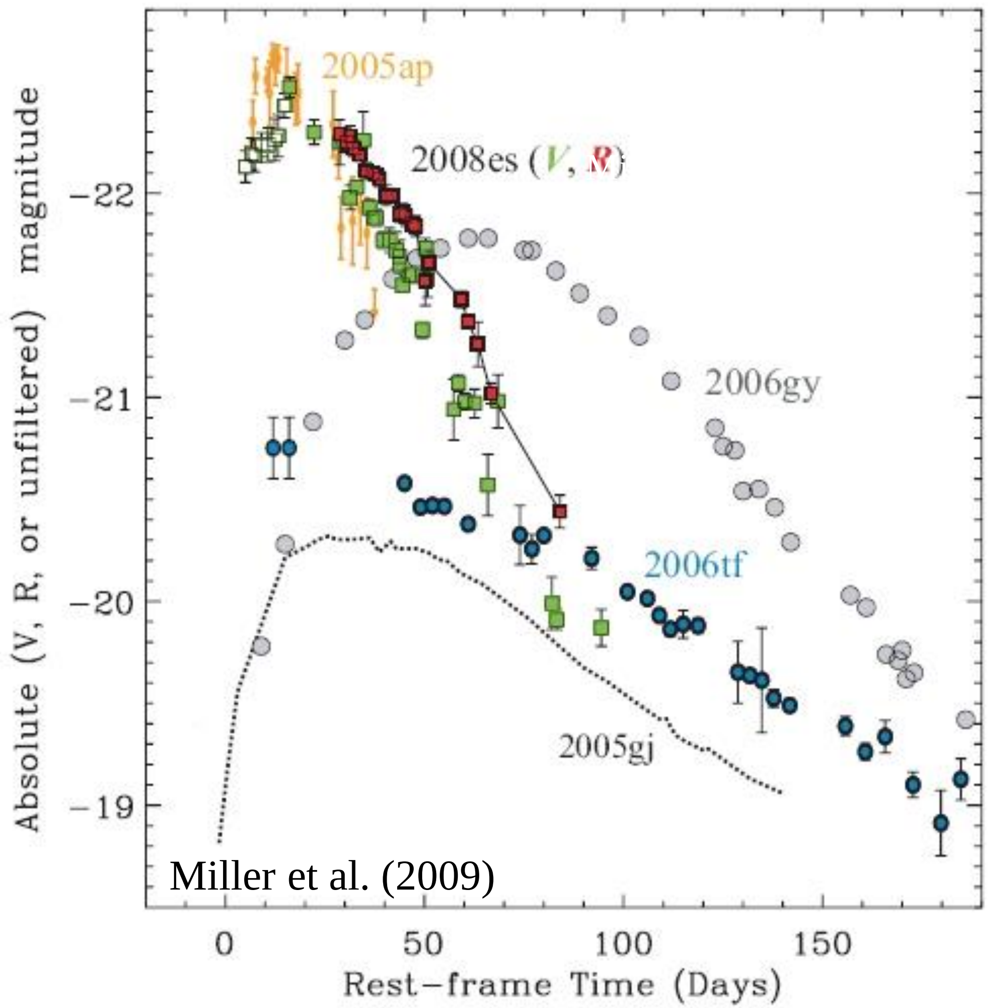
Progenitor detections and Type II SNe: Ni yields



Smartt (2009)

Ejecta-Circumstellar interaction/collision and very luminous CC SNe

Exceptionally luminous Type II SNe



Wide-field optical imaging surveys with increasing depth and time coverage (e.g. Bramich et al. 2008) are unveiling a variety of transients

The Texas SN search (Quimby 2006) uncovered the five most luminous SNe to date:

SN 2005ap (Quimby et al 2007)
SN 2008am (Yuan et al. 2008)
SN 2006gy (Ofek et al. 2007; Simth et al. 2007, 2008b)
SN 2006tf (Simth et al. 2008a)
SN 2008es (Miller et al. 2009)

Exceptionally luminous events: explosion of the most massive stars?

- **Opaque, shocked-shell model** (Smith & McCray 2007; Smith et al. 2008):

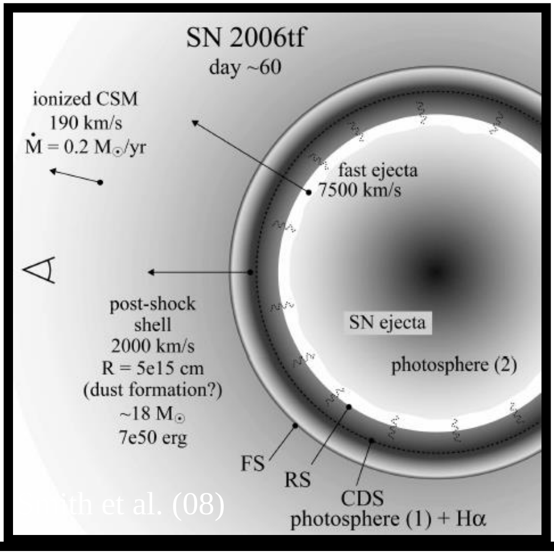
 * Conversion of kinetic energy of the ejecta into thermal energy to be radiated with little adiabatic loss ($t_{diff} \sim t_{exp}$)

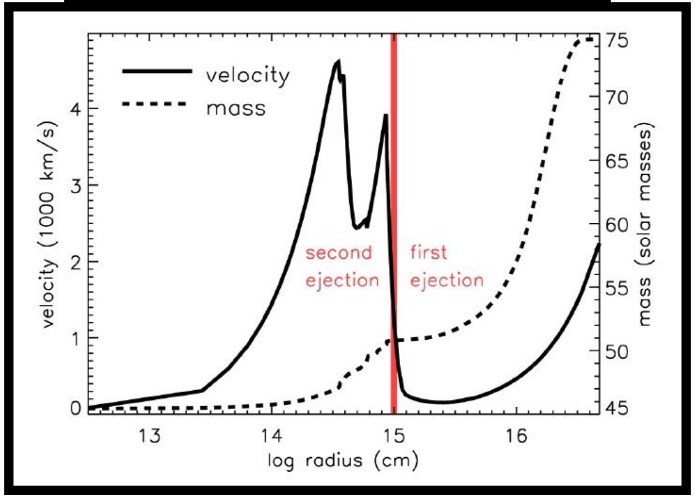
 * Ejecta imping on a massive ($\sim 10\ M_\odot$) shell at large radius produced by the star ~10 years before explosion (mass loss ~1 $M_\odot$/year)

- **Pulsational pair instability SN model** (Woosley et al. 2007) for stars with main sequence mass 95-130 $M_\odot$:

 * Collision of two shells launched when the core becomes thermally unstable against the creation of electron-positron pairs

Smith et al. (2008)





Woosley et al. (2007)

Exceptionally luminous events: explosion of the most massive stars?

- A different view of 2006gy: energetic SN impinging on massive clumps (Agnoletto et al. 2006)
  - *CSM distributed in massive clumps at large radius → the SN is not completely hidden*
  - CC-SN *from a compact progenitor*
  - Impact of ejecta on clumps triggers another ‘explosion’