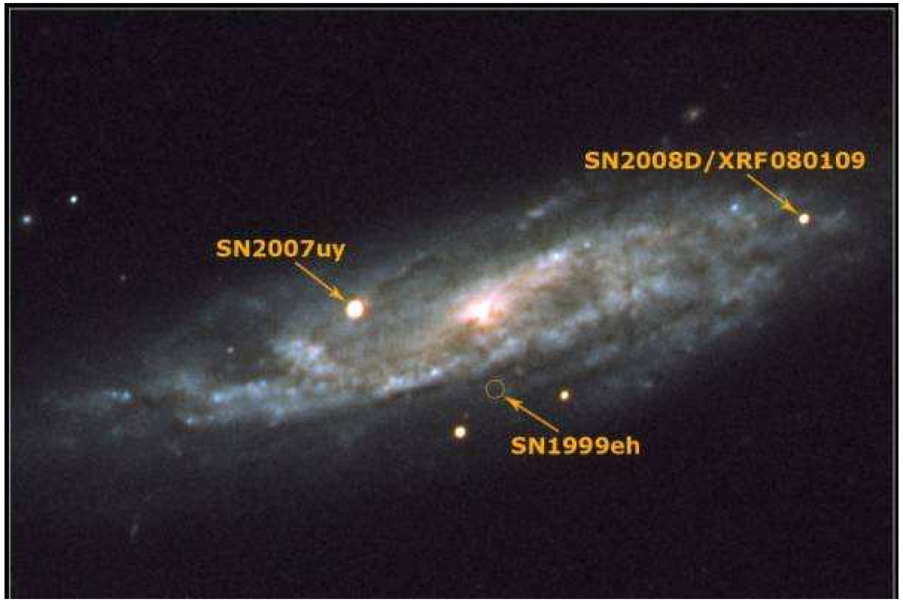
Hydrodynamical Models of Core-Collapse Supernovae

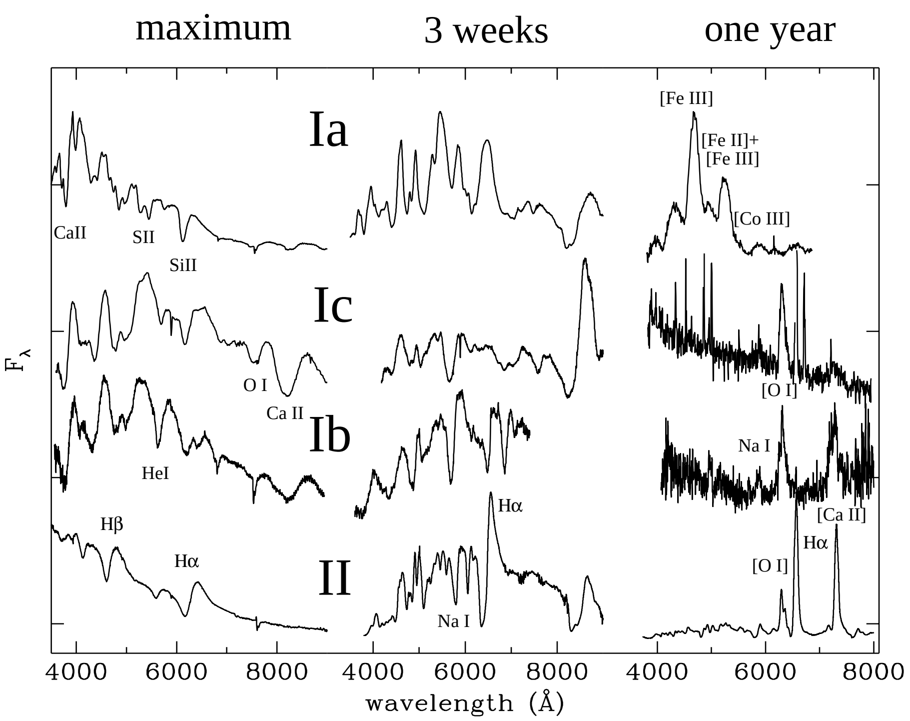
Melina Cecilia Bersten

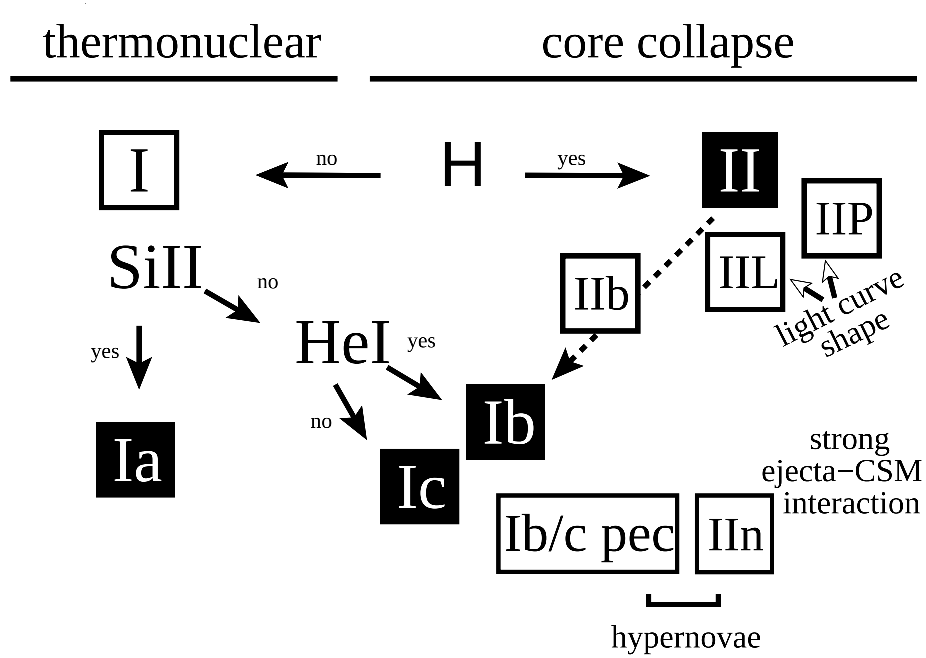


Credit: NASA/Phillip Newman

Supernova diversity

- Final stages of stellar evolution
- Type IIb-Ib-Ic: Stripped envelope SNe — WR pre-SN structures
- Broad line Ic ($v \sim 30000$ km s^{-1}) connected to LGRBs
- Which type of progenitor correspond to each subtype of CCSNe? Single or binary scenario?

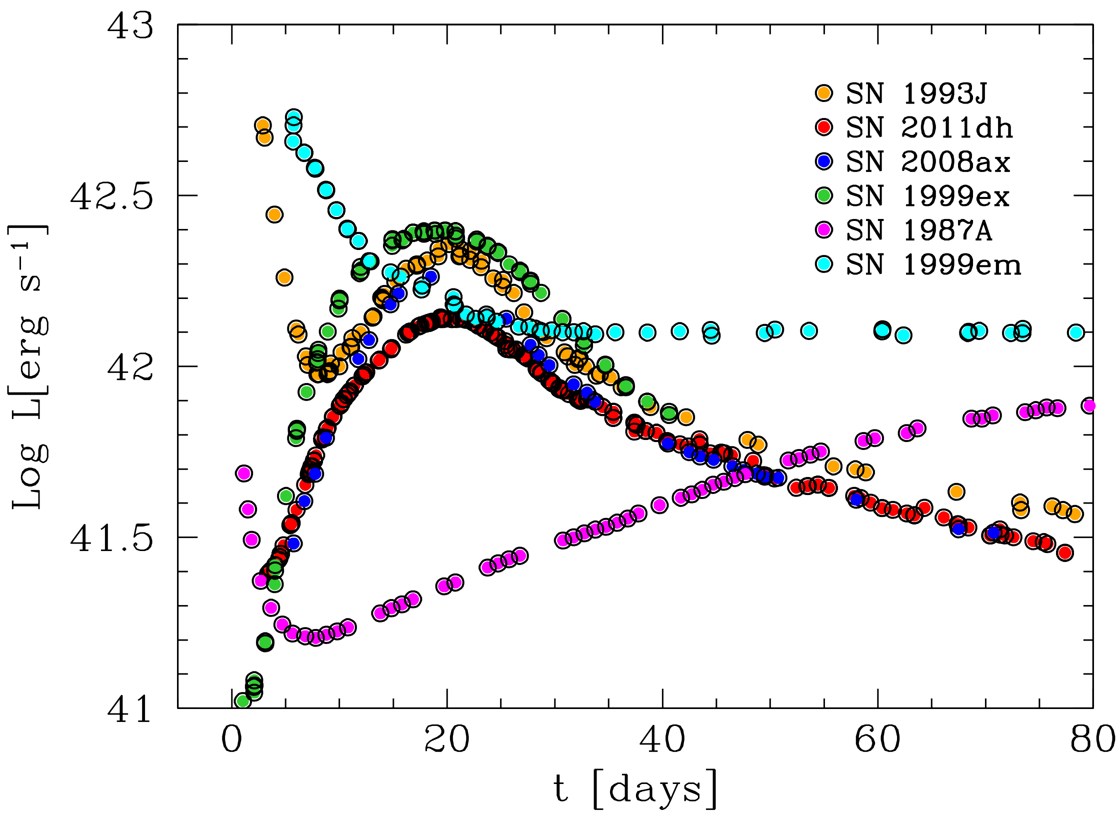




Turatto (2003)

Progenitor info

- Pre-explosion images
- Environmental & metallicity studies
- SN rates
- Mass-loss rates from radio & X-rays
- Hydrodynamic modeling: light curve (LC) + expansion velocity



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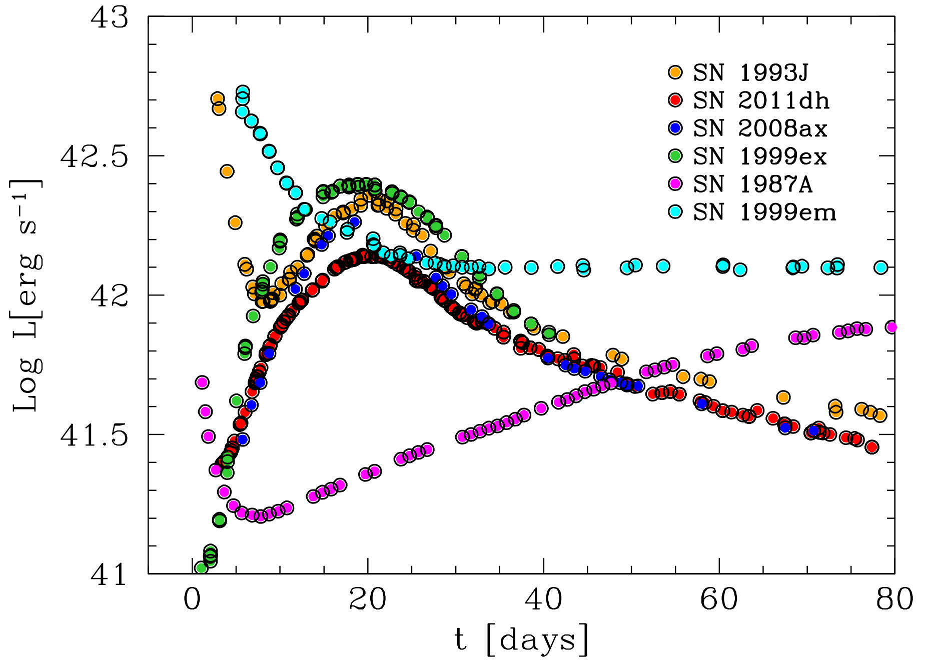


Morphology of the LCs related to

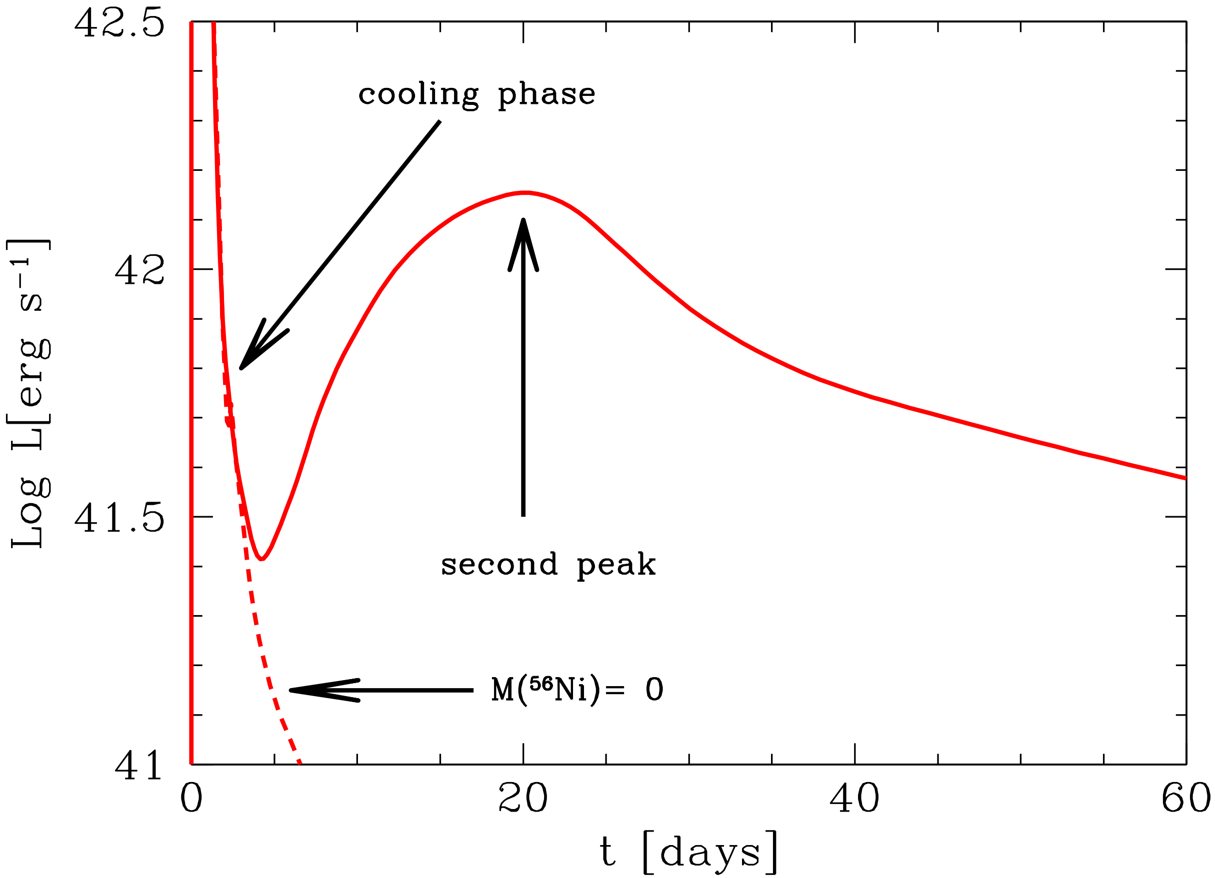
$M_{\rm ej}$, R , $E_{\rm exp}$ and $M_{\rm Ni}$

Hydrodynamical model

- One-dimensional Lagrangian code with flux-limited radiation diffusion and gray transfer for gamma-rays (Bersten et al 2011)
- Pre-SN model: Wolf-Rayet stars with different He core mass from single stellar evolutionary calculations (Nomoto et al)
  - SNe Ib $\Longrightarrow$ He star
  - SNe IIb $\Longrightarrow$ He star + thin H envelope ($M \lesssim 0.1 M_\odot$)

Light curve of stripped-envelope SNe

- Cooling phase with strong dependence on progenitor radius
- Second peak powered by radioactive decay
  Depends on $E_{\rm exp}$, $M_{\rm ej}$, $M_{\rm Ni}$ and $^{56}{\rm Ni}$ distribution



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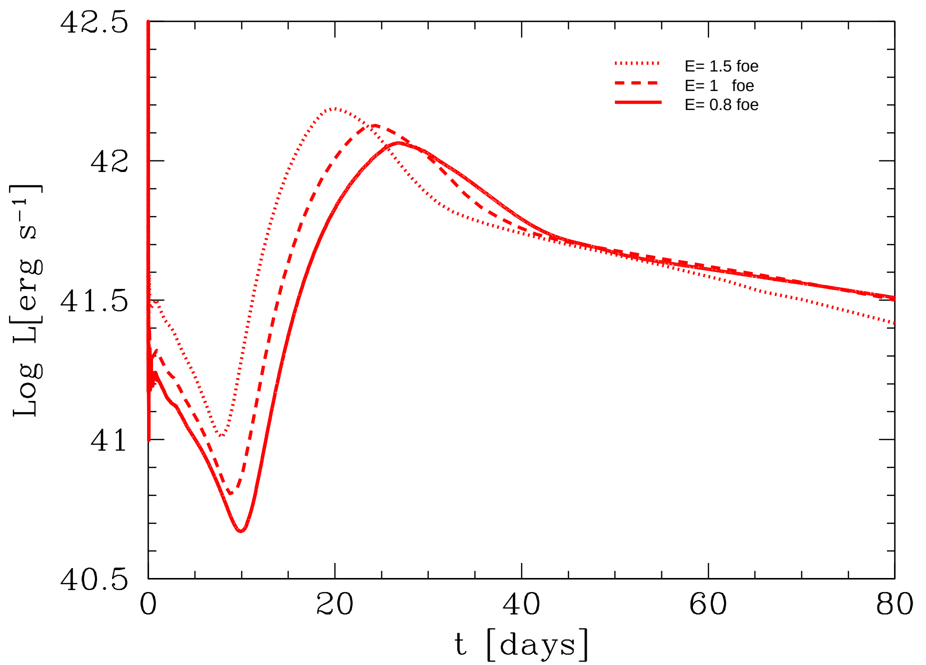

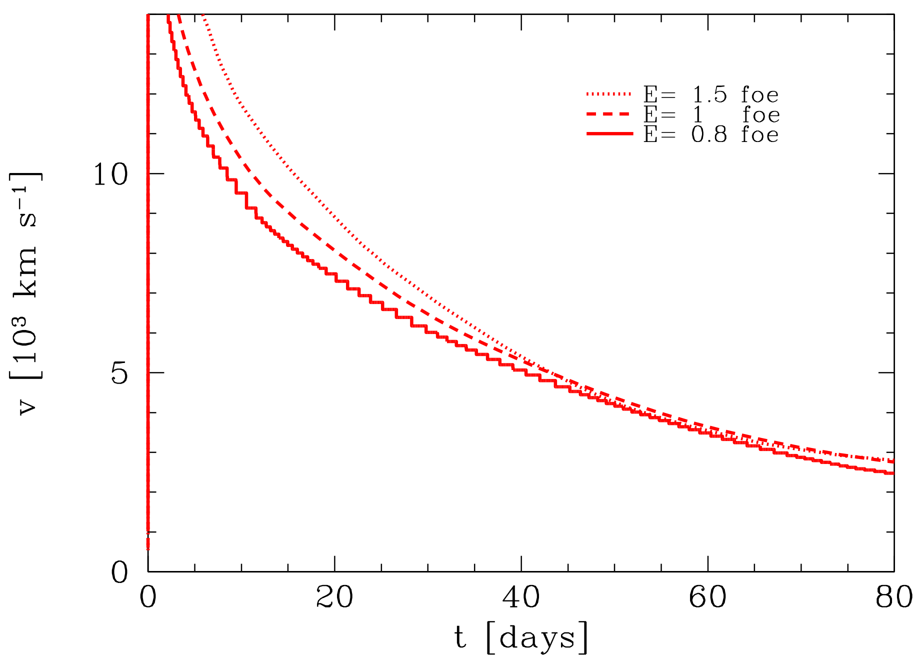

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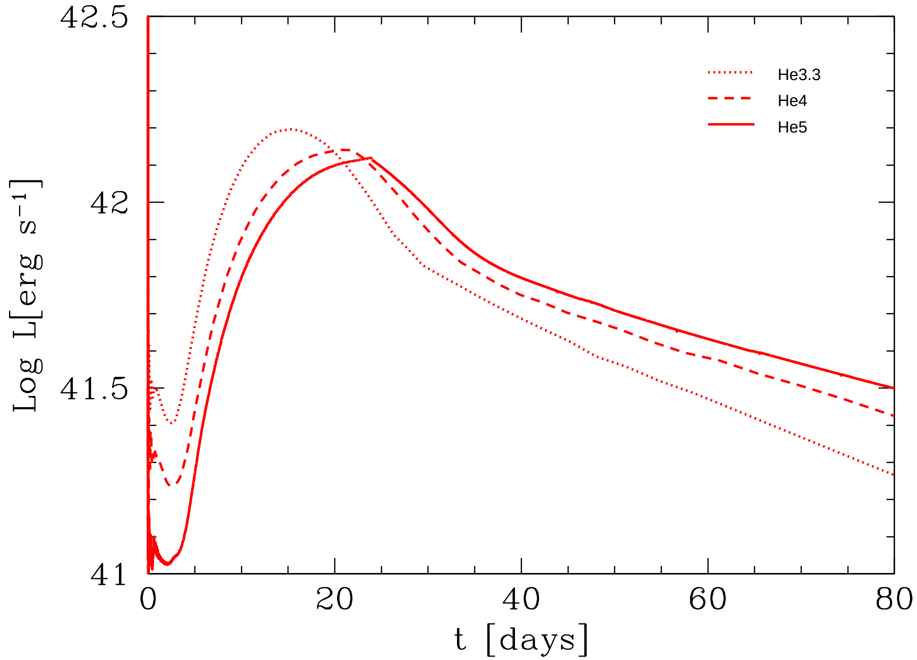

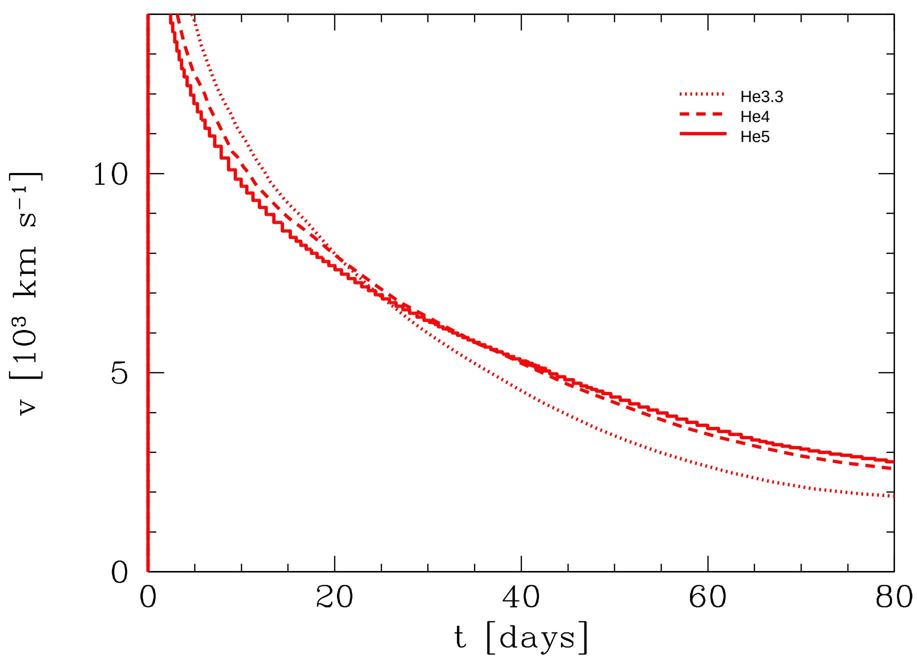

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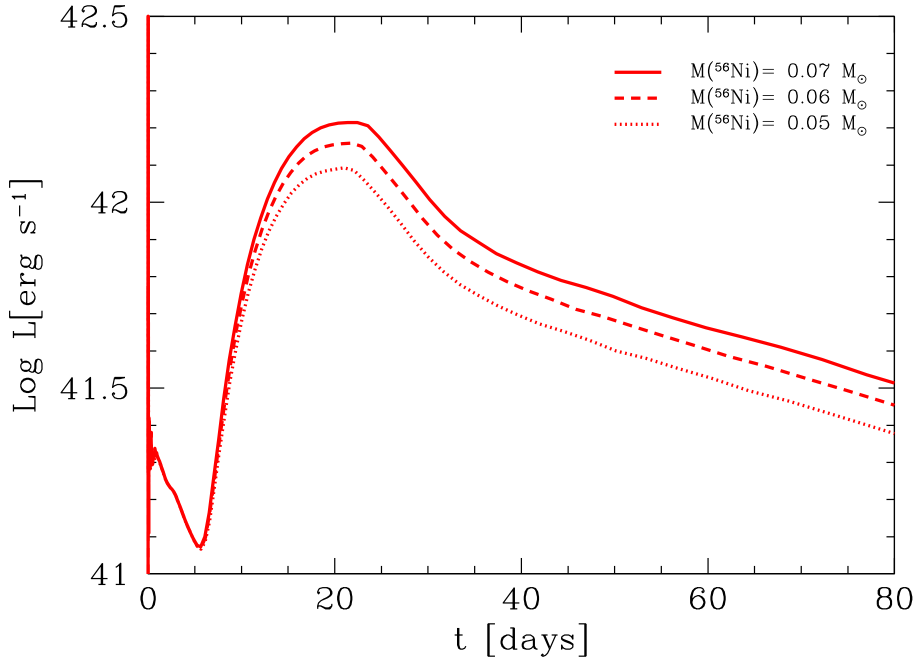
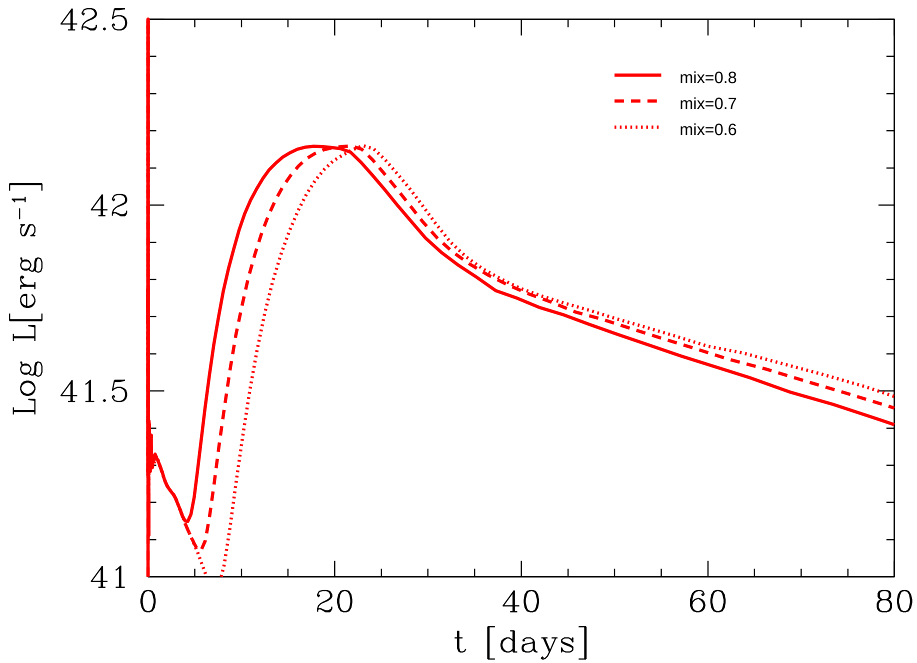
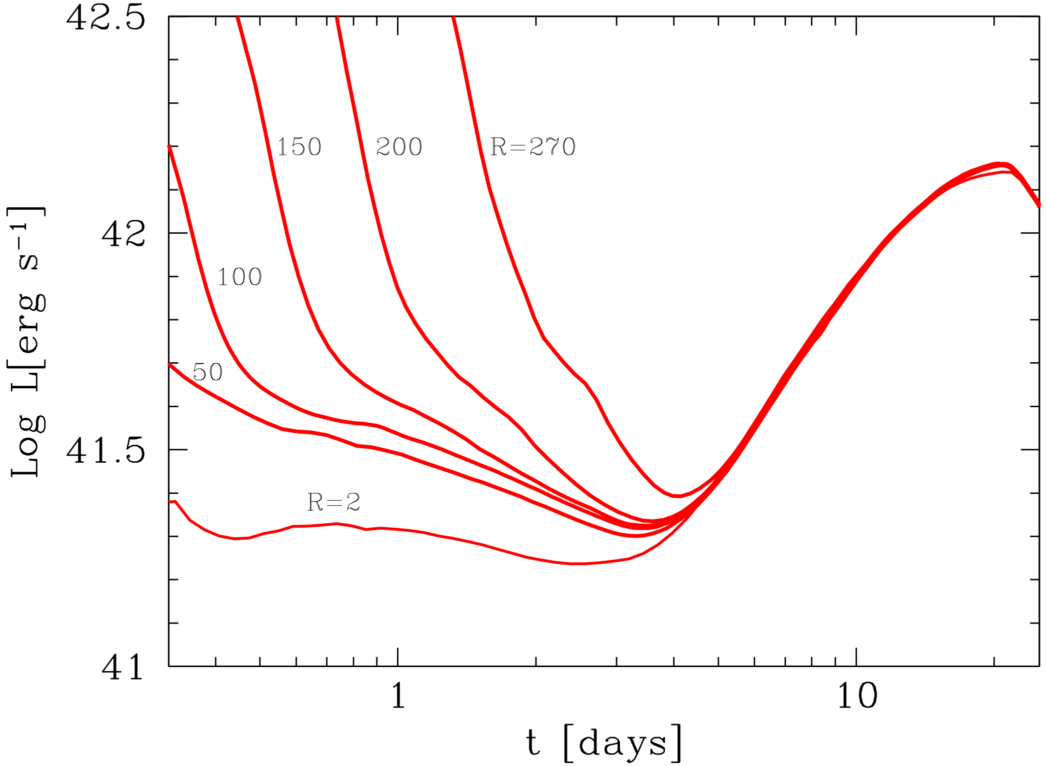




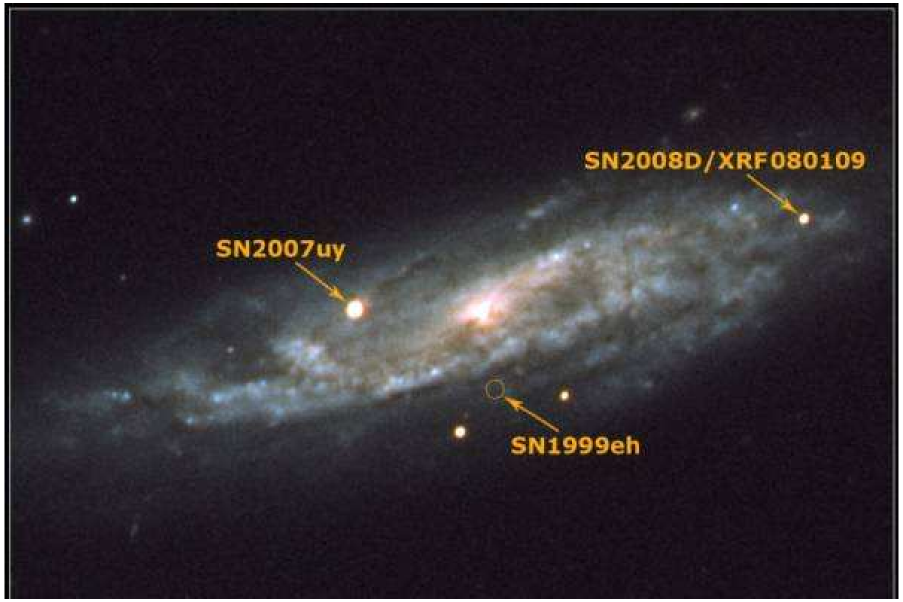
Light curve of stripped-envelope SNe

- Cooling phase with strong dependence on progenitor radius
- Second peak powered by radioactive decay
  Depends on E_{exp}, M_{ej}, M_{Ni} and $^{56}\mathrm{Ni}$ distribution
- A handful of SNe observed during cooling phase,
  e.g. SN 2008D and SN 2011dh



SN 2008D

- Initial broad spectral lines as in Type Ic-bl
- Development of He lines $\longrightarrow$ transition to Type Ib
- Associated weak X-ray flash (XRF)
- No GRB found
- Early UV/optical observations
- Light Curve (LC) shows two peaks



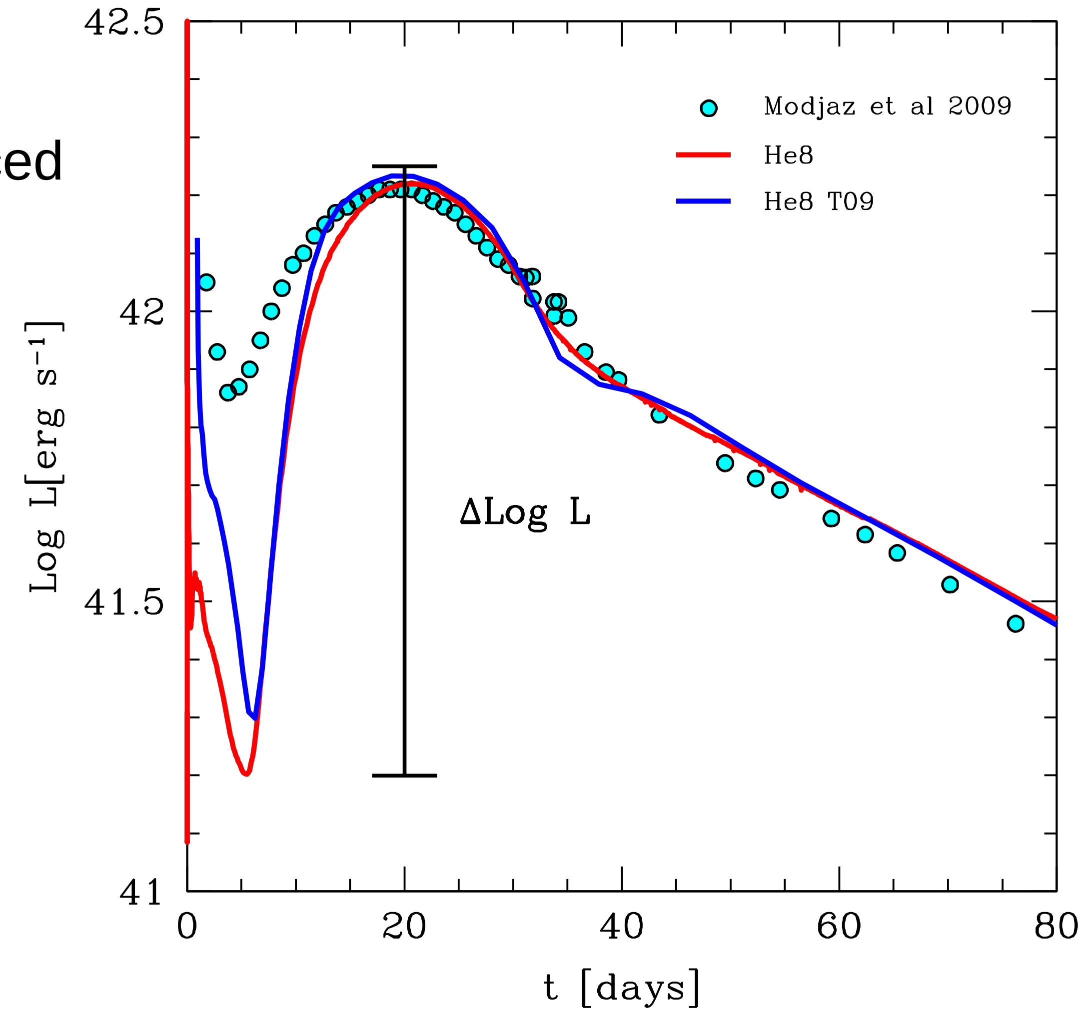
Hydro-model of SN 2008D

- Same model and physical parameters as Tanaka et al. 2009 (T09): He core of 8 $M_\odot$, $R = 1.4\ R_\odot$, $E_K = 8.4$ foe, and $M_{\rm Ni} = 0.07\ M_\odot$ (He8)
- Good agreement between models
- Main peak is well reproduced but not the cooling phase

$\Downarrow$

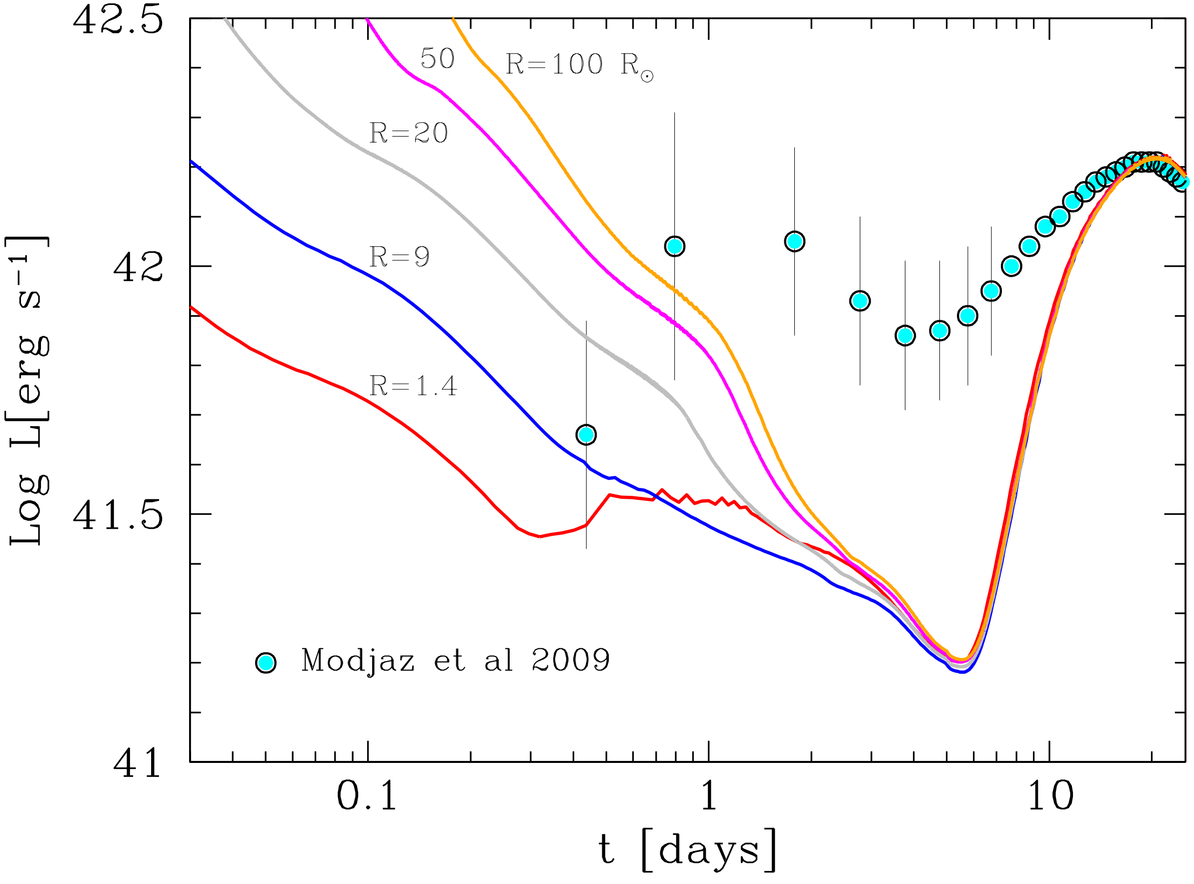
large difference in $\Delta \mathrm{Log} L$

- Models: $\Delta \mathrm{Log}\, L \gtrsim 0.9$
- SN 2008D: $\Delta \mathrm{Log}\, L \approx 0.35$



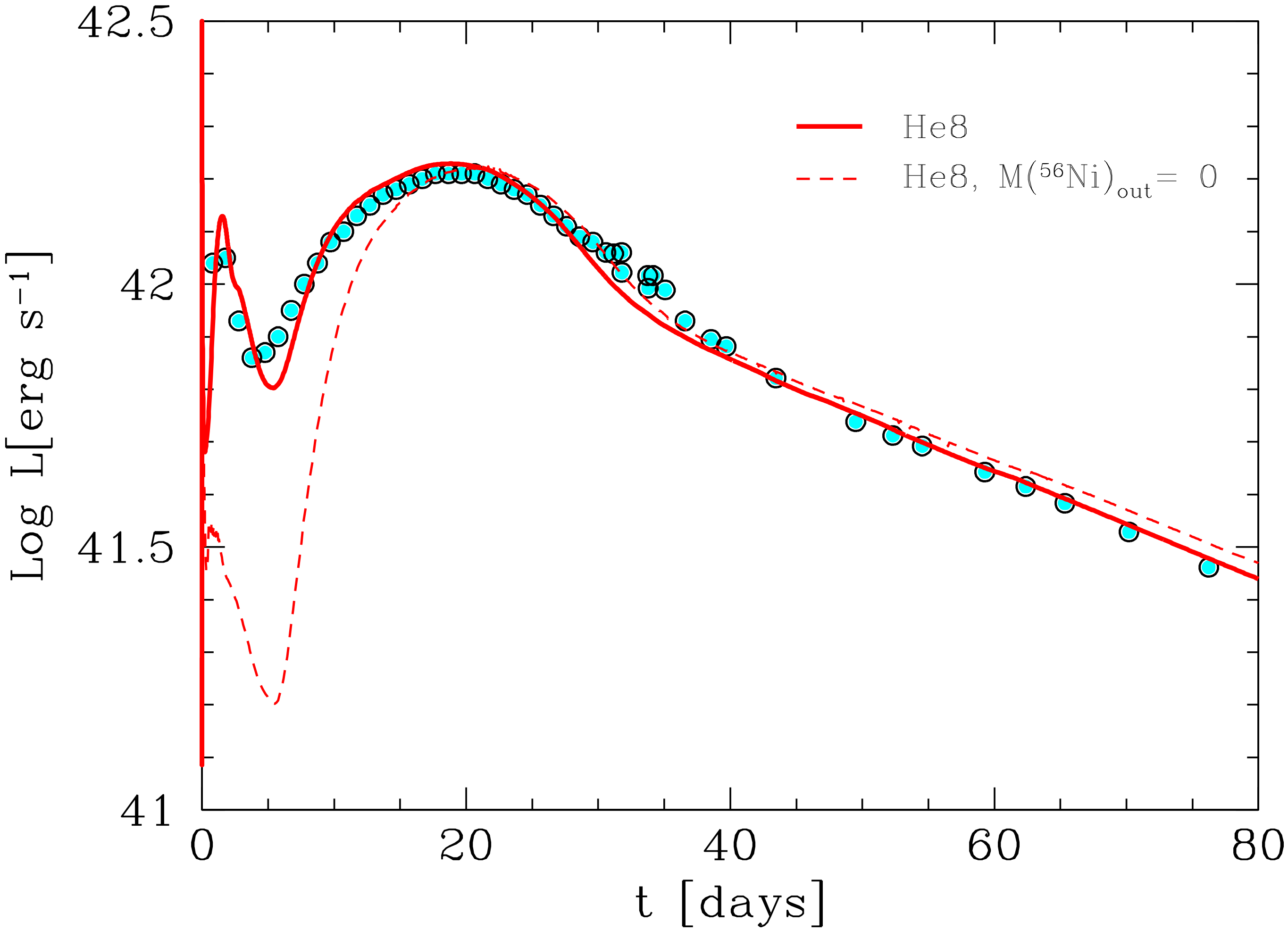
Progenitor radius

- We tested envelopes of different radii attached to the He8 model.
- Models with larger radius cannot reproduce the early LC either



Optimal model

- He8 model with 0.01 $M_{\odot}$ of ^{56}Ni in the outermost layers
- This material may have been carried by a jet, as suggested by spectropolarimetry (Maund et al. 2009).



SN 2011dh

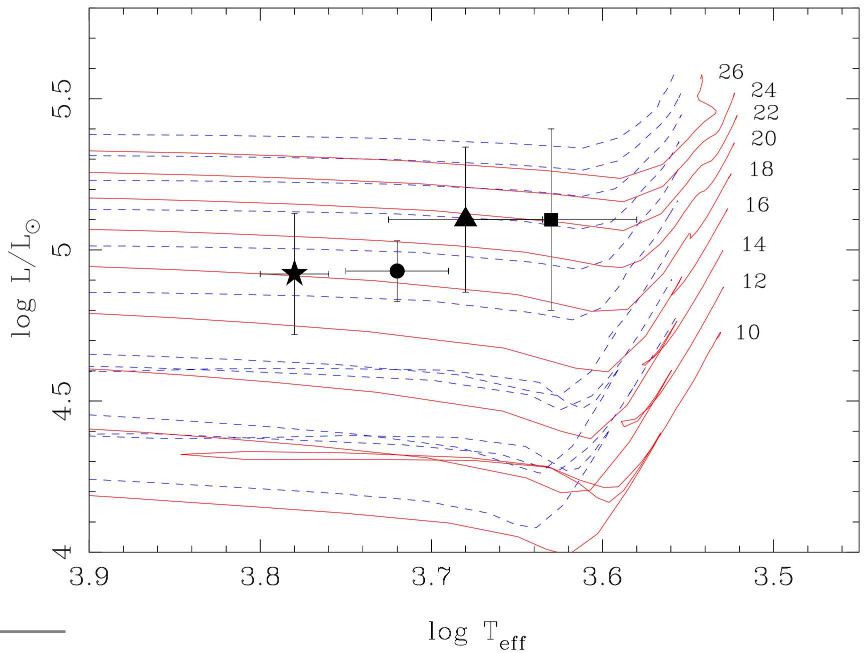
- Type IIb: first H lines, then He
- Third brigthest SN of 2011 ($V \approx$ 12 mag)
- Discovered in M51 ($d \sim$ 8 Mpc; other two SNe: SN 1994I and 2005cs)

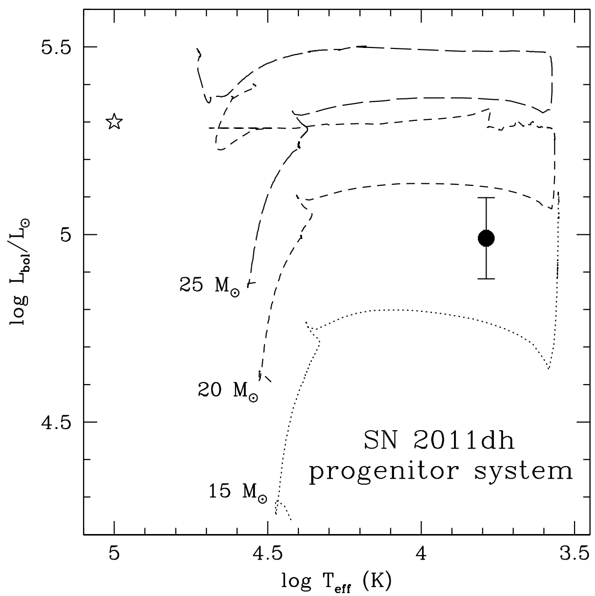
Credit: Stephane Bailey

- Strong constraint of the explosion time whitin 0.6 days
- HST pre-SN images $\Longrightarrow$ YSG star with $R \sim 270 R_{\odot}$ at SN position
- Controversy about YSG star: progenitor, binary companion, or unrelated object?

Progenitor of SN 2011dh

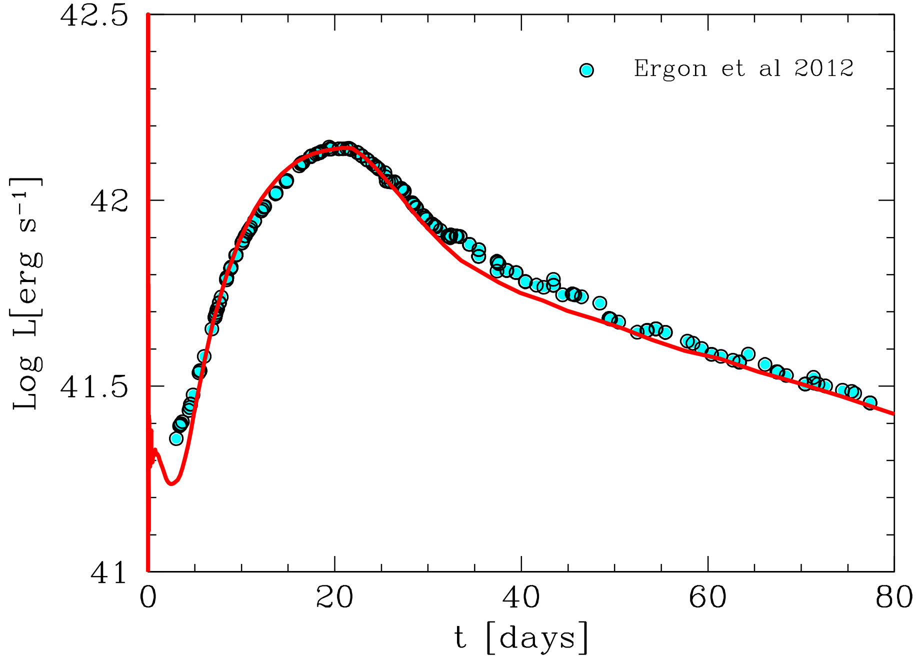
- HST pre-SN photometry + evolutionary tracks
  - Maund et al. (2011) found $M_{\rm ZAMS} = 13 \pm 3 M_\odot$
  - Van Dyk et al. (2011) found $M_{\rm ZAMS} = 18 - 21 M_\odot$
- Stellar population analysis are in favor of lower mass estimation (Murphy et al. 2011)
- But Arcavi et al. (2011) and Soderberg et al. (2011) suggested a compact progenitor ($\sim$1 $R_\odot$) based on radio and early LC properties

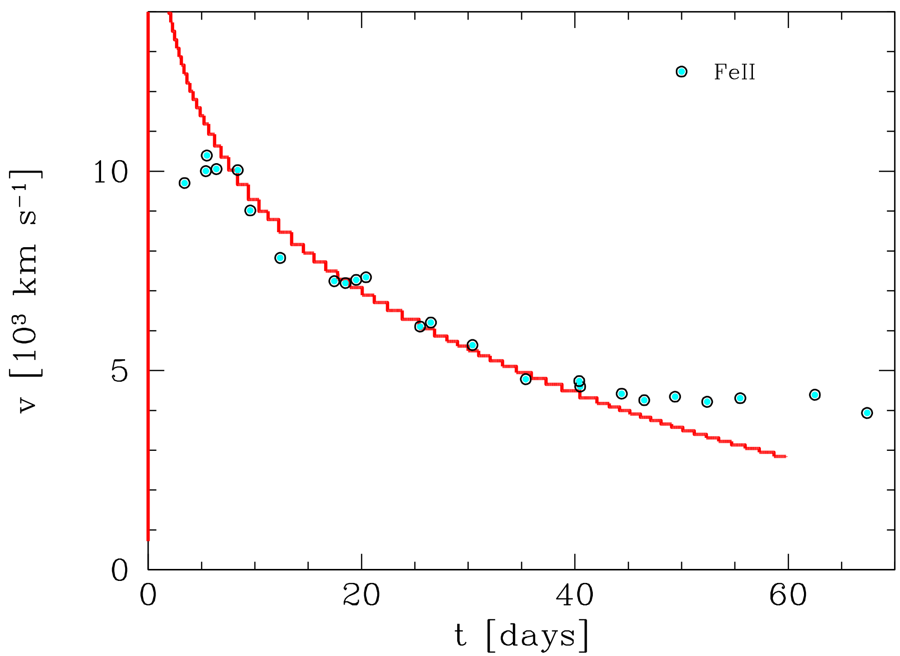




Hydro-model of SN 2011dh

- Optimal model: He core mass ≈4 $M_\odot$ ($M_{\rm ZAMS} = 12 - 15 M_\odot$), $E_{\rm exp} = 8 \times 10^{50}$ erg, and $M_{\rm Ni} = 0.063\ M_\odot$





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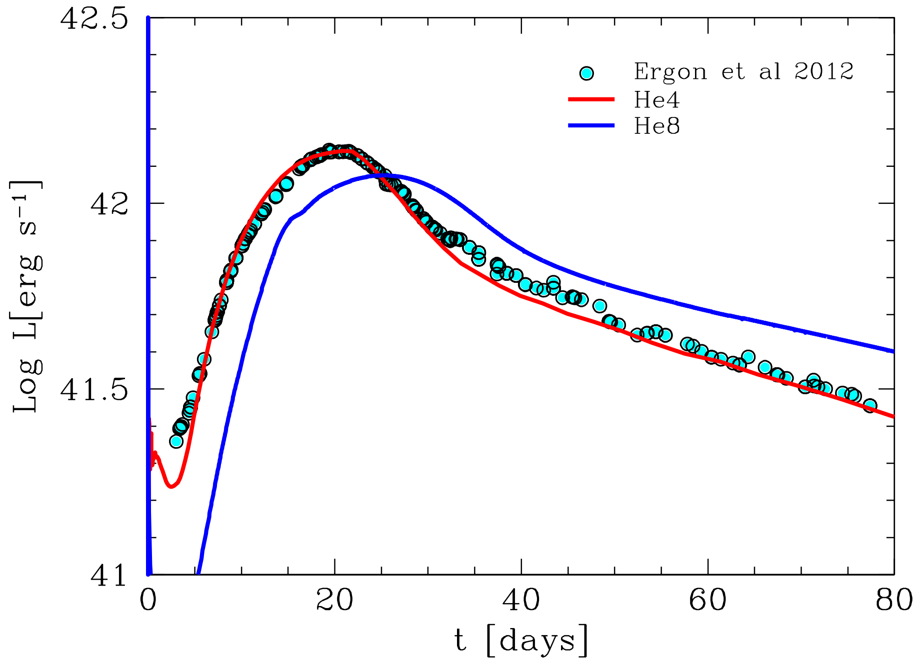
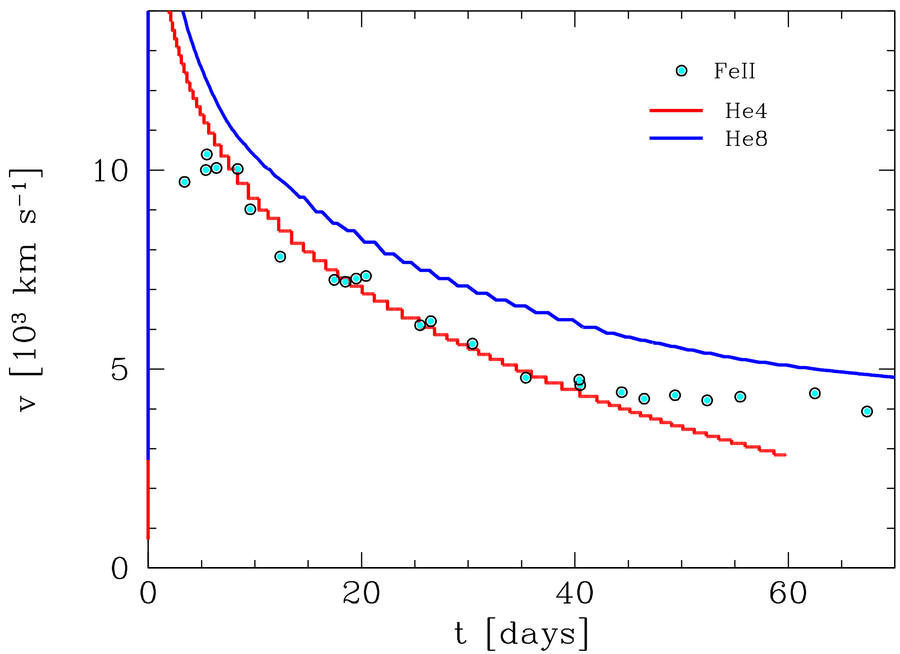
- He core mass $\gtrsim 8\ M_\odot$ ($M_{\rm ZAMS} \gtrsim 25\ M_\odot$) is ruled out





Compact vs. extended progenitor

- He core of $4\ M_{\odot}$ (He4) with $R = 2\ R_{\odot}$
- He4 model with an attached envelope (He4R270) for $T_{\rm eff}$ and L consistent with pre-SN images $\Longrightarrow R = 270\ R_{\odot}$

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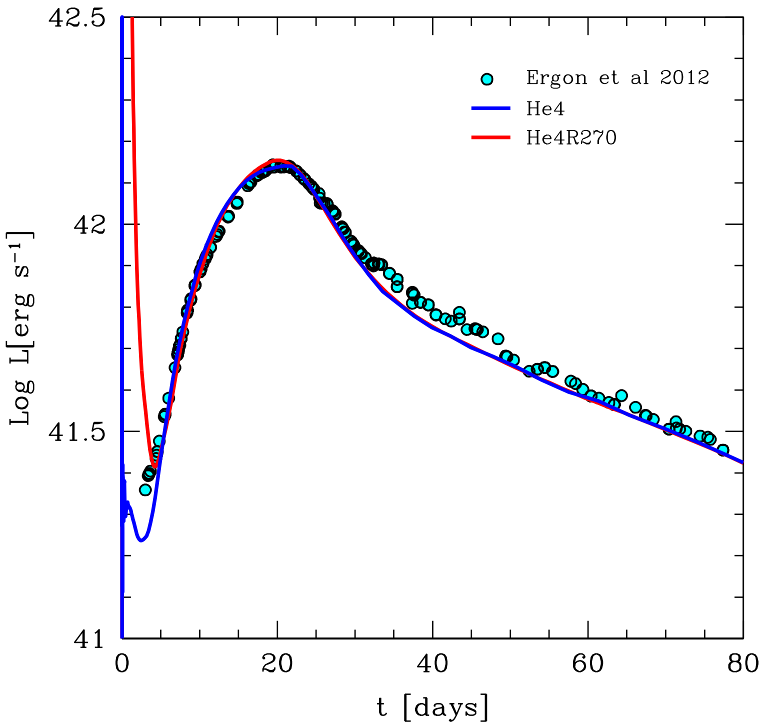
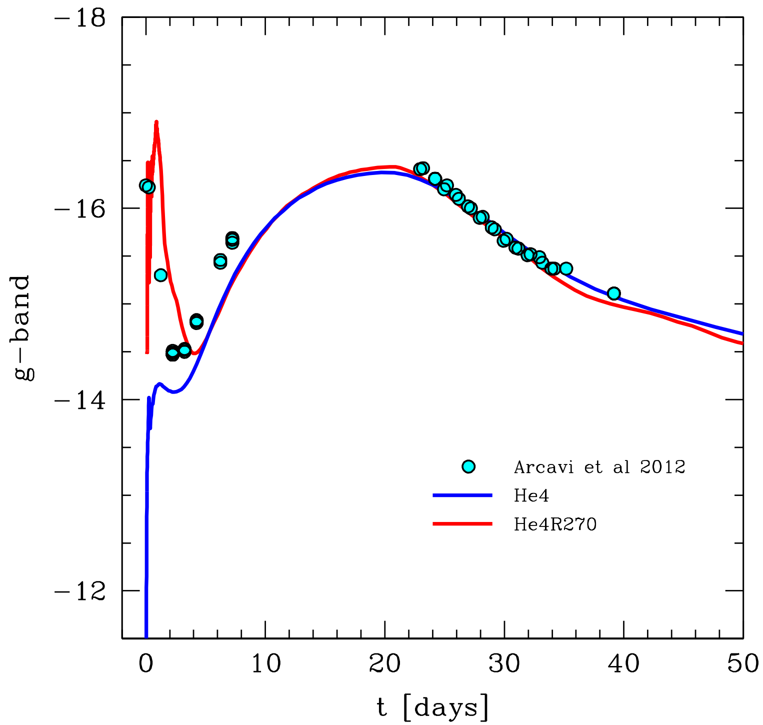
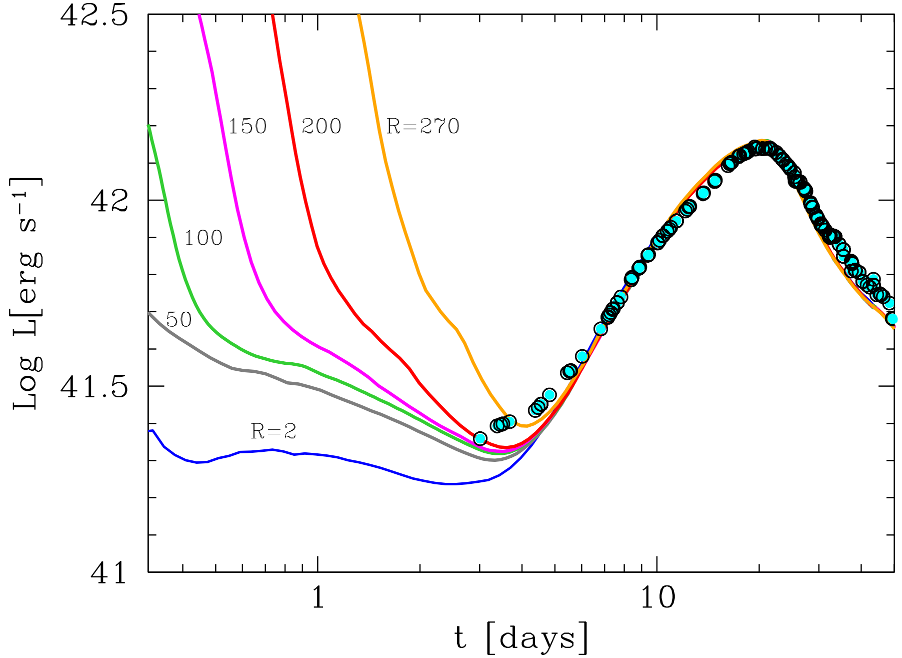
- He4 model with an attached envelope (He4R270) for $T_{\rm eff}$ and L consistent with pre-SN images $\Longrightarrow R = 270\ R_\odot$
- Compact model cannot reproduce the early spike shown in the observations

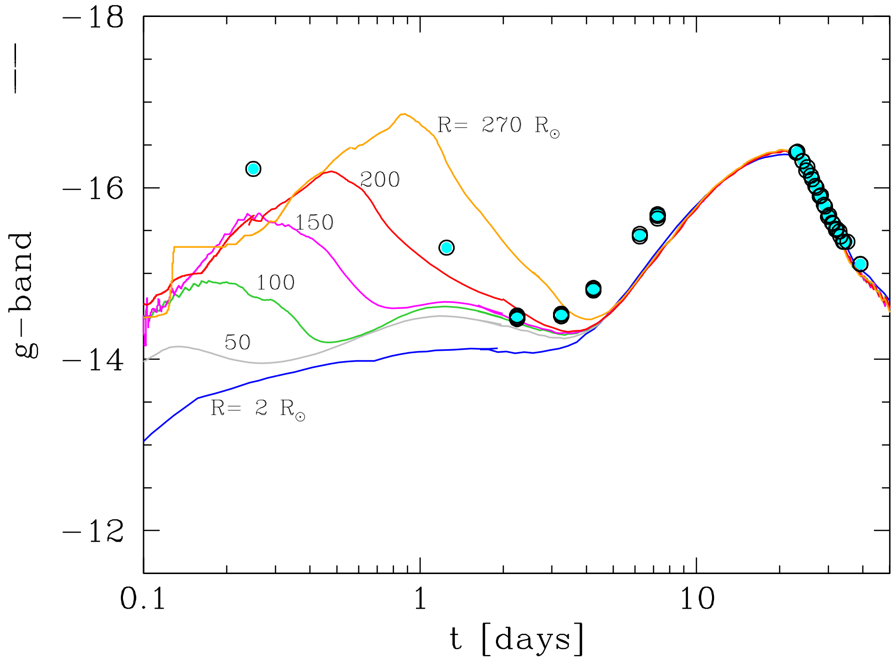




Compact vs. extended progenitor

- We tested envelopes with different radii attached to the He4 model.
- Models with $R \gtrsim 150 R_\odot$ are required

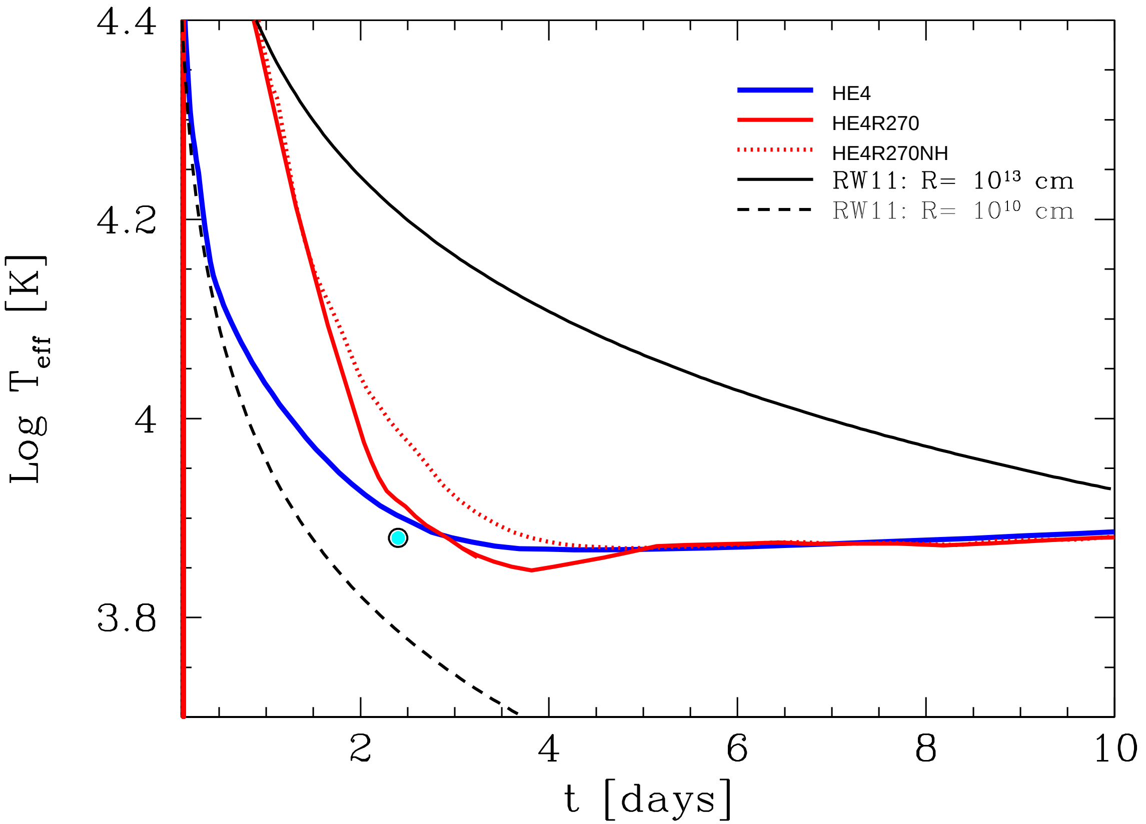




Compact vs. extended progenitor

- Almost no differences in $T_{\rm eff}$ for $t \gtrsim 2$ days
- $T_{\rm eff} \approx 8000$ K at $t = 2.4$ days compatible with temperature from spectrum (cyan dot; Arcavi et al 2012)
- Analytic models by Rabinak & Waxman (2011) $\Longrightarrow$ strong dependence on radius

Effective temperature



Single vs binary Scenario

- Single, massive ($\gtrsim 25\ M_\odot$) Wolf-Rayet stars with strong winds
  $\Longrightarrow$ He core mass $\gtrsim 8\ M_\odot$
- He stars in interacting binaries

Single vs binary Scenario

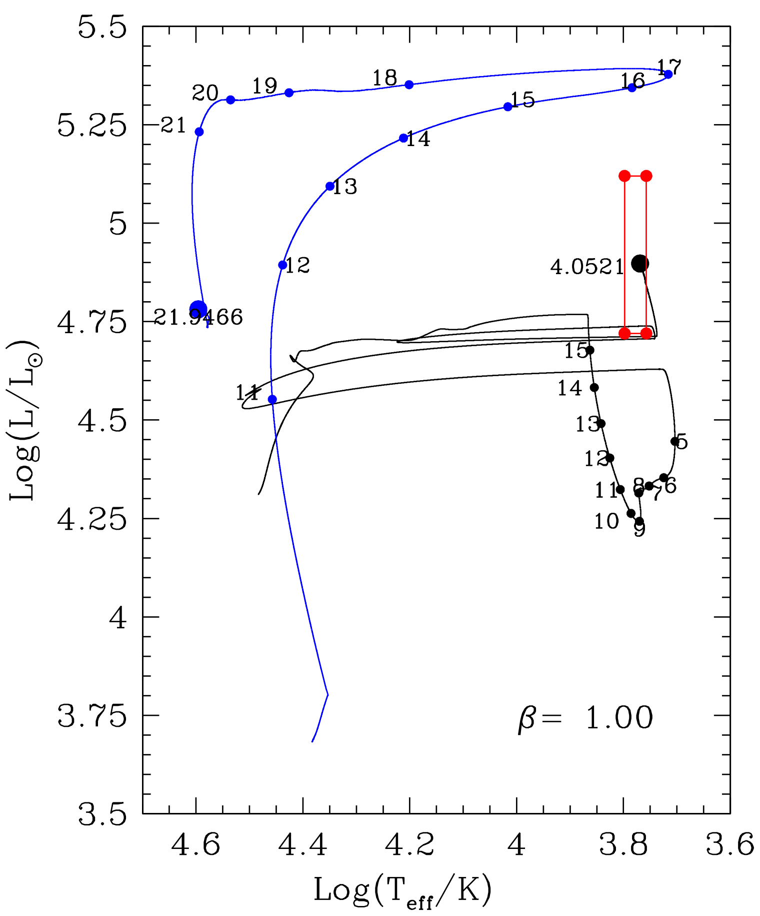
- Single, massive ($\gtrsim$ 25 $M_\odot$) Wolf-Rayet stars with strong winds
$\Longrightarrow$ He core mass $\gtrsim$ 8 $M_\odot$ ruled out in our models
- He stars in binaries $\Longrightarrow$ binary stellar evolution for SN 2011dh using a code by Benvenuto & De Vito 2003
  - Primary star of $16\ M_\odot$ and period of 100 days
  - Secondary star of $10 - 14\ M_\odot$
  - Conservative and non-conservative mass accretion

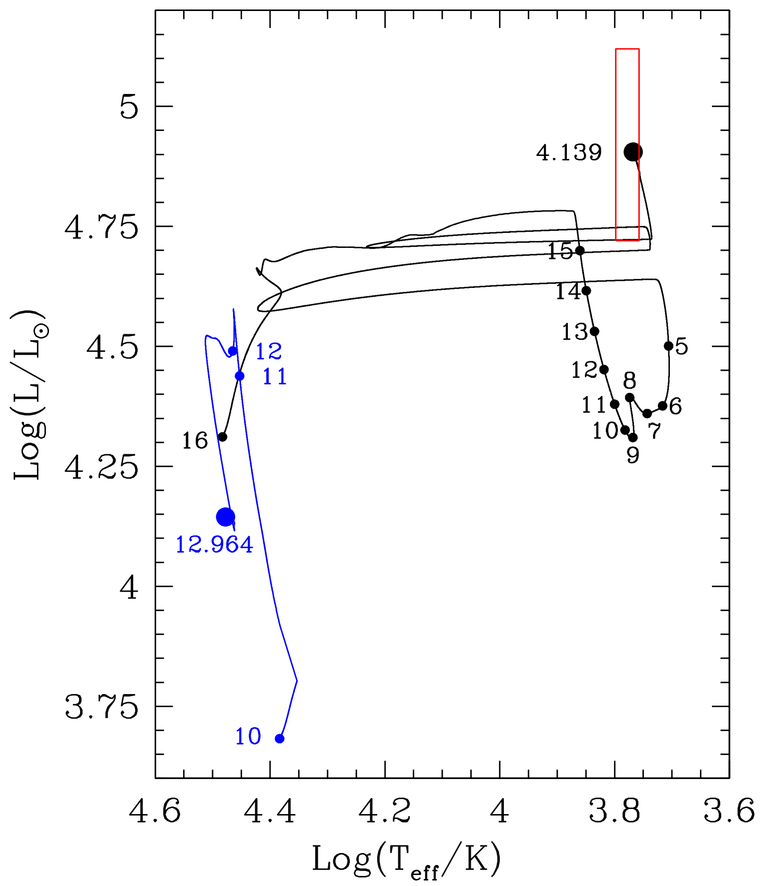
$$\Downarrow$$

  - Primary ends as YSG with He core mass of $\approx$4 $M_\odot$
and H mass of $\approx 5 \times 10^{-3} M_\odot$

Binary stellar evolution for SN 2011dh

- 16 $M_\odot$ + 10 $M_\odot$ with P = 100 days
- Primary ends as YSG with He core mass of ≈4 $M_\odot$ and H mass of $\approx 5 \times 10^{-3} M_\odot$





Summary

SN 2008D:

- Early behavior incompatible with cooling phase of WR star even for larger initial radius
- Good fit to early LC assuming $\approx 0.01 M_\odot$ of ^{56}Ni in the outer ejecta. This type of ^{56}Ni distribution may indicate the presence of jets.

SN 2011dh:

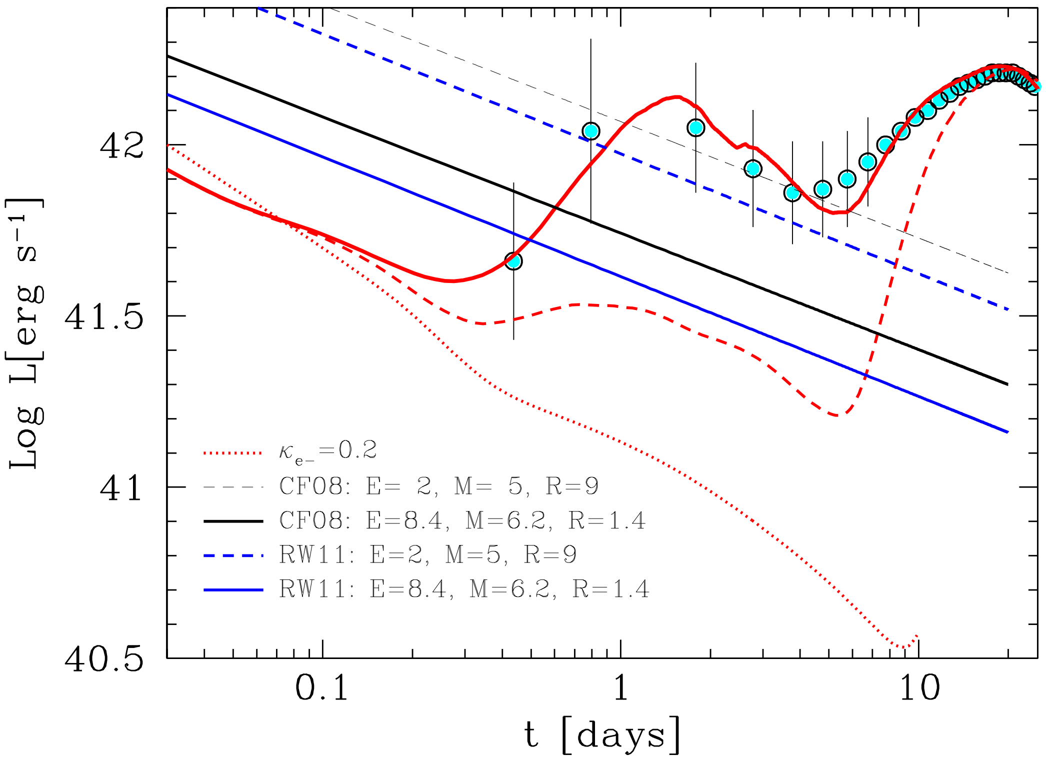
- Models with He core mass of $\approx$ 4 $M_\odot$ ($M_{\rm ZAMS} \approx 15 M_\odot$), $E_{\rm exp} \approx 8 \times 10^{50}$ erg and $M_{\rm Ni} \approx 0.063\ M_\odot$ reproduce very well the observations
- Large $R \sim 200 R_\odot$, consistent with the pre-SN imaging, required to reprocude the early LC. No contradiction with the temperature
- He core mass $\gtrsim$ 8 $M_\odot$ ($M_{\rm ZAMS} \gtrsim$ 25 $M_\odot$) ruled out $\Longrightarrow$ single star evolution unlikely
- Binary models give right position on HR diagram, and mass of H for a SN IIb $\Longrightarrow$ YSG may be the progenitor

Comparison with analytic models

- Models for early emission by Chevalier & Fransson (2008) (CF08), and Rabinak & Waxman (2011) (RW11): (1) constant opacity, and (2) $\rho \propto r^{-n}$ valid while the photosphere is in the outer shock-accelerated part of the ejecta.

- $\kappa_{e^-} = 0.2$ g cm^{-2} $\longrightarrow$ breaks at $t \approx 0.5$ d

- $t \approx 1.5$ d $\longrightarrow$ photosphere begins to recede in ejecta



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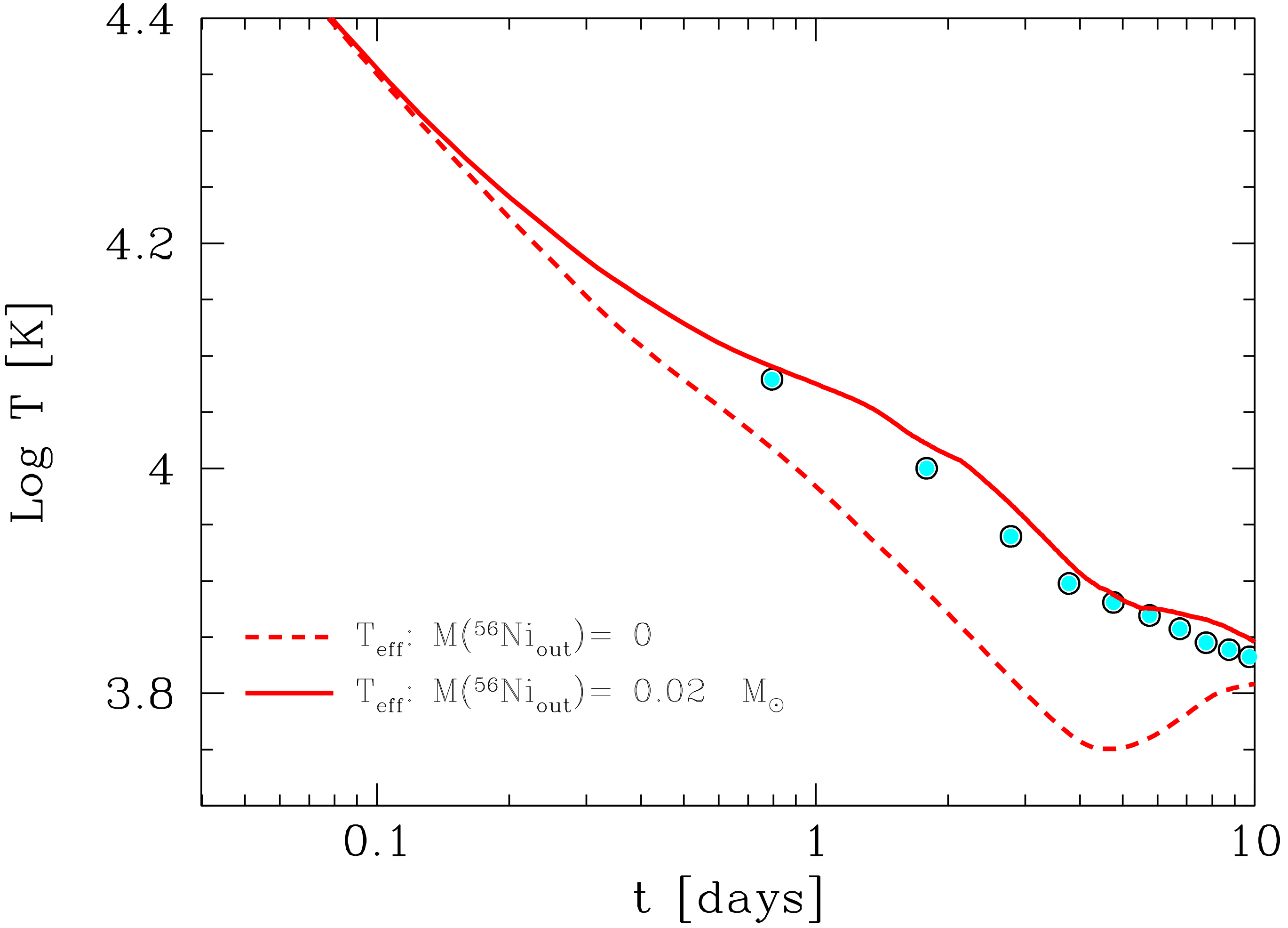

Double-peaked ^{56}Ni Distributions

- ^{56}Ni in the outermost layers produces an effect in the early light curve
- Depends on the amount and distribution