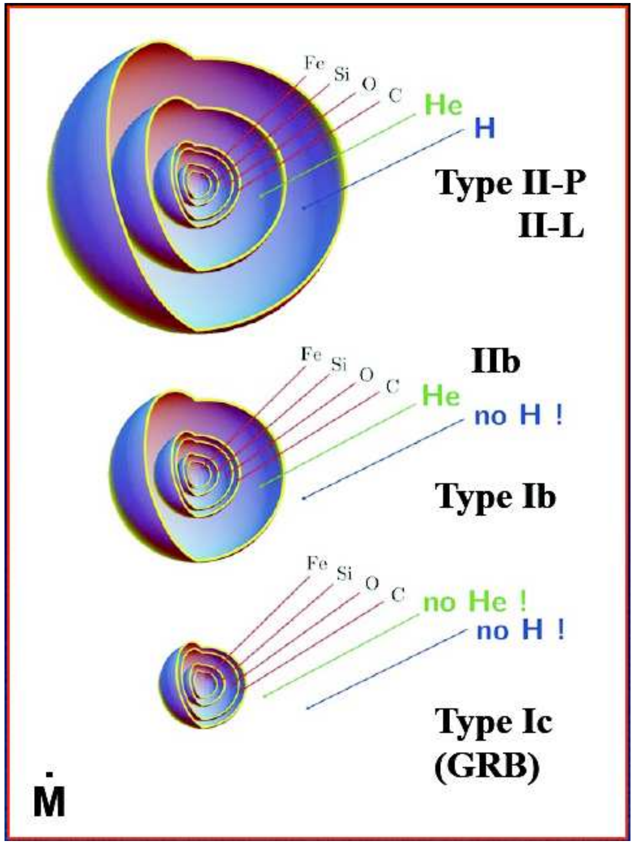
Light Curve modeling of Stripped Envelope SNe

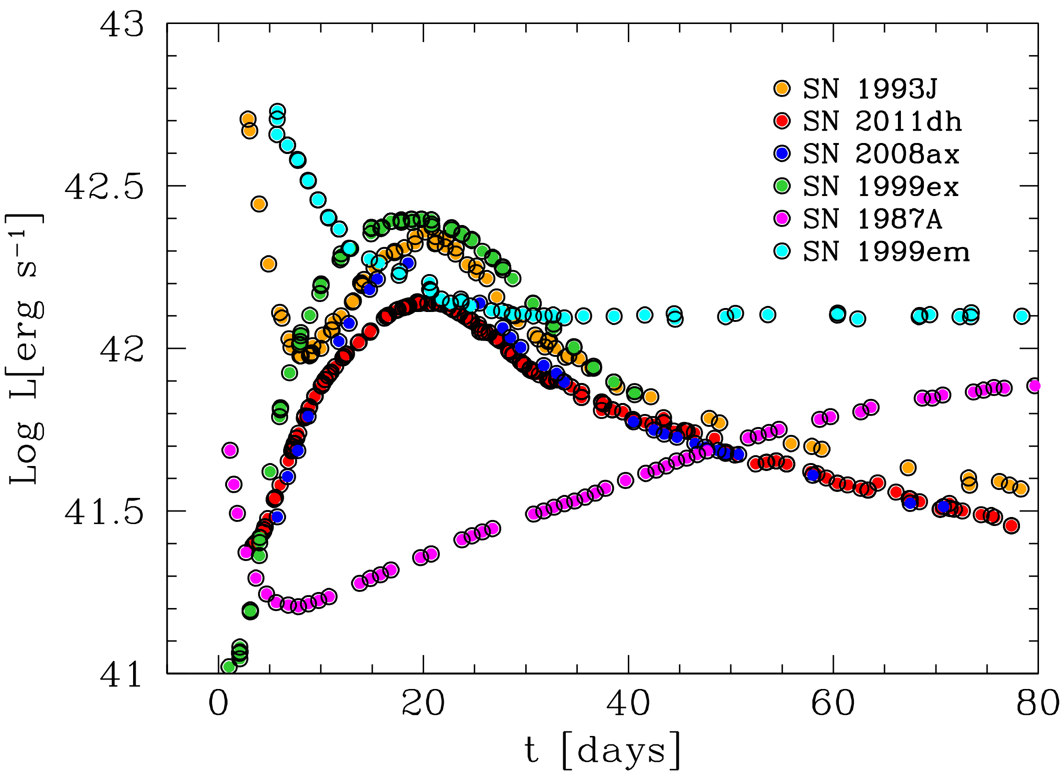
Melina Cecilia Bersten

KAVLI IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

Core-Collapse Supernovae

- End of massive stars ($M_0 \gtrsim 8M_\odot$)
- Which type of progenitor correspond to each type of SN?
- Single or binary system?
- Hydrodynamic modeling: light curve (LC) + expansion velocity

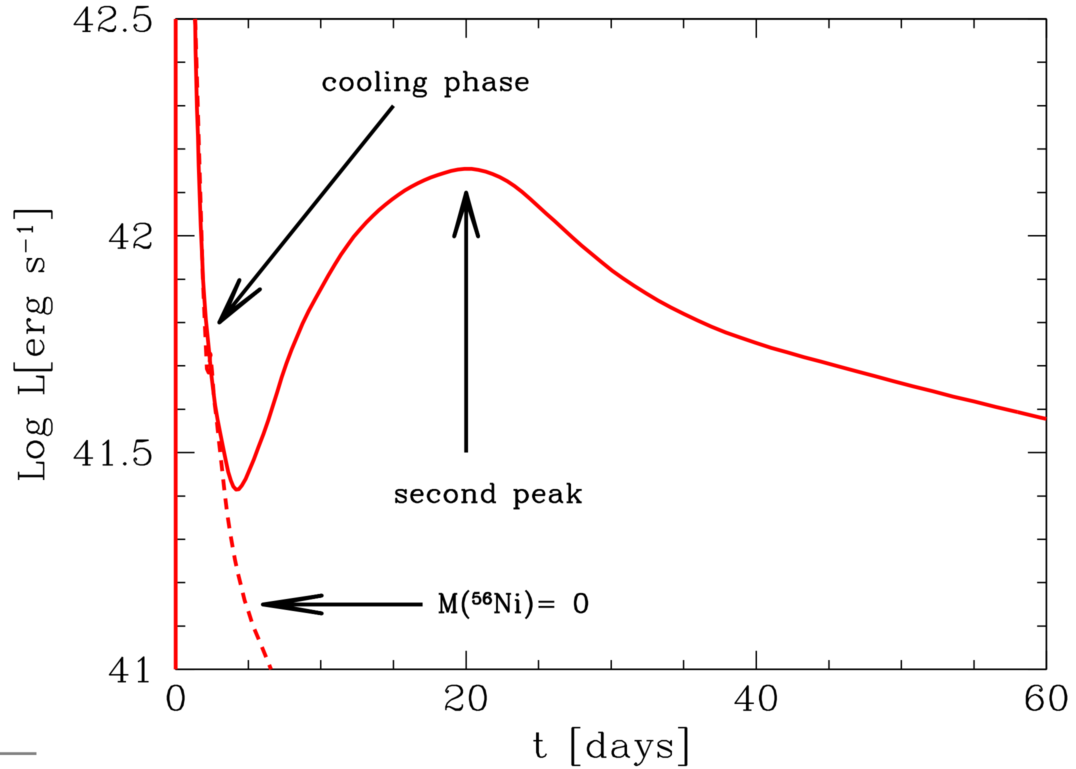




Credit: Modjaz

Light curve models

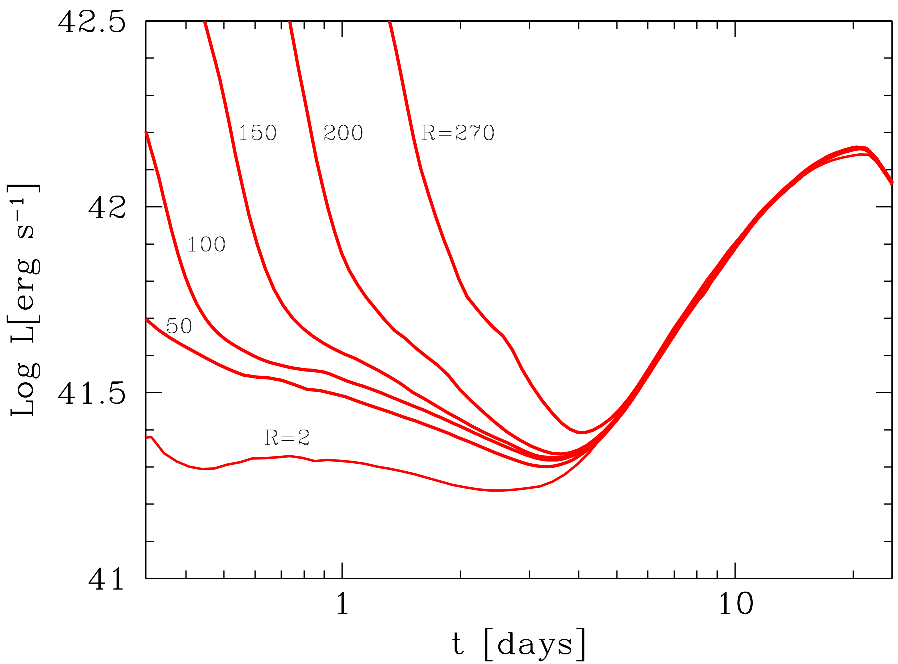
- One-dimensional Lagrangian code with flux-limited radiation diffusion and gray transfer for gamma-rays (Bersten et al 2011)
- Initial models from stellar evolutionary calculations
- Type IIb-Ib-Ic: Stripped envelope SNe



- Cooling phase $\longrightarrow$ radius
- Second peak $\longrightarrow$ mass, energy, ^{56}Ni mass, ^{56}Ni distribution

Early Emission

- Cooling phase with strong dependence on progenitor radius
- Models for compact progenitors show initial plateau

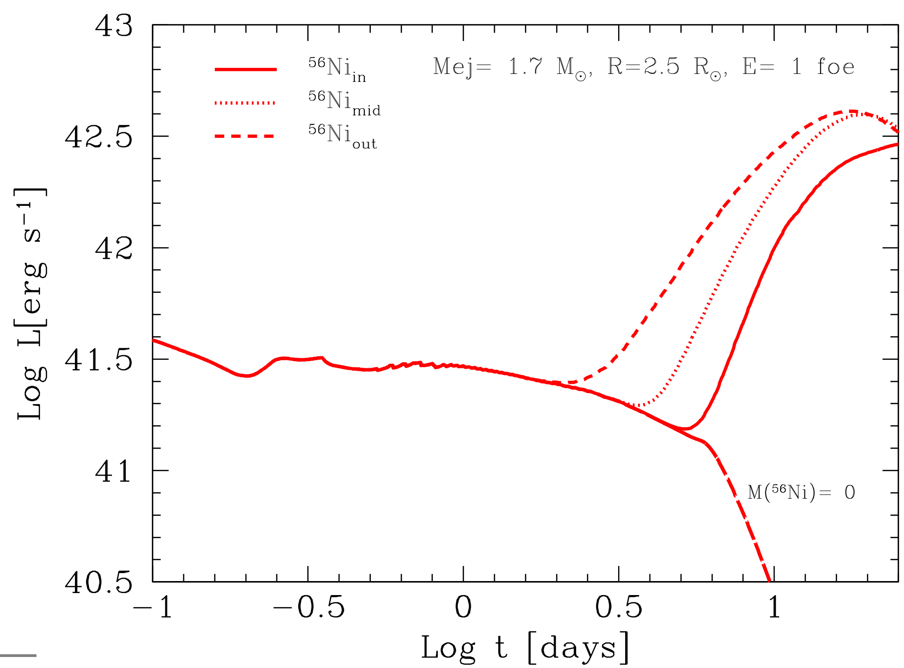


Early Emission

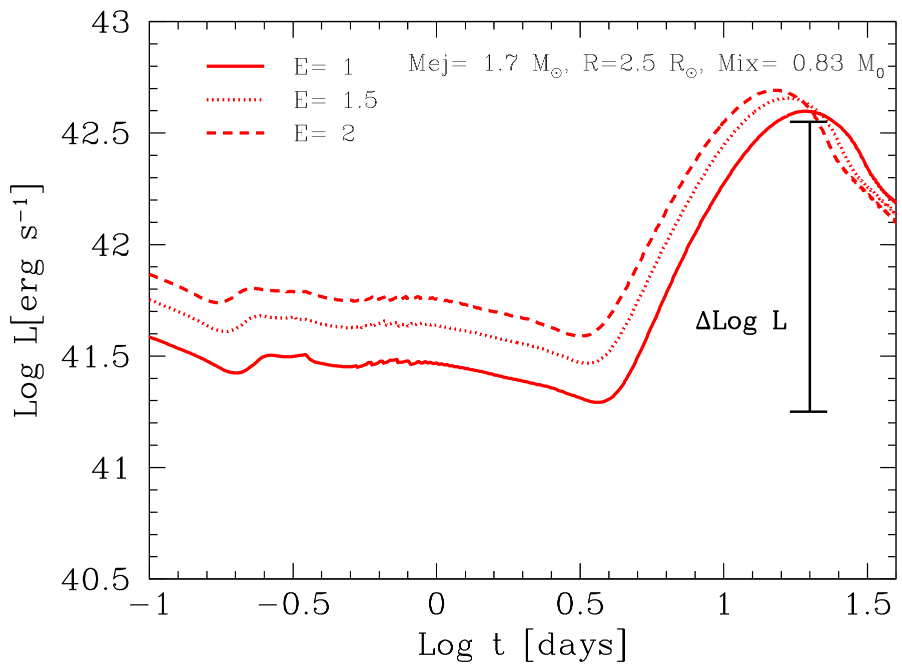
- Models for compact progenitors show initial plateau
  - $\Delta t_p \approx 4 - 10$ days, not dependent on the energy
  - $\Delta \log L \approx 1$

$\Longrightarrow$ should be possible to detect

^{56}Ni mixing



Explosion Energy



Early Emission

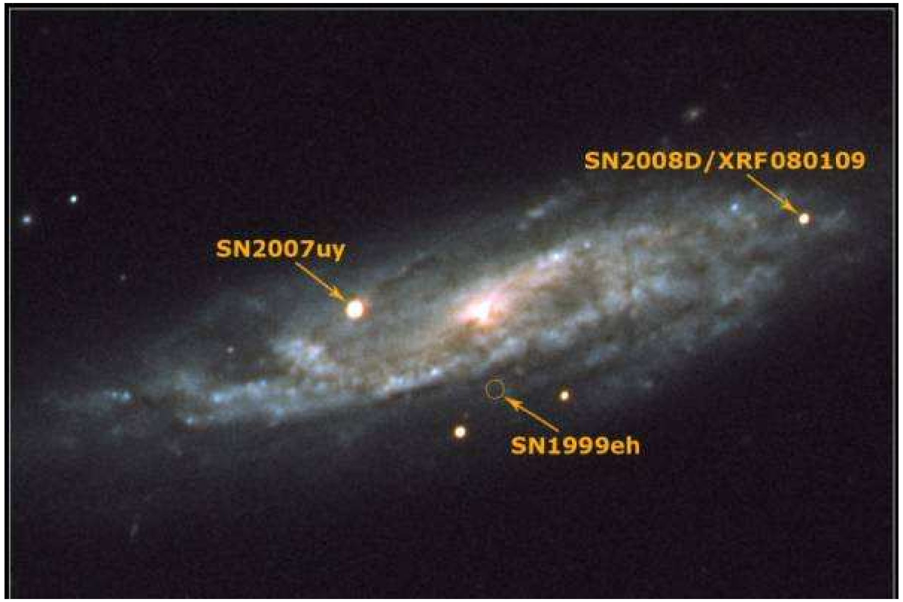
- Early emission provide important clues on the progenitor structure and the mixing process of radioactive material

- A handful of SNe observed during cooling phase, e.g. SN 2008D and SN 2011dh

- Increasing numbers of earlier times observation (SDSS, PTF, Pan-STARRS, ...) $\Longrightarrow$ opportunity to study the early emission in detail

The Type Ib 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



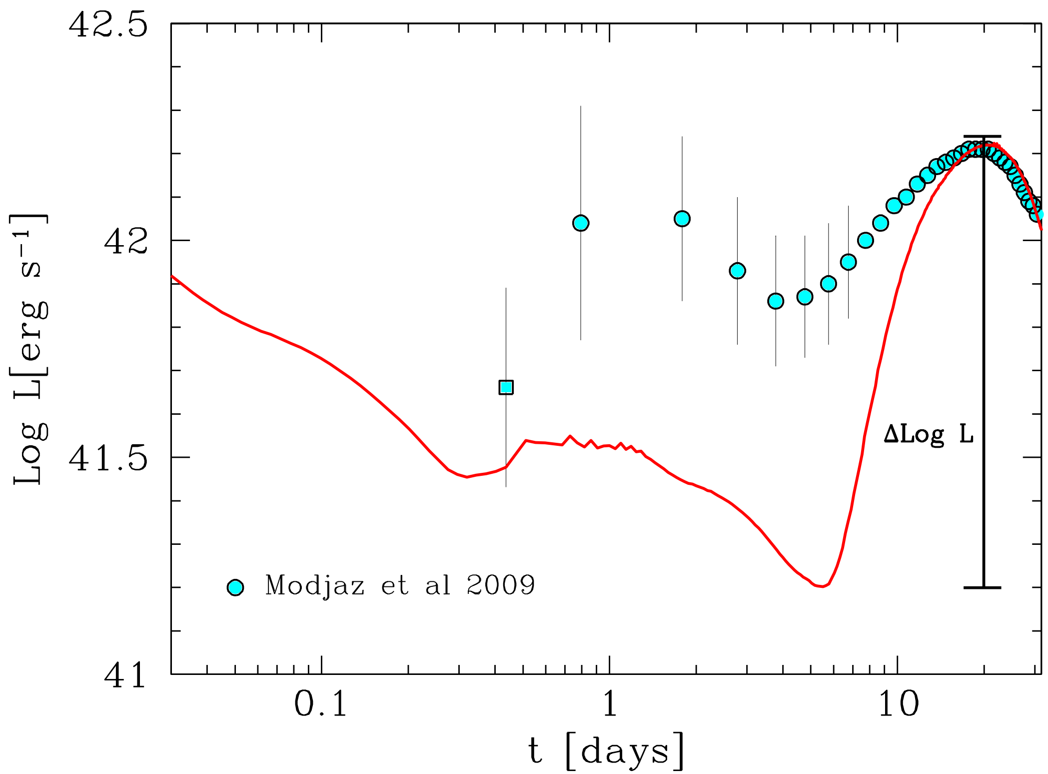
The Type Ib SN 2008D

- 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)
- Main peak is well reproduced but not the cooling phase

$\Downarrow$

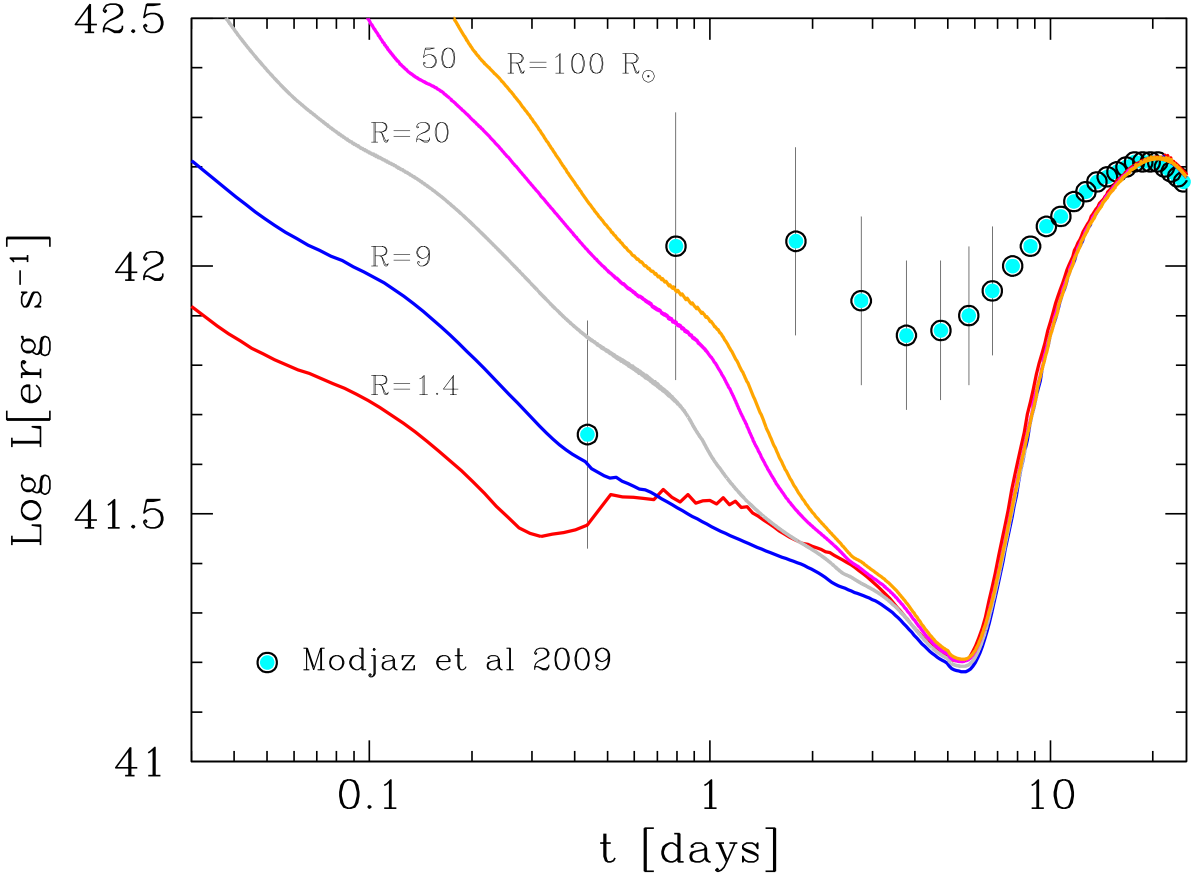
large difference in $\Delta {\rm Log} L$

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



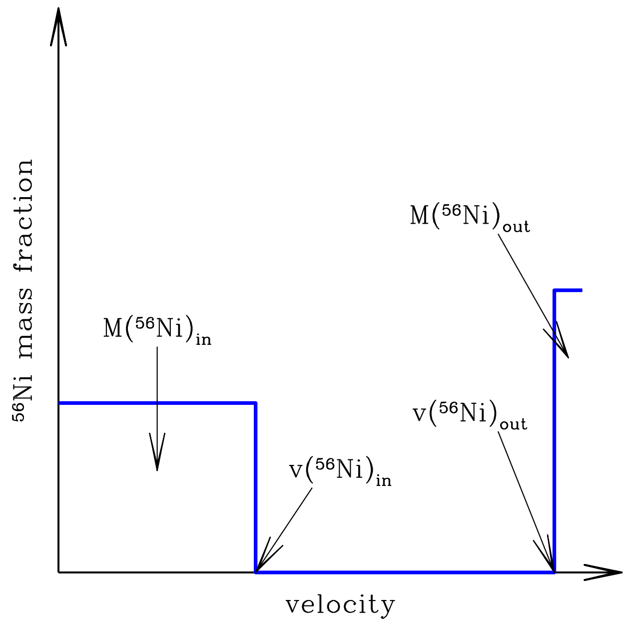
Progenitor radius

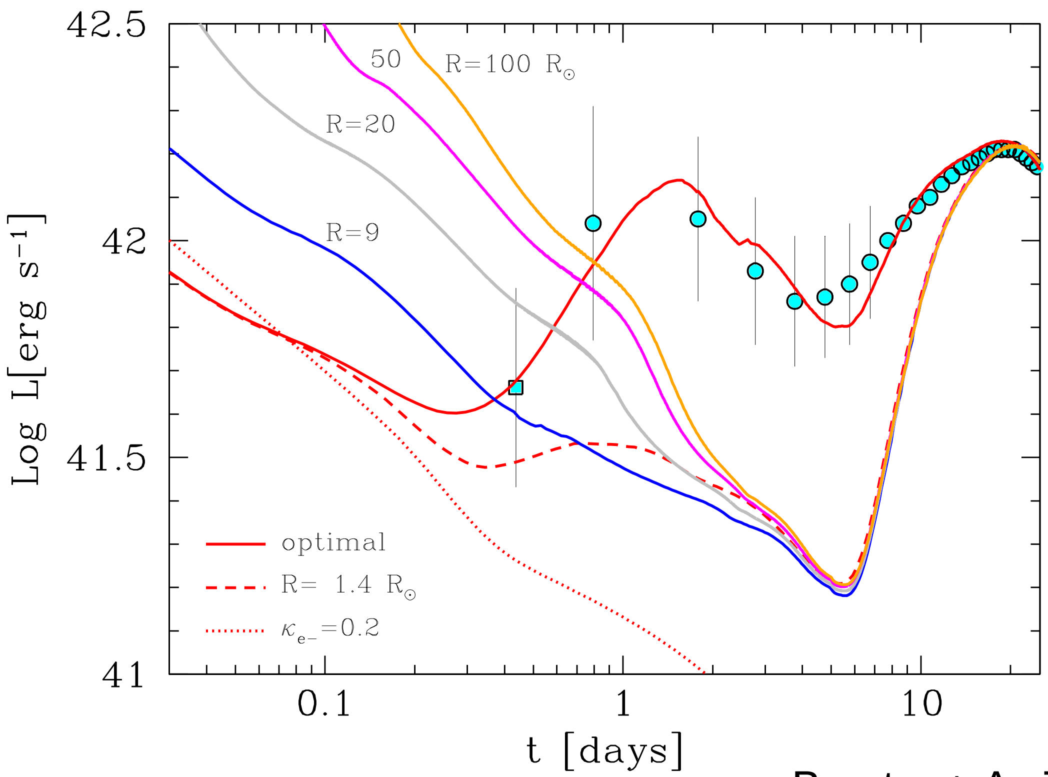
- We tested envelopes of different radii attached to the He8 model.
- Models with larger radius cannot reproduce the early LC either



The Type Ib SN 2008D

- Early emission incompatible with cooling phase of a normal WR star
- Very 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.



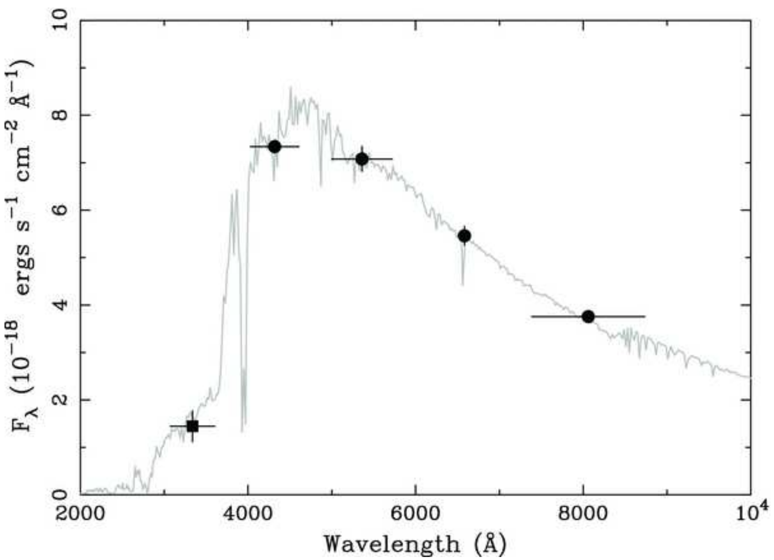


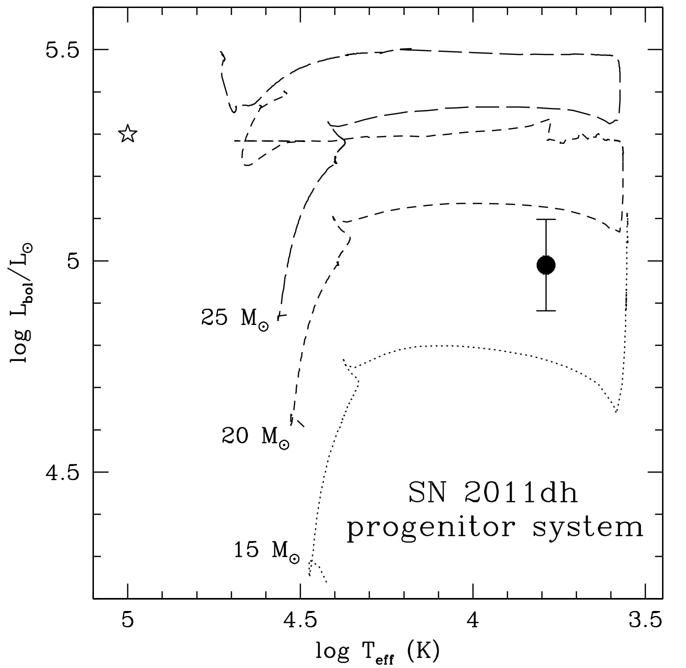
Bersten+ ApJ subm.

The Type IIb SN 2011dh

- Third brightest SN of 2011 (M51; $d \approx 8$ Mpc)
- HST pre-SN images $\Longrightarrow$ YSG star with $R \approx 270 R_\odot$ at SN position
- Controversy about YSG star: progenitor, binary companion, or unrelated object?

- A compact progenitor ($\sim$1 $R_\odot$) was suggested based on radio and early light-curve properties





Van Dyk+'11; Maund+'11

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(1) Is the YSG star the actual progenitor?

(2) How can we explain the explosion of a YSG star?

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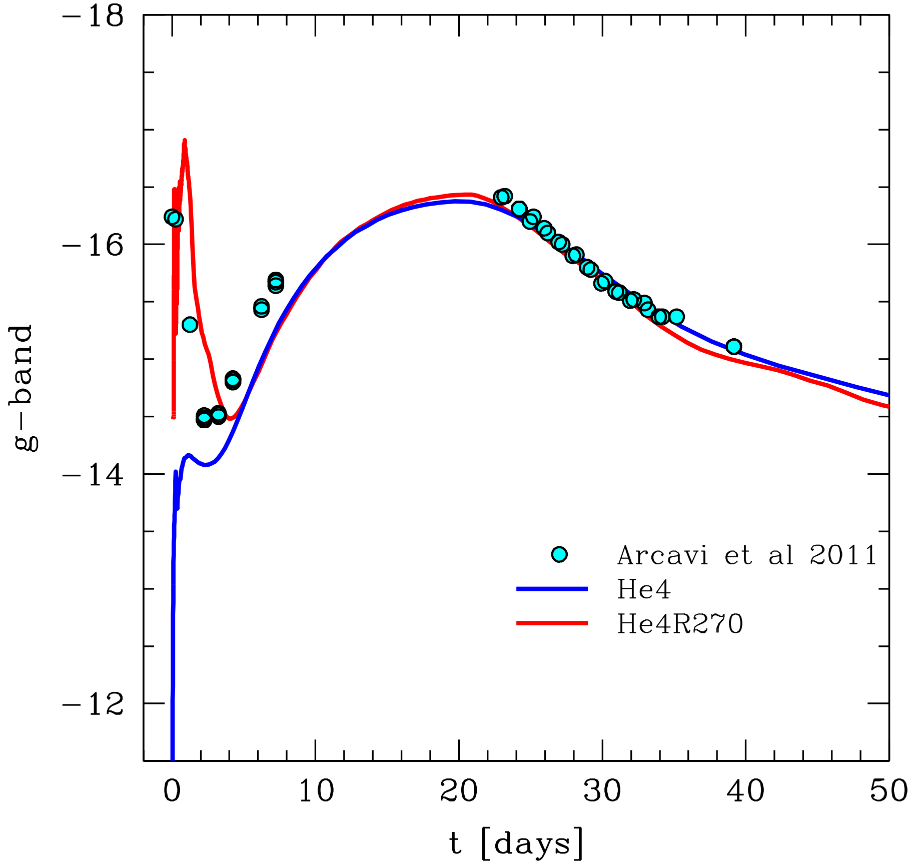
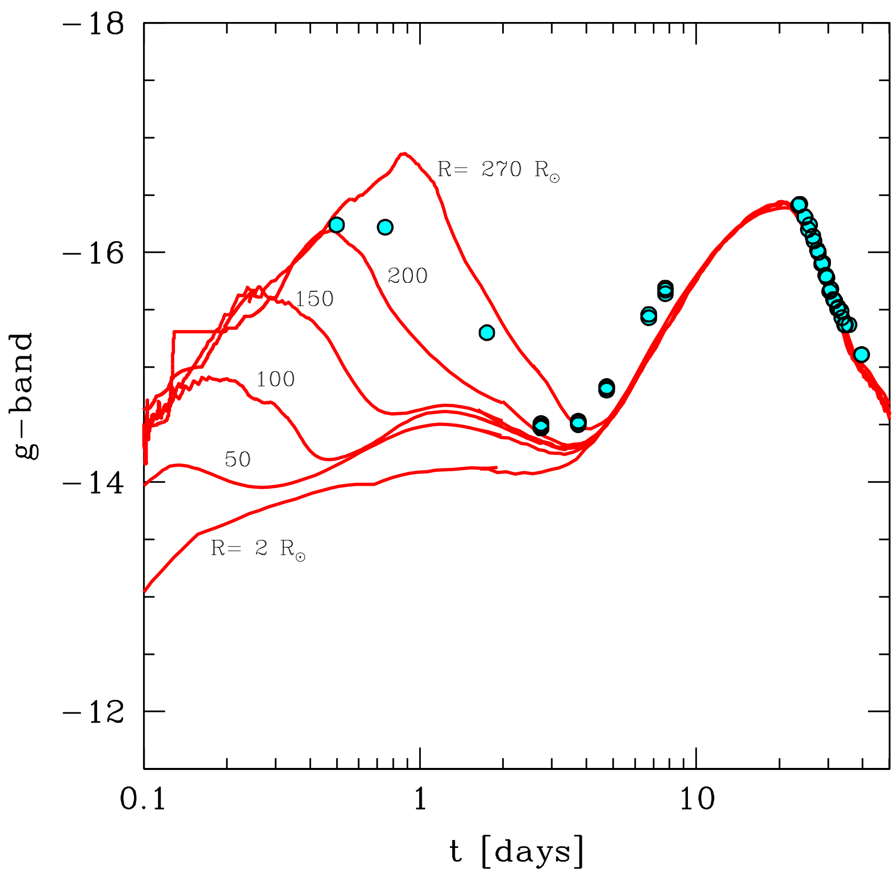
- He4 model with an attached envelope (He4R270) for $T_{\rm eff}$ and L consistent with pre-SN images $\Longrightarrow R = 270\ R_\odot$
- Compact model cannot reproduce the early spike shown in the observations



Bersten et al. 2012

Compact vs. extended progenitor

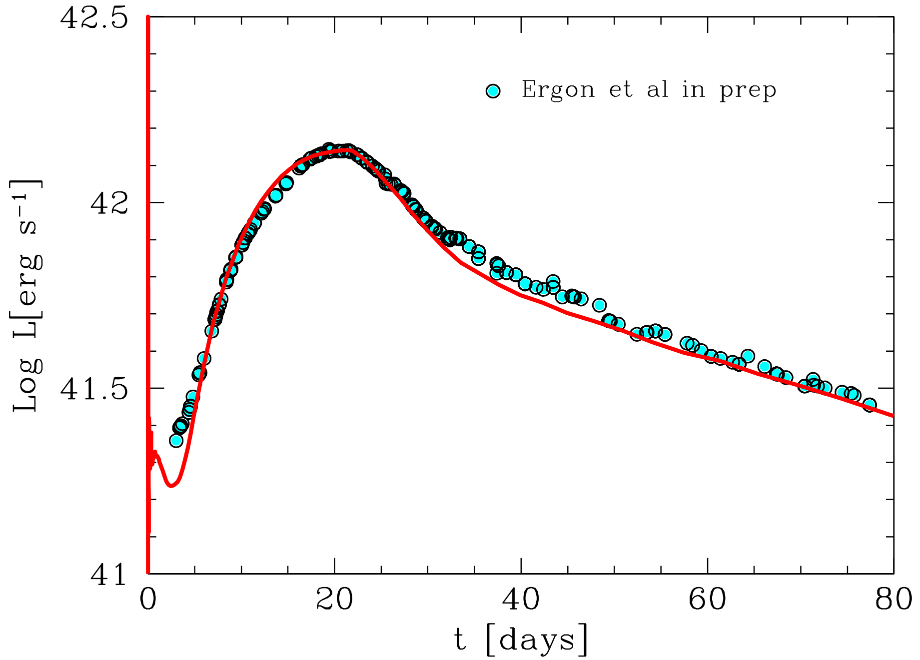
- We tested envelopes with different radii attached to the He4 model.
- Hydro models $\Longrightarrow$ extended progenitor with $R \gtrsim 200 R_\odot$ consistent with the YSG star

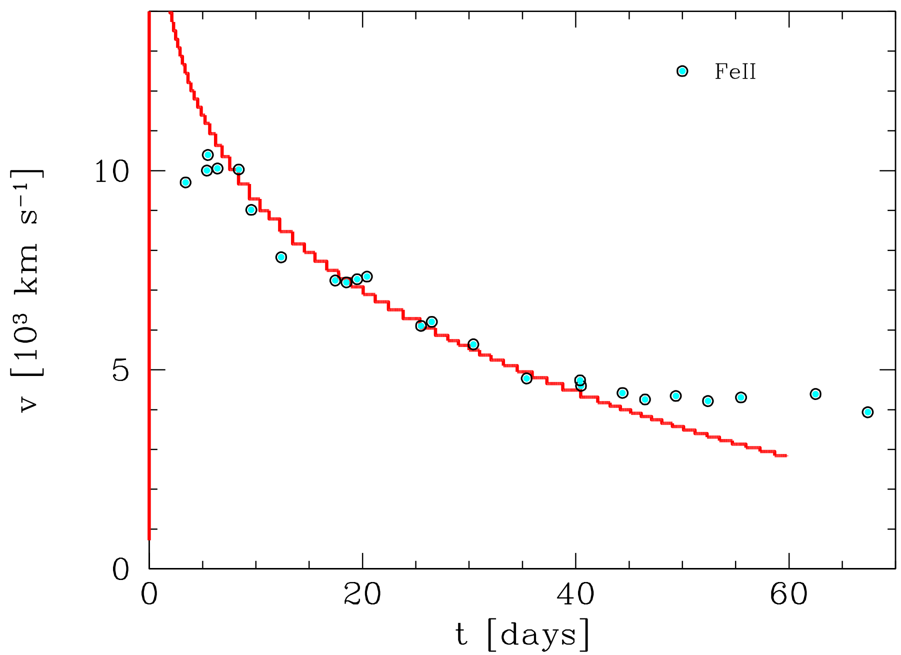


Bersten et al. 2012

Light Curve Model of SN 2011dh

- He core mass $M(\mathrm{He}) \approx$ 4 $M_\odot$ ($M_0 = 12 - 15 M_\odot$), $E_{\mathrm{exp}} = 8 \times 10^{50}$ erg and $M_{\mathrm{Ni}} = 0.06\ M_\odot$





Light Curve Model of SN 2011dh

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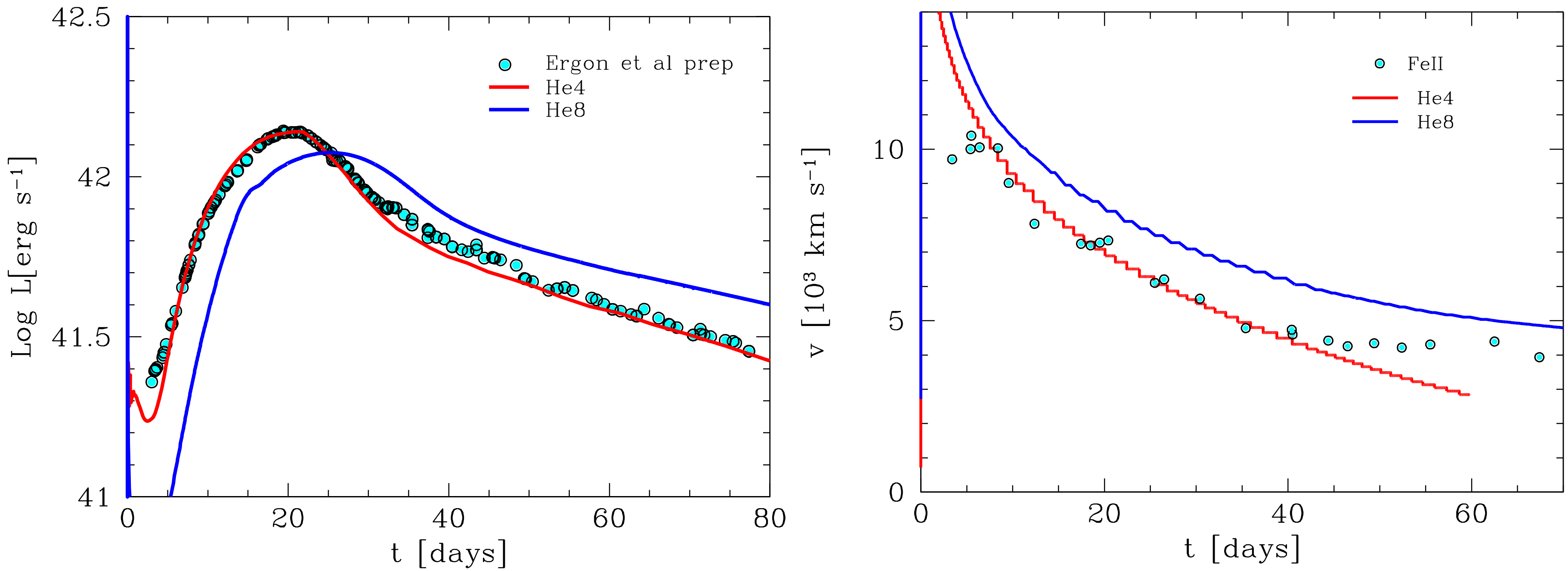
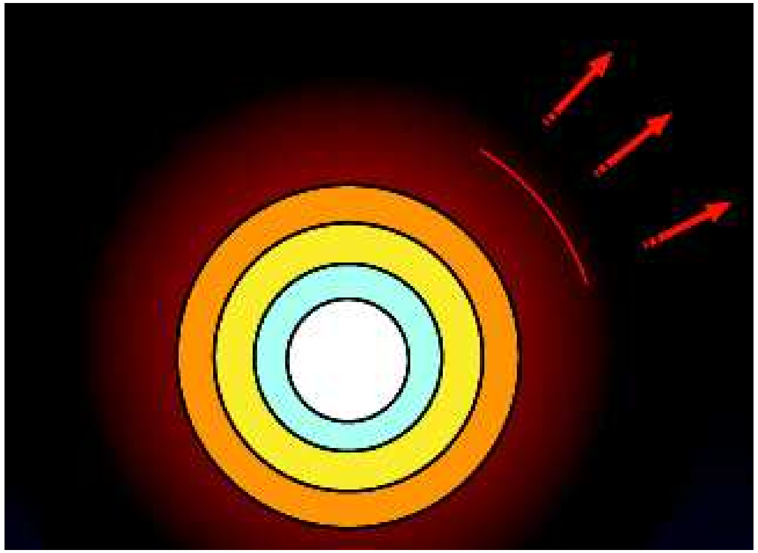
- $M(\mathrm{He}) \gtrsim 8$ ($M_0 \gtrsim 25\ M_\odot$) ruled out
- How was the H envelope expelled?



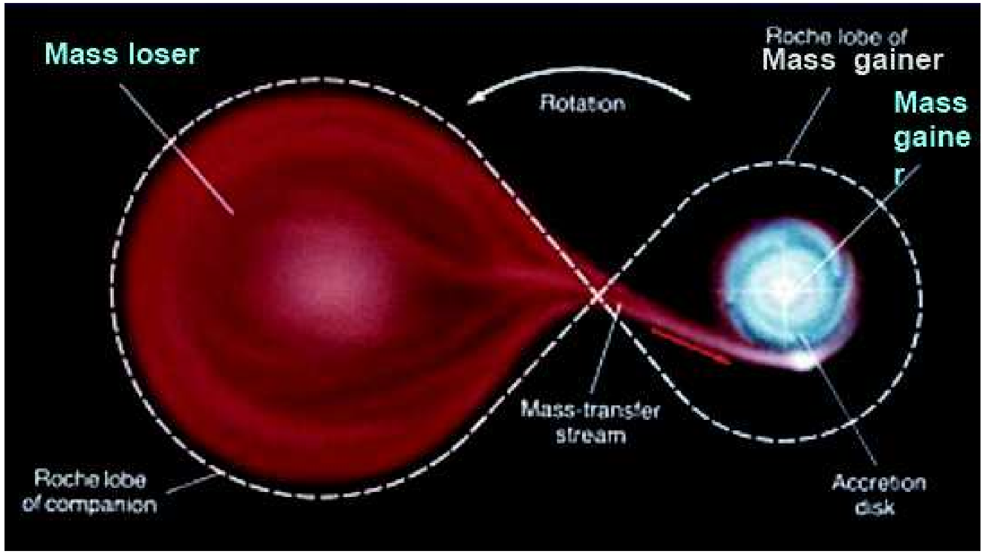
Mass-loss Mechanism

- Single, massive ($\gtrsim 25\ M_\odot$) Wolf-Rayet stars with strong winds $\Longrightarrow$ He core mass $\gtrsim 8\ M_\odot$ $\Longrightarrow$ unlikely for SN 2011dh
- Interacting binaries can make lower-mass stars lose their envelopes

Single-star mass-loss



Binary-star mass-transfer

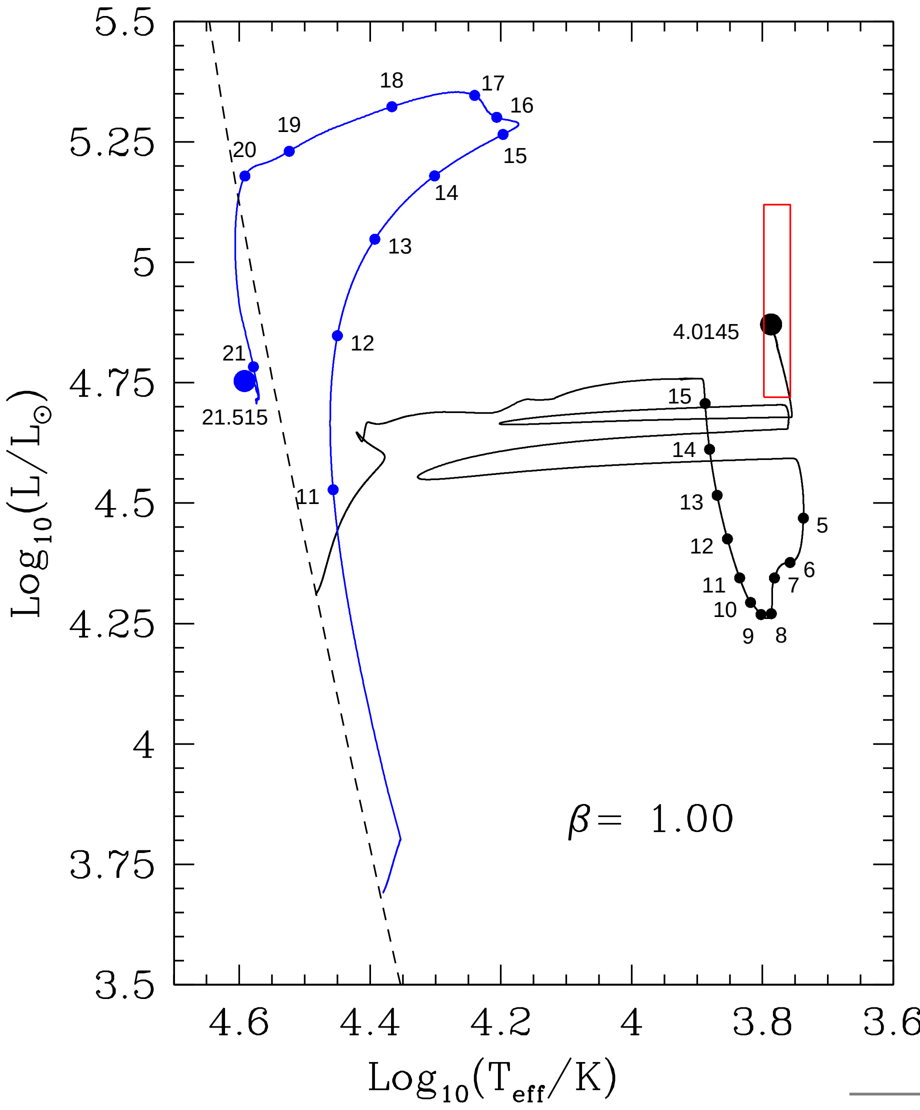


SN 2011dh: Binary Evolution

- Close binary system of 16 $M_\odot$ + 10 $M_\odot$, and $P = 100$ days

- Primary (donor) star ends as YSG with:
  - He core mass: $\approx 4\ M_\odot$
  - H mass: $\approx 5 \times 10^{-3} M_\odot$

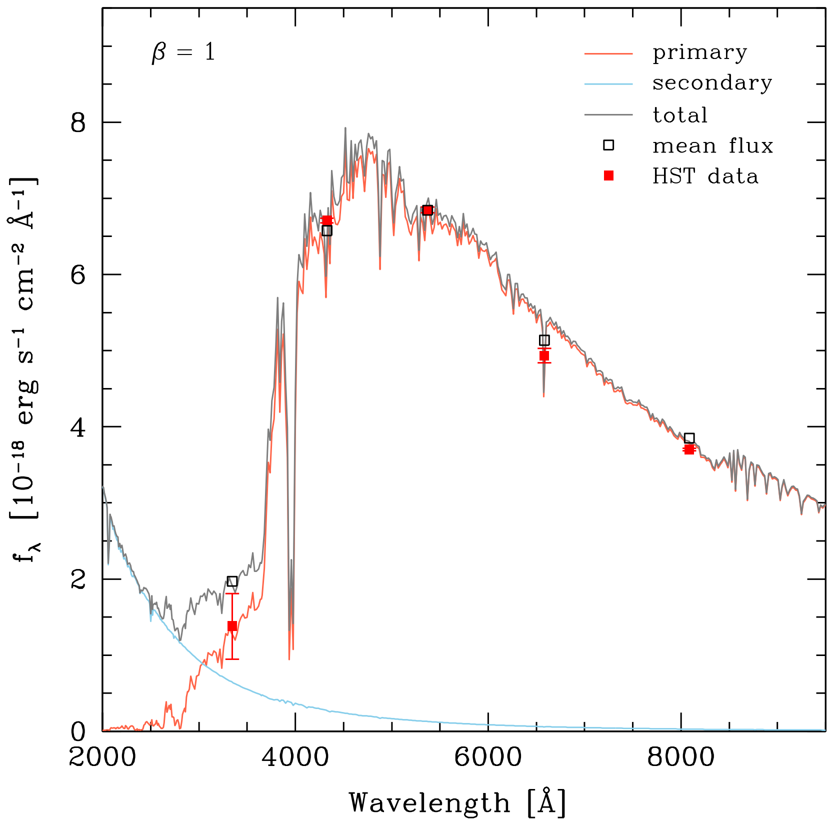
- Very hot (blue) companion star remains

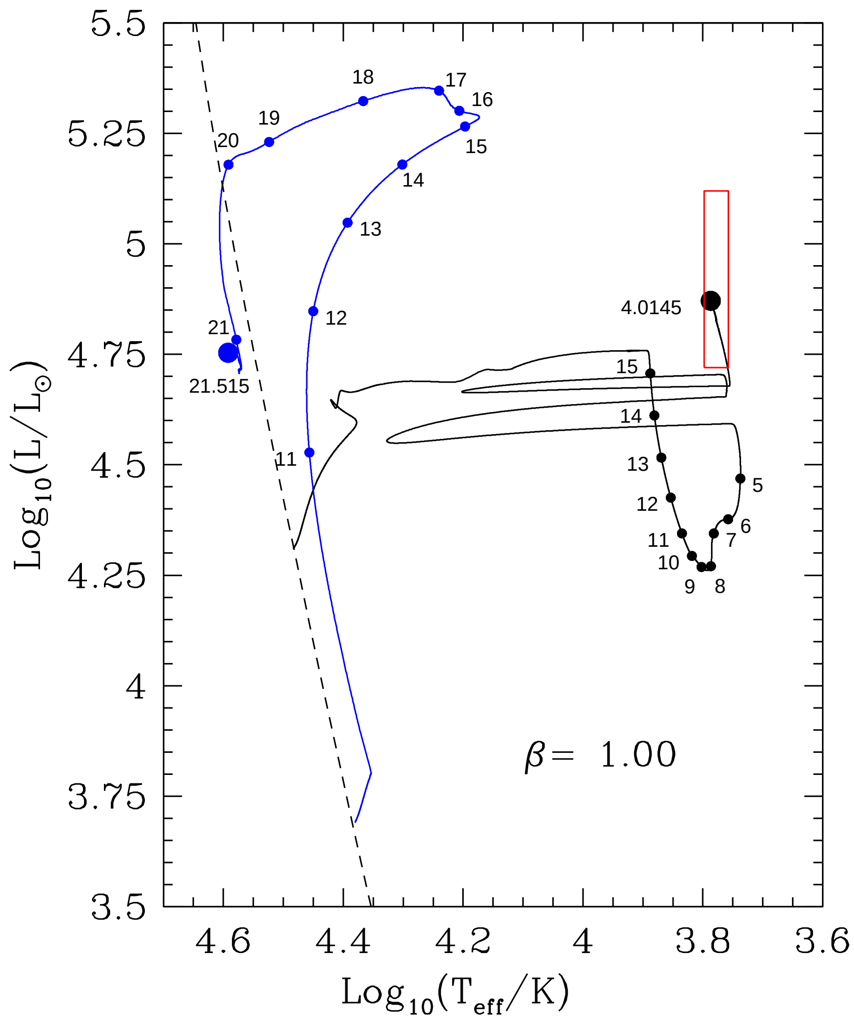


Benvenuto, Bersten & Nomoto, ApJ accepted

Companion Star

- Marginal detection in the bluest band of HST imaging
- It can be recovered with future observations





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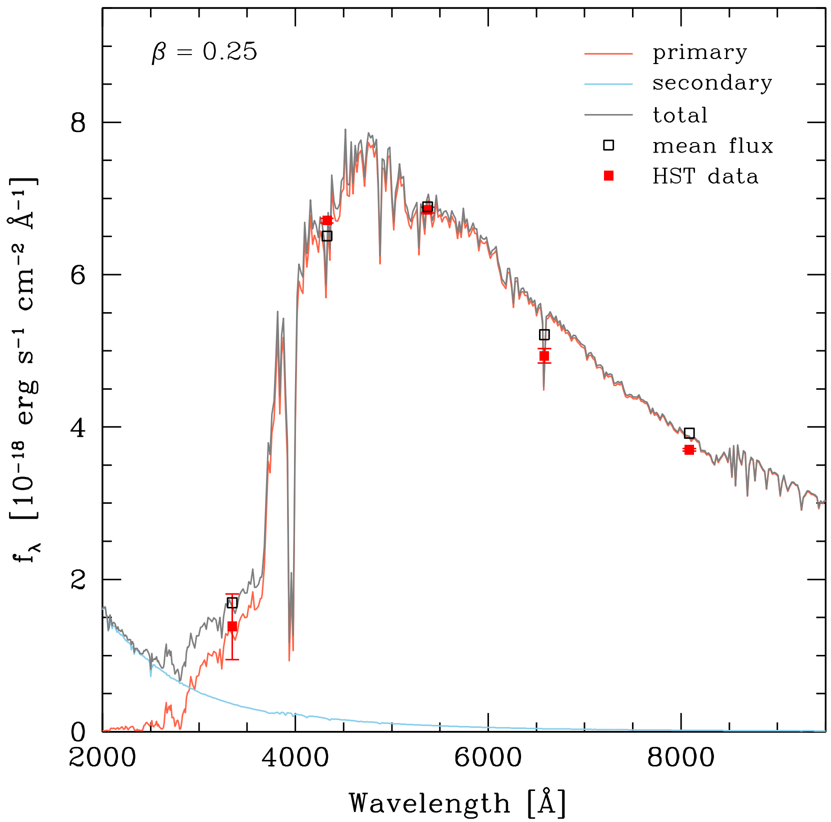

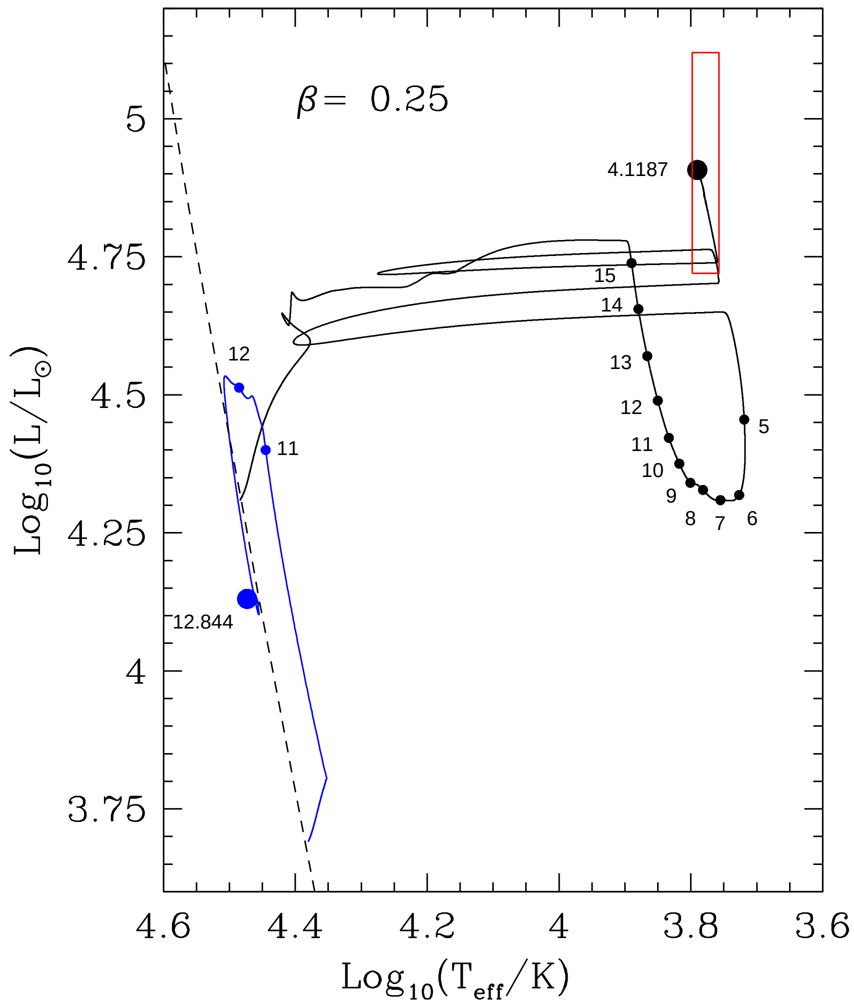

Summary

- Hydrodynamical modeling is a useful tool to derive physical properties of SN progenitors and thus test stellar evolution models

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.

Summary

- Hydrodynamical modeling is a useful tool to derive physical properties of SN progenitors and thus test stellar evolution models

SN 2011dh:

- Hydrodynamical models of SN 2011dh
  - Large radius ($R \sim 200 R_{\odot}$), consistent with pre-SN imaging, required to reprocude the early light curve.
  - He core mass $\gtrsim$ 8 $M_{\odot}$ ($M_0 \gtrsim$ 25 $M_{\odot}$) ruled out $\Longrightarrow$ single-star progenitor unlikely
- Binary evolution models of SN 2011dh
  - Natural explanation of YSG star as pre-SN, with just enough H to produce a type IIb event
  - Predict the existence of a very hot companion, which can be tested in the near future