A double-peaked ^{56}Ni distribution for SN 2008D

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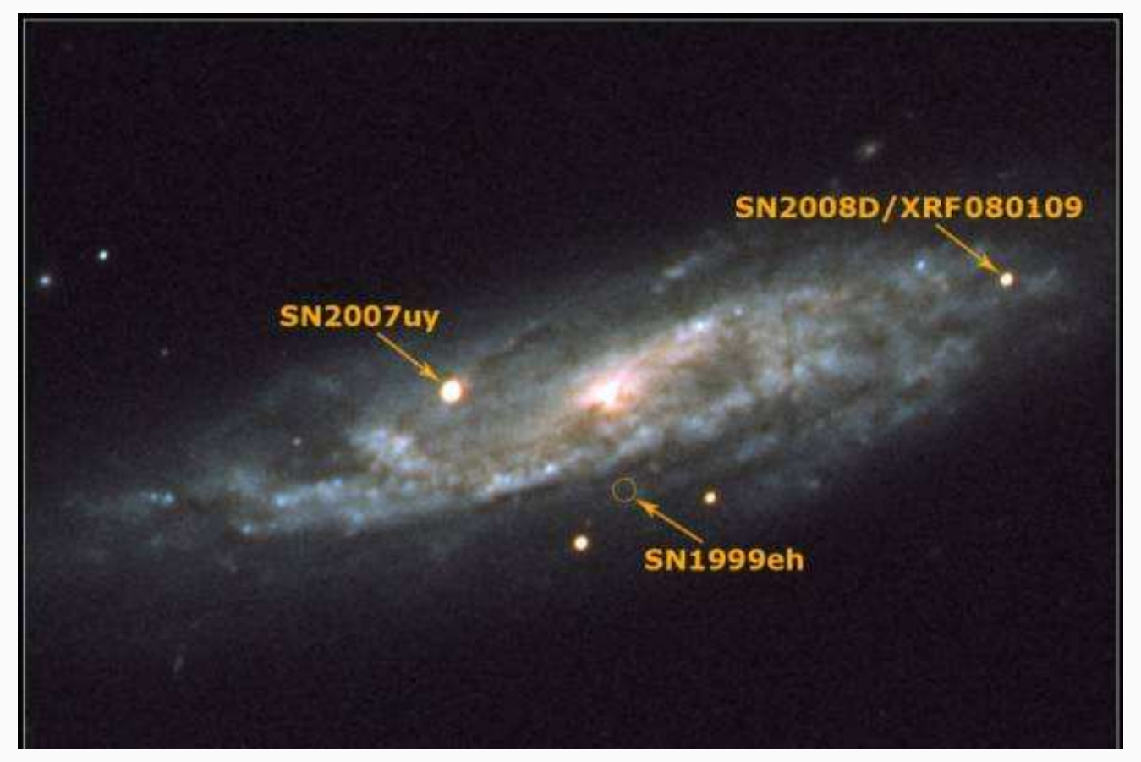


Credit: NASA/Phillip Newman

Abstract

We present a model for the Type Ib SN 2008D, associated with the X-ray Flash 080109, which assumes a double-peaked ^{56}Ni distribution. This assumption is introduced to explain the early behavior observed in the light curve a few days after the explosion. The presence of this high-velocity radioactive material may be caused by the formation of jets during the explosion. We briefly discuss the alternative scenarios that have been suggested for this supernova.

Introduction

SN 2008D attracted a lot attention due to its unusual features:

- Initial broad spectral lines as in Type Ic HNe
- Development of He lines ⟶ transition to Type Ib
- Associated weak X-ray flash (XRF)
  - Thermal ⟶ $R = 9\ R_\odot$ (Chevalier & Fransson 2008; CF08),
  - Non-thermal:
    - shock breakout in dense CSM (Soderberg et al. 2008)
    - mildly relativistic jet (Mazzali et al. 2008), and
- Early UV/optical observations

The observed bolometric LC of SN 2008D shown here (cyan dots) are taken from Modjaz et al. (2009), and the expansion velocities are from Tanaka et al. (2009) (T09).

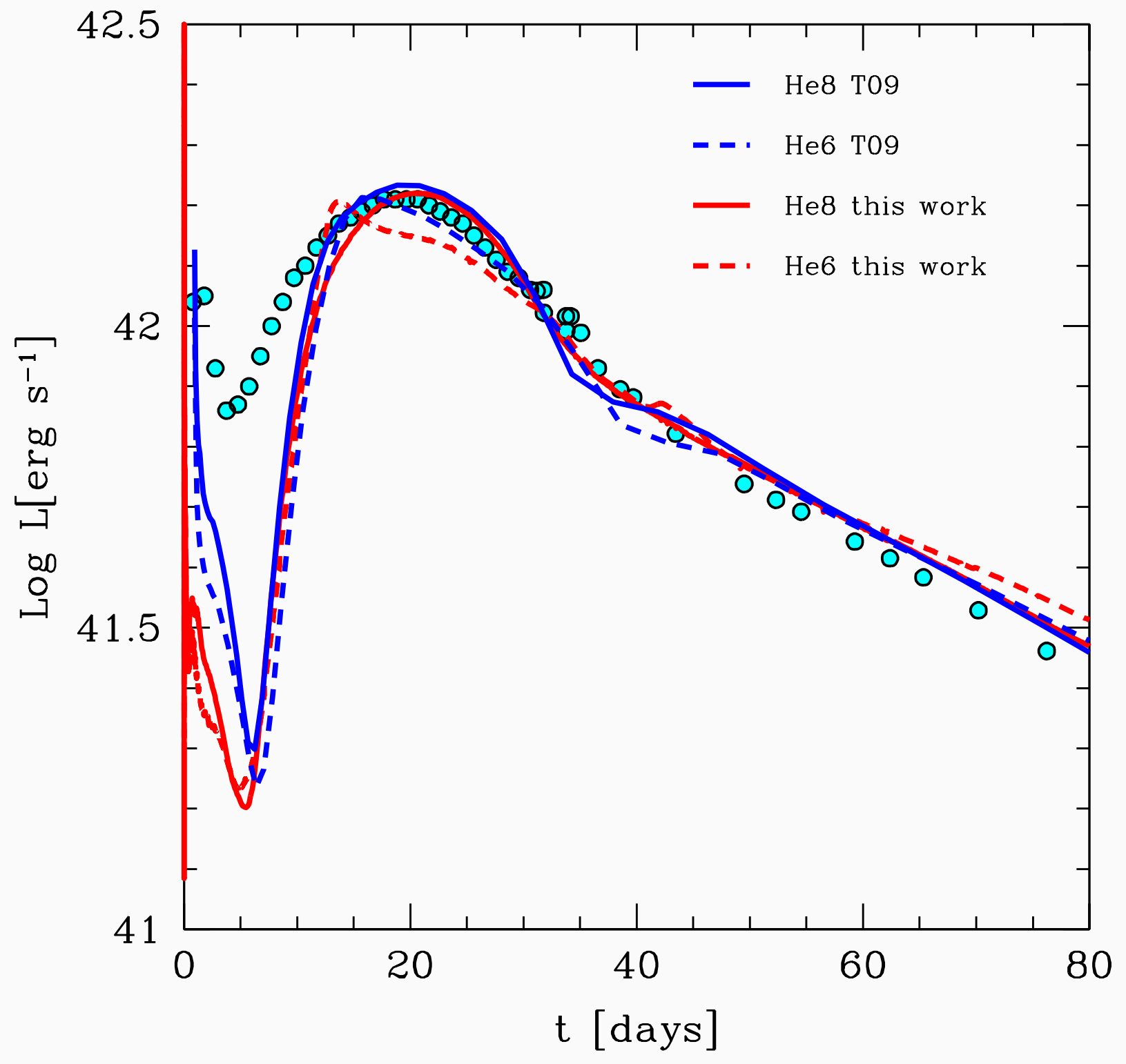
Light Curve Models

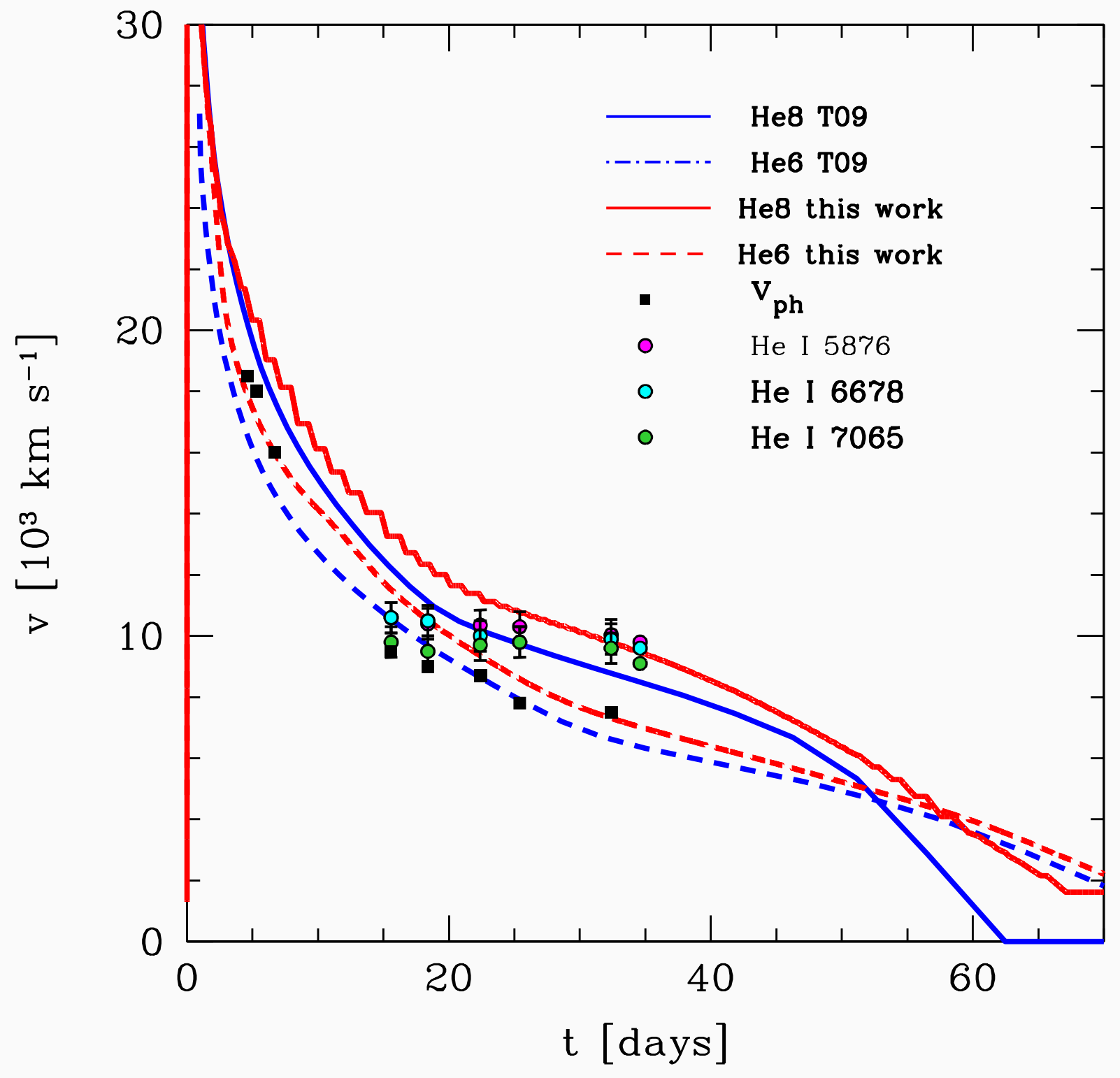
- One-dimensional, Lagrangian, flux-limited, hydrodynamical code including γ-ray transfer in gray approximation for any distribution of ^{56}Ni (Bersten et al. 2011)
- T09 found good fits for $t > 4$ d using:
  - He core of 6 $M_\odot$, $R = 2.2\ R_\odot$, $E_K = 3.7$ foe, and $M_{\rm Ni} = 0.065\ M_\odot$ (He6)
  - 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)
- We adopt the same pre-SN models and physical parameters as above
- Unlike T09, we solve hydrodynamics coupled to radiative transfer ⟶ we can consistently model the earliest phases

Comparison with T09

Bolometric LC and photospheric velocity evolution for models He6 and He8

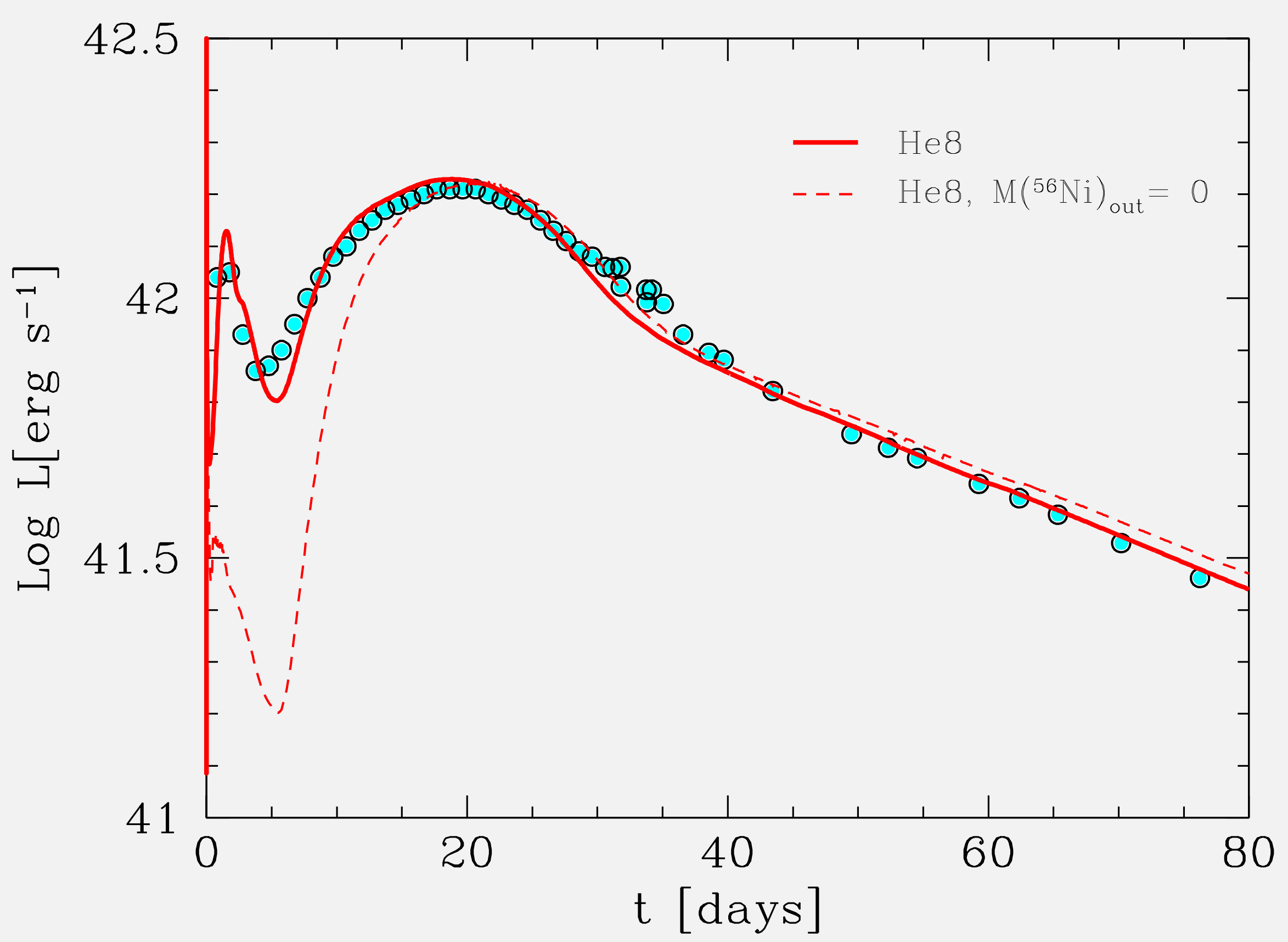
- Very good agreement between models
- Observed early LC behavior is not well reproduced





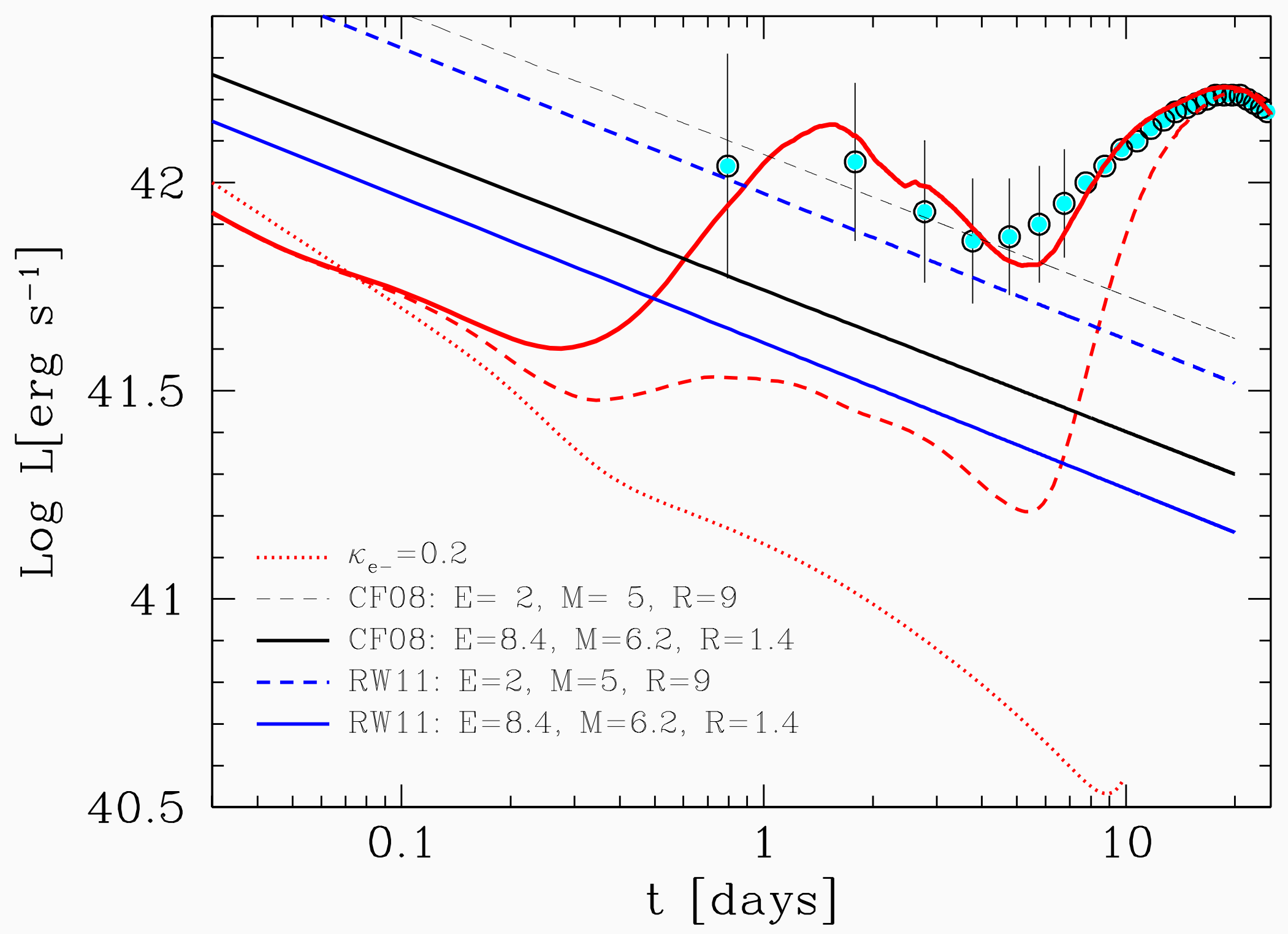
Optimal Model

Extra energy in the outer layers is needed in order to reproduce the early LC.
We artificially placed $0.02\ M_\odot$ of ^{56}Ni at $v > 23,000$ km s^{-1} (see schematic plot to the right), and keep all the other explosion parameters fixed.
This material may have been carried by a jet produced during an aspherical explosion as suggested by spectropolarimetry (Maund et al. 2009).



Comparison with Analytic Models

Models for early emission by CF08 (including photon diffusion), and Rabinak & Waxman (2011) (RW11) assuming: (1) self-similar solution during free-expansion phase, (2) constant opacity, and (3) $\rho \propto r^{-n}$ valid while the photosphere is in the outer shock-accelerated part of the ejecta.



- $\kappa_{e^-} = 0.2$ g cm^{-2} ⟶ breaks at $t \approx 0.5$ d
- $t \approx 1.5$ d ⟶ photosphere begins to recede in ejecta
- $R = 9\ R_\odot$ and $E = 2$ foe give good fit as opposed to $R = 1.4\ R_\odot$ and $E = 8.4$ foe

References

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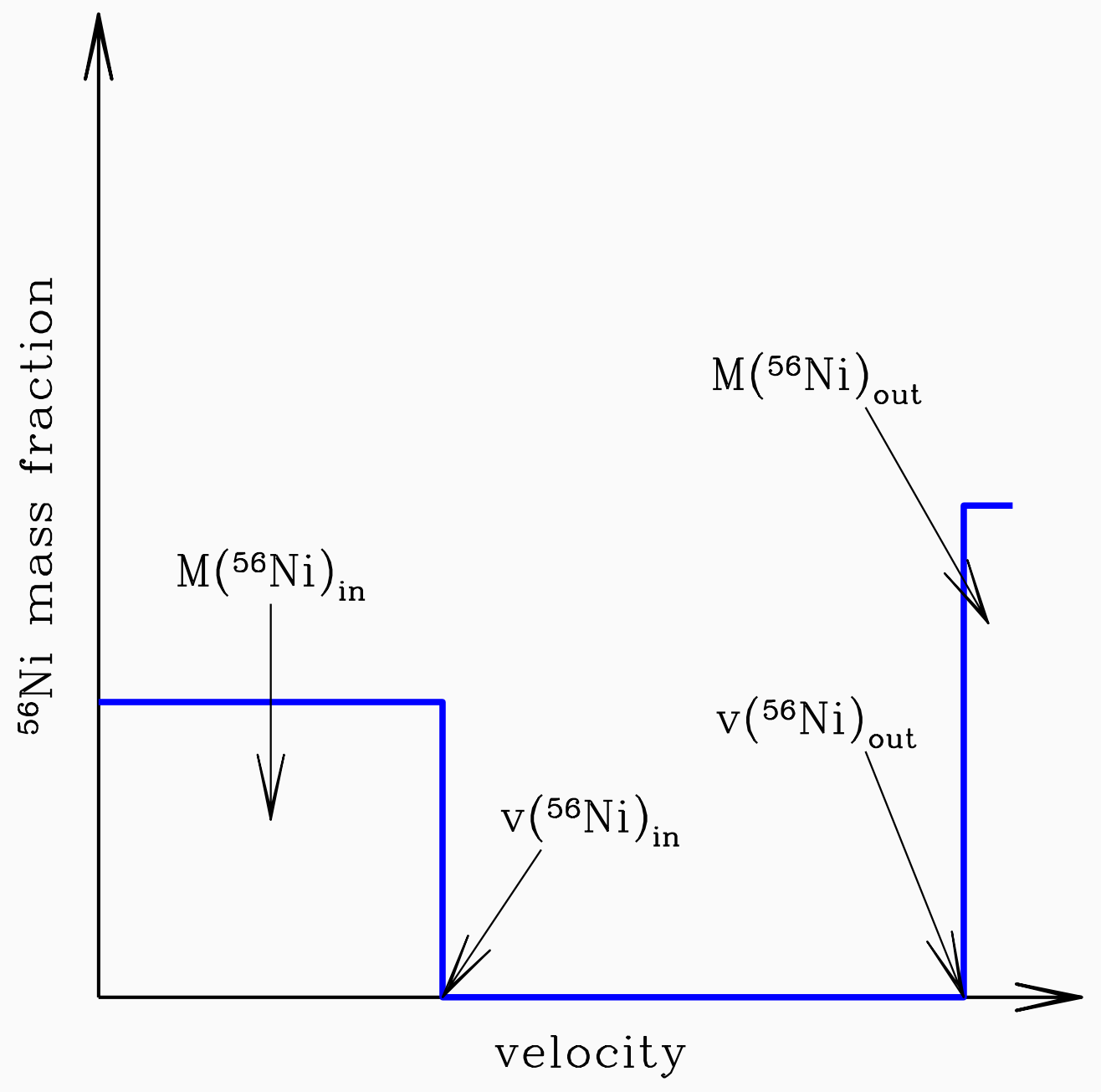
Double-peaked ^{56}Ni Distributions

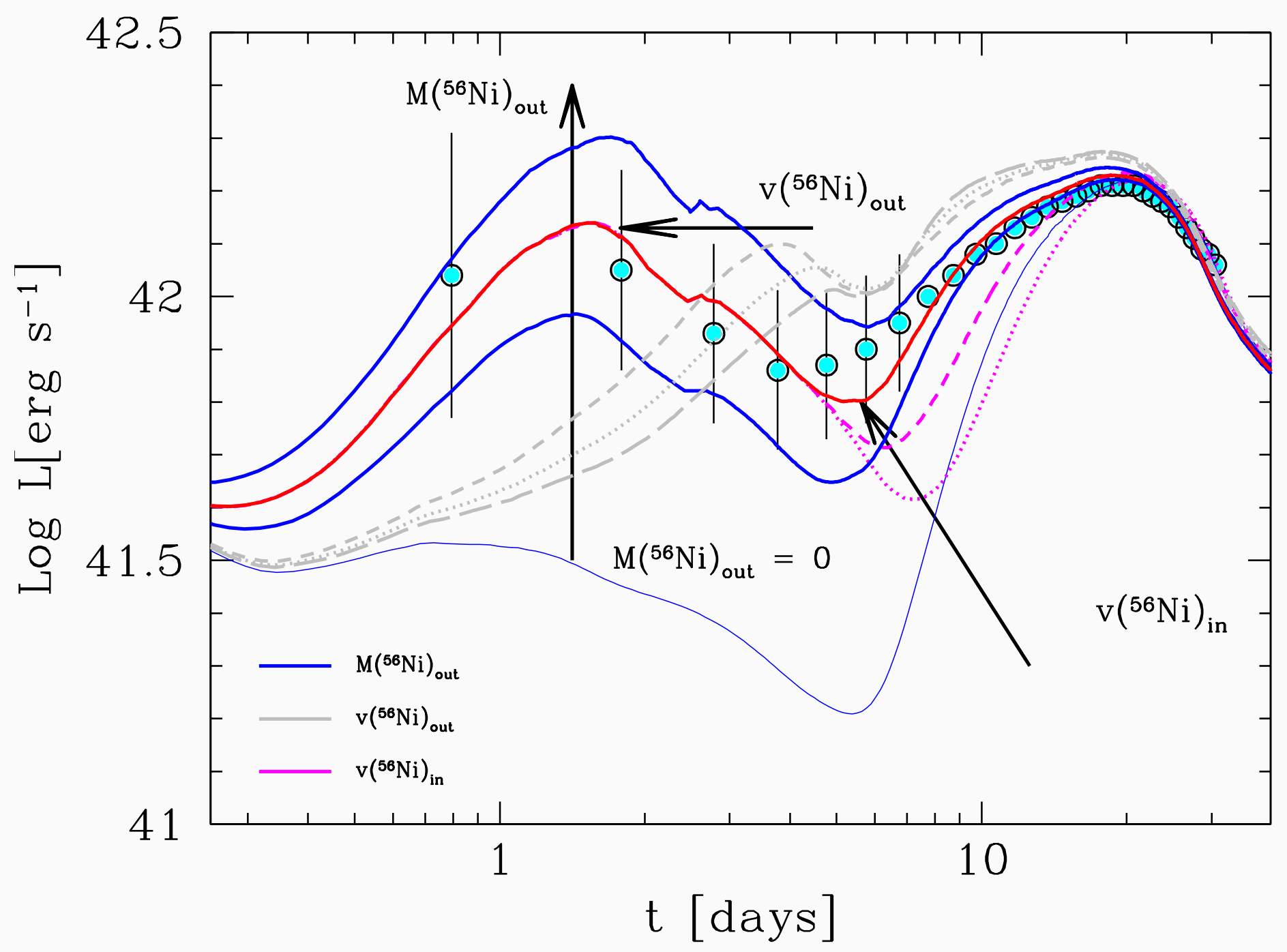
Effect of ^{56}Ni distribution on the early LC characterized by three parameters: $M(^{56}{\rm Ni})_{\rm out}$, $v(^{56}{\rm Ni})_{\rm out}$ and $v(^{56}{\rm Ni})_{\rm in}$

- Larger $M(^{56}{\rm Ni})_{\rm out}$ ⟶ more luminous first peak
- Higher $v(^{56}{\rm Ni})_{\rm out}$ ⟶ earlier first peak
- Lower $v(^{56}{\rm Ni})_{\rm in}$ ⟶ deeper and later minimum

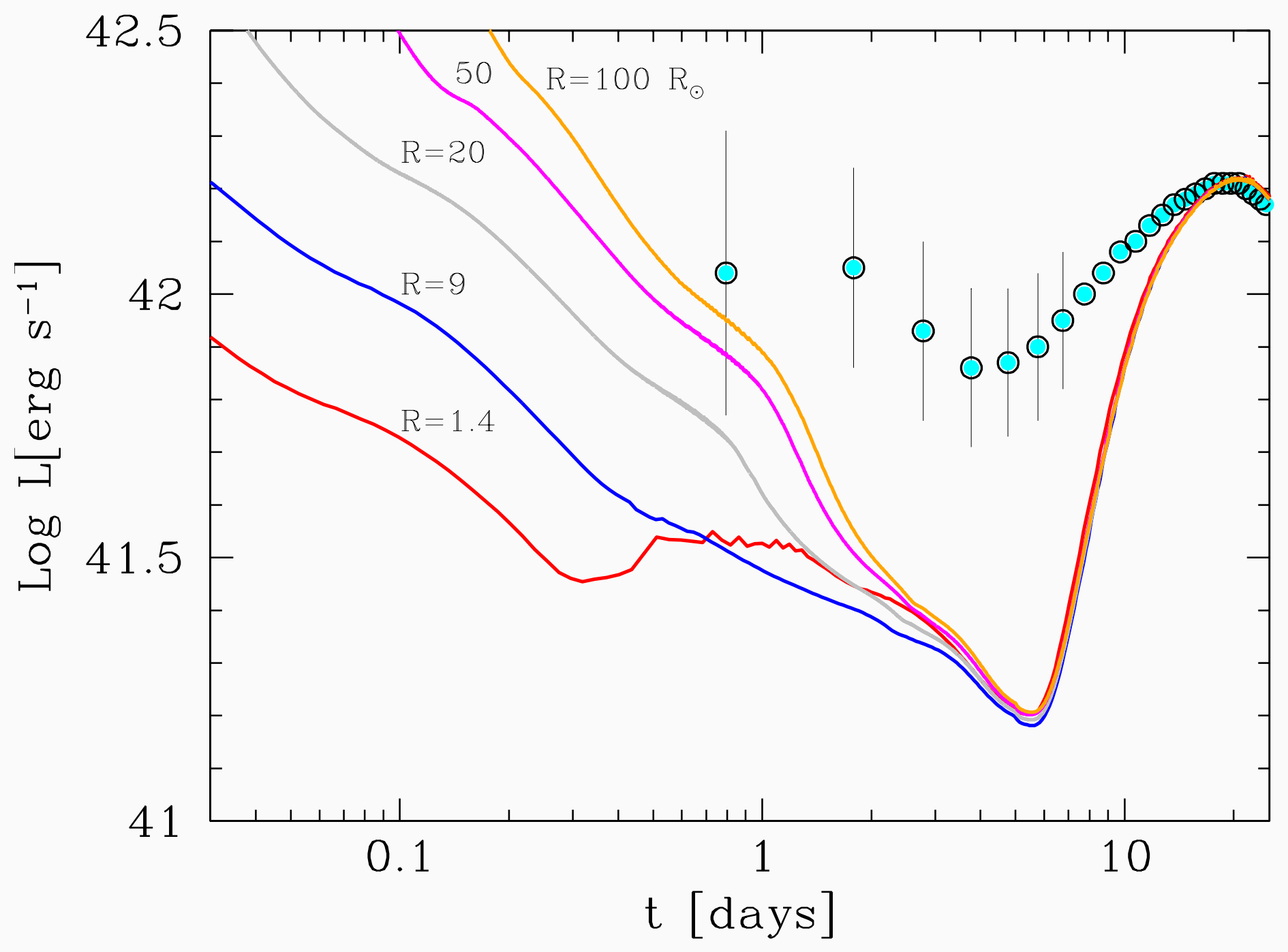
For the optimal model (left) we adopted:

$M(^{56}{\rm Ni})_{\rm out} = 0.02\ M_\odot$, $v(^{56}{\rm Ni})_{\rm out} = 23,000$ km s^{-1}, and $v(^{56}{\rm Ni})_{\rm in} = 10,000$ km s^{-1}





Different Radii



We tested envelopes with different radii attached to the He8 model.

Models with $R \sim 100\ R_\odot$ are more consistent with the early-time data.

Differences in LCs due to the radius are relevant only until $t \sim 1$ d.

Summary

The early behavior of SN 2008D can be very well reproduced by assuming $0.02\ M_\odot$ of ^{56}Ni mixed out to high velocity ($v > 20,000$ km s^{-1}). This type of ^{56}Ni distribution may indicate the presence of jets.

We cannot reproduce the early LC with large initial radii (up to 100 $R_\odot$) and leaving the other explosion parameters fixed.

Our simulations indicate that differences in the progenitor radius are noticeable only until $t \sim 1$ d. Unfortunately, no data of SN 2008D are available at such phases.

The validity of the analytic models is restricted to $t < 1$ d.