Early light curves of SNe Ia and ASASSN-14lp

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Motivation

What can we learn about SNe progenitors?

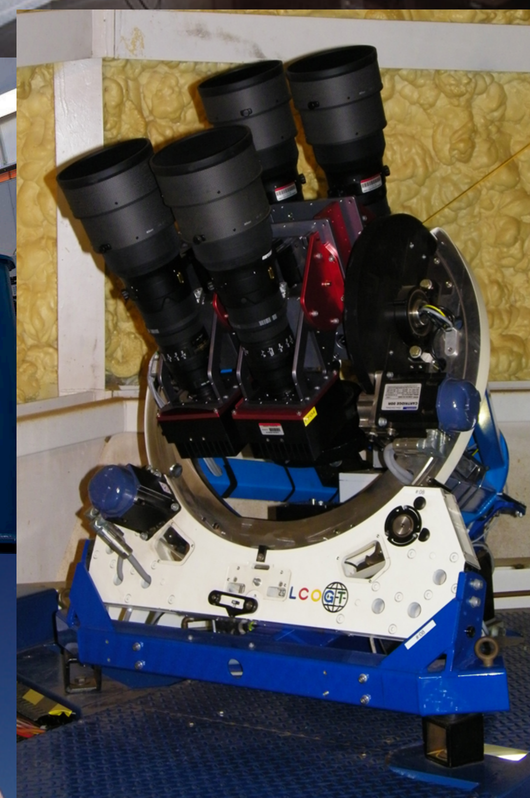
- Are all SNe Ia from M_{Ch} or a variety of white dwarf masses?
- What are the companion stars that donate mass?
- What is the nature of the explosive burning?
- What are the underlying causes for their diversity and various classes (91T, 91bg, etc)?

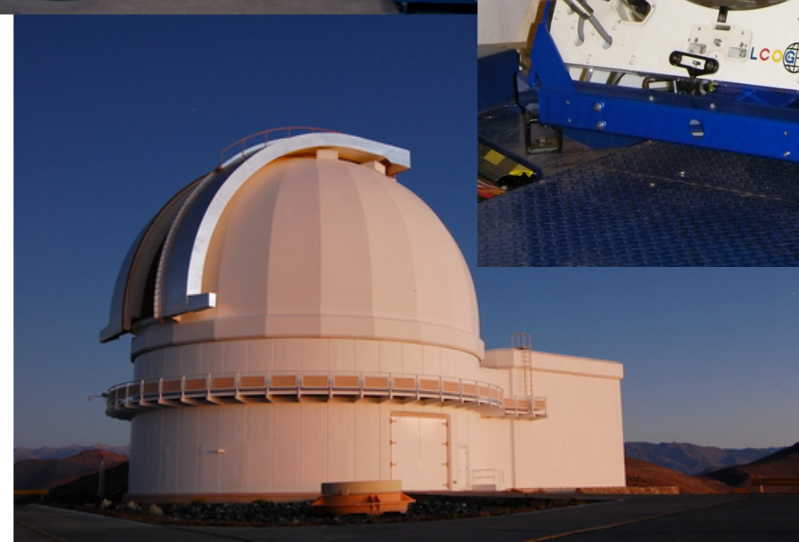
Early observations can provide unique information for answering these questions.

Transient observations

This is an ideal time for making these early observations:

- Palomar Transient Factor (PTF)
- Las Cumbres Observatory Global Telescope (LCOGT)
- All-Sky Automated Survey for Supernovae (ASAS-SN)
- Carnegie Supernova Project (CSP)



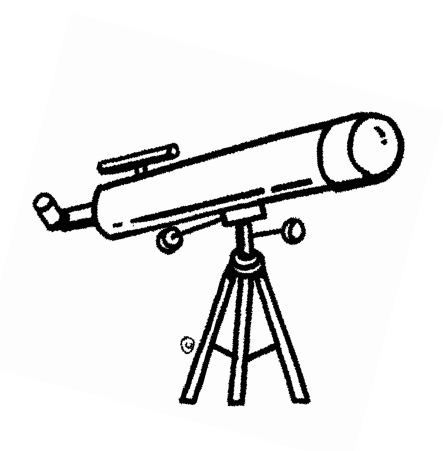


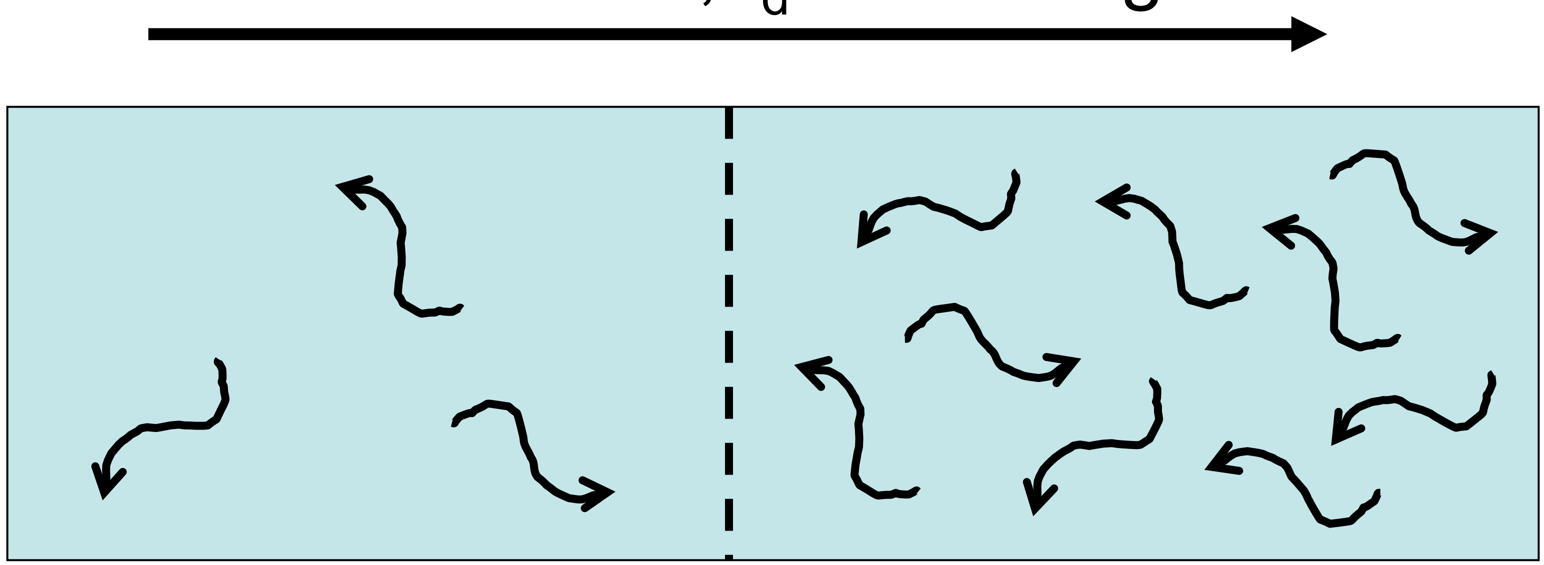
Probing an Exploding Star with Thermal Diffusion

Photons reach the surface on a "thermal diffusion time"

$$t_d \sim \tau \frac{r}{c} \;\; + \;\; \tau \sim \rho \kappa r \sim \frac{M\kappa}{r^2} \;\; = \;\; t_d \sim \frac{M\kappa}{rc}$$

Into the star, t_d increasing





What do we hope to actually measure?

Three main sources of emission:

1. Cooling of shock-heated white dwarf

2. Interaction of the ejecta with the companion

3. Radioactive heating from ^{56}Ni

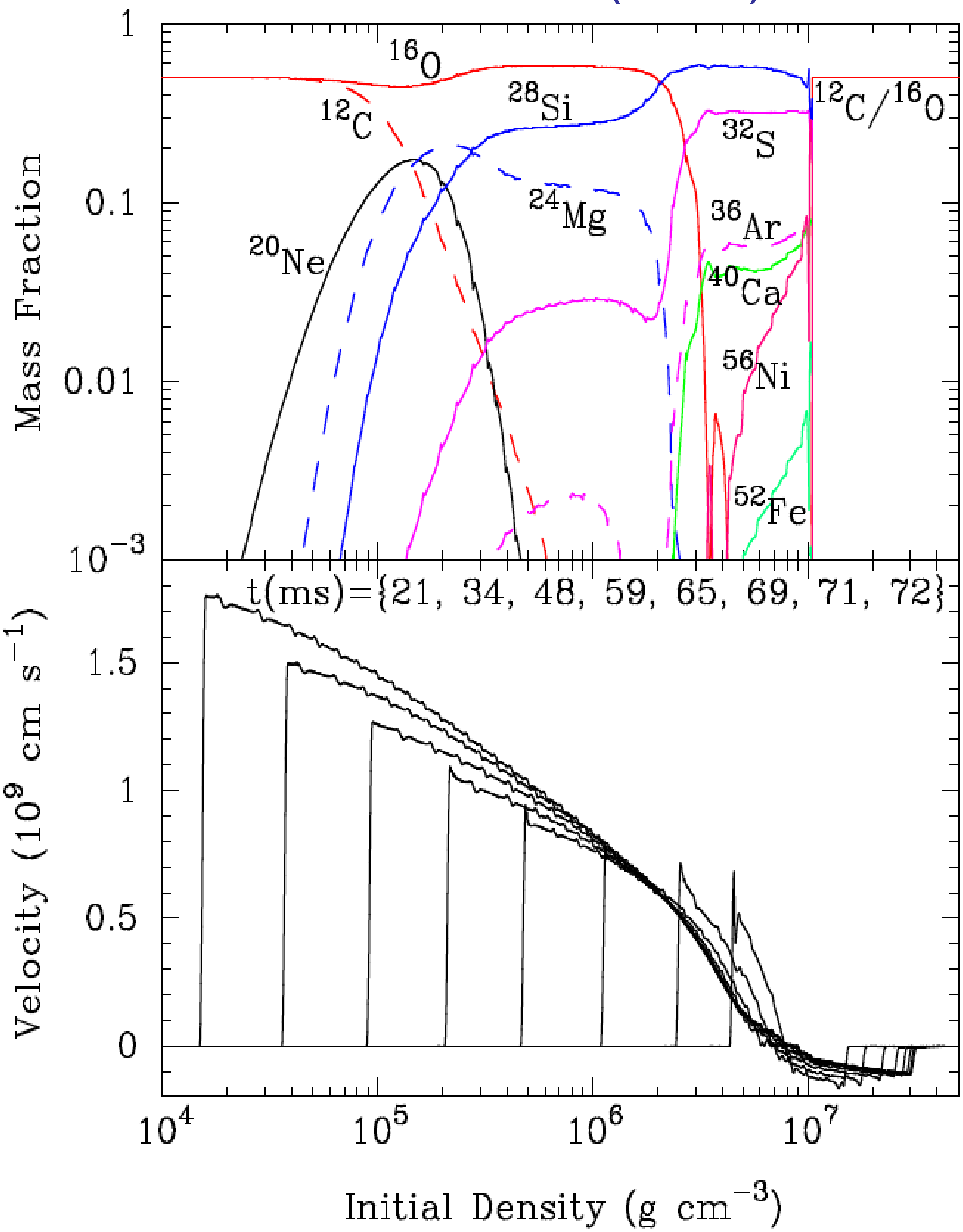
Shock-Heated Surface Layers

The first optical emission from SNe is shock cooling

Luminosity proportional to initial radius

$$L \sim \frac{R_0 c}{\kappa} \frac{E}{M}$$

Piro et al. (2010)



Back of the envelope shock cooling

Thermal diffusion timescale: $t \sim \frac{M\kappa}{rc}$

$$L \sim \frac{r^3 a T^4}{t} \sim \frac{r^4 c a T^4}{M\kappa} \sim \frac{R_0^4 c a T_0^4}{M\kappa} \sim \frac{R_0 c}{\kappa}\frac{E_0}{M}$$

$$T \propto r^{-1} \qquad R_0^3 a T_0^4 \sim E_0$$

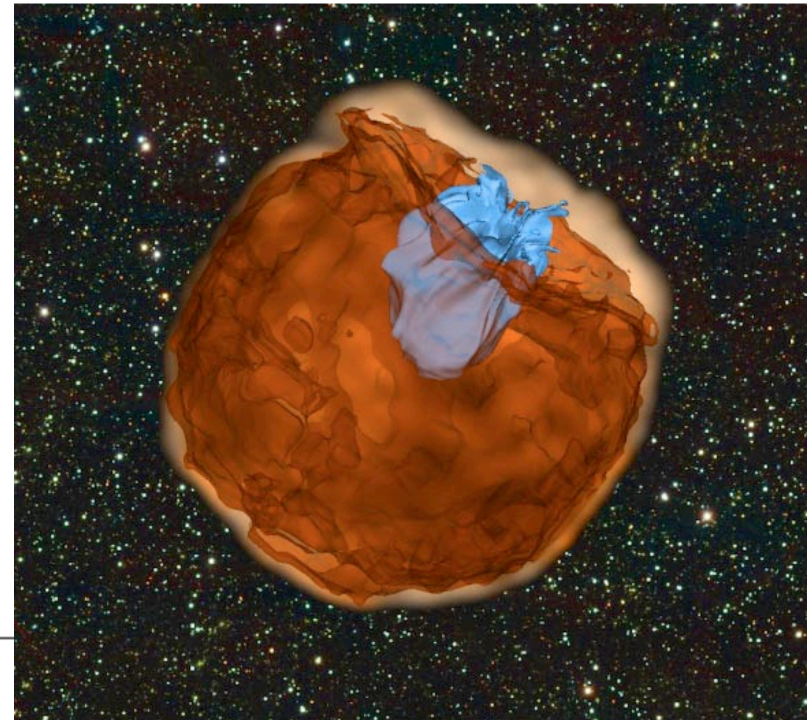
Luminosity is proportional to **progenitor radius!**

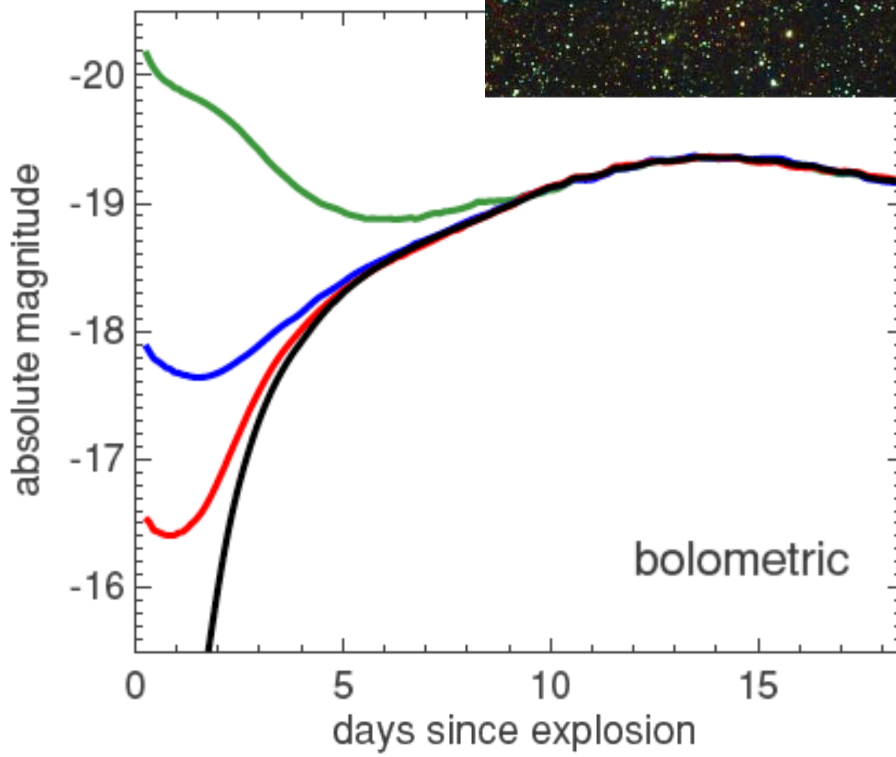
Interaction with Companion

Supernova ejecta slams into companion

Creates a funnel of hot emission

Emission roughly scales **proportional to to the companion radius** with a strong directional dependence (see Kasen 2010)

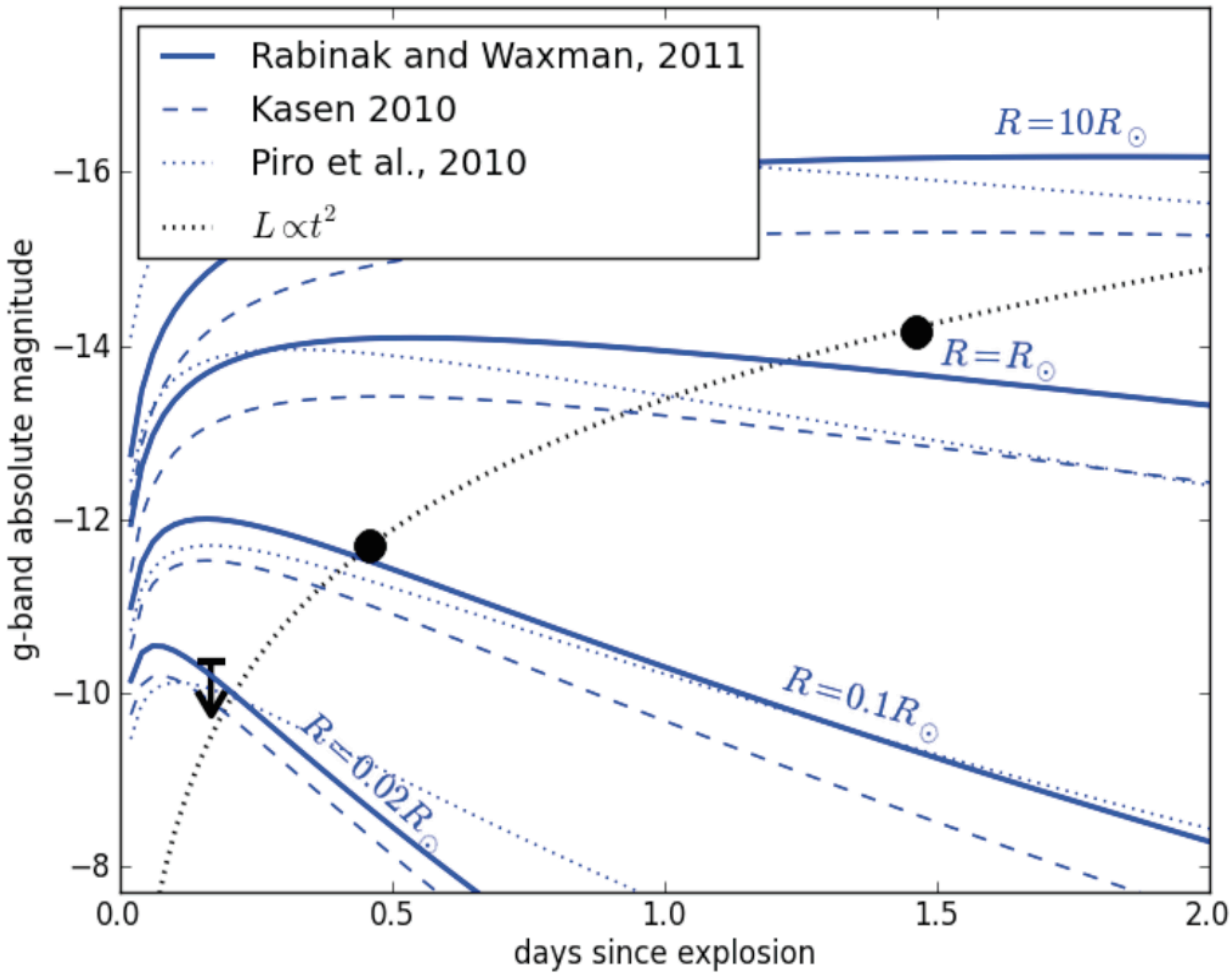




Rising Light Curve of SN 2011fe

Bloom et al. (2011) ApJL 744 17

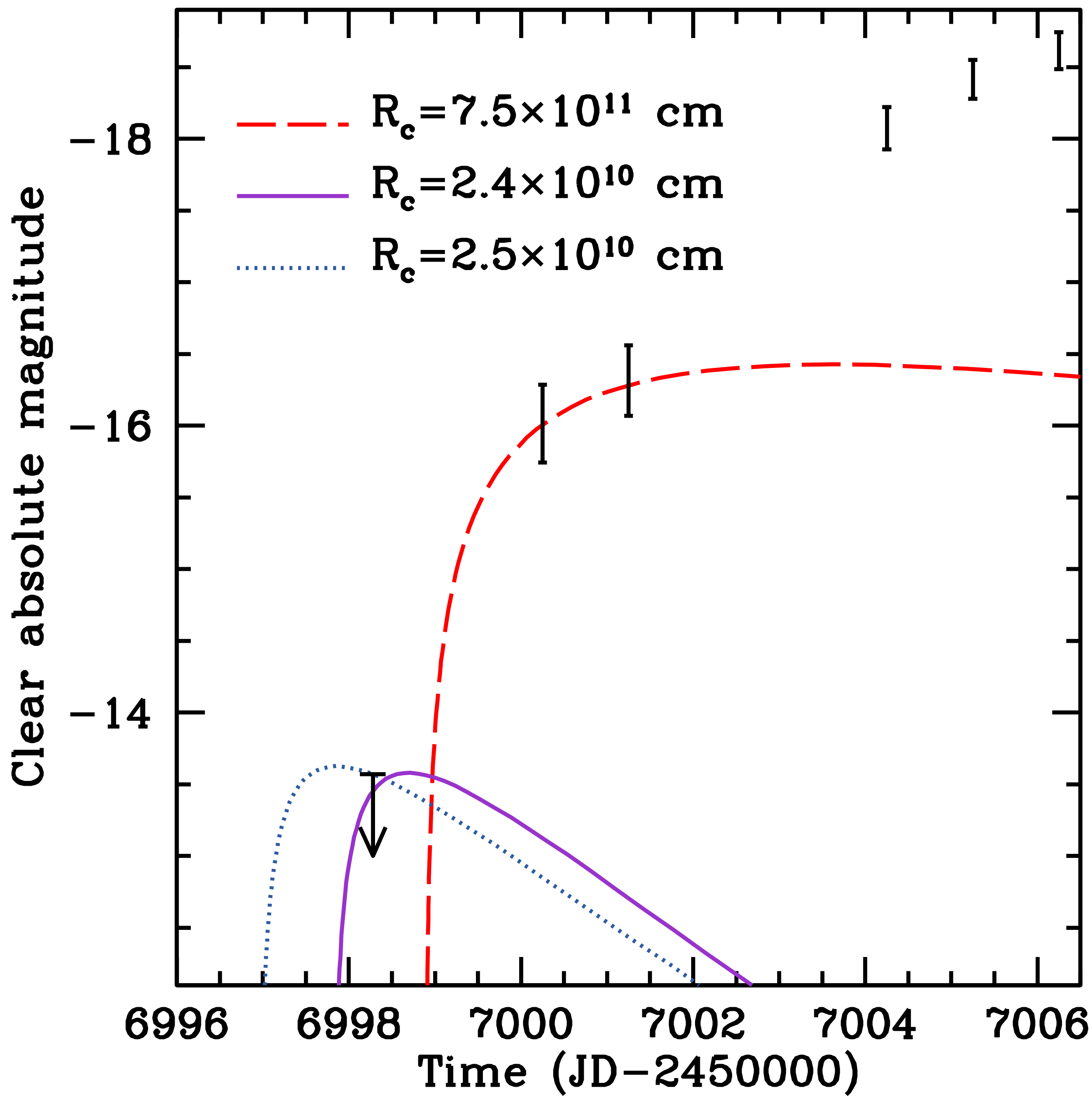
- No detection of cooling from shock heating
- Exploding star's radius is less than 2.2 R_{Earth}
- **First direct evidence that Type Ia SNe come from white dwarfs!**



The importance of the explosion time

Shappee, Piro, et al. (2015)

- Even without a clear shock detection, we would like to make constraints
- But constraints depend strongly on the **explosion time**
- What are the best ways to constrain the explosion time?



What about a t^2 rise?

Attempts have been made to estimate the explosion time by assuming a t^2 rise.

Problems:

- t^2 is not generally expected theoretically (Piro 2012)

$$L \propto \Delta M_{\rm diff} X_{56} \propto t^{2(1+1/n)/(1+1/n+\beta)} X_{56}$$

$$L \propto t^{1.8} X_{56}$$

- t^2 in a single band means bolometric certainly can't be t^2!
- Bolometric light curves (e.g., 2011fe, Piro & Nakar 2014) are not t^2

Maybe just fit arbitrary power law?

Using the velocity evolution

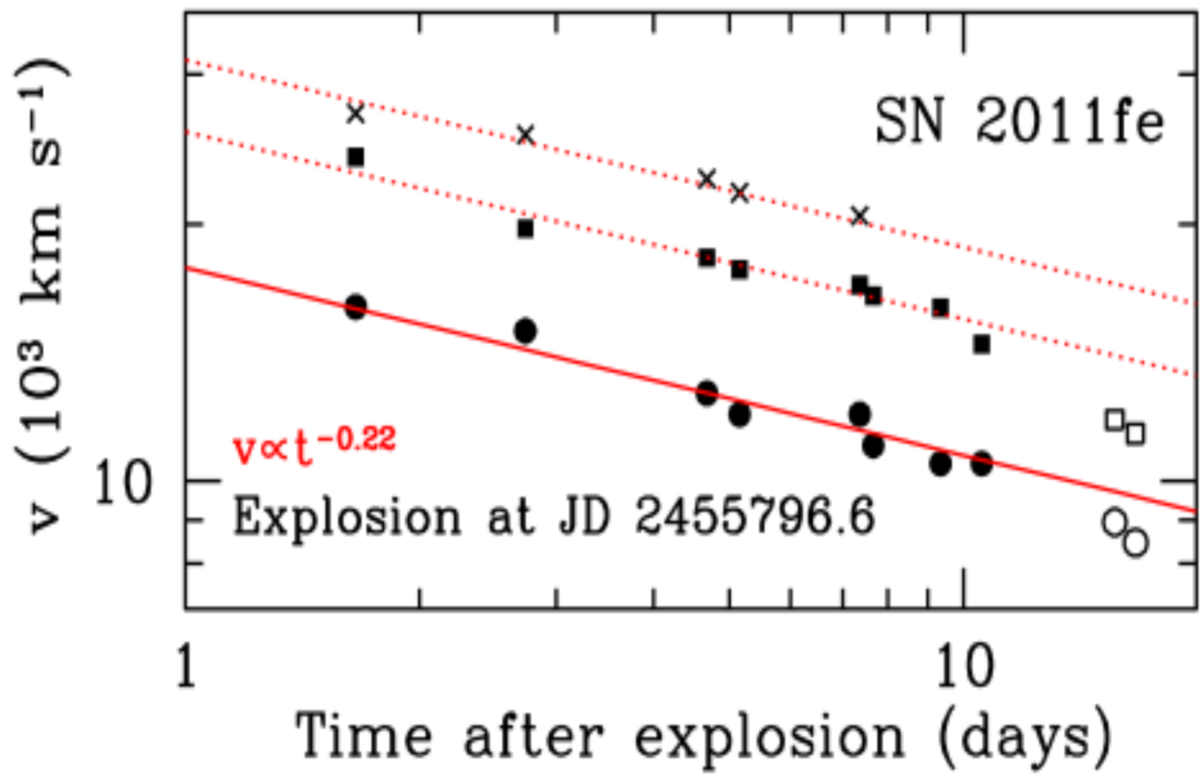
- For accelerating shock, the photophere evolves as

$$v_{\rm ph} \propto t^{-0.22}$$

- Fitting to power-law constrains the explosion time

- Unfortunately, power-law index is model dependent and cannot be fit independently

Piro & Nakar (2014)



Explosion time within ~0.5 days of estimate from light curve

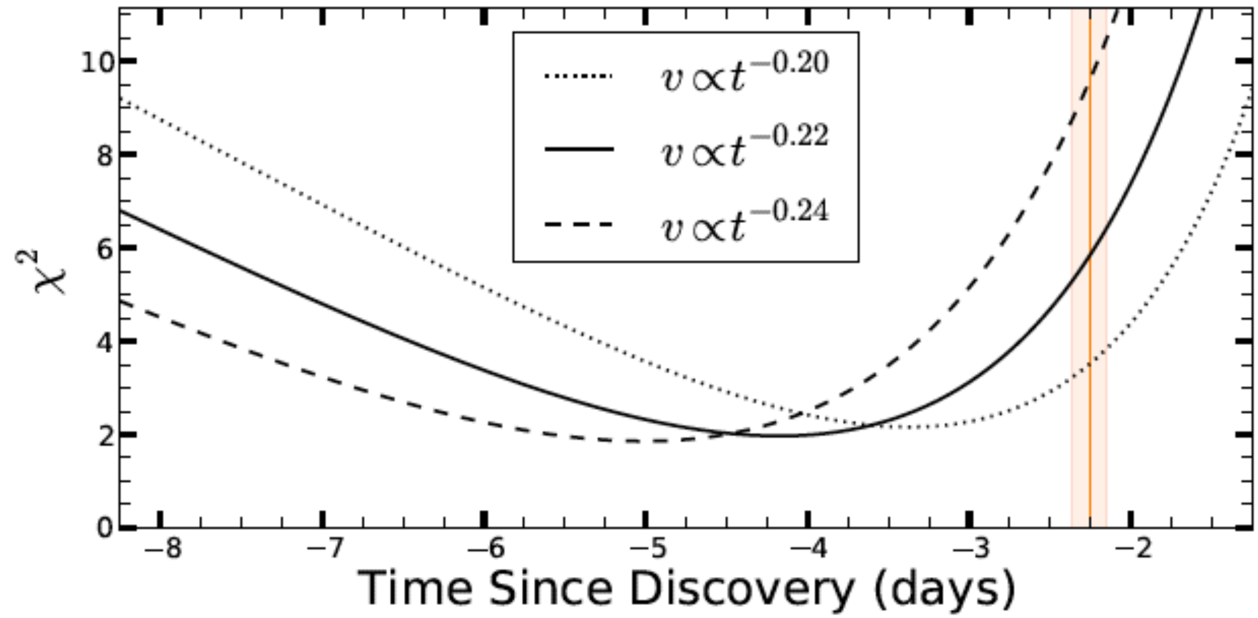
ASASSN-14lp

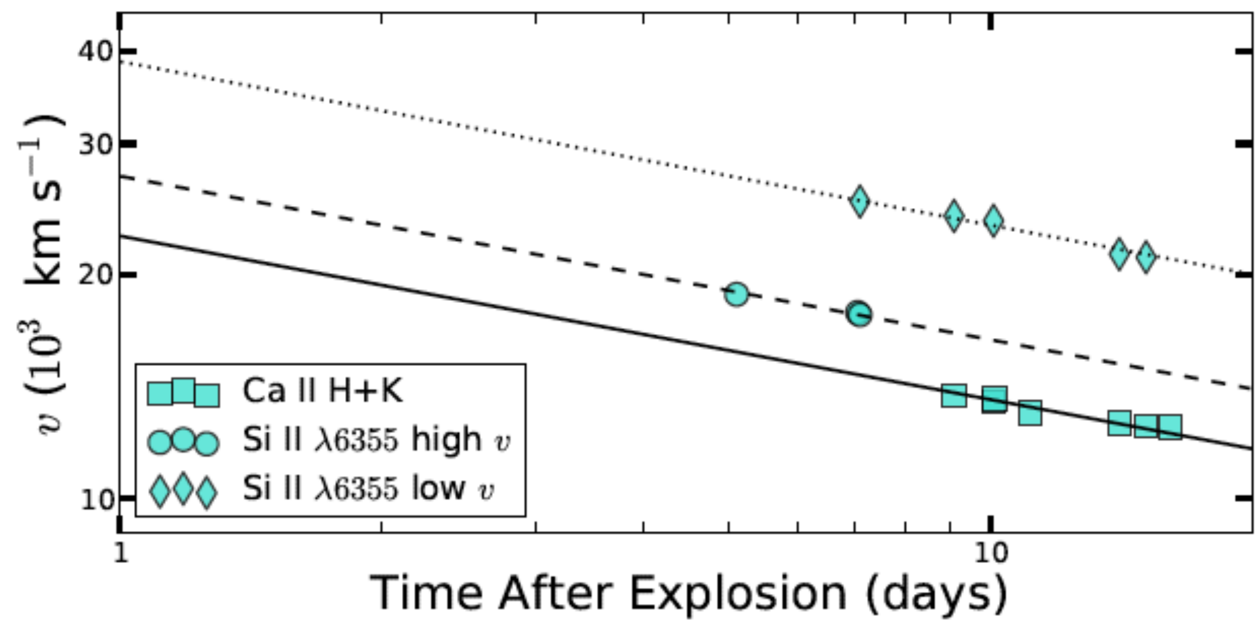
Shappee, Piro, et al. (2015)

SN Ia with early photometry and spectroscopy

Explosion time estimated by both extrapolating light curve and velocities

Explosion time estimates different by ~2 days!



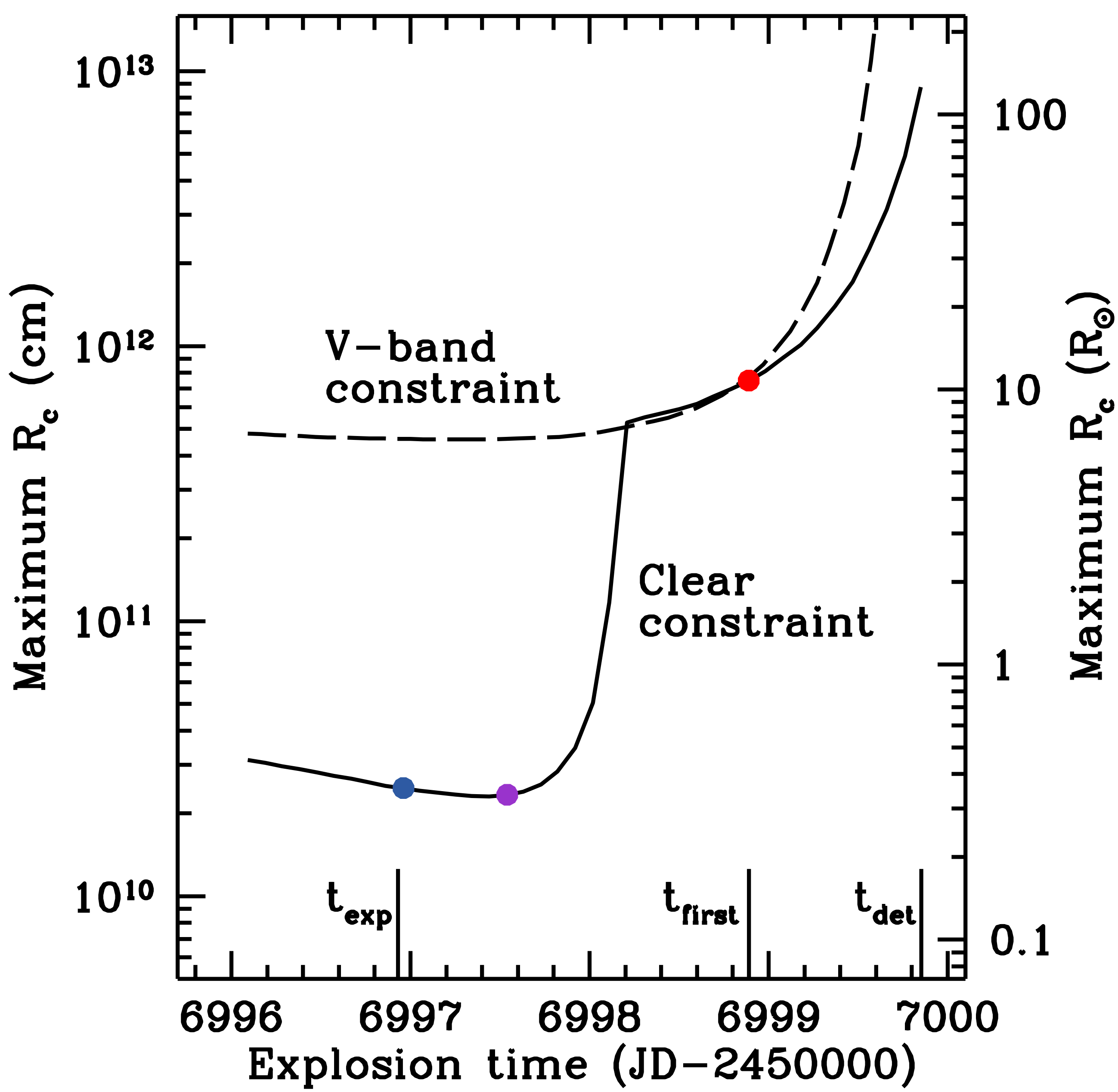


Companion constraints for 14lp

Uncertainties in explosion time motivate considering a range of explosion times

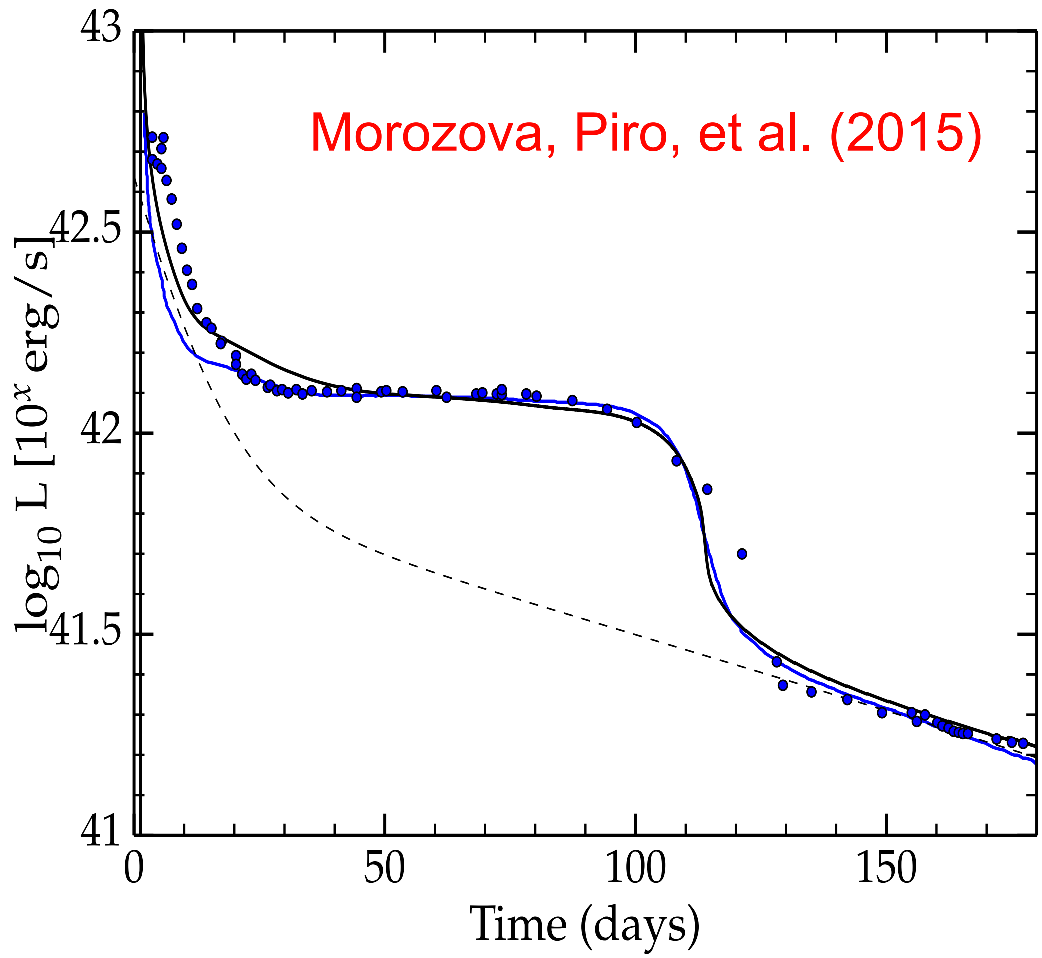
Companion **unlikely to be a red super giant** unless poor viewing angle

What does explosion time discrepancy mean? (also seen for 09ig, but not for 11fe and 12cg)



SuperNova Explosion Code (SNEC)

- 1D Lagrangian hydrodynamics
- Explosions triggered with a thermal bomb or piston
- Hydrodynamics and radiative diffusion solved together
- Thermodynamic equilibrium
- Gray opacity using OPAL and includes partial ionization
- Follows gamma-ray diffusion from ^{56}Ni



- Generates both bolometric LCs and specific bands
- Relatively fast which is useful for numerical experiments

OPEN SOURCE! http://stellarcollapse.org/snec

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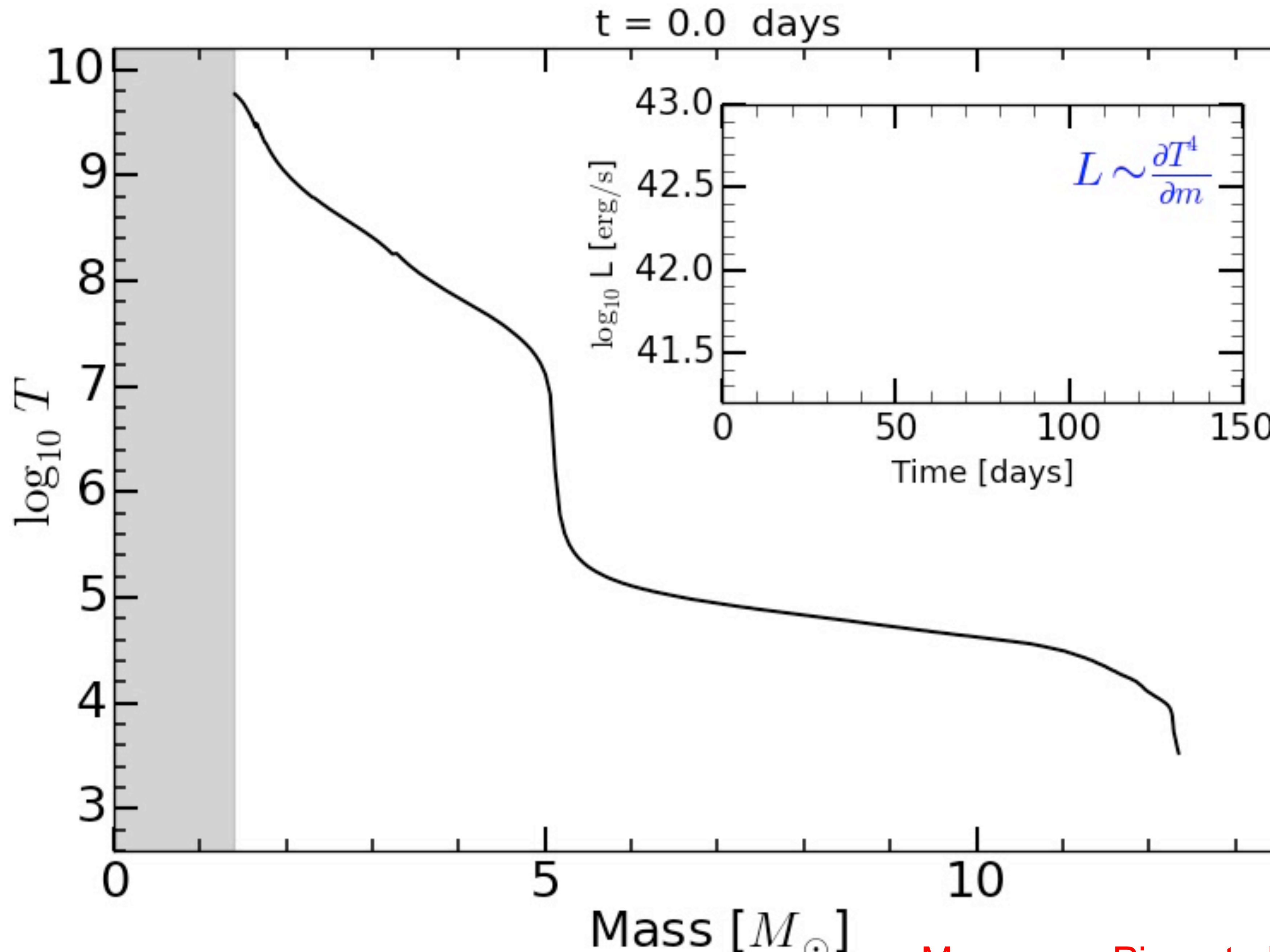
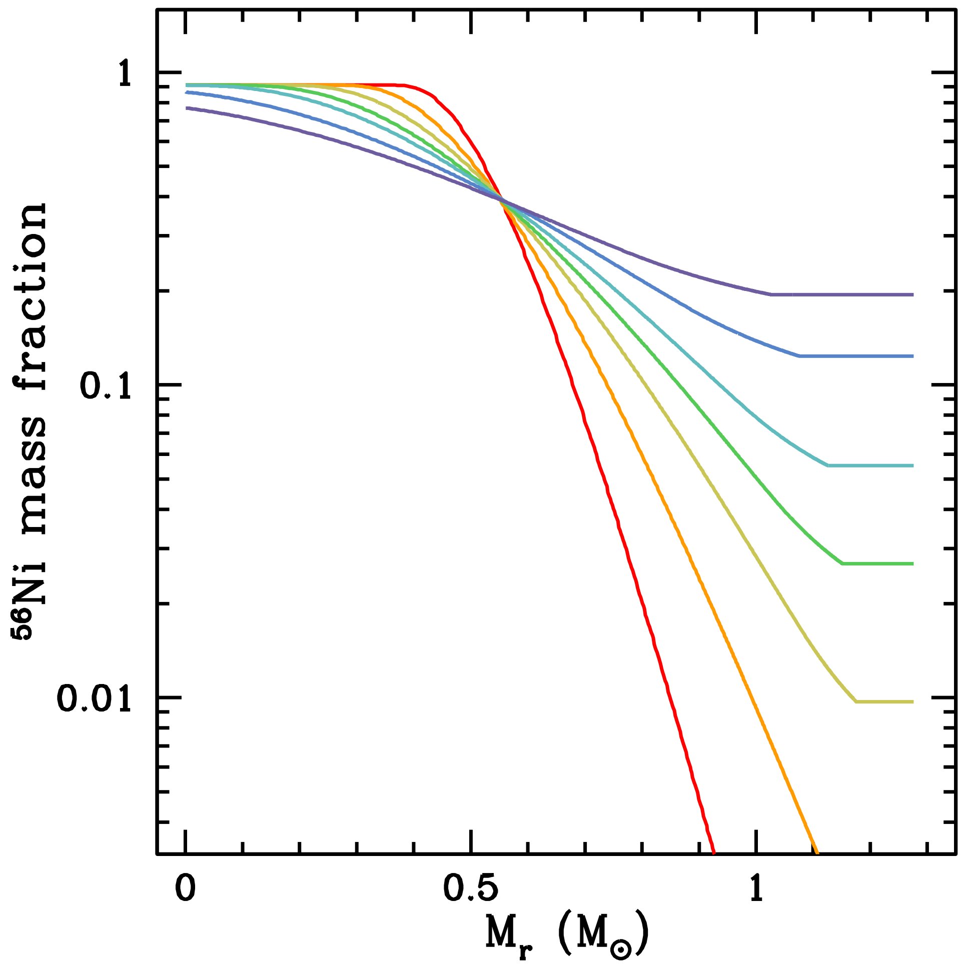
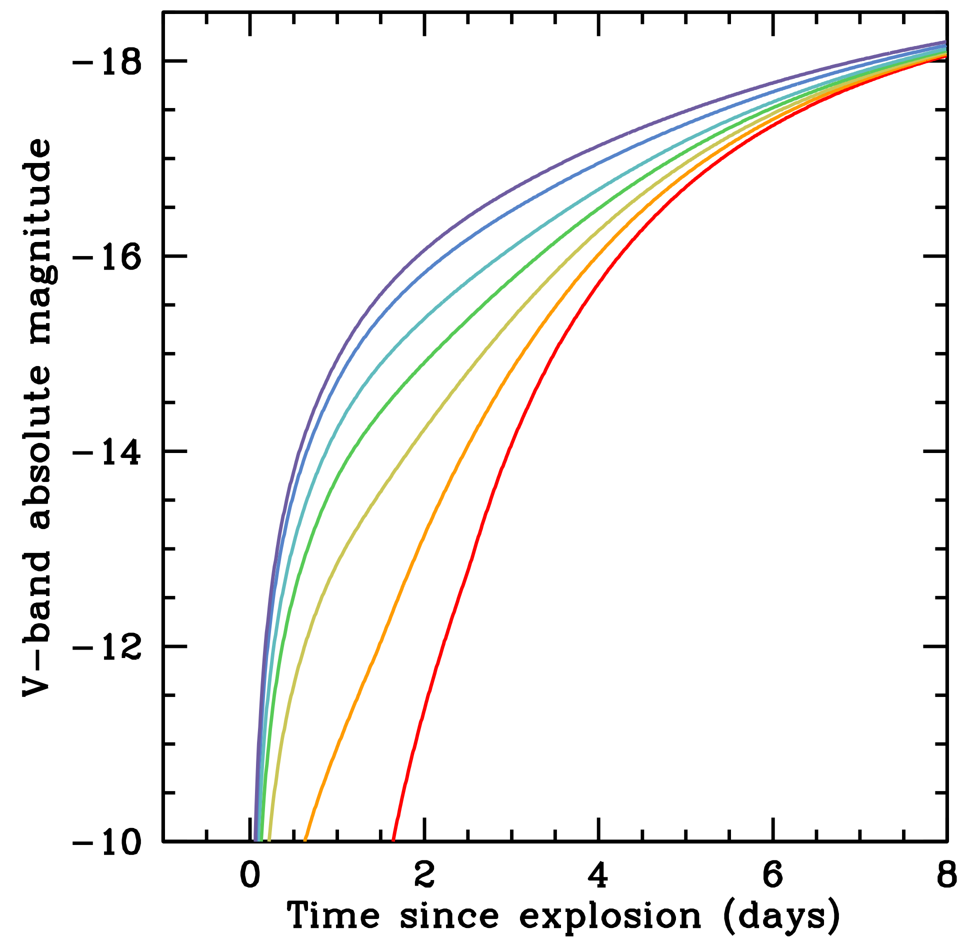


Morozova, Piro, et al. (2015)

Varying the ^{56}Ni distribution

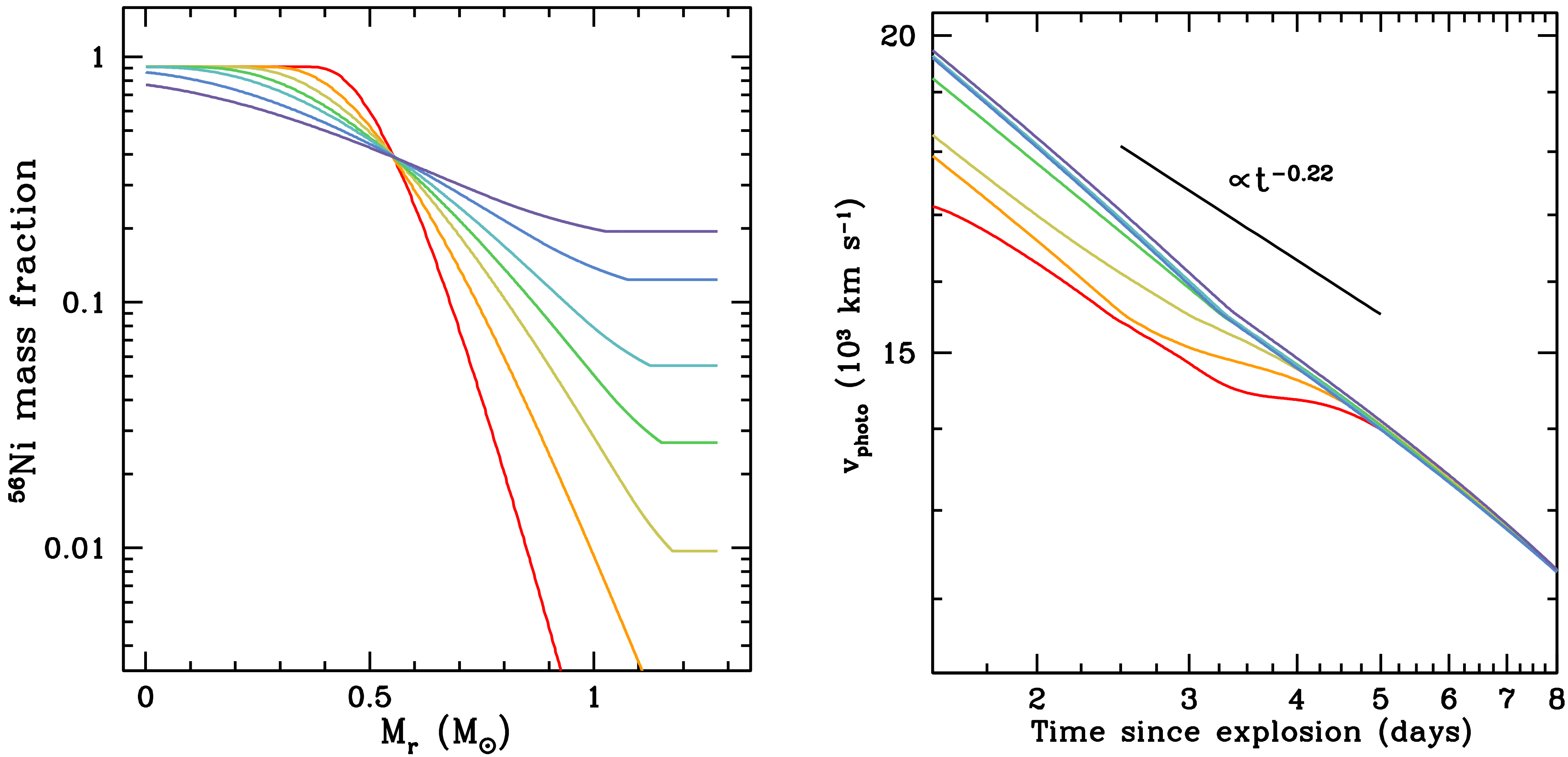




Shallow ^{56}Ni →

- Steep early light curve
- Less of a “dark phase” (Piro & Nakar 2013)

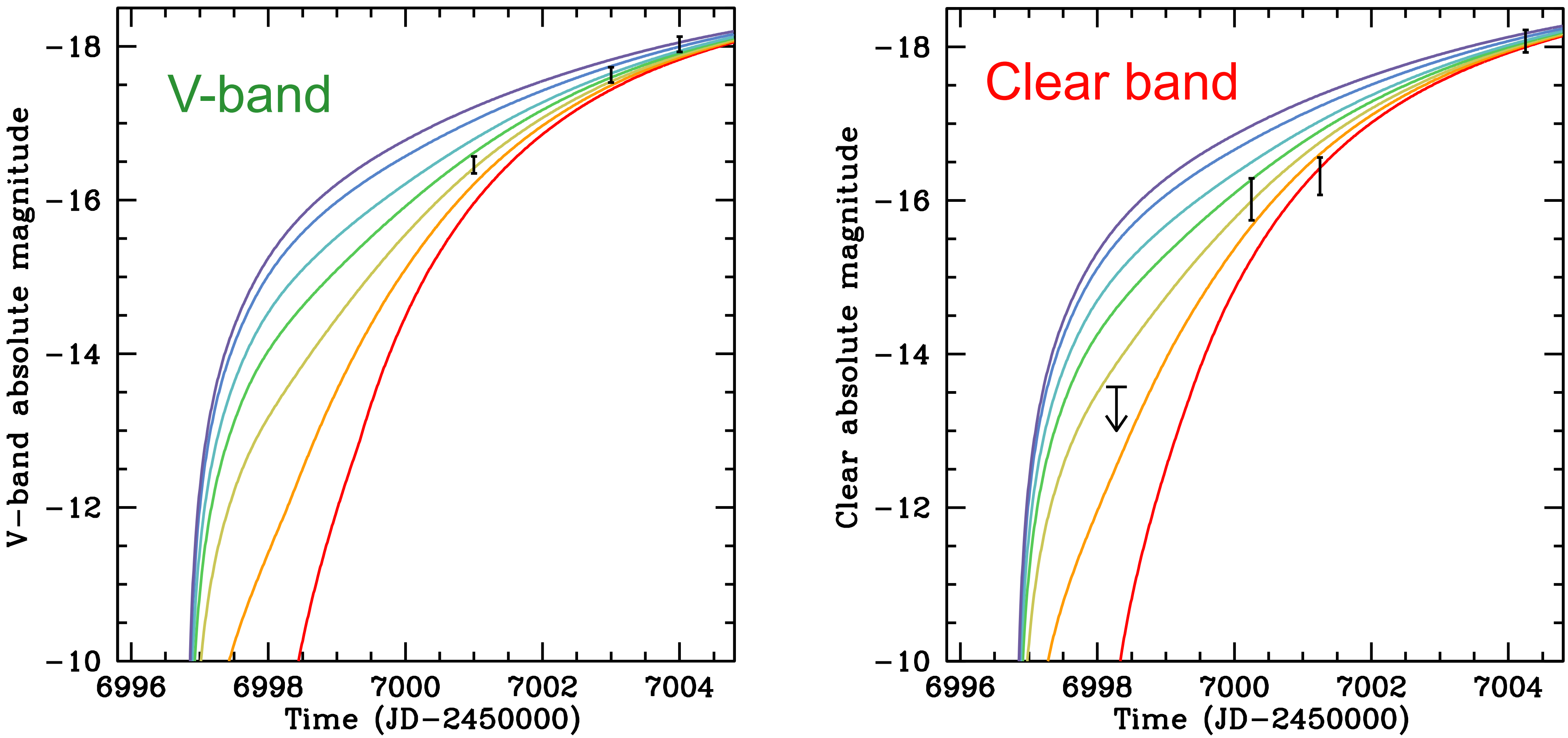
Impact on photospheric velocity



- Power law evolution once nickel heating is important
- Slightly steeper than previous analytic result
- Does this point to an even earlier explosion time?

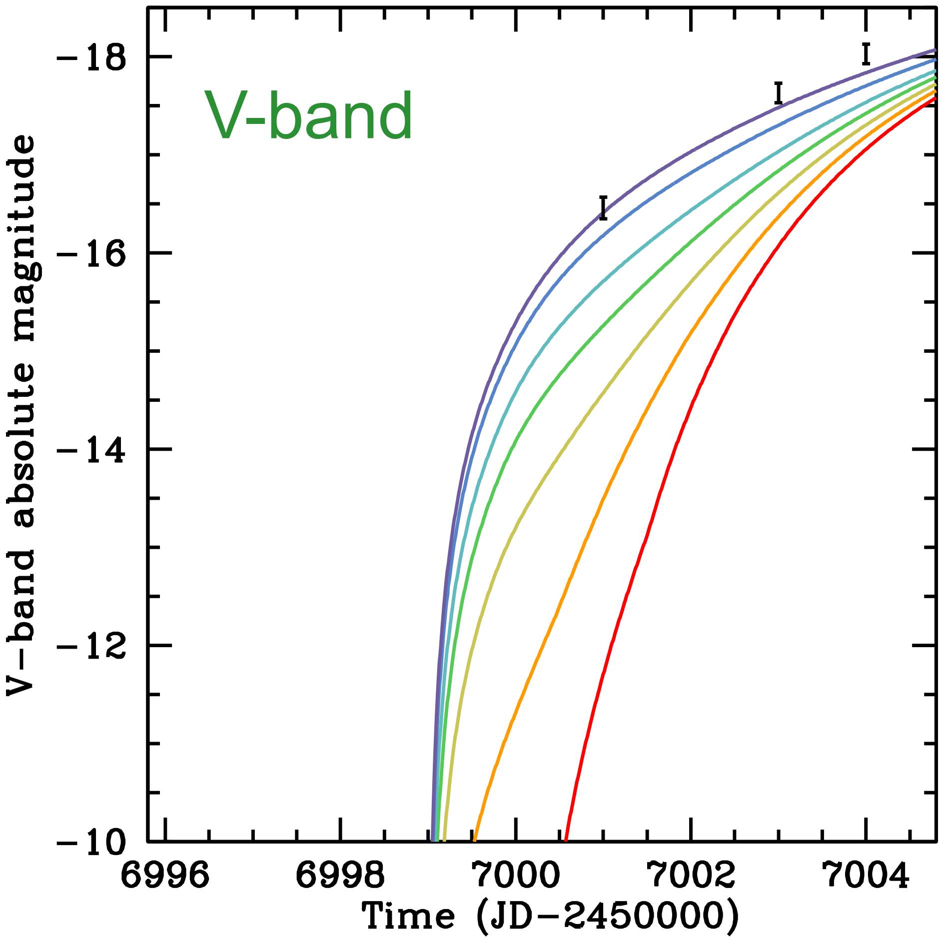
Revisiting ASASSN-14lp

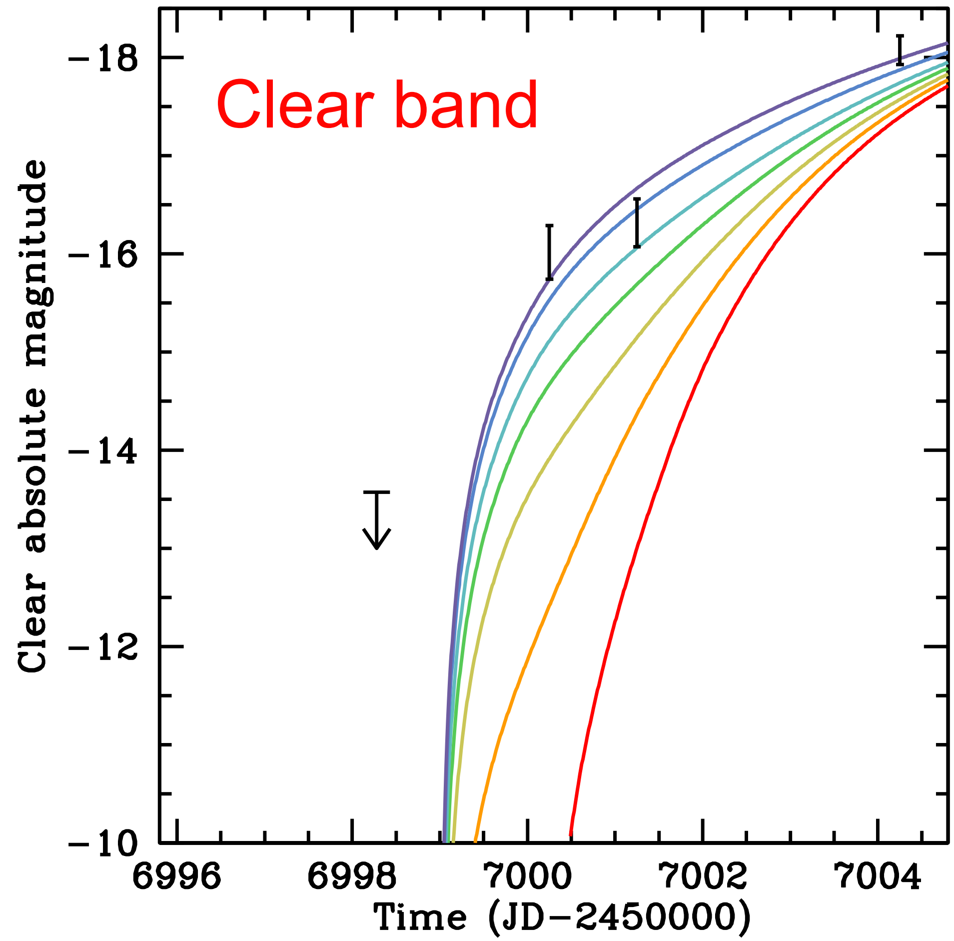
Comparison with **EARLY** explosion time



Revisiting ASASSN-14lp

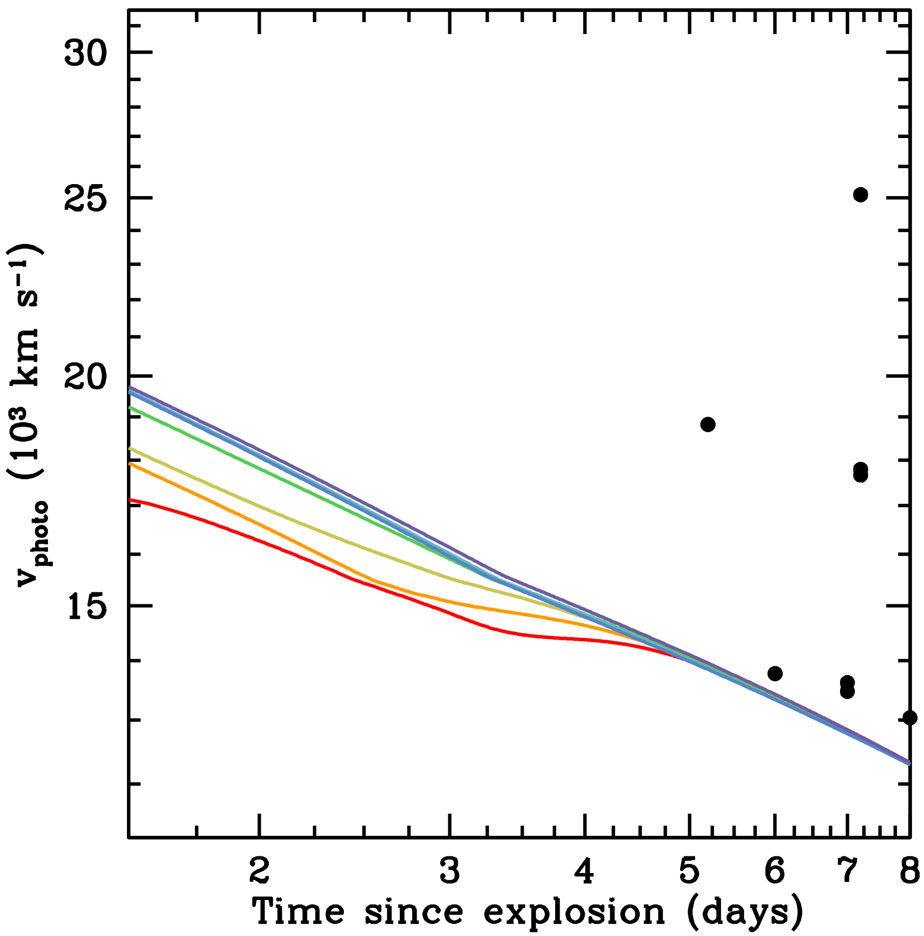
Comparison with **LATE** explosion time



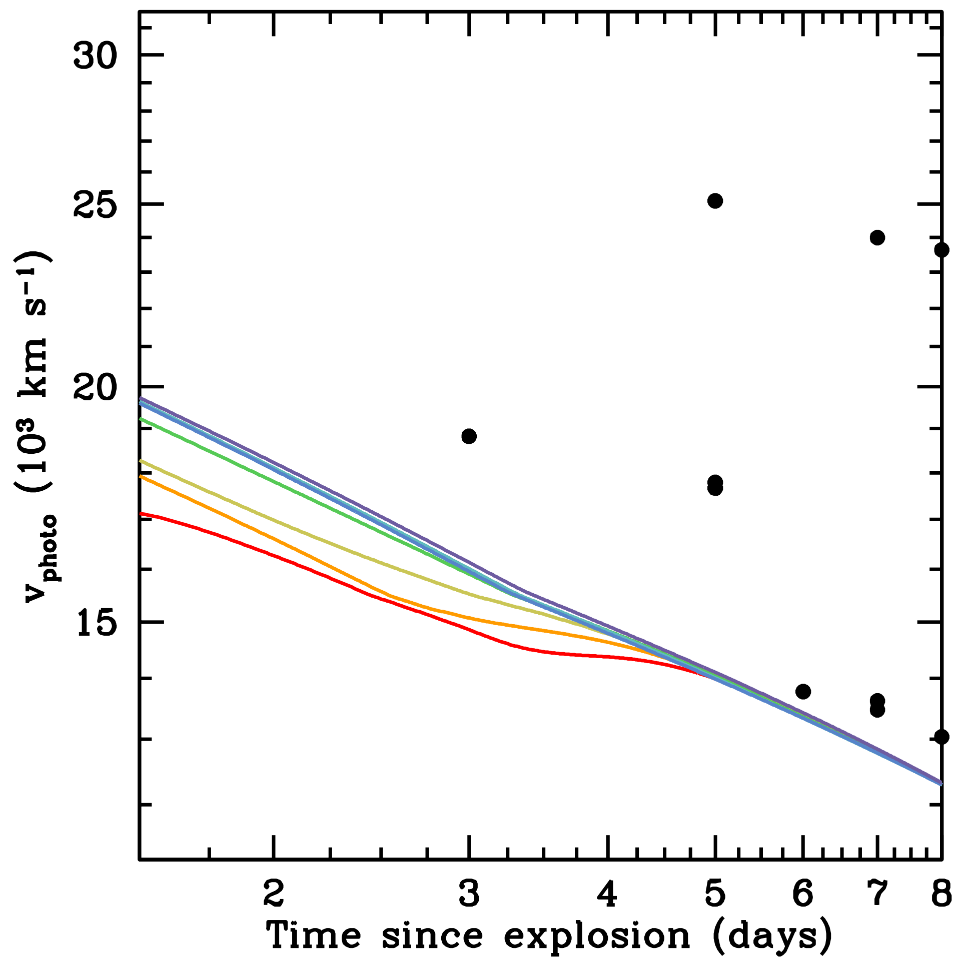


Revisiting ASASSN-14lp

Early explosion time



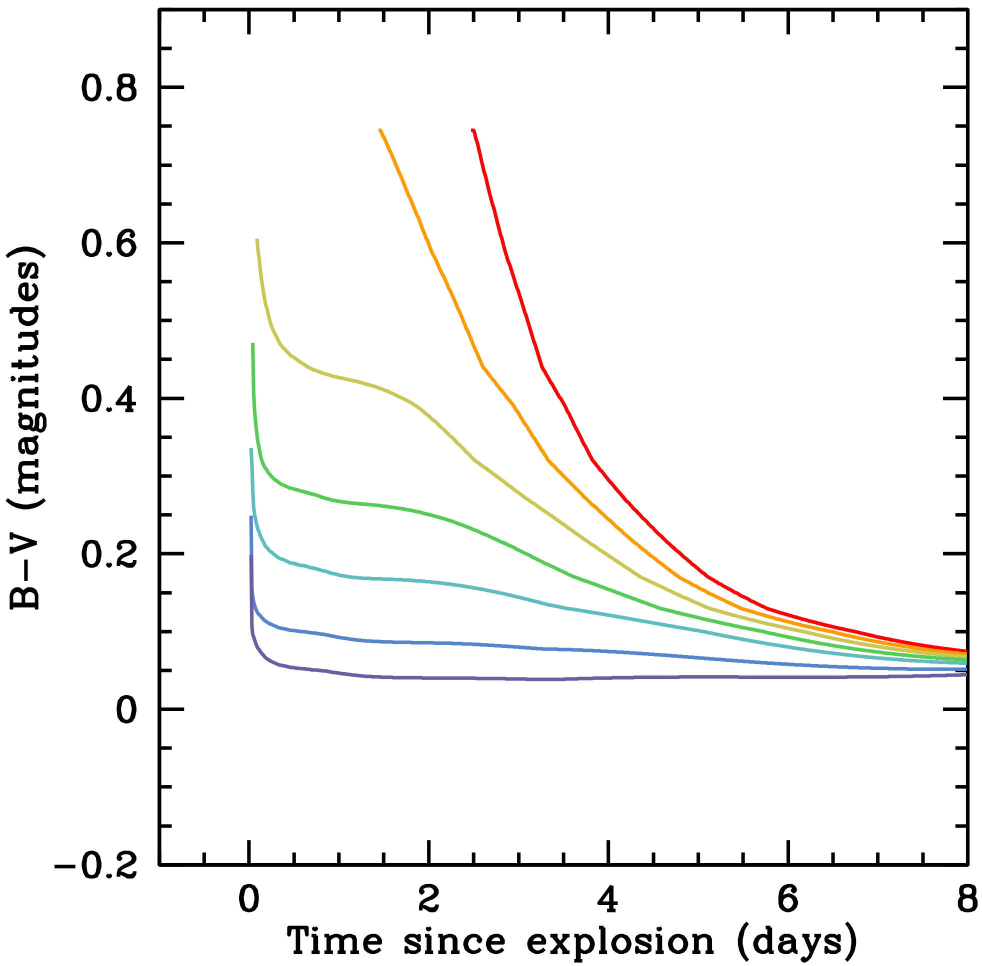
Late explosion time

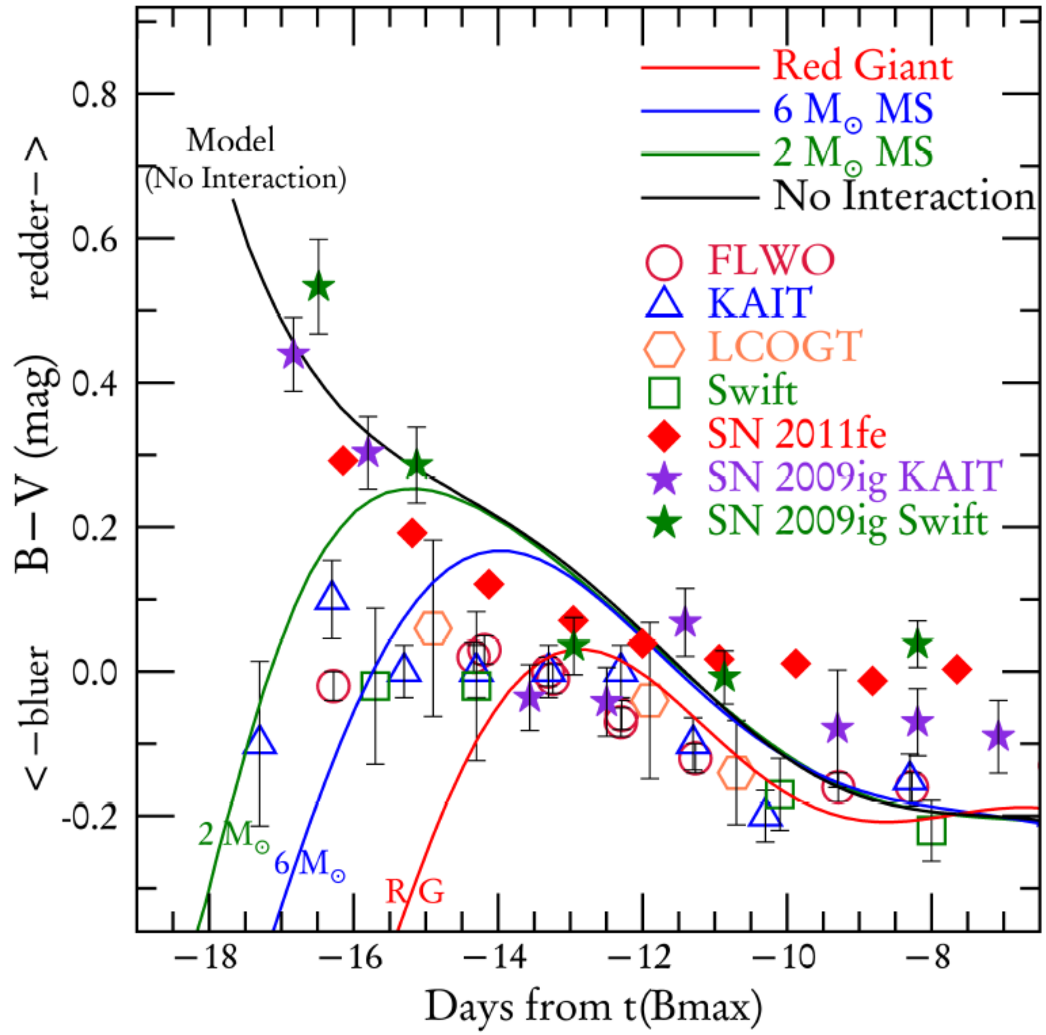


Difficult to decide between these 2 cases with current data

Clues from color evolution?

Marion, et al. (2015)





Flatter color evolution indicates more shallow ^{56}Ni

(Note: scaling with peak makes comparison by eye difficult!)

Conclusions

Early light curves are important

- Constrain progenitor radius
- Constrain companion radius
- Measure surface nickel distribution

Knowing the time of explosion is critical

- Light curve slope
- Photospheric velocity evolution
- Color evolution

Multiple photometric/spectroscopic observations before ~4 days after explosion is key

Future Work

What are the optimum observing strategies?

- What cadence?
- What depth?
- Photometric versus spectroscopic?
- How bad are different explosion time constraints?

What else can early light curves illuminate?

- Circumstellar material (from a merger? nova?)
- Non-trivial nickel distributions (double detonation?)
- SNEC will be a key tool (http://stellarcollapse.org/snec)