Early Light Curves of Supernovae

Tony Piro

CSP Team Meeting, 2014

Motivation

New observational efforts are finding SNe early and often

What can we learn about SNe progenitors?

- Are all SNe Ia from M_{WD}=M_{Ch} or a variety of M_{WD}?
- What are the companions in SNe Ia?
- What is the nature of the explosive burning in SNe Ia?
- What are the progenitors of stripped core-collapse?
- Implications for stellar evolution, binary stars, chemical enrichment, and more!

Outline of Talk

(1) The physics of thermal diffusion

(2) What can we learn from shock cooling?

(3) Results from SNe Ia, Ib, Ic, and IIb

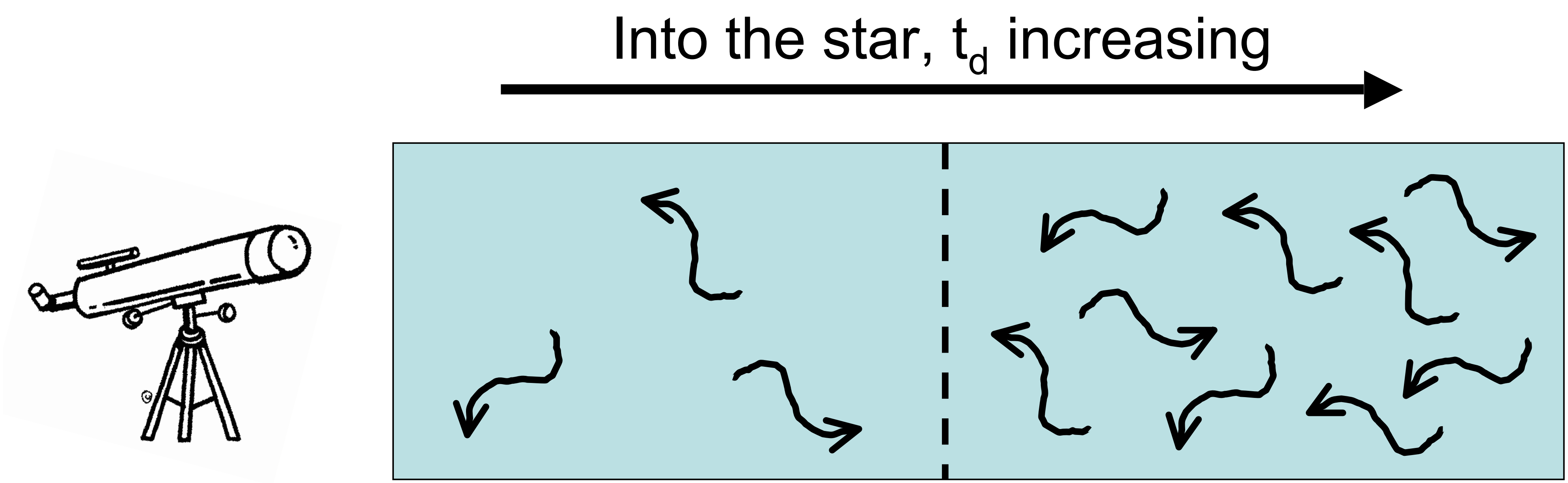
(4) Conclusions and future work

Tomorrow: ^{56}Ni distributions from SNe Ia

Probing an Exploding Star with Thermal Diffusion

Photons reach the surface on a "thermal diffusion time"

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



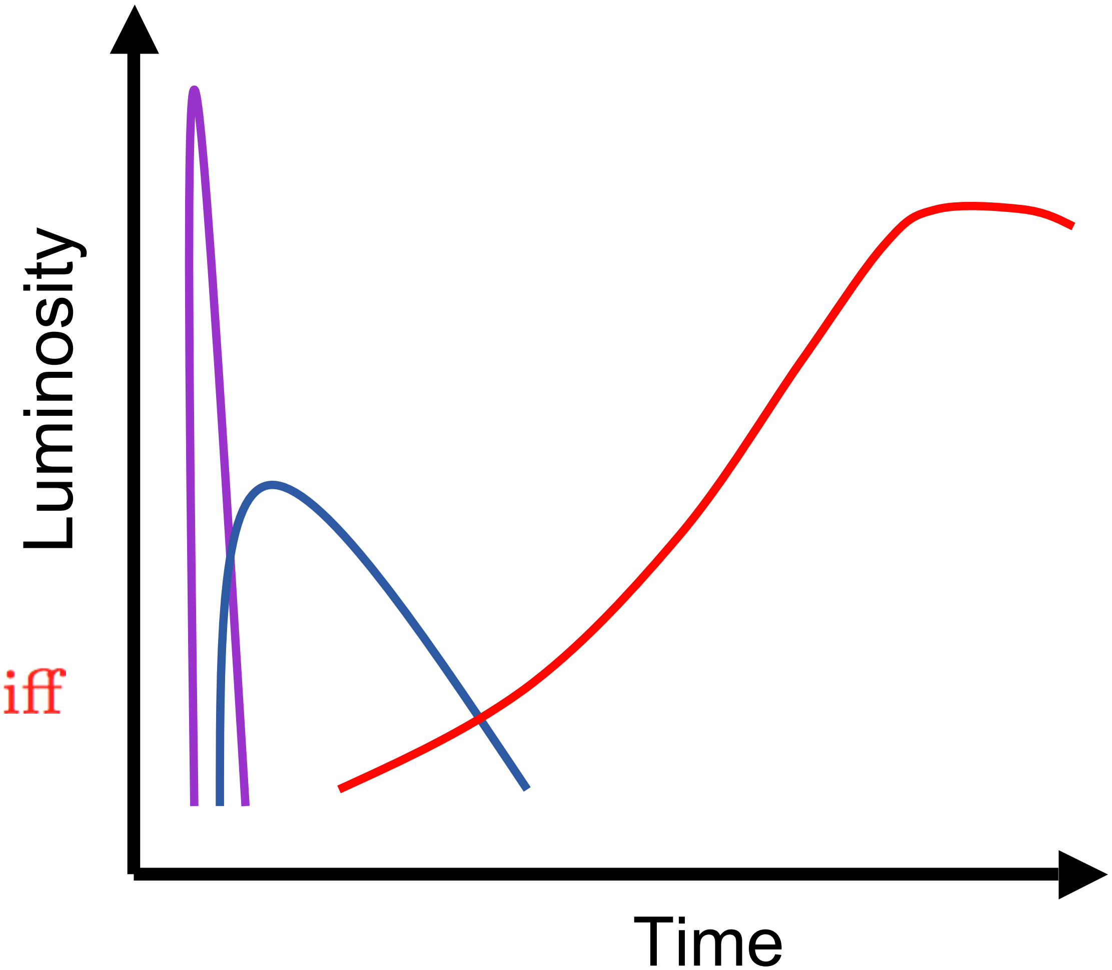
The Composition of a SN Light Curve

Piro & Nakar (2013)

Roughly 3 different pieces:

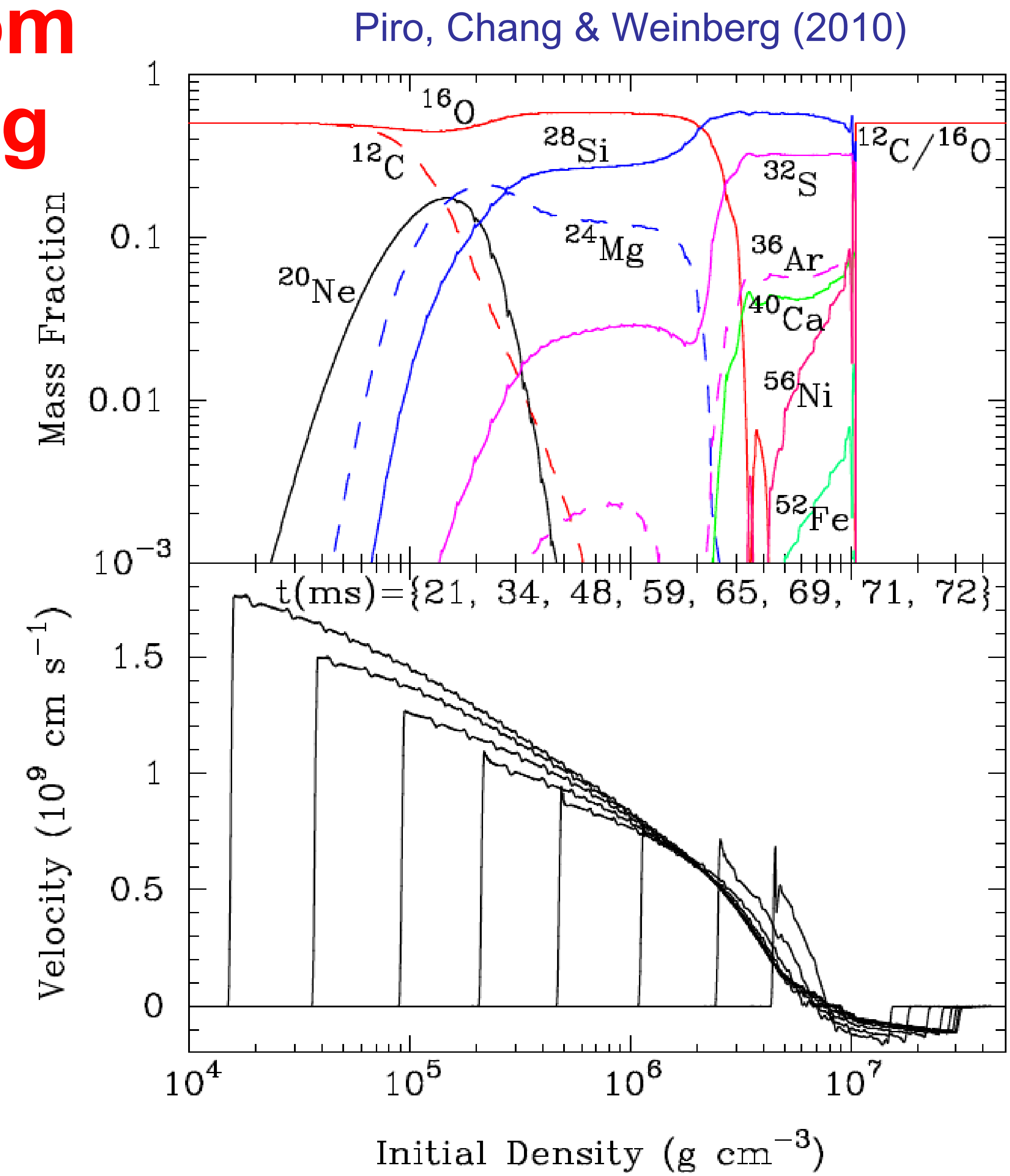
- Shock breakout
- Shock cooling
- Radioactive heating

$$L \propto M_{56} \sim X_{56} \Delta M_{\rm diff}$$



Shock Heating from Explosive Burning

- Detonation wave turns into a shock at low densities
- Surface layers are shock-heated



Back of the envelope shock cooling

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

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

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

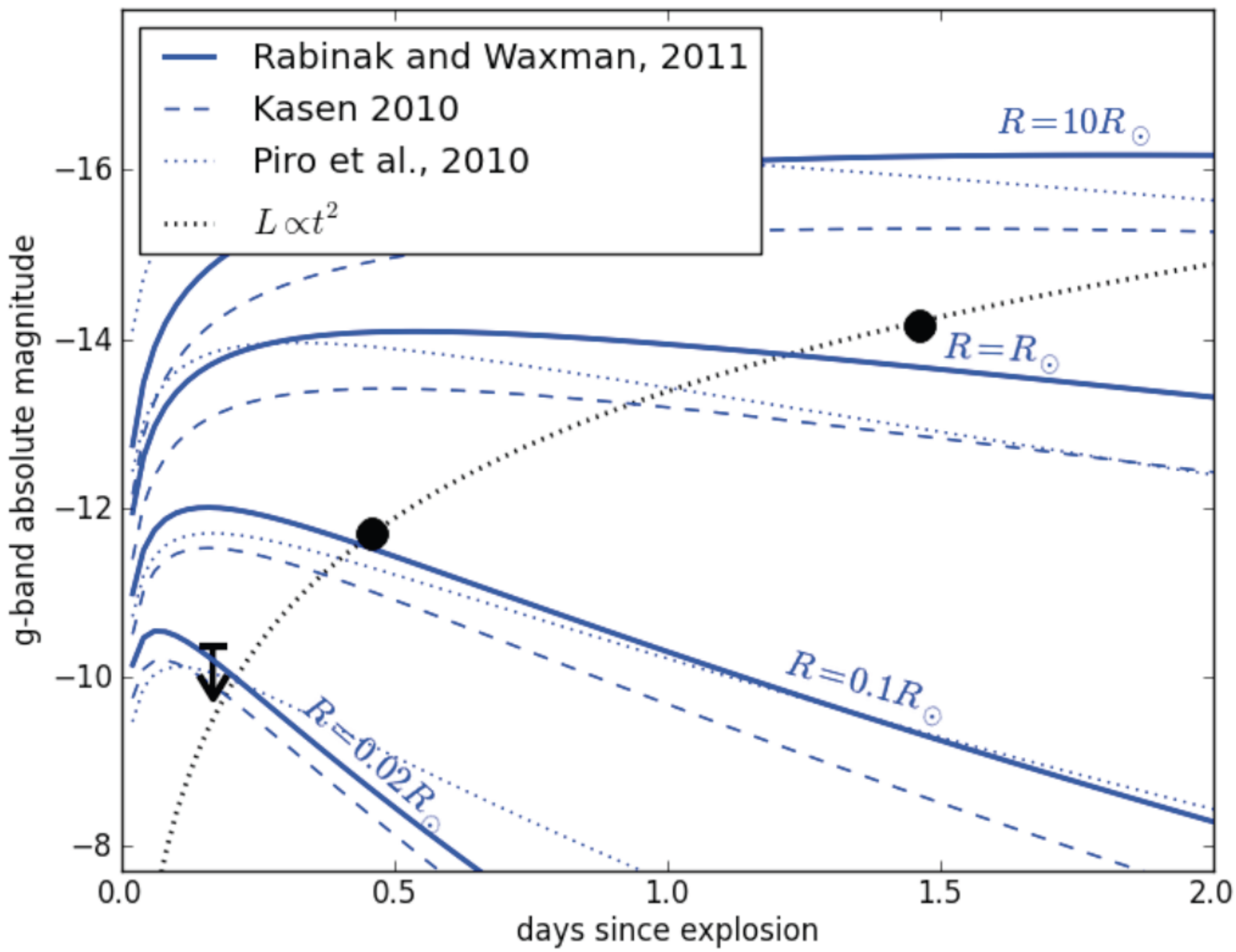
Good News: Luminosity is proportional to progenitor radius

Bad News: This luminosity is small! (~1000x dimmer than peak)

Rising Light Curve of SN 2011fe

- No evidence of shock cooling
- Upper limits require that progenitor radius is <0.02 R_{sun}
- First direct evidence that Type Ia SNe come from white dwarfs!

Bloom et al. (2011) ApJL 744 17



PTF 10vgv

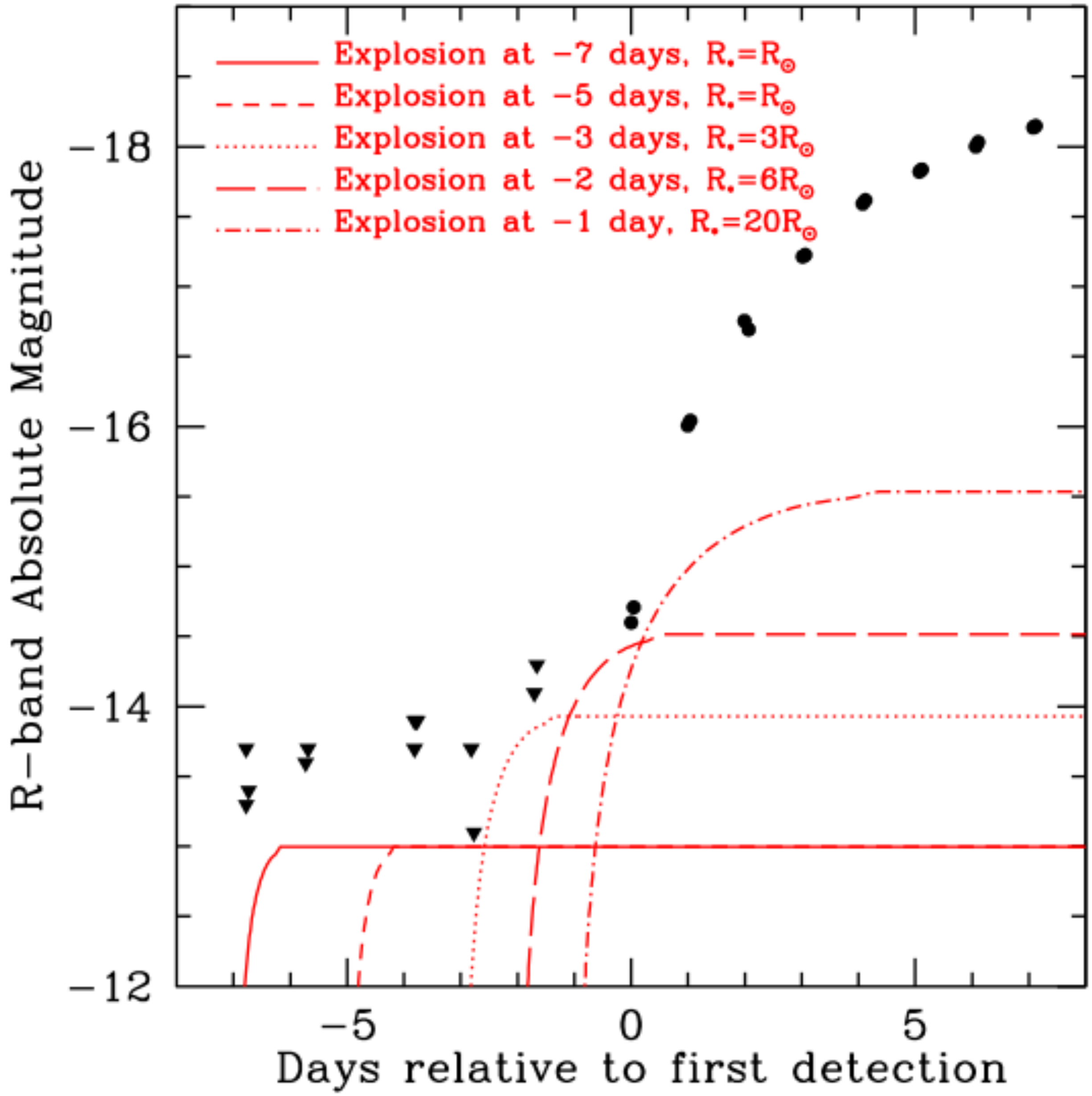
Type Ic with non-detection of shock cooling

Can still place interesting limits

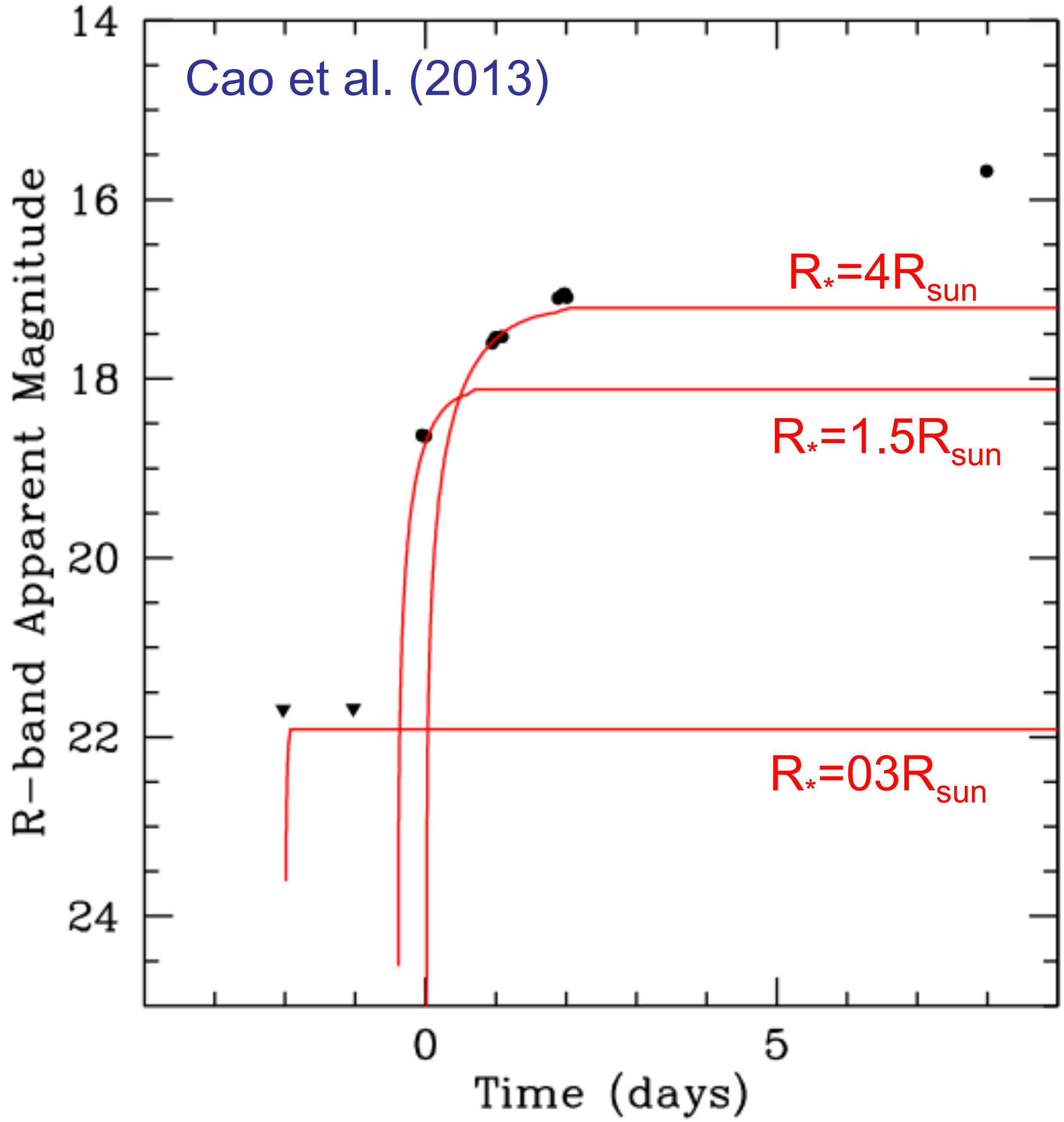
$M_{ej} \sim 2M_{sun}$

$R_* < 3R_{sun}$

Piro & Nakar (2013)

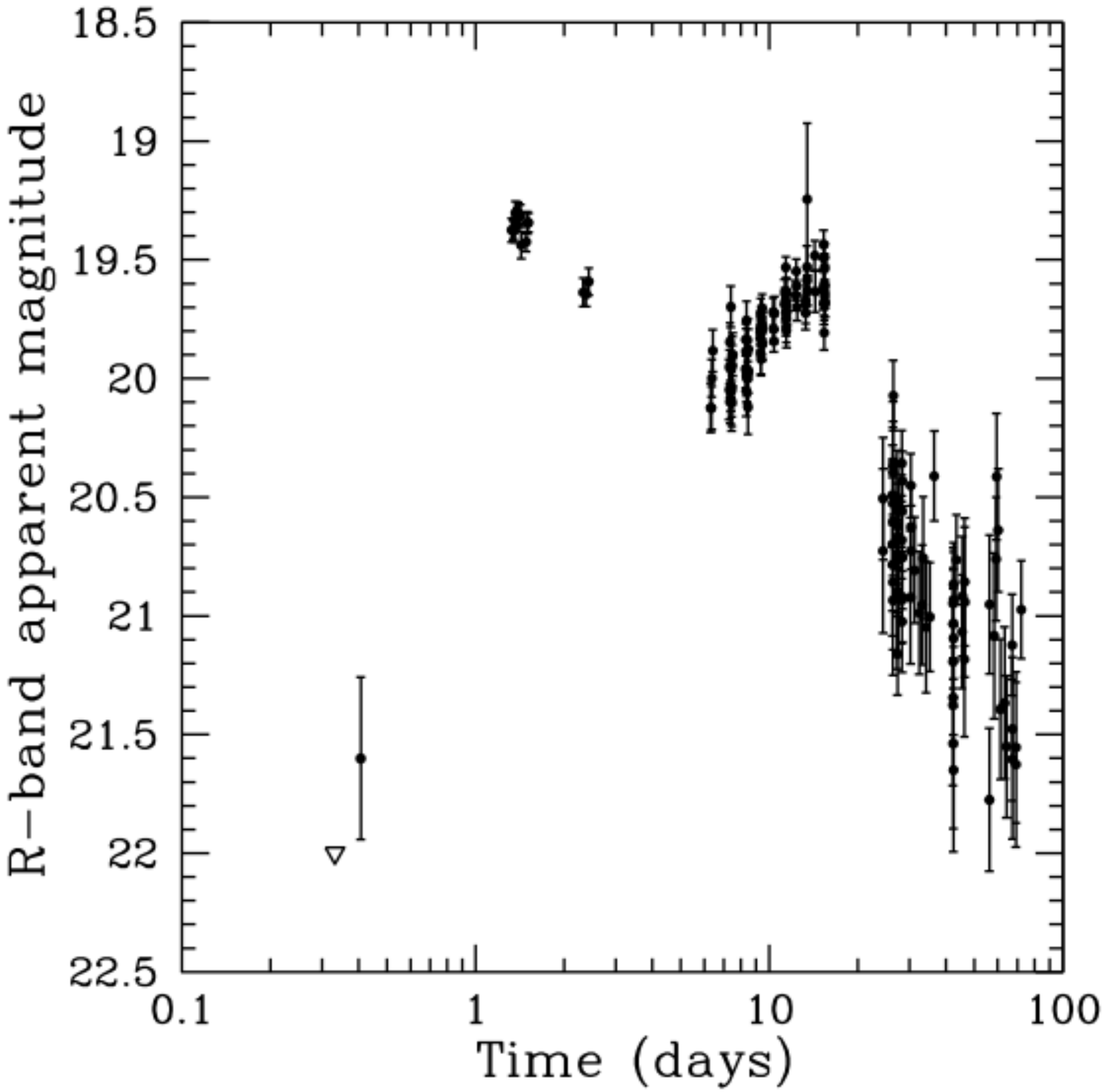


PTF 13bvn



- Type Ib
- $R_* \sim 1.5 R_{sun}$
- Radio emission and pre-explosion photometetry consistent with a hot, mass losing star

Double-peaked supernovae



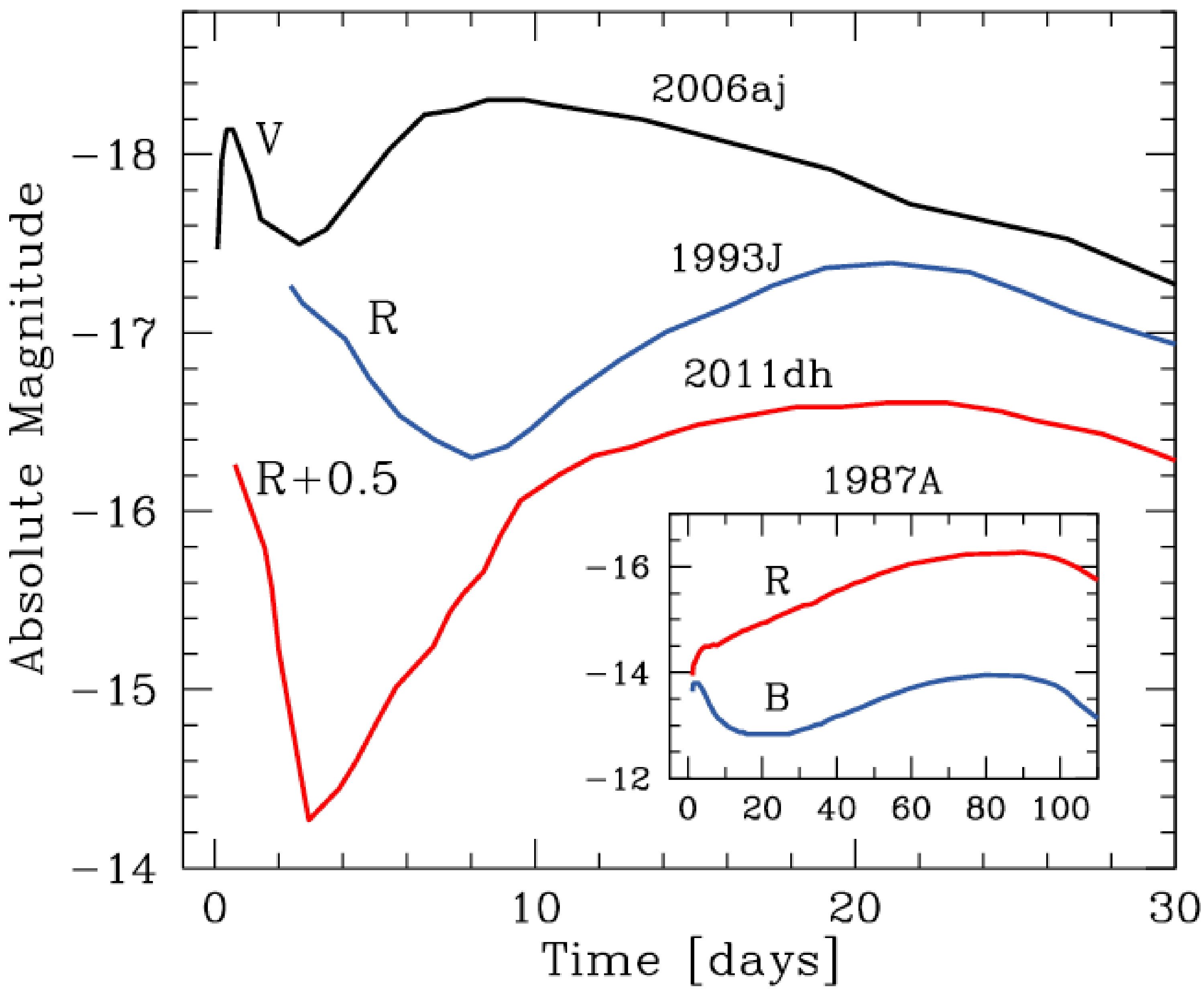
~ half dozen of these seen (e.g., 2011dh), including Types IIb, Ibn, and Ic

Some have **yellow supergiant progenitors**

What structure must the star have?

(also see numerical work of Bersten et al.)

Note: Double-peaked ALSO in R-band



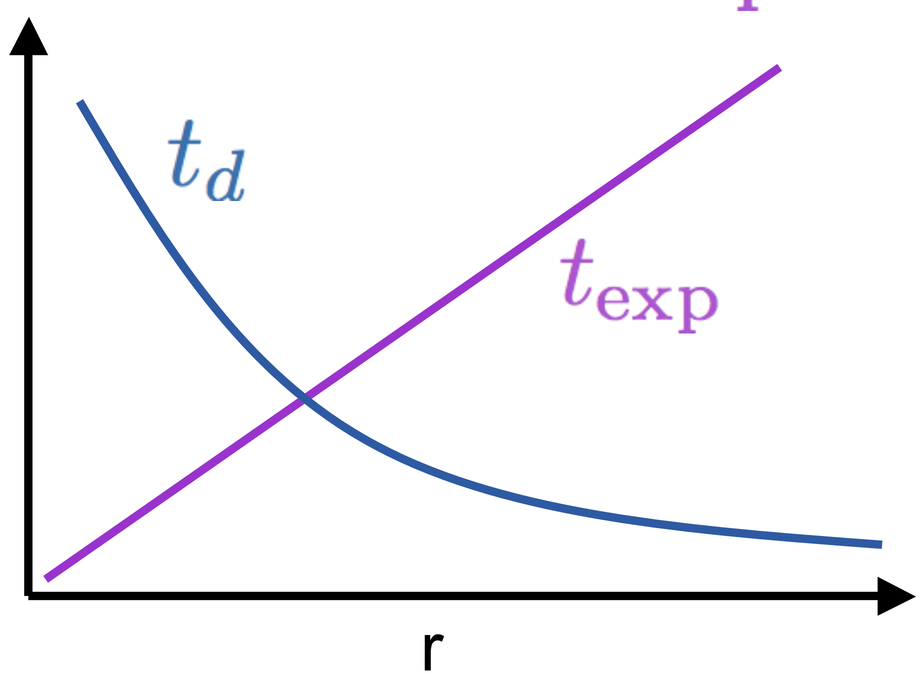
Why do light curves peak?

Photons reach the surface on a "thermal diffusion time"

$$t_d \sim \frac{M\kappa}{rc}$$

Photons adiabatically cool on an "expansion time"

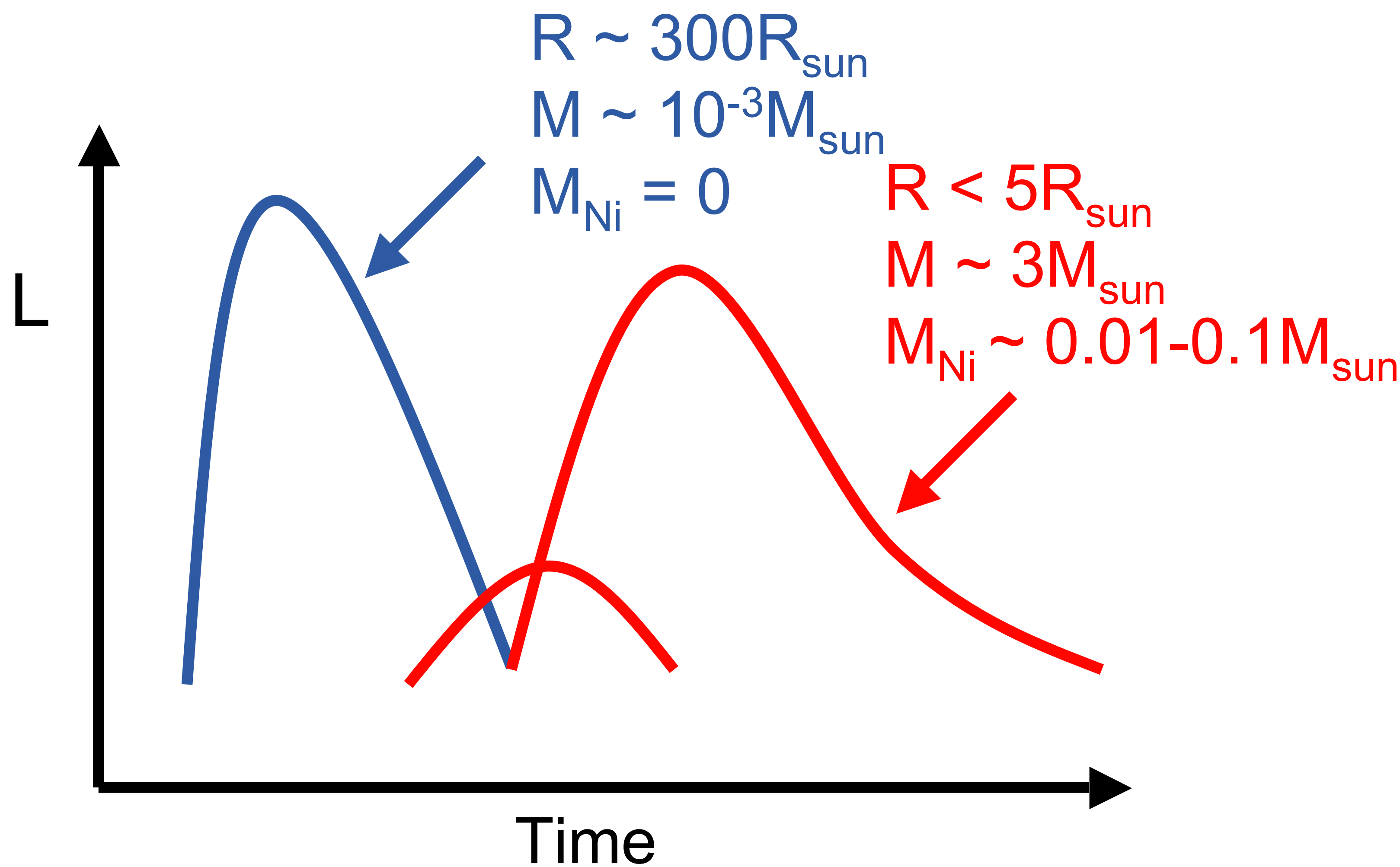
$$t_{\rm exp} \sim r/v$$



Light curve peaks when $t_d \sim t_{\rm exp}$

$$t_p \sim \left(\frac{M\kappa}{vc}\right)^{1/2}$$

Solution: Analyze double-peaked SNe as two SNe at the same time



Compact core with extended envelope

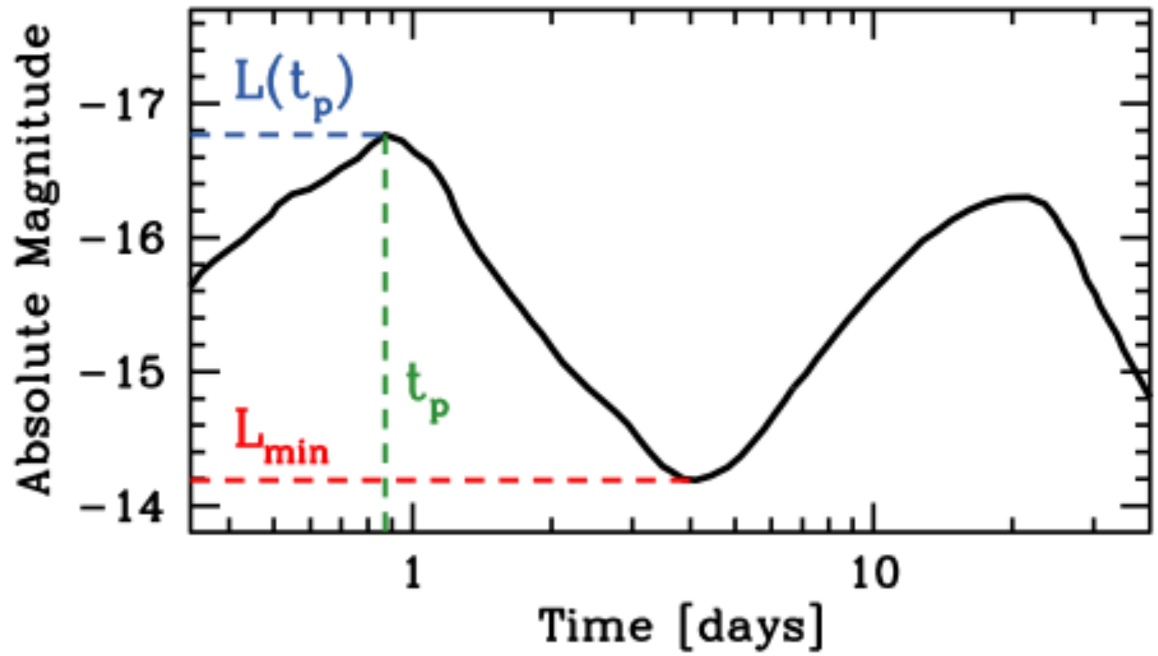
- Peak luminosity measures radius of extended material

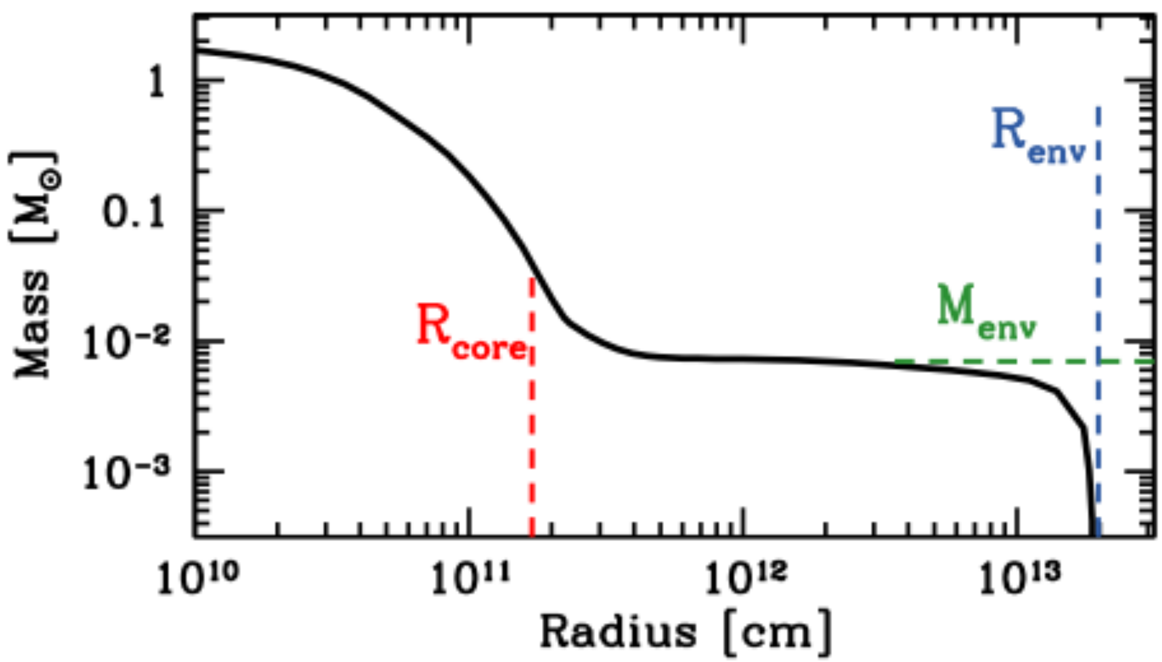
- Time of peak measures mass of extended material

- Minimum luminosity provides an upper limit to the core radius

See Nakar & Piro (2014) for analytic expressions

Nakar & Piro (2014), models from Bersten et al.





What's Next?

Developing a new Lagrangian, radiation-hydrodynamics code called **SNEC** (SuperNova Explosion Code)

- Investigate light curves with controlled numerical experiments
- Include additional physics such as metal recombination, supernovae through winds, and more
- Basic radiation and hydro complete, working on opacities and equation of state
- First results on SNe Ia expected by the end of summer

Conclusions

Early light curves are important probes of SN progenitors

- Upper limits on shock cooling constrain the radii of SN Ia, Ib, and Ic progenitors
- Double-peaked SNe allow constraints on: (1) extended radius, (2) extended mass, (3) core radius, (4) core mass, and (5) ^{56}Ni yield
- Ongoing work to develop numerical models to test these mostly semi-analytic studies (explosion modeling and new progenitors)

Tomorrow: ^{56}Ni distributions from SNe Ia