^{56}Ni Distribution in Type Ia Supernovae

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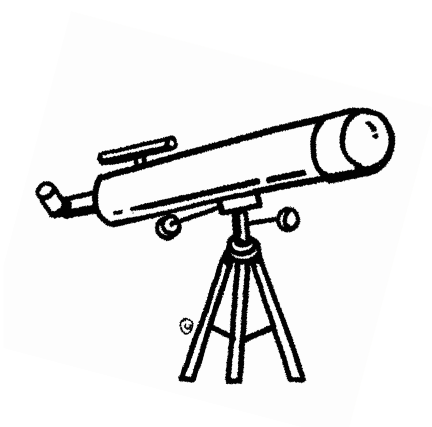
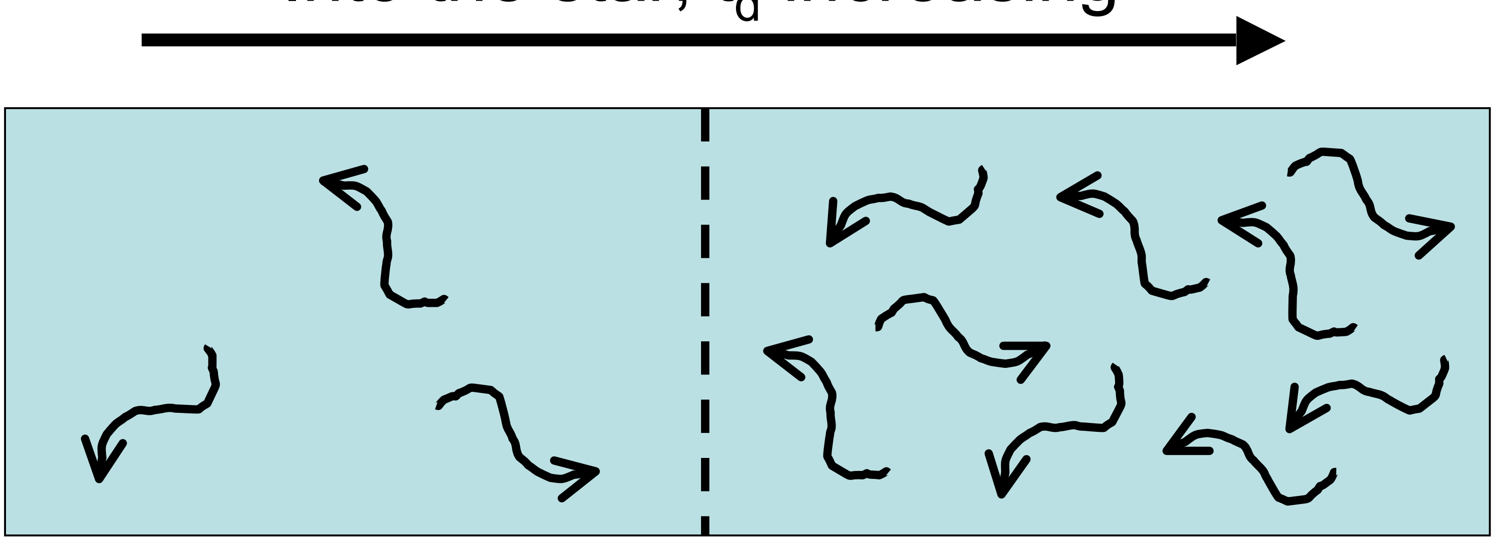
Probing an Exploding Star with Thermal Diffusion

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





Radioactive Heating

- Eventually diffusion wave reaches depths where ^{56}Ni heating beats shock heating
- Powered by radioactive decay of ^{56}Ni => ^{56}Co => ^{56}Fe
- ^{56}Ni distribution probed by the resulting rising light curve

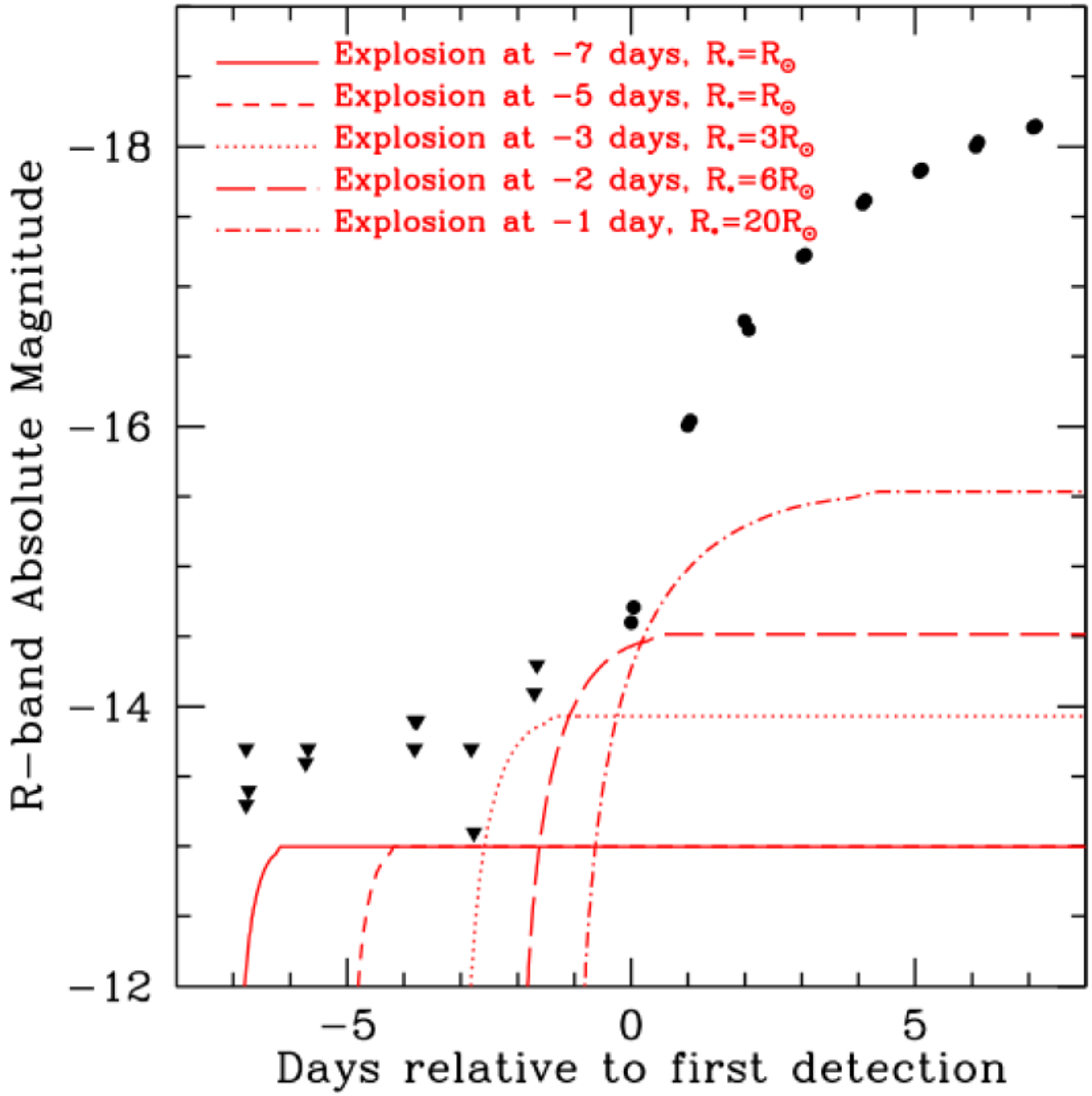
$$L \sim M_{56} \sim X_{56} \Delta M_{\rm diff}$$

- To infer X_{56}, we must know ΔM_{diff}, i.e., the time of explosion
- Best ways: (1) shock breakout, (2) shock cooling

No Shock Heating Detection

- Almost all SNe are found without detecting shock cooling
- This will impact both ^{56}Ni and progenitor radius constraints
- How can we make meaningful inferences from such observations?

Piro & Nakar (2013)



What about the t^2 rise?

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

Problems:

- No theoretical expectation of t^2 (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 almost certainly can't be t^2!

- Bolometric light curves (e.g., 2011fe, Piro & Nakar 2014) are not t^2

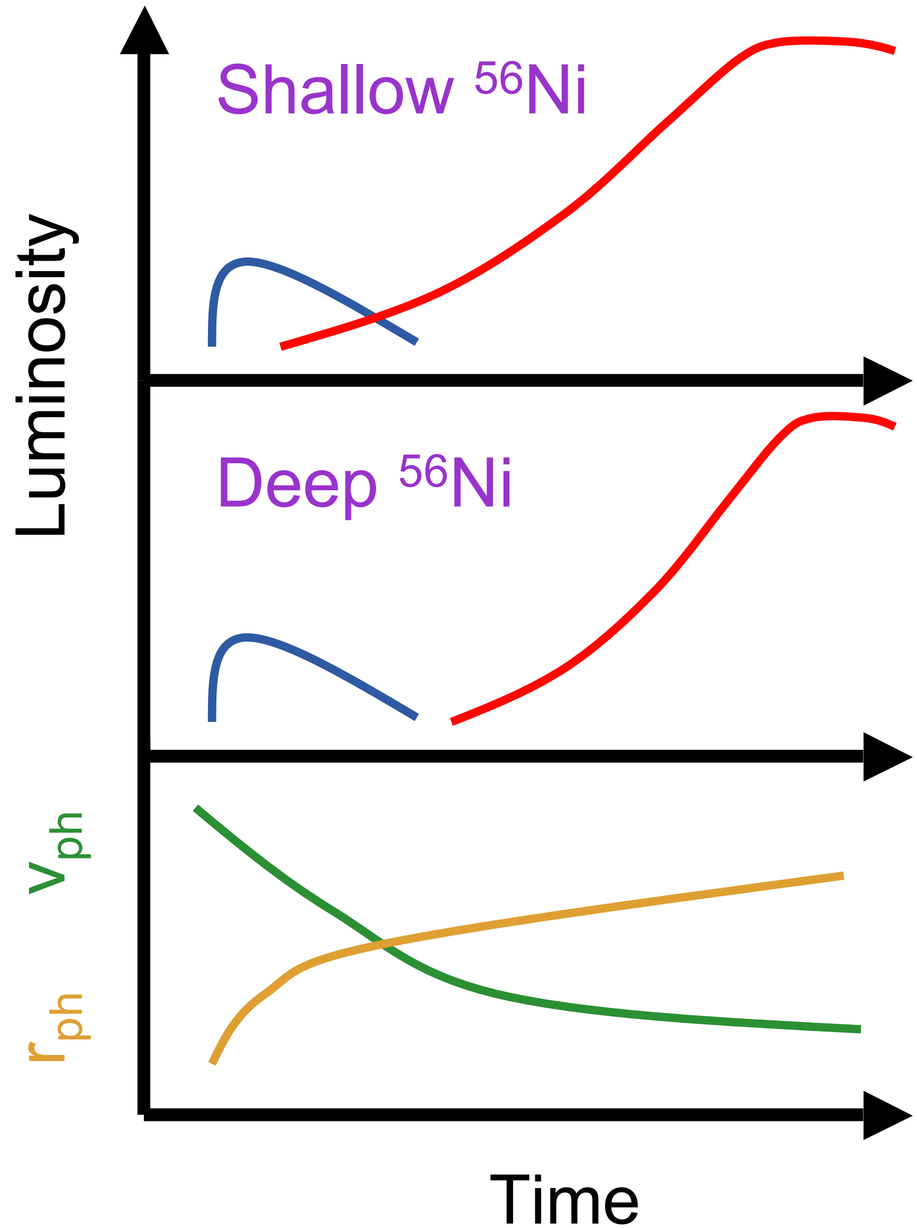
Clues to the Depth of ^{56}Ni

Other features of a SN may provide clues about ^{56}Ni depth.

Everything else being equal, a larger ^{56}Ni depth implies:

- Lower photospheric velocities
- Smaller velocity gradient
- Lower temperature
- Luminosity increasing faster than radius expands implies an increasing temperature

There correlations need to be checked with more detailed radiative transfer models.



Constraining the Explosion Time

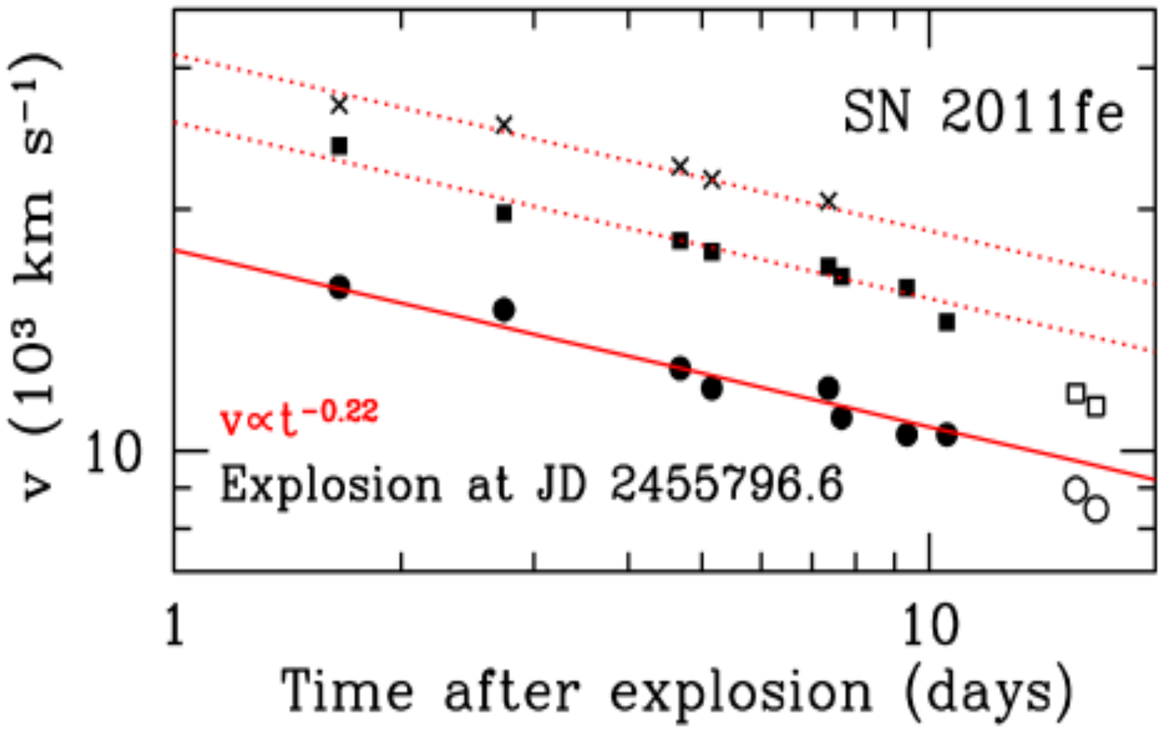
- For accelerating shock, the photophere evolves as

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

- Fitting to power-law constrains the explosion time

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

Piro & Nakar (2014)

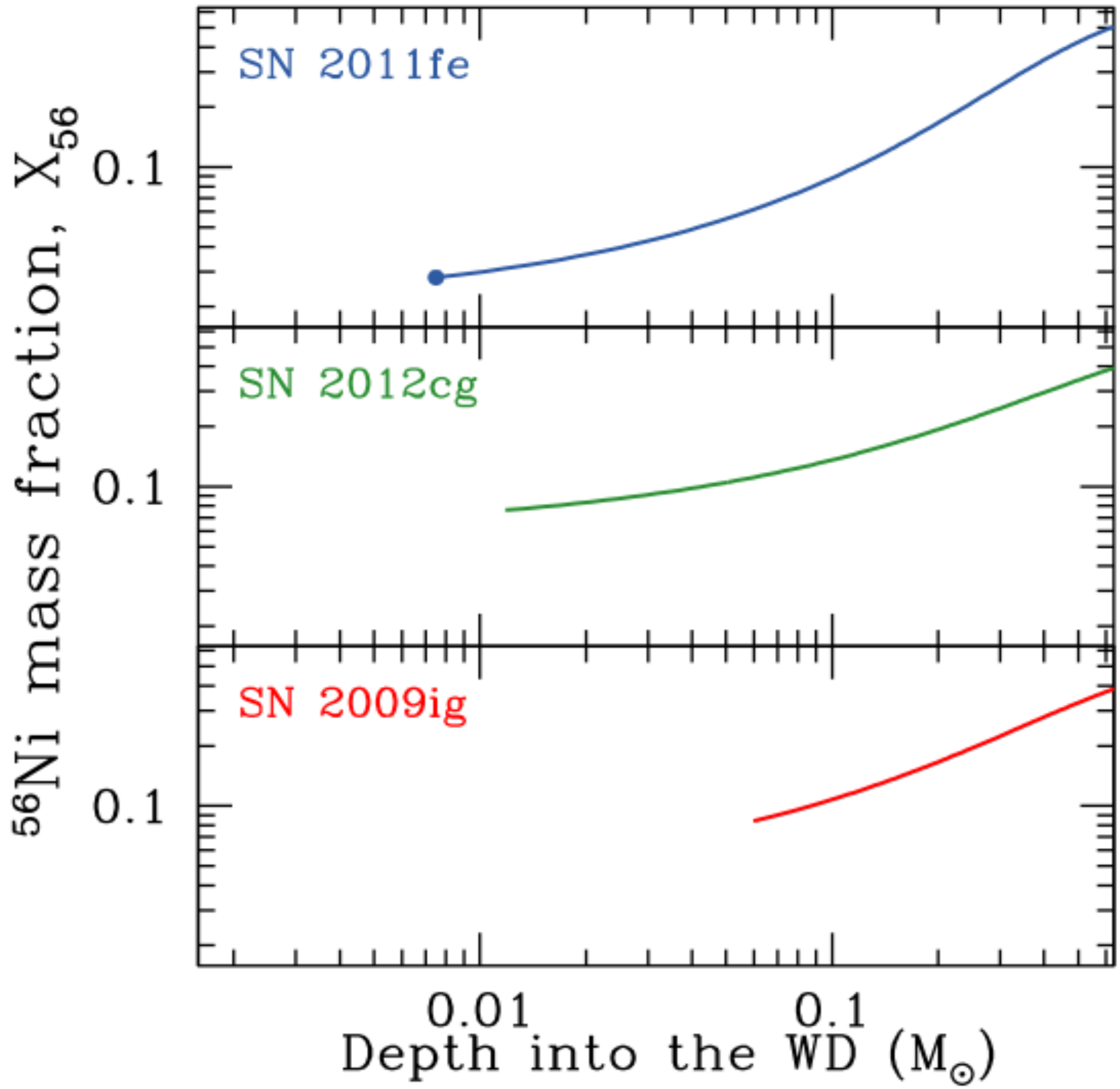


Explosion time constrained with ~0.5 day. Radius constraints only slightly weakened (~0.1Rsun)

The Shallow Distribution of ^{56}Ni

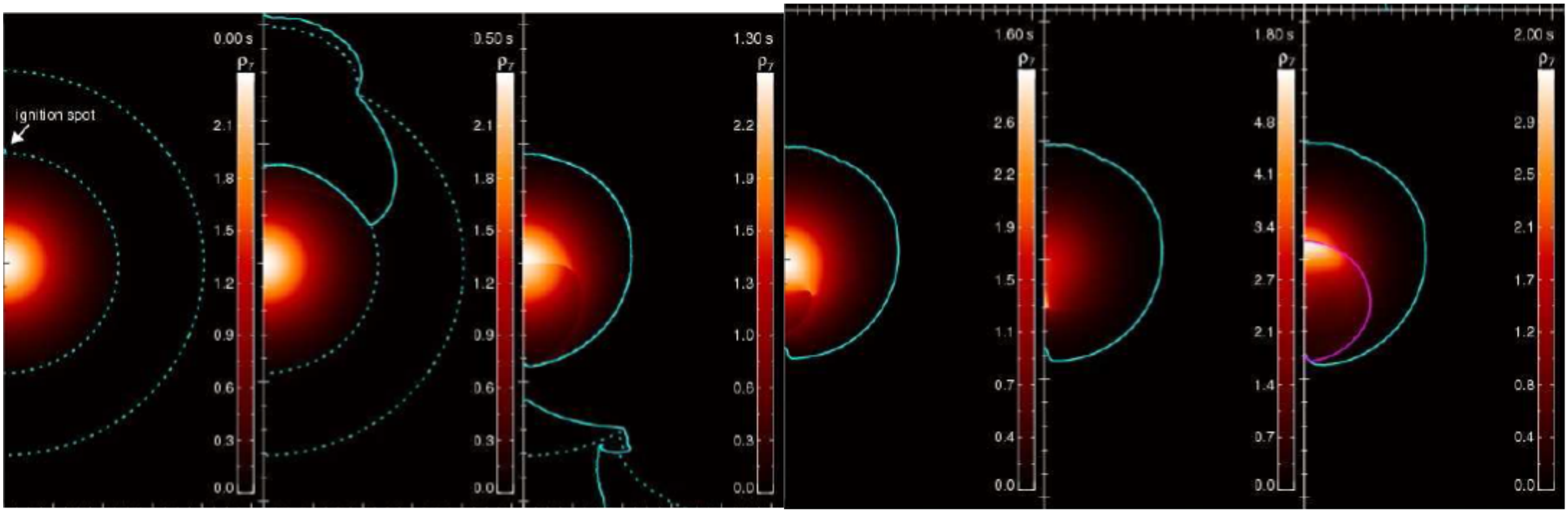
- Rising light curves probe the shallowest ^{56}Ni deposits
- This shows that ^{56}Ni is rather close to the surface (<0.1Msun from the surface)
- Shallow ^{56}Ni confirmed by spectroscopic modeling (Mazalli et al. 2013)
- Does this argue for a certain progenitor model?

Piro & Nakar (2014)



Models with Shallow ^{56}Ni?

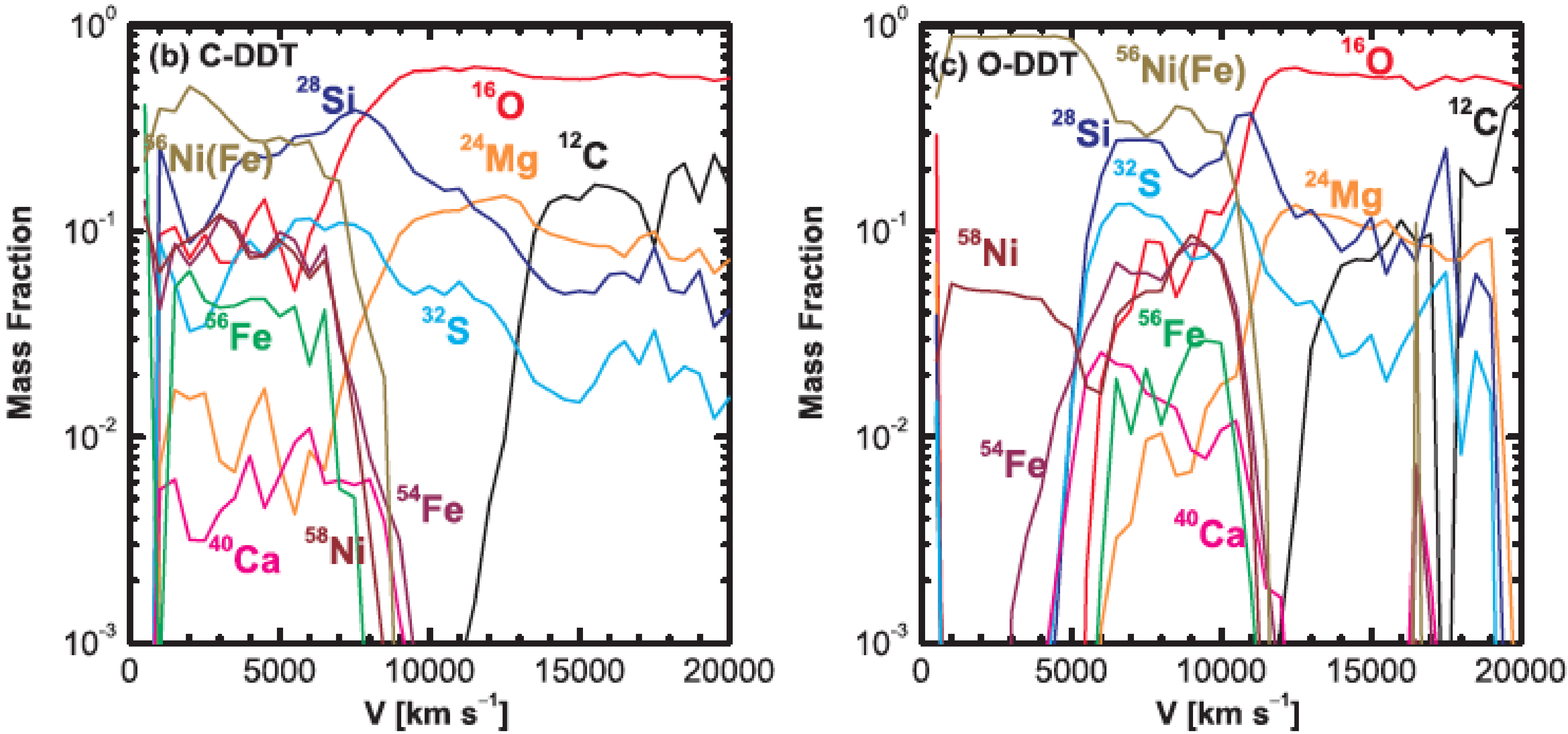
Surface helium detonation?



Fink et al. 2010

Models with Shallow ^{56}Ni?

Off-center burning?

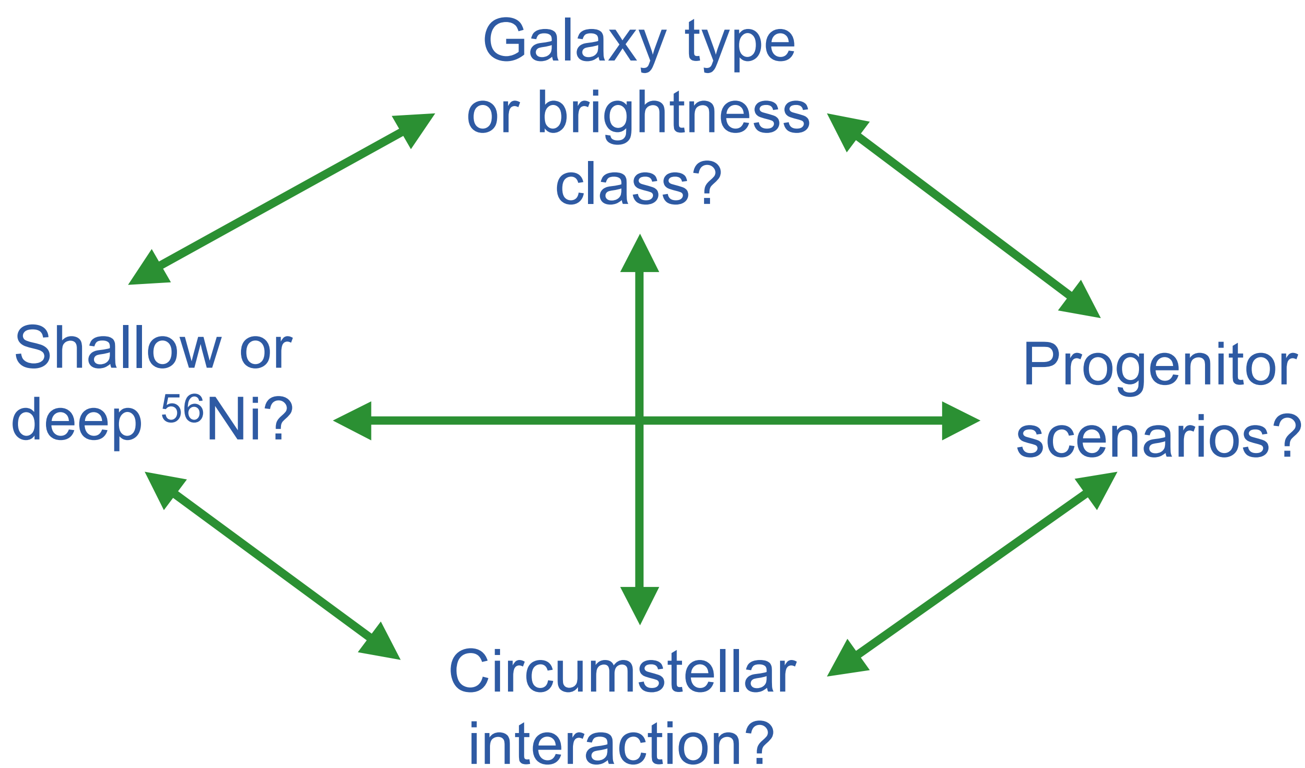


Maeda et al. 2010

Detailed checks will require more/better forward modeling

What’s Next For SN Ia?

As a larger number of early light curves are collected, we should look for correlations between the various properties



Such studies will be important for maximizing the science that can be done with these observations.

Mass-stripped SNe Puzzles

What determines Type **Ib** versus **Ic**?

• Is it just higher mass loss?

• Helium lines require non-thermal excitation (Dessart et al. finds that X_{56}~0.01 can be the difference between ~2.5-3.5M_{sun} of helium being seen or not!)

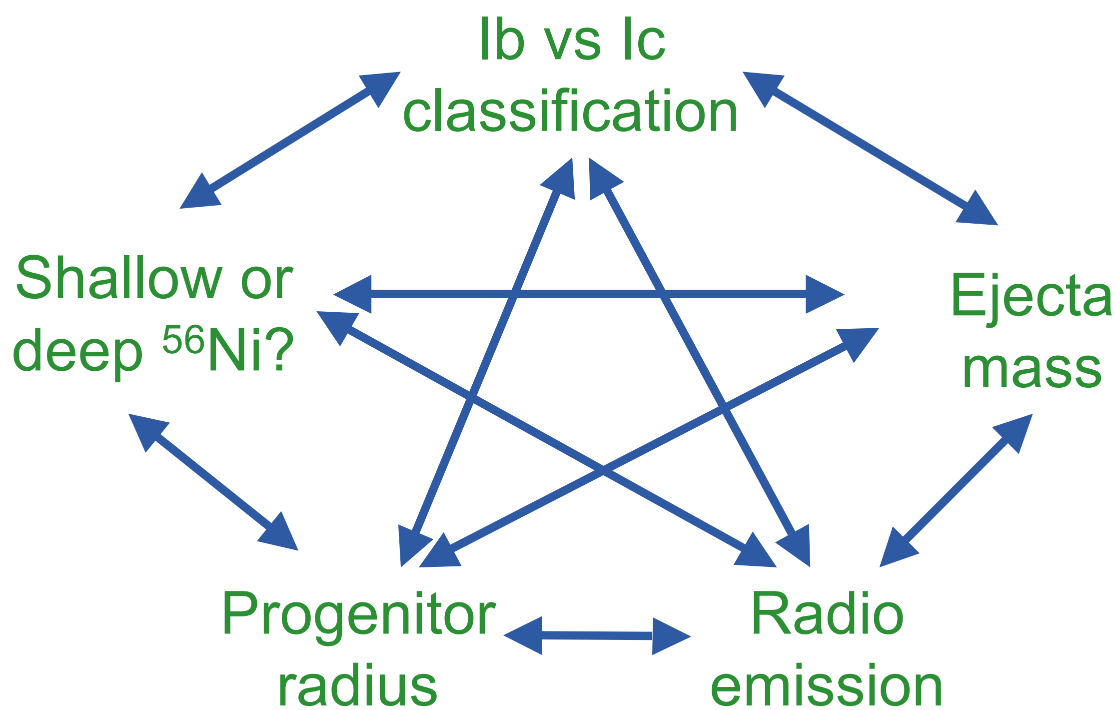
What fraction are caused by **stellar winds** versus **binaries**?

• ~2/3 of massive stars undergo mass transfer during their life with ~1/3 of those merging (Sana et al. 2012)

• Many Type Ib/Ic show short rises of ~15 days, indicative of ~1-4 M_{sun} of ejecta

What's Next For SNe Ib/c?

Correlations between a larger range of parameters crucial for a fuller understanding of these events.



This should help teach us (1) what determines the detection of helium and (2) what is the role of binarity vs stellar winds

Luminosity Distribution of SNe Ia

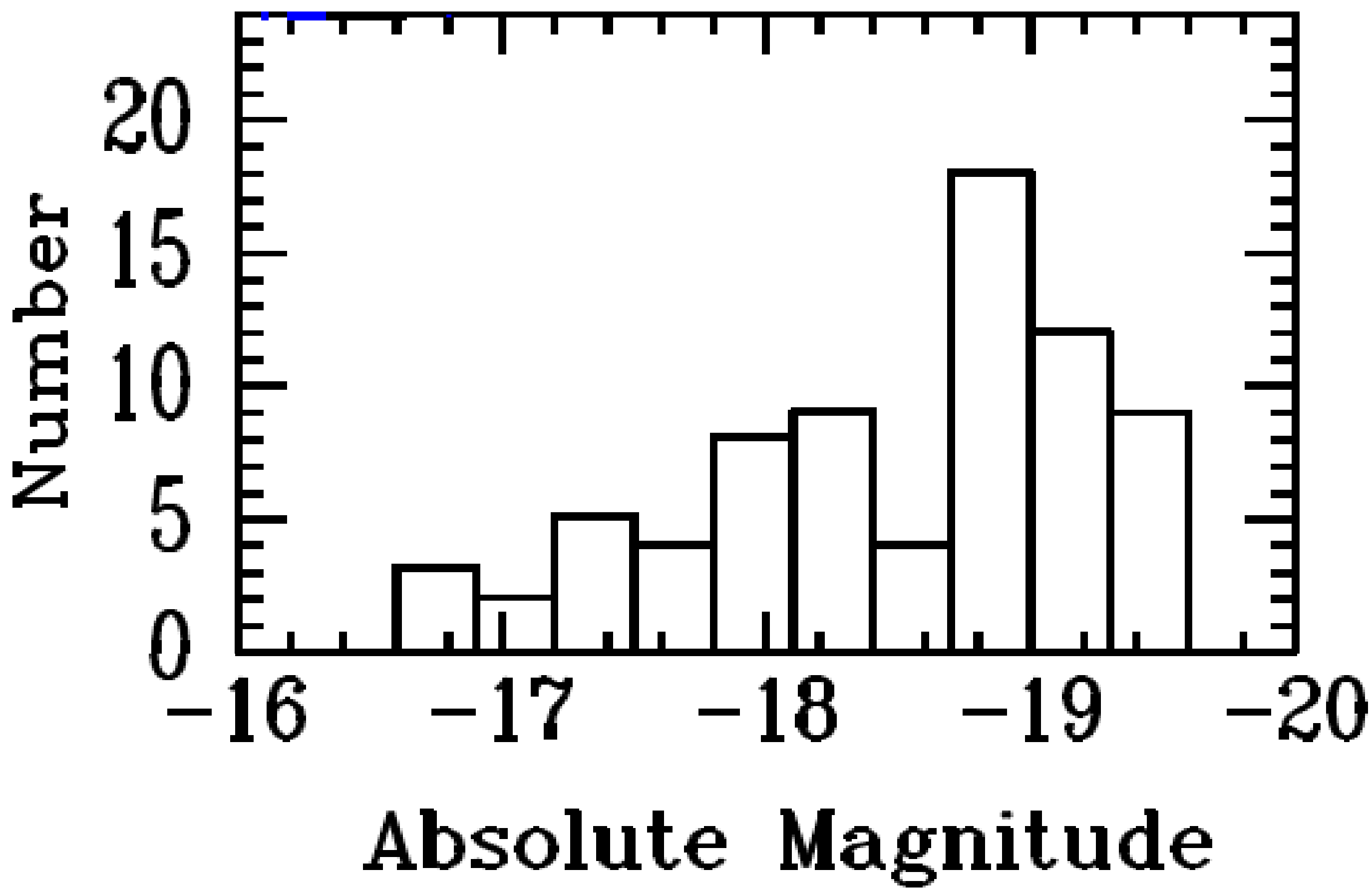
74 SNe Ia within 80 Mpc

What is the distribution of ^{56}Ni in a volume limited sample?

Does this show features not seen in cosmological surveys?

Can this provide clues about progenitors?

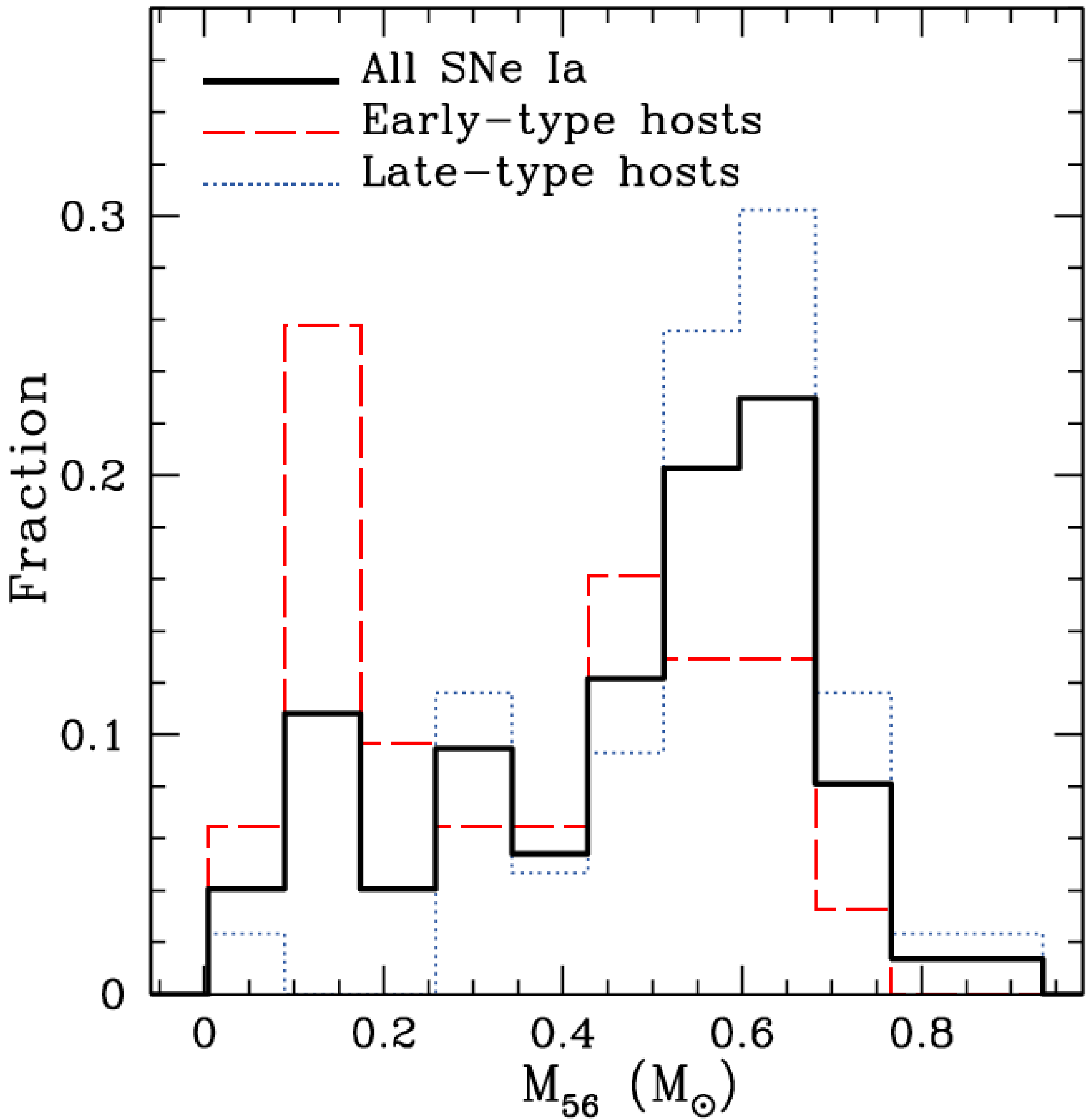
Lick Observatory SN Search, Li et al. (2011)



^{56}Ni Distribution of SNe Ia

Piro, Thompson, and Kochanek (2014)

- Use Δm_{15} vs M56 relation from Mazzali et al. ('07)
- Δm_{15} not available for 6 of the 91bg-like SNe
- Peaks around 0.55-0.6M_{sun}
- Distinct peak from 91bg-likes in early-type galaxies (Howell et al. '07)

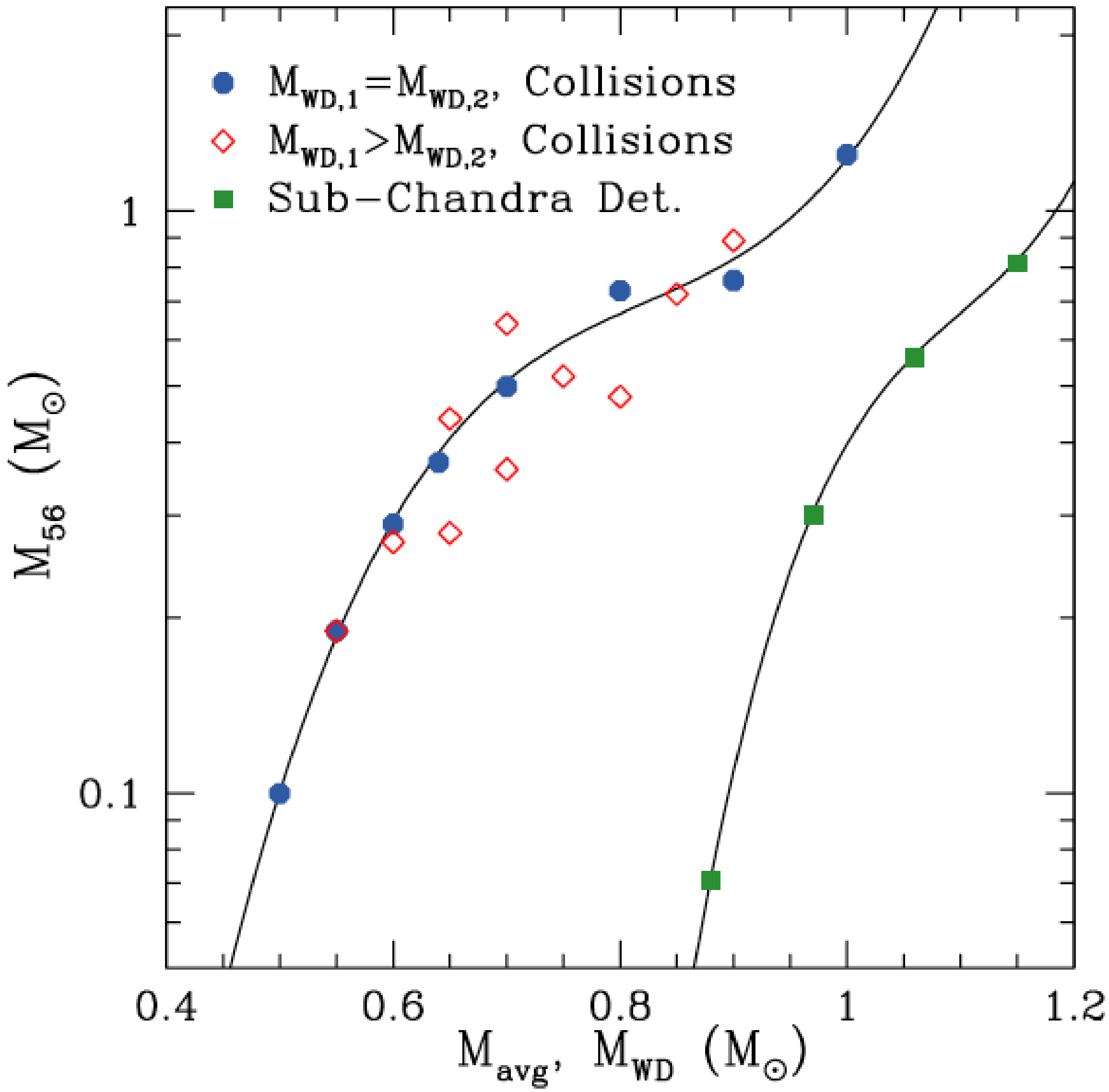


Connection with SN Ia Progenitors

Piro, Thompson, and Kochanek (2014)

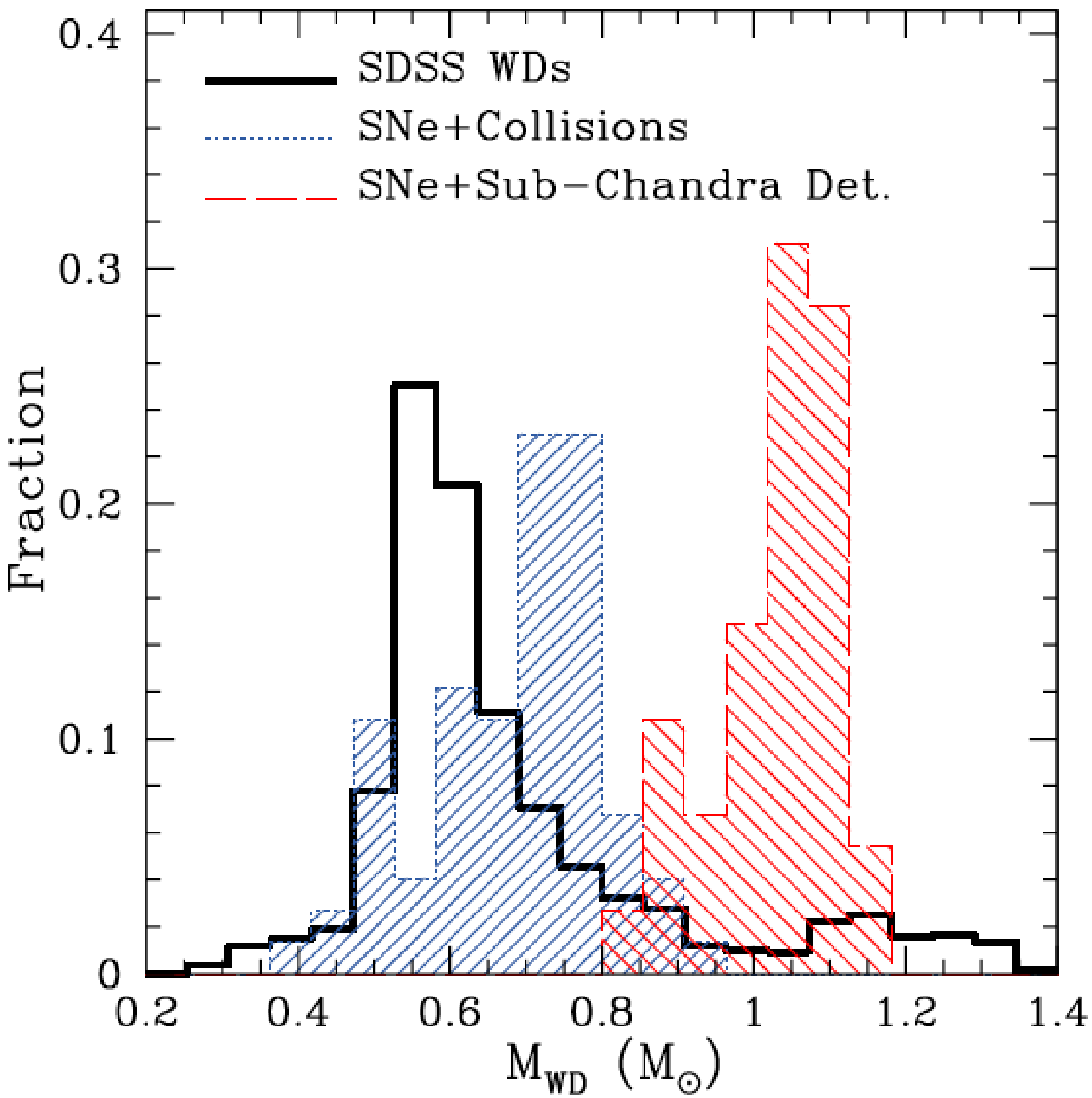
^{56}Ni yields from detonation (Sim et al. '10) and collision (Kushnir et al. '13) models mainly depend on the WD mass

We can therefore infer M_{56} => M_{WD}



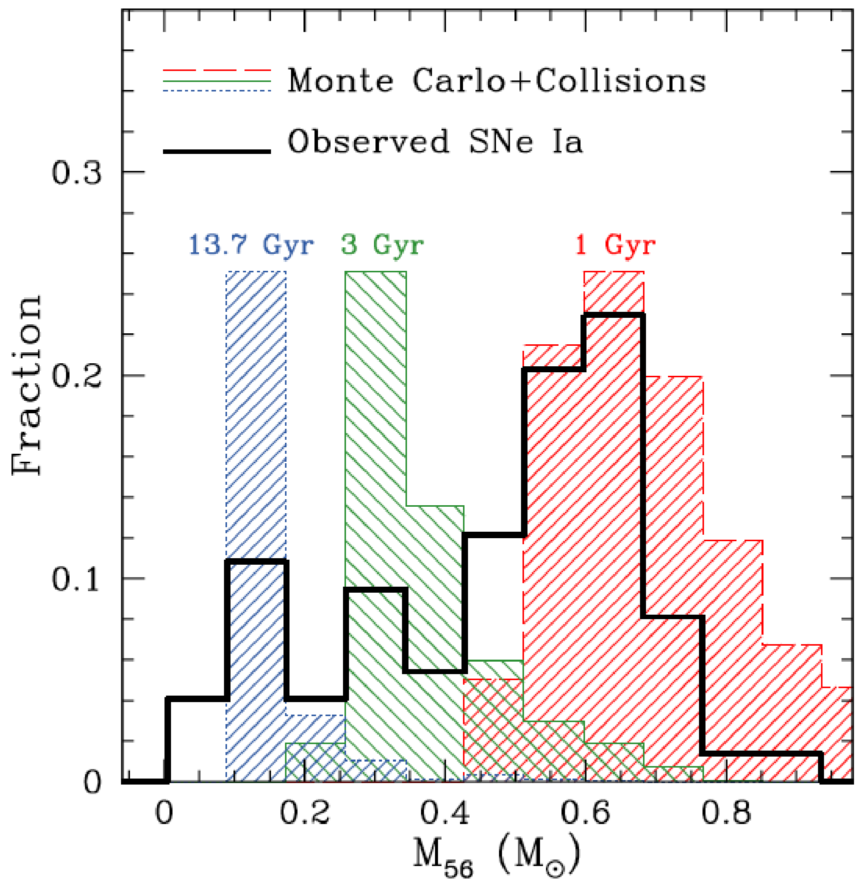
Which WDs must be exploding?

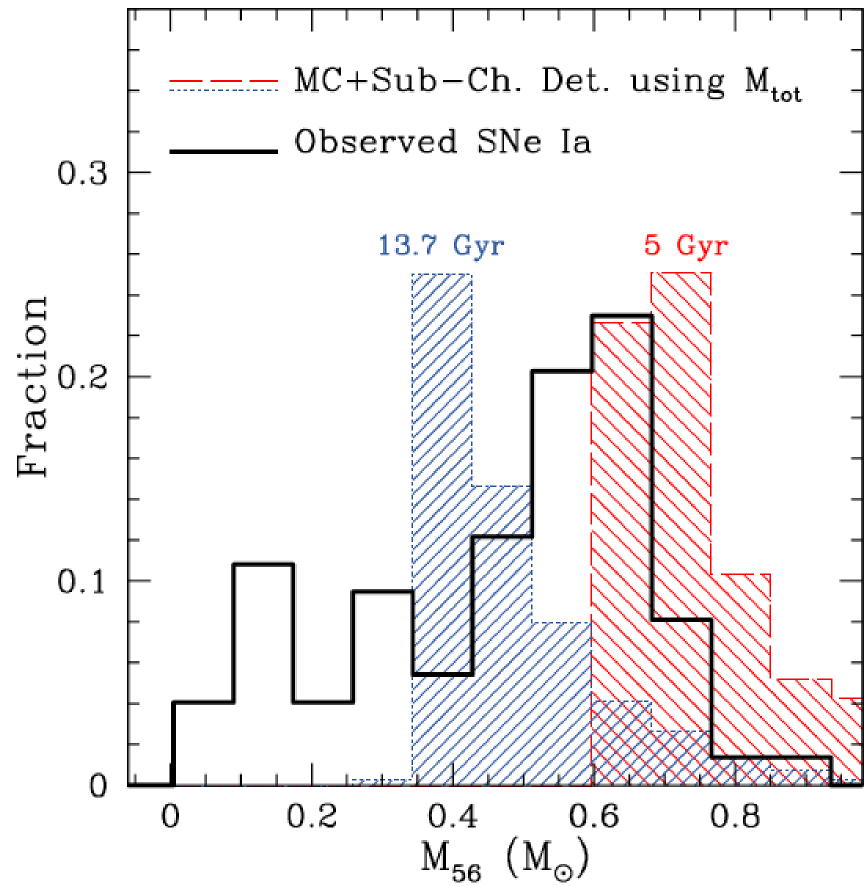
Piro, Thompson, and Kochanek (2014)



White dwarf masses vs age

Piro, Thompson, and Kochanek (2014)





Normal/bright SNe Ia require young stellar environments or accretion (Ruiter et al. 2013)

Collisions naturally explain luminosity and preponderance of 91bg-like events in old stellar environments (evidence? Dong et al. '14)

Conclusions

Early, rising light curves probe ^{56}Ni distribution in outer layers

Evidence for X_{56} ~ 0.01-0.1 at ~0.01-0.1M_{sun} from WD surface

Volume limited sample highlights:

- The need for accretion or young environments
- Prominence of 91bg-like events in old environments

Future work:

Observations: Larger volume limited samples and ^{56}Ni estimates, more early light curves (Ia and Ib/Ic/IIb)

Theory: New numerical models of shock cooling, 56Ni rise, progenitor scenarios, mass loss effects