^{56}Ni– t_0 distribution of calcium-rich supernovae

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Supernovae – general picture

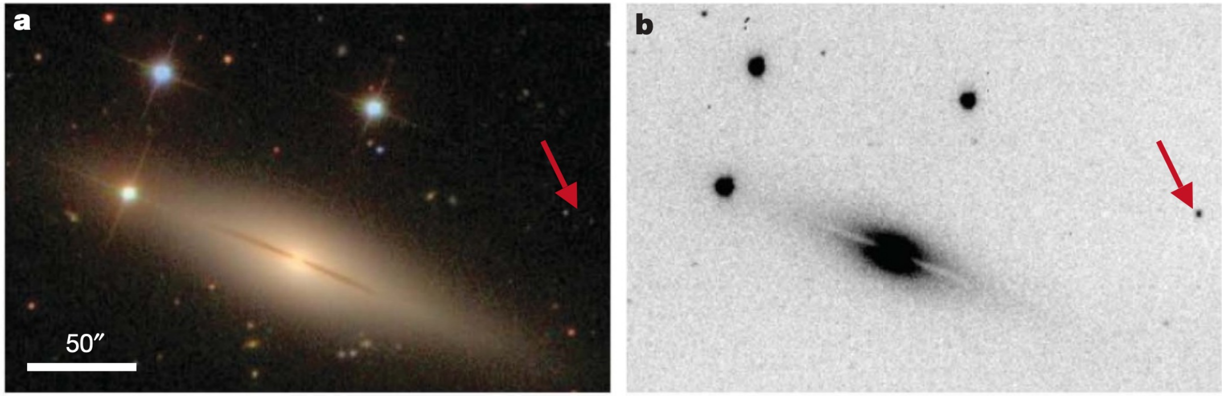
Supernovae are the terminal explosion of stars

	Type Ia	**Core collapse**
Progenitor	White dwarf	Massive star
Power source	Thermonuclear	Gravitational collapse
Location	All types of galaxies	Star forming galaxies

Ca-rich supernovae are poorly understood

Ca-rich Supernovae (SNe) are a new and a mysterious transient

- Faint and fast
- Strong lines of Ca in nebular spectra
- Many explode in the far outskirts of their host galaxies
- Unclear if WD or CC origin – modelling needed!



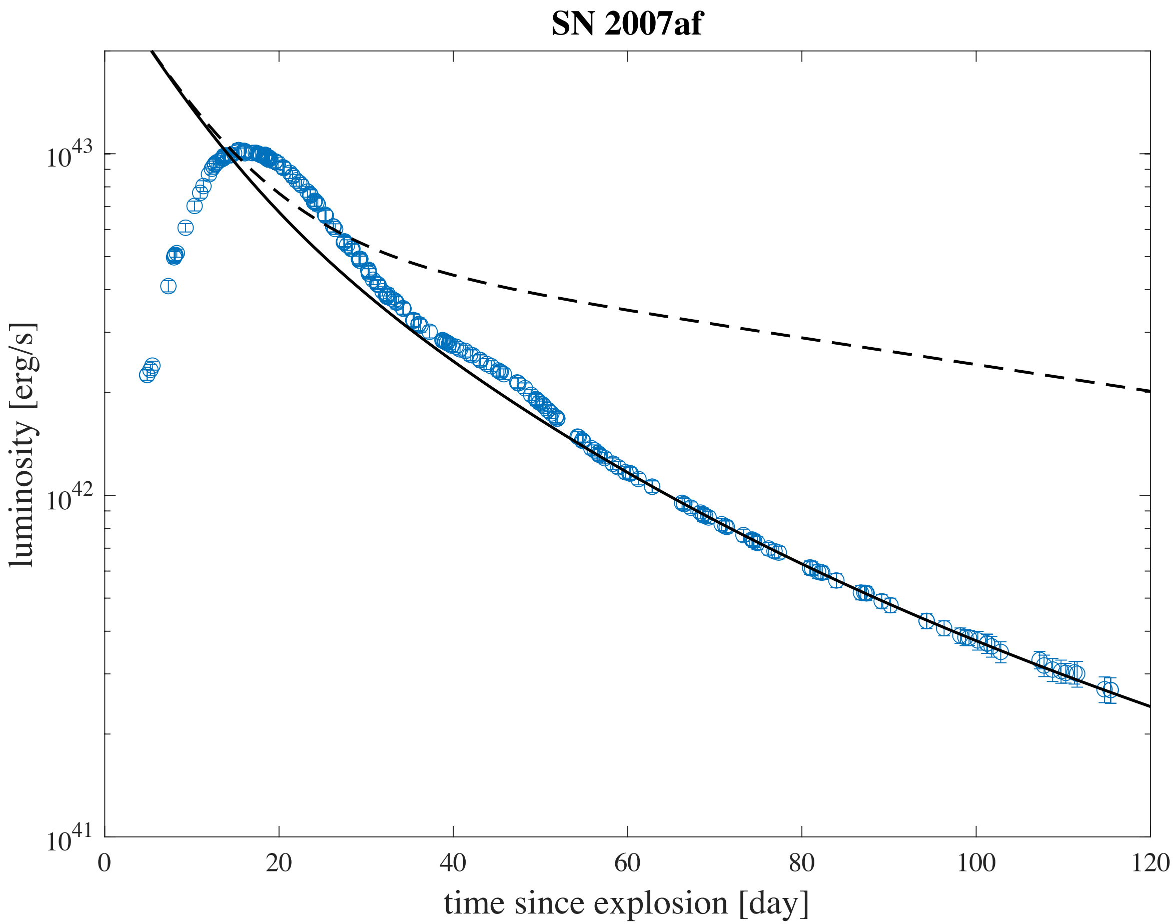
Perets+ 2010

Modeling supernovae is hard

- Simulating the explosion is hard - hydrodynamics, nuclear reactions, asymmetry, neutrinos...
- Radiation transfer simulations are hard - opacity constitutes from thousands of atomic transitions

➢ Can we bypass radiation transfer calculations?

SNe light curves are powered by ^{56}Ni decay



6 days   77 days

$$^{56}\mathrm{Ni} \longrightarrow {}^{56}\mathrm{Co} \longrightarrow {}^{56}\mathrm{Fe}$$

$$Q_{\mathrm{Ni56}}(t) = Q_{\gamma}(t) + Q_{\mathrm{pos}}(t)$$

Late times expectation:

$$L(t) = Q_{\mathrm{Ni56}}(t)$$

$$Q_{\mathrm{dep}}(t) = Q_{\gamma}(t) f_{\mathrm{dep}}(t) + Q_{\mathrm{pos}}(t)$$

The late time γ-ray deposition function is determined by the column density

At early times, γ-rays are trapped and $f_{\mathrm{dep}} = 1$.

At late times, the deposition fraction is: (homologous expansion $r = v \cdot t$)

$$f_{\mathrm{dep}} = \kappa_{\mathrm{eff}} \langle \Sigma \rangle_{\mathrm{Ni56}} = t_0^2/t^2\,, \quad t \gg t_0$$

$$t_0 = \sqrt{\kappa_{\mathrm{eff}} t^2 \langle \Sigma \rangle_{\mathrm{Ni56}}} \propto M_{ej}/\sqrt{E_{kin}}\,,$$

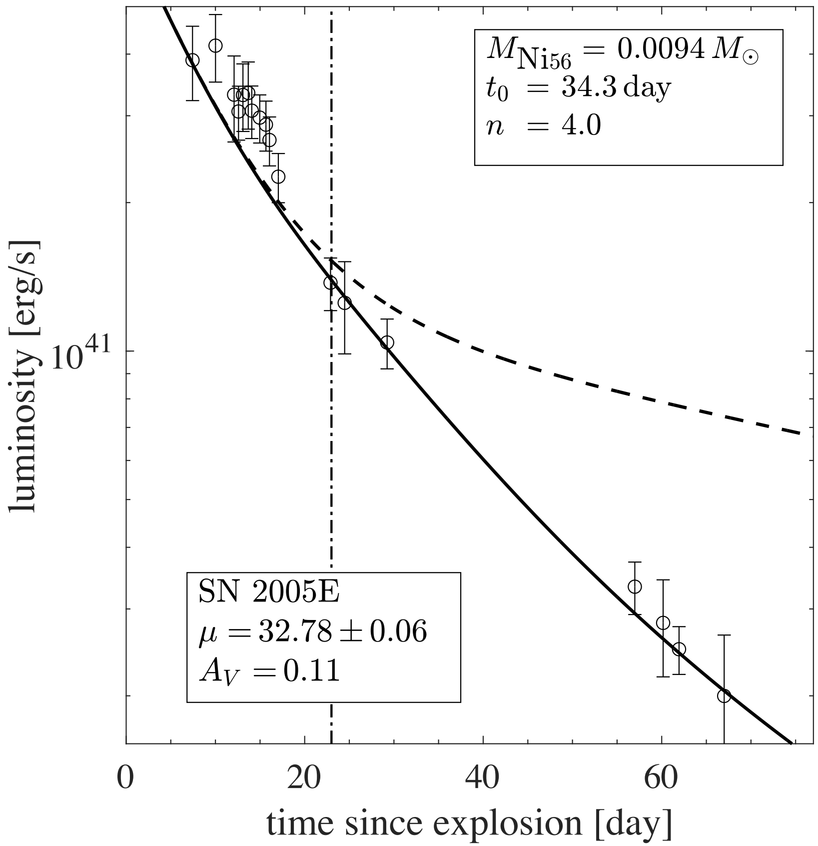
- $\langle \Sigma \rangle_{\mathrm{Ni56}}$ is the average column density ($\propto 1/t^2$).
- κ_{eff} - effective γ-ray opacity from Compton scattering (known!)

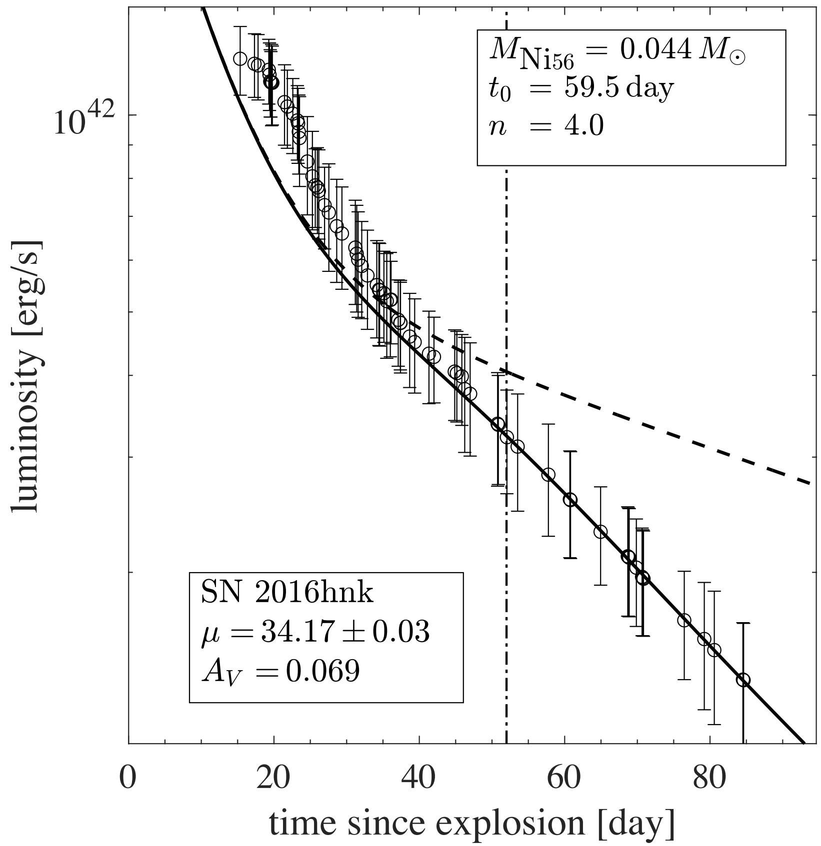
➢ Easily recovered from models

The method

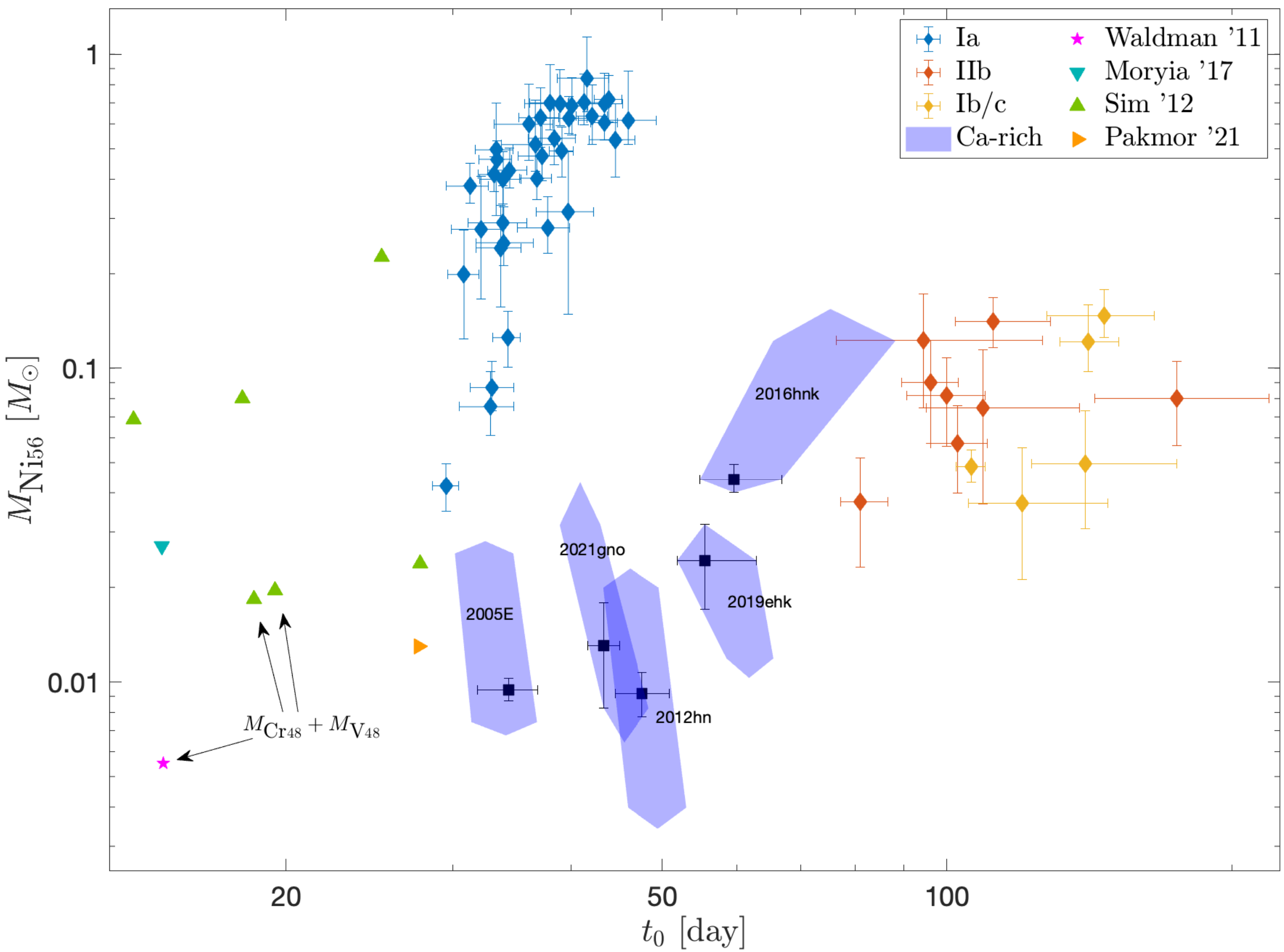
- Acquire a sample of bolometric light curves of Ca-rich SNe.
- Study the γ-ray deposition history and obtain observables - ^{56}Ni mass, t_0
- Constrain models using γ-ray transfer simulations.

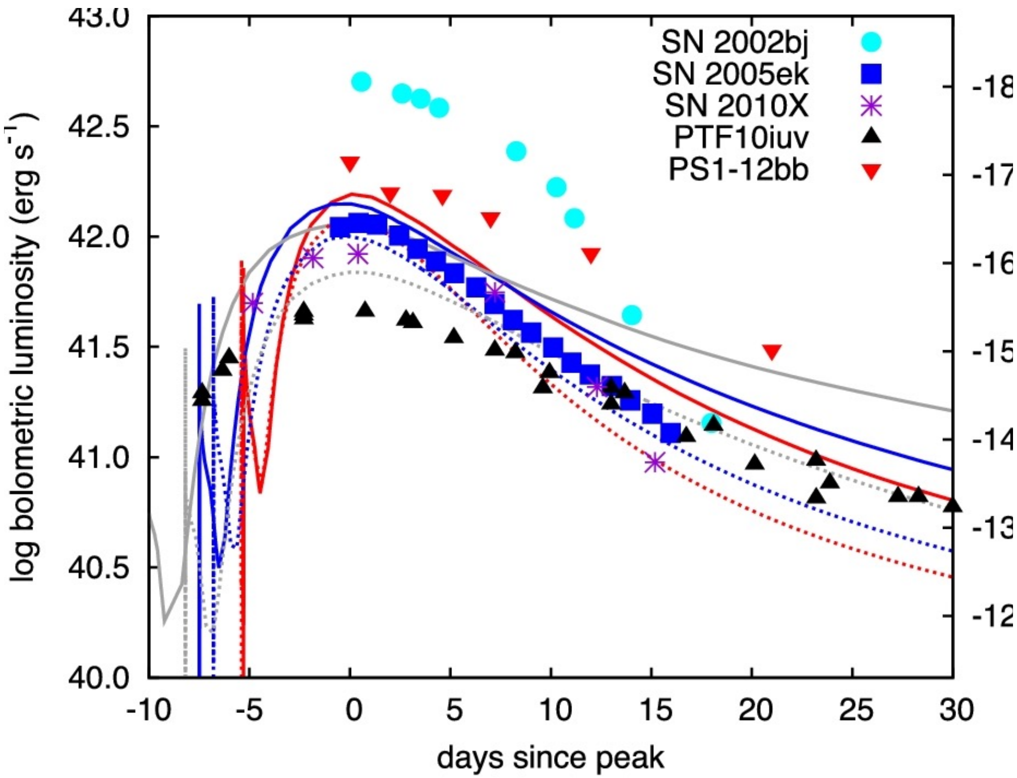
Results: Fitting Ca-rich SNe



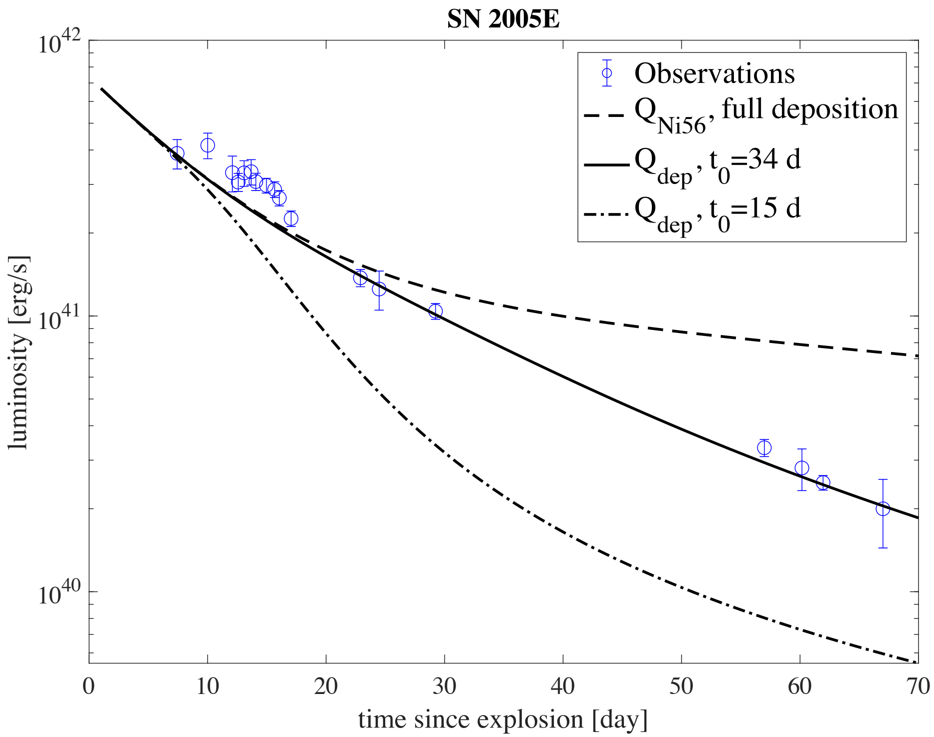


Results: Observed $t_0 - M_{\mathrm{Ni56}}$ distribution with Ca-rich models

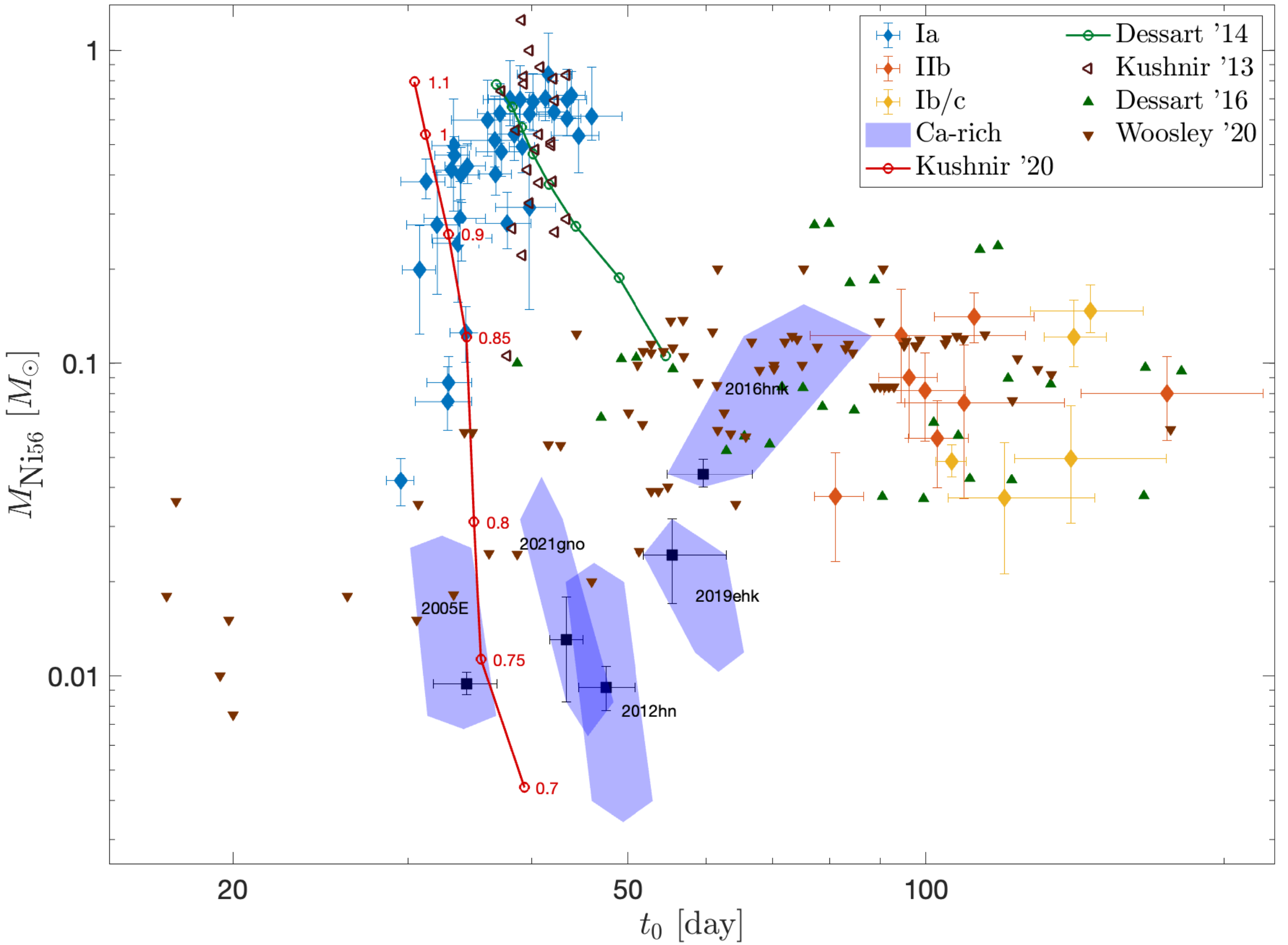



SN 2002bj
SN 2005ek
SN 2010X
PTF10iuv
PS1-12bb
log bolometric luminosity (erg s^{-1})
days since peak
43.0
42.5
42.0
41.5
41.0
40.5
40.0
-10
-5
0
5
10
15
20
25
30
-18
-17
-16
-15
-14
-13
-12

Moriya+ 2017


SN 2005E
Observations
Q_{Ni56}, full deposition
Q_{dep}, t_0=34 d
Q_{dep}, t_0=15 d
luminosity [erg/s]
time since explosion [day]
10^{42}
10^{41}
10^{40}
0
10
20
30
40
50
60
70

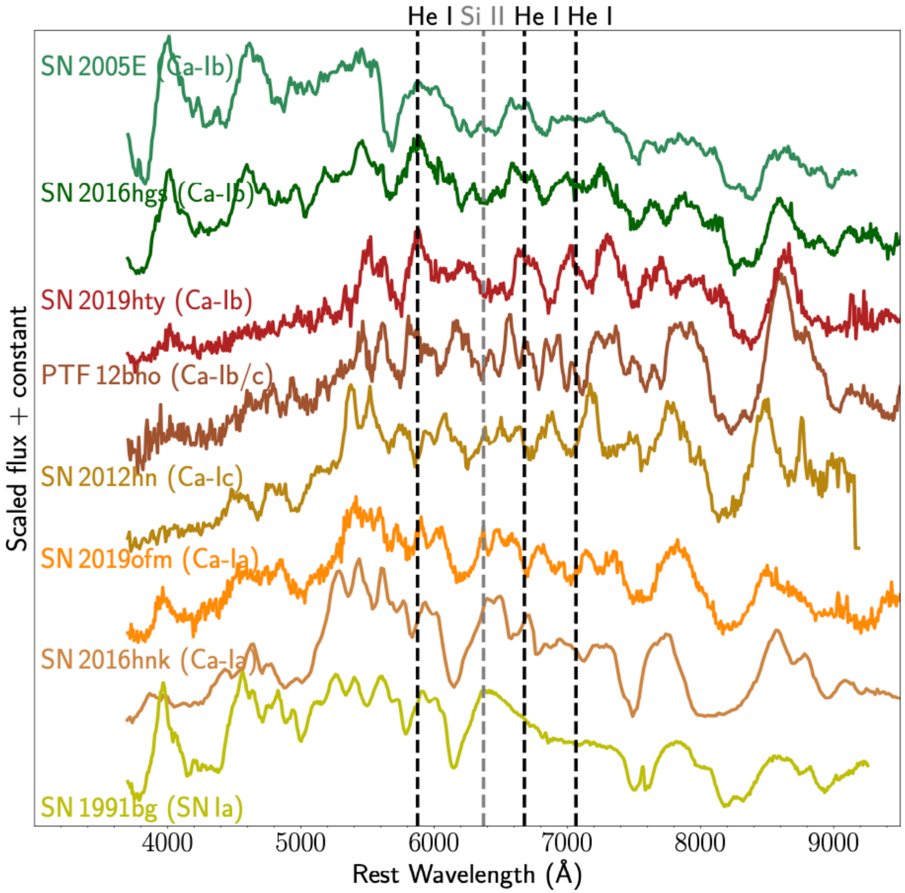
Observed $t_0 - M_{\mathrm{Ni56}}$ distribution with other SNe models



Conclusions

- Ca-rich SNe γ-ray escape times are $t_0 \approx 35 - 60$ days
- Very low mass models (WD He shells, ultra-stripped stars) disagree with observations
- Possible models: Low-mass WDs, SESN
- Connects Type Ia and SE SN?

Spectroscopic continuum agreement



De+ 2020

Energy conservation arguments remove M_{Ni56} and t_0^2 degeneracy for Type Ia SNe.

t_0 has been measured for Type Ia SNe by fitting Q_{dep} to L (direct method).

A different approach to measure t_0 is based on the Katz integral (Katz et al 2013):

$$\int_0^t Q_{\mathrm{dep}}\, t'dt' = \int_0^t L\, t'dt' + t'E(t')|_0^t,$$

where E is the thermal energy of the ejecta.

For Type Ia SNe, $tE(t)$ is small for early and late times, so:

$$\frac{Q_{\mathrm{dep}}}{\int_0^t Q_{\mathrm{dep}} t'dt'} = \frac{L}{\int_0^t L t'dt'}, \quad \text{at} \quad L(t) = Q_{\mathrm{dep}}(t),$$

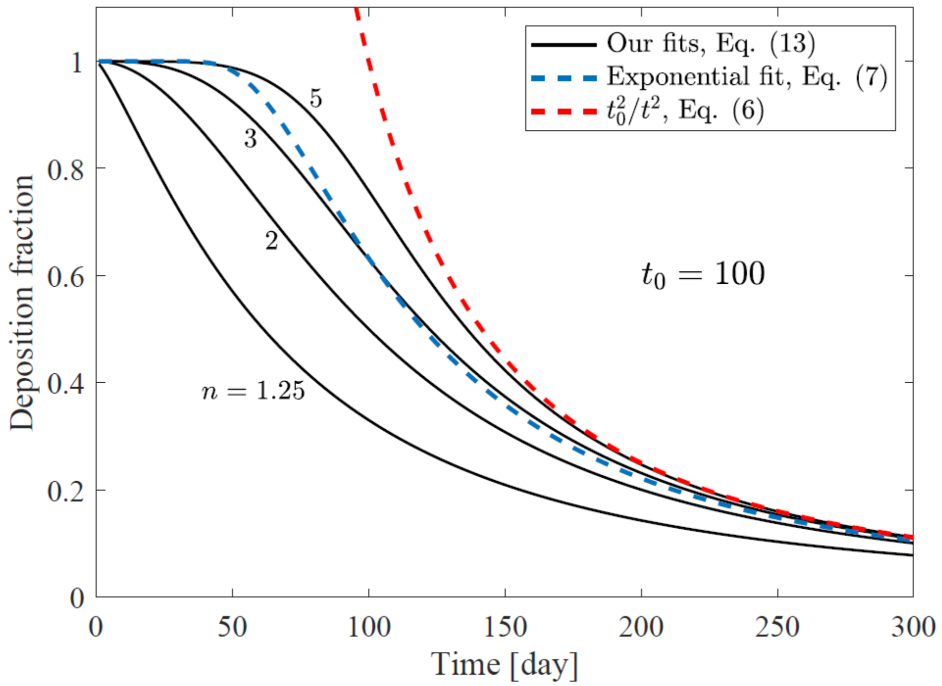
which does not depend on M_{Ni56}.

SE SNe require a more versatile interpolation function and accounting for *ET*

SE SNe have $t_0 \sim 100$ day - $f_{\rm dep} = t_0^2/t^2$ not valid in most measurements.

Interpolating function cannot be parametrized by one equation - another parameter n is introduced and:

$$f_{\rm dep} = \frac{1}{(1 + (t/t_0)^n)^{\frac{2}{n}}}$$



ET is non negligible for SE SNe – can reach ~few$\times 10^{54}$ erg s, ~10% of the time weighted luminosity.

Deducing 4 ejecta properties from the bolometric light curve

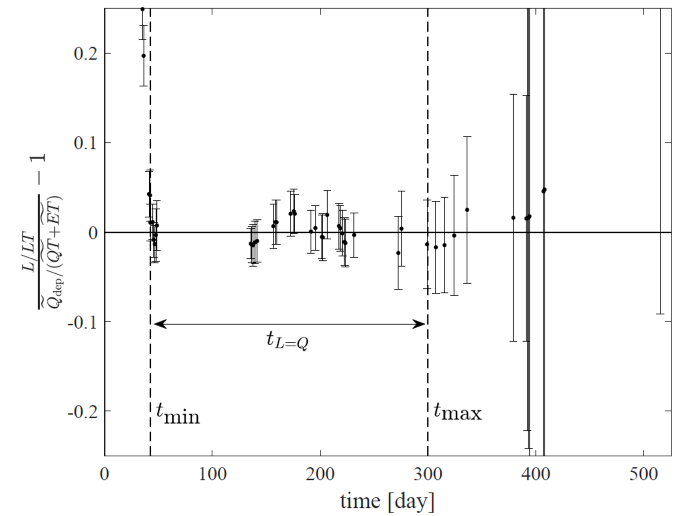
We use the integral method to find $\{t_0, \widetilde{ET}, n\}$ that minimize:

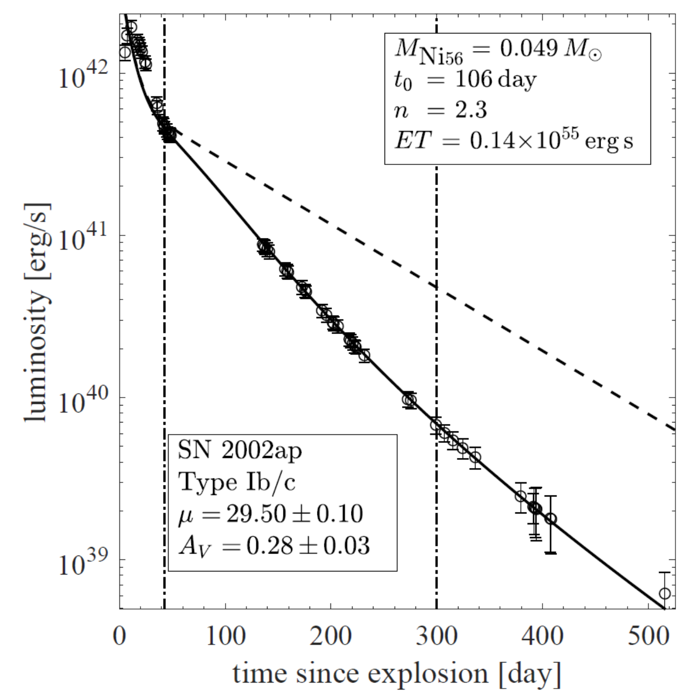
$$\frac{N_{\text{bins}}}{N_{\text{meas}}} \sum_{t_i \in t_{L=Q}} \left[\left(\frac{L(t_i)}{LT(t_i)} - \frac{\tilde{Q}_{\text{dep}}(t_i)}{\widetilde{QT}(t_i) + \widetilde{ET}} \right) \frac{LT(t_i)}{L_{\text{err}}(t_i)} \right]^2$$

Where:

- Tilde quantities are normalized by M_{Ni56}. For example $\widetilde{ET} = ET/M_{\text{Ni56}}$.
- $t_{L=Q}$ is the time range where $L = Q_{\text{dep}}$ is valid.
- N_{bins} is the number of independent time bins. Size of each bin is ~5 day for SE SNe.

The uncertainty of the parameters is calculated with a MCMC algorithm.





Constructing bolometric light curves

The bolometric light curve construction is made of the following steps:

- Missing data interpolation and extrapolation
- Extinction correction
- SED construction – UV and IR treatment
- Luminosity calculation
- Errors – statistical and systematic