#### γ-ray deposition histories of core collapse supernovae

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# SNe light curves strongly depend on the $\gamma$ -ray deposition function

During the SN, <sup>56</sup>Ni is synthesized, and decays via:

$$^{56}$$
Ni  $\rightarrow$   $^{56}$ Co  $\rightarrow$   $^{56}$ Fe

with  $t_{1/2}$  of 6 day and 77 day, respectively.

The decay product are  $\gamma$ -rays and positrons that heat the ejecta. The deposited energy is:

$$Q_{\rm dep} = Q_{\gamma} f_{\rm dep} + Q_{\rm post}$$

where  $f_{dep}$  is the deposition function. At most times  $Q_{pos} \simeq 0.03 Q_{\gamma}$ .

At late times,  $L(t) = Q_{dep}(t)$ , so the deposition function has a large impact on the shape of the light curve.



## The deposition fraction is parametrized by the $\gamma$ -ray escape time $t_0$

- At early times,  $\gamma$ -rays are trapped and  $f_{dep} = 1$ .
- At late times, the optical depth  $\tau \propto \rho r \propto r^{-2} \propto t^{-2}$ , so the deposition fraction is  $f_{dep} = t_0^2/t^2$
- An interpolating function was used to connect the optically thick and thin regions:

$$f_{\rm dep} = 1 - e^{-t_0^2/t^2}$$

A method to directly measure  $t_0$  is based on the Katz integral (Katz et al 2013):

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

Type Ia SNe  $t_0$  values found by this method were 35 - 40 day.



#### What is it good for?

- $t_0 \propto M/\sqrt{E_{\rm kin}}$  fundamental properties of the SNe.
- No complicated radiation transfer simulations
- Can constrain models

## Can we apply it for other types of SNe?

Yes! But other types of SNe have different ejecta parameters:

- Different values of  $t_0$
- Non zero values of  $t'E(t')|_0 = ET$ .
- Mixing?

#### **Objectives**

- Acquire a sample of bolometric light curves of different types of SNe, with an emphasis on core-collapse SNe. Photometry must include IR measurements.
- Study the  $\gamma$ -ray deposition history the sample. Expand the Katz integral for CC SNe.
- Constrain models using  $\gamma$ -ray transfer simulations.

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

SE SNe have  $t_0 \sim 100 \text{ day} - f_{dep} = t_0^2/t^2$  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×  $10^{54}$  erg s, ~10% of the time weighted luminosity.



## Deducing 4 ejecta properties from the bolometric light curve

We use the integral method to find 4 parameters:  $\{t_0, M_{Ni56}, n, ET\}$ 



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

## **Results:** $t_0 - M_{Ni56}$ distribution of our sample

The distribution of  $t_0 - M_{Ni56}$  shows:

- The Type Ia  $t_0$  range of 30-45 day is recovered
- Type lb/c have  $t_0 \approx 105 140$  day
- Type IIb have  $t_0 \approx 80 110$  day
- Type IIP have  $t_0 \gtrsim 400$  day

- Average  $M_{\text{Ni56}}$  of each type satisfies:  $\langle M_{\text{Ni56}}^{\text{Ia}} \rangle > \langle M_{\text{Ni56}}^{\text{SE}} \rangle > \langle M_{\text{Ni56}}^{\text{IIP}} \rangle$
- Possible negative correlation between  $t_0$  and  $M_{Ni56}$  for Type IIP.



#### **Results:** ET distributions

The *ET* distribution show:

- Type IIb have small ET values
- Type lb/c have non negligible ET
- Possible correlation between  $t_0$  and ET

Errors are ~10% order, so we treat these values as tentative



## Constraining ejecta parameters with $\gamma$ -ray transfer simulations

Monte Carlo  $\gamma$ -ray transfer simulations have known physics and are easy to implement.

We can estimate the deposition parameters  $\{t_0, n\}$  for models from the literature.

- $t_0$  constrains the ratio  $t_0 \propto \sqrt{\int \rho dv}$  $\propto M_{\rm ej}/\sqrt{E_{\rm kin}}$ .
- *n* parameter indicates the amount of mixing.



### Conclusions

Unique properties for each SN type. SNe can be distinguished according to its  $t_0$  value.

The  $\gamma$ -ray deposition histories, combined with radiation transfer codes, provide a powerful tool to constrain models.

A bigger sample of CC SNe would:

- Fill the  $t_0$  gap between SE and Type IIP SNe.
- Clarify the range of *ET* values of SE SNe constraints on the progenitor system.
- Correlation between  $M_{\rm Ni56}$  and  $t_0$  of Type IIP implication on the explosion mechanism.