Light curve models for superluminous supernovae

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SLSNe : overview of observational properties

- **Definition** : A SN reaching intrinsic brightness <-21 mag in any band *(Gal-Yam 2012)*.
- **History** : The first such SNe were reported in 1999 (SN 1999as and SN 1999bd), the third one in 2005 (SN 2005af). Today we have a few dozen reported.
- **Types** : So far all SLSNe are either Type IIn or Type Ic.
- **Emitted energies** : Between $(0.6 - 4) \times 10^{51}$ erg *(Gal-Yam 2012)* (Also a single object at 13×10^{51} erg)

SLSNe : overview of model classes

A model needs to have an energy source giving $E \gtrsim 10^{51}$ erg and a mechanism to transform this to UVOIR radiation over the time-scales observed.

Radioactivity	Neutron star rotation energy	BH/NS accretion	Ejecta kinetic energy
$E \approx 10^{51} \left(\frac{M(^{56}\mathrm{Ni})}{5 M_\odot}\right)$	$E \approx 10^{51} \left(\frac{P}{5\ \mathrm{ms}}\right)^{-2}$	$E \approx 10^{51} \left(\frac{M_{acc}}{1\ M_\odot}\right)$	$E \approx 10^{51}$
Gamma-ray thermalization.	Magnetic spin-down + thermalization of pulsar wind.	Fall-back + Disk wind thermalization	Circumstellar interaction + X-ray thermalization.

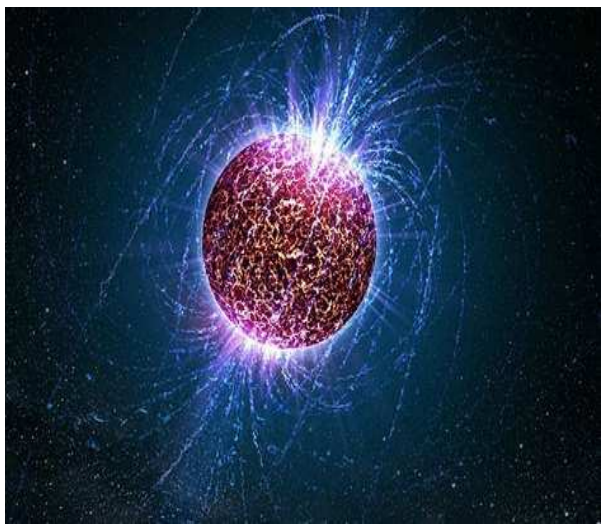
Magnetar model - overview

- Ostriker & Gunn 1971 : fast-spinning and strongly magnetized pulsars can have significant impact on the early SN display.
- Idea largely forgotten until Kasen & Bildsten 2010 revived it as a model for SLSNe.

$$E = 10^{51} \left(\frac{P}{5\ \mathrm{ms}} \right)^{-2} \ erg$$

$$P(t) = L_0 \left(\frac{B}{P^2} \right) \left(1 + \frac{t}{\tau_{spin-down}(B/P)} \right)^{-2}$$

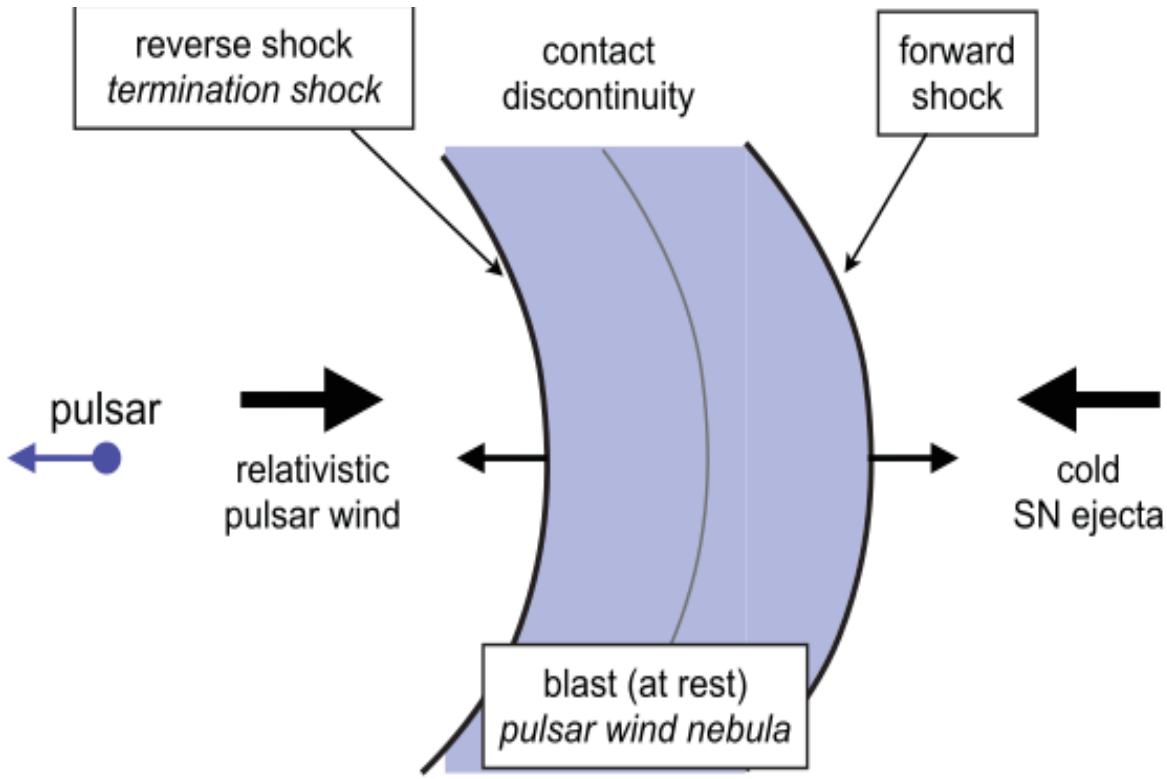
$$\tau_{spin-down} = 120d \left(\frac{B}{10^{14}\,G} \right)^{-2} \left(\frac{P}{5\ ms} \right)^{2}$$



Magnetar model - powering mechanism Kotera+2013,

Metzger+2014

- Energy flux of pulsar wind is dominated by relativistic e-/e+ pairs
- At SN base, synchrotron emission gives X-ray emissivity. Inverse Compton scattering of these X-ray photons gives GeV-TeV gamma ray photons. These make again e-/e+ pairs by pair production.



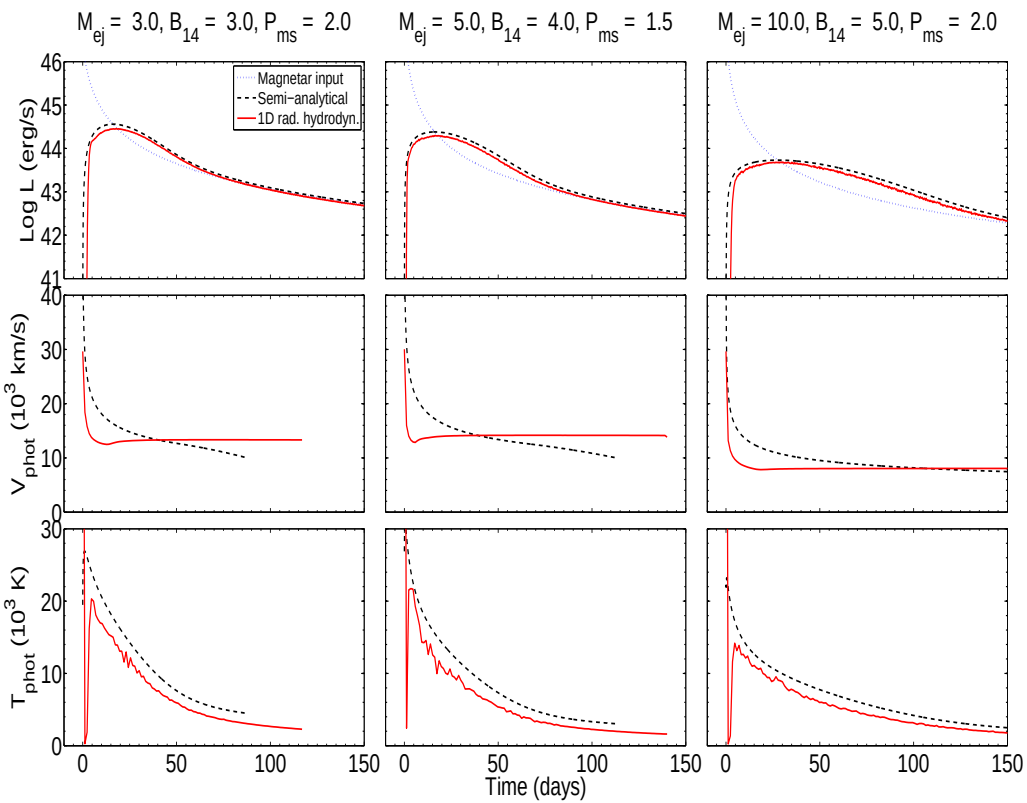
Kotera+2013

Magnetar model - producing light curves

- Arnett 1982 formalism:

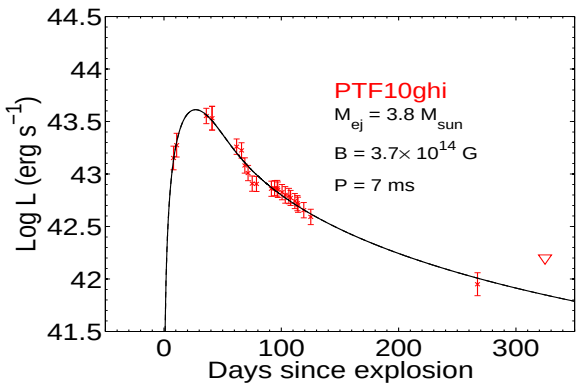
$$L(t) = \int_0^t P(t') f(t', \tau) dt' \qquad \tau = C \kappa^{1/2} M_{ej}^{3/4} E^{-1/4}$$

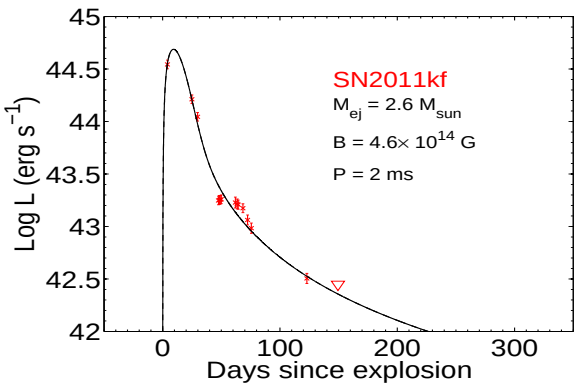
- Comparisons with Kasen & Bildsten 2010 hydrodynamic solutions show that method works well if we choose $E = \frac{1}{2}\left(E_{initial} + E_{final}\right)$

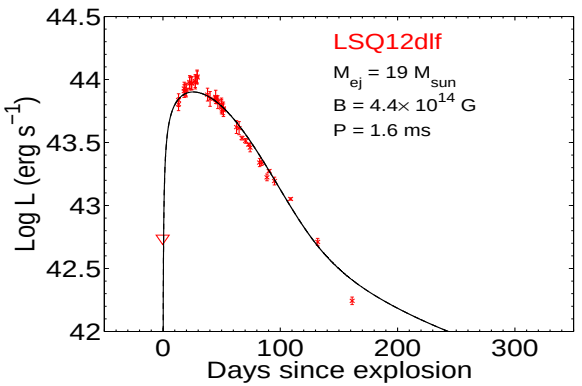


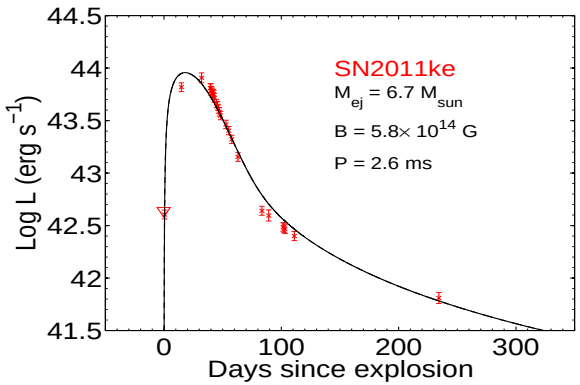
Inserra+2013

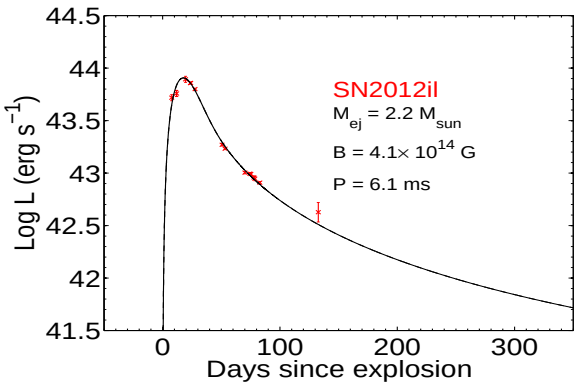
Magnetar model - light curve fits *Inserra+2013, Nicholl+2014*

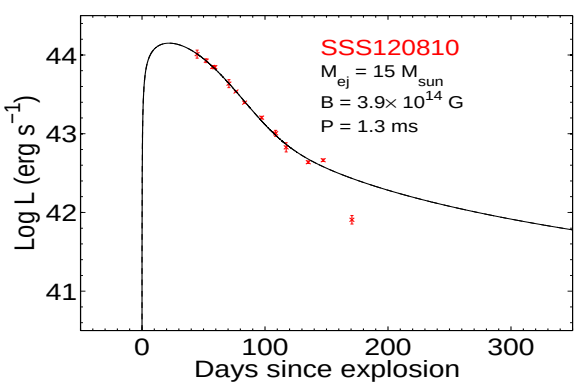


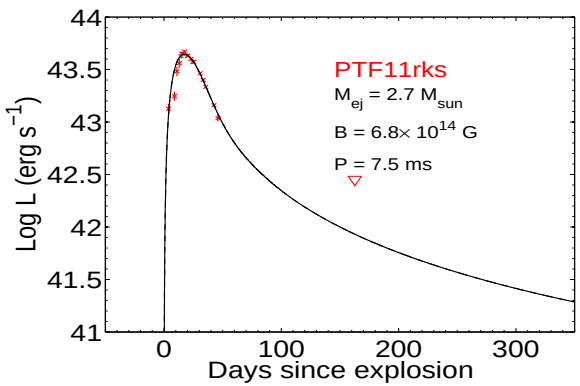


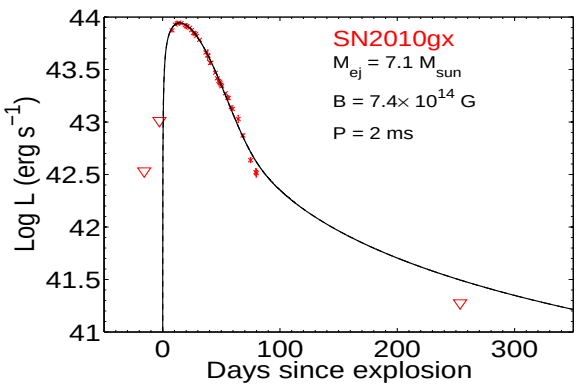


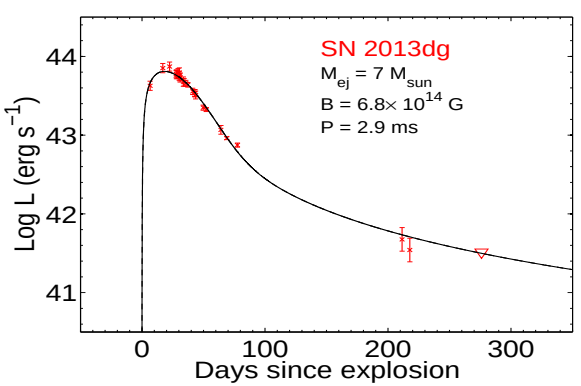




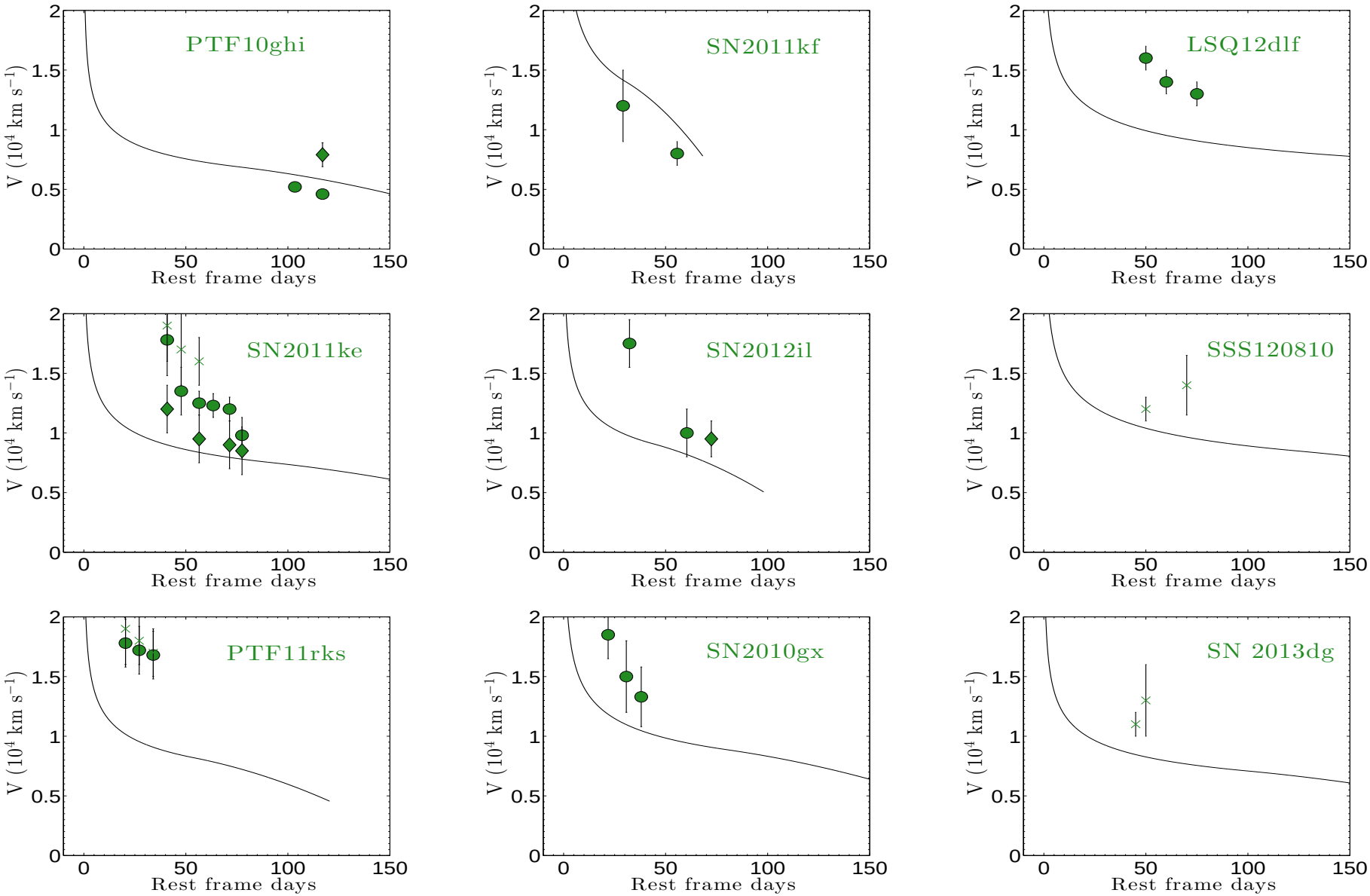




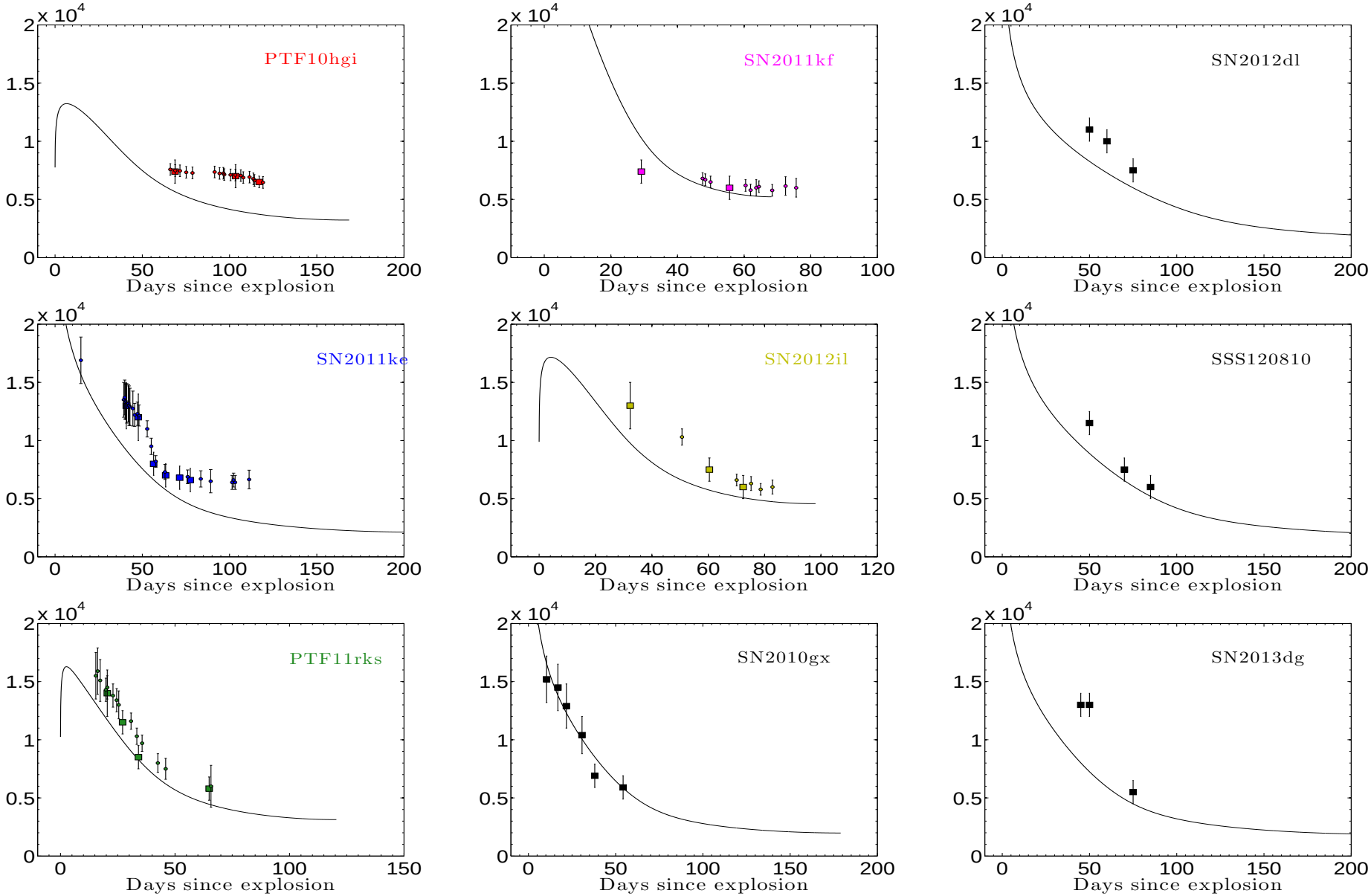




Magnetar model - photospheric velocities *Inserra+2013, Nicholl+2014*

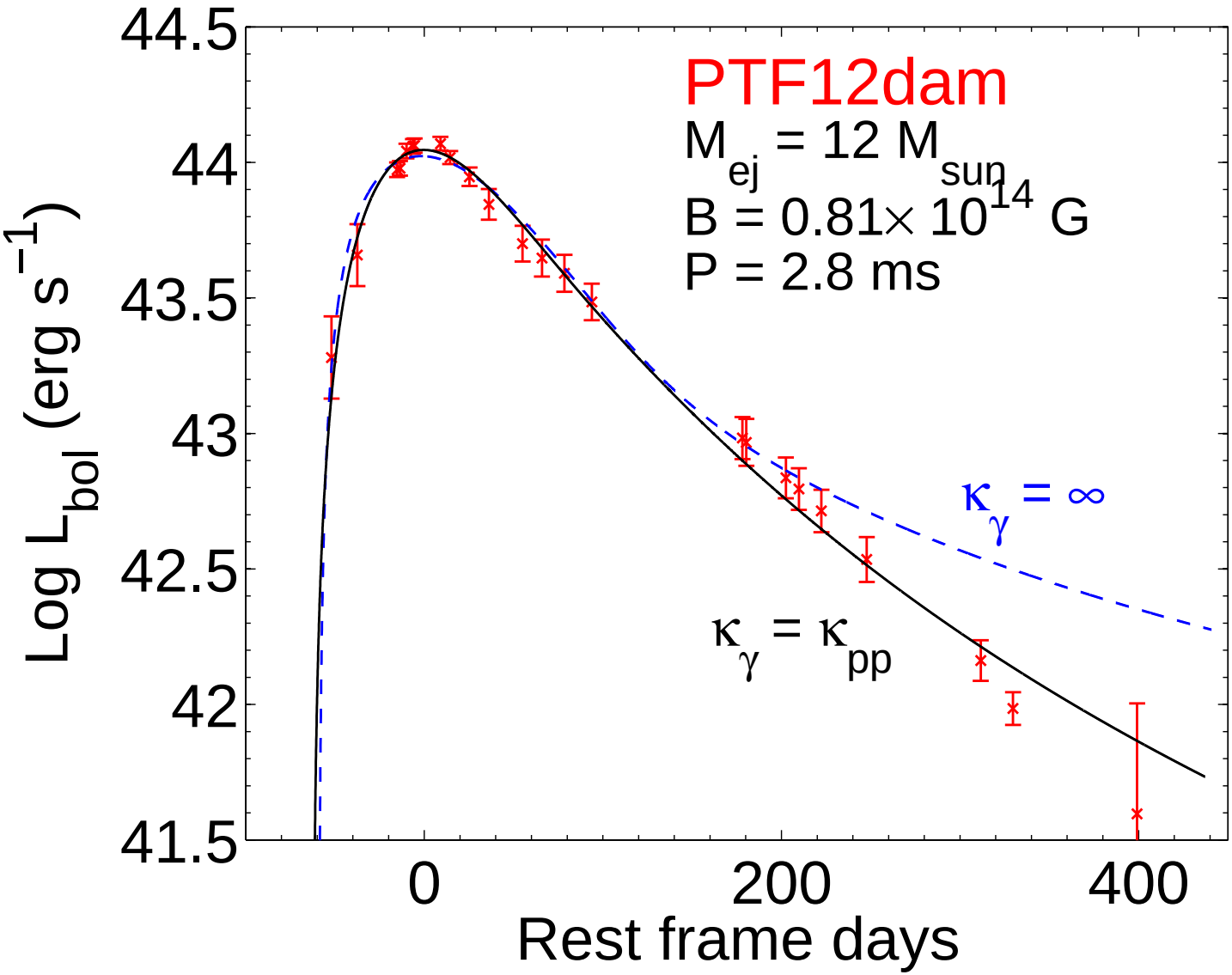


Magnetar model - photospheric temperatures *Inserra+2013, Nicholl+2014*



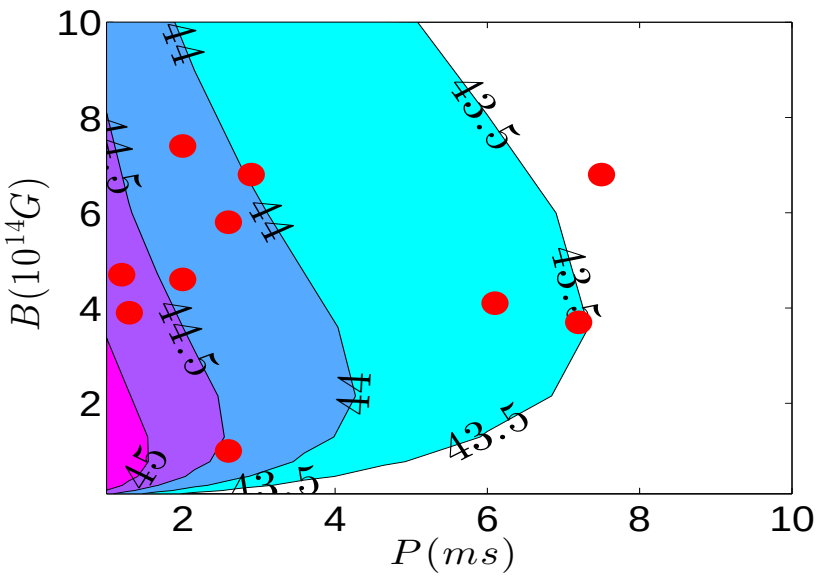
PTF12dam - 500 days light curve *Chen+2014, in prep.*

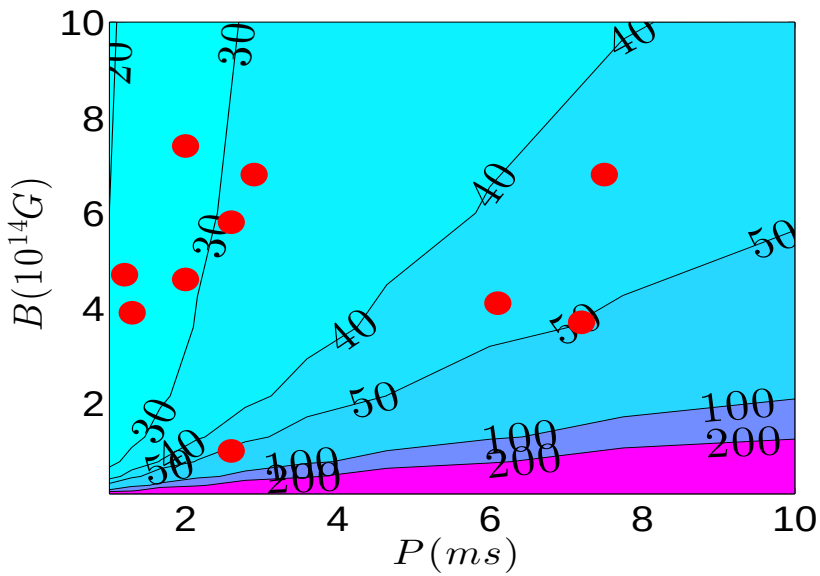
- Magnetar model requires breakout of high-energy radiation at 200 days



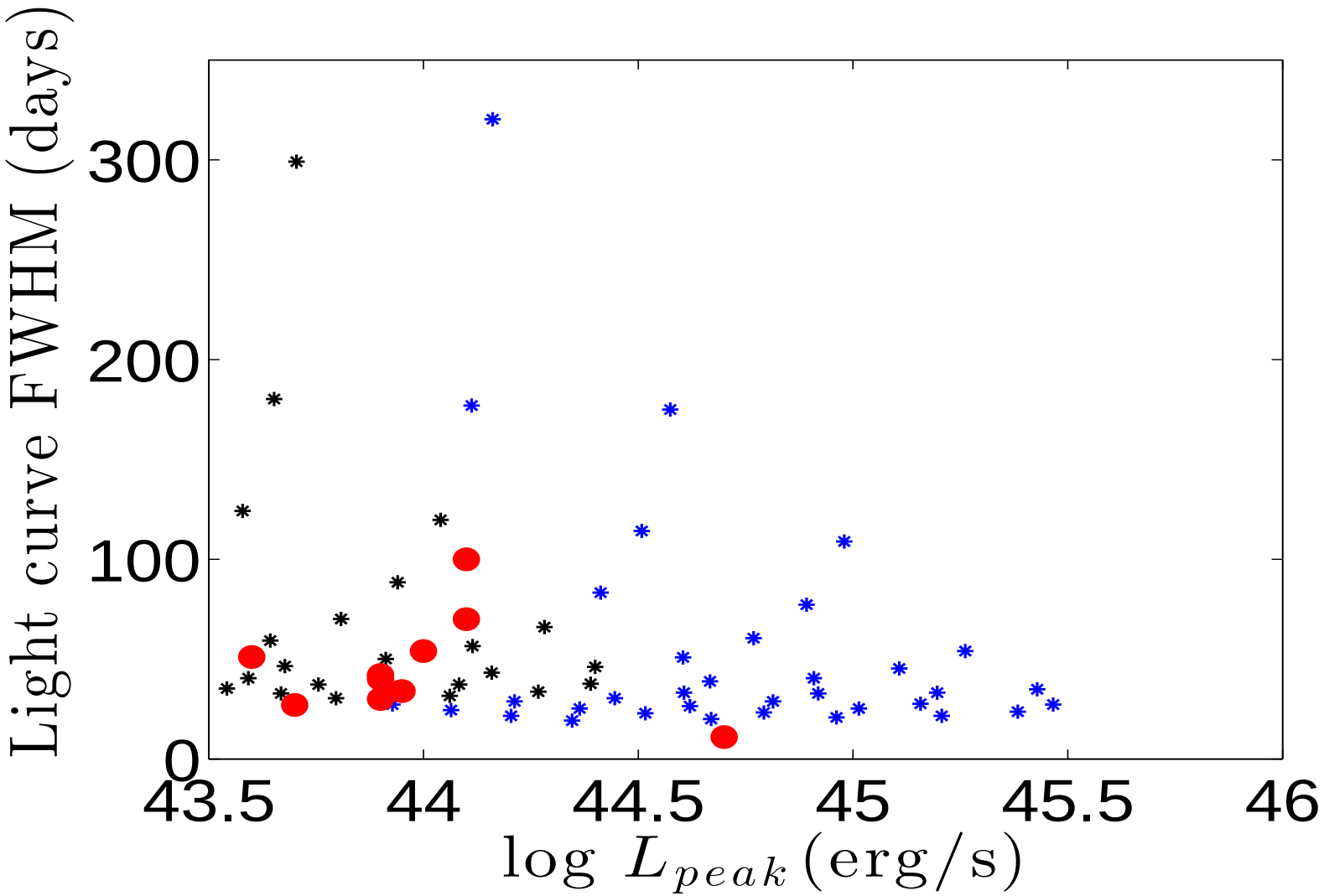
Magnetar models - B and P width space

- For ejecta masses of a few $M_\odot$, maximum brightness occurs for $B =$ a few $\times 10^{14}$ G.



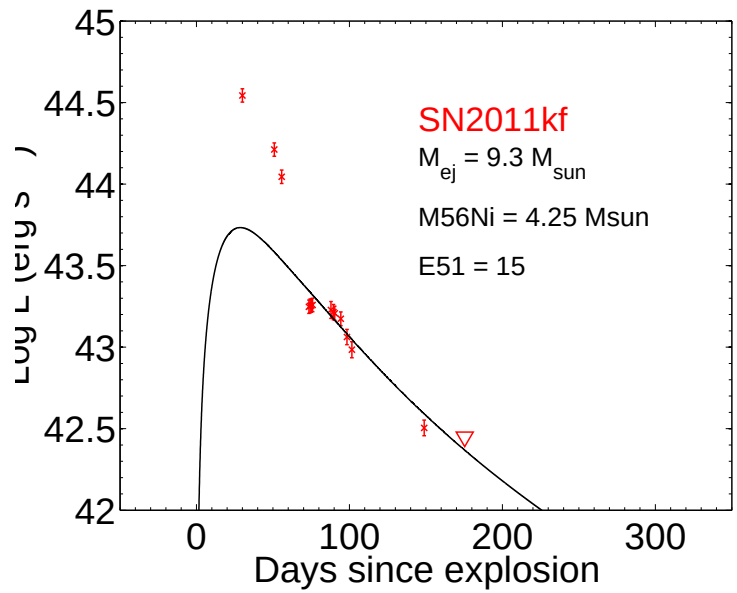


Magnetar models - L_{peak} and light curve duration space



Radioactivity models

- $E = 10^{51} \left(\frac{MNi}{5 M_{\odot}} \right)$
- Spectra (both early and late) look like Ic's and not Ia's $\rightarrow$ ejecta mass likely $\gtrsim 20$ $M_{\odot}$.
- For most objects, radioactivity models fail.



Inserra+2013

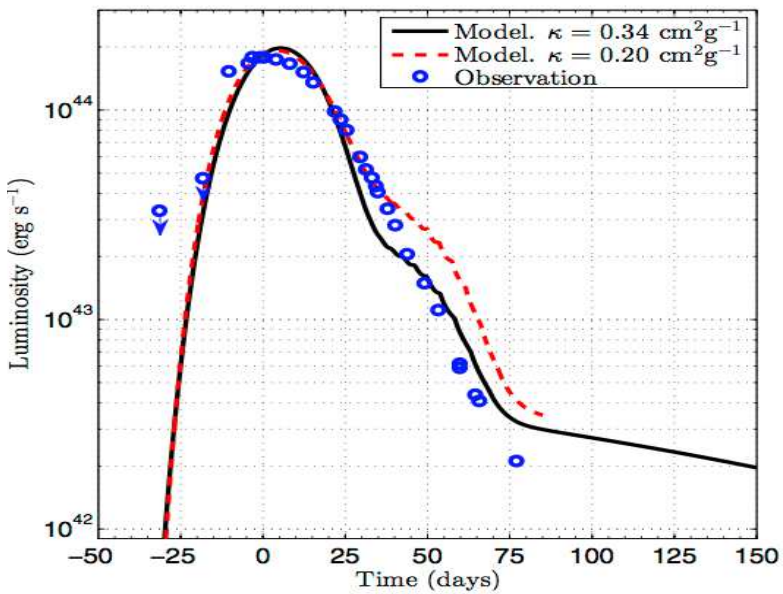
- Specific models: Pair Instability SN, CCSN with high explosion energy.

Circumstellar interaction models

- Simplest picture : plastic collision of two shells, no adiabatic losses

$$E_{rad} = E_{SN} \frac{M_{shell}}{M_{SN} + M_{shell}} \tag{1}$$

- Need $M_{shell} \gtrsim M_{SN}$ to produce enough luminosity. Also need high M_{shell} to avoid production of narrow lines (as in IIn SNe)
- Specific models : Pulsational PISN, CC of LBV



Ginzburg & Balberg 2012

Summary

- Type Ic superluminous SNe require emit $\sim 10^{51}$ erg of UVOIR radiation over a time scale of weeks/months.
- **Radioactivity models** fail to reproduce the light curves as they cannot generate enough luminosity per unit mass. **Accretion models** may work, but not the ones investigated so far.
- Two remaining models (proposed so far) are **magnetars** and **circumstellar interaction**. Both models are capable of reproducing light curves and photospheric properties. Magnetar fit to ten SLSNe gives $P = 1 - 8$ ms, $B = 10^{14} - 10^{15}$ G, $M_{ej} = 2 - 20\ M_{\odot}$.