Superluminous supernovae and their origin

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Core-collapse SNe

Typical properties

kinetic energy: ~1e51 erg

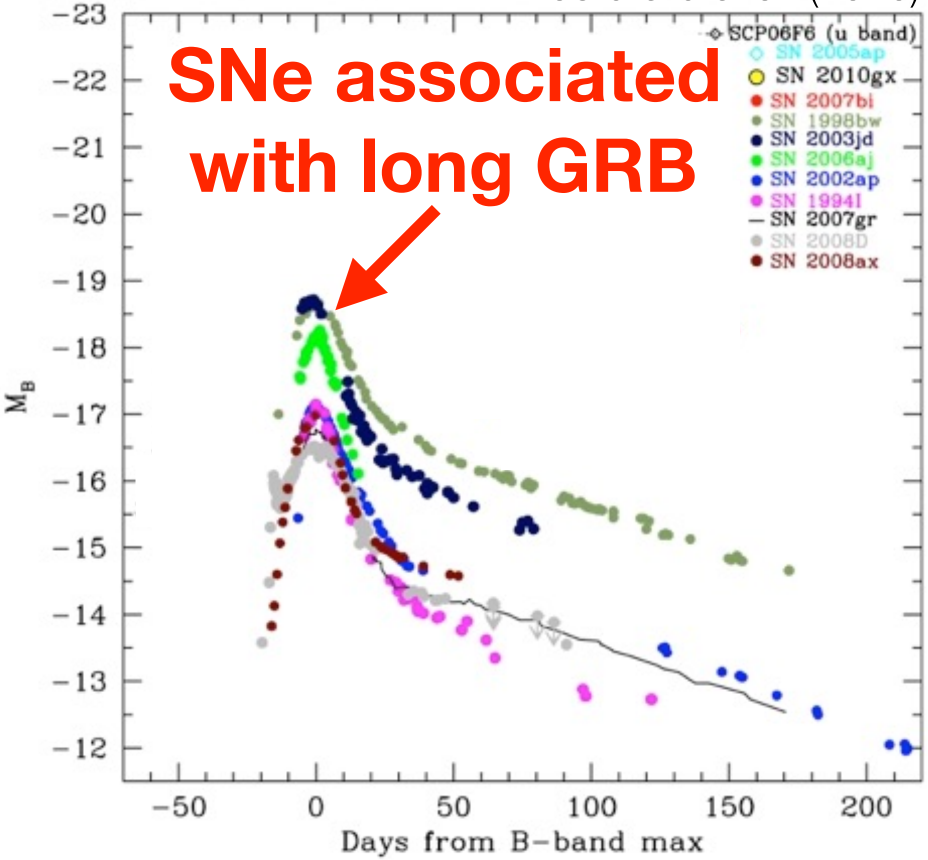
peak magnitude: up to -19 mag

(~ 1e43 erg/s)

radiation energy: ~1e49 erg

ejecta mass: ~ 1 - 10 Msun

Pastorello et al. (2010)



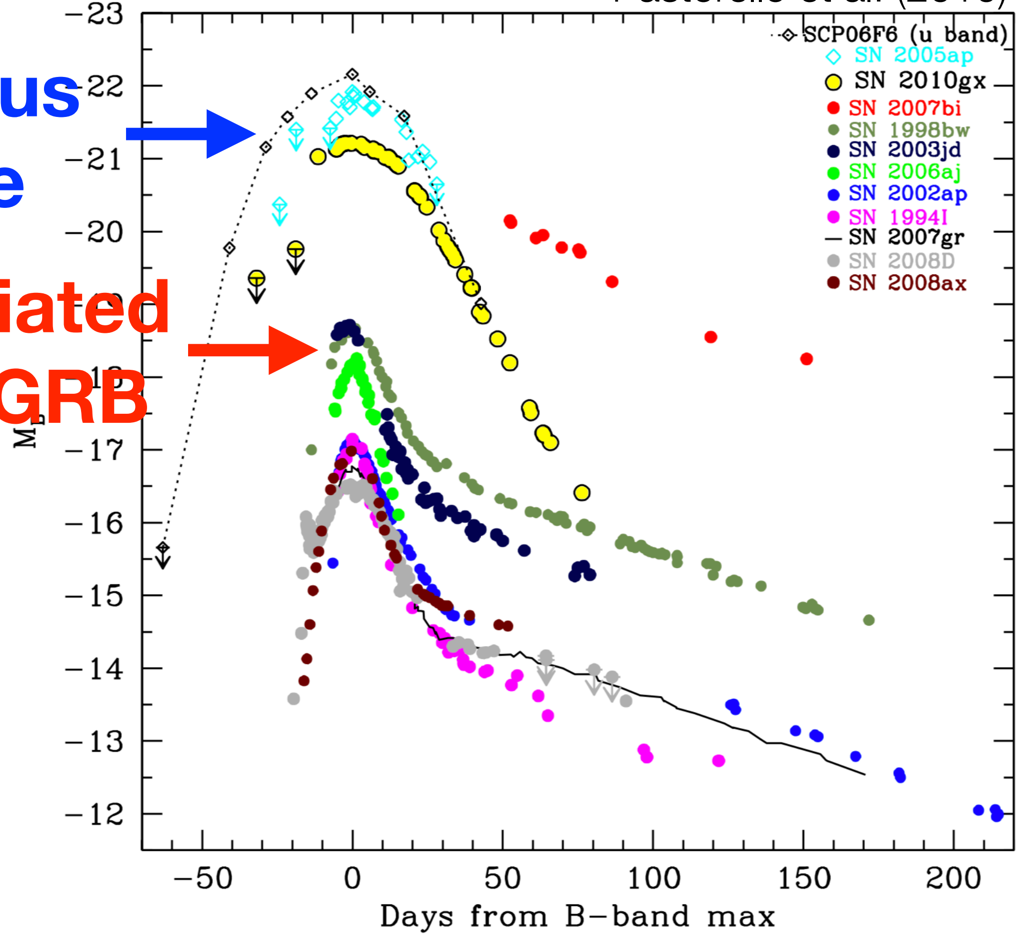
Superluminous supernovae (SLSNe)

- more than ~ 10 times brighter than other core-collapse SNe
  - often emit more than 1e51 erg just by radiation

Pastorello et al. (2010)

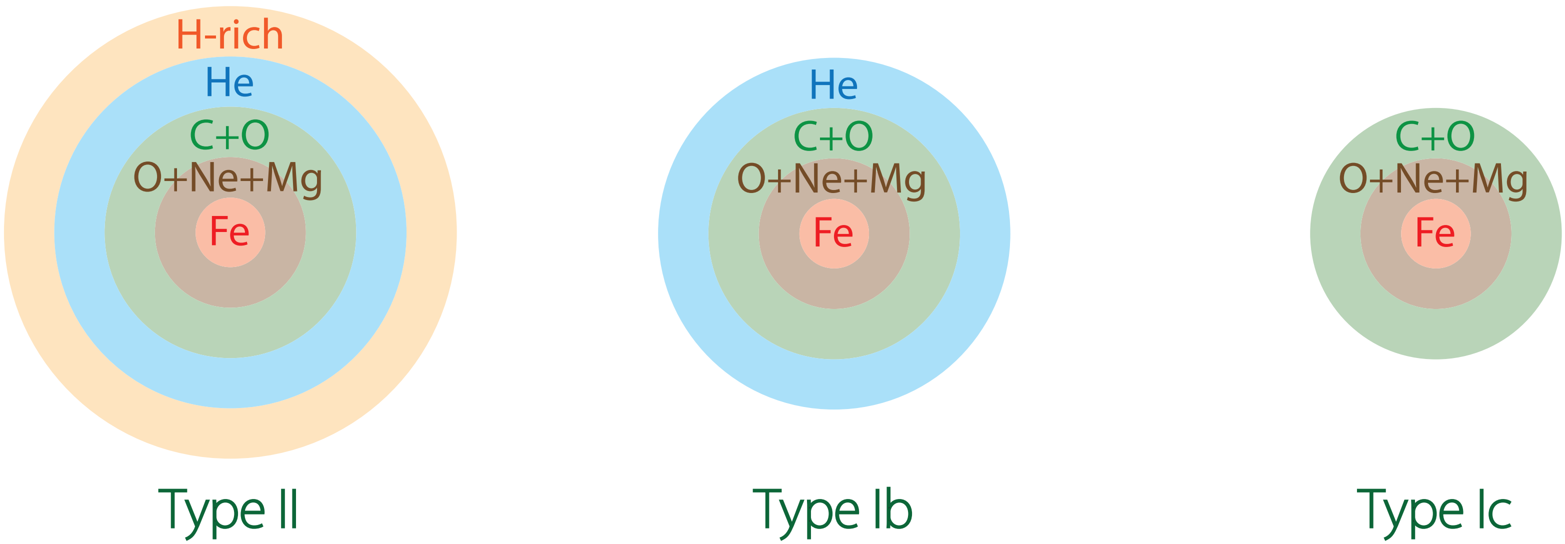
superluminous supernovae

SNe associated with long GRB



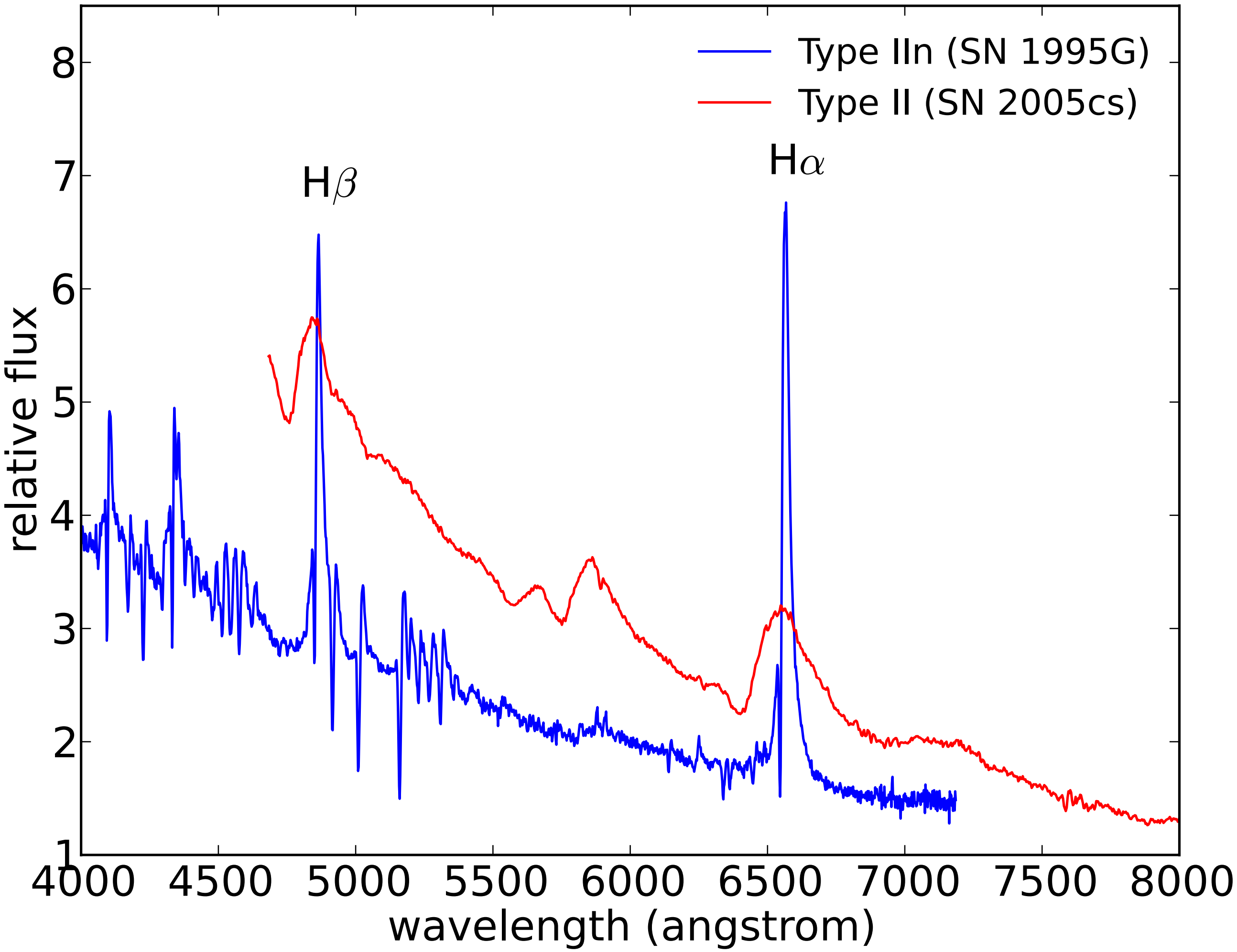
Two spectroscopic types

- Type II (with hydrogen)
- Type I (without hydrogen)



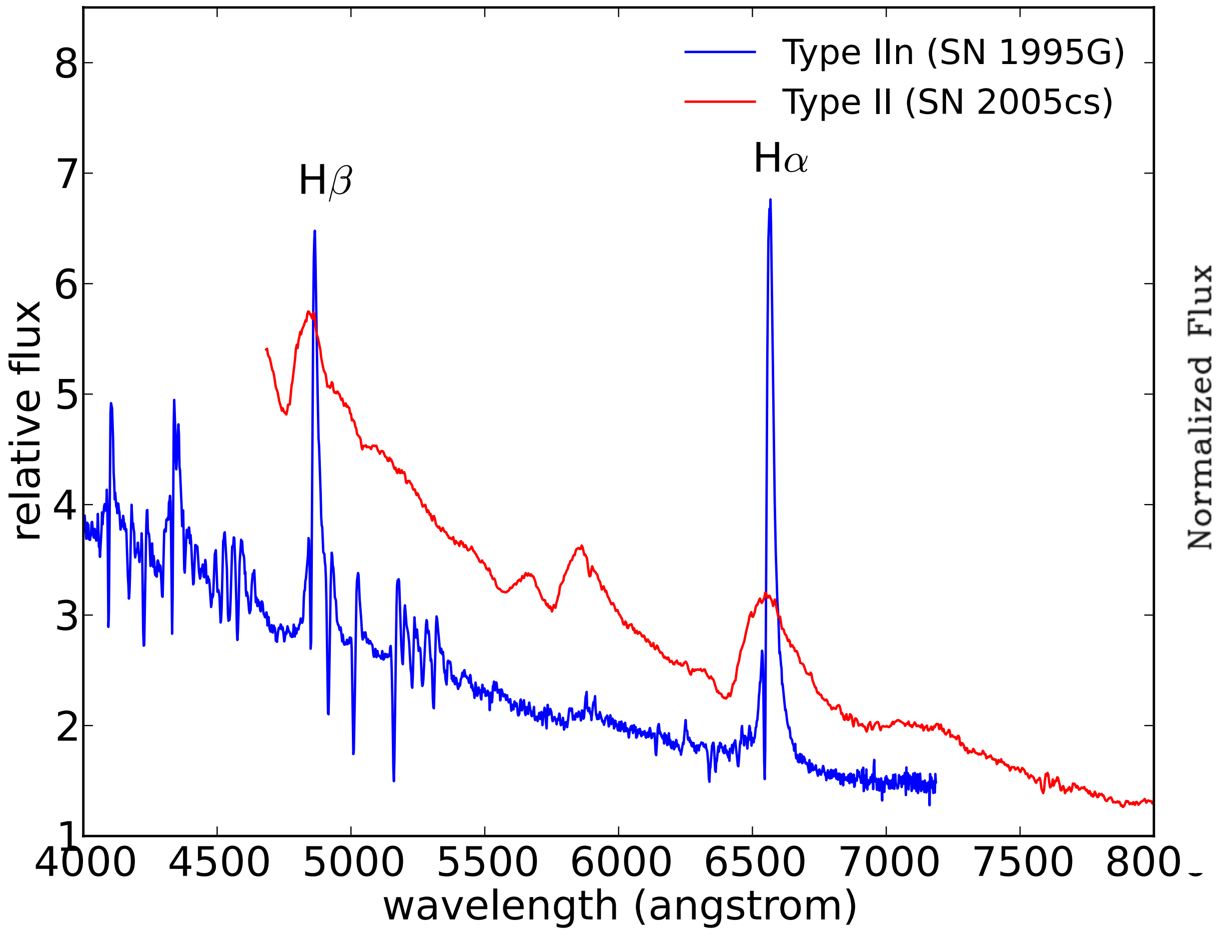
Type II SLSNe

- most of them are Type IIn (a few exceptions)
  - 'n' from narrow

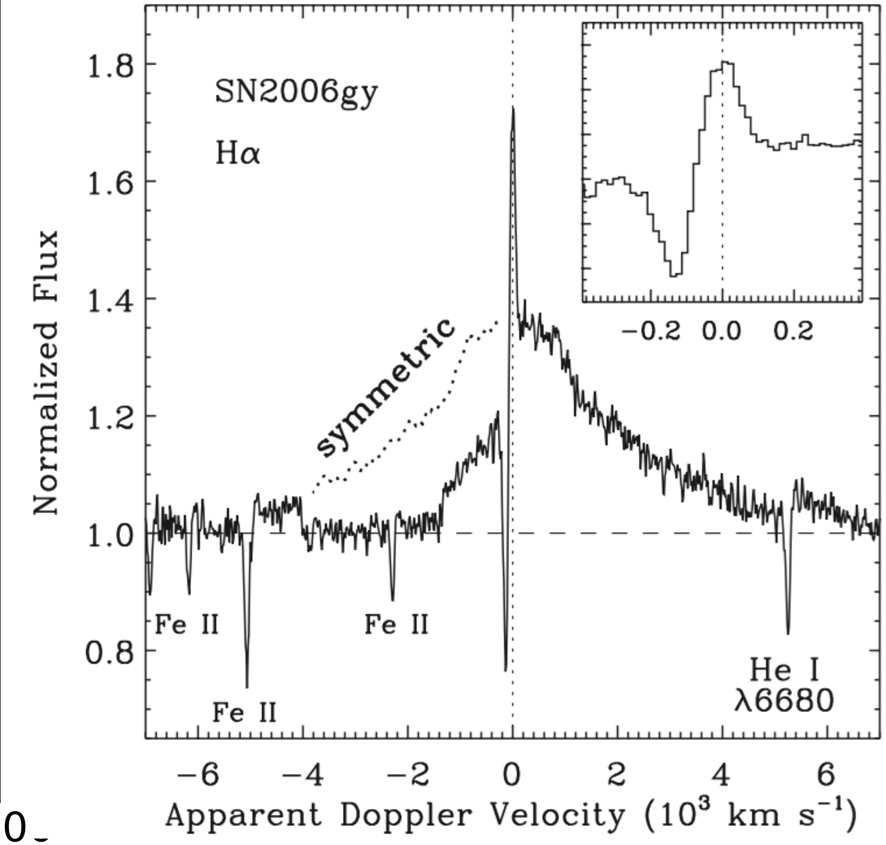


Type IIn SNe

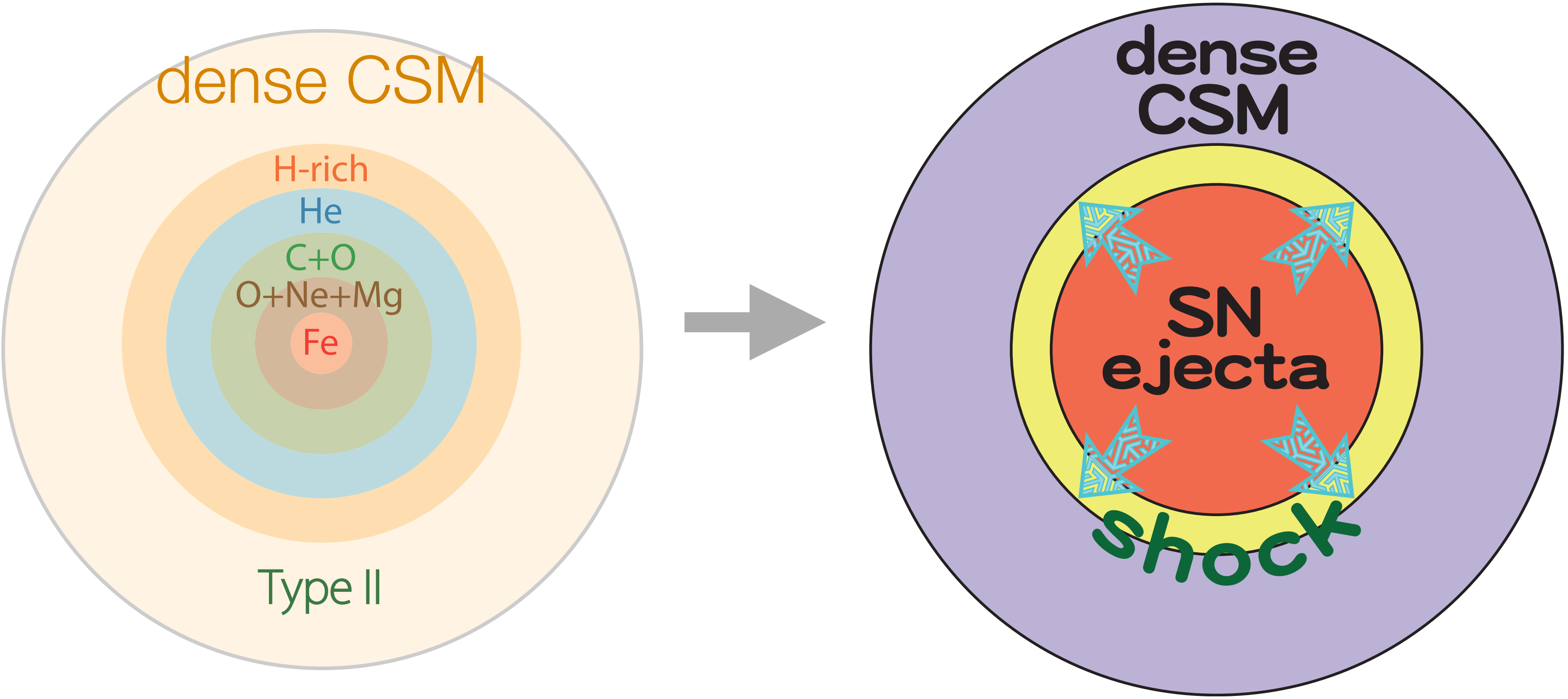
- outflow with ~ 100 km/s
  - too slow to be from SN ejecta (~ 10000 km/s)



Smith et al. (2007)

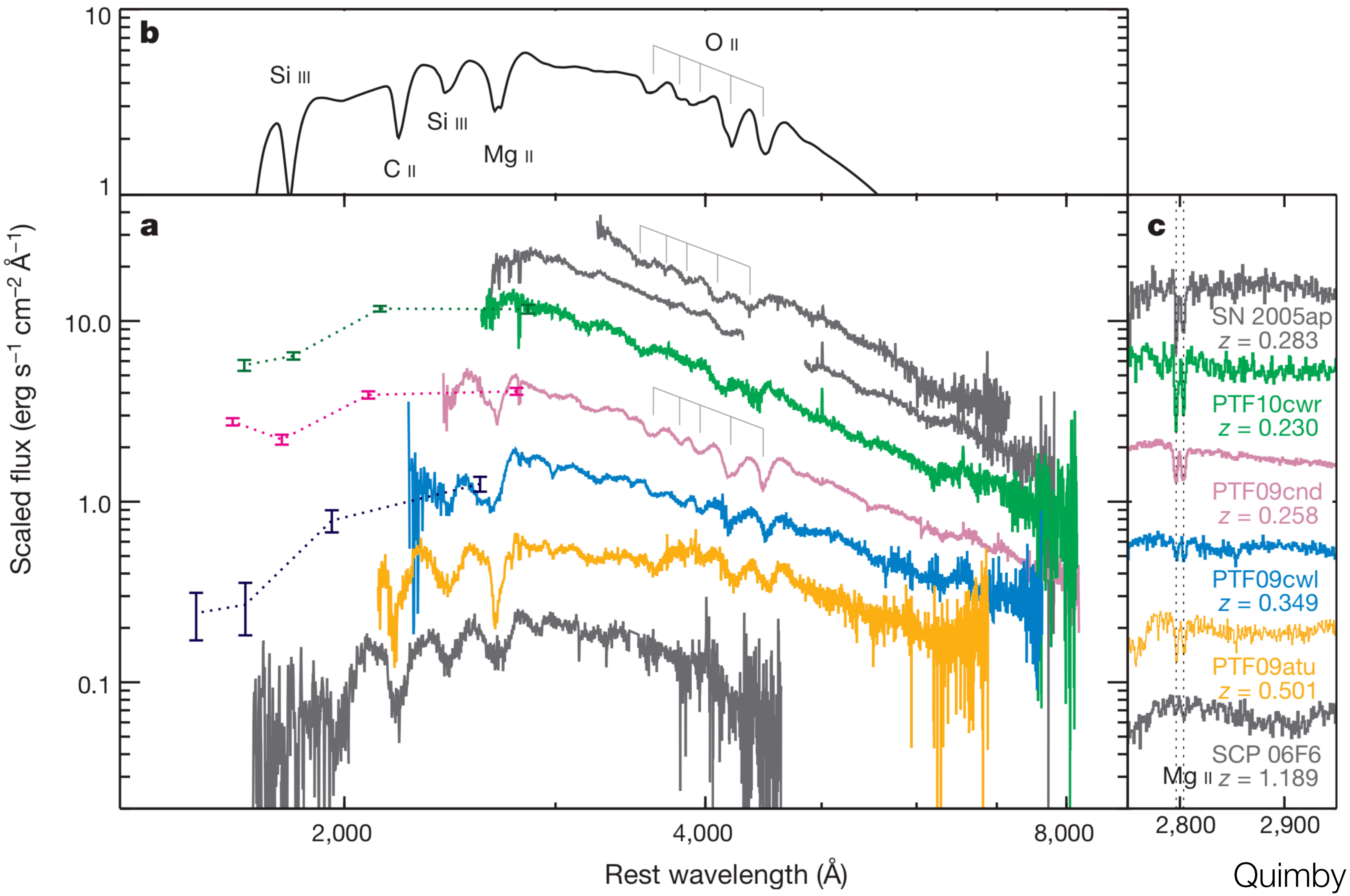


Explosions with dense circumstellar media (CSM)



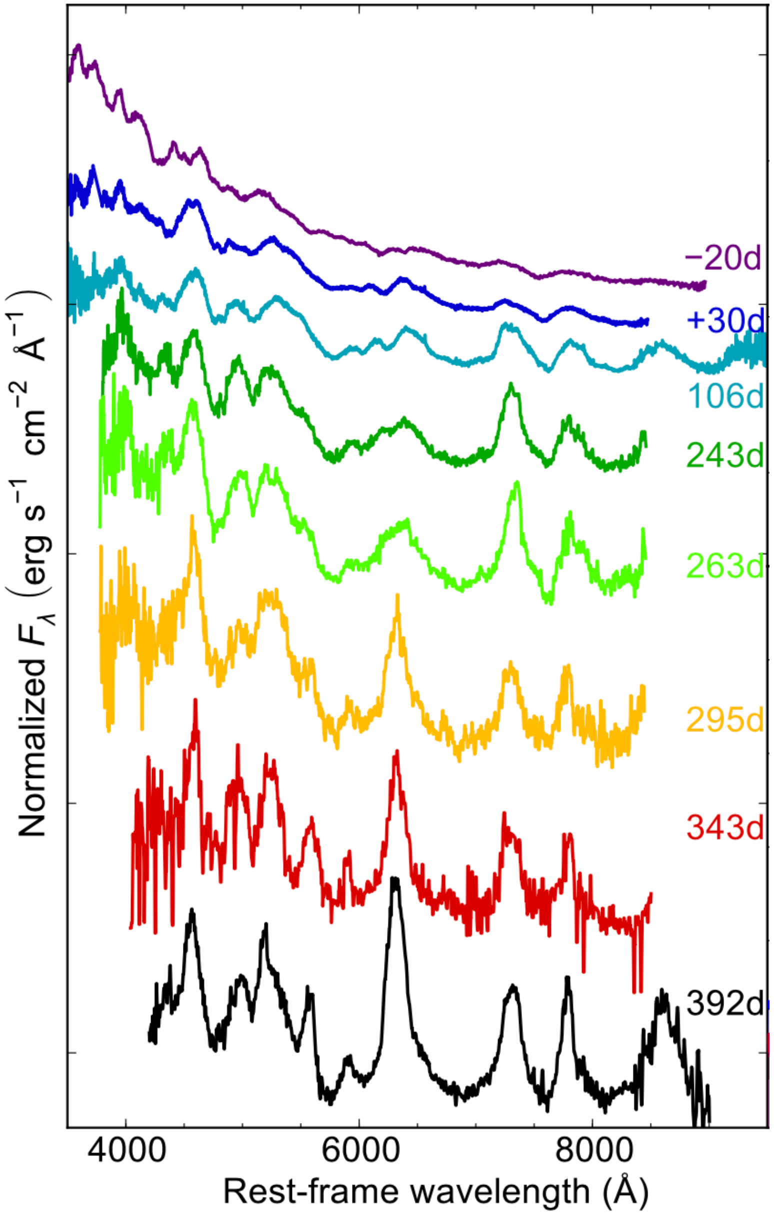
- around 10 Msun of dense CSM needed near the progenitor
  - mass-loss rate ~ 0.1 Msun/yr or even higher — how?

Type I SLSNe



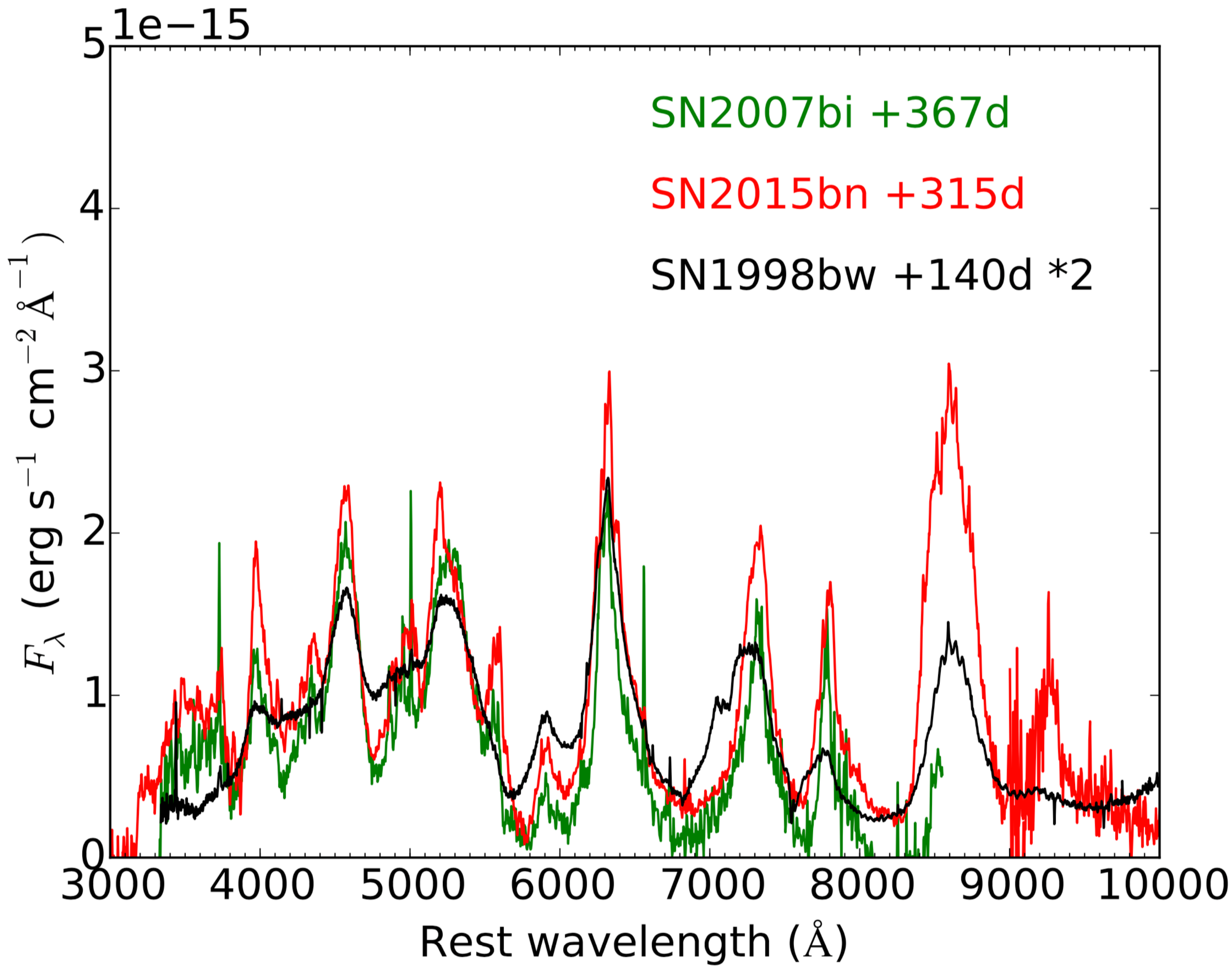
Quimby et al. (2011)

Type I SLSNe



Nicholl et al. (2016)

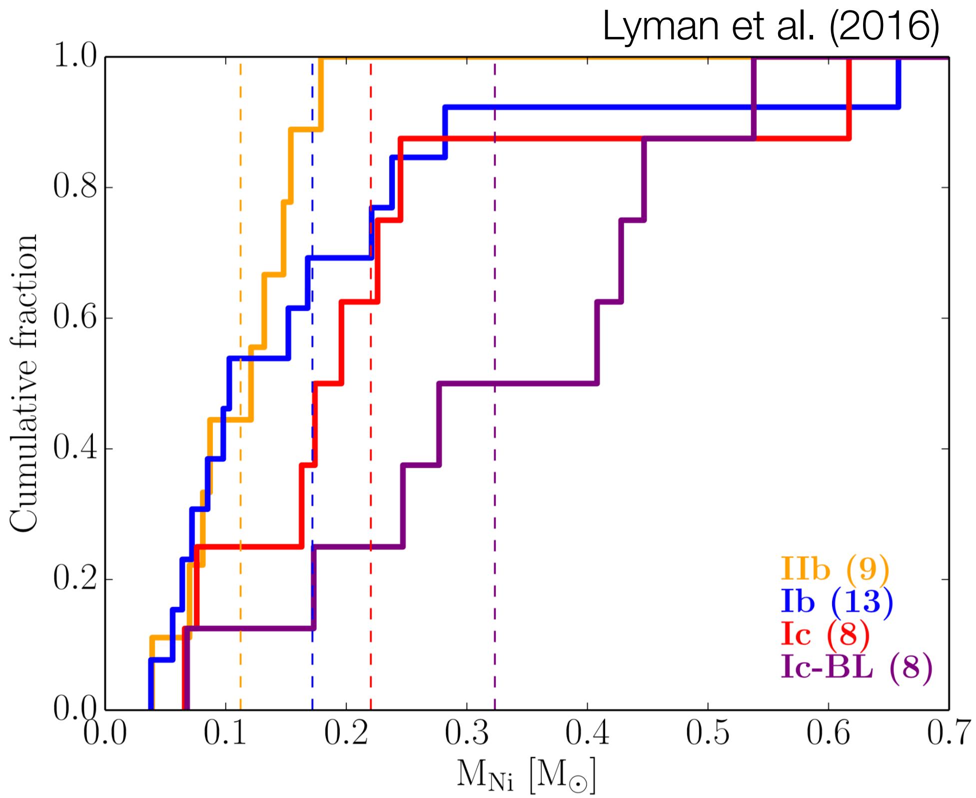
Late-phase spectra: similar to SNe with GRBs

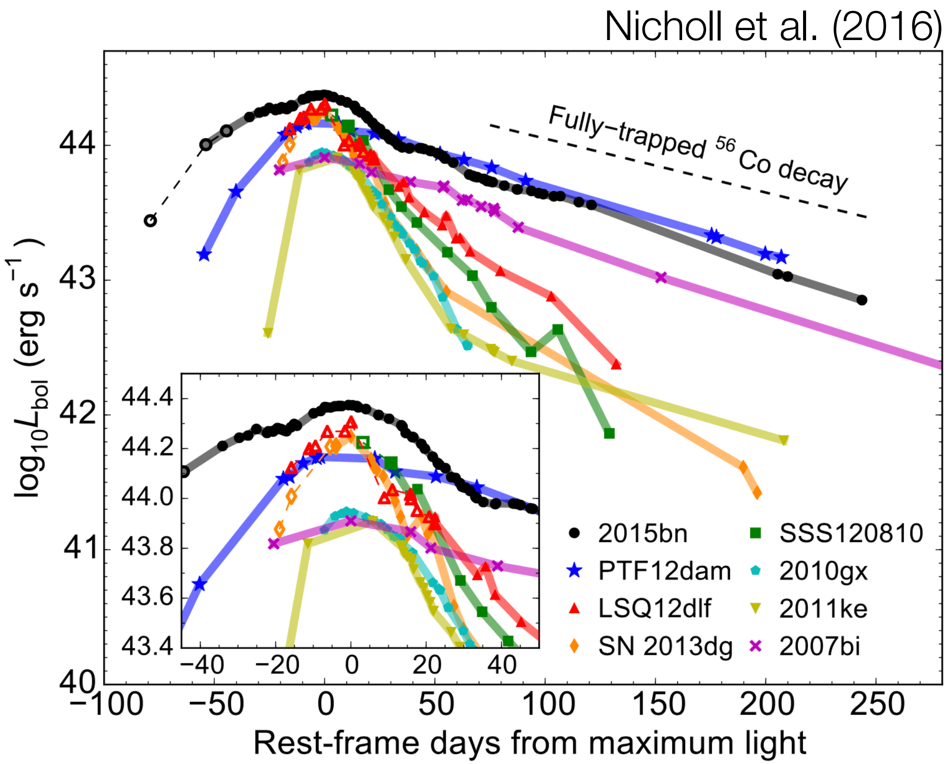


Jerkstrand et al. (2017)

How do they become superluminous?

- large production of 56Ni for SLSNe?
  - more than 5 Msun of 56Ni required
  - light curve decline is often consistent with the 56Co decay
  - rapidly declining SLSNe are inconsistent — another model required

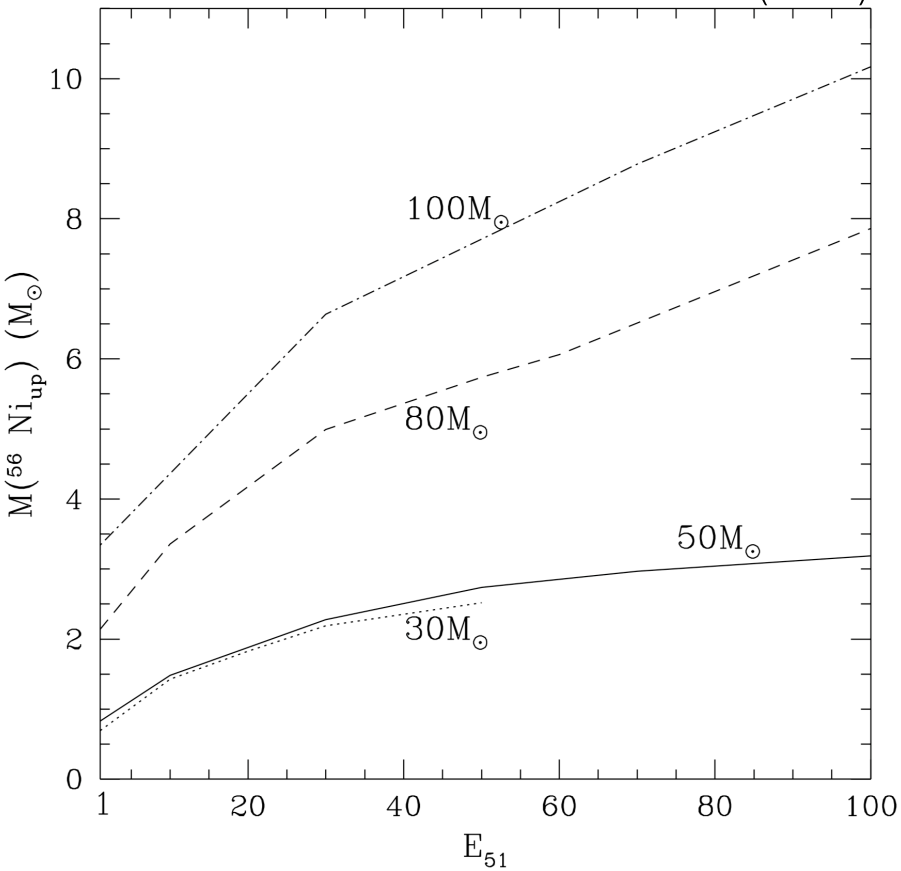




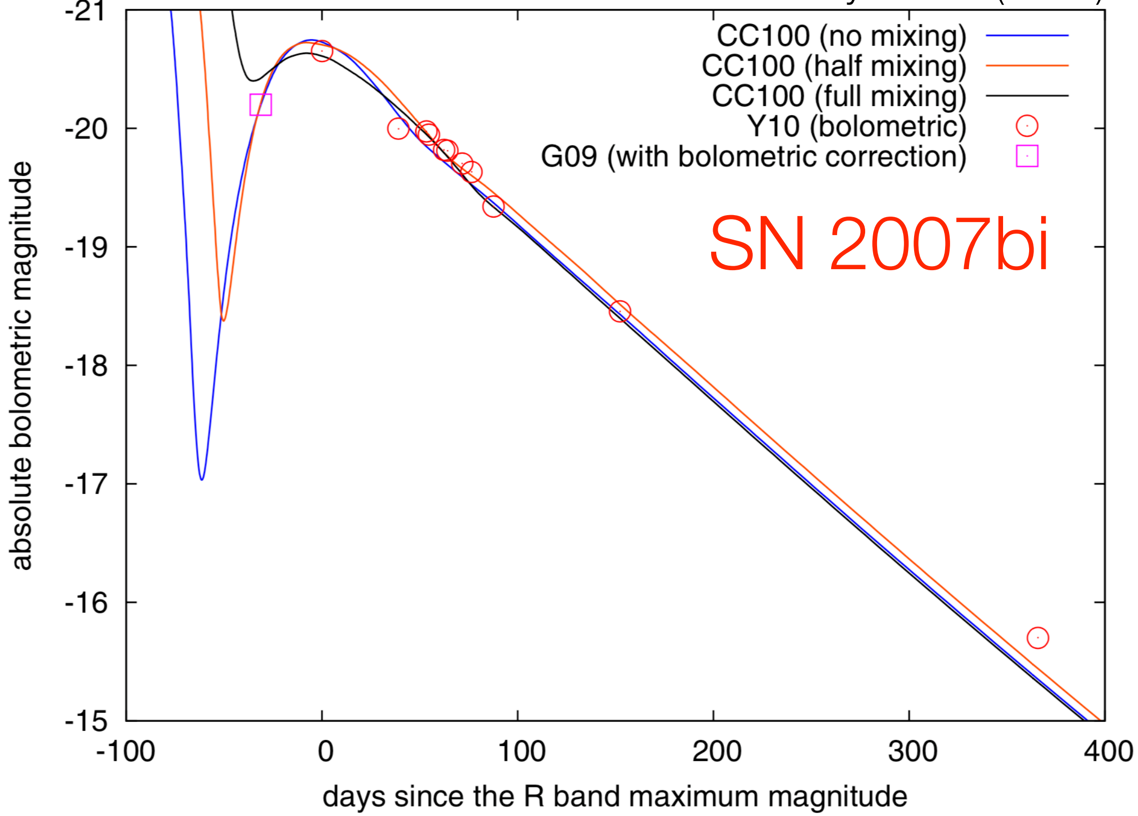
56Ni synthesis — energetic core-collapse SNe

- energetic explosion of massive core-collapse SN progenitor
  - ~ 40 Msun C+O star exploding with ~ 4e52 erg → ~ 6 Msun of 56Ni

Umeda & Nomoto (2008)

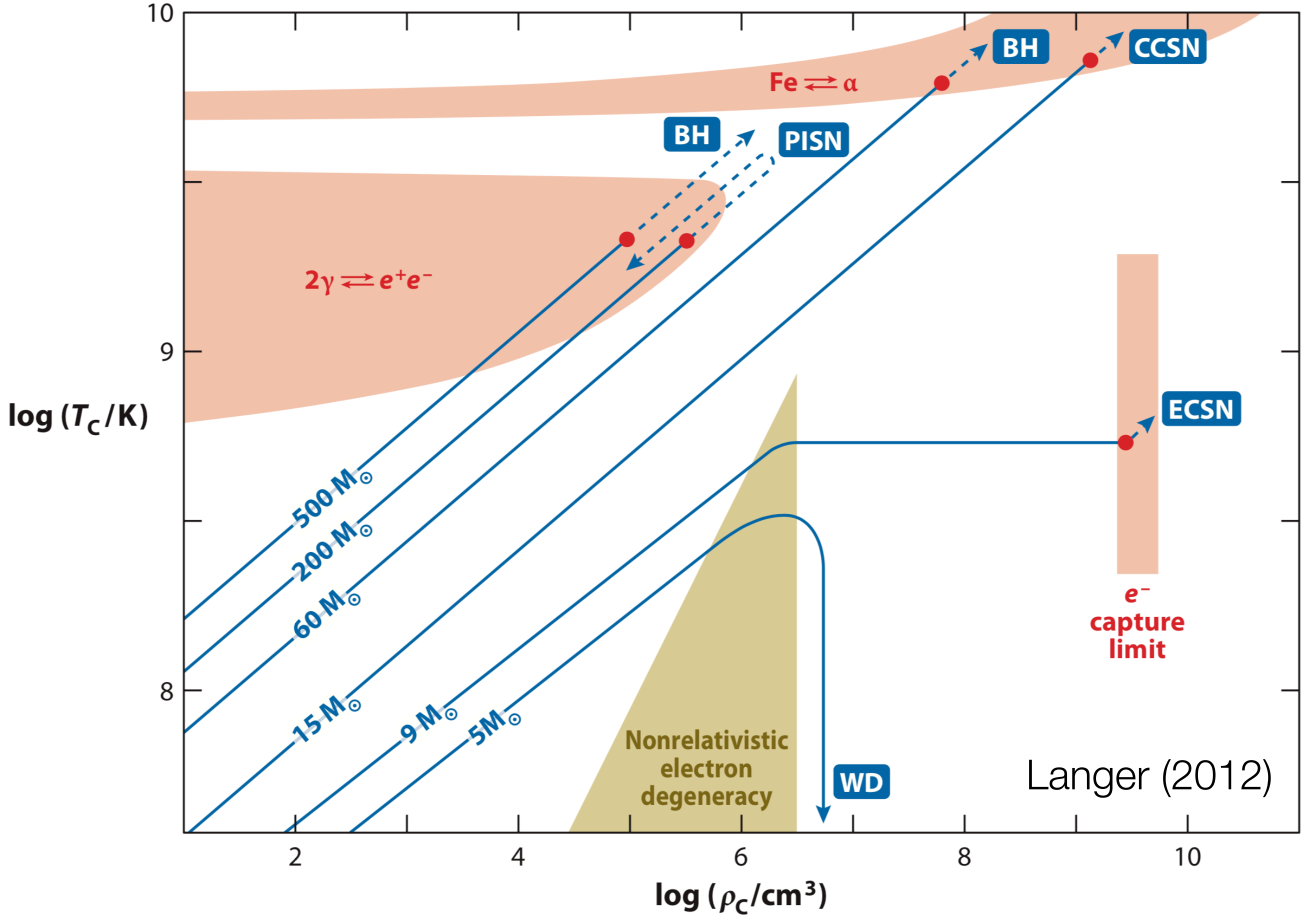


Moriya et al. (2010)



56Ni synthesis — pair-instability SNe

- pair-instability SNe
  - thermonuclear explosions of very massive stars
  - helium core mass between ~ 70 Msun and ~ 130 Msun



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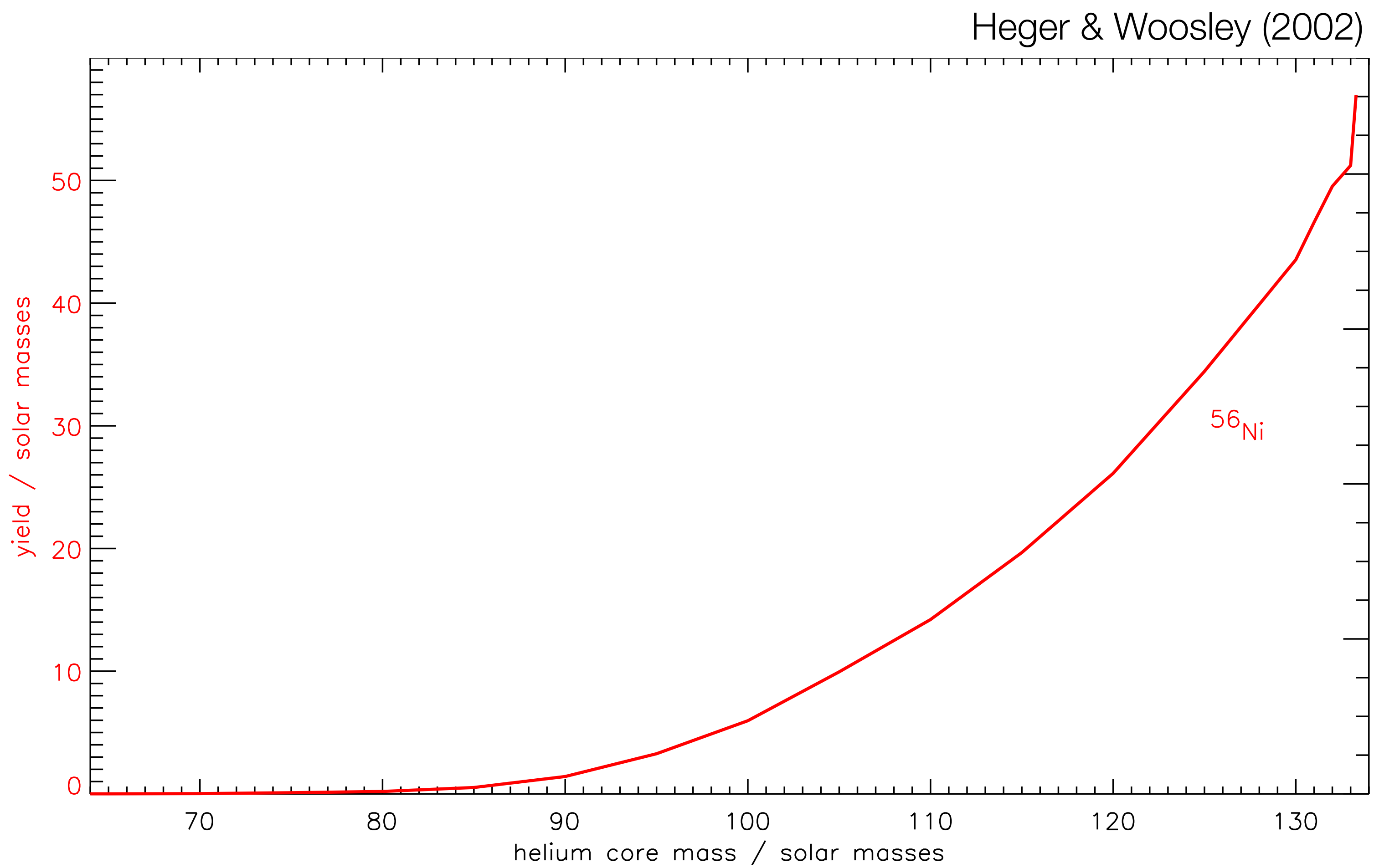
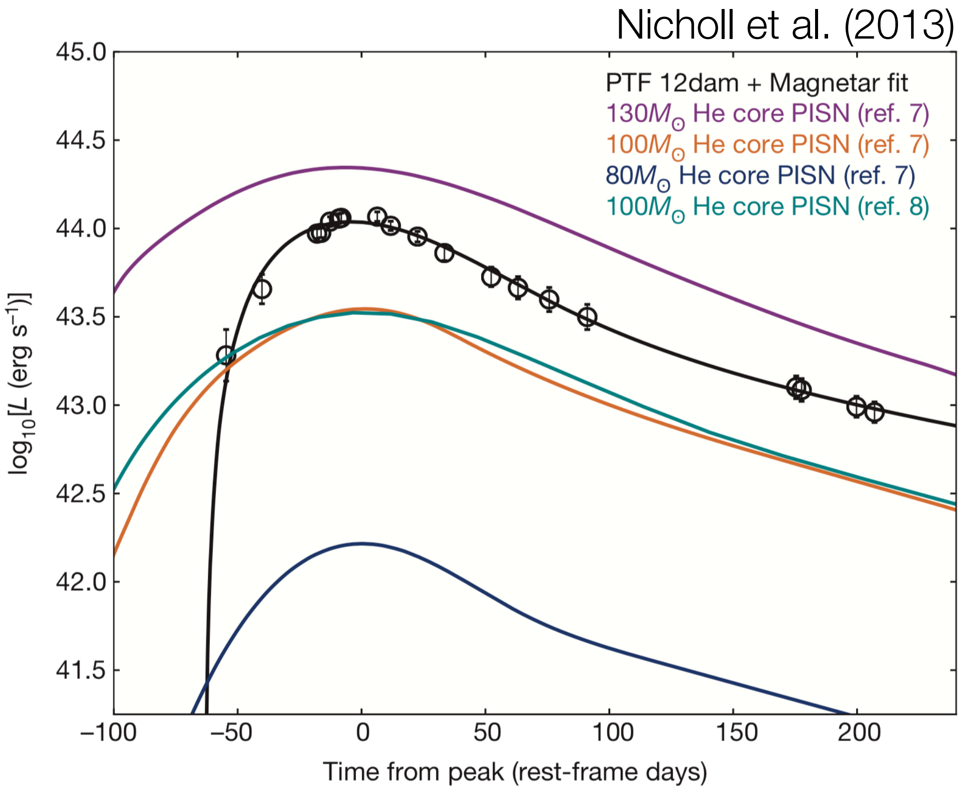
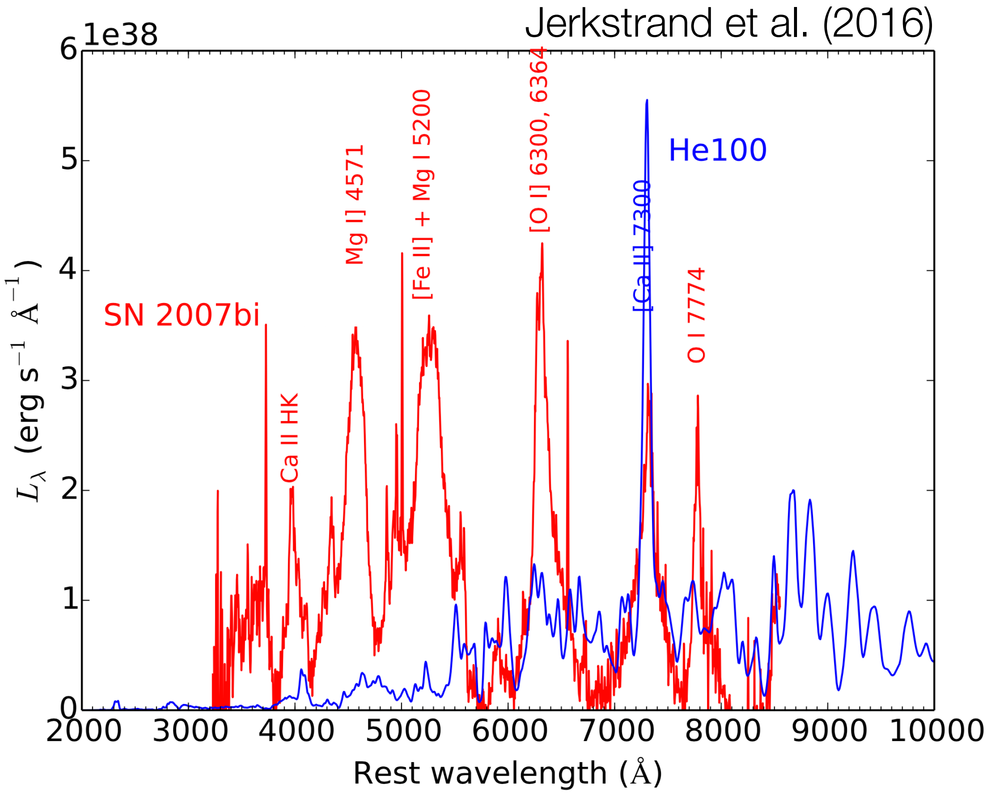


PISNe are inconsistent with SLSNe





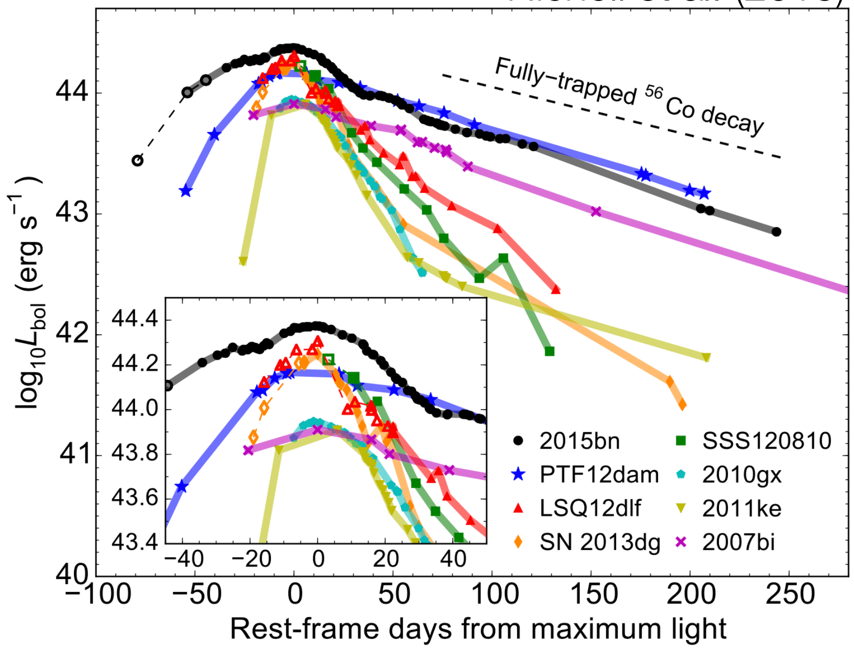
Powering SLSNe without 56Ni

- rapidly declining SLSNe are NOT powered by the 56Ni decay
  - slowly declining SLSNe are not necessarily powered by 56Ni

- late-phase similarity to SNe associated with GRBs
  - SLSN center similar to those of long GRBs?
    - the existence of a central energy input?

- proposed central engines
  - magnetars
  - BH accretion
  - …

Nicholl et al. (2016)

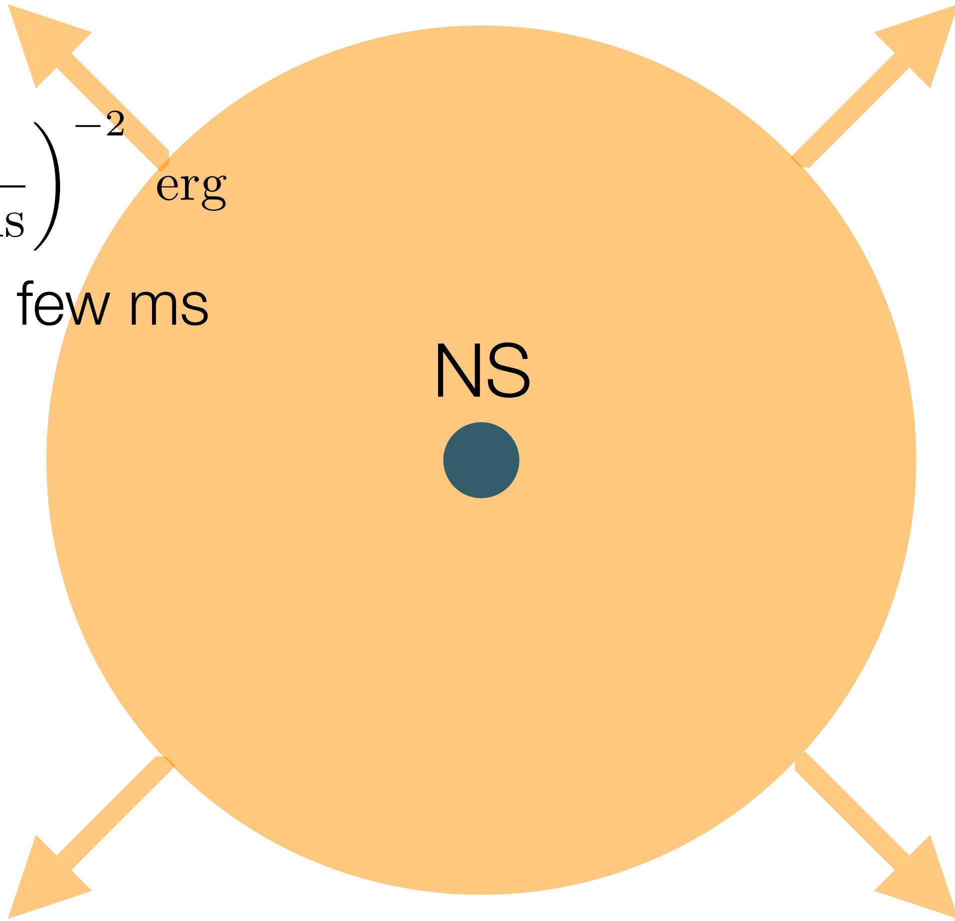


Magnetars

- efficient release of rotational energy of neutron stars (NSs)
  - rotational energy

$$E_{\rm rot} = \frac{1}{2} I_{\rm NS} \Omega^2 \simeq 2 \times 10^{52} \left(\frac{P}{1 \text{ ms}} \right)^{-2} \text{erg}$$

  - SLSNe emit ~ 1e51 erg -> a few ms



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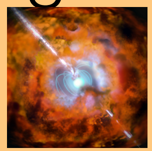
    - SLSNe emit ~ 1e51 erg -> a few ms
  - magnetic field
    - spin down caused by poloidal fields

$$t_m = \frac{6 I_{\rm NS} c^3}{B_{\rm dipole}^2 R_{\rm NS}^6 \Omega^2} \simeq 5 \left(\frac{B_{\rm dipole}}{10^{14} \ G} \right)^{-2} \left(\frac{P}{1 \ {\rm ms}} \right)^{2} {\rm days}$$

    - SLSN timescales: ~ 10 - 100 days → ~ 1e14 - 1e13 G

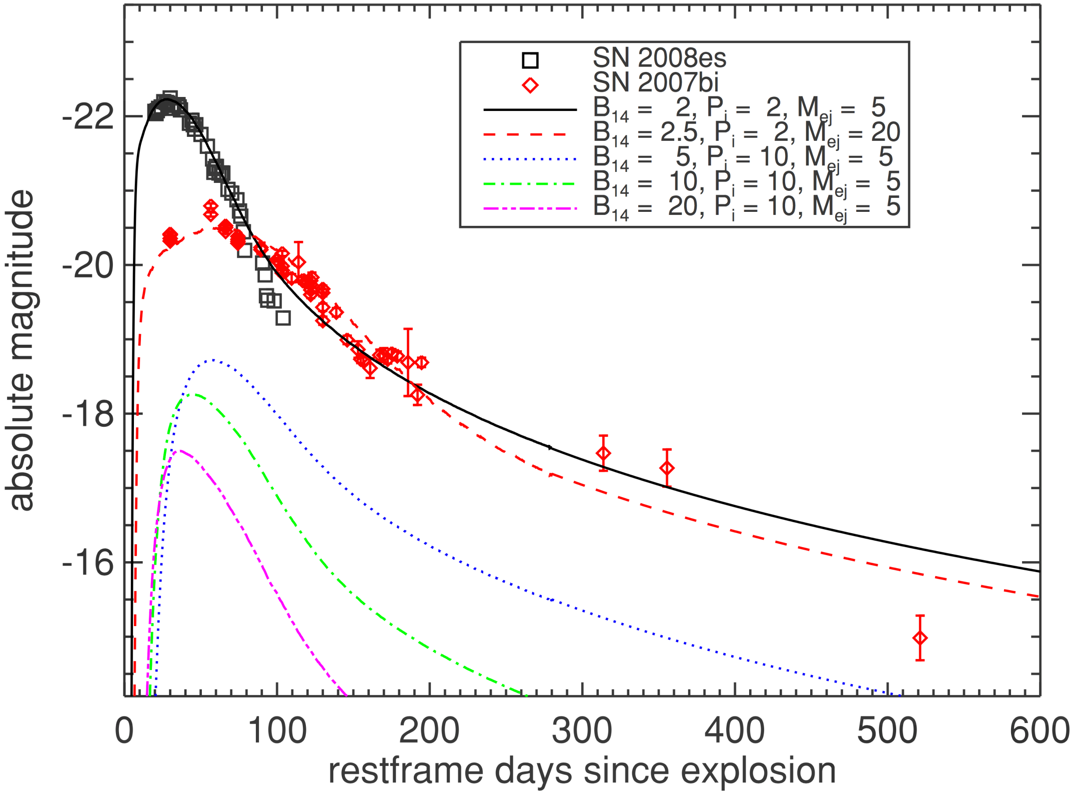
magnetar



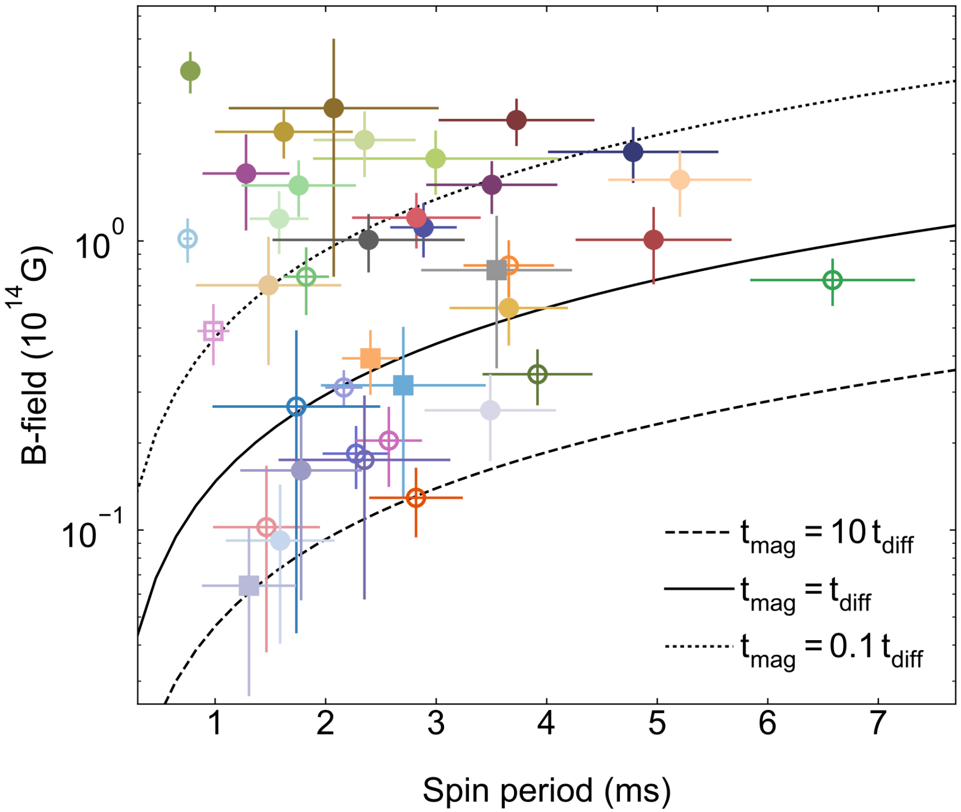
Magnetars

- both LCs and spectra match
    - Mej ~ 5-10 Msun, Eej ~ 5e51 erg (e.g., Nicholl et al. 2017)

Kasen & Bildsten (2010)

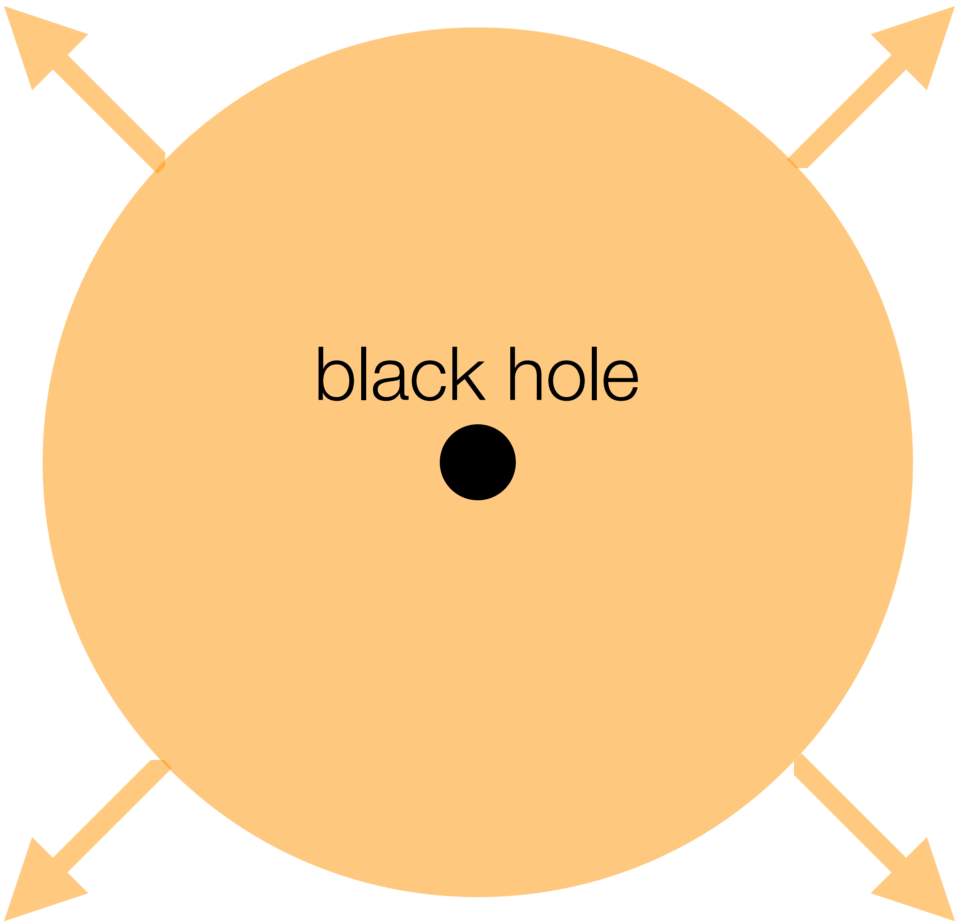


Nicholl et al. (2017)



Fallback accretion

- long lasting central accretion towards the central BH



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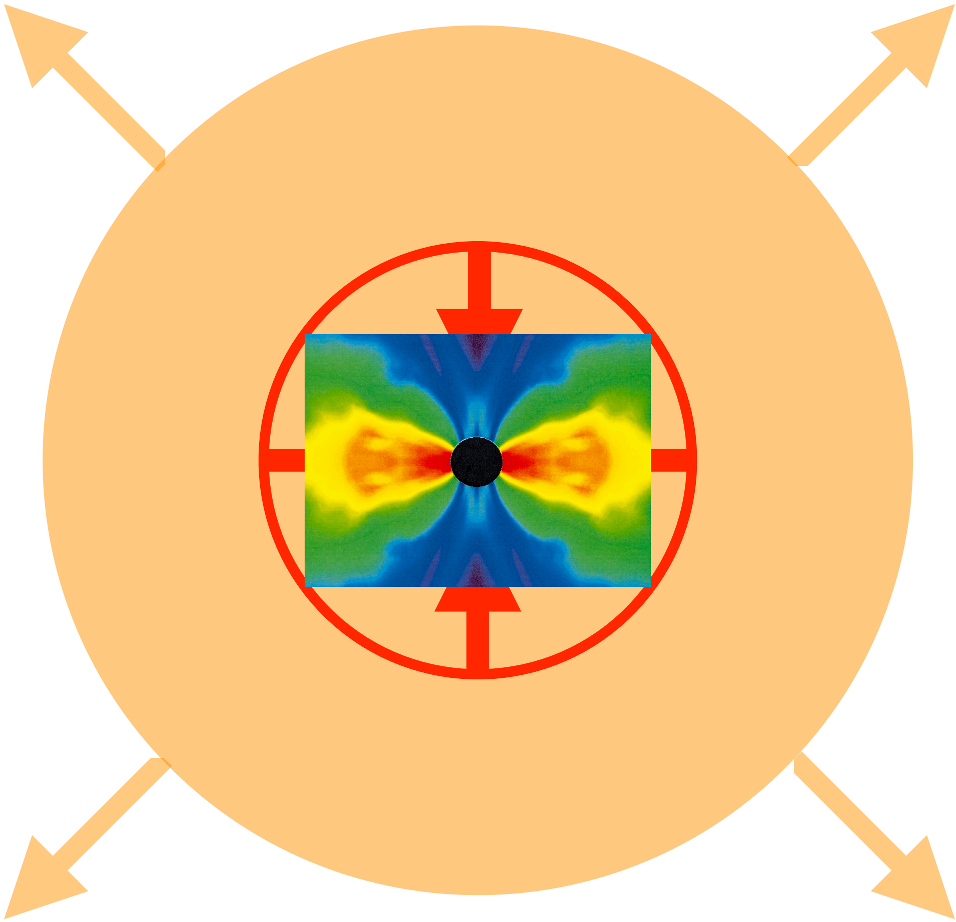
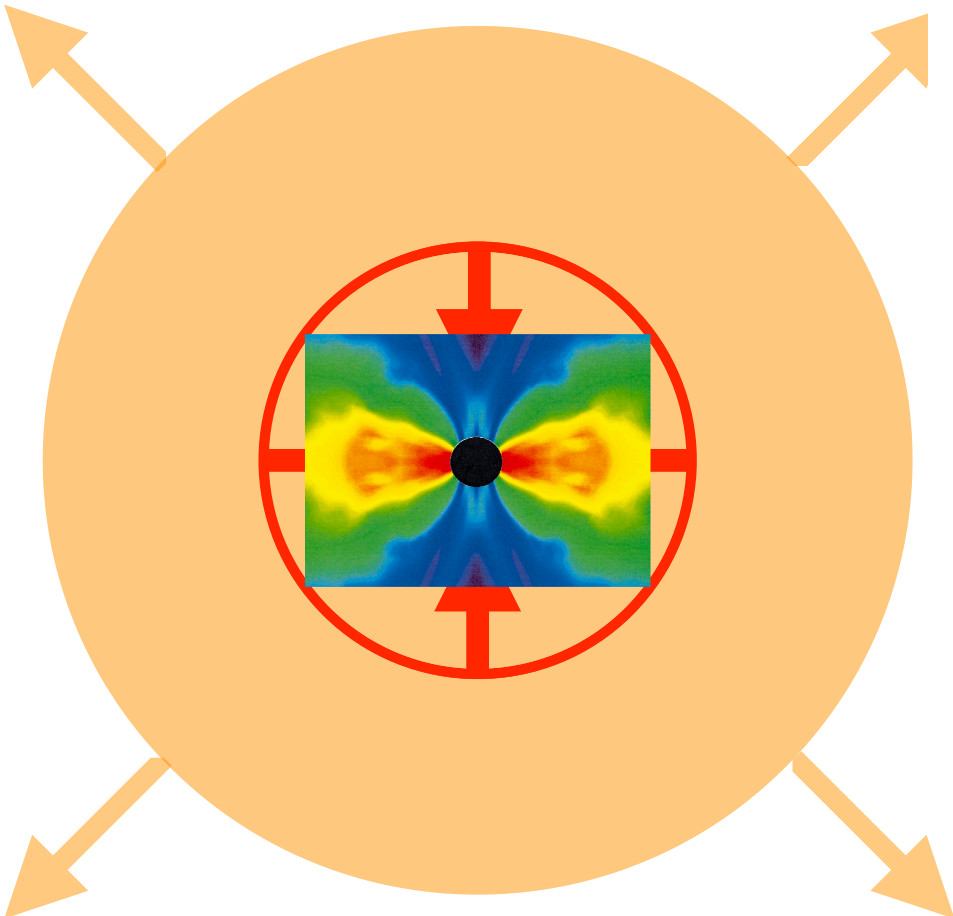
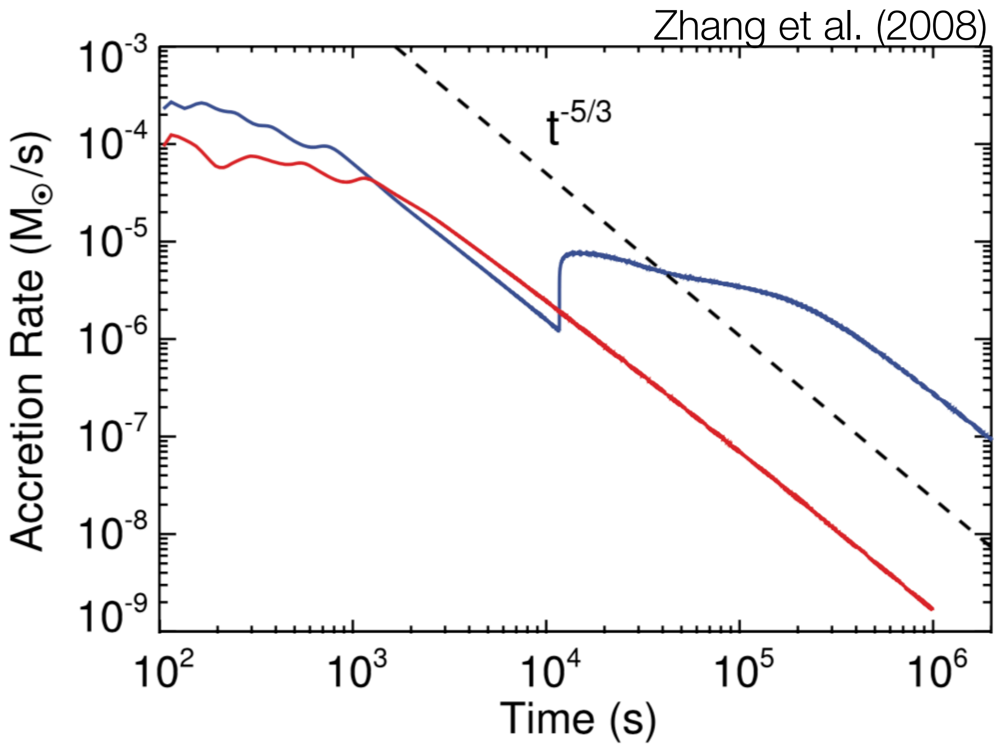


Fallback accretion

- long lasting central accretion towards the central BH
  - suggested by Dexter & Kasen (2013) but not investigated much

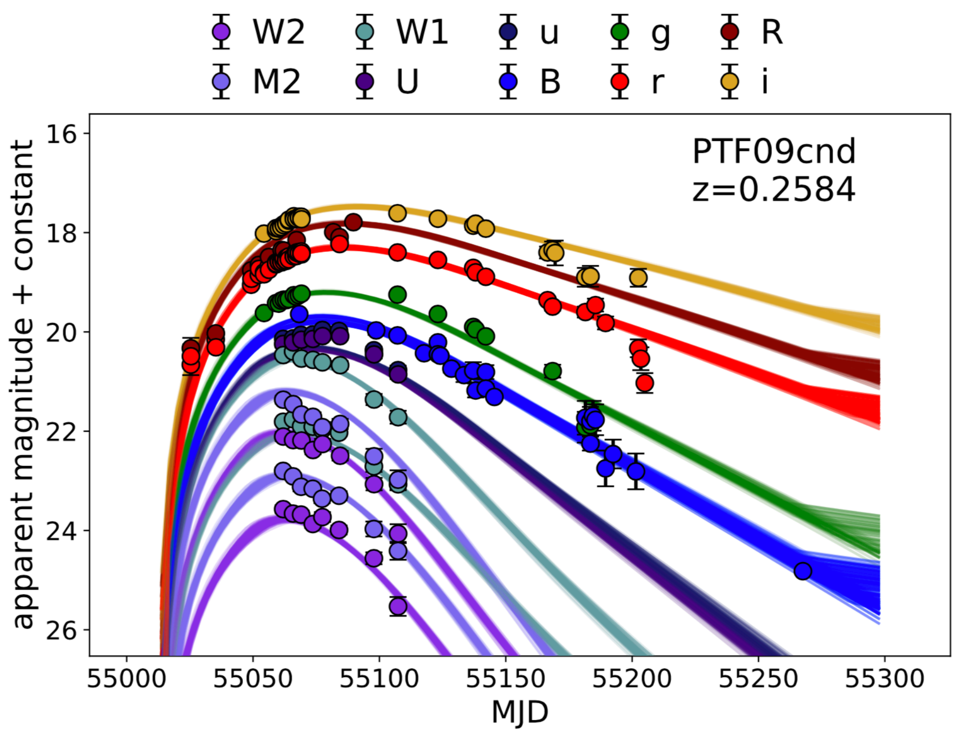


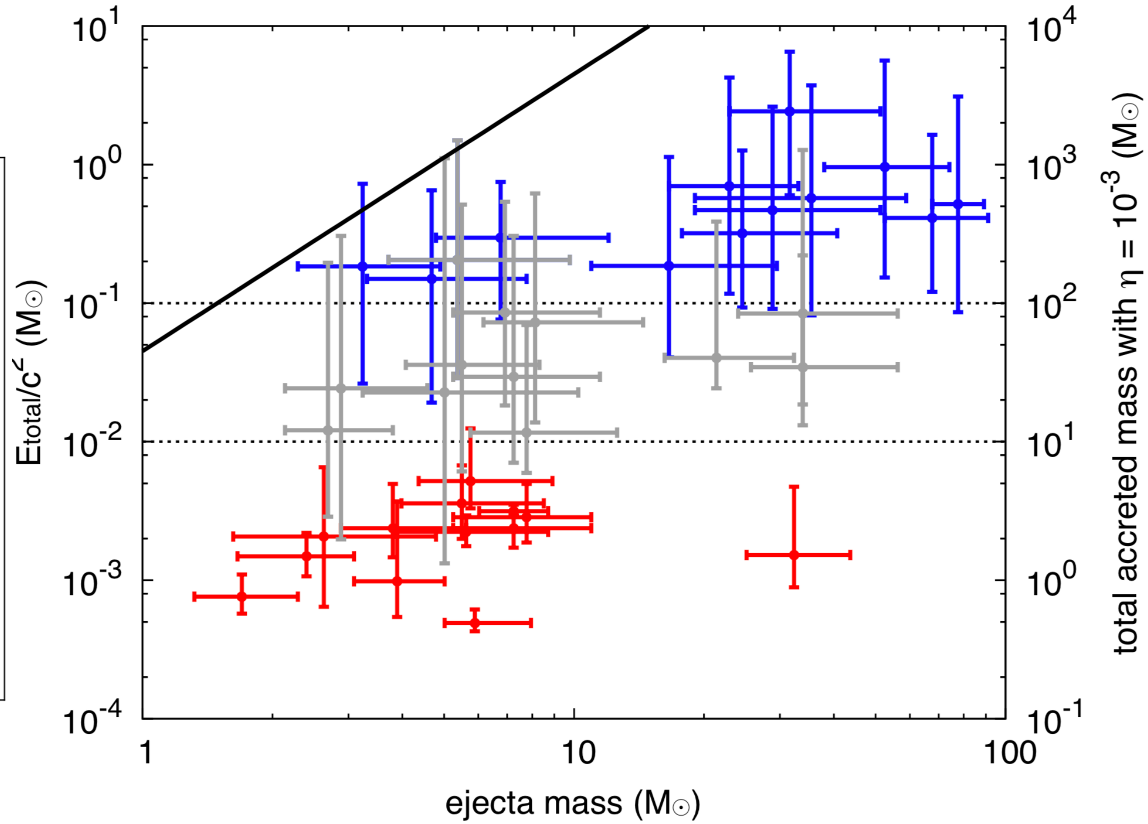


$$L_{\rm fallback}(t) = \begin{cases} L_1 \left(\frac{t_{\rm tr}}{1 \ \rm sec}\right)^{-\frac{5}{3}} \equiv L_{\rm flat} & (t < t_{\rm tr}) \\ L_1 \left(\frac{t}{1 \ \rm sec}\right)^{-\frac{5}{3}} & (t \geq t_{\rm tr}) \end{cases}$$

Total released energy at the center by fallback

- light curve fitting using MOSFiT
  - Bayesian parameter estimates using MCMC
    - based on the Arnett formula (Arnett 1980)
  - the same approach used for the magnetar model (Nicholl et al. ’17)

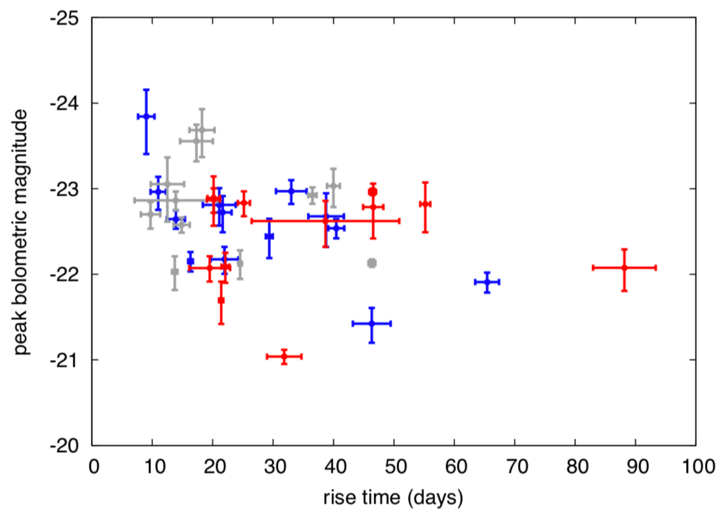


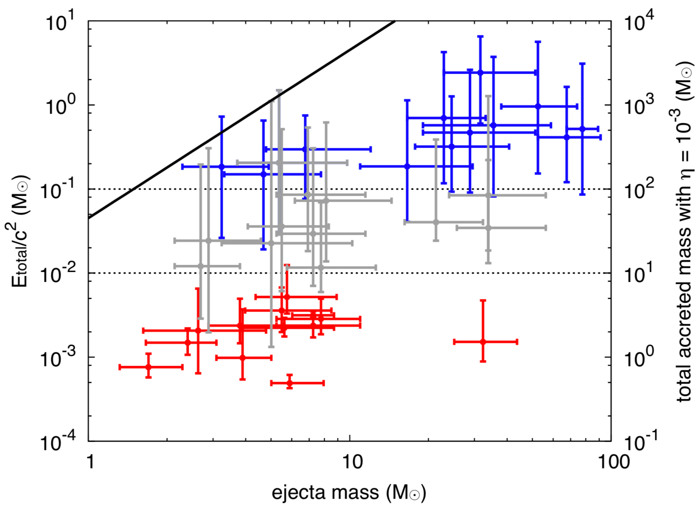


Moriya, Nicholl, & Guillochon (2018)

Fallback accretion as the central power of SLSNe

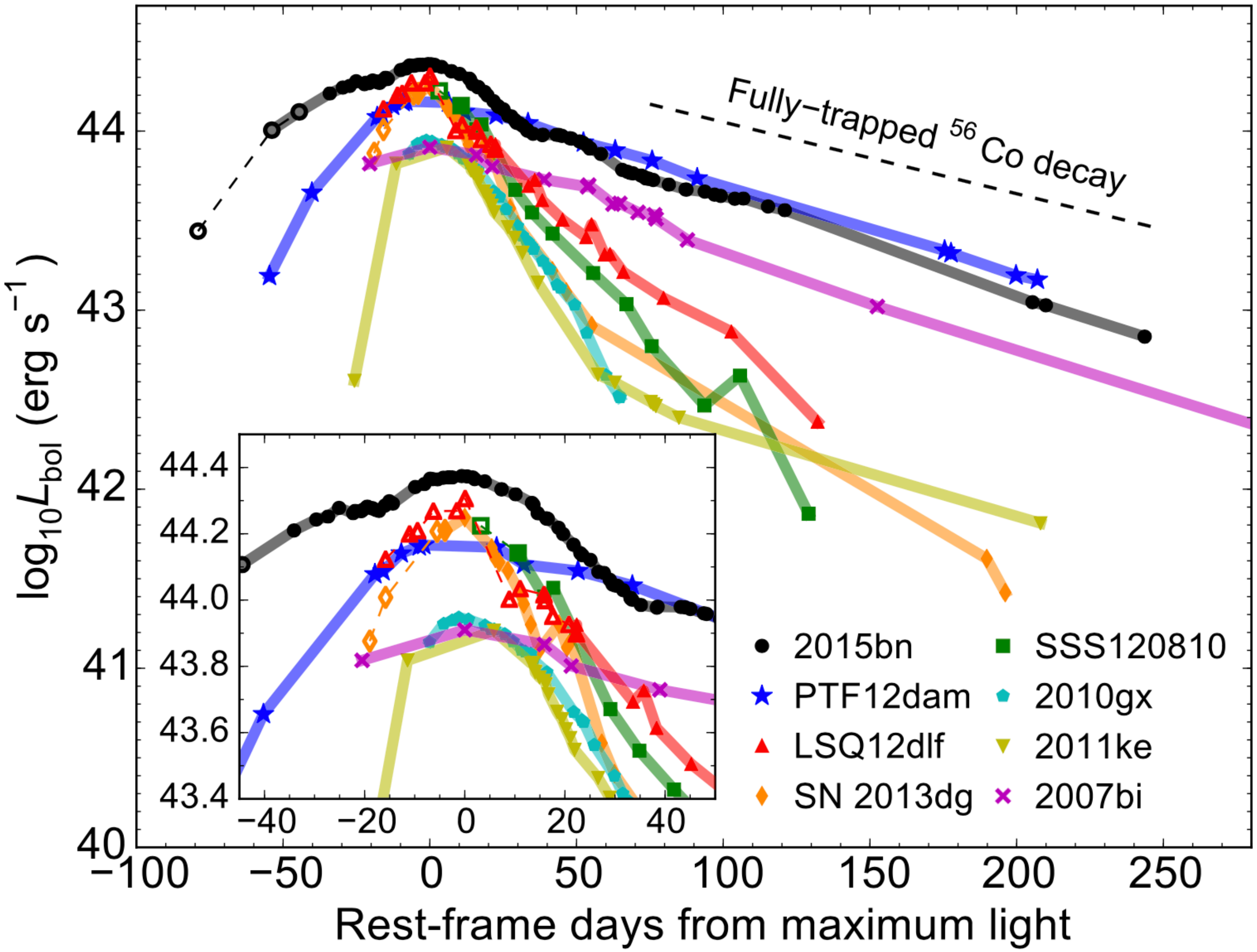
- required energy to be released: 0.002 Msun c^2 - 0.7 Msun c^2
  - depending on the energy conversion efficiency from accretion to outflow, the enormous amount of mass accretion is required
  - if we adopt ~ 0.001 (estimated by Dexter & Kasen 2013), 2 Msun - 700 Msun need to be accreted
  - hard to be distinguished by light curves
  - spectra with little Fe group elements?
    - SLSNe tend to have strong Fe lines (e.g., Nicholl et al. 2018)





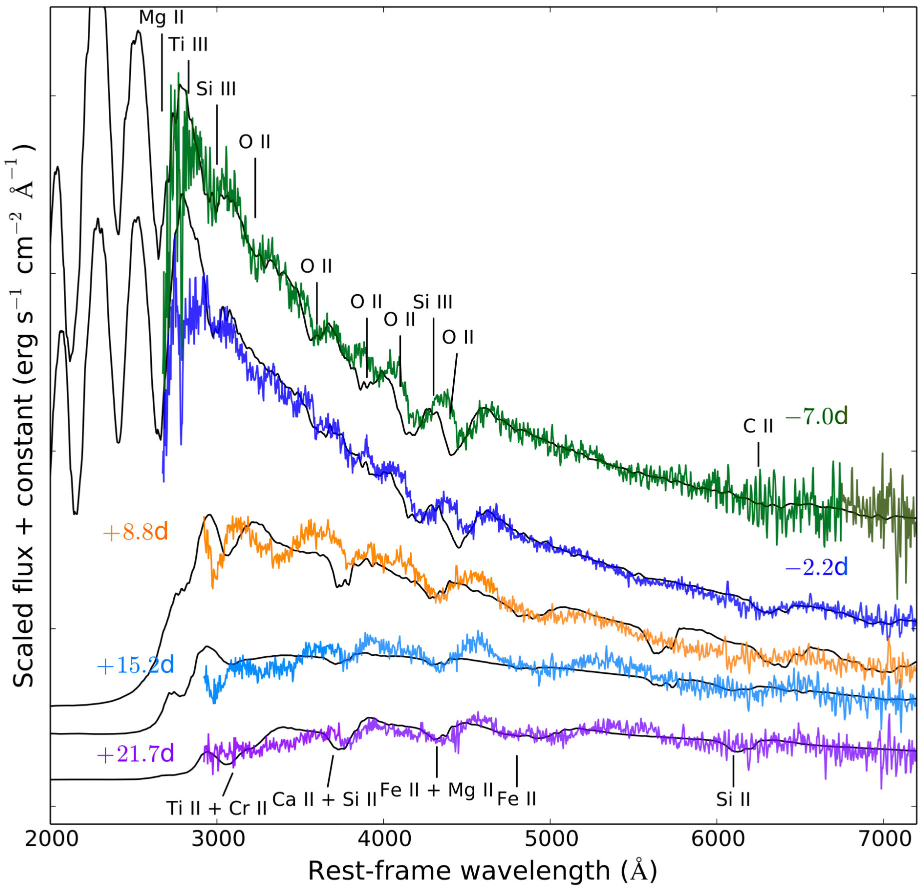
Central heating is not enough

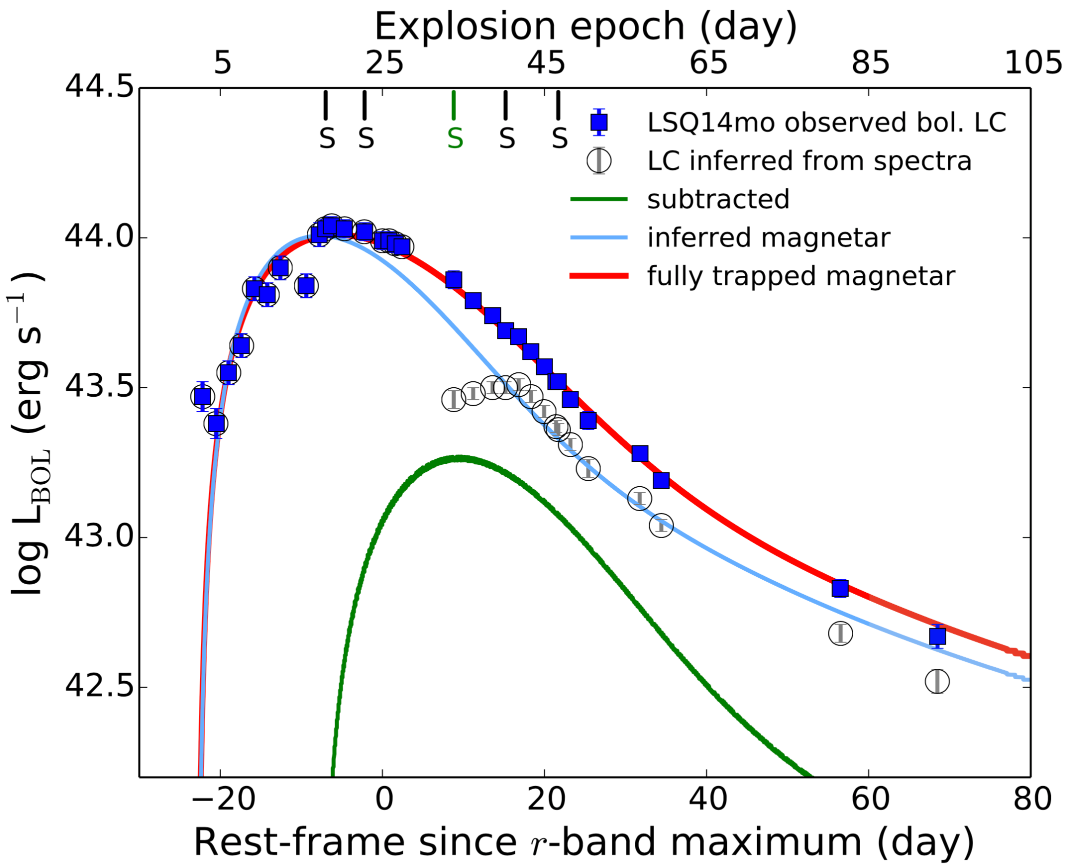
Nicholl et al. (2016)



Central heating is not enough

- LSQ14mo (Chen et al. 2017)
    - extra heating from outside?





- light echo (Lunnan et al. 2018), late-phase H emission (Yan et al. 2017)

Summary

- SLSNe — new class of extremely luminous SNe
- SLSNe with hydrogen
  - mostly Type IIn — CSM interaction is the power source
  - ~ 10 Msun of CSM required — how?

- SLSNe without hydrogen
  - late-phase similarity to SNe associated with GRBs
  - 56Ni power is not likely in many cases
  - central heating source?
    - magnetar model working well — smoking gun?
    - fallback accretion model requires too massive accretion
  - heating from outside is also needed