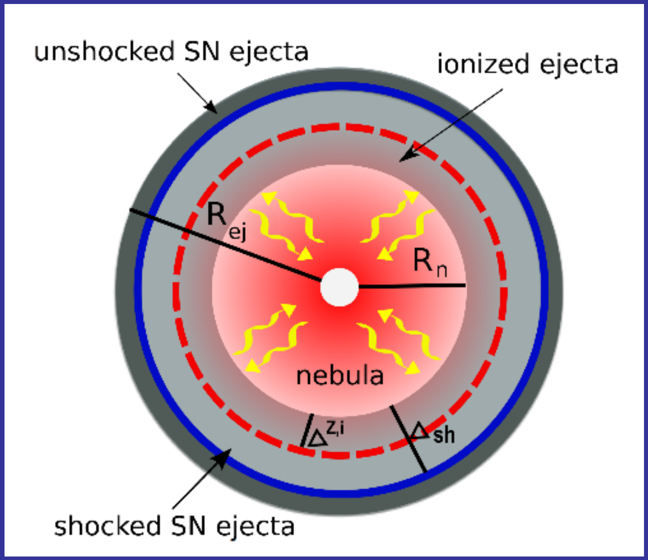
Ionization Break-Out from Millisecond PWNe:
Testing the Origin of Superluminous Supernovae

Brian Metzger
Columbia University



In Collaboration with

Indrek Vurm, Romain Hascoet, Andrei Beloborodov (Columbia)
Andrew Levan (Warwick), Tony Piro (Caltech)

BDM, Vurm, Hascoet & Beloborodov (2014), MNRAS, 437, 703

Levan, Read, BDM, Wheatley, & Tanvir (2013) ApJ, 771, 136)

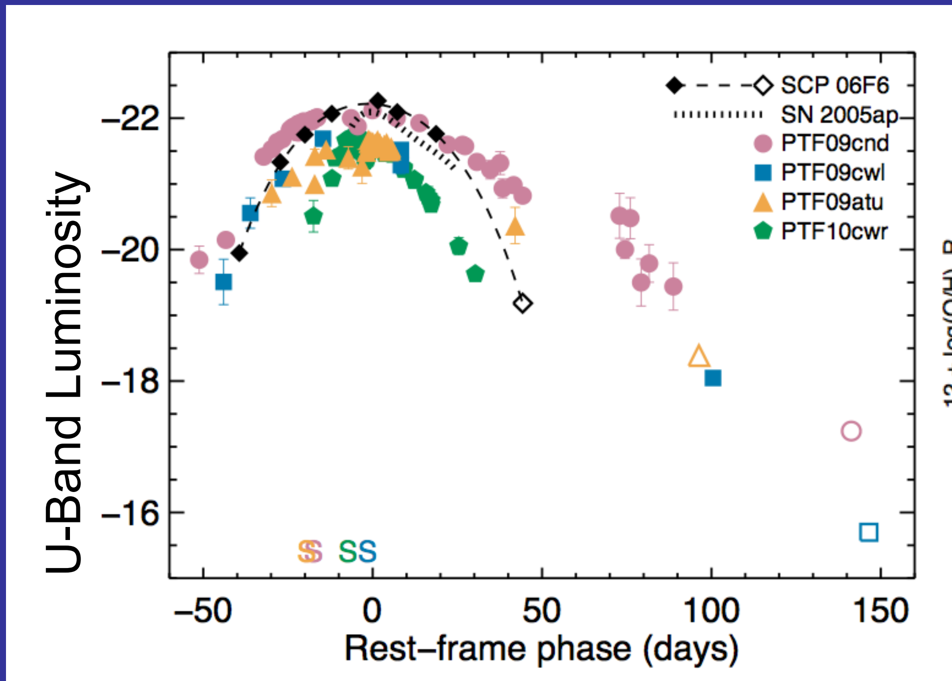
BDM & Piro (2014), MNRAS, 439, 3916

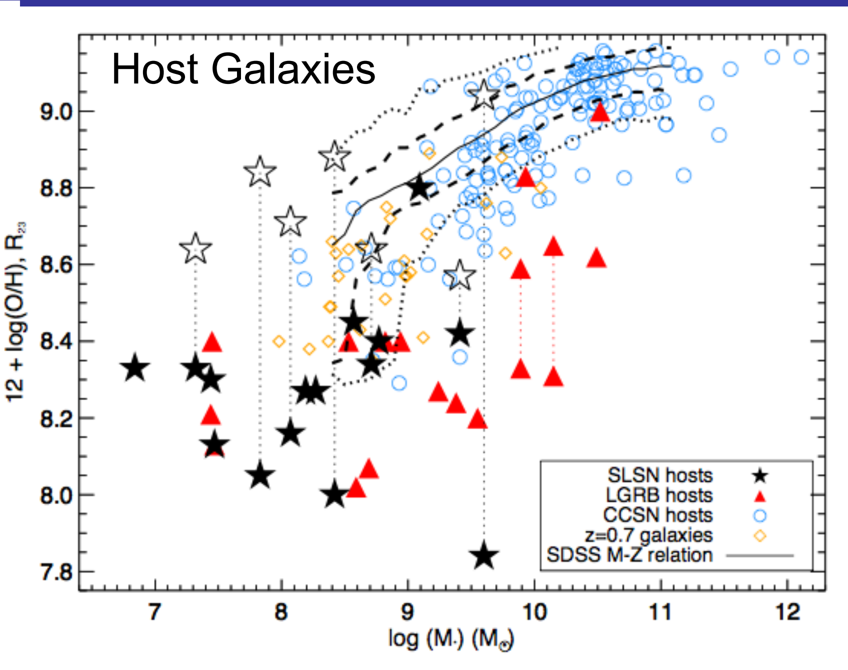
Relativistic Plasma Astrophysics, Purdue University - May 13, 2014

H-Poor ‘Superluminous’ Supernovae

Quimby+07, Barbary+09, Pastorello+10, Chomiuk+11, Leloudas+12, Berger+12, Lunnan+13, Inserra+13

Quimby et al. 2011



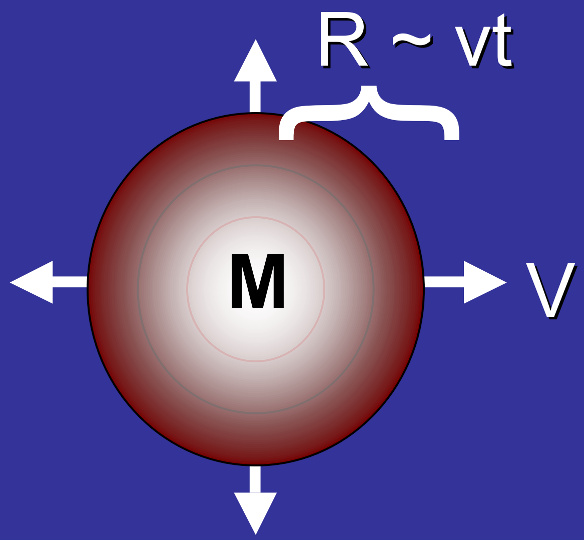


Lunnan et al. 2014

- $L_{peak} > 10^{44}$ erg s^{-1}, $E_{rad} \sim 10^{50\text{-}51}$ ergs (10-100 × normal SNe)
- UV-rich spectrum with intermediate mass elements (CNO)
- Faint metal-poor host galaxies, similar to long GRBs
  (Quimby+11, Neill+11, Chomiuk+11, Chen+13; Lunnan+14; but see Berger+13, Chornock+13)
- Extremely Rare: ~10^{-4} of core collapse SN rate

How Supernovae Shine

ejecta with mass M, velocity v, opacity κ



$R_0 \sim 10^{11.5}$ cm

$E_{th,0} \sim Mv^2 \sim 10^{51}$ ergs

$E_{th,pk} \sim E_{th,0}(R_0/R_{pk}) \sim 10^{-4} E_{th,0} \sim 10^{47}$ ergs

$L_{pk} \sim 10^{47}$ ergs / $t_{pk} \sim 10^{41}$ erg s^{-1}

$$\mathrm{R = v\,t} \qquad \rho \sim M/R^3$$

$$\tau \sim \kappa\rho \mathrm{R} \qquad t_{\mathrm{diff}} \sim \tau R/c \propto t^{-1}$$

PdV work → radiation

$$\frac{dE_{\mathrm{th}}}{dt} = -\frac{E_{\mathrm{th}}}{t} - \frac{E_{\mathrm{th}}}{t_{\mathrm{diff}}} + ???$$

Luminosity peaks when $t \sim t_{\mathrm{diff}} \Rightarrow$

$$t_{\mathrm{pk}} \sim \mathrm{month}\left(\frac{\mathrm{v}}{10^4\ \mathrm{km\ s^{-1}}}\right)^{-1/2}\left(\frac{M}{3M_\odot}\right)^{1/2}\left(\frac{\kappa}{0.1\ \mathrm{cm^2 g^{-1}}}\right)^{1/2}$$

$$R_{\mathrm{pk}} \sim 3\times 10^{15}\mathrm{cm}\left(\frac{\mathrm{v}}{10^4\ \mathrm{km\ s^{-1}}}\right)^{1/2}\left(\frac{M}{3M_\odot}\right)^{1/2}\left(\frac{\kappa}{0.1\ \mathrm{cm^2 g^{-1}}}\right)^{1/2}$$

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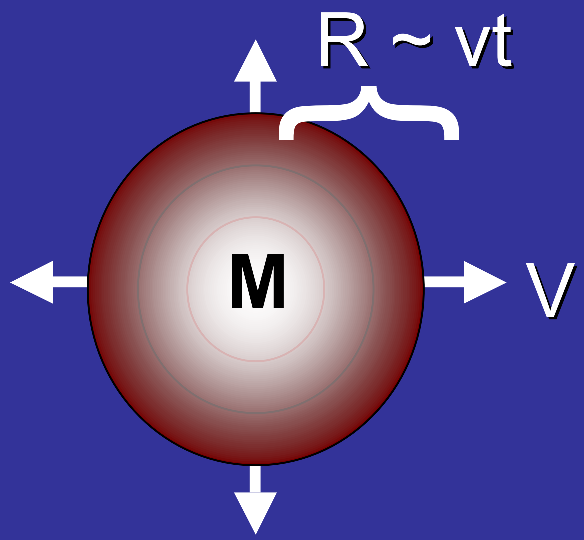

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PdV work — radiation

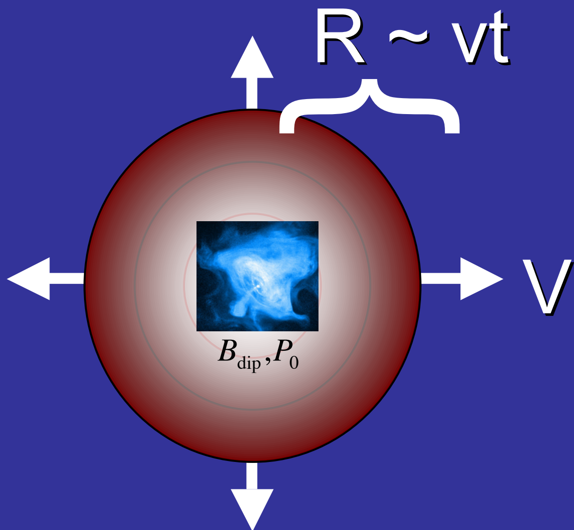
$$\frac{dE_{th}}{dt} = -\frac{E_{th}}{t} - \frac{E_{th}}{t_{diff}} + \dot{E}_{Ni56}$$

Luminosity peaks when $t \sim t_{diff} \Rightarrow$

$$\dot{E}_{Ni56} \sim \frac{M_{Ni56}\varepsilon}{\tau} e^{-t/\tau} \sim 10^{43}\left(\frac{M_{Ni56}}{0.2 M_\odot}\right) e^{-t/10d} \text{erg s}^{-1}$$

Pulsar Powered Supernovae

(Ostriker & Gunn 1971; Kasen & Bildsten 2010; Woosley 2010)



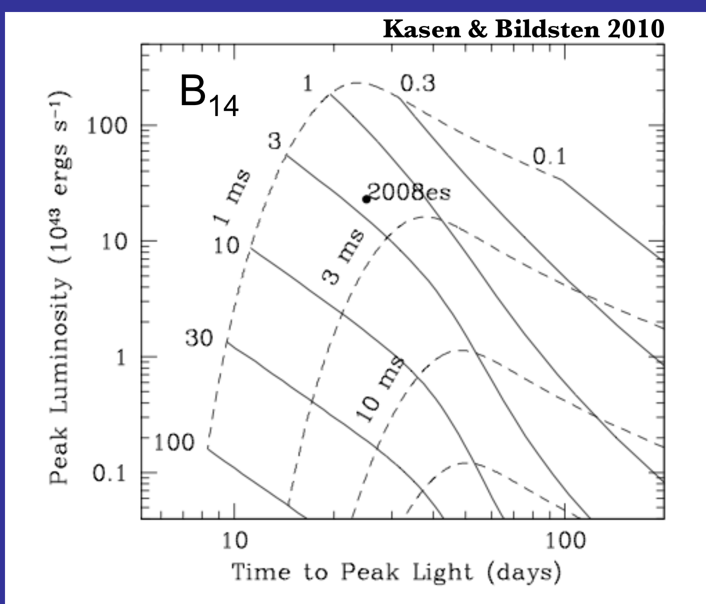
PdV work — radiation

$$\frac{dE_{th}}{dt} = -\frac{E_{th}}{t} - \frac{E_{th}}{t_{diff}} + \dot{E}_{pulsar}$$

$$\dot{E}_{pulsar} = \frac{\mu^2 \Omega^4}{c^3} \approx 4 \times 10^{45} \left(\frac{P}{2\ \mathrm{ms}}\right)^{-4} \left(\frac{B_{dip}}{10^{13.5}\ \mathrm{G}}\right)^{2} \mathrm{erg\ s^{-1}}$$

$$\tau_{sd} = \frac{E_{rot}}{L_{sd}} \approx \text{ month} \left(\frac{P_0}{2\ \mathrm{ms}}\right)^{2} \left(\frac{B_{dip}}{10^{13.5}\ \mathrm{G}}\right)^{-2}$$

$$t_{pk} \sim \text{month} \left(\frac{v}{10^4\ \mathrm{km\ s^{-1}}}\right)^{-1/2} \left(\frac{M}{3M_\odot}\right)^{1/2} \left(\frac{\kappa}{0.1\ \mathrm{cm^2 g^{-1}}}\right)^{1/2}$$



Increase SN luminosity if $\tau_{sd} \sim t_{pk} \Rightarrow B_{dip} \sim 10^{13\text{-}14}$ G, P ~ 1-few ms

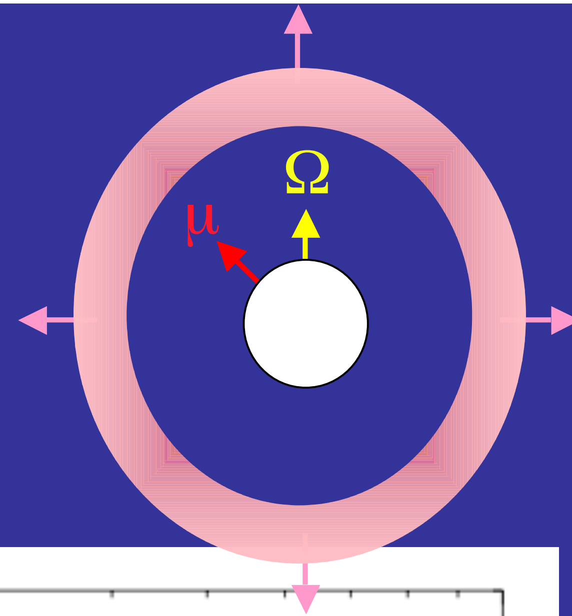
Signatures of Magnetar Birth

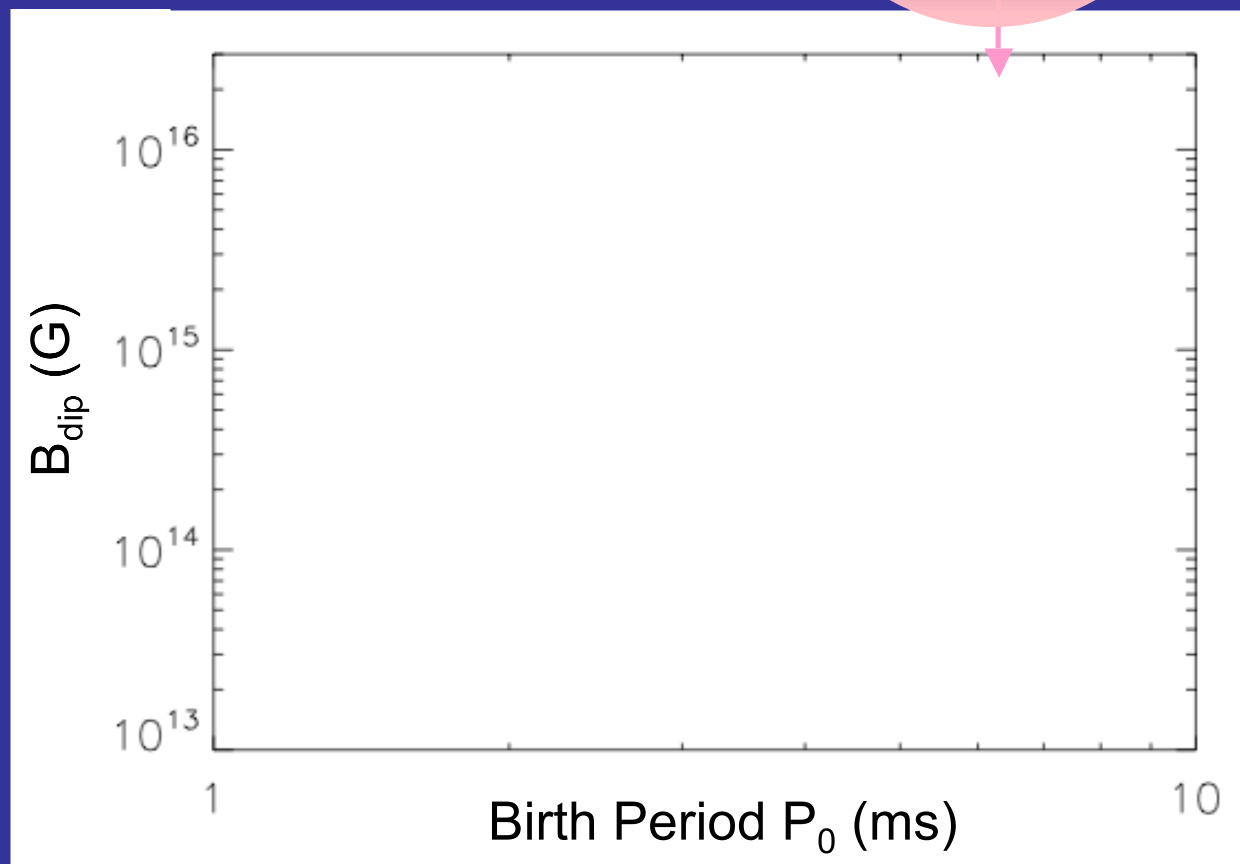
spin-down luminosity :

$$L_{sd} = \frac{\mu^2 \Omega^4}{c^3} \approx 6 \times 10^{49} \left(\frac{P}{1\text{ ms}}\right)^{-4} \left(\frac{B_{dip}}{10^{15}\text{ G}}\right)^{2} \text{erg s}^{-1}$$

spin-down time :

$$\tau_{sd} = \frac{E_{rot}}{L_{sd}} \approx 10 \left(\frac{P_0}{1\text{ ms}}\right)^{2} \left(\frac{B_{dip}}{10^{15}\text{ G}}\right)^{-2} \text{min}$$





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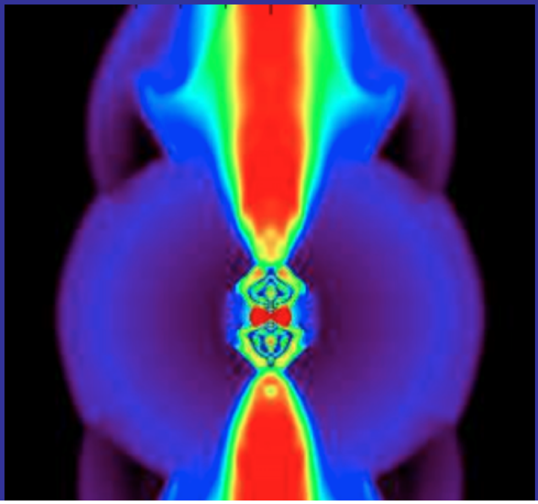

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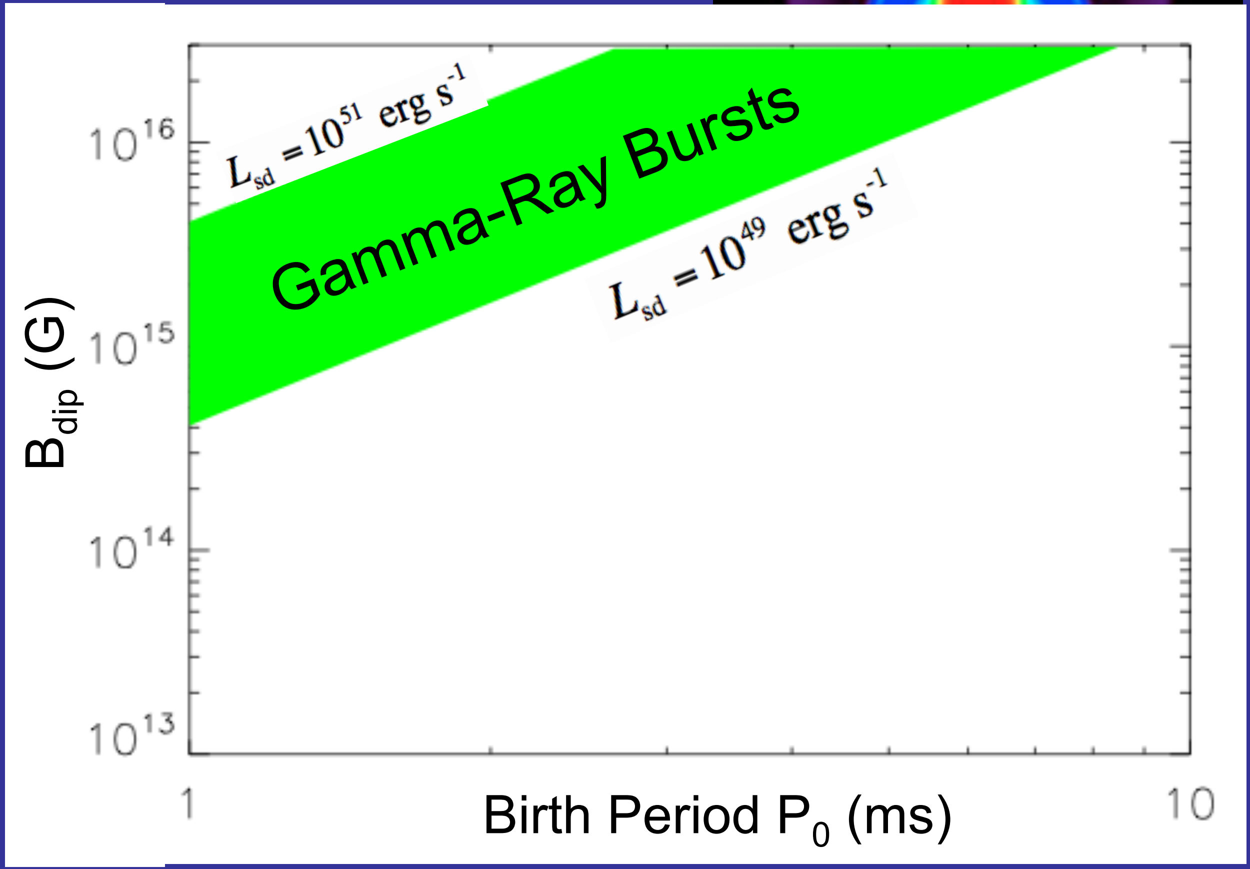
Gamma-Ray Burst

- Jet punches successfully through star (???)
- $L_{sd} \sim L_\gamma \sim 10^{49\text{-}51}$ erg s^{-1}
- τ_{sd} ~ minutes-hours



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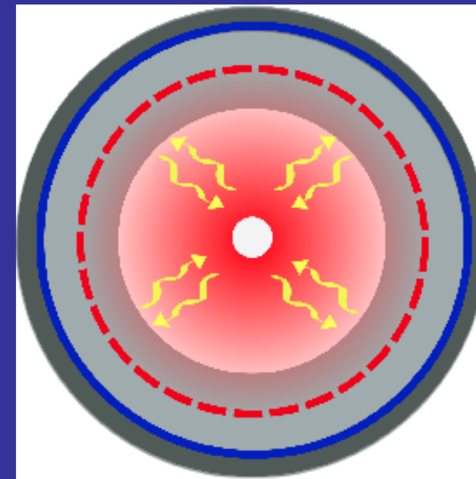

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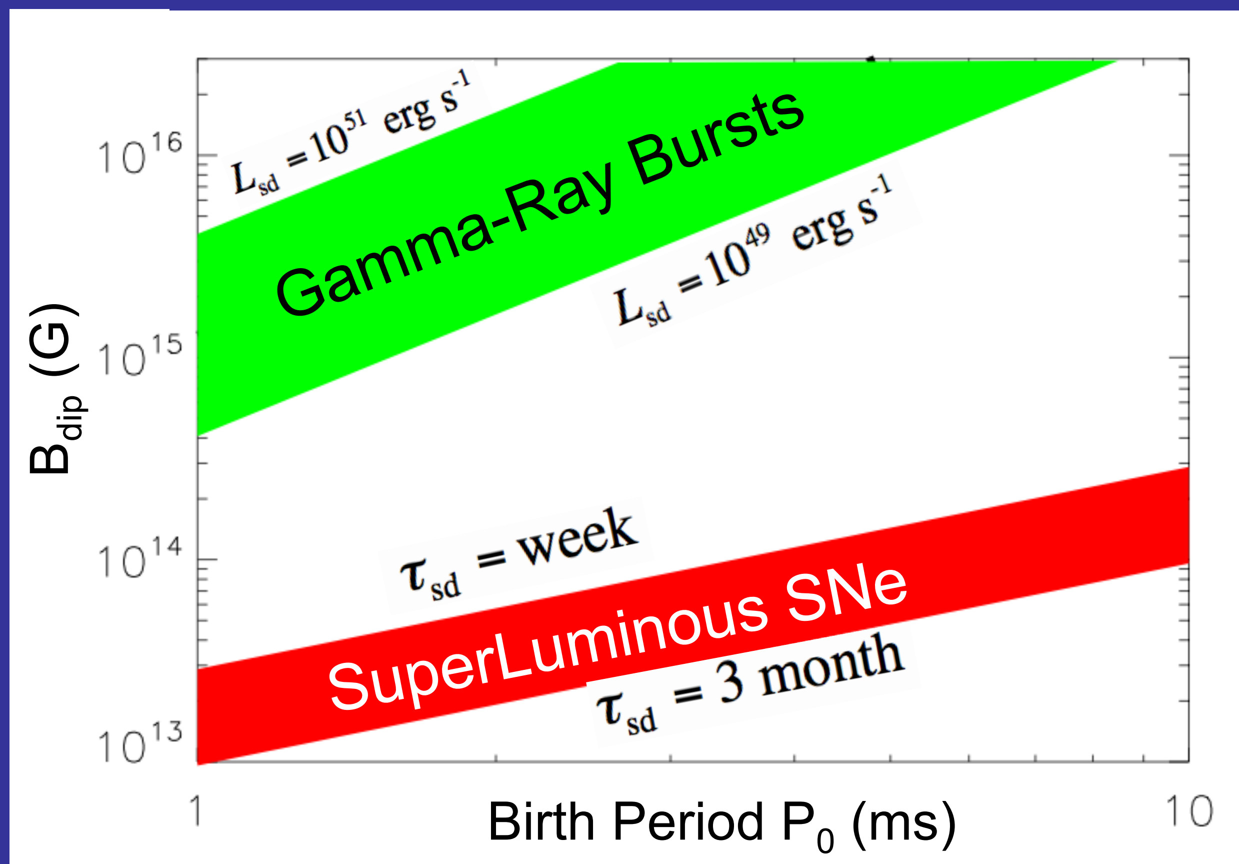
Gamma-Ray Burst

- Jet punches successfully through star (???)
- $L_{sd} \sim L_{\gamma} \sim 10^{49-51}$ erg s^{-1}
- τ_{sd} ~ minutes-hours

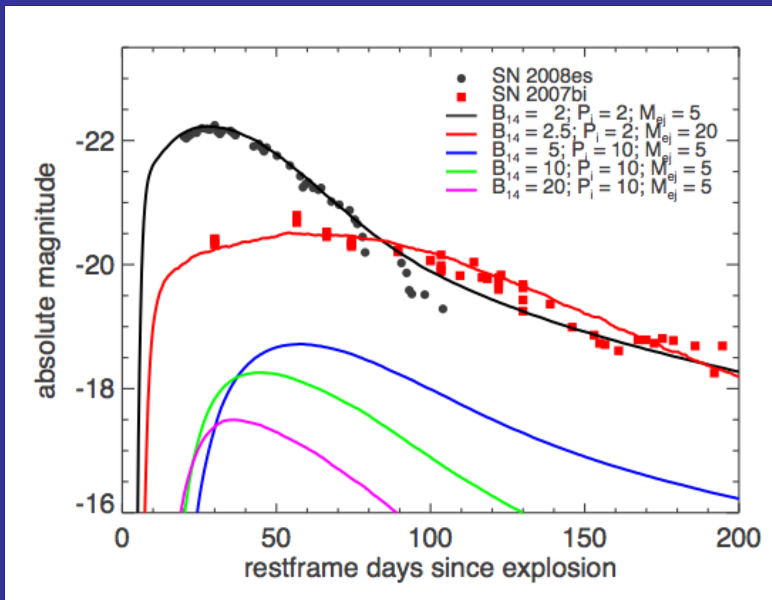
Super-Luminous SN

- Jet stifled, but optical SN powered diffusively
- $L_{sd} \sim L_{SN} \sim 10^{43-45}$ erg s^{-1}
- τ_{sd} ~ week - months

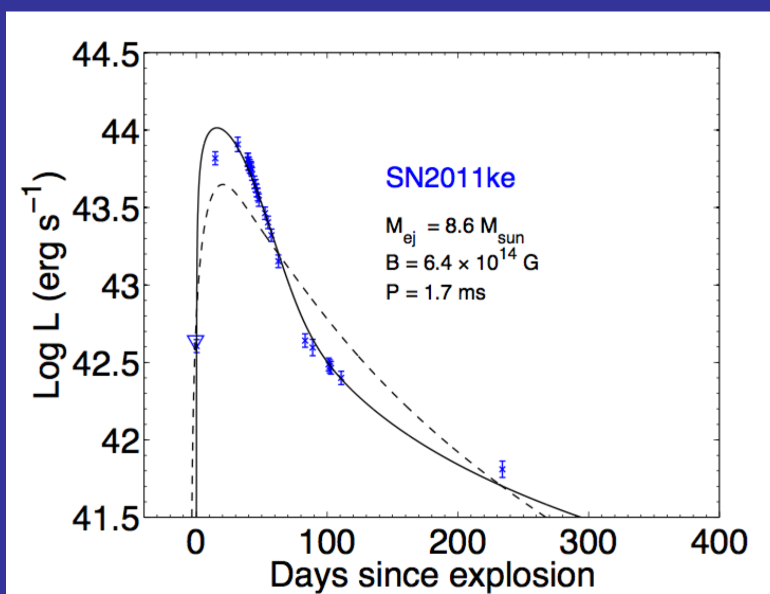


“Magnetar” Model for Superluminous SNe

Kasen & Bildsten 2010



Inserra et al. 2013



PROS

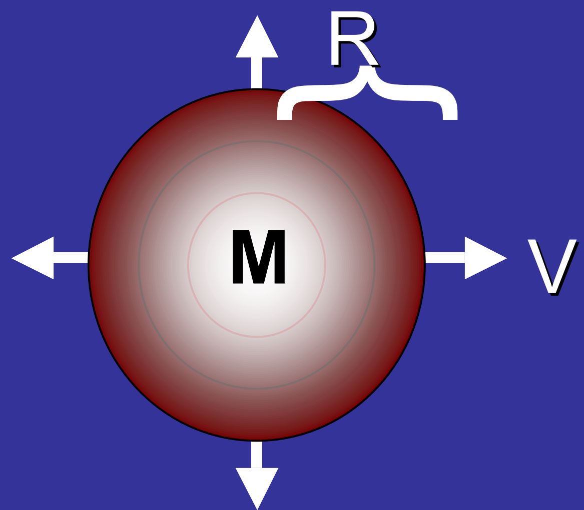
- “Explains” similar host galaxies to long GRBs (both require rapid rotating progenitor)
- Can reproduce diversity of rise times and peak luminosities

CONS

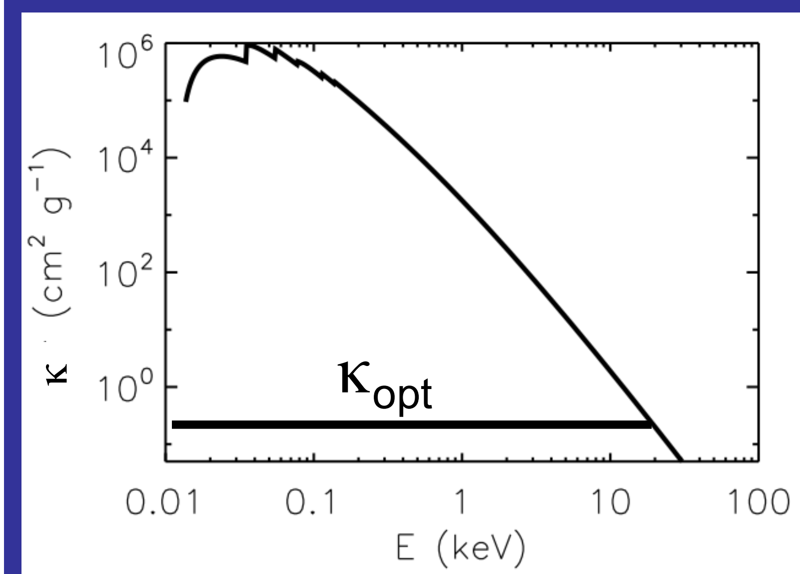
- Can reproduce diversity of rise times and peak luminosities (hard to test)
- How to distinguish from other hidden energy sources (optically-thick CSM interaction)
- Assumes pulsar wind thermalizes with 100% efficiency.

Reality: Poynting flux ⇒ $e^{+/-}$ pairs ⇒ non-thermal radiation ⇒ thermal radiation

Can we see inside nebula directly?



UV/X-ray opacity of neutral oxygen



Light escapes when $t > t_{diff} \Rightarrow$

$$t > \text{month} \left(\frac{v}{10^4 \text{ km s}^{-1}}\right)^{-1/2} \left(\frac{M}{3M_\odot}\right)^{1/2} \left(\frac{\kappa}{0.1 \text{ cm}^2\text{g}^{-1}}\right)^{1/2}$$

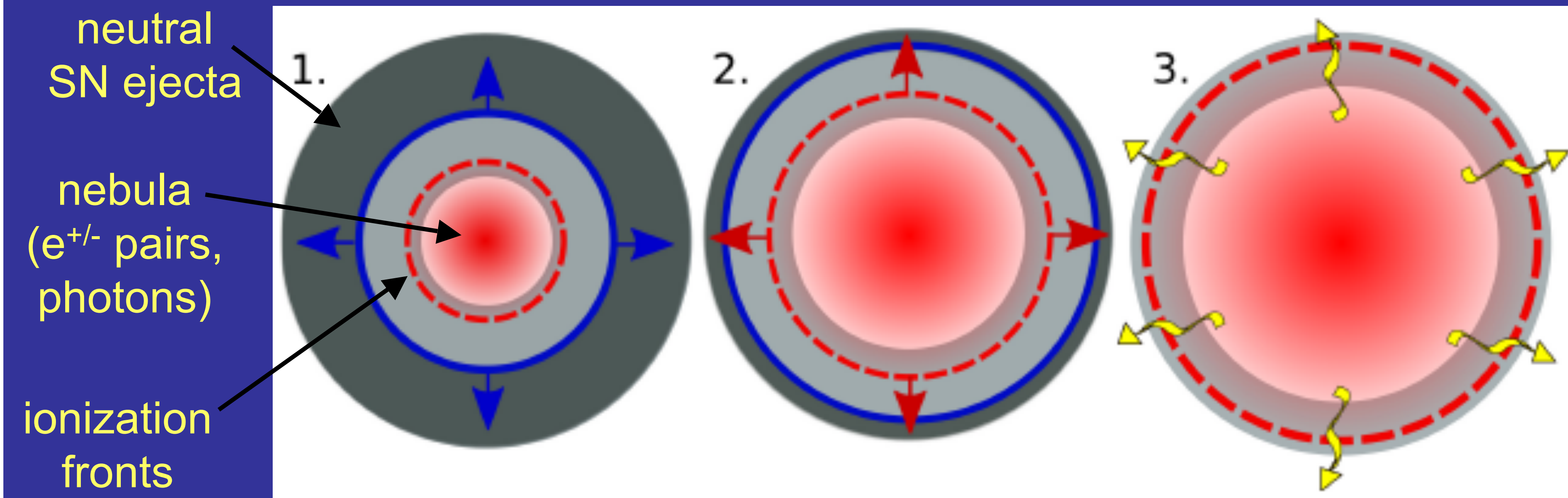
Optical ($\kappa \sim 0.1$ cm^2 g^{-1}) $\Rightarrow$ t ~ month

Hard X-ray ~ 10 keV ($\kappa \sim 30$ cm^2 g^{-1})
$\Rightarrow$ t ~ few years

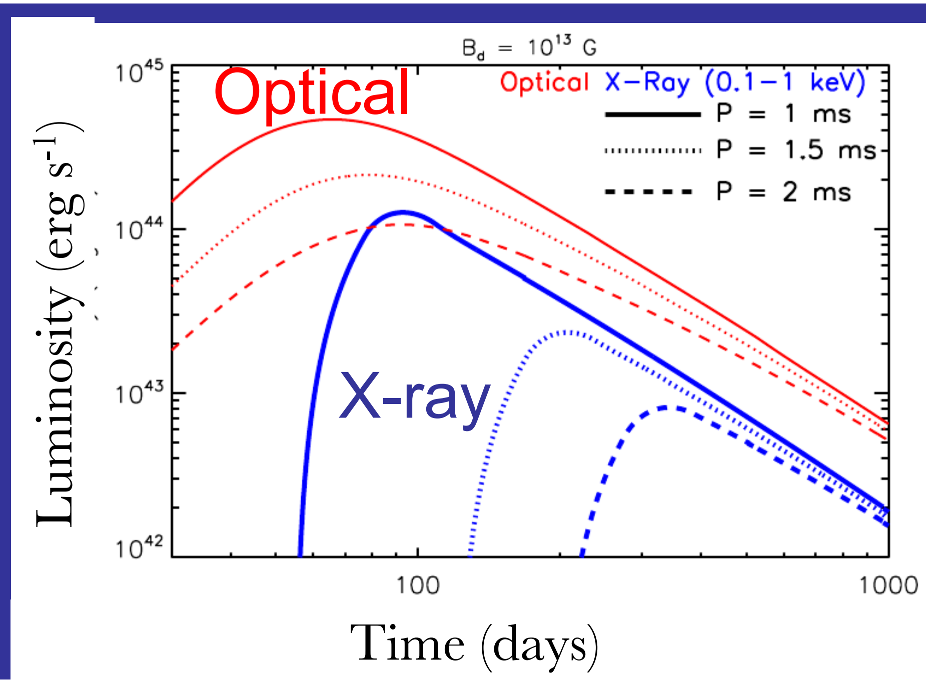
Soft X-ray ~0.1 keV ($\kappa \sim 10^5$ cm^2 g^{-1})
$\Rightarrow$ t ~ 100 years

X-ray Ionization Break-Out

(BDM, Vurm, Hascoet & Beloborodov 2013)



1. Pulsar inflates nebular cavity.
2. Nebula X-rays ionize inner exposed surface of ejecta
3. Ionization front reaches outer surface ⇒
   X-rays escape to observer.



Model for Evolution of Millisecond Pulsar Wind Nebulae

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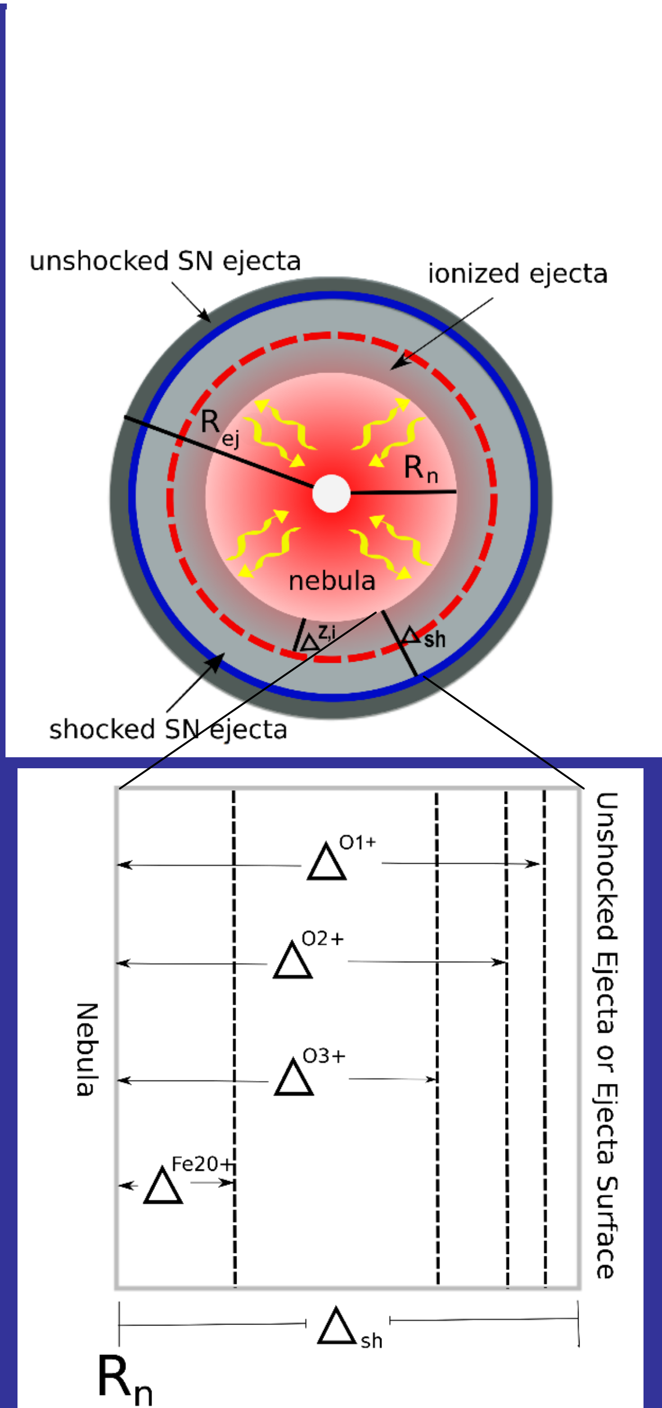
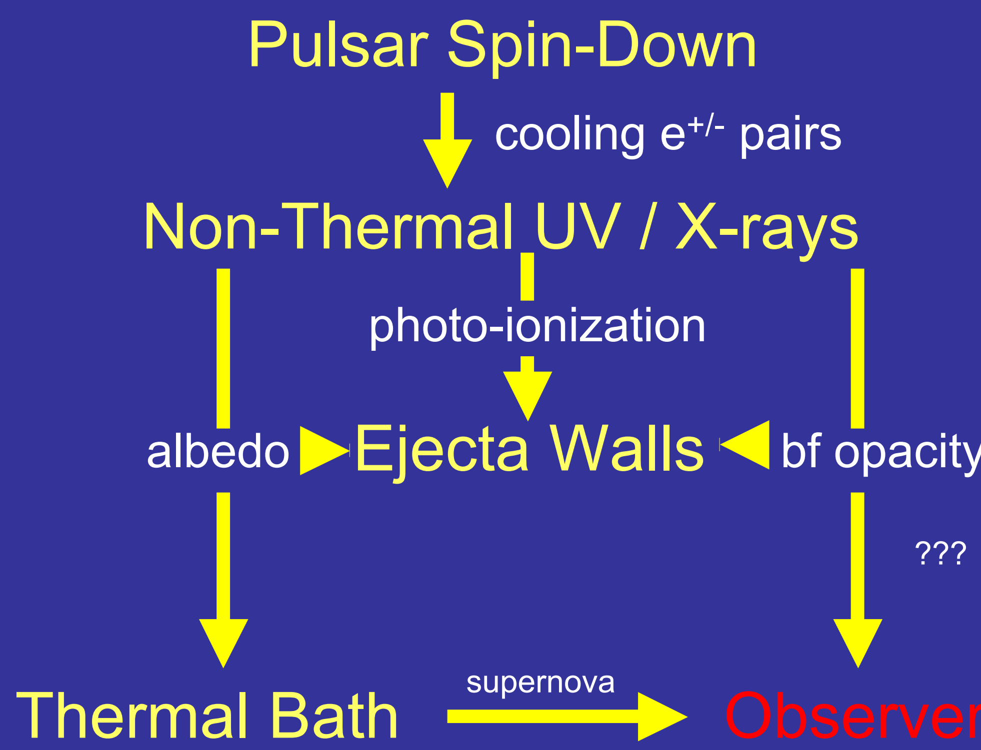




Pairs injected into nebula at rate

$$\dot{N}_\pm = \mu_\pm \dot{N}_{\rm GJ} \simeq 5\times 10^{37}\mu_\pm B_{13}P_{-3}^{-2}(1+t/t_{\rm sd})^{-1}{\rm s}^{-1}$$

…with energy per particle

$$\epsilon_\pm = \frac{L_{\rm sd}}{\dot{N}_\pm} \simeq 1.1\times 10^{8}\,{\rm erg}\,\mu_\pm^{-1}B_{13}P_{-3}^{-2}\,(1+t/t_{\rm sd})^{-1}$$

…and particle lorentz factor

$$\gamma_\pm = \frac{\epsilon_\pm}{m_e c^2} \simeq 1.3\times 10^{14}\mu_\pm^{-1}B_{13}P_{-3}^{-2}\,(1+t/t_{\rm sd})^{-1}$$

…which will actually be limited by cooling to a much lower value:

$$\gamma_\pm^{\rm max} = \sqrt{\frac{3e}{\sigma_{\rm T}B_{\rm n}}} \simeq 5\times 10^{6}\epsilon_{\rm B,-2}^{-1/4}L_{45}^{-1/4}\nu_9^{1/2}M_3^{1/4}\left(\frac{t}{t_{\rm d,0}}\right)^{1/2}$$

…producing photons of energy:

$$\hbar e B_{\rm n}(\gamma_\pm^{\rm max})^2/m_e c \sim 100\,{\rm MeV}$$

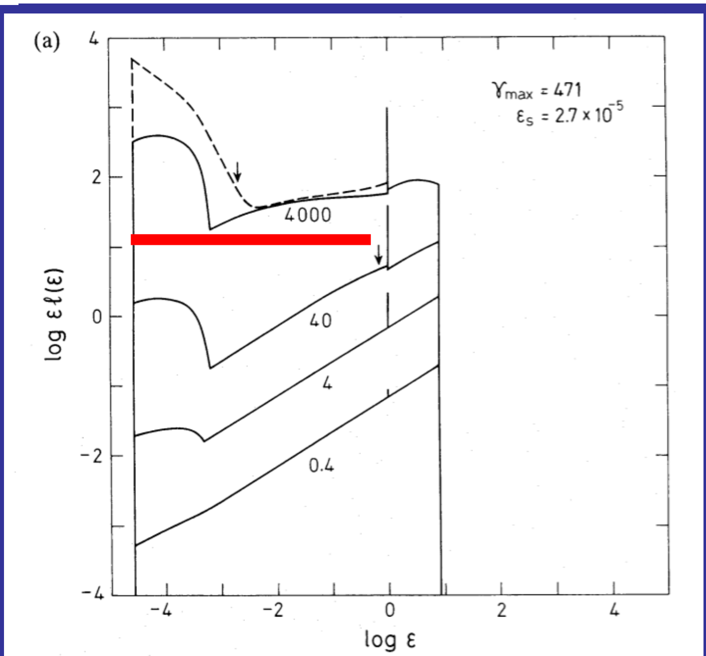
sufficient to create pairs, which given the high compactness of the nebula,

$$\ell \equiv \frac{E_{\rm nth}\sigma_{\rm T}R_{\rm n}}{V_{\rm n}m_e c^2} \approx 2.1(1-\bar{\mathcal{A}}_\nu)^{-1}L_{45}\nu_9^{-1/2}M_3^{-1/2}\left(\frac{t}{t_{\rm d,0}}\right)^{-1}$$

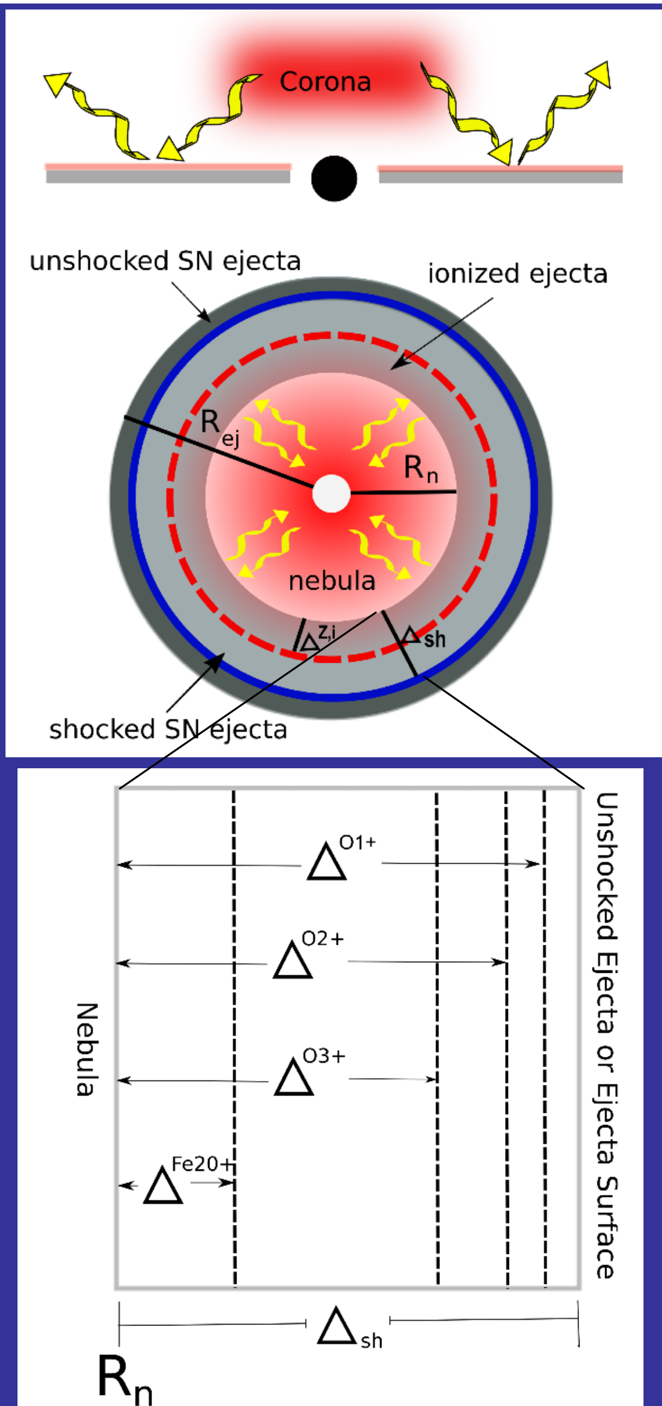
"saturated" pair cascades ⇒ flat photon spectrum

$$\dot{E}_{{\rm sd},\nu} \simeq \frac{L_{\rm sd}}{14\nu} \qquad (3kT_{\rm th} \sim 1\,{\rm eV} \lesssim h\nu \lesssim 1\,{\rm MeV})$$

e.g. Zdziarski & Lightman 1985



Svensson 1987



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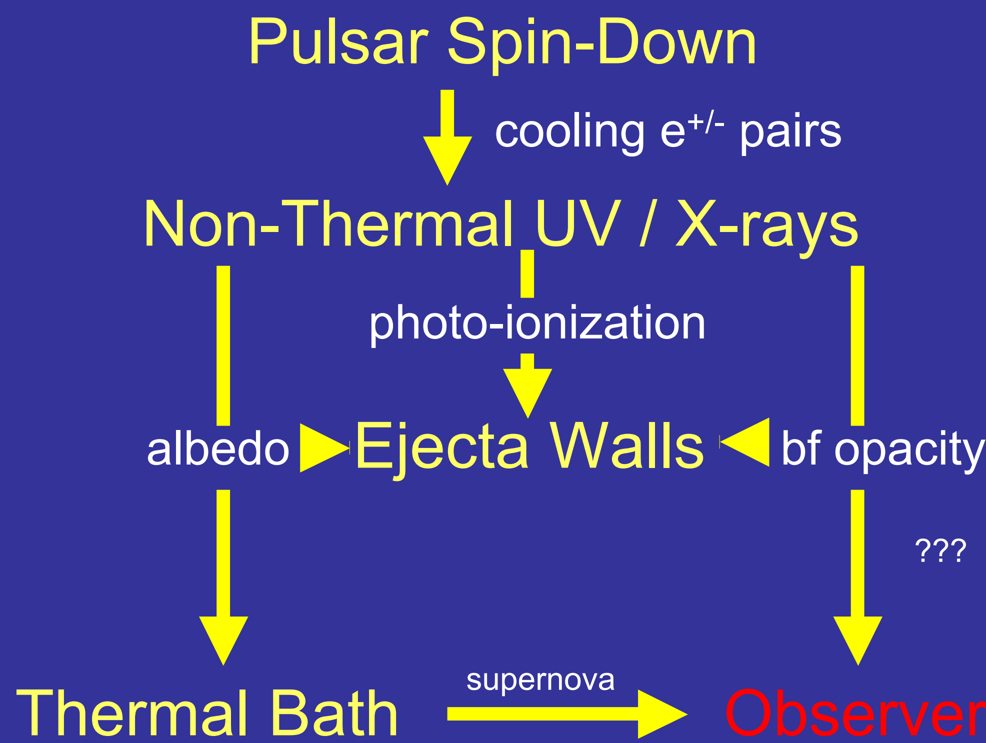
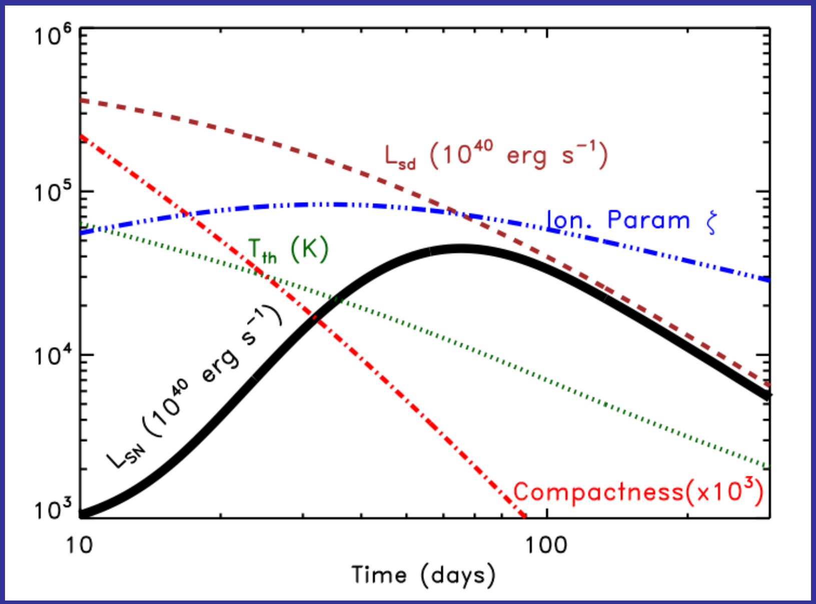
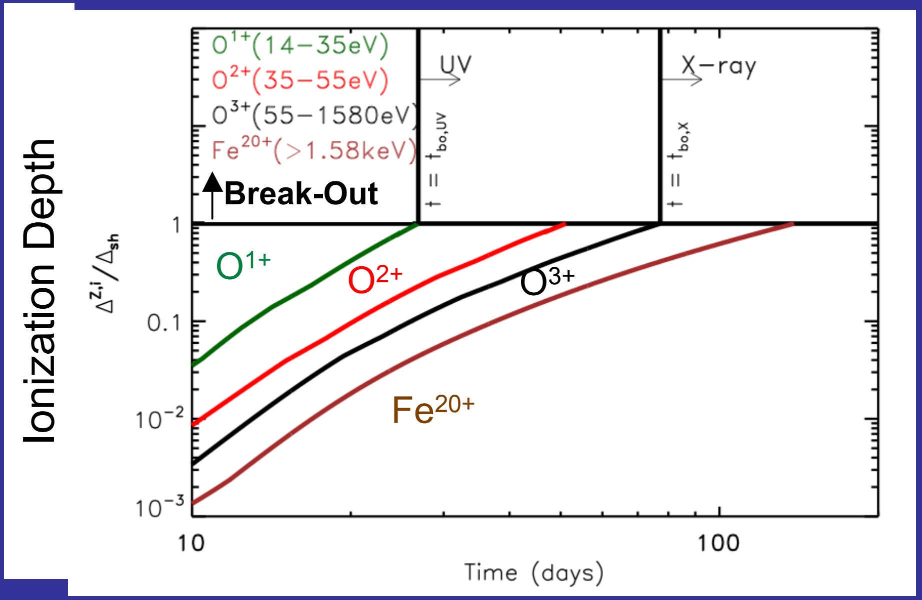


analogy to AGN accretion disks

Example: $B = 10^{13}$ G, $P = 1$ ms, $M_{ej} = 3\ M_\odot$

BDM et al. 2014





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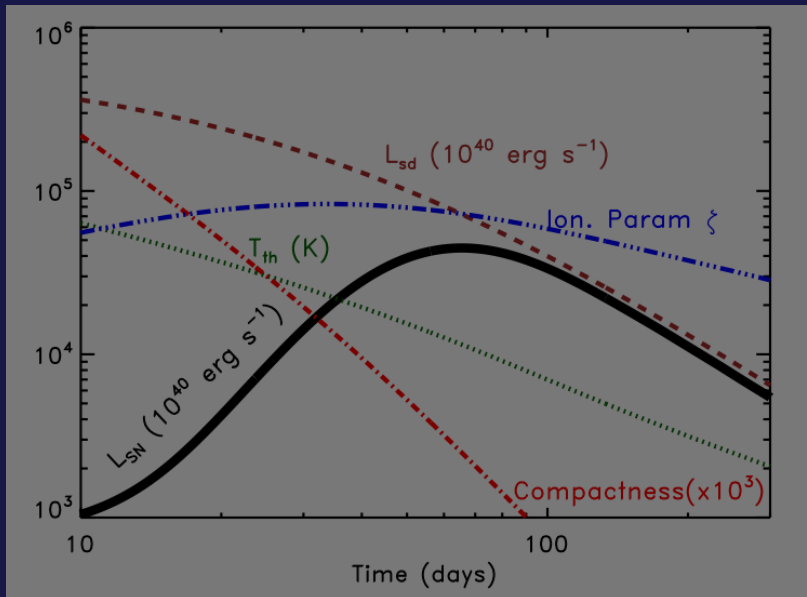
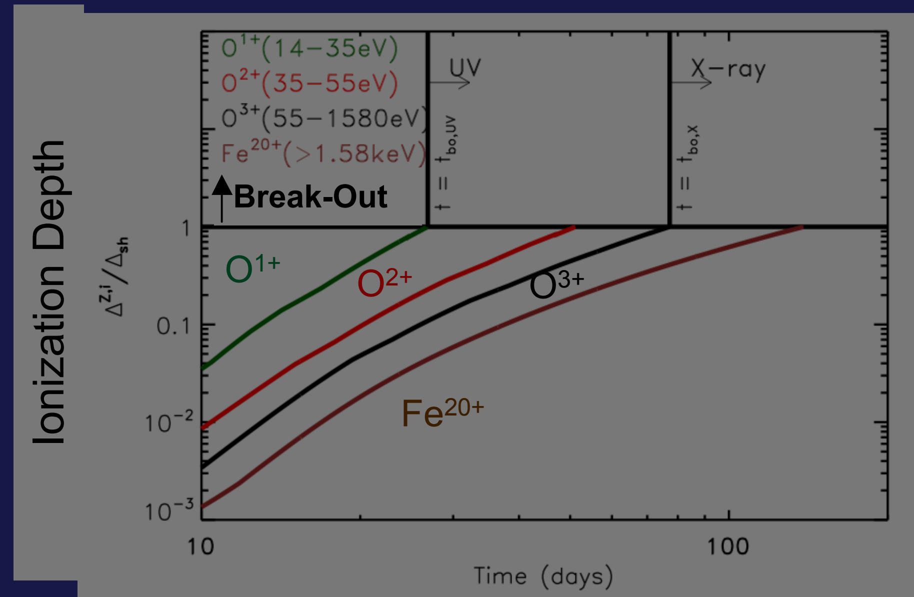
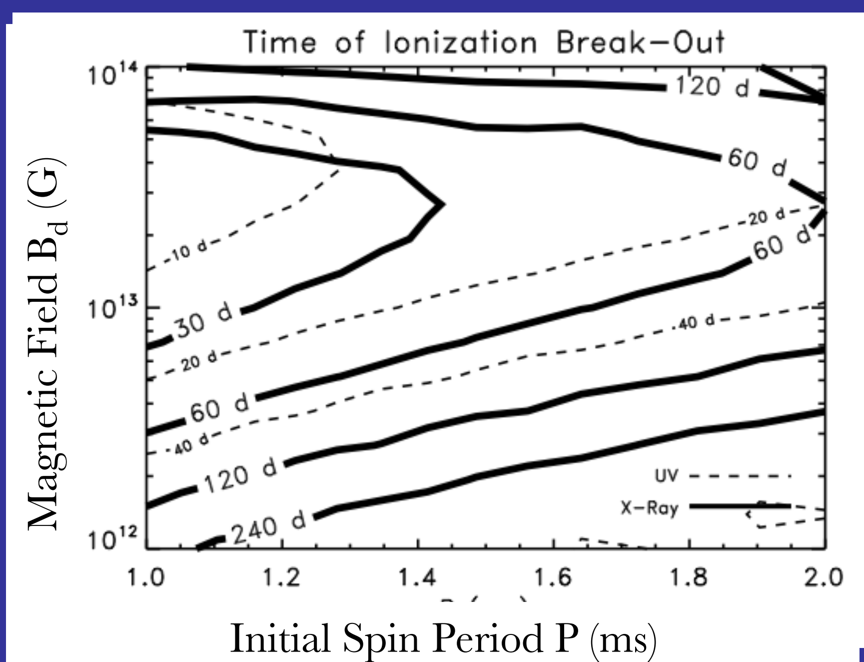
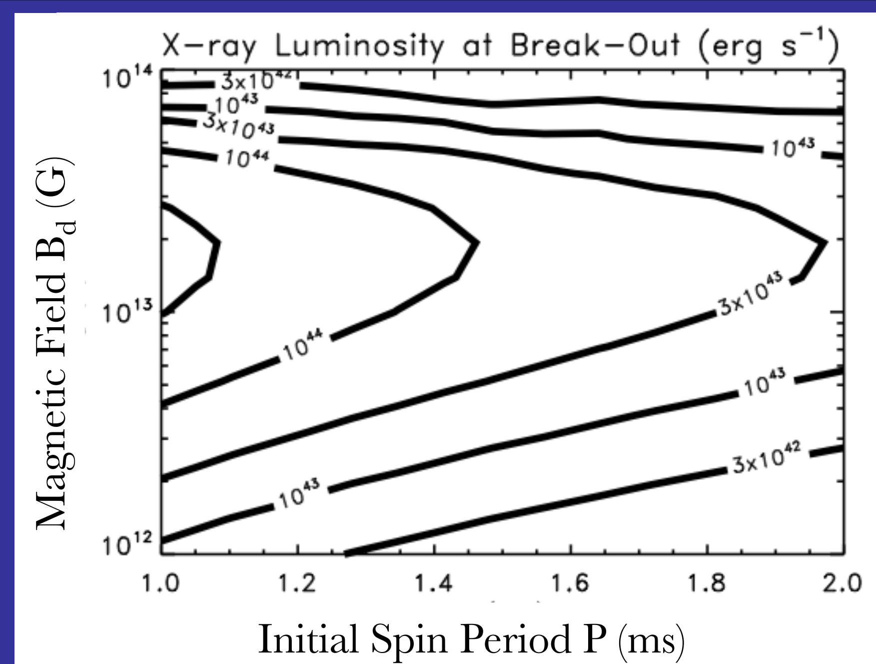




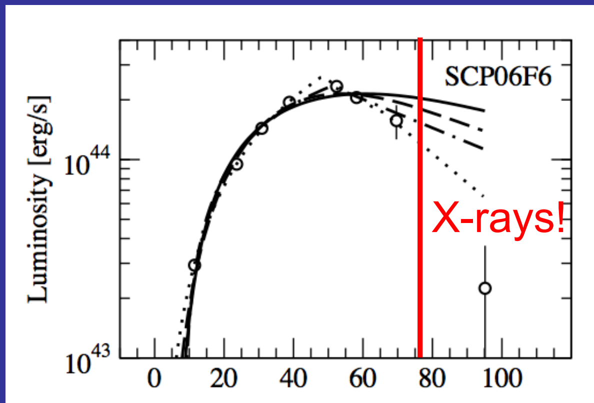


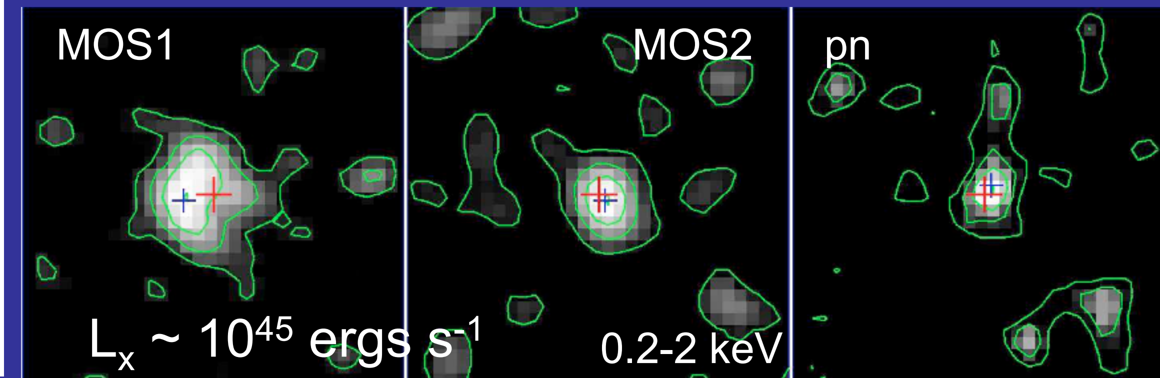


Superluminous X-rays from a Superluminous SN

(Levan, Read, BDM, Wheatly, Tanvir 2013)

Chatzopoulos et al. 2013
(cf. Barbary et al. 2009)





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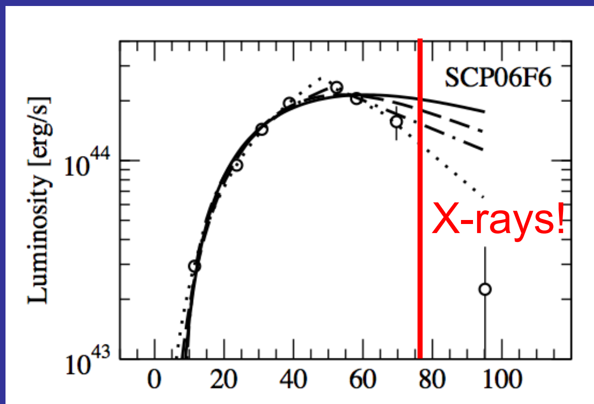
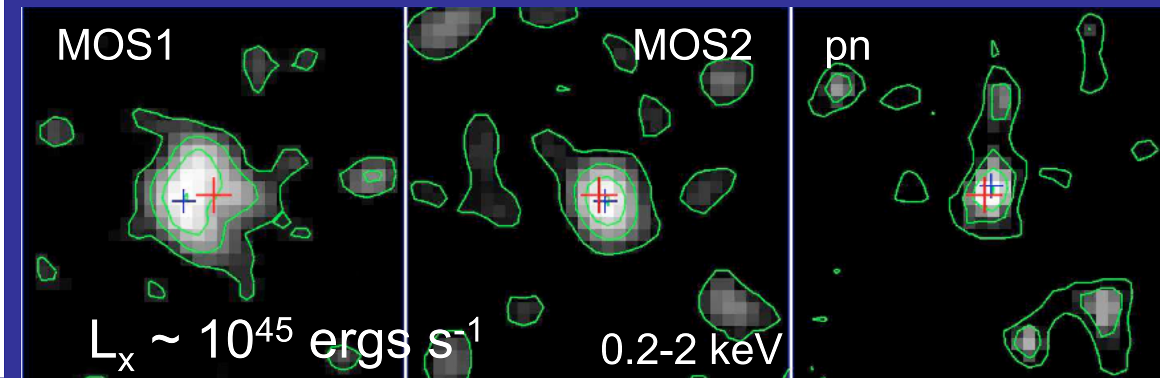
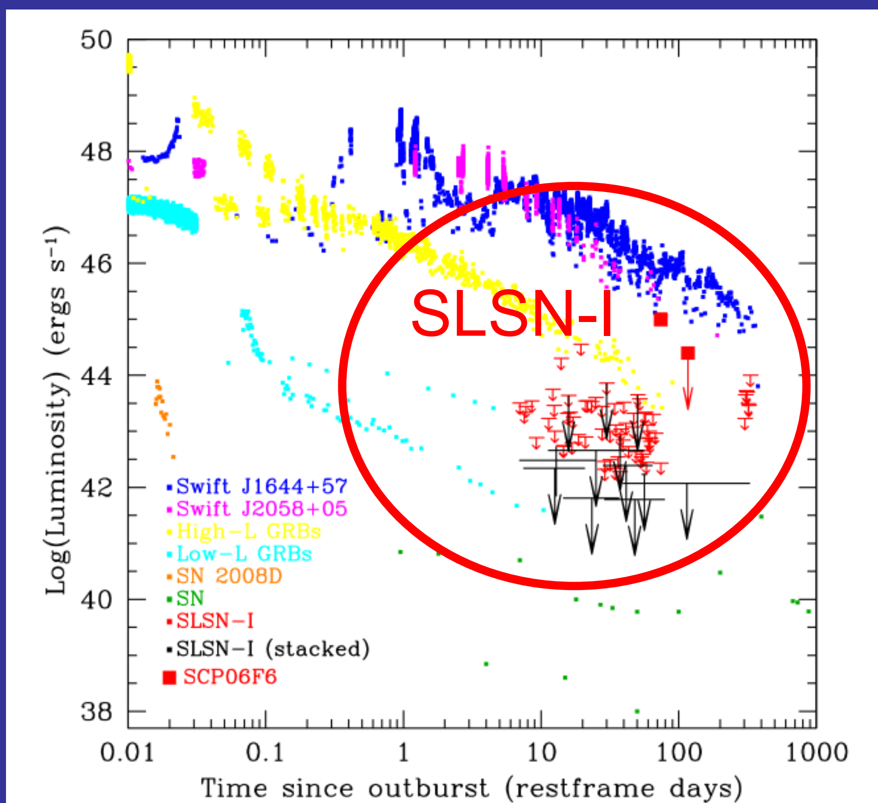




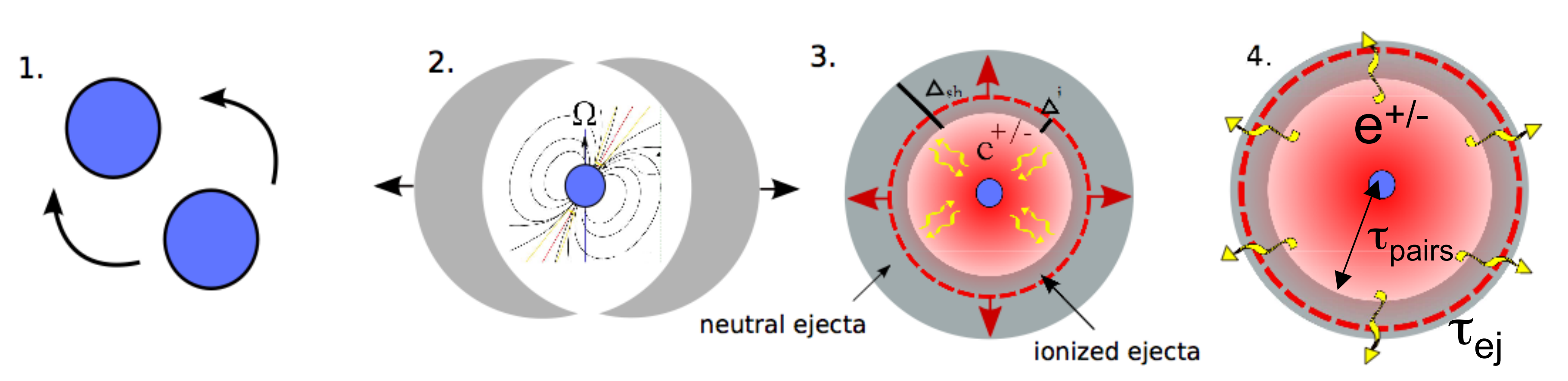
Levan et al. 2013



- ➢ No X-ray detections from other SLSNe
- ➢ Limits $L_x < 10^{42}$-10^{44} erg s^{-1} on timescales < 70 days (usually too early!)
- ➢ Future: X-ray follow-up *after* optical peak confirm/constrain pulsar model for SLSNe

Application to Binary Neutron Star Mergers

BDM & Piro 2014



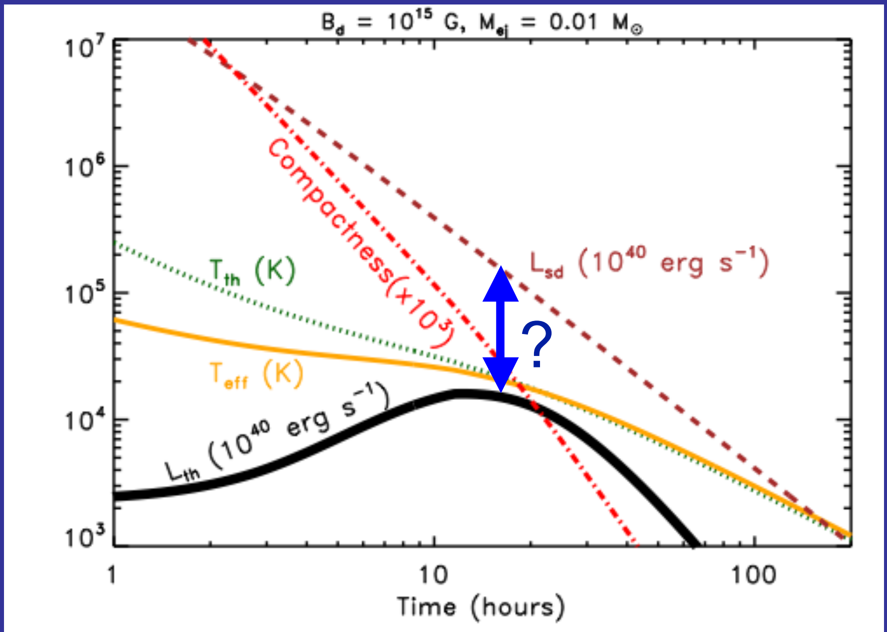
peak optical luminosity

$$L_{\rm opt,peak} \approx \chi^{-3/2} L_{\rm sd}\Big|_{t_{\rm peak}}$$

$$\chi \equiv \frac{\tau_{\rm pairs}}{\tau_{\rm ej}}\Bigg|_{t_{\rm peak}} \approx 2.7\left(\frac{B_{\rm d}}{10^{15}\,{\rm G}}\right)^{-2/3}\left(\frac{M_{\rm ej}}{10^{-2}\,M_{\odot}}\right)^{-2/3}\left(\frac{v_{\rm ej}}{c}\right)^{5/6}$$

$\chi > 1 \Rightarrow$ X-rays lose energy to PdV work before reaching walls (thermalization)

example ($M_{ej}=10^{-2}\,M_{\odot}$; $B_d = 10^{15}$ G)



Summary

- Hydrogen-Poor SLSNe may be powered by spin-down of nascent millisecond pulsar
- However, previous models [1] challenging to test (degenerate) and [2] assume pulsar luminosity thermalizes
- We have developed a model for the evolution of millisecond PWNe that couples X-ray to thermal radiation via interaction with ejecta walls (self-consistent)
- Pulsar wind ⇒ $e^{+/-}$ pairs ⇒ X-rays ⇒ thermal (optical) photons ⇒ observer (optical SN)
- High X-ray opacity of neutral matter normally prevents X-rays from escaping SN ejecta for > decades after explosion
- But… high X-ray luminosity of millisecond PWNe can re-ionize ejecta within months of optical peak (Ionization Break-Out)
- Pulsar wind ⇒ $e^{+/-}$ pairs ⇒ X-rays ⇒ observer
- Luminous X-rays from SCP 06F consistent with ionization break-out ⇒ evidence that some SLSNe are engine-driven.