Supernovae powered by magnetars that transform into black holes

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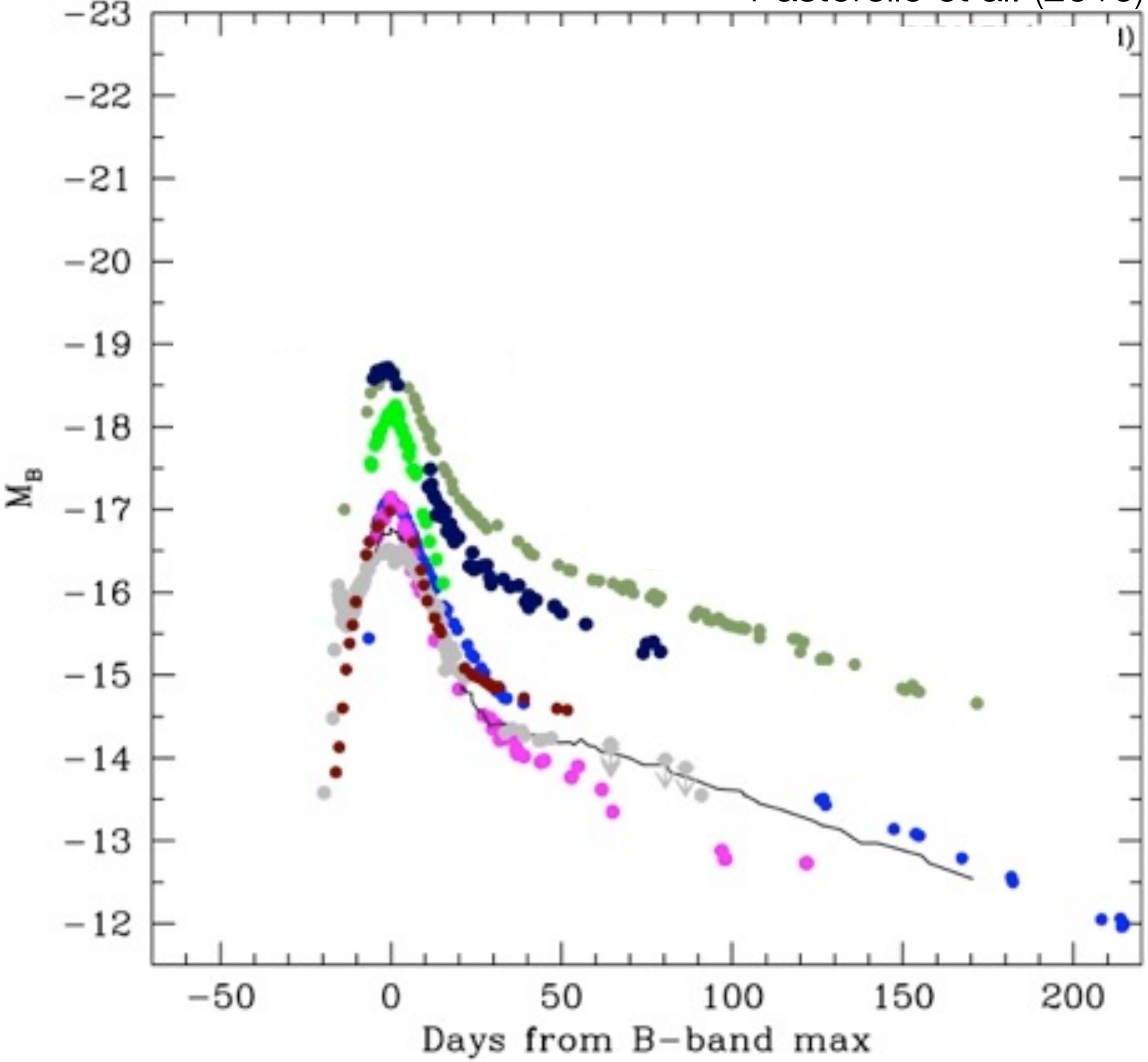
Classical core-collapse SNe

- until ~ 2006 (but SN 1999as)

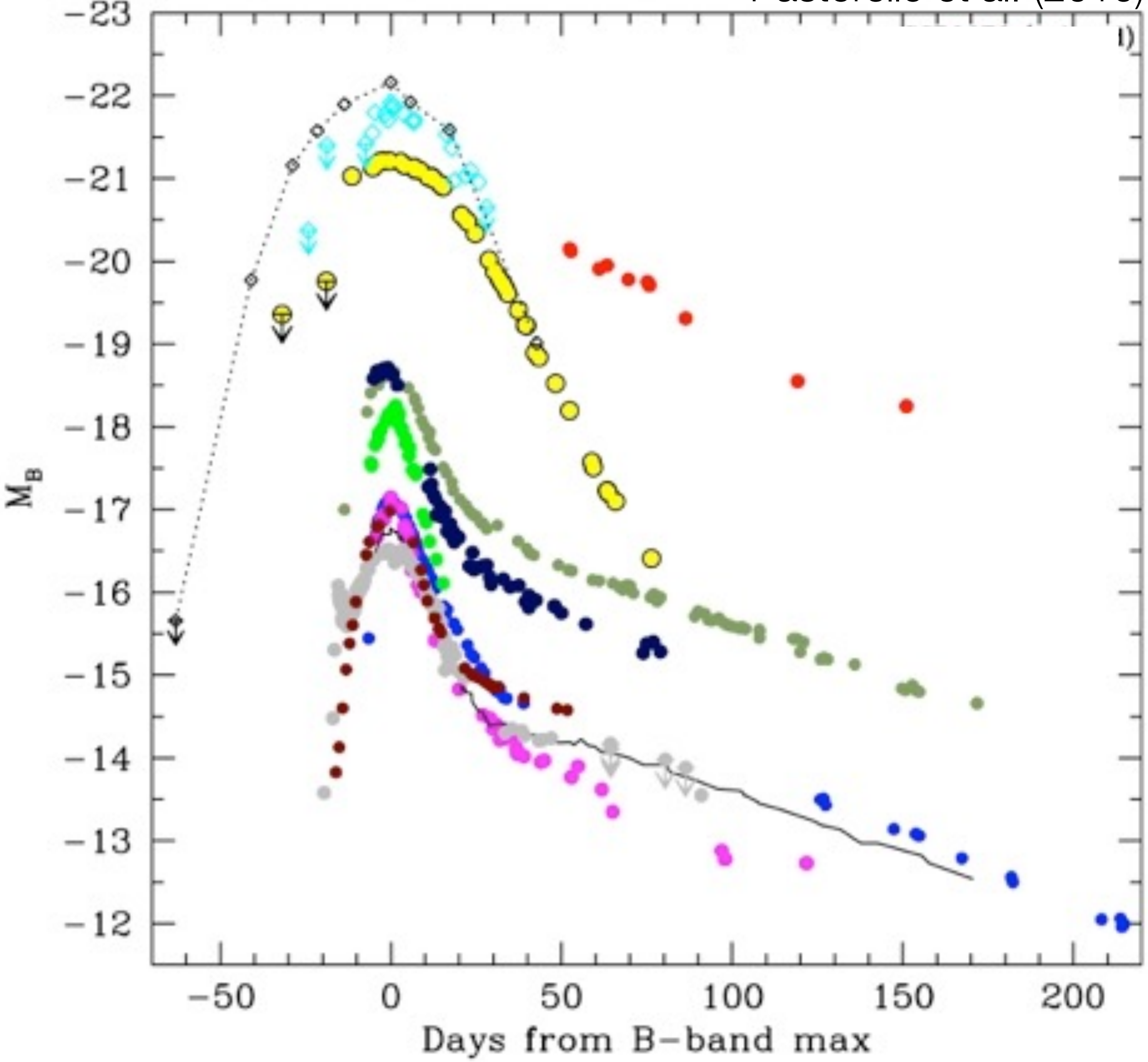
Pastorello et al. (2010)



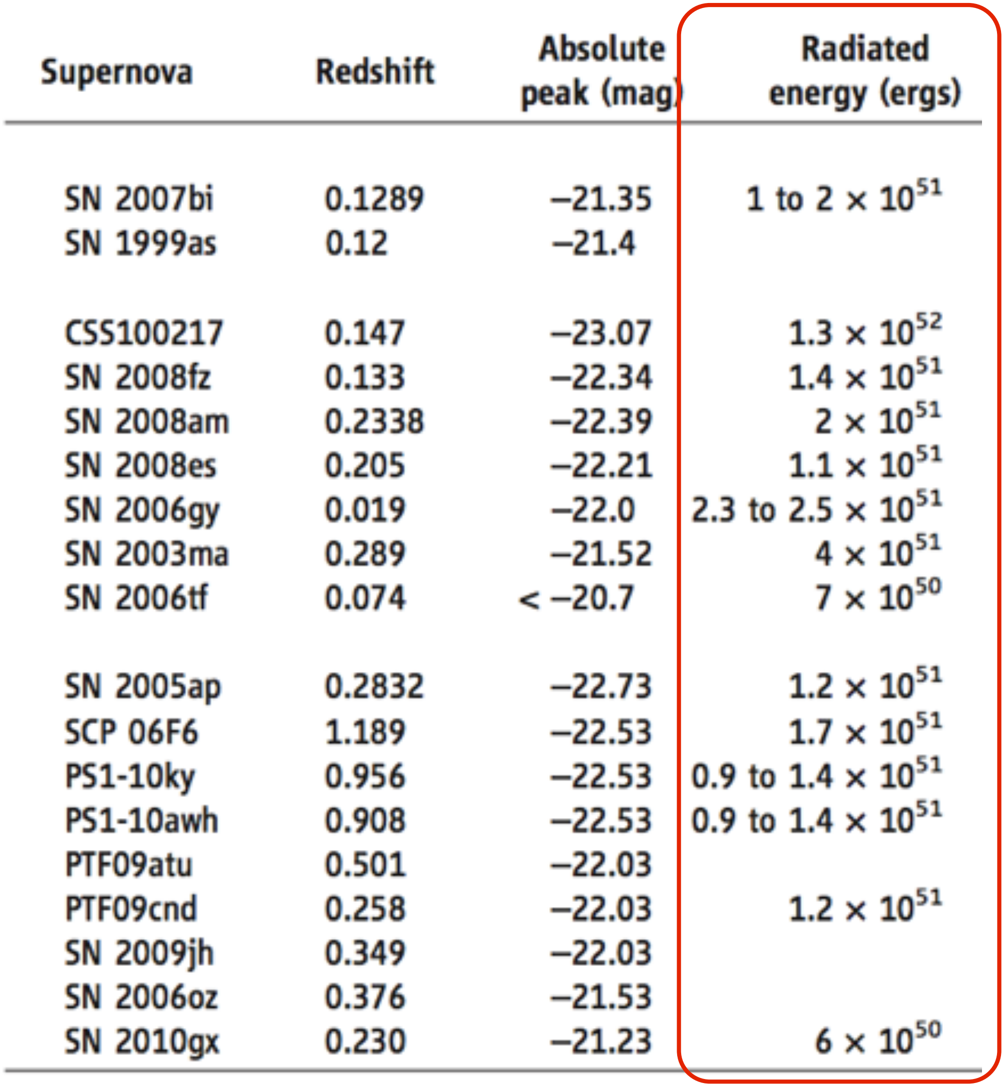
Superluminous SNe (SLSNe)

- SNe brighter than ~1e44 erg/s (or -21 mag in optical)

Pastorello et al. (2010)



SLSN properties



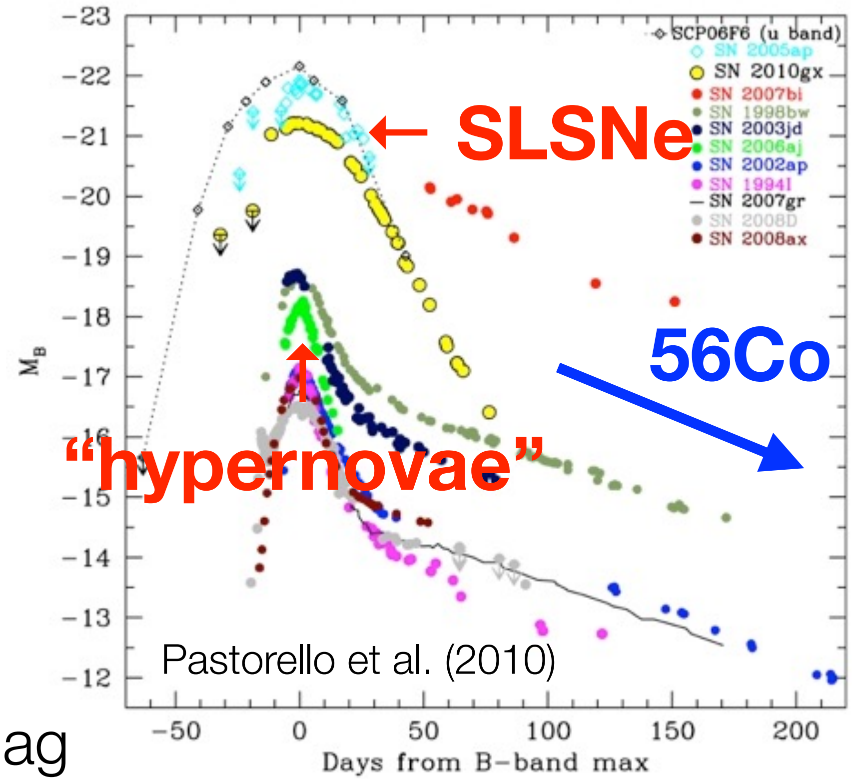
Supernova	Redshift	Absolute peak (mag)	Radiated energy (ergs)
SN 2007bi	0.1289	−21.35	1 to 2 × 10^{51}
SN 1999as	0.12	−21.4	
CSS100217	0.147	−23.07	1.3 × 10^{52}
SN 2008fz	0.133	−22.34	1.4 × 10^{51}
SN 2008am	0.2338	−22.39	2 × 10^{51}
SN 2008es	0.205	−22.21	1.1 × 10^{51}
SN 2006gy	0.019	−22.0	2.3 to 2.5 × 10^{51}
SN 2003ma	0.289	−21.52	4 × 10^{51}
SN 2006tf	0.074	< −20.7	7 × 10^{50}
SN 2005ap	0.2832	−22.73	1.2 × 10^{51}
SCP 06F6	1.189	−22.53	1.7 × 10^{51}
PS1-10ky	0.956	−22.53	0.9 to 1.4 × 10^{51}
PS1-10awh	0.908	−22.53	0.9 to 1.4 × 10^{51}
PTF09atu	0.501	−22.03	
PTF09cnd	0.258	−22.03	1.2 × 10^{51}
SN 2009jh	0.349	−22.03	
SN 2006oz	0.376	−21.53	
SN 2010gx	0.230	−21.23	6 × 10^{50}

Gal-Yam (2012)

“Hypernovae” v.s. SLSNe

- “hypernovae”
  - broad-line “Type Ic” SNe
  - peak luminosity: -18 - -19 mag
    - 56Ni mass: 0.5 - 1 Msun
  - red spectra

- SLSNe
  - Type II and Ic
  - peak luminosity: more than ~ -21 mag
    - 56Ni mass: > ~ 5 Msun (often more than 10 Msun)
  - blue spectra



← SLSNe

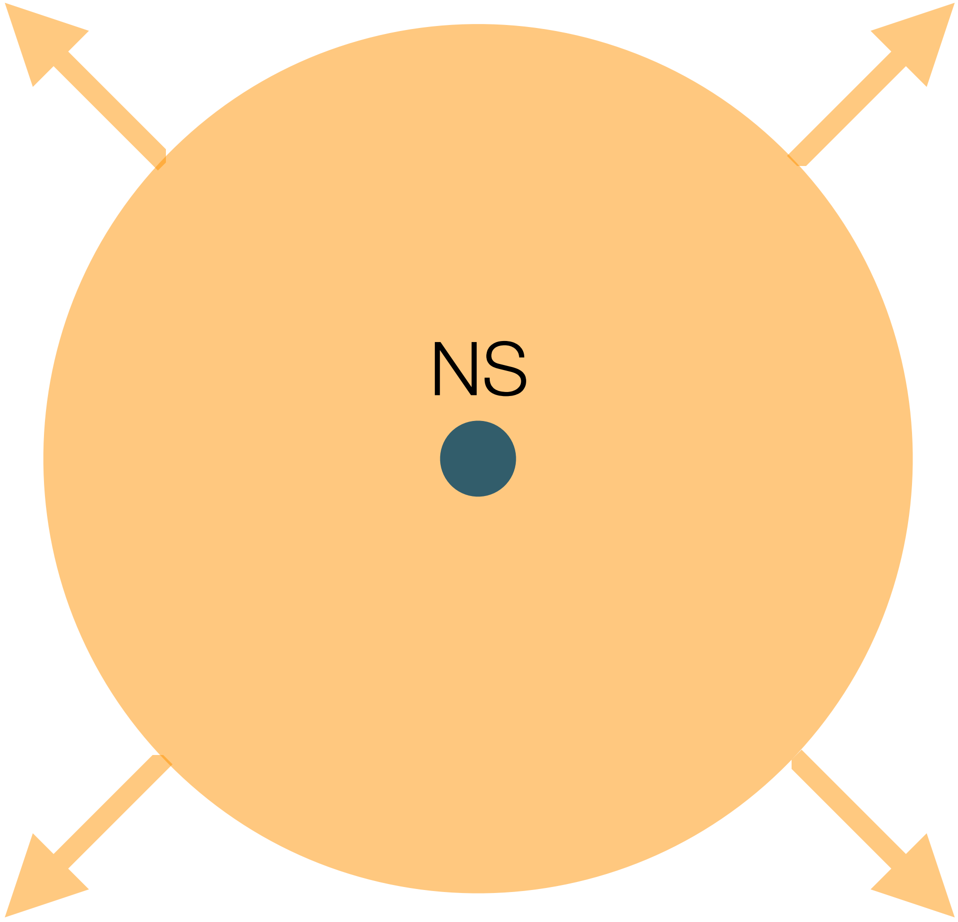
“hypernovae”

56Co

Pastorello et al. (2010)

Why are Type Ic SLSNe bright?

- rotational radiation of magnetars (Kasen & Bildsten 2010, …)



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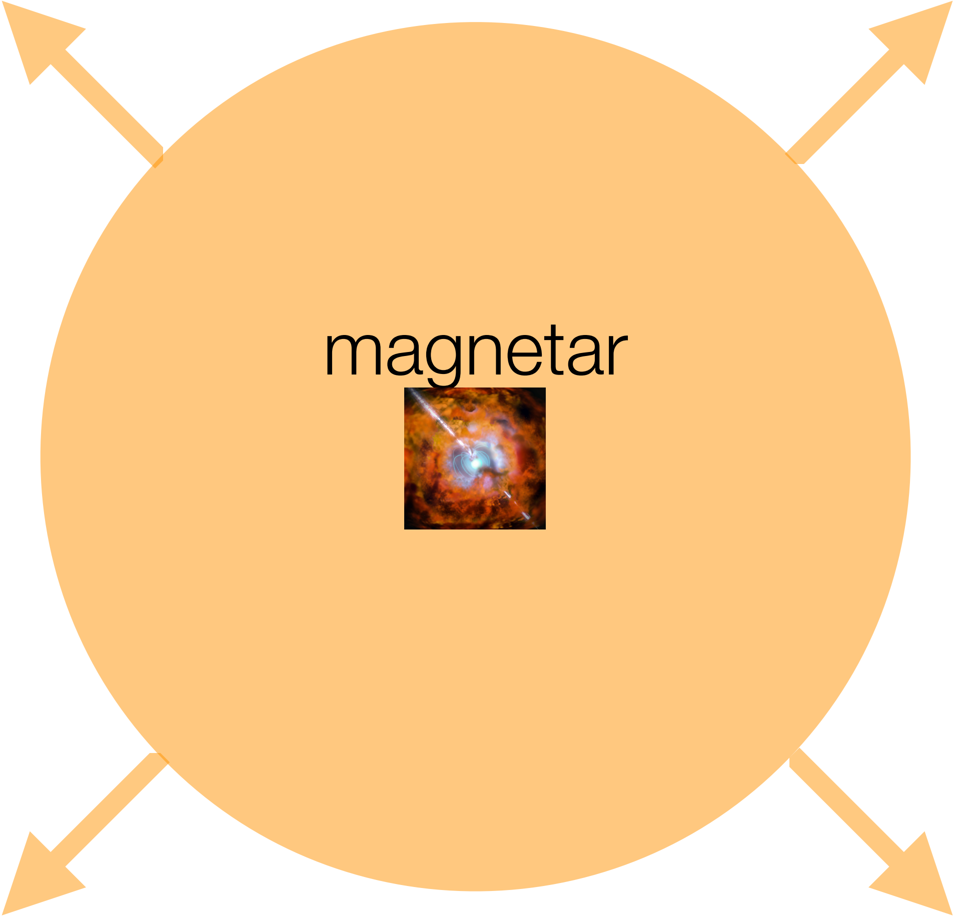


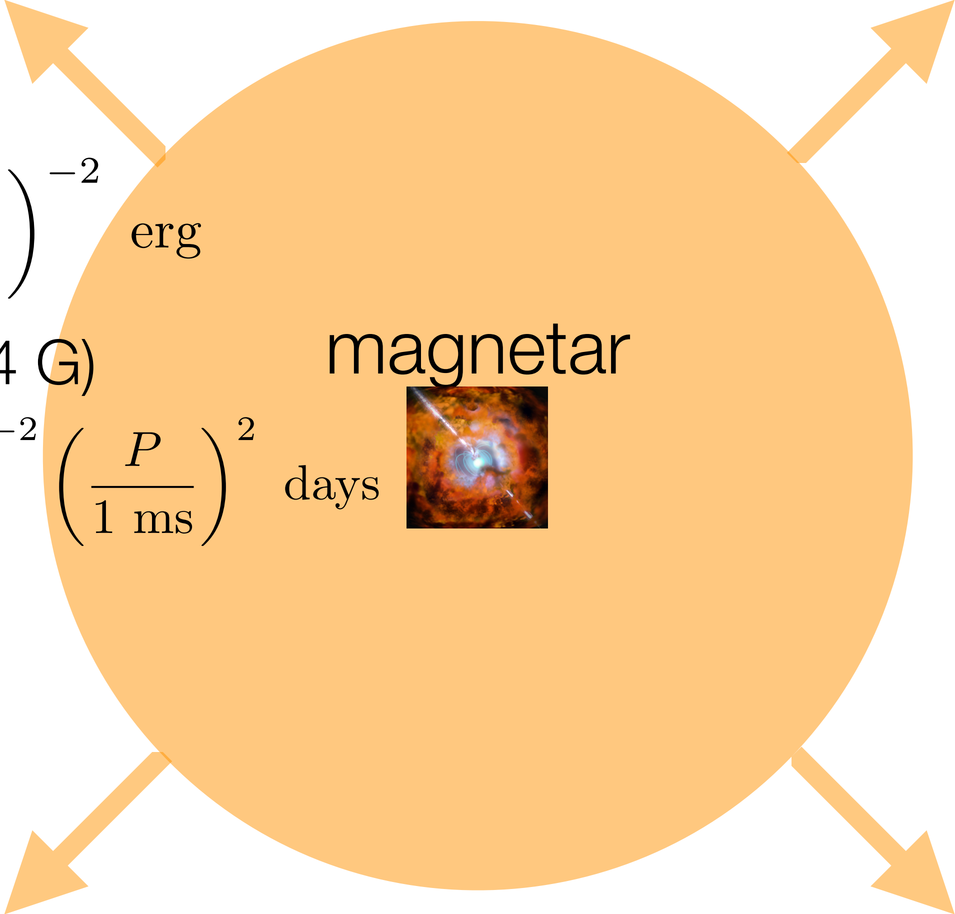
Why are Type Ic SLSNe bright?

- rotational radiation of magnetars (Kasen & Bildsten 2010, …)
  - neutron stars with
    - rapid rotation (~ 1 ms)

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

    - strong magnetic field (~ 1e14 G)

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



Why are Type Ic SLSNe bright?

- rotational radiation of magnetars (Kasen & Bildsten 2010, …)
    - neutron stars with
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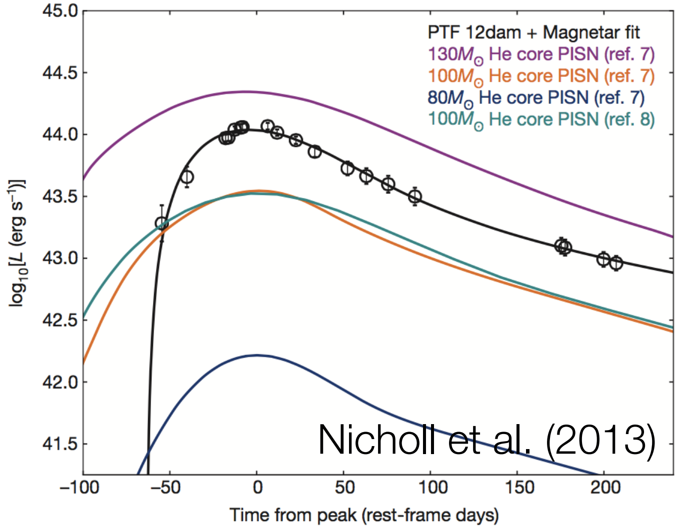
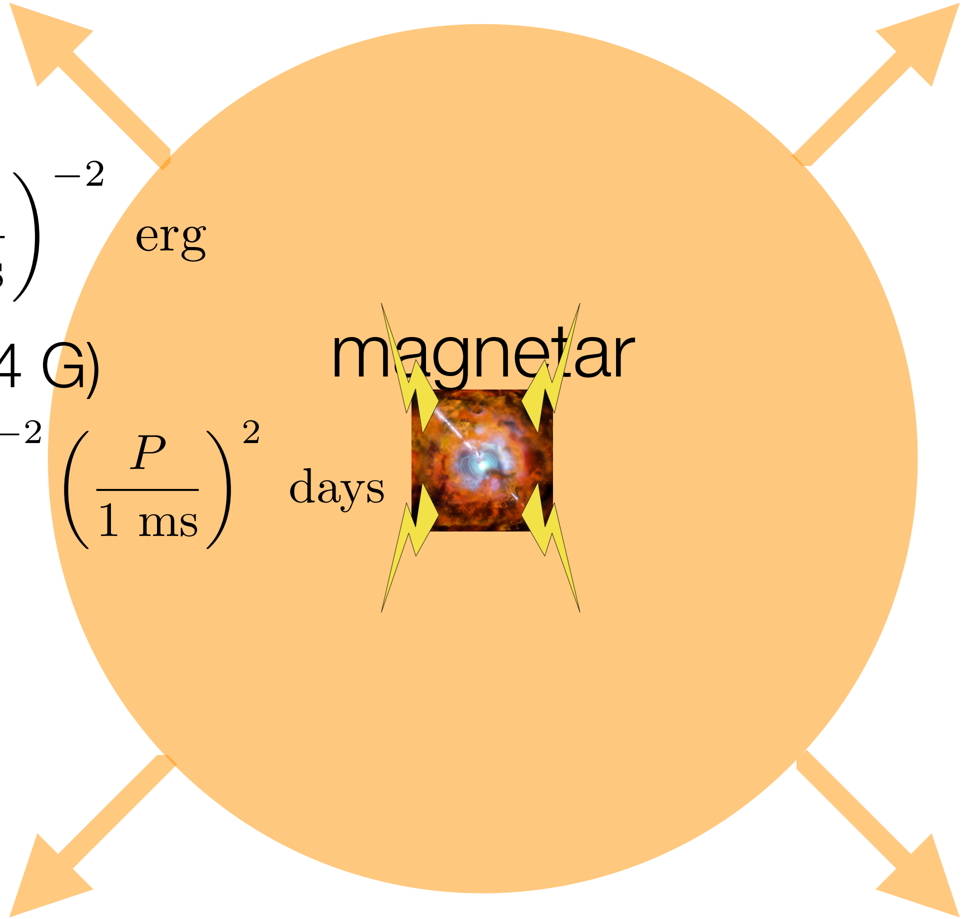
$$E_{\rm rot} = \frac{1}{2} I_{\rm NS} \Omega^2 \simeq 2 \times 10^{52} \left(\frac{P}{1\ {\rm ms}} \right)^{-2} \ {\rm erg}$$

        - strong magnetic field (~ 1e14 G)

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

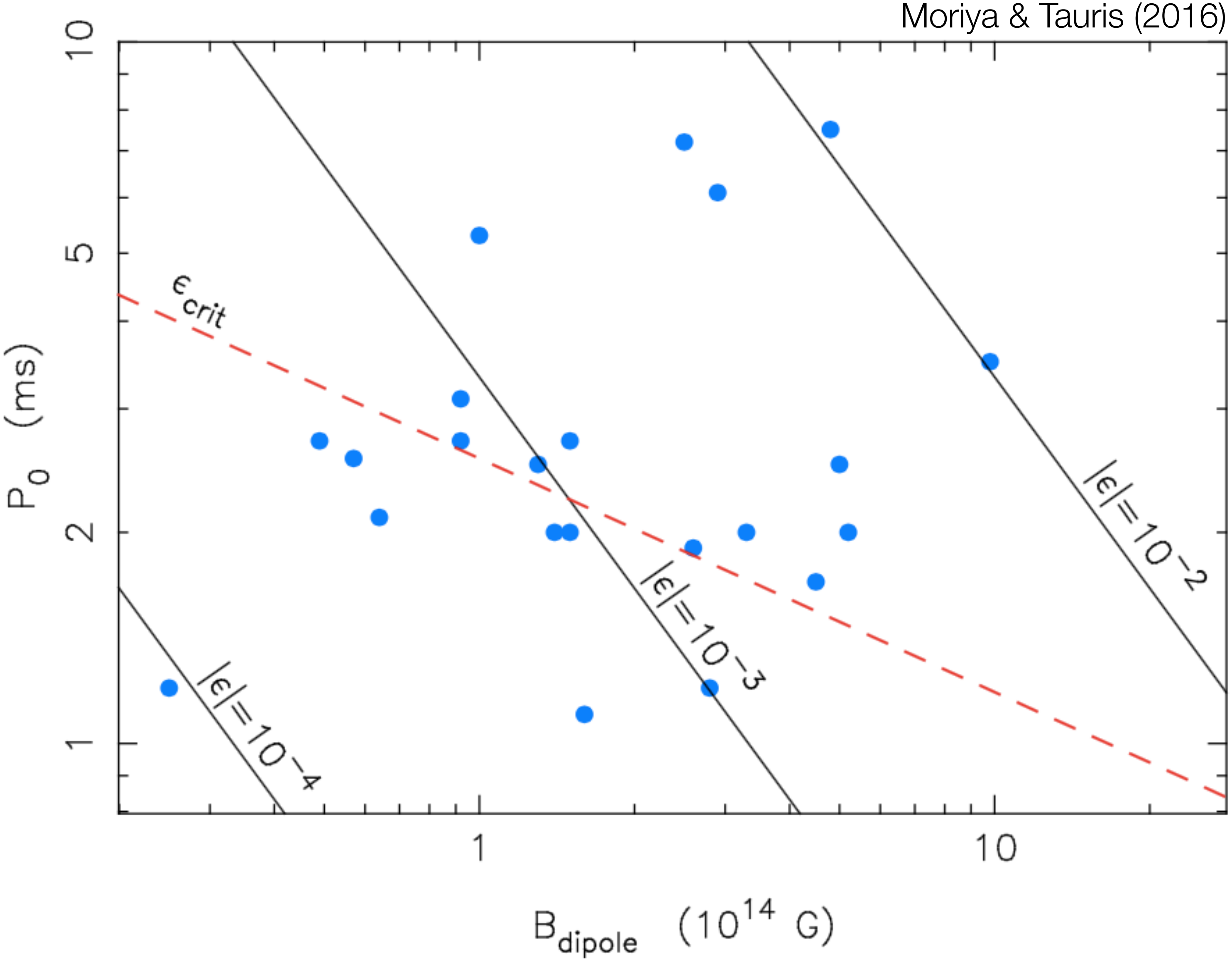


Nicholl et al. (2013)



Estimated initial dipole magnetic field and spin

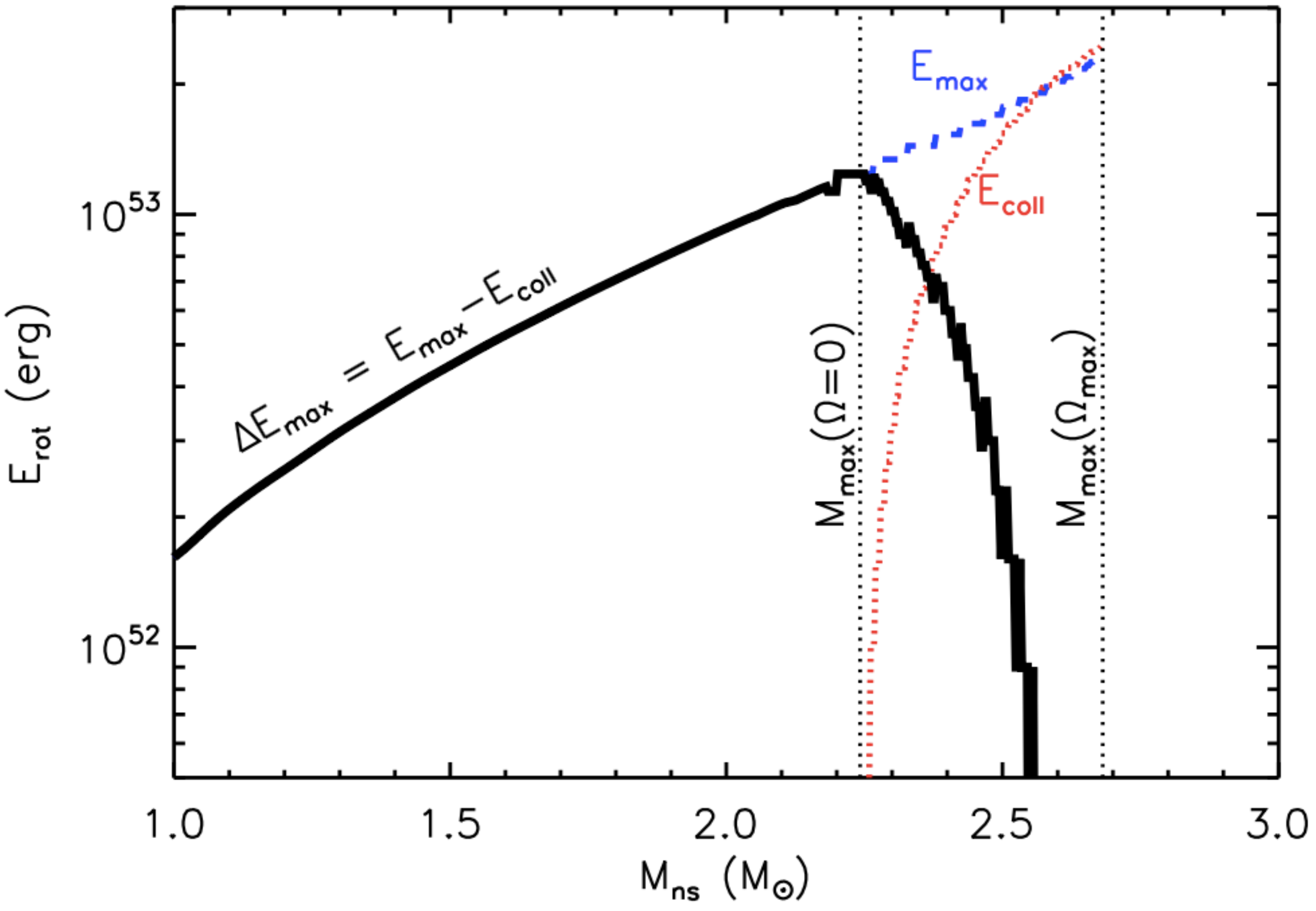
Moriya & Tauris (2016)



Maximum rotational energy of NSs

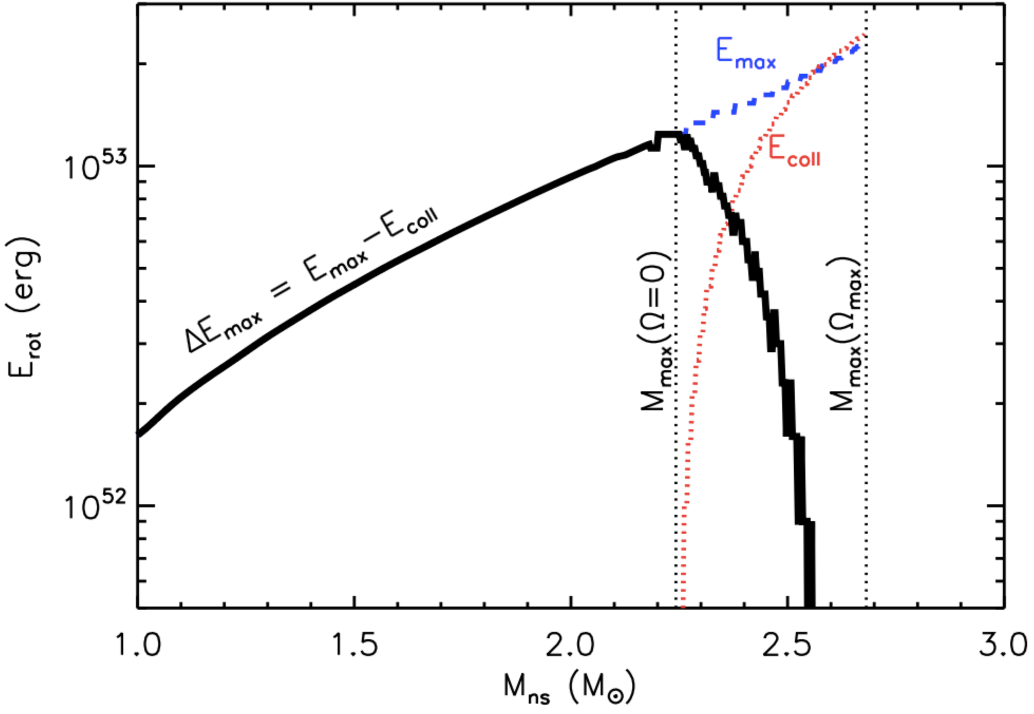
- for an EoS consistent with the current NS constraints

Metzger et al. (2015)



Magnetars may collapse to BHs

- sudden loss of the central heating sources



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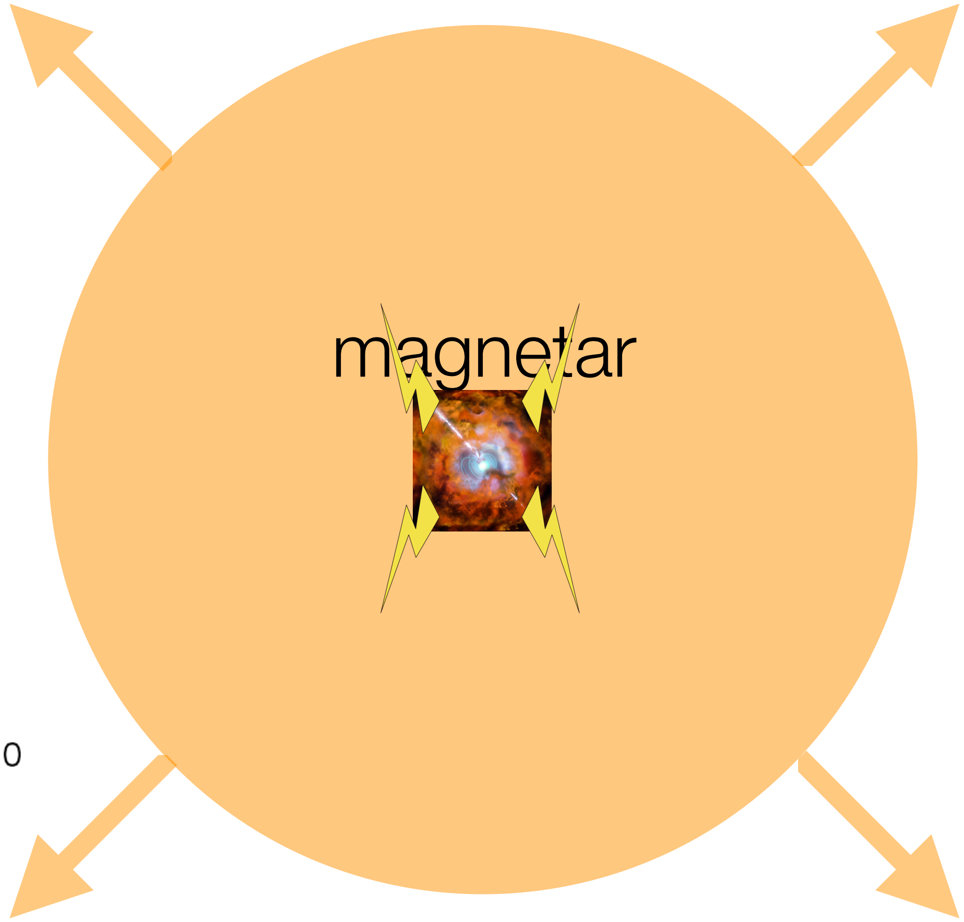

magnetar

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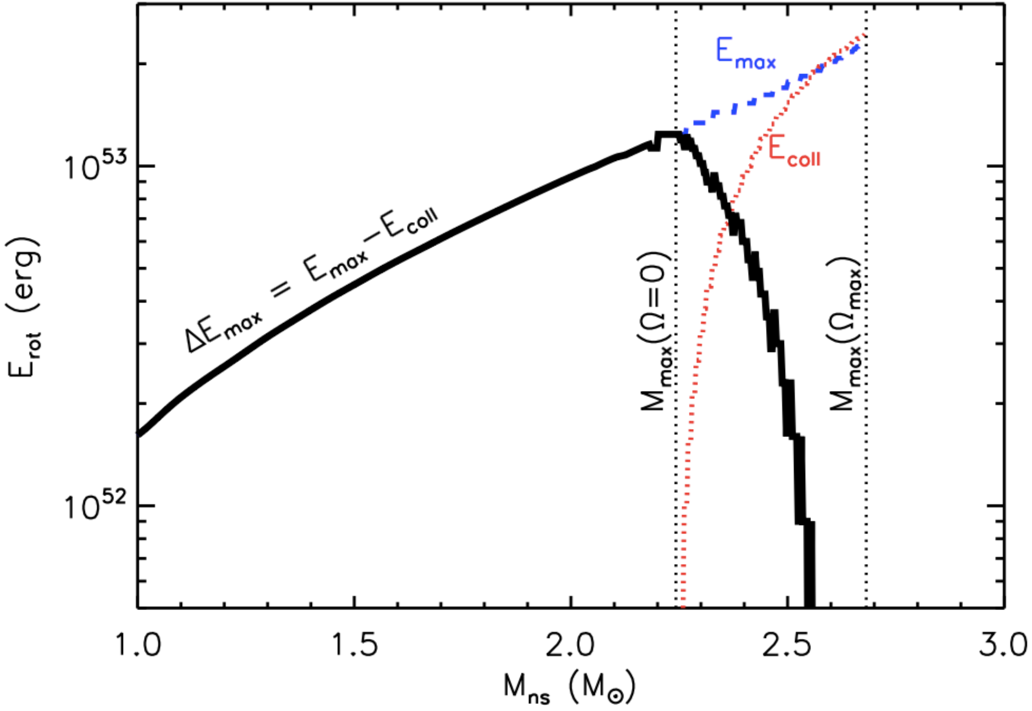
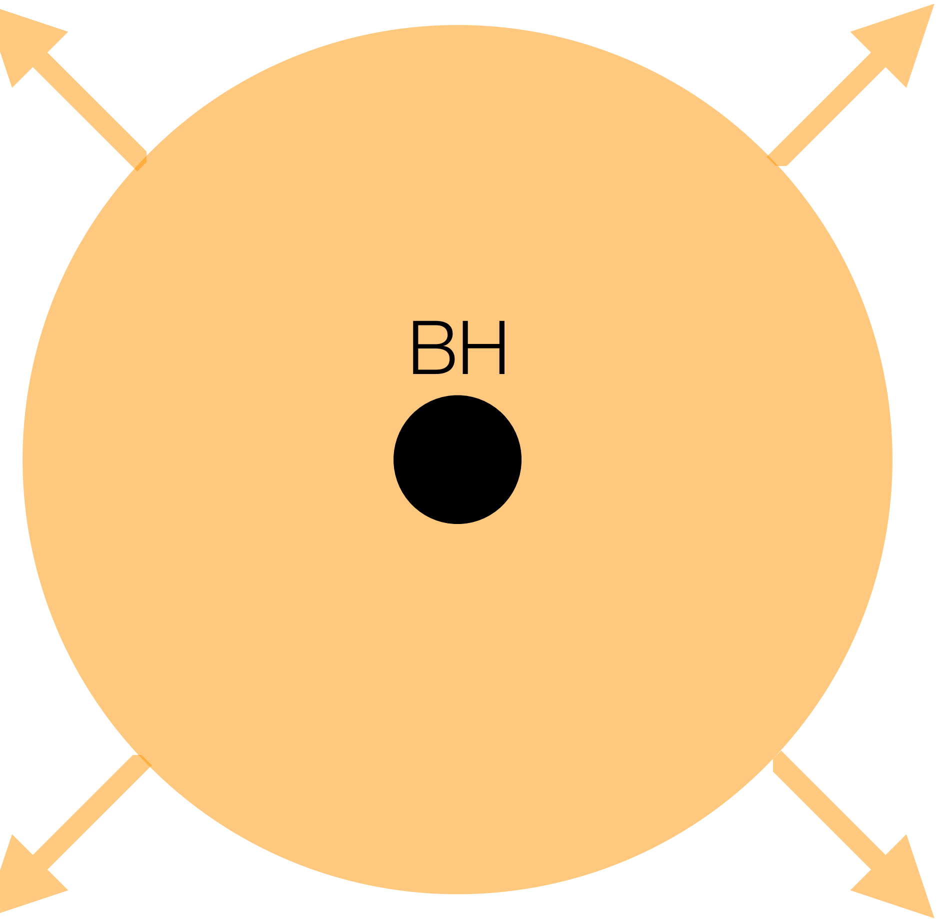




When do magnetars collapse to BHs?

- rotational energy loss by dipole radiation
    - t_m: spin-down timescale
    - E_m: initial rotational energy of magnetars

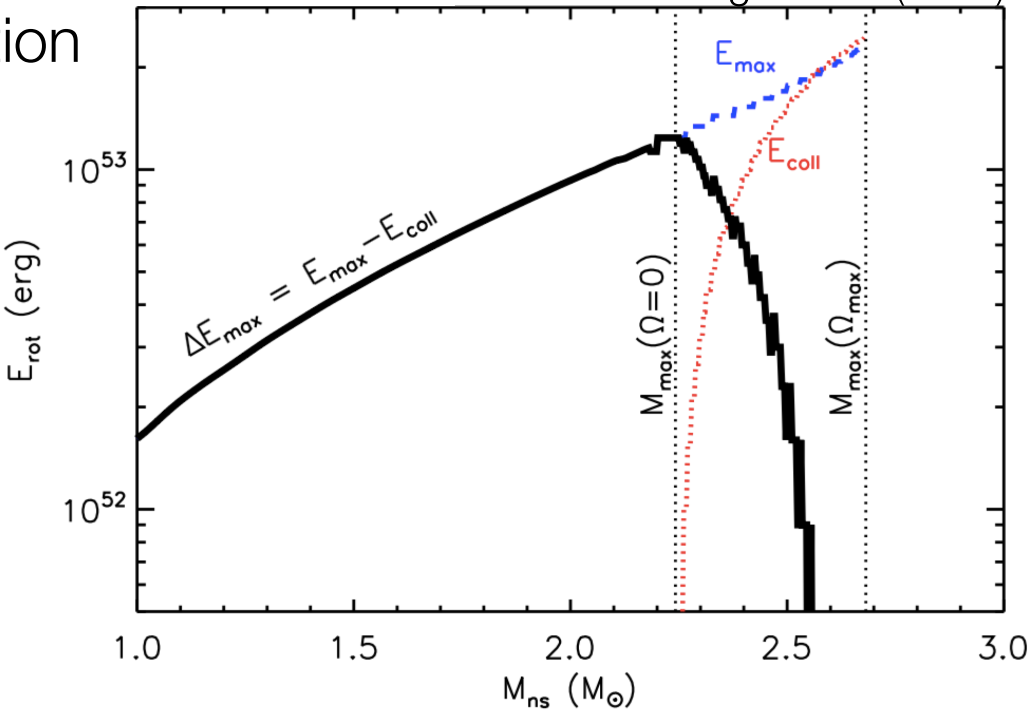
$$L_{\mathrm{mag}}(t) = \frac{E_m}{t_m}\left(1+\frac{t}{t_m}\right)^{-2}$$

- t_{BH}: time of the BH transformation

$$t_{\mathrm{BH}} = \frac{\Delta E}{E_{\mathrm{coll}}} t_m$$

$$\Delta E \equiv E_m - E_{\mathrm{coll}}$$

Metzger et al. (2015)



Time of BH transformation

$$t_{\mathrm{BH}} = \frac{\Delta E}{E_{\mathrm{coll}}} t_m \qquad \Delta E \equiv E_m - E_{\mathrm{coll}}$$

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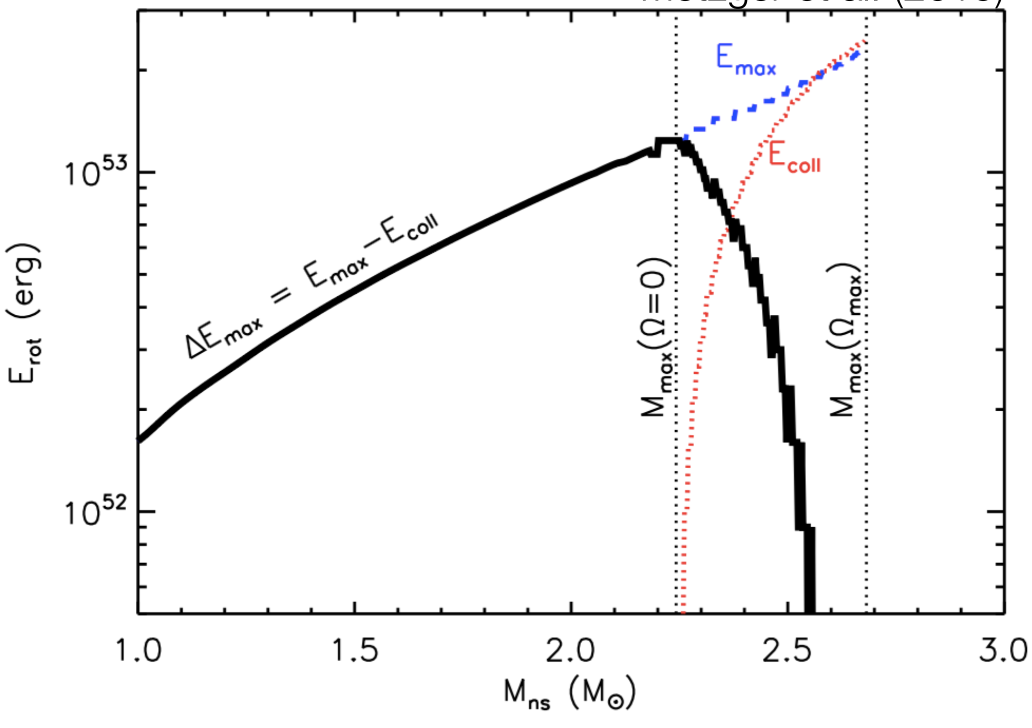
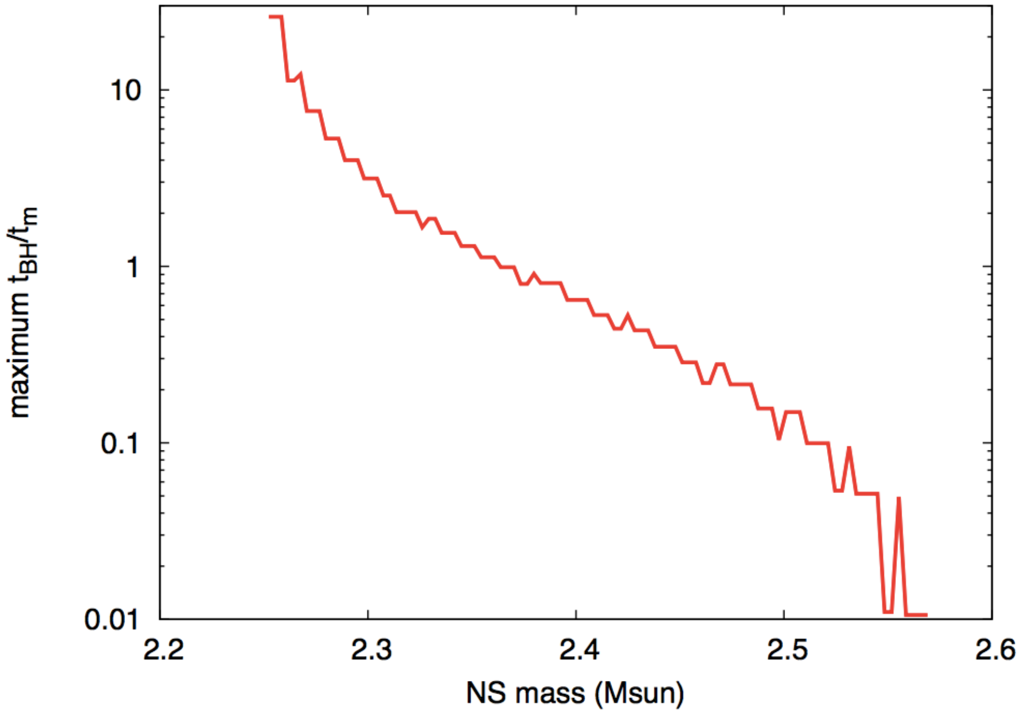


Moriya et al. (2016)



- 1/2 of the initial rotational energy is emitted in t_m

Effect of BH transformation on light curves

- semi-analytic method (Arnett 1982)

$$L(t) = \int_0^{\frac{t}{\tau_m}} 2\tau_m^{-2} L_{\mathrm{mag}}(t')t' e^{\left(\frac{t'-t}{\tau_m}\right)^2} dt'$$

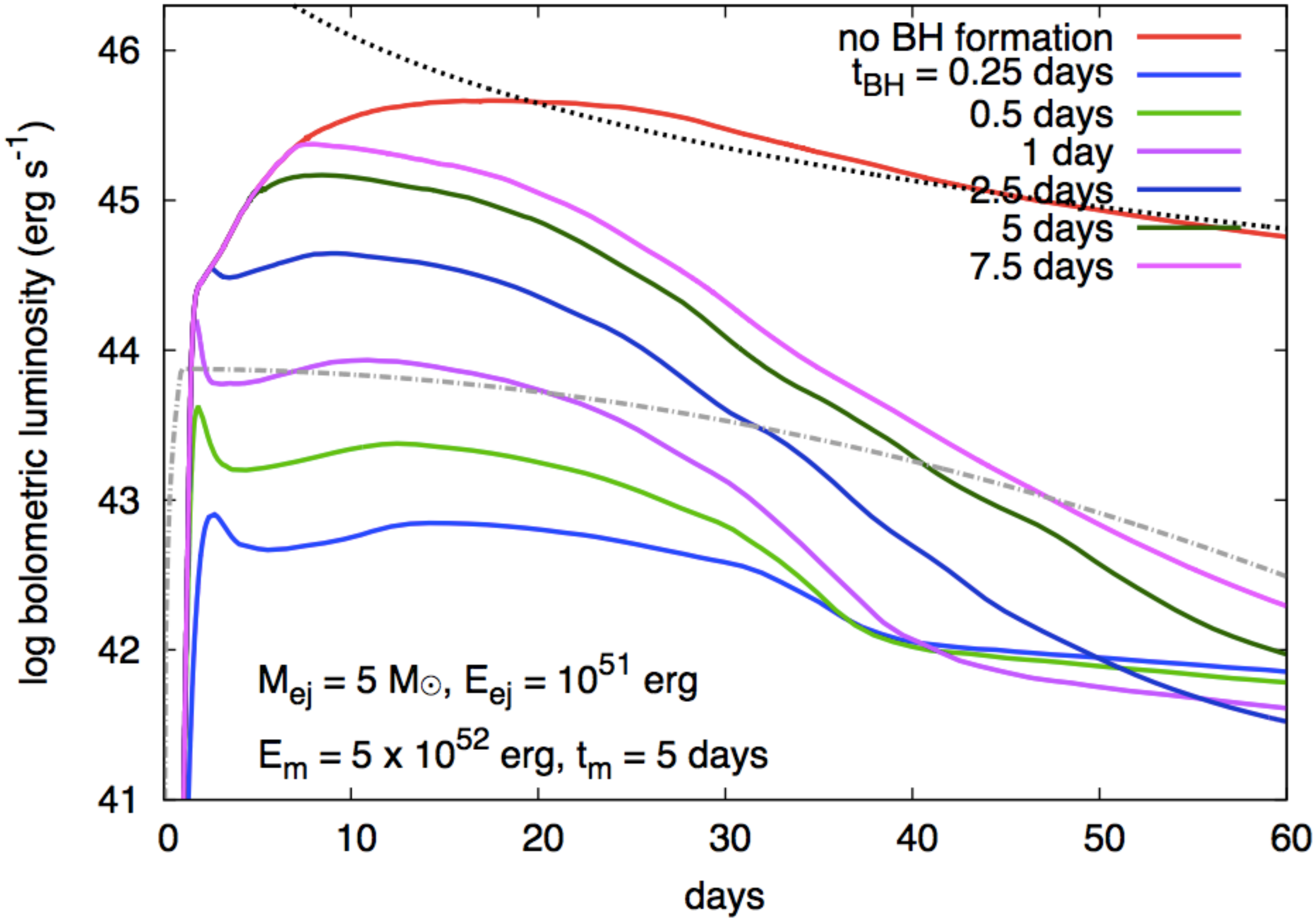
$$\tau_m = 1.05 \left(\frac{\kappa_e}{\beta c}\right)^{0.5} M_{\mathrm{ej}}^{0.75} E_{\mathrm{ej}}^{-0.25}$$

- numerical method
  - 1D radiation hydro code STELLA (Blinnikov et al.)
  - spin-down energy is put as thermal energy

- 100% thermalization of dipole spin-down energy is assumed

Effect of BH transformation on light curves

Moriya et al. (2016)



Effect of BH transformation on light curves

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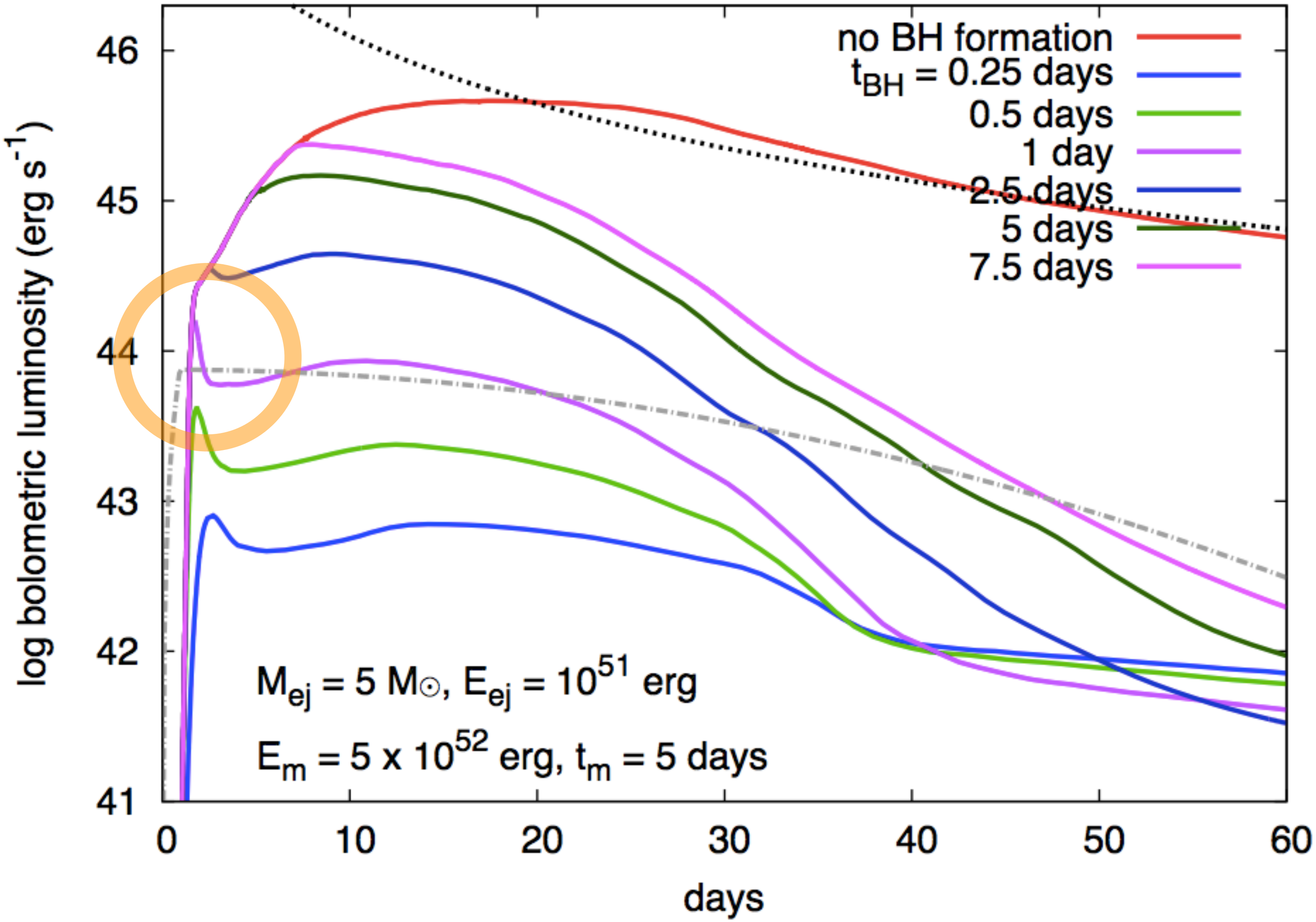
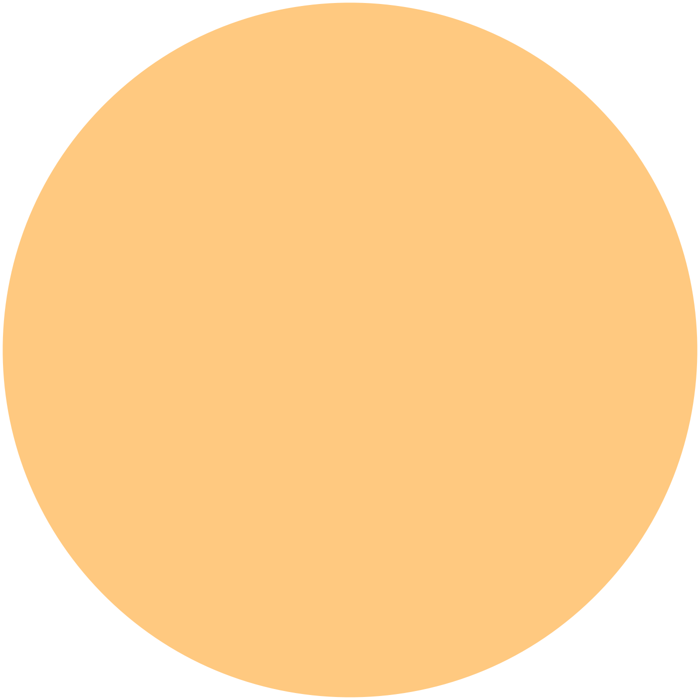


Magnetar-driven shock breakout

- magnetar-driven shock breakout (Kasen et al. 2016)



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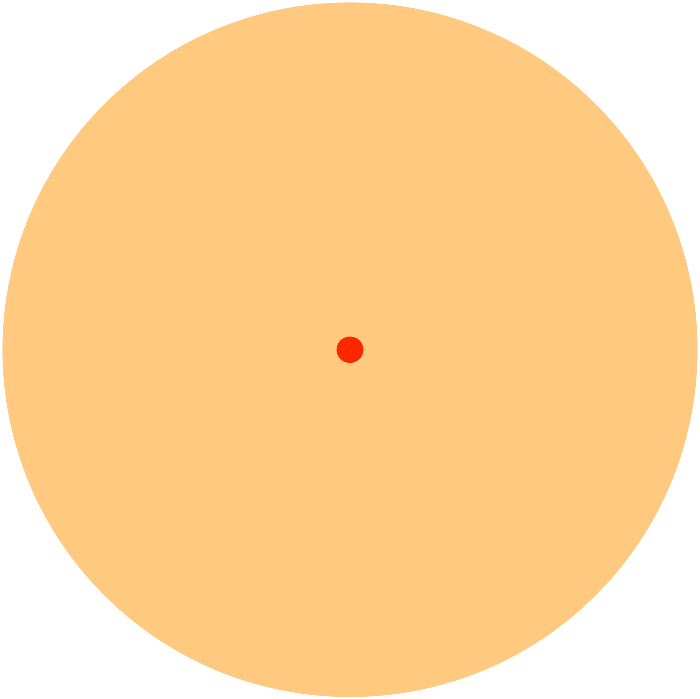

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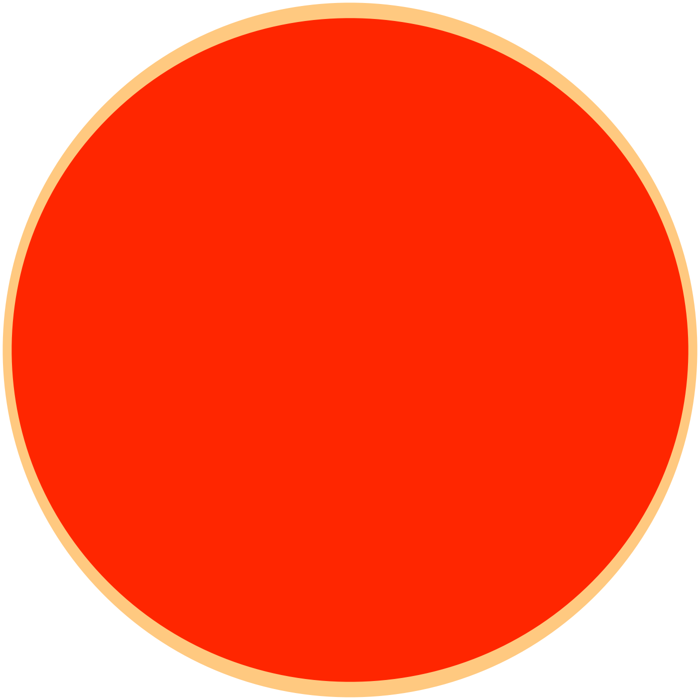

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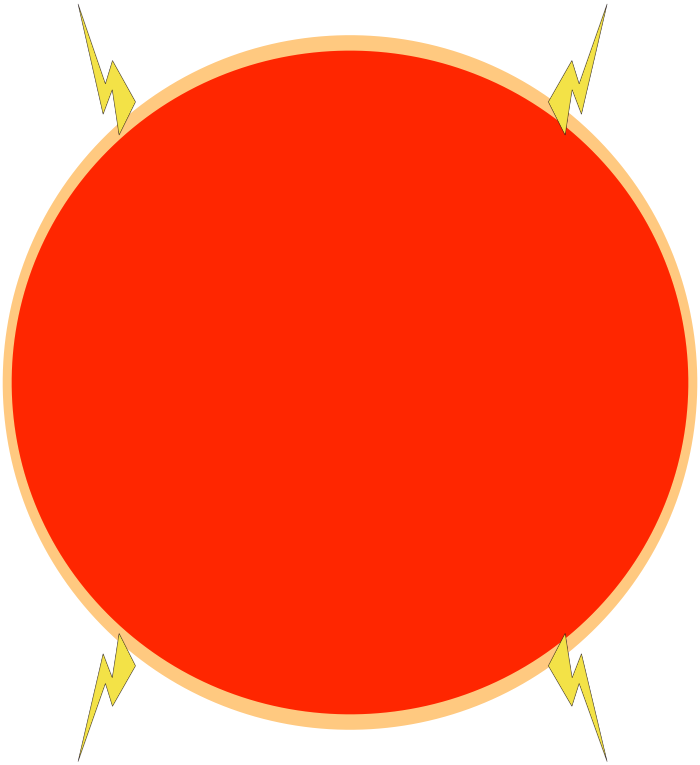

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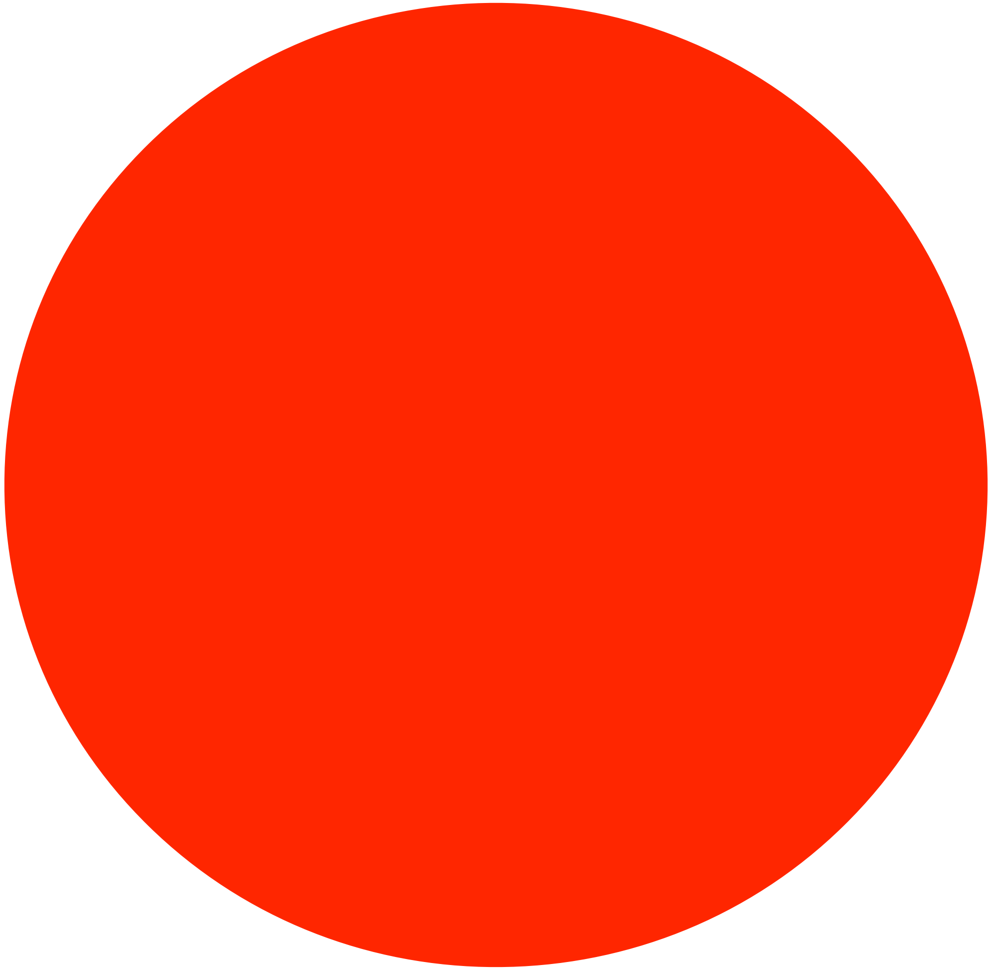

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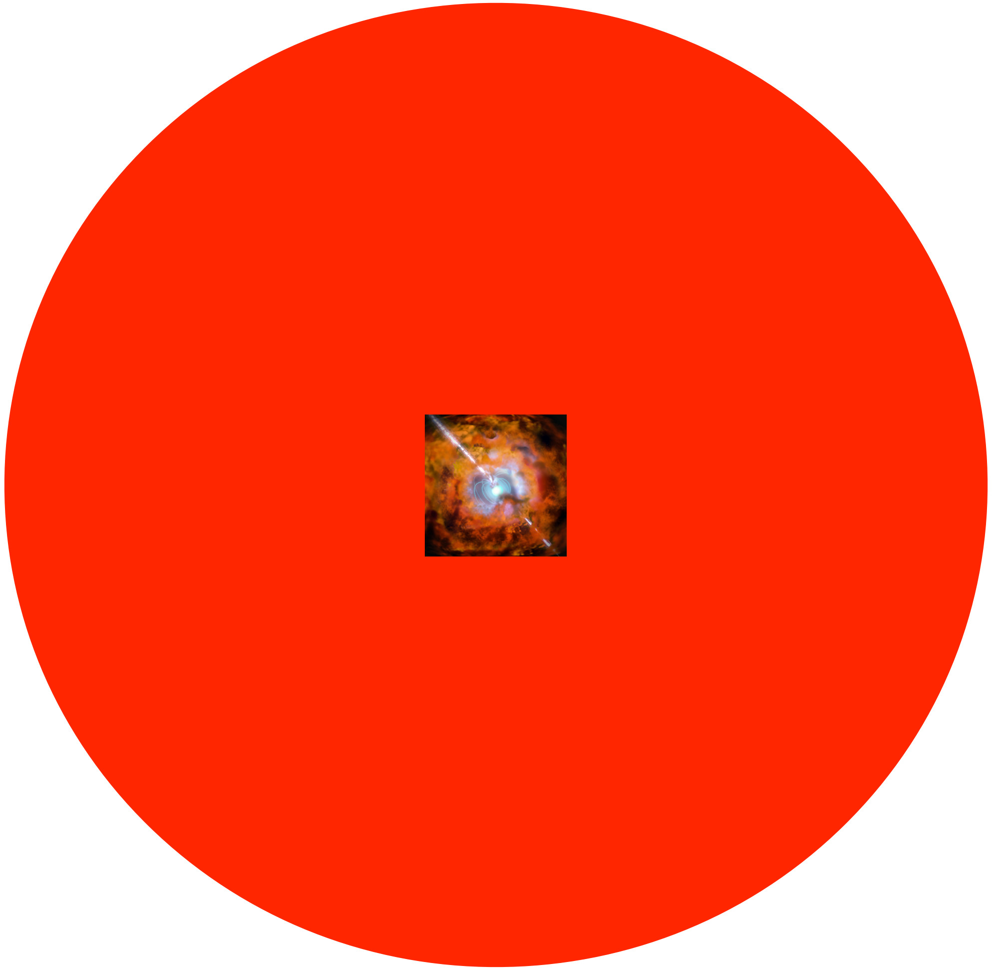

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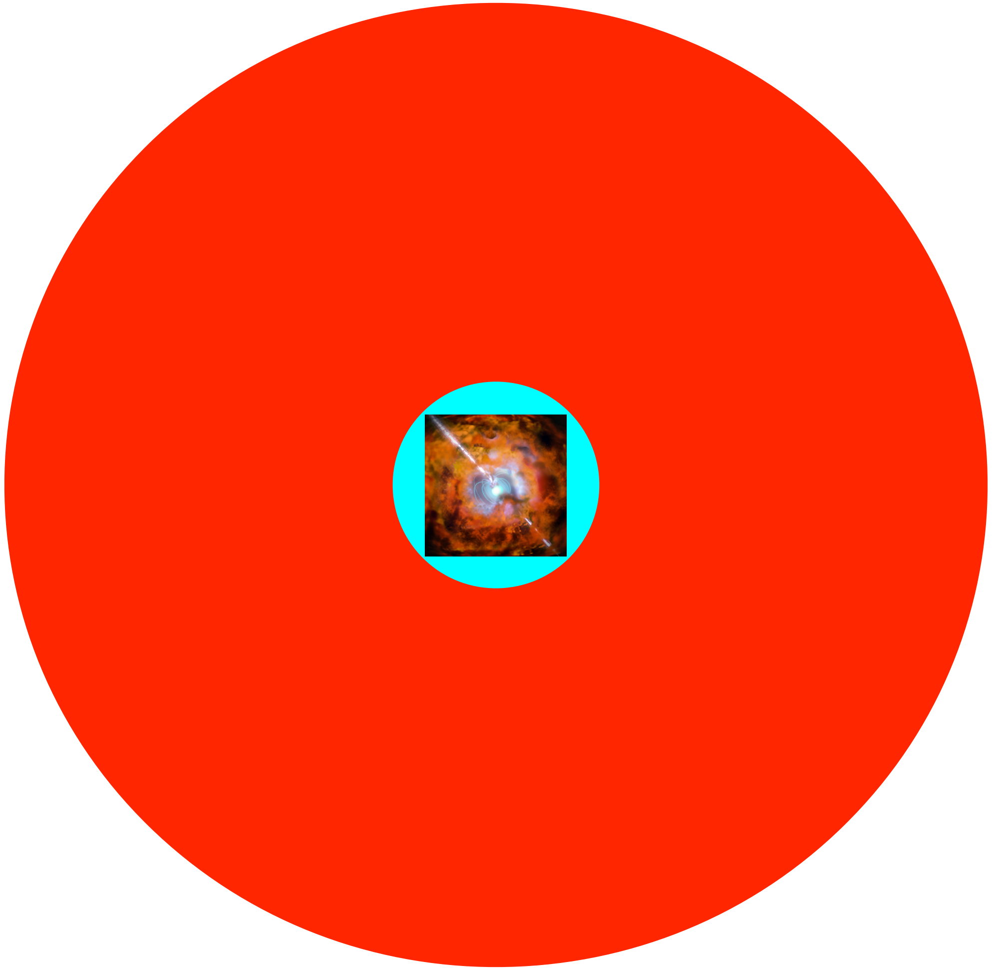

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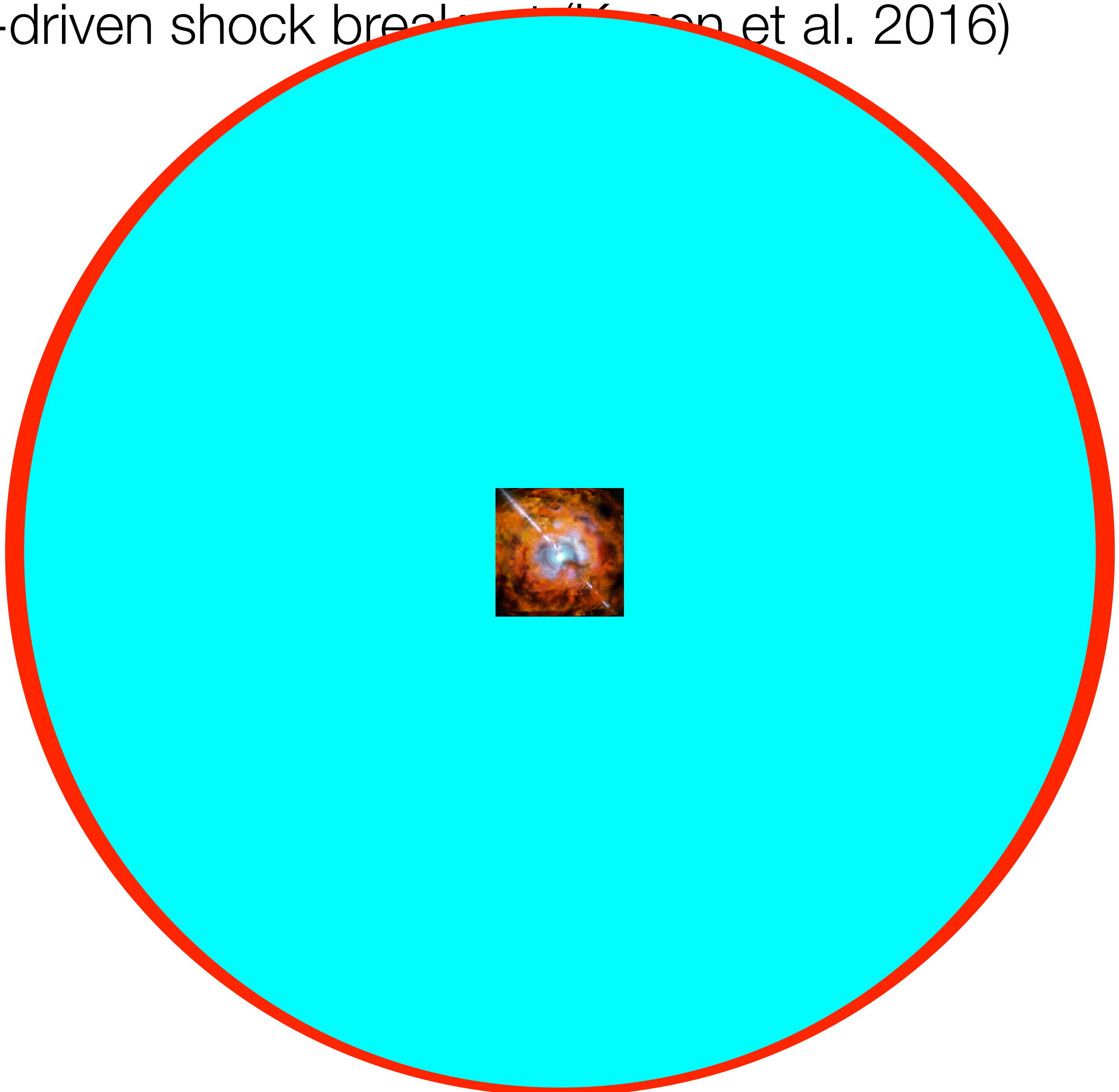

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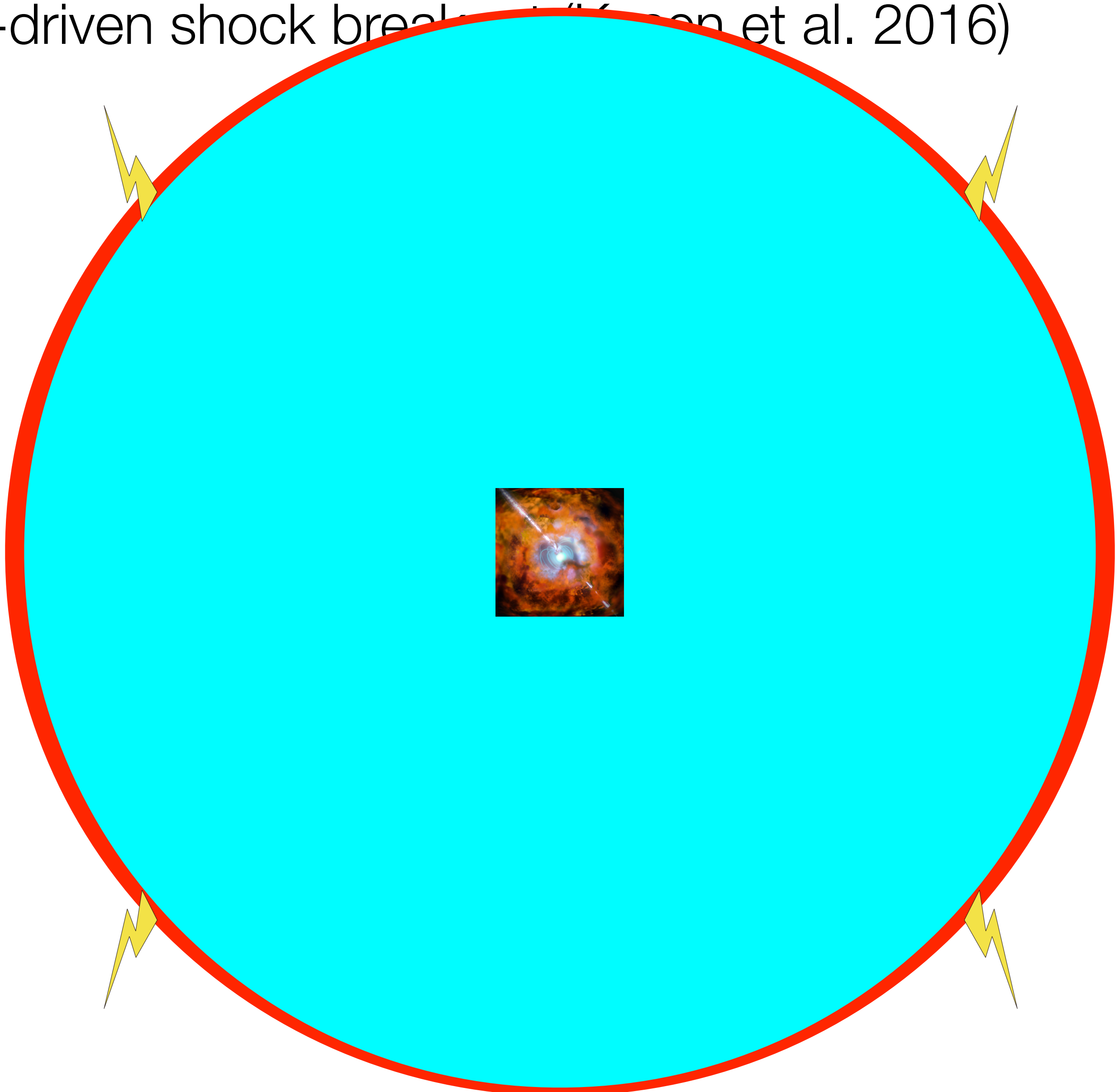
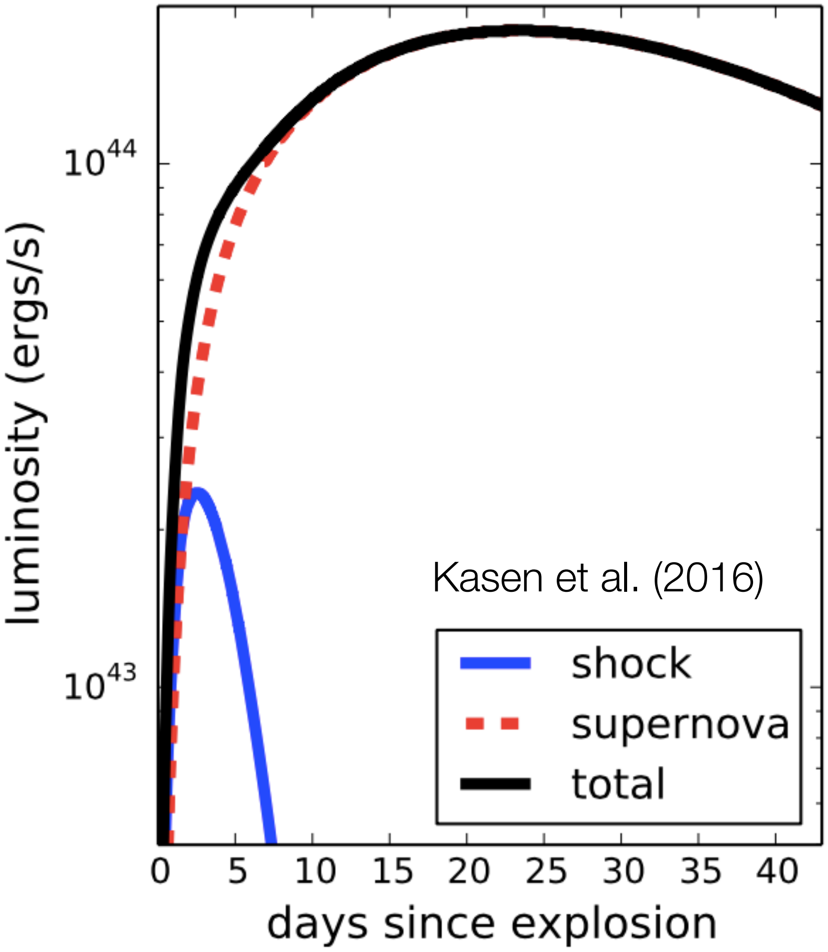


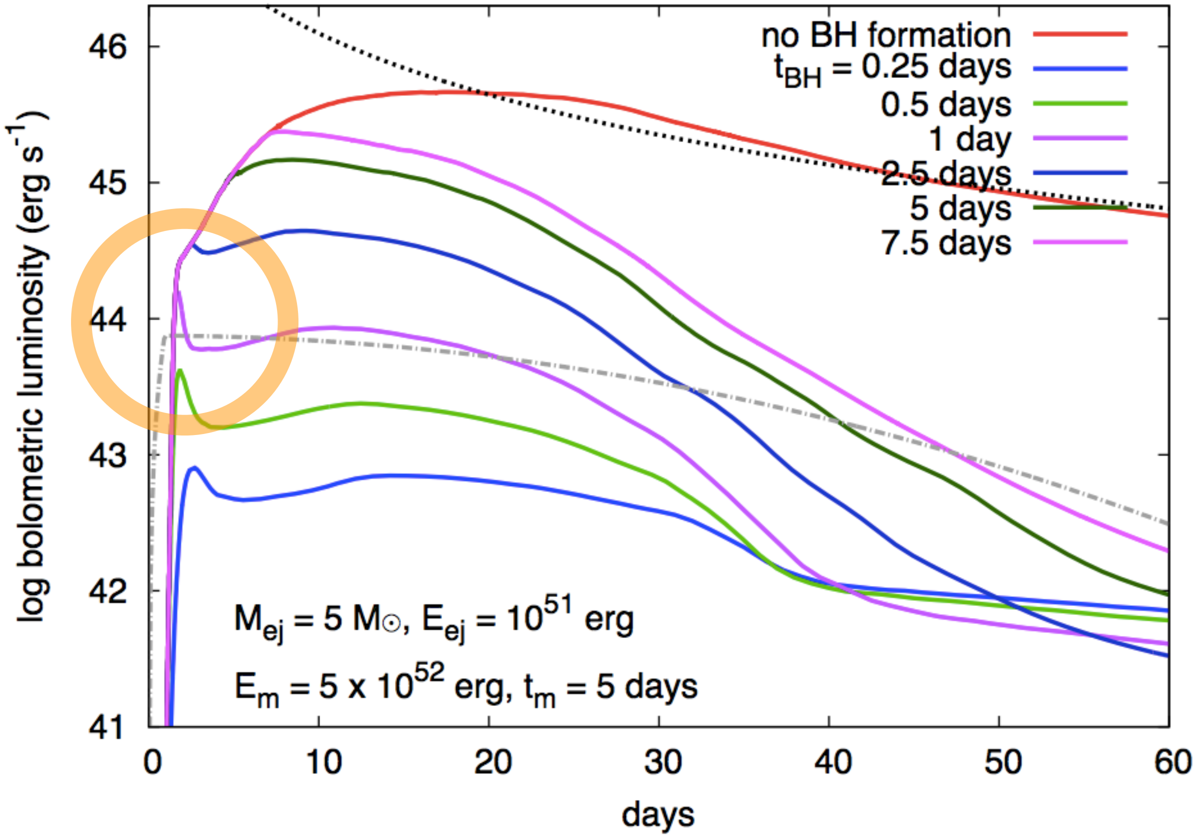
Magnetar-driven shock breakout

- It can occur in magnetar-powered SNe without the BH transformation
  - but it is not significant



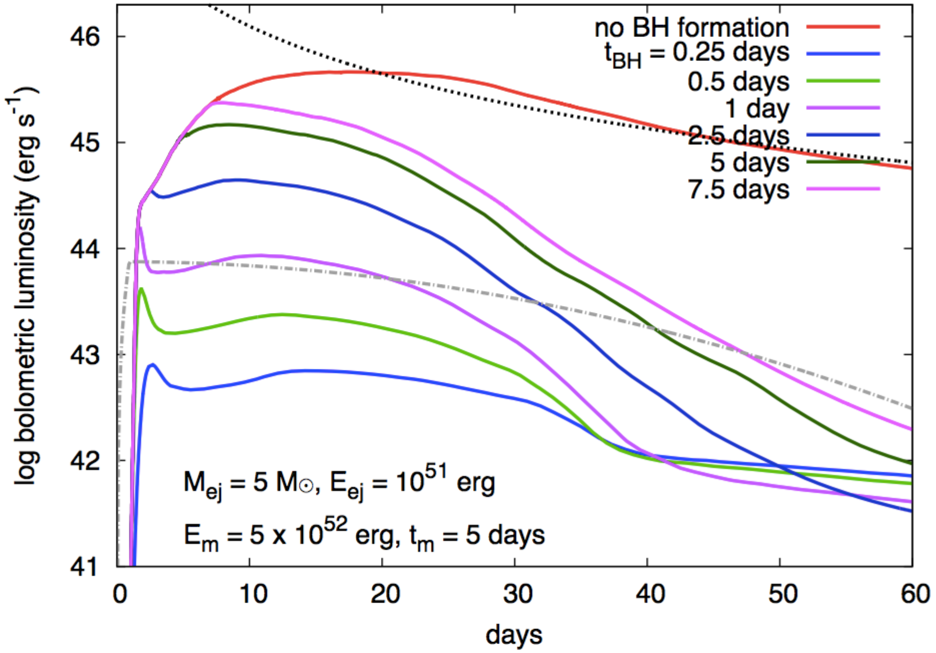
Kasen et al. (2016)

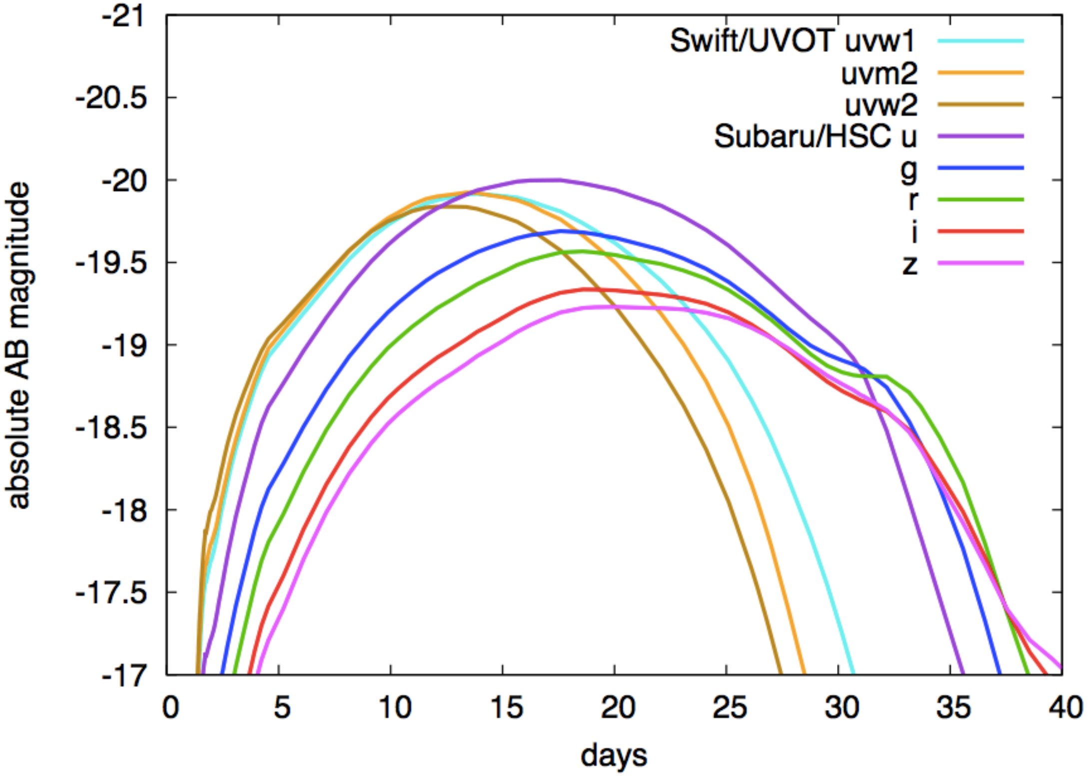
Moriya et al. (2016)

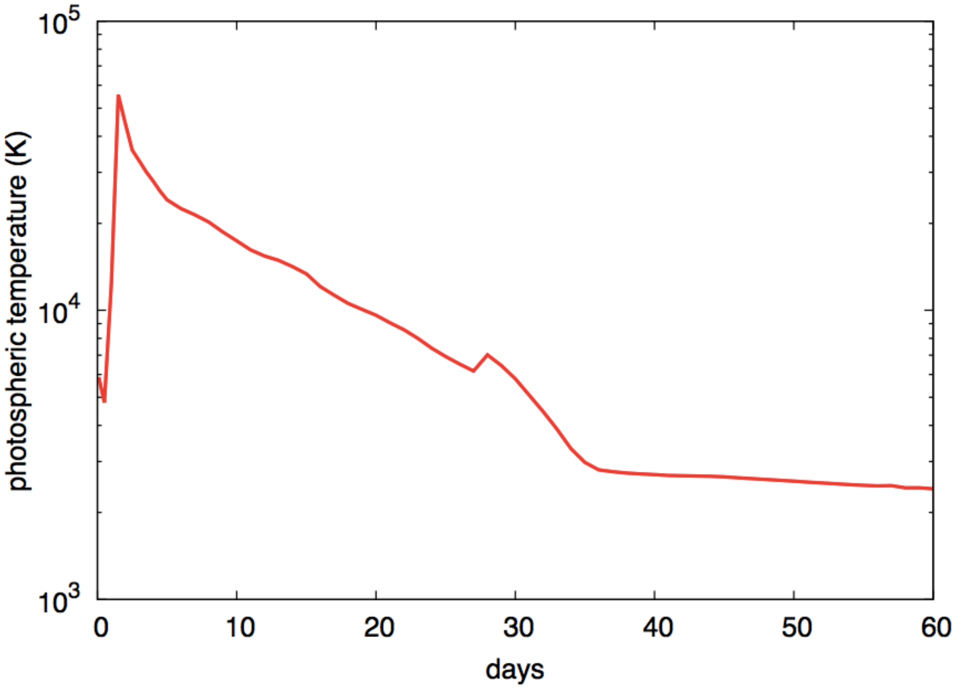


Optical and NUV light curves

- faint in optical and NUV
  - high photospheric temperature



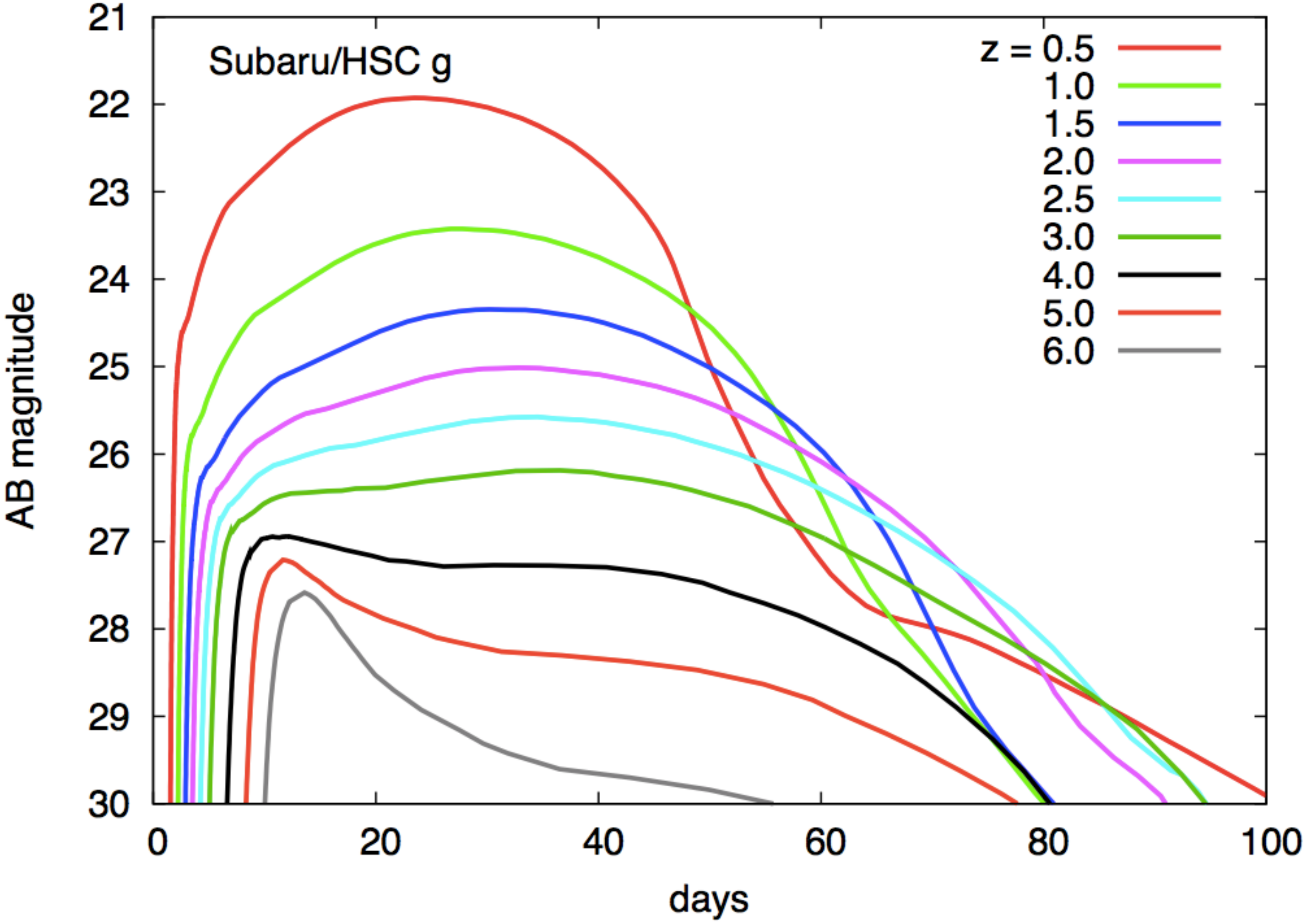




Moriya et al. (2016)

Detecting magnetar-driven shock breakout

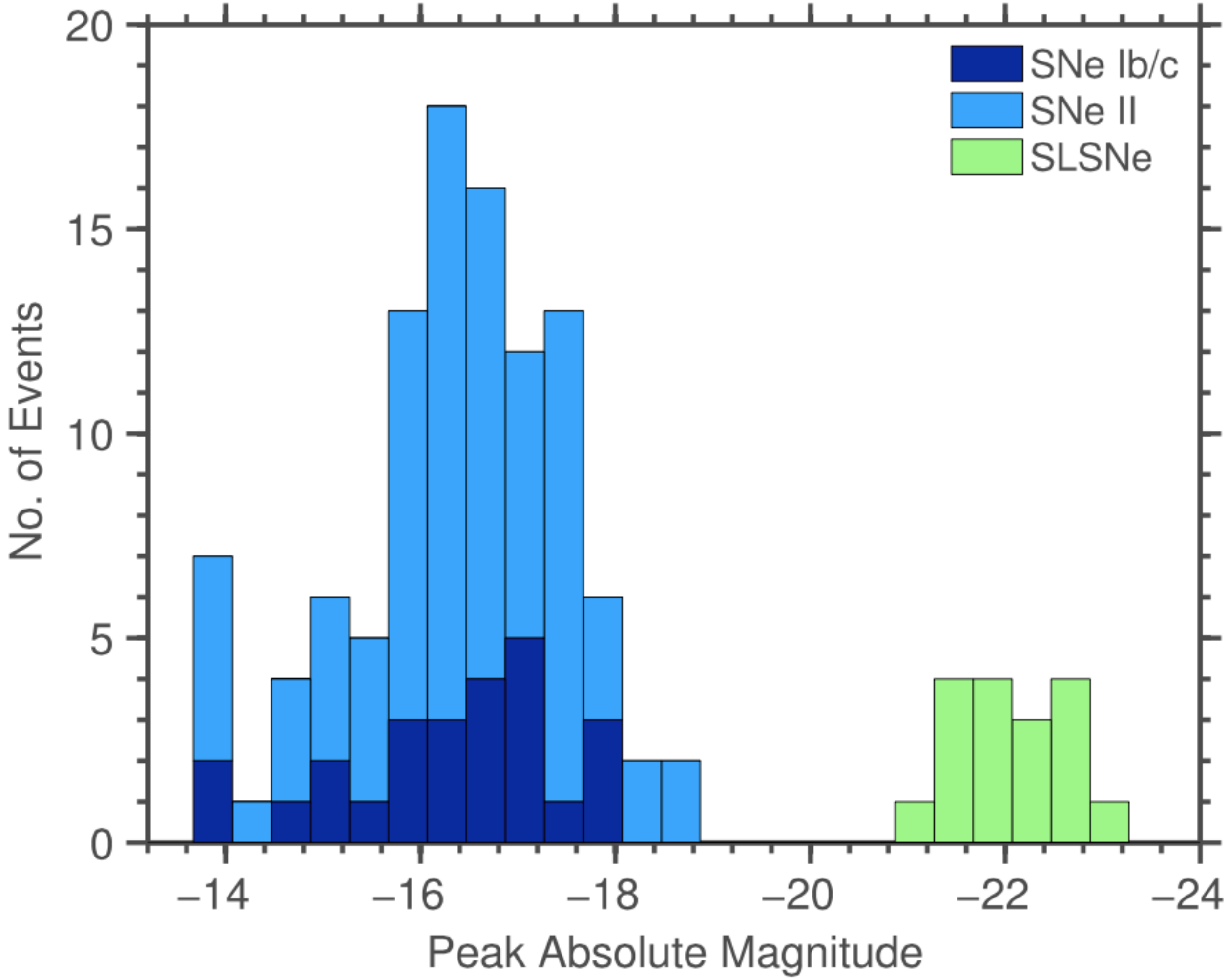
- we need those at high redshifts



Moriya et al. (2016)

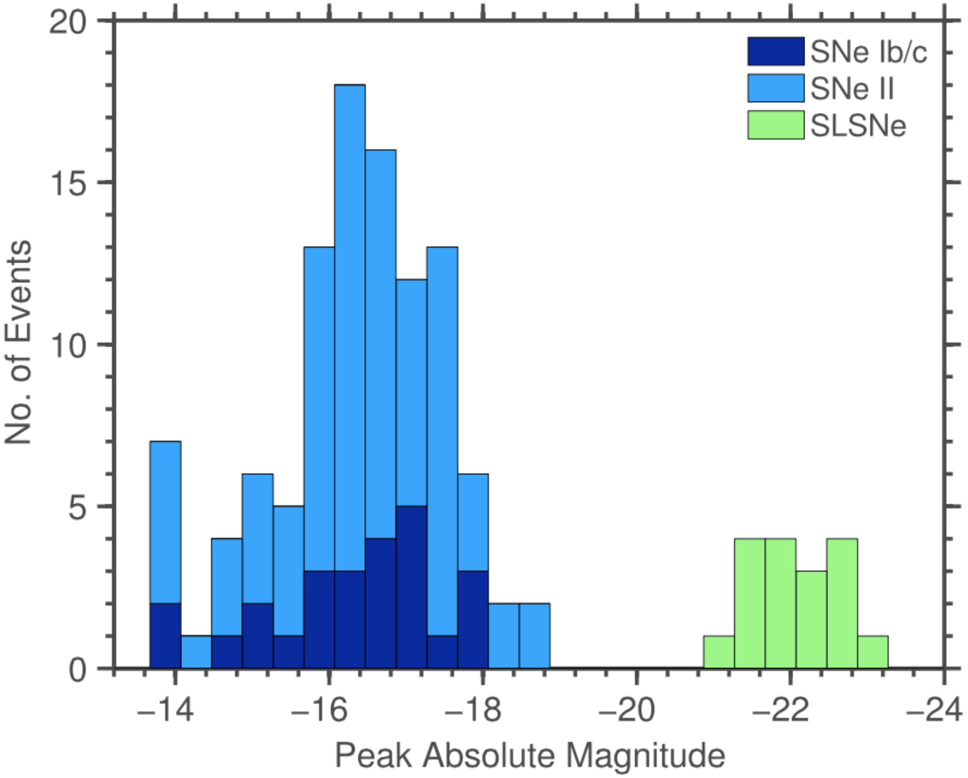
SN - SLSN gap

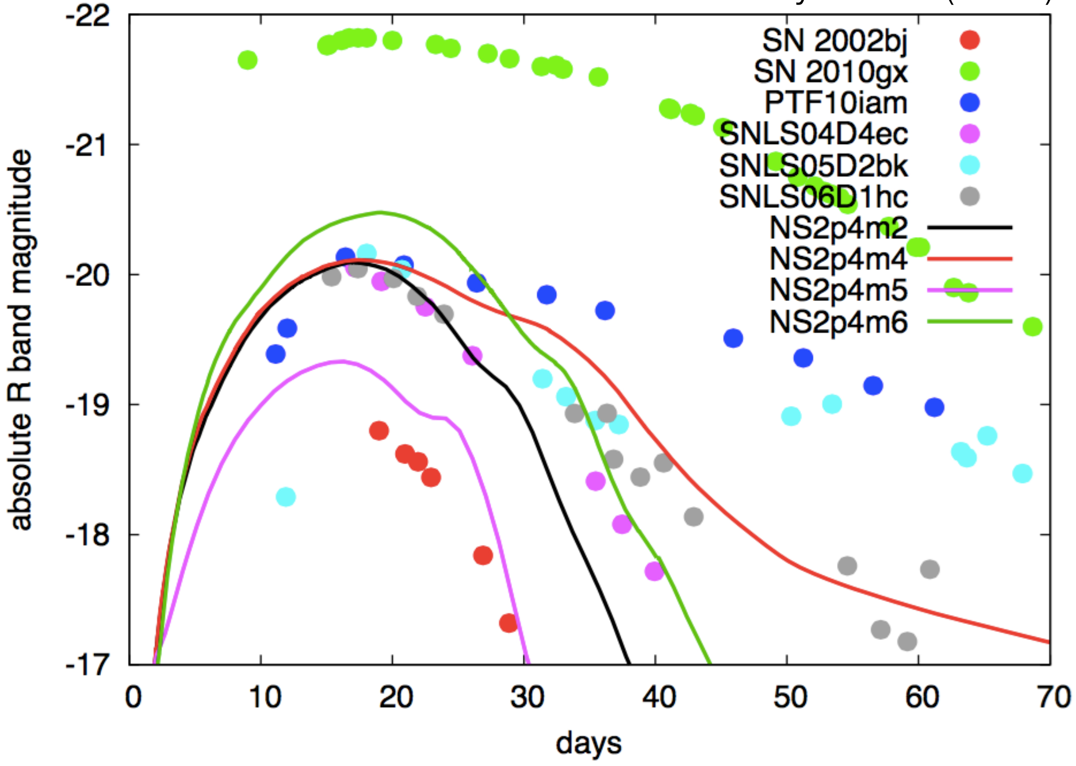
- Arcavi et al. (2016)
    - possible luminosity jump?



Some transients in the gap are observed

- Arcavi et al. (2016)
  - reported several transients in the gap
  - they could not fit them by the standard magnetar-powered SN models




Moriya et al. (2016)

Summary

- some SNe, like SLSNe, may be powered by magnetar spin-down
- supramassive magnetars have minimum rotational energy to support themselves
    - they transform into BHs when they lose too much rotational energy
    - SNe powered by supramassive magnetars may suddenly lose their energy input because of the BH transformation
- the BH transformation can have significant effect on the observational properties of SNe powered by magnetars
    - magnetar-driven shock breakout signals can be more significant
    - they can be observed as the SN - SLSN gap transients
- if confirmed…
    - SLSNe to the gap transients ratio may indicate the mass fraction of normal mass NSs to supramassive NSs

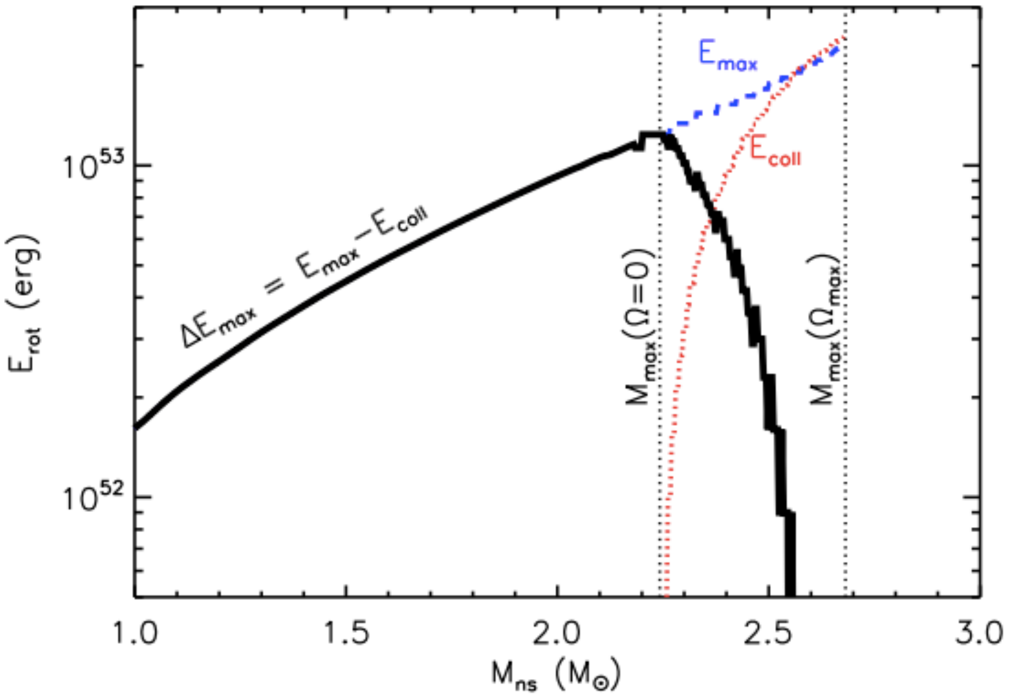


Figure 4. Maximum extractable rotational energy from an NS, $\Delta E_{\rm max} \equiv E_{\rm max} - E_{\rm coll}$ (black solid line), as a function of the NS mass M, where $E_{\rm max}$ (blue dashed line) is the maximum rotational energy at the mass-shedding limit and $E_{\rm coll}$ (red dotted line) is the minimum rotational energy required for support of a supramassive NS against collapse to a BH. The structure of the solid-body rotating NS is calculated using the RNS code assuming a parametrized piecewise polytropic EOS with an adiabatic index $\Gamma = 3$ above the break density of $\rho_1 = 10^{14.7}$ g cm^{-3} at a pressure of $P_1 = 3.2 \times 10^{34}$ dyn cm^{-2}. We find that the maximum value of $\Delta E_{\rm max}$ lies within the relatively narrow range of 0.9–1.65 $\times 10^{53}$ erg across a wide range of $\Gamma - P_1$ consistent with constraints on the maximum mass of a non-rotating NS.

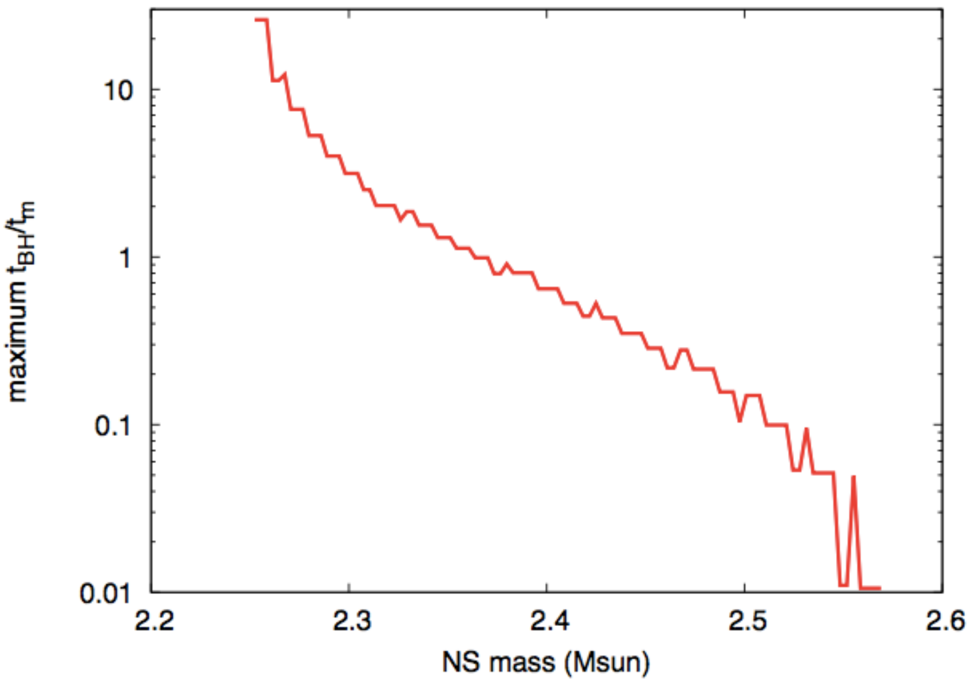


Figure 1. Maximum allowed ratio of BH formation time $t_{\rm BH}$ to magnetar spin-down time t_m, as a function of the NS gravitational mass, based on Figure 4 in Metzger et al. (2015). The structure of the solid-body rotating NS is calculated using the `rns` code (Stergioulas & Friedman 1995) assuming a parametrized piecewise polytropic EOS with an adiabatic index $\Gamma = 3$ above the break density of $\rho_1 = 10^{14.7}$ g cm^{-3} at a pressure of $P_1 = 3.2 \times 10^{34}$ dyn cm^{-2} (Margalit et al. 2015). The chosen EOS results in a 1.4 $M_\odot$ NS radius of 10.6 km and maximum non-rotating mass of $\approx 2.24\ M_\odot$, consistent with observational constraints.

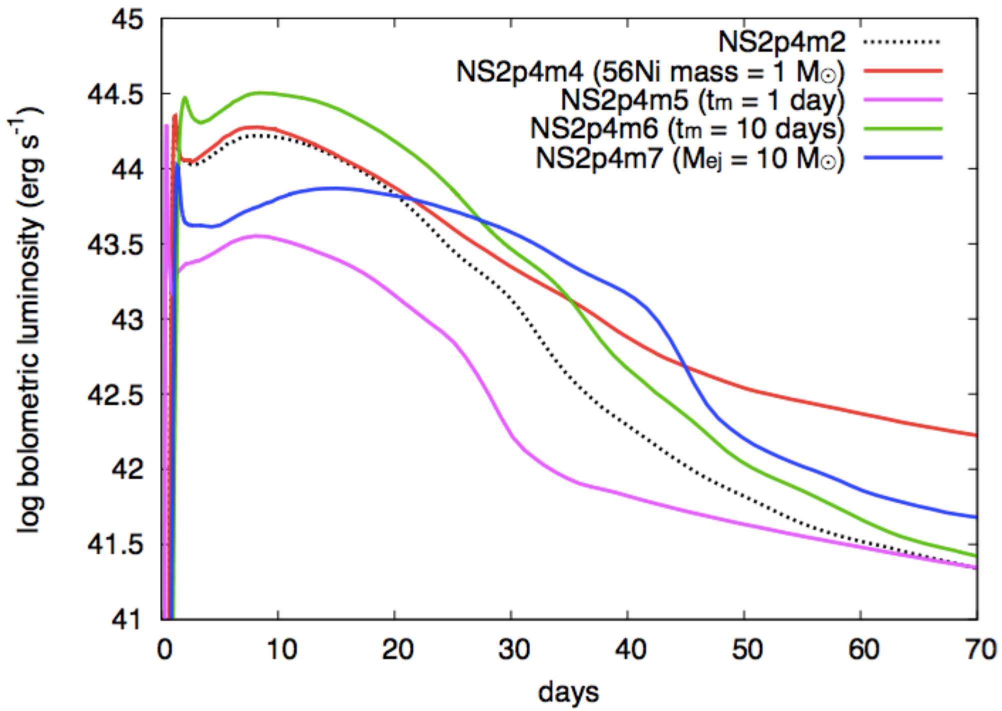


Figure 7. Numerical LC models with different SN ejecta and magnetar properties. The magnetar initial rotational energy ($E_m = 1.1 \times 10^{53}$ erg) and the NS mass ($2.4\ M_\odot$, i.e., $E_{\rm coll} = 9.3 \times 10^{52}$ erg) are the same those in NS2p4m2. The difference between NS2p4m2 ($M_{\rm ej} = 5\ M_\odot$, $E_{\rm ej} = 10^{51}$ erg, ^{56}Ni mass of $0.1\ M_\odot$, and $t_m = 5$ days) and the other models are indicated in the figure.