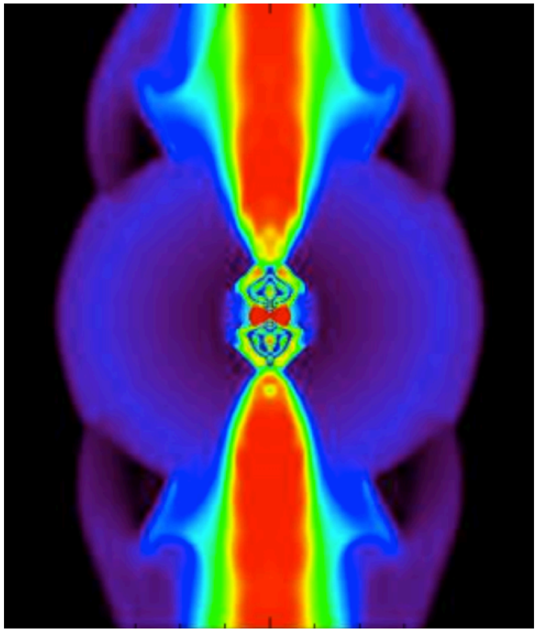
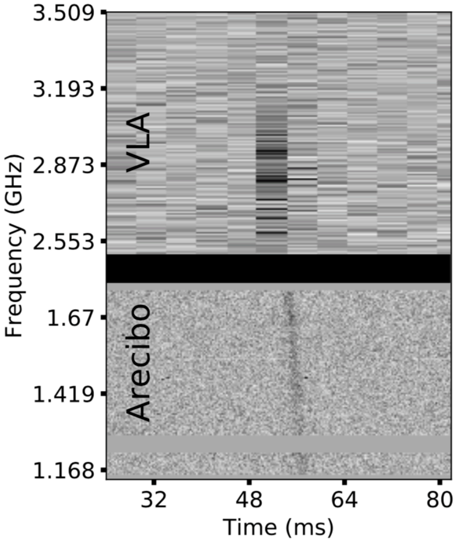
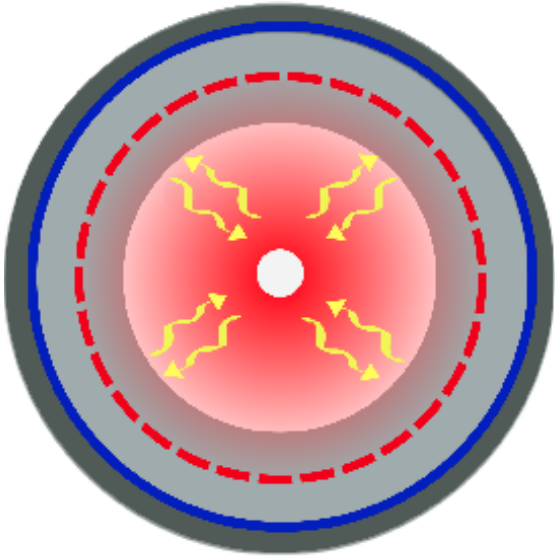
Connecting FRB 121102 to Magnetar Birth

Gamma-Ray Bursts





Super-Luminous
Supernovae



Brian Metzger
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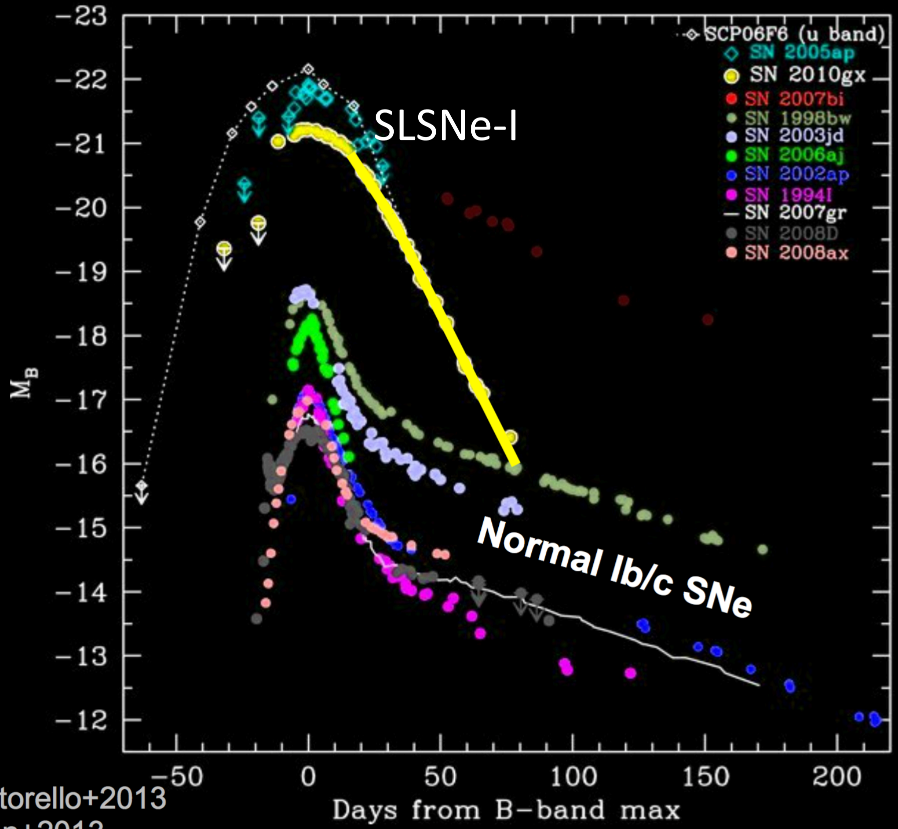
Primary Collaborators

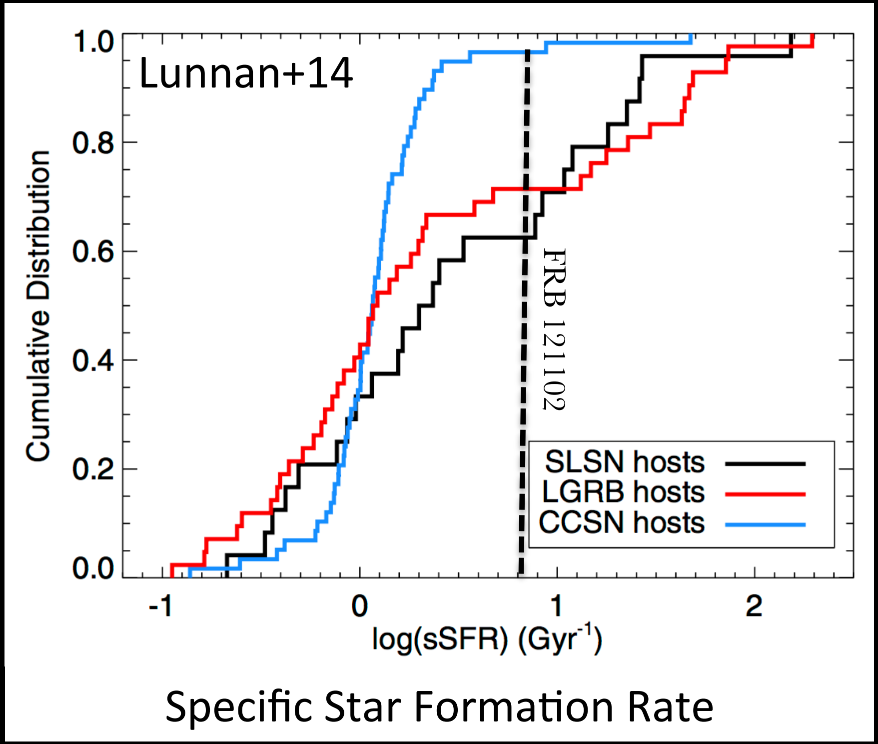
Edo Berger, Matt Nicholl (Harvard CfA), **Ben Margalit** (Columbia)
Eliot Quataert, Dan Kasen (Berkeley), Todd Thompson, Tuguldur Sukhbold (OSU)
Peter Williams, Terraneh Eftekhari, Kate Alexander, Ashley Villar (Harvard CfA)

Workshop on Fast Radio Bursts – McGill University, June 14, 2017

Type I Super-Luminous Supernovae



Pastorello+2013
Chen+2013

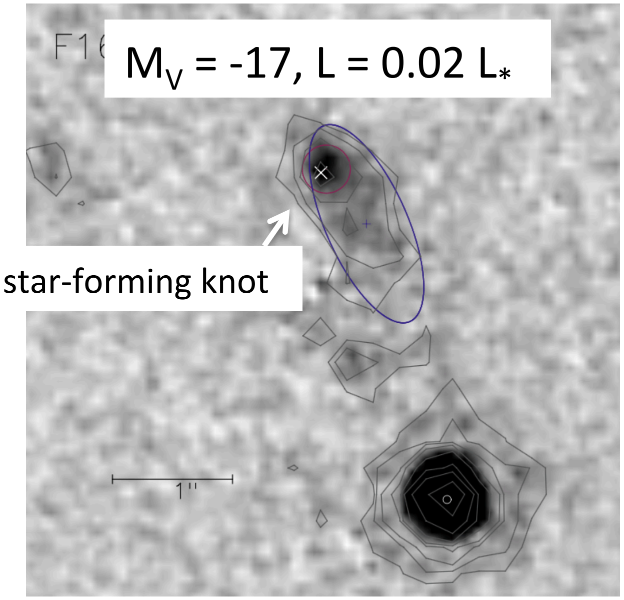


Specific Star Formation Rate

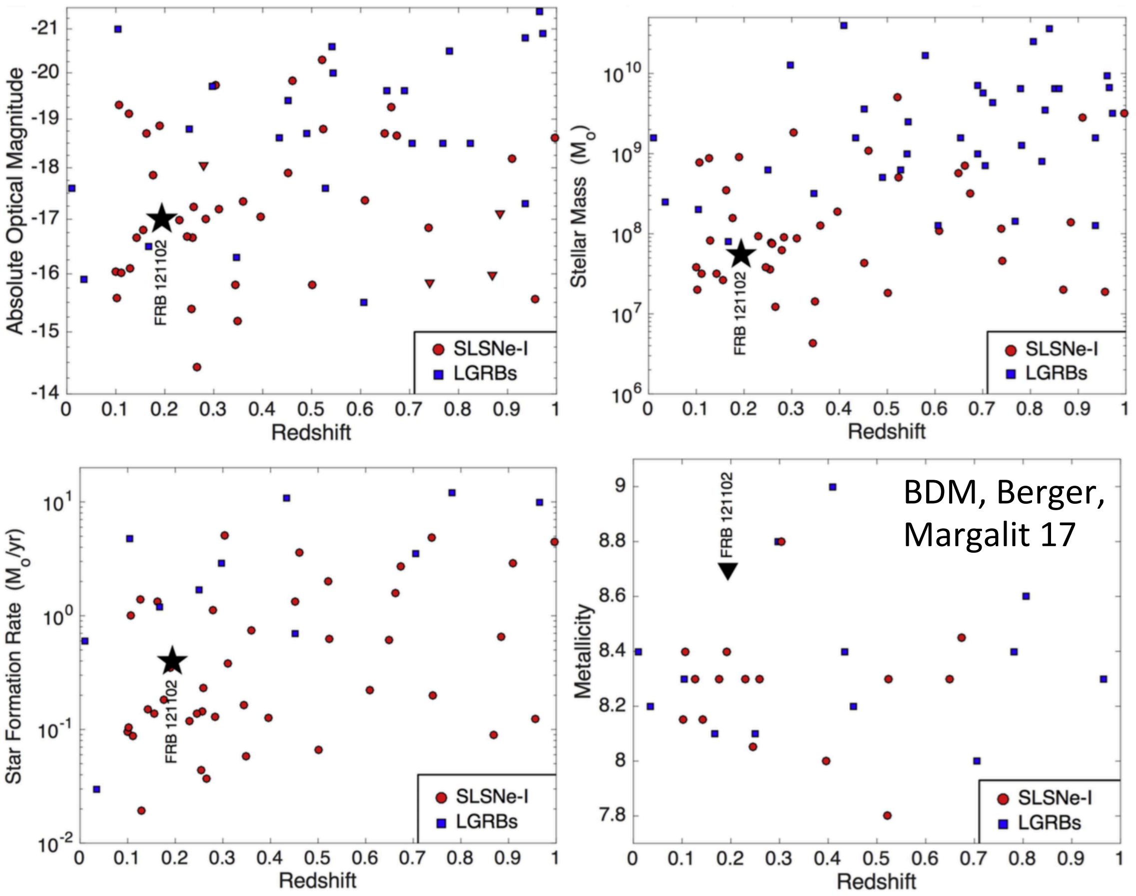
- $L_{peak} > 10^{44}$ erg s^{-1}, $E_{rad} \sim 10^{50\text{-}51}$ ergs (10-100 × normal SNe)
- Faint metal-poor host galaxies, similar to long GRBs
  (Quimby+11, Neill+11, Chen+13, Chornock+13, Lunnan+14, Vergani+15, Perley+16, Schulze+16)
- Luminosity not powered by ^{56}Ni decay

=> Central Engine (millisecond magnetar or black hole)

1st clue: puny host galaxy of FRB 121102



Tendulkar+17, Bassa+17, Kukobo+17



BDM, Berger, Margalit 17

- Only a small fraction of total stellar mass M_* and SFR in the Universe in galaxies as small as the host of 121102
- 121102 host remarkably similar to SLSNe/LGRBs galaxies.
- Magnetars previously proposed as engines of LGRBs (Thompson+04), SLSNe (Kasen & Bildsten 10) and FRBs (e.g. Lyubarsky 14)

FRB 121102 as juvenile flaring magnetar

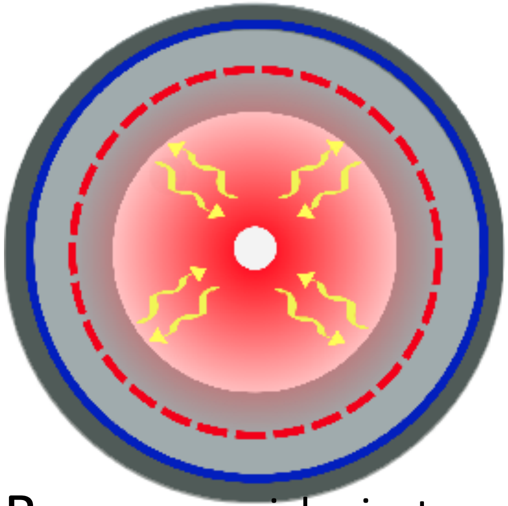
(Popov & Postnov 13; Thornton+13; Kulkarni+15; Lyubarsky 14; Pen & Connor 15; Popov & Pshirkov 16; Chatterjee+17; BDM, Berger, Margalit 17)

Radio bursts of energy E_{iso} ~ 10^{38}-10^{40} erg, irregularly every hour to day (Spitler+14,16; Scholz+16; Chatterjee+17)

Active for > 4 years

Association with compact (<0.7 pc) bright quiescent synchrotron radio source (Chatterjee+17; Marcote+17)

$$E_B = 3.10^{49}\left(B/10^{16}\,G\right)^2 \text{ erg}$$



oxygen-rich ejecta

$M_{ej} \sim 3\text{-}20\ M_\odot$

$v_{ej} \sim 10^4$ km s^{-1}

- How did the magnetar get here?

  potential association with past SLSNe or LGRB

- How old is it?

  ~10-100 years

- Explanation for Quiescent Radio Source?

  several natural ones

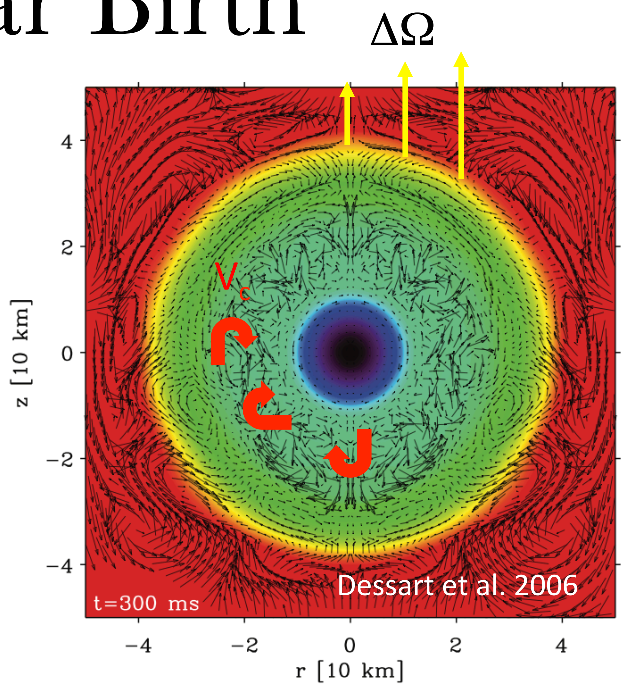
- Predictions?

Millisecond Magnetar Birth

Neutron stars are born as hot, differentially-rotating proto-neutron stars

$$E_{\rm rot} = \frac{1}{2} I\Omega^2 \sim 3\times10^{52}\left(\frac{P}{1\ \rm ms}\right)^{-2}\ \rm erg$$

$$\Rightarrow B \sim 10^{17}\left(\frac{\Delta\Omega}{\Omega/2}\right)^{2}\left(\frac{P}{1\ \rm ms}\right)^{-2}\ \rm G$$



Dessart et al. 2006

Magnetic field amplification

- Magneto-rotational Instability

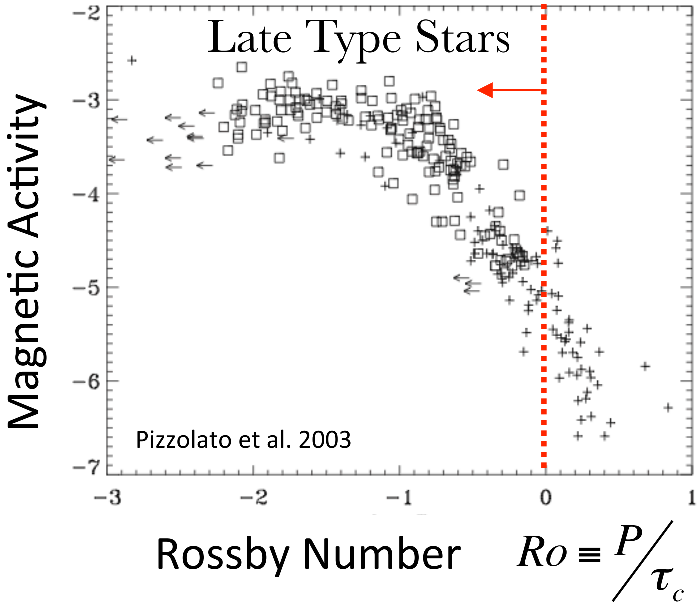
(Akiyama+03; Mosta+15)

- α-Ω dynamo (threshold at P ~ 1 ms)

(Thompson & Duncan 93)

Alternative: flux freezing

Most galactic magnetars (>10% of NSs)
probably born slowly-rotating

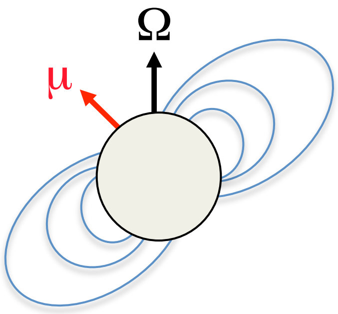


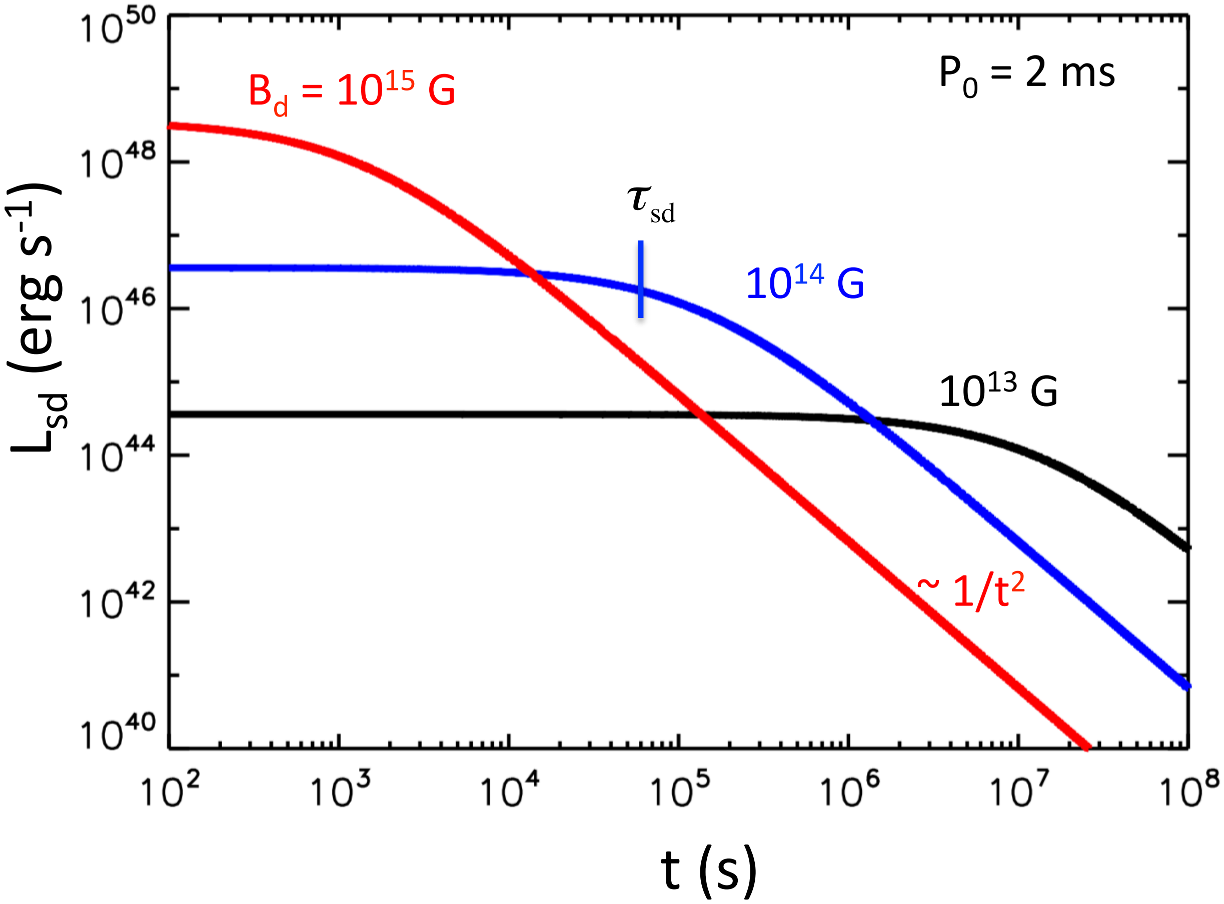
Pizzolato et al. 2003

Magnetic Dipole Spin-Down

Spin-down luminosity $$L_{sd} = \frac{\mu^2\Omega^4}{c^3} \approx 6\times10^{47} \left(\frac{P}{1\text{ ms}}\right)^{-4}\left(\frac{\mathrm{B_d}}{10^{14}\text{ G}}\right)^{2} \text{erg s}^{-1} = \frac{d}{dt}\frac{1}{2}I\Omega^2$$

Spin-down time $$\tau_{sd} = \left.\frac{E_{rot}}{L_{sd}}\right|_{t=0} \approx 0.6 \left(\frac{P_0}{1\text{ ms}}\right)^{2}\left(\frac{\mathrm{B_d}}{10^{14}\text{ G}}\right)^{-2} \text{day}$$





Diversity of Magnetar Birth

Spin-down luminosity

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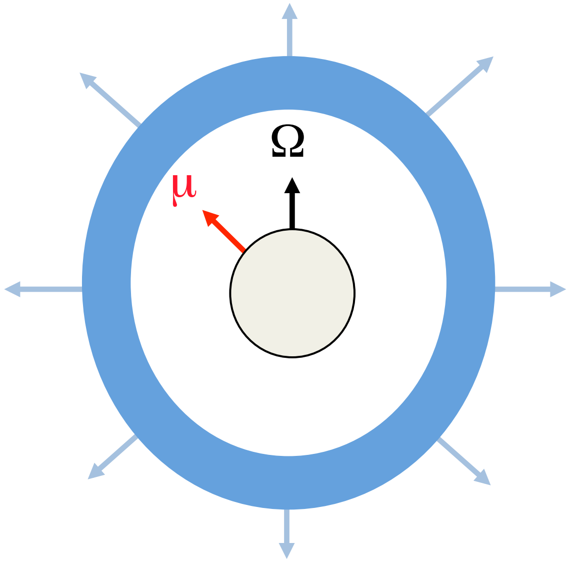
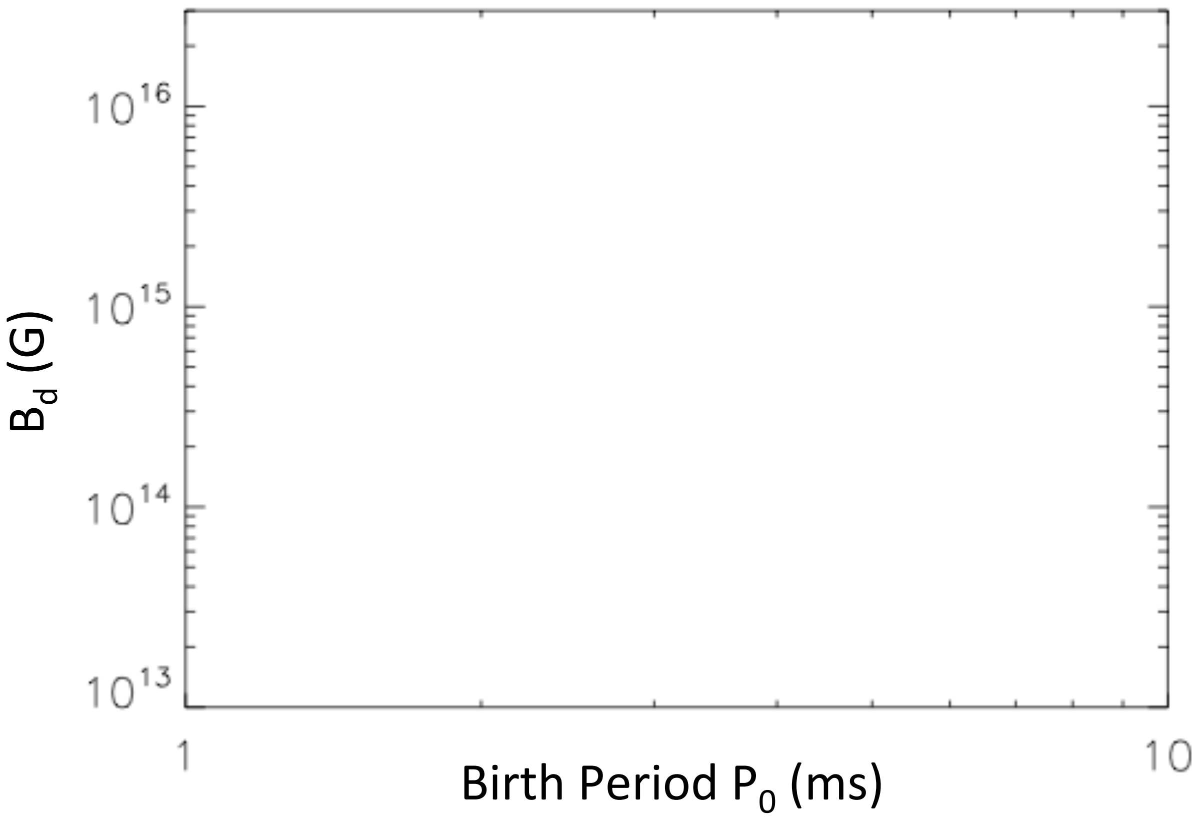


M_{ej} ~ 3-20 $M_\odot$
$E_{KE,0}$ ~ 10^{51}-10^{52} erg
v_0 ~ 10^4 km s^{-1}



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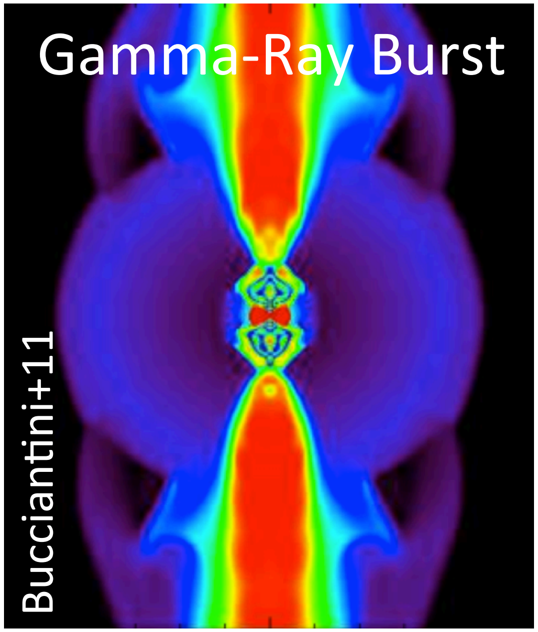
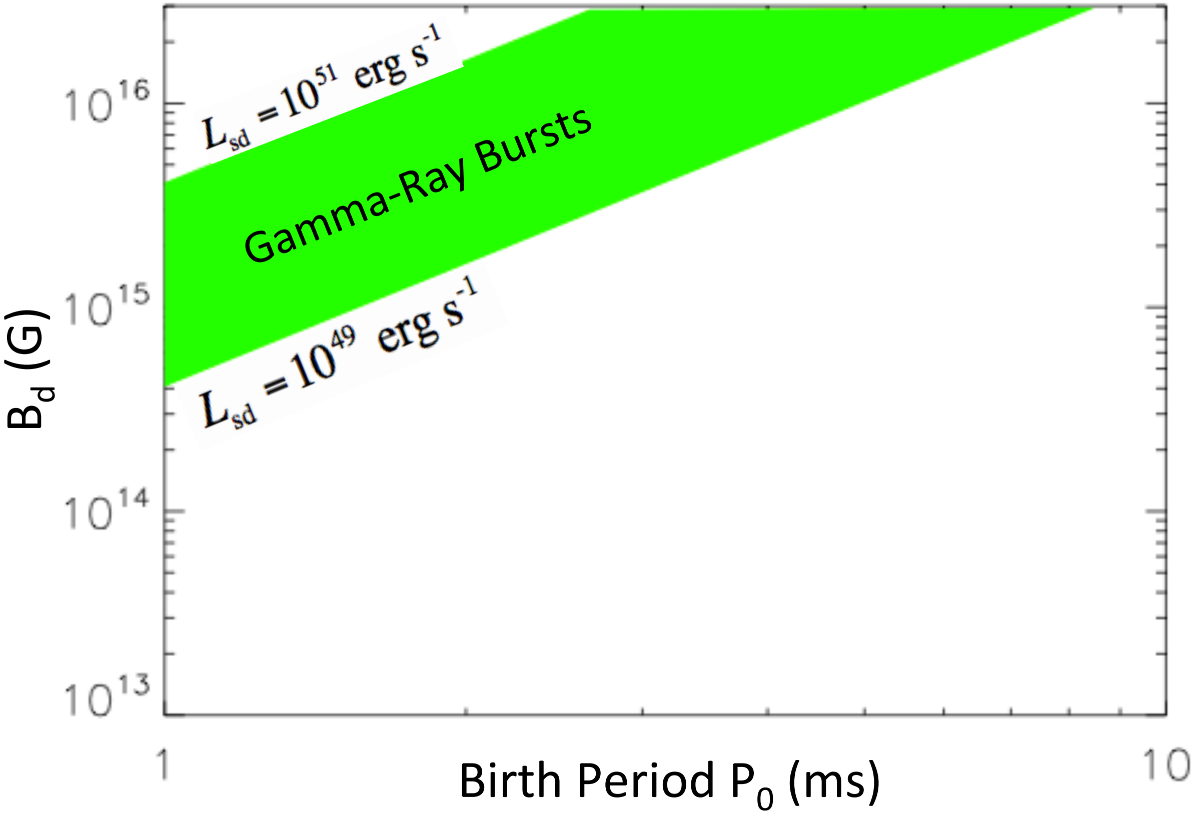


Jet punches through star

$L_{sd} \sim L_\gamma \sim 10^{49\text{-}51}$ erg s^{-1}

τ_{sd} ~ minutes-hours



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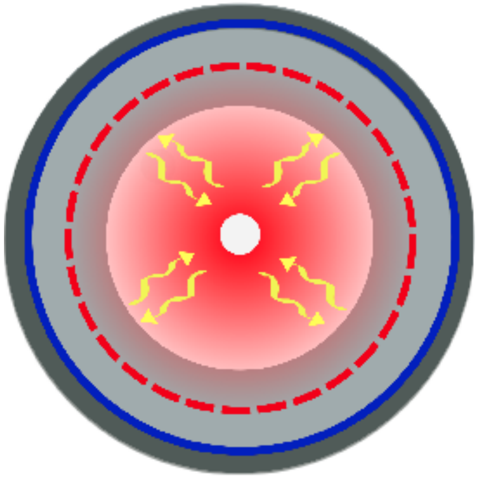
Super-Luminous SNe

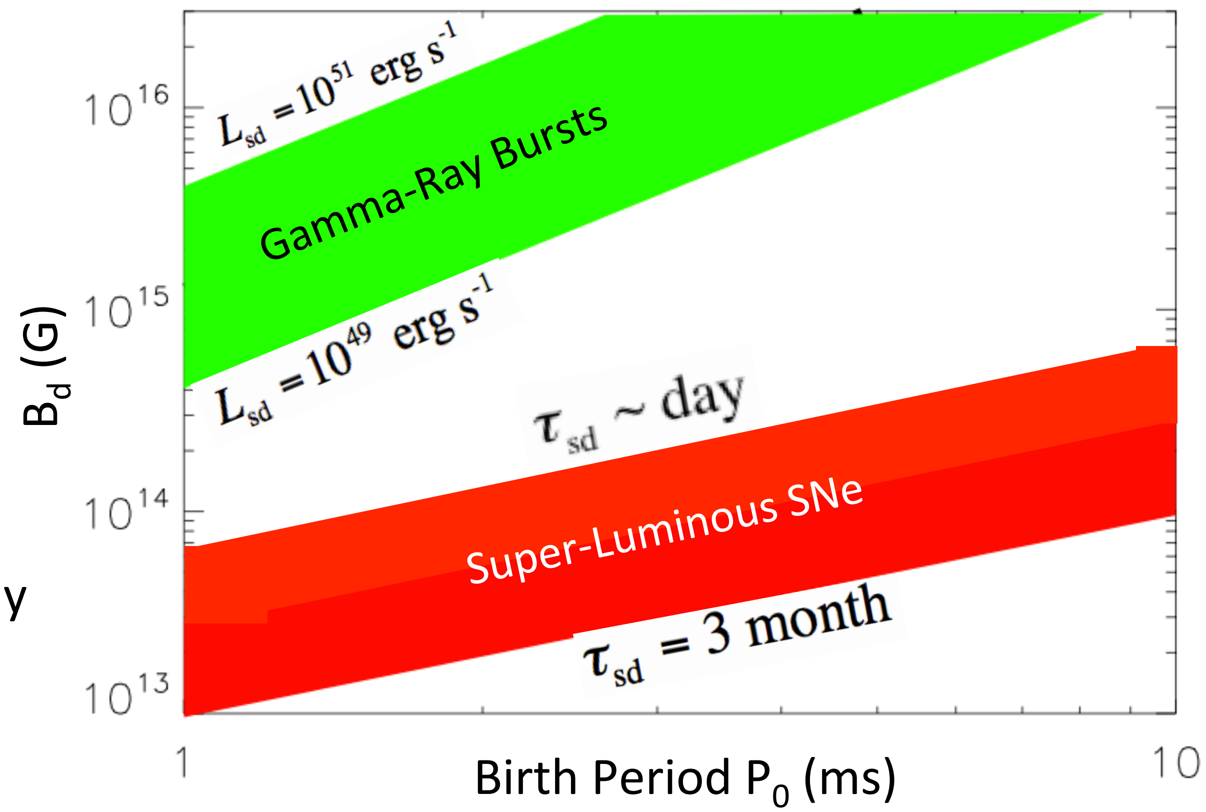
Kasen & Bildsten 2010, Woosley 2010



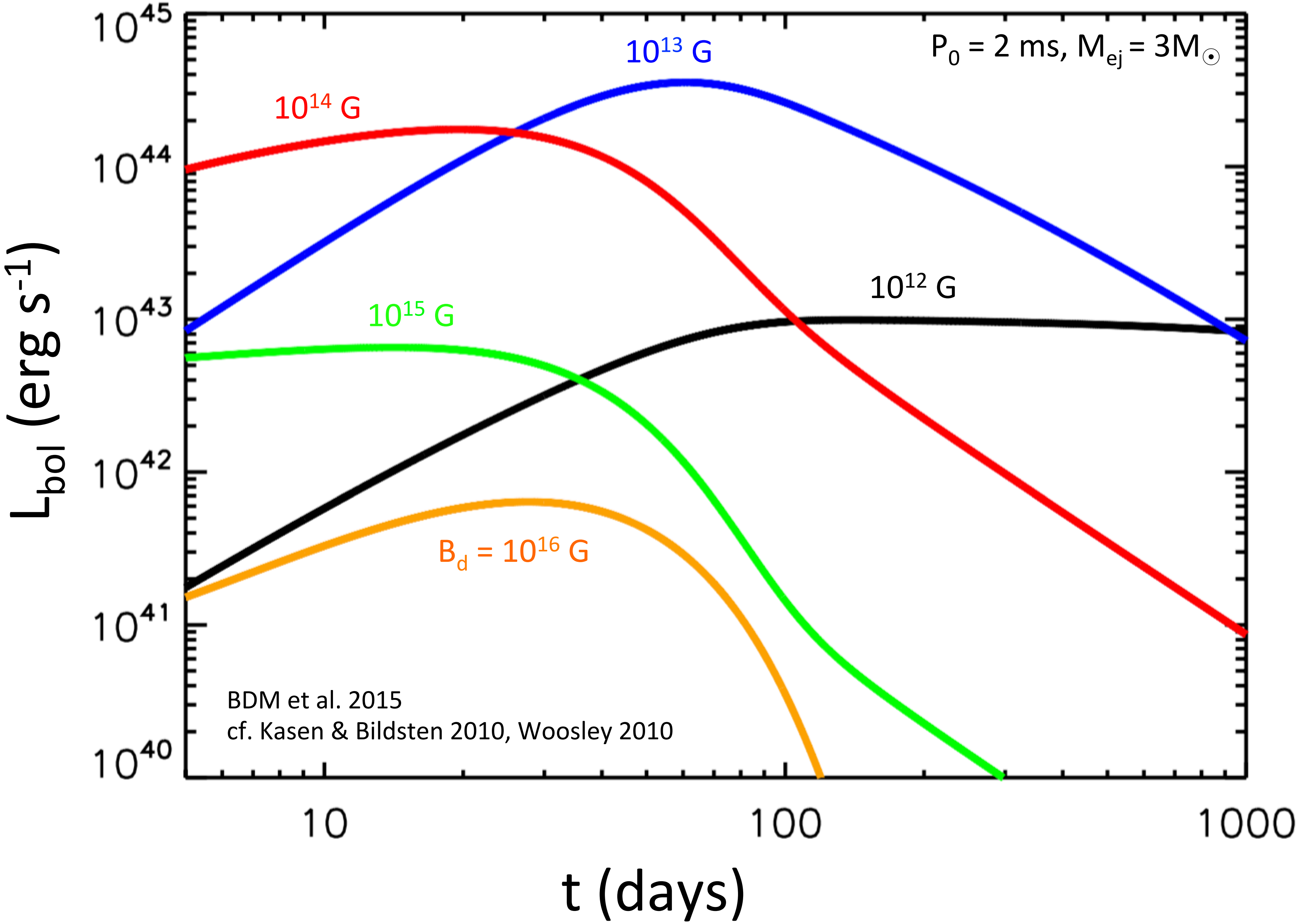
Jet *may* fail, but spin-down power can escape diffusively

$L_{sd} \sim L_{\gamma} \sim 10^{43\text{-}45}$ erg s^{-1}

τ_{sd} ~ days-months



Magnetar SLSN Light Curves



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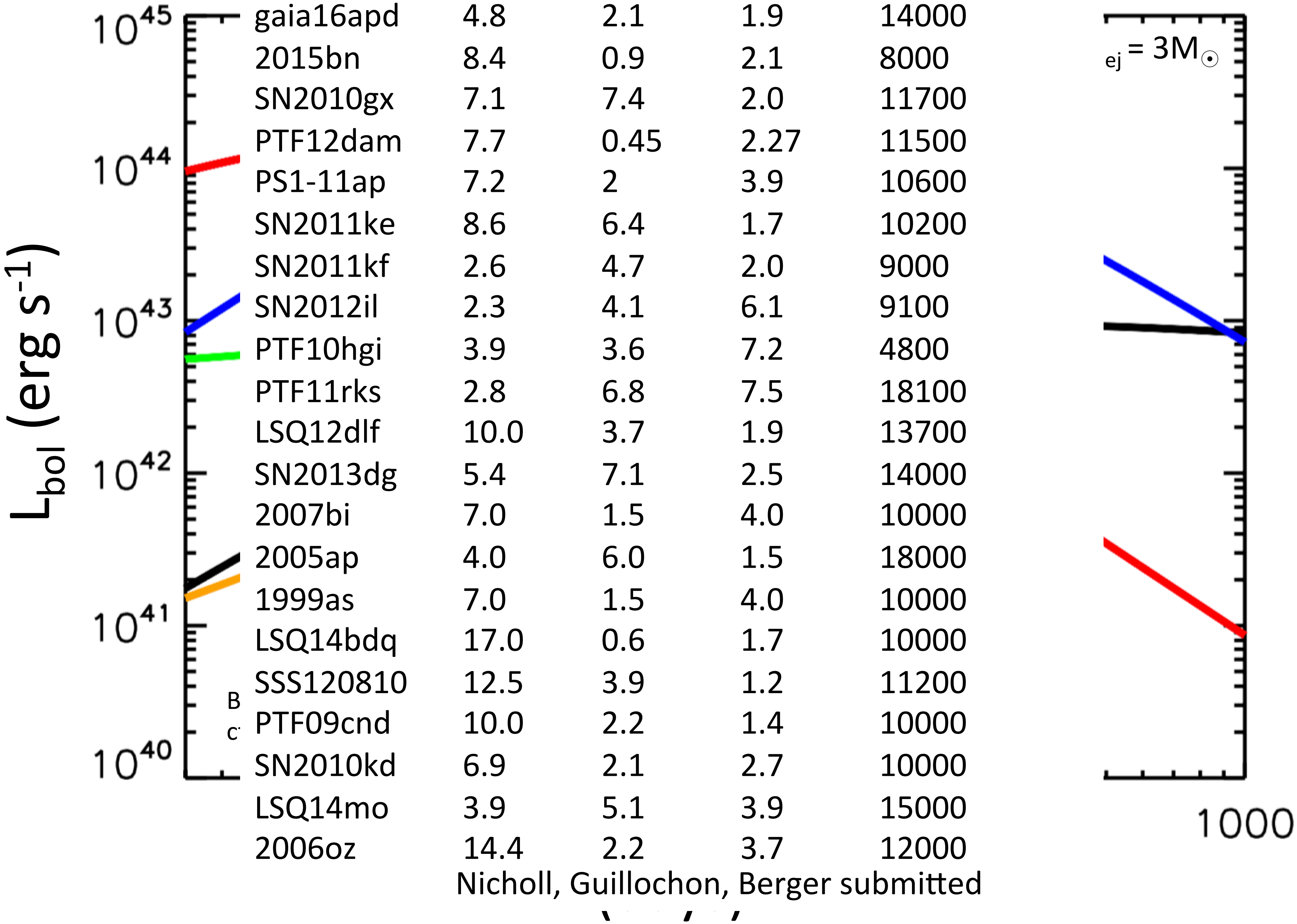

NAME	M_{ej} ($M_\odot$)	B_d (10^{14} G)	P_0 (ms)	v_{ej} (km s^{-1})
gaia16apd	4.8	2.1	1.9	14000
2015bn	8.4	0.9	2.1	8000
SN2010gx	7.1	7.4	2.0	11700
PTF12dam	7.7	0.45	2.27	11500
PS1-11ap	7.2	2	3.9	10600
SN2011ke	8.6	6.4	1.7	10200
SN2011kf	2.6	4.7	2.0	9000
SN2012il	2.3	4.1	6.1	9100
PTF10hgi	3.9	3.6	7.2	4800
PTF11rks	2.8	6.8	7.5	18100
LSQ12dlf	10.0	3.7	1.9	13700
SN2013dg	5.4	7.1	2.5	14000
2007bi	7.0	1.5	4.0	10000
2005ap	4.0	6.0	1.5	18000
1999as	7.0	1.5	4.0	10000
LSQ14bdq	17.0	0.6	1.7	10000
SSS120810	12.5	3.9	1.2	11200
PTF09cnd	10.0	2.2	1.4	10000
SN2010kd	6.9	2.1	2.7	10000
LSQ14mo	3.9	5.1	3.9	15000
2006oz	14.4	2.2	3.7	12000

Nicholl, Guillochon, Berger submitted

Diversity of Magnetar Birth

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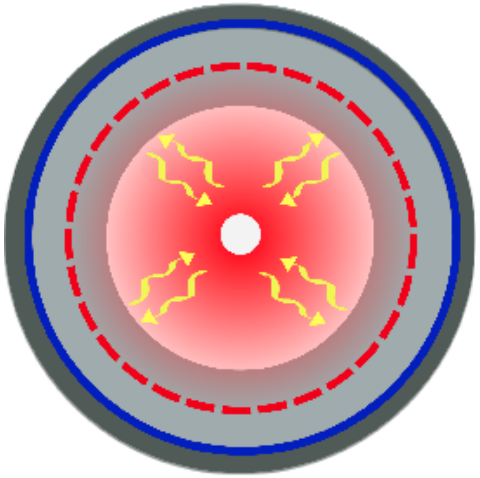
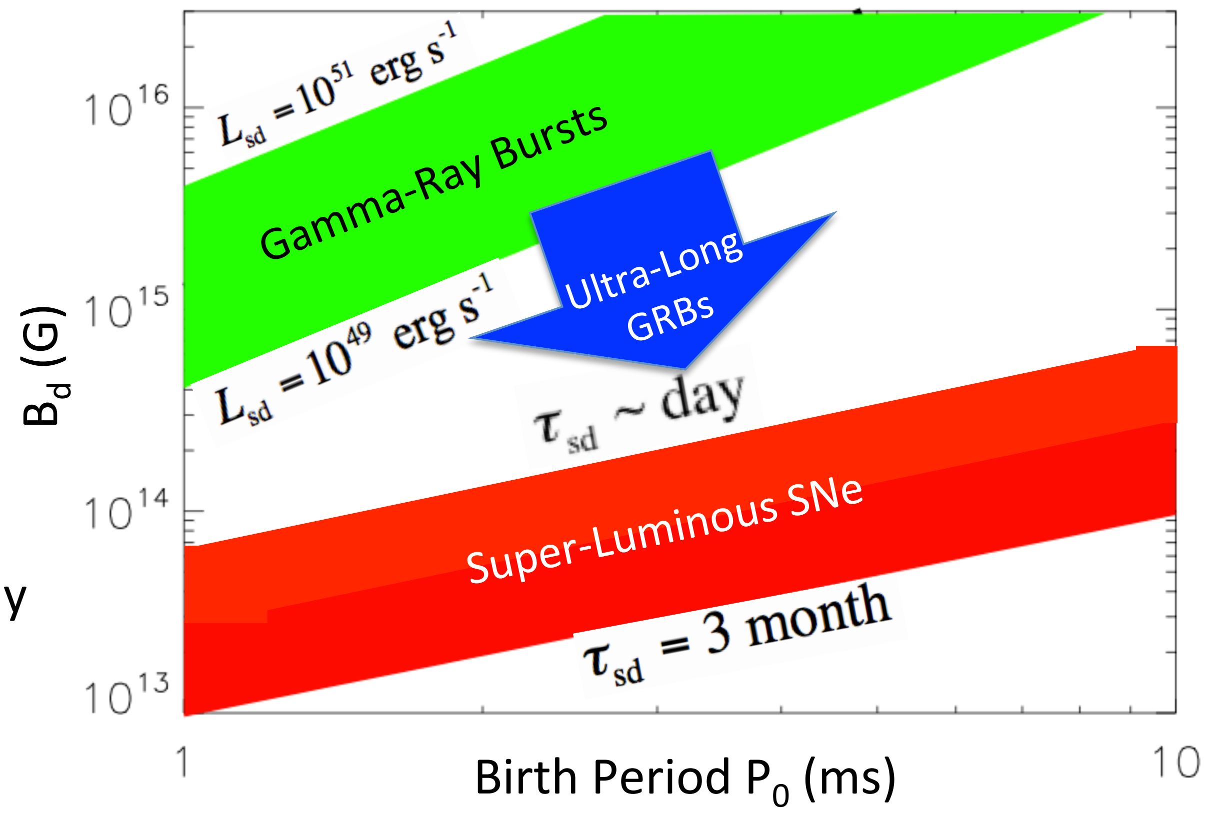


Jet *may* fail, but spin-down power can escape diffusively

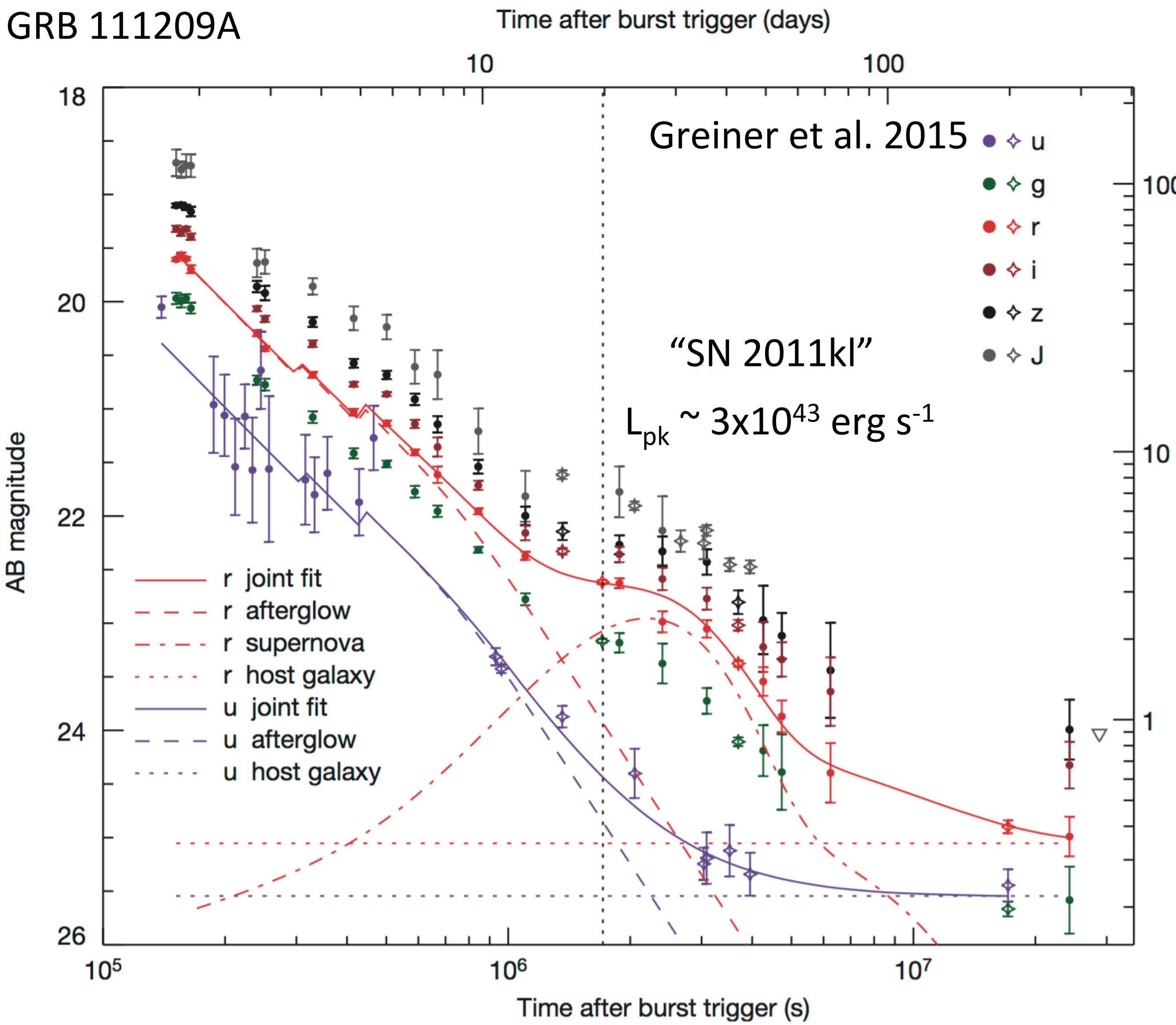
L_{sd} ~ L_γ ~ 10^{43-45} erg s^{-1}

τ_{sd} ~ days-months



A very luminous magnetar-powered supernova associated with an ultra-long γ-ray burst

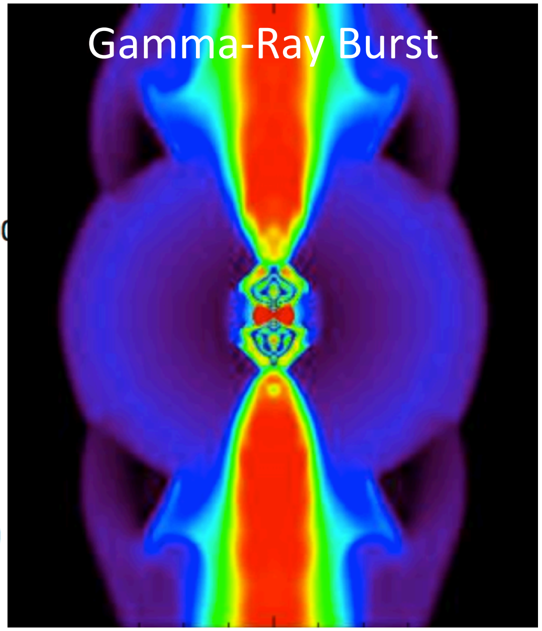
GRB 111209A



Greiner et al. 2015

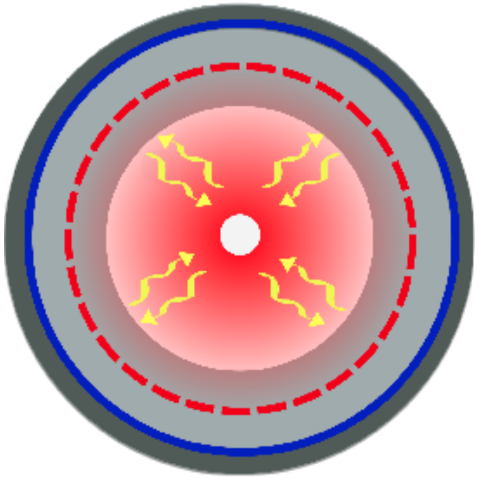
“SN 2011kl”

L_{pk} ~ 3×10^{43} erg s^{-1}



Gamma-Ray Burst

SLSNe



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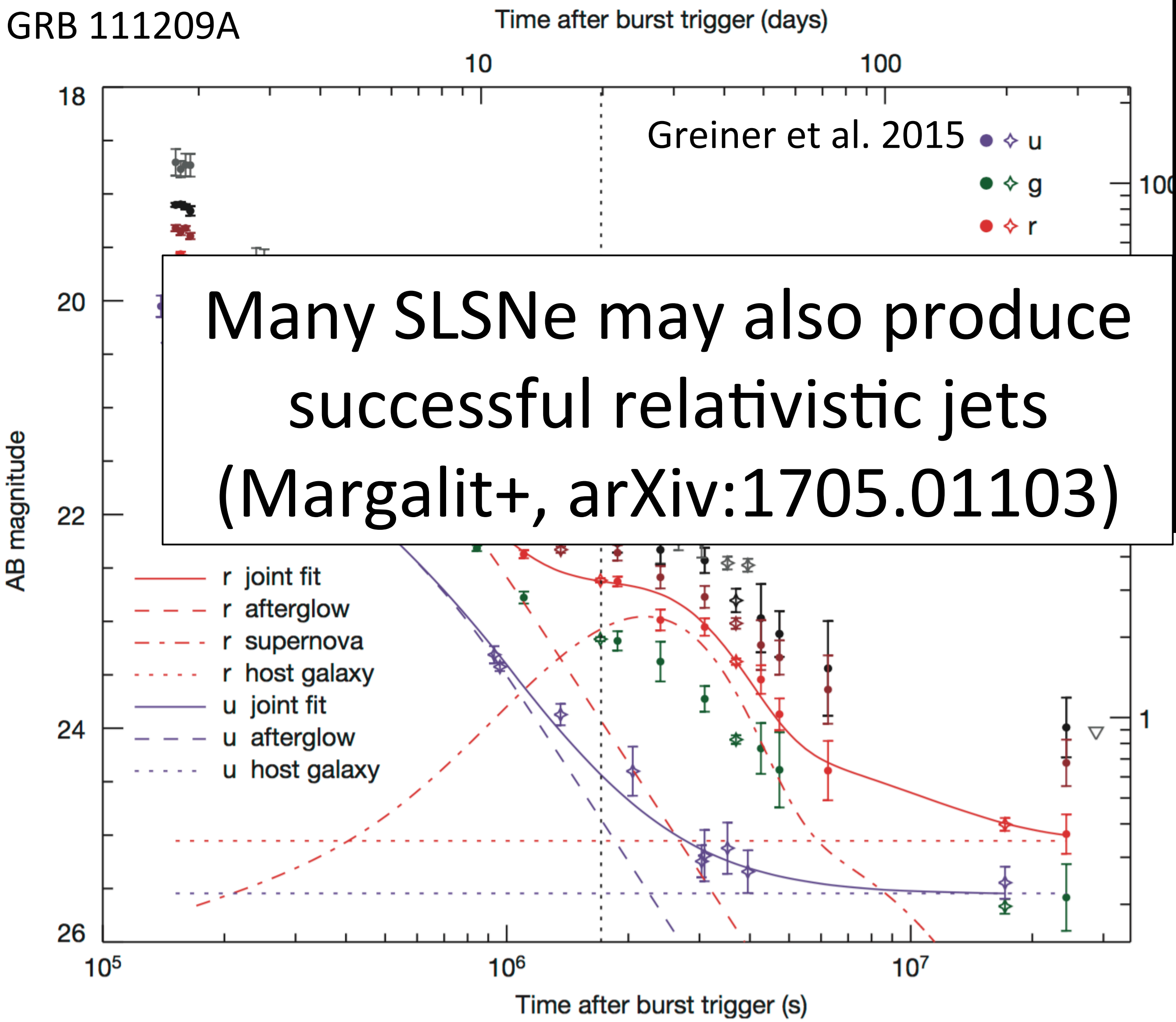
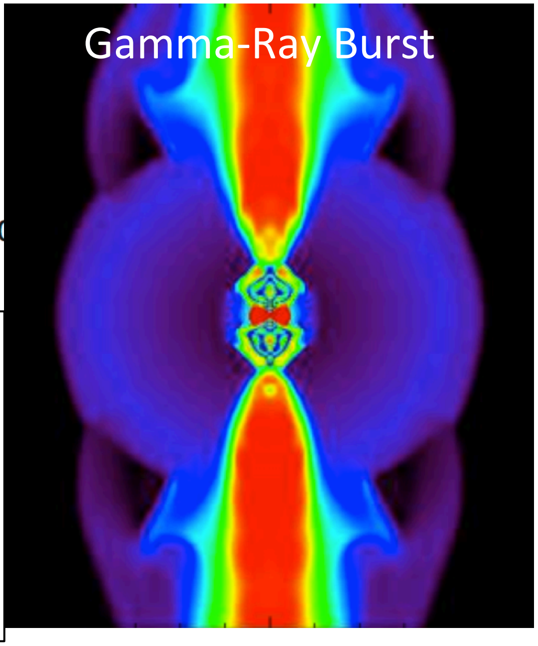
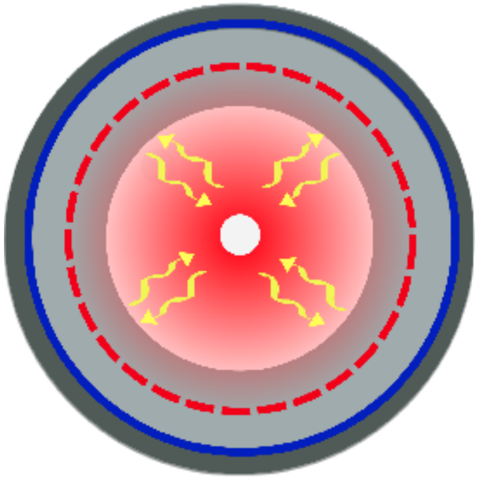


Many SLSNe may also produce successful relativistic jets (Margalit+, arXiv:1705.01103)



SLSNe



Age of FRB 121102 $t_{\rm age} \sim$ 10-100 yr

- Size of Quiescent Source ($R_Q < 0.7$ pc)

$t_{\rm age} = R_Q/v$ → **$t_{\rm age} <$ 2 yr** ($v = c$), **$t_{\rm age} <$ 70 yr** ($v = 10^4$ km s^{-1})

- Ejecta transparent to free-free absorption

$$t_{\rm ff} \simeq 9.85\,{\rm yr}\;\bar{g}_{\rm ff}^{1/5}\left(\frac{f_{\rm ion}}{0.1}\right)^{2/5}\nu_{\rm GHz}^{-2/5}T_4^{-3/10}M_1^{2/5}v_9^{-1}$$

→ **$t_{\rm age} >$ 10 yr**

NOTE: oxygen not fully ionized, ejecta velocity higher than in normal CCSNe

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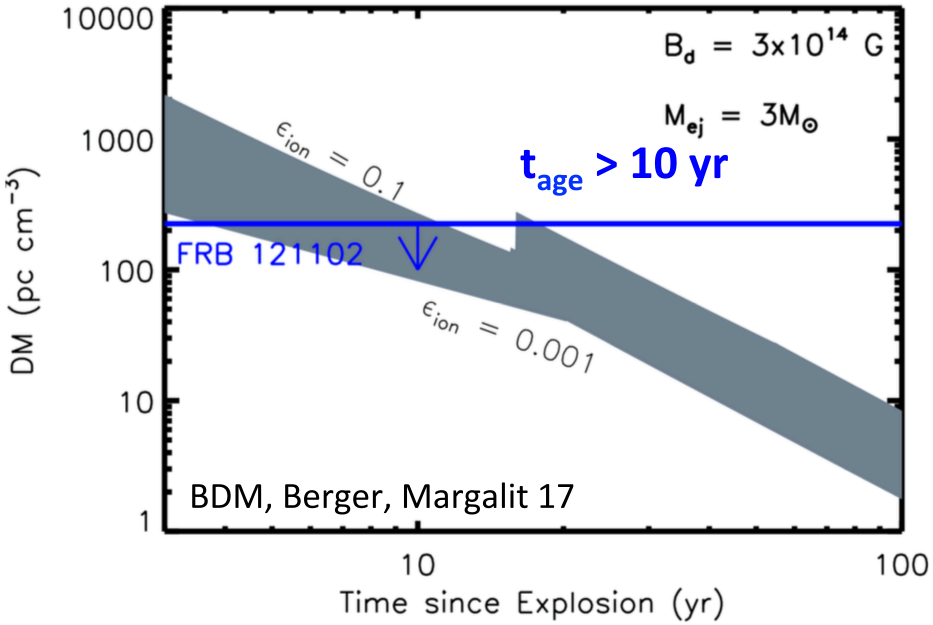
➡ **$t_{age} >$ 10 yr**

NOTE: oxygen not fully ionized, ejecta velocity higher than in normal CCSNe

- Local DM < 140 pc cm^{-3} and (d/dt)DM < 2 pc cm^{-3} yr^{-1} (Piro 16)



BDM, Berger, Margalit 17

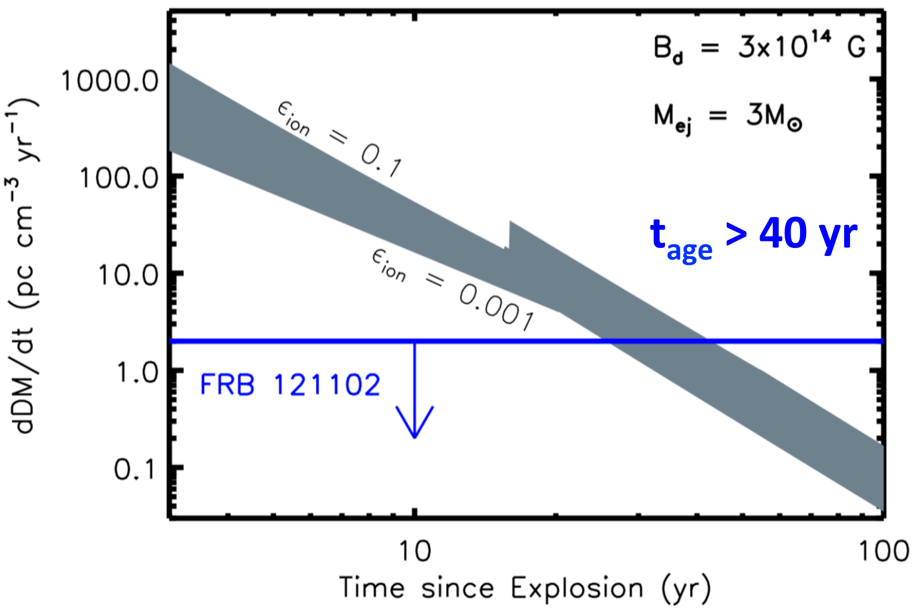
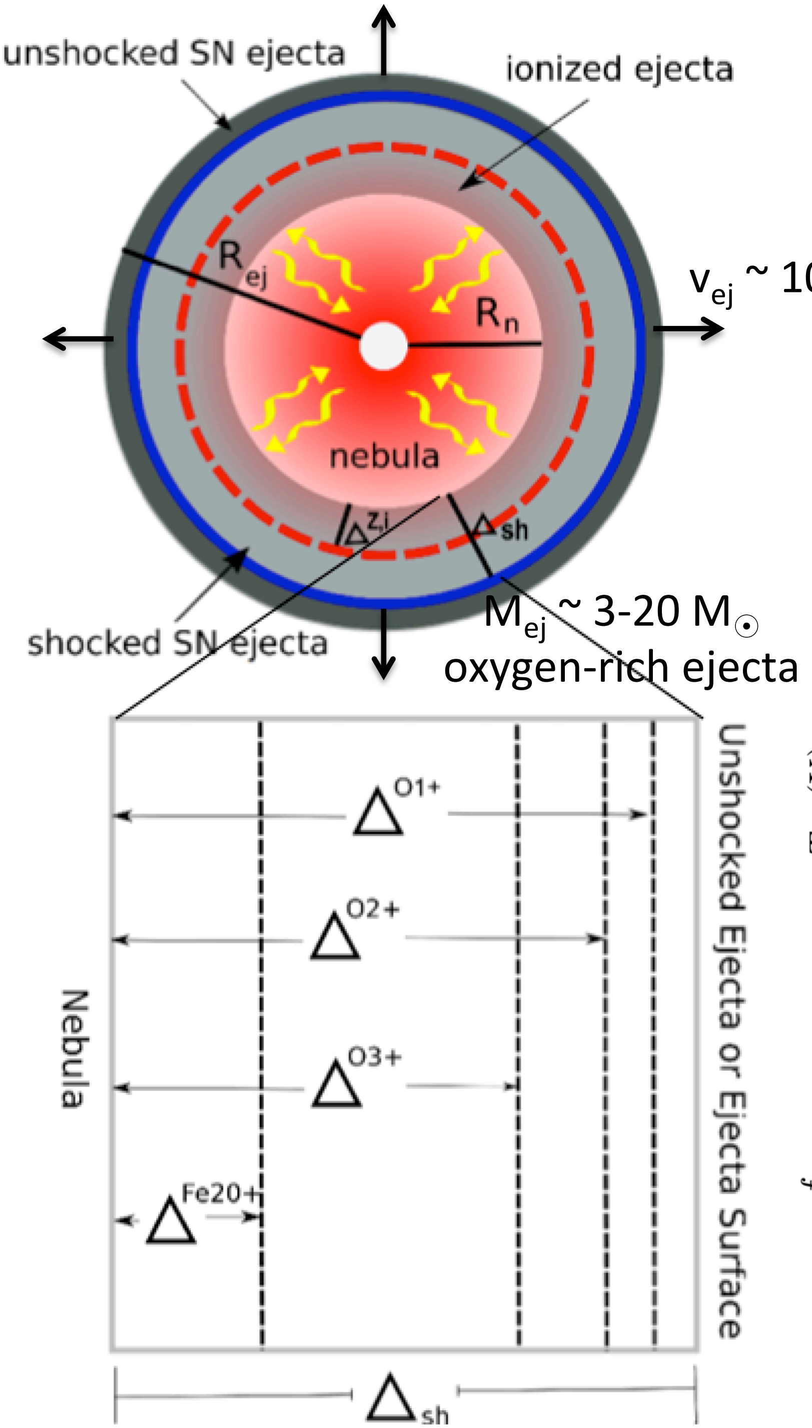


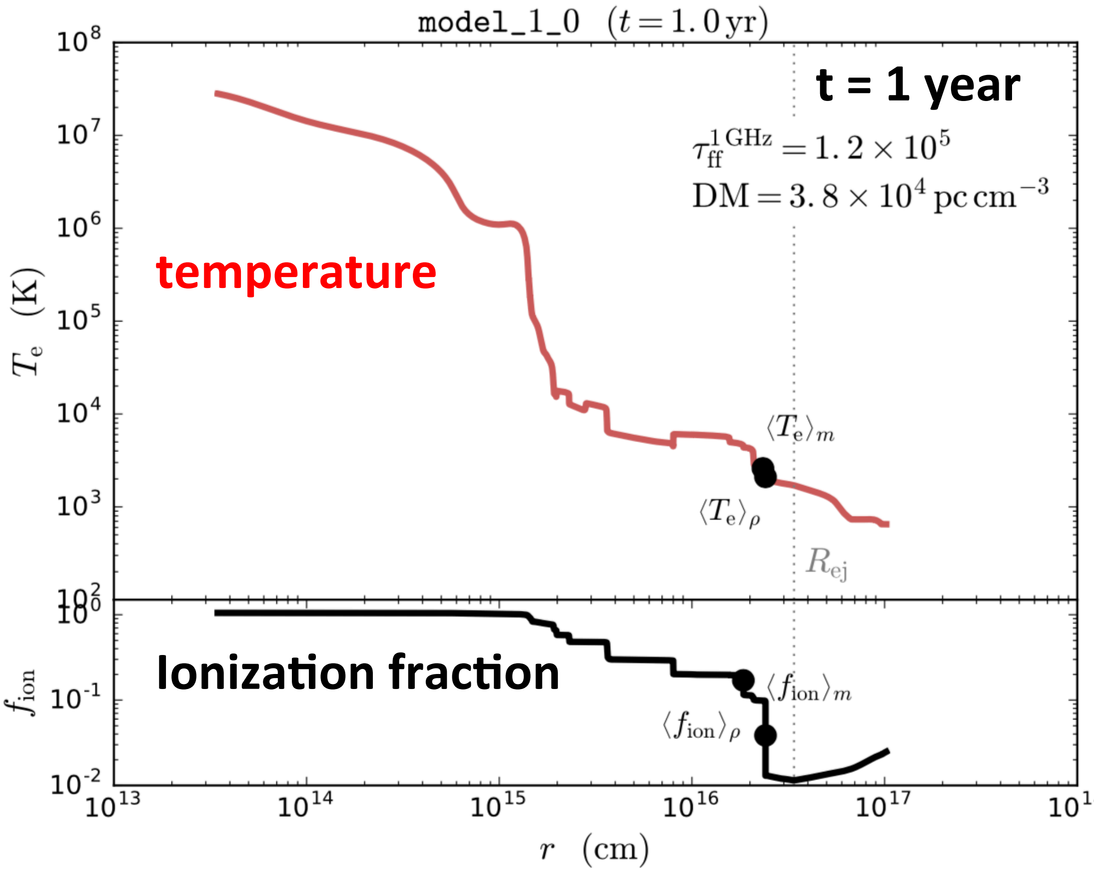
Photo-ionization of SN ejecta by magnetar nebula (Margalit+ in prep)



v_{ej} ~ 10^4 km s^{-1}

M_{ej} ~ 3-20 $M_\odot$
oxygen-rich ejecta

$B_{dip} = 10^{14}$ G, $P_0 = 1$ ms,
$M_{ej} = 10M_\odot$, $v_{ej} = 10^4$ km s^{-1}, $f_{UV/X} = 10^{-3}$



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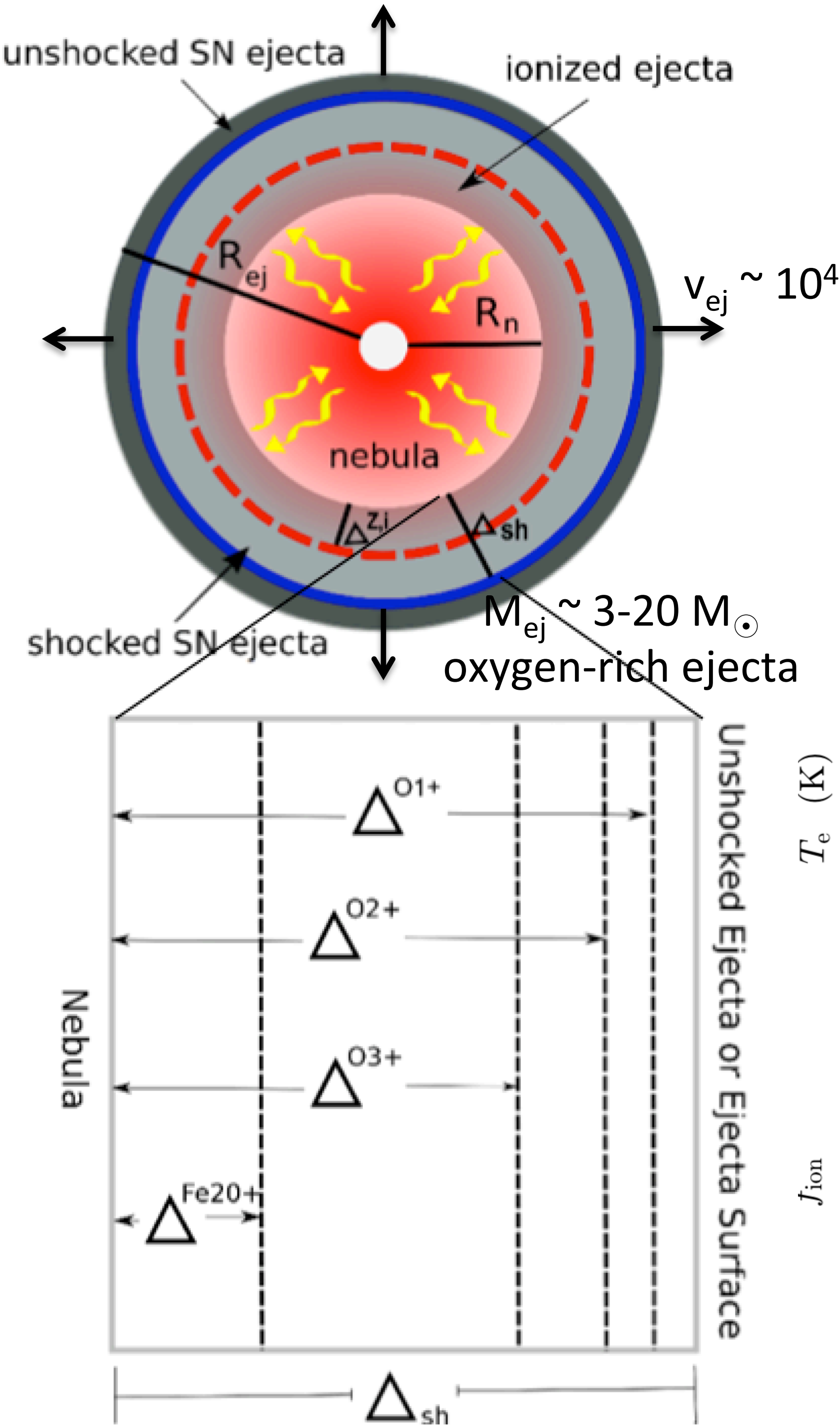

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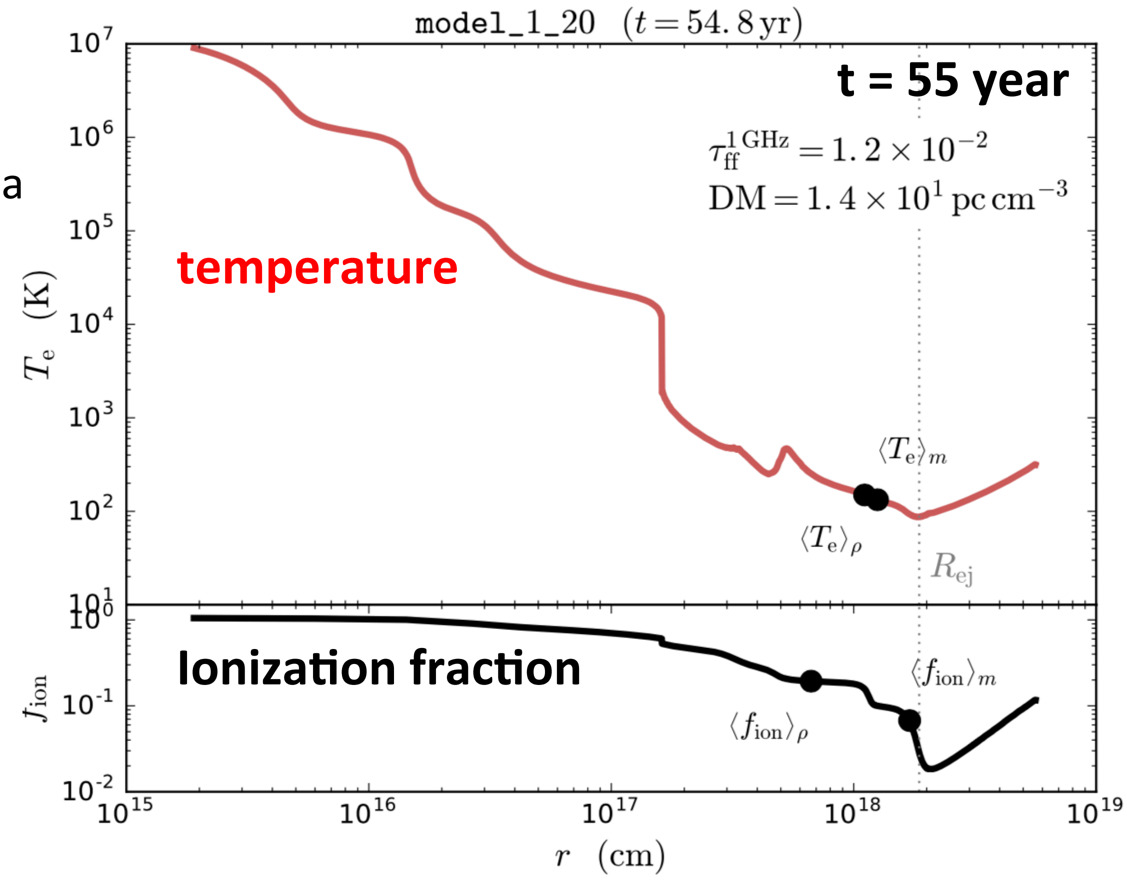

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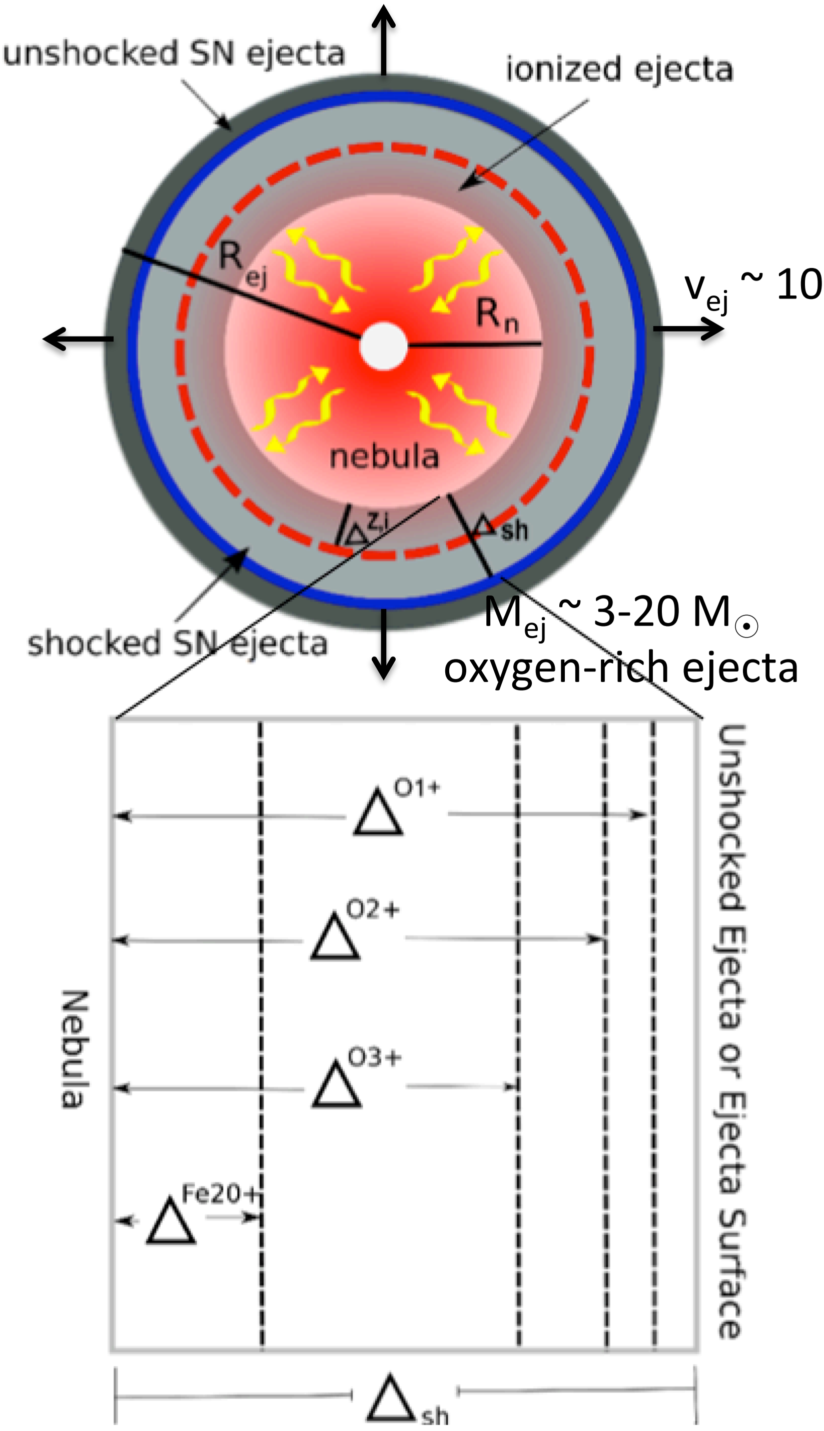
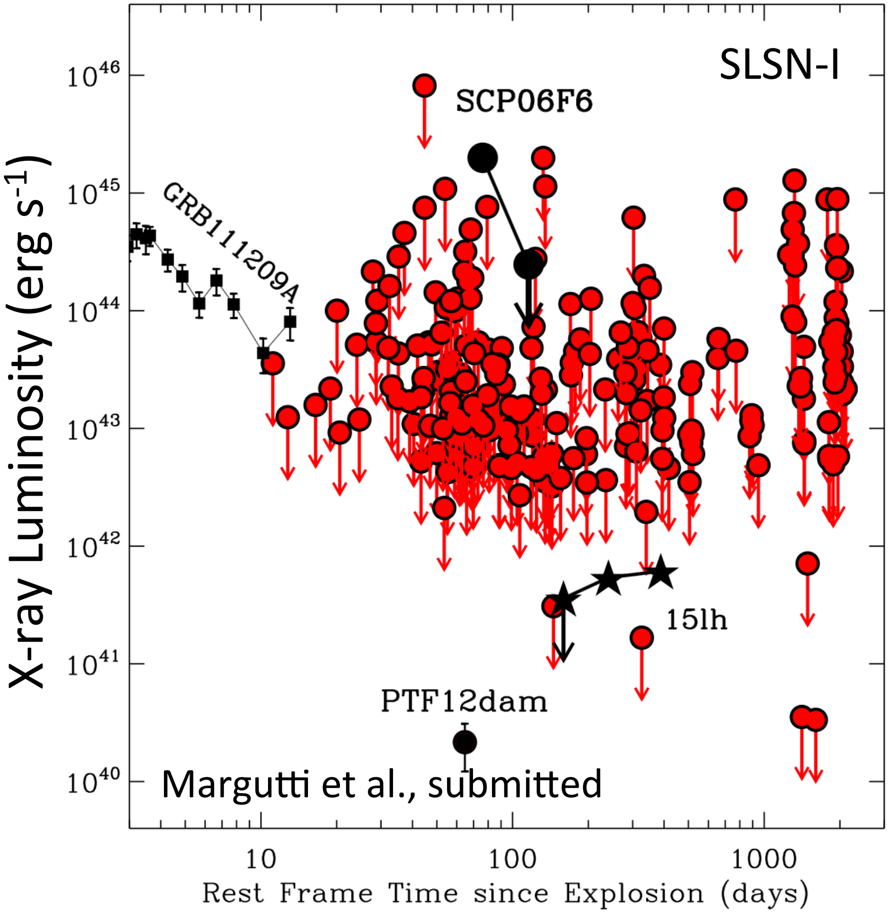


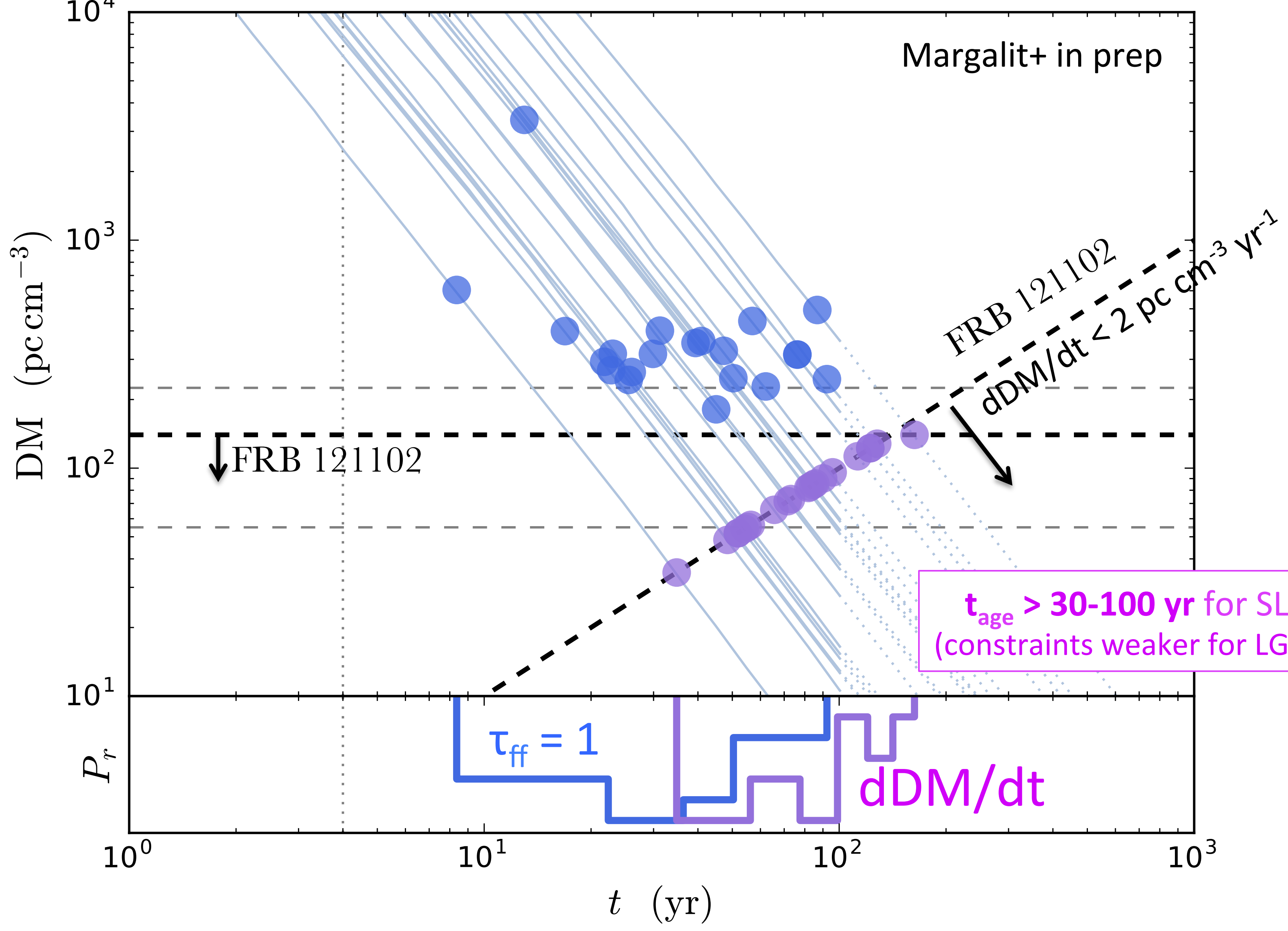
$v_{ej} \sim 10^4$ km s^{-1}

$M_{ej} \sim 3\text{-}20\ M_{\odot}$
oxygen-rich ejecta

X-ray upper limits on old SLSN-I:
consistent with weakly-ionized ejecta



Time evolution of DM and (d/dt)DM for sample of 21 SLSNe with (B_d, P_0, M_{ej}, v_{ej})

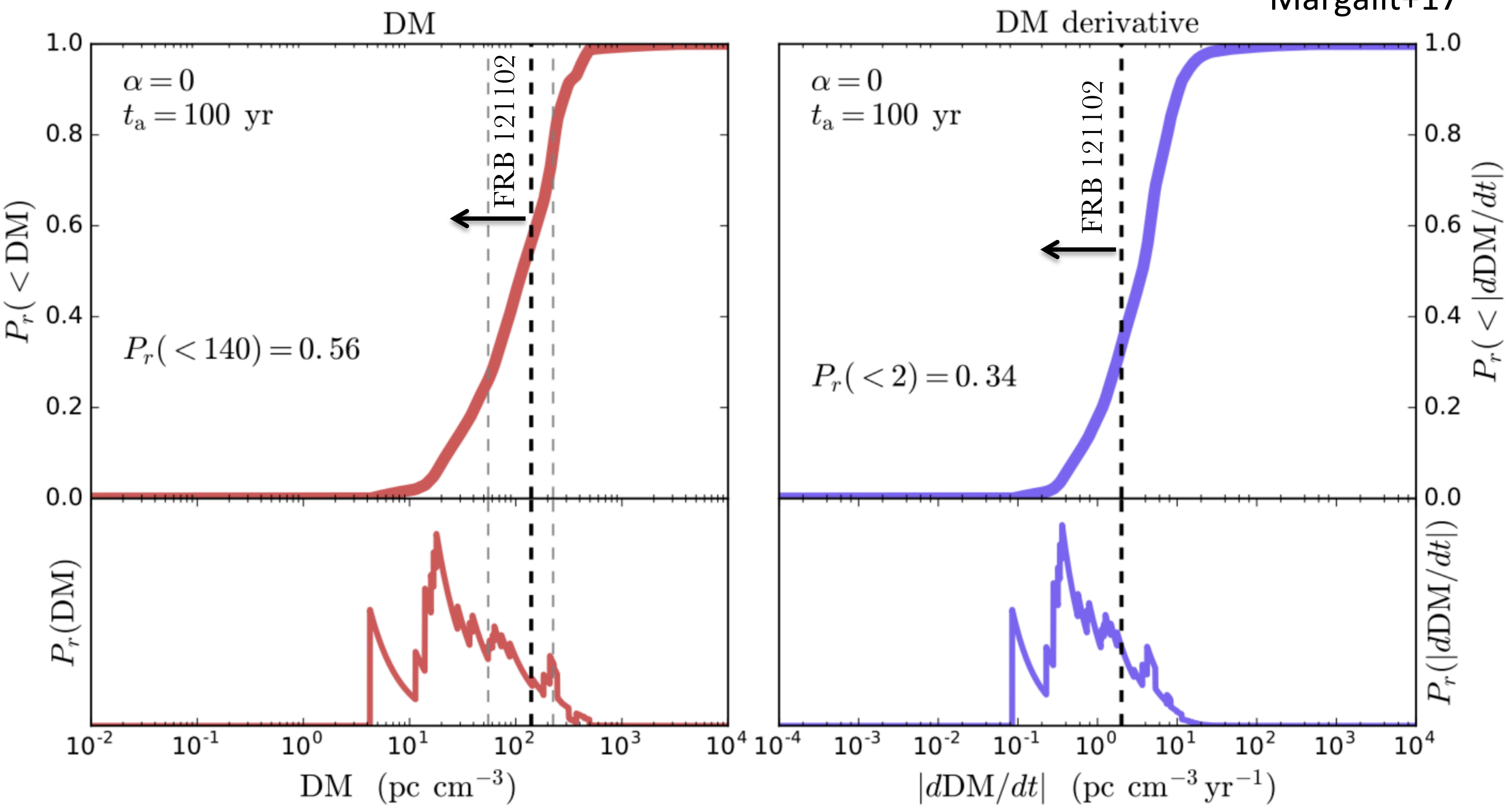


t_{age} > 30-100 yr for SLSN
(constraints weaker for LGRBs)

Supernova Ejecta DM Probability Distribution

assumed magnetar activity time t_a = 100 yr

Margalit+17



DM and dDM/dt of FRB 121102 “typical” of expected range for SLSNe population

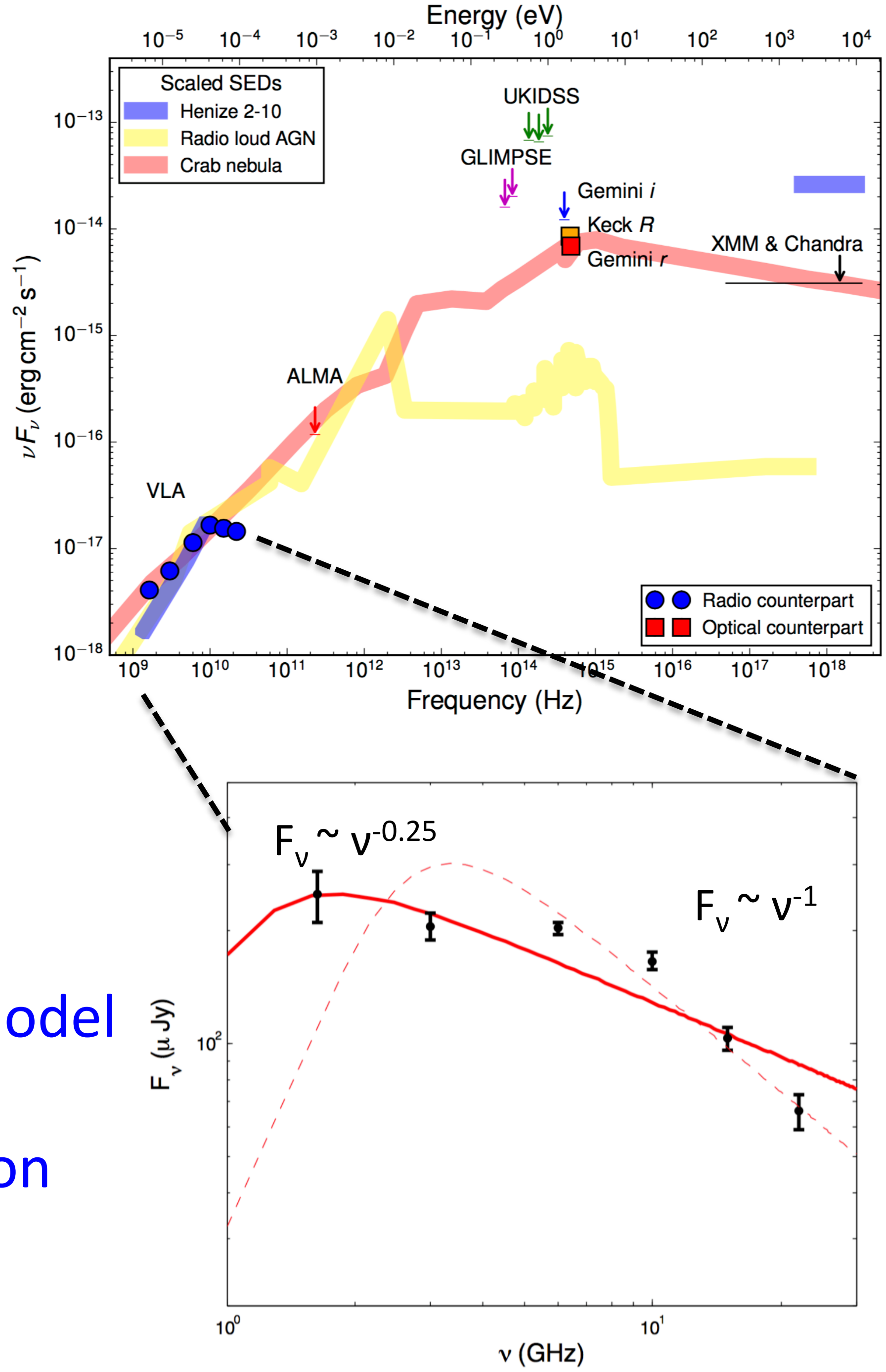
Quiescent Synchrotron Radio Source

Chatterjee+17, Marcote+17

- $L_{\rm rad} \sim 10^{39}$ erg s^{-1} in 1-20 GHz
  $E_{\rm rad} \sim L_{\rm rad} t_{\rm age} \sim 10^{48}$-$10^{49}$ erg
- Spectral break at $\nu \sim 10$ GHz
  - Cooling, Self Absorption, Injection?
- Lack of SSA places lower limit on source size

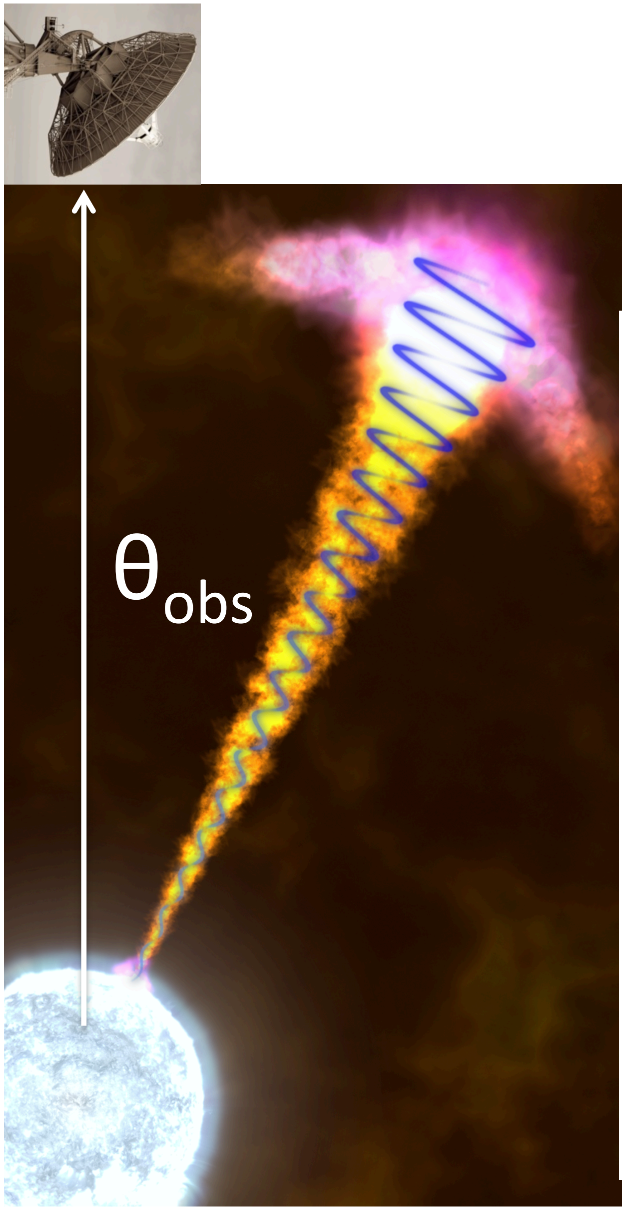
$$R_{\rm rad} \gtrsim 0.13(\gamma_e/10)^{-1/2}\ {\rm pc}$$

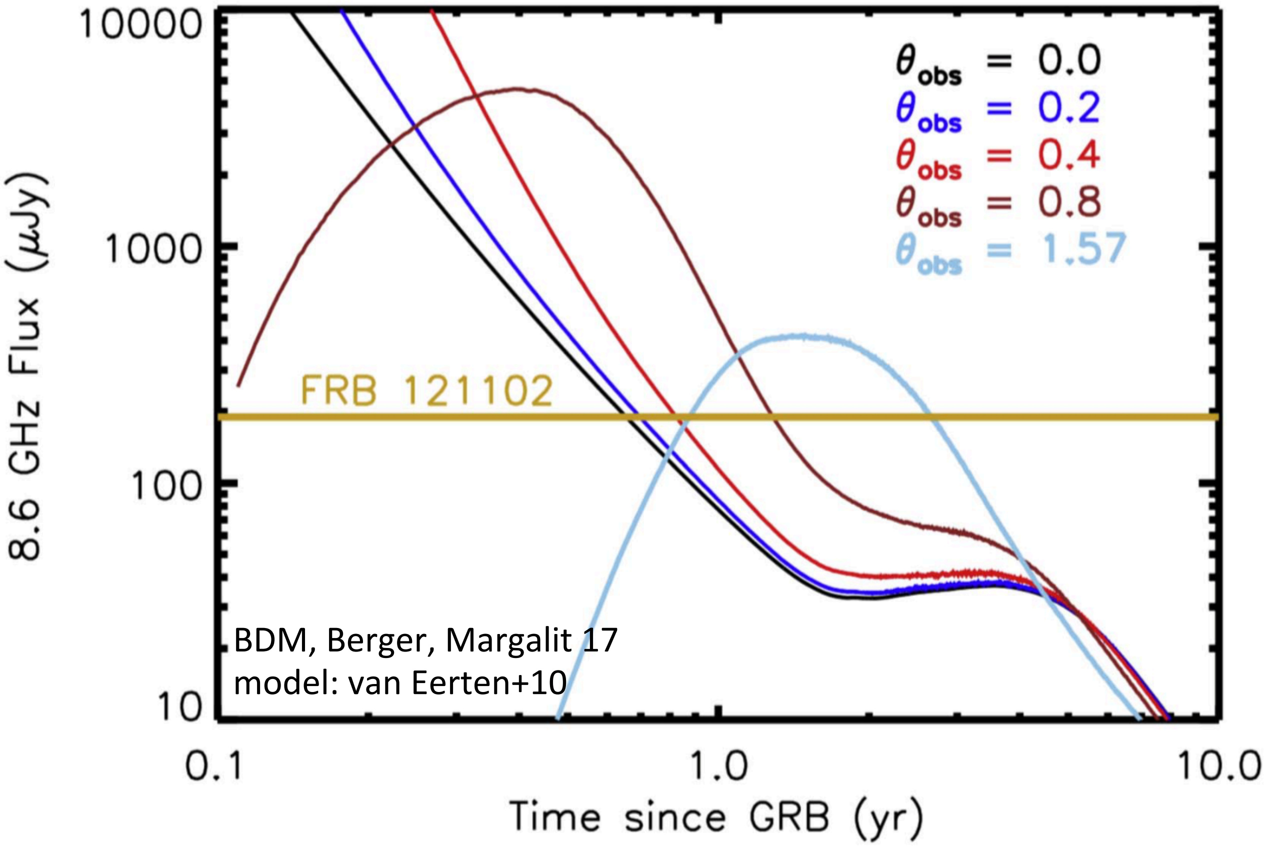
- Three Explanations in Magnetar Model
  1) Off-axis LGRB afterglow
  2) SN ejecta-CSM shock interaction
  3) "Magnetar Nebula"



Possibility #1:

Off-Axis LGRB jet



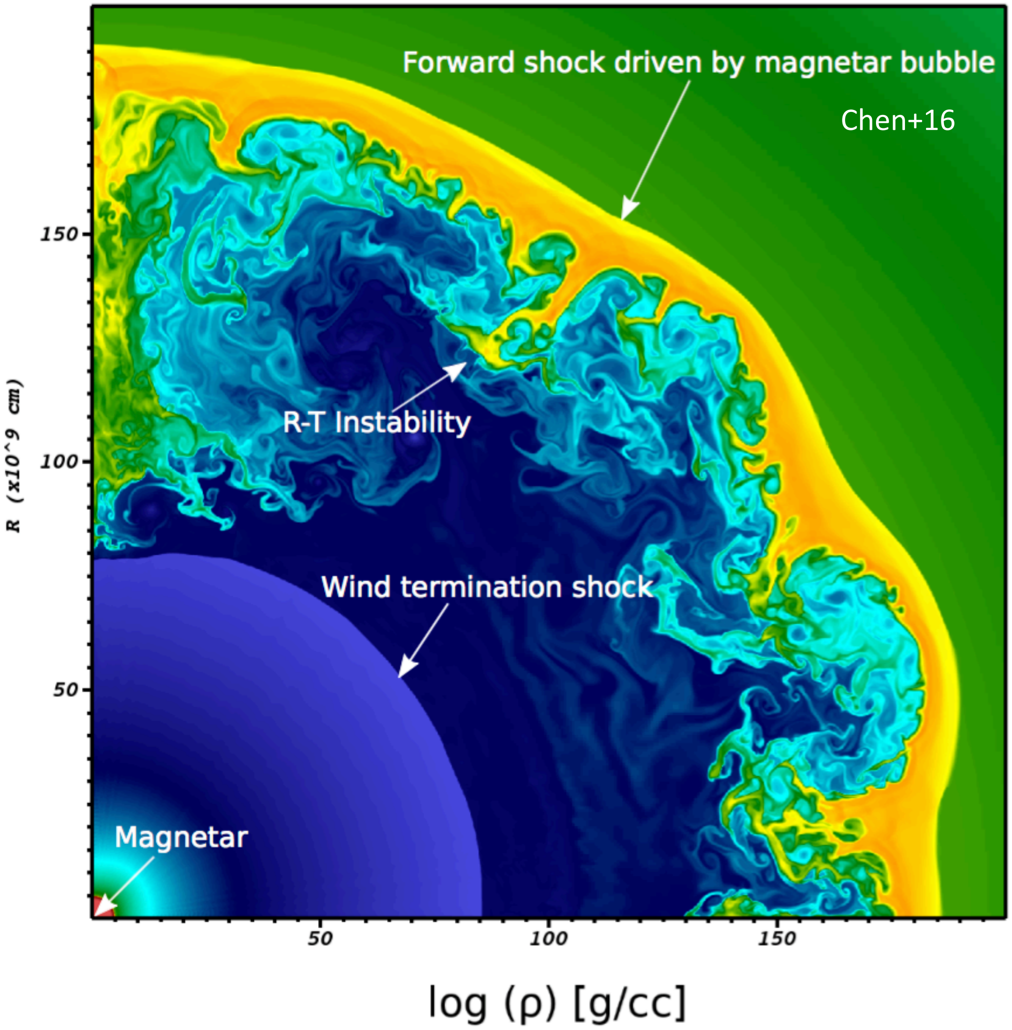


BDM, Berger, Margalit 17
model: van Eerten+10

Probably requires source to be too young (lower ISM density?)

Possibility #2: CSM Shock Interaction

Kasen, BDM, Bildsten 16;
Chen, Woosley & Sukhbold 16; Suzuki & Maeda 16



- Magnetar wind inflates nebula behind supernova ejecta.
- If $E_{rot} > E_{KE}$ nebula drives shock through outer layers of SN ejecta, accelerating small mass to trans-relativistic velocities.

$$\rho(v) \propto v^{-\beta}, \text{ where } \beta \approx 5\text{–}6$$

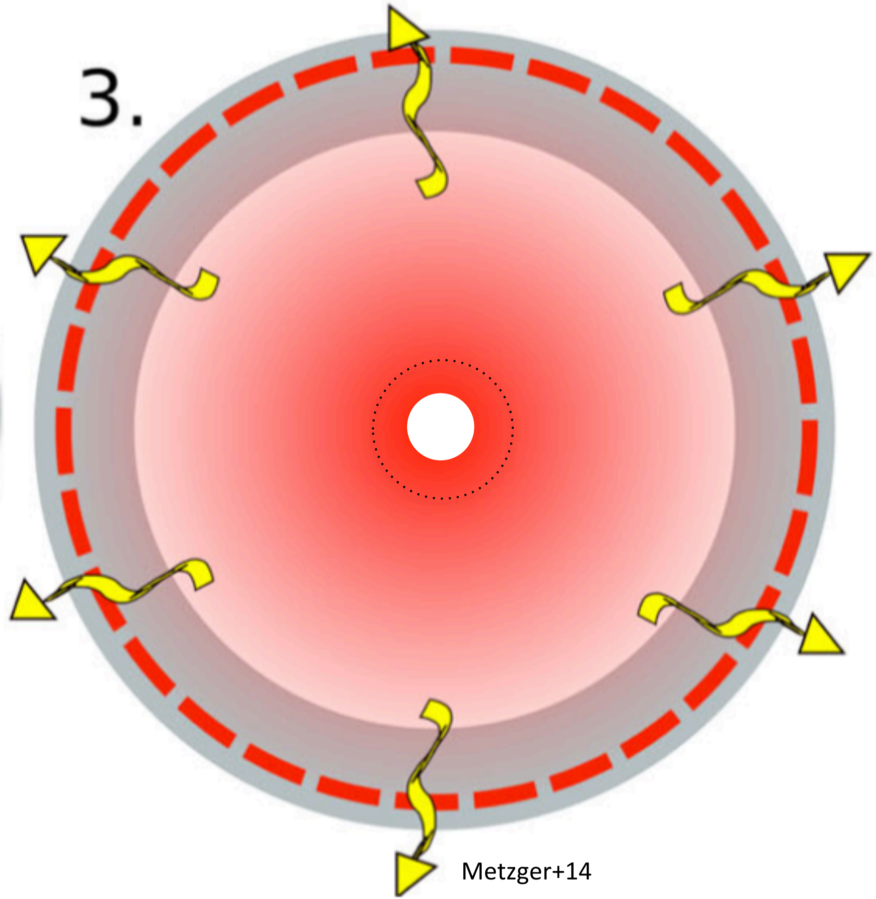
Suzuki & Maeda 16

- Shock deceleration of SN ejecta by dense progenitor star wind powers synchrotron emission.

$$F_\nu \underset{p=2.3}{\approx} 34\mu\text{Jy}\ \nu_{\text{GHz}}^{-0.65}\epsilon_{B,-1}^{0.83}\epsilon_{e,-1}^{1.3}\ t_{10}^{-1.55} A_\star^{0.925} M_{10}^{0.9} v_9^{2.7}$$

But…no radio detections yet in SLSNe at earlier times (SSA?)

Possibility #3: Magnetar Nebula

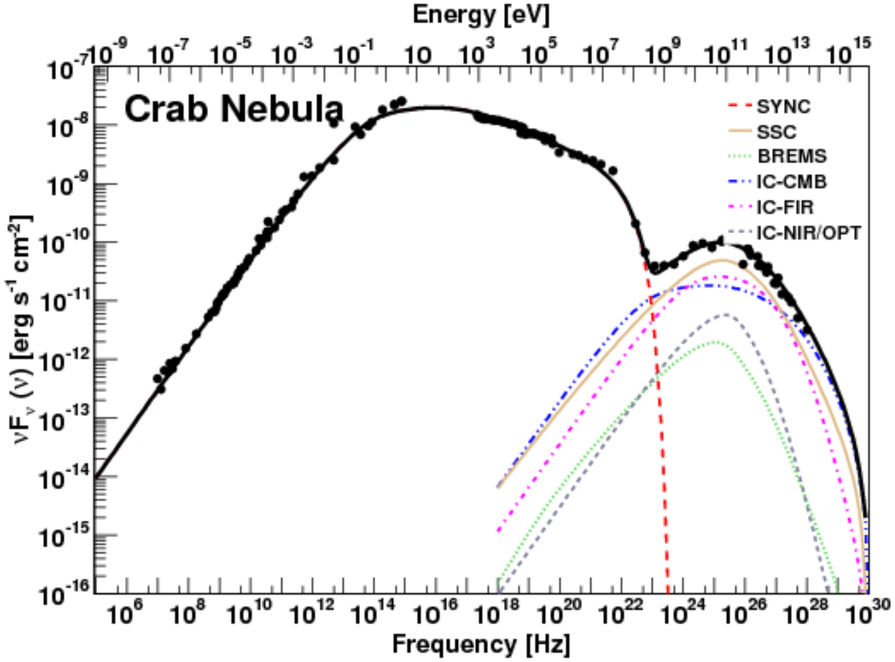


Metzger+14

Rotationally Powered?

(e.g. BDM+14, Murase+14)

$$L_{\rm sd} \underset{t \gg t_{\rm sd}}{\approx} 8 \times 10^{40} B_{14}^{-2} t_{10}^{-2}\ {\rm erg\ s}^{-1}$$



Magnetically Powered?

(Beloborodov 17)

$E_{\rm rad} \sim L_{\rm rad} t_{\rm age} \sim 10^{48}\text{-}10^{49}$ erg $\sim E_{\rm mag}$

Rates: are all FRB from magnetars?

(Nicholl+17; Law+17)

Rates

millisecond magnetar birth

SLSNe-I (z < 0.5) $\langle R_{\rm SLSN}\rangle \approx 40\ {\rm Gpc}^{-3}\ {\rm yr}^{-1}$

LGRB (z < 0.5) $\langle R_{\rm LGRB}\rangle \approx 100\ {\rm Gpc}^{-3}\ {\rm yr}^{-1}$

beaming-corrected

FRB $R_0\tau \approx 160\,(\eta\zeta)^{-1}\ {\rm Gpc}^{-3} \approx 10^4\ {\rm Gpc}^{-3}$

assuming luminosity function of repeater

τ = source lifetime, η = beaming fraction,
ζ = active duty cycle

➡ τ = 100 years > $t_{\rm age}$ ✓

Total Magnetar Birth $2.5 \times 10^4\ {\rm Gpc}^{-3}\ {\rm yr}^{-1}$

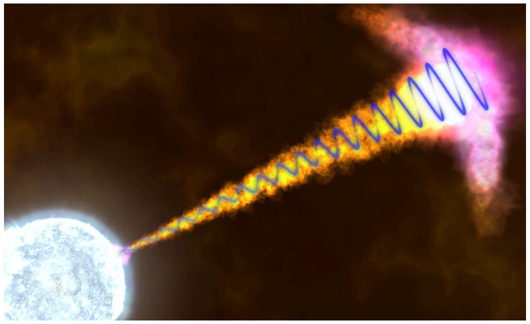
(~10% Core Collapse SNe)

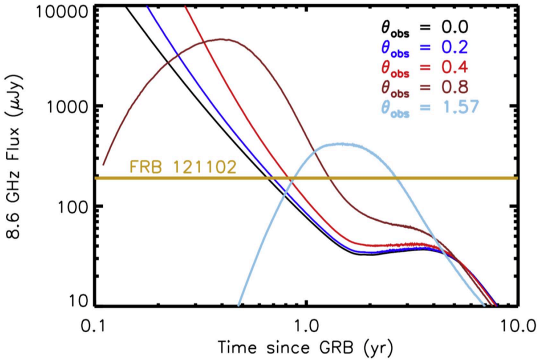
➡ τ < 1 yr (!) ✗

Predictions

Quiescent source will **fade** on timescale ~ current age

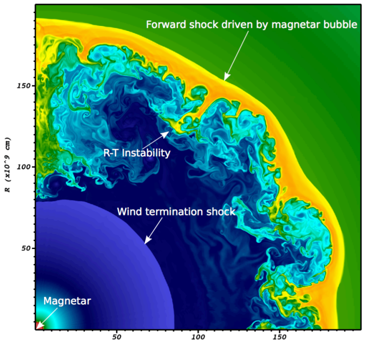
LGRB Afterglow



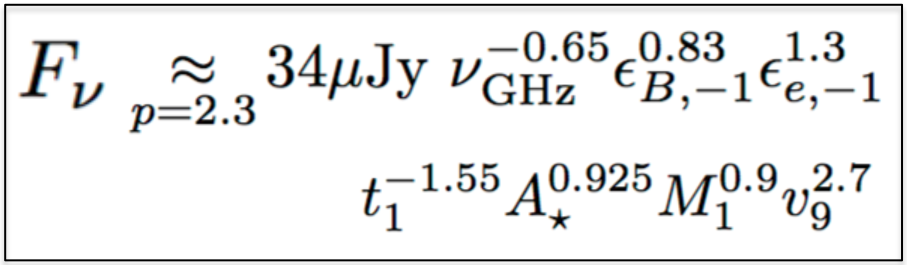


$$F_\nu \propto (t / t_{age})^{-1}$$

Ejecta-CSM Interaction

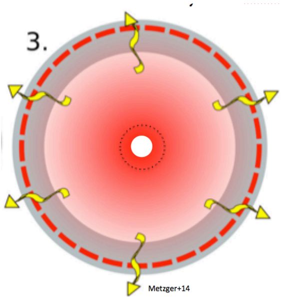


log (ρ) [g/cc]



$$F_\nu \underset{p=2.3}{\approx} 34\mu\mathrm{Jy}\ \nu_{\mathrm{GHz}}^{-0.65}\epsilon_{B,-1}^{0.83}\epsilon_{e,-1}^{1.3} t_1^{-1.55} A_\star^{0.925} M_1^{0.9} v_9^{2.7}$$

Magnetar Nebula



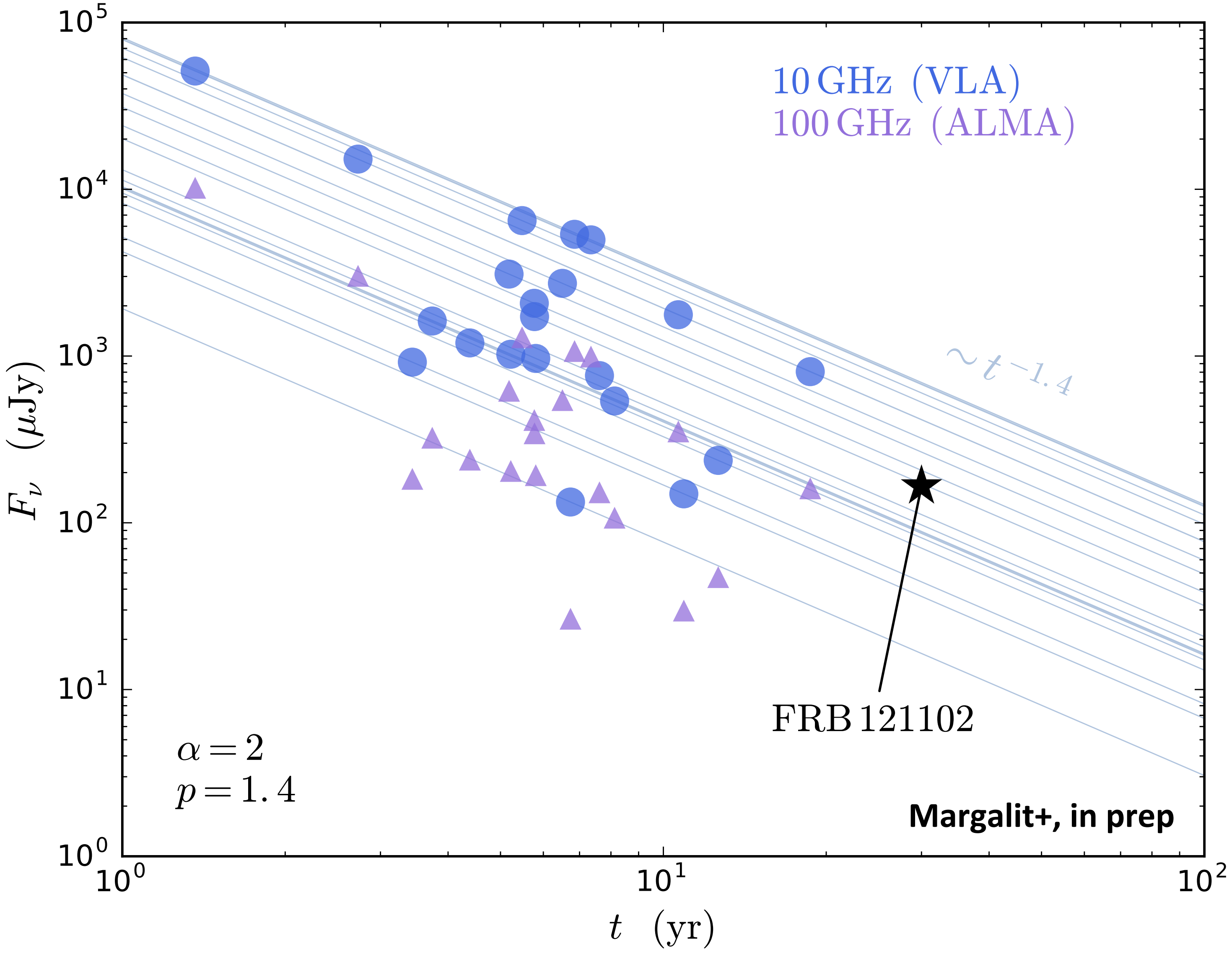
May depend on timescale of ambipolar diffusion in magnetar core

(Beloborodov 17, Li & Beloborodov 16)

Predictions

FRBs & compact synchrotron sources coincident w old SLSNe/GRB

(BDM, Berger, & Margalit 17; Omand+17)



Margalit+, in prep

Predictions

FRBs & compact synchrotron sources coincident w old SLSNe/GRB

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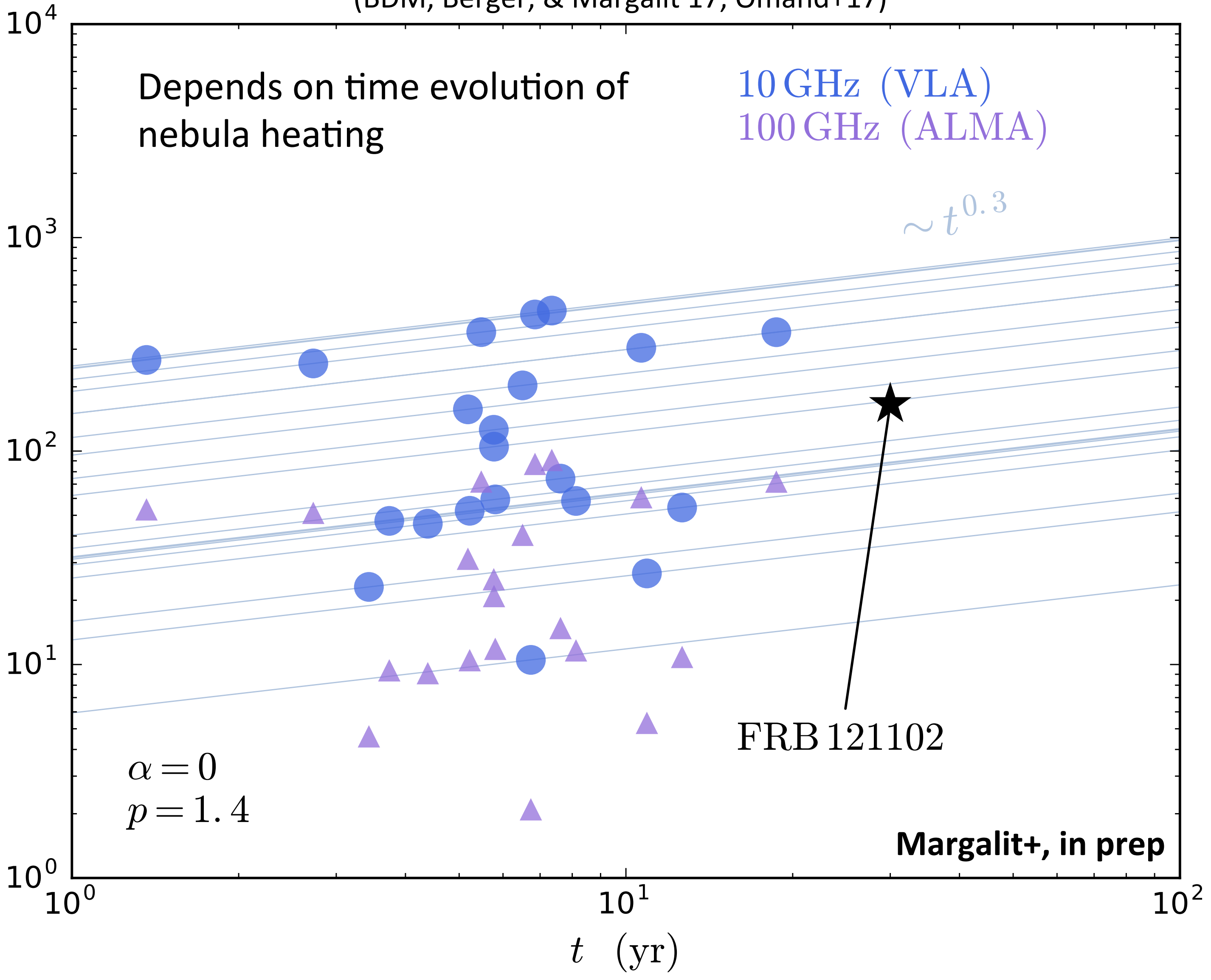
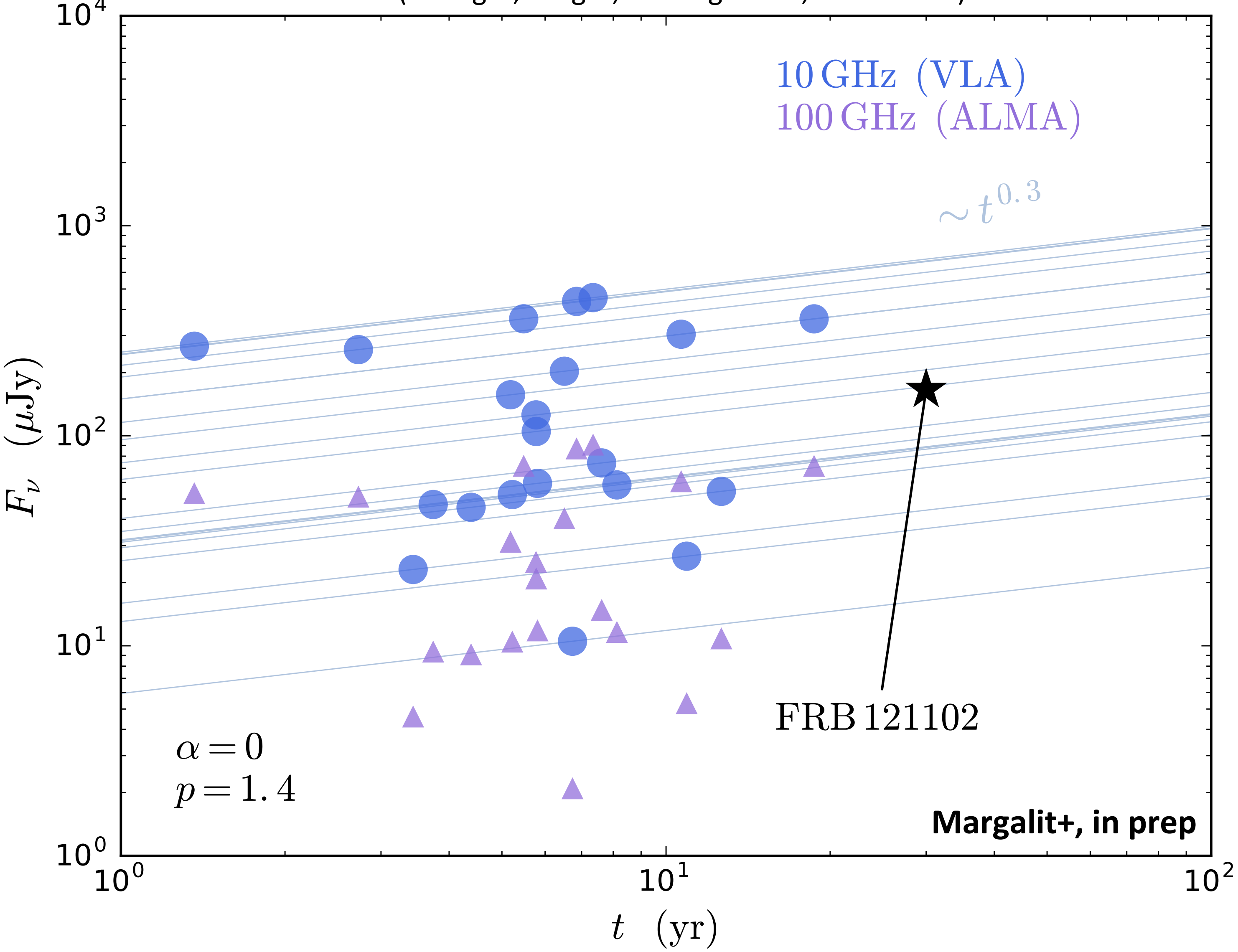


Predictions

FRBs & compact radio sources coincident w old SLSNe/GRB

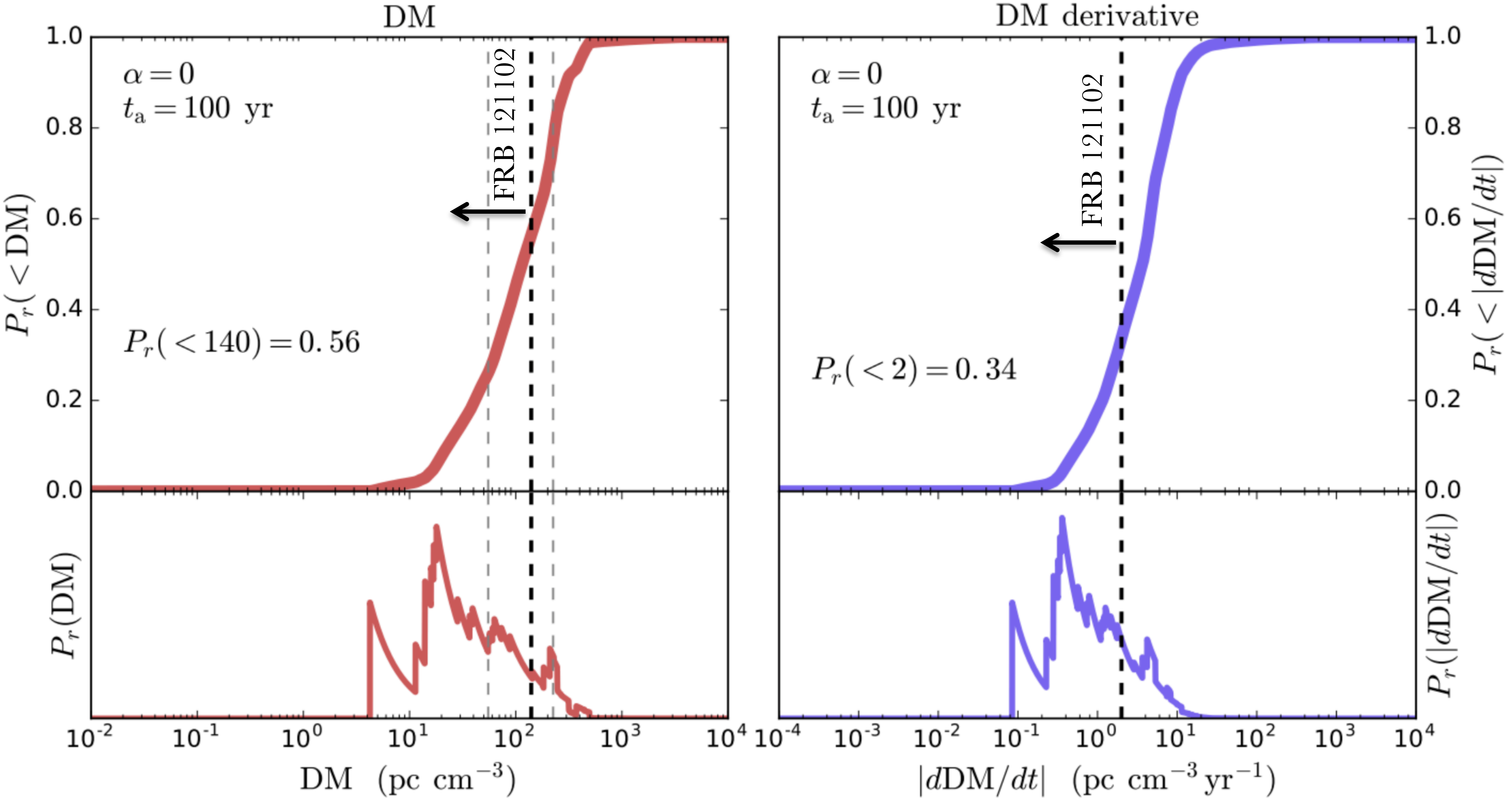
(Metzger, Berger, & Margalit 17; Omand+17)



Margalit+, in prep

Predictions

Measurable local DM or dDM/dt in future repeating FRB?

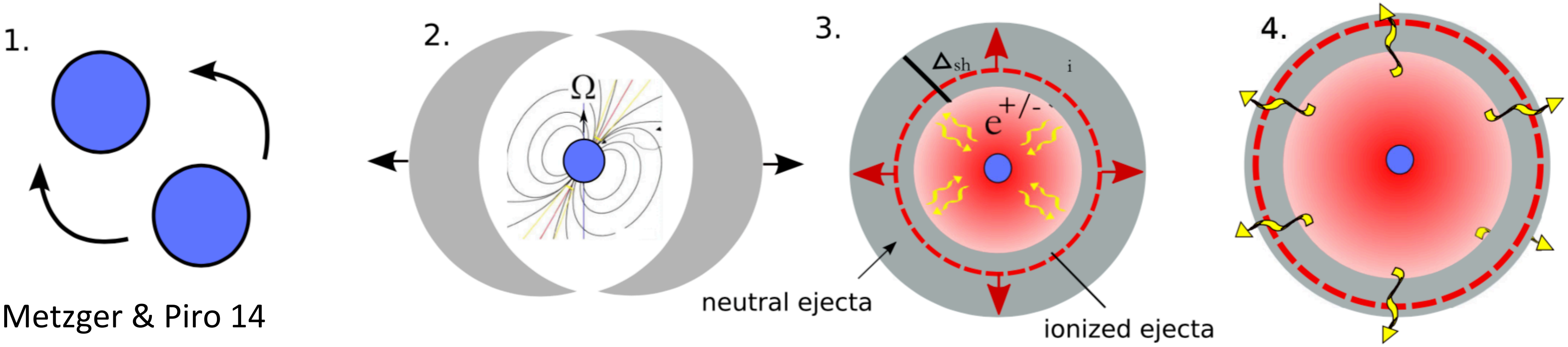


Margalit+ in prep

Predictions

FRB from Stable Remnants of Neutron Star Mergers?

Nicholl+17



Metzger & Piro 14

- Possibility of stable remnant very sensitive to NS EOS
- FRB can escape low mass ejecta within months of merger
  follow-up short GRBs or LIGO sources?
- Range of host galaxies (both elliptical and star-forming)

Conclusions

- Long GRBs and SLSNe-I are powered by a rapidly-rotating central compact object, attributed by some to a millisecond magnetar.
- Magnetars also proposed as FRB sources prior to localization of 121102, which established a similar (and rare) host galaxy to LGRB/SLSNe.
- Young flaring magnetar is embedded in SN remnant comprised of ~3-20 solar masses of partially-ionized oxygen-rich ejecta expanding at v ~ 10,000 km/s.
- Ejecta ionization state/DM controlled by photo-ionization by UV/X-ray radiation of nascent magnetar wind nebula (singly/doubly ionized).
- Source age t_{age} ~ 10-100 yr, based on upper limits from size of quiescent source and lower limits from no DM change over 4 years.
- If magnetar remains active for ~100 years, then UL on DM derivative from ejecta not unexpected, though future events could show measurable higher values.
- Coincident compact synchrotron source has several potential sources (LGRB afterglow, CSM interaction, nebula), which should fade over ~decade timescale.
- Rates of SLSNe/LGRBs are (very roughly) consistent with total FRB rate for an assumed source age ~100 years.
- What distinguishes SLSNe/GRB from Galactic magnetars? Rapid rotation at birth?
- Other tests: search for FRB or quiescent radio sources from decade-old SLSNe/LGRB, or maybe NS-NS mergers.