Constraining the ellipticity of magnetars powering superluminous supernovae

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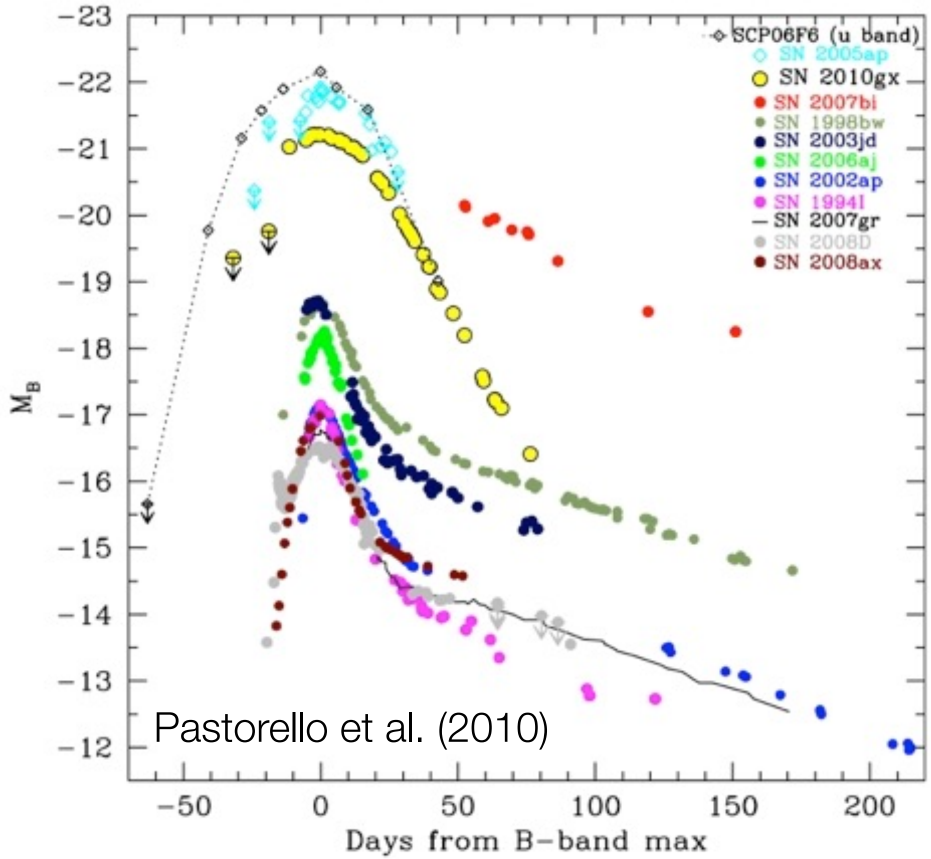
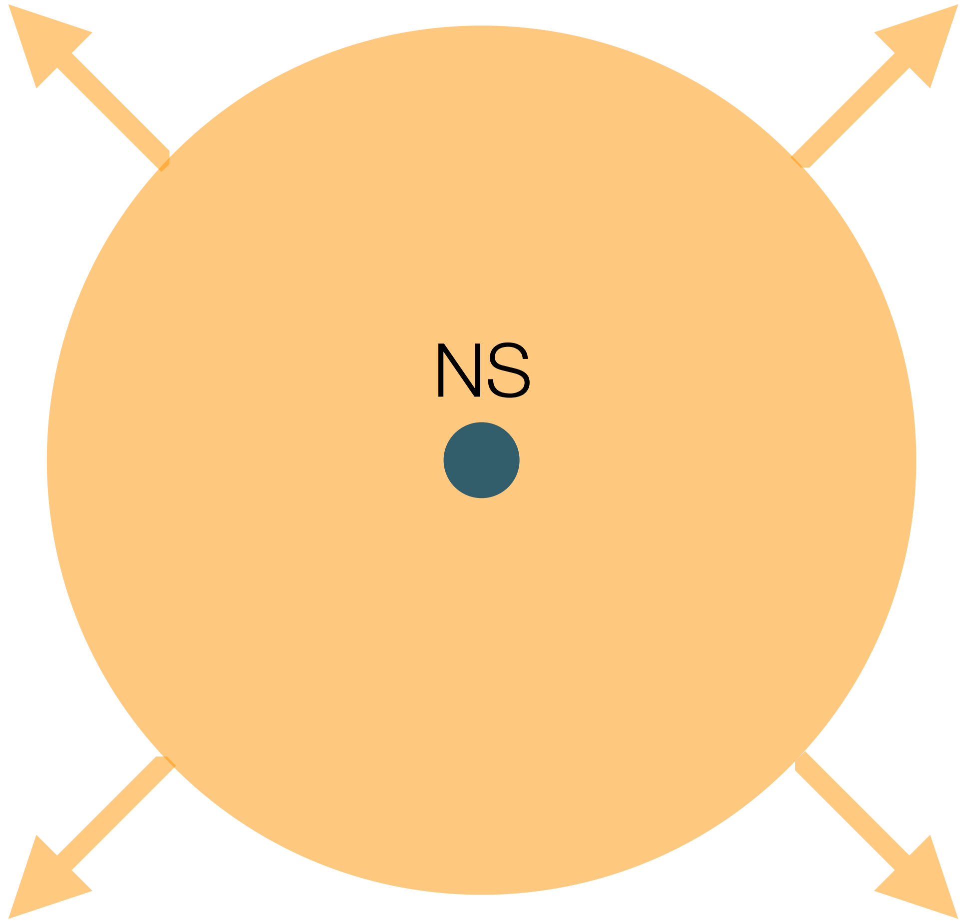
Superluminous supernovae (SLSNe)

- SNe brighter than ~ -21 mag (or ~ 1e44 erg/s)
- total radiation energy exceeds 1e51 erg
  - usual SNe emit ~ 1e49 erg
  - comparable to kinetic energy of usual SNe

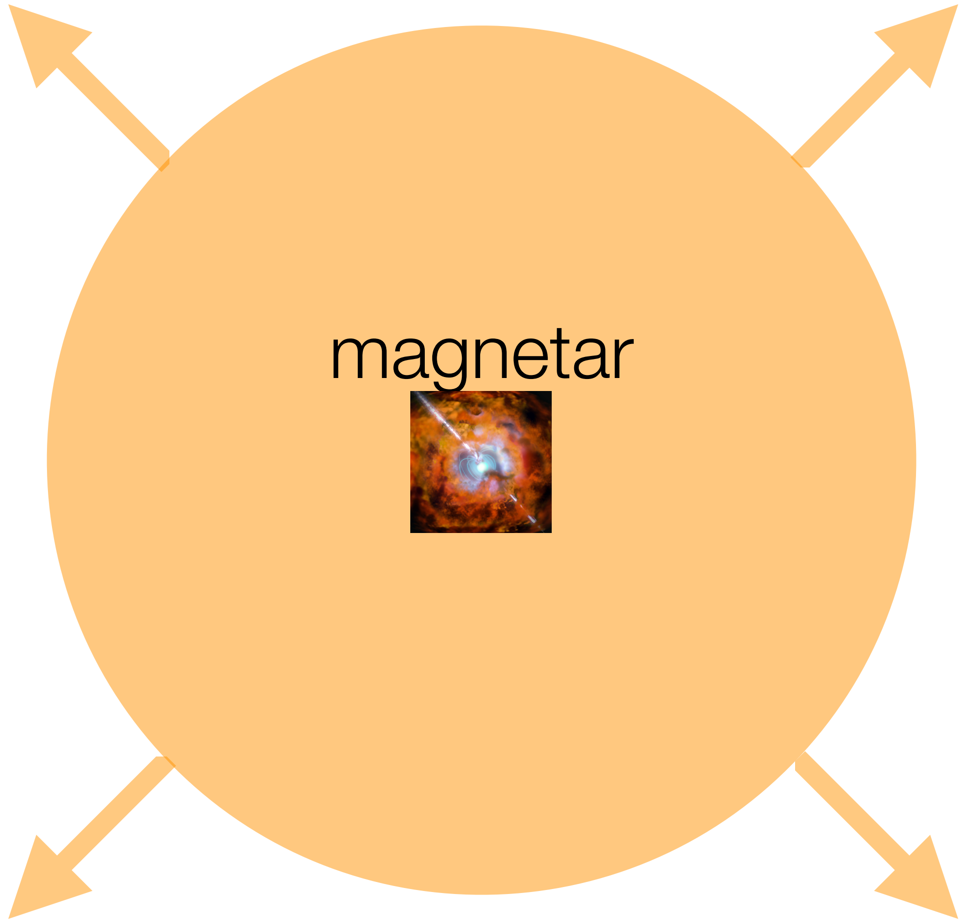


Magnetar model for SLSNe



Magnetar model for SLSNe

- magnetar



Magnetar model for SLSNe

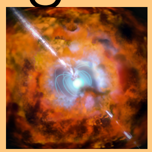
- magnetar
  - neutron star with
    - rapid rotation

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

    - strong magnetic field

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

magnetar



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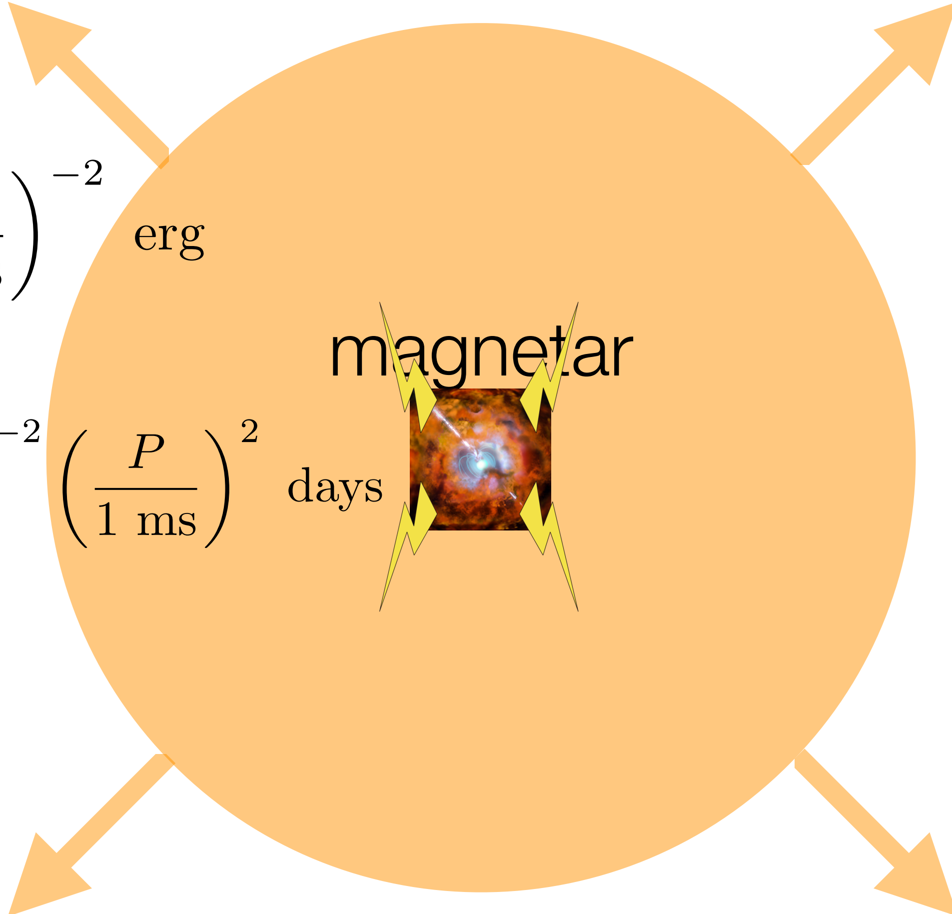
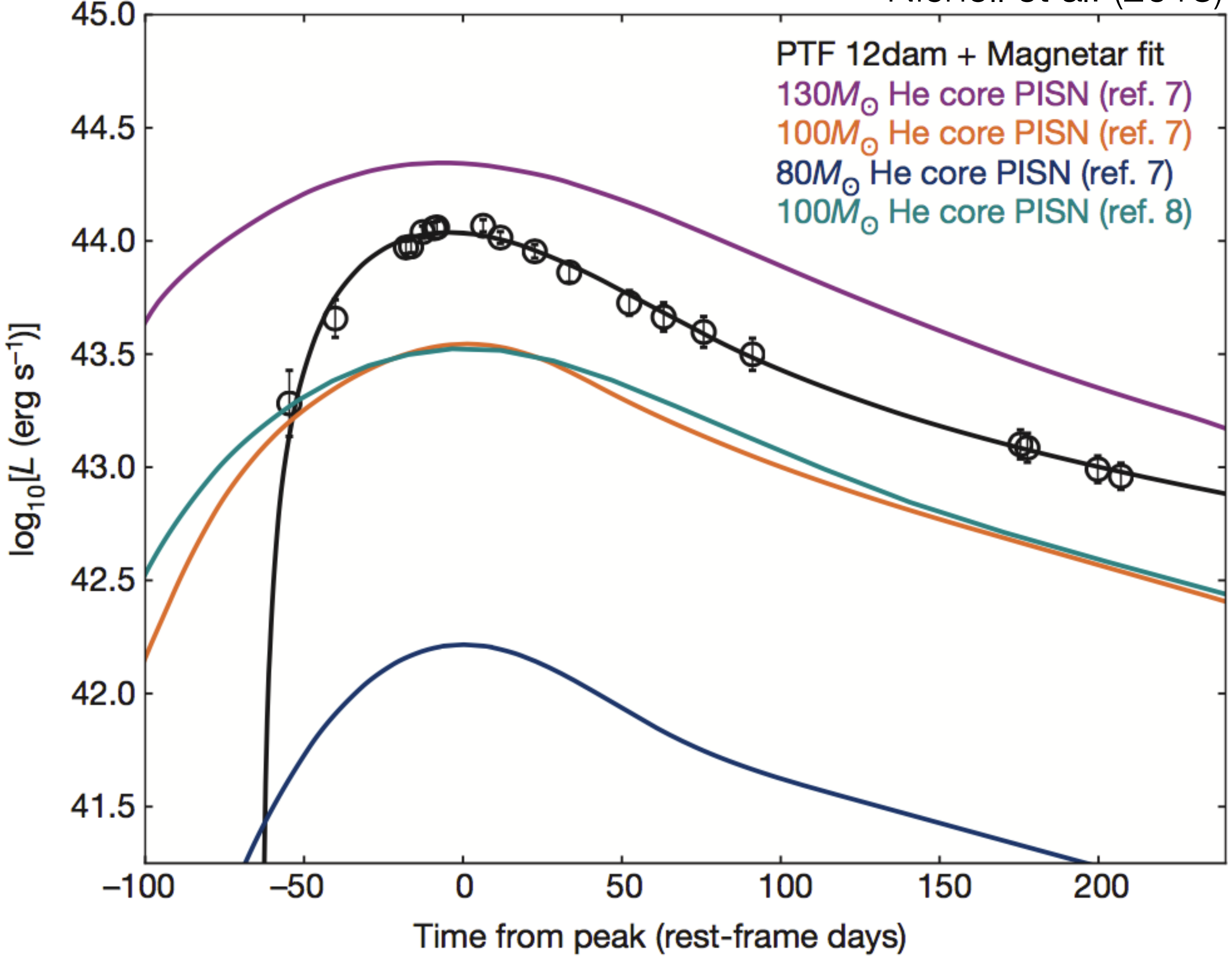


Light curve models

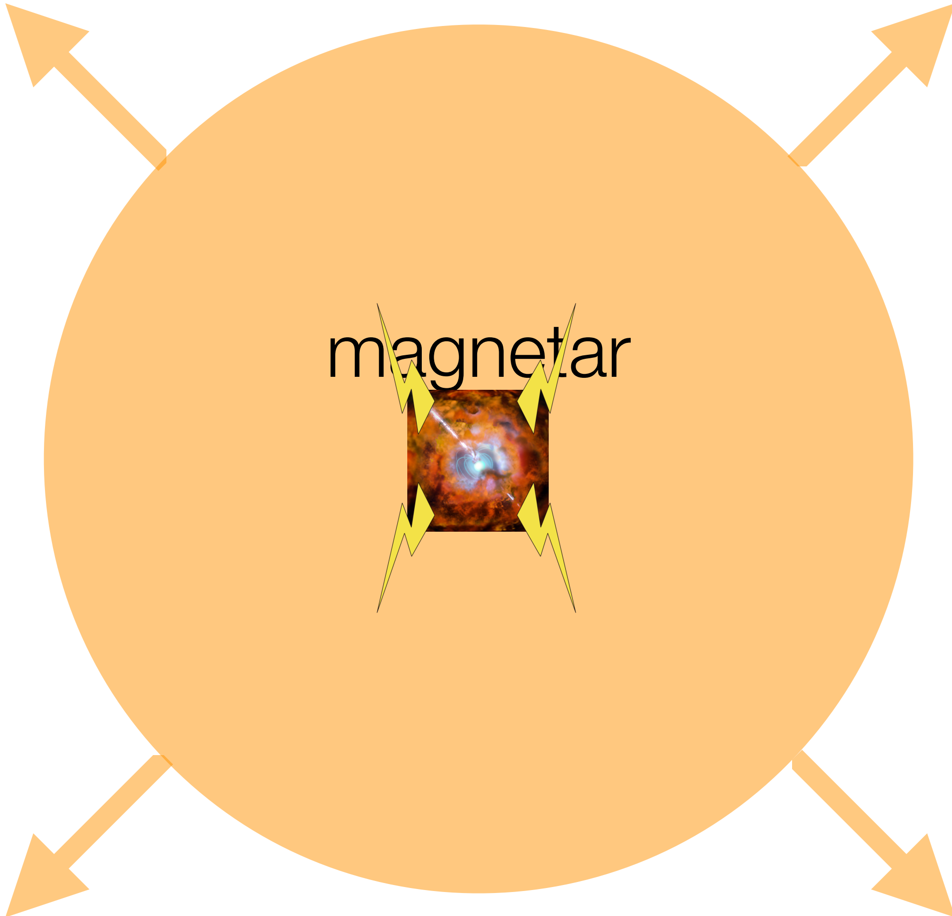
- B = 1e14 G, P = 2.6 ms

Nicholl et al. (2013)



NSs are GW sources

- magnetars need to convert rotational energy to thermal energy almost in situ for SLSNe
- if magnetars are highly distorted, GW emission will be dominant way to lose their rotational energy



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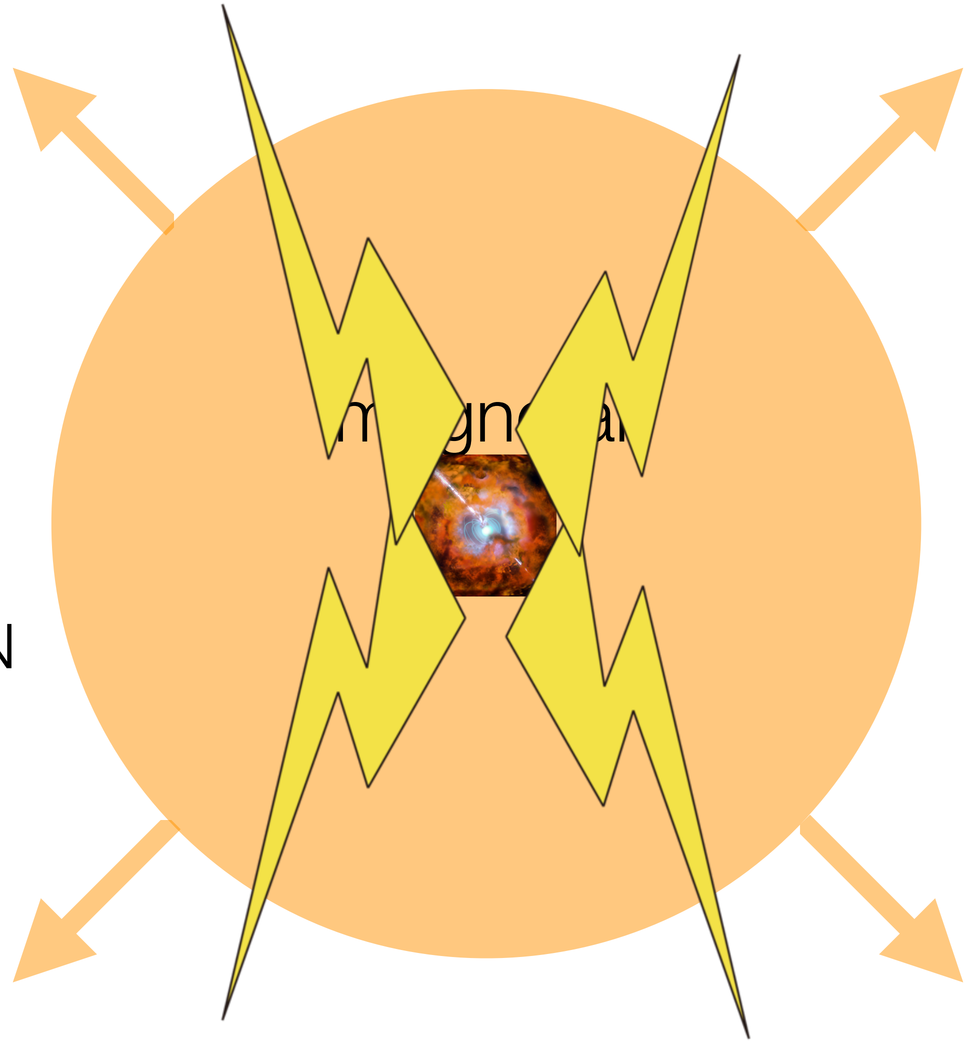

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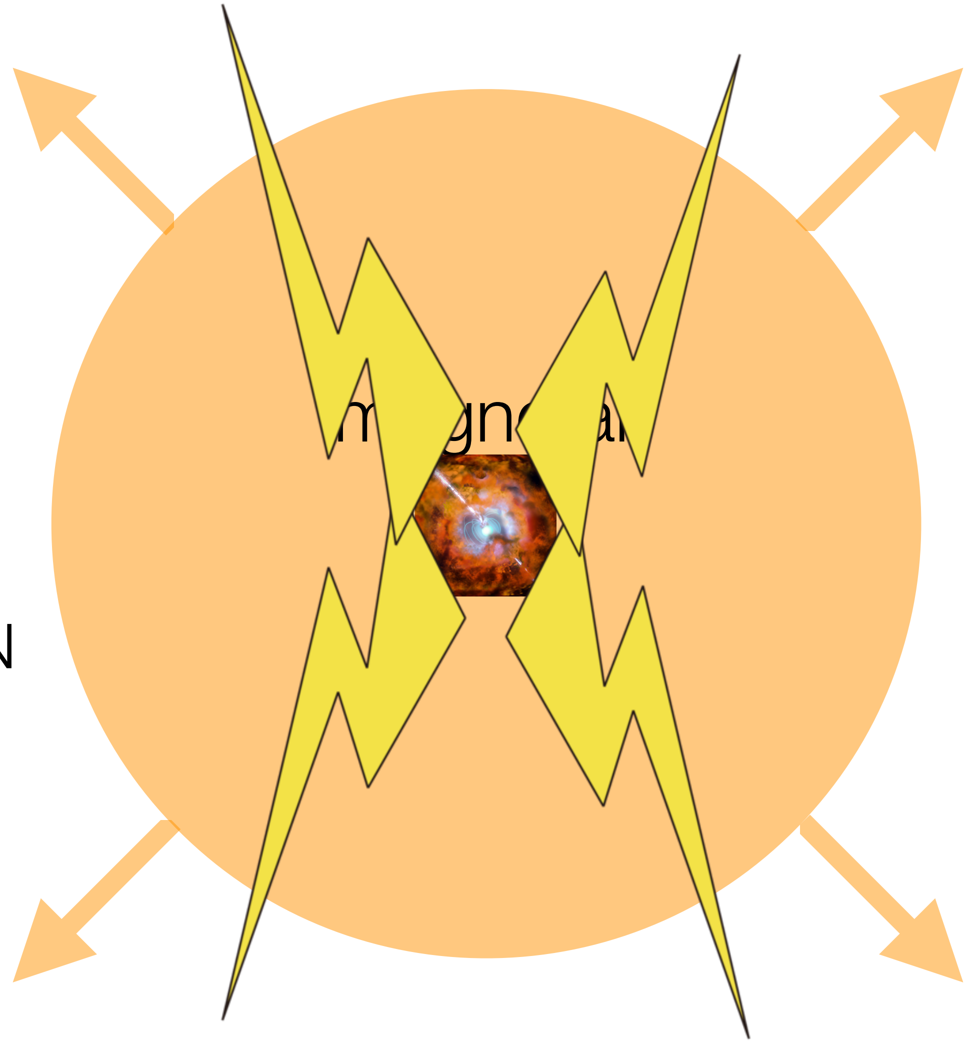
- if magnetars are highly distorted, GW emission will be dominant way to lose their rotational energy
- GW emission will just leave the SN ejecta without heating the ejecta.
- magnetars in SLSNe should not be highly distorted!



EM emission vs GW emission

- EM emission timescale (dipole)

$$\tau_{\rm EM} = \frac{3}{4\pi^2} \frac{I c^3 P_0^2}{B_{\rm dipole}^2 R^6 \sin^2 \alpha}$$

- GW emission timescale

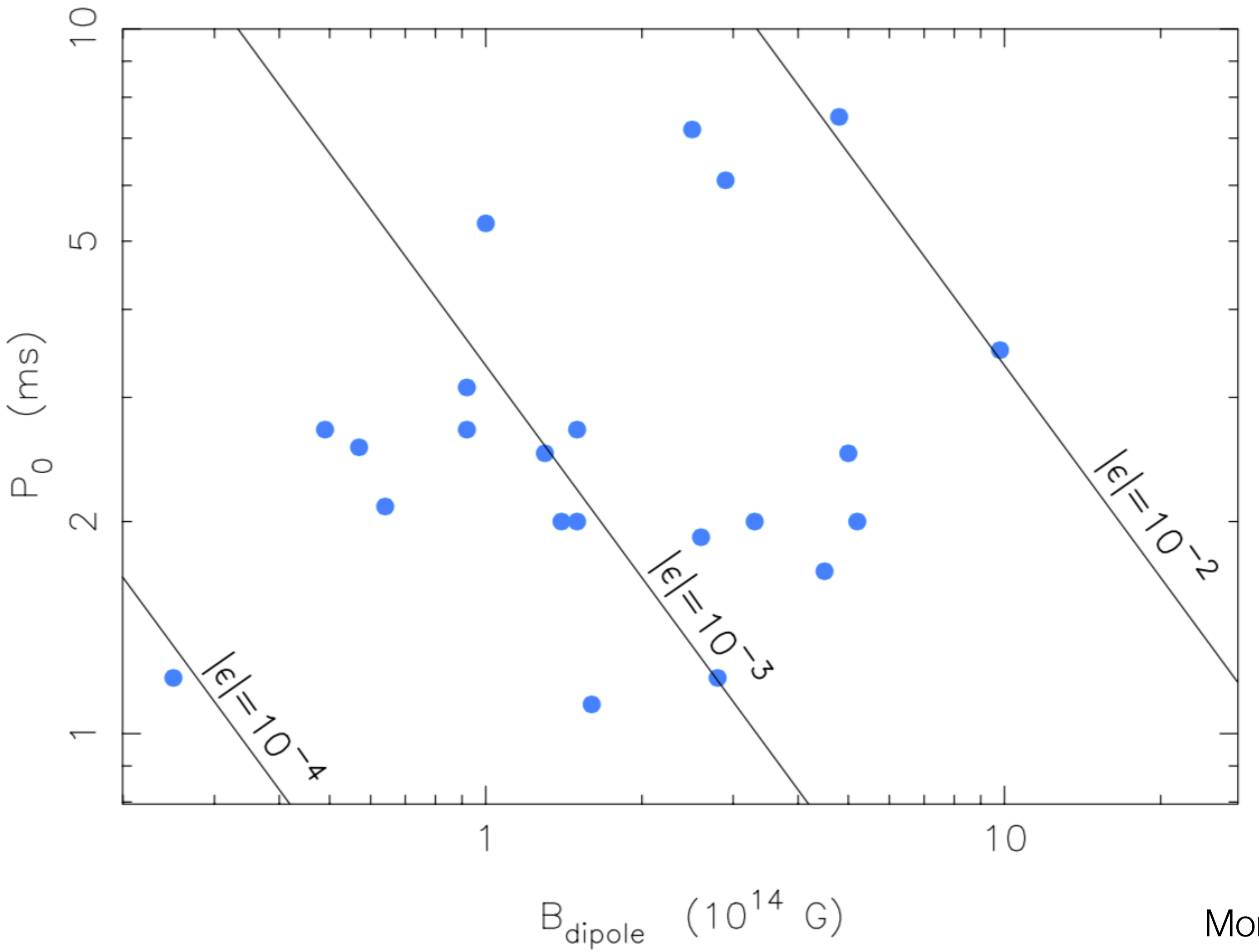
$$\tau_{\rm GW} = \frac{5}{2^{10}\pi^4} \frac{c^5 P_0^4}{G I \varepsilon^2}$$

- for SLSNe

$$\tau_{\rm GW} > \tau_{\rm EM}$$

Constraint on magnetar ellipticities for SLSNe

$$|\varepsilon| < \sqrt{\frac{5}{3G}} \frac{cR^3 P_0 B_{\rm dipole}}{2^4 \pi I} \simeq 3.0 \times 10^{-4} \left(\frac{B_{\rm dipole}}{10^{14}\,{\rm G}}\right)\left(\frac{P_0}{1\,{\rm ms}}\right)$$



Moriya & Tauris (2016)

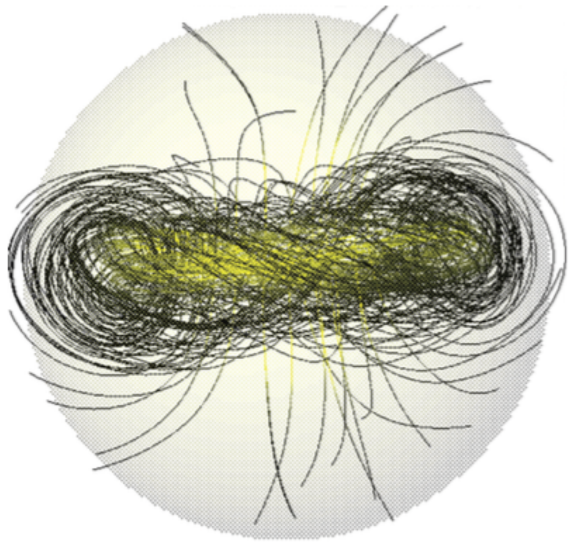
Probable origin of ellipticities: toroidal fields

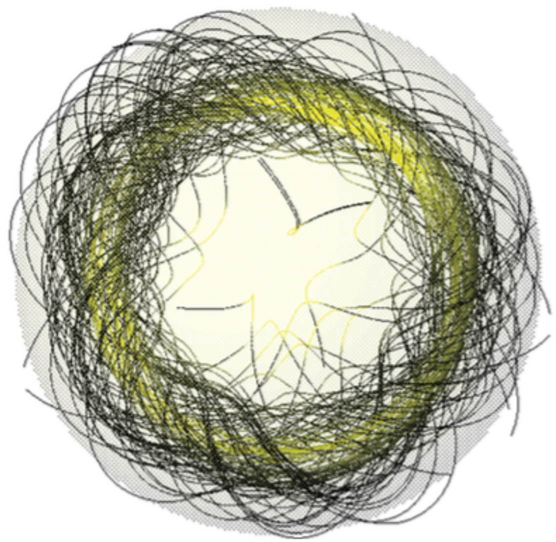
$$|\varepsilon| \simeq 1.6\times10^{-4}(B_{\mathrm{toroidal}}/10^{16}\,\mathrm{G})^2$$

Cutler (2002)

$$|\varepsilon| < \sqrt{\frac{5}{3G}}\frac{cR^3P_0B_{\mathrm{dipole}}}{2^4\pi I} \simeq 3.0\times10^{-4}\left(\frac{B_{\mathrm{dipole}}}{10^{14}\,\mathrm{G}}\right)\left(\frac{P_0}{1\,\mathrm{ms}}\right)$$

$$B_{\mathrm{toroidal}} \lesssim 1.4\times10^{16}\,\mathrm{G}\left(\frac{B_{\mathrm{dipole}}}{10^{14}\,\mathrm{G}}\right)^{1/2}\left(\frac{P_0}{1\,\mathrm{ms}}\right)^{1/2}$$





Braithwaite (2009)

Constraint on toroidal field strengths

SN name	$B_{\rm dipole}$ 10^{14}G	P_0 ms	$\lvert\varepsilon\rvert$ 10^{-3}	$B_{\rm toroidal}$ 10^{16} G	Reference
SN 2005ap	0.92	3.1	<0.85	<2.4	Chatzopoulos et al. (2013)
SCP06F6	1.3	2.5	<0.98	<2.5	Chatzopoulos et al. (2013)
SNLS 06D4eu	1.4	2.0	<0.85	<2.3	Howell et al. (2013)
SN 2007bi	0.92	2.7	<0.75	<2.2	Chatzopoulos et al. (2013)
SN 2010gx	5.2	2.0	<3.1	<4.5	Inserra et al. (2013)
SN 2010kd	1.5	2.7	<1.2	<2.8	Chatzopoulos et al. (2013)
SN 2010kl	9.8	3.5	<10	<8.2	Bersten et al. (2016)
PTF10hgi	2.5	7.2	<5.4	<5.9	Inserra et al. (2013)
SN 2011ke	4.5	1.7	<2.3	<3.9	Inserra et al. (2013)
SN 2011kf	3.3	2.0	<2.0	<3.6	Inserra et al. (2013)
PTF11rks	4.8	7.5	<11	<8.4	Inserra et al. (2013)
SN 2012il	2.9	6.1	<5.3	<5.9	Inserra et al. (2013)
PTF12dam	0.49	2.7	<0.39	<1.6	Chen et al. (2015)
CSS121015	1.5	2.0	<0.90	<2.4	Nicholl et al. (2014)
LSQ12dlf	2.6	1.9	<1.5	<3.1	Nicholl et al. (2014)
SSS120810	2.8	1.2	<1.0	<2.6	Nicholl et al. (2014)
SN 2013dg	5.0	2.5	<3.7	<5.0	Nicholl et al. (2014)
iPTF13ajg	1.6	1.1	<0.54	<1.9	Vreeswijk et al. (2014)
iPTF13ehe	0.57	2.55	<0.43	<1.7	Wang et al. (2015)
DES13S2cmm	1.0	5.3	<1.6	<3.2	Papadopoulos et al. (2015)
SN 2015bn	0.64	2.1	<0.40	<1.6	Nicholl et al. (2016)
ASASSN-15lh	0.25	1.2	<0.090	<0.77	Bersten et al. (2016)

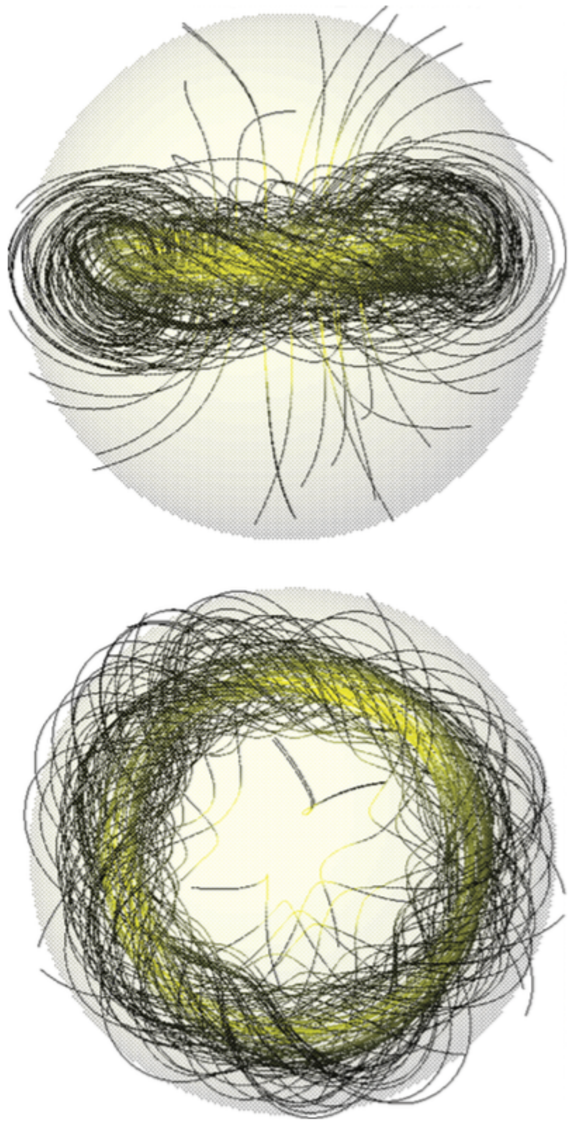
Btoroidal < ~ 1e16 G

Moriya & Tauris (2016)

Toroidal fields are required for stable poloidal fields

- Bdipole ~ 1e14 G (from LC modeling)
- Btoroidal < ~ 1e16 G (from ellipticities)

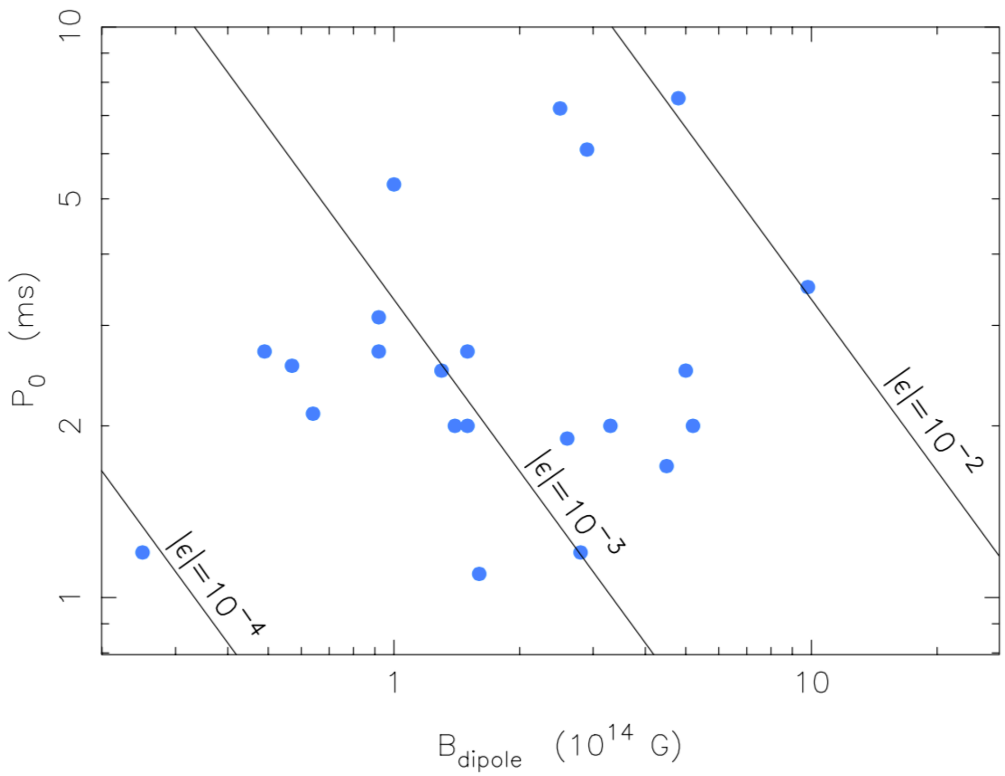
- Bdipole/Btoroidal > ~ 0.01
  - still OK (dipole field can be stable)
  - all SLSNe must have stable dipole if they are powered by magnetars
    - a test for the SLSN magnetar model

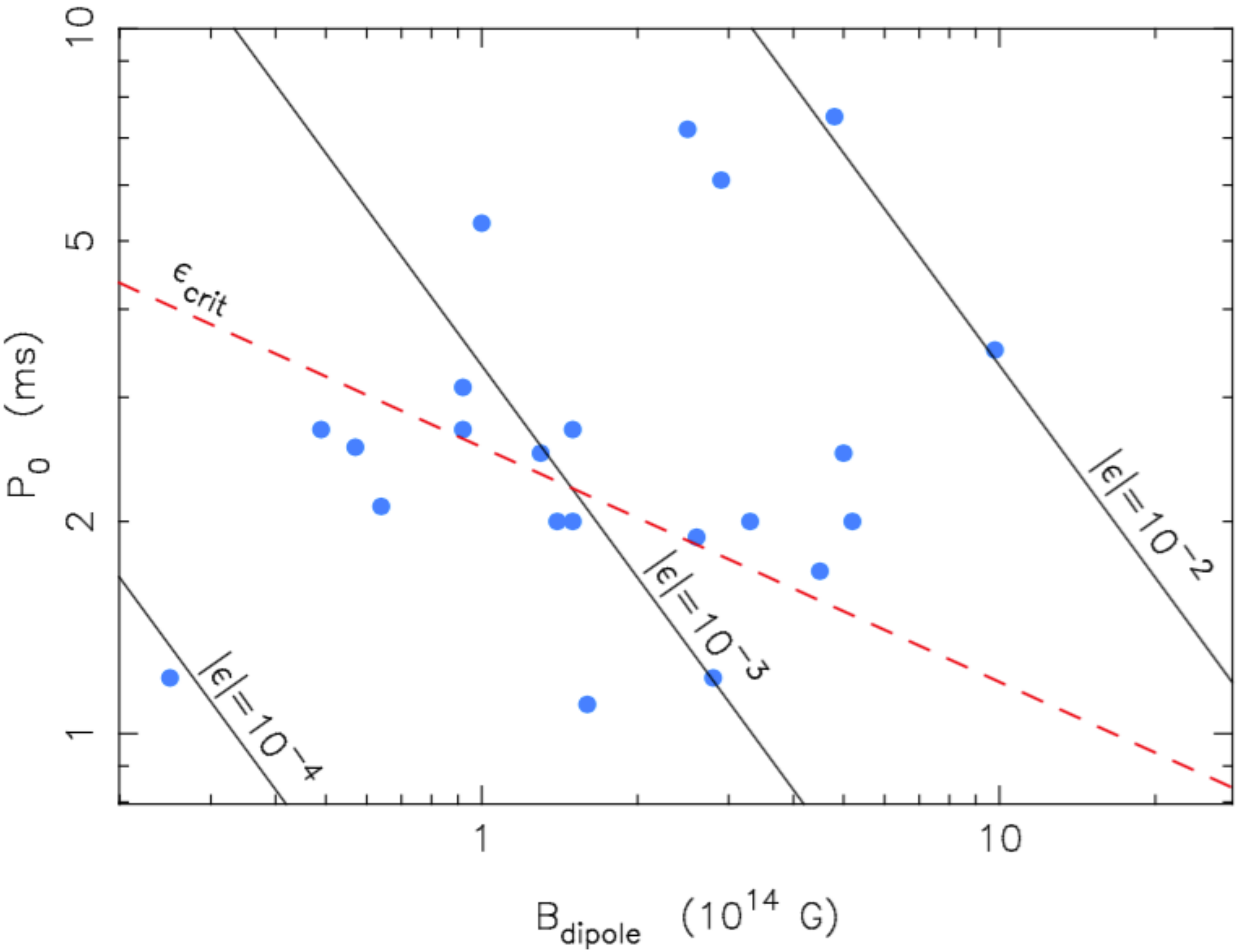


Braithwaite (2009)

Summary

- SLSNe may be powered by magnetars
  - Bdipole ~ 1e14 G, P ~ 1 ms
- magnetars must lose their rotational energy as EM emission
  - magnetar ellipticities must be small enough to avoid GW emission
- magnetar ellipticities must be less than ~ 1e-3
  - Btoroidal < ~ 1e16 G
- Bdipole/Btoroidal > ~ 0.01
  - dipole field can be stable
- a test for SLSN magnetar model





10
5
2
1
P_0 (ms)
1
10
B_{dipole} (10^{14} G)
ϵ_{crit}
$|\epsilon|=10^{-2}$
$|\epsilon|=10^{-3}$
$|\epsilon|=10^{-4}$