Fast radio bursts from magnetars

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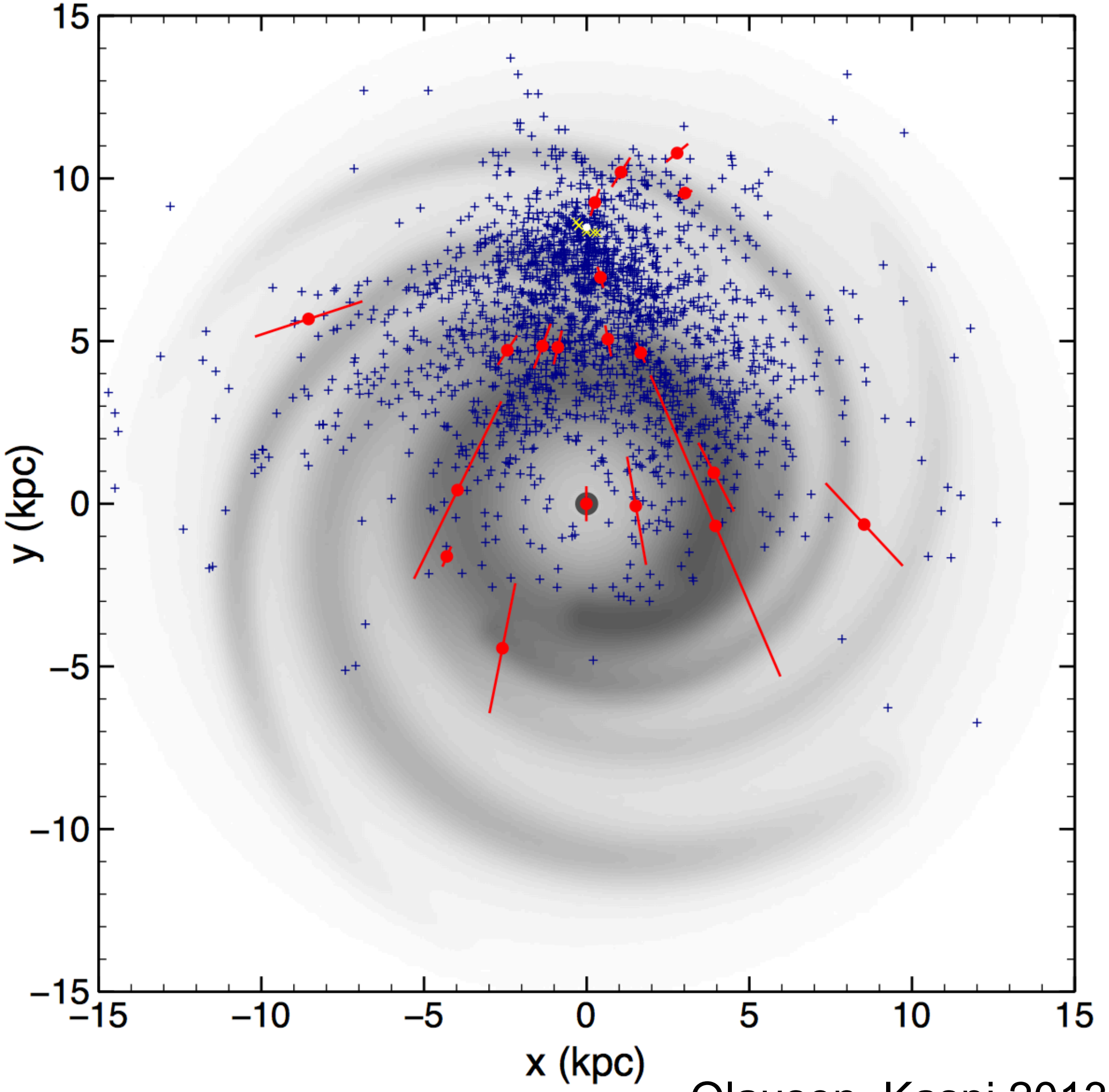
magnetar = powered by magnetic energy
(not rotation, as in the ms magnetar model)

ApJL, in press

Observed magnetars:

age ~ kyr

intermittent activity,
multiple bursts,
giant flares

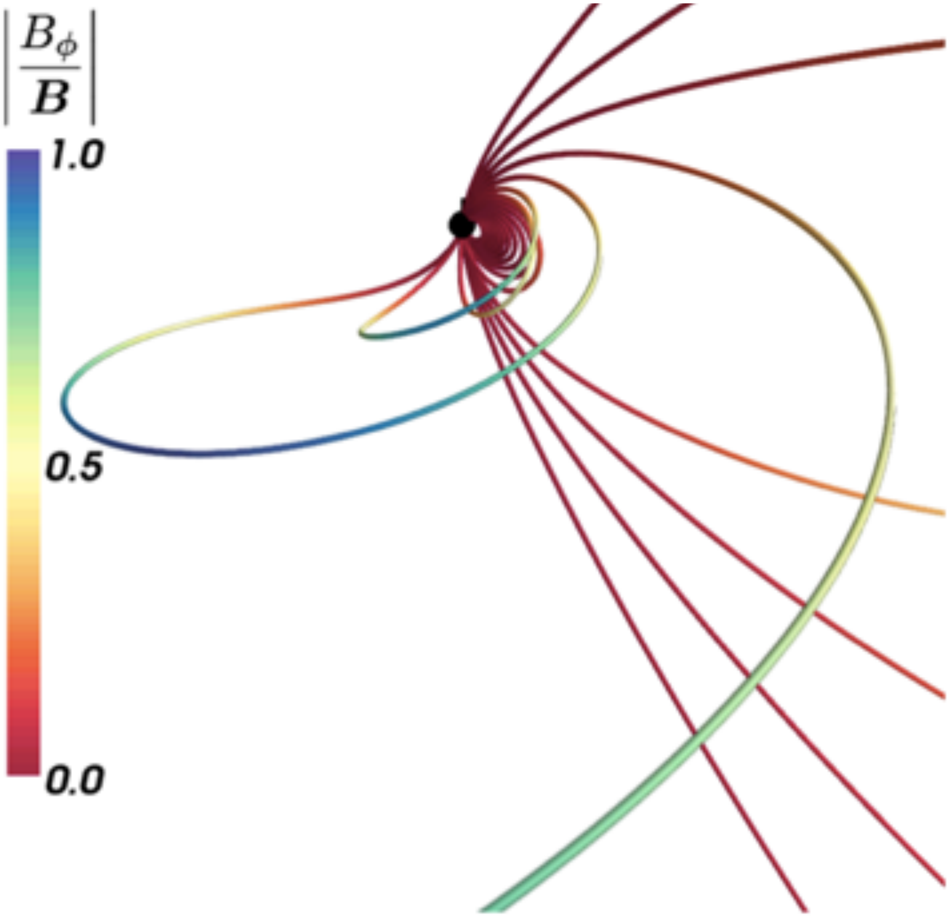


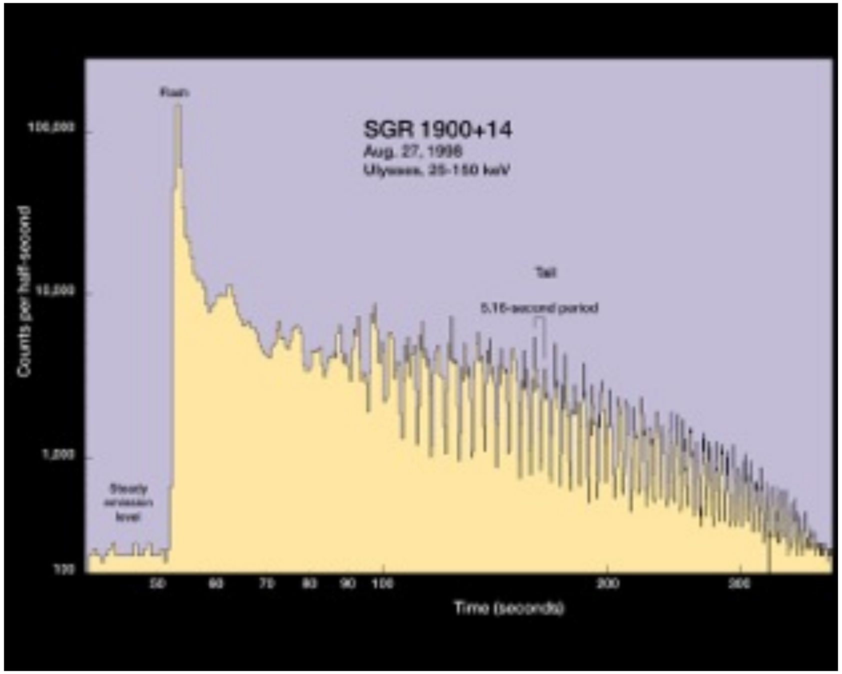
Olausen, Kaspi 2013

energy budget:

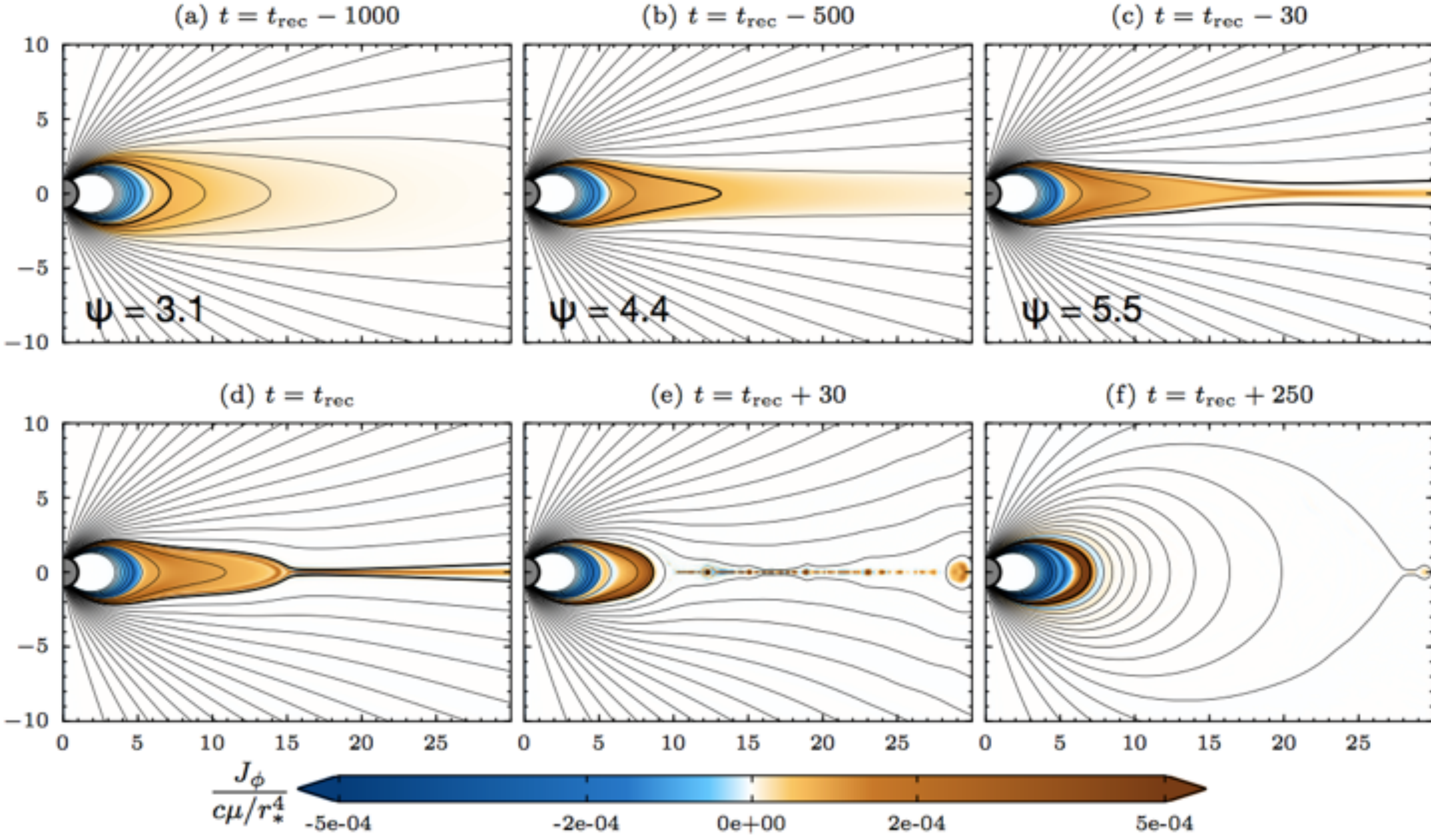
$$E_\star \sim (R_\star^3 B_\star^2/6) \sim 2\times10^{49} B_{\star,16}^2 \text{ erg}$$

Over-twisted magnetospheres: flares

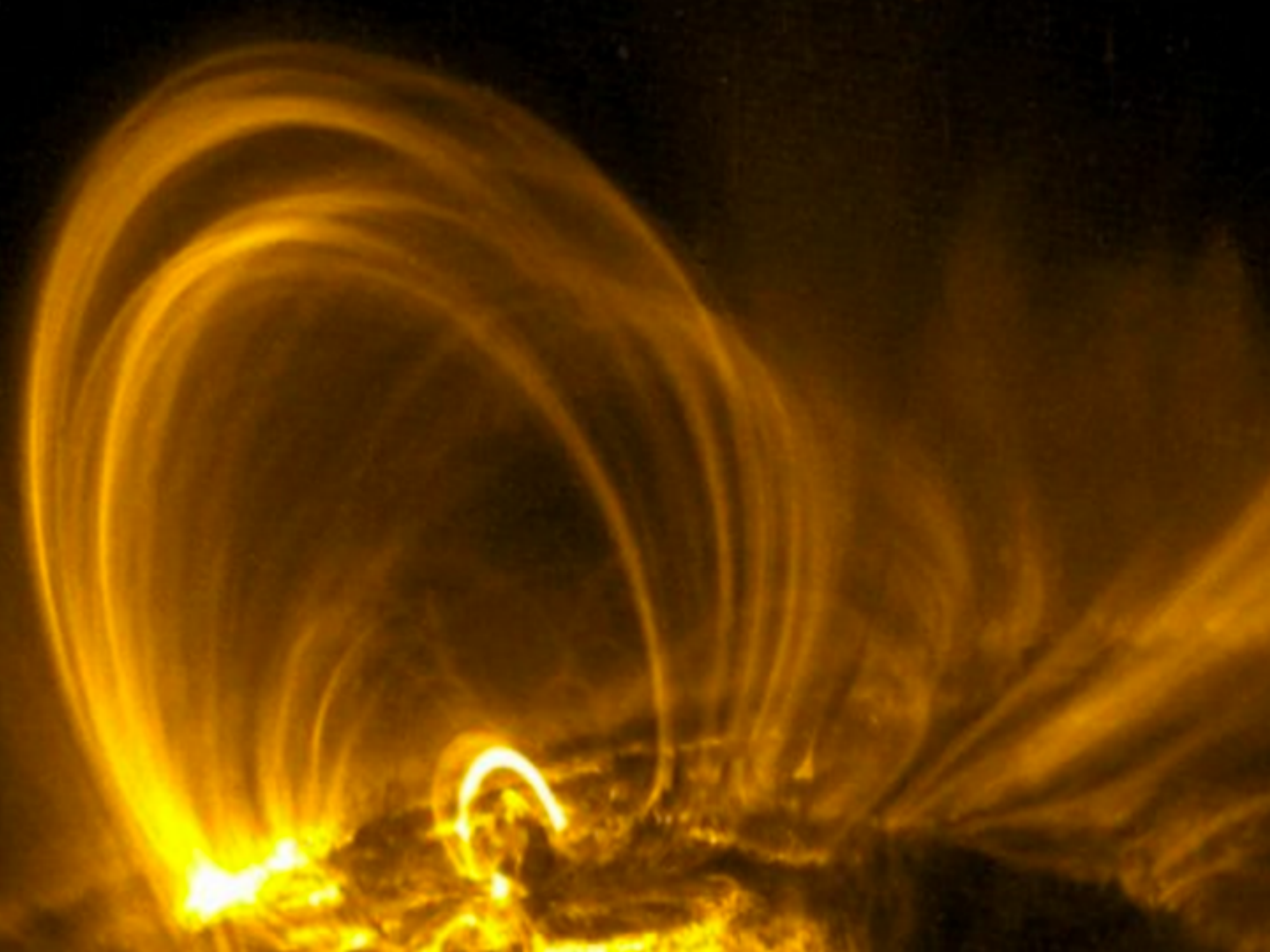




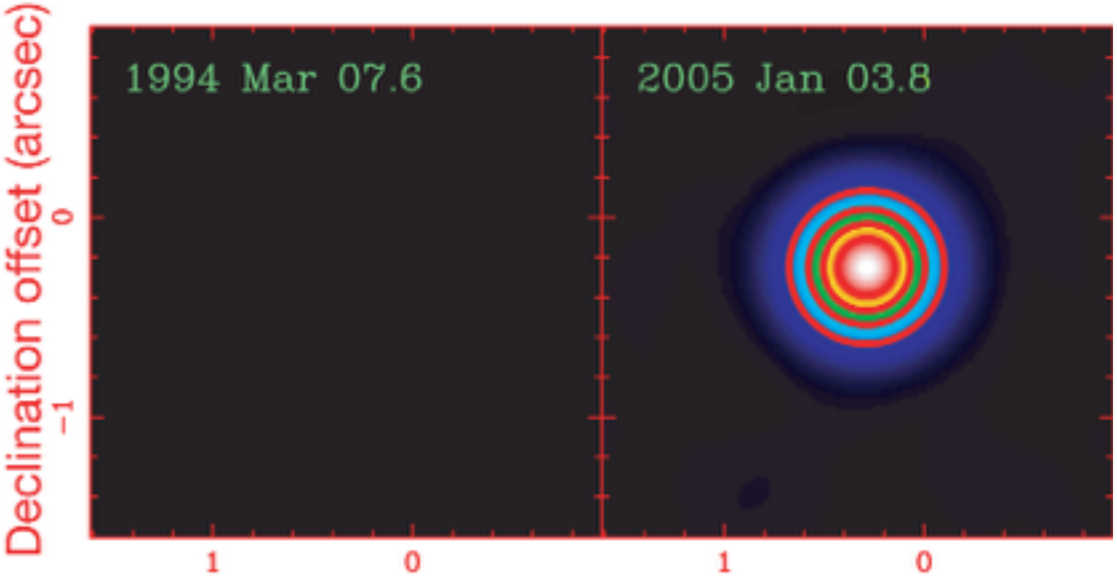
Loss of magnetic equilibrium and reconnection



Parfrey et al. (2013)



Ejecta from the giant flare of SGR 1806-20



Radio afterglow (Gaensler et al. 2005 Granot et al. 2006)

$$E > 10^{44}\ \mathrm{erg}$$

$$N > 10^{48}\mathrm{particles}$$

$$v \sim (0.3 - 0.5)c$$

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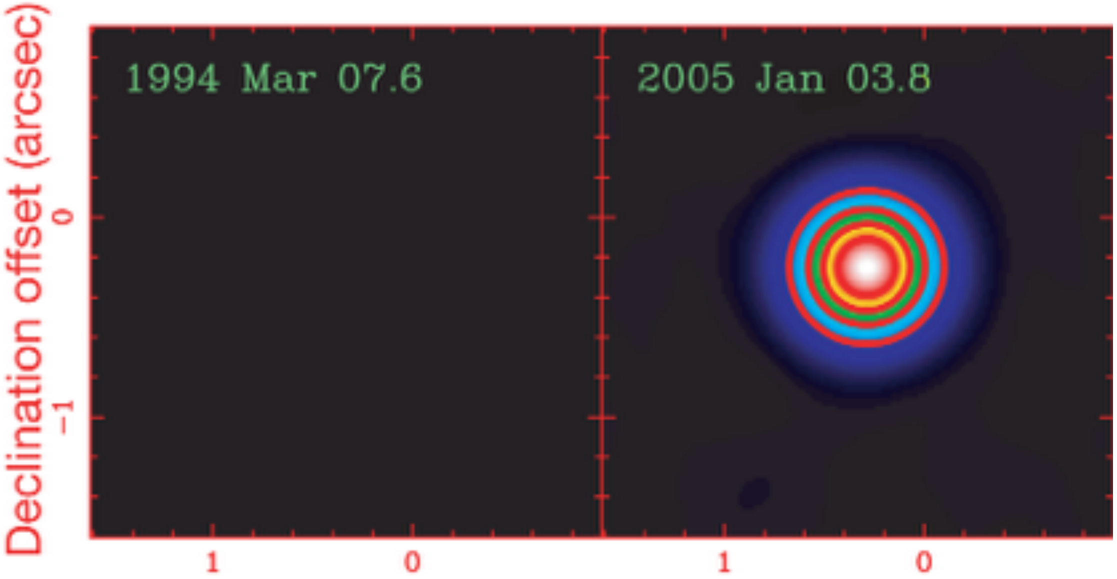

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FRBs from giant flares?

Lyubarsky 2014; AB 2017

Magnetar-FRB connection: FRB 121102

- repeating ms radio bursts with energies $10^{38} - 10^{39}$ erg

- persistent radio counterpart:

$$L_\nu \approx 10^{29} \nu_{10}^{-0.2}\ \mathrm{erg} \quad \Rightarrow \quad NB \sim 2 \times 10^{50}\ \mathrm{G}$$

particle number

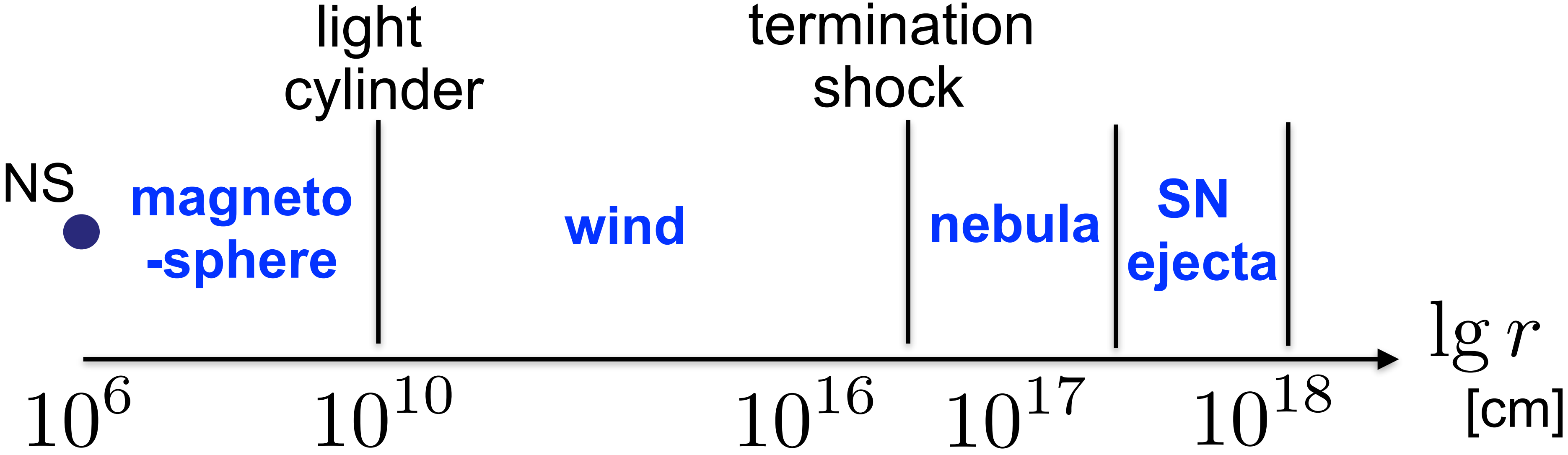
$$B \sim 0.06\, \sigma^{2/7} R_{17}^{-6/7}\ \mathrm{G}$$

$$\boxed{\begin{aligned} N &\sim 3 \times 10^{51}\, \sigma^{-2/7} R_{17}^{6/7} \\ E_N &\sim 10^{48}\, \sigma^{-3/7} R_{17}^{9/7}\ \mathrm{erg} \end{aligned}}$$

$$\nu_c \approx 2\, t_9^{-2} \sigma^{-6/7} R_{17}^{18/7}\, \mathrm{GHz}$$

$$\nu_{\mathrm{abs}} \approx 1\, \sigma^{2/35} R_{17}^{-34/35}\ \mathrm{GHz}$$

– consistent with a magnetar nebula inflated by giant flares inside a young supernova remnant


light cylinder
termination shock
NS
magneto -sphere
wind
nebula
SN ejecta
10^6 10^{10} 10^{16} 10^{17} 10^{18}
$\lg r$ [cm]

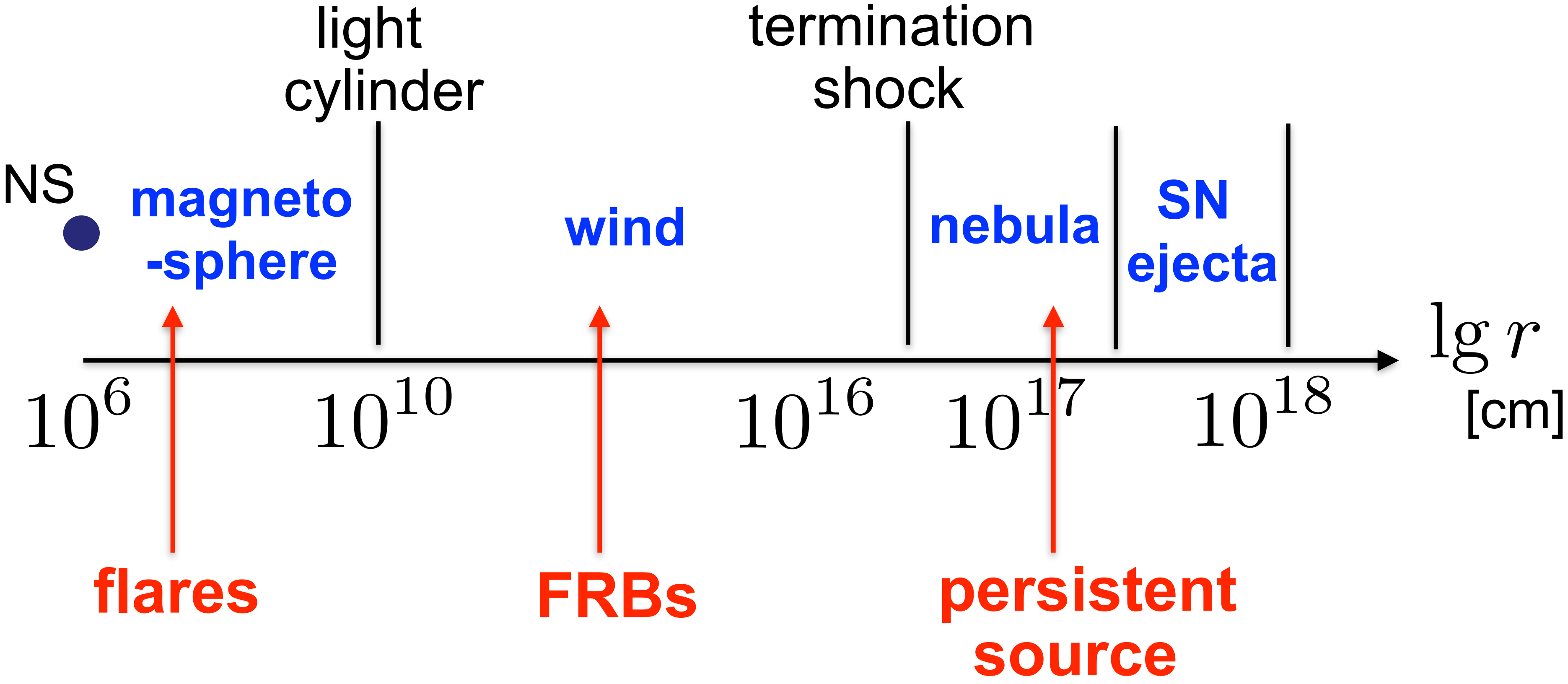
Flare efficiency of baryon ejection (per erg):

$$10^2 < \xi \equiv \frac{N}{E} < 10^4 \ \mathrm{erg}^{-1}$$

$$N \sim 10^{52} \left(\frac{\xi}{10^3/\mathrm{erg}} \right) E_{49}$$

– consistent with the particle number in the nebula.

Huge radio efficiency because of heating by waves from the variable outflow from the magnetar.



light cylinder

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SN ejecta

$\lg r$ [cm]

10^6 10^{10} 10^{16} 10^{17} 10^{18}

flares

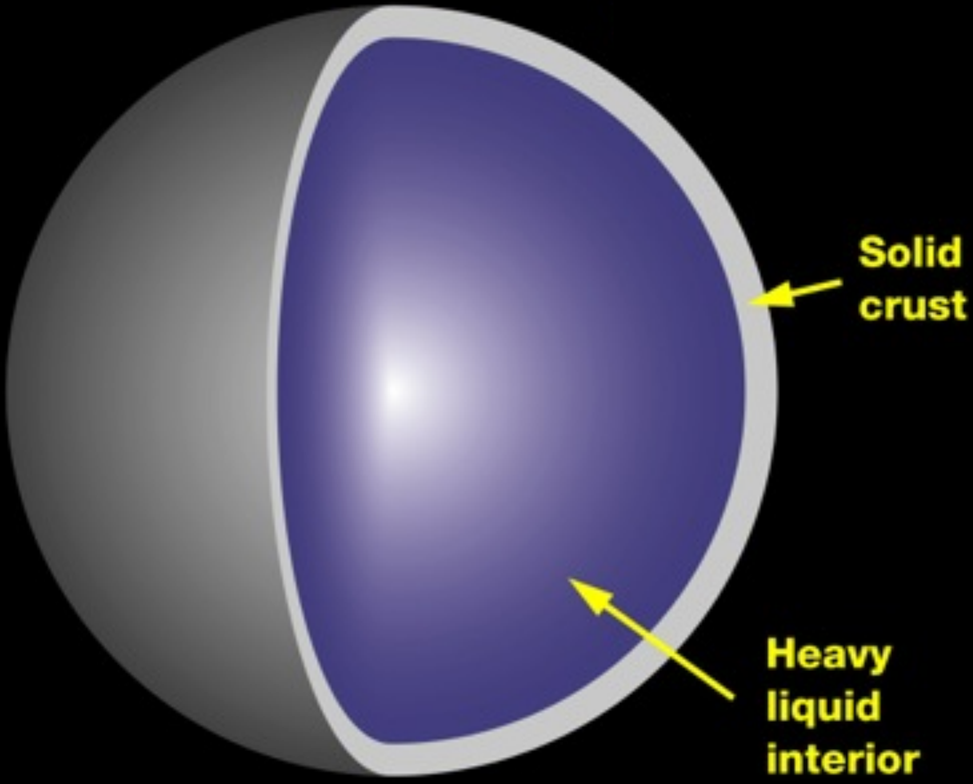
FRBs

persistent source

Spindown power is low (compared with magnetic power):

$$L_{\rm sd} \approx \frac{c^3\mathcal{I}^2}{4\mu^2 t^2} \approx 7\times 10^{36}\,\mu_{33}^{-2}t_9^{-2}\ \mathrm{erg/s}$$

Source of activity



Development of unbalanced magnetic stresses:
ambipolar diffusion and Hall drift

Ambipolar diffusion in the magnetar core

$$\frac{(\nabla \times \mathbf{B}) \times \mathbf{B}}{4\pi} = n_e \nabla(\Delta\mu) + \frac{n_e m_p \mathbf{v}}{\tau_{pn}}$$

$$\dot{q}_h = \frac{\rho_p v^2}{\tau_{pn}} \sim \frac{\tau_{pn}}{\rho_p} \left(\frac{B\,\delta B}{4\pi L} \right)^2$$

$$C_V \frac{dT_{\rm core}}{dt} = -\dot{q}_\nu + \dot{q}_h$$

Goldreich, Reisenegger 1992

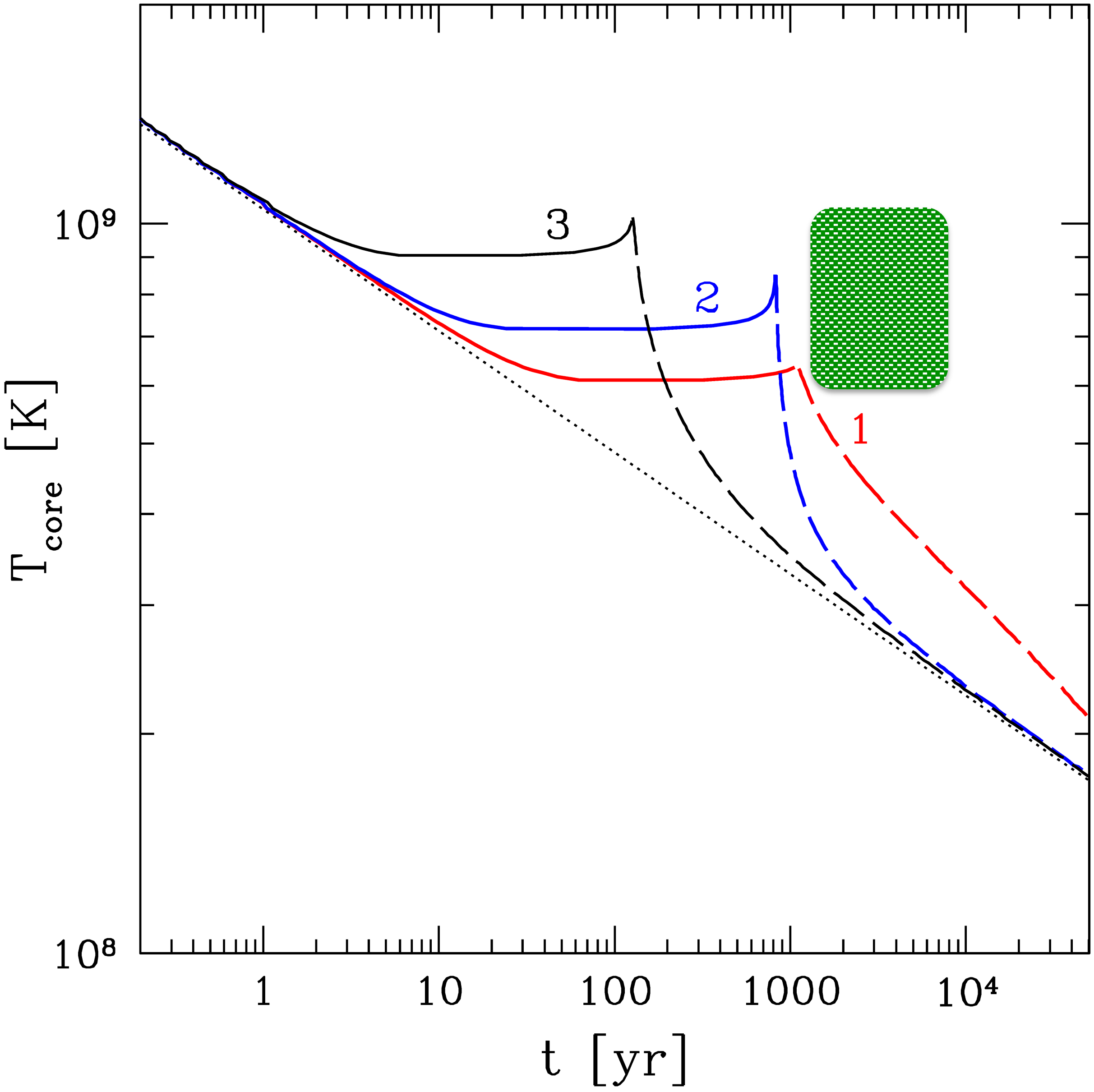
Thompson, Duncan 1996

AB & Li 2016

$$\boxed{\begin{aligned} T_{\rm bal} &= (8-9) \times 10^8 \left(\frac{B_{16}\,\delta B_{16}}{L_5} \right)^{0.2} \ \mathrm{K.} \\ t_{\rm diss} &\sim 10^3 \left(\frac{T_9 L_5}{B_{16}} \right)^2 \ \mathrm{yr} \end{aligned}}$$

(MURCA cooling
no superfluidity)

Core temperature evolution



AB & Li 2016

Energy output: $L \sim \dfrac{E_\star}{t_{\rm amb}} \sim 10^{40}\, E_{\star,49}\, t_{\rm amb,9}^{-1}\ {\rm erg/s}$

$$E_\star \sim (R_\star^3 B_\star^2/6) \sim 2\times 10^{49}\, B_{\star,16}^2\ {\rm erg}$$

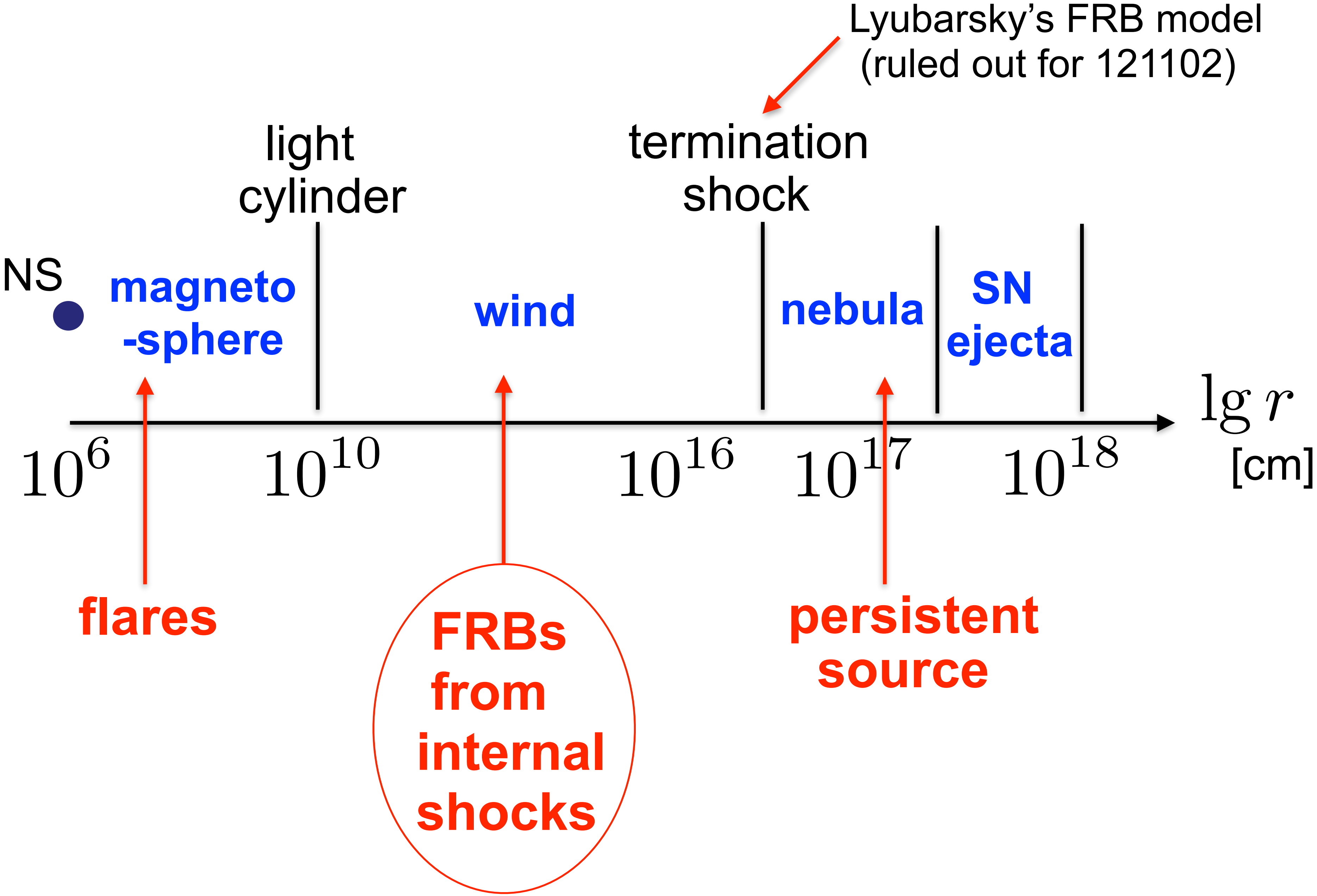
$$\boxed{\begin{gathered} t_{\rm amb} \sim 10^2\, (B_\star/3\times 10^{16}\ {\rm G})^{-1.2} k_{-5}^{-1.6}\ {\rm yr} \\ k \sim 2\pi/R_\star \end{gathered}}$$

– if minimum (MURCA) neutrino cooling,
or faster, if DURCA or Cooper pairing

Factors boosting hyper-activity

- fast rotation at birth (=> stronger B)
- high mass (=> faster cooling)

(both expected when low metallicity)



Lyubarsky's FRB model
(ruled out for 121102)

light
cylinder

termination
shock

NS

magneto
-sphere

wind

nebula

SN
ejecta

$\lg r$
[cm]

10^6 10^{10} 10^{16} 10^{17} 10^{18}

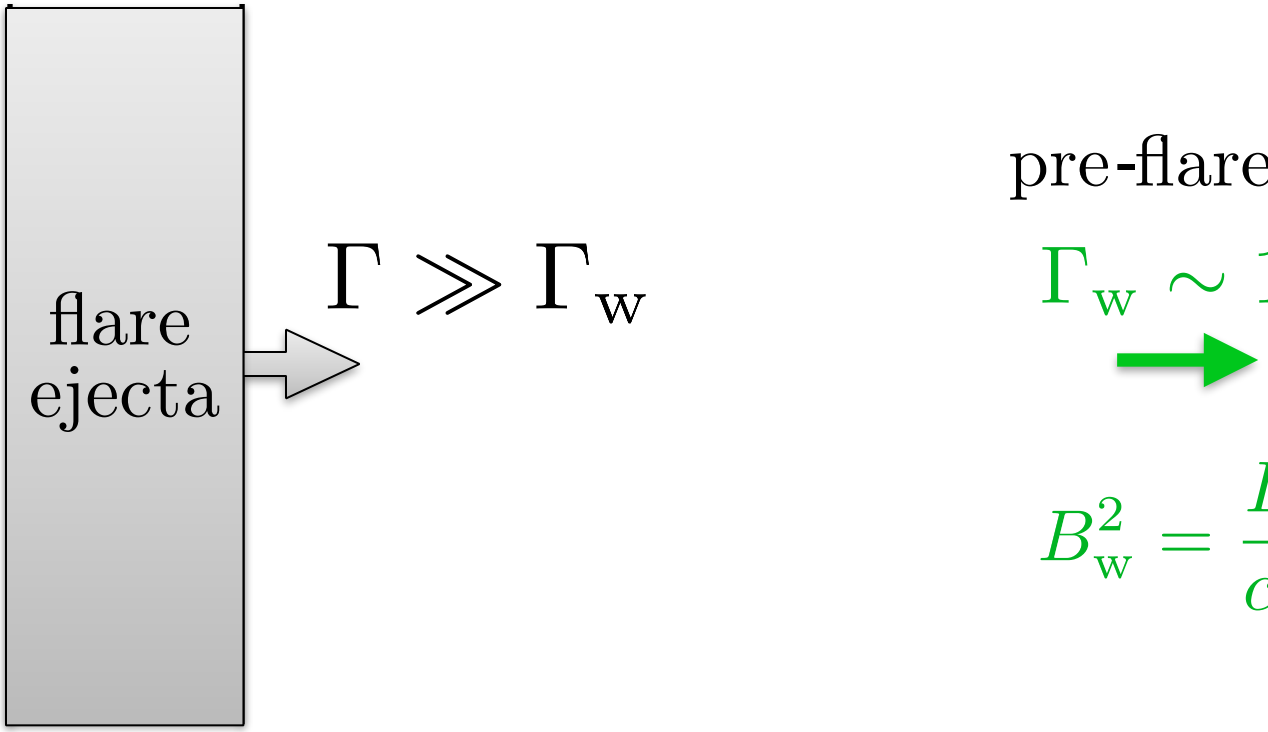
flares

FRBs
from
internal
shocks

persistent
source

FRB mechanism: blast wave from the flare

(cf. solar CME)



$\mathcal{E} \sim 10^{44}\mathrm{erg}$

flare ejecta

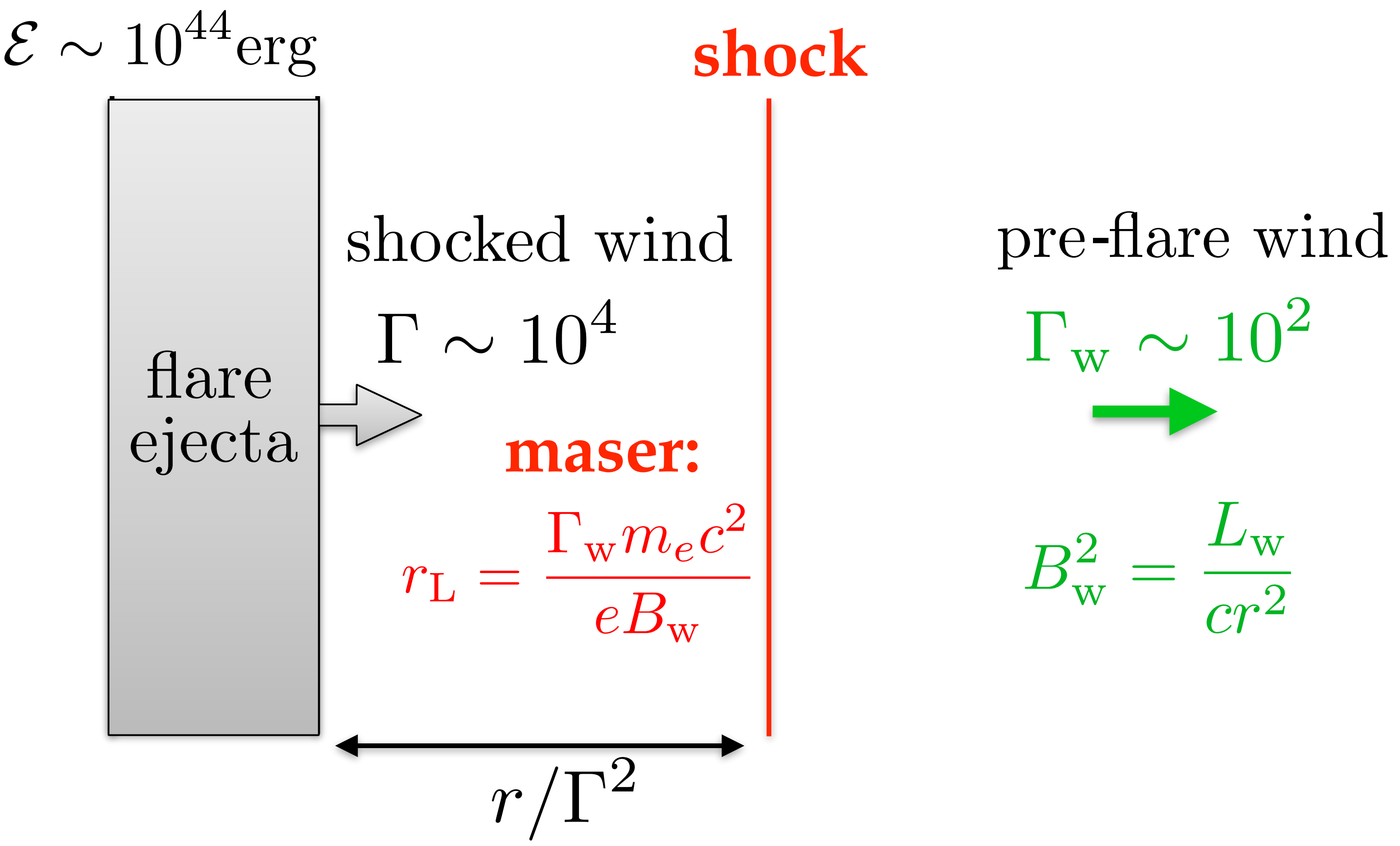
$\Gamma \gg \Gamma_{\mathrm{w}}$

pre-flare wind

$\Gamma_{\mathrm{w}} \sim 10^2$

$$B_{\mathrm{w}}^2 = \frac{L_{\mathrm{w}}}{cr^2}$$

FRB mechanism: blast wave from the flare



$\mathcal{E} \sim 10^{44}\text{erg}$

flare ejecta

shocked wind

$\Gamma \sim 10^4$

maser:

$$r_{\rm L} = \frac{\Gamma_{\rm w} m_e c^2}{e B_{\rm w}}$$

shock

pre-flare wind

$\Gamma_{\rm w} \sim 10^2$

$$B_{\rm w}^2 = \frac{L_{\rm w}}{c r^2}$$

r/Γ^2

$$\Gamma \approx \Gamma_{\rm w} \left(\frac{L_{\rm f}}{L_{\rm w}}\right)^{1/4} = 10^4\, \Gamma_{\rm w,2} \left(\frac{L_{\rm f,47}}{L_{\rm w,39}}\right)^{1/4}$$

Expected FRB parameters in the model

$$\tau_{\rm obs} \sim \frac{r}{\Gamma^2 c} \approx 3 \times 10^{-6}\, r_{13} \Gamma_4^{-2}\ {\rm s} \qquad \checkmark$$

$$\mathcal{E}_{\rm FRB} \sim 10^{39}\, r_{13}\, \varepsilon_{-2}\, \sigma_{\rm w}^{-1}\, \Gamma_{\rm w,2}^{-2} (L_{\rm f,47} L_{\rm w,39})^{1/2}\ {\rm erg} \qquad \checkmark$$

$$\nu_{\rm obs} \sim \frac{\Gamma\, c}{2\pi r_{\rm L}} = \frac{e\,(L_{\rm f} L_{\rm w})^{1/4}}{2\pi m_e c^{3/2}\, r} \approx \frac{3\ {\rm GHz}}{r_{13}} (L_{\rm f,47} L_{\rm w,39})^{1/4} \qquad \checkmark$$

(PIC simulations of shock masers: Gallant et al. 1992)

Magnetar model for FRBs: summary

- energy source: magnetic field rather than rotation (certainly for bursts, likely for persistent emission)

- flare ejecta form a nebula much different from the Crab, with huge radio efficiency

- young magnetars are expected to be hyper-active for ~century, because of fast ambipolar diffusion in the core

- low progenitor metallicity can boost the activity in two ways:
  faster natal rotation => stronger B => more magnetic energy
  higher mass => stronger cooling => faster energy release.
  "Ordinary" (galactic) magnetars may also produce FRBs.

- burst mechanism: ultra-relativistic blast waves from giant flares propagating in the magnetar wind