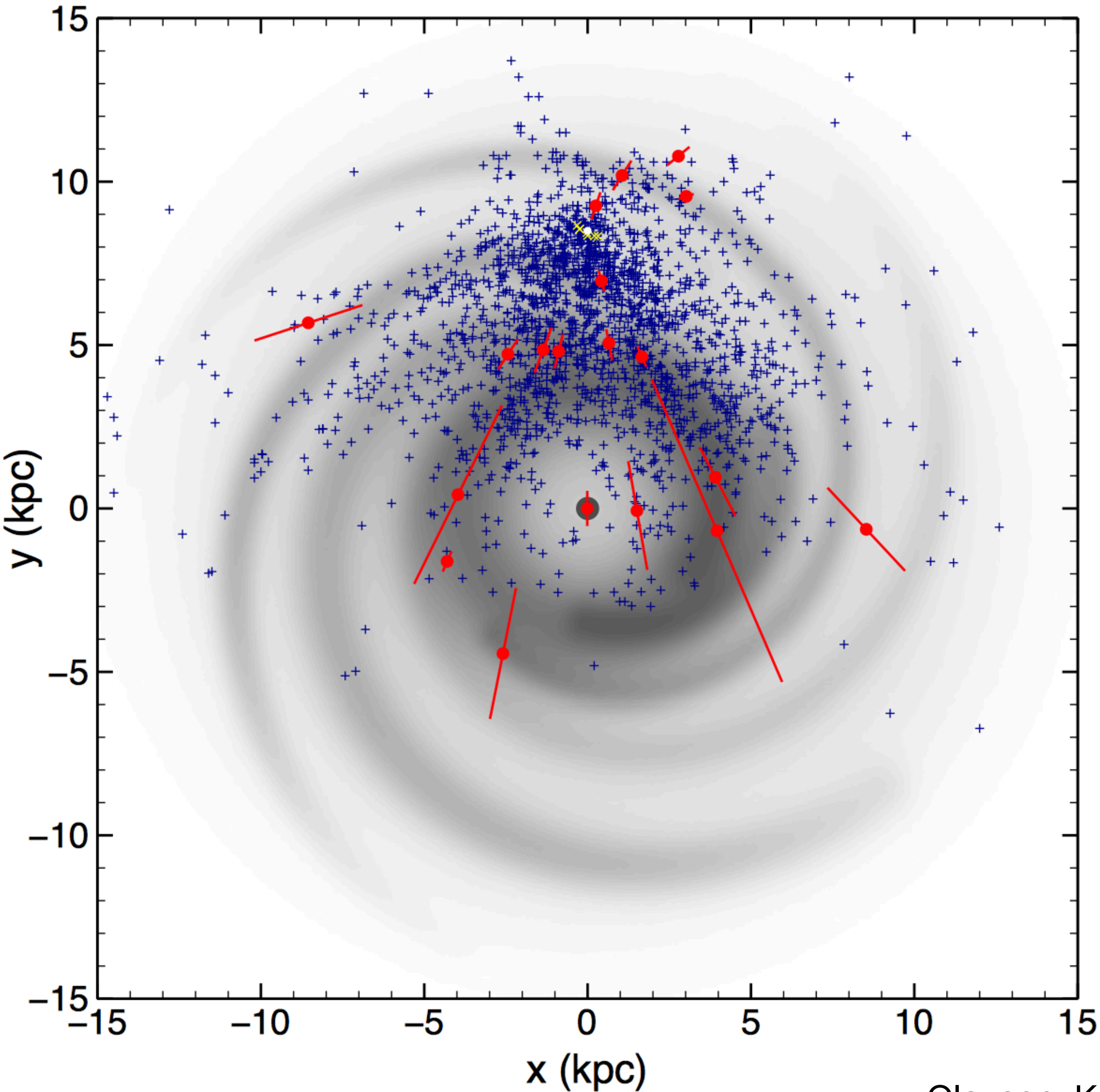
Magnetar flares and Fast Radio Bursts

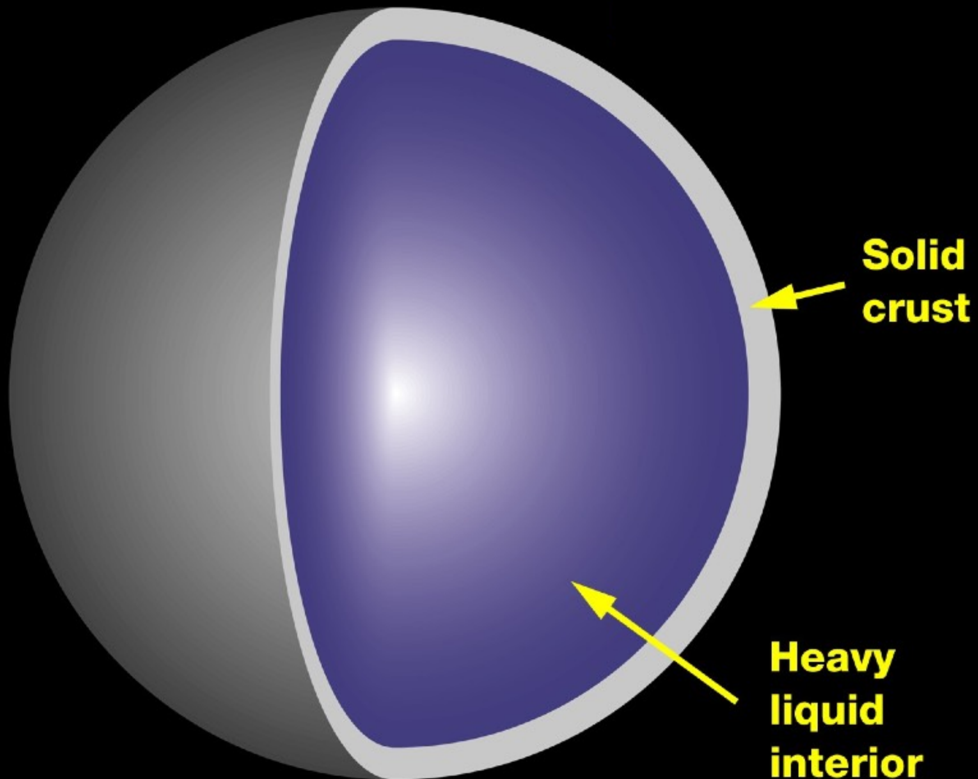
Andrei Beloborodov
Columbia University and MPA

Magnetar population (30 objects)



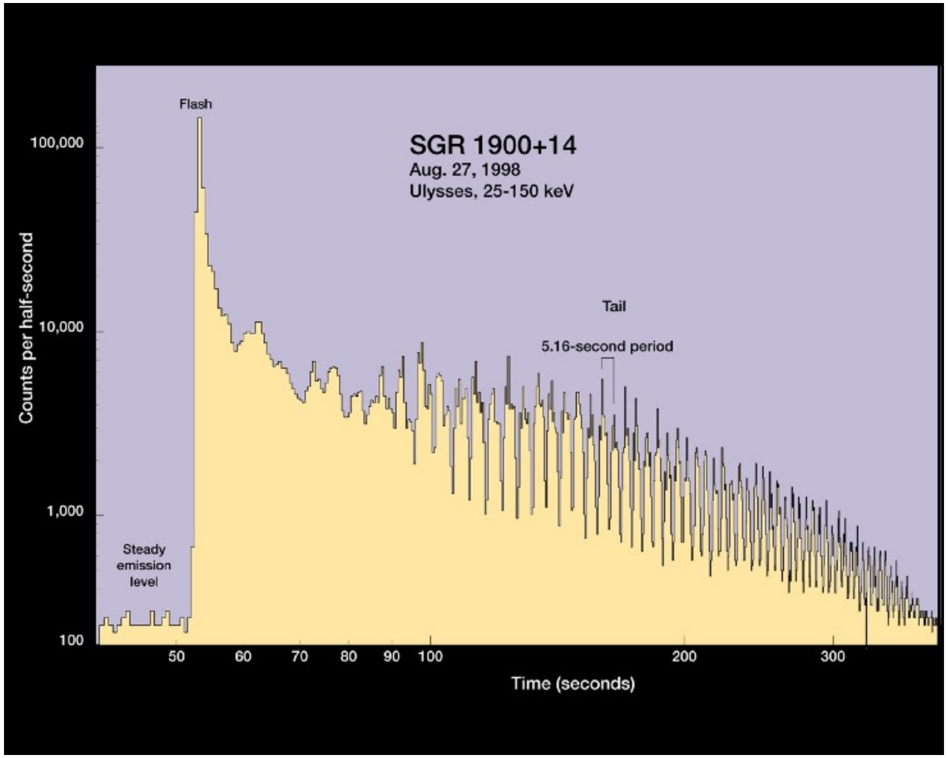
- concentrated near disk plane h ~ 20-30 pc
- kick velocities ~200 km/s
- ~1/3 found in SN remnants
- no binaries
- age 1-10 kyr
- period 2-12 s

Olausen, Kaspi (2013)



Development of unbalanced magnetic stresses: ambipolar diffusion and Hall drift

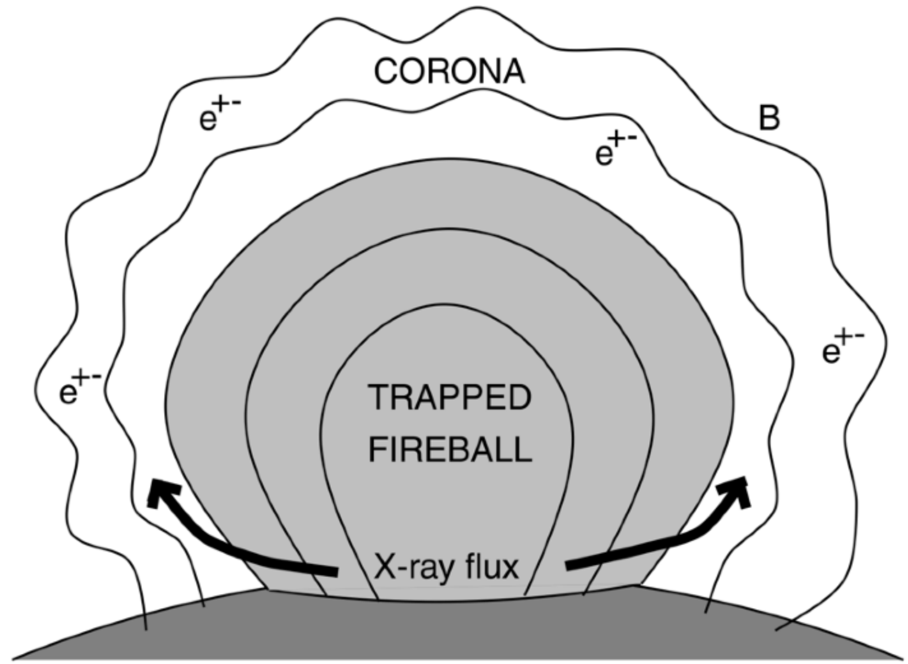
Giant flares



Tail of the flare:

6 minutes (many rotations)

$$E_{\rm tail} \sim 10^{44}\ {\rm erg}$$



Thompson, Duncan 1996, 2001
Thompson, Blaes 1998

Is the fireball heated by turbulence cascade?

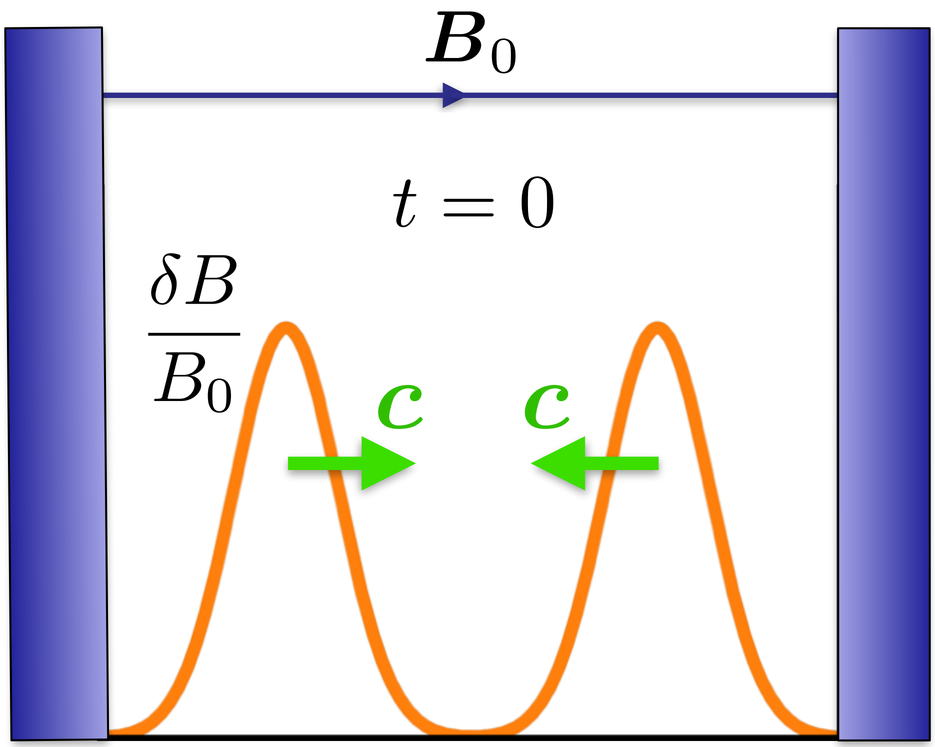
Heating source for giant flares:

I. Turbulence

Sudden deformation of the magnetosphere leads to an Alfven wave cascade

How long does it take to dissipate the waves?

Simulation setup: colliding Alfven wave packets



uniform background field

two symmetric wave packets

$\delta \boldsymbol{B} \perp \delta \boldsymbol{E} \qquad \delta \boldsymbol{B}, \delta \boldsymbol{E} \perp \boldsymbol{B}_0$

reflecting boundaries
(<=> periodic box)

force-free electrodynamics

3D

Parameter: $\xi \equiv \frac{\delta B_{\max}}{B_0}$

Li, Zrake, AB 2019

Force-free electrodynamics (FFE)

$$\partial_t \boldsymbol{B} = -\nabla \times \boldsymbol{E}$$

$$\partial_t \boldsymbol{E} = \nabla \times \boldsymbol{B} - \boldsymbol{J}$$

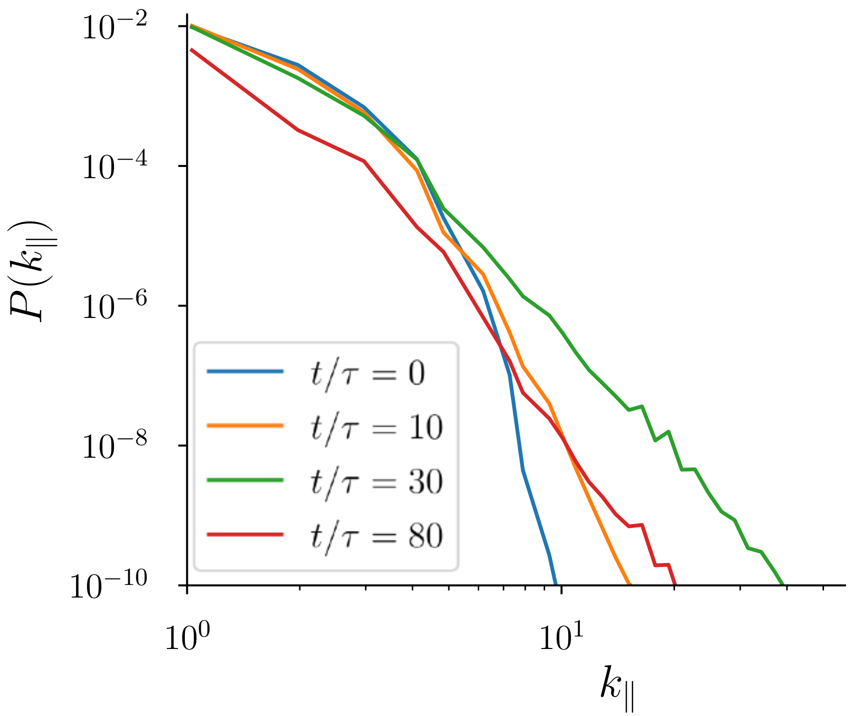
$$\rho \boldsymbol{E} + \frac{\boldsymbol{J} \times \boldsymbol{B}}{c} = 0 \quad \Rightarrow \quad \boldsymbol{J} = \frac{\boldsymbol{B} \cdot \nabla \times \boldsymbol{B} - \boldsymbol{E} \cdot \nabla \times \boldsymbol{E}}{B^2} \boldsymbol{B} + \nabla \cdot \boldsymbol{E} \frac{\boldsymbol{E} \times \boldsymbol{B}}{B^2}$$

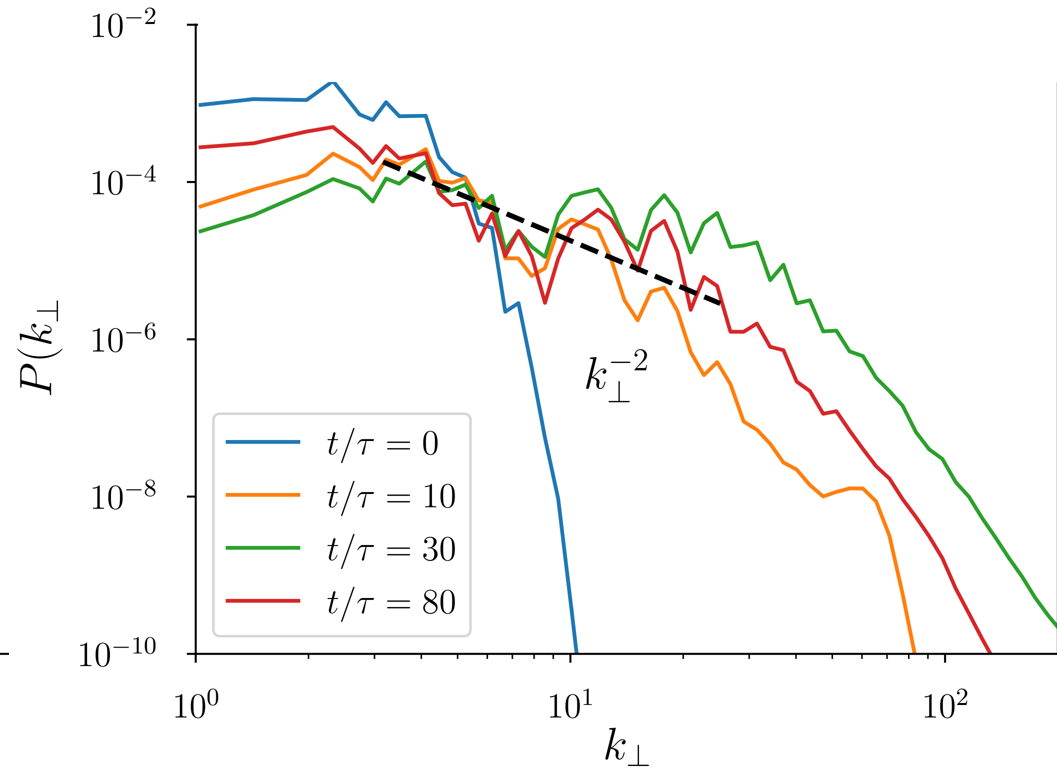
Eigen modes in FFE:

- Alfven wave
- "Fast" wave (no electric current, as if in vacuum)

Both modes propagate with the speed of light

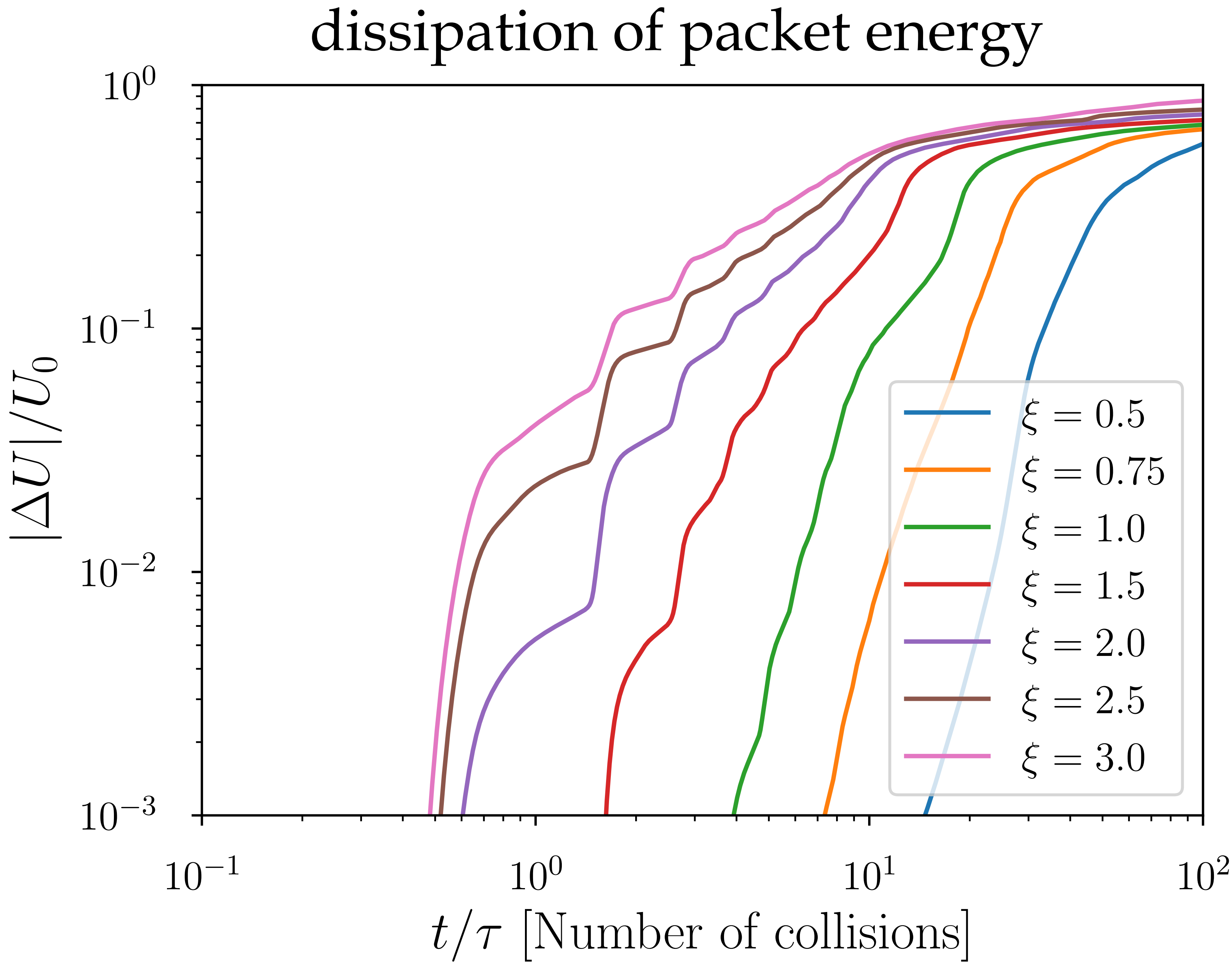
Development of turbulence cascade





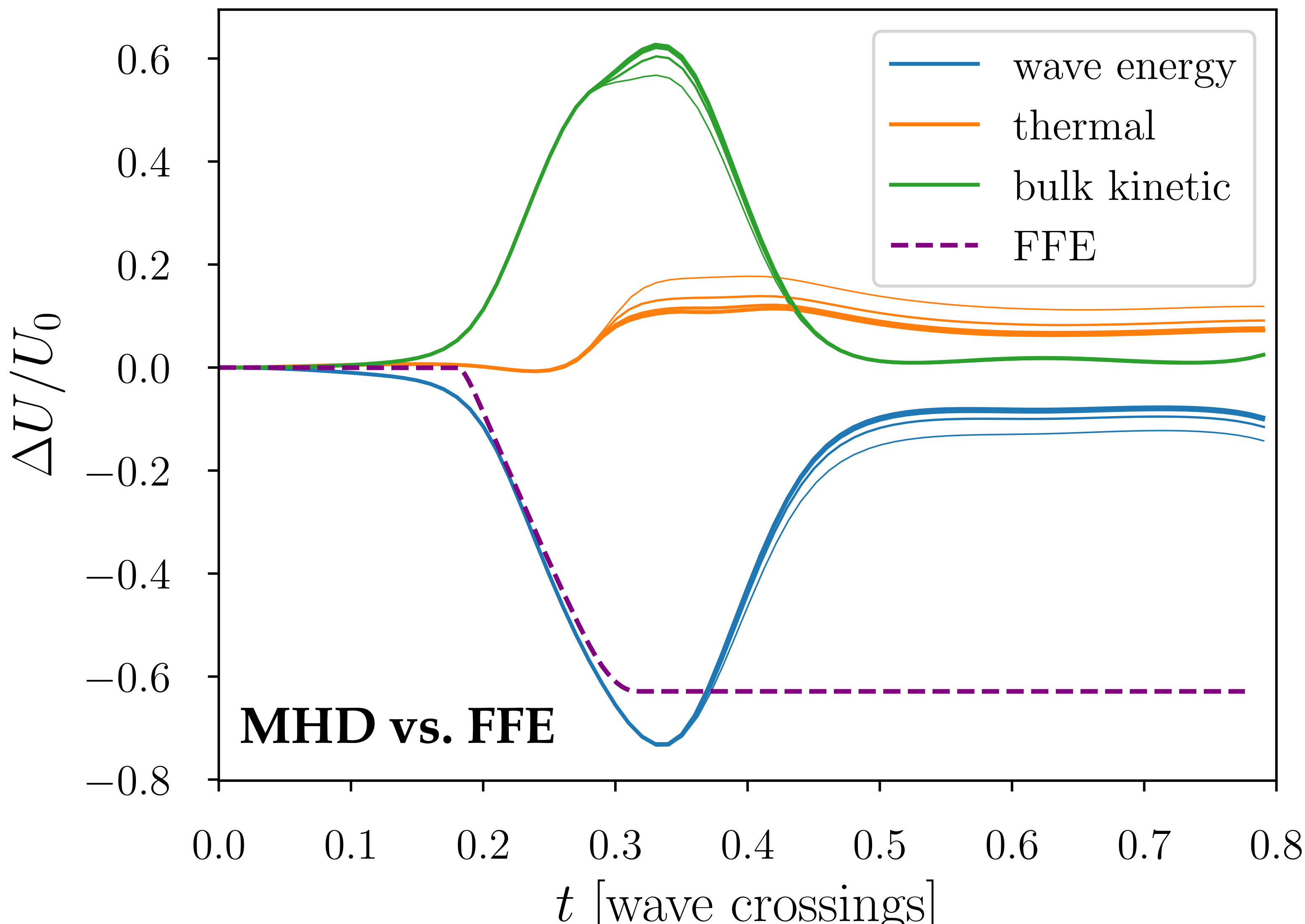
the cascade is dominated by waves with $k_\perp \gg k_\parallel$

(wavevectors almost perpendicular to $\boldsymbol{B}_0$)



dissipation of packet energy
$|\Delta U|/U_0$
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-1}
10^0
10^1
10^2
t/τ [Number of collisions]
$\xi = 0.5$
$\xi = 0.75$
$\xi = 1.0$
$\xi = 1.5$
$\xi = 2.0$
$\xi = 2.5$
$\xi = 3.0$

Remark 1. Wave polarization and limitations of FFE



Li, Zrake, AB 2019

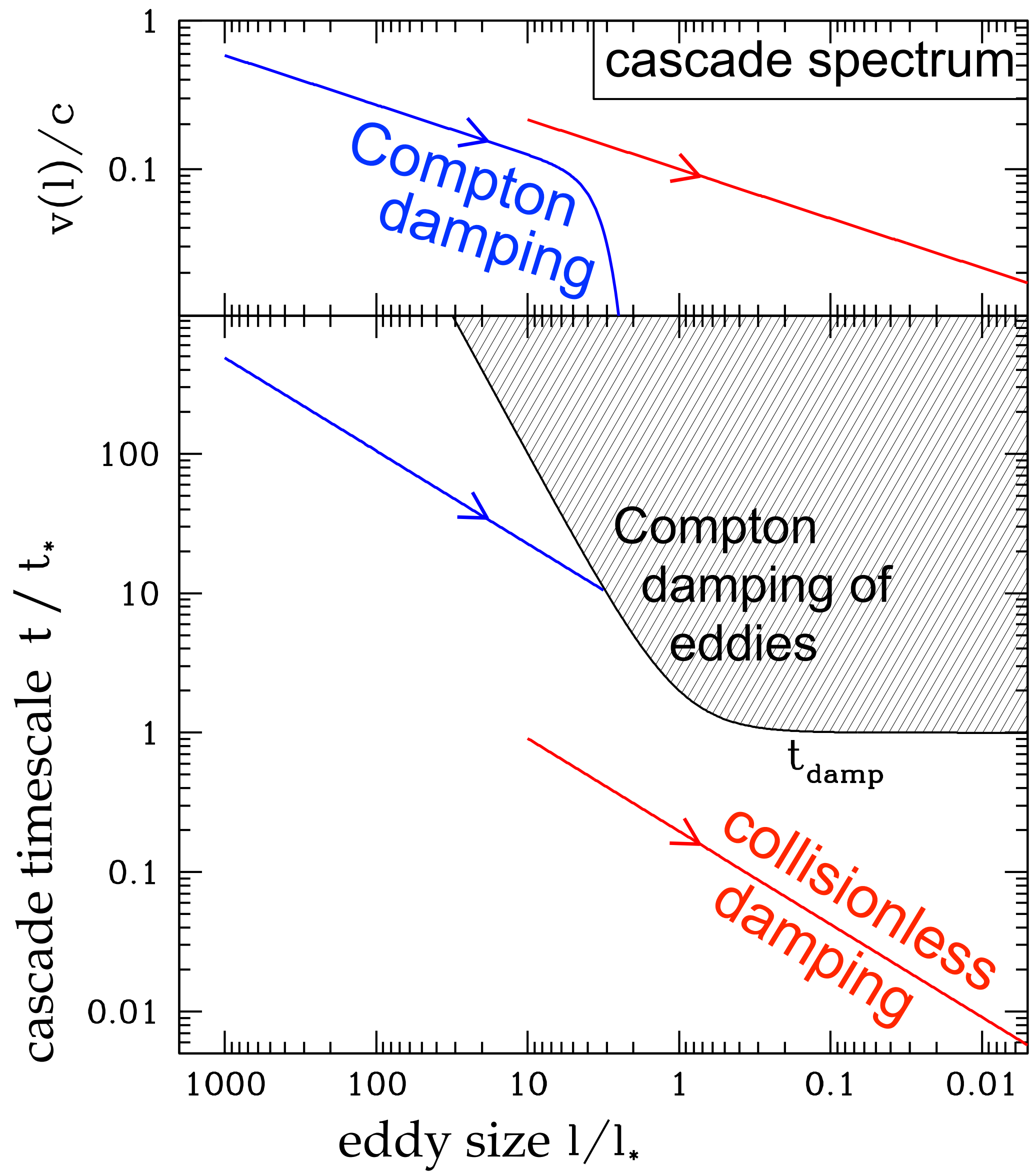
Remark 2. Cascade is dissipated by Compton drag

$$\tau > \left(\frac{v_0}{c} \, \frac{1+w}{w} \right)^3$$

Compton damping

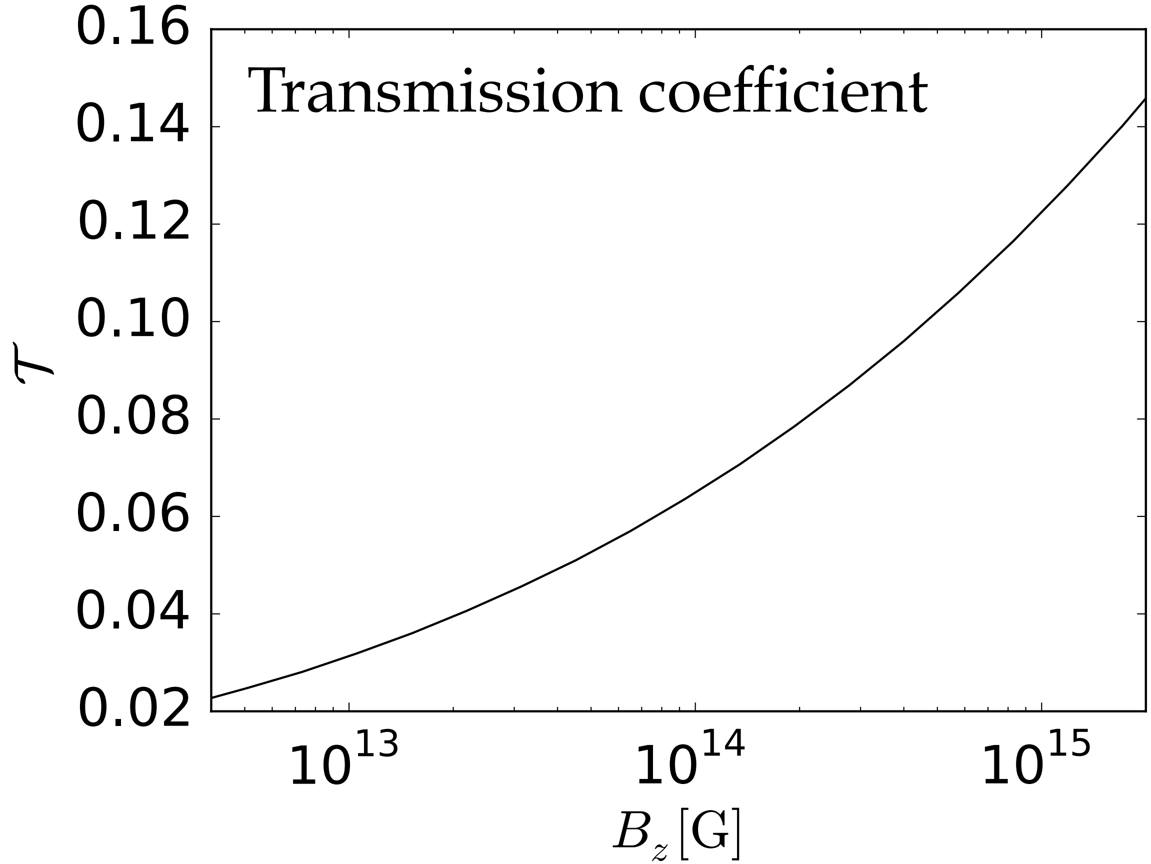
$$\left[w \equiv \frac{U+P}{\rho c^2} \right]$$

relativistic enthalpy



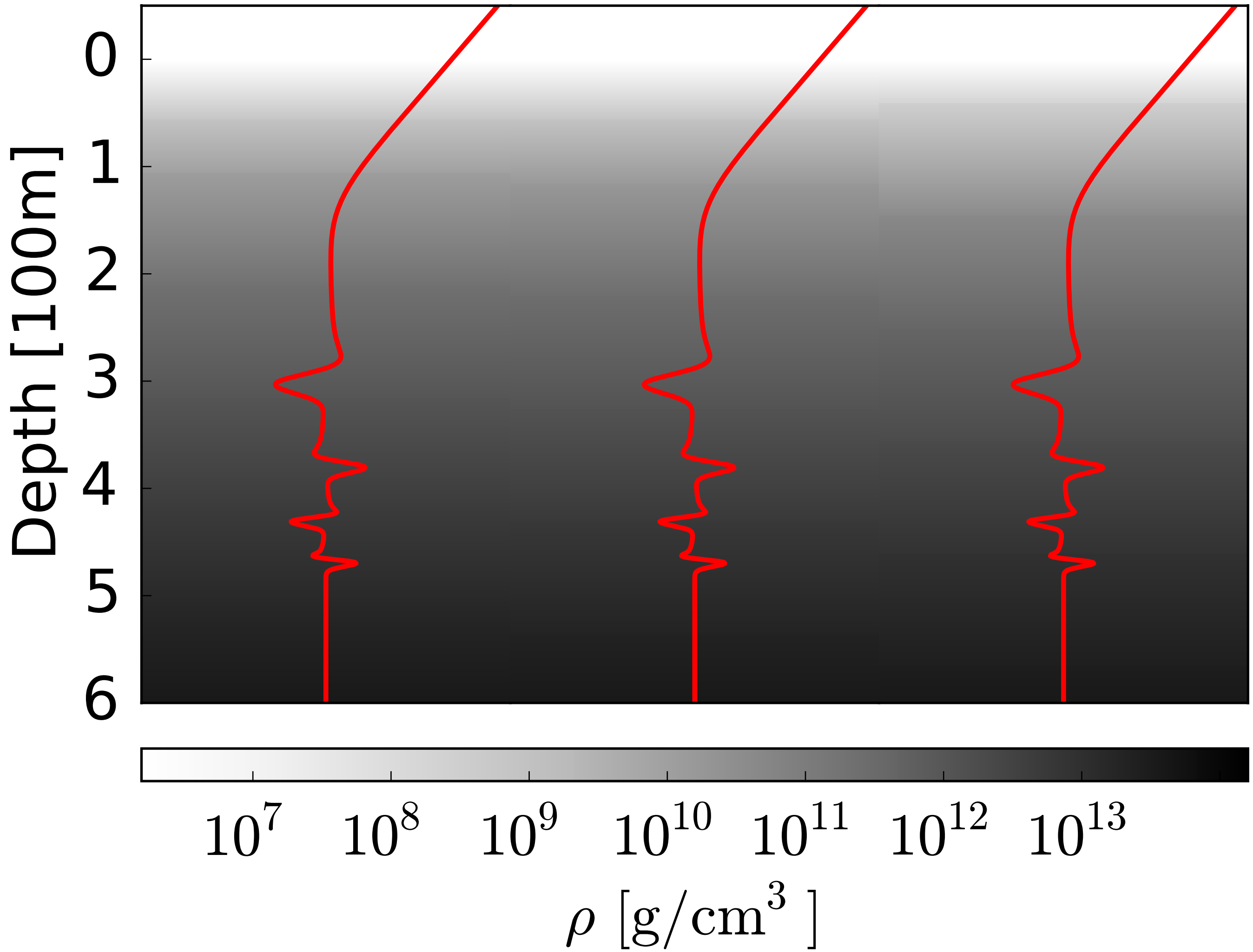
Zrake, AB, Lundman 2019

Remark 3. Draining turbulence into the star



Li & AB 2015

$$v^2(z) = \frac{B_z^2/4\pi + \mu(z)}{B_z^2/4\pi c^2 + \rho(z)}$$

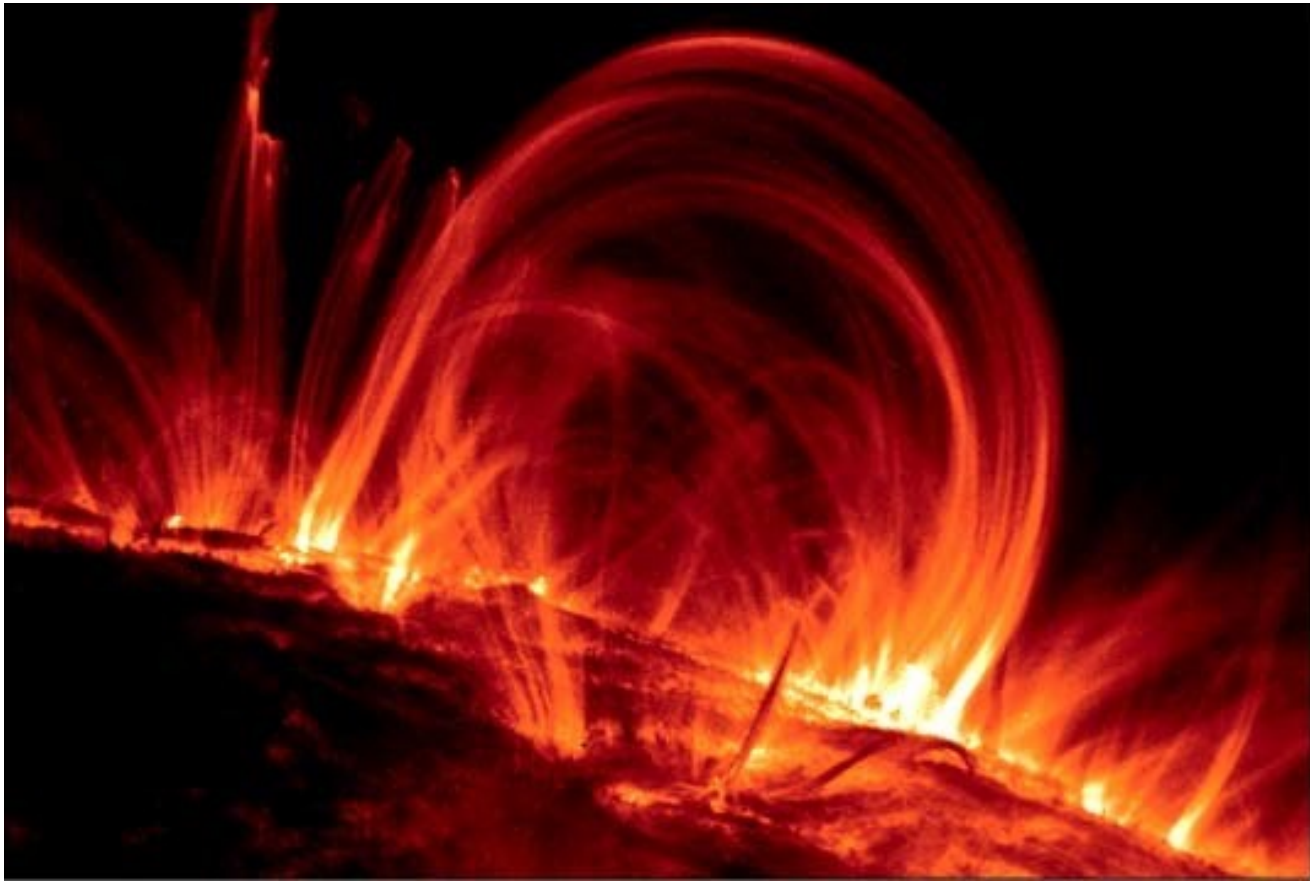


Li & AB 2015

Plastic damping of waves melts the crust; afterglow ~ month

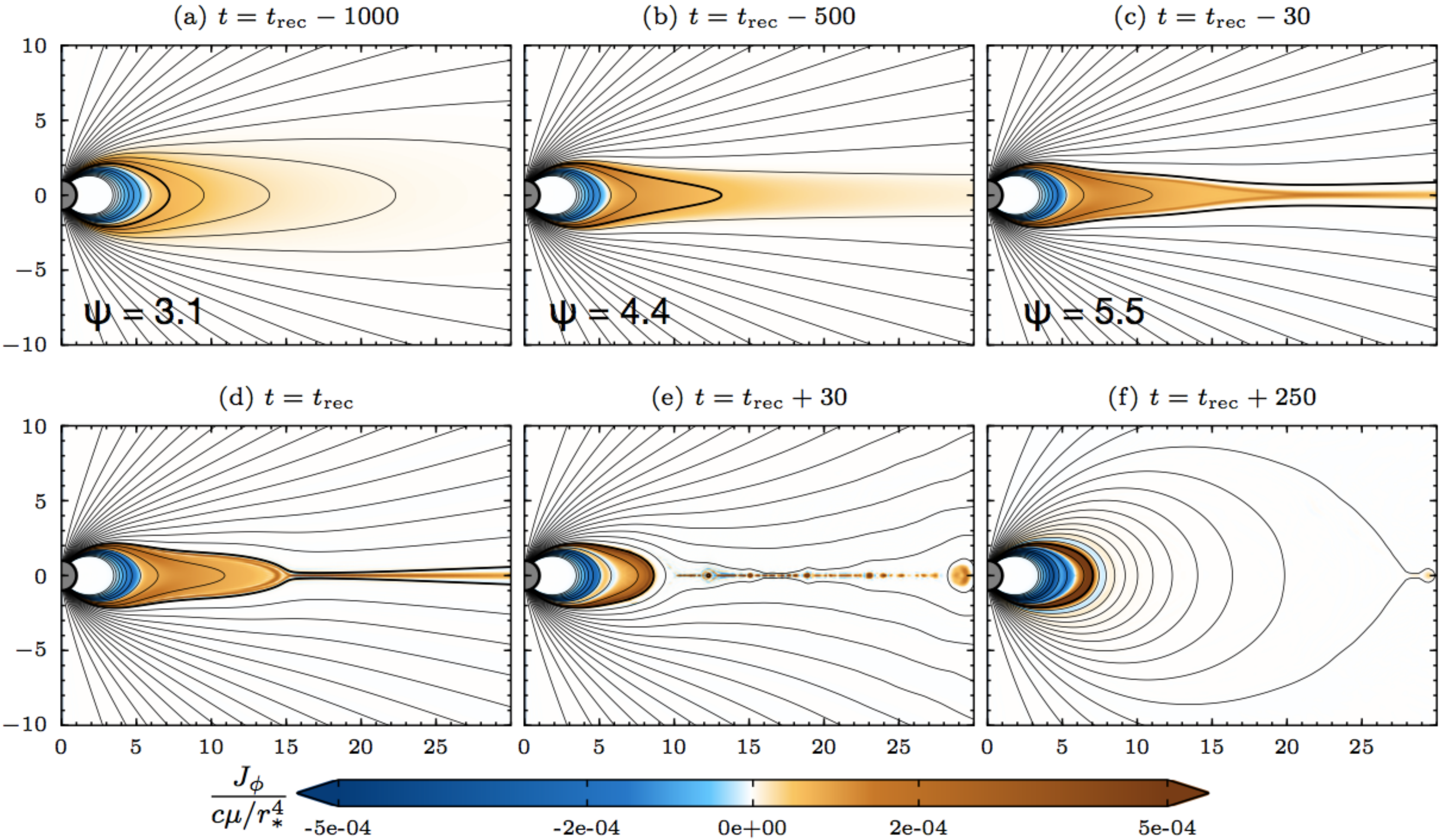
Heating source for giant flares:
II. Magnetic reconnection

Overtwisted magnetic loops (cf. solar flares)



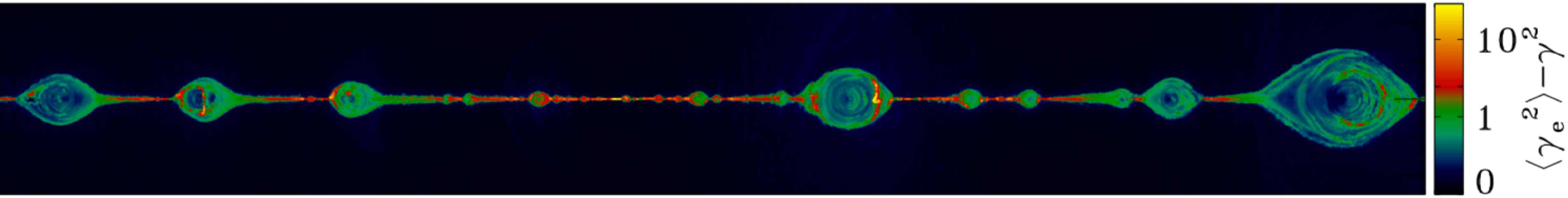
Thompson & Duncan 1996
Lyutikov 2006
Parfrey, AB, Hui 2013
Carrasco et al. 2019

Loss of magnetic equilibrium and reconnection



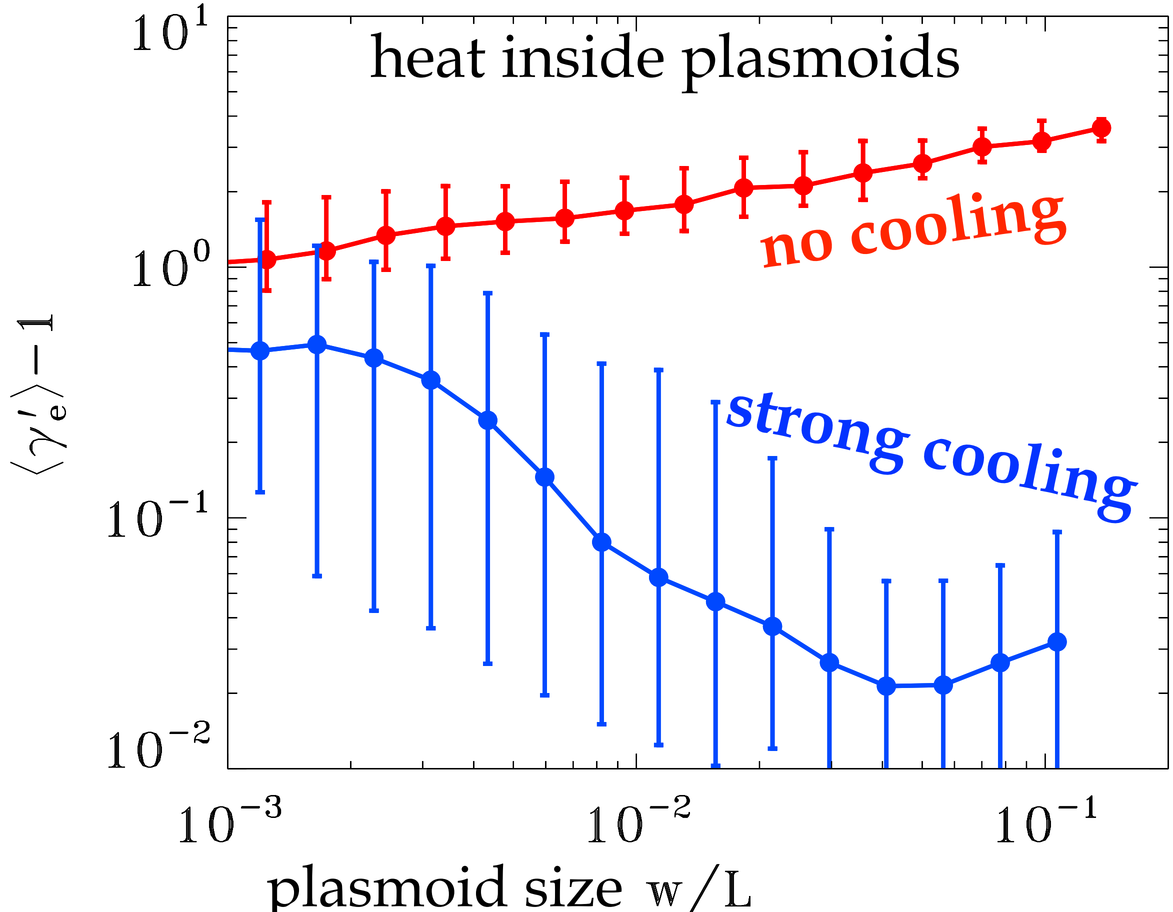
Parfrey, AB, Hui 2013

Radiative reconnection

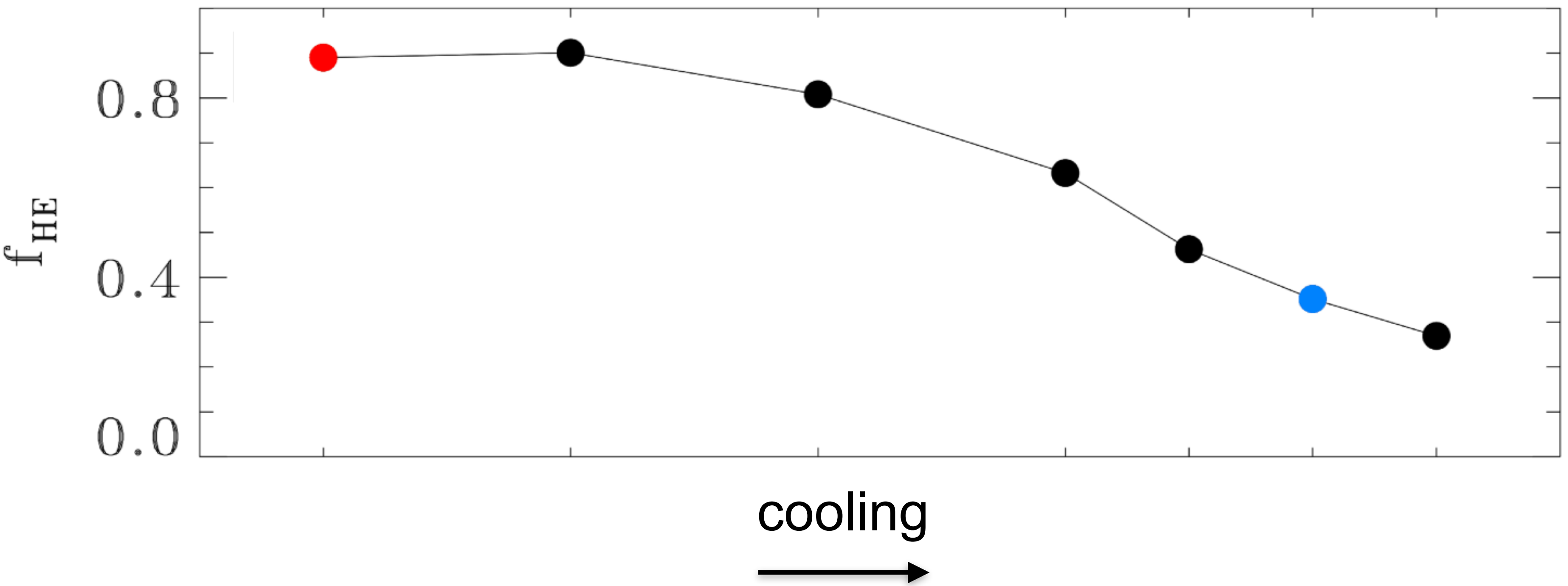


$t_{\rm cool} \ll L/c$

AB 2017
Werner et al. 2019
Sironi & AB 2019



Sironi & AB 2019



Magnetars:
"ultra-radiative"
reconnection

Blast waves from magnetar flares and cosmological fast radio bursts (FRBs)

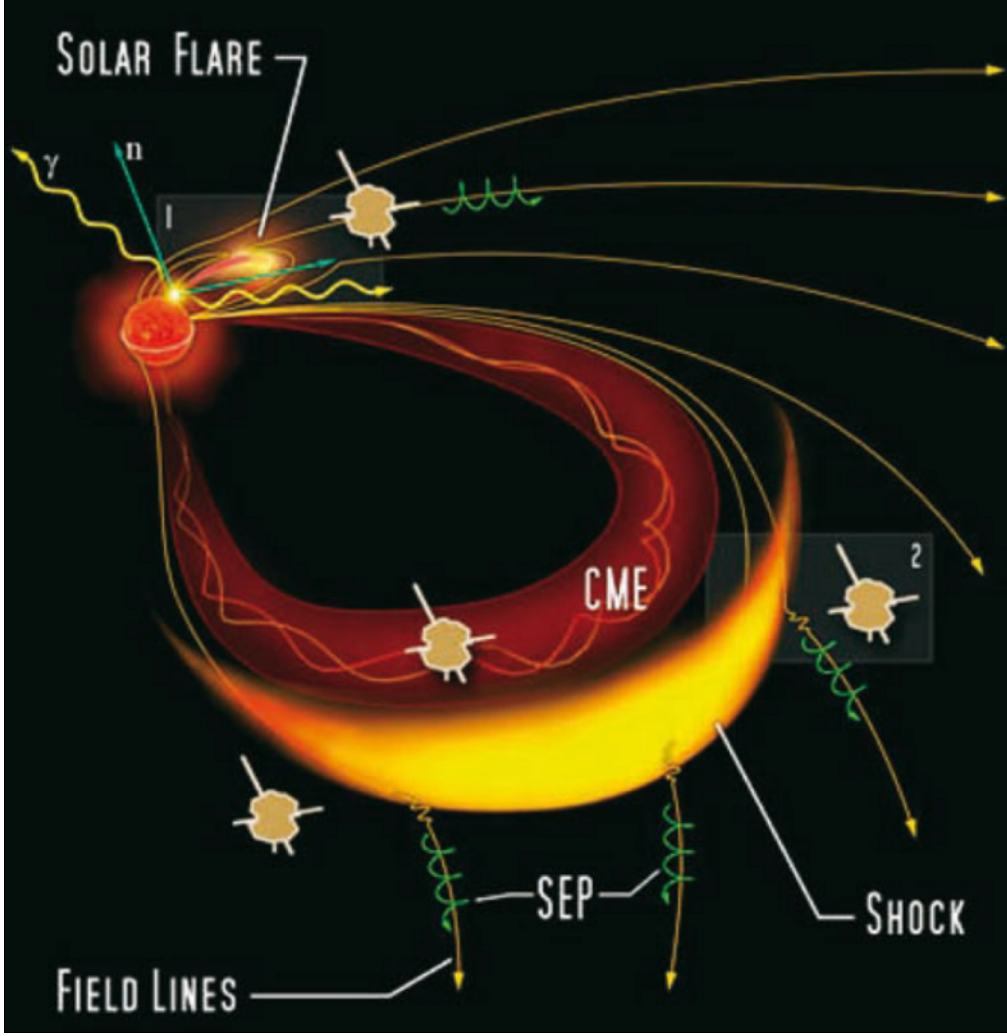
reconnection ejects ultra-relativistic plasmoids
into the magnetar wind
(cf. solar flares)

Blast waves from magnetar flares:

blast Lorentz factor

$$\frac{\Gamma}{\Gamma_{\rm w}} \approx 100 \left(\frac{L_{\rm f,47}}{L_{\rm w,39}}\right)^{1/4}$$

pre-shock wind Lorentz factor



cf. solar CME

AB 2017, 2019
Metzger et al. 2019

Pre-flare wind from the rotating twisted magnetosphere

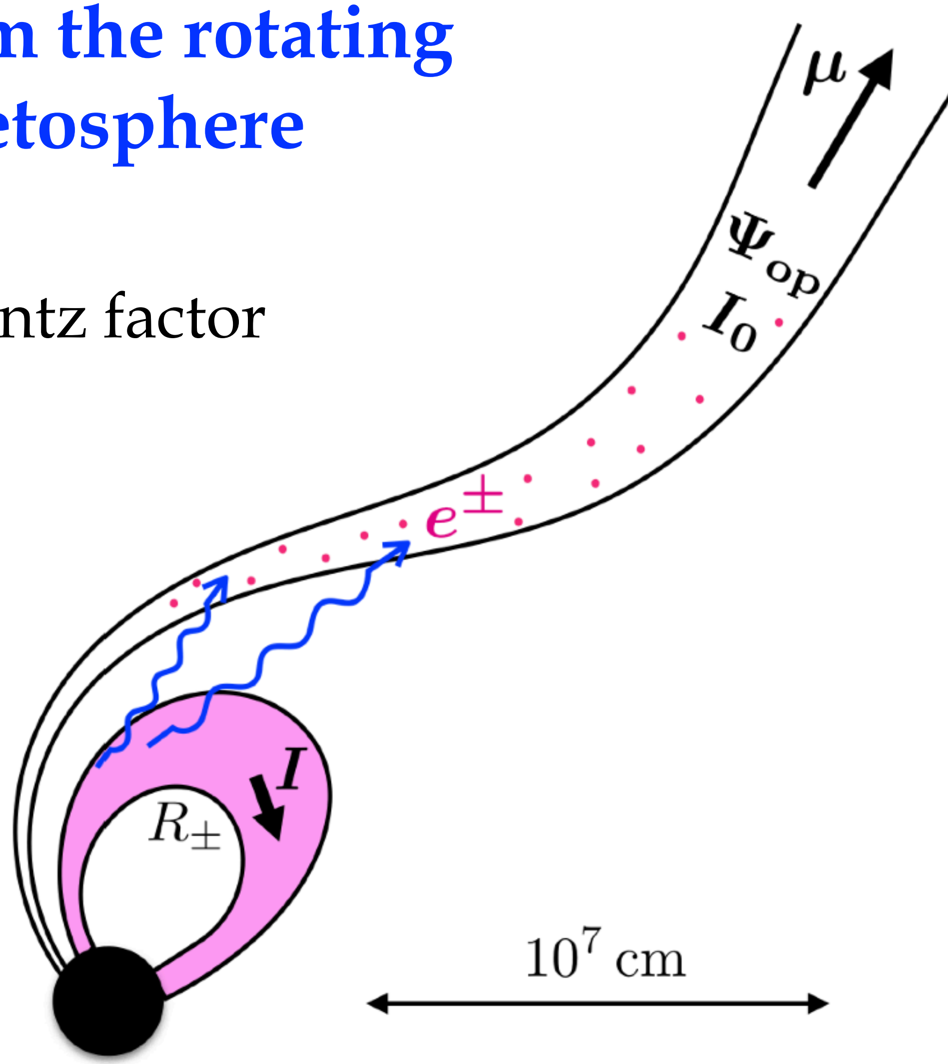
e+- loading determines Lorentz factor of the wind: $\Gamma_{\rm w} \approx 3\eta^{1/3}$

$$\eta = \frac{L_{\rm w}}{\dot{N} m_e c^2} \sim 10^2 - 10^4$$

(wind energy per unit rest mass)

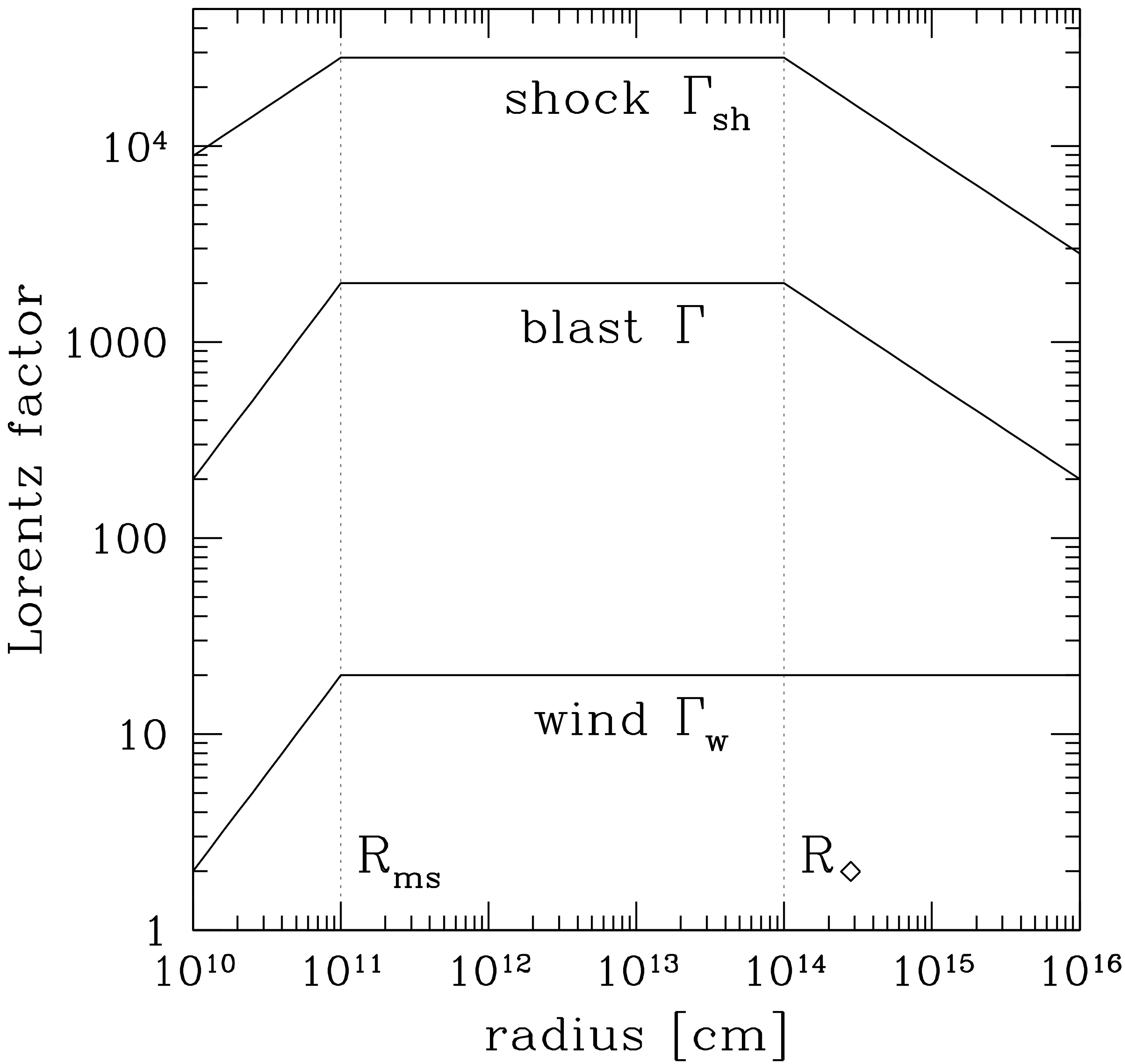
$$L_{\rm w} \sim 10^{38} - 10^{39}\ {\rm erg/s}$$

$$\sigma_{\rm w} \Gamma_{\rm w} = \eta$$



AB 2019

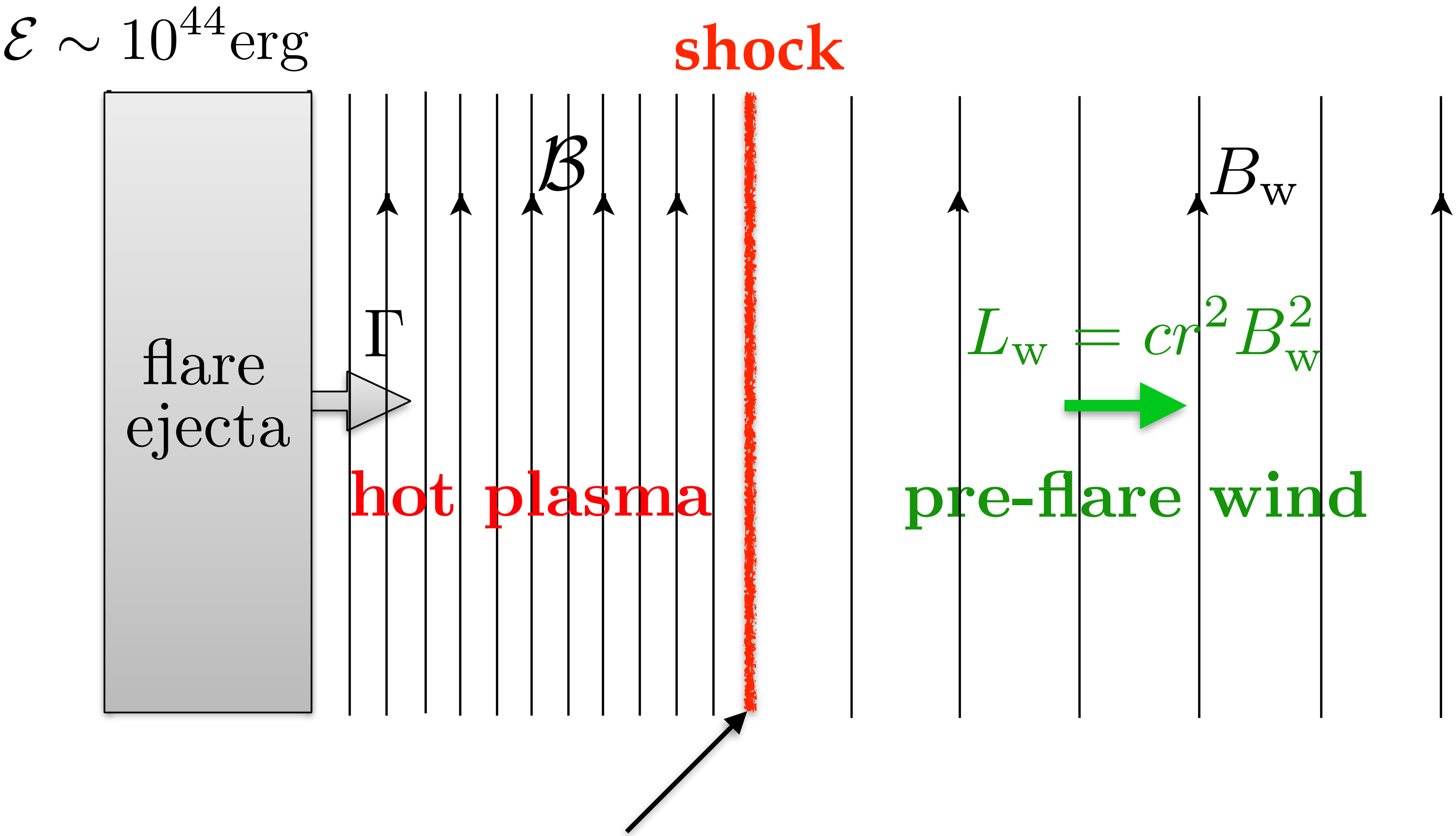
Flare ejecta drives a blast wave in the wind



Ejecta deposits all its energy into the blast wave in the wind at

$$R_\diamond \sim 10^{14}\,\mathrm{cm}$$

Then the blast wave begins to decelerate



maser:

Larmor rotation

$$r_{\rm L} = \frac{\Gamma_{\rm rel} m_e c^2}{e\mathcal{B}}$$

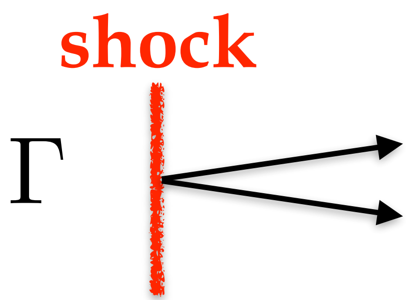
PIC simulations:

Gallant et al. 1992
Sironi & Spitkovsky 2009
Iwamoto et al. 2017, 2018
Plotnikov & Sironi 2019

=> Radio burst:

- Frequency: $\nu_{\rm obs} \sim \frac{3\,\Gamma c}{2\pi r_{\rm L}} \approx \frac{2\,{\rm GHz}}{r_{14}} \left(L_{\rm f,47} L_{\rm w,39}\right)^{1/4}$ drifts high to low

- Beaming:



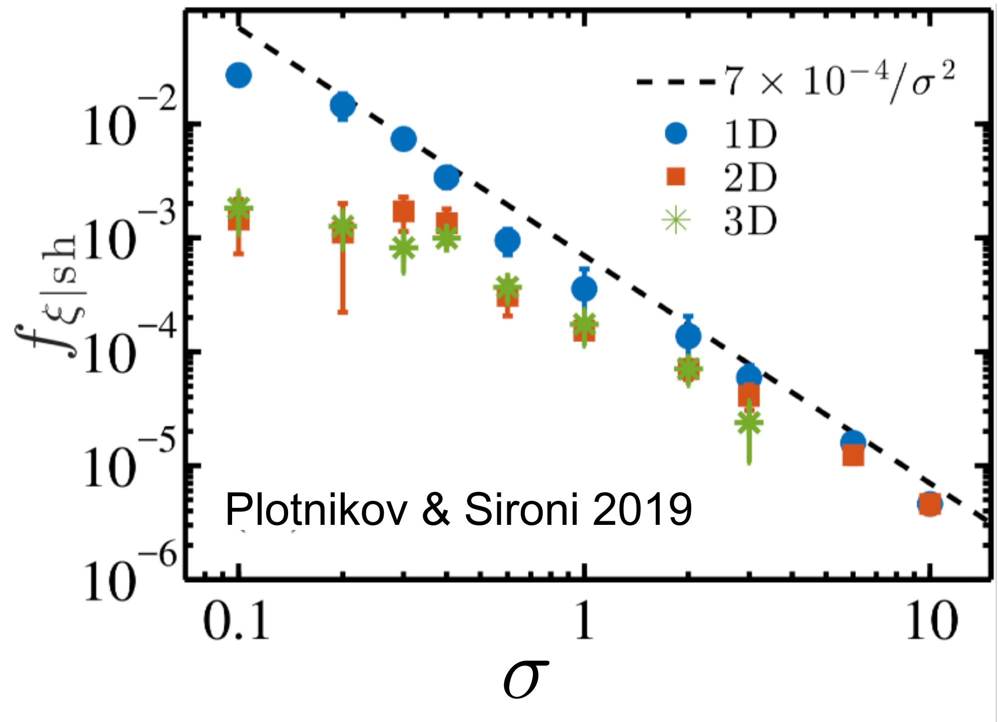
$$\theta_{\rm b} \approx \frac{1}{\Gamma_{\rm sh}} \approx \frac{1}{\Gamma \sigma_{\rm w}^{1/2}}$$

Doppler factor $D = \Gamma(1+\beta\cos\theta) \approx 2\Gamma$

- Duration: $t_{\rm obs} \sim \frac{r}{\Gamma_{\rm sh}^2 c} \lesssim 1\ {\rm ms}$

- Radiative efficiency:

$$\frac{\mathcal{E}_{\rm FRB}}{\mathcal{E}_{\rm bw}} \sim \frac{10^{-3}}{\sigma_{\rm w}^2} \sim 10^{-5}$$



- Polarization: linear, position angle is set by the magnetar rotation axis (=> constant)

- Bursts repeat. Energy budget over magnetar lifetime

$$\sim 10^{-5}\,\mathcal{E}_B \sim 10^{44}\,\mathrm{erg}$$

Wave strength parameter $a = \frac{eE}{m_e c \omega} \approx 2 \frac{L_{42}^{1/2}}{r_{13}}$

for the shock maser $a \sim \frac{1}{\sigma_{\rm w}} \left(\frac{\mathcal{E}_{44}}{L_{\rm w,39}} \right)^{1/4}$

Does the radio burst escape?

Thomson optical depth of the wind: $\tau_{\rm T} \sim 10^{-9} \, r_{13}^{-1}$

Induced Compton scattering of the beam: $\frac{\Delta \nu}{\nu} = -\alpha \mathcal{N} \frac{2h\tilde{\nu}}{m_e c^2} (1 - \cos \tilde{\theta}_b) \, \tilde{\Omega}_b \, \tau_{\rm T}$

$\frac{|\Delta \nu|}{\nu} < 1$ requires $L_{\rm w} / \dot{N} m_e c^2 > 50$

Observed cosmological Fast Radio Bursts (FRBs)

- Rate in the universe ~ rate of magnetar giant flares
- Some repeat frequently (in particular FRB 121102)
- Durations ~1 ms
- Frequency drifts (high to low)
- Energies 1e38-1e41 erg
- Linear polarization (~100% in FRB 121102, constant angle)
- Persistent radio nebula around FRB 121102 is consistent with magnetar ejecta

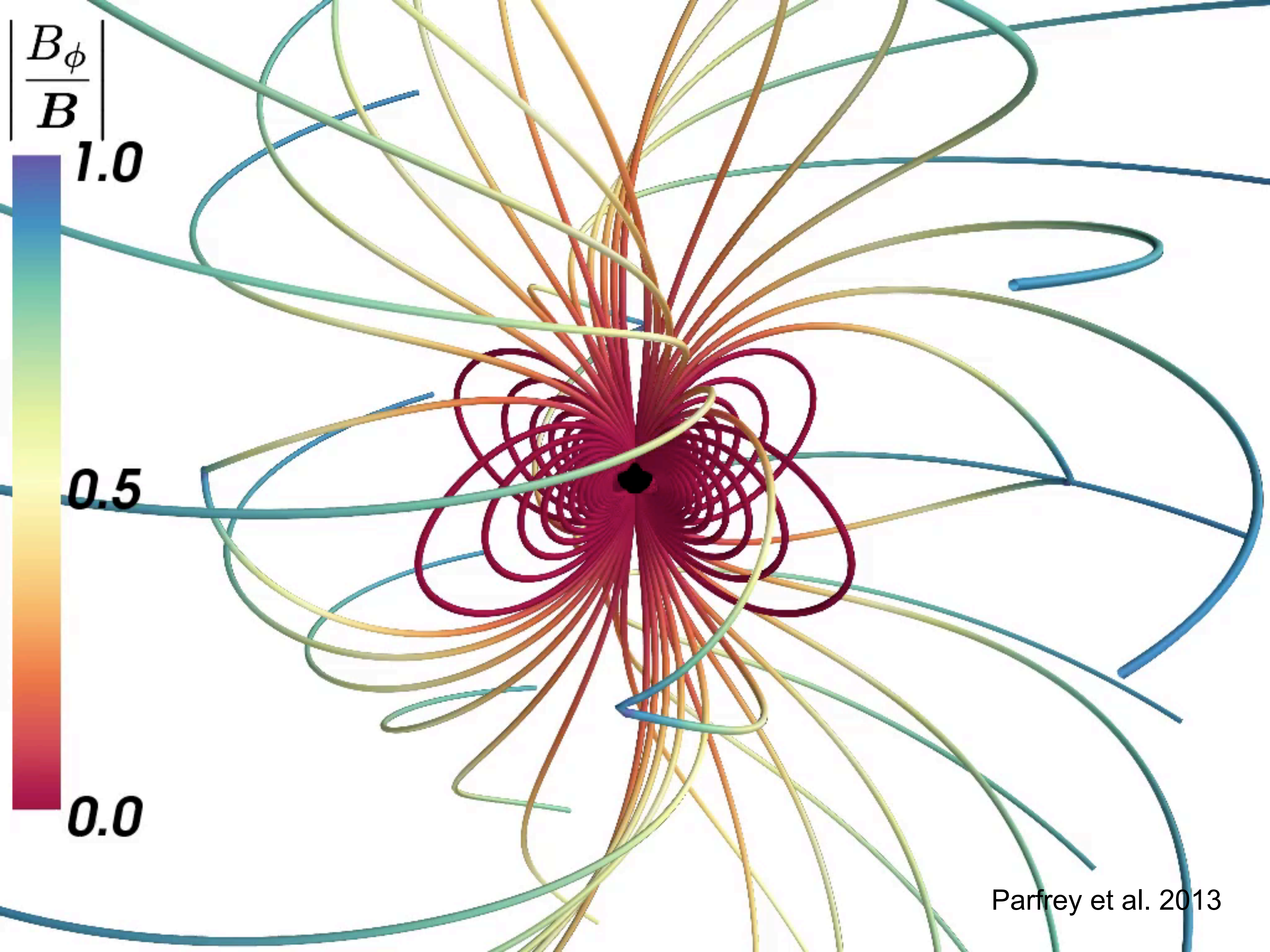
Summary

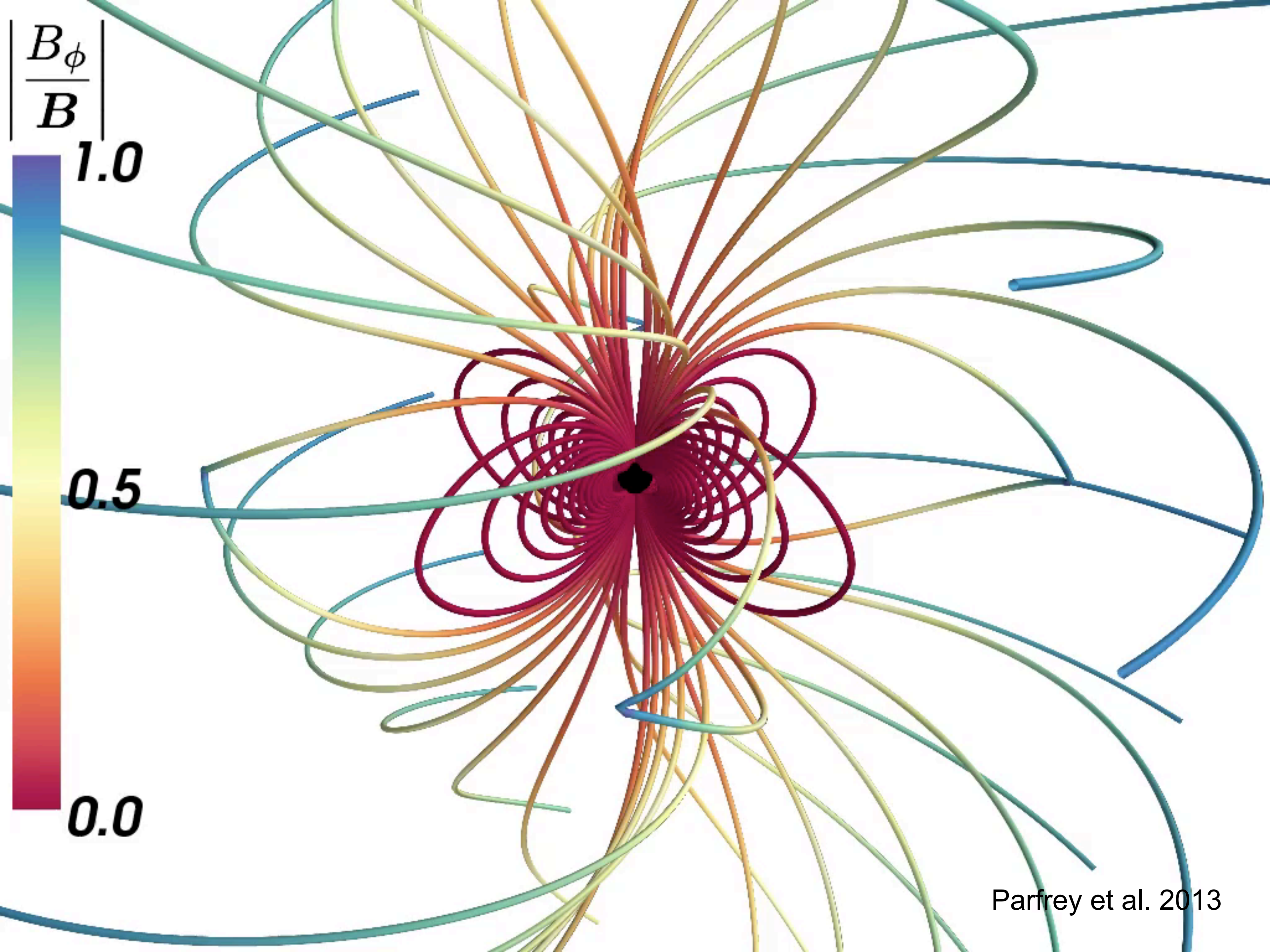
- Huge sudden dissipation events around magnetars are caused by strong deformations of their magnetospheres

- Dissipation occurs through magnetic reconnection and turbulence cascade. They create bulk motions, which convert to radiation through Compton drag

- Ultra-relativistic ejecta from giant flares drive blast waves into the magnetar wind

- The blast waves emit radio bursts by the shock maser mechanism. The bursts are consistent with observed FRBs


$\left|\frac{B_\phi}{B}\right|$
1.0
0.5
0.0
Parfrey et al. 2013


$\left|\frac{B_\phi}{B}\right|$
1.0
0.5
0.0
Parfrey et al. 2013