Fast radio bursts and their high-energy counterpart from magnetar magnetospheres

Yuan-Pei Yang (杨元培)

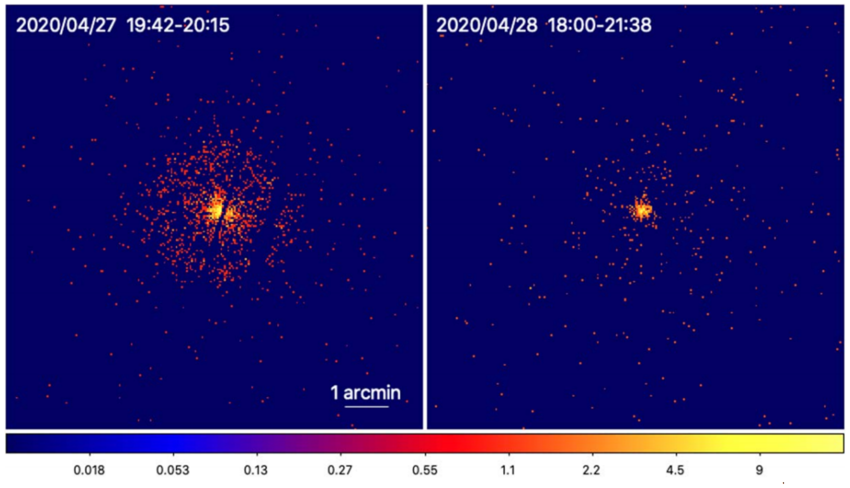
Collaborator: Bing Zhang

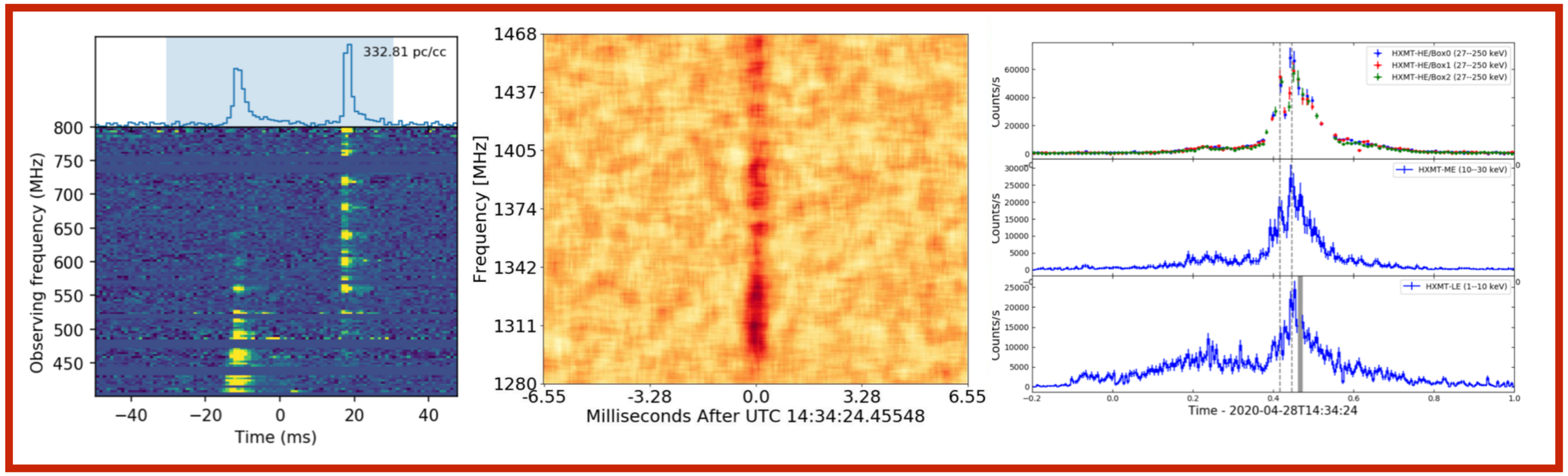
Reference: Yang & Zhang, arXiv: 2104.01925

2021/07/08, Video conference, FRB section @ MG XVI

Galactic FRB from a magnetar

X-ray of SGR 1935+2154

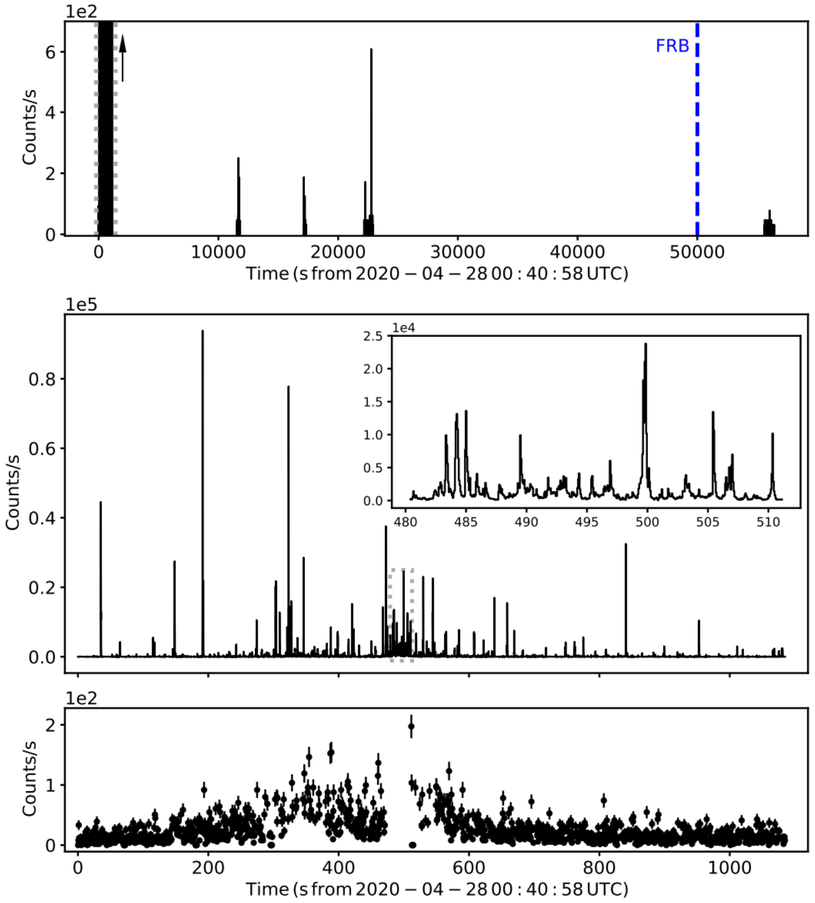




CHIME bursts

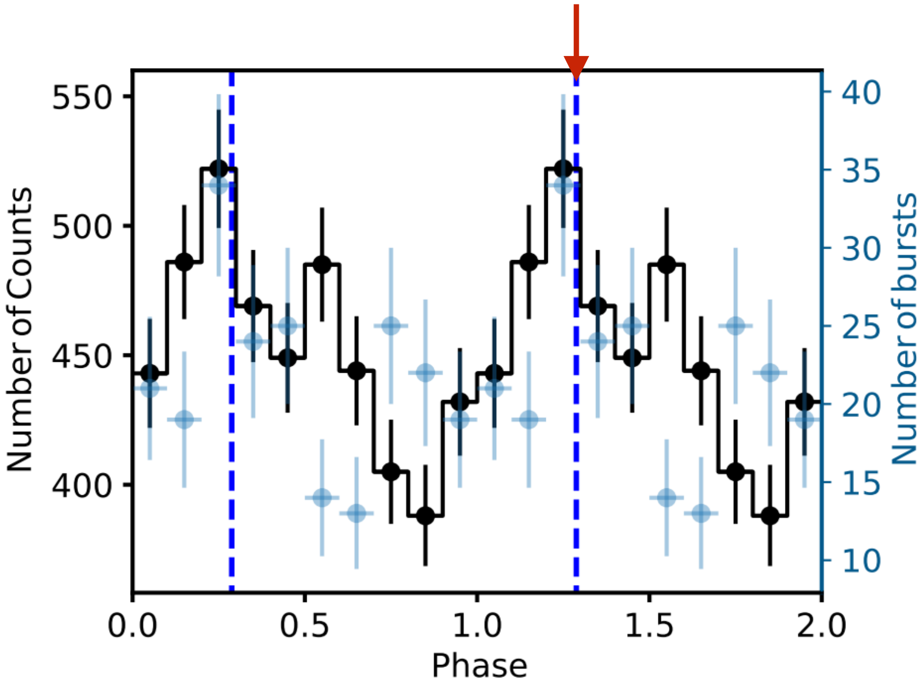
STARE2 burst

HXMT X-ray burst



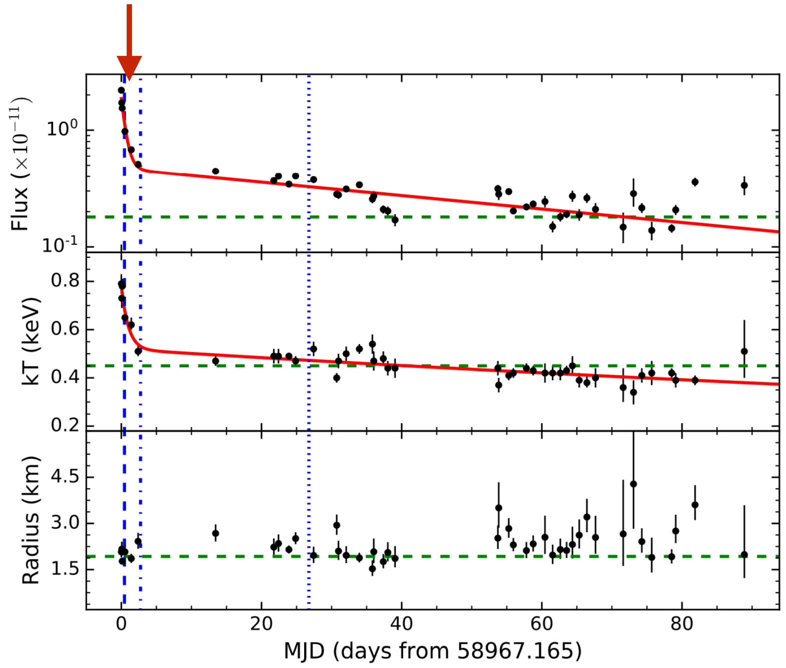
Burst storm by FRB 200428

FRB 200428



Pulse profiel of X-ray persistent emission

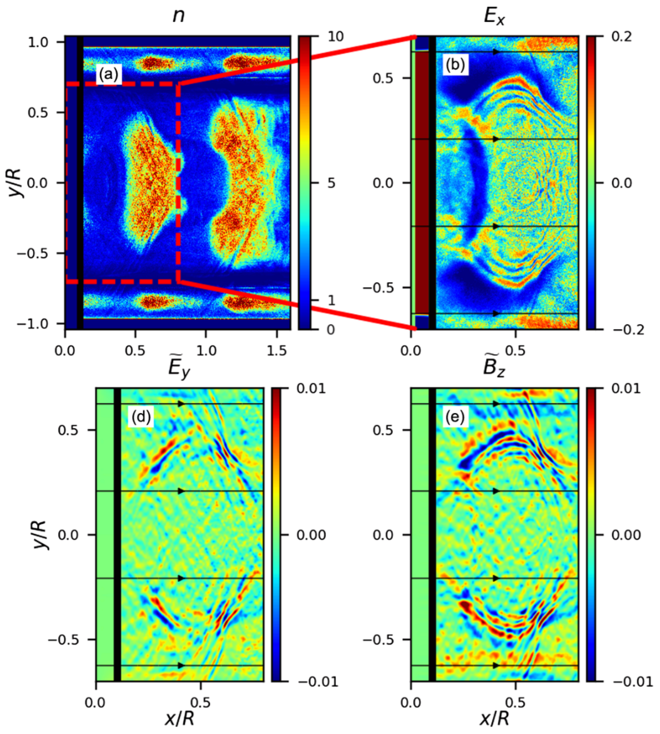
FRB 200428



Evolution of persistent emission

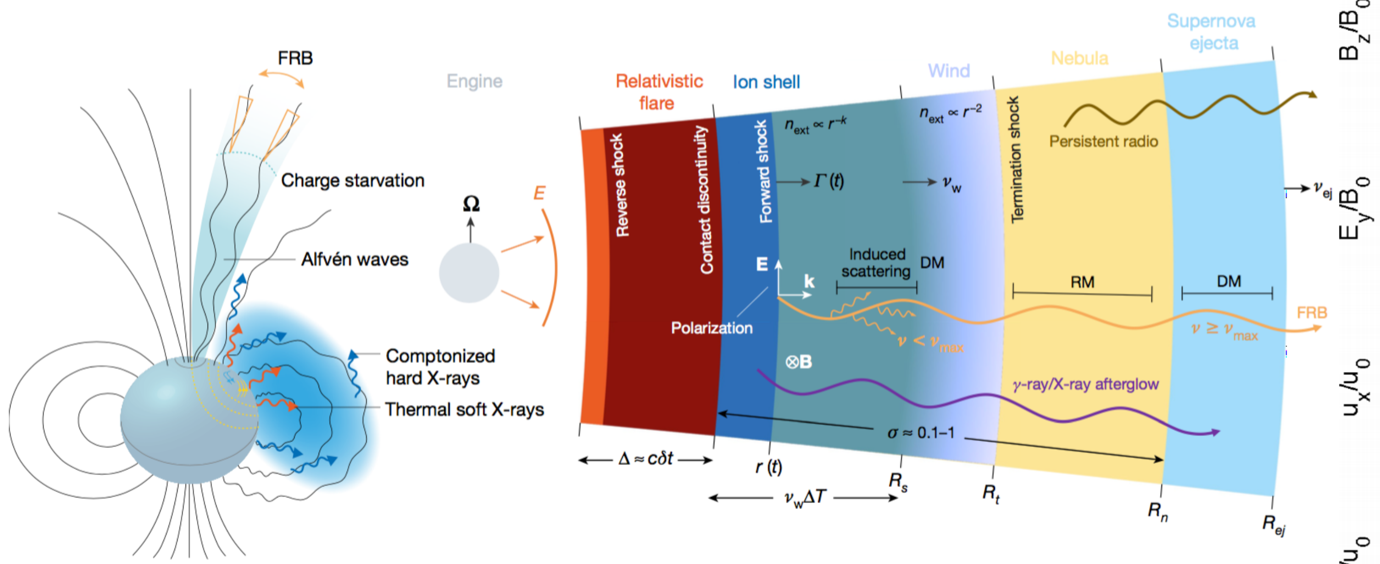
Bochenek +,2020 Nature; CHIME, 2020, Nature; Li +, 2020, NA; Lin +, 2020, Nature; Younes +, 2020, ApJ

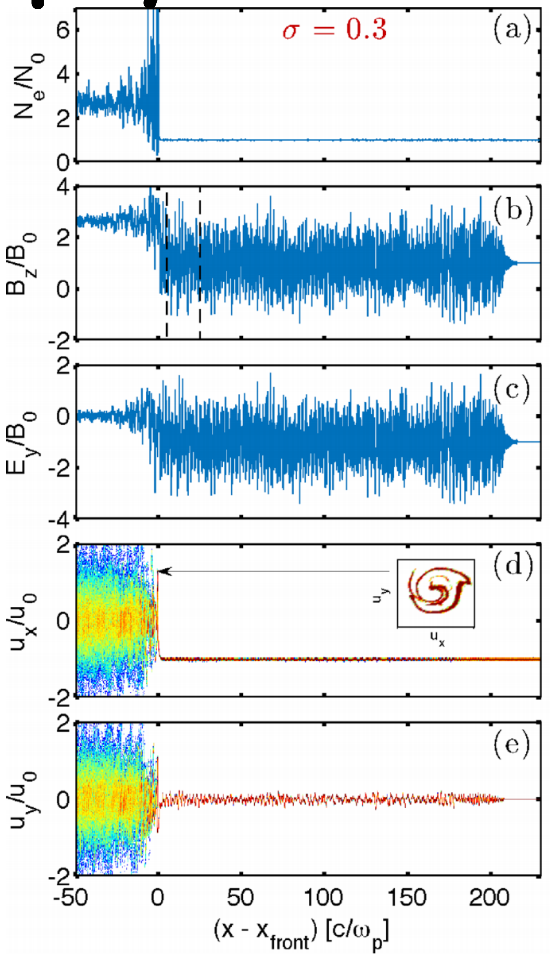
FRB models and energy supply



Pulsar-like model

GRB-like model





Magnetic energy

Rotation energy

Coherent plasma emission

$$\boxed{\left|\frac{\partial}{\partial t}\int \frac{B^2}{8\pi}\, dV\right|} \gg \left|I_{\rm ns}\Omega_{\rm ns}\dot{\Omega}_{\rm ns}\right|$$

Synchrotron maser

- The magnetic energy inside the magnetar may be estimated as

$$E_B \sim \frac{B^2}{8\pi}\left(\frac{4\pi}{3}R^3\right) \simeq 1.7\times 10^{47}\ {\rm erg}\ B_{15}^2,$$

much larger than FRB energy

Metzger + 2019, MNRAS; Lu +, 2020, MNRAS; also see Zhang, 2020, Nature Philippov+,2020, PRL; Plotnikov & Sironi, 2019, MNRAS

Active age of repeating FRB sources

- The FRB burst event rate of **FRB 121102** is about

$$R(>E) \simeq R_0 \left(\frac{E}{E_0}\right)^{-\alpha},$$

- where $\alpha \sim 0.8,\ R_0 \sim (10^4 - 10^5)\ \mathrm{burst\ yr^{-1}}$ **extremely high event rate**

- The total released energy for a repeating source during the age of tau would be

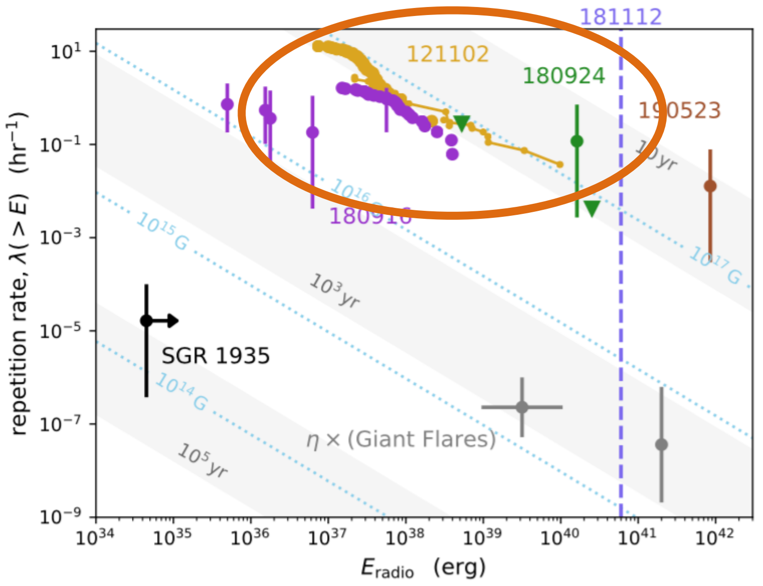
$$E_{\rm tot}(\tau) = 1.0 \times 10^{47}\ {\rm erg} \left(\frac{E_{\rm max}}{10^{40}\ {\rm erg}}\right)^{0.2} \left(\frac{E_0}{10^{38}\ {\rm erg}}\right)^{0.8} \times \left(\frac{R_0}{10^4\ {\rm yr^{-1}}}\right) \left(\frac{\tau}{10\ {\rm kyr}}\right),$$

- Such a burst energy is sustainable by a magnetar for a duration of

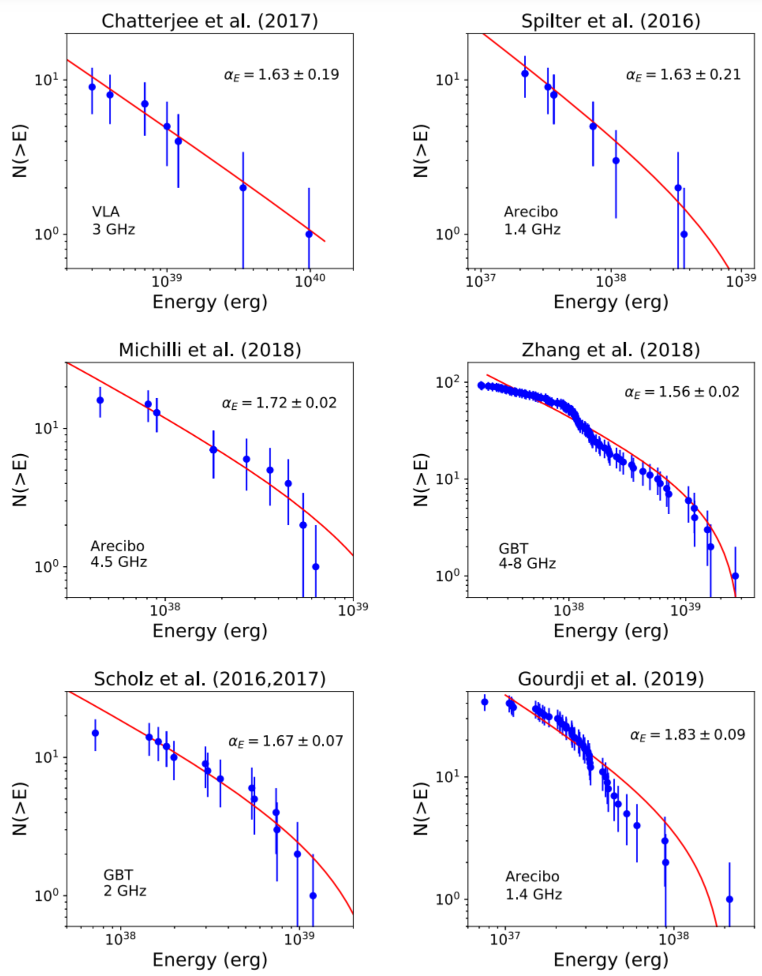
$$E_{\rm tot}(\tau) < \eta E_B \longrightarrow \tau \lesssim 17\ {\rm yr}\ \eta_{-3} B_{15}^2,$$ **<< magnetar's age**

- Extremely high FRB event rate **only lasts for a relatively short period** comparing with the typical magnetar lifetime.

- Active FRB repeaters: very young and highly magnetized magnetars.



Event rate at different frequency



Yang & Zhang, 2021

Margalit +,2020, ApJ; Wang & Zhang, 2019, ApJ

FRBs triggered by crust fracturing

- The critical condition for magnetic shear stress reaching the threshold is given by

$$\frac{B\delta B}{4\pi} \simeq \sigma_{\rm cr} \equiv \theta_{\rm max}\mu,$$

- The critical value of the bent angle is

A small bending angel

$$\theta_{B,c} = \left(\frac{4\pi\mu}{B^2}\right)\theta_{\rm max} = 10^{-3}\ {\rm rad}\ \mu_{28}B_{15}^{-2}\theta_{{\rm max},-2}.$$

- The magnetic field evolution in plasma can be generally written as

$$\frac{\partial \boldsymbol{B}}{\partial t} = \cancel{\nabla\times(\boldsymbol{v}\times\boldsymbol{B})} - \cancel{\nabla\times(\eta\nabla\times\boldsymbol{B})} - \nabla\times\left(\frac{\boldsymbol{J}\times\boldsymbol{B}}{n_e e}\right)$$

Hall term

- The Hall timescale is given by

$$\tau_{\rm Hall} = \frac{en_eL}{J} = \frac{4\pi en_eL^2}{cB}, \simeq 11\ {\rm yr}\ Y_{e,-1}\rho_{{\rm nu},-3}L_4^2B_{15}^{-1},$$

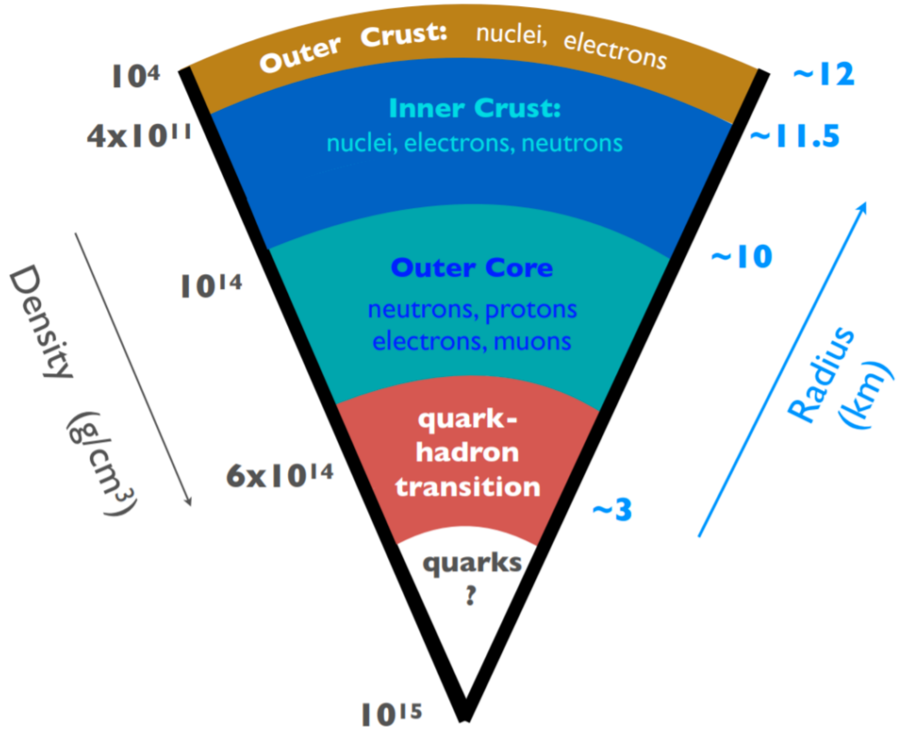
- The typical timescale triggering crustal cracking would be much shorter than the Hall drift timescale

$$\Delta t_{\rm cra} \sim \theta_{B,c}\tau_{\rm Hall} \ll \tau_{\rm Hall}$$

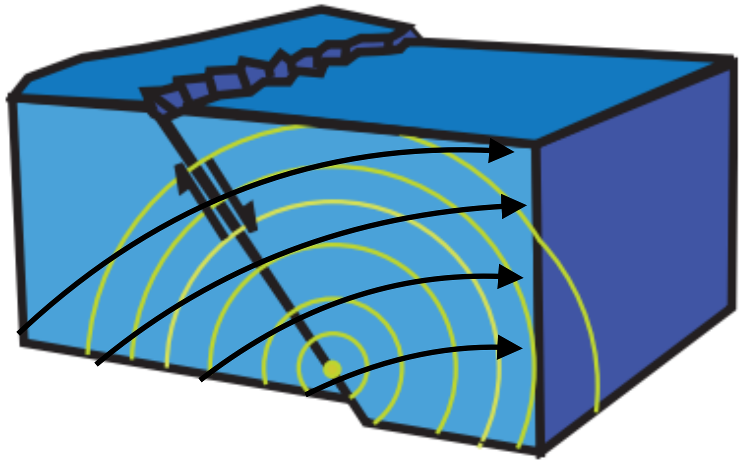
- The burst rate is then estimated as

$$\boxed{\mathcal{R} = \Delta t_{\rm cra}^{-1} \simeq 0.26\ {\rm day}^{-1}\ Y_{e,-1}^{-1}\rho_{{\rm nu},-3}^{-7/3}L_4^{-2}B_{15}^3\theta_{{\rm max},-2}^{-1}.} \rightarrow \boxed{\mathcal{R} \propto B^3}$$

NS structure



crust fracture due to field line bend



Yang & Zhang, 2021

FRBs triggered by crust fracturing

- In long term, the magnetic field in the crust would decay via Ohmic dissipation. Two mechanisms dominate this process:

$$\frac{\partial \boldsymbol{B}}{\partial t} = \nabla \times (\boldsymbol{v} \times \boldsymbol{B}) - \boxed{\nabla \times (\eta \nabla \times \boldsymbol{B}) - \nabla \times \left(\frac{\boldsymbol{J} \times \boldsymbol{B}}{n_e e}\right)}$$

- The long-term magnetic field evolution by Hall cascades can be approximated by (Colpi et al. 2000)

$$dB/dt \simeq -AB^2 \text{ with } A = 10^{-18}\ \mathrm{G^{-1} yr^{-1}}$$

- The magnetic decay may be quantified as

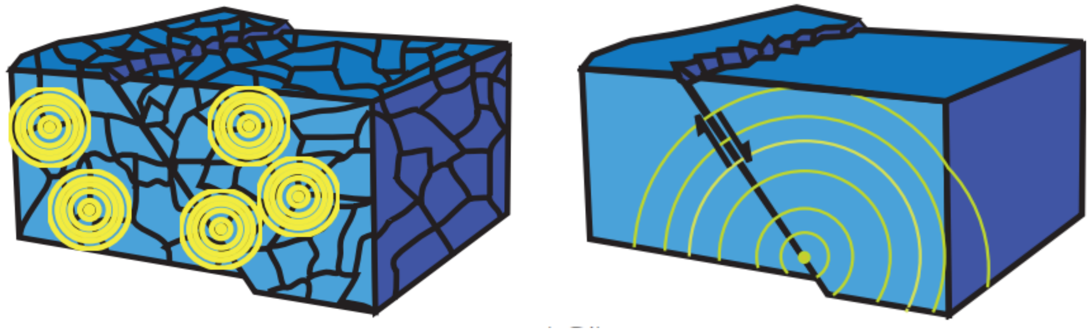
$$B = \frac{B_0}{1 + AB_0 t}, \qquad \tau_B = \frac{1}{AB_0} = 100\ \mathrm{yr}\ B_{0,16}^{-1}$$

- Therefore, the event rate satisfies

$$\boxed{\mathcal{R} \propto \begin{cases} t^0, & \text{for } t \ll \tau_B \\ t^{-3}, & \text{for } t \gg \tau_B . \end{cases}}$$

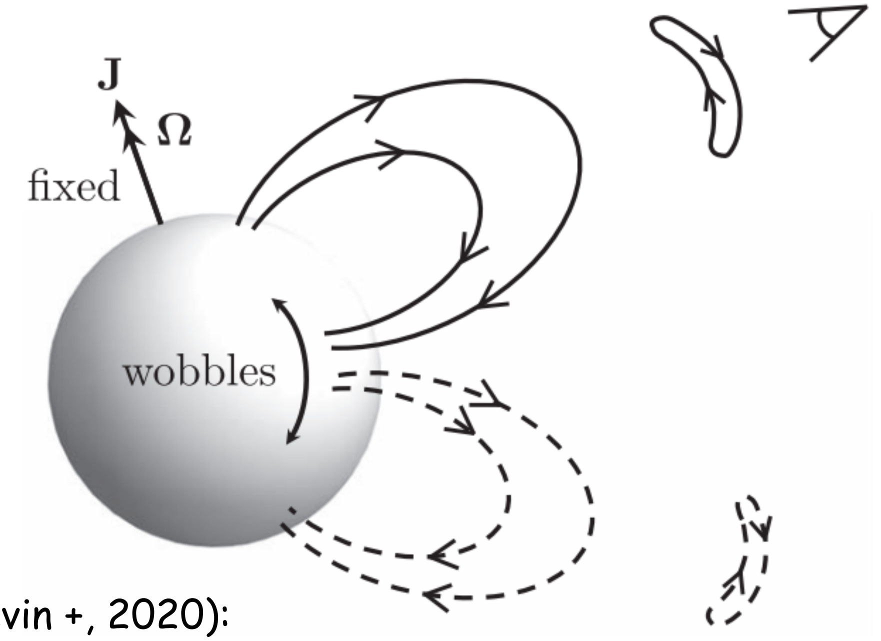
- Active repeating FRBs are proposed to originate from young magnetars with strong magnetic fields

Yang & Zhang, 2021



Young magnetar

Old magnetar



Precession period (Levin +, 2020):

$$P_{\rm pr} \approx \frac{P_{\rm spin}}{\epsilon}$$

$$\approx 20\ k_{0.01}^{-1} \left(\frac{B_{\rm int}}{10^{16}\ \mathrm{G}}\right)^{-2} \frac{B_{\rm dip}}{10^{15}\ \mathrm{G}} \left(\frac{t}{30\ \mathrm{yr}}\right)^{1/2} \text{ days.}$$

Levin +, 2020, ApJ

see Dongzi's report

Fragile regions in magnetar crust

- Since the polar regions have much stronger fields, crust fracturing may more easily occur in the polar regions.
- For an axisymmetric multipolar magnetic field, strength of magnetic field is

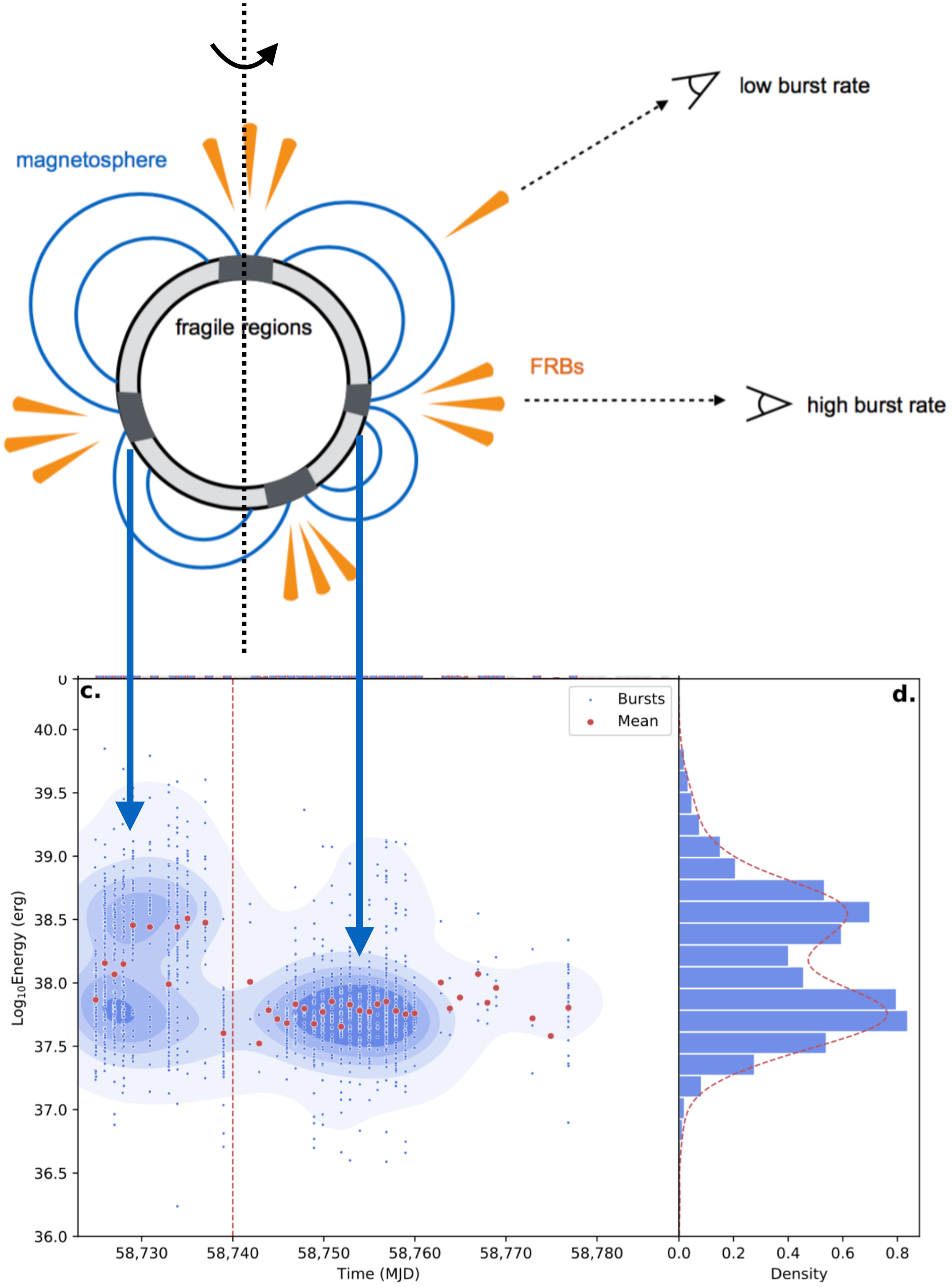
$$B = \sqrt{\frac{4\pi}{2l+1}\frac{q_{l0}}{R^{l+2}}}\sqrt{(l+1)^2 P_l(\cos\theta)^2 + P_l'(\cos\theta)^2}$$

- Therefore, the fracturing rate satisfies $\boxed{\mathcal{R} \propto B^3.}$ One may estimate the fracturing rate as

$$\boxed{\mathcal{R}(\theta) \propto \left[(l+1)^2 P_l(\cos\theta)^2 + P_l'(\cos\theta)^2\right]^{3/2}}$$

- Bursts of FRB 121102 appears to have two components in the energy distribution, which might correspond to two fragile regions sweeping the line of sight.

Yang & Zhang, 2021



Li +, 2021, Nature accepted

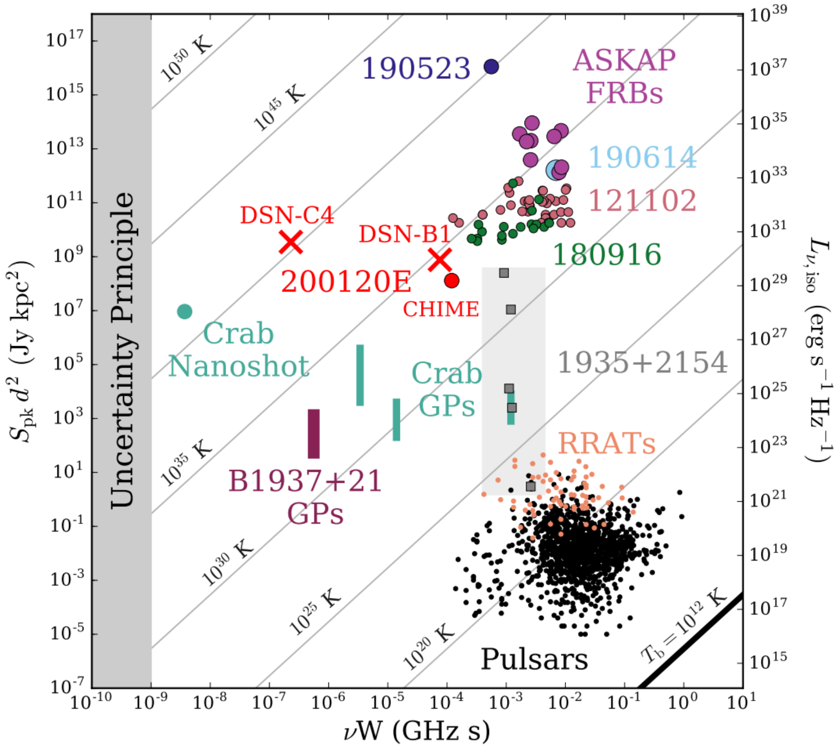
see Di's report

FRBs and Pulsars

- The extremely high brightness temperature of FRBs, typically ~10^35 K, implies that the radiation mechanism of FRBs must be coherent.

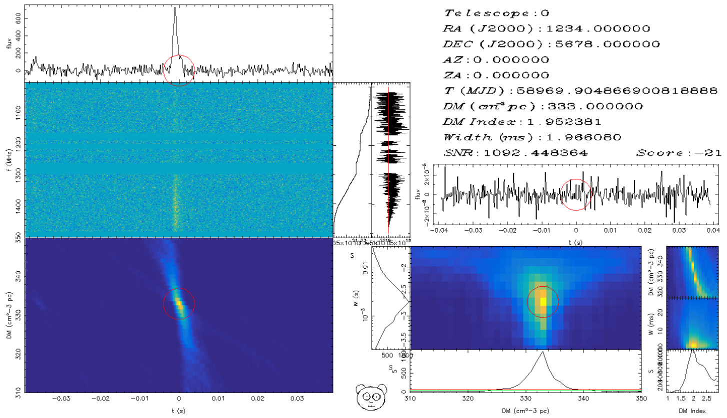
- The connections between FRBs and radio pulsars are manifested by the following facts
  - FRBs and radio pulsars are the most coherent sources in all kinds of astrophysical phenomena.
  - Periodic radio pulses, bright radio burst and FRB 200428 were emitted from Galactic magnetar SGR J1935+2154

Most coherent sources: Pulsars & FRB



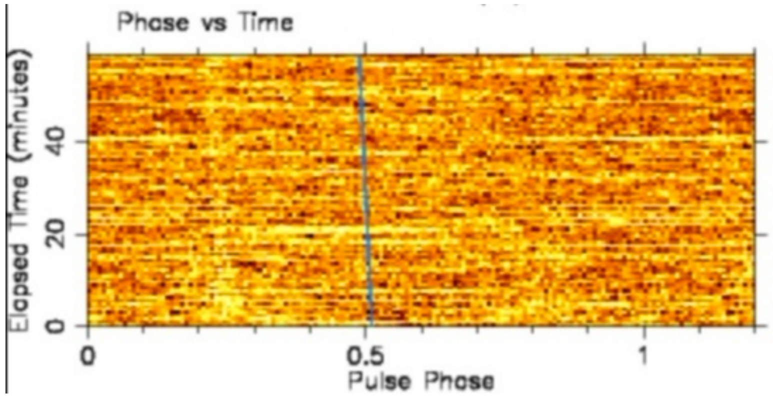
Majid +, 2021, arXiv

Radio burst from SGR J1935+2154



```
Telescope:0
RA (J2000):1234.000000
DEC (J2000):5678.000000
AZ:0.000000
ZA:0.000000
T (MJD):58969.904866900818888
DM (cm^3 pc):333.000000
DM Index:1.952381
Width (ms):1.966080
SNR:1092.448364          Score:-21
```

Periodic radio pulse from SGR J1935+2154



Zhang +, 2020, ATel; Zhu +, 2020, ATel

Alfven wave by crust fracturing

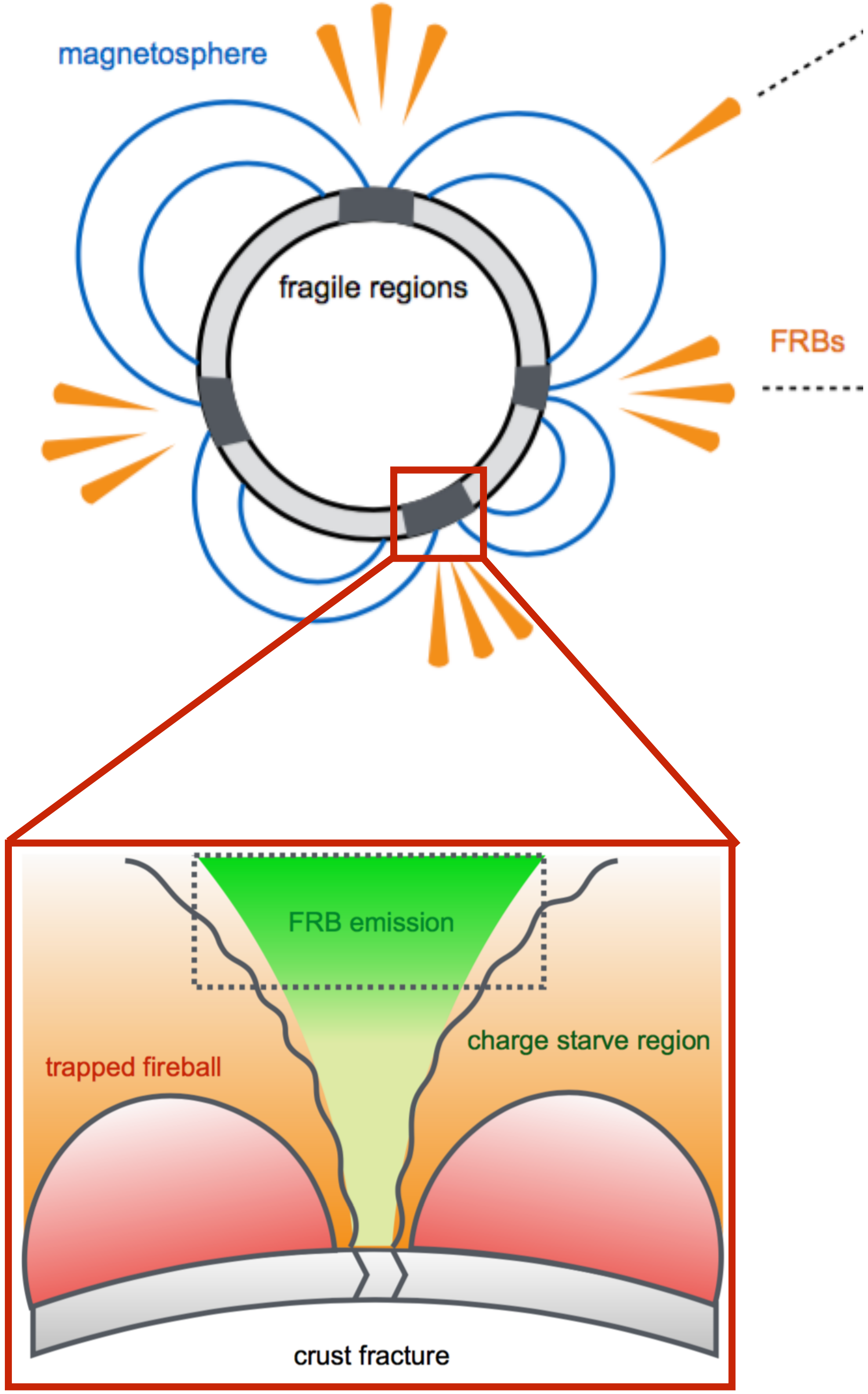
- When the crust cracks, a magnetic field disturbance is produced by the wiggling of the magnetic field foot points by the crust fracturing motion
- $$\delta B \sim \frac{v}{c} B_p \sim \frac{1}{c}\left(\frac{\mu}{\rho}\right)^{1/2} B_p \simeq 6 \times 10^{12}\ \mathrm{G}\ B_{p,15}\rho_{\mathrm{nu},-3}^{1/6},$$
- The Alfven wave packet travels along magnetic field lines and its amplitude decreases with distance.
- A strong parallel electric field is induced at critical radius of ~ 10R where charge starvation occurs (Kumar & Bosnjak, 2020).
- At the charge starved region, the parallel electric field is

$$\begin{aligned} E_{\mathrm{gap}} &= \frac{k_\perp}{k_\parallel}\left(\frac{r_{\mathrm{rc}}}{R}\right)^{-3/2} \delta B \\ &= 2 \times 10^{10}\ \mathrm{V\ cm^{-1}}\ \eta_{k,-1} B_{p,15}\rho_{\mathrm{nu},-3}^{1/6} r_{\mathrm{cr},7}^{-3/2}, \end{aligned}$$

- Consider that the accelerating electric field in the gap region is E_gap, then the amplitude of electrostatic wave is

$$E_x \sim \xi_L E_{\mathrm{gap}} \qquad \xi_L \sim (0.1-1)$$

large-amplitude oscillation of ES wave



Yang & Zhang, 2021

Coherent plasma radiation

- For an O-mode wave, the Maxwell's equations give

$$\partial_t\left(\frac{1}{c^2}\partial_t \underset{\substack{\uparrow\\ \text{ES wave}}}{E_x} + \underset{\simeq 0}{\frac{4\pi}{c^2} j_x}\right) + \boxed{\partial_y\left(\partial_x \underset{\substack{\uparrow\\ \text{EM wave}}}{E_y} - \partial_y E_x\right)} \underset{\simeq 0}{=} 0.$$

- The most important condition to generate electromagnetic wave is **nonuniform pair creation across magnetic field lines**.

- Define an angle between the normal to plasma injection front and the background magnetic field, then the amplitude of electromagnetic wave is about

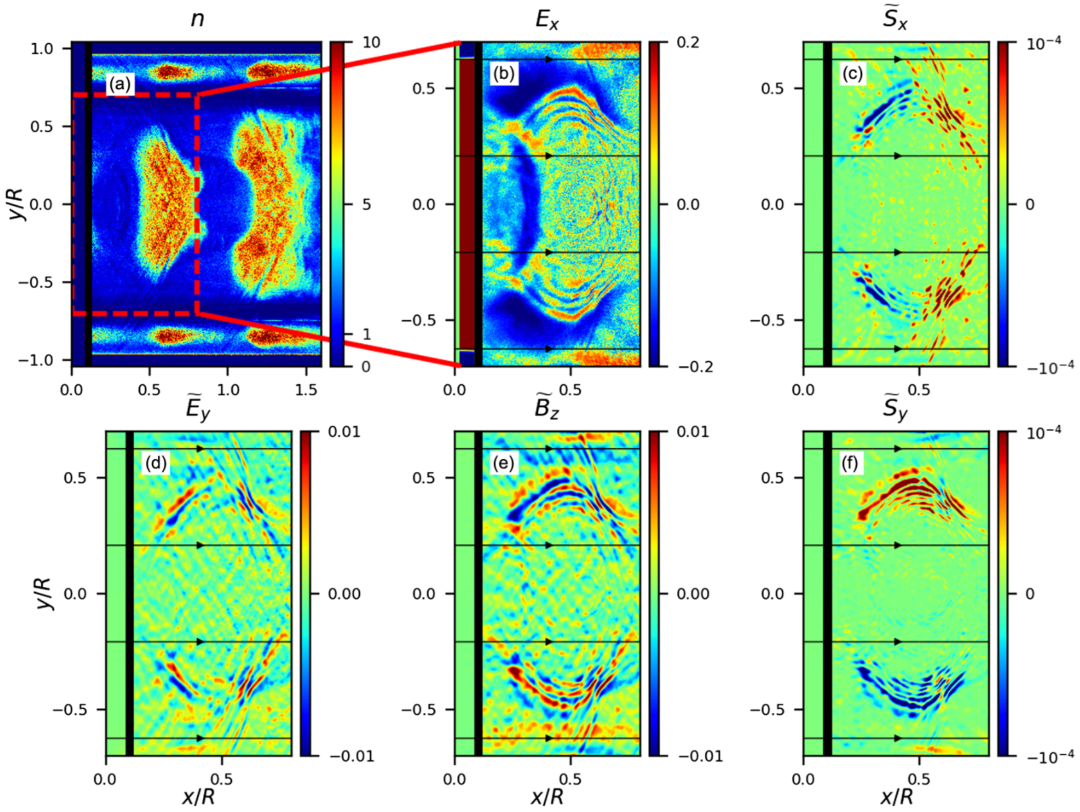
depend on inclination

$$E_w \sim E_y \simeq \frac{k_\perp}{k_\parallel}\xi_L E_{\rm gap} \qquad \eta_k \equiv \frac{k_\perp}{k_\parallel} \sim 0.1$$

- On the other hand, the electric field of FRB at emission region

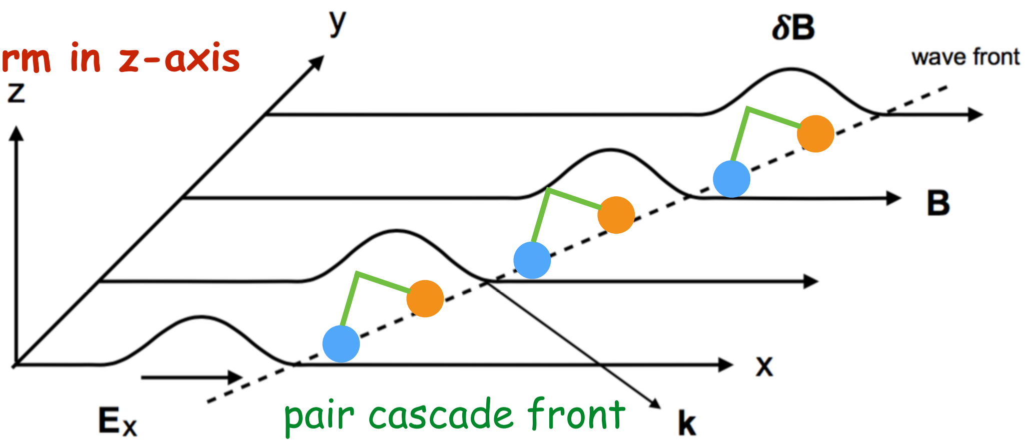
$$E_w \simeq \left(\frac{4\pi\nu F_\nu}{c}\right)^{1/2}\frac{d}{r} \simeq 6\times 10^8\ {\rm V\ cm^{-1}}\,\nu_{\rm GHz}^{1/2}F_{\nu,{\rm Jy}}^{1/2} d_{\rm Gpc} r_7^{-1}$$

based on FRB observation



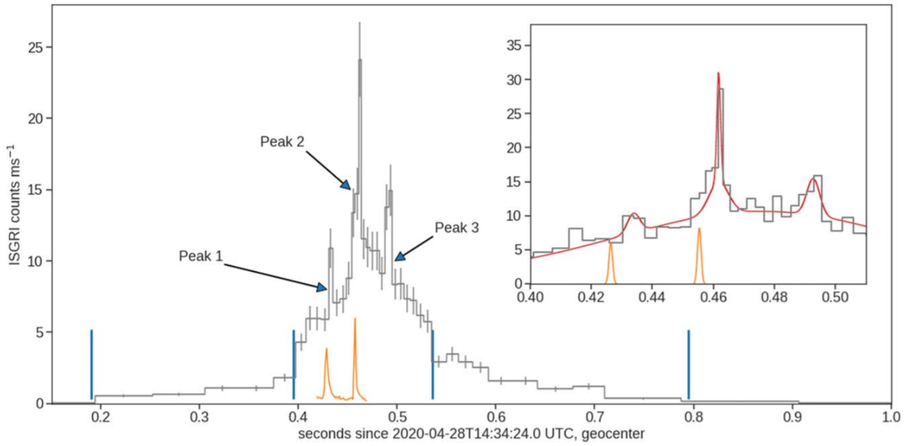
Philippov +, 2020, PRL

uniform in z-axis

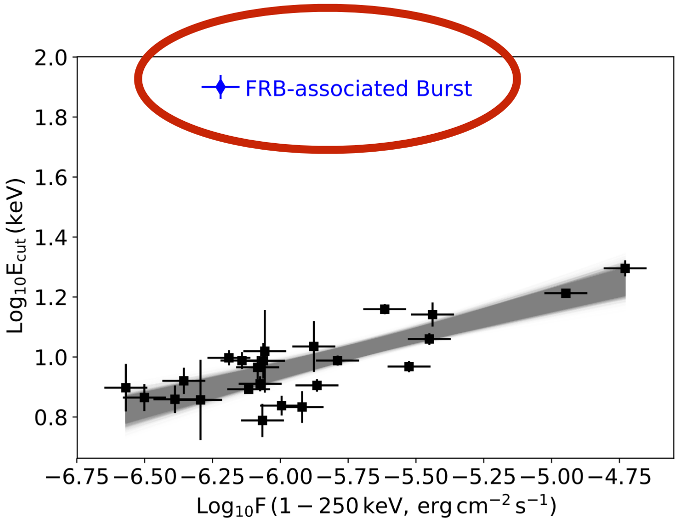


Yang & Zhang, 2021

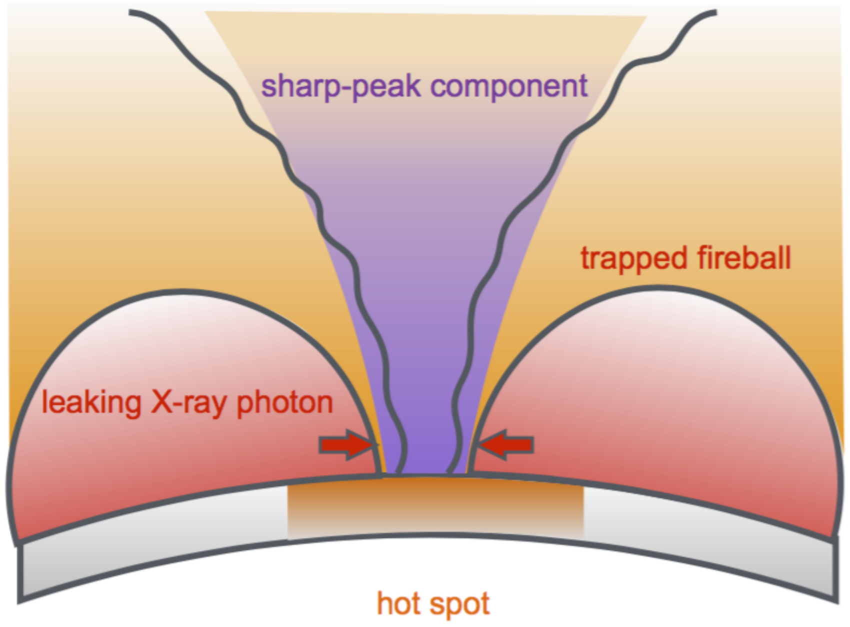
FRB-associated XRB



light curves of FRB and XRB



Higher cut-off energy of XRB



- E-mode photons escape from the base of a trapped fireball, and resonantly scattered by at region between two adjacent trapped fireballs.

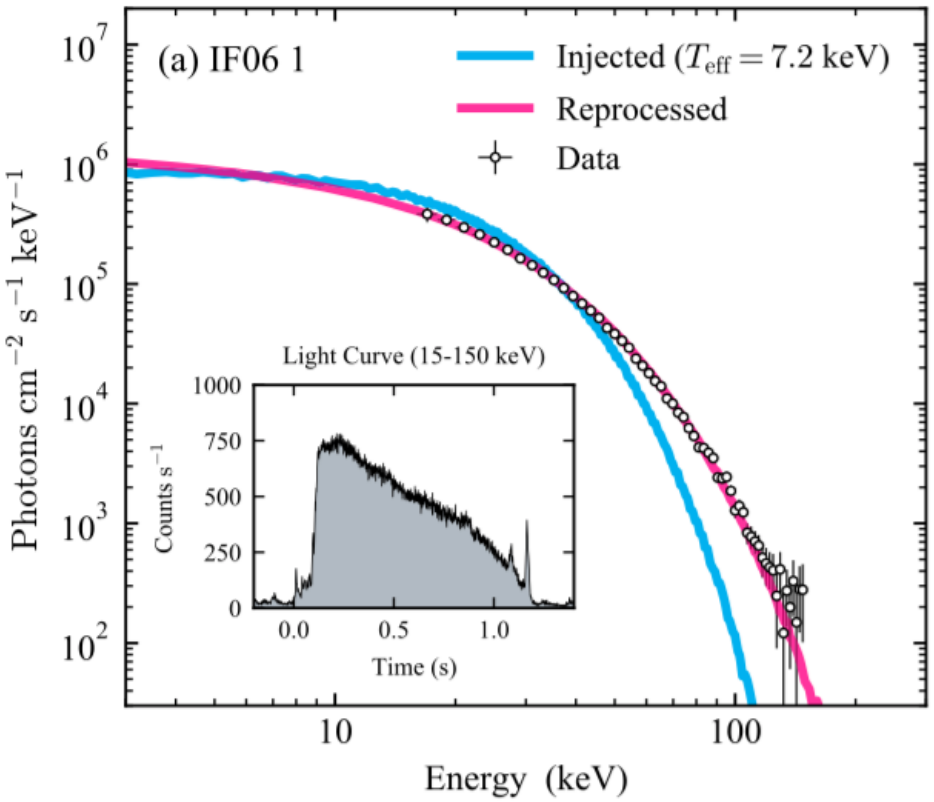
- The balancing velocity of the electron under radiative force is

$$\beta_{\rm res} = \cos\theta_{kB}; \qquad \gamma_{\rm res} = \frac{1}{\sin\theta_{kB}}.$$

- The energy of the scattered photon is about

$$\epsilon_s \sim \gamma_{\rm res}^2 \epsilon$$

- The cutoff energy of the X-ray emission would be increased by several times compared with those without resonant Compton scattering process .



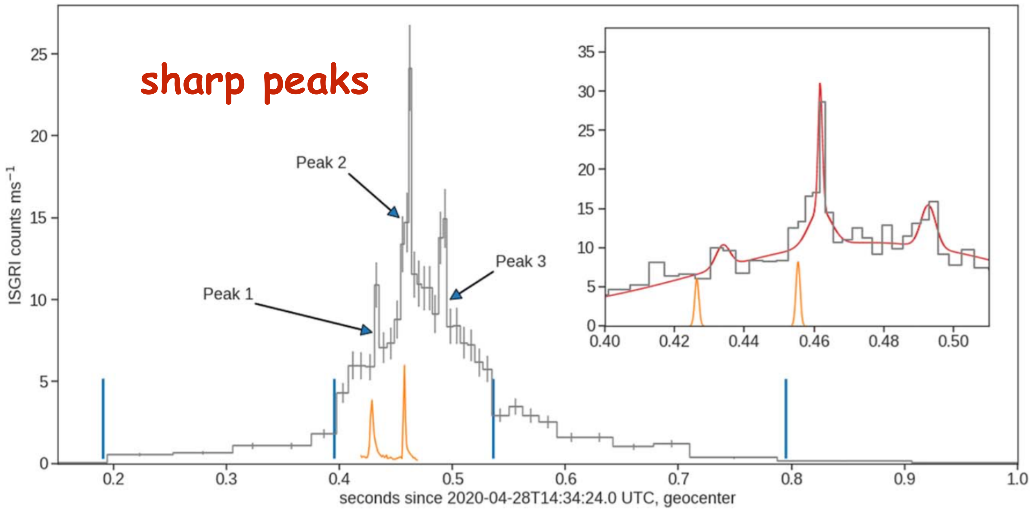
higher cutoff by by resonant scattering (Yamaski +, 2020)

Mereghetti +, 2020, ApJ; Younes +, 2020, ApJ; Yamasaki +, 2020, MNRAS

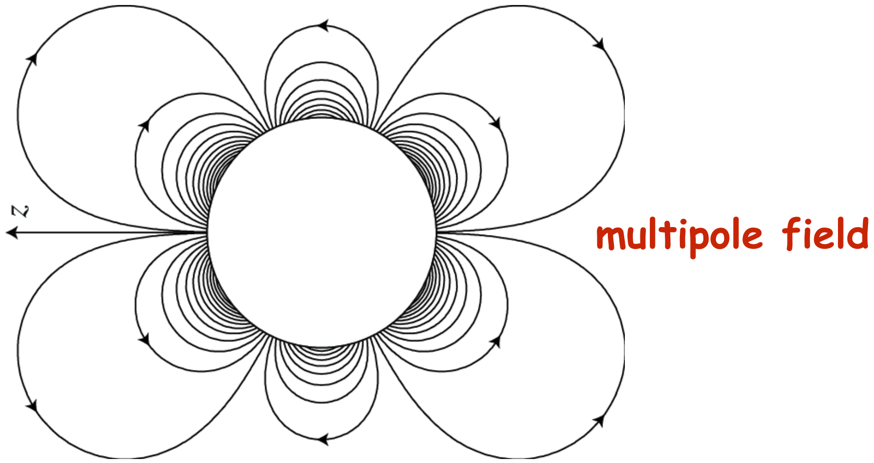
Resonant Compton scattering

- We assume an axisymmetric multipolar magnetic field, then the opening angle of a field line at one pole may be estimated as

$$\theta_{\rm open} \sim \left(\frac{R}{R_{\rm max}}\right)^{l/2} \longleftarrow \quad r \sim R_{\rm max} \sin^{2/l}\theta,$$



- Thus, multipolar fields have much narrower opening angles than dipole fields.

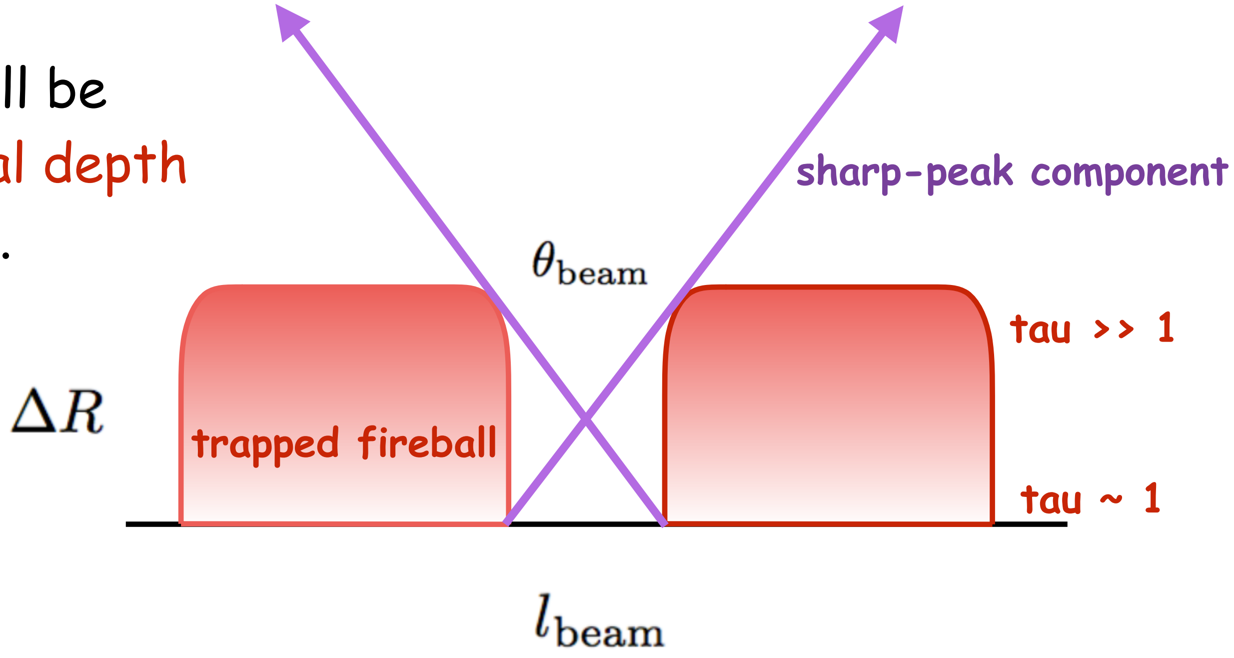


- The region scale between two adjacent trapped fireballs is

$$l_{\rm beam} = R\theta_{\rm open} \sim R\left(\frac{R}{R+\Delta R}\right)^{l/2}.$$

- When the X-ray photons enter the region, they will be confined in a beaming angle due to the large optical depth at the top region of the trapped fireball around it.

$$\theta_{\rm beam} \sim \frac{l_{\rm beam}}{\Delta R} \simeq \frac{R}{\Delta R}\left(\frac{R}{R+\Delta R}\right)^{l/2}$$



Yang & Zhang, 2021

Persistent X-ray emission

- Persistent X-ray emission properties:

  A. double-peaked pulse profile

  B. Arrival time of FRB aligned with the brightest peak

  C. Temperature decreases rapidly in the early stage

  D. the size of the emitting area remains the same.

- The internal energy stored by ions in the outer crust is

$$U_i = \frac{3}{2} N_i kT = 3.1 \times 10^{38}\ \mathrm{erg}\ \rho_{\mathrm{nuc},-3} T_{\mathrm{keV}} L_4 \Delta R^2_{\mathrm{hs},5},$$

- The internal energy could be produced by **~ 1% of XRB energy**

- The temperature evolution is given by $dU_i/dt = -\Delta R^2_{\mathrm{hs}} \sigma T^4$

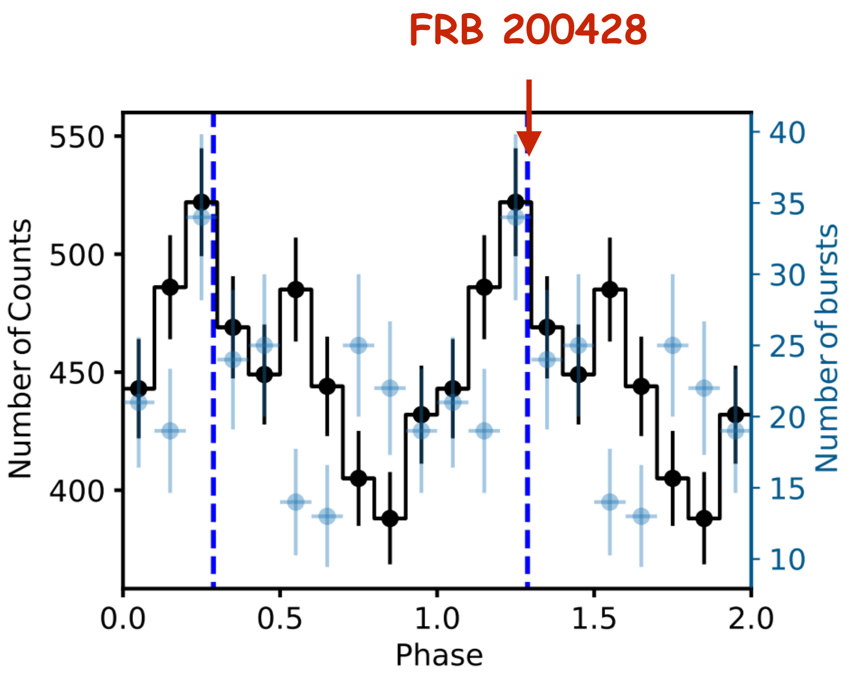
- The typical cooling time is defined as

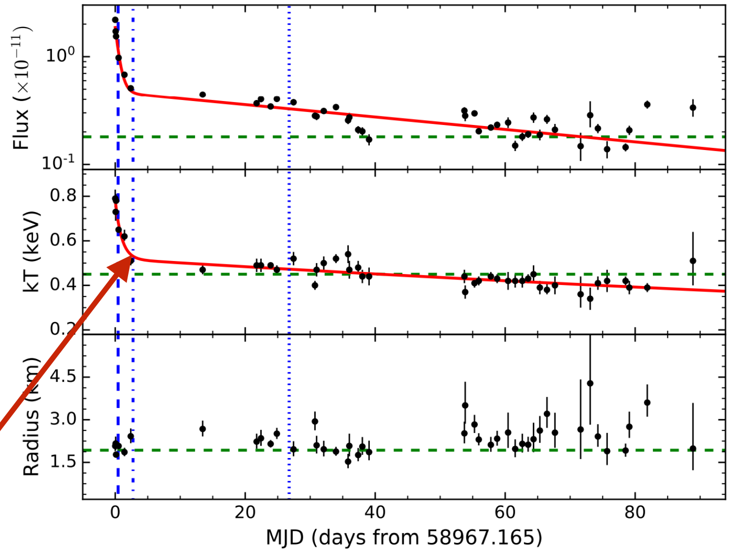
$$t_{\mathrm{cool}} = \frac{U_i}{\Delta R^2_{\mathrm{hs}} \sigma T^4} = \boxed{0.3\ \mathrm{day}\ \rho^{2/3}_{\mathrm{nuc},-3} T^{-3}_{\mathrm{keV}} L_4,}$$

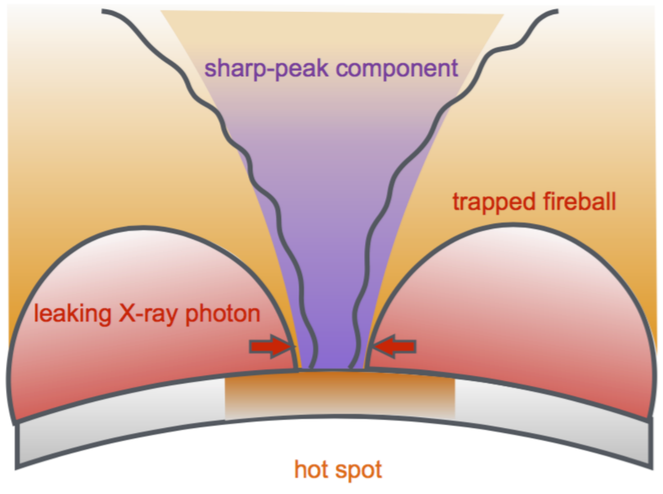
- The cooling time from T_0 to T is

$$\Delta t = t - t_0 = \frac{k\rho L}{2 A m_p \sigma} \left(\frac{1}{T^3} - \frac{1}{T_0^3} \right),$$

Yang & Zhang, 2021

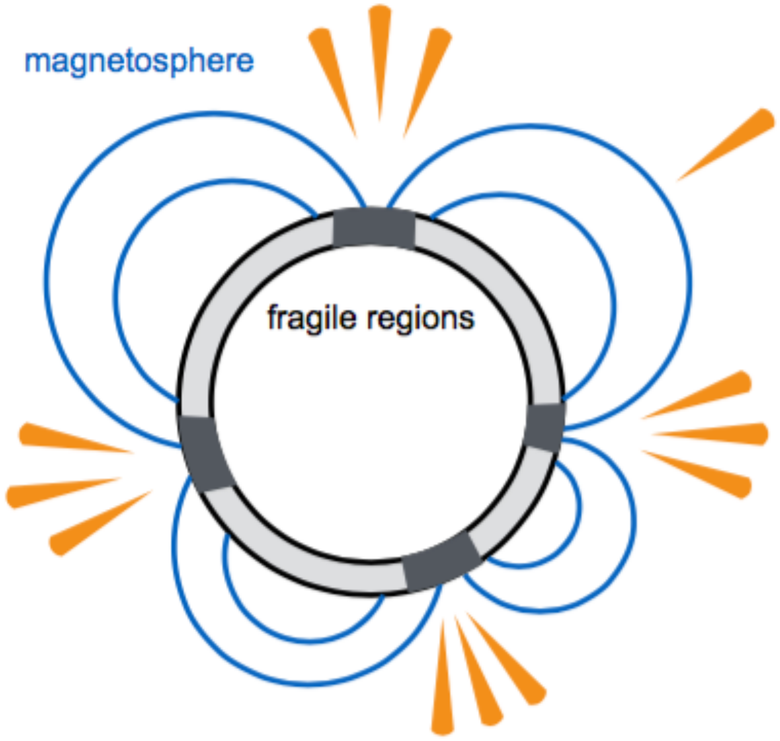


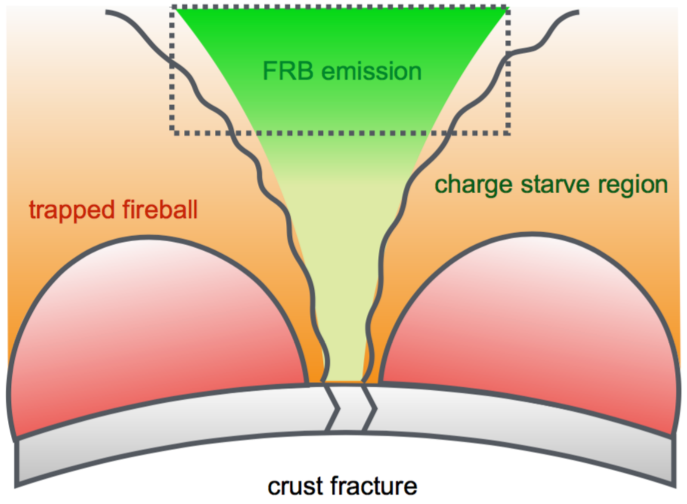


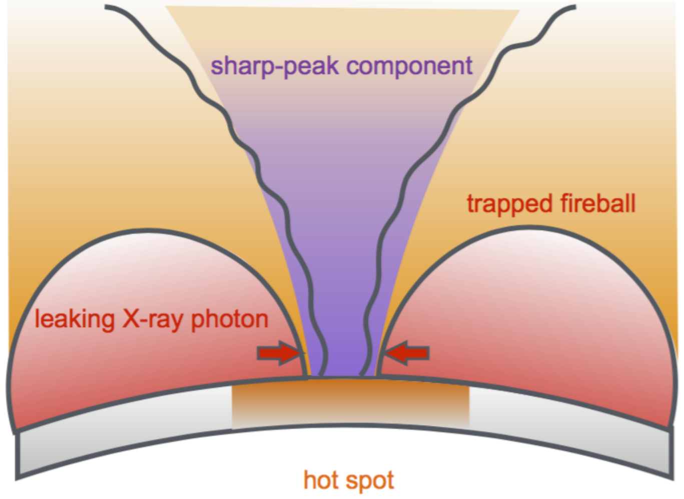


Summary

- FRBs are proposed to be triggered by crust fracturing of magnetars, with the burst event rate depending on the magnetic field strength in the crust.
- Crust fracturing produces Alfven waves, forming a charge starved region in the magnetosphere.
- An FRB is produced by coherent plasma emission due to nonuniform pair production across magnetic field lines.
- The sharp-peak hard X-ray component in association with FRB 200428 is from a region between adjacent trapped fireballs.
- The persistent X-ray emission is from a hot spot heated by the magnetospheric activities.
- Within this picture, magnetars with stronger fields tend to produce brighter and more frequent repeated bursts.







Thank You!