X-ray Spectrum & Radiative Acceleration of Expanding Pair Fireball in magnetar bursts

ICRR, University of Tokyo,

Institute for Cosmic Ray Research
University of Tokyo

TOMOKI WADA

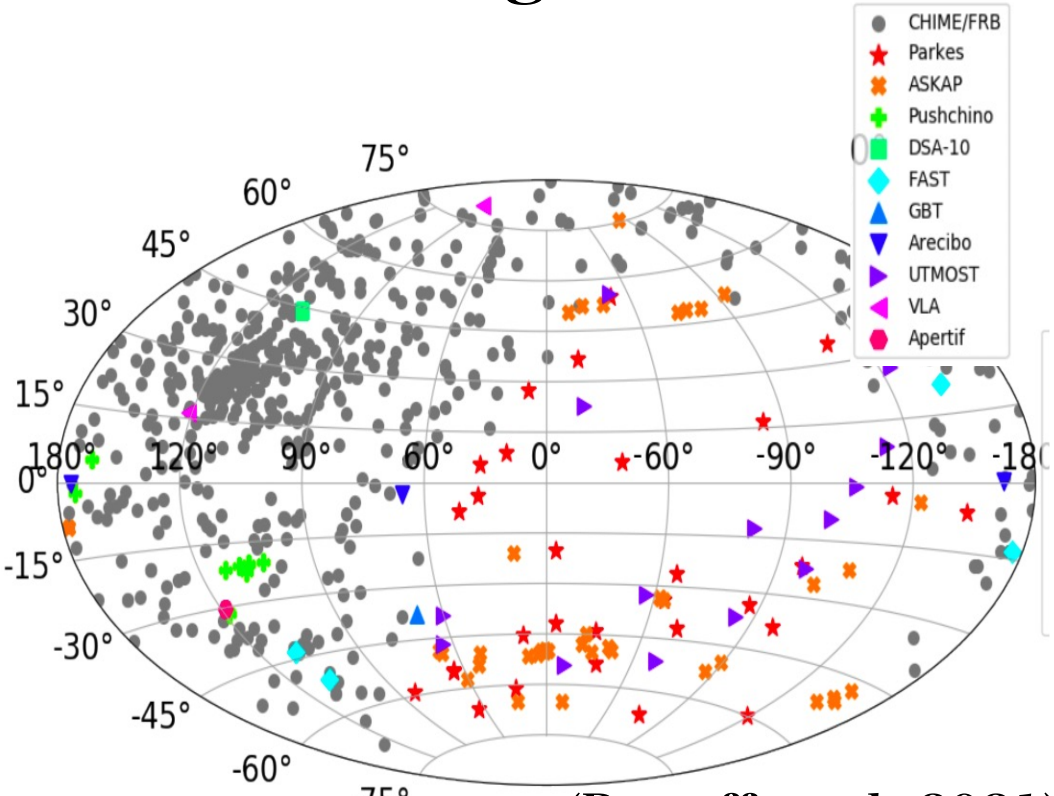
collaborator: Katsuaki Asano

231102マルチメッセンジャー天文学の展開

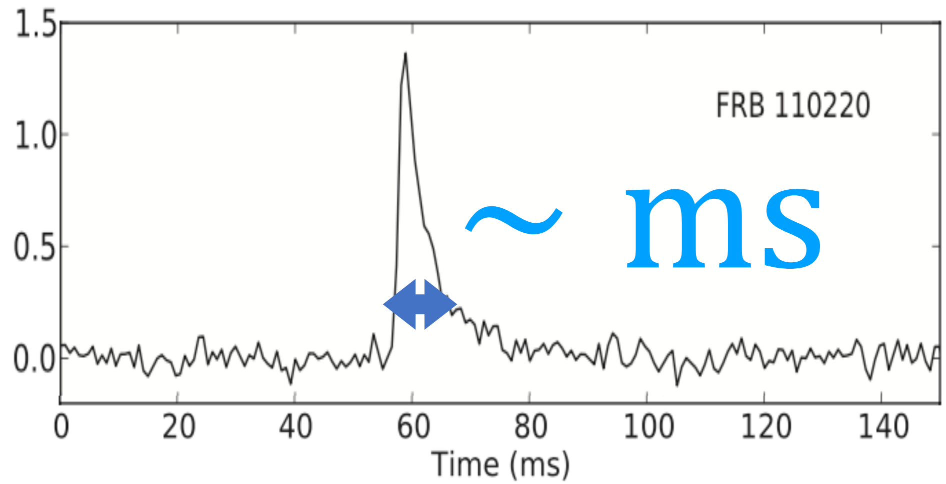
Fast Radio Burst

Brightest radio transient in the universe!

- Short Duration $\Delta t \sim \mathcal{O}(\mathrm{ms})$
- Radio Band $150\,\mathrm{MHz} - 8\,\mathrm{GHz}$
- Bright $L \sim 10^{41}\,\mathrm{erg\,s^{-1}}$
- Cosmological $D_\mathrm{L} \sim 4\,\mathrm{Mpc} - z \sim 2$



(Petroff et al. 2021)



(Thornton et al. 2013)

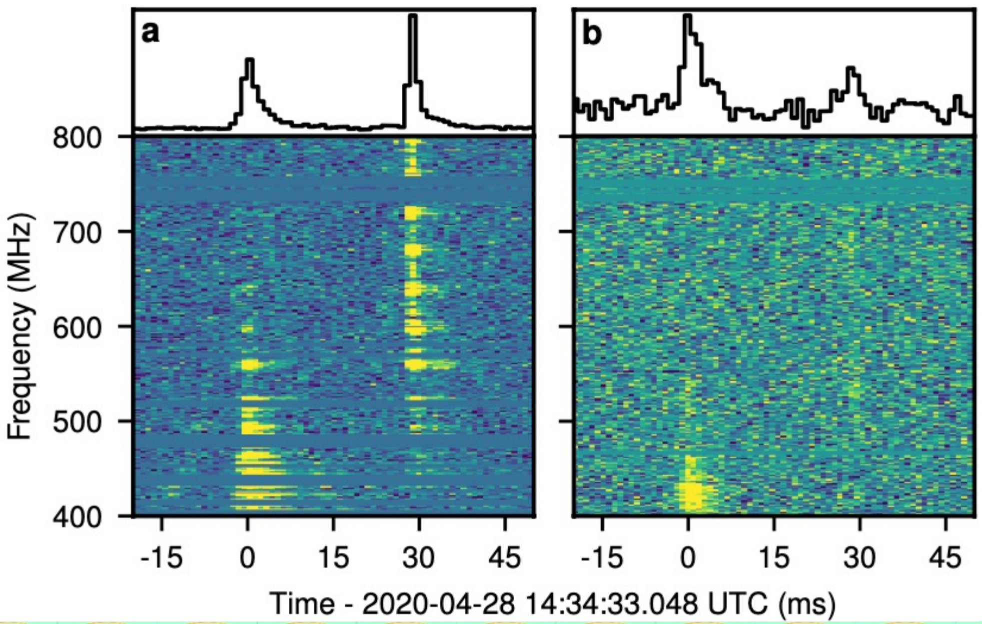
FRB 20200428A

FRB & X-ray short burst from a galactic magnetar SGR 1935+2154!

FRB luminosity

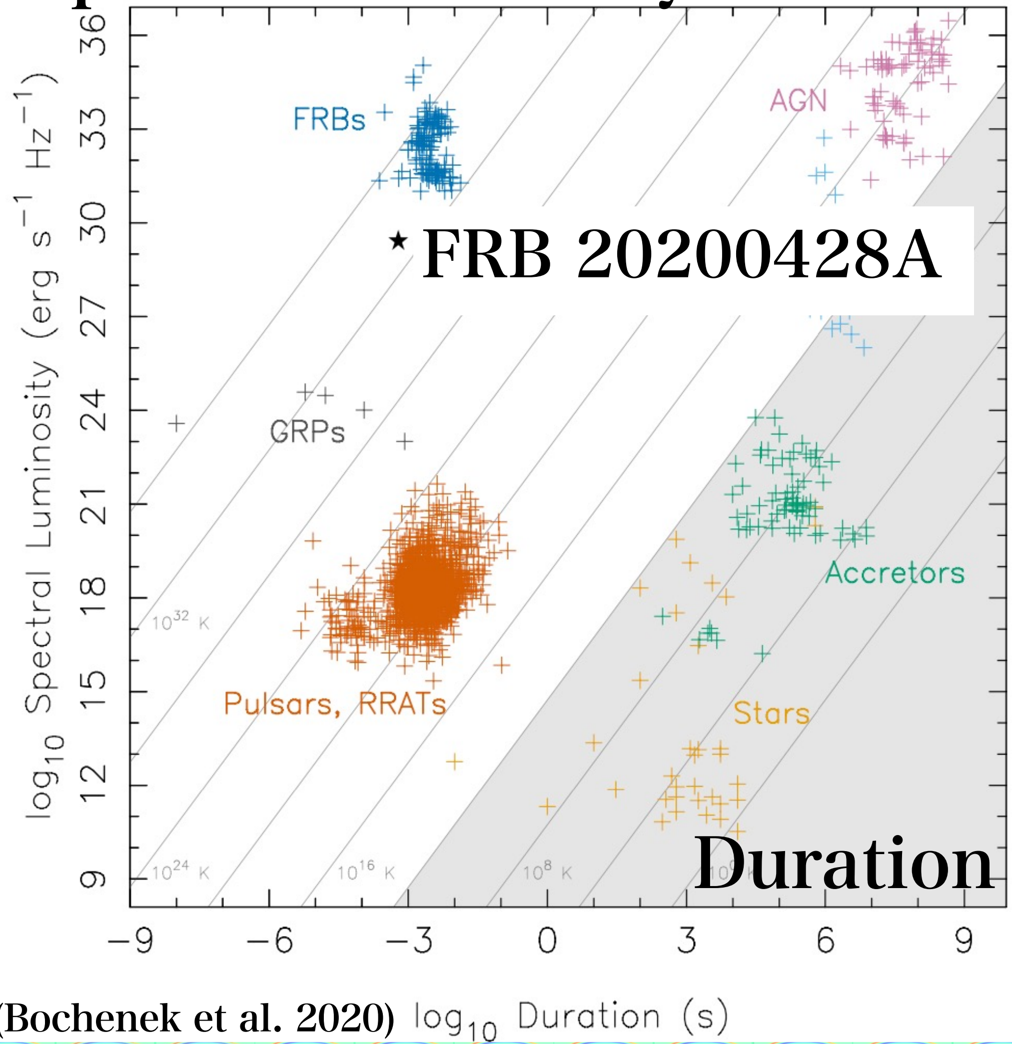
$$L_{\mathrm{FRB}} \sim 10^{38} \mathrm{erg\,s^{-1}}$$

Fainter than others



(CHIME 2020)

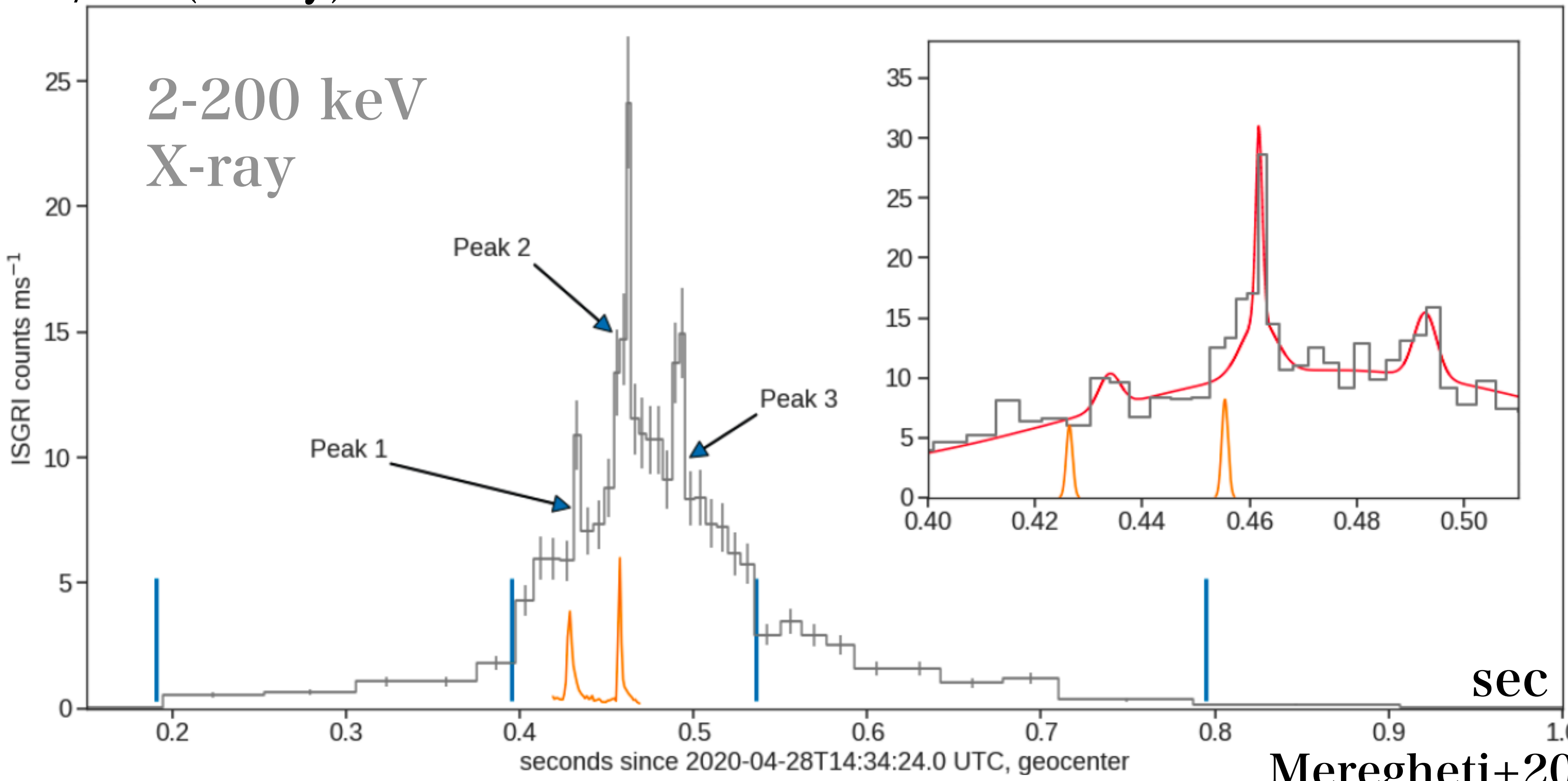
Spectral luminosity



(Bochenek et al. 2020)

FRB & X-ray association

count/ms (X-ray)



Meregheti+2020

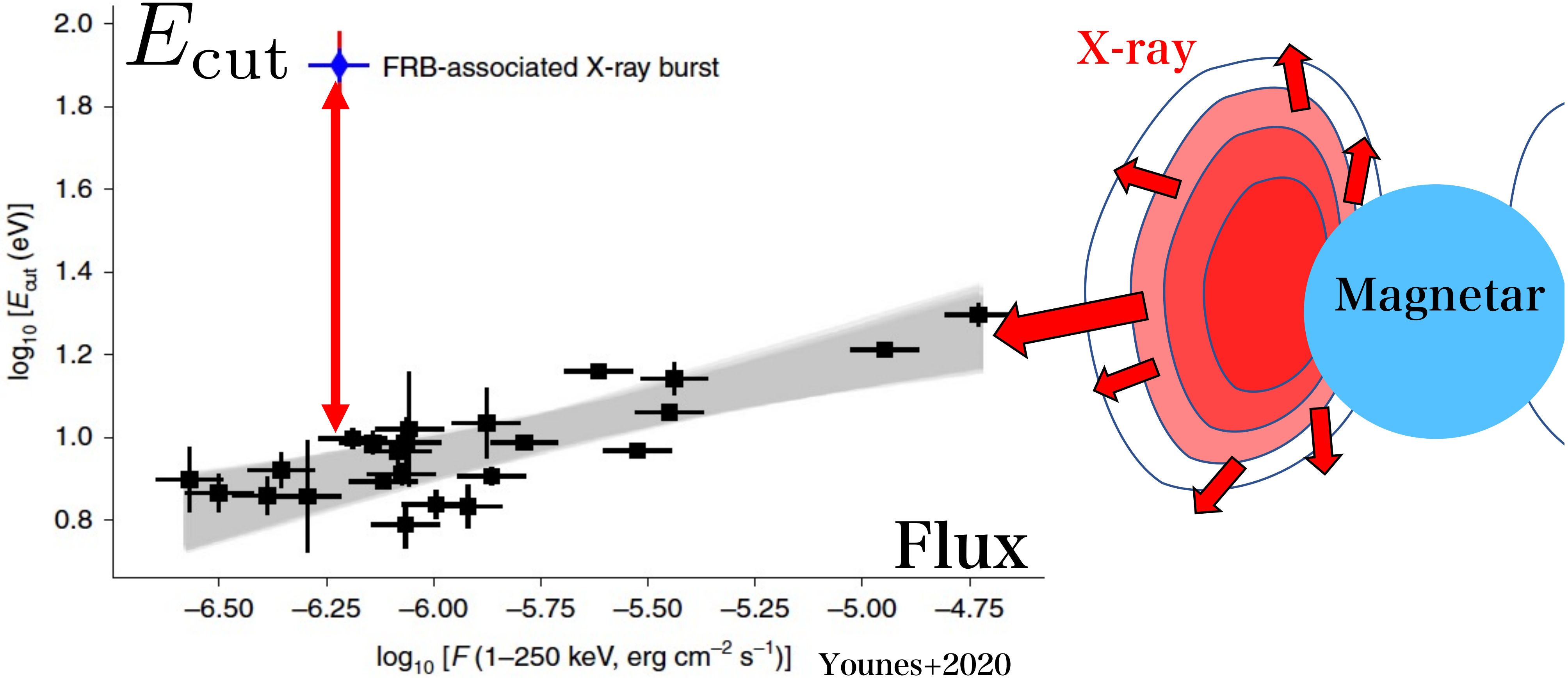
FRB !!

Dim FRB & X-ray short burst from galactic magnetar (SGR 1935+2154)

-> Connection between magnetar burst & FRB

X-ray short burst associated with FRB

High cut-off energy $E^{-\alpha}\exp(-E/E_{\rm cut})$



Younes+2020

$$E_{\rm cut} \sim 80\,{\rm keV}$$

c.f., Trapped fireball model

$$T_{\rm eff} \sim 8\,{\rm keV}\,B^{1/3} R_6^{-1/3} g_{*,14}^{1/6}$$

High-temperature of X-ray & Radio burst

$$E_{\rm cut} \sim 80\,{\rm keV}$$

Relativistic motion of outflow

$$\Gamma \propto r^{3/2}$$

$$T \propto r^{-3/2}$$

- **Observed temperature**

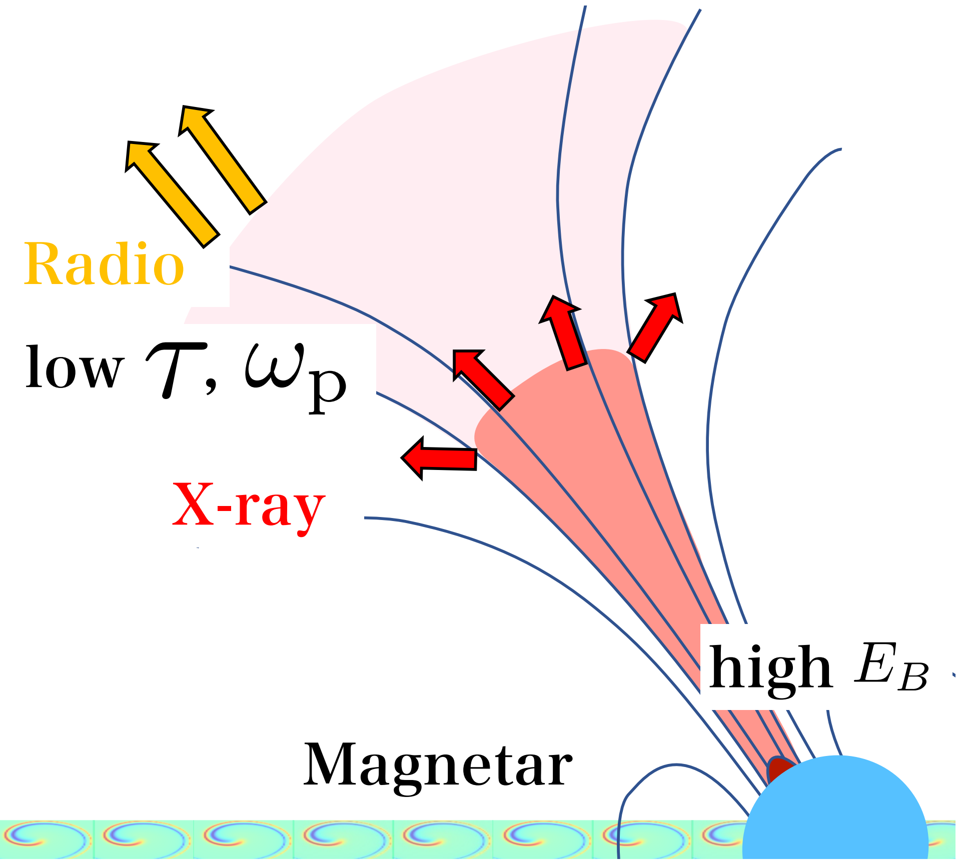
$$T_{\rm obs} \sim \Gamma T = T_0$$

↑ Doppler shift

High $T_{\rm obs}$ for high initial T_0

$$E_{\rm FRB} \sim 10^{-3} E_{\rm X}$$

Kinetic Energy of outflow
Converted to radio burst
@ outer region



Fireball model

Wada & Ioka 2023

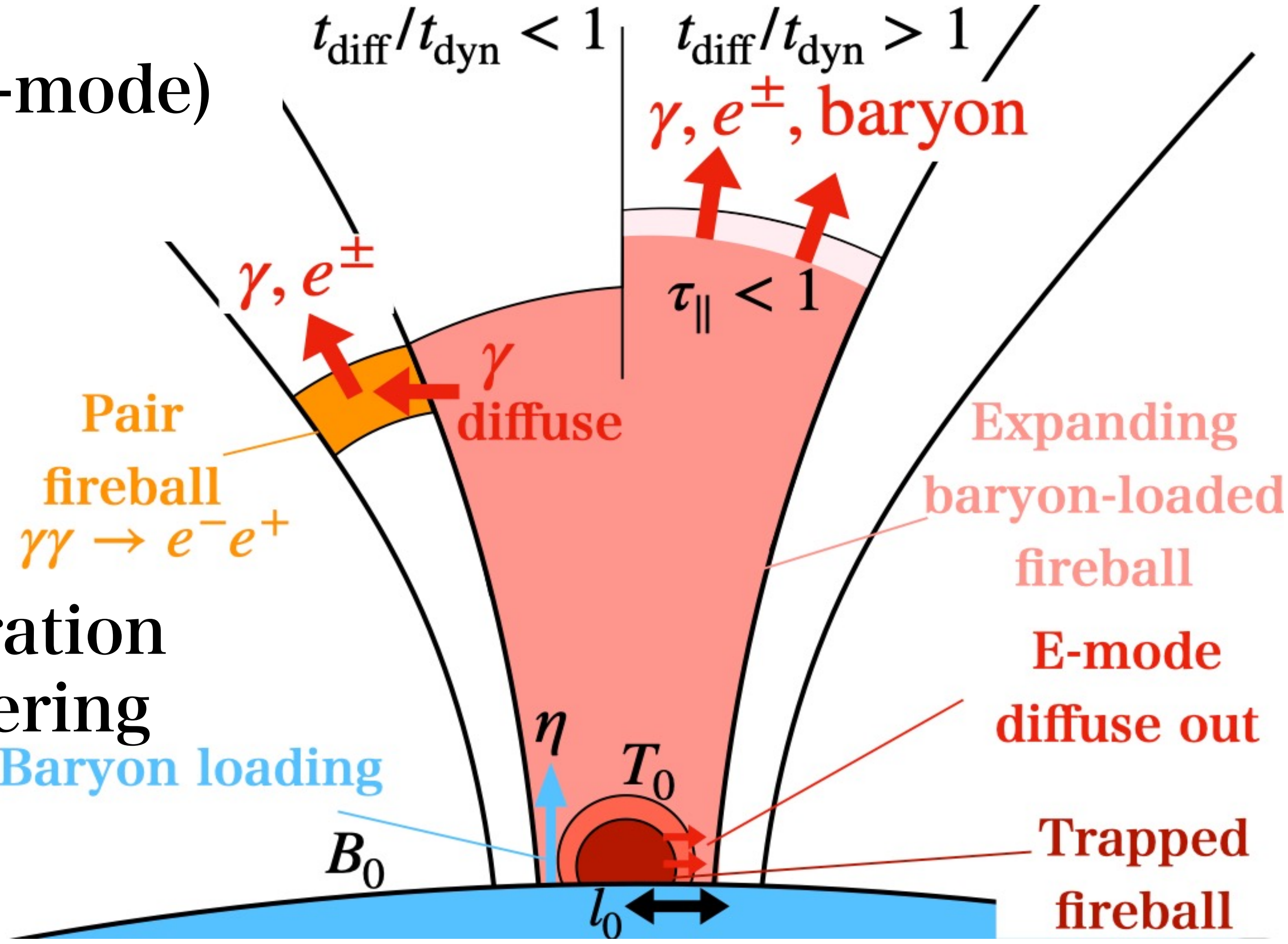
Fireball expanding along flux tube of a magnetar

1. Strong $\vec{B}$
   - number density
   - cross section (E-mode)

2. Baryon loading

3. Lateral diffusion of photons

4. Radiative acceleration w/resonant scattering



Fireball dynamics

Initially (optically thick), Fireball acceleration & cooling

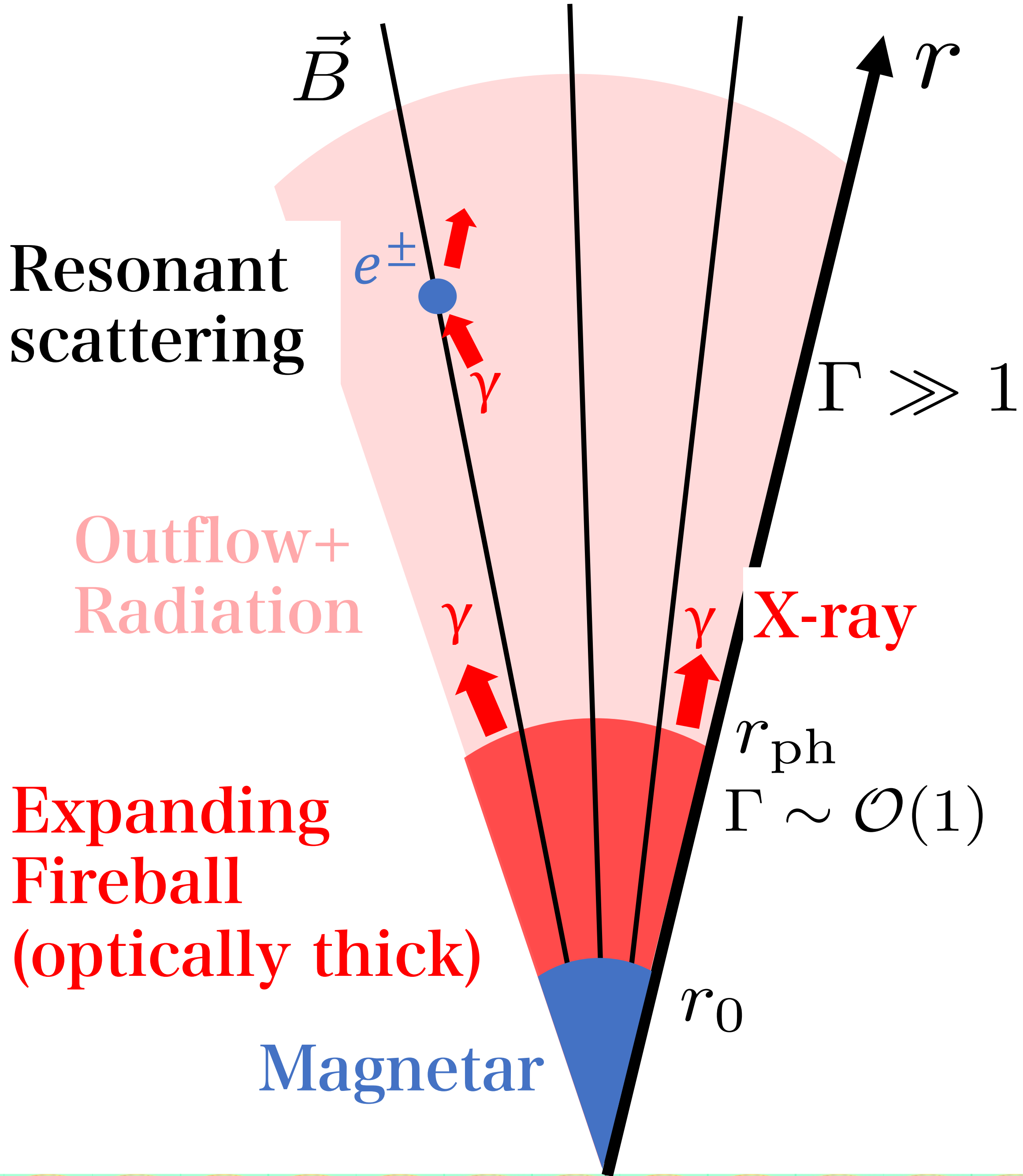
$$\Gamma \propto r^{3/2}$$

$$T \propto r^{-3/2}$$

In optically thin region Radiative force

$$F_{\rm rad} \propto \frac{\sigma F}{c}$$

σ : **cross section**
F : **X-ray flux**

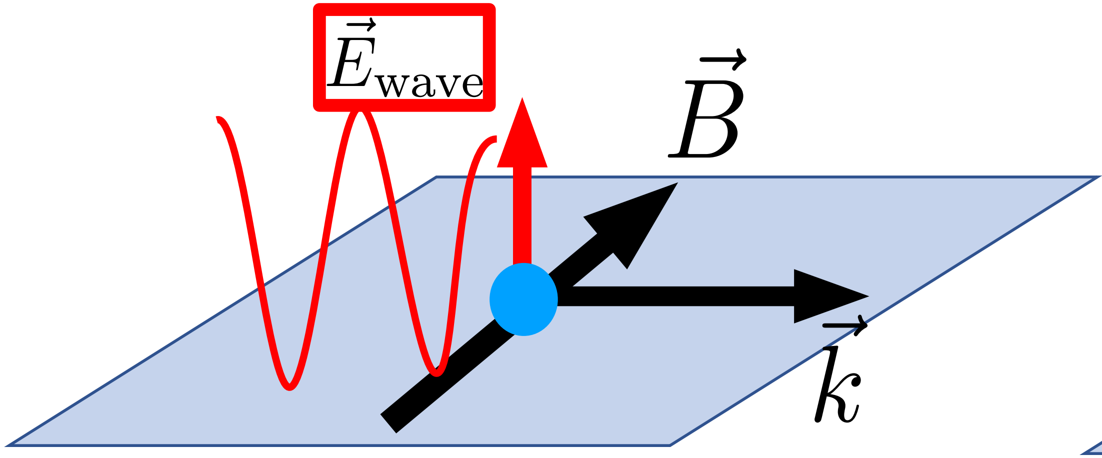


Normal mode in magnetized pair plasma

There are two mode in magnetized plasma

X-mode

$\vec{E}_{\rm wave} \perp (\vec{k} \times \vec{B}_{\rm bg})$

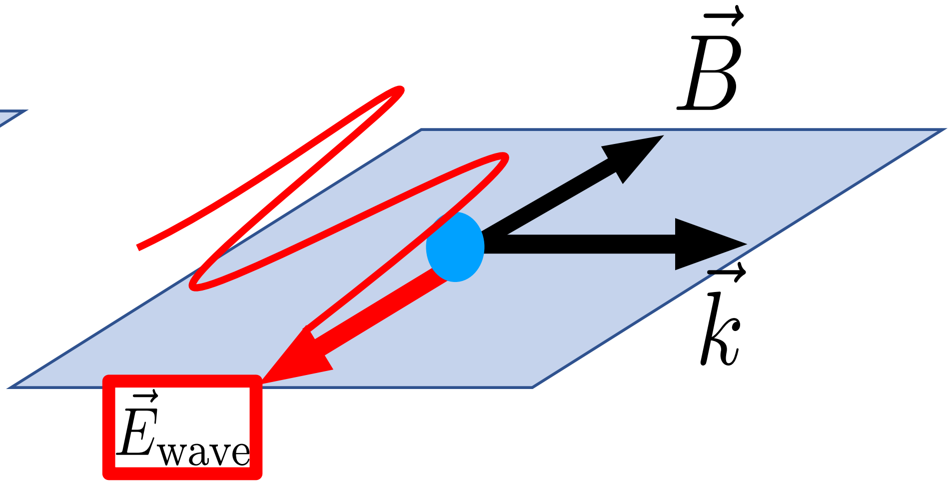


$$\sigma_E \sim \sigma_{\rm T} \times \min(1, \omega^2/\omega_B^2)$$

$$+ \sigma_{\rm res}\delta(\omega - \omega_B)$$

O- mode

$\vec{E}_{\rm wave}$ in $\vec{k}$, $\vec{B}_{\rm bg}$ plane



$$\sigma_O \sim \sigma_{\rm T}$$

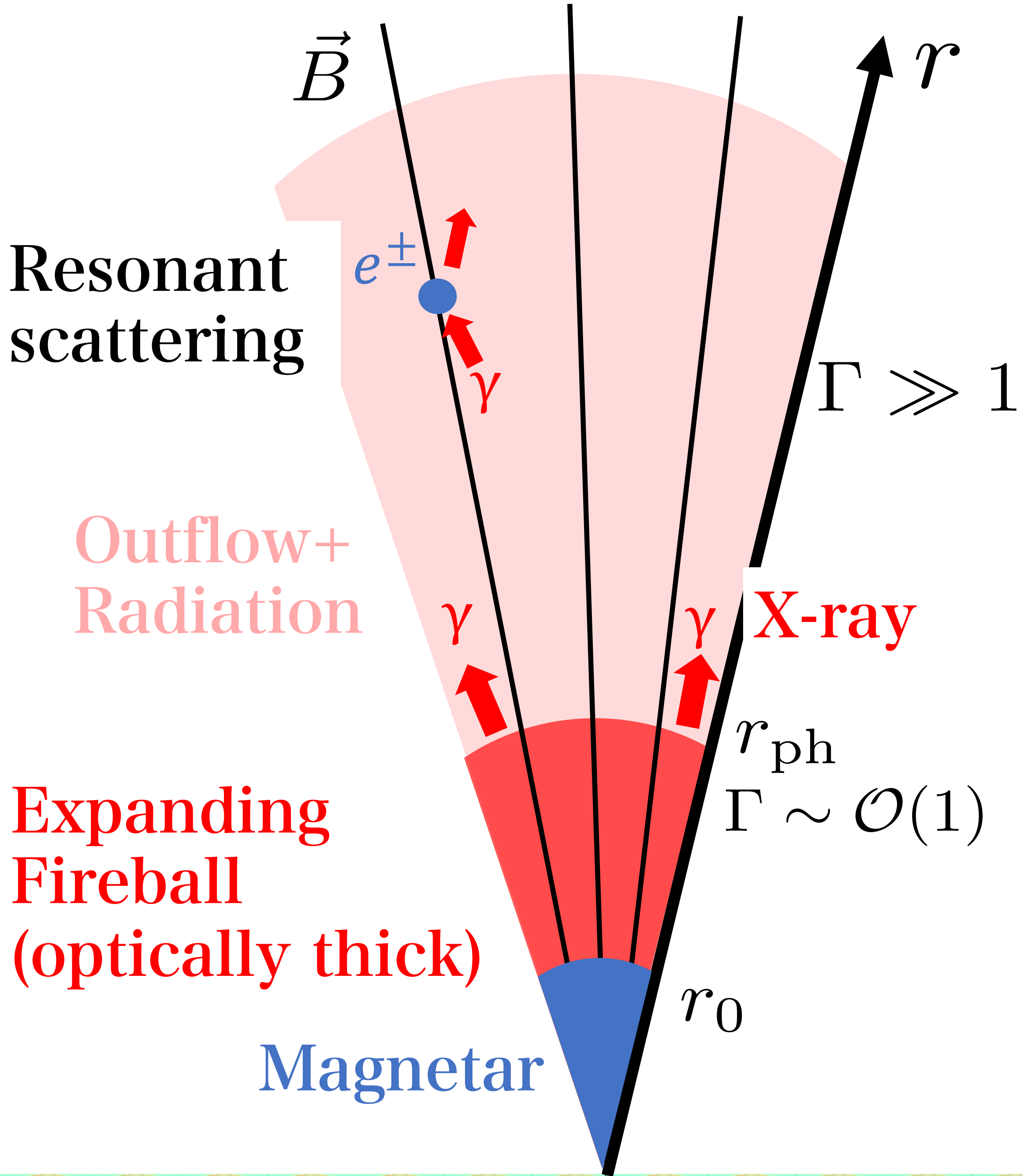
Radiative acceleration @optically thin region

In optically thin region
Radiative force

$$F_{\rm rad} \propto \frac{\sigma_{\rm res} F}{c}$$

$\sigma_{\rm res}$: resonant cross section
F : X-ray flux

➔ Acceleration by Resonant scattering
➔ High kinetic energy



Basic Equations

Plasma : spherically symmetric fluid equation,
particle are ground state of Landau level ($p_\perp = 0$)

Solve
a steady flow

$$\partial_t(r^2\rho\Gamma) + \partial_r(r^2\rho\Gamma\beta) = 0,$$

$$\partial_t\left[r^2\left(\rho h_\parallel \Gamma^2 - p_\parallel\right)\right] + \partial_r\left[r^2\rho h_\parallel \Gamma^2\beta\right] = r^2 G^t,$$

$$\partial_t\left[r^2\rho h_\parallel \Gamma^2\beta\right] + \partial_r\left[r^2\left(\rho h_\parallel \Gamma^2\beta^2 - p_\parallel\right)\right] = r^2 G^r,$$

Radiative Force

$$h_\parallel = 1 + \frac{e_{\rm th}}{\rho} + \frac{p_\parallel}{\rho}, \quad p_\parallel = (\hat\Gamma - 1)e_{\rm th}, \quad \hat\Gamma = 3$$

Radiation : Radiation transfer equation,
solved by Monte-Carlo scheme

$$p^\mu\left(\frac{\partial}{\partial x^\mu} - \Gamma^\rho_{\mu\nu}p^\nu\frac{\partial}{\partial p^\rho}\right)F(x,p) = \left(\frac{dF}{d\tau}\right)_{\rm coll}$$

$$\left(\frac{dF}{d\tau}\right)_{\rm coll} = n(x)\left[-\kappa(x,p)F(x,p) + \int dP'\kappa(x,p')\zeta(x;p'\to p)F(x,p')\right],$$

Physical & numerical setup

Initial condition :
Analytic solution of fireball

Optically thin region:
Solved numerically

Solve radiation in a given plasma profile

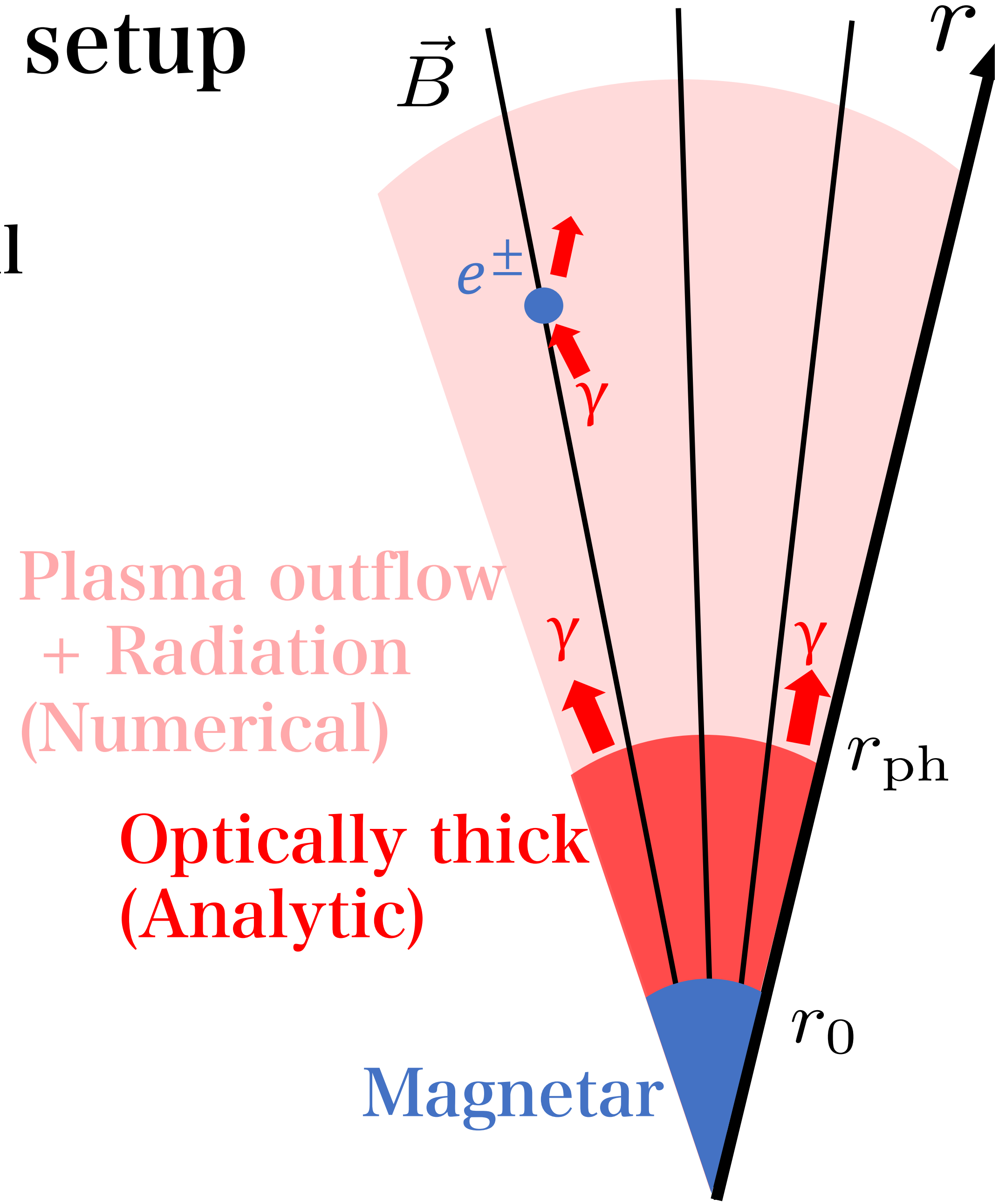
↓ Radiative force

Solve the plasma

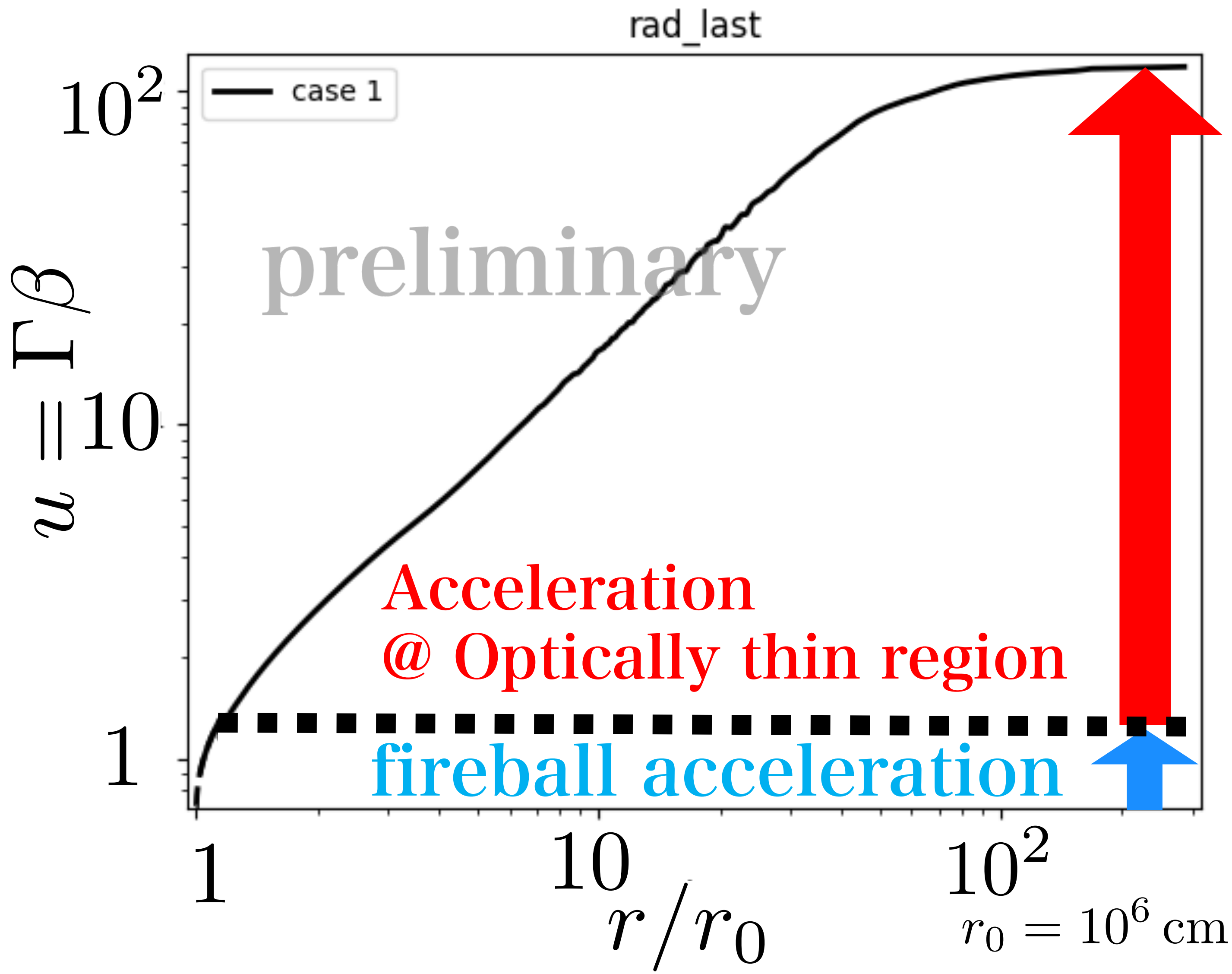
↓ Plasma profile ↑ Radiative force

Solve the radiation

Iteration
-> steady solution



Result: radiative acceleration



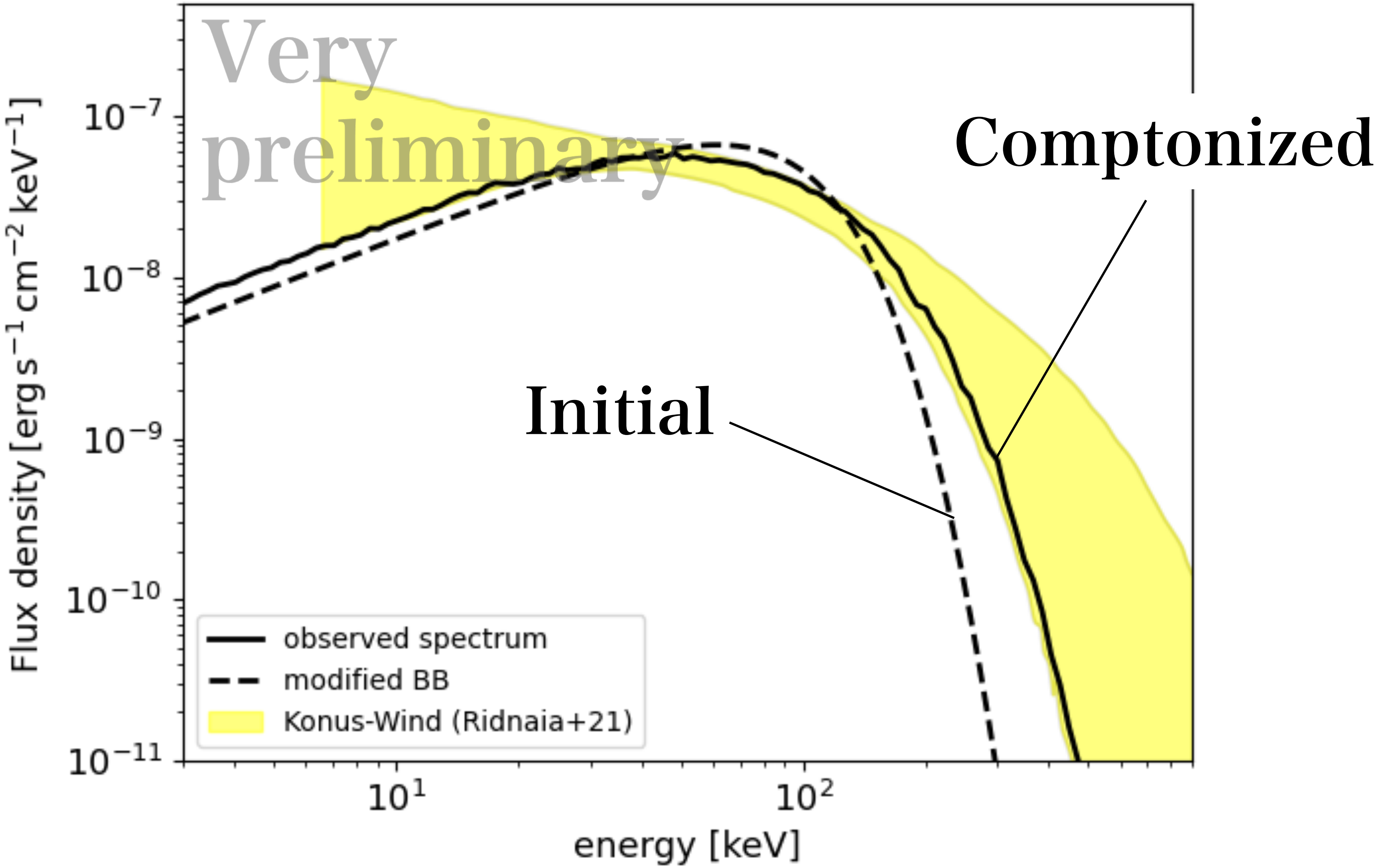
Acceleration by radiation force

$\Gamma \sim \times 100$

Energy budget of the FRB?

Radiative force acceleration
-> ultra relativistic outflow

Result: X-ray spectrum



X-ray is weakly Comptonized
-> Observed spectrum can be created

Neutrino emission

w/ baryon precursor of fireball

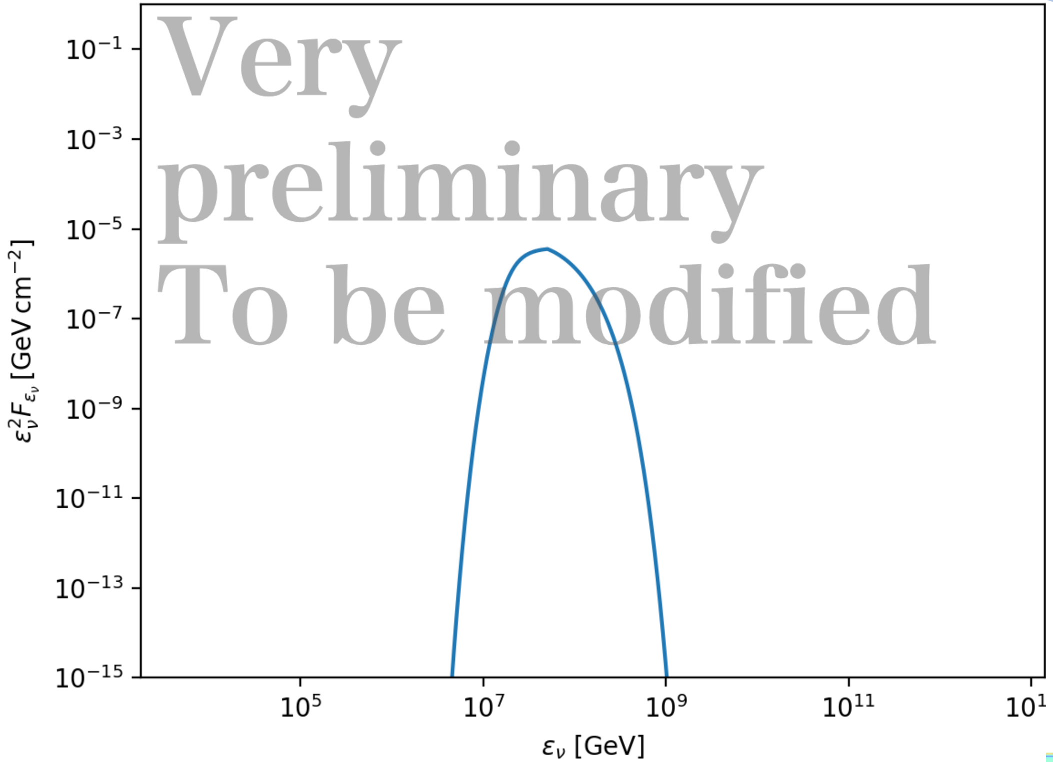
@ outer region

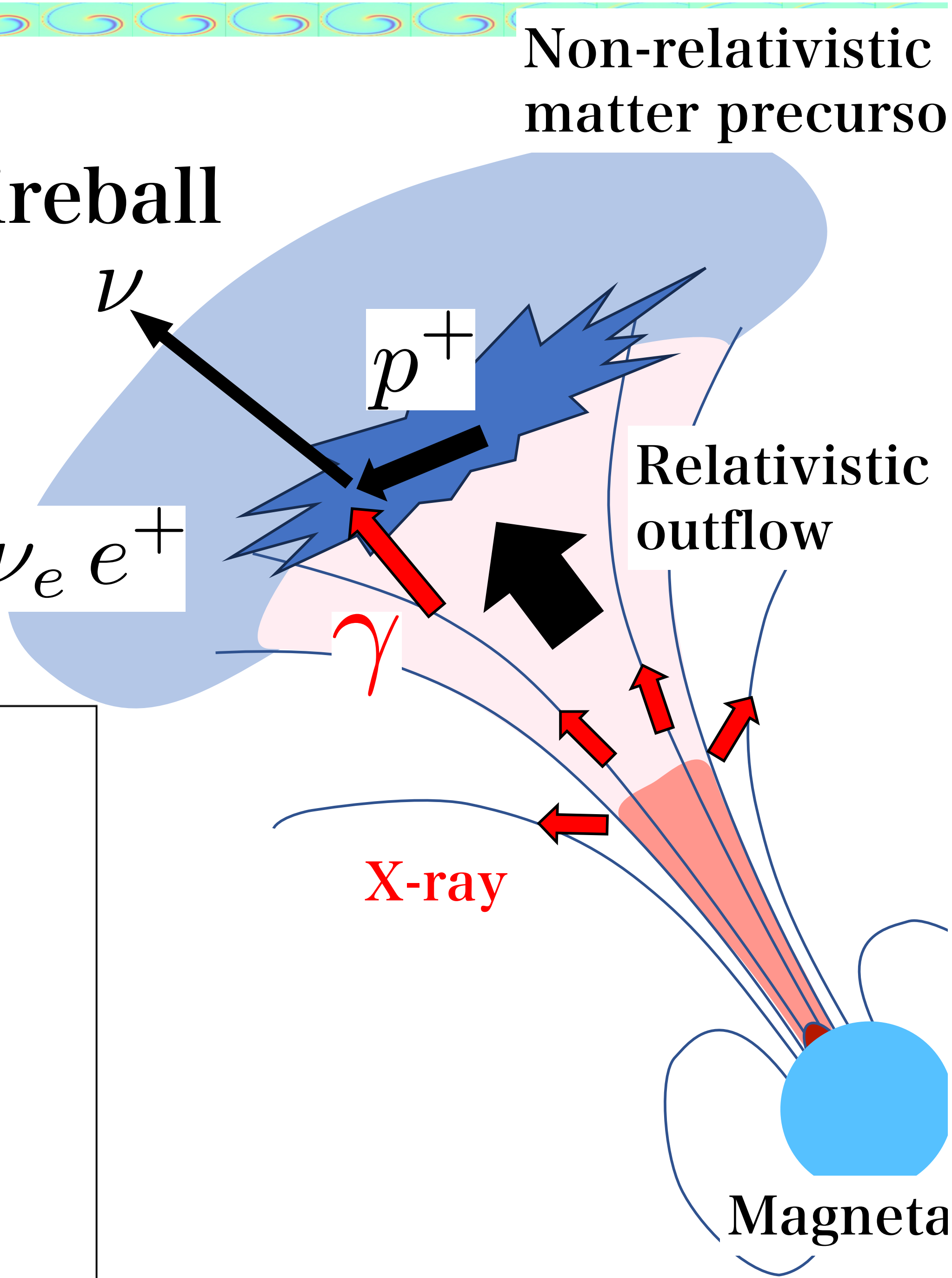
outflow will form shock

-> Particle acceleration

$$p^+\gamma \rightarrow \Delta^+ \rightarrow \nu_\mu\,\bar{\nu}_\mu\,\nu_e\,e^+$$

->neutrino emission





Summary

- We study the X-ray spectrum & outflow kinetic luminosity in magnetar short bursts.

- Relativistic outflow is strongly accelerated by the radiation via the resonant scattering.

- X-ray is weakly Comptonized.
  It can be the origin of the observed X-ray spectrum.

- Ultra relativistic outflow can emit neutrinos.