Spectrum & Radiative Acceleration of Expanding Pair Fireball

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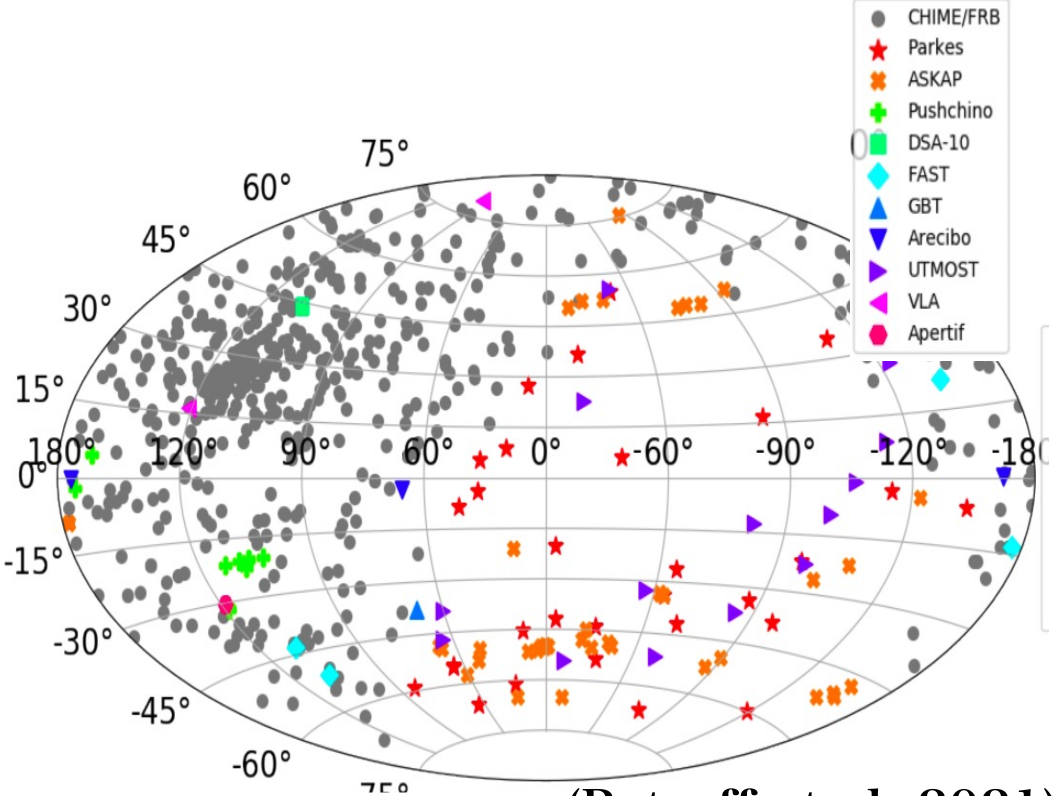
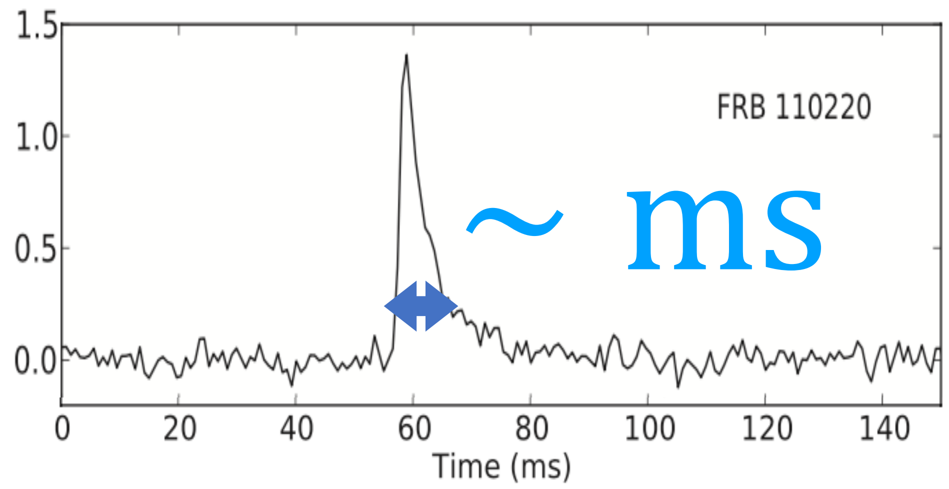
Fast Radio Burst

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)

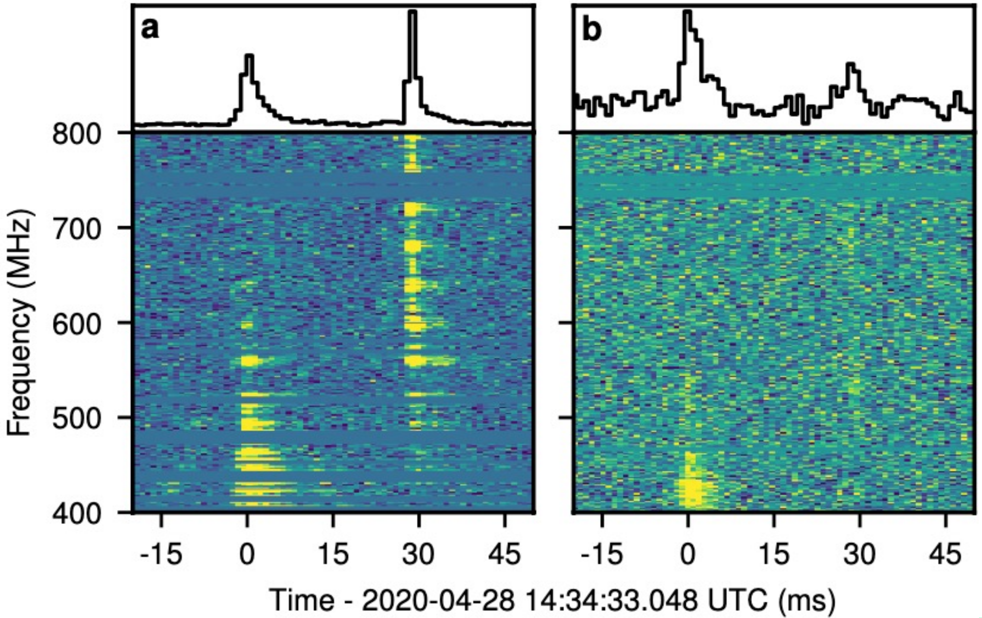
FRB 20200428A

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

FRB luminosity

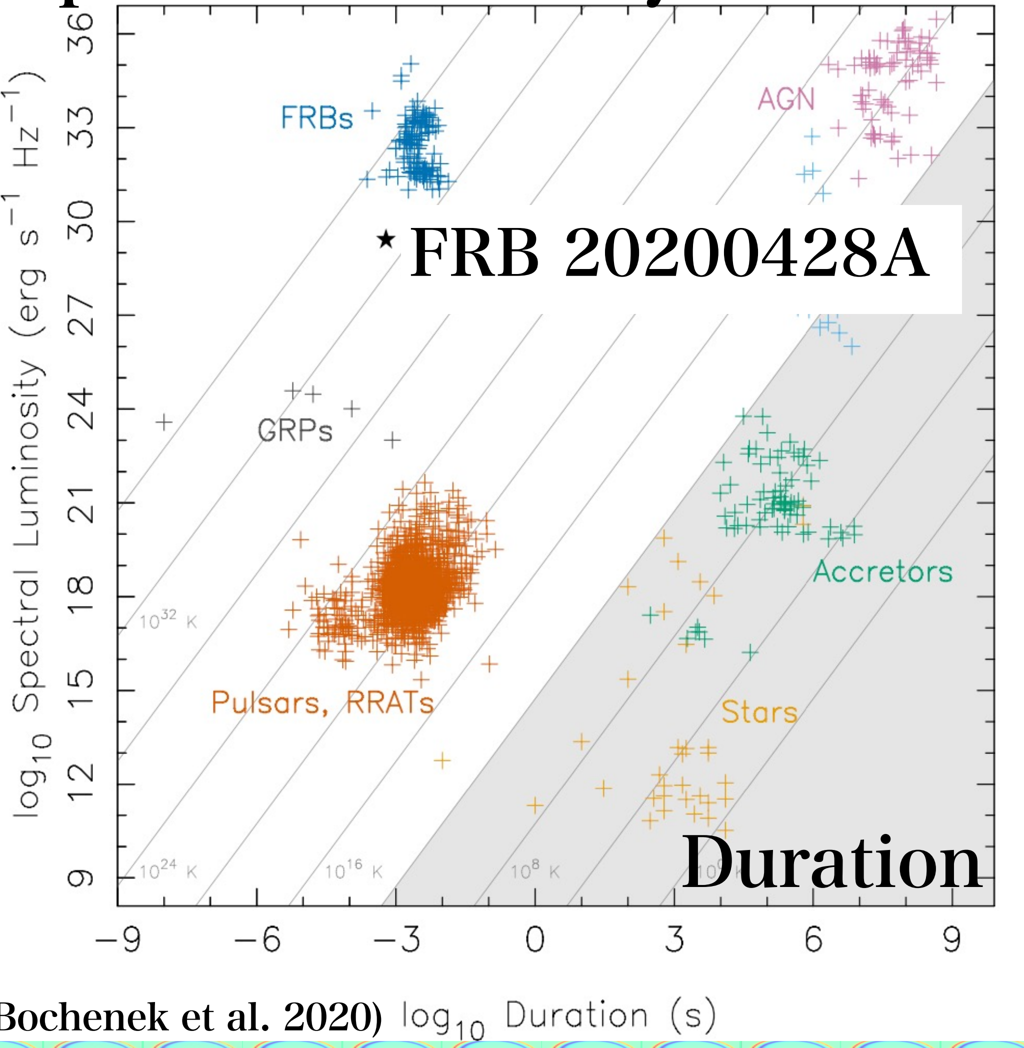
$$L_{\mathrm{FRB}} \sim 10^{38} \mathrm{erg\,s^{-1}}$$

Fainter than others



(CHIME 2020)

Spectral luminosity



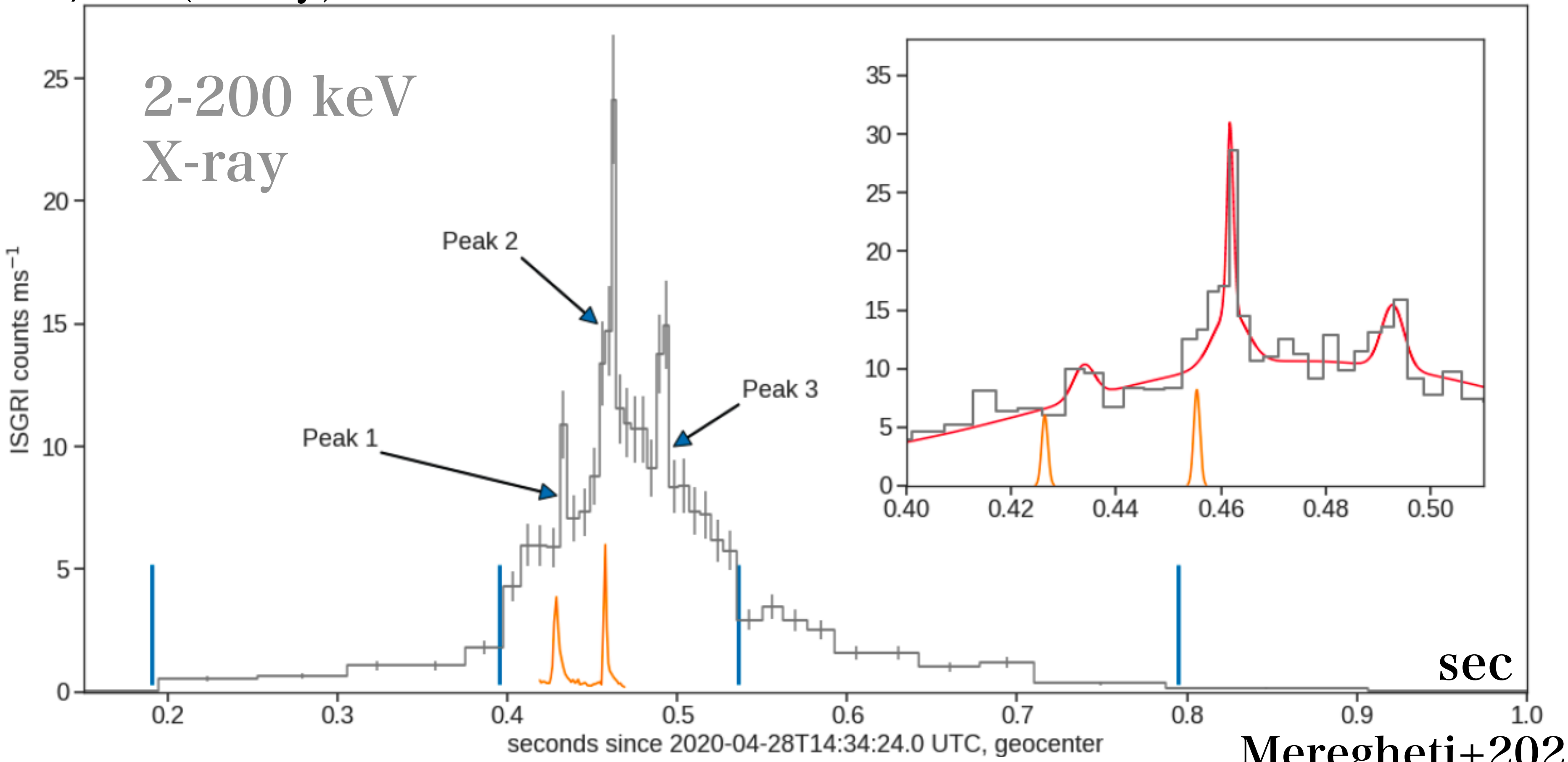
★ **FRB 20200428A**

Duration

(Bochenek et al. 2020)

FRB & X-ray association

count/ms (X-ray)



sec

Meregheti+2020

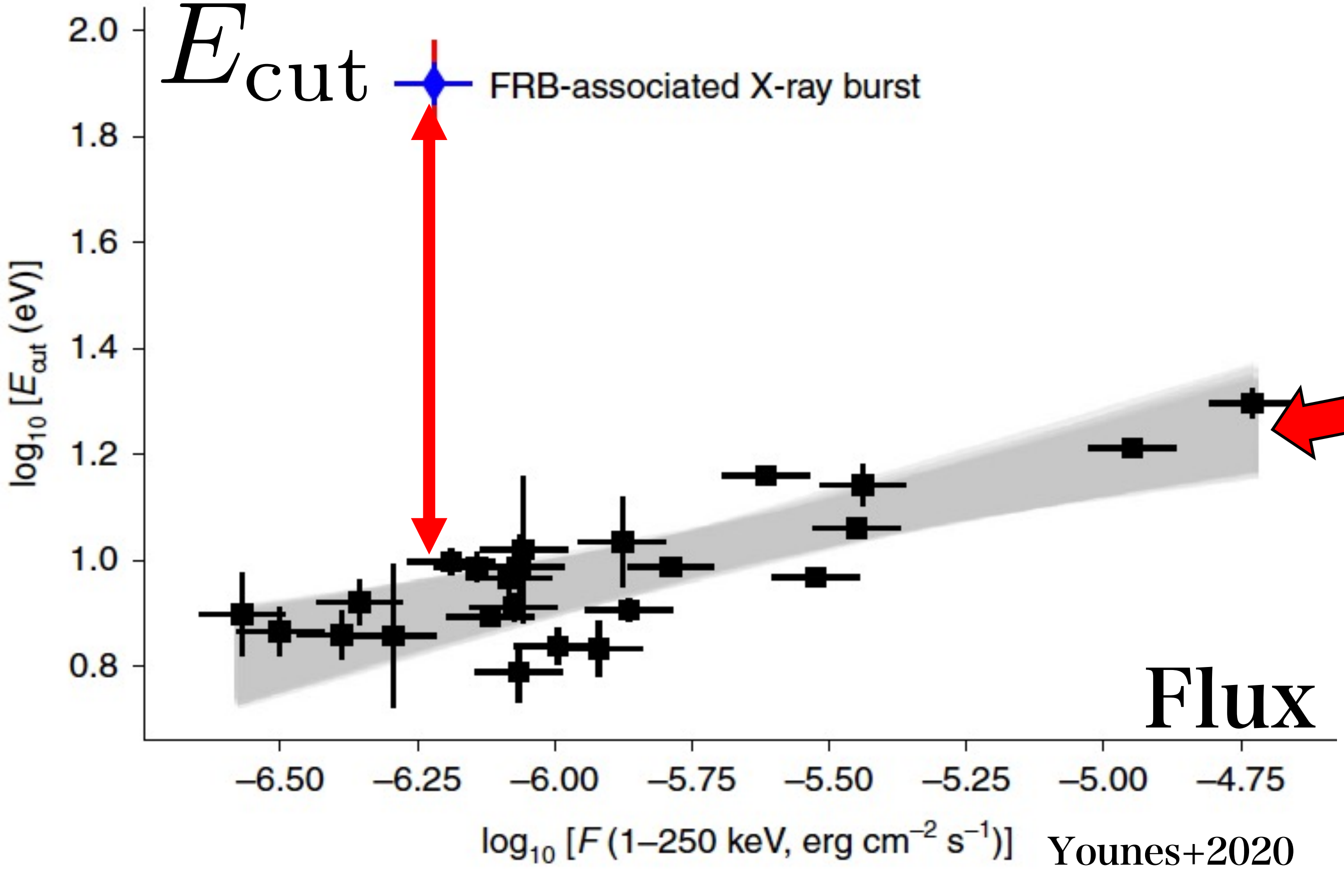
FRB !!

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

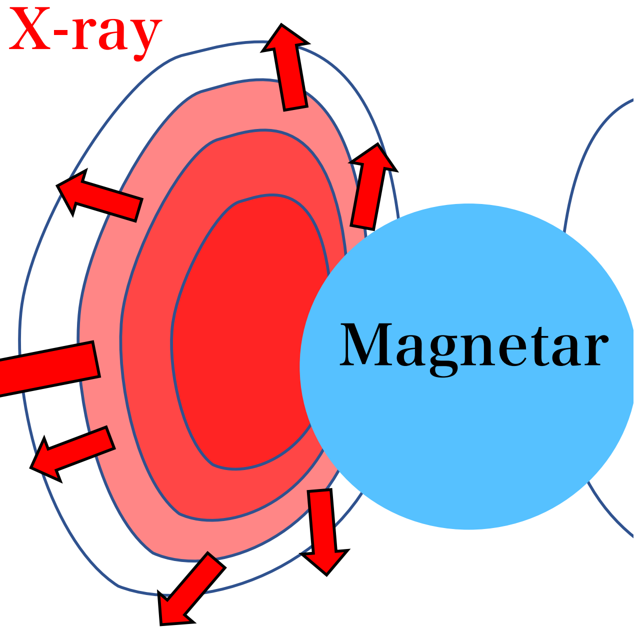
-> Connection between magnetar burst & FRB

X-ray short burst associated with FRB

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



Younes+2020



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

c.f., Trapped fireball model

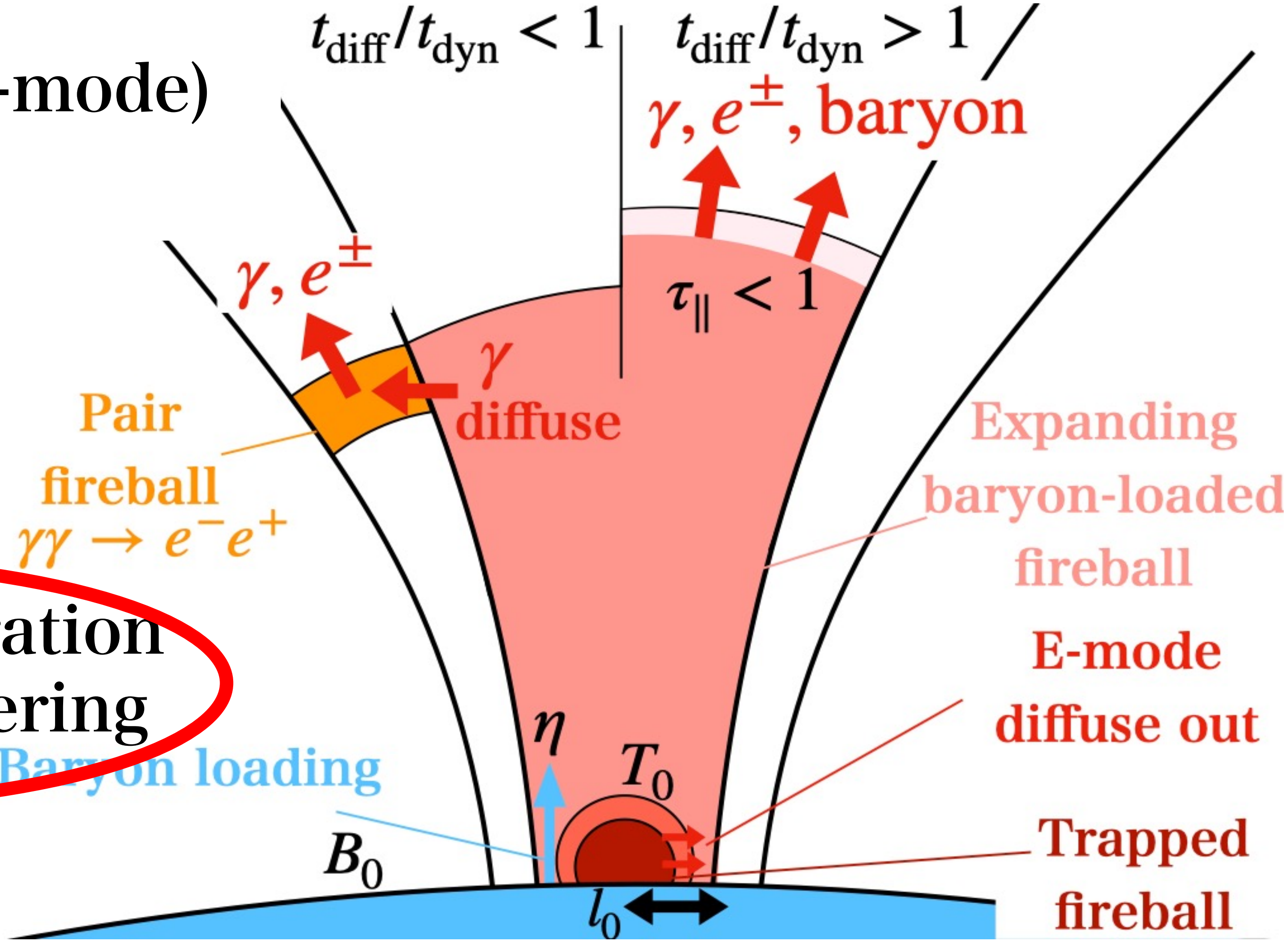
$$T_{\rm eff}\sim 8\,{\rm keV}\,B^{1/3}R_6^{-1/3}g_{*,14}^{1/6}$$

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



High-temperature of X-ray & Radio burst

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

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

Relativistic motion of outflow

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

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

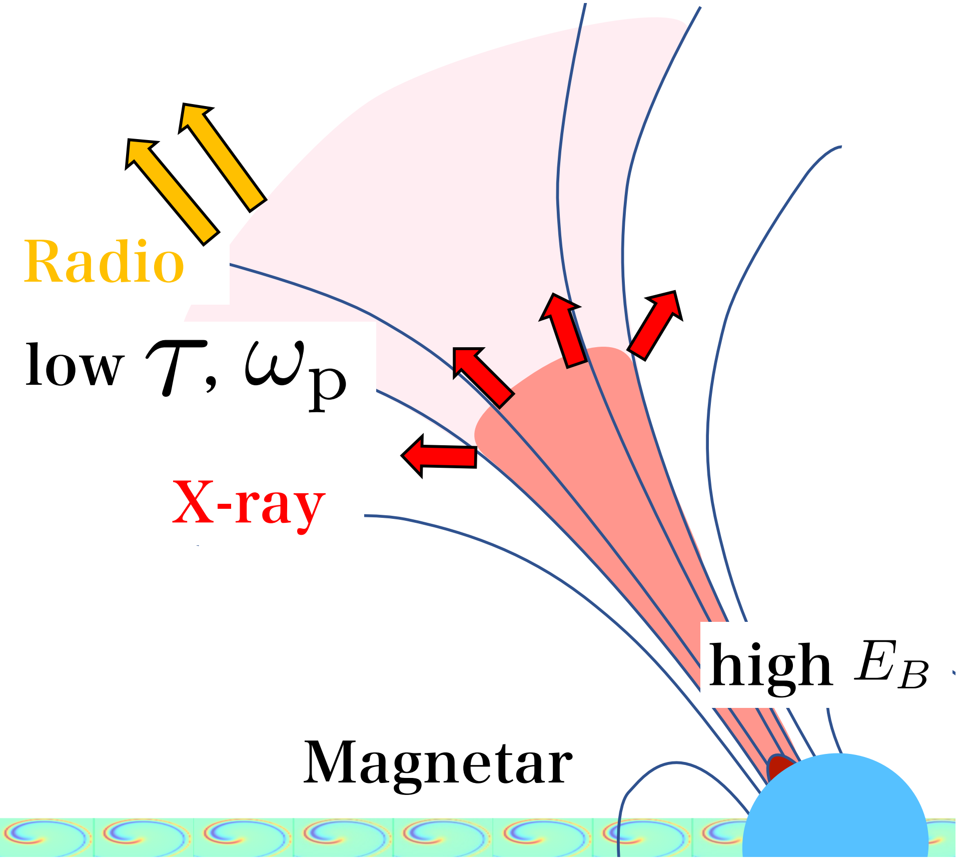
- Observed temperature

$$T_{\rm obs} \sim \underset{\substack{\Uparrow \\ \text{Doppler shift}}}{\Gamma} T = T_0$$

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

Kinetic Energy of outflow

Converted to radio burst
@ outer region



Fireball dynamics

Initially (optically thick),
Fireball acceleration &
cooling

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

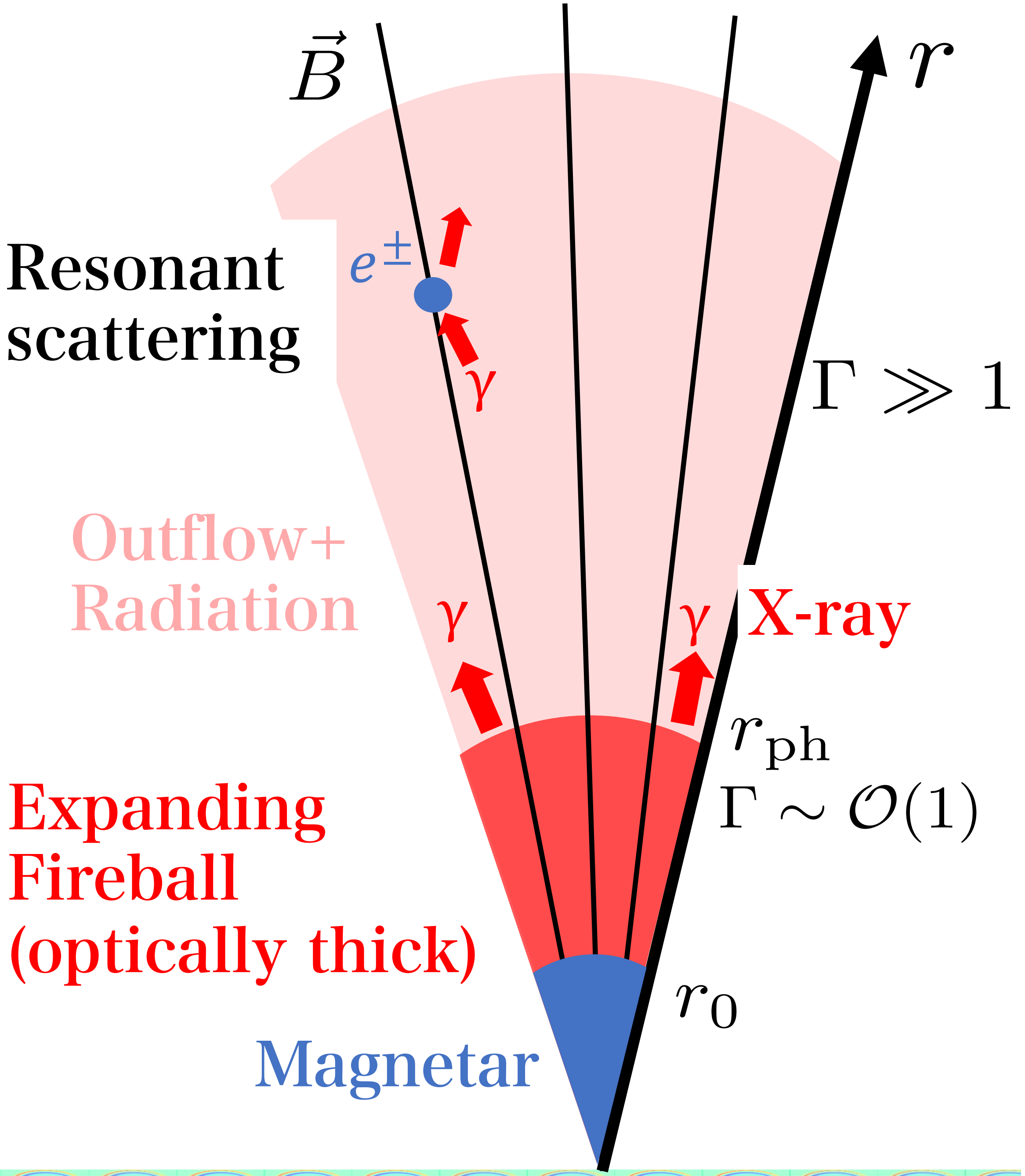
$$T \propto r^{-3/2}$$

$$n \propto \exp\left(-\frac{m_e c^2}{T}\right)$$

In optically thin region
Radiative force

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

σ : cross section
F : X-ray flux

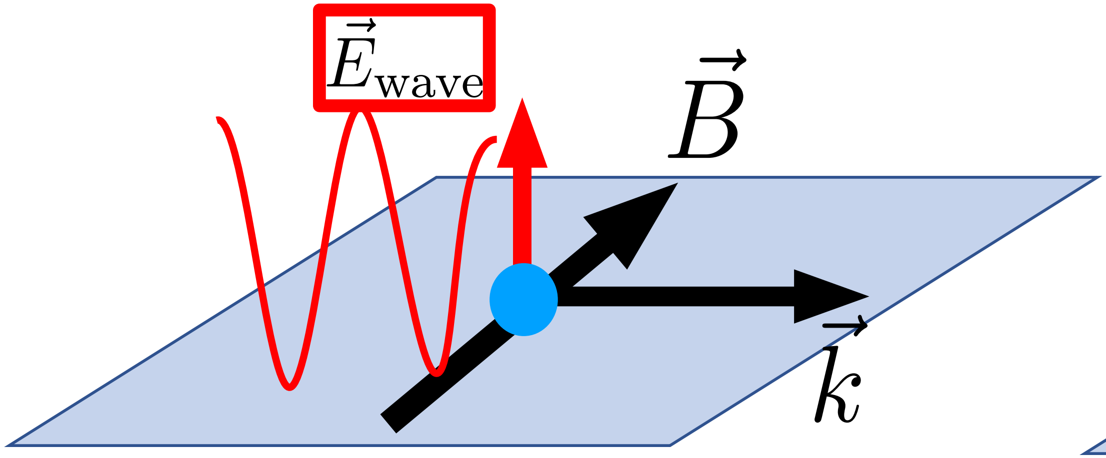


Normal mode in magnetized pair plasma

There are two mode in magnetized plasma

X-mode

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

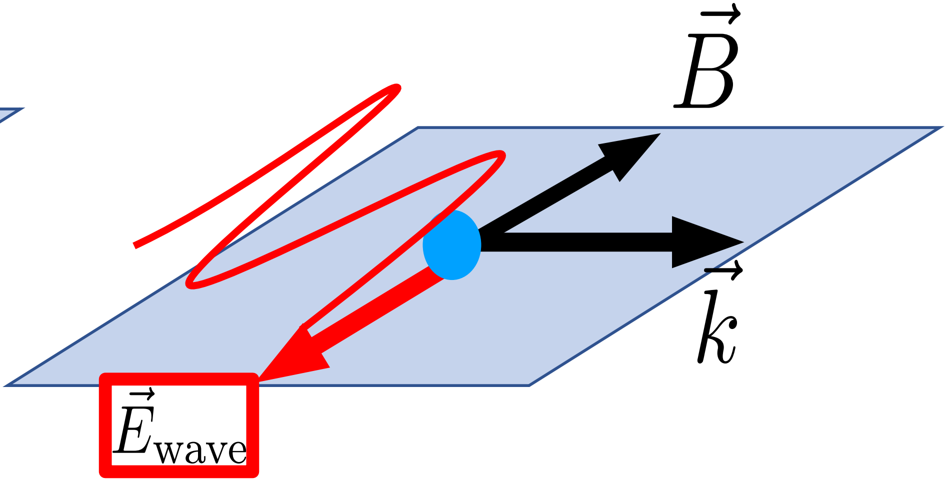


$$\sigma_{\mathrm{E}}(T,\, B) = \frac{4\pi^2}{5} T^2 B^{-2} \sigma_{\mathrm{T}}$$

$$< \sigma_{\mathrm{T}}$$

O- mode

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



$$\sigma_{\mathrm{O}}(T,\, B) = \sigma_{\mathrm{T}}$$

Cross section in magnetized plasma

- **O-mode:** $\vec{E}_{\rm wave}$ in $\vec{k}, \vec{B}_{\rm bg}$ plane

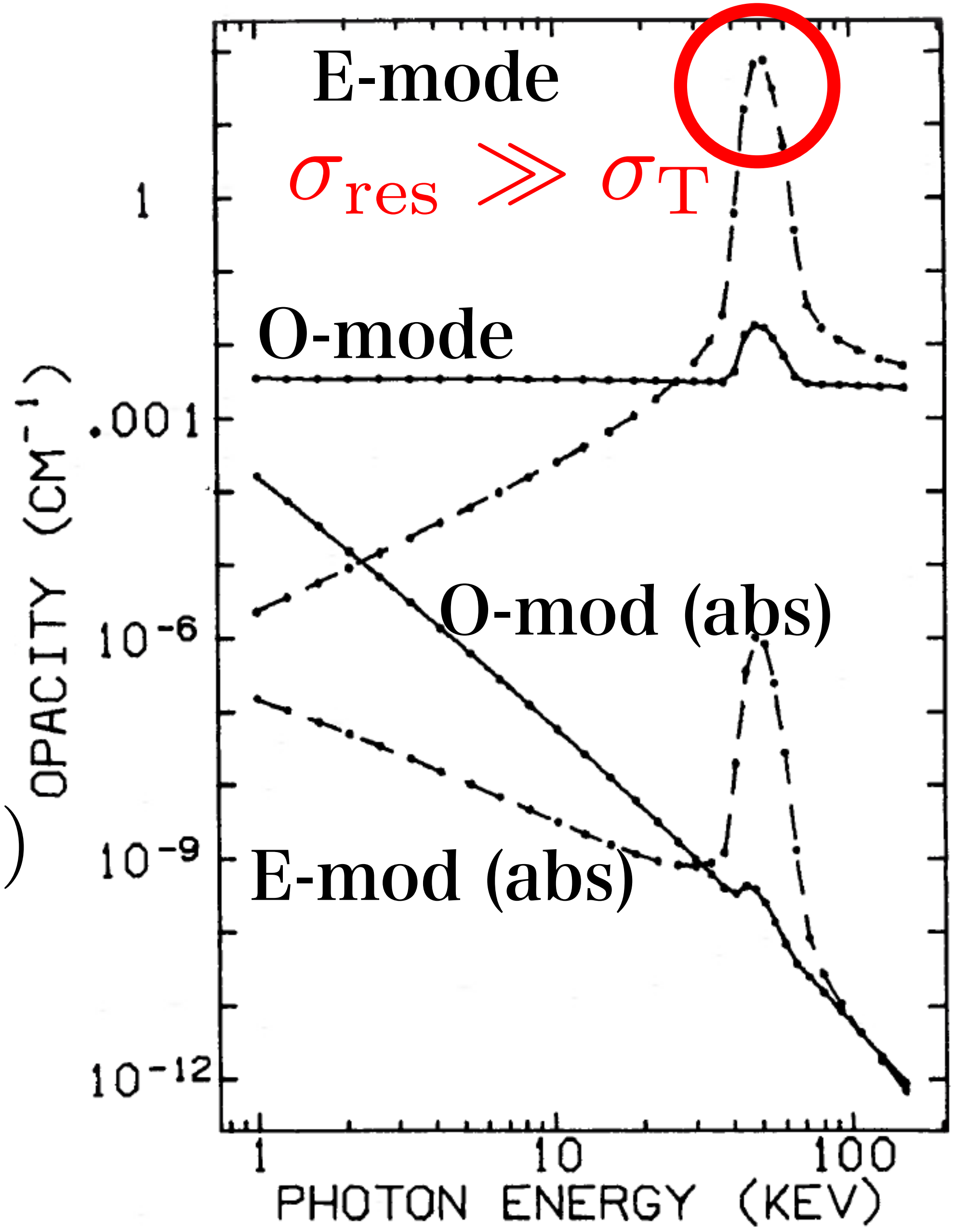
$$\sigma_O \sim \sigma_{\rm T}$$

- **X-mode:** $\vec{E}_{\rm wave} \perp (\vec{k} \times \vec{B}_{\rm bg})$

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

Suppression

& Resonance @ $\omega_B = \dfrac{eB}{m_e c}$



Nagel 81

Radiative acceleration @optically thin region

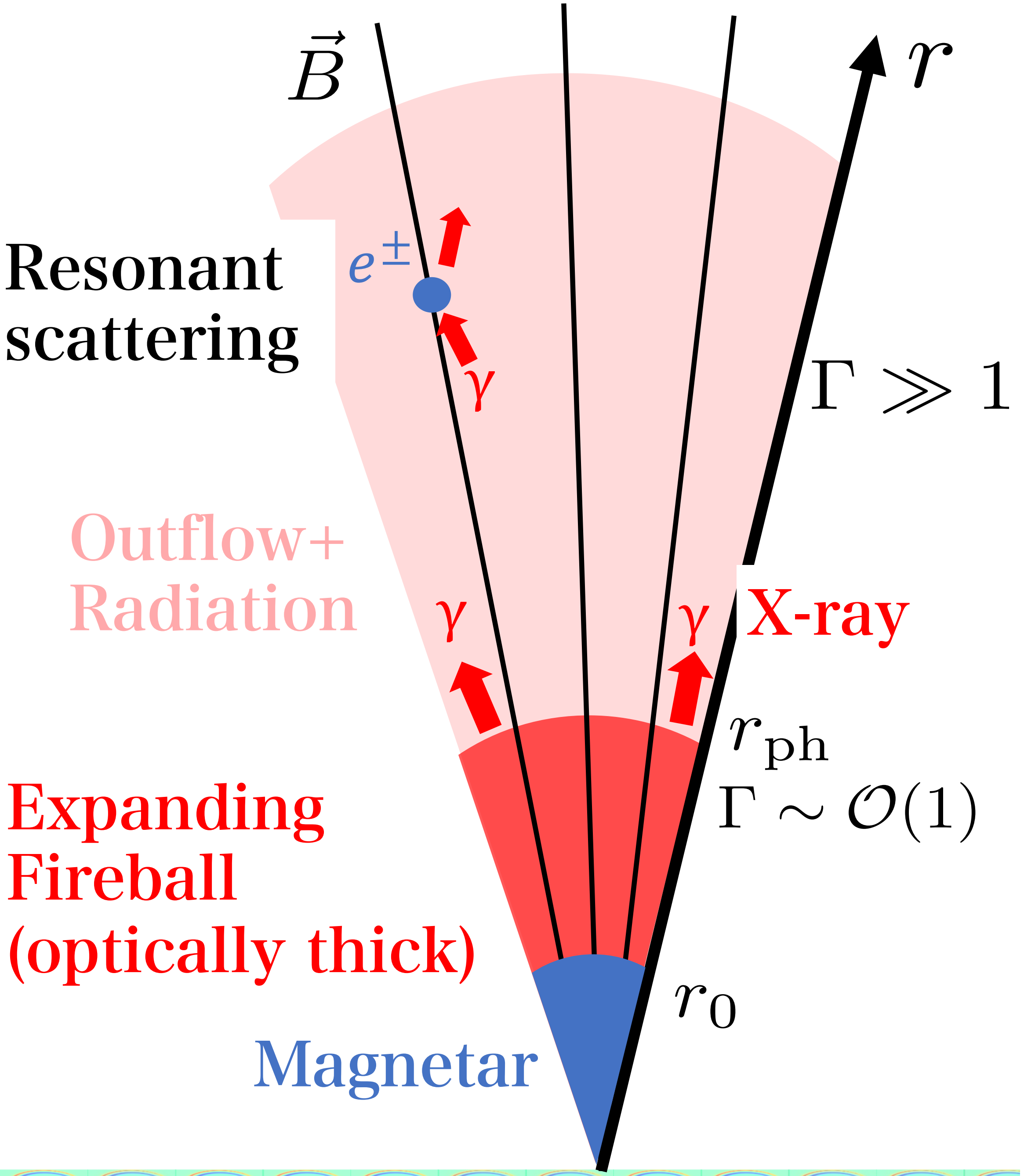
In optically thin region
Radiative force

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

σ_{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 to be
a steady flow

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

$$\begin{array}{r} \cancel{\partial_t\left[r^2\left(\rho h_\parallel\Gamma^2 - p_\parallel\right)\right]} + \partial_r\left[r^2\rho h_\parallel\Gamma^2\beta\right] = \\ \cancel{\partial_t\left[r^2\rho h_\parallel\Gamma^2\beta\right]} + \partial_r\left[r^2\left(\rho h_\parallel\Gamma^2\beta^2 - p_\parallel\right)\right] = \end{array} \boxed{\begin{array}{l} r^2G^t, \\ r^2G^r, \end{array}}$$

Radiative
Force

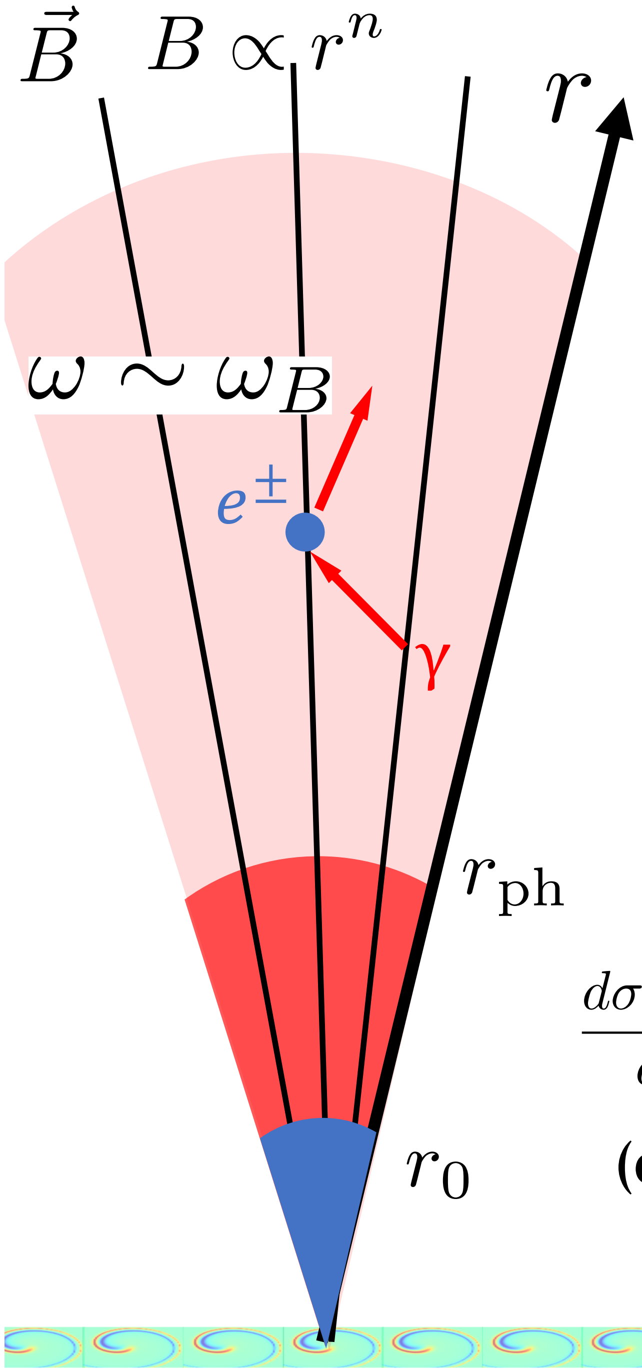
$$h_\parallel = 1 + \frac{e_{\rm th}}{\rho} + \frac{p_\parallel}{\rho}, \quad p_\parallel = (\hat\Gamma - 1)e_{\rm th}\ , \ \hat\Gamma = 3$$

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

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

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

Scattering process of photons



For a scattering,
a target electron is chosen
from 1D Maxwellian

$$f_{\rm 1D}(p_\parallel, T_\parallel)\,dp_\parallel = \frac{\exp\left(-\frac{\sqrt{m^2c^4+p_\parallel^2c^2}}{T_\parallel}\right)}{mcK_1(mc^2/T_\parallel)}\,dp_\parallel$$

@ guiding-center rest frame,
scattered photon (X/O-mode, angle)
are randomly determined.

$$\frac{d\sigma^{\rm X\to O}}{d\Omega} = \frac{3\sigma_{\rm T}}{32\pi}\cos^2\theta' \left(\frac{\omega^2}{(\omega^2+\omega_B)^2+\gamma_e^2} + \underline{\frac{\omega^2}{(\omega^2-\omega_B)^2+\gamma_e^2}}\right)$$

(e.g., of cross sections)

Resonant scattering

Physical & numerical setup

Initial condition :
Analytic solution of fireball

Optically thin region:
Solved numerically

Solve radiation in a given plasma profile

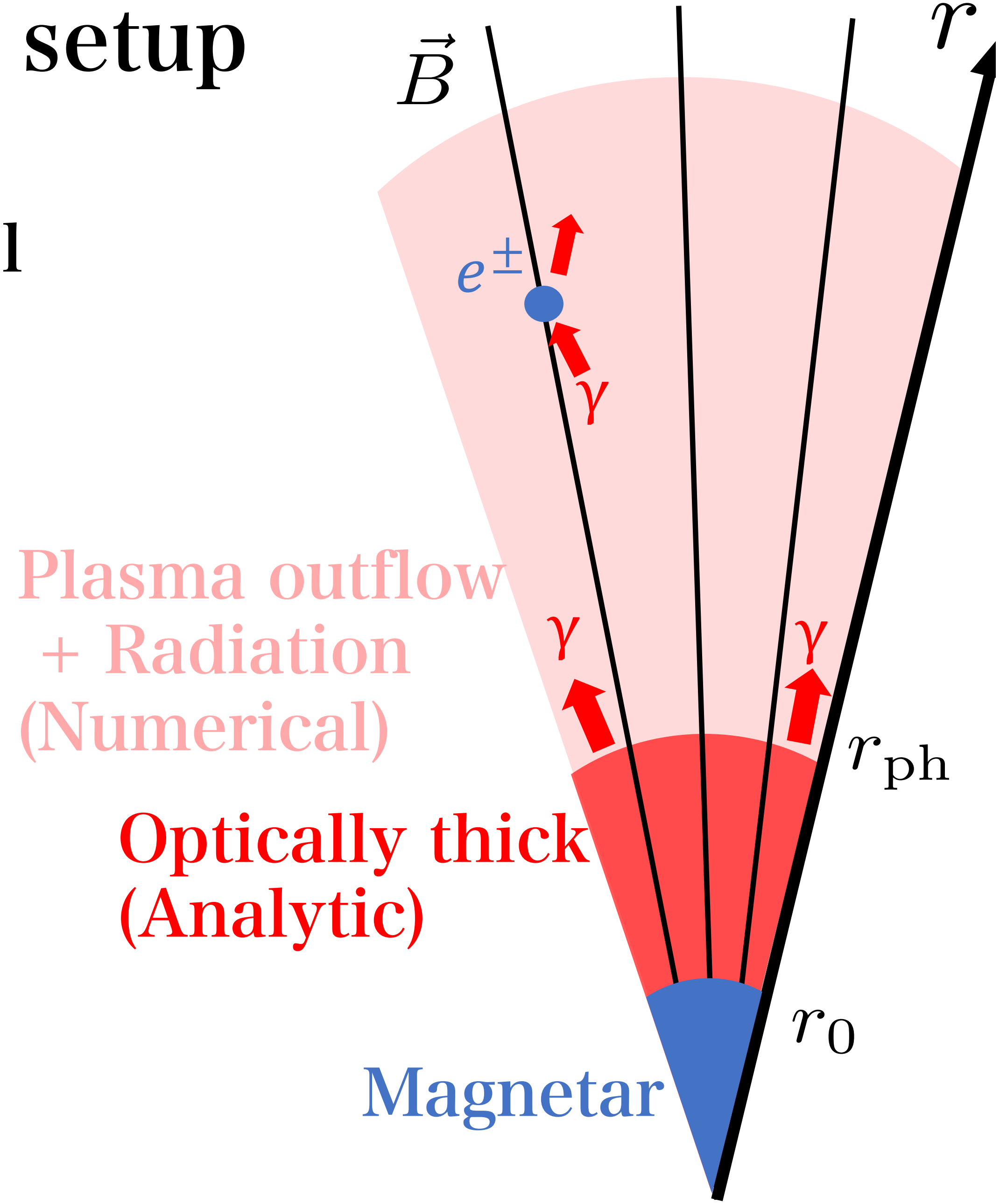
↓ Radiative force

Solve the plasma

↓ Plasma profile ↑ Radiative force

Solve the radiation

Iteration
-> steady solution

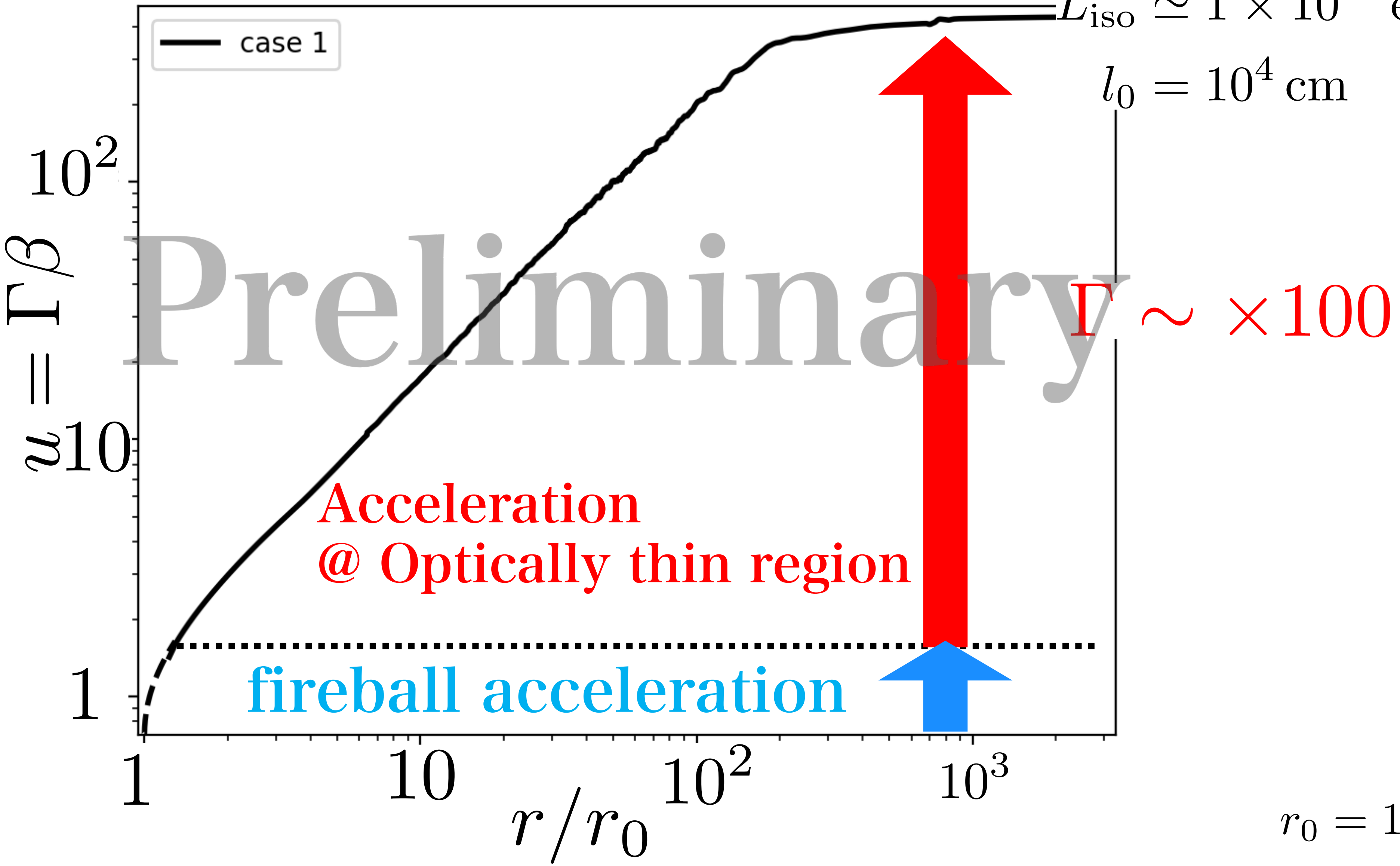


Result: radiative acceleration

$B_0 = 2 \times 10^{14}\,\mathrm{G}$

$L_{\mathrm{iso}} \simeq 1 \times 10^{40}\,\mathrm{erg\,s^{-1}}$

$l_0 = 10^4\,\mathrm{cm}$



$\Gamma \sim \times 100$

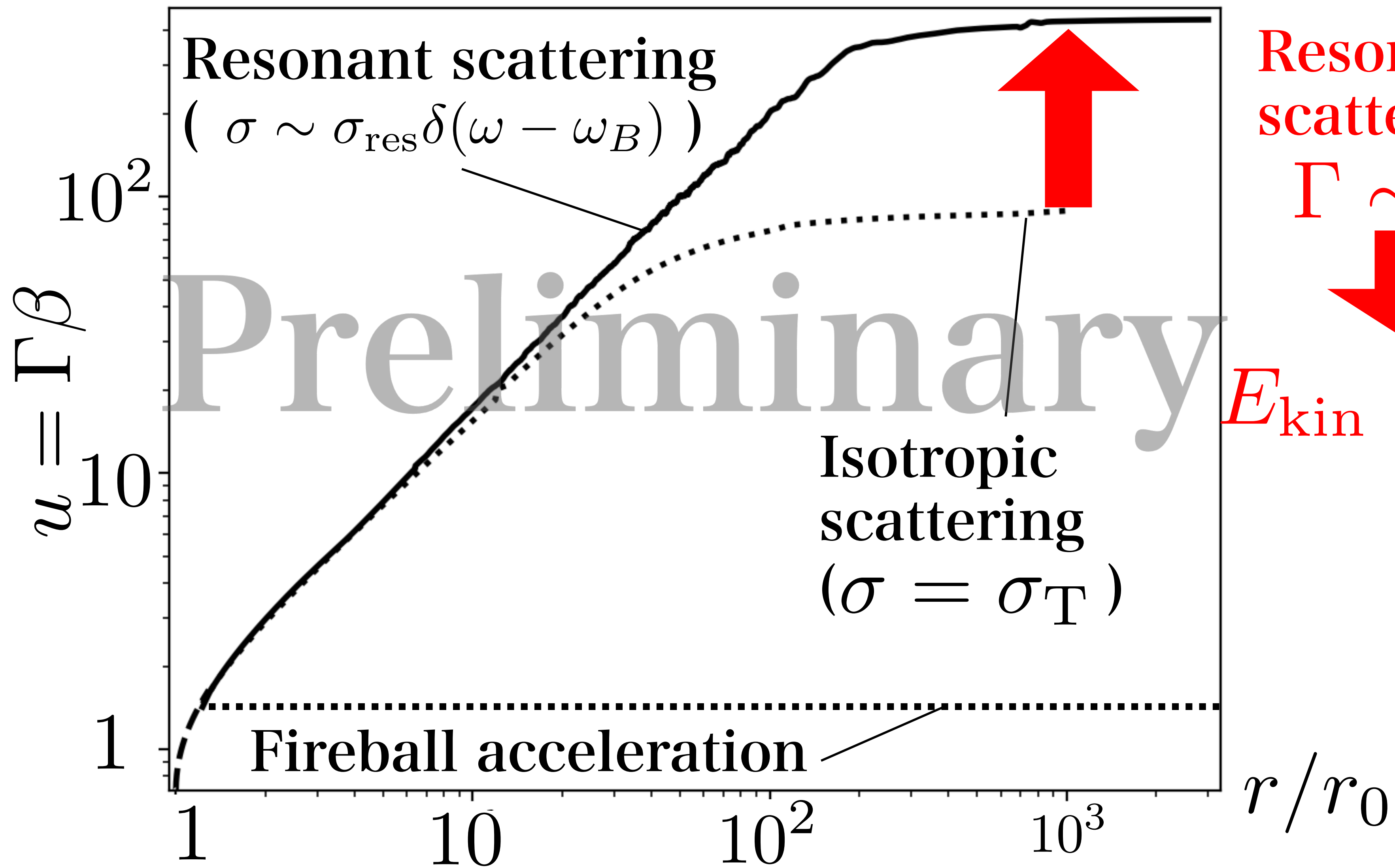
Acceleration
@ Optically thin region

fireball acceleration

$r_0 = 10^6\,\mathrm{cm}$

Plasma outflow is accelerated by the radiation

Result: radiative acceleration



Resonant scattering

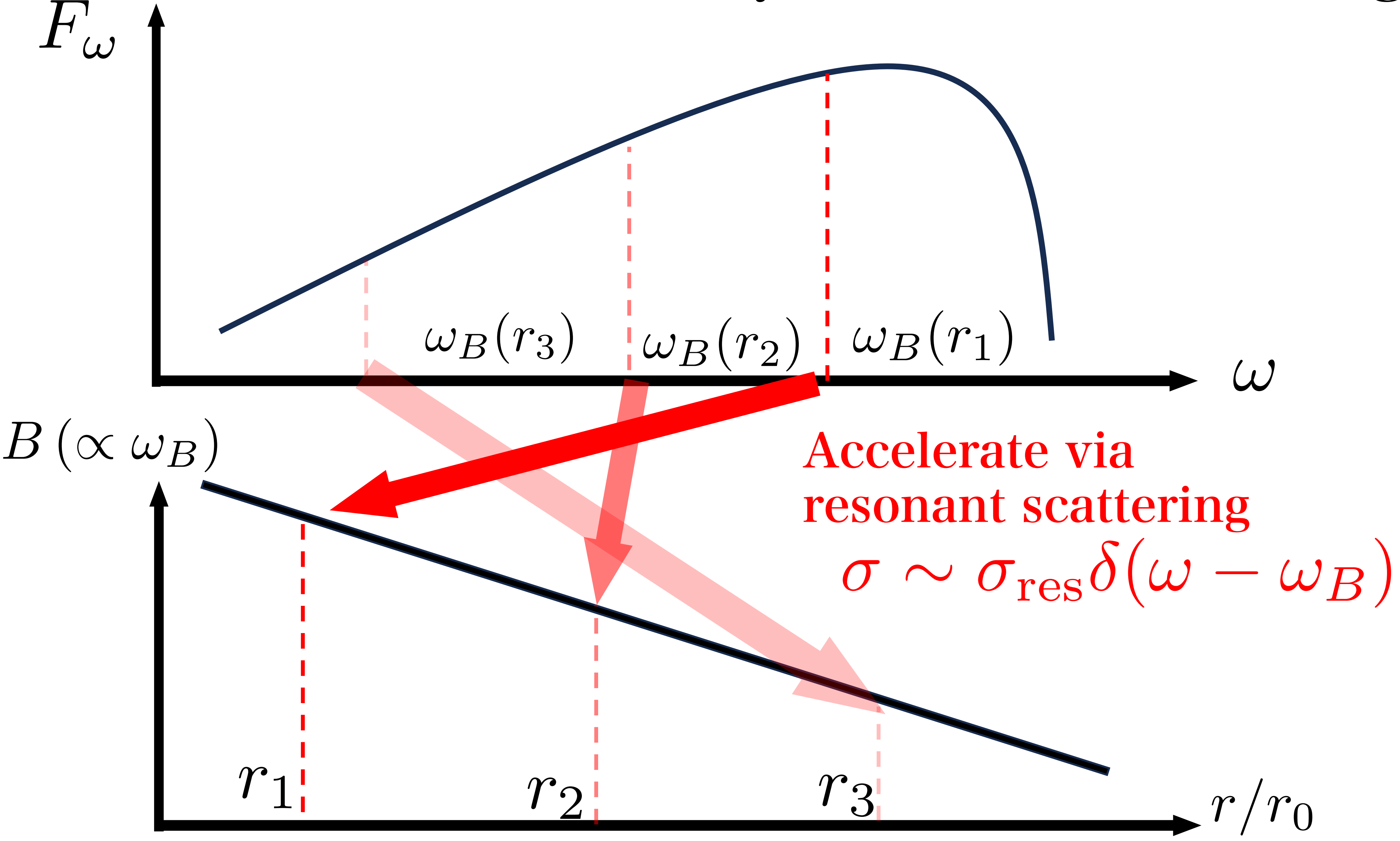
$\Gamma \sim \times 5$

$E_{\rm kin} \propto \Gamma^2$

$\sim \times 30$

The resonant scattering accelerate outflow to a higher Lorentz factor

Radiative acceleration by resonant scattering

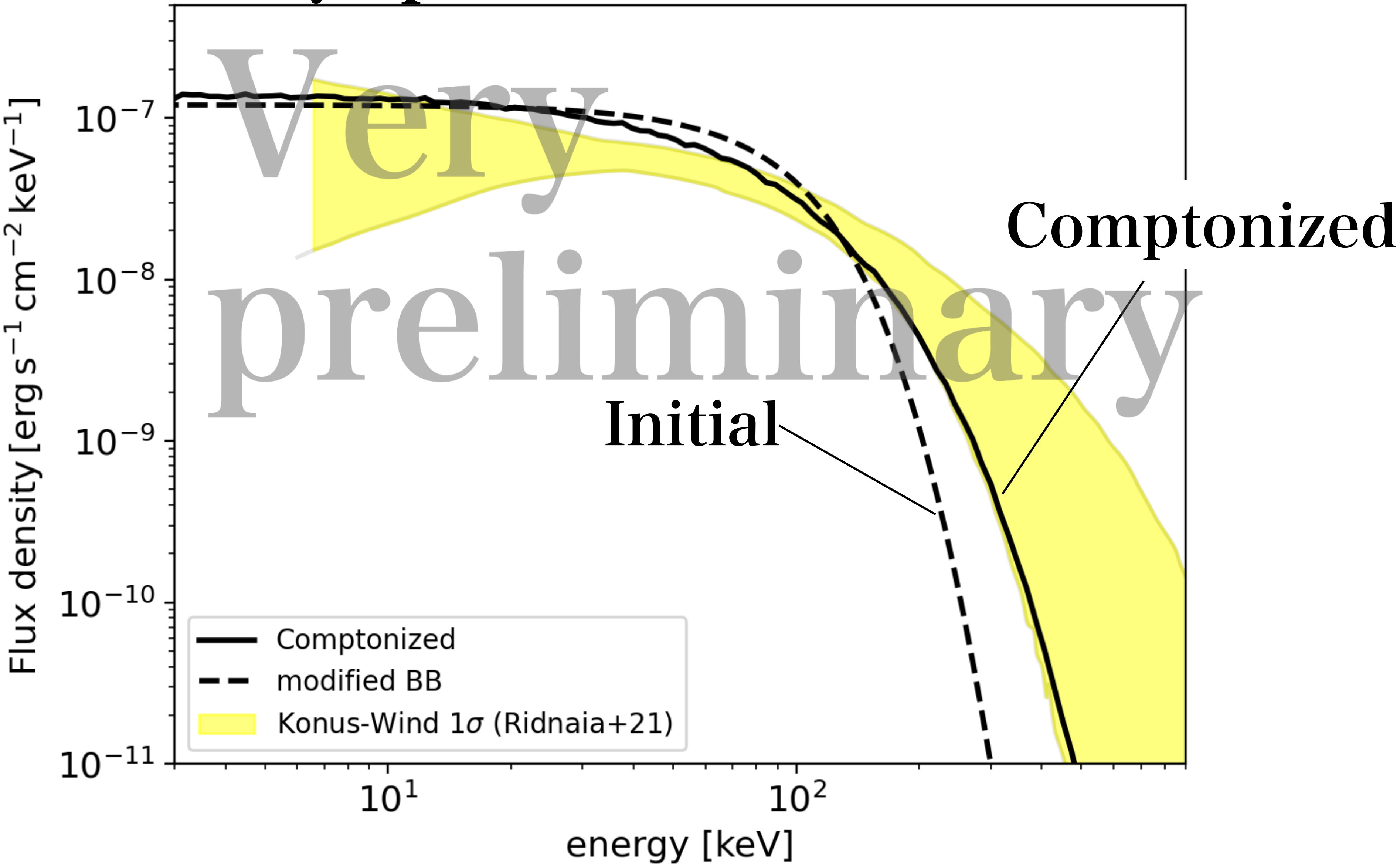


Accelerate via resonant scattering

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

Depend on magnetic field & X-ray spectrum

Result: X-ray spectrum



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

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.

Resonant scattering $\Gamma \sim \times 5$ $\Rightarrow$ $E_{\mathrm{kin}} \sim \times 30$

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

- Future plans..
  Including baryons
  -> circular polarization of X-ray? & high kinetic Energy