# Expanding Fireball in Magnetar Bursts and Fast Radio Bursts

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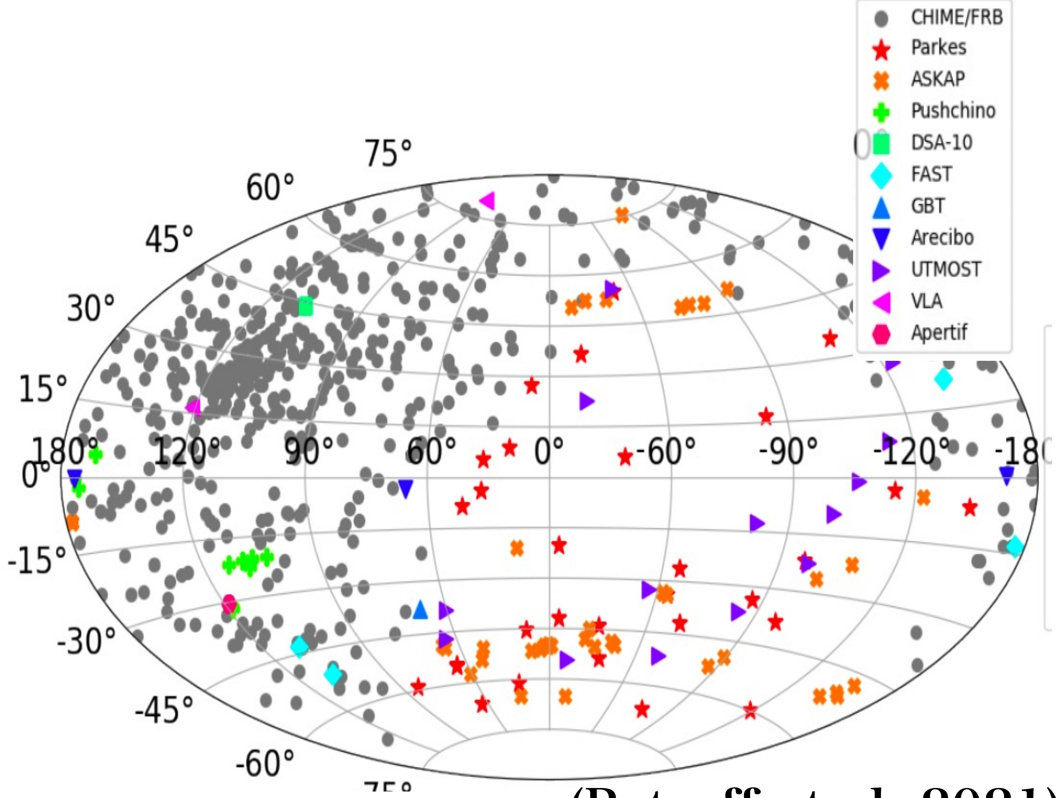
2310 High Energy Phenomena in Relativistic Outflows 8

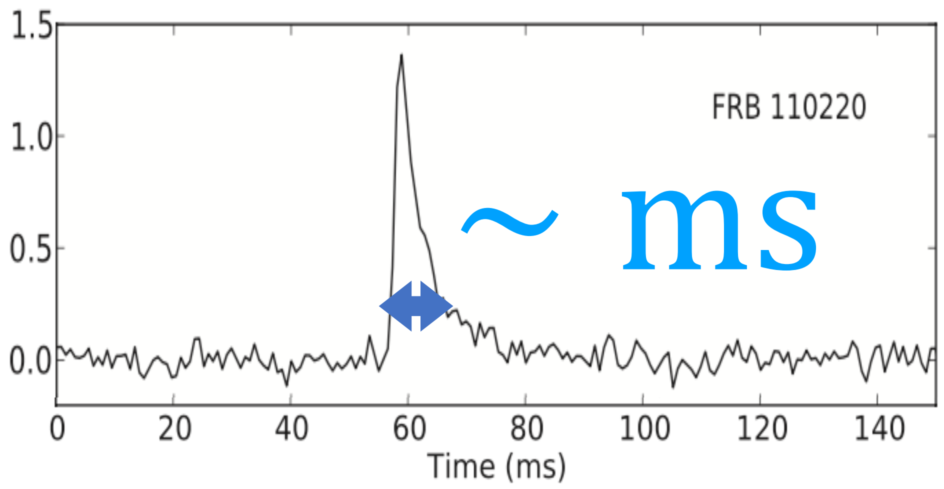
# Fast Radio Burst

**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)



$\sim \mathrm{ms}$

(Thornton et al. 2013)

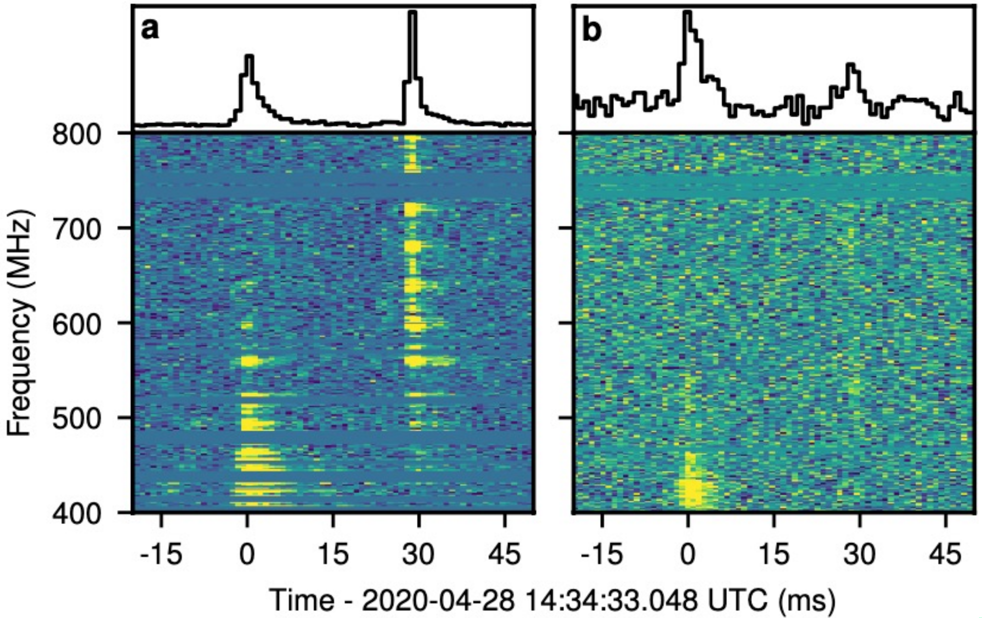
# FRB 20200428A

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

FRB luminosity

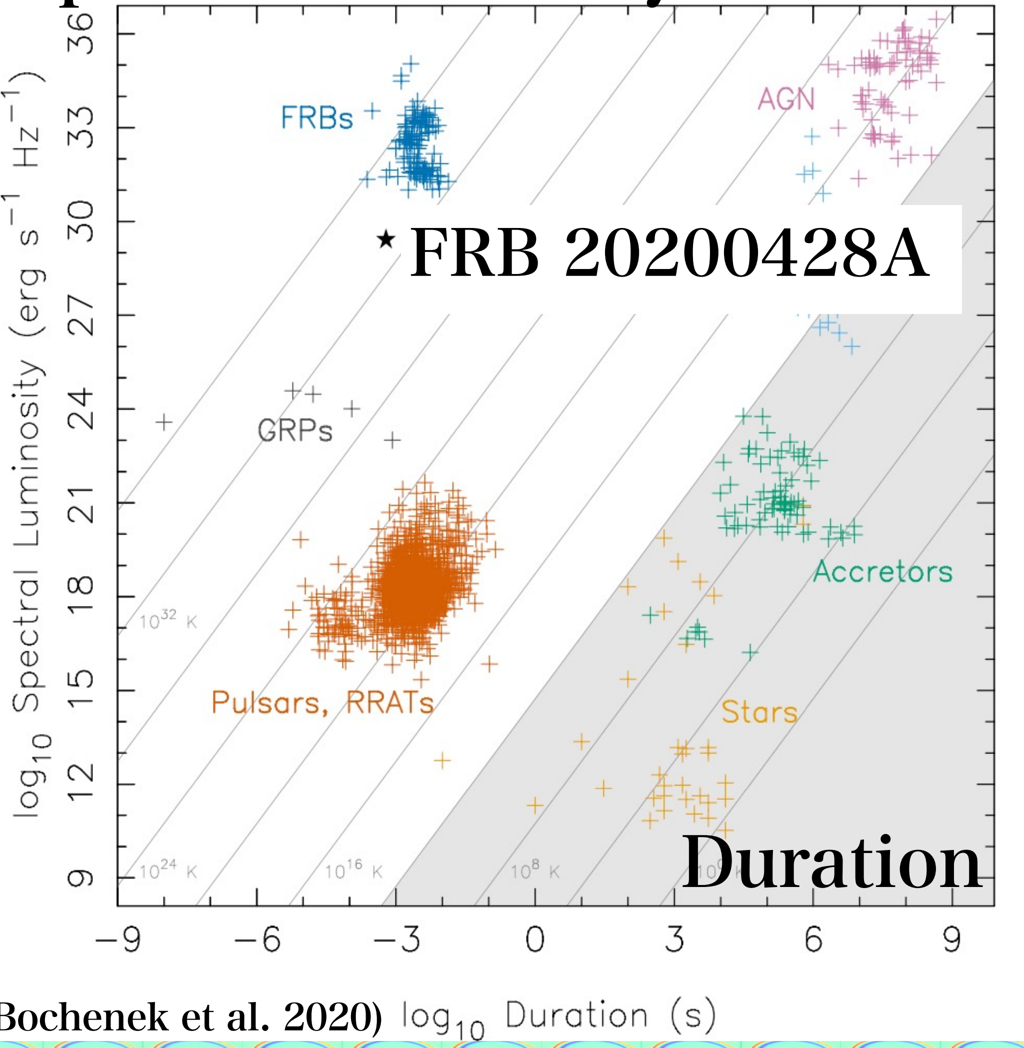
$$L_{\mathrm{FRB}} \sim 10^{38}\,\mathrm{erg\,s^{-1}}$$

Fainter than others



(CHIME 2020)

Spectral luminosity



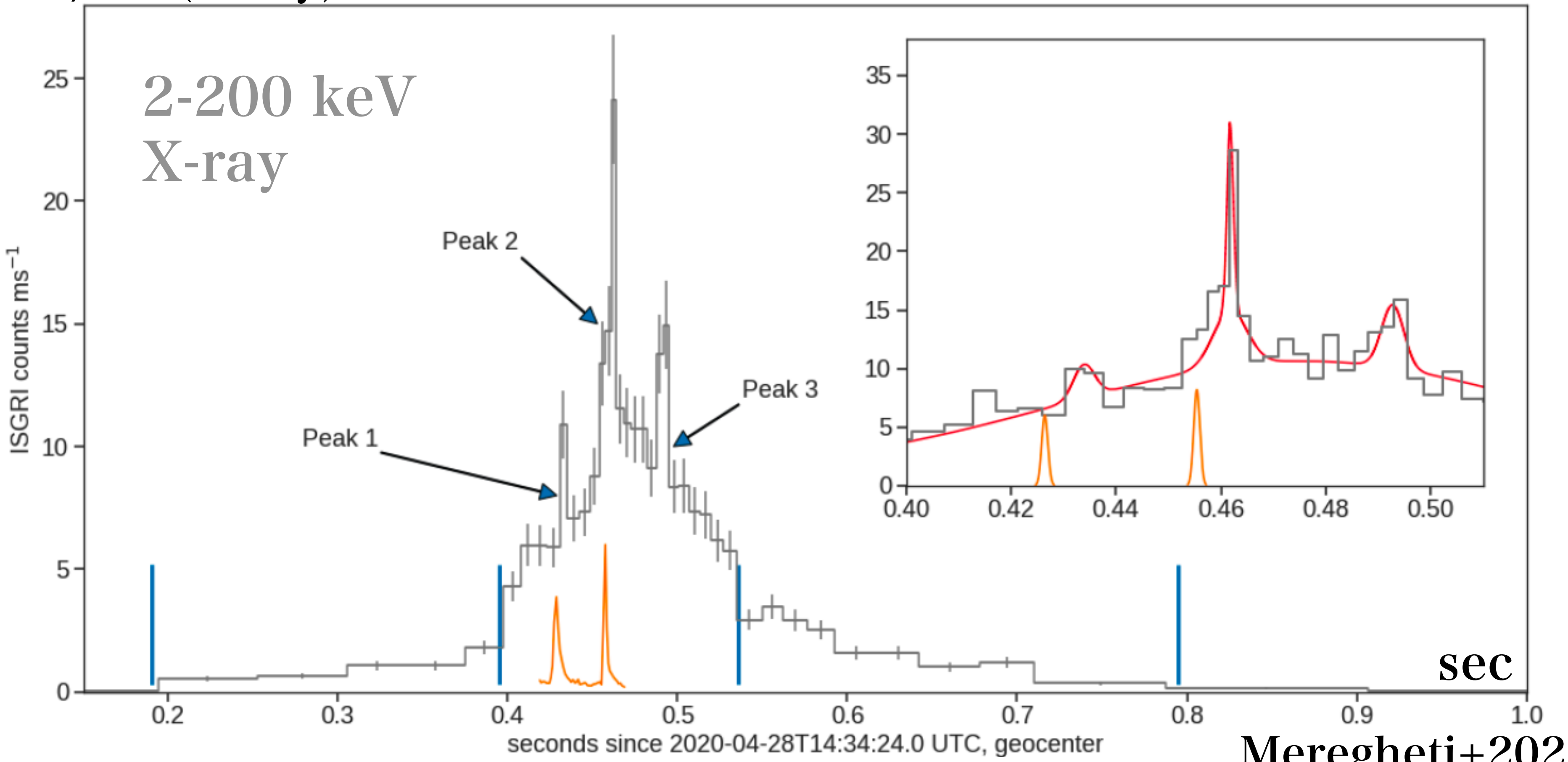
★ FRB 20200428A

Duration

(Bochenek et al. 2020)

# FRB & X-ray association

count/ms (X-ray)



2-200 keV
X-ray

sec

Meregheti+2020

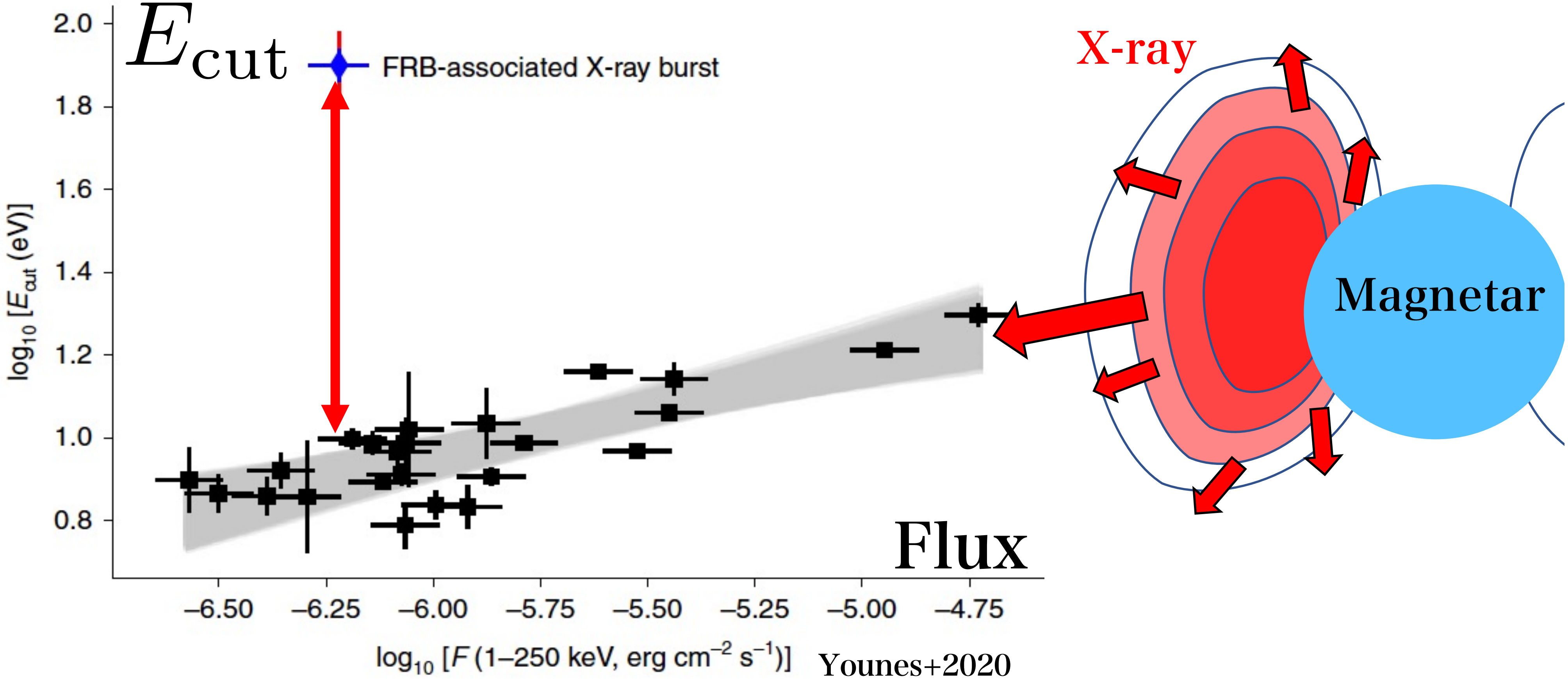
FRB !!

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**

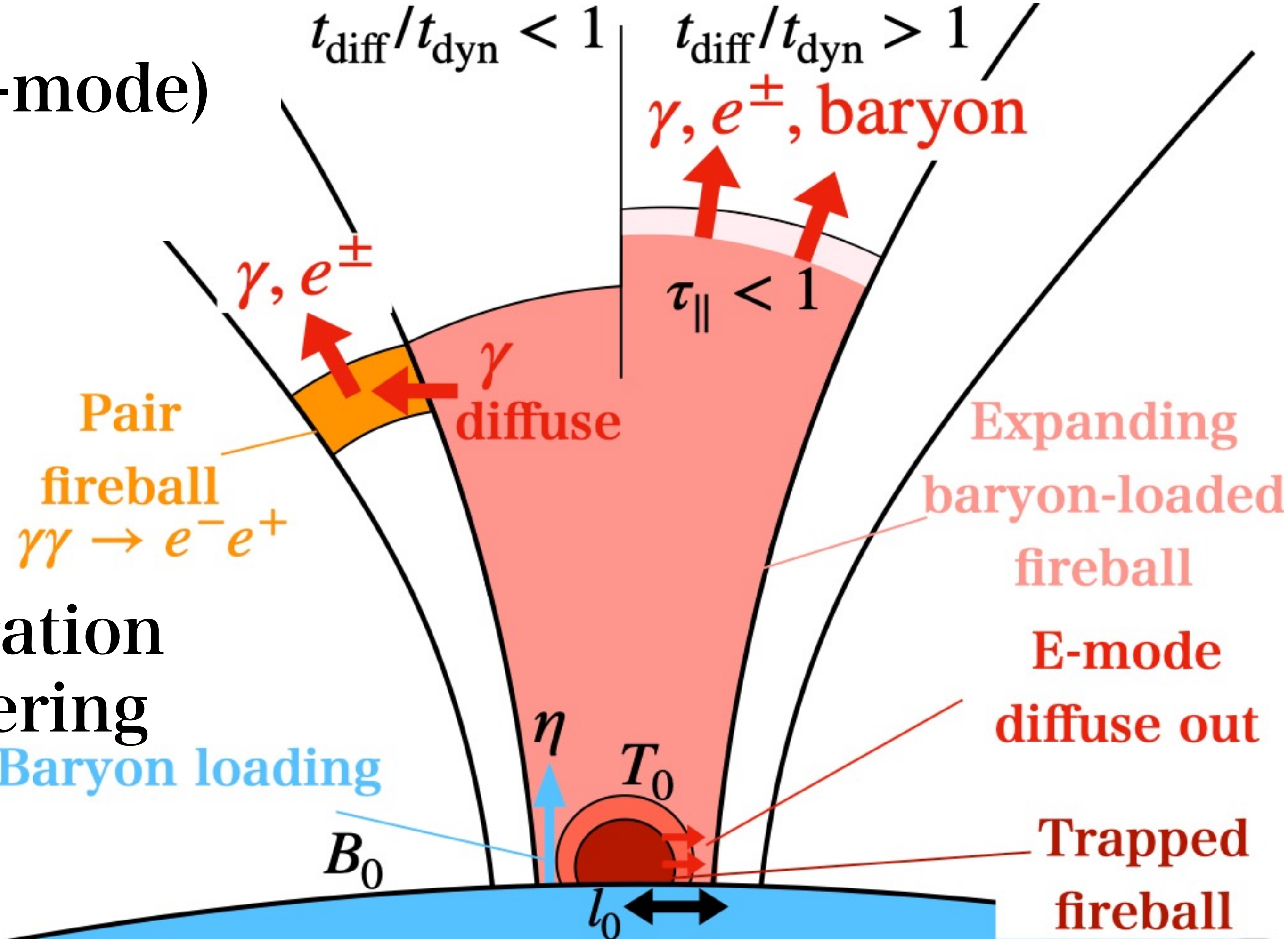
$$T_{\rm eff}\sim 8\,{\rm keV}\,B^{1/3}R_6^{-1/3}g_{*,14}^{1/6}$$

# Expanding 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 & FRB

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

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

**Relativistic motion of outflow**

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

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

- Observed temperature

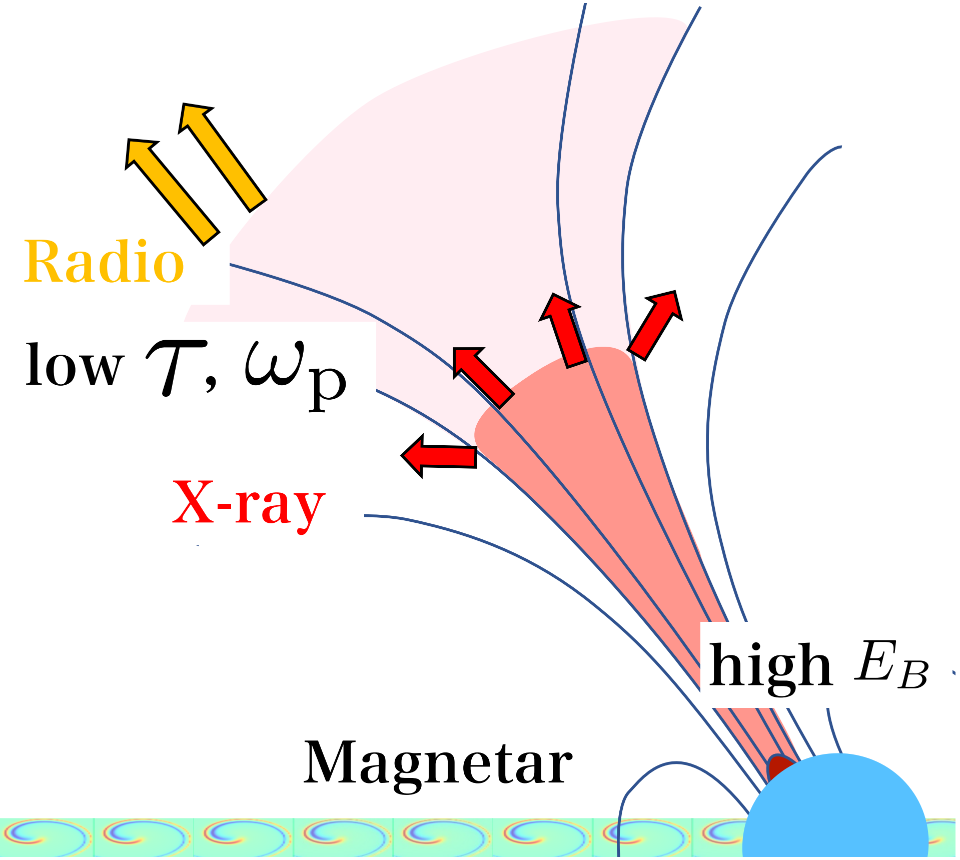
$$T_{\rm obs} \sim \Gamma T = T_0$$

Doppler shift

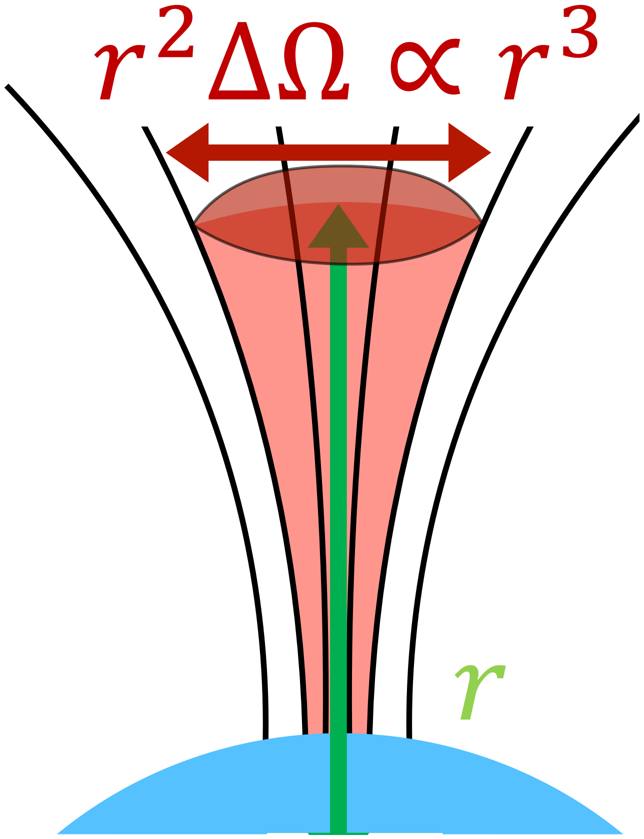
High $T_{\rm obs}$ for high initial $T_0$

**Kinetic Energy of outflow**

Converted to radio burst
@ outer region



# Dipolar fireball: Dynamics



Conservation low

- Baryon number $r^2\Delta\Omega\,\rho\Gamma\beta = \text{const.}$
- Entropy $r^2\Delta\Omega\,e^{3/4}\Gamma\beta = \text{const.}$
- Energy $r^2\Delta\Omega\,(\rho + 4e/3)\Gamma\beta = \text{const.}$

Dipole flux tube $\Delta\Omega \propto r$

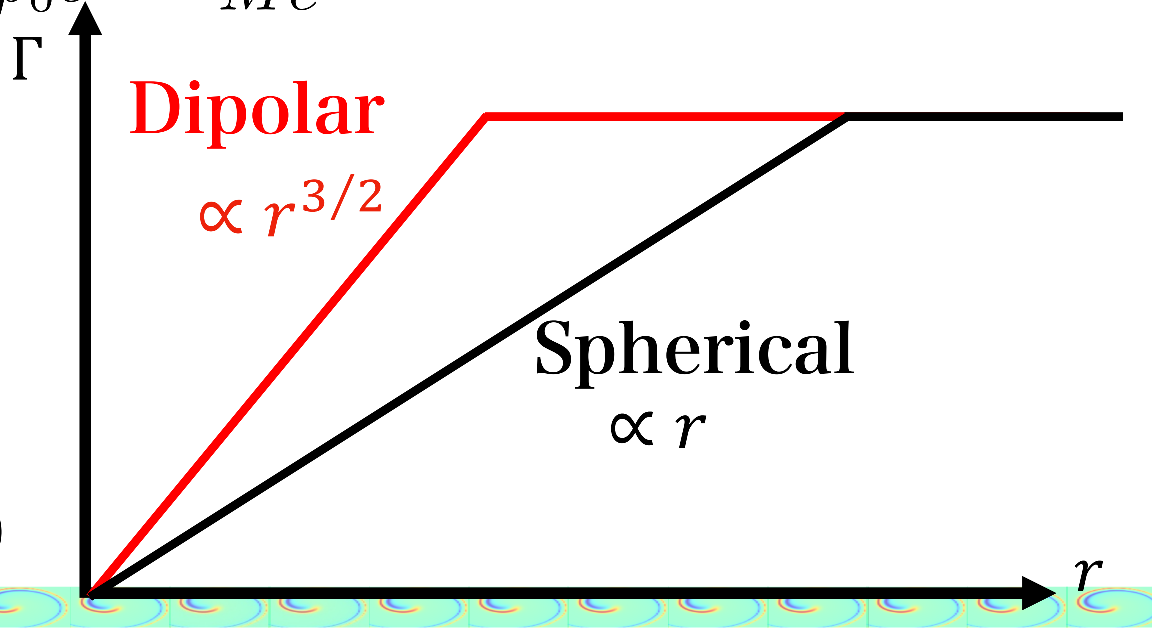
Baryon loading $\eta = \dfrac{e_0}{\rho_0 c^2} = \dfrac{L_0}{\dot{M} c^2}$

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

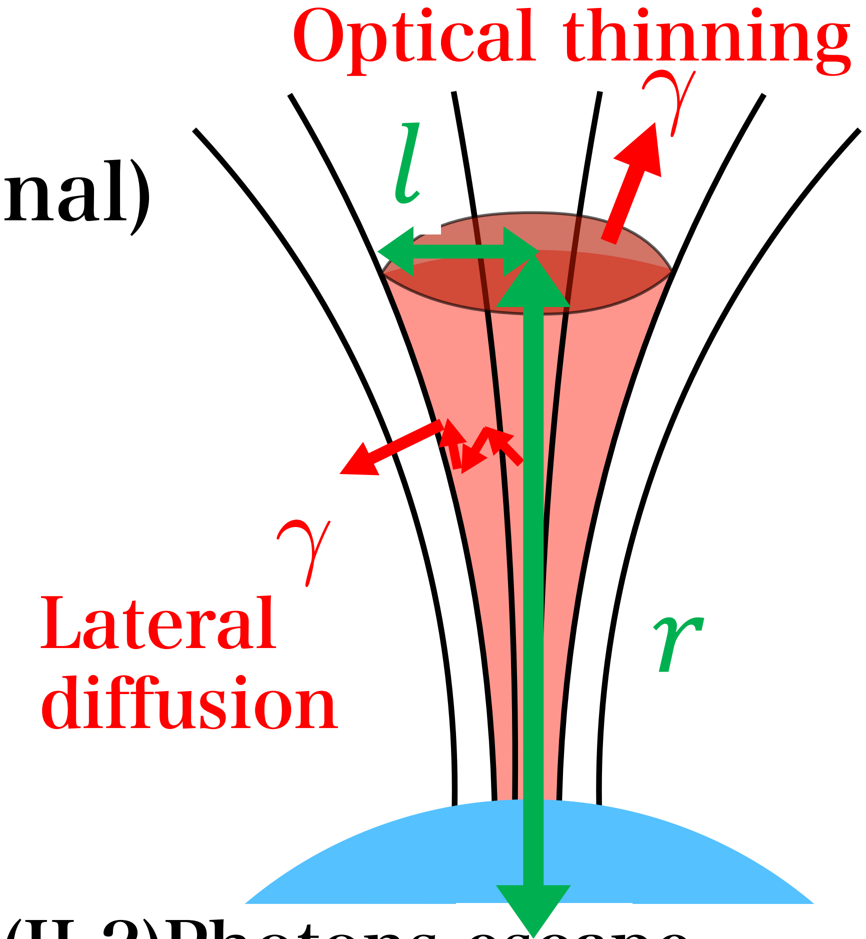
$$\Gamma \propto r^{3/2}$$

$$\rho \propto r^{-9/2}$$

(Radiation-dominated)



# Photon escape



## (I) Optical thinning (longitudinal)

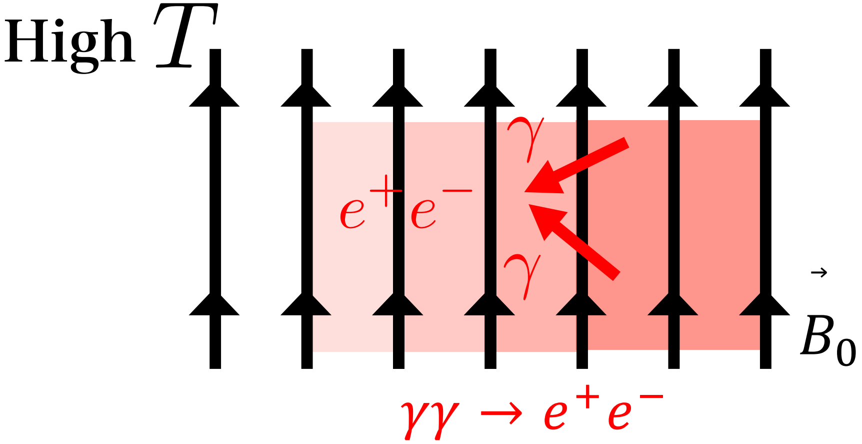
$$@ \ \tau_{\parallel} = n\sigma \frac{r}{\Gamma} < 1$$

## (II) Diffusion (lateral)

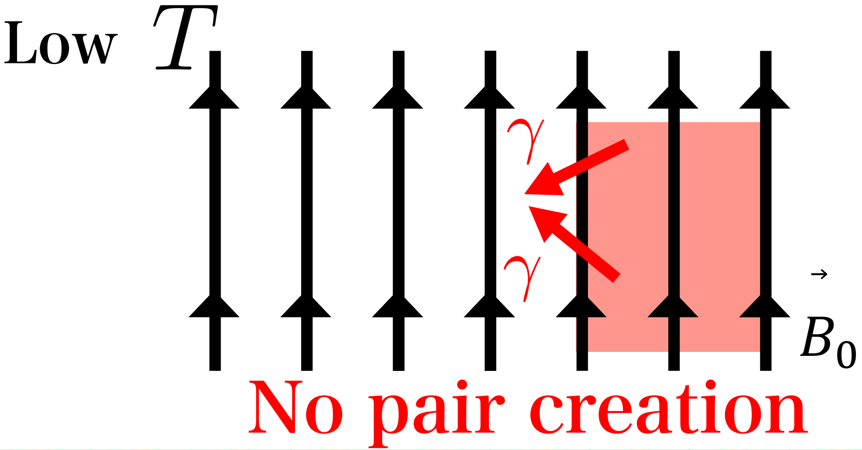
$$@ \ t_{\rm diff} = n\sigma l \frac{l}{c} < \frac{r}{c\Gamma} = t_{\rm dyn}$$

After diffusion,

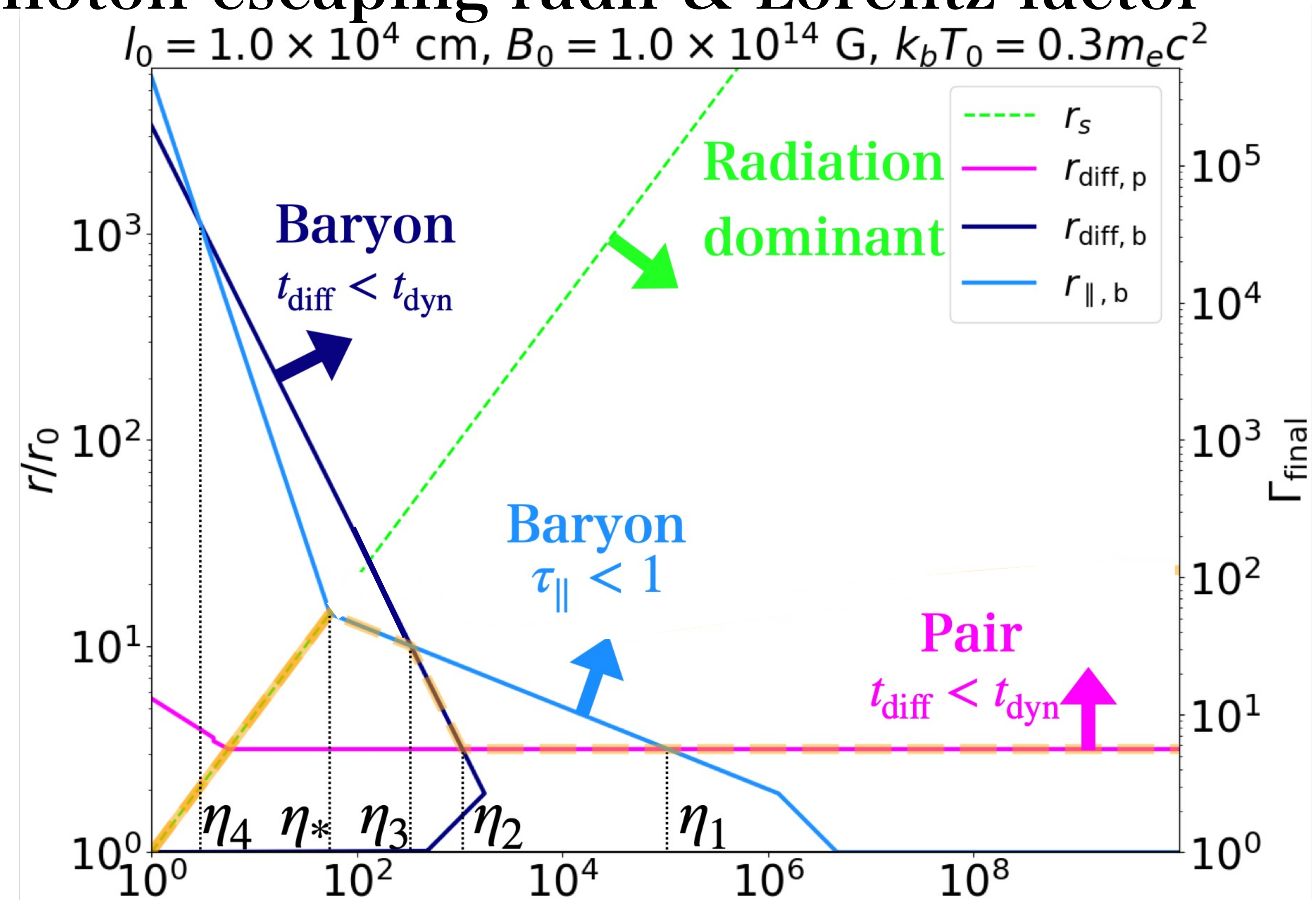
(II-1)Fireball expand laterally



(II-2)Photons escape



# Photon escaping radii & Lorentz factor

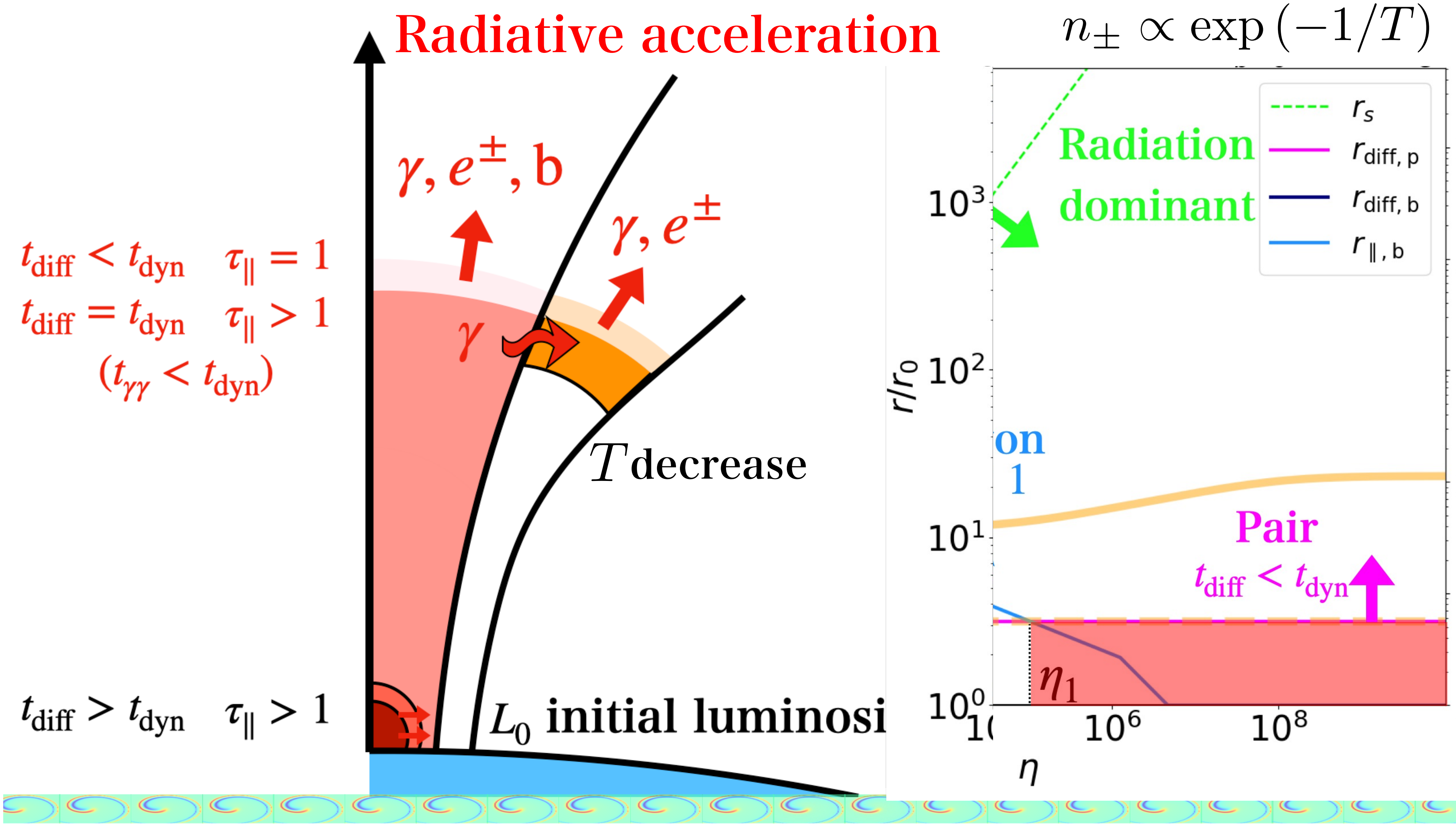


Baryon rich

Baryon poor

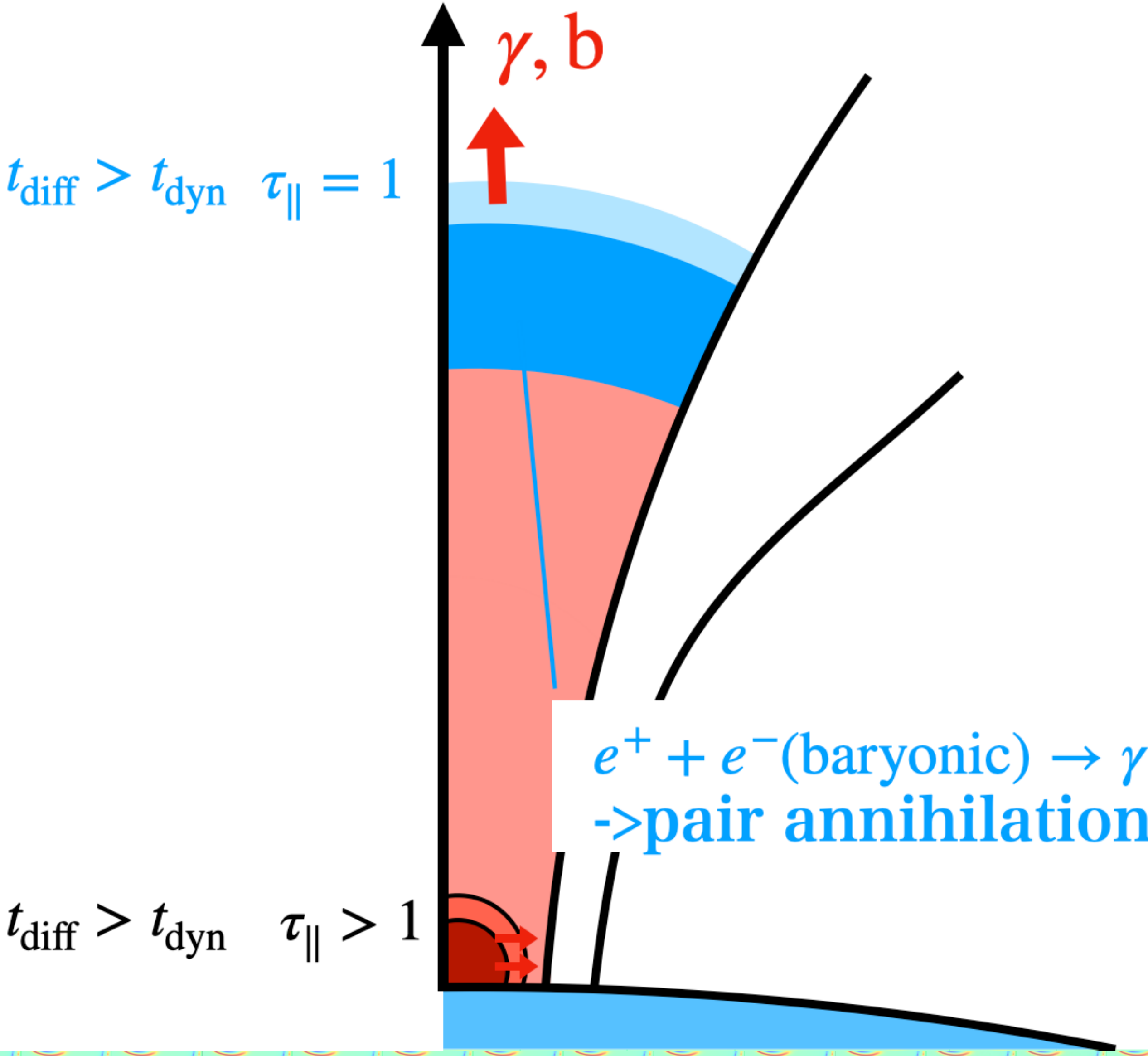
# Example1: Pair-diffusion case

Photons diffuse out from the initial flux tube
Lateral diffusion -> Optical thinning



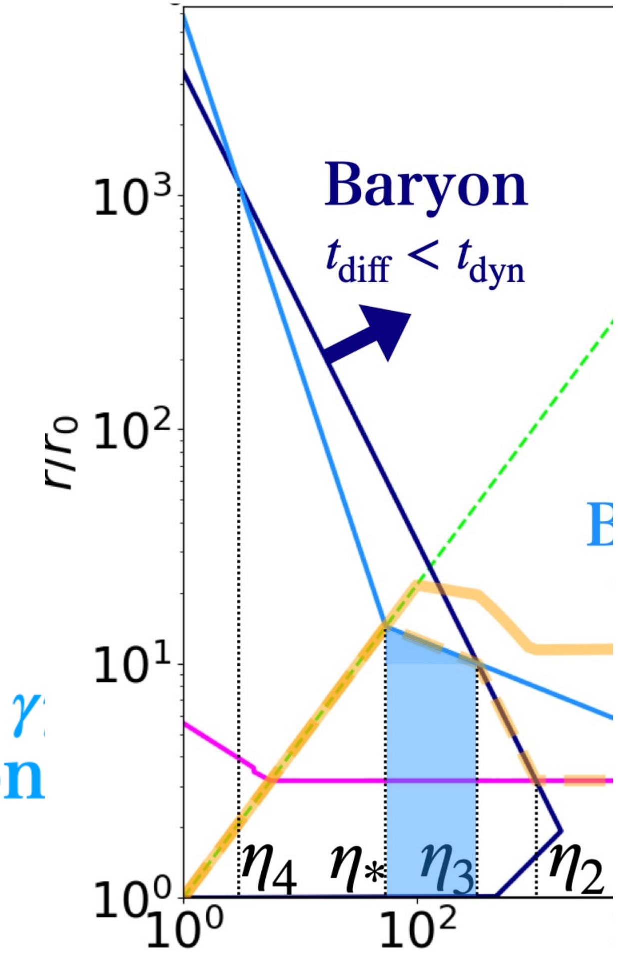
# Example 2: Baryon-photosphere case

## Photons escape from fireball after optical thinning



$e^{+} + e^{-}$(baryonic) → $\gamma$

**->pair annihilation**



# Radiative acceleration after optical thinning

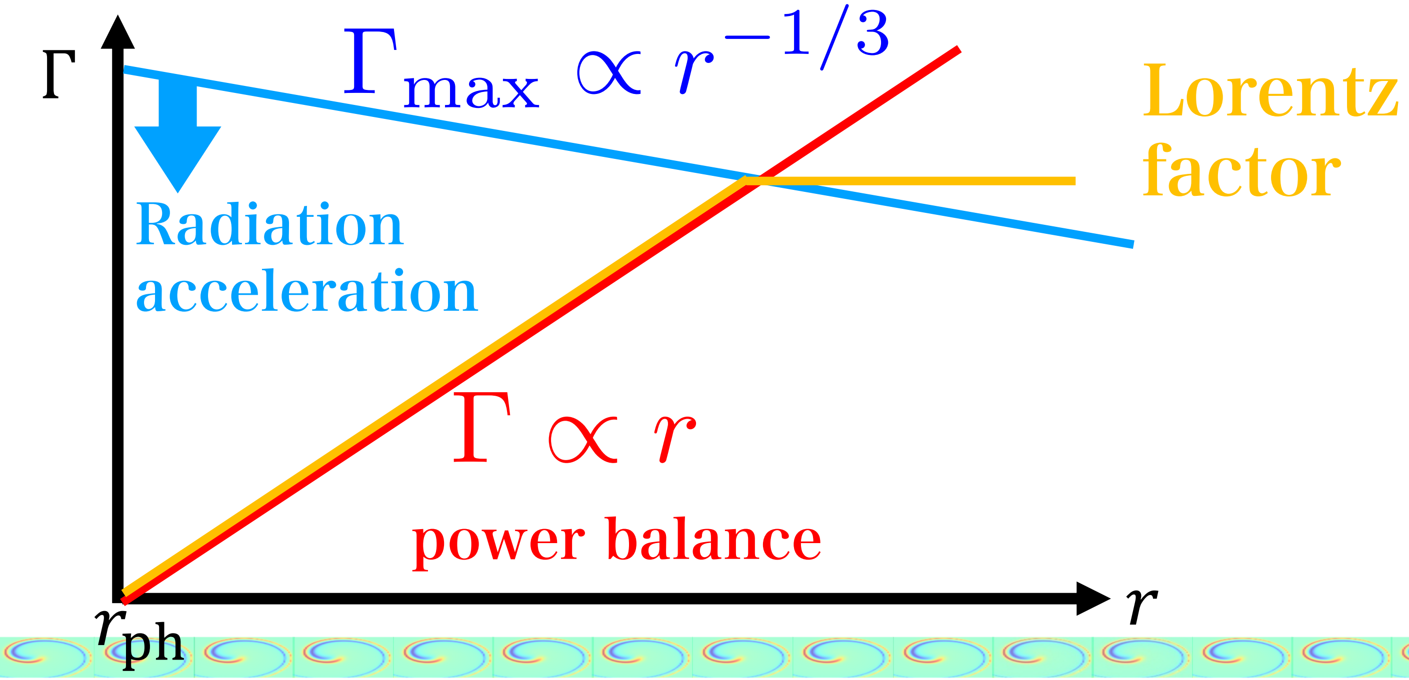
Radiation accelerates particles @ $\tau < 1$

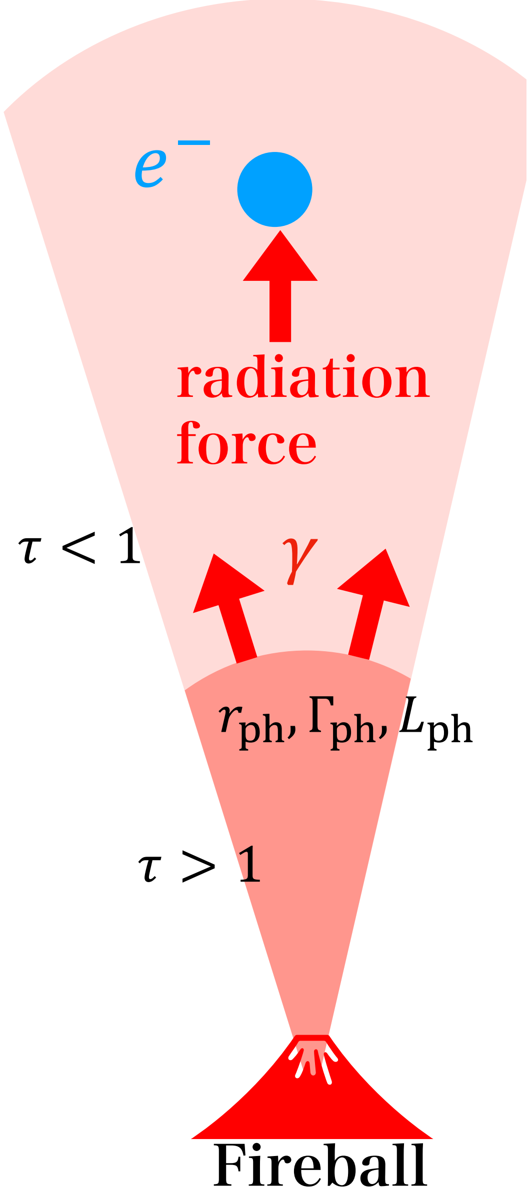
- Power Balance @ comoving frame of e

$$\Gamma \simeq \Gamma_{\rm ph} \left( \frac{r}{r_{\rm ph}} \right)$$

During (work by radiation) > (rest mass)

$$\frac{\sigma_{\rm T} L_{\rm iso}}{4\pi r^2 \Gamma^2} > \bar{m} c^2 \qquad \bar{m} = \frac{m_{\rm e} n_{\pm} + m_{\rm p} n_b}{n_{\pm} + n_b}$$

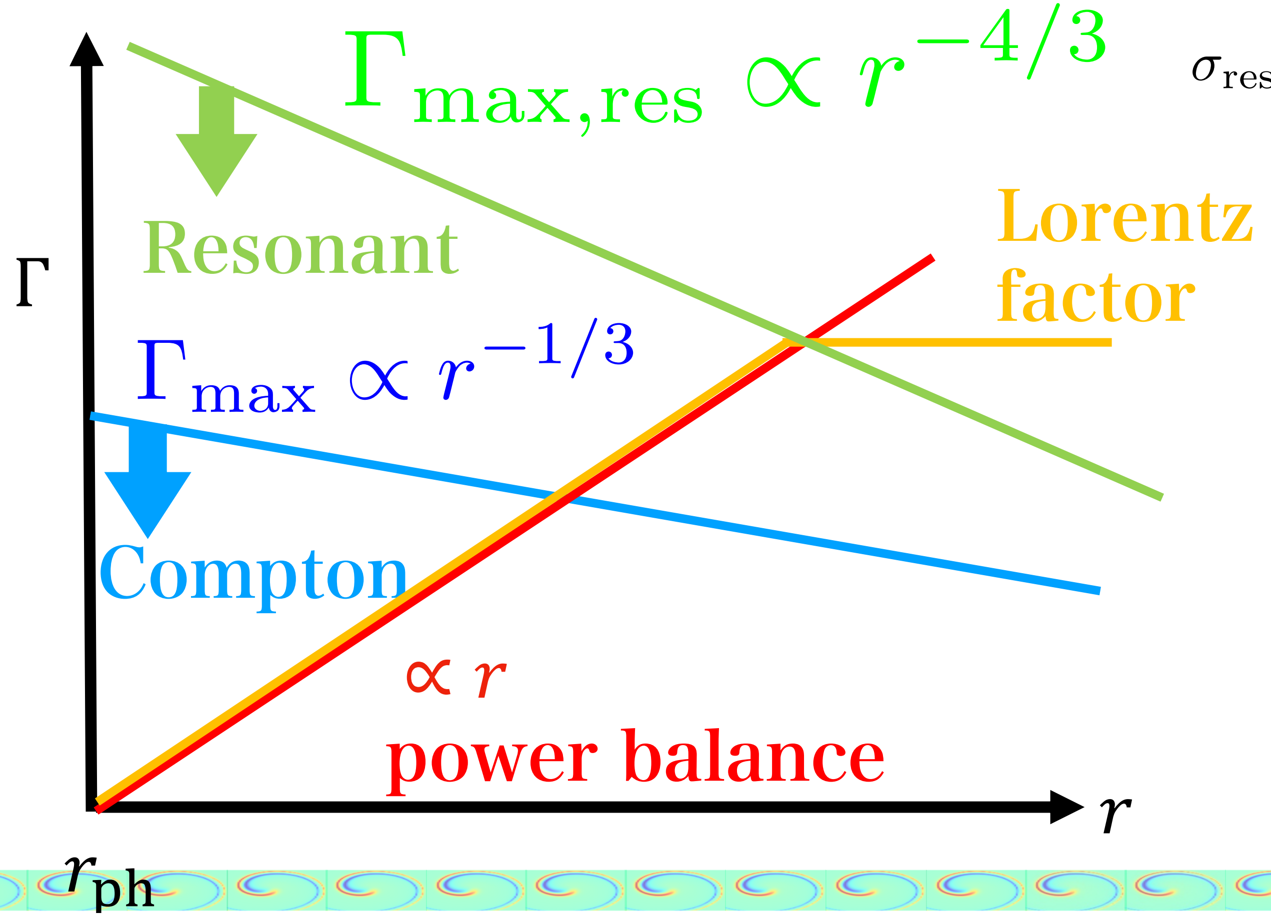


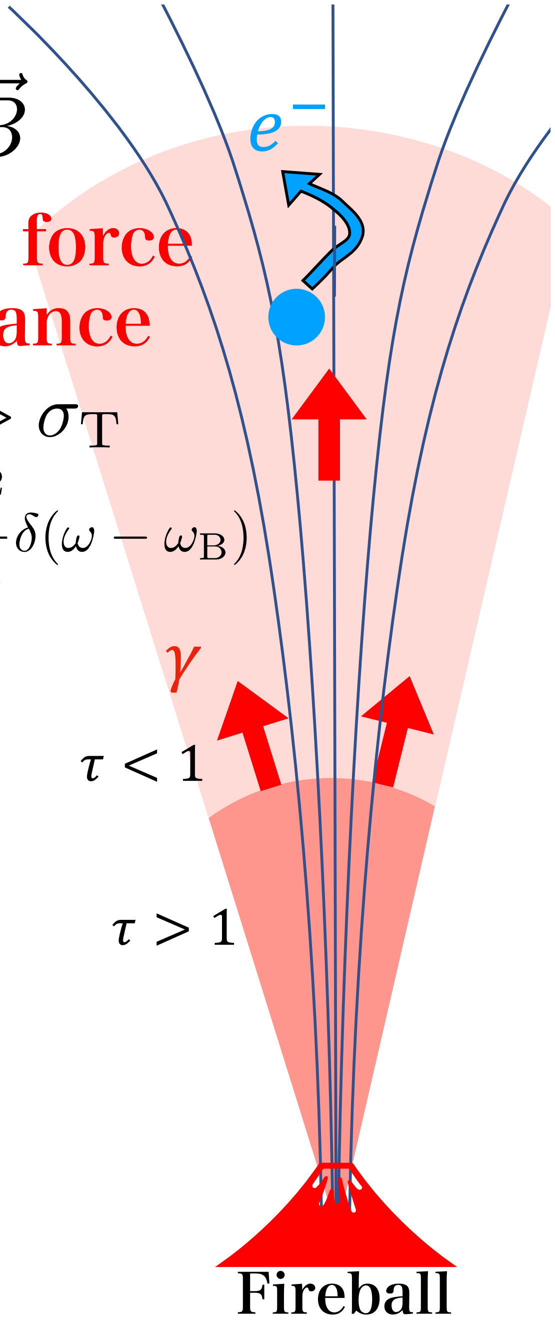


# Radiation acceleration w/resonant scattering

Work by rad is modified
(assuming blackbody)

$$\frac{\sigma_{\rm res} L_{\rm iso}}{4\pi r^2 \Gamma^2} > \bar{m} c^2$$



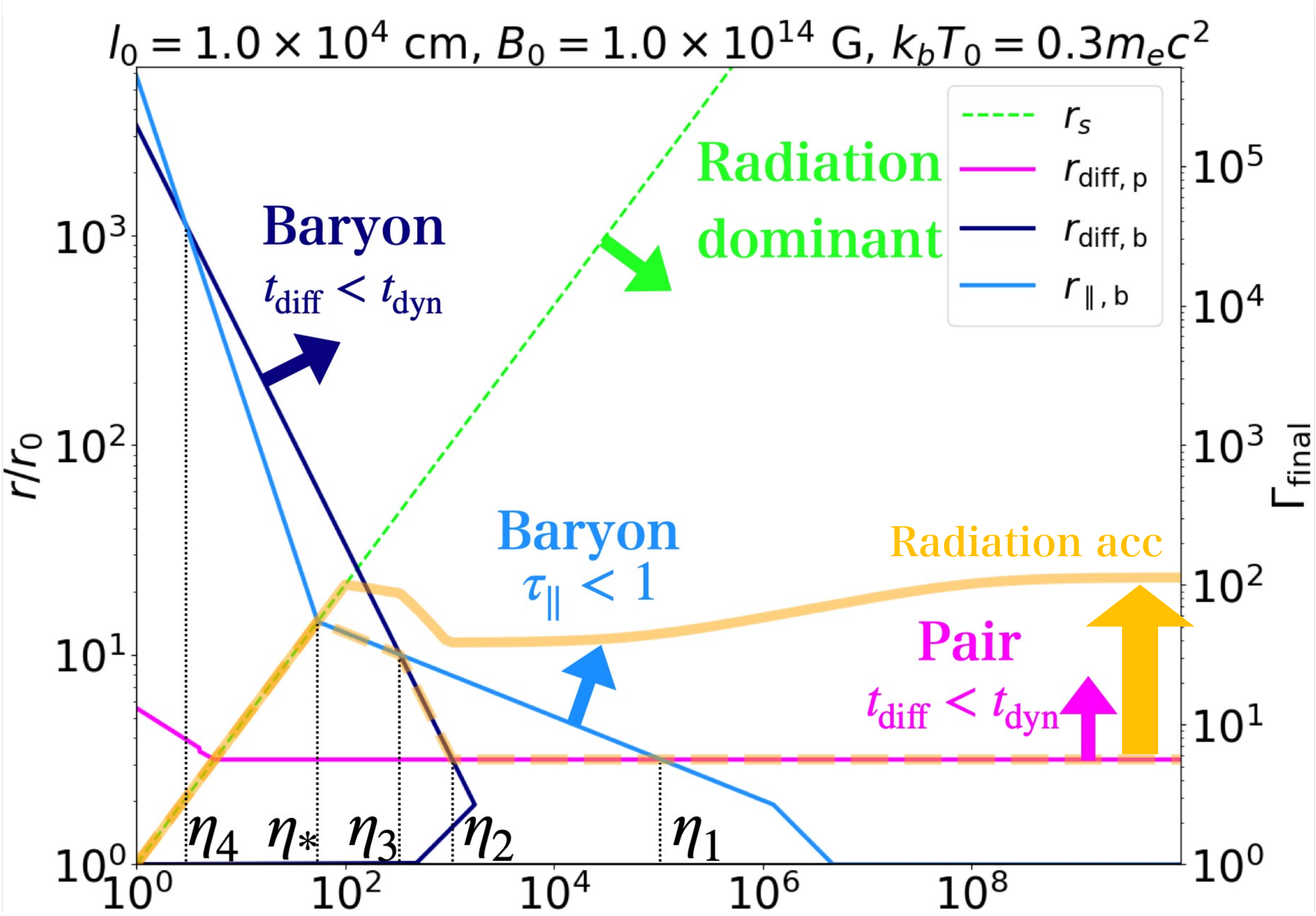


Radiative force via resonance

$$\sigma_{\rm res} \gg \sigma_{\rm T}$$

$$\sigma_{\rm res} \sim \frac{\pi^2 e^2}{m_{\rm e} c} \delta(\omega - \omega_{\rm B})$$

# Radiative acceleration and Lorentz factor



**Radiation dominant**

**Baryon**
$t_{\mathrm{diff}} < t_{\mathrm{dyn}}$

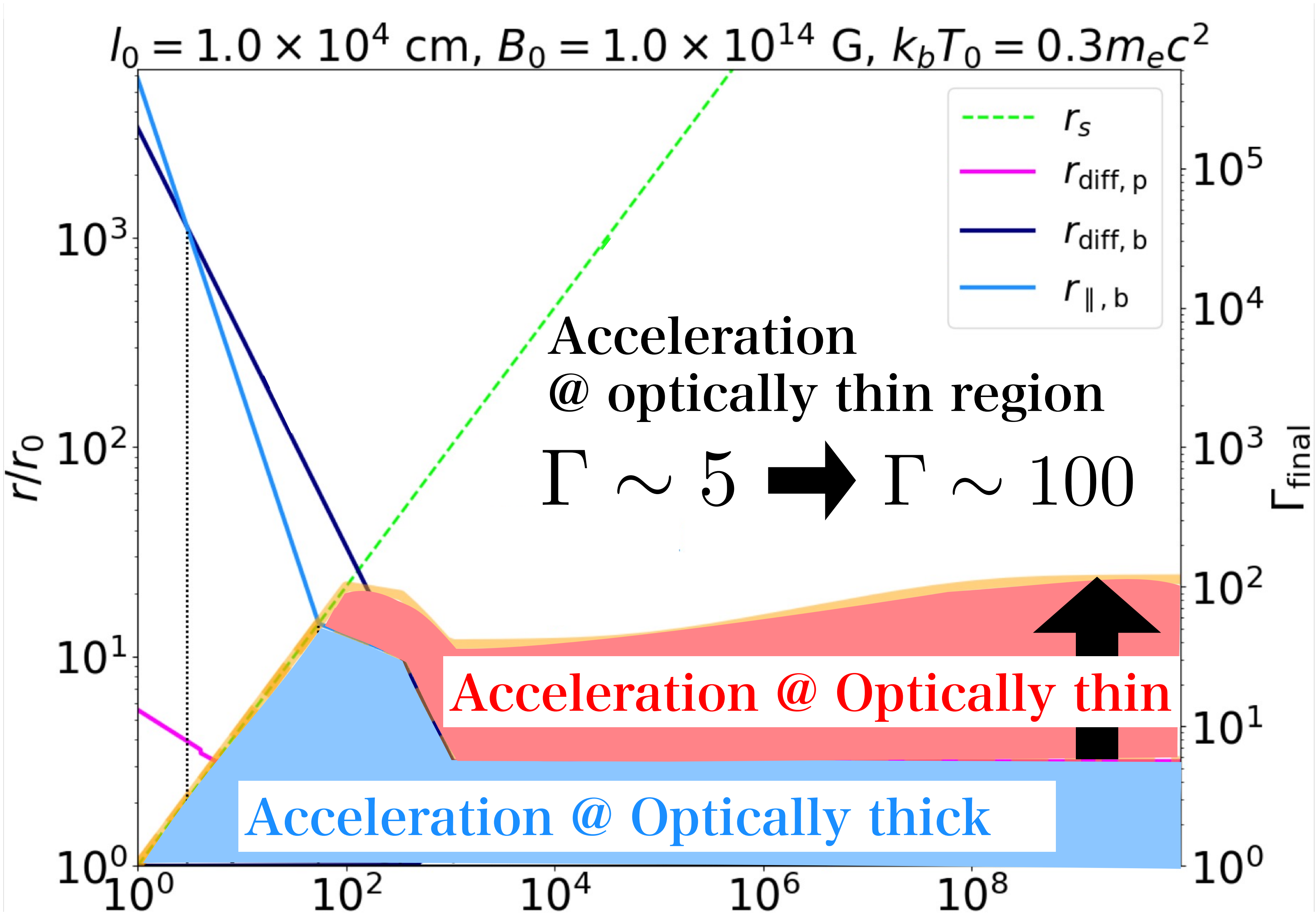
**Baryon**
$\tau_{\parallel} < 1$

Radiation acc

**Pair**
$t_{\mathrm{diff}} < t_{\mathrm{dyn}}$

**Baryon rich** **Baryon poor**

# Radiative acceleration and Lorentz factor



Acceleration
@ optically thin region

$\Gamma \sim 5$ ➡ $\Gamma \sim 100$

Acceleration @ Optically thin

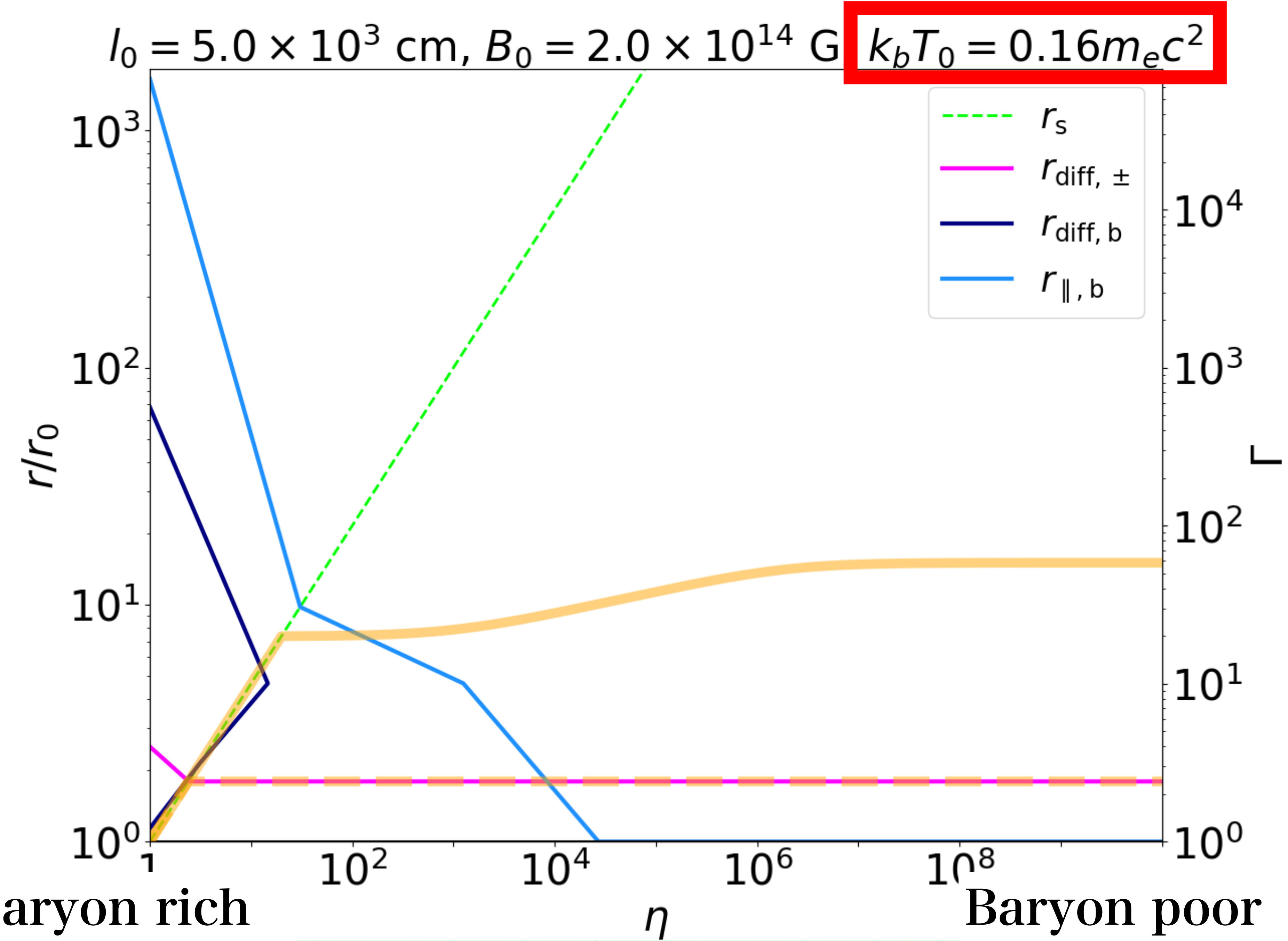
Acceleration @ Optically thick

Baryon rich

Baryon poor

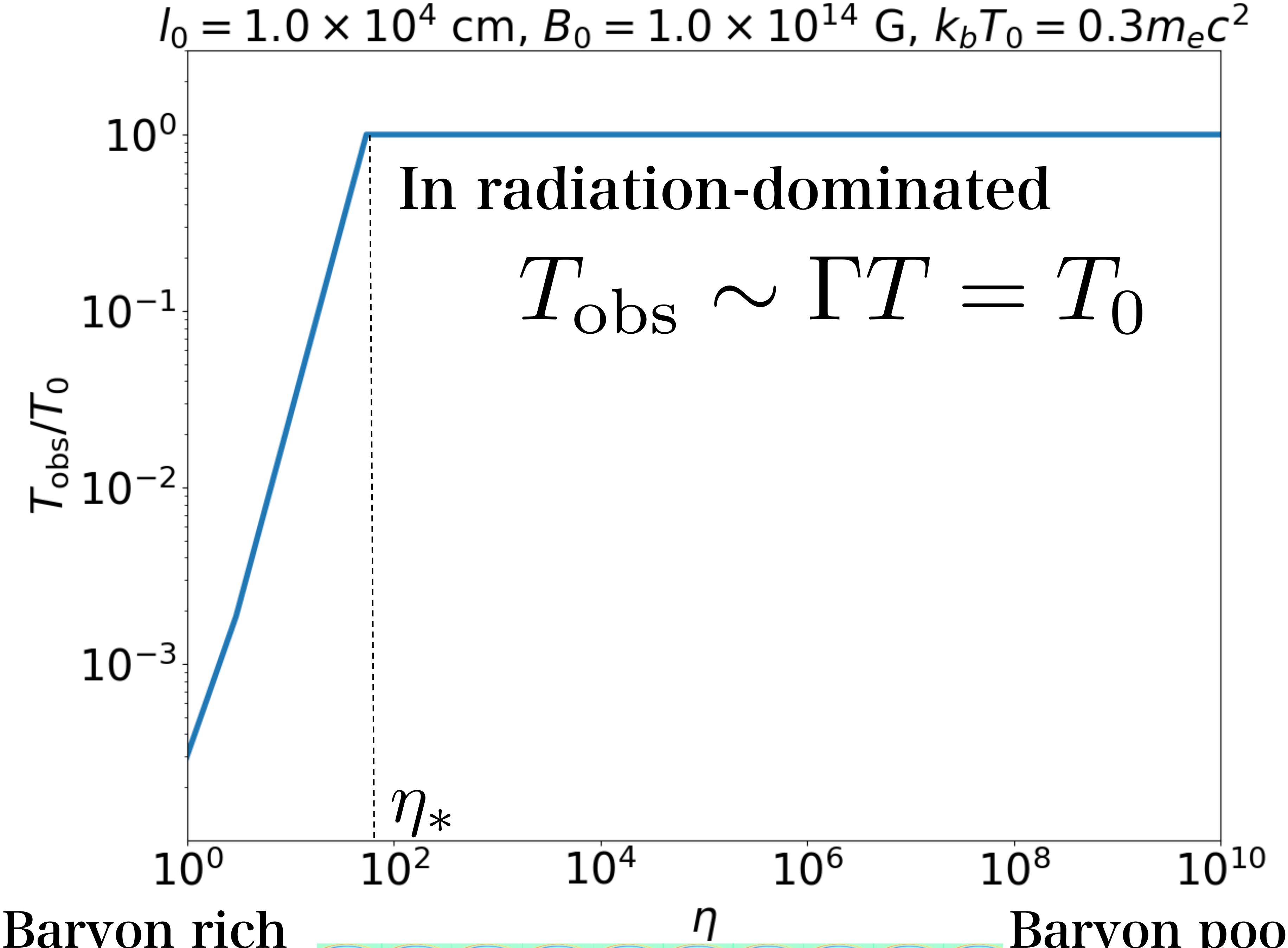
# FRB 20200428 case

$$L_{\rm X} \sim \pi l_0^2 a_{\rm rad} T_0^4 c$$



**Baryon rich** **Baryon poor**

# Observed temperature



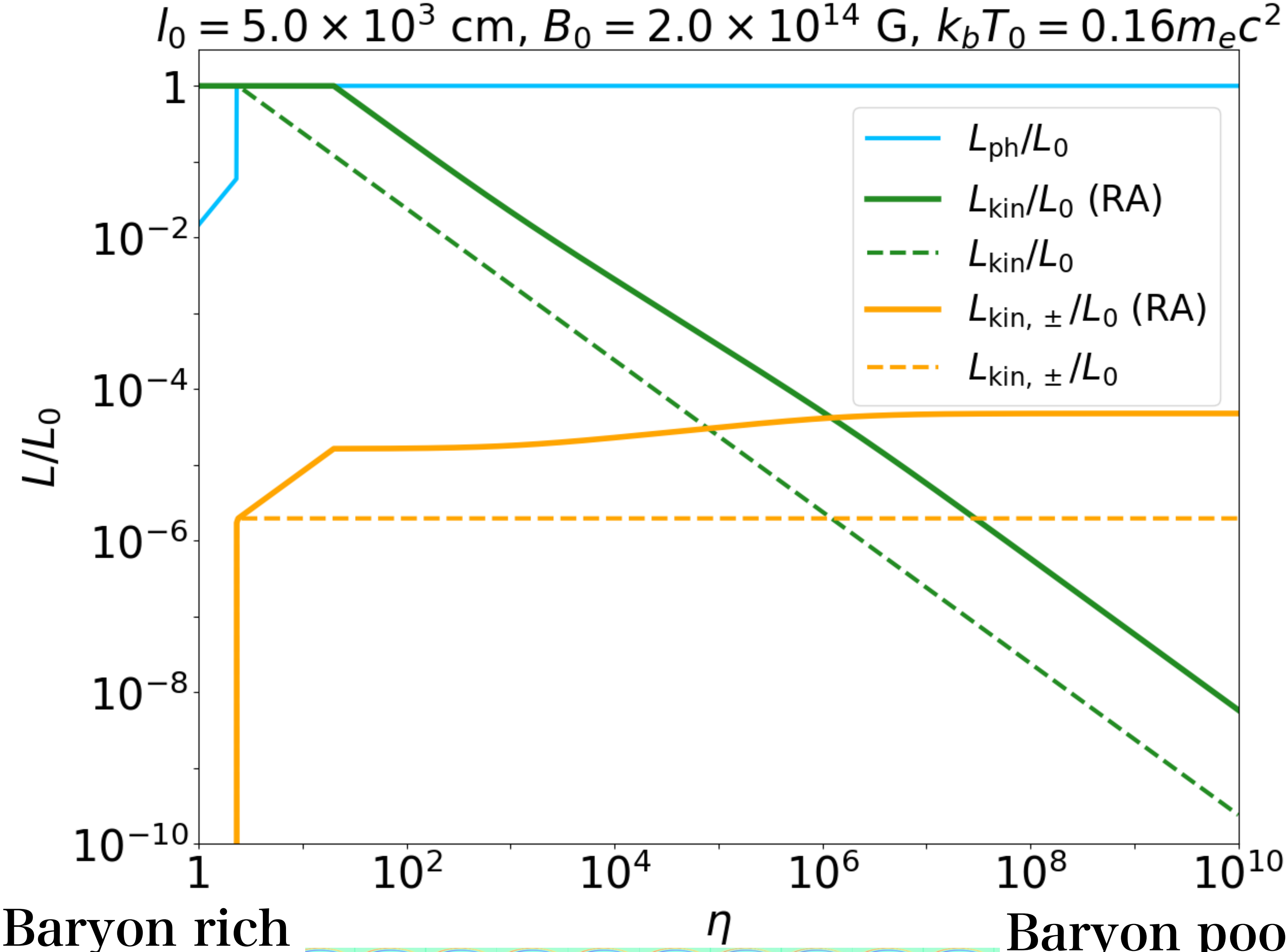
**In radiation-dominated**

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

**Baryon rich**

**Baryon poor**

# FRB 20200428 case

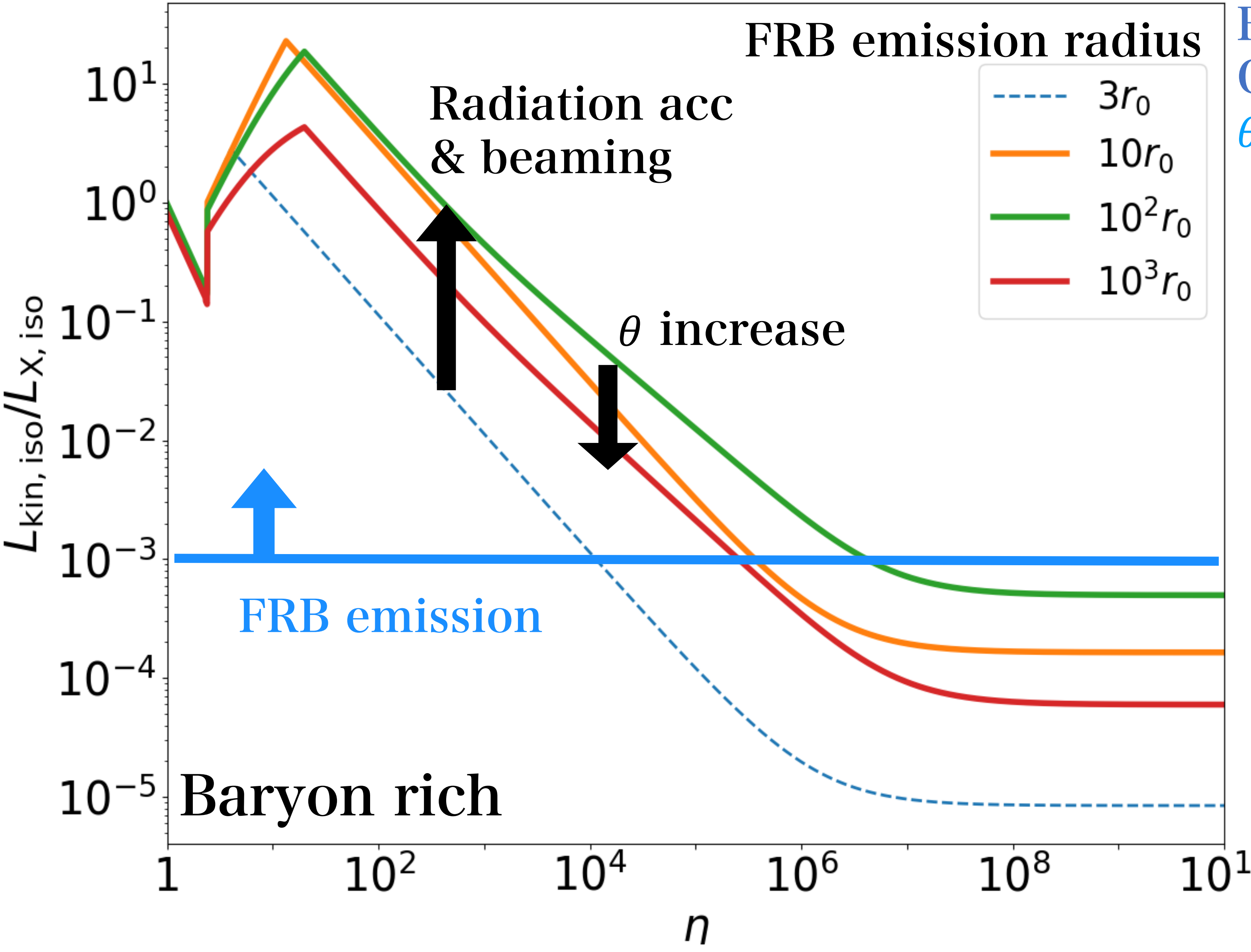


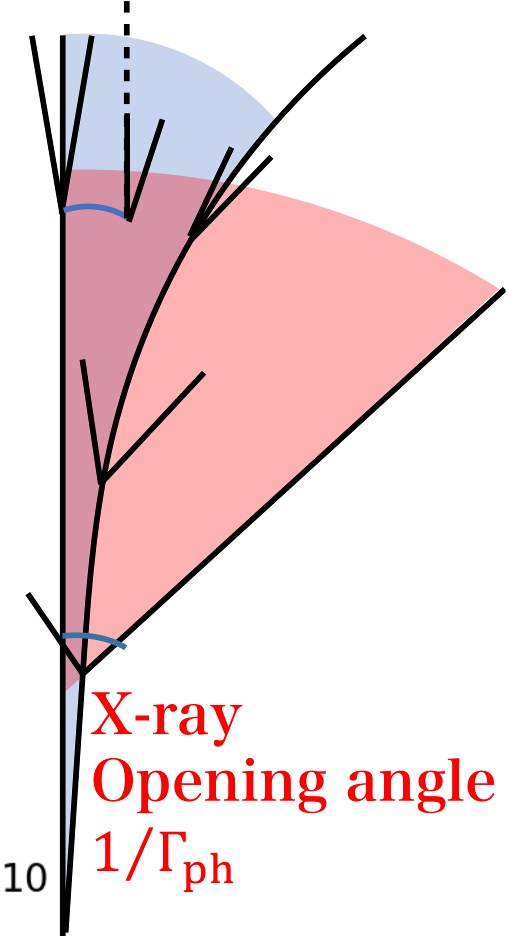
Baryon rich

Baryon poor

# Luminosity ratio

$$L_{\mathrm{kin,iso}} = \frac{4}{(\theta(r) + \Gamma^{-1}(r))^2} L_{\mathrm{phys}}(r)$$





FRB Opening angle $\theta_{\mathrm{dip}}(r) + \Gamma(r)^{-1}$

X-ray Opening angle $1/\Gamma_{\mathrm{ph}}$

**Upper limit on $\eta$ for given emission radius**

# Summary

- We analytically modeled the expanding fireball along open magnetic field lines of a magnetar.
  w/ strong magnetic field, diffusion, radiative acceleration

- high observed temperature X-ray emission & a relativistic outflow can be realized.
  Radiative acceleration is important.

- We apply our model to the X-ray short burst associsated eith FRB 20200428A.
  X-ray -> photospheric emission
  FRB -> kinetic luminosity is enough to energize FRB

$$E_{\rm ph} \sim E_X \qquad E_{\rm kin} > E_{\rm FRB}$$

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