Baryon Loaded Fireball in Magnetar flare & FRB emission

ICRR

Tomoki Wada

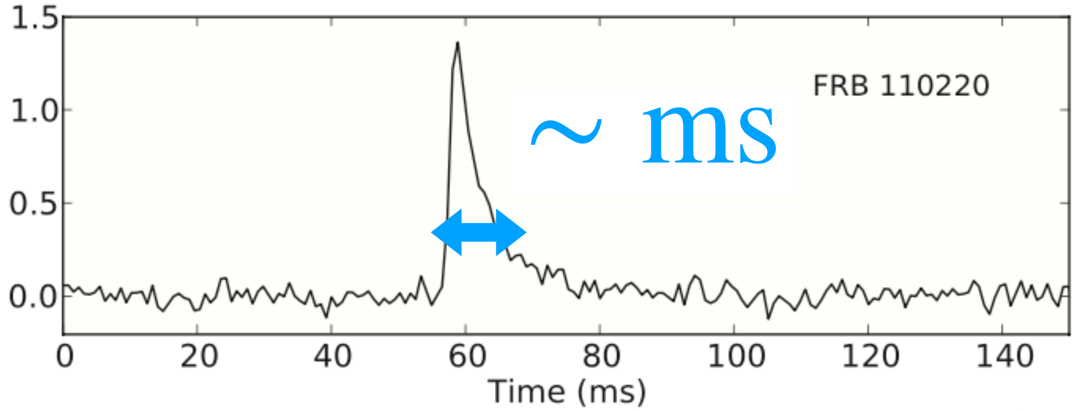
with Ioka-san

ICRR
Institute for Cosmic Ray Research
University of Tokyo

2022 6/6 Fast Radio Bursts and Cosmic Transients

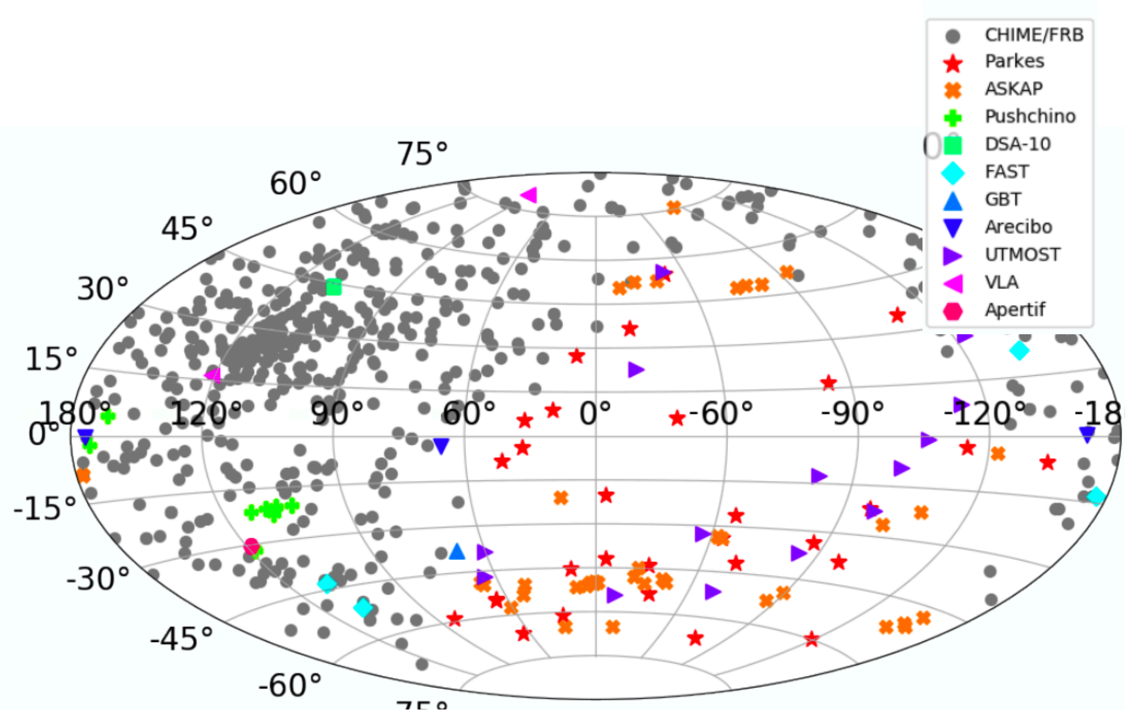
Fast Radio Burst

Brightest radio transient in the universe!

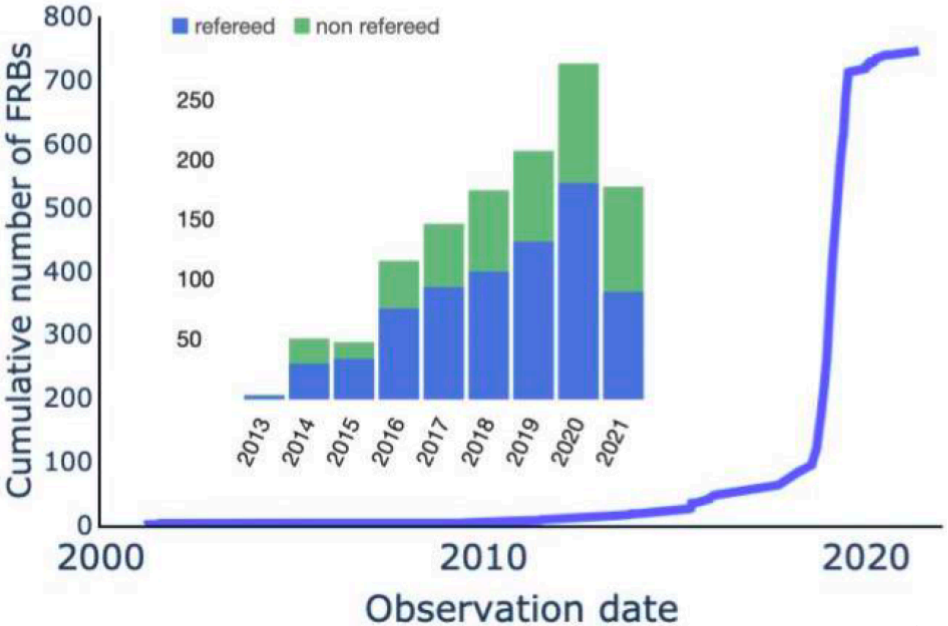


(Thornton et al. 2013)

Luminosity	$L \sim 10^{41}\,\mathrm{erg\,s^{-1}}$
Duration	$\Delta t \sim O(\,\mathrm{ms})$
Frequency	$150\,\mathrm{MHz} < \nu < 8\mathrm{GHz}$
Event rate	$10^4\,\mathrm{sky^{-1}day^{-1}}$ $(3.5\times10^4\,\mathrm{Gpc^{-3}yr^{-1}})$



(Petroff et al. 2021)



(Petroff+2021)

Two big problems

The origin and the emission mechanism are not understood.

Source

- magnetosphere of NS
- NS + other effect
- Binary white dwarf
- Binary neutron star
- collapse of NS

etc.. ..

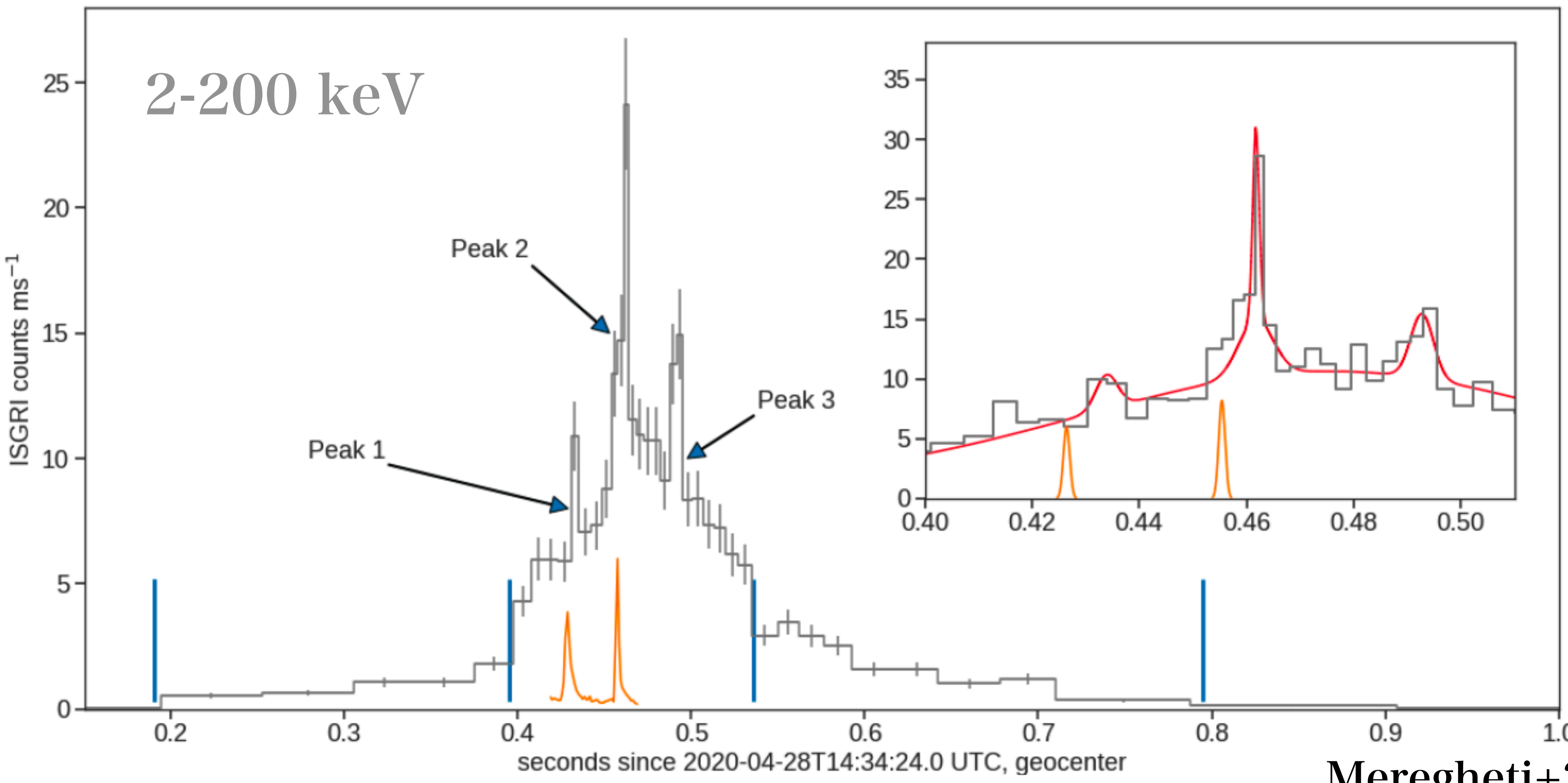
Emission mechanism

- coherent bunch emission
- Synchrotron maser instability
- Decay of plasma waves

- Event rate & z dependence
- Properties of host galaxies
- Counterpart

- Spectrum
- down-drifting
- time variation

FRB 200428 & Magnetar flare



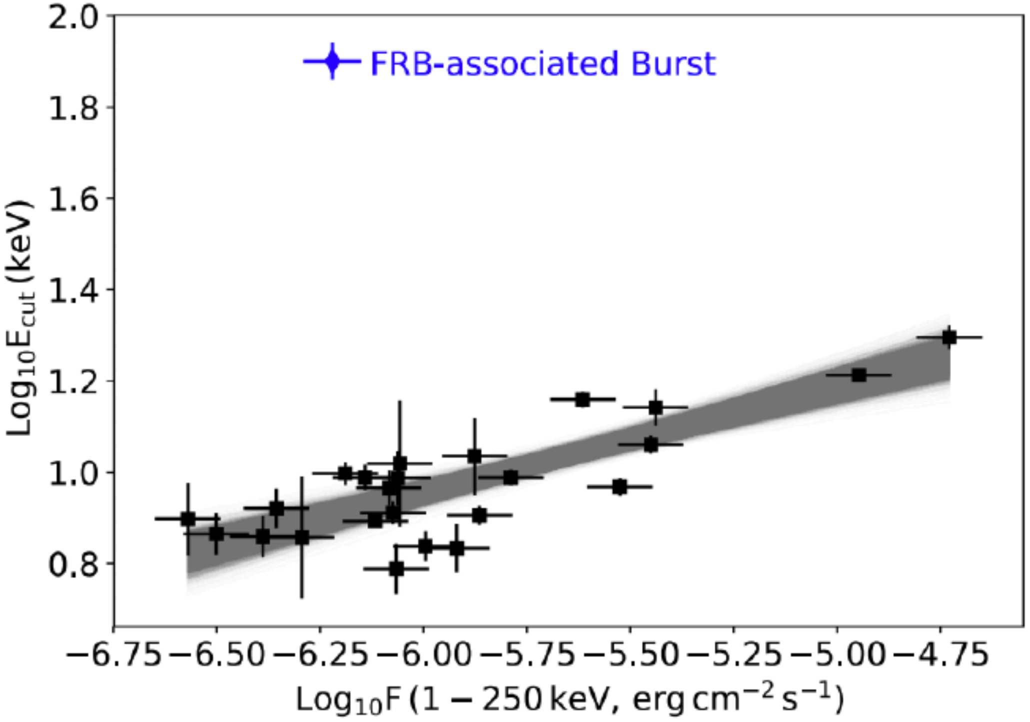
radio pulse

Meregheti+2020

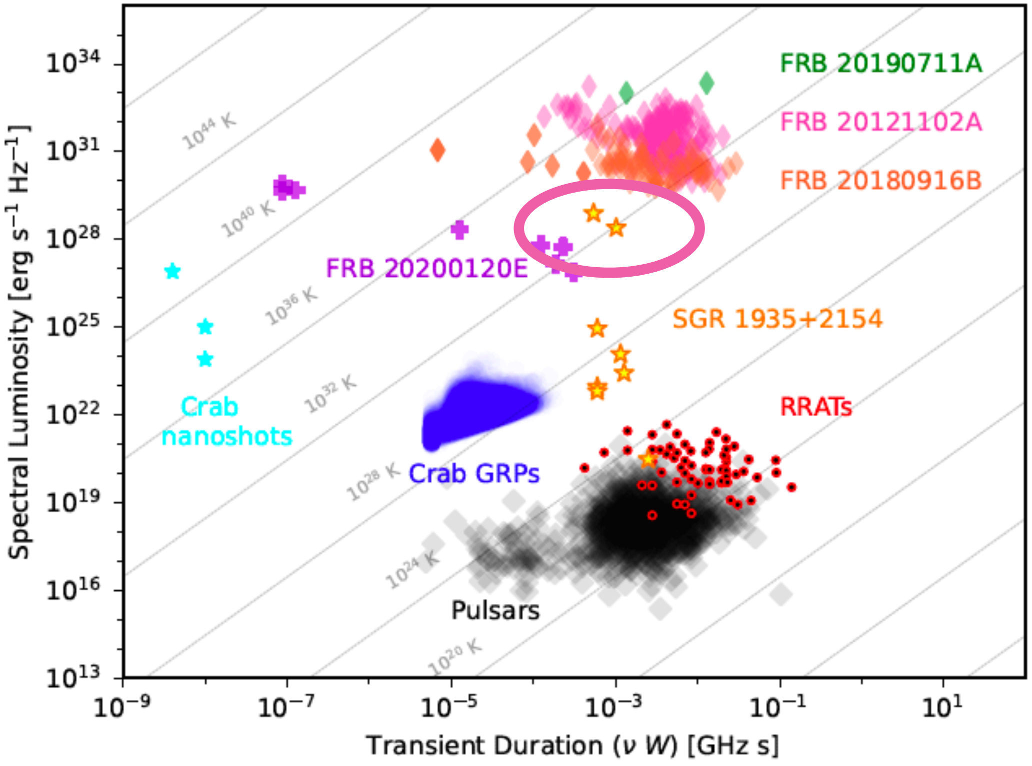
Dim FRB from galactic magnetar SGR 1935+2154
& X-ray burst

-> connection between magnetar flare & FRB.

Luminosity of FRB & X-ray



Younes+2020



Petroff+2021

X-ray burst : $L \sim 10^{41}\,\mathrm{erg\,s^{-1}}$

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

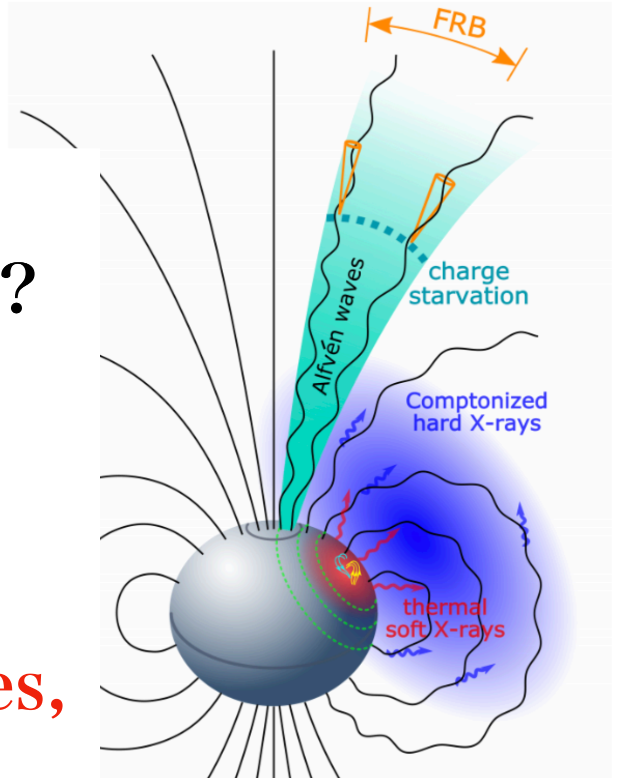
1. Some fraction of X-ray energy is converted to Radio?
2. High-temperature ($\sim 100\,\mathrm{keV}$) X-ray flare with FRB

Fireball models

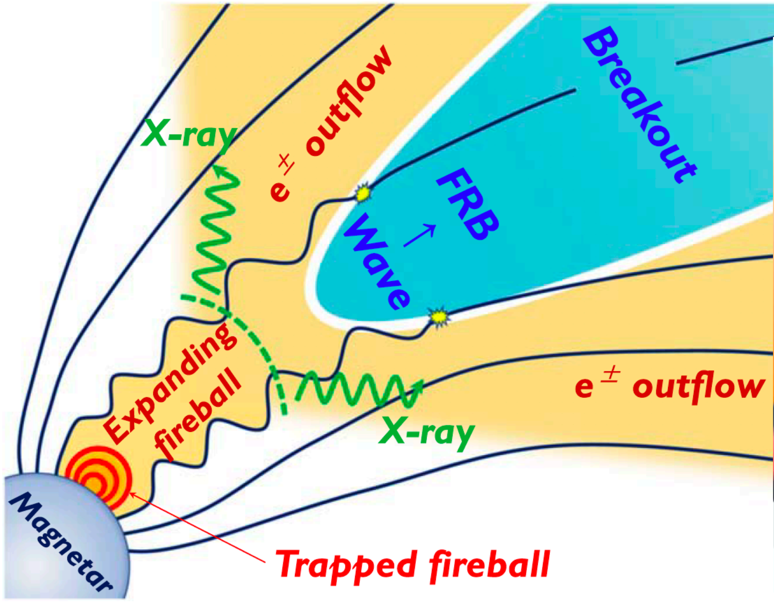
How…

1. some of X-ray energy is converted to FRB?
2. High-temperature is realized?

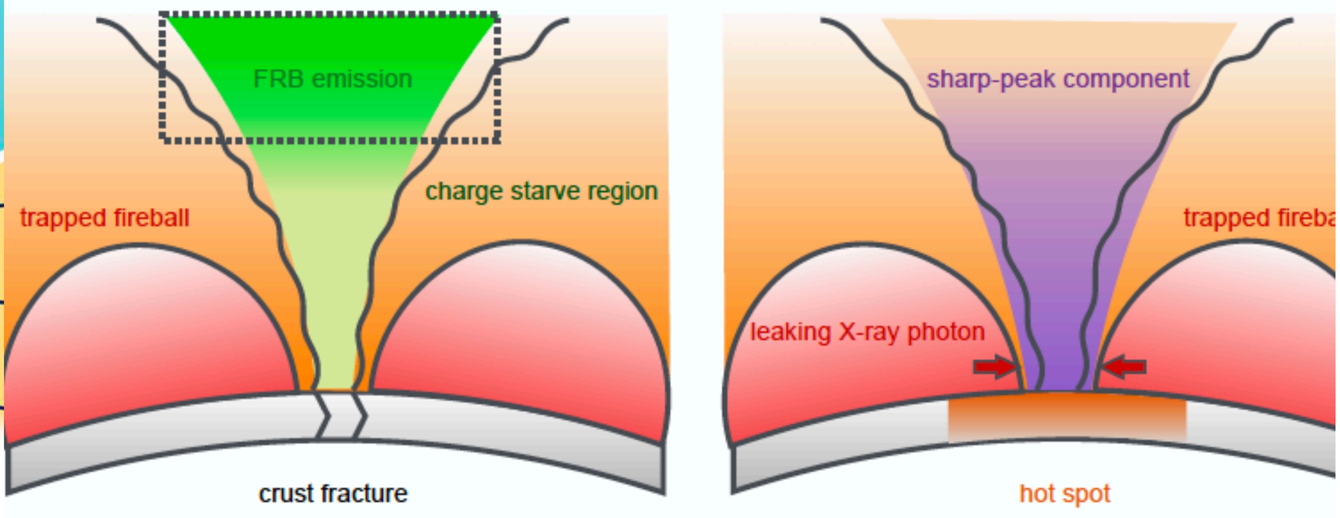
As a starting point, we clarify the dynamics of the fireball along open magnetic field lines, including magnetic field/ dipolar structure



(Lu et al. 2020



(Ioka 2020)



(Yang Zhang 2020)

Trapped fireball (X-ray flare)

$L > L_{\rm Edd}$, long duration, $\sim 10\,{\rm keV}$ is realized by a trapped firebal

key factors

- E-mode diffusion from a trapped fireball
- Magnetic Eddington flux

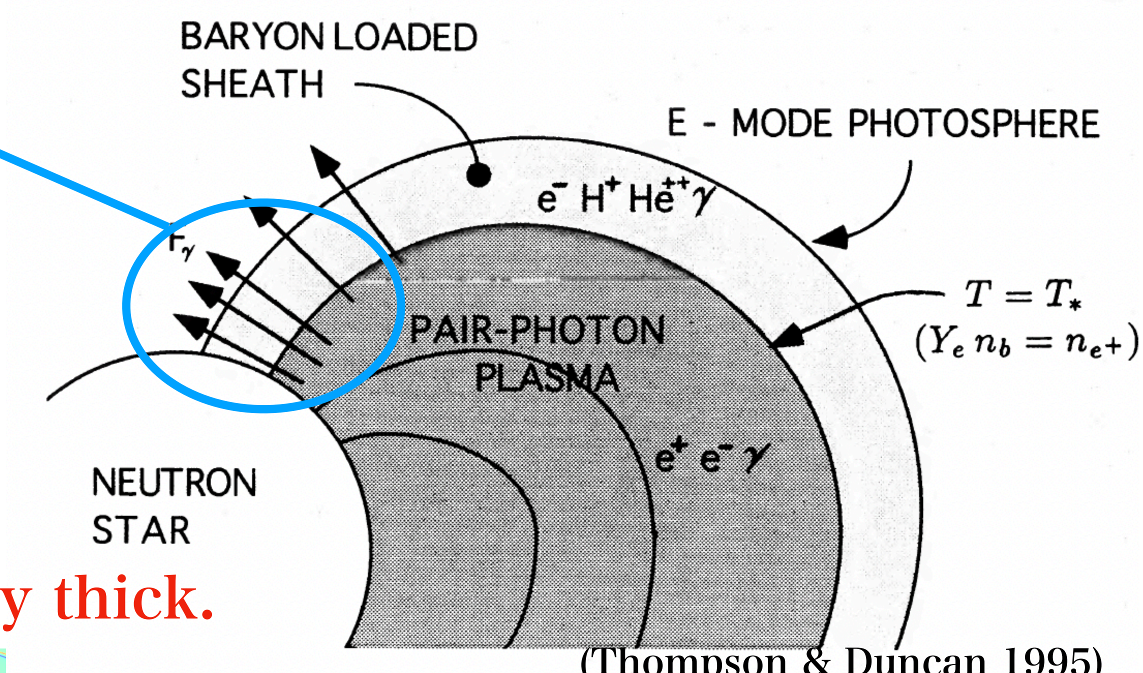
Strong radiation put baryons in surface.

$$F^B_{\rm Edd} = \frac{m_p g(R) c}{\left(Y_- + Y_+\right) \sigma(B,T)} \qquad \sigma_{\rm E} = \frac{4\pi^2}{5} T^2 B^{-2} \sigma_{\rm T} \ \left(< \sigma_{\rm T} \right)$$

$$\begin{aligned} L^B_{\rm Edd}(R) &= 4\pi R^2 F^B_{\rm Edd} \\ &\simeq 6 \times 10^{40}\,{\rm ergs}^{-1} \gg L_{\rm Edd} \end{aligned}$$

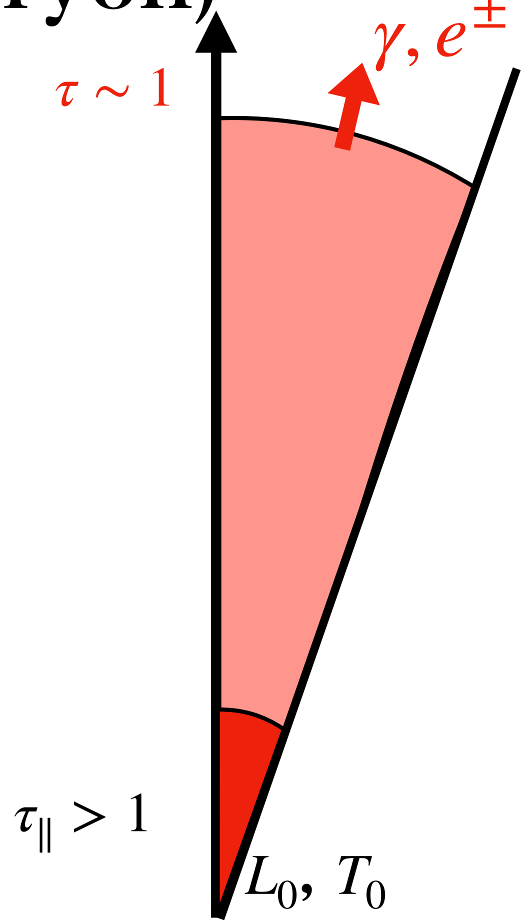
$$T_{\rm eff} = \left(\frac{2F^B_{\rm Edd}}{\sigma_{\rm SB}} \right) \simeq 7\,{\rm keV}$$

For $\sim 100\,{\rm keV}$, fireball is optically thick.



(Thompson & Duncan 1995)

Spherically expanding fireball (no baryon)



1. Temperature $T \propto r^{-1}$ decrease (comoving)

   -> Pair number density also

   decrease $n_{\pm} \propto T^{3/2} \exp\left(-m_e/T\right)$

2. $\tau_{\parallel} = 1$ is realized @$r_{\rm ph}$

3. Photons decouple from the fireball.

In radiation-dominated case

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

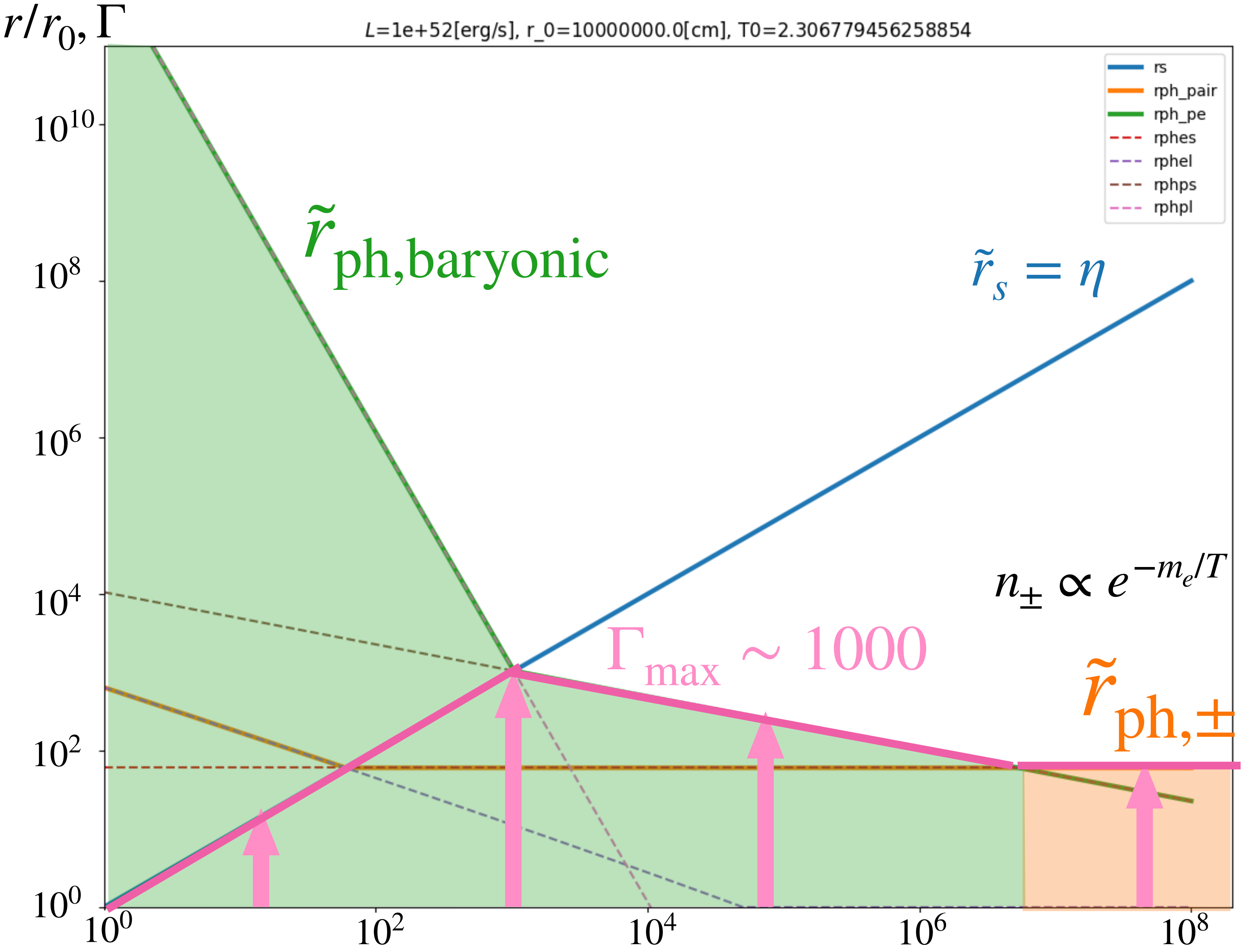
$$L_{\rm ph} \sim L_0$$

Observed temperature

~ Initial temperature

value	radiation dominant
T	$\tilde{r}^{-1}$
Γ	$\tilde{r}$
ρ	$\tilde{r}^{-3}$
$\tilde{r}_s$	η

Baryon loading (GRB case)



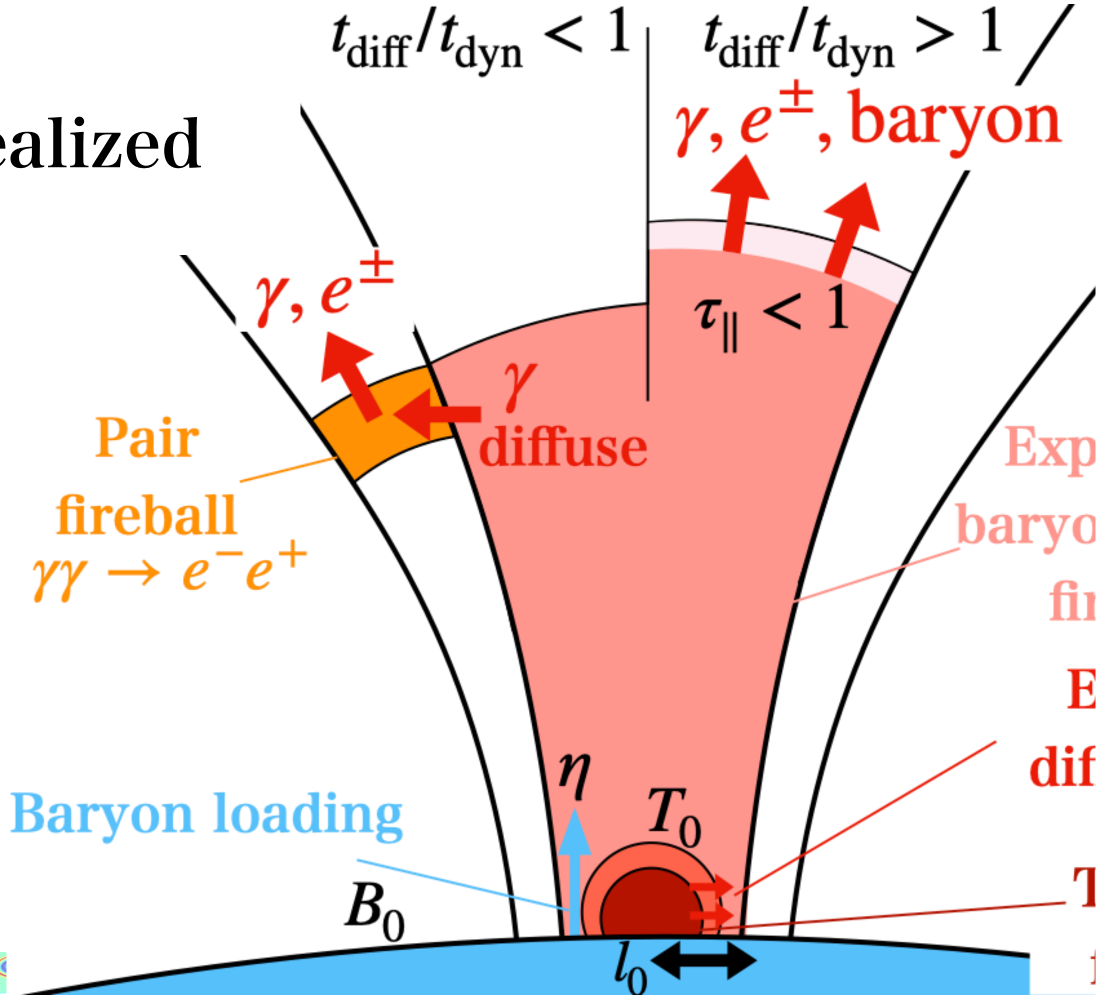
$$\eta = \frac{e_0}{\rho_0 c^2}$$

Fireball is more accelerated due to the baryonic component.

Fireball model along dipolar field

A fireball expanding along open magnetic field lines

1. high kinetic luminosity if baryons are loaded.
   -> Energy budget for FRB
2. Expanding fireball
   -> High-temperature is realized



Fireball model along dipolar field

two key points···

1. Strong magnetic field
   - number density of electron

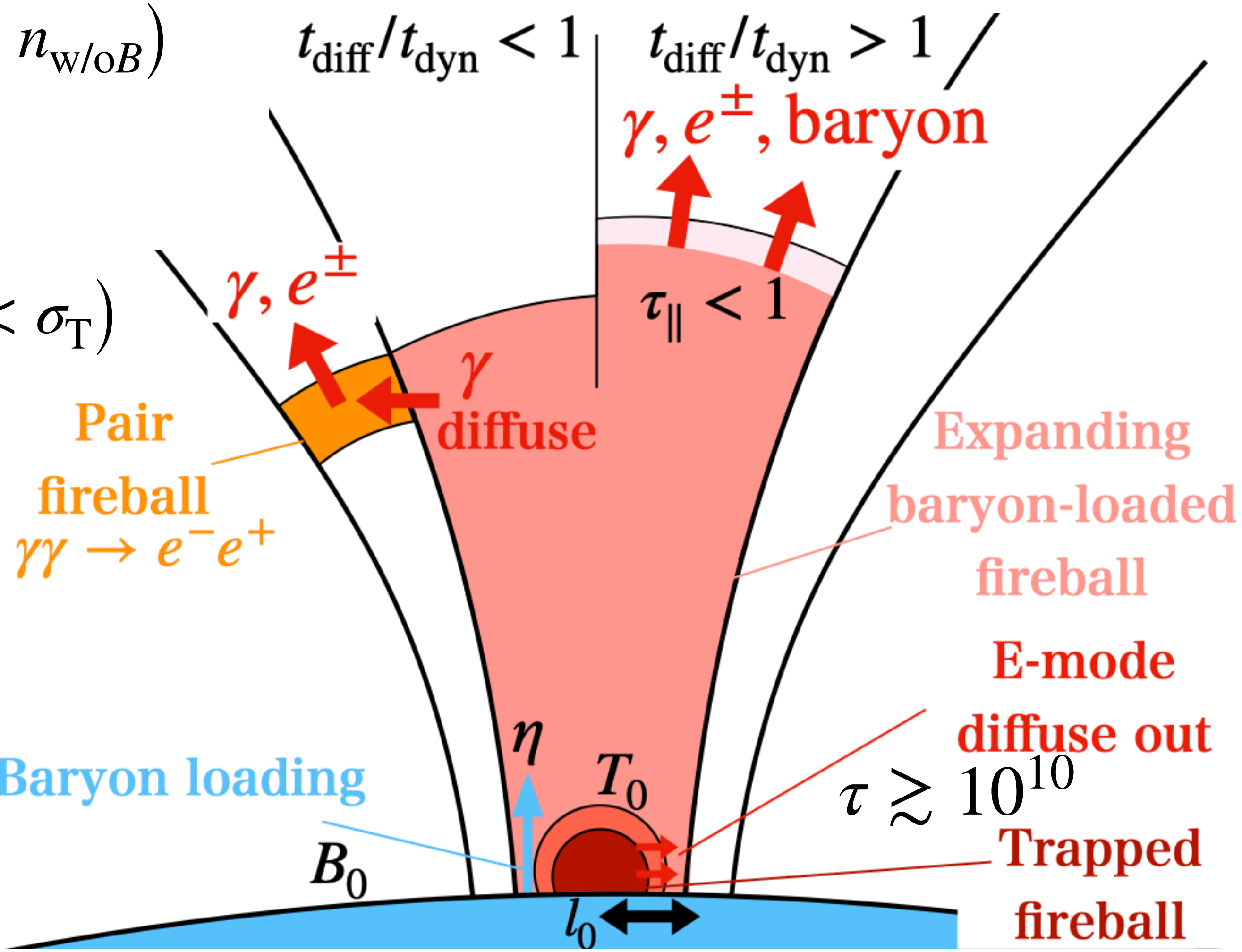
$$n_{\mathrm{w}/B} = n_{\mathrm{w/o}B} T^{-1} B \ \left(> n_{\mathrm{w/o}B} \right)$$

   - cross section

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

2. baryon

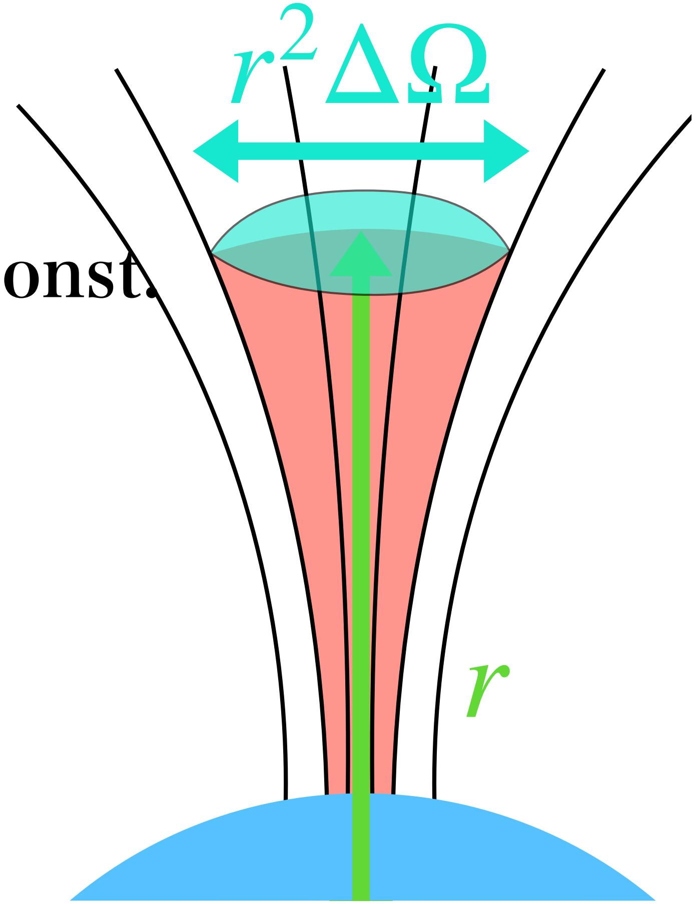
$$\eta = \frac{e_{\mathrm{rad}}}{\rho c^2}$$

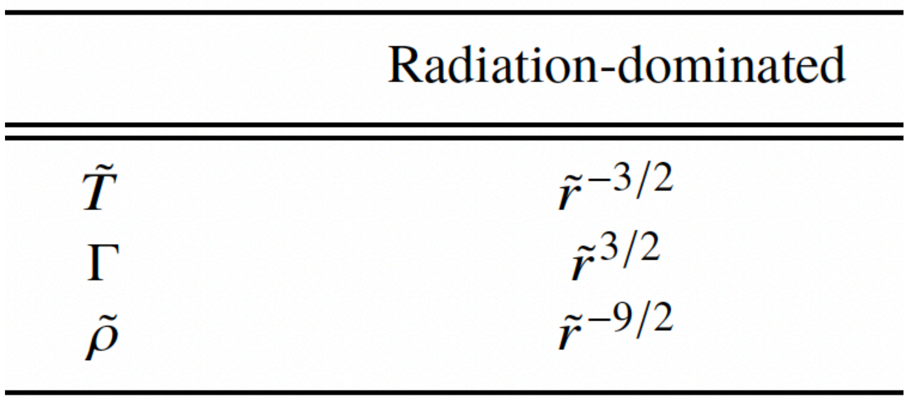


Expansion along magnetic field

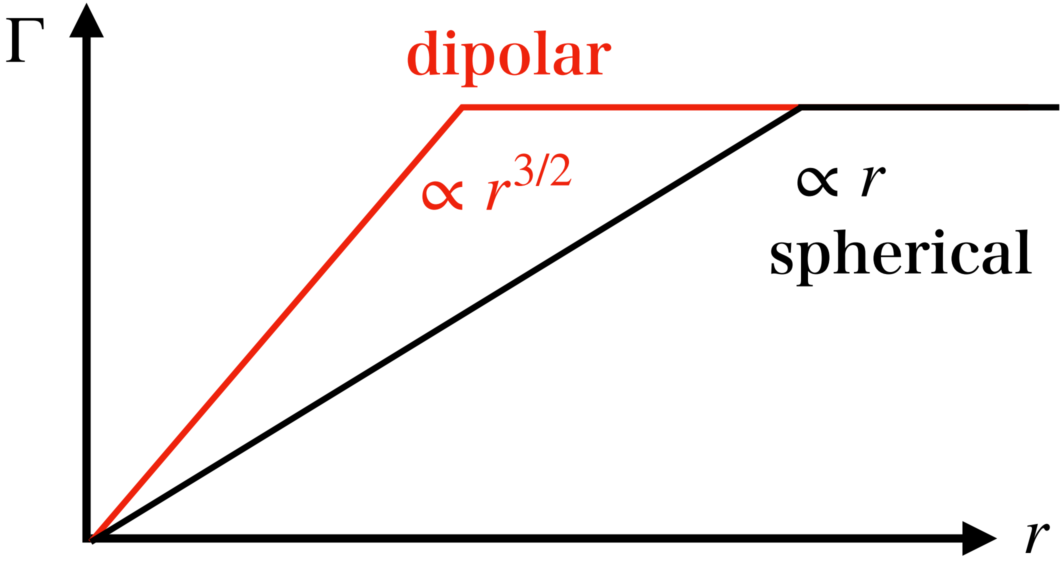
Conservation low

- Baryon number density $r^2\Delta\Omega\,\rho\Gamma\beta =$ const.
- entropy $r^2\Delta\Omega\, e^{3/4}\Gamma\beta =$ const.
- energy $r^2\Delta\Omega \left(\rho + \frac{4}{3}e\right)\Gamma^2\beta^2 =$ const.
- spherical symmetric -> $\Delta\Omega \propto r^0$
- dipolar field -> $\Delta\Omega \propto r$





	Radiation-dominated
$\tilde{T}$	$\tilde{r}^{-3/2}$
Γ	$\tilde{r}^{3/2}$
$\tilde{\rho}$	$\tilde{r}^{-9/2}$



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

Photon escape

1. Optical thinning (longitudinal)

fireball becomes optically thin

$$@\ \tau_{\parallel} = \left(n_+ + n_-\right)\sigma(T,B)\frac{r}{\Gamma} = 1$$

2. Diffusion (lateral)

fireball becomes diffusively thin

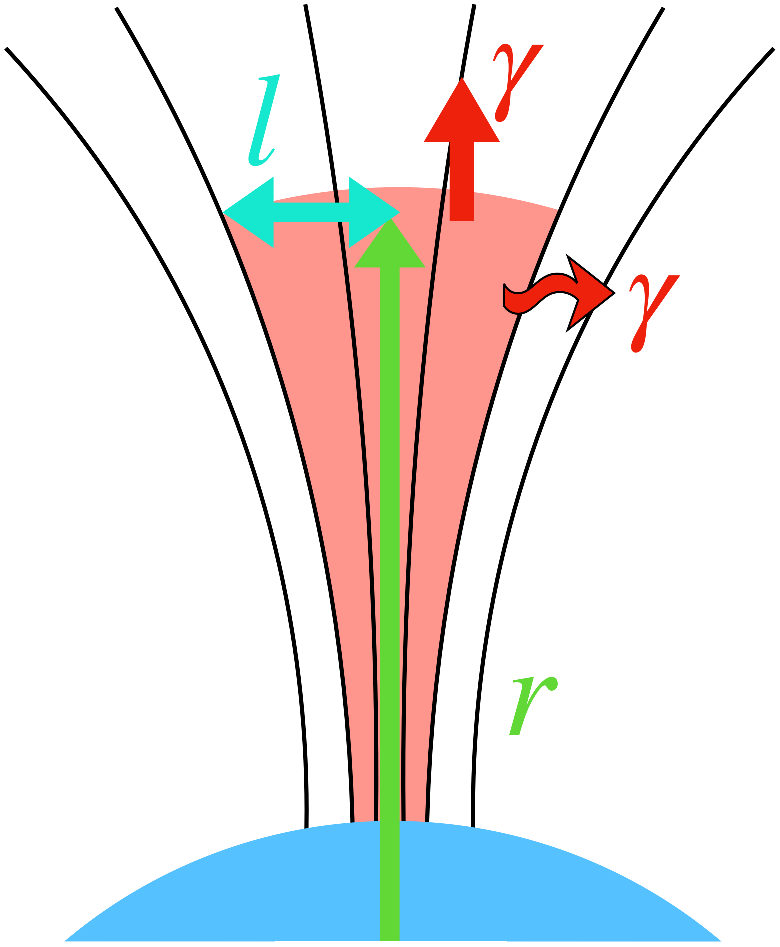
$$@\frac{t_{\rm diff}}{t_{\rm dyn}} = \frac{\left(n_+ + n_-\right)\sigma(T,B)l^2/c}{r/c\Gamma} = 1$$

Thermal pair

$e^+ + e^-$

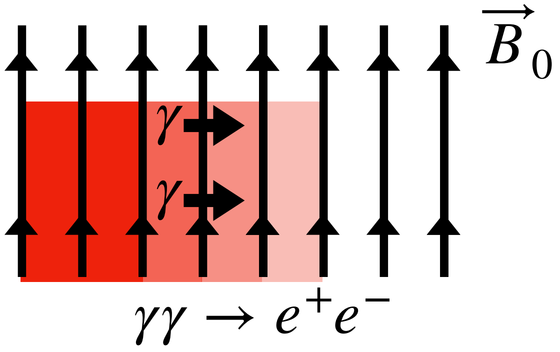
baryonic electron

e^-

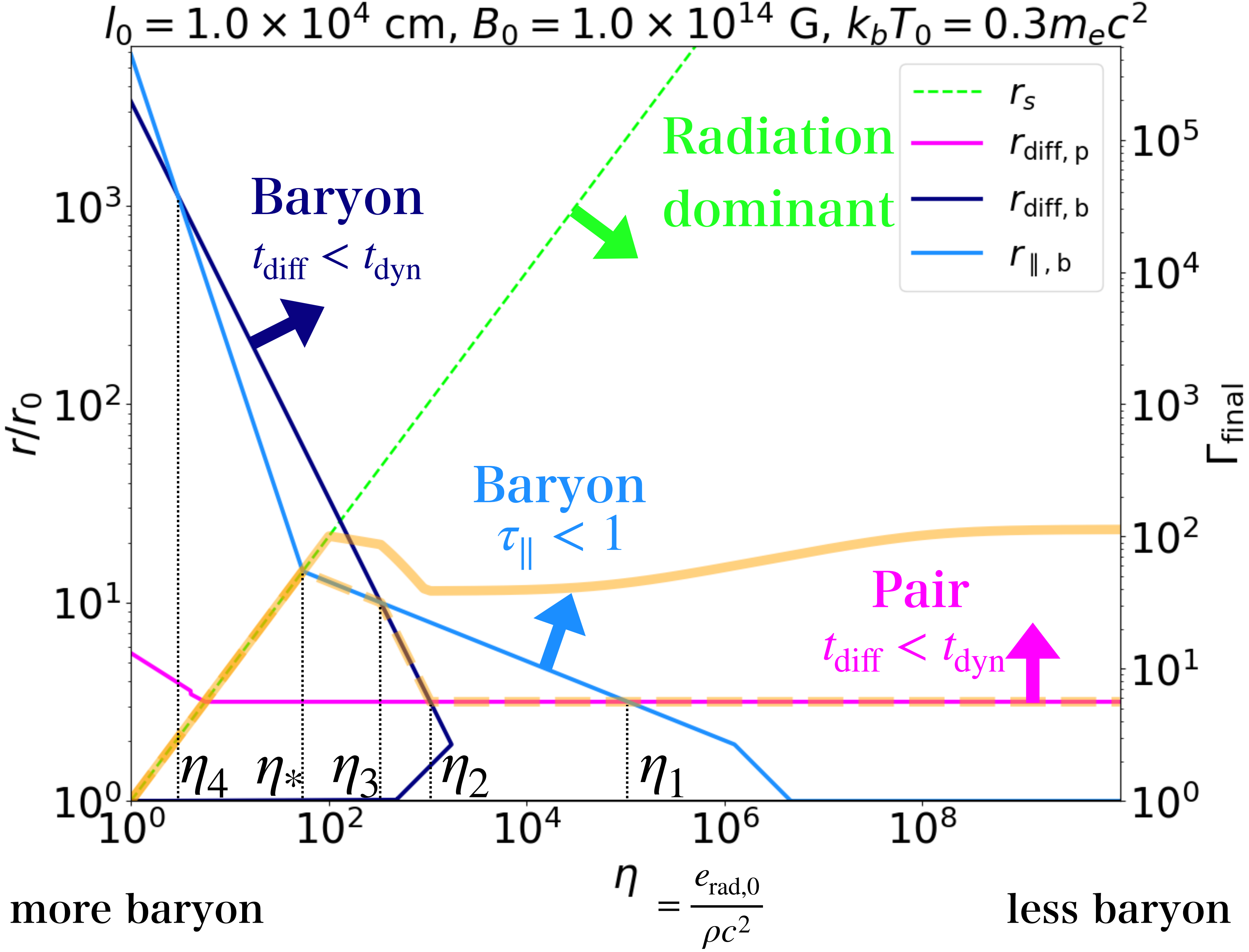


Pair plasma or baryonic electron component determine the opacity of the fireball

pair: $n_- \propto \exp(-m_e/T)$, baryonic: $n_- \propto T^3$



Baryon loading



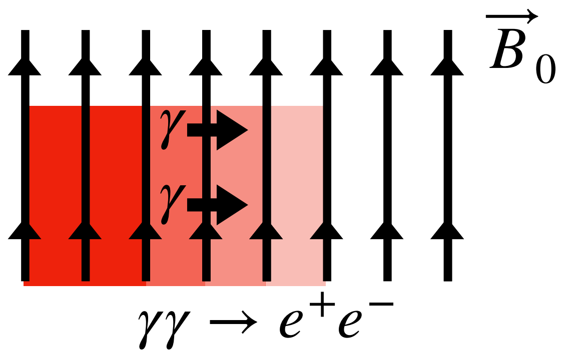
Pair-lateral case $\eta_1 < \eta$

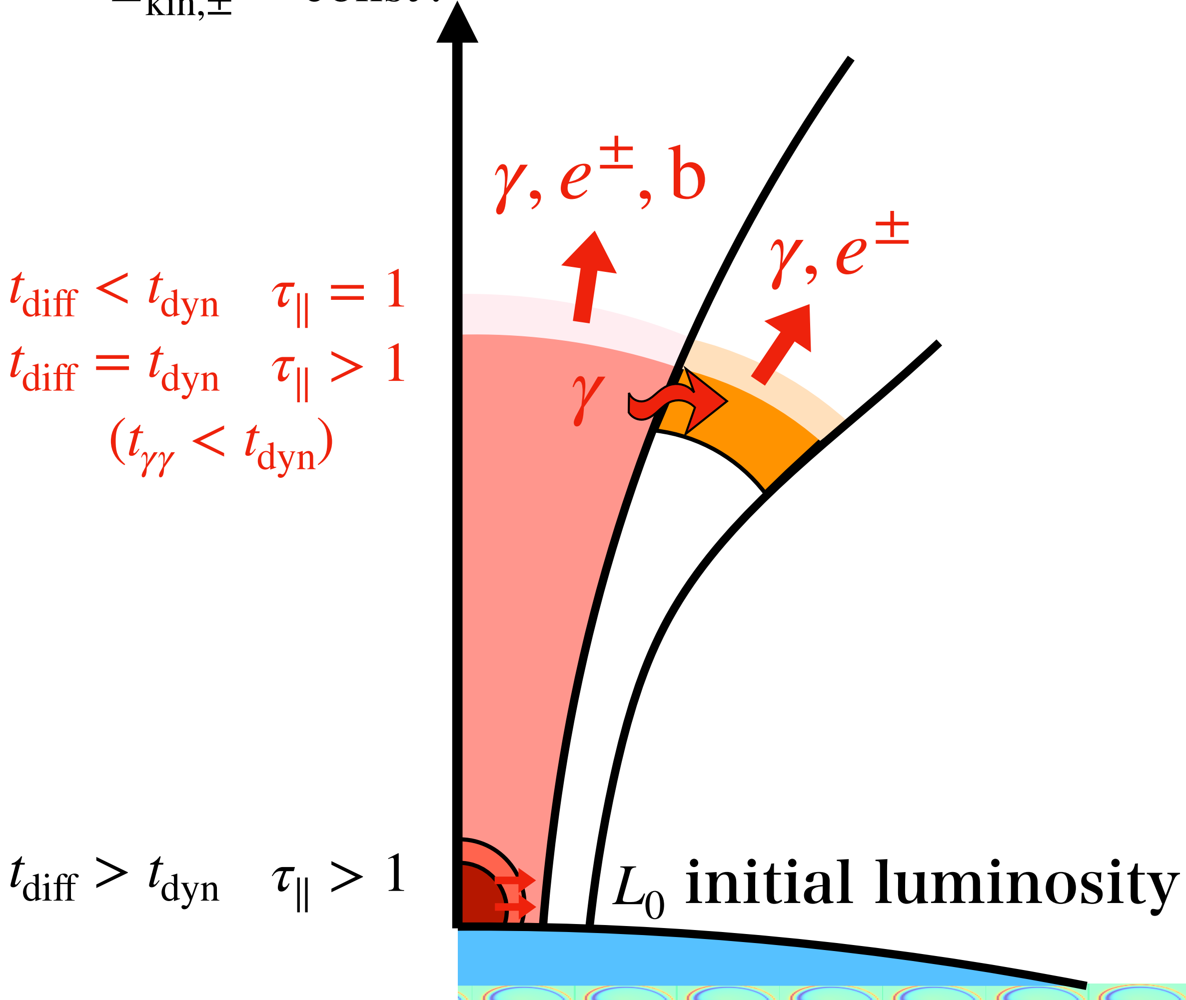
Photons begin diffuse out from the initial flux tube.

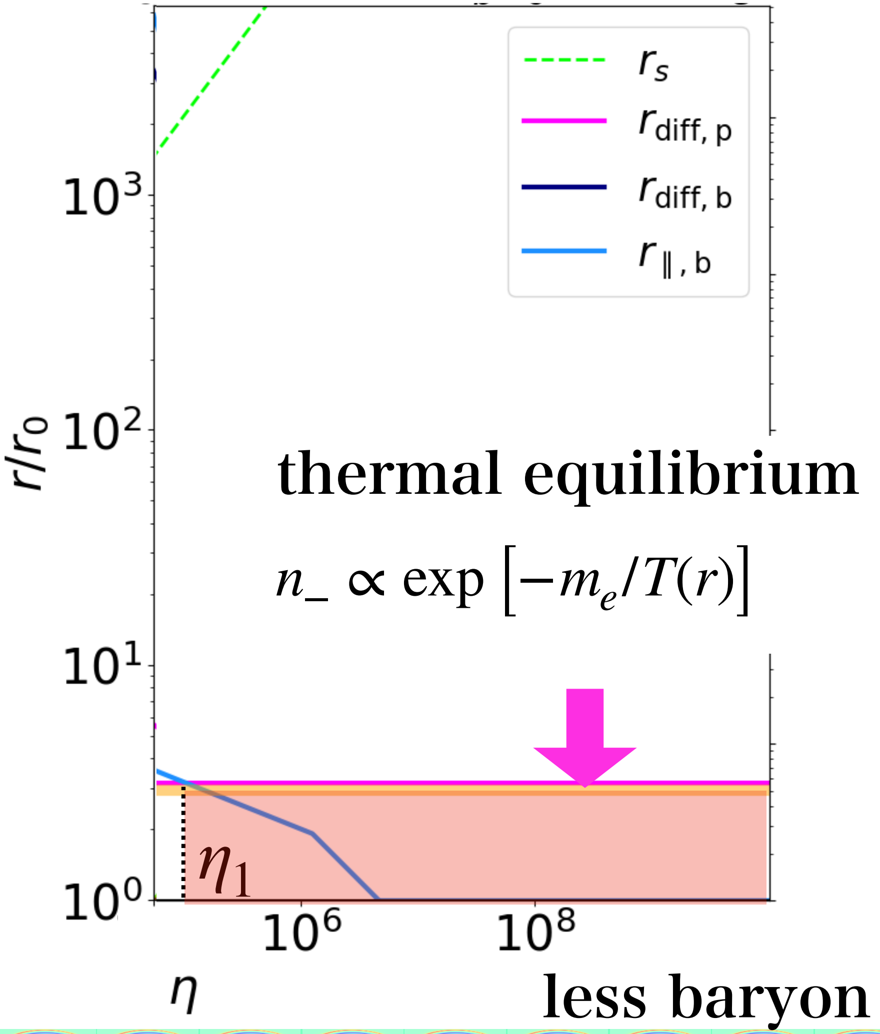
$$L_{\rm ph} \simeq L_0$$

$$L_{\rm kin} \propto \rho \propto \eta^{-1}$$

$$L_{{\rm kin},\pm} = {\rm const}\,.$$







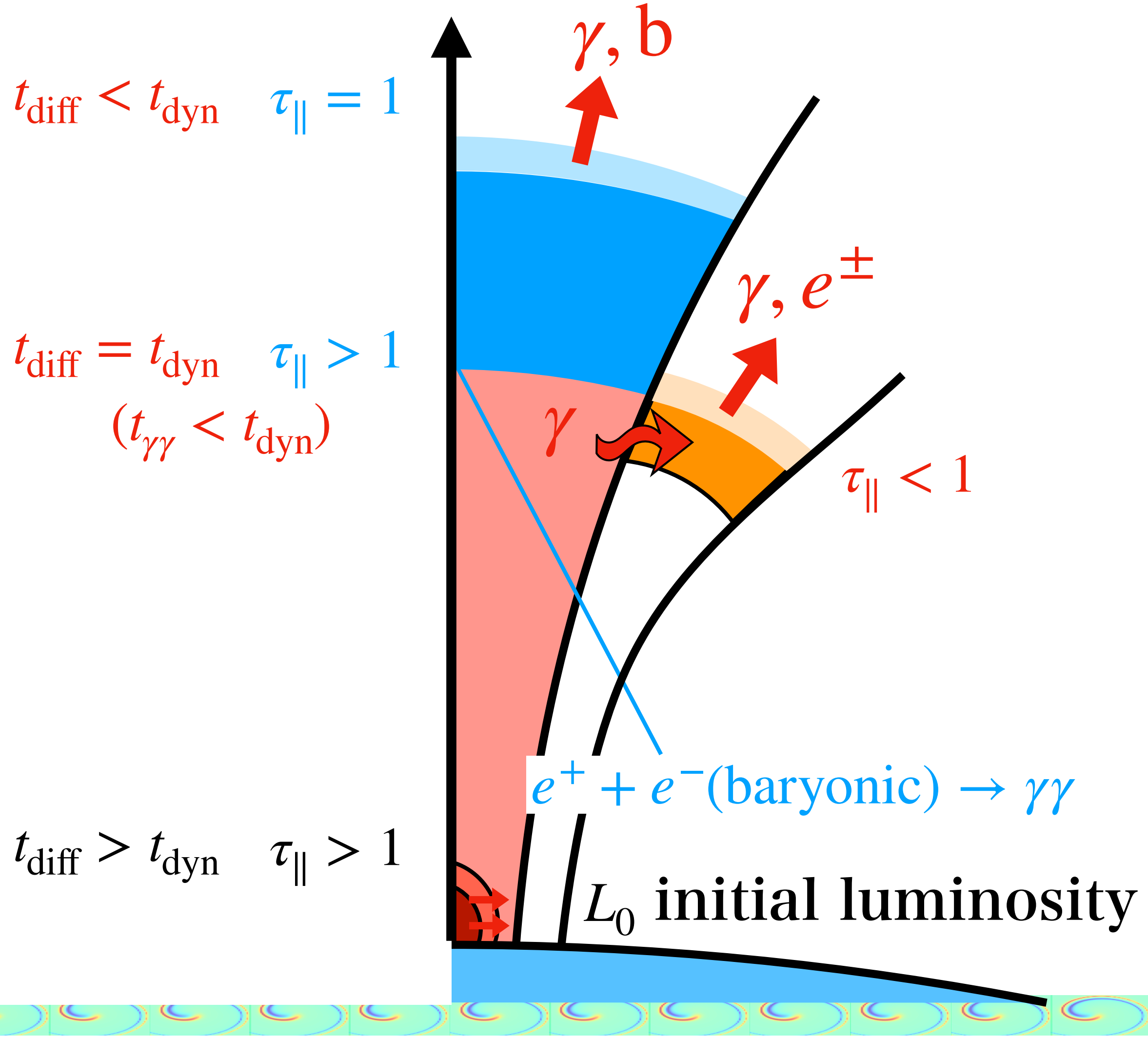
Pair-lateral-baryon-thick case $\eta_2 < \eta \leq \eta_1$

Photons begin diffuse out, but optically thick in the initial flux tube.

$$L_{\rm ph} \simeq L_0$$

$$L_{\rm kin} \propto \eta^{-1}$$

$$L_{\rm kin,\pm} = {\rm const}\,.$$



γ, b

$t_{\rm diff} < t_{\rm dyn}$ $\tau_\parallel = 1$

$\gamma, e^{\pm}$

$t_{\rm diff} = t_{\rm dyn}$ $\tau_\parallel > 1$

$(t_{\gamma\gamma} < t_{\rm dyn})$

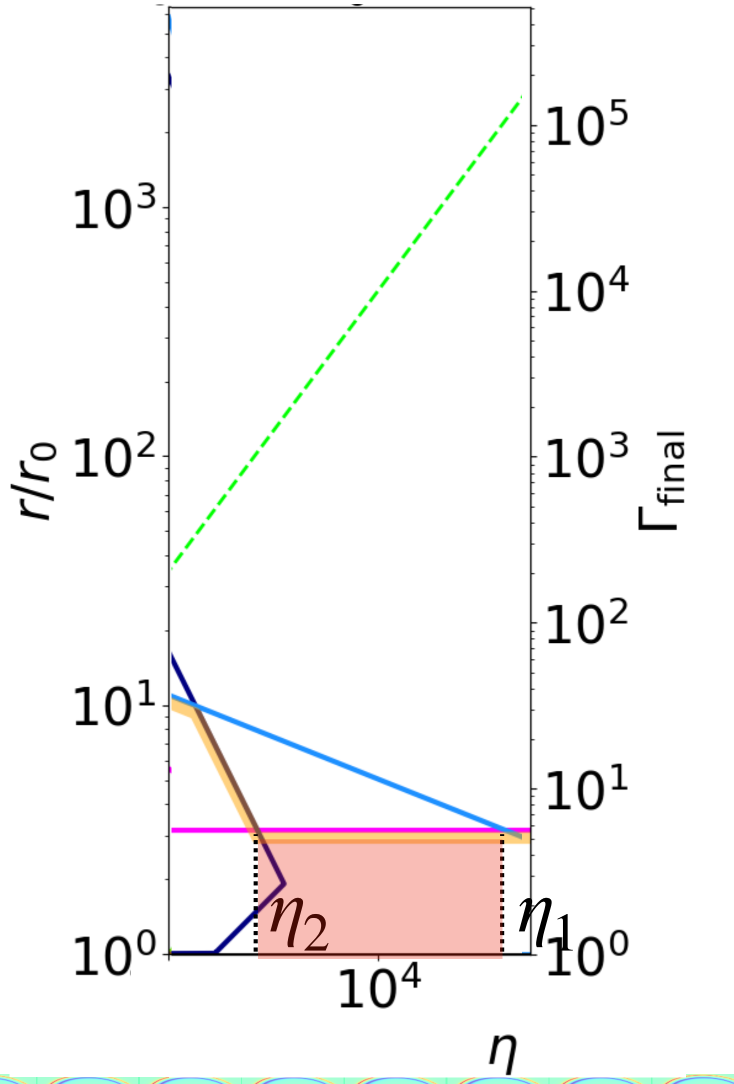
γ

$\tau_\parallel < 1$

$e^+ + e^-(\text{baryonic}) \rightarrow \gamma\gamma$

$t_{\rm diff} > t_{\rm dyn}$ $\tau_\parallel > 1$

L_0 **initial luminosity**



Baryon-lateral case

$\eta_3 < \eta \le \eta_2$

$$L_{\rm ph} = \left(2\pi l c t_{\rm dyn}\right) e_{\rm rad} \frac{c}{\tau_\perp} \Gamma^2$$

$$\sim 2\pi l^2 e_{\rm rad} c \Gamma^2$$

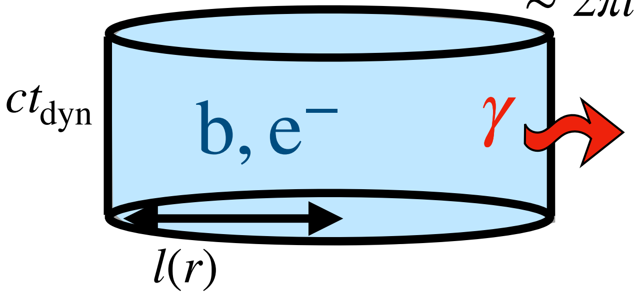
Photons diffuse out,

but pair creation does not occur.

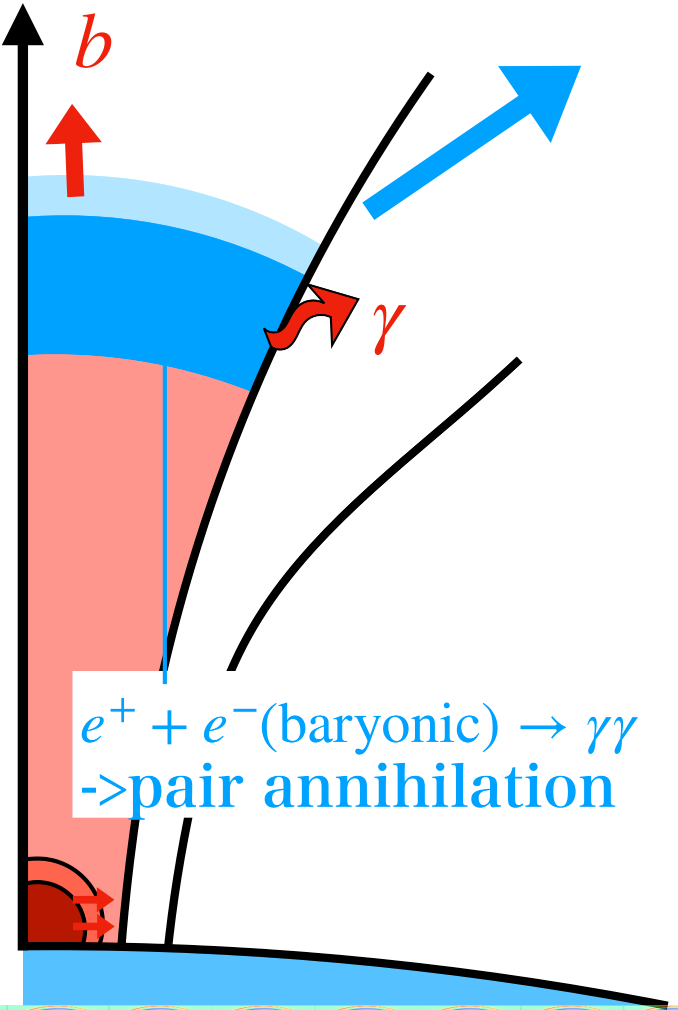
$L_{\rm ph} \simeq L_0$

$L_{\rm kin} \propto \eta^{-5/2}$

$L_{\rm kin,\pm} \sim$ (exp decay)



$$\left(\tau_\perp \frac{l}{c} \sim t_{\rm dyn}\right)$$

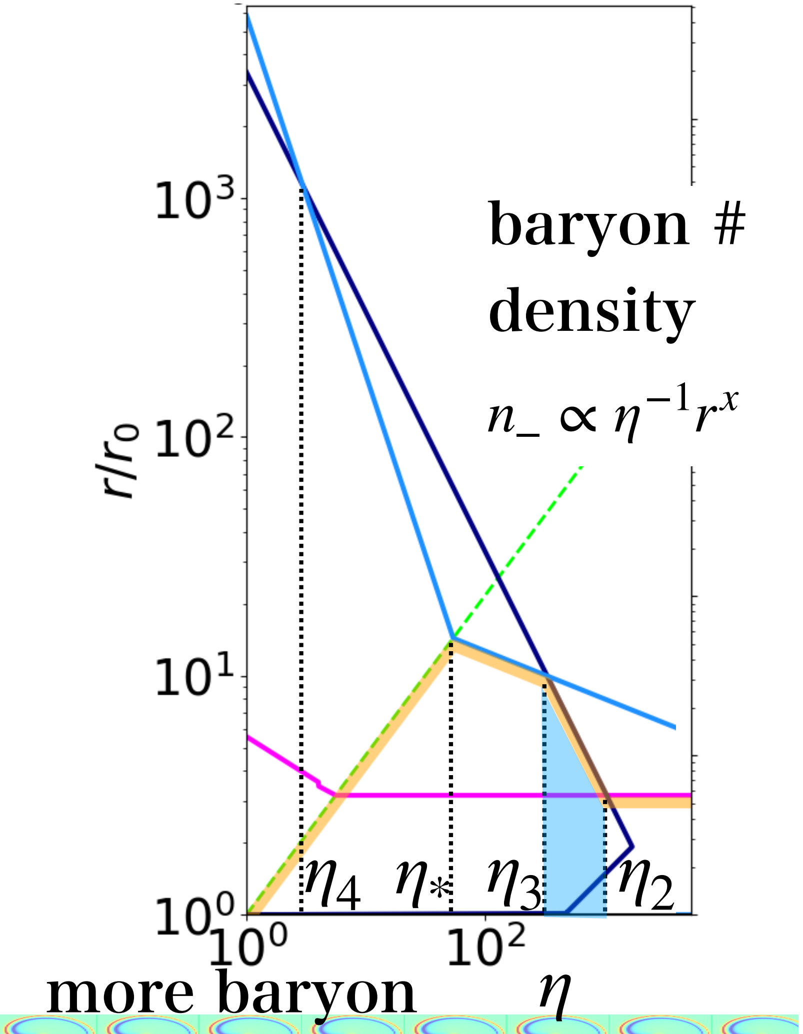


$t_{\rm diff} < t_{\rm dyn}$ $\tau_\parallel = 1$

$t_{\rm diff} = t_{\rm dyn}$ $\tau_\parallel > 1$
$(t_{\gamma\gamma} > t_{\rm dyn})$

$e^+ + e^-$(baryonic) $\rightarrow \gamma\gamma$
->pair annihilation

$t_{\rm diff} > t_{\rm dyn}$ $\tau_\parallel > 1$



baryon # density

$n_- \propto \eta^{-1} r^x$

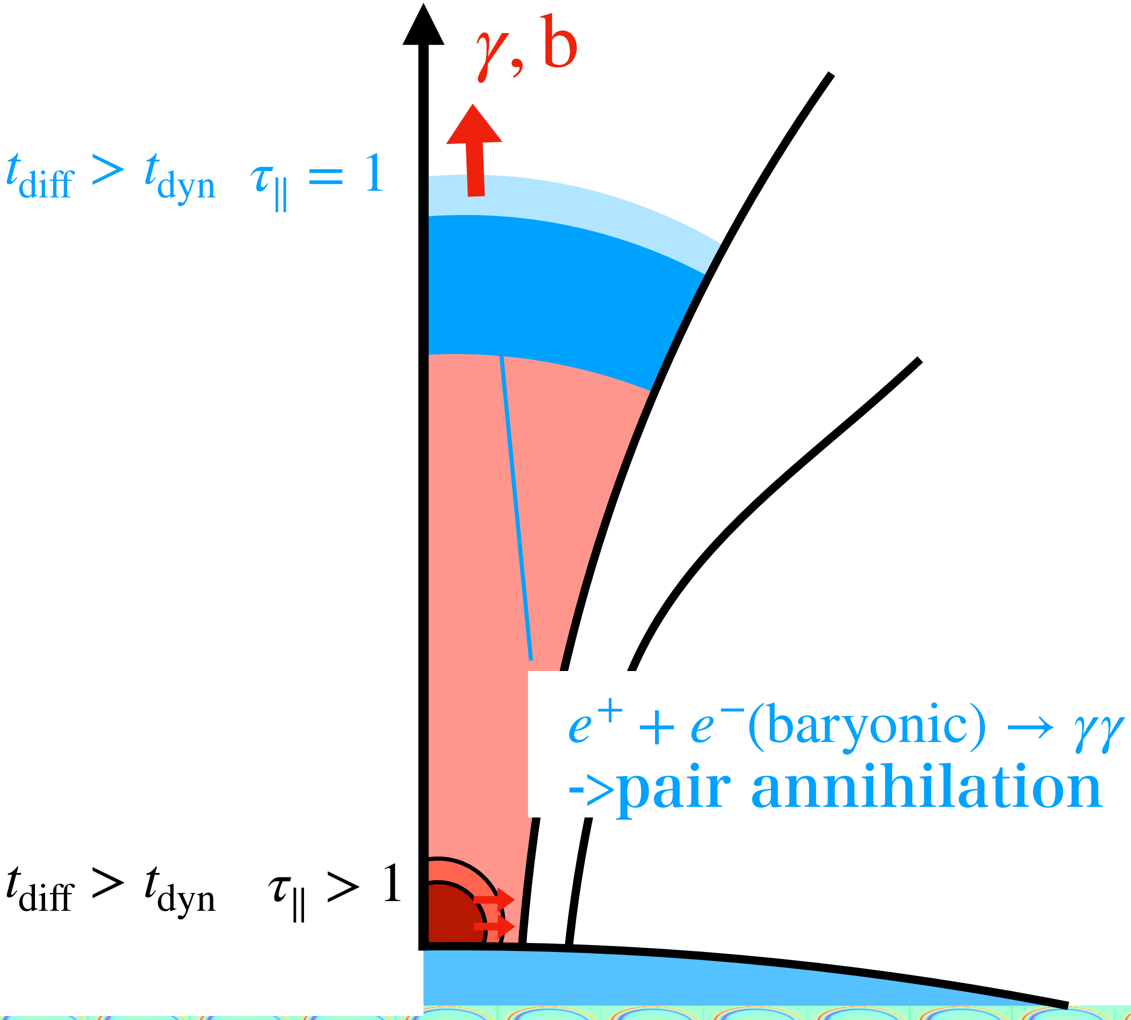
Baryon-longitudinal case $\eta_* < \eta \leq \eta_3$

Fireball becomes optically thin at photospheric radius.

$$L_{\rm ph} \simeq L_0$$

$$L_{\rm kin} \propto \eta^{-13/10}$$

$$L_{\rm kin,\pm} \sim \text{(exp decay)}$$



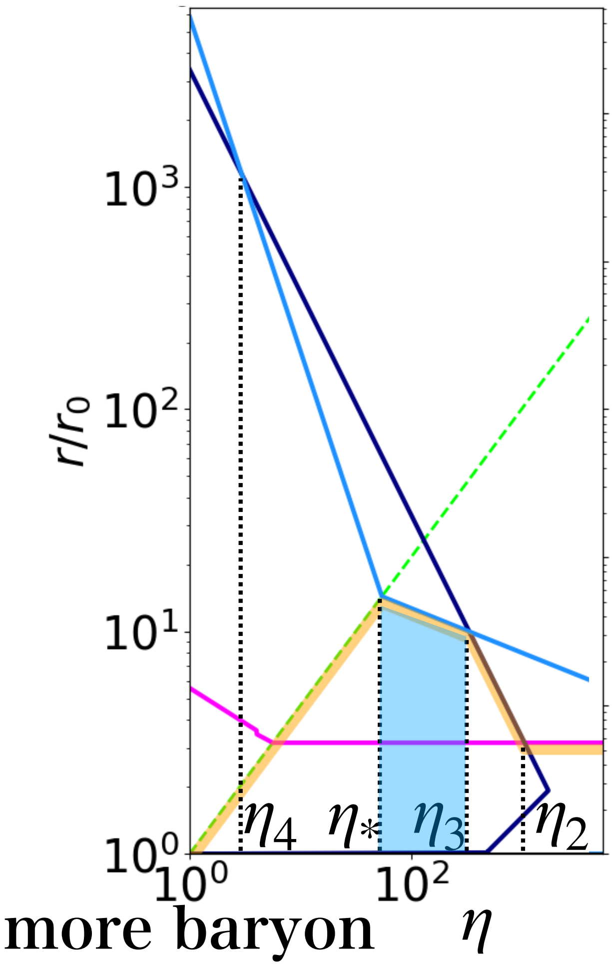
γ, b

$t_{\rm diff} > t_{\rm dyn} \quad \tau_{\parallel} = 1$

$e^+ + e^-(\text{baryonic}) \rightarrow \gamma\gamma$

->pair annihilation

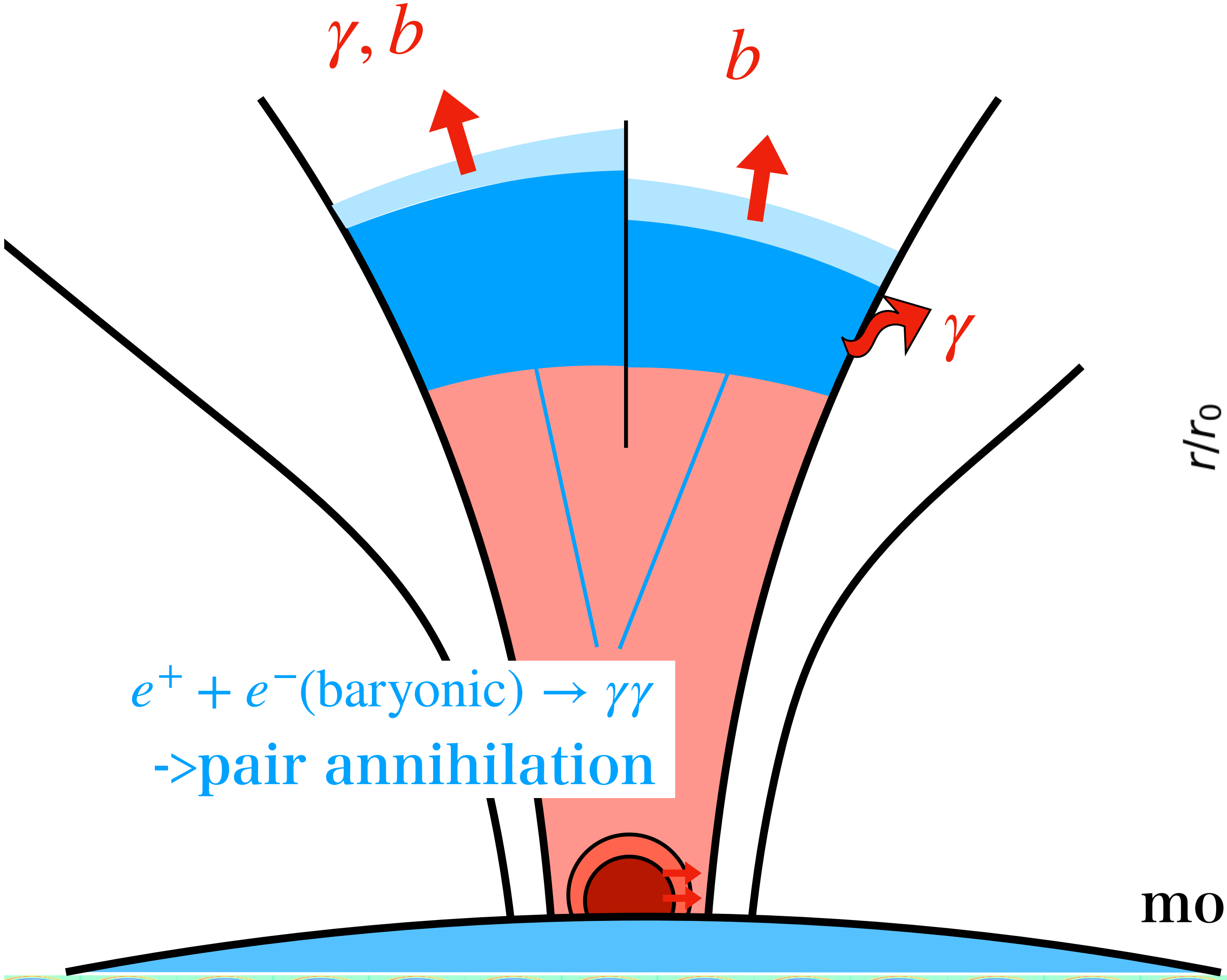
$t_{\rm diff} > t_{\rm dyn} \quad \tau_{\parallel} > 1$



Baryon-dominant case $\eta \leq \eta_*$

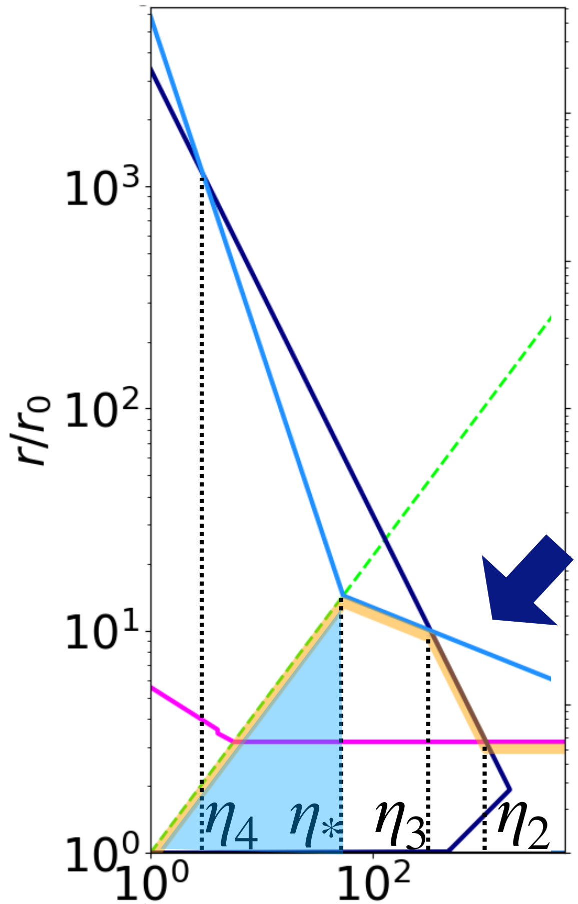
Almost all injected energy is converted to the kinetic energy of baryon.

$$L_{\rm ph} \propto \eta^{+X}$$
$$L_{\rm kin} \simeq L_0$$
$$L_{{\rm kin},\pm} \ll L_0$$



$e^+ + e^-(\text{baryonic}) \to \gamma\gamma$

->pair annihilation



baryon nu

density

$n_- \propto \eta^{-1} r^x$

more baryon η

Radiation acceleration

-After fireball besoms optically thin, radiation accelerate particles ($L_{\rm ph} > L_{\rm kin}$)

-> Balance of power in the comoving frame

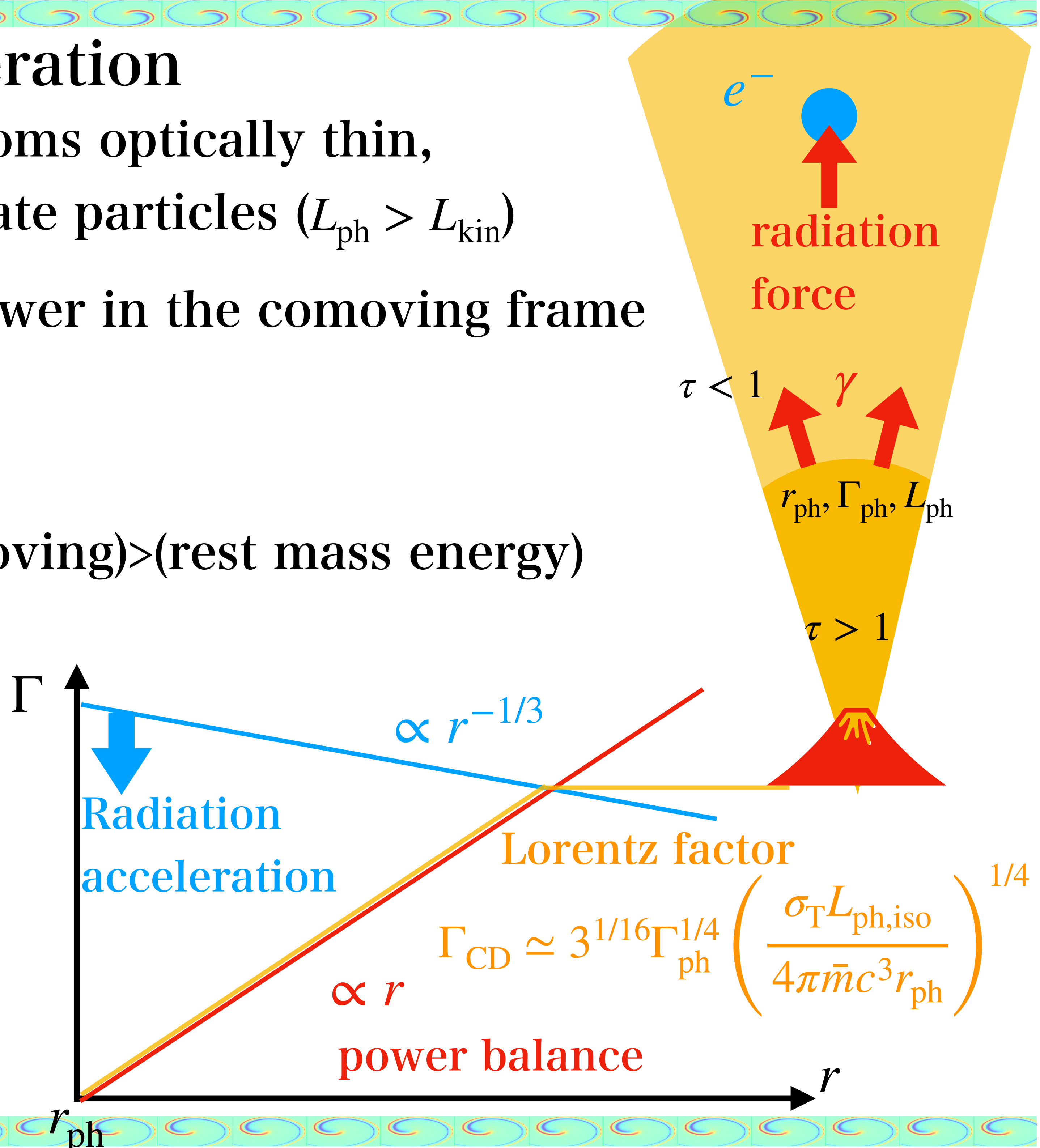
$$\Gamma \simeq 3^{1/4}\Gamma_{\rm ph}\left(\frac{r}{r_{\rm ph}}\right)$$

-> (work in comoving)>(rest mass energy)

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

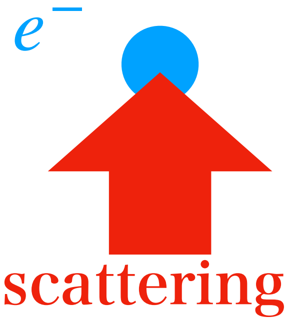
$$\bar{m} = \frac{m_p n_p + m_e n_e}{n_p + n_e}$$

$$\Gamma < \left(\frac{\sigma_{\rm T}L_{\rm ph,iso}}{4\pi\bar{m}c^3 r}\right)^{1/3}$$



$$\Gamma_{\rm CD} \simeq 3^{1/16}\Gamma_{\rm ph}^{1/4}\left(\frac{\sigma_{\rm T}L_{\rm ph,iso}}{4\pi\bar{m}c^3 r_{\rm ph}}\right)^{1/4}$$

Radiation acceleration by resonant scattering



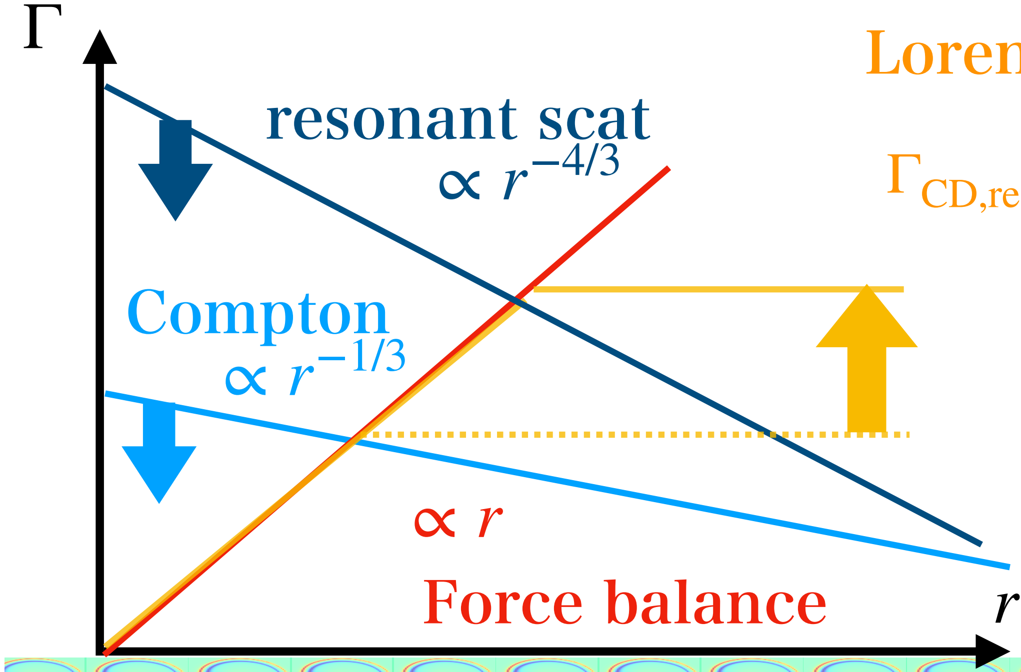
The work in comoving frame

$$\frac{r}{\Gamma}\frac{\sigma_{\rm res}\left(\omega L_{{\rm ph,iso},\omega}\right)_{\omega=\omega_c}}{4\pi r^2 c\Gamma^2} > \bar{m}c^2$$

$$\omega = \frac{eB}{mc}$$

The ratio of force (assuming blackbody spectrum)

$$\frac{F_{\rm resonance}}{F_{\rm Thomson}} \simeq 25b^2t^{-3} \propto r^{-3}$$ **where** $b = B/B_{\rm Q}$, $t = k_bT/m_ec^2$。

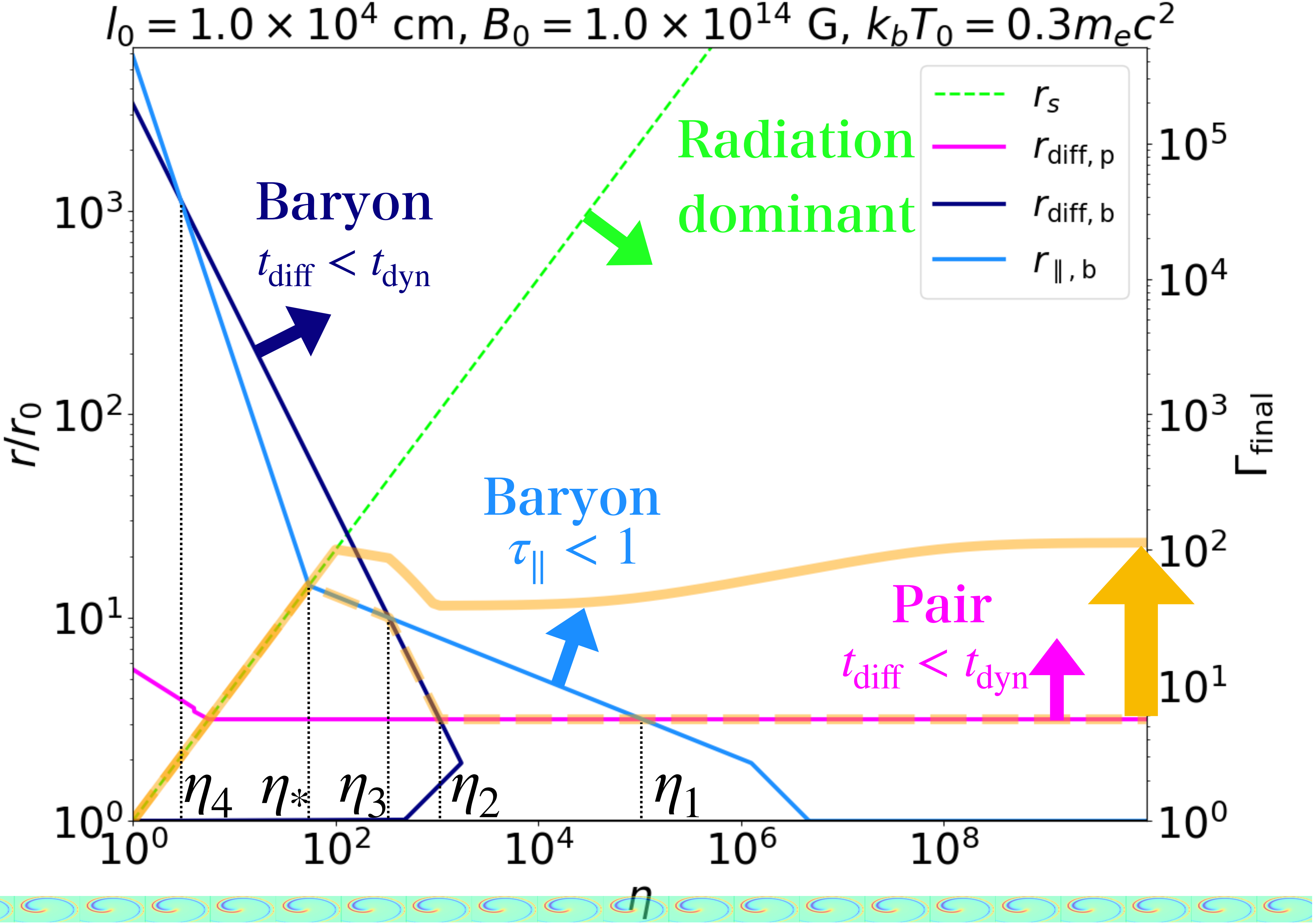


Lorentz factor

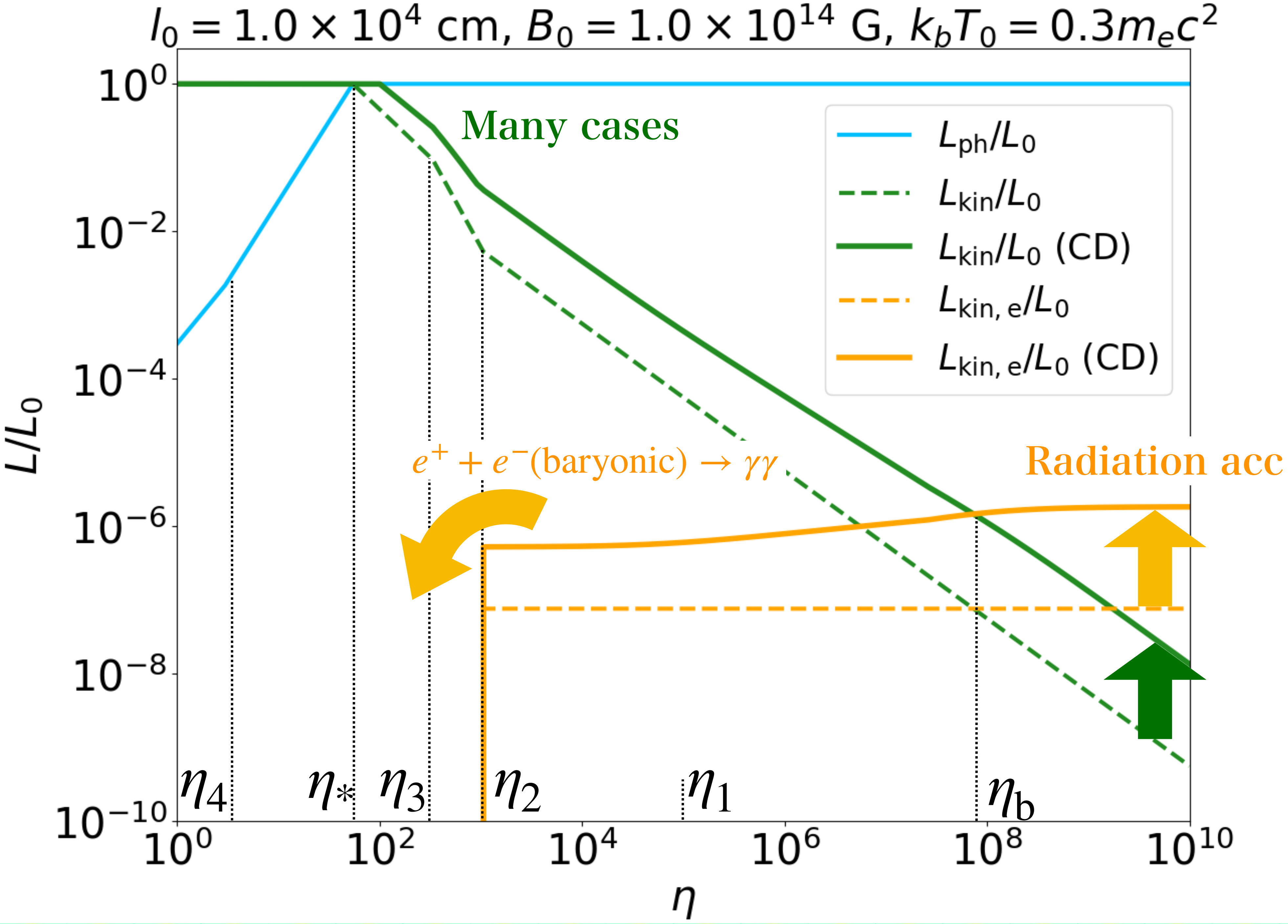
$$\Gamma_{\rm CD,res} \simeq \left(\frac{135}{8\pi^3\alpha}\right)^{1/7}\left(\frac{\sigma_{\rm T}L_{\rm ph,iso}}{4\pi\bar{m}c^3r_{\rm ph}}\right)^{1//7}\Gamma_{\rm ph}^{4/7}B_{\rm ph}^{2/7}T_{\rm ph}^{-3/7}$$

$$\sim 50L_{\rm ph,iso,41}^{1/7}B_{0,14}^{2/7}T_{0,100{\rm keV}}^{-3/7}\tilde{r}_{0.5}^{1/2}$$

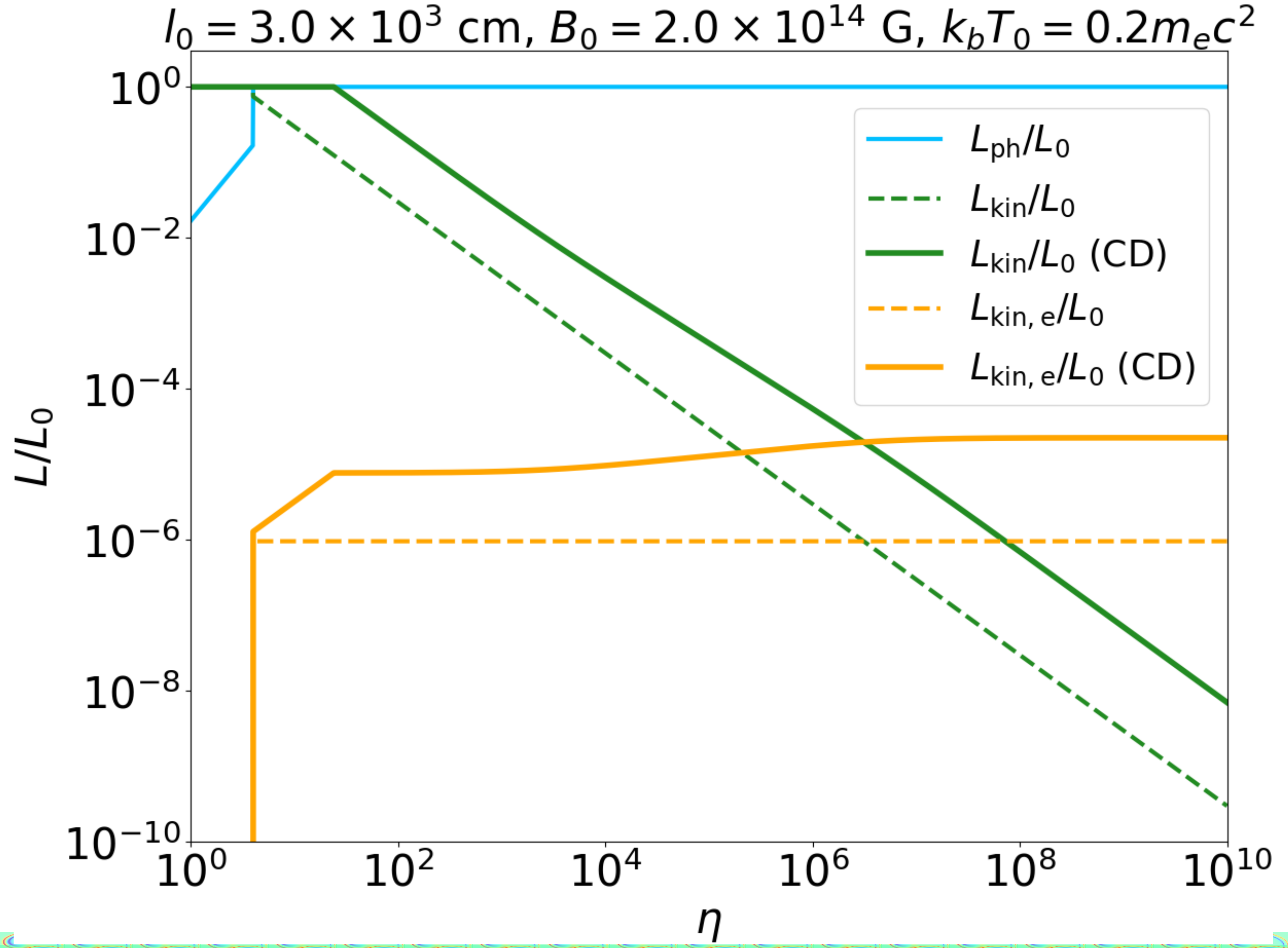
Final Lorentz factor



Luminosity


$l_0 = 1.0 \times 10^4$ cm, $B_0 = 1.0 \times 10^{14}$ G, $k_bT_0 = 0.3m_ec^2$
L/L_0
10^0
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
η
10^0
10^2
10^4
10^6
10^8
10^{10}
Many cases
$e^+ + e^-$(baryonic) $\rightarrow \gamma\gamma$
Radiation acc
$L_{\rm ph}/L_0$
$L_{\rm kin}/L_0$
$L_{\rm kin}/L_0$ (CD)
$L_{\rm kin,\,e}/L_0$
$L_{\rm kin,\,e}/L_0$ (CD)
η_4
η_*
η_3
η_2
η_1
$\eta_{\rm b}$

FRB 200428 like event



Isotropic Luminosity

The ratio of isotropic luminosity

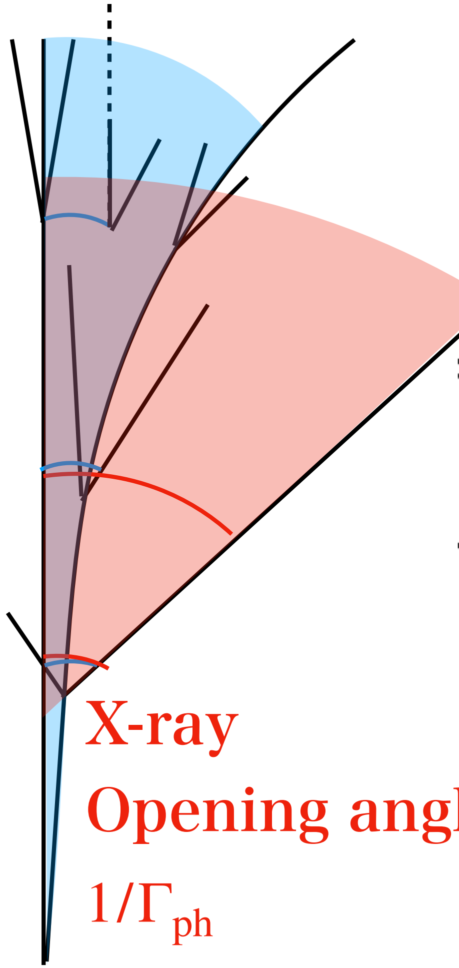
FRB is emitted at r.

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

Radiation

Opening angle

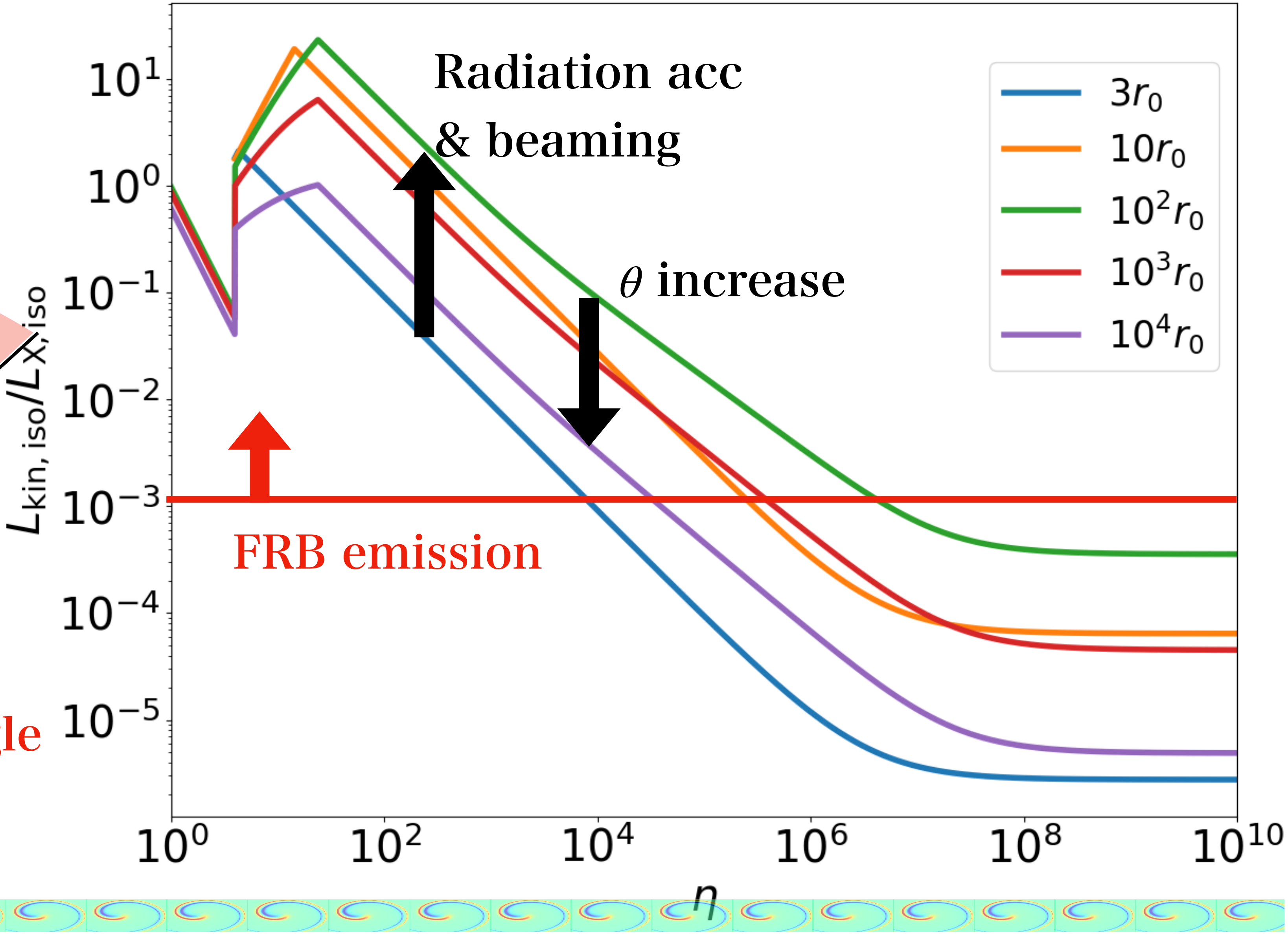
$\theta_{\mathrm{dip}}(r) + \Gamma(r)^{-1}$



X-ray

Opening angle

$1/\Gamma_{\mathrm{ph}}$



Summary

- The expanding fireball along a dipolar magnetic flux tube shows diverse cases of its outflows.

- Photons escapes from the fireball in two ways.
  Lateral-diffusion & longitudinal-thinning

- Compton drag for resonant scattering accelerates particles.
  The kinetic luminosities are determined by Compton drag.

- For FRB emission by the kinetic luminosity,
  $\eta \lesssim 10^6$ is needed if FRB is emitted at $r \sim 10^3 r_0$.