Magnetosphere origin of Fast Radio Bursts

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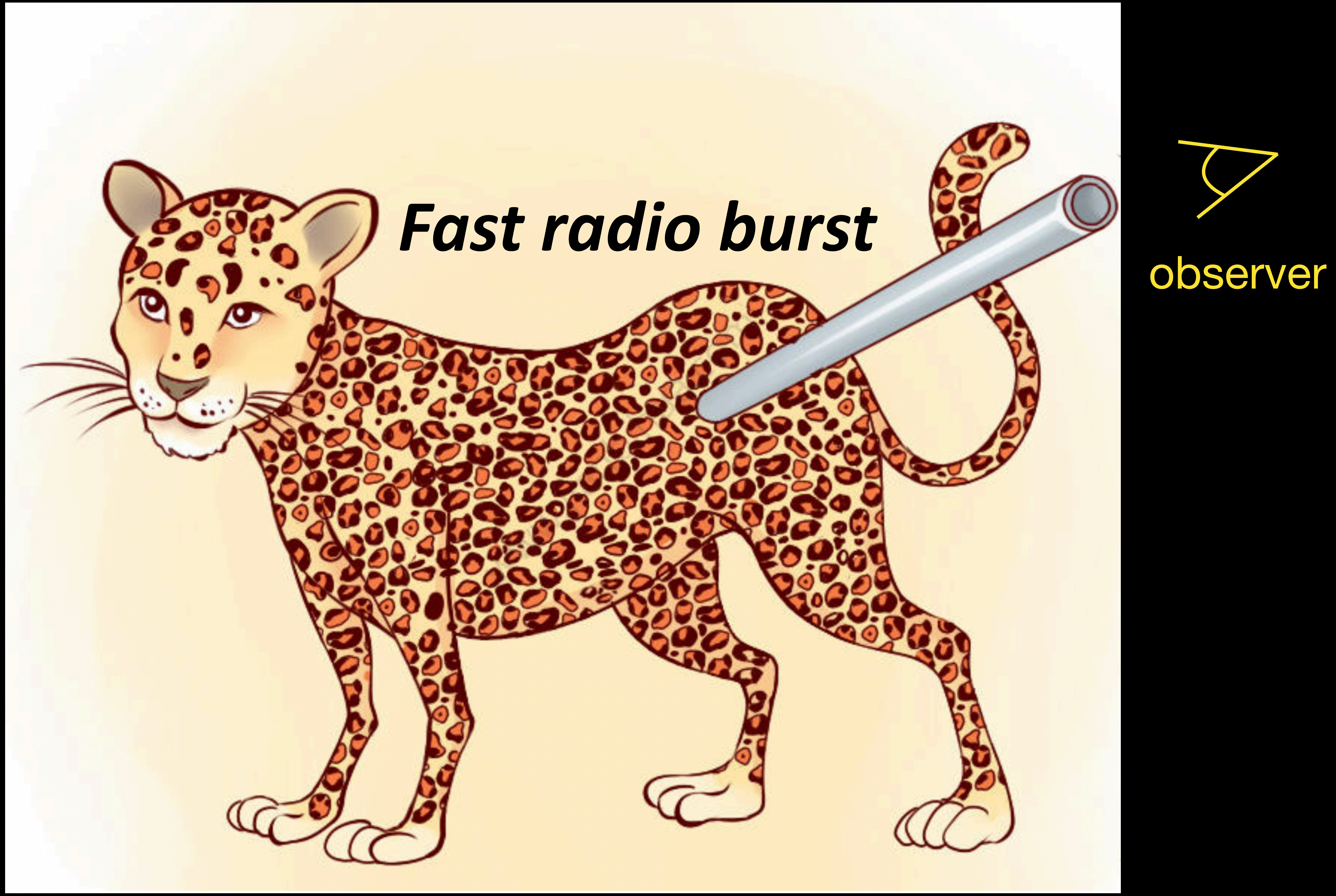
Outline:

1. Multi-messenger: neutrino emission?
2. Plasma effect on bunching mechanisms
3. Propagation in the magnetosphere

YITP June 07, 2022

管中窥豹 Look at a leopard through a tube

FRB could origin from magnetosphere



We need to collect observational results to predict the origin of FRB

Highly dispersed short radio pulse

Dispersion

$$t(\nu) - t(\infty) = (4.416\ \mathrm{s})\ \nu_{\mathrm{GHz}}^{-2} \frac{\mathrm{DM}}{10^3\ \mathrm{pc\ cm^{-3}}}$$

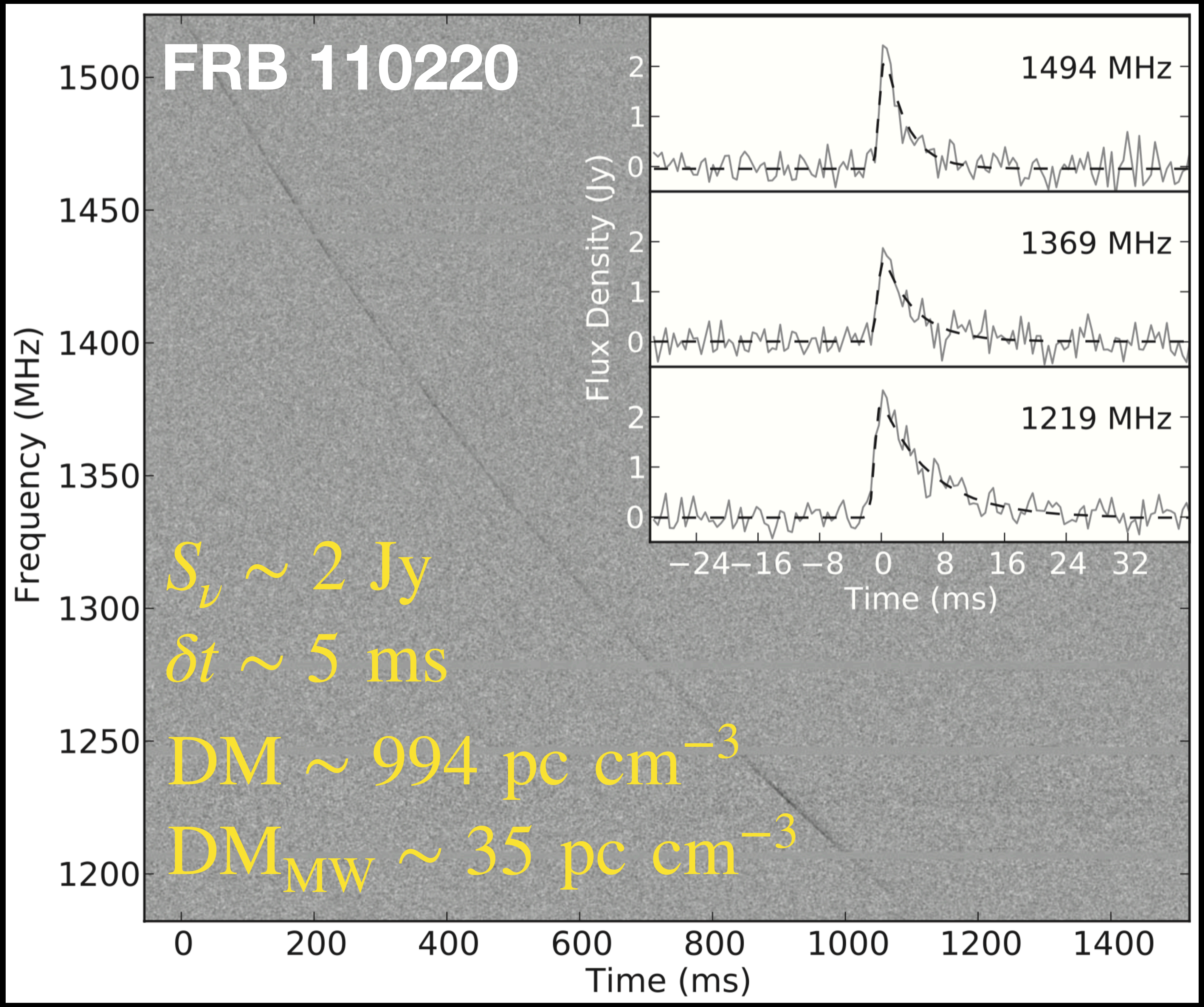
Brightness temperature

$$T_b \sim \frac{F_\nu D_A^2}{2\pi k \nu^2 \delta t^2} \simeq 10^{35}\ \mathrm{K} \left(\frac{F_\nu}{\mathrm{Jy}}\right) \left(\frac{\nu}{\mathrm{GHz}}\right)^{-2} \left(\frac{\delta t}{\mathrm{ms}}\right)^{-2} \left(\frac{D_A}{\mathrm{Gpc}}\right)^{2}$$

Strong wave factor

Luan & Goldreich 2014

$$a = \frac{eE_w}{m_e c \omega} = \frac{eL_{\mathrm{frb}}^{1/2}}{m_e c^{3/2} \omega r} \simeq 1.6 \times 10^4\ L_{\mathrm{frb},42}^{1/2} \nu_9^{-1} r_9^{-1}$$

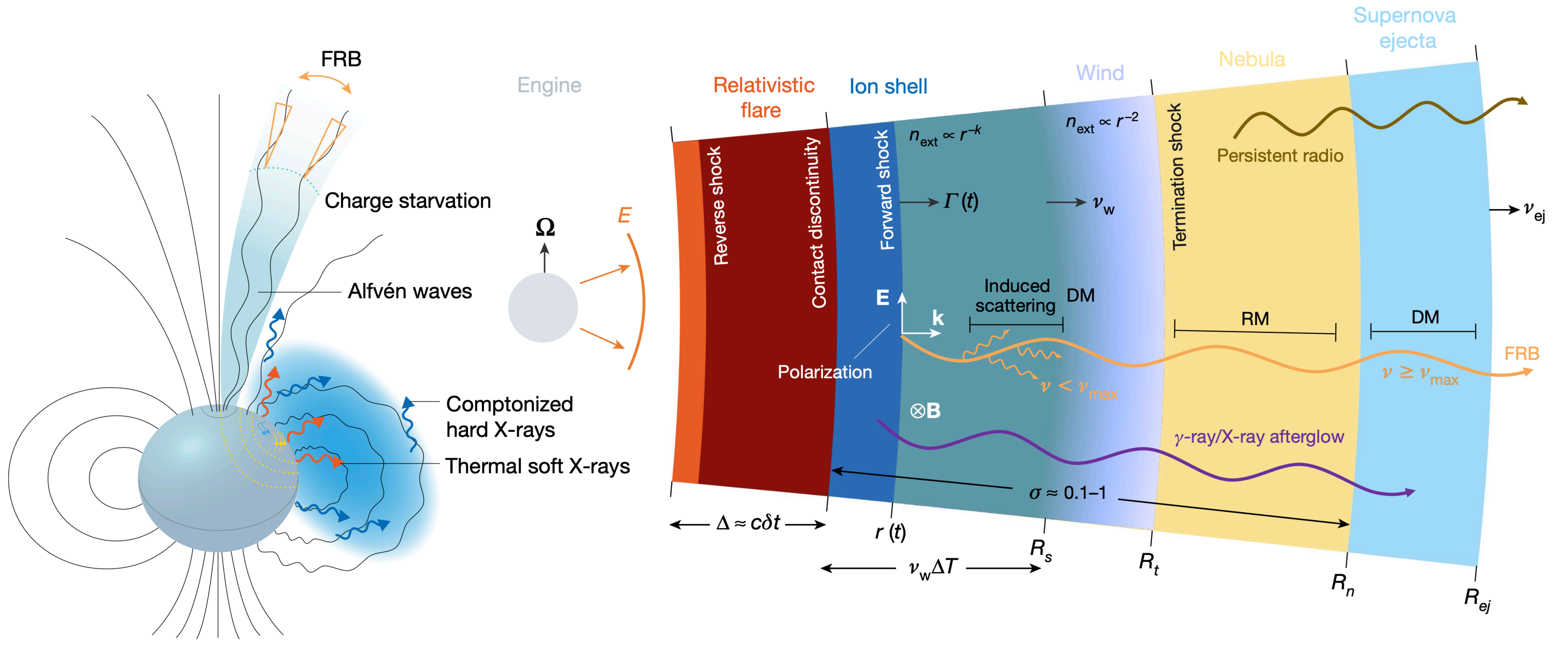


Thornton et al. 2013

FRB Radiation Mechanisms

Kumar et al. 2017
Yang & Zhang. 2018
Lu et al. 2020
Kumar & Bosnjak. 2020
Zhang. 2022

Metzger et al. 2019
Yuan et al. 2020
Waxman. 2017
Beloborodov. 2020
Sironi et al. 2021
Plotnikov & Sironi. 2019



Zhang. 2020

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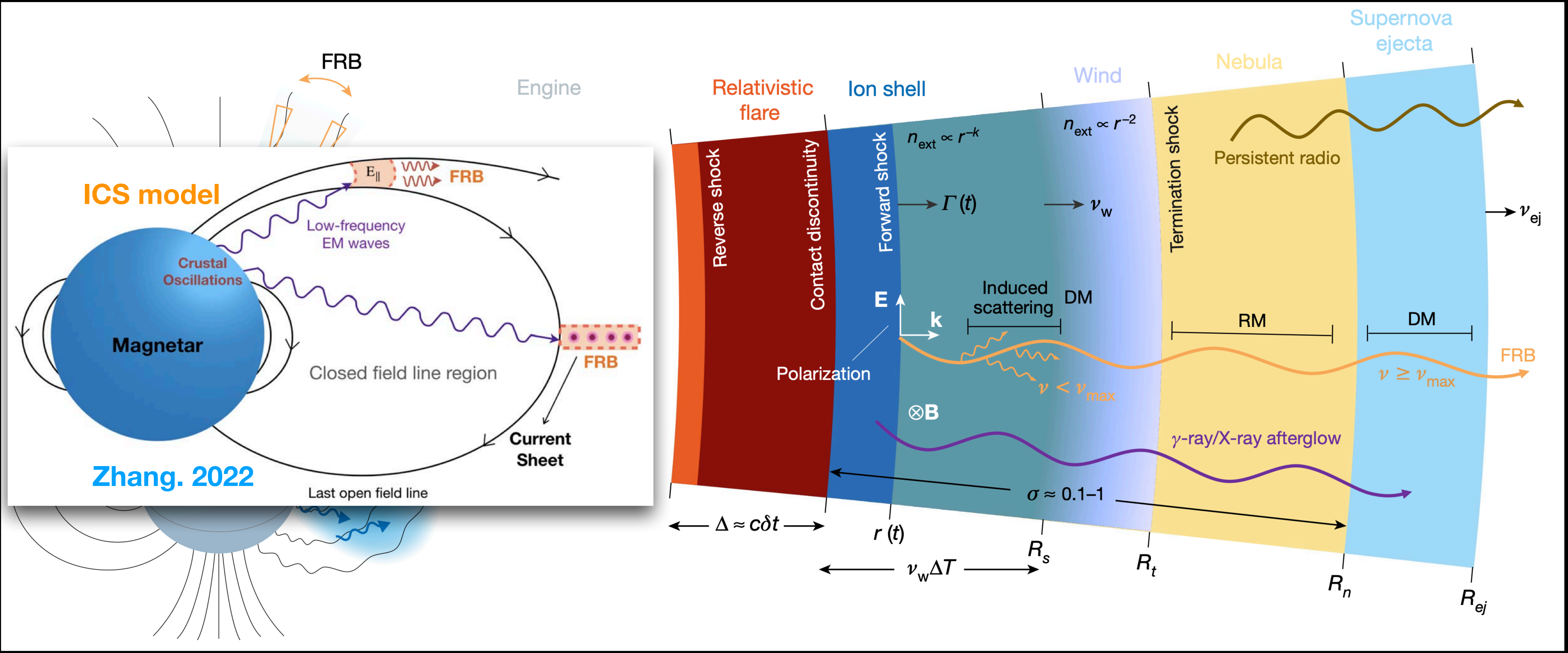


Zhang. 2020

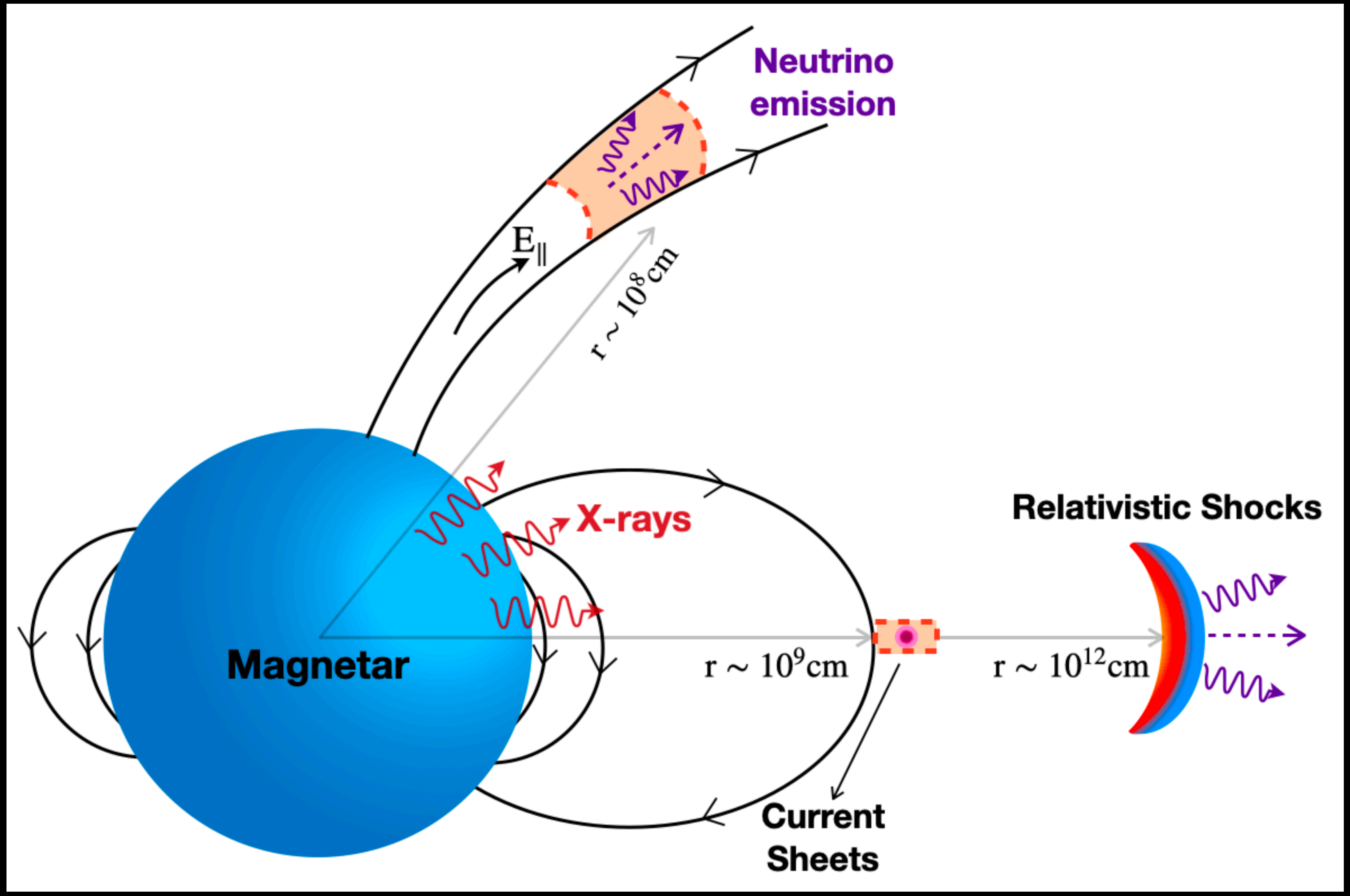
Neutrino emission from FRB-emitting magnetars?

Qu & Zhang 2022 (2111.04121)

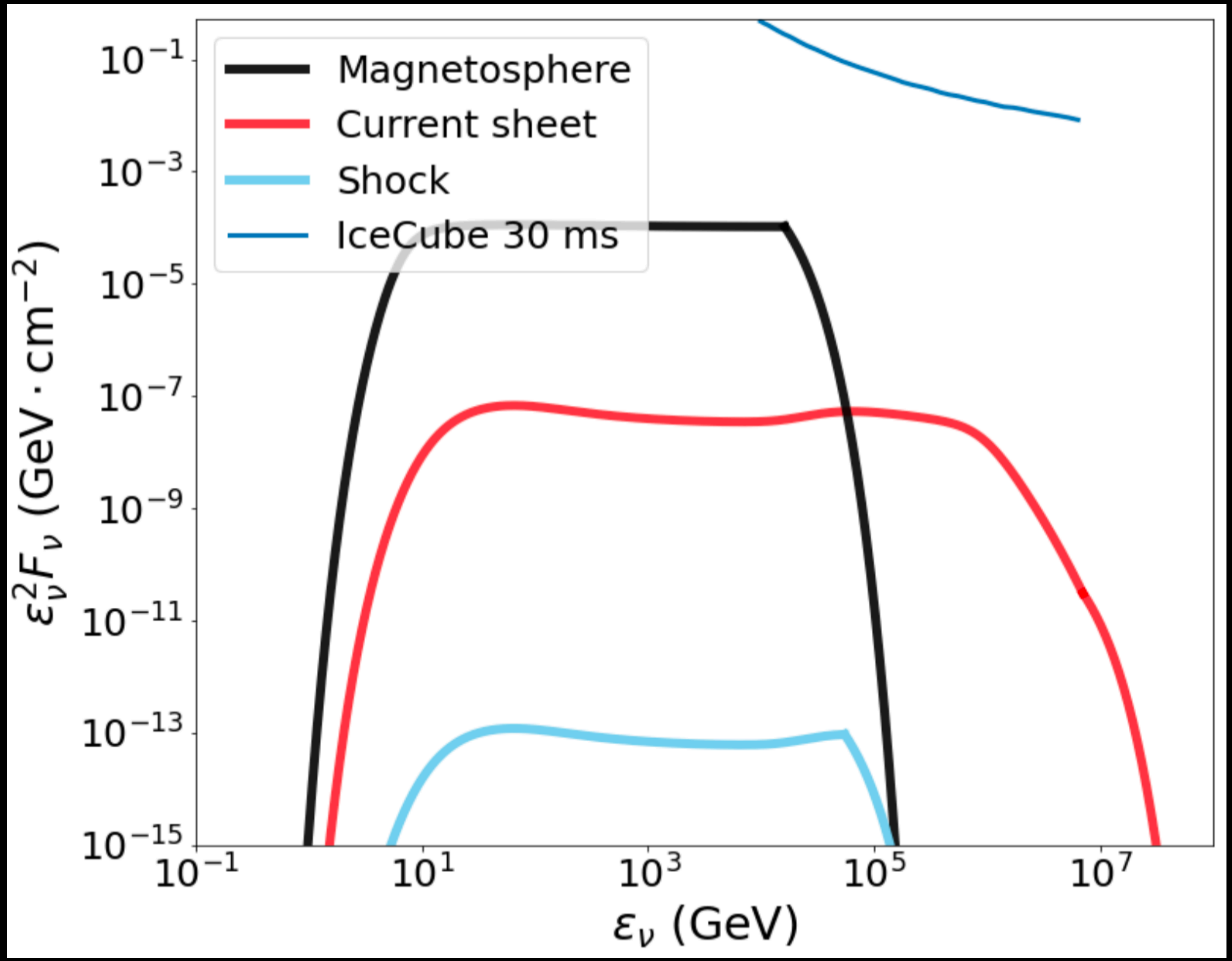
Metzger et al. 2020 (shock acceleration)

Photomeson interaction

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



FRB 200428



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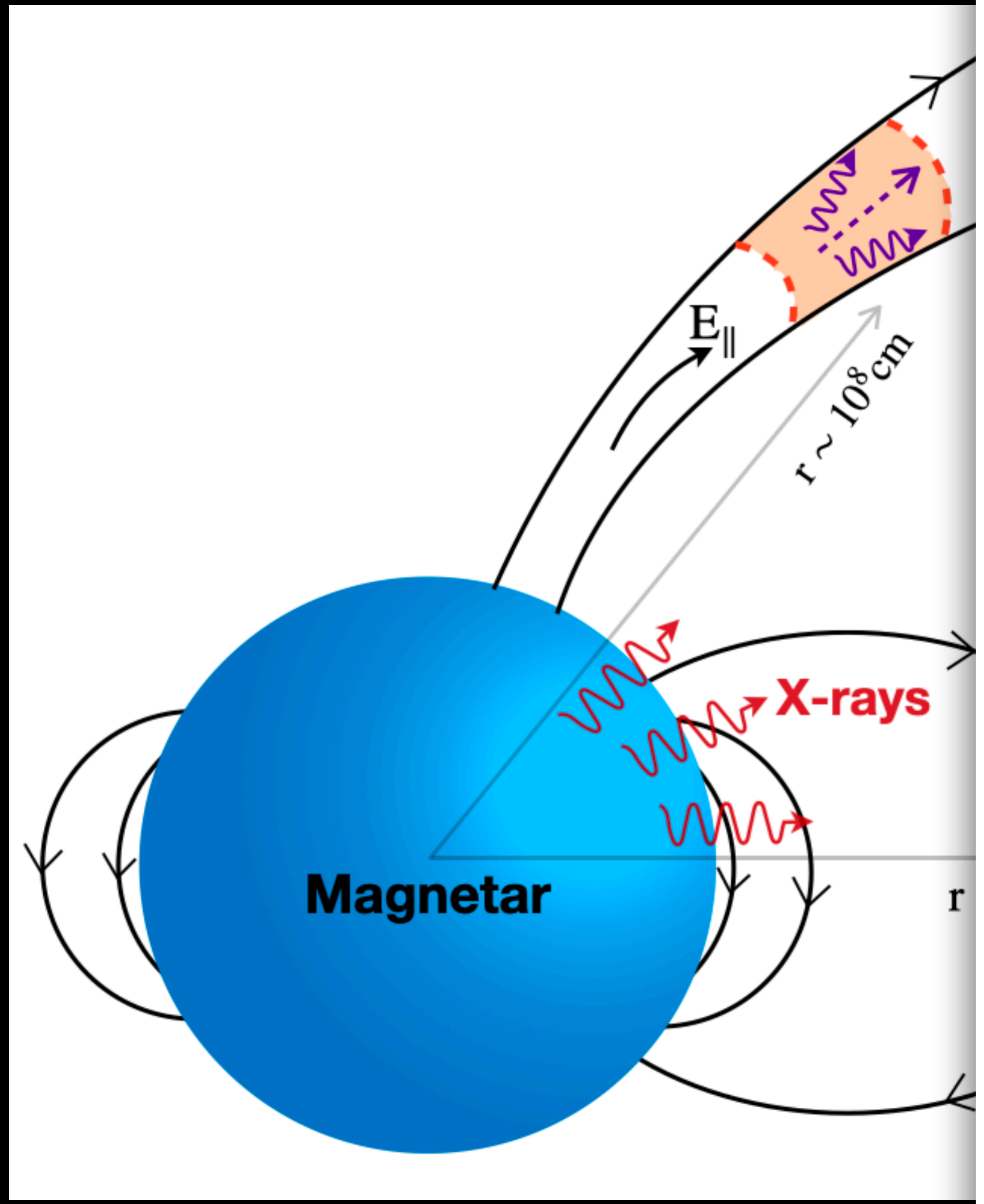

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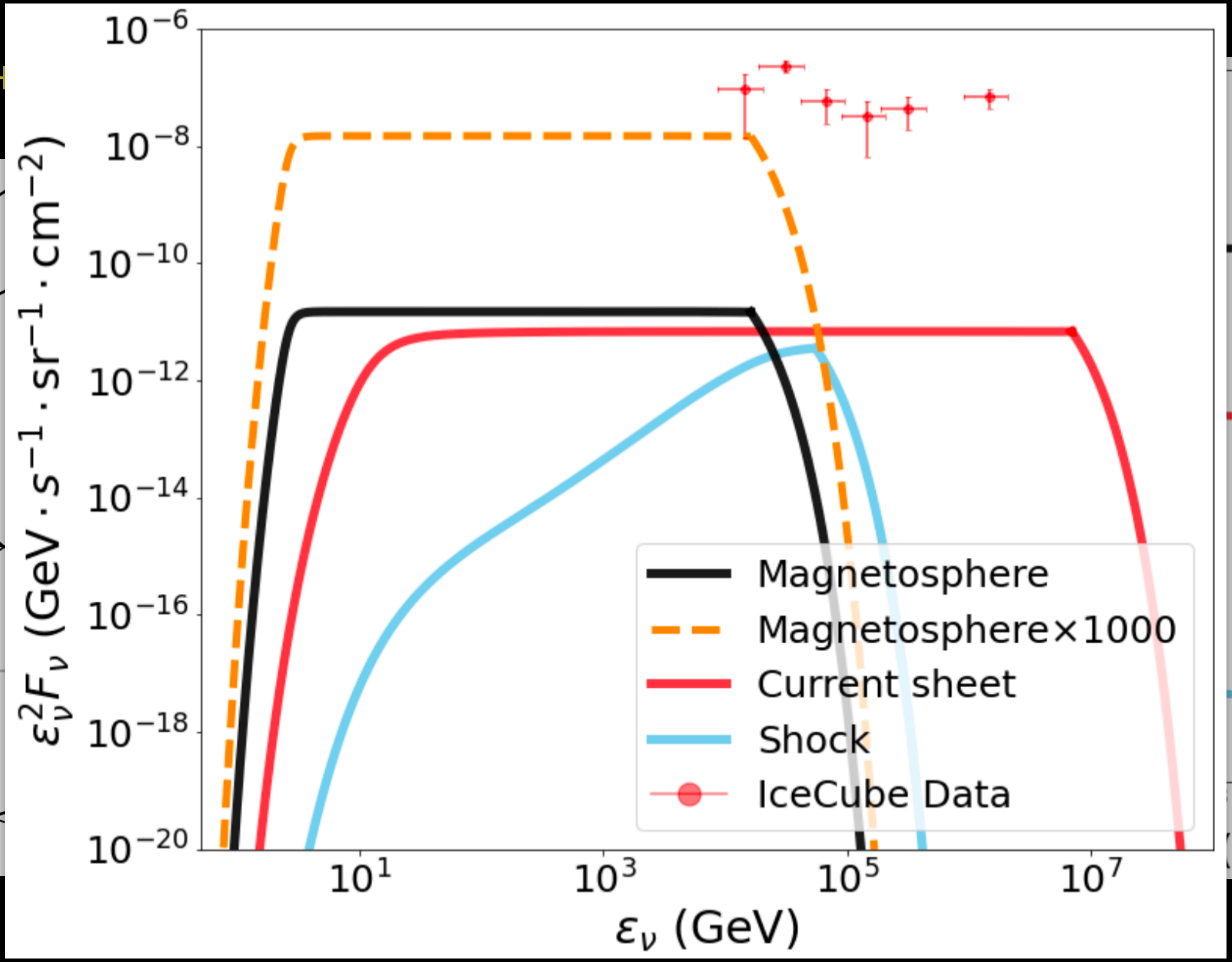
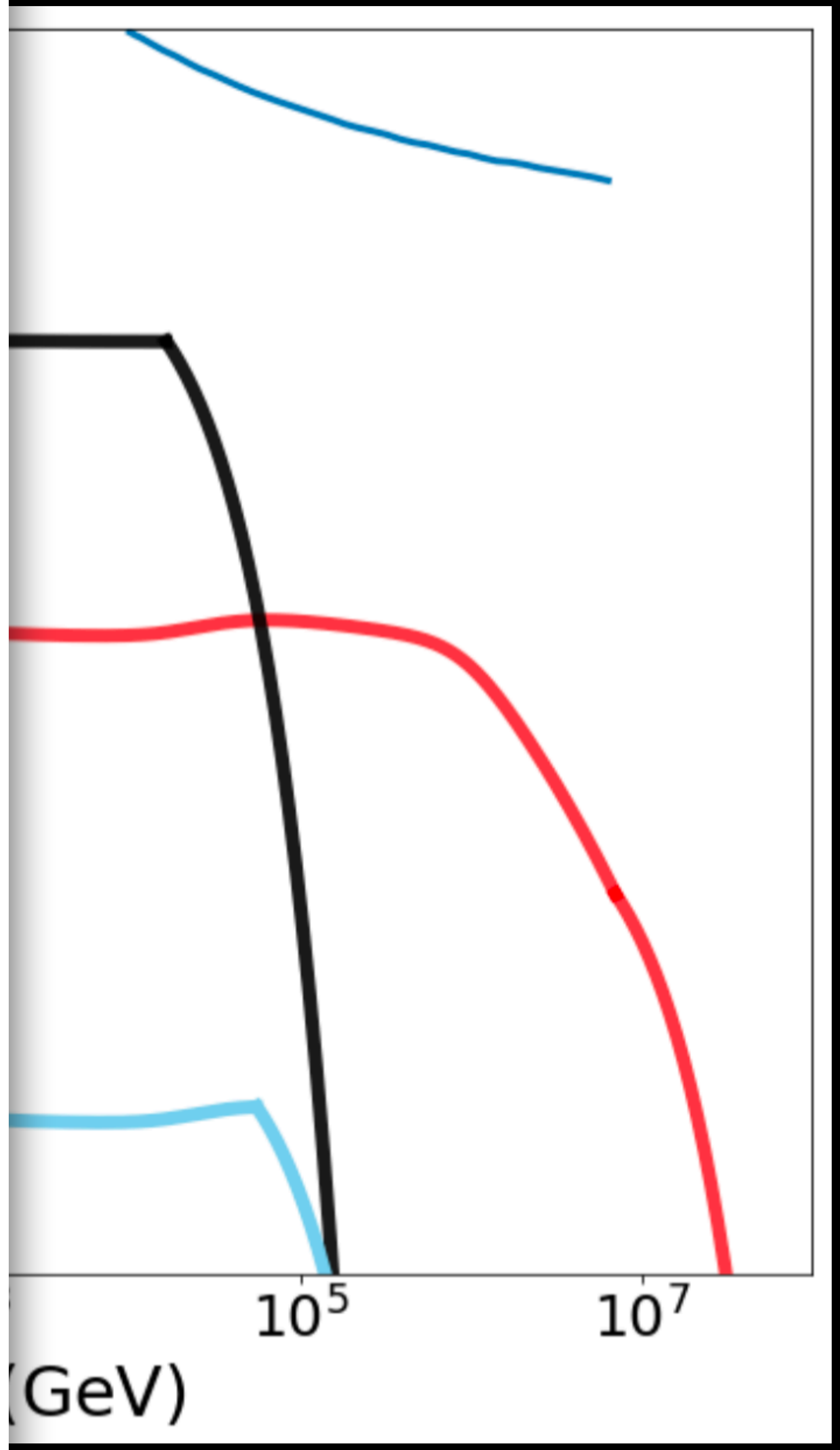
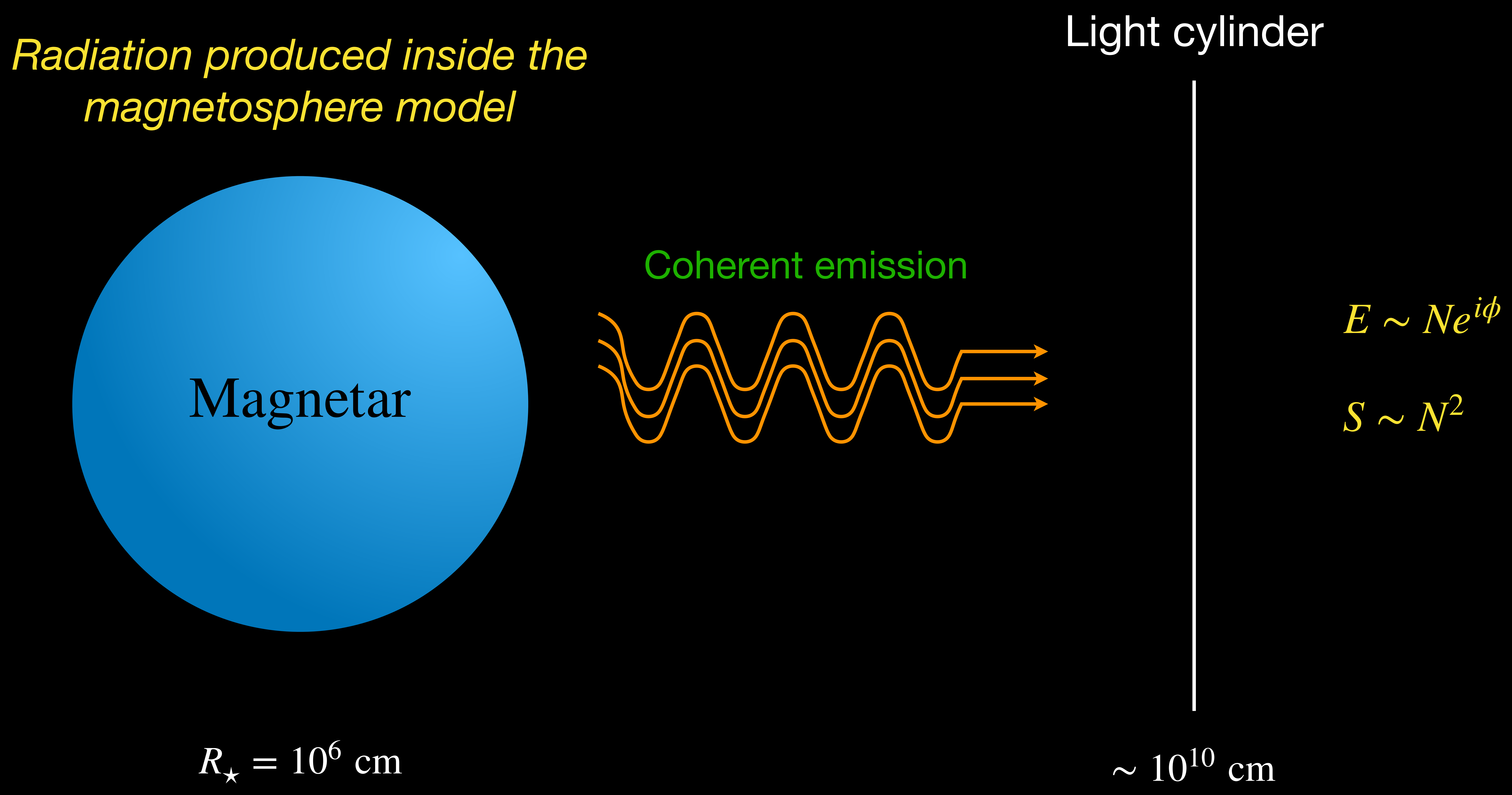
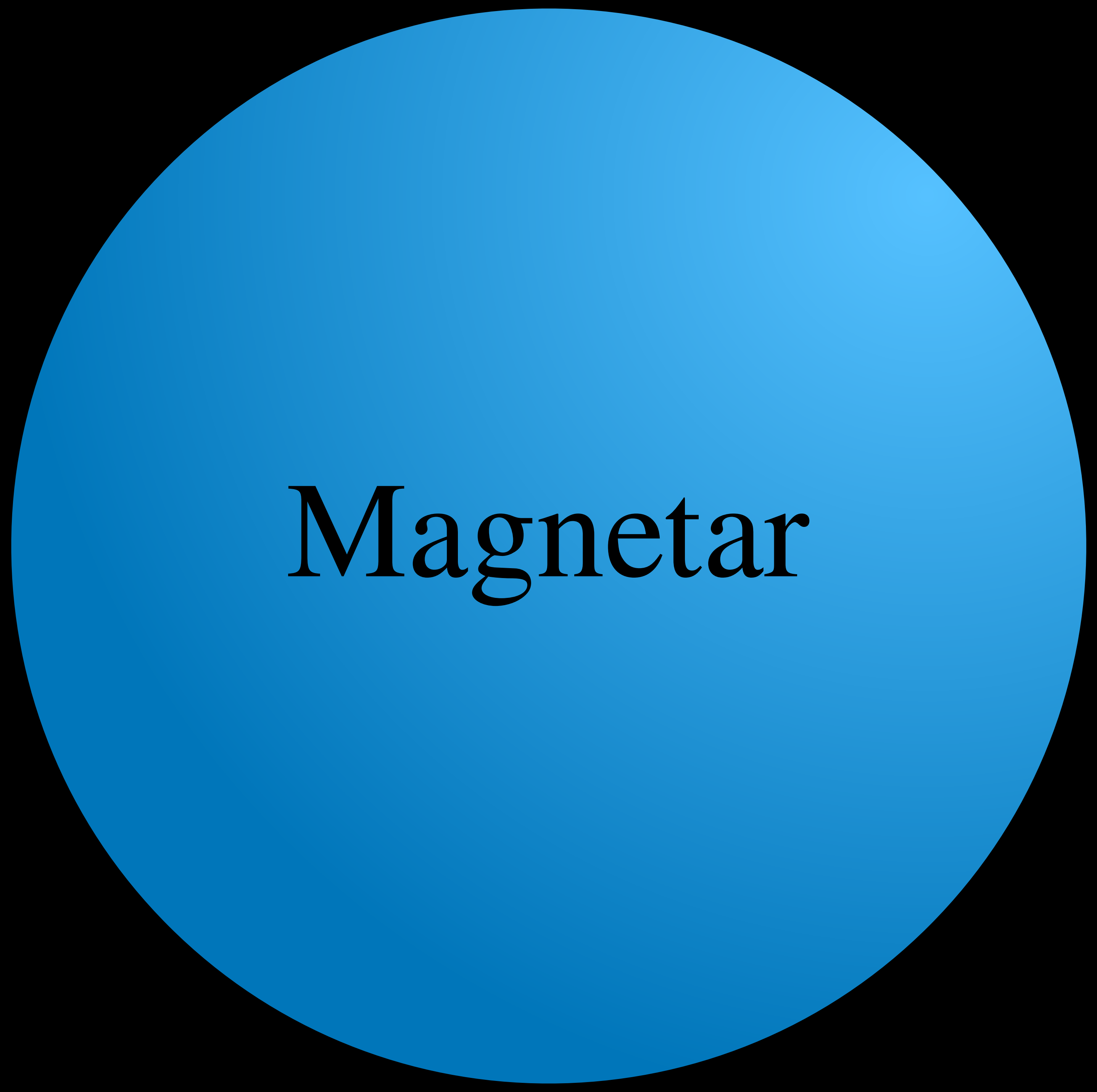




Diffuse background neutrino fluence spectrum for all FRB-emitting magnetars


Radiation produced inside the magnetosphere model
Light cylinder
Magnetar
Coherent emission
$E \sim Ne^{i\phi}$
$S \sim N^2$
$R_\star = 10^6$ cm
$\sim 10^{10}$ cm

Radiation produced inside the magnetosphere model



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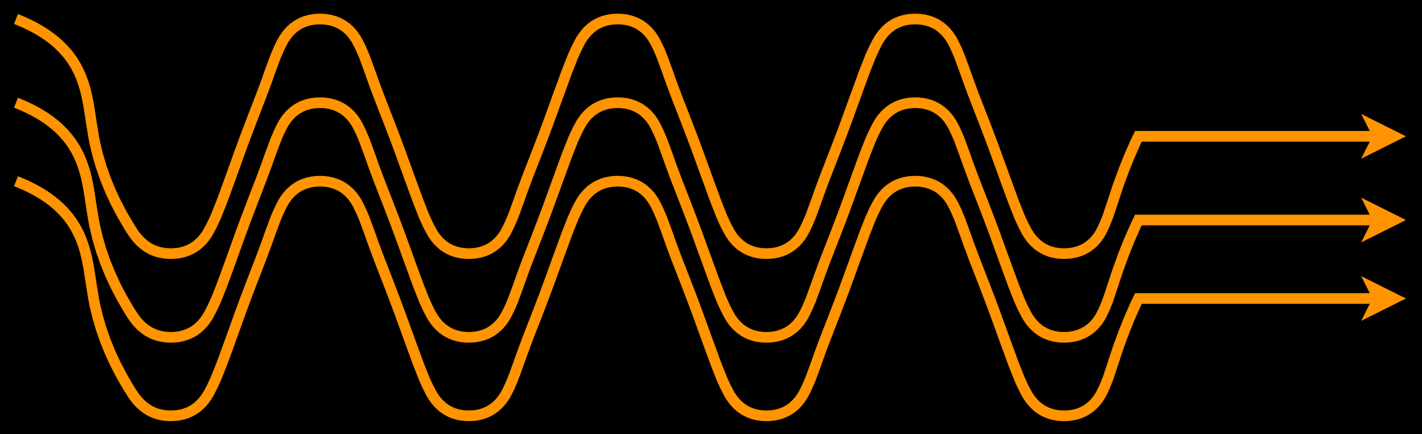
Coherent emission



The 1st question is

Can FRB photons be suppressed by pair plasma?

Gil et al. 2004

Lyubarsky. 2021

Light cylinder

$\sim 10^{10}$ cm

$E \sim N e^{i\phi}$

$S \sim N^2$

Physical conditions for significant plasma suppression

Qu & Zhang 2021 (2111.12269)

$$\omega_p \gg \omega_{\rm FRB} \;\Rightarrow\; \xi \gg 10^2$$

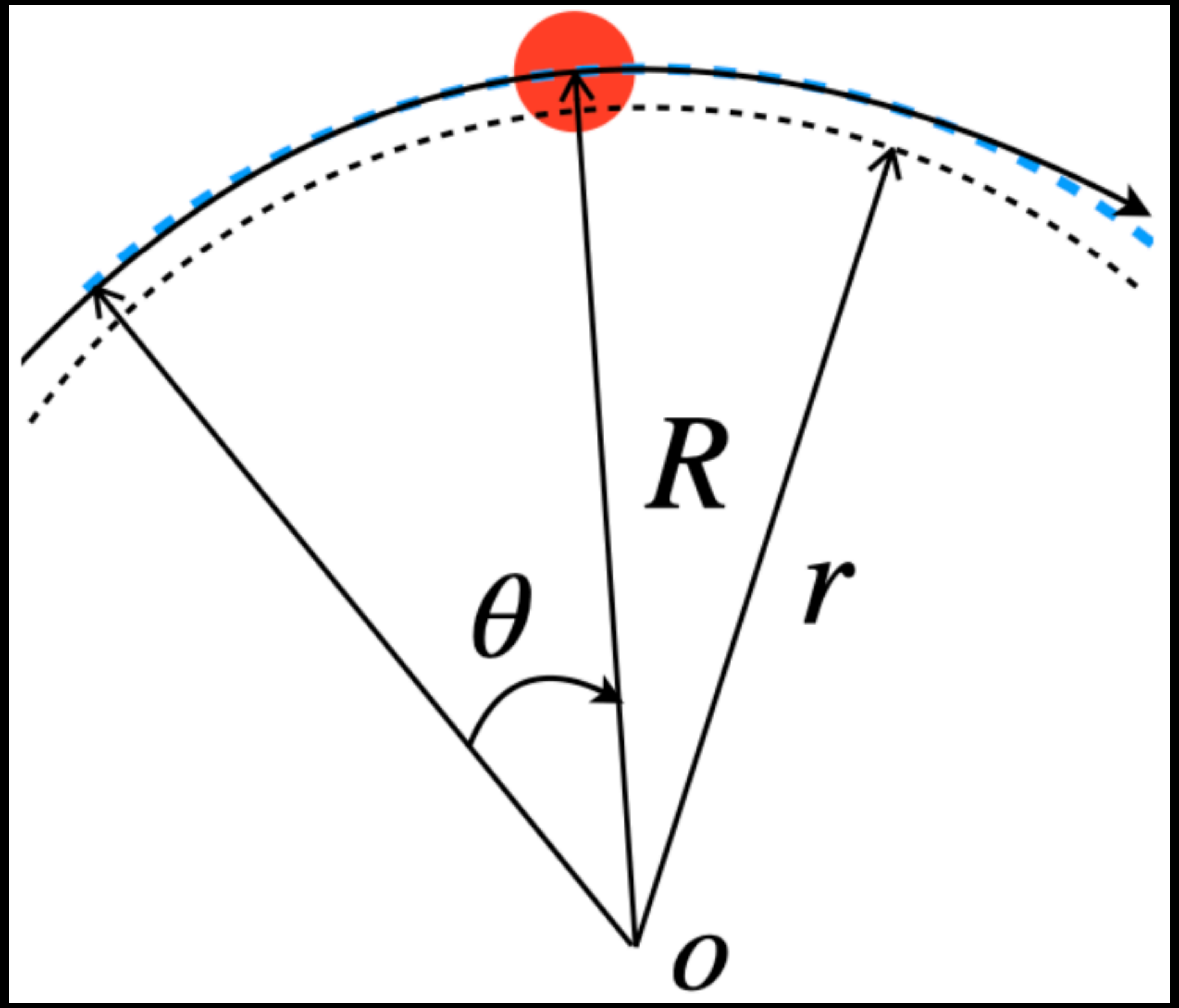
Parallel electric field is required

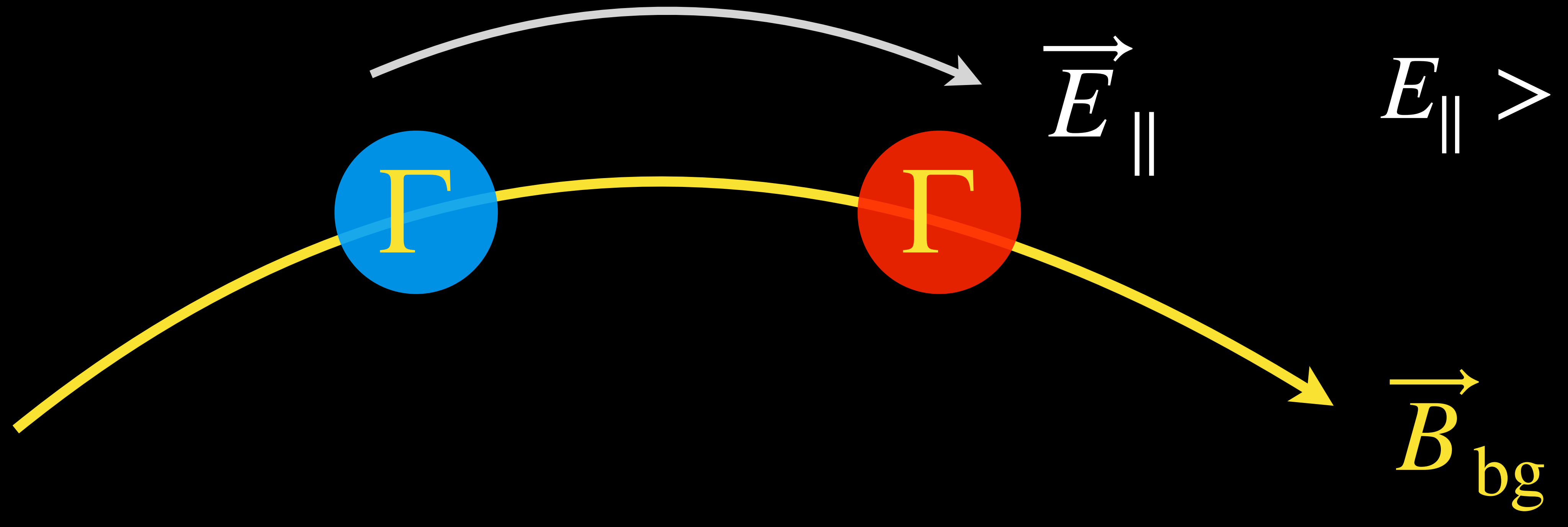
$N^2 P_e = N e E_\parallel c$ **Kumar & Bosnjak. 2020**

Critical parallel electric field

$$E_{c,\parallel} \simeq \frac{eN}{\lambda_{\rm FRB}^2} \simeq (2.7\times10^7\ {\rm esu})\ \xi_2 B_{\star,15} P^{-1} \hat{r}_2^{-3} \nu_9^{-4}$$

$$E_\parallel < E_{c,\parallel}$$





$$E_\parallel > E_{c,\parallel}$$

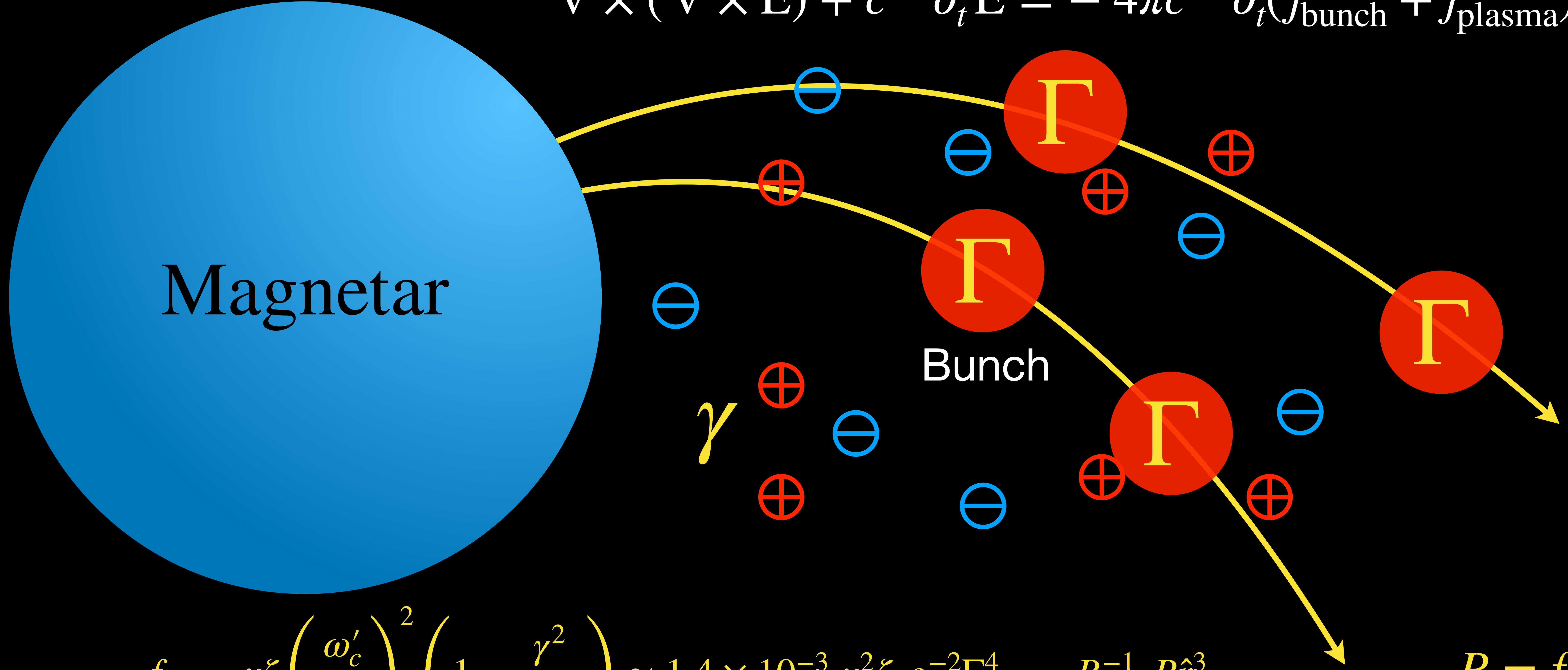
This scenario can interpret the narrow spectra of FRBs **Yang et al. 2020**

Plasma effect on coherent radio emission mechanism

Qu & Zhang 2021 (2111.12269)

Electrons can only stay at Landau levels in strong magnetic fields $$\frac{d(\gamma m_e v)}{dt} = eE_\theta$$

$$\nabla \times (\nabla \times \mathrm{E}) + c^{-2}\partial_t^2 \mathrm{E} = -4\pi c^{-2}\partial_t (j_{\rm bunch} + j_{\rm plasma})$$



$$n = n_0 + \delta n$$

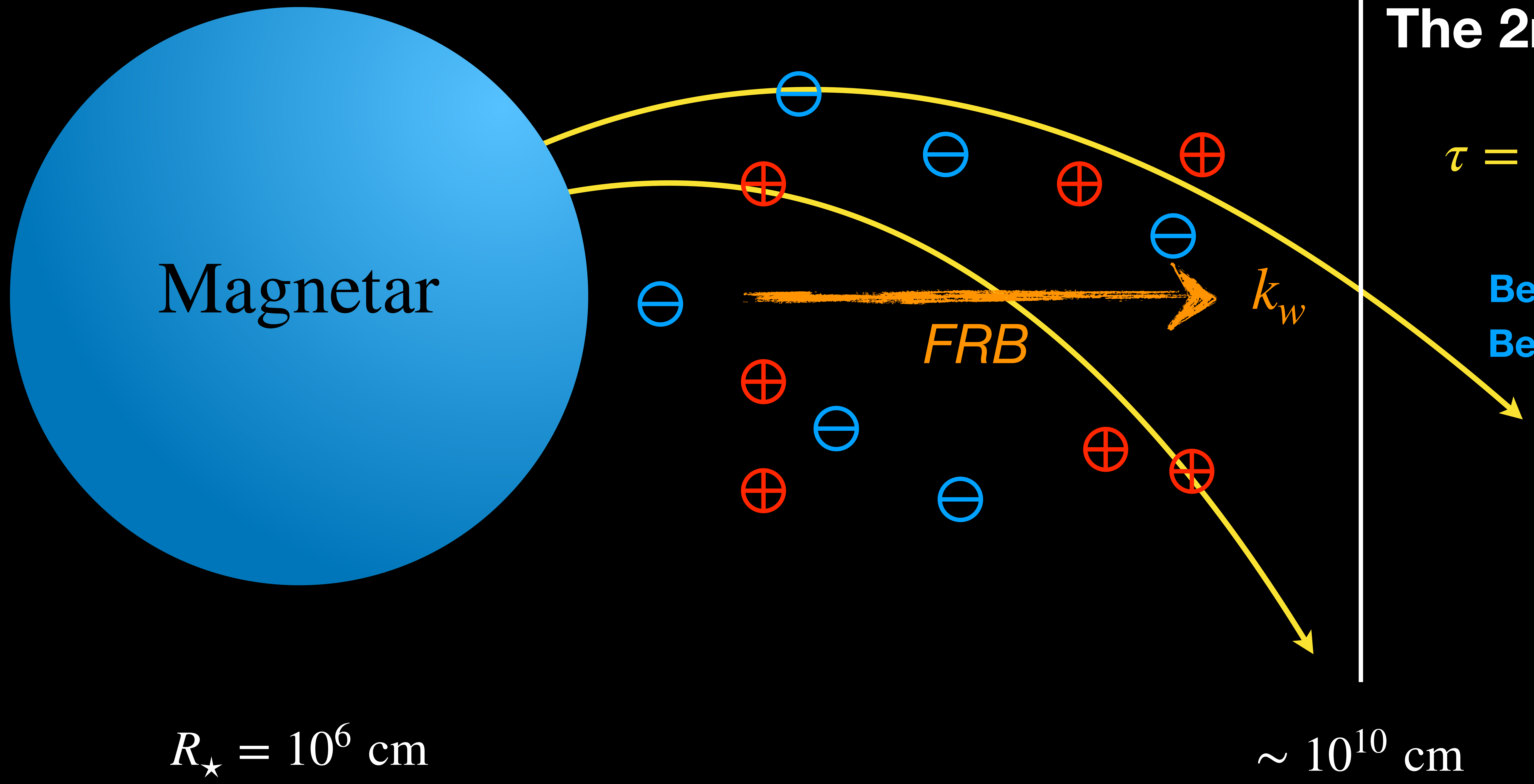
Perturbation is needed

$$f_{\rm cur} = \gamma\zeta \left(\frac{\omega_c'}{\omega_p'}\right)^2 \left(1 - \frac{\gamma^2}{\Gamma_{\rm cur}^2}\right) \simeq 1.4 \times 10^{-3}\ \gamma_1^2 \zeta_2 \rho_8^{-2} \Gamma_{\rm cur,2.38}^4 B_{\star,15}^{-1} P \hat{r}_2^3$$

$$P = f_{\rm cur} P_e \simeq 10^{-3} P_e$$

Radiation produced inside the magnetosphere model

Light cylinder



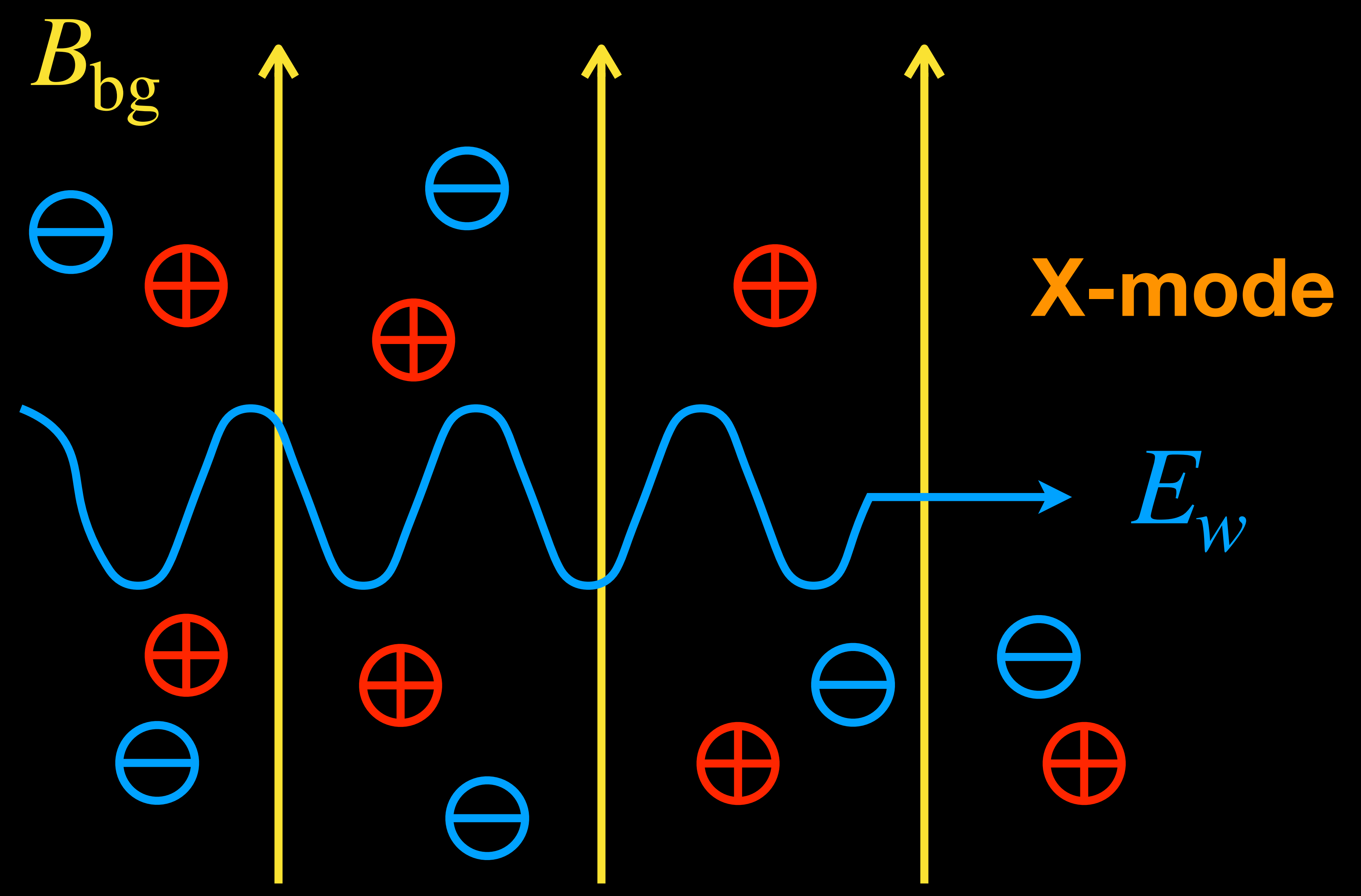
The 2nd question is

$$\tau = \int n_e \sigma dl \leq 1 \quad \textbf{?}$$

Beloborodov. 2021a

Beloborodov. 2021b

Classical scattering theory



$$a = \frac{eE_w}{m_e c\omega} \sim 10^4\ L_{\rm frb,42}^{1/2} r_9^{-1}$$

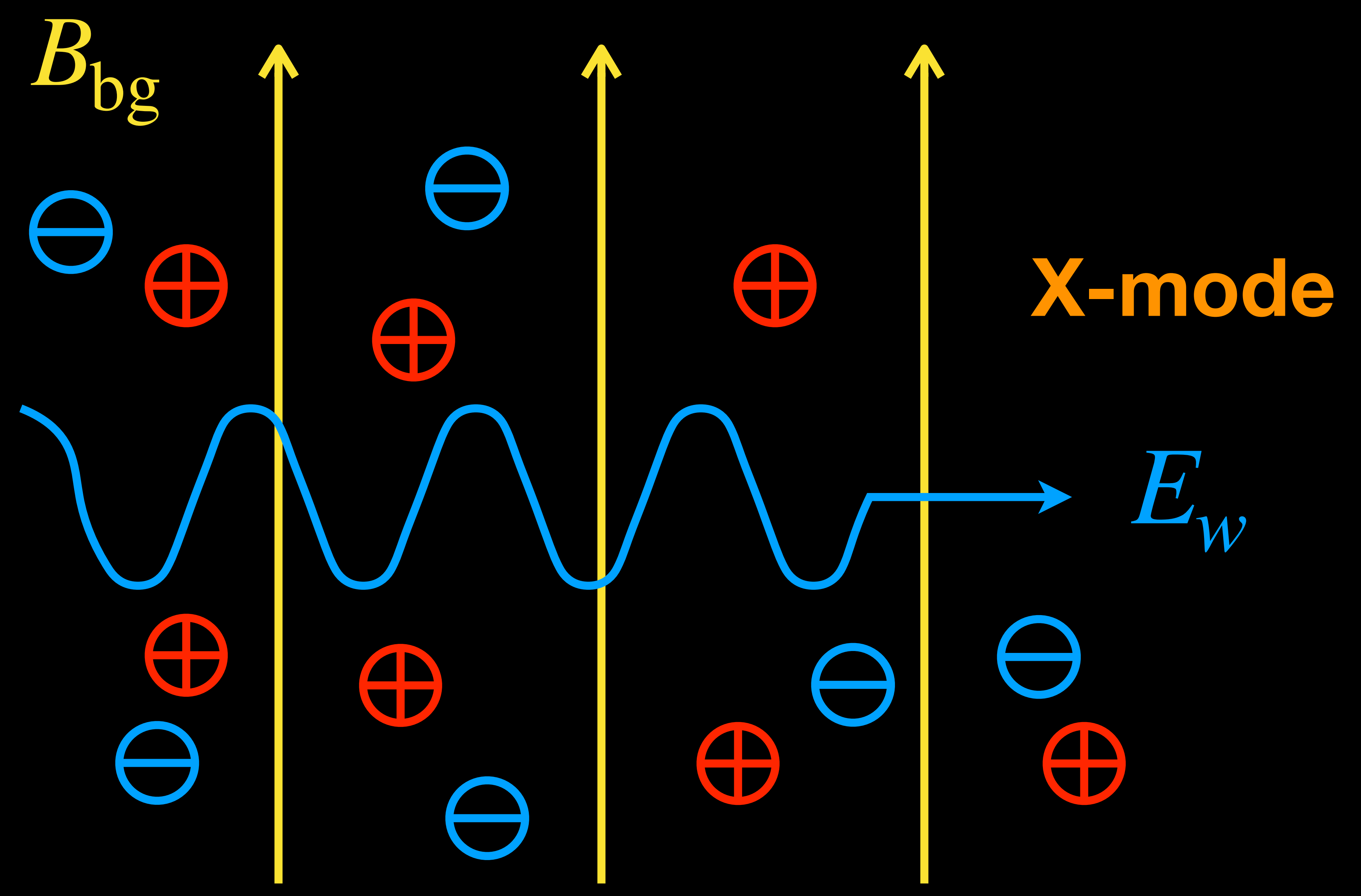
$$\frac{\omega_B}{\omega} = \frac{eB_{\rm bg}}{m_e c\omega} \sim 10^3\ r_9^{-1}$$

$$\sigma \sim \left(\frac{\omega^2}{\omega_B^2}\right)\sigma_{\rm T}$$

Assumption: $\omega_B \gg \omega \;\Rightarrow$ The cross-section is suppressed for the EM X-mode photons

Canuto et al. 1971
Gunn & Ostriker 1971
Herold, H. 1979

Classical scattering theory



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Classical theory is invalid when $E_w \gg B_{\rm bg}$

$E_w > B_{\rm bg} \Rightarrow a > \frac{\omega_B}{\omega}$ $\qquad \sigma \simeq a^2 \sigma_{\rm T}$

Within the magnetosphere
$\omega_{\rm FRB} \ll \omega_p \ll \omega_B$
$E_w \sim r^{-1}$
$B_{\rm bg} \sim r^{-3}$
Magnetar
Emission point
$r_{\rm em}$
FRB
$\sim 10^7 - 10^8$ cm
Turning point
$R_{\rm E}$
$E_w > B_{\rm bg}$
$\sim 10^9$ cm
$\min(R_\omega, R_{\rm lc})$
$\sim 4.8 \times 10^9$ cm
Light cylinder

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$\omega_{\rm FRB} \ll \omega_p \ll \omega_B$
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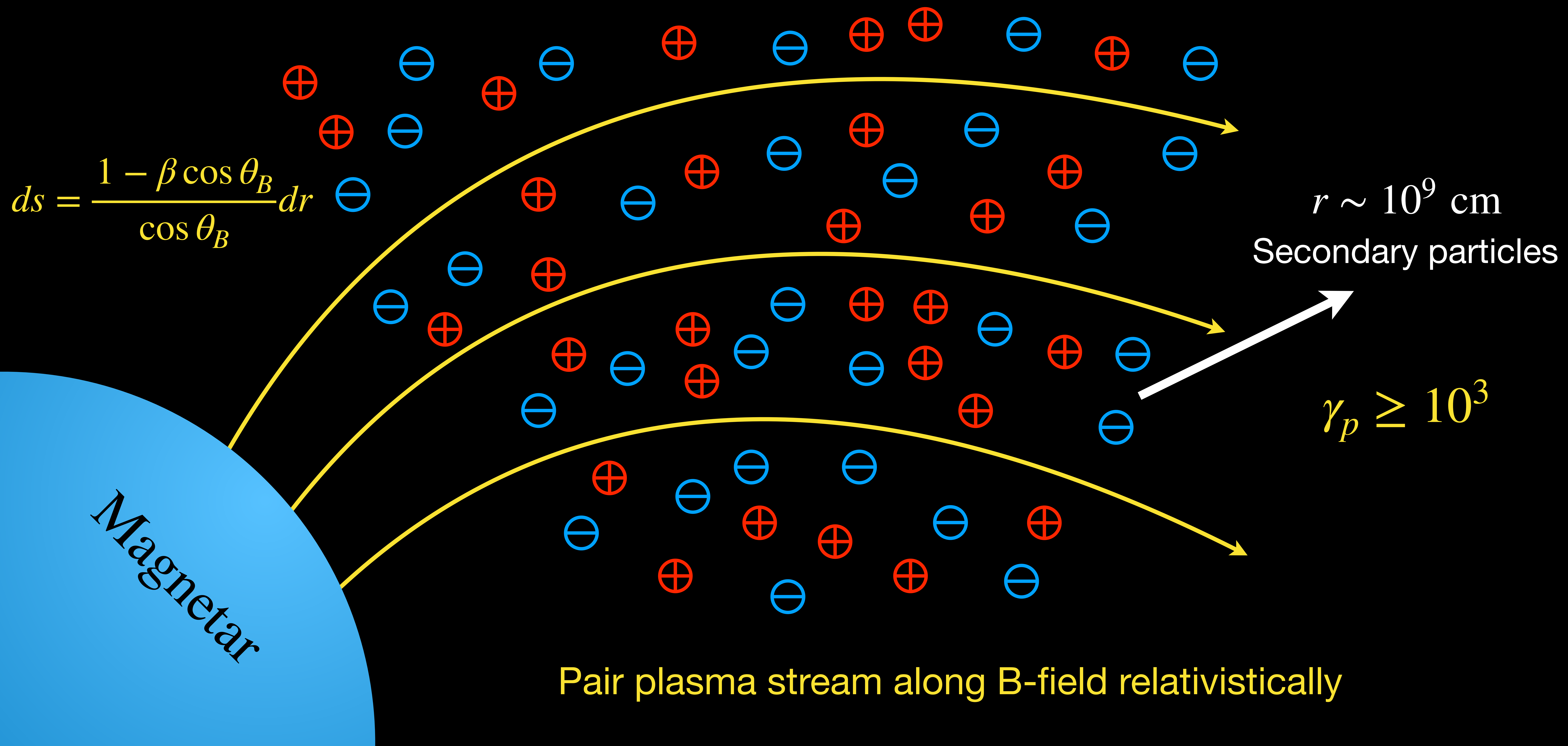
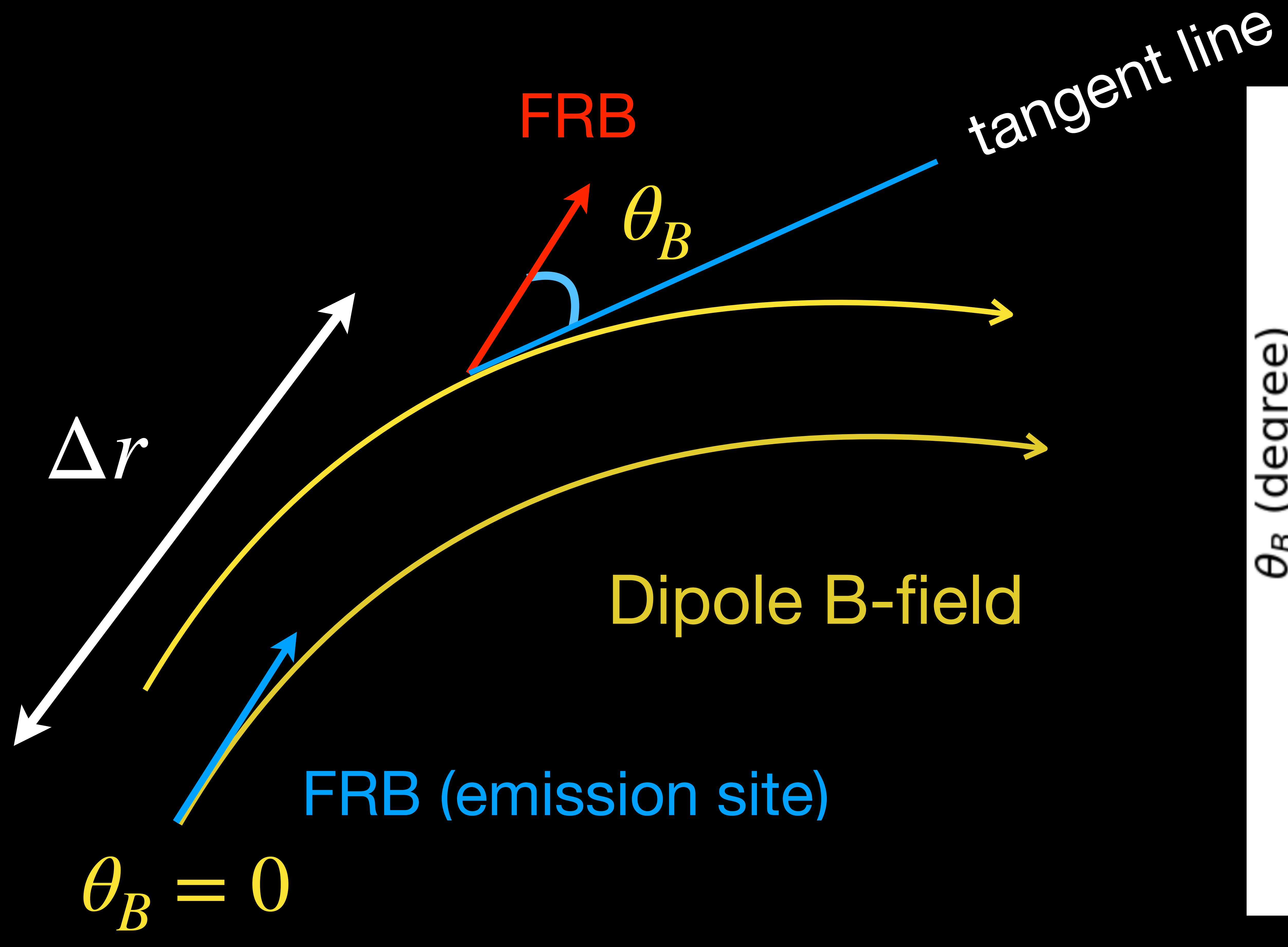
$E_w > B_{\rm bg}$
$\sim 10^9$ cm
Emission point
$r_{\rm em}$
FRB
$\sim 10^7 - 10^8$ cm
Magnetar
Strong wave effect dominates!
Light cylinder

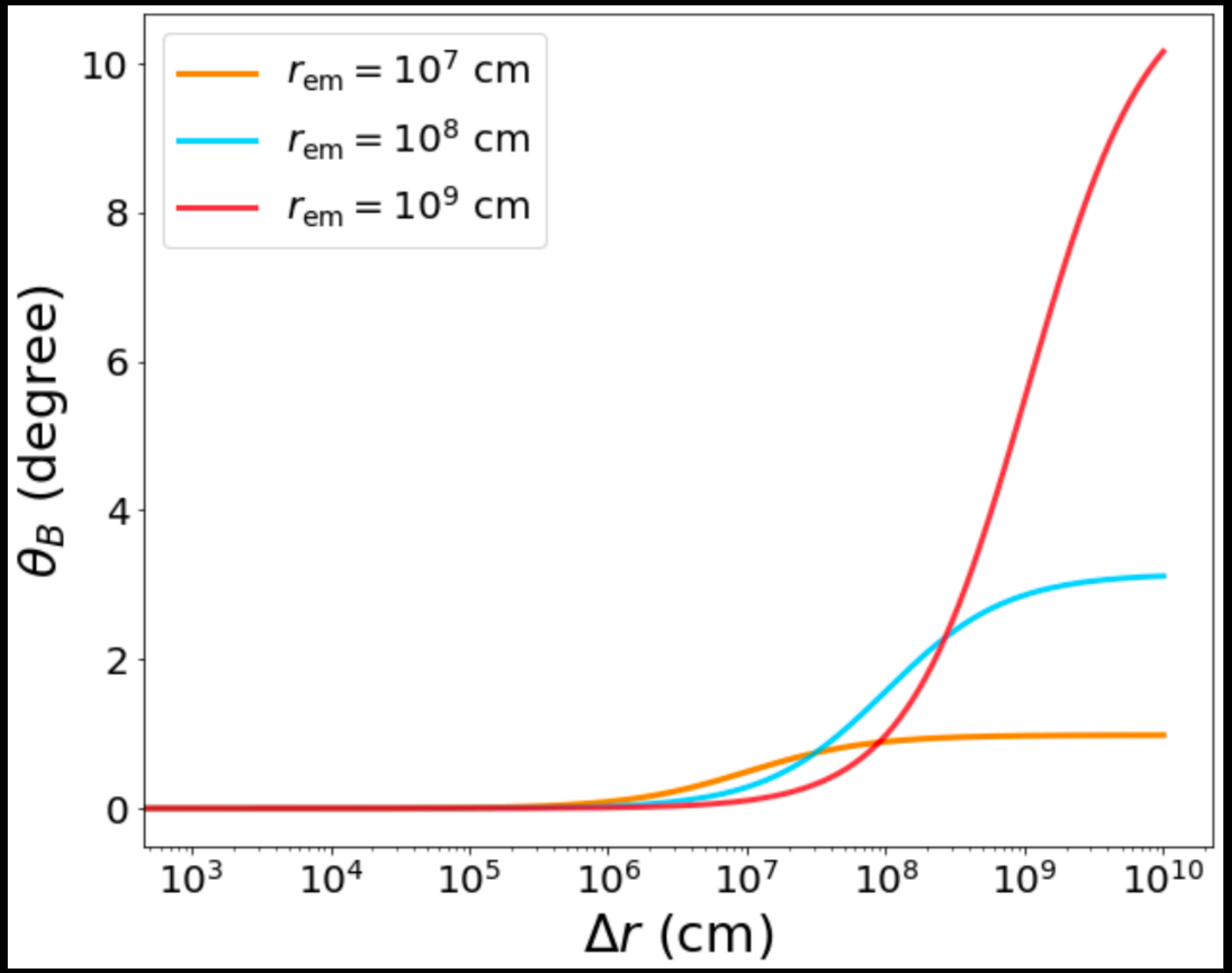
Standard NS magnetosphere scenario



Pair plasma stream along B-field relativistically

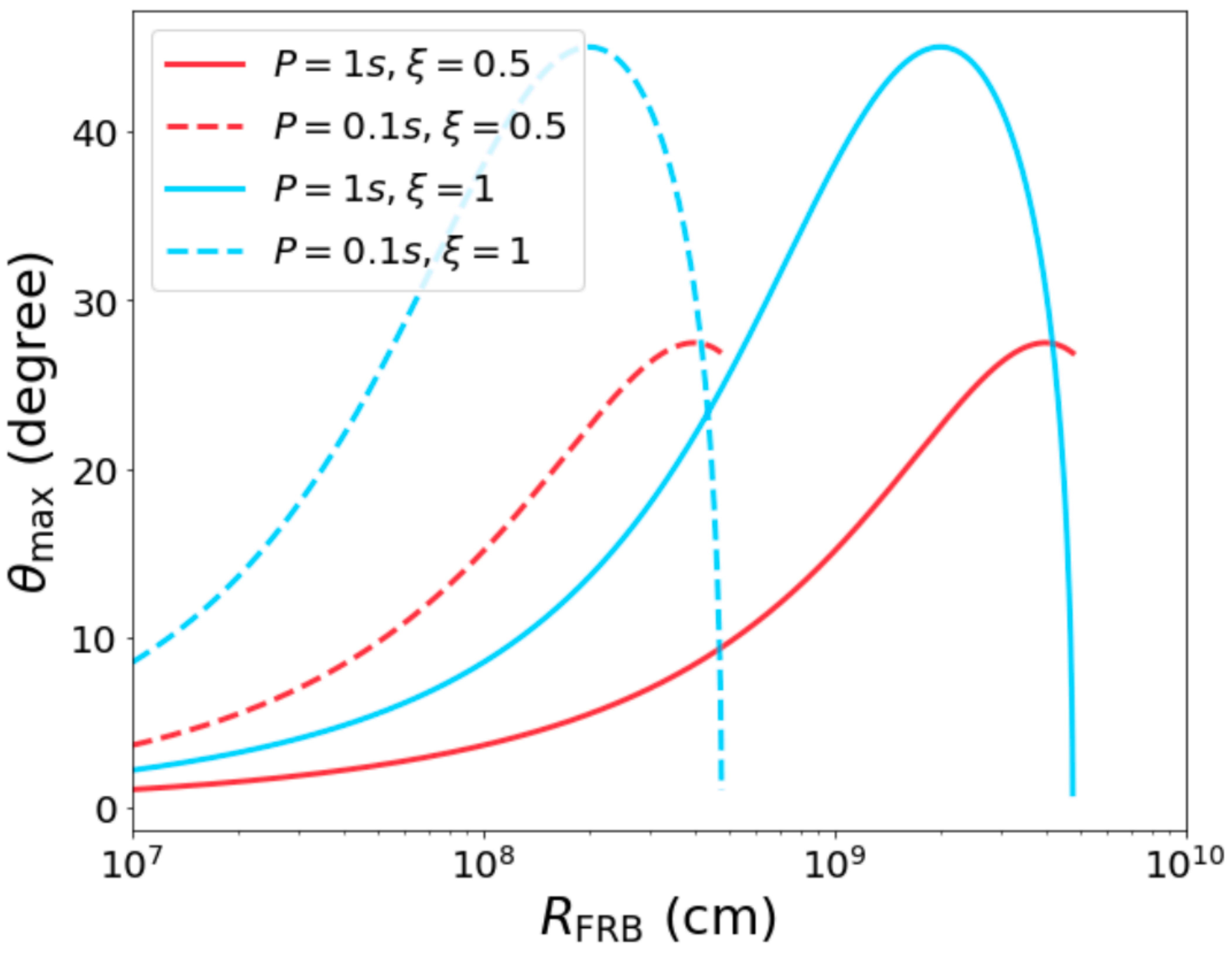
Angle between k-B is important to cross section

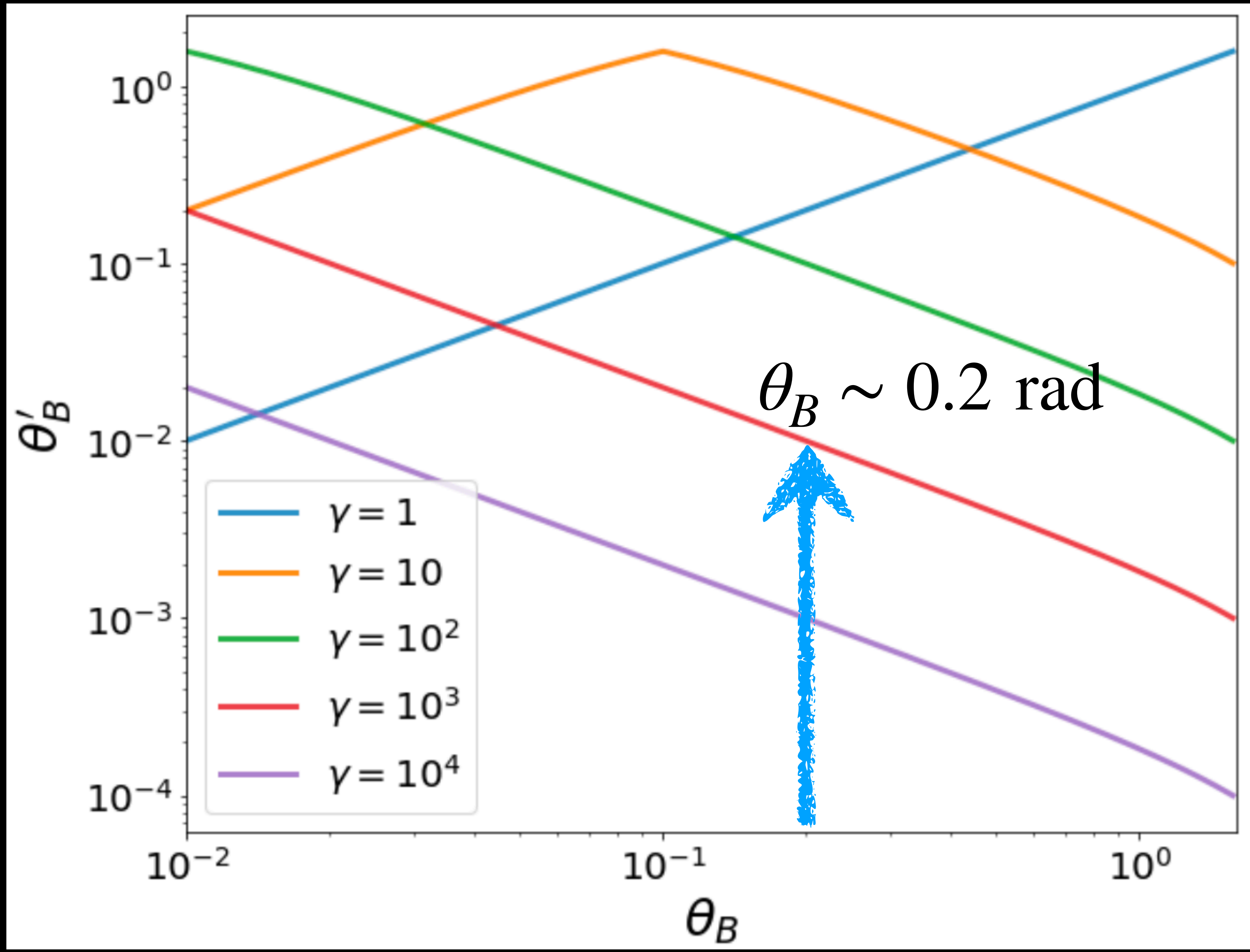




Qu, Kumar & Zhang 2022 (2204.10953)

Fiducial value: $P = 1$ s $R_{\rm FRB} = 10^8$ cm $\theta_{\rm max} \sim 10$ degree ~ 0.2 rad



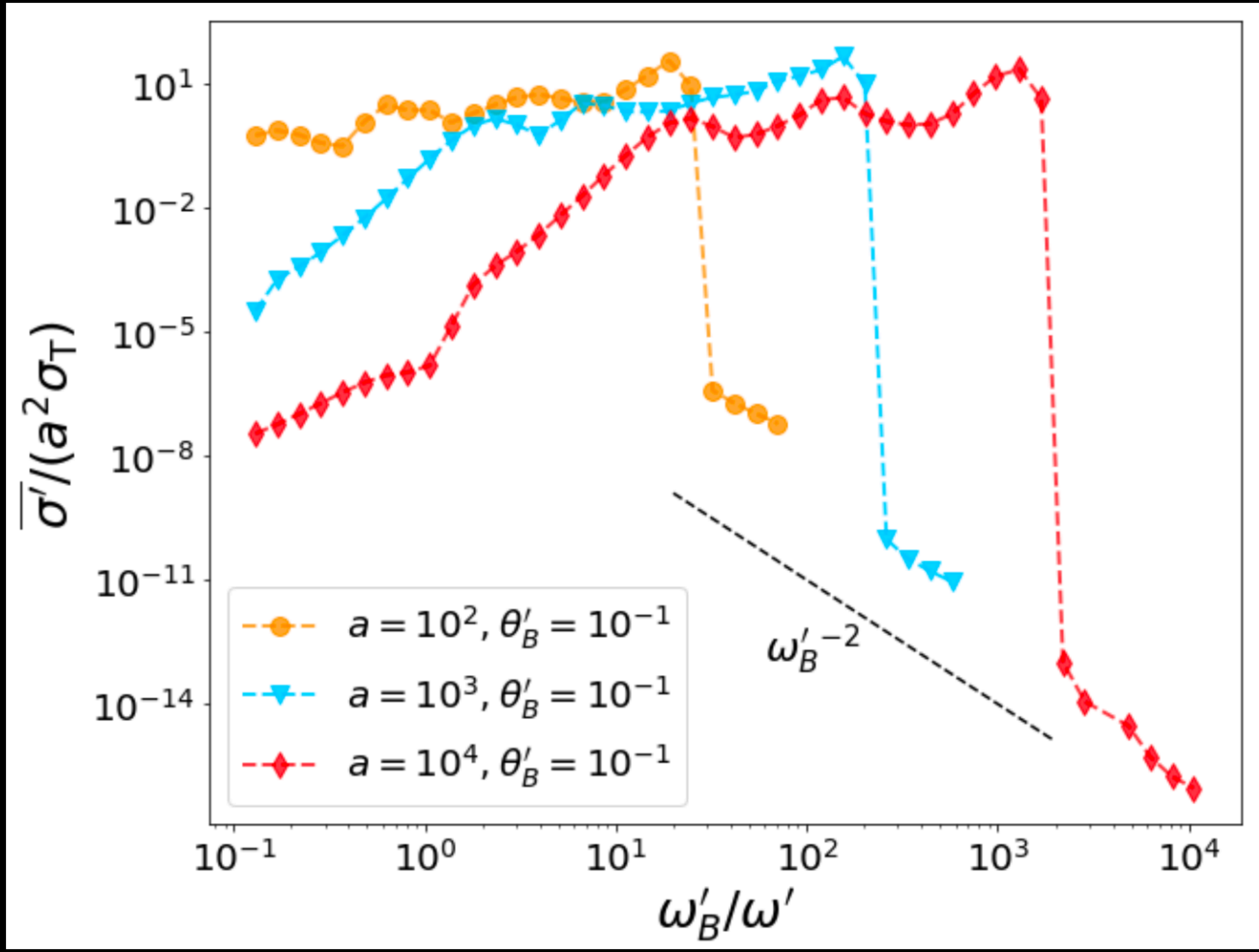


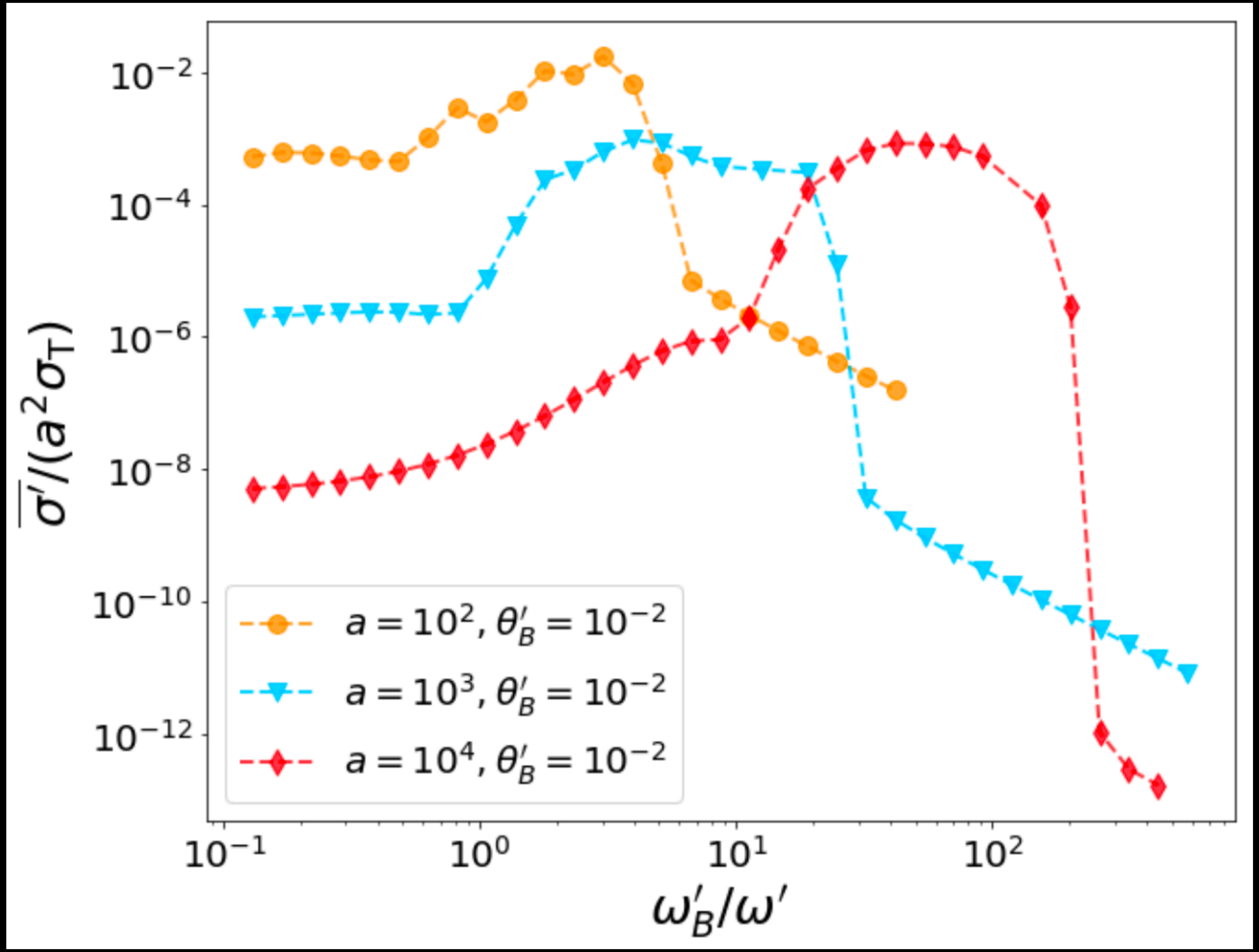
Maximum angle θ_B

Transformation to the plasma co-moving frame

Qu, Kumar & Zhang 2022 (2204.10953)

Numerical Results

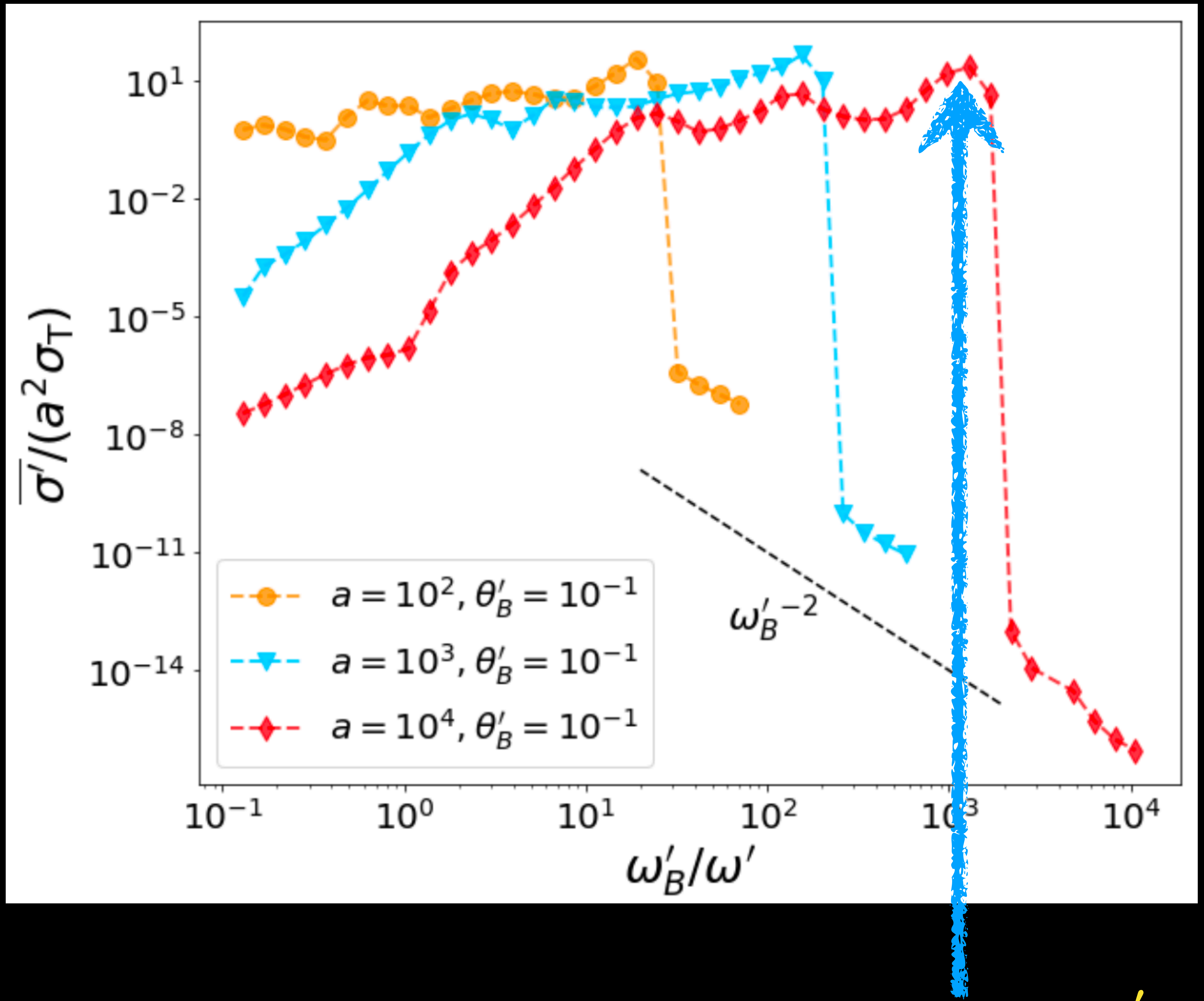




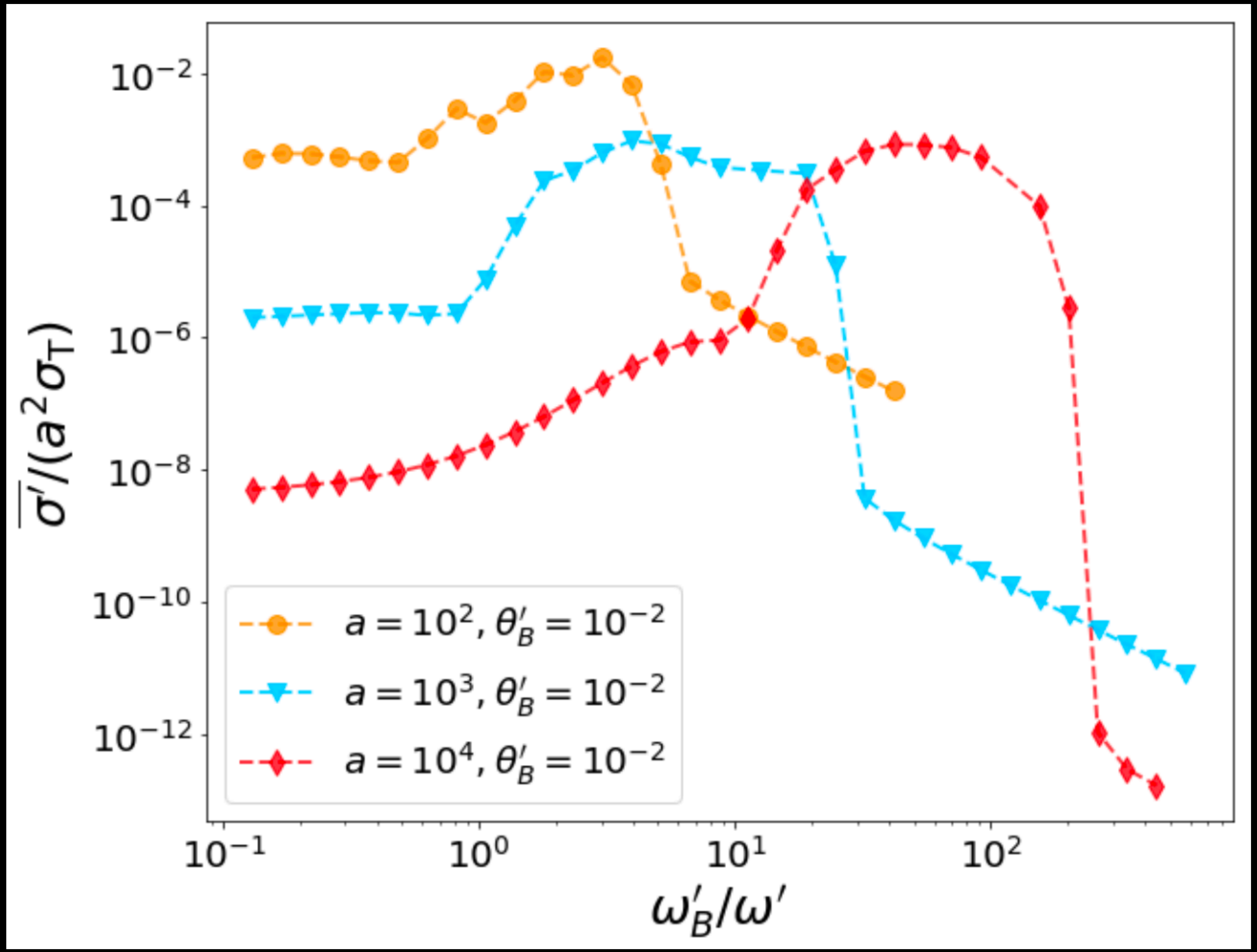
Qu, Kumar & Zhang 2022 (2204.10953)

Numerical Results

$\theta'_B = 10^{-1}$ rad



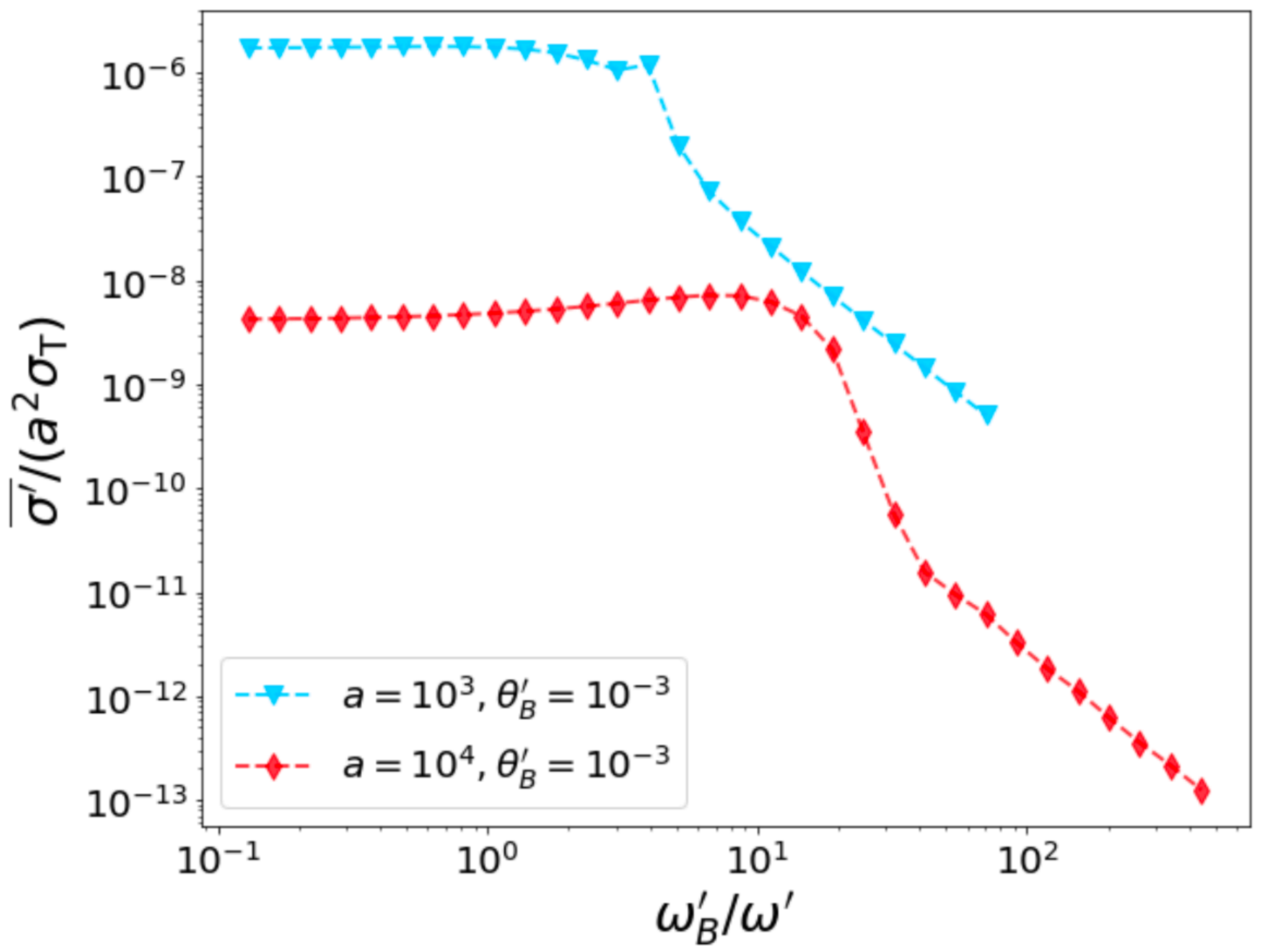
$\theta'_B = 10^{-2}$ rad



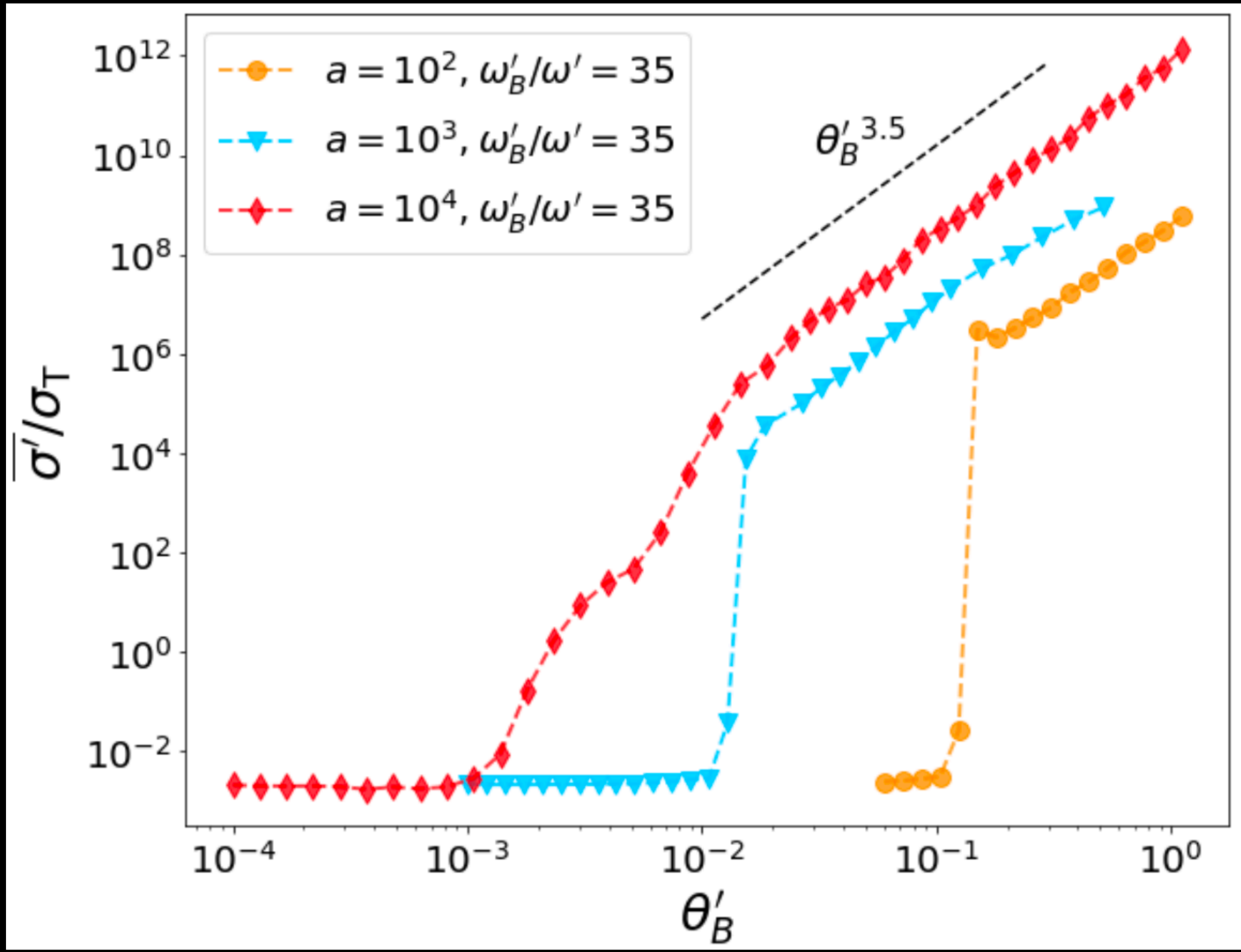
New turning point $\frac{\omega'_B}{\omega'} = a\theta'_B$

Numerical Results

$\theta'_B = 10^{-3}$ rad



$\sigma' \sim \theta_B'^{3.5}$



Smaller θ_B, smaller cross section

Within the magnetosphere
$\omega_{\rm FRB} \ll \omega_p \ll \omega_B$
FRB can propagate freely
Turning point
$\max(R_{\theta_B}, R_{\rm E})$
$\min(R_\omega, R_{\rm lc})$
$\sim 4.8 \times 10^9$ cm
Emission point
$r_{\rm em}$
FRB
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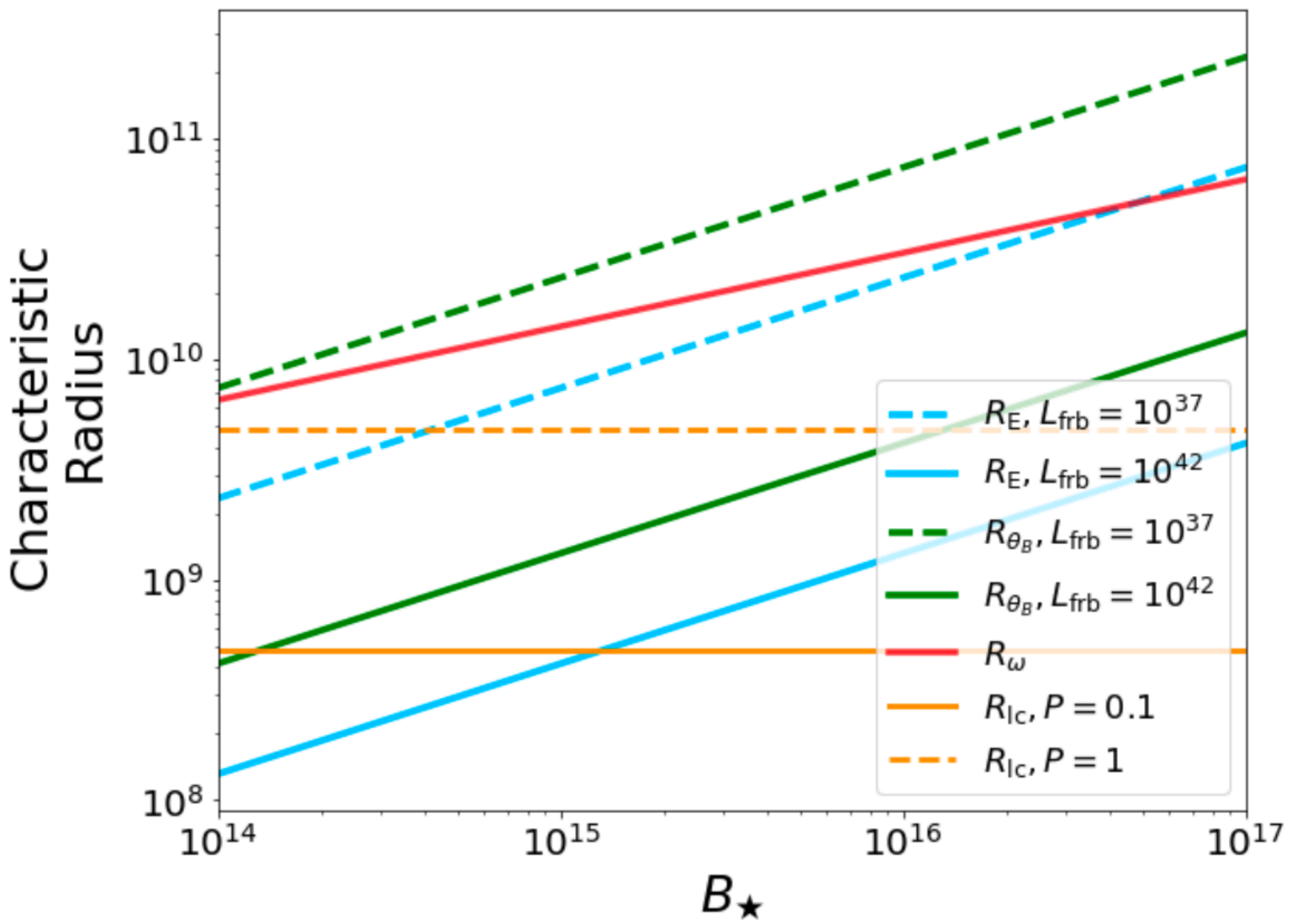
Characteristic radius

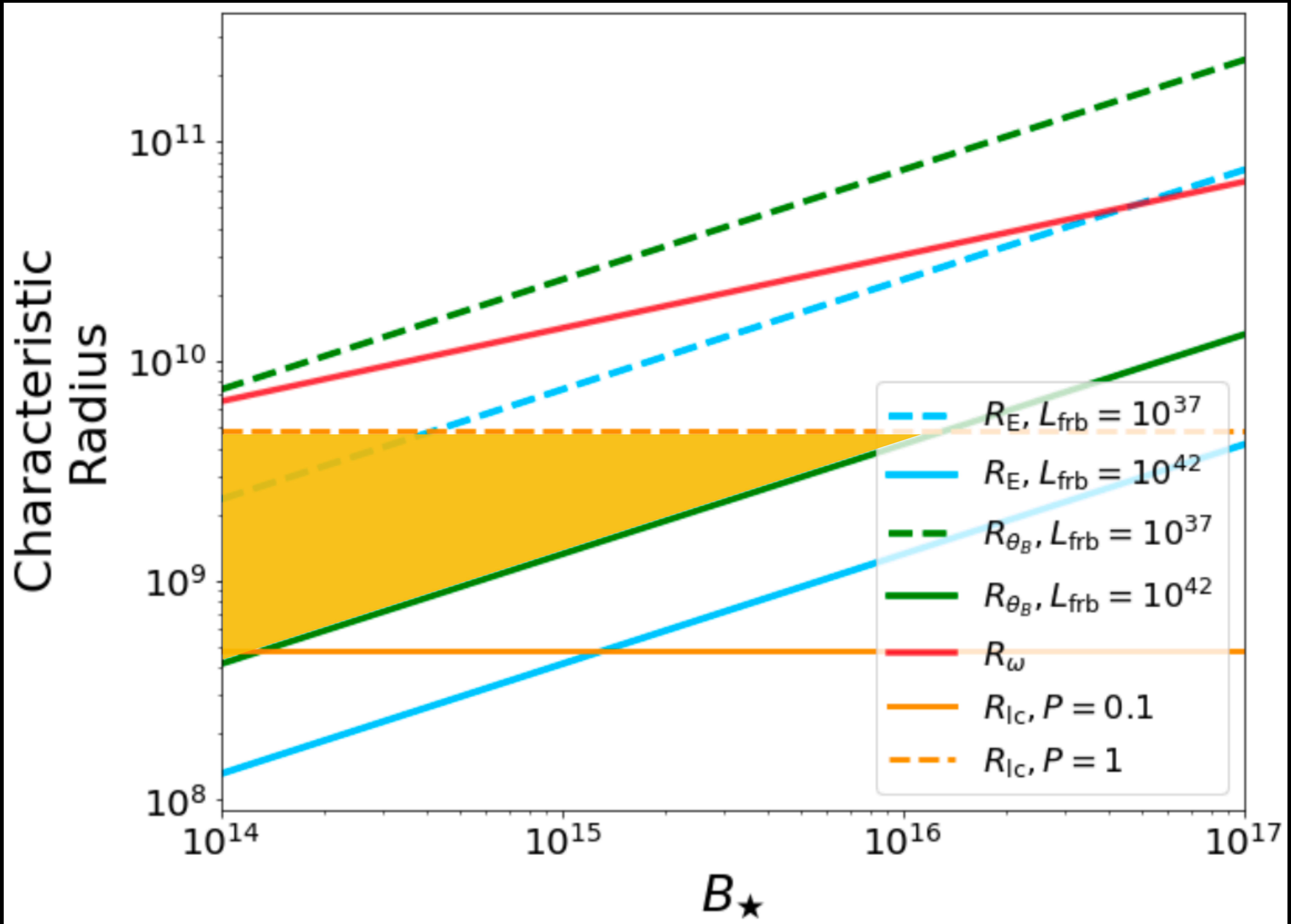


$$\max(R_E, R_{\theta_B}) \leq R \leq \min(R_\omega, R_{lc})$$

Characteristic radius

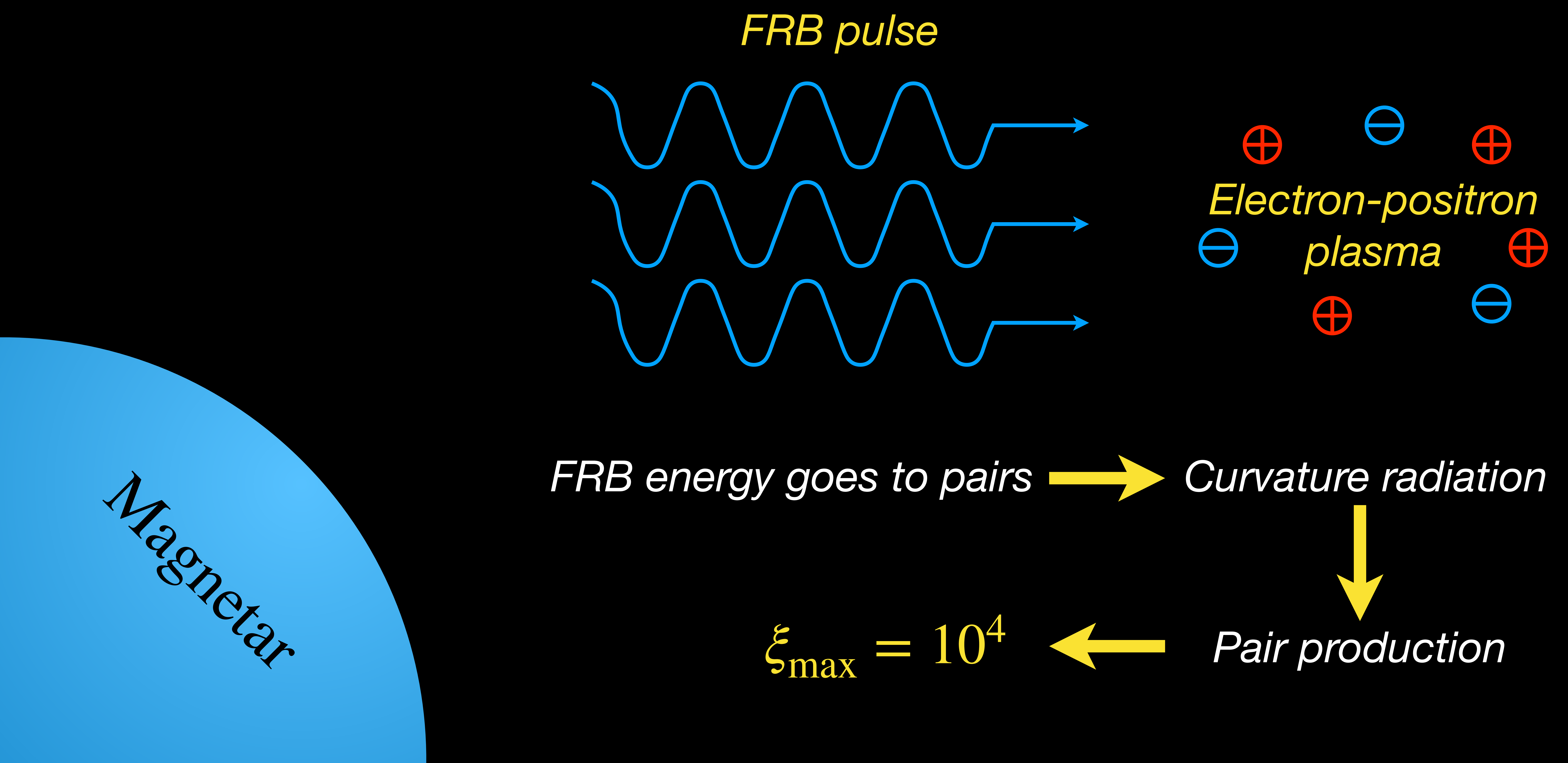
$L_{\mathrm{frb}} = 10^{42}$ erg s^{-1}

$P = 1$ s



$$\max(R_\mathrm{E}, R_{\theta_B}) \leq R \leq \min(R_\omega, R_\mathrm{lc})$$

Estimation of maximum multiplicity

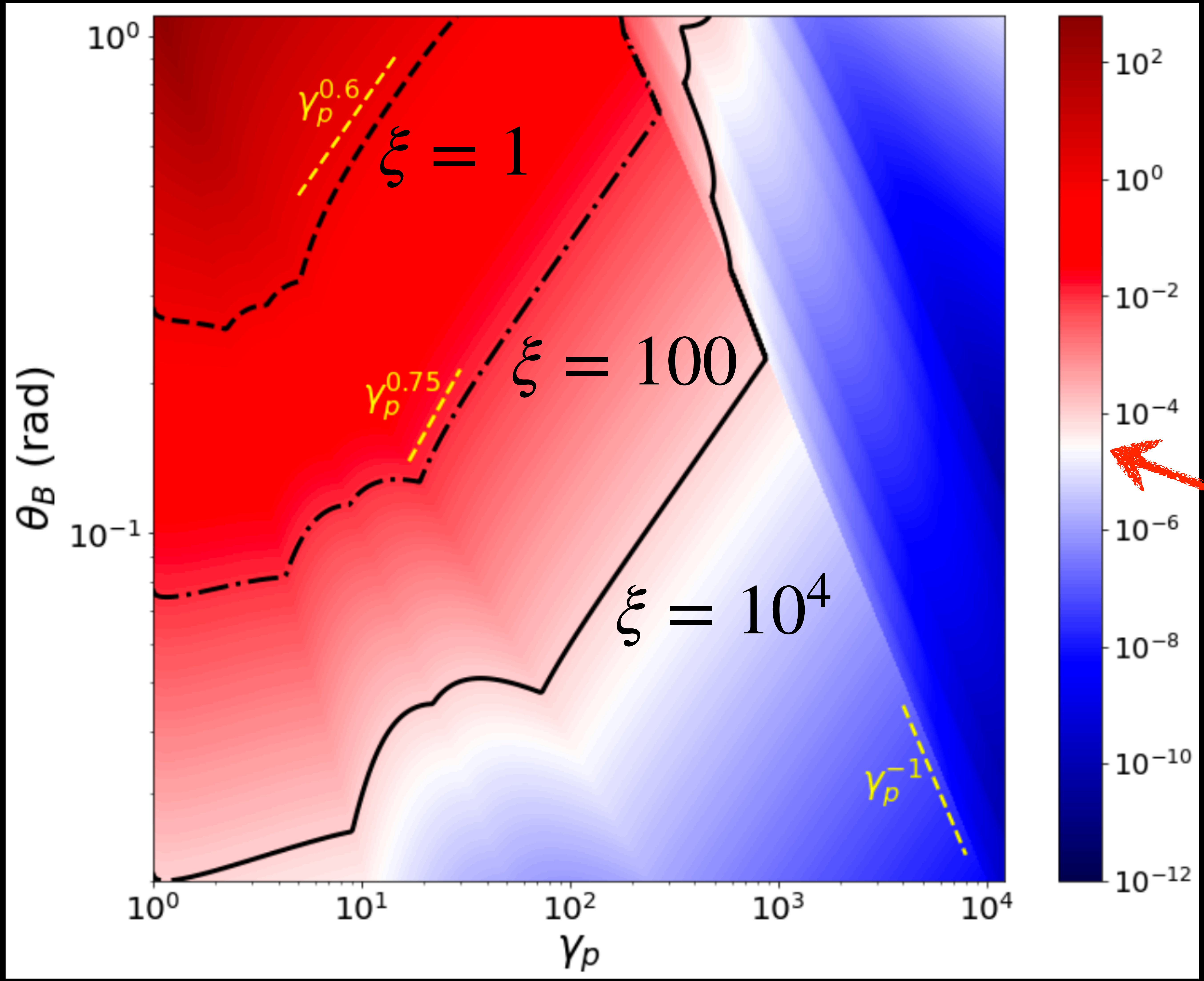


Optical depth as a function of γ_p and θ_B

Transparency condition

$\tau = 1$

(The three black lines)



optical depth

Qu, Kumar & Zhang 2022 (2204.10953)

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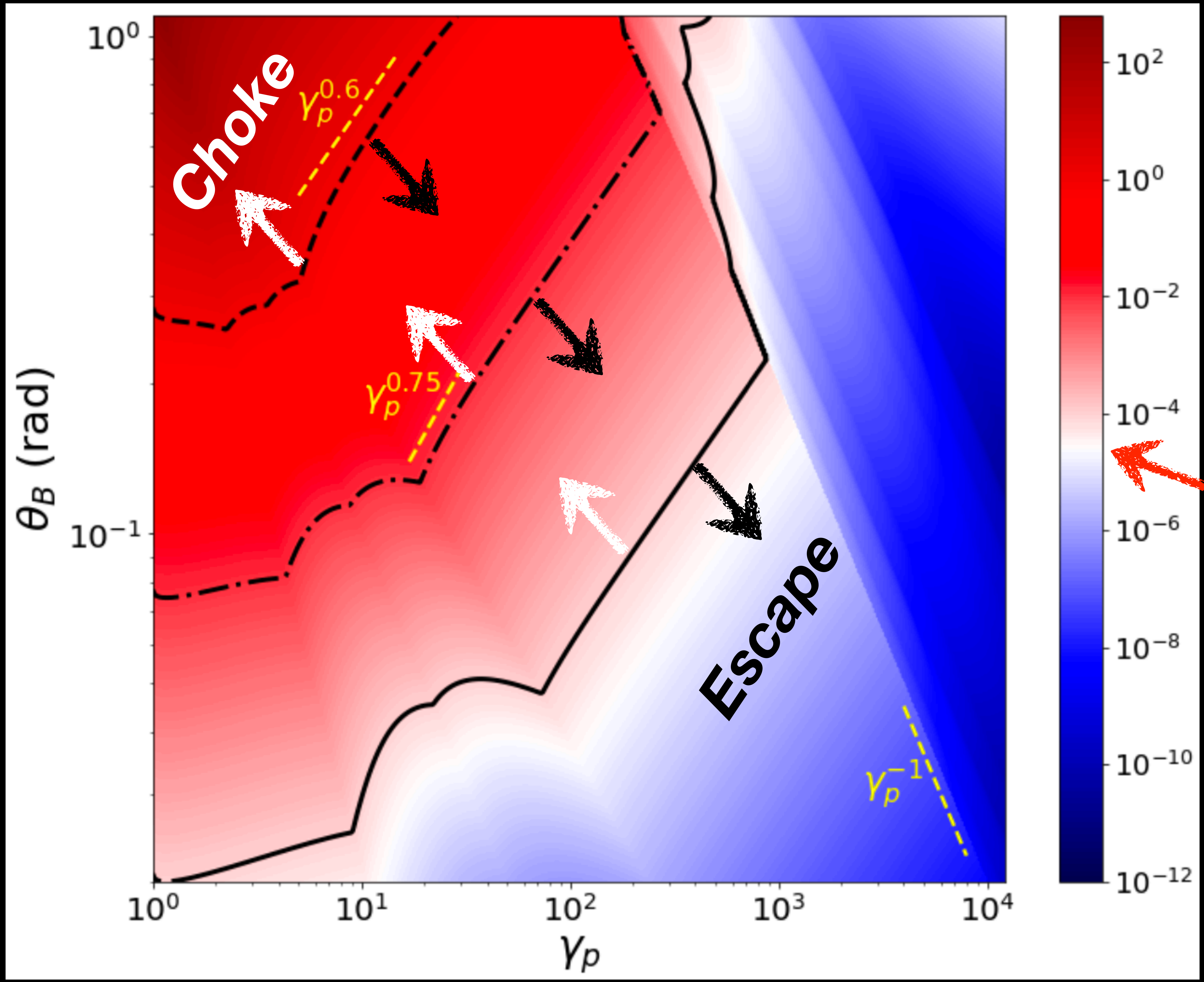

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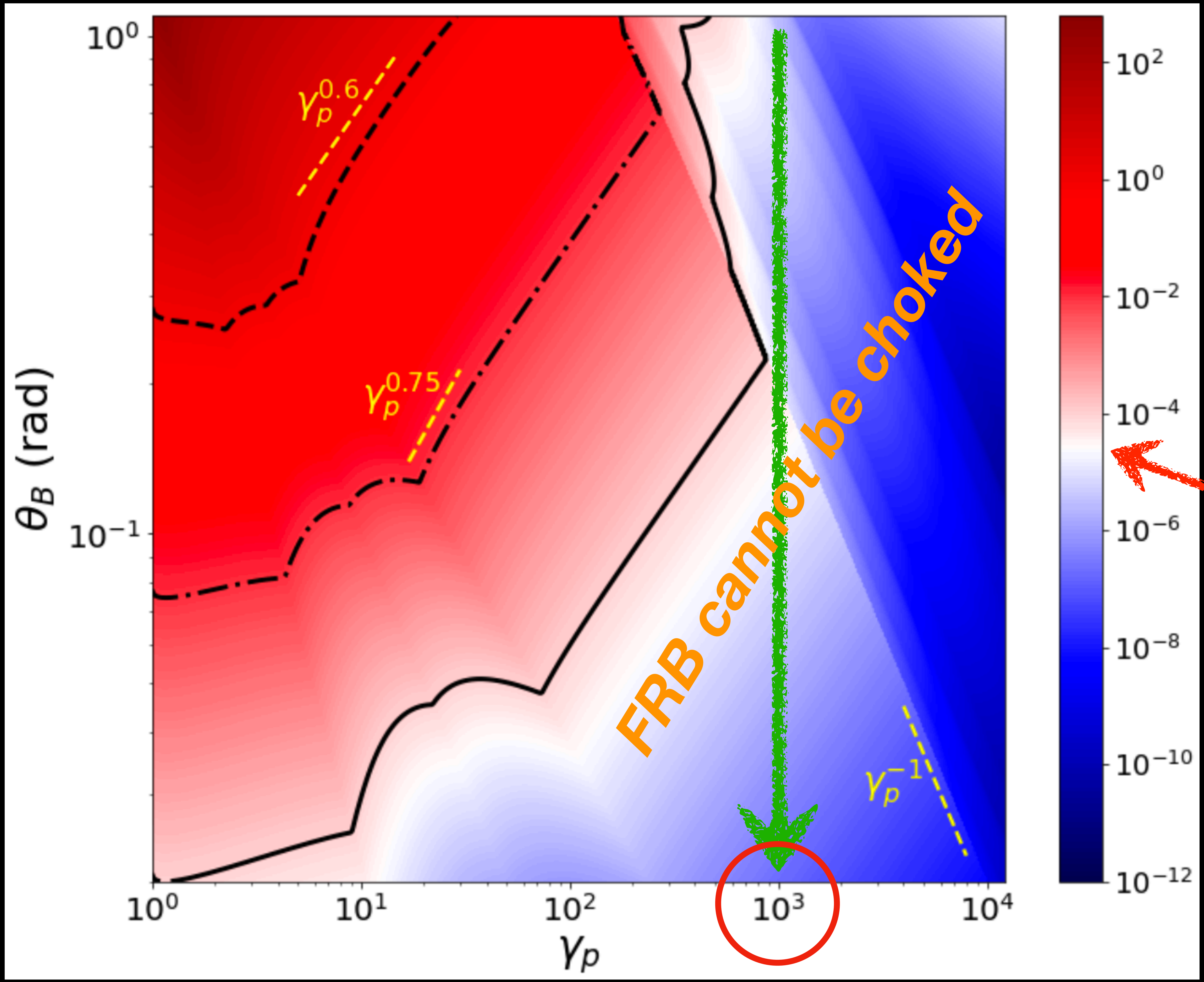

optical depth

Qu, Kumar & Zhang 2022 (2204.10953)

Summary

1. The detection or non-detection of neutrino may provide a diagnosis on the radio emission site in magnetars.

2. The plasma suppression effect can be ignored in the bunching mechanisms.

3. FRB can propagate freely in the magnetar magnetosphere.