

Crust Quakes Triggering FRBs and Nonlinear Scattering

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Outline:

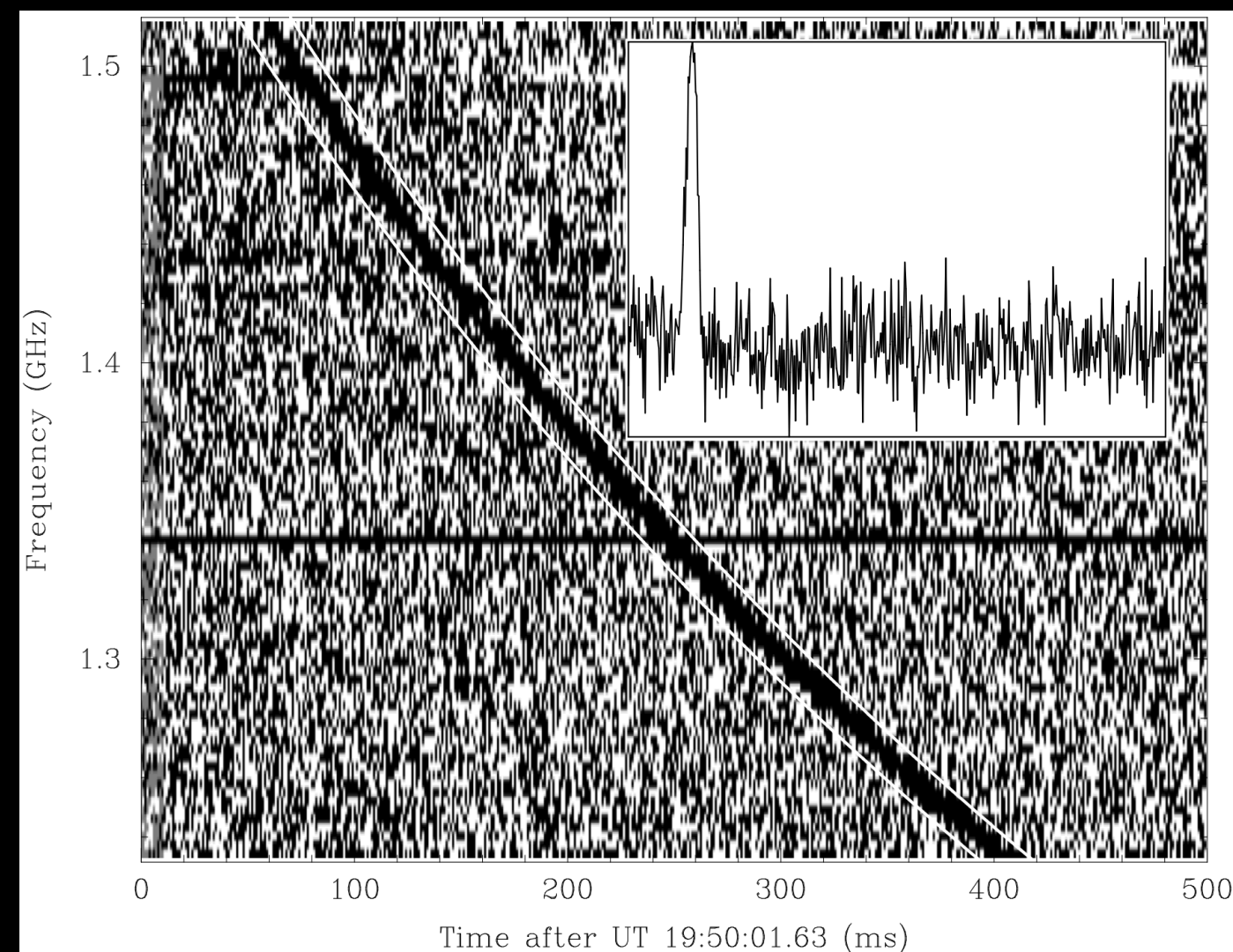
★ **Magnetar crust quakes**

★ **Nonlinear scattering**

with: Bing Zhang (HKU, UNLV), Pawan Kumar (UT Austin), Ashley Bransgrove (Princeton)

Fast Radio Bursts

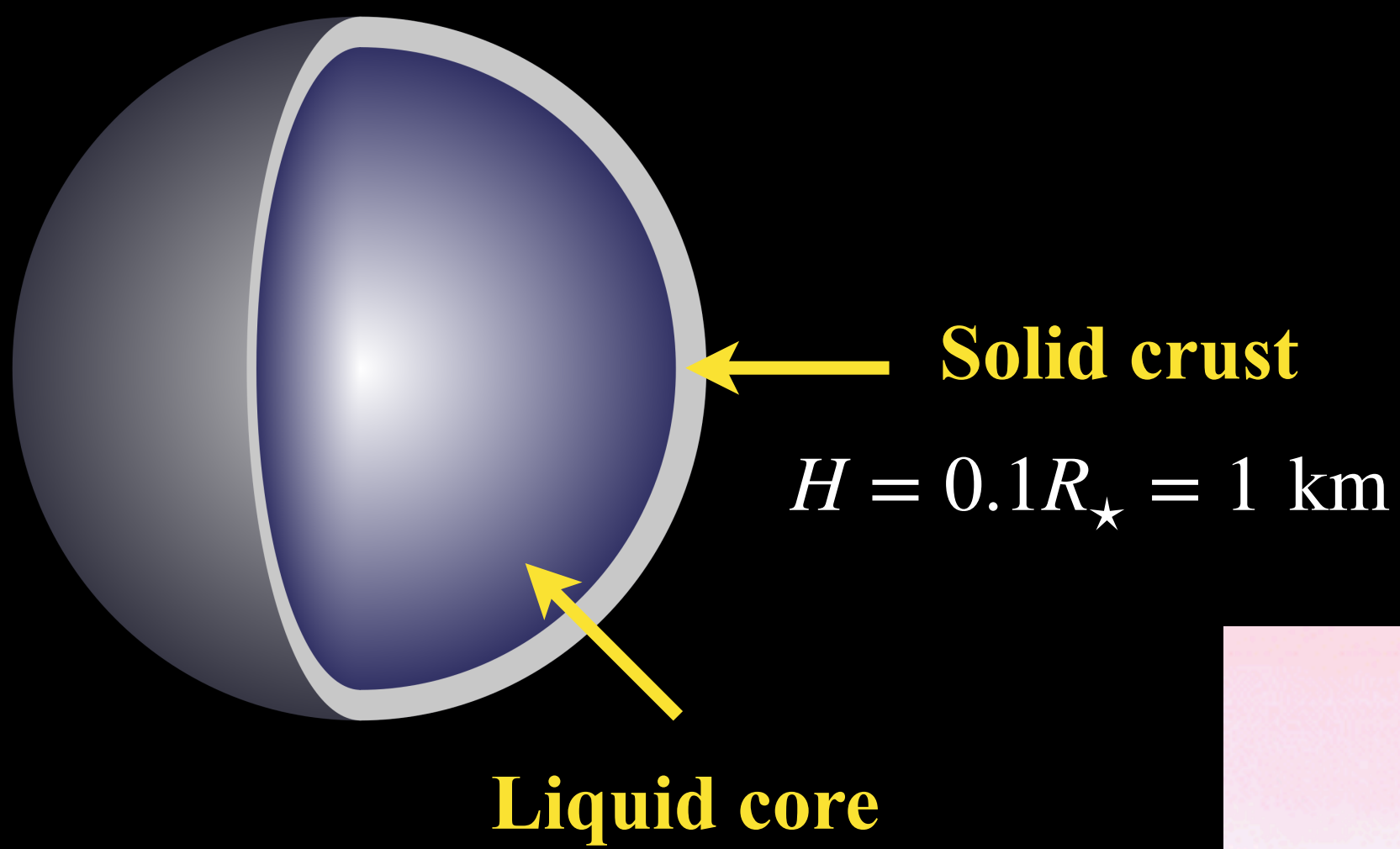
Lorimer et al. 2007



0. Some magnetars can produce FRBs

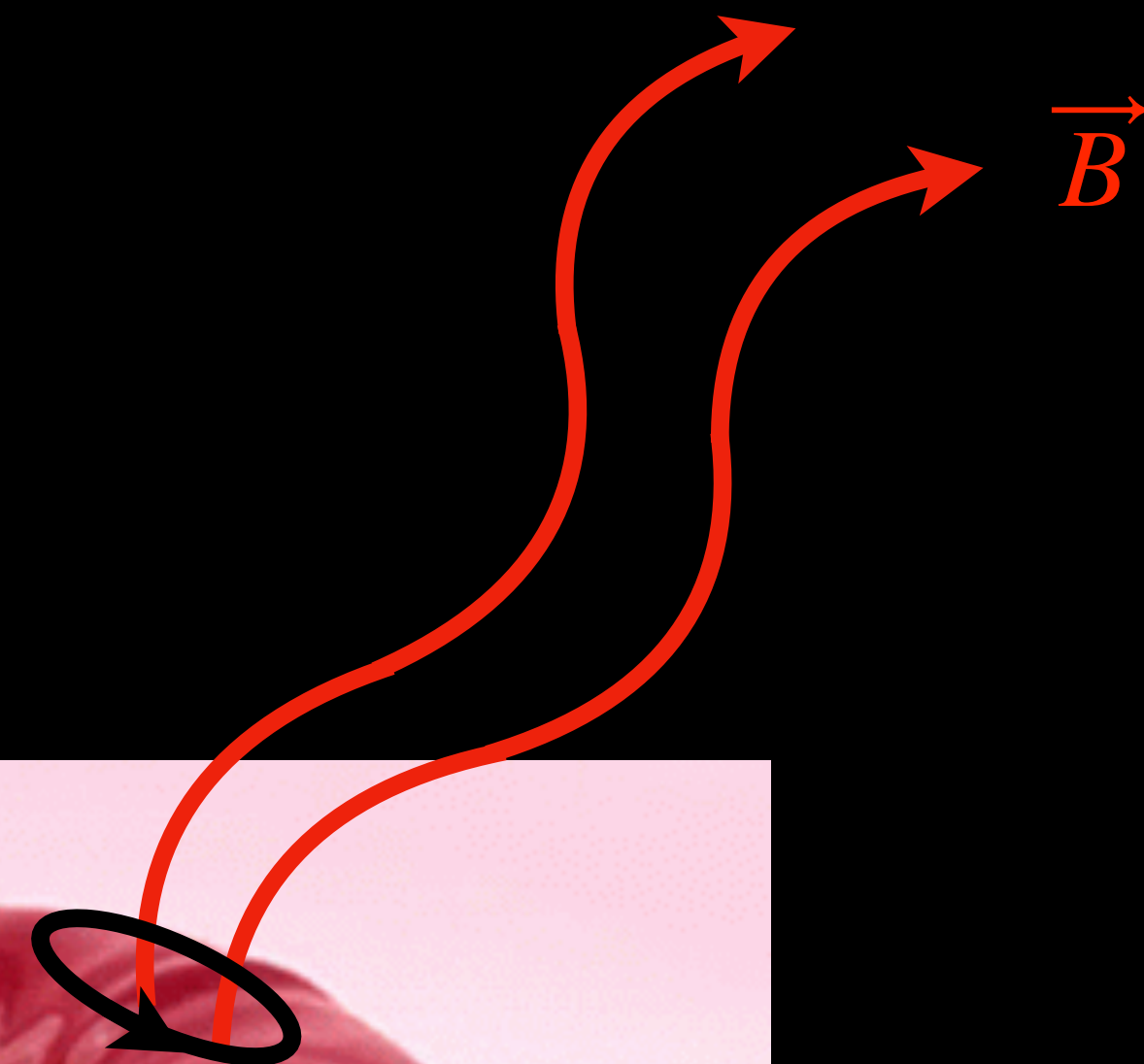
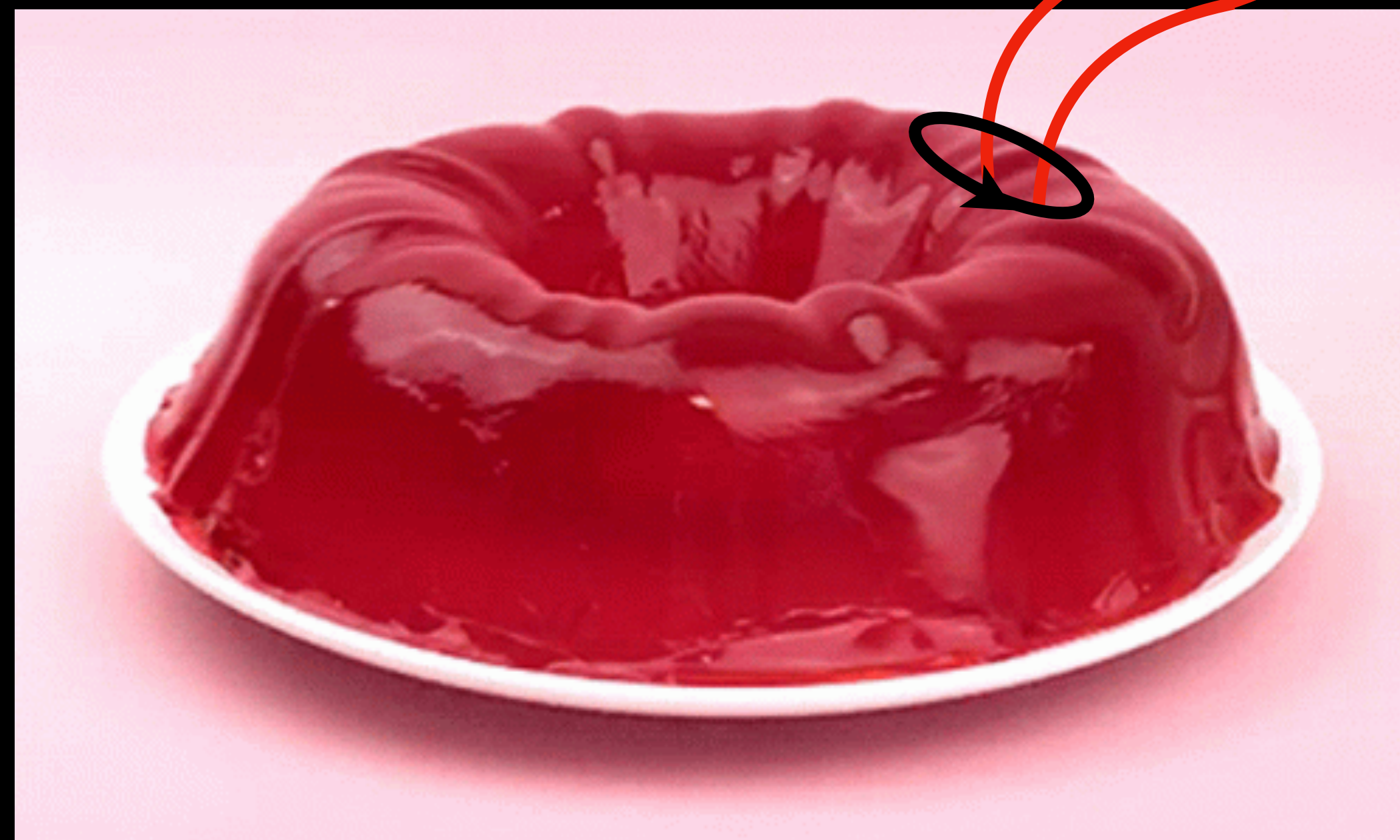
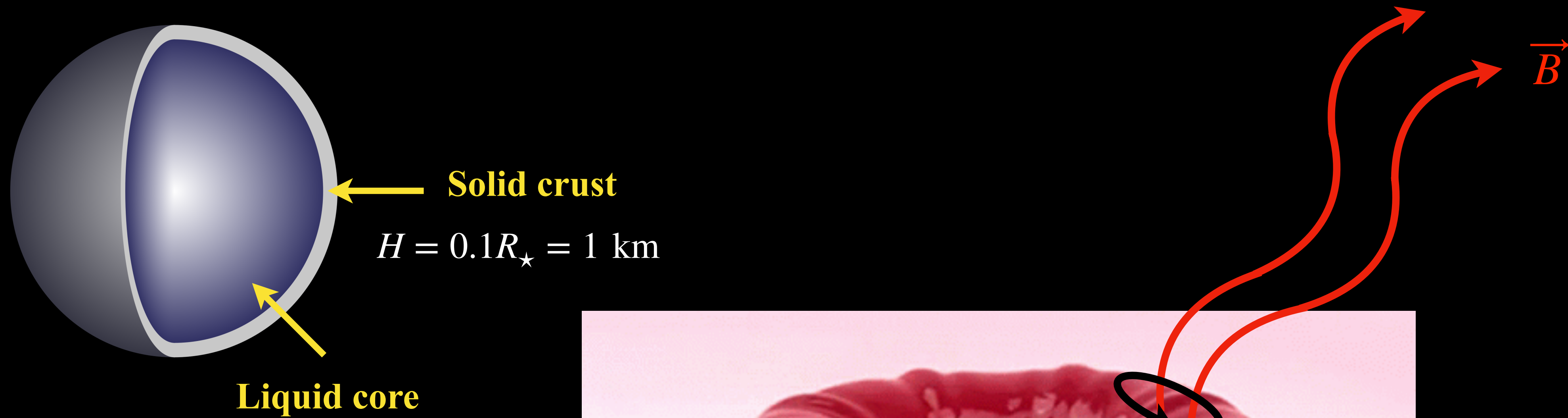
1. FRB radiation mechanisms are triggered by **two MHD modes**:
Alfvén and fast magnetosonic waves

2. FRBs are **strong** waves



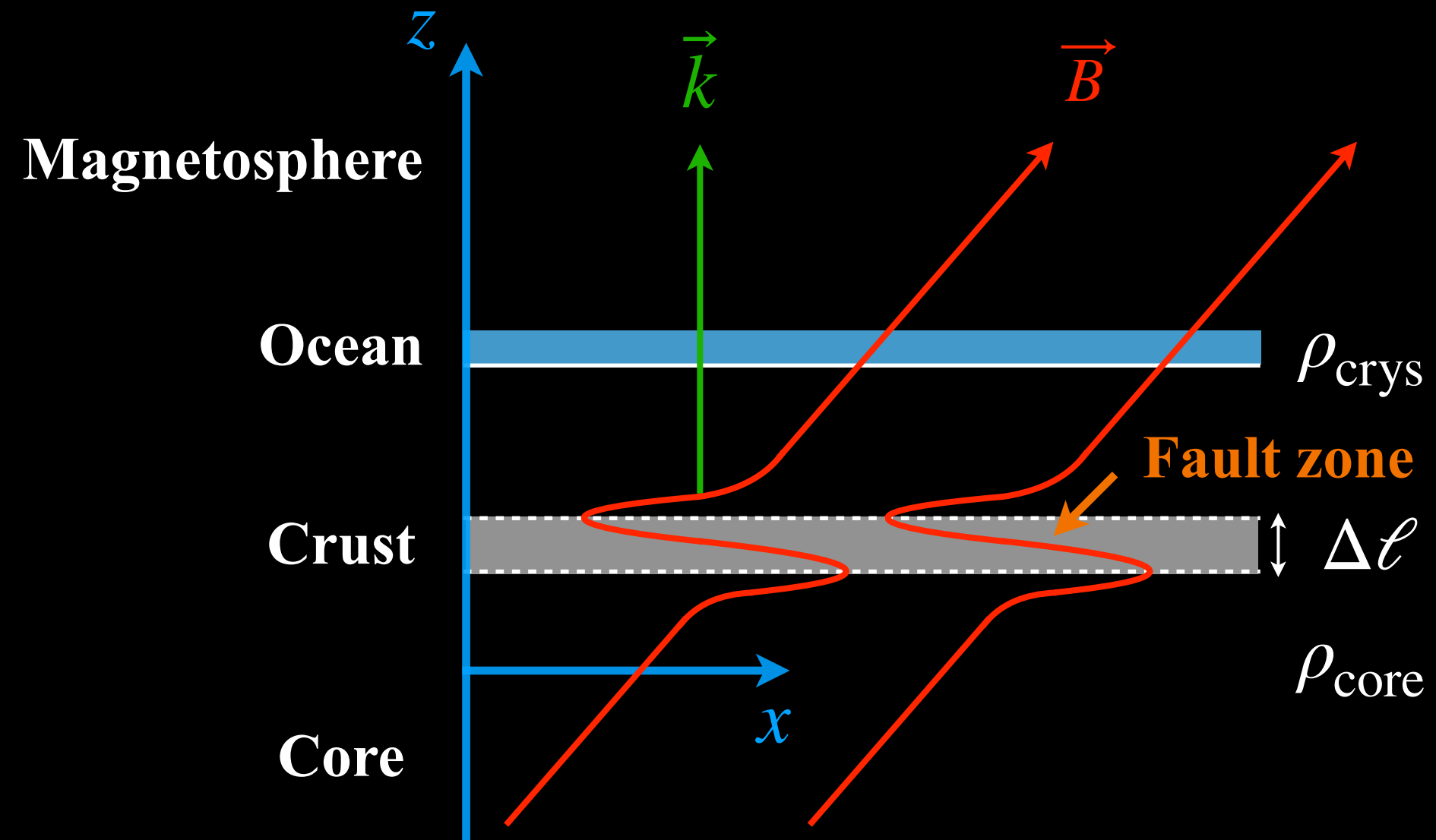
Crust is not perfectly rigid

$\vec{B}$



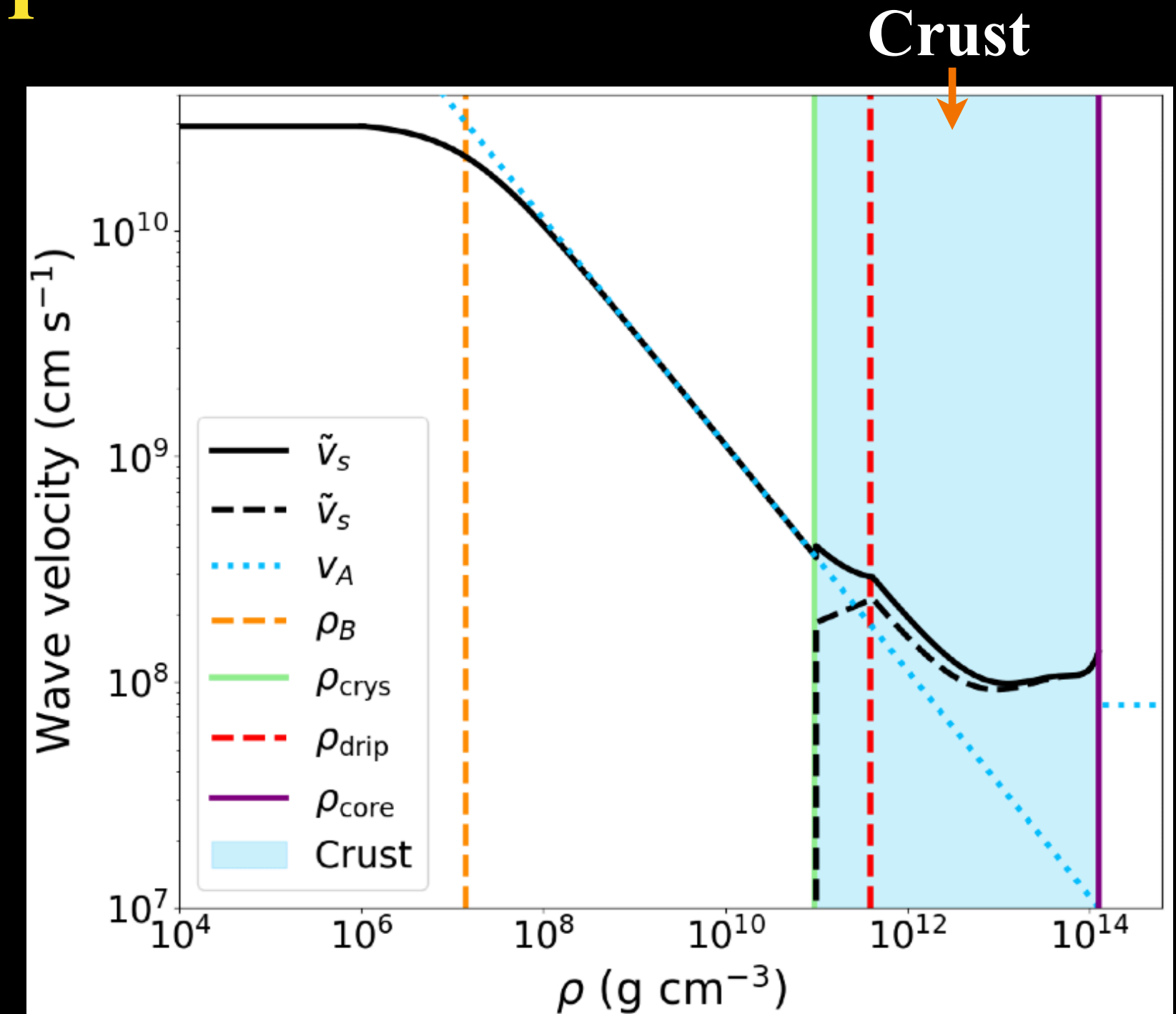
B-field and crust are moving together and launching waves into the magnetosphere

Magnetar crust quakes



Magnetic stress is very large to break the crust.
The horizontal displacements are incompressible

$$E_Q \approx \mu \epsilon_{\text{yield}}^2 \Delta\ell A \approx (10^{43} \text{ erg}) A_{Q,11} \Delta\ell_4$$



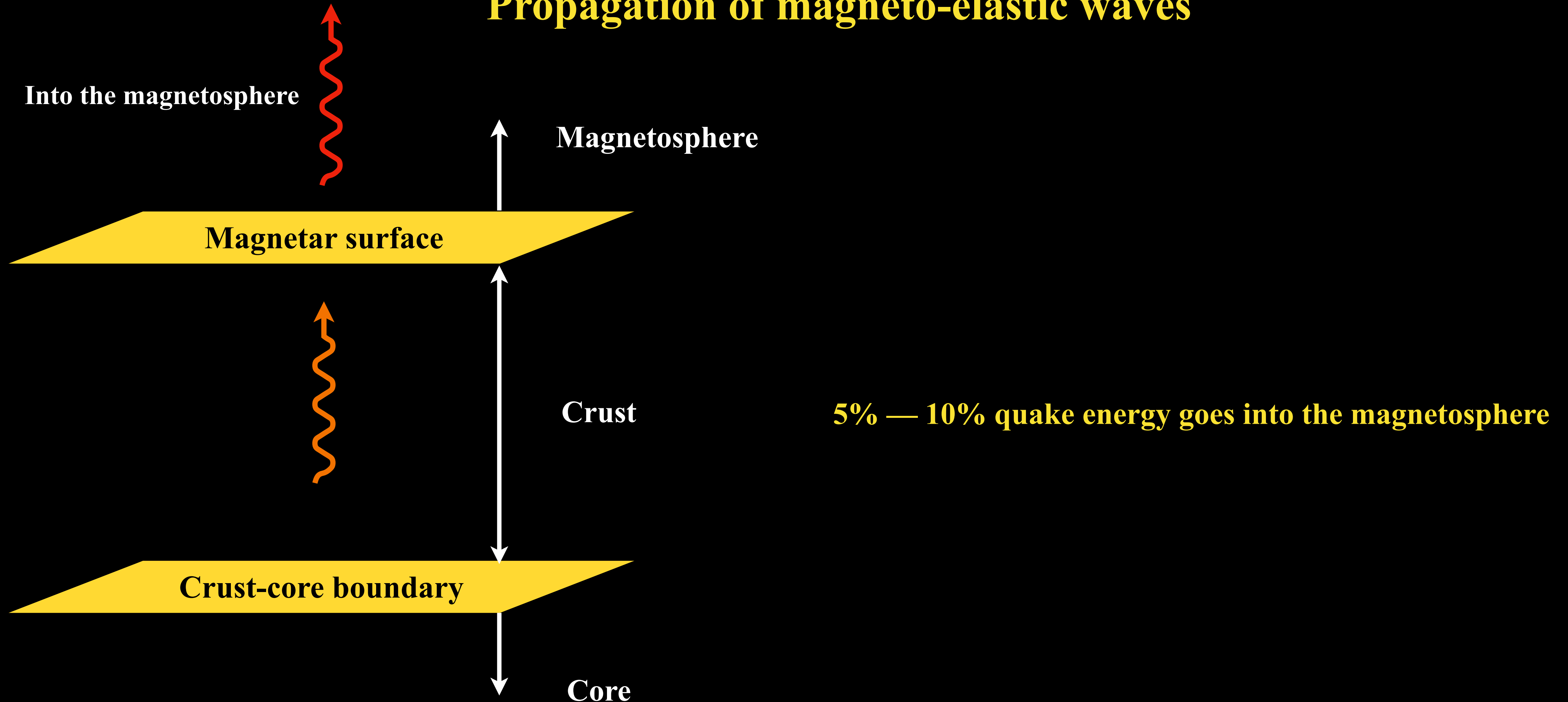
Magneto-elastic wave speed in the crust

$$\tilde{v}_s \sim 0.01c$$

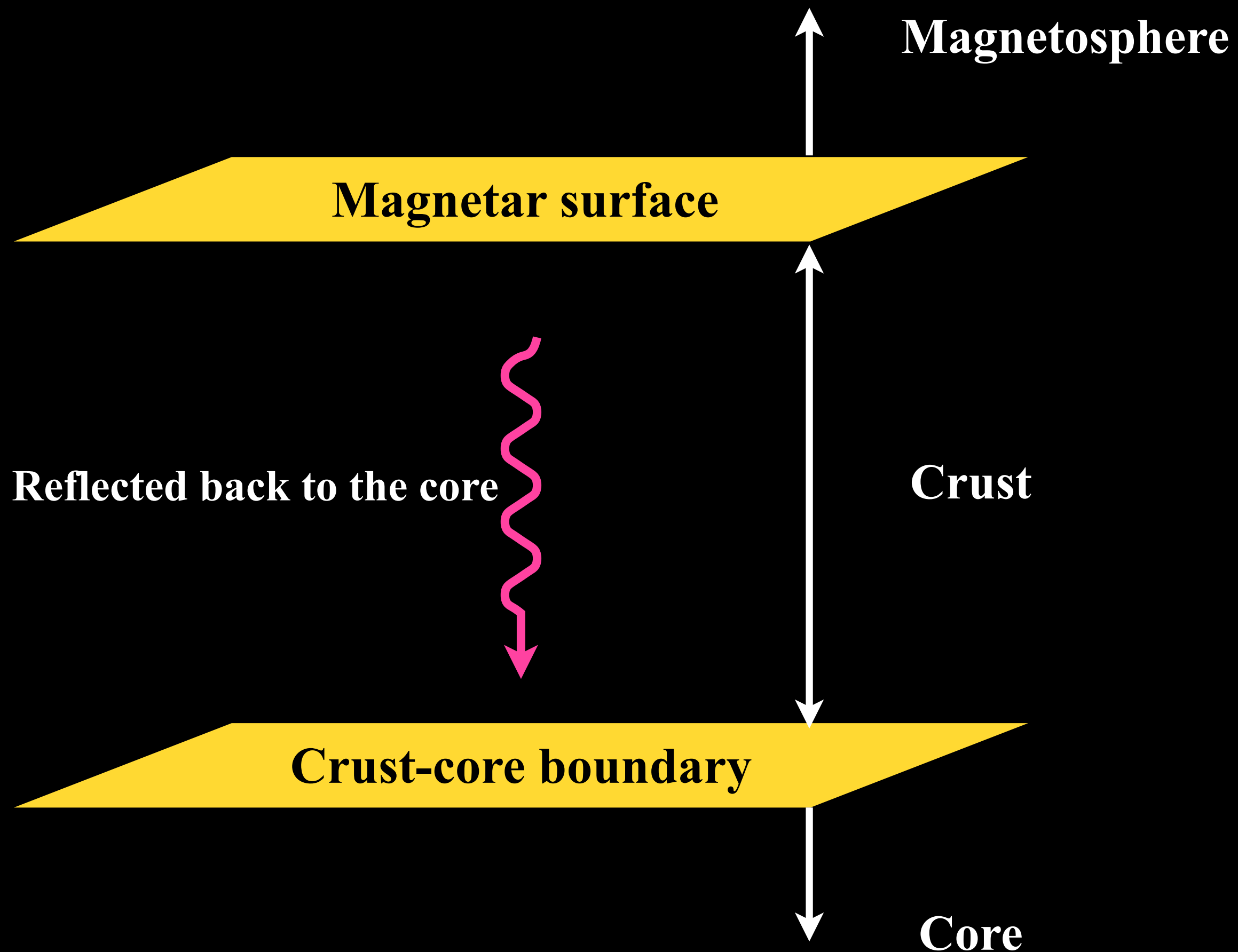
Characteristic frequency of seismic waves

$$\omega_Q \sim \frac{v_s}{\ell_0} \sim 10 \text{ kHz}$$

Propagation of magneto-elastic waves



Propagation of magneto-elastic waves



Transmission coefficient into the core

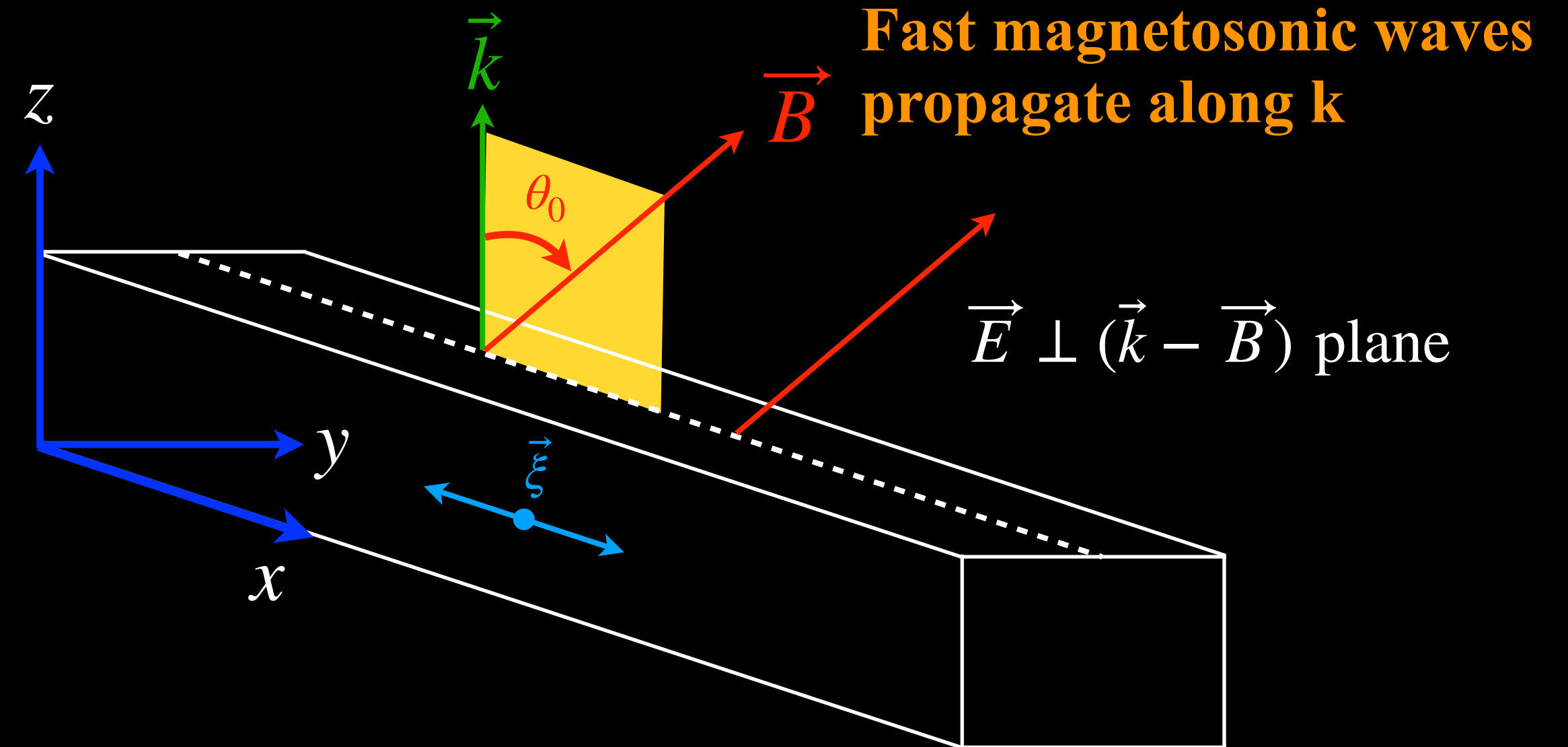
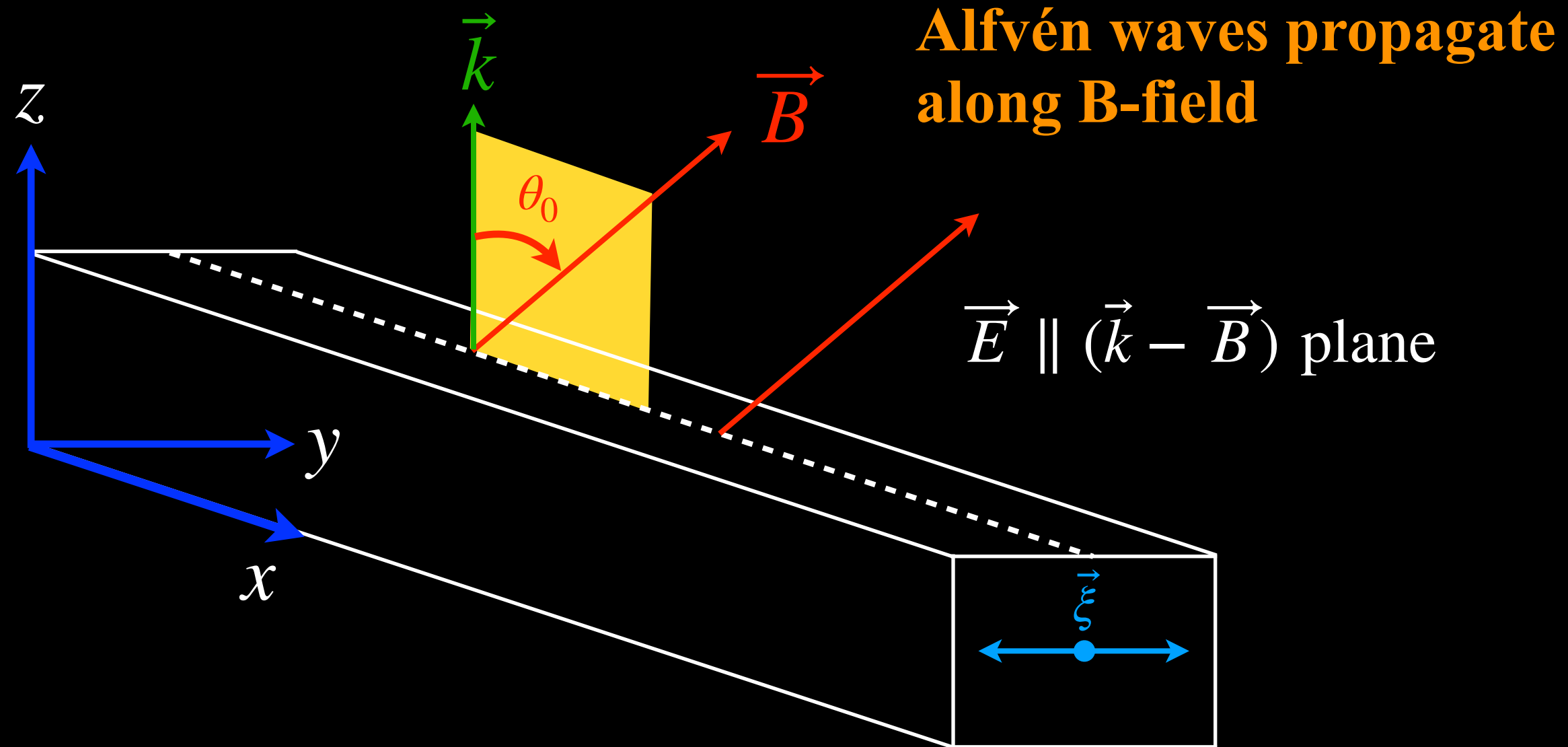
$$T_{\text{core}} \approx 20 \% B_{\star,14}^{1/2}$$

Timescale for the quake energy to dissipate

$$\tau_{\text{core}} \approx \frac{2\tau_c}{T_{\text{core}}} \sim 10 \text{ ms}$$

Generation of two MHD waves

$$\vec{E} = -\frac{\vec{v}}{c} \times \vec{B}$$



3D Magneto-Elastic Dynamics of the crust

$$\rho_{\xi}^{\ddot{\xi}} + \rho_B^{\ddot{\xi}_{\perp}} = \boxed{(\nabla \mu \cdot \nabla) \vec{\xi} - (\vec{\xi} \cdot \nabla) \nabla \mu + \mu \nabla^2 \vec{\xi}} + \boxed{\frac{1}{4\pi} \{ \nabla \times [\nabla \times (\vec{\xi} \times \vec{B})] \} \times \vec{B}}$$

↑
Elastic force

↑
Lorentz force

Crust →

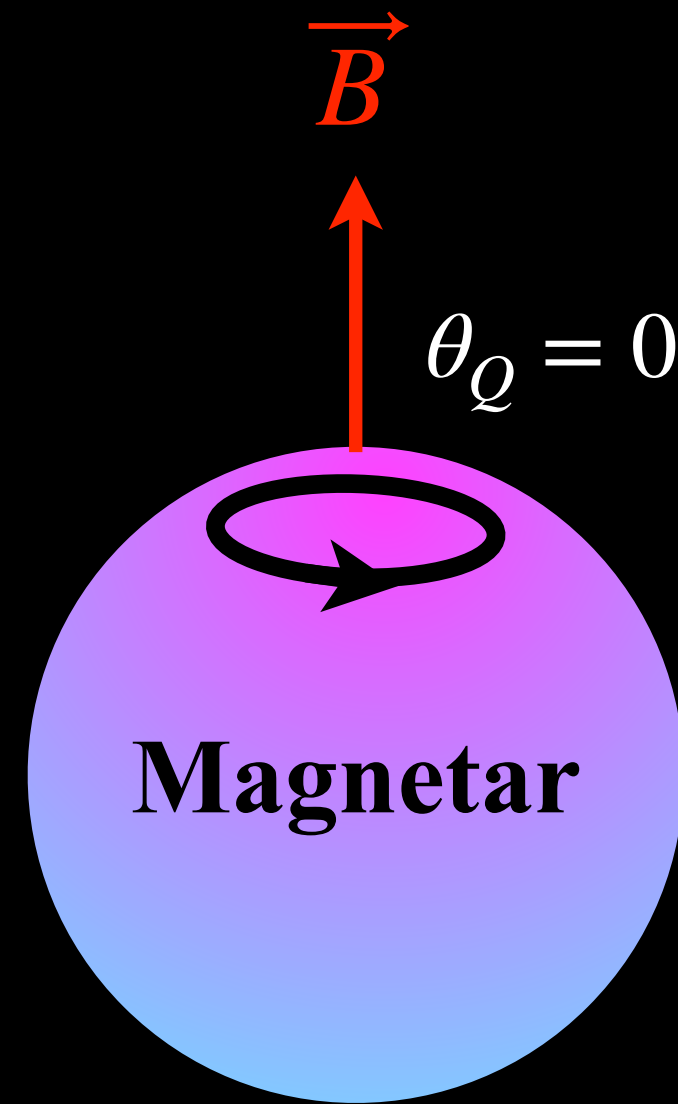
$z/R_{\star}$

$x/R_{\star}$

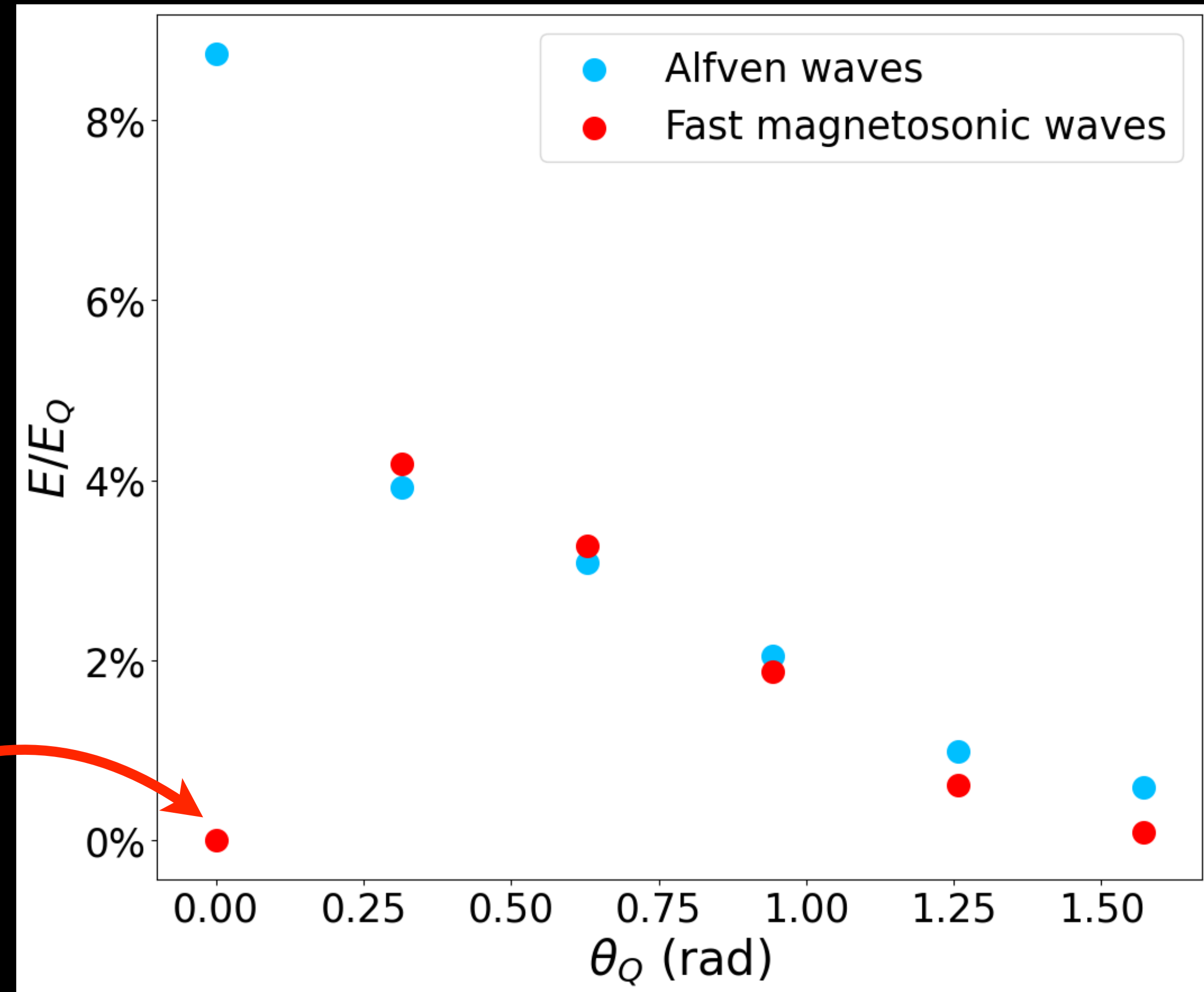
v_{ϕ} (Alfven)

v_{θ} (Fast)

Energy emitted into Alfven and fast modes



When $\theta_Q = 0$, **only Alfven waves** are produced



Nonlinear scattering of GHz FRBs

$$B_{\text{bg}} \sim r^{-3} \quad (\text{dipole magnetic field})$$

$$E_w \sim r^{-1}$$

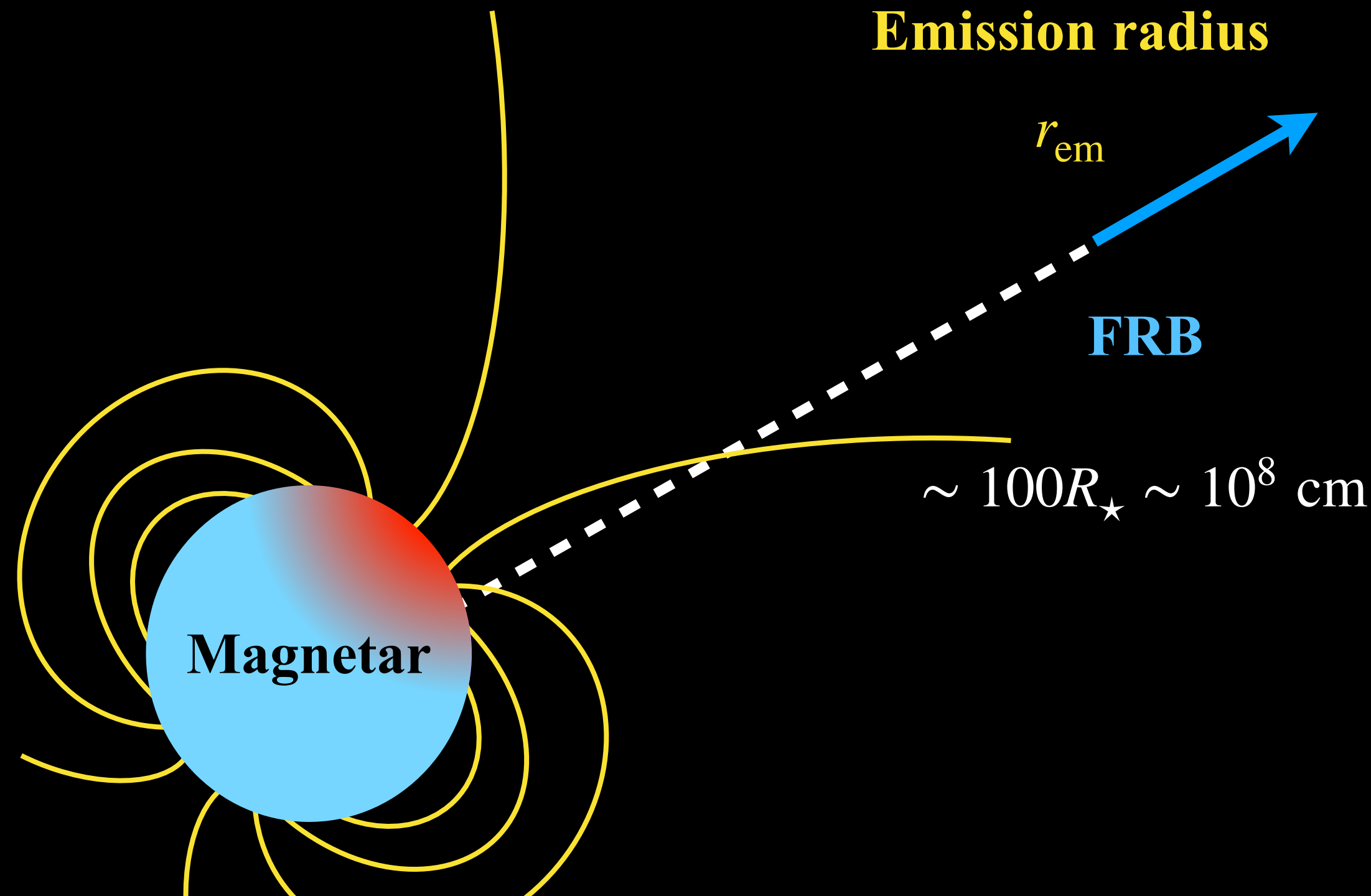
$$E_w \ll B_{\text{bg}}$$

Emission radius

r_{em}

FRB

$$\sim 100R_{\star} \sim 10^8 \text{ cm}$$



Nonlinear scattering of GHz FRBs

$$B_{\text{bg}} \sim r^{-3} \quad (\text{dipole magnetic field})$$

$$E_w \sim r^{-1}$$

Nonlinear radius

Nonlinear regime

Light cylinder

$$\sim 5 \times 10^9 \text{ cm}$$

$$R_{\text{frb}}$$

$$E_w \ll B_{\text{bg}}$$

Emission radius

$$r_{\text{em}}$$

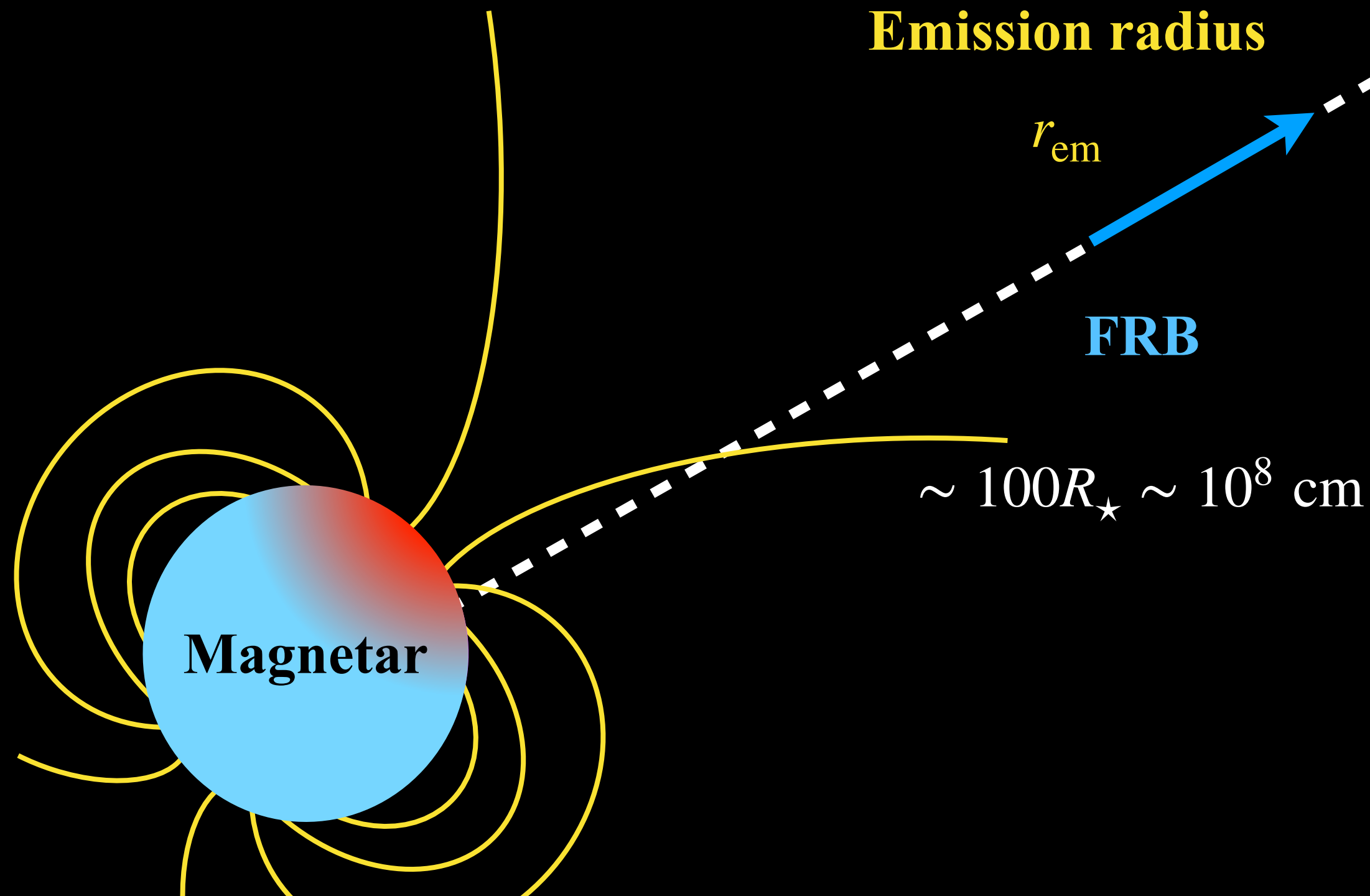
$$E_w > B_{\text{bg}}$$

$$\sim 10^9 \text{ cm}$$

FRB

$$\sim 100R_{\star} \sim 10^8 \text{ cm}$$

Magnetar



Nonlinear scattering

Nonlinear parameter

$$a = \frac{eE_w}{m_e c \omega} \sim \frac{v}{c}$$

electric force

wave angular frequency

$$B_{\text{bg}} = 0$$

$$\sigma = \frac{P}{S} \sim a^2 \sigma_{\text{T}}$$

A well known result in laser field

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A well known result in laser field

$$\text{FRBs: } a \sim 10^4 r_9^{-1} L_{\text{frb},42}^{1/2} \nu_{\text{GHz}}^{-1} \gg 1$$

Ten orders of magnitude larger than radio pulsars

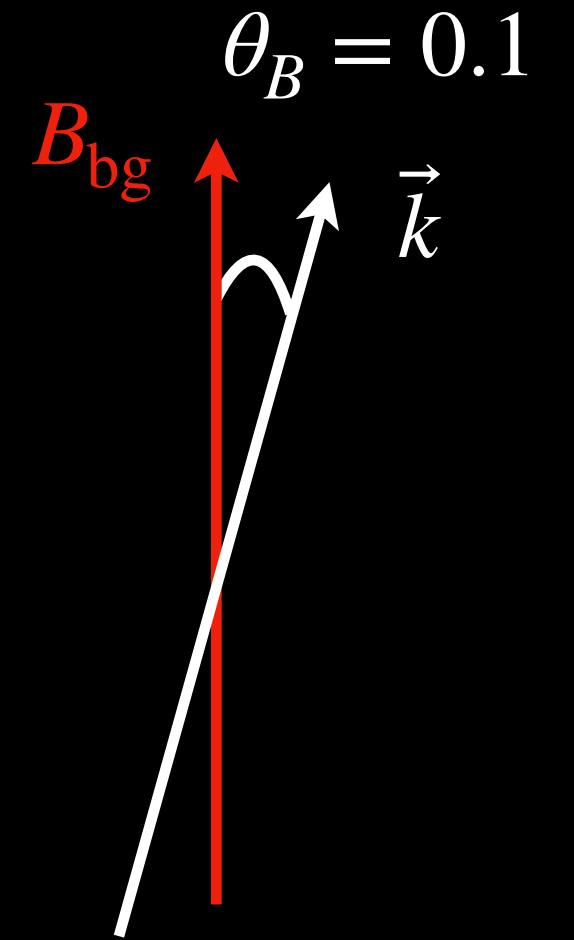
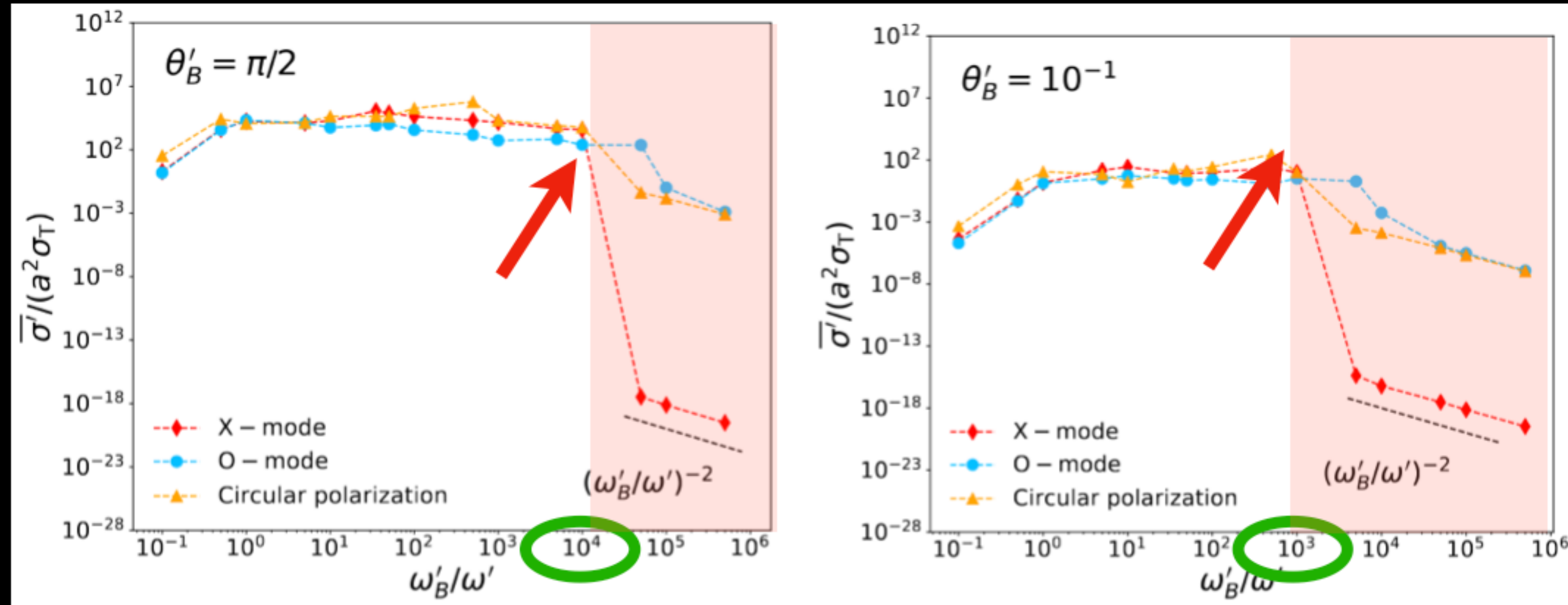
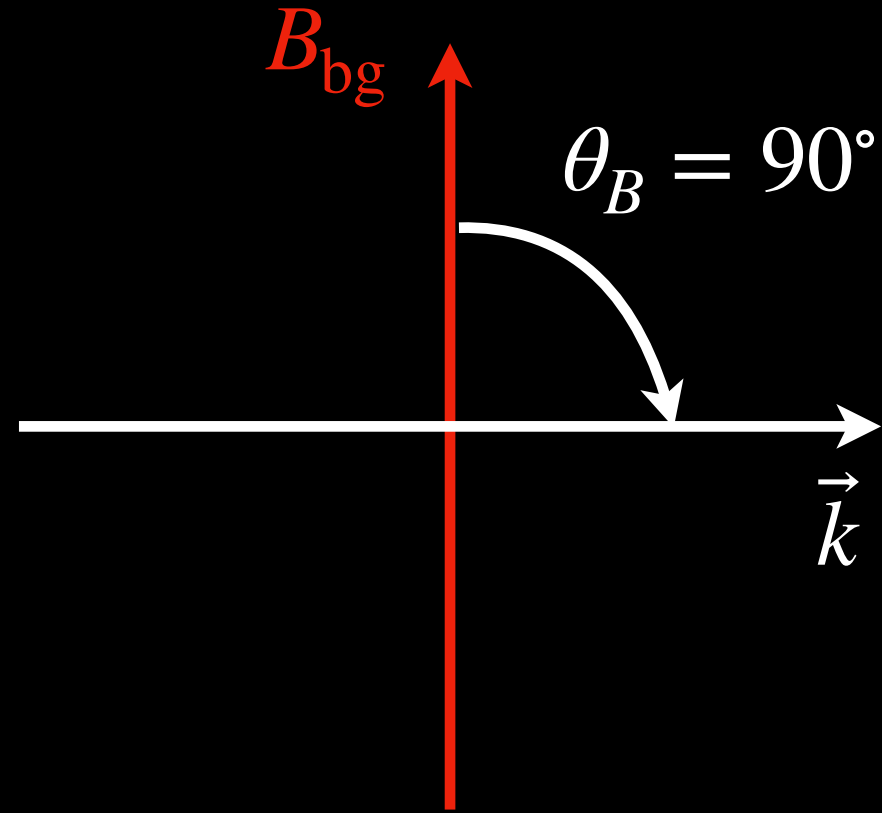
$$B_{\text{bg}} \neq 0$$

Large-amplitude waves

$$a > 1$$

$$E_w > B_{\text{bg}} \Rightarrow a > \frac{\omega_B}{\omega}$$

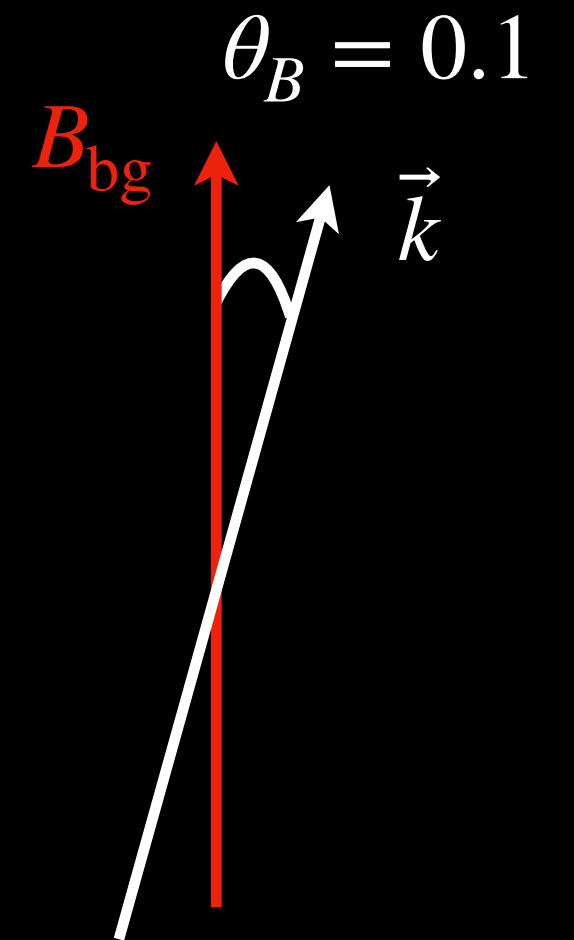
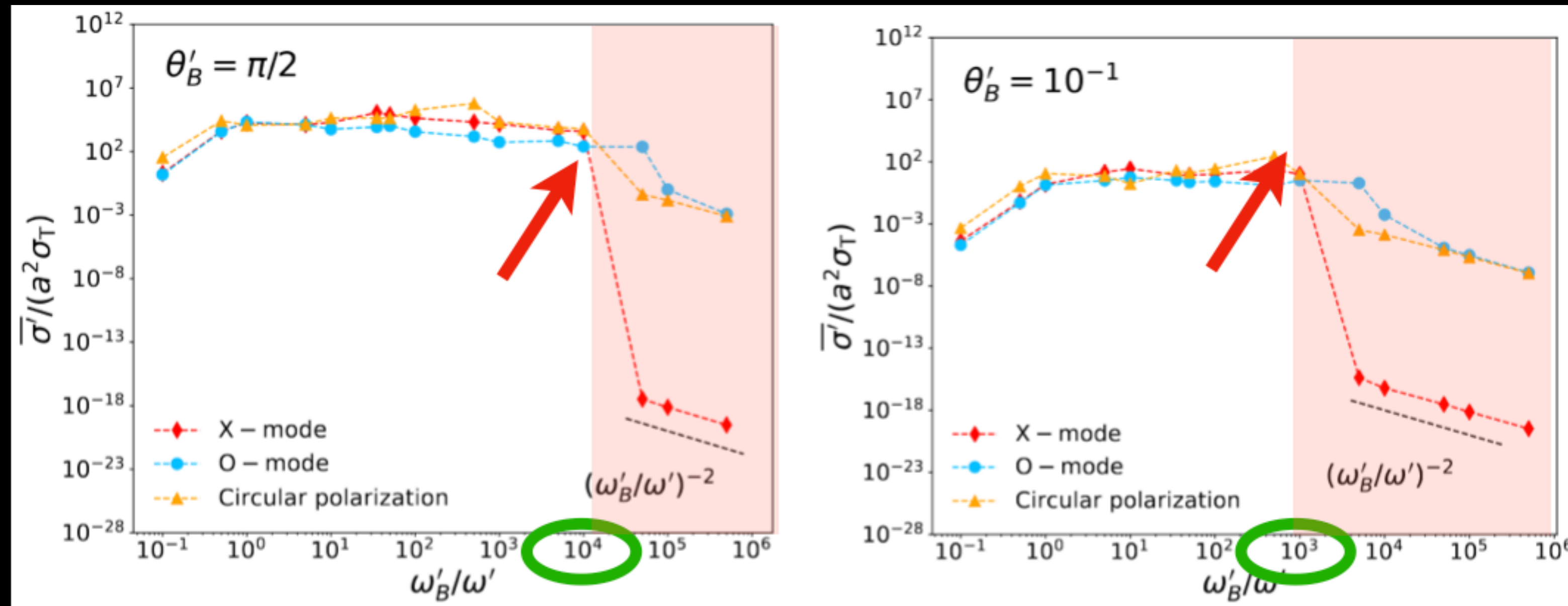
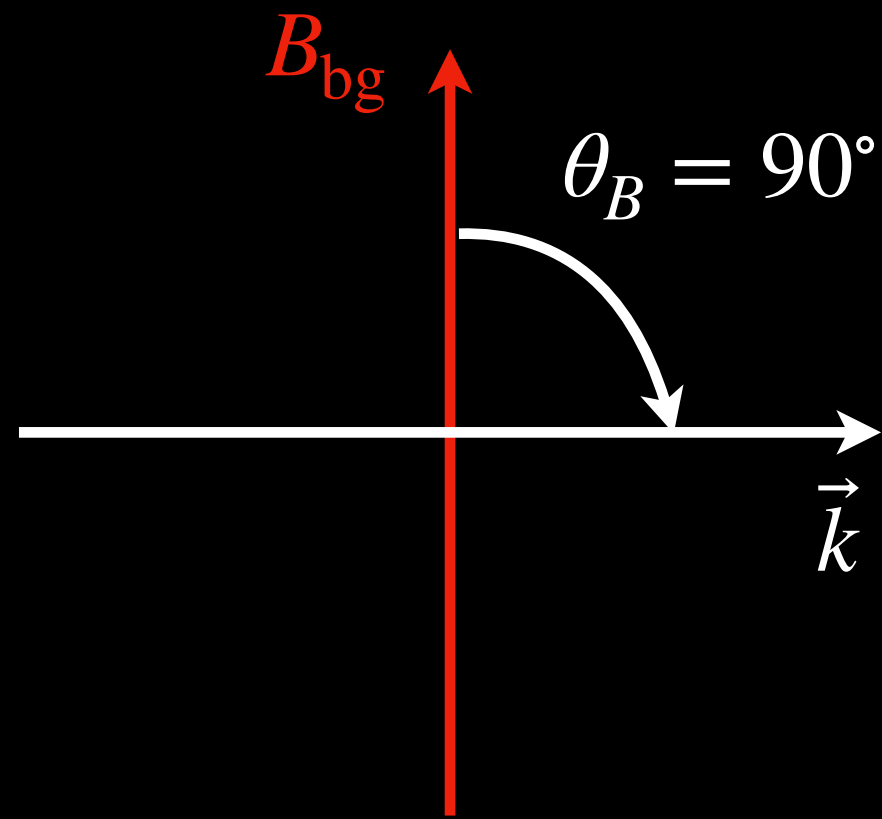
Scattering cross sections



1. Waves can remain in the linear scattering regime even when $a \gg 1$

$$\sigma_X \approx \sigma_T \left(\frac{\omega}{\omega_B} \right)^2 \quad \sigma_O \approx \sigma_T \sin^2 \theta_B$$

Scattering cross sections



1. Waves can remain in the linear scattering regime even when $a \gg 1$

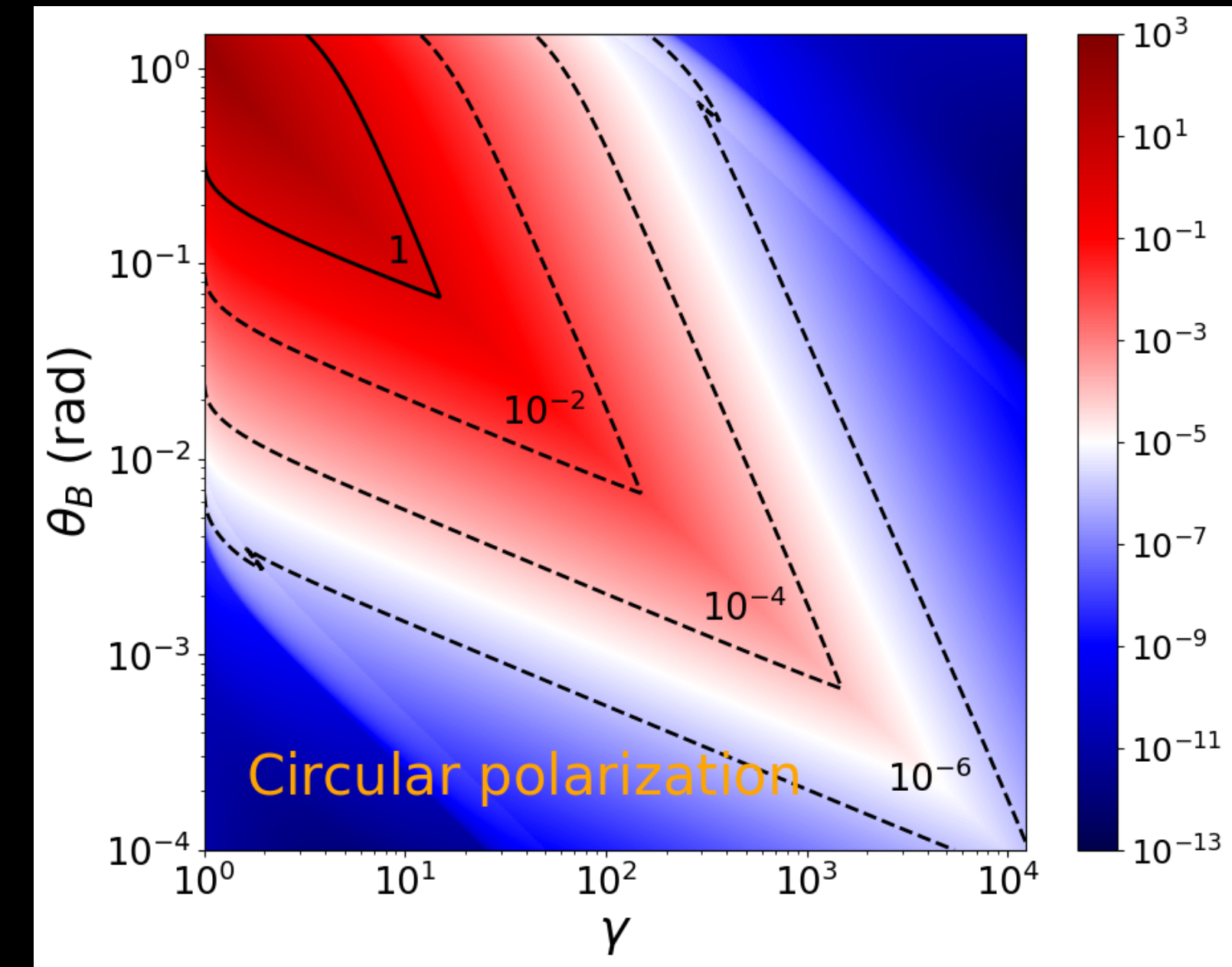
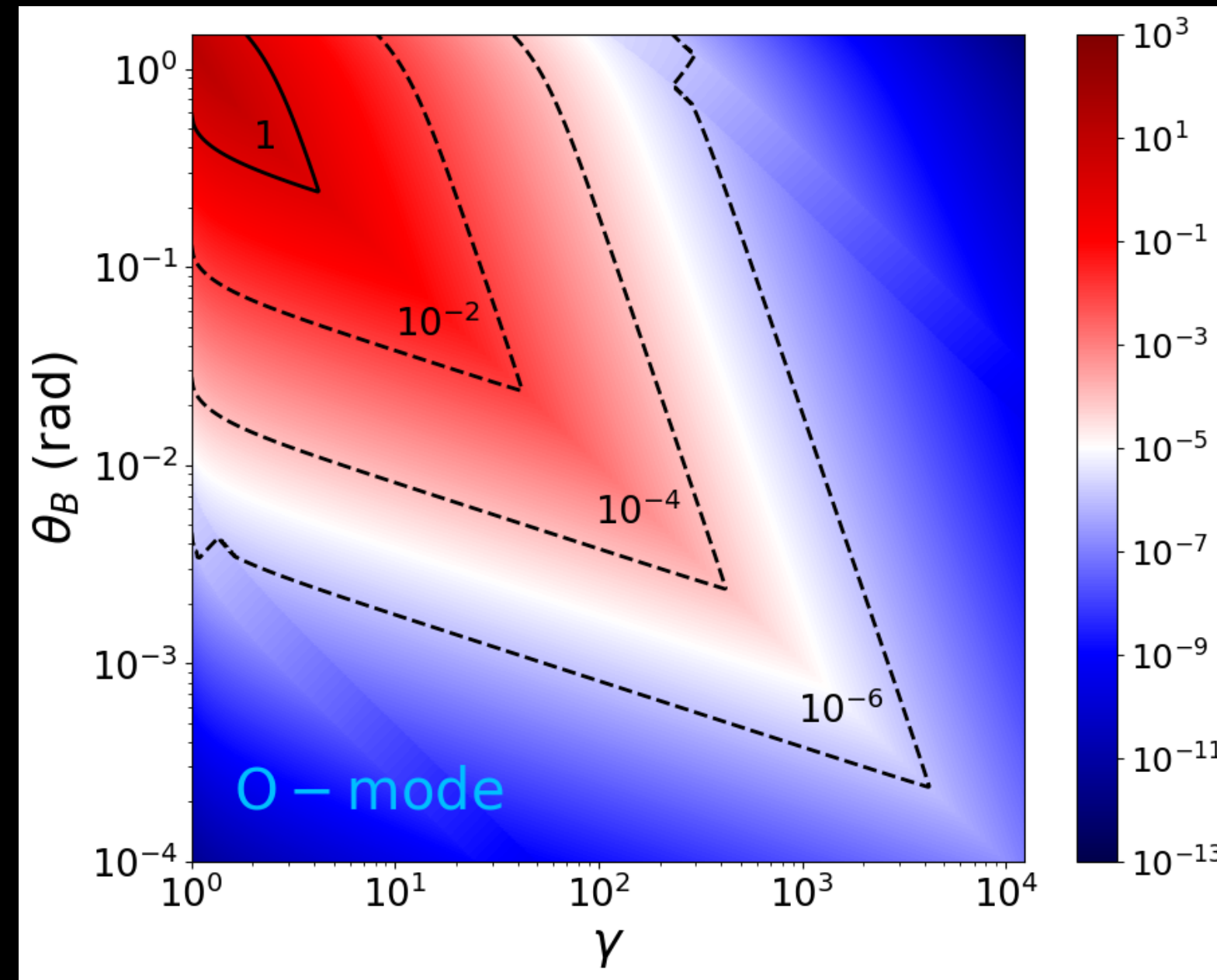
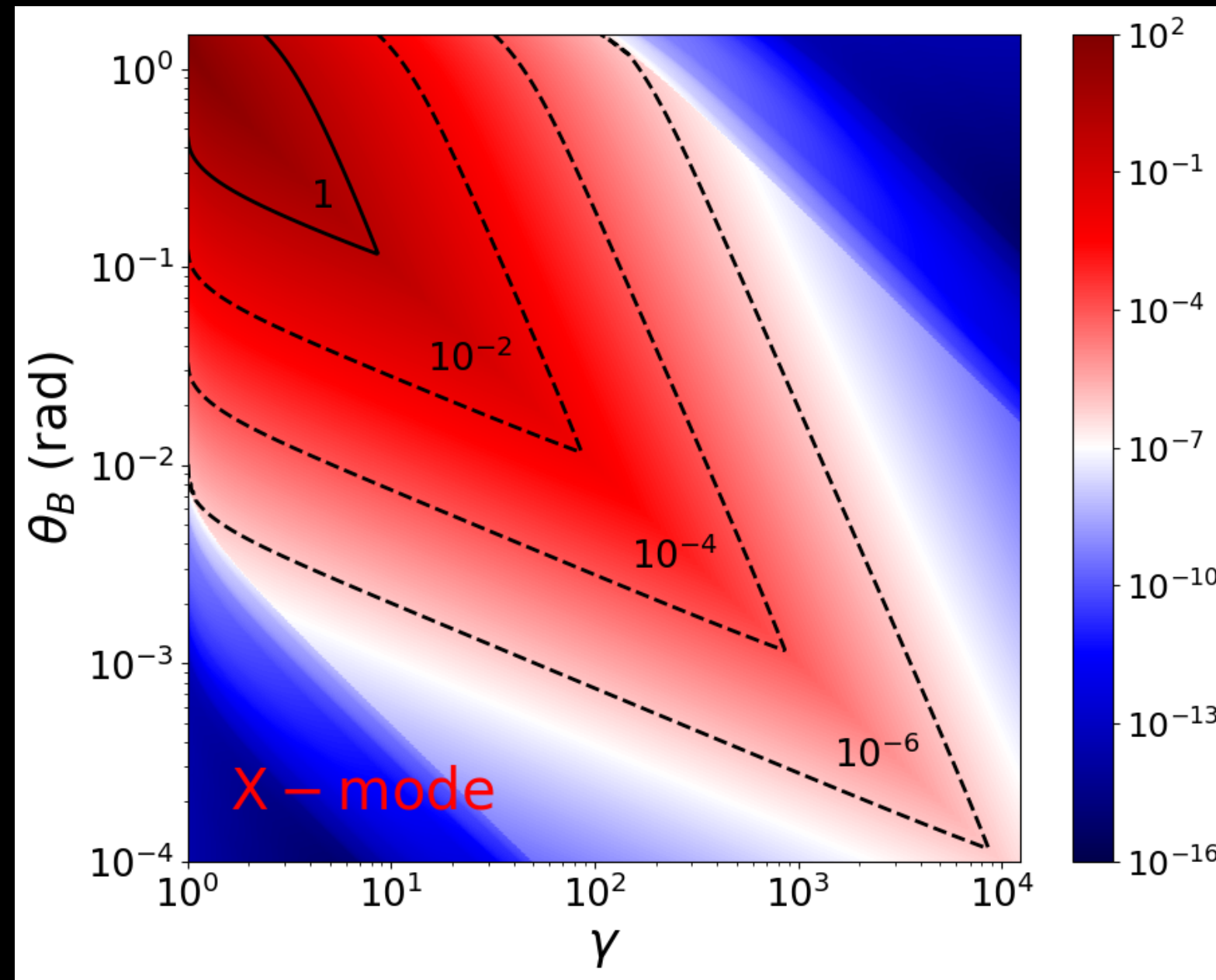
$$\sigma_X \approx \sigma_T \left(\frac{\omega}{\omega_B} \right)^2 \quad \sigma_O \approx \sigma_T \sin^2 \theta_B$$

2. Nonlinear scattering condition:

$$E_w > B_{bg} \Rightarrow a > \frac{\omega_B}{\omega} \quad \text{only correct when } k \perp B_{bg}$$

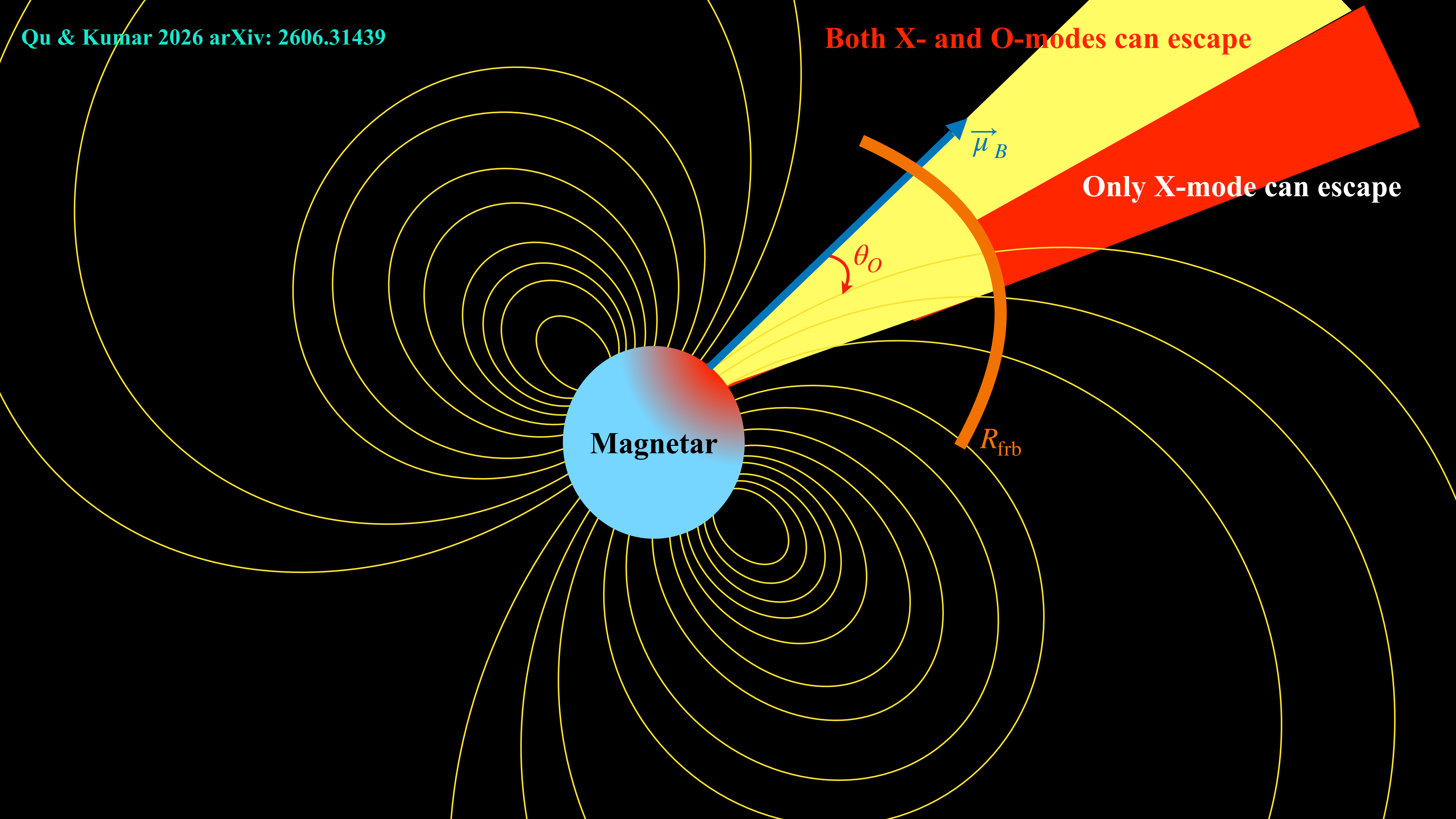
$$a \sin \theta_B > \frac{\omega_B}{\omega}$$

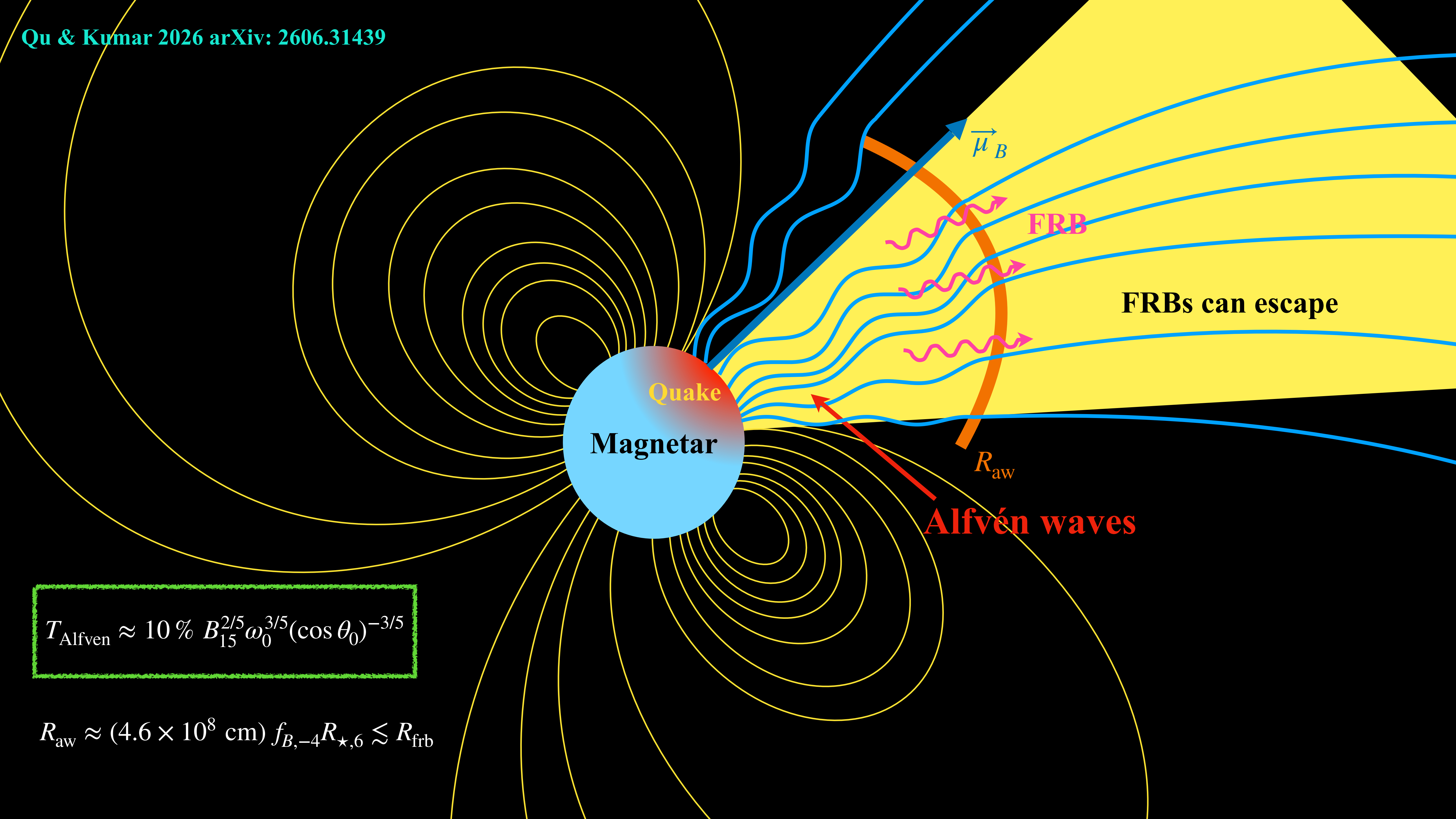
Scattering optical depth



Strong FRB waves can escape if $\gamma \gtrsim 100$

Qu & Kumar 2026 arXiv: 2606.31439





Summary

1. Crust quakes can generate **Alfven and fast modes as the trigger mechanism** for FRBs.
2. FRBs can freely propagate **in the open field line region** of the magnetar magnetosphere.
Crust quake-induced **Alfven waves can open up the B-fields** and reduce the non-linear scattering