Bursts and relativistic ejecta from magnetars

Andrei Beloborodov
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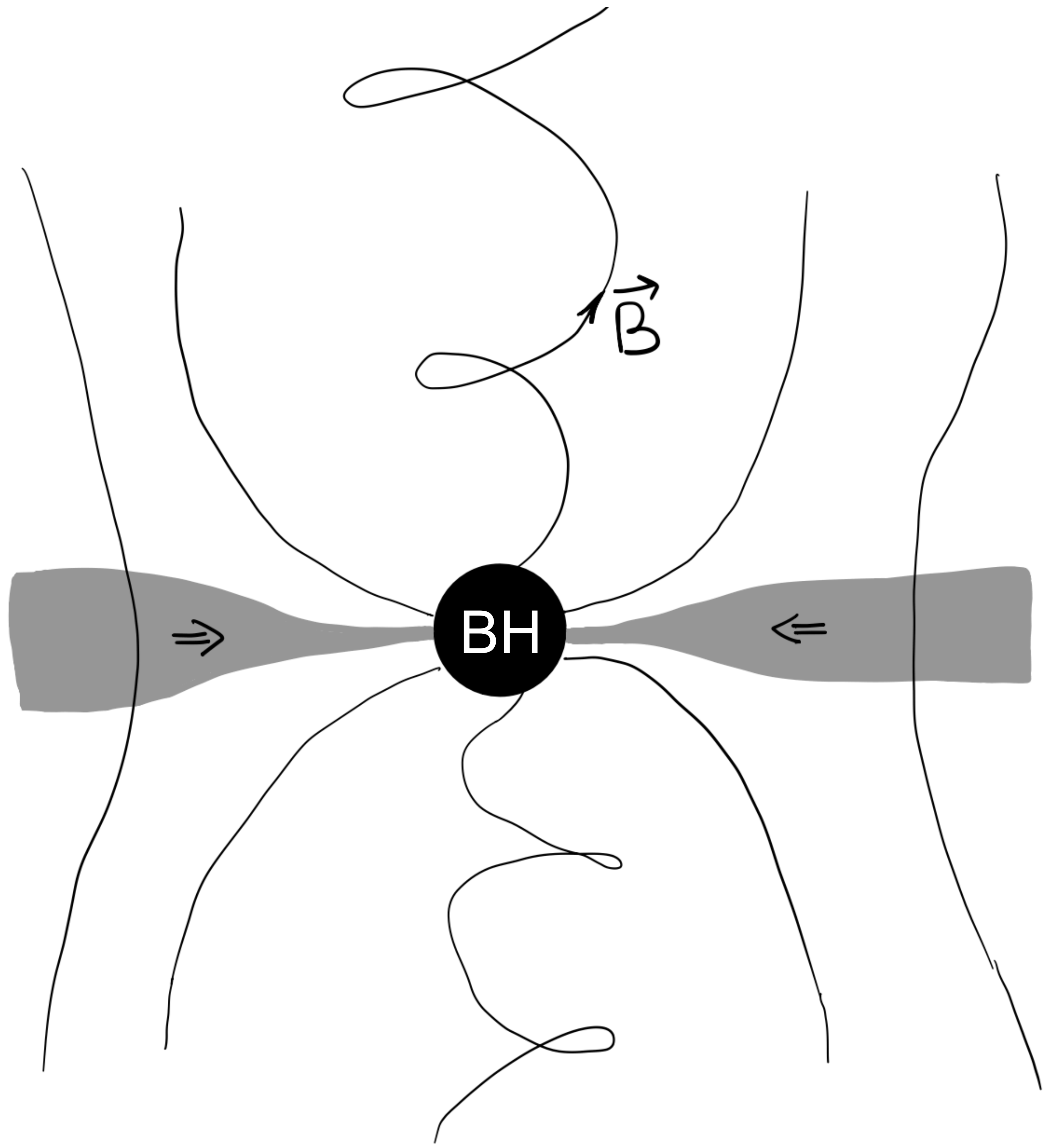
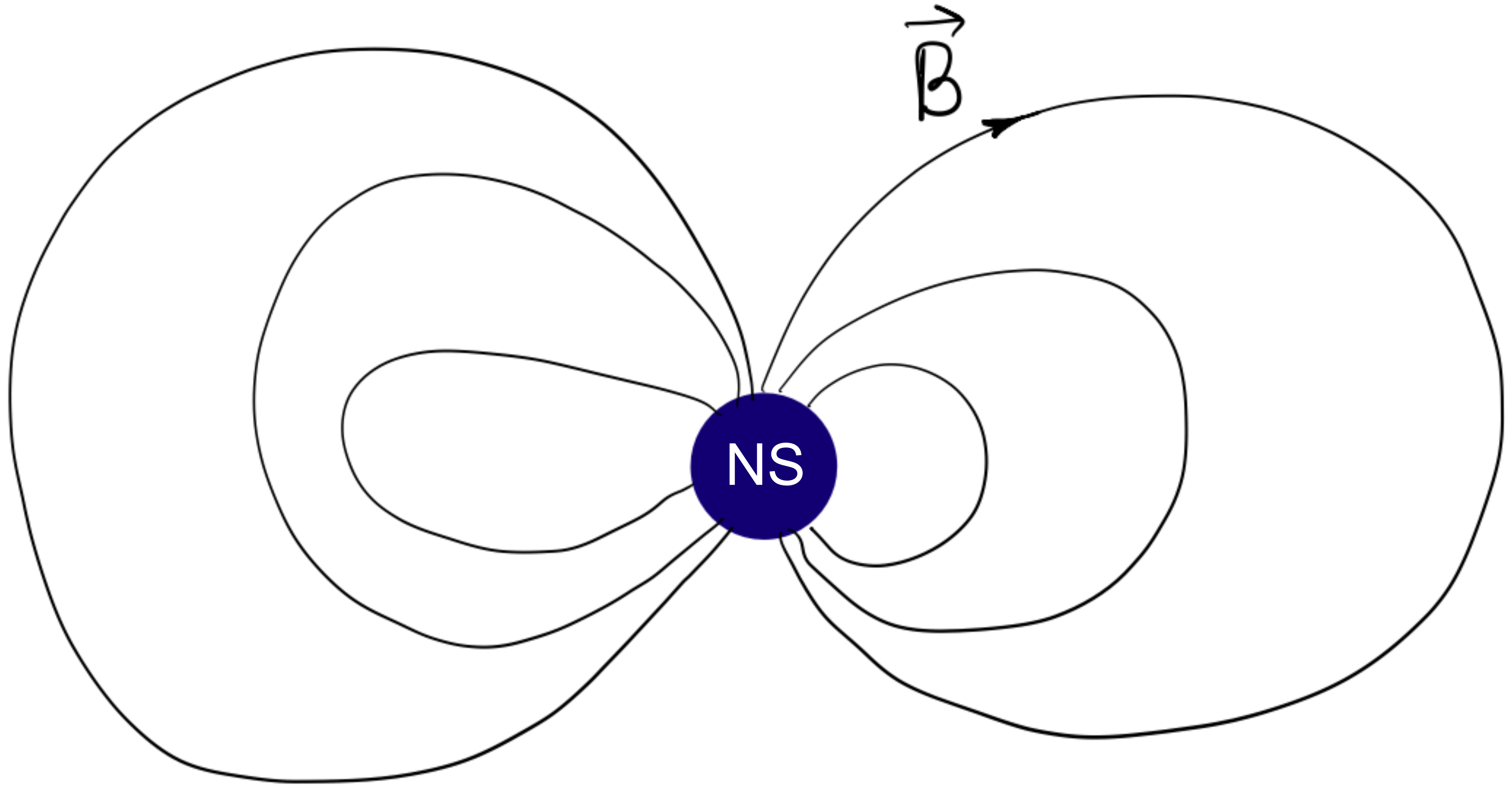
- Quakes
- Nonlinear waves and monster shocks
- Relativistic ejecta
- Bursts (X/gamma and radio)



Black holes have externally imposed magnetic fields (brought by accretion)



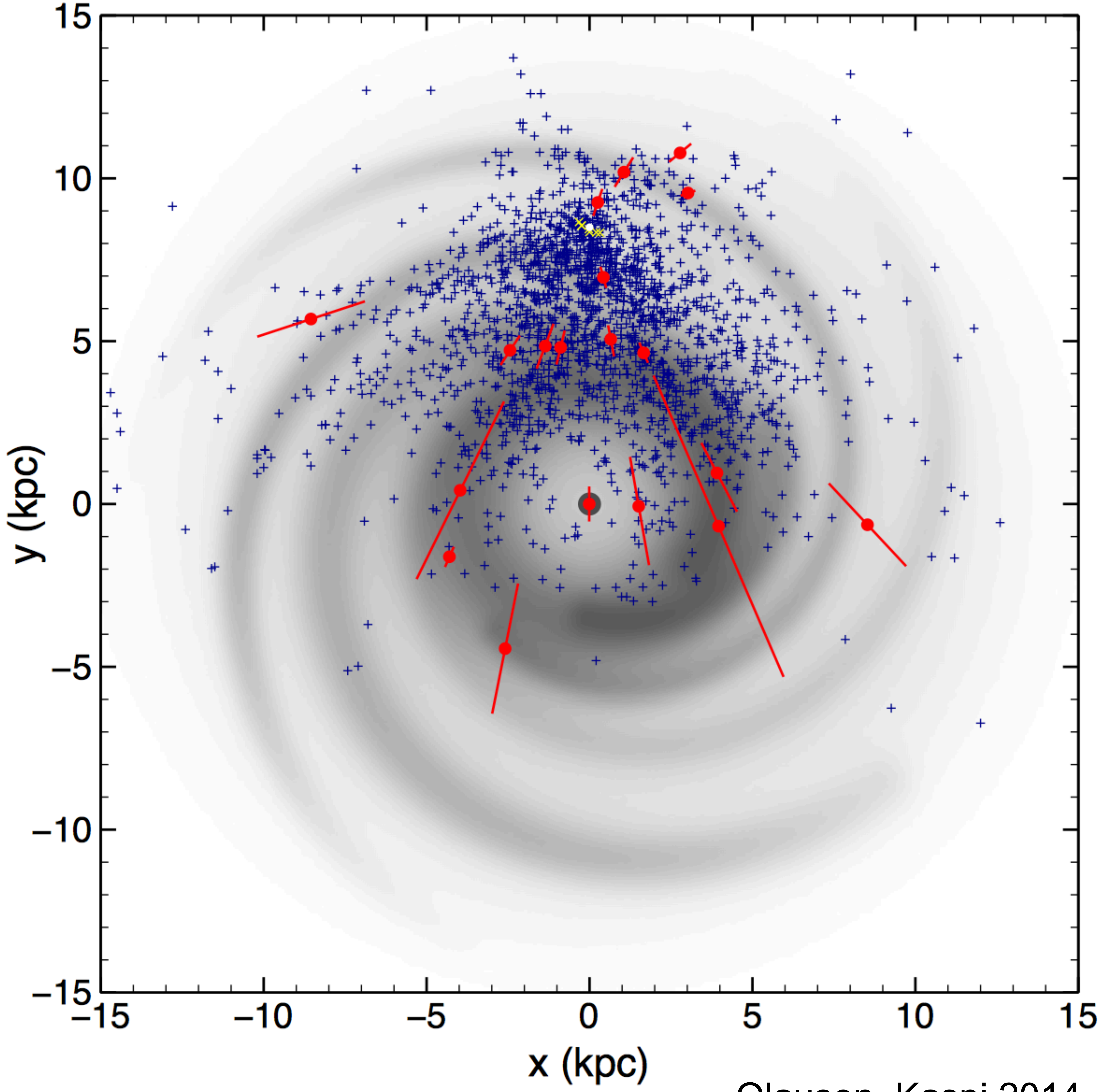
Neutron stars hold long-lived ulstrastromg magnetic fields; become alive and bursting when $B \gg 10^{14}$ G ("magnetars")

Magnetars

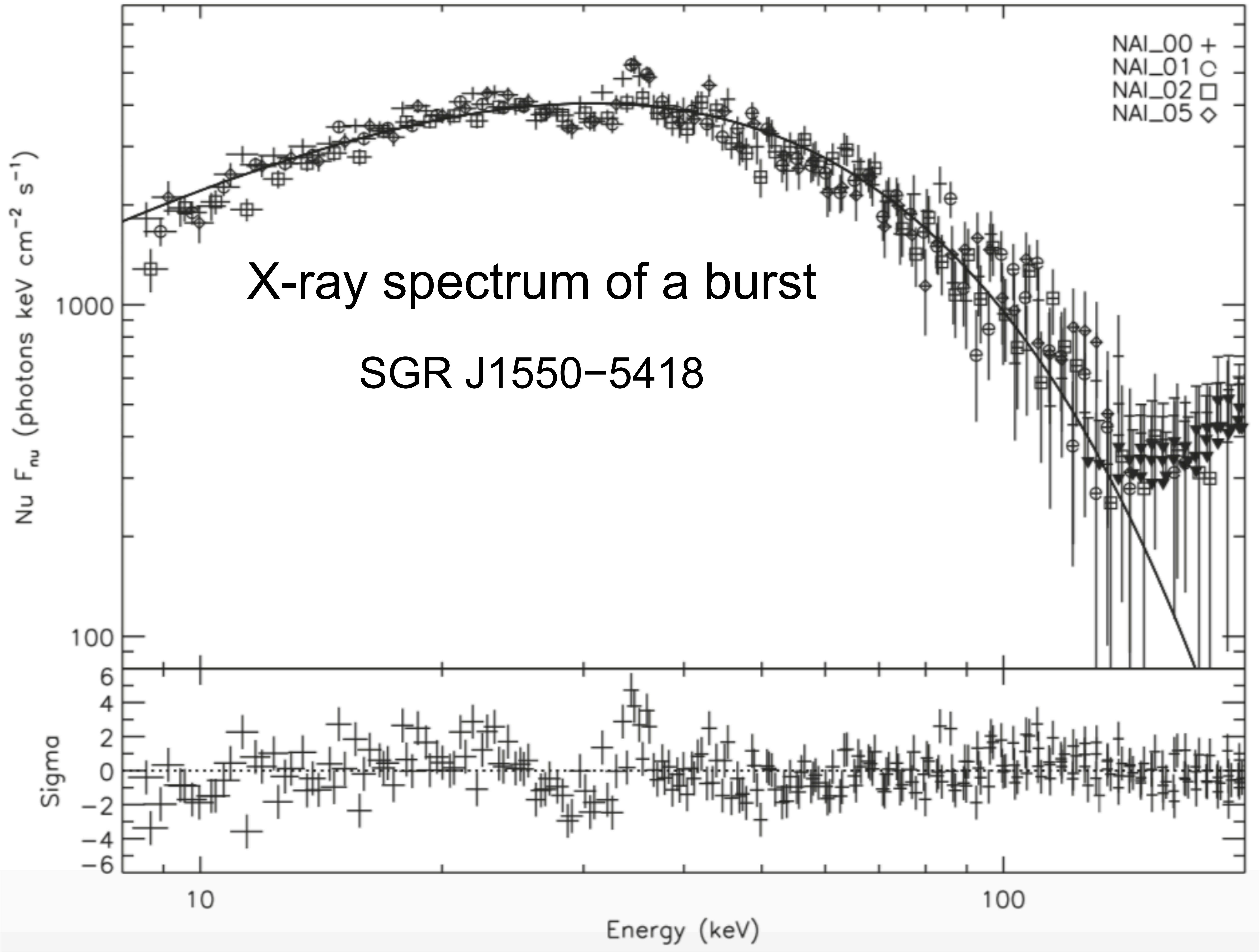
– bursting neutron stars powered by magnetic energy

- >10% of NS are born as magnetars
- active ~10 kyr
- spin P = 2-12 s

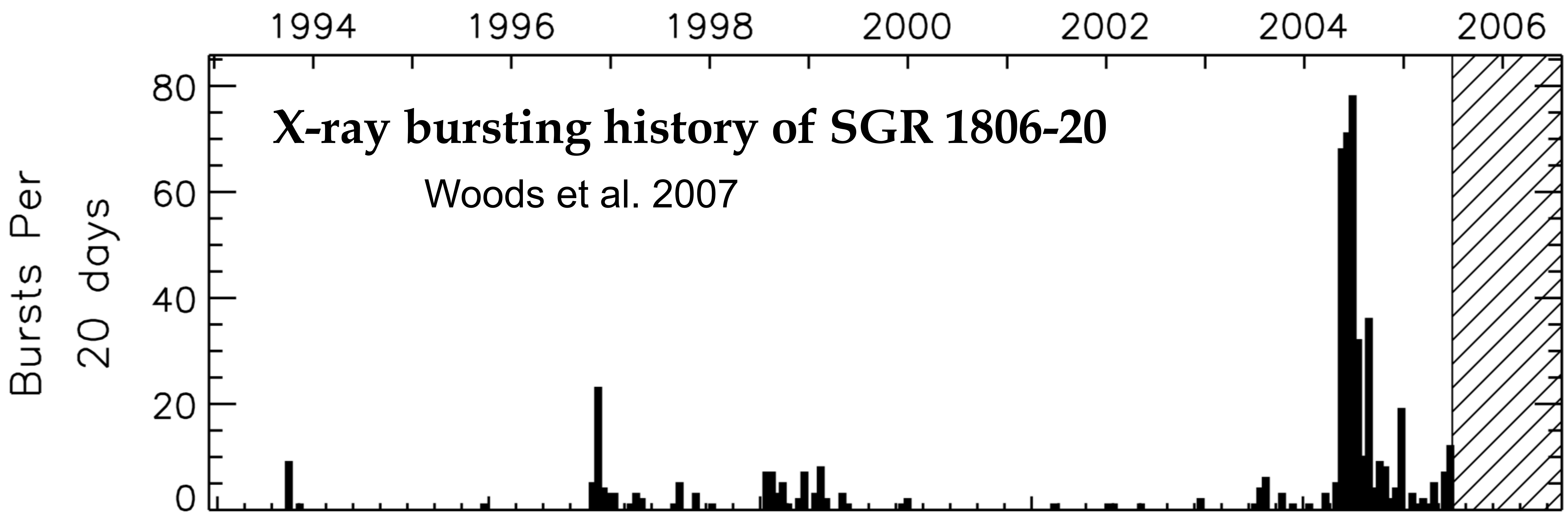
Why bursting?



Olausen, Kaspi 2014



van der Horst et al. 2012



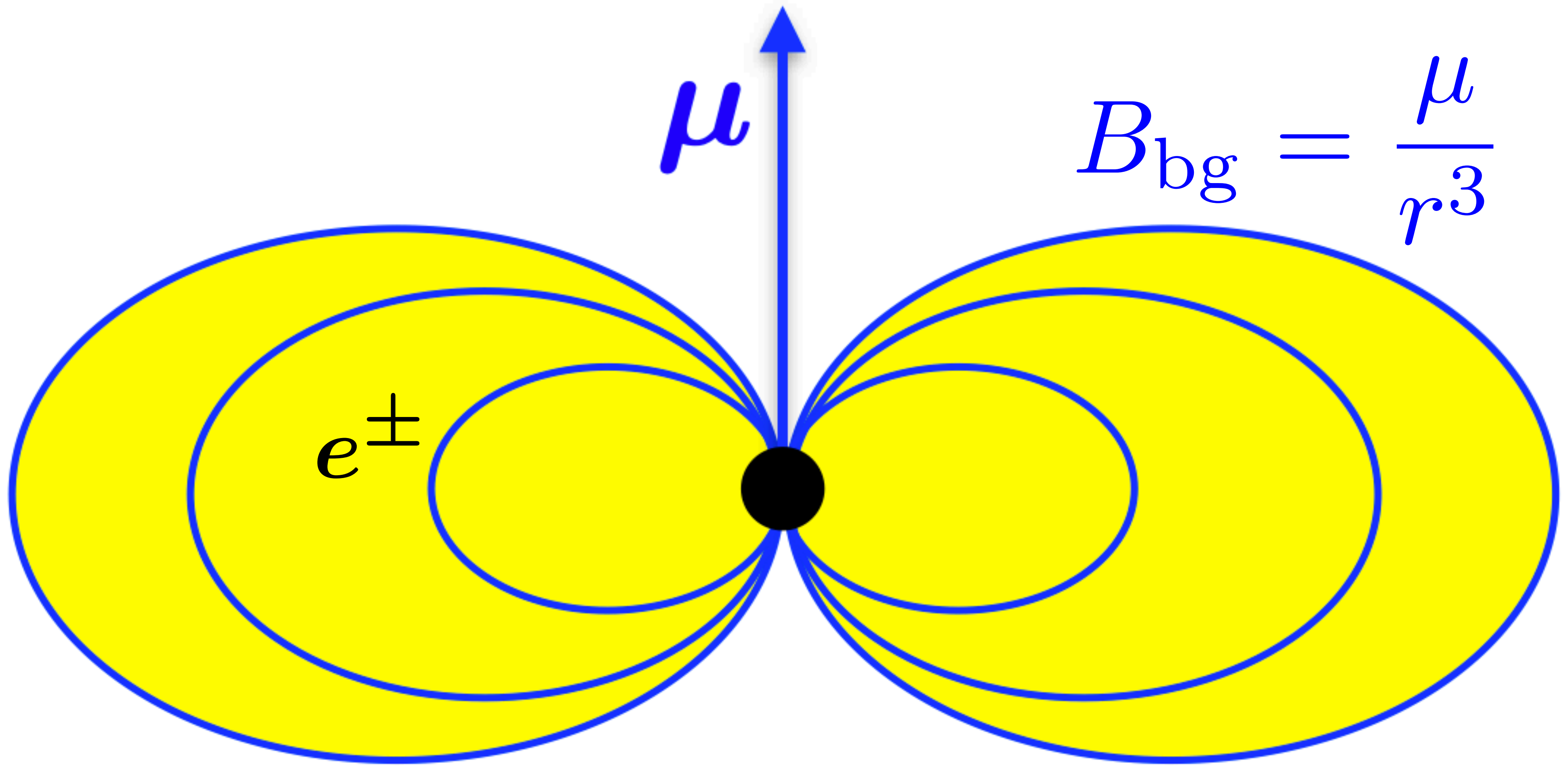
events of fast dissipation of magnetic energy

Burst durations ~ 0.1 s luminosities $10^{41} - 10^{47}$ erg/s

Thompson, Duncan 1995: starquakes excite magnetospheric Alfven waves

New: **quakes produce monster shocks and ejecta, emitting X-ray and radio bursts**

Magnetosphere of a neutron star



– perturbed by quakes

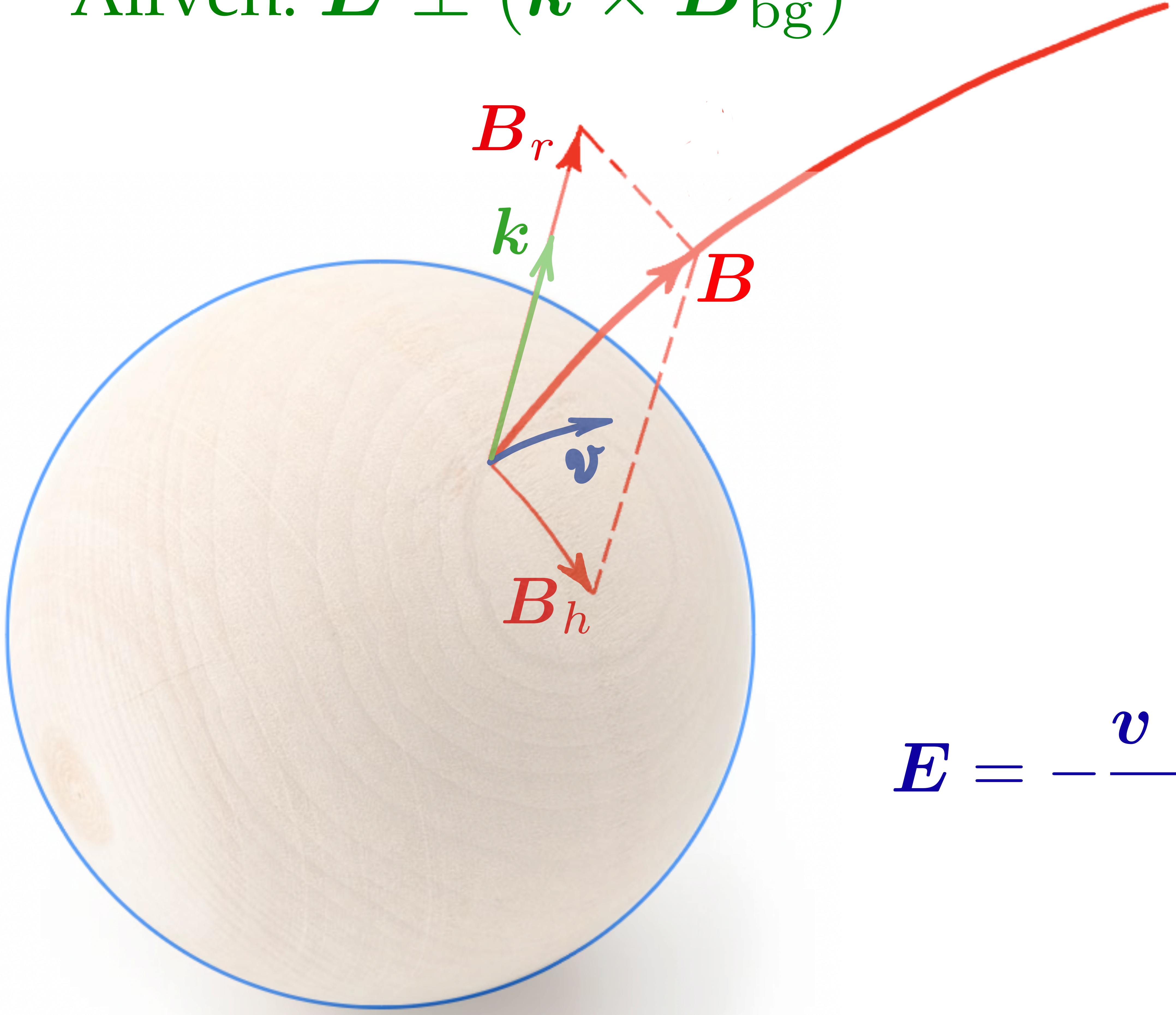
perturbation frequency in kHz band

$$L \approx 10^{46} \left(\frac{\delta B_\star}{10^{12}\,\mathrm{G}} \right)^2 \frac{\mathrm{erg}}{\mathrm{s}}$$

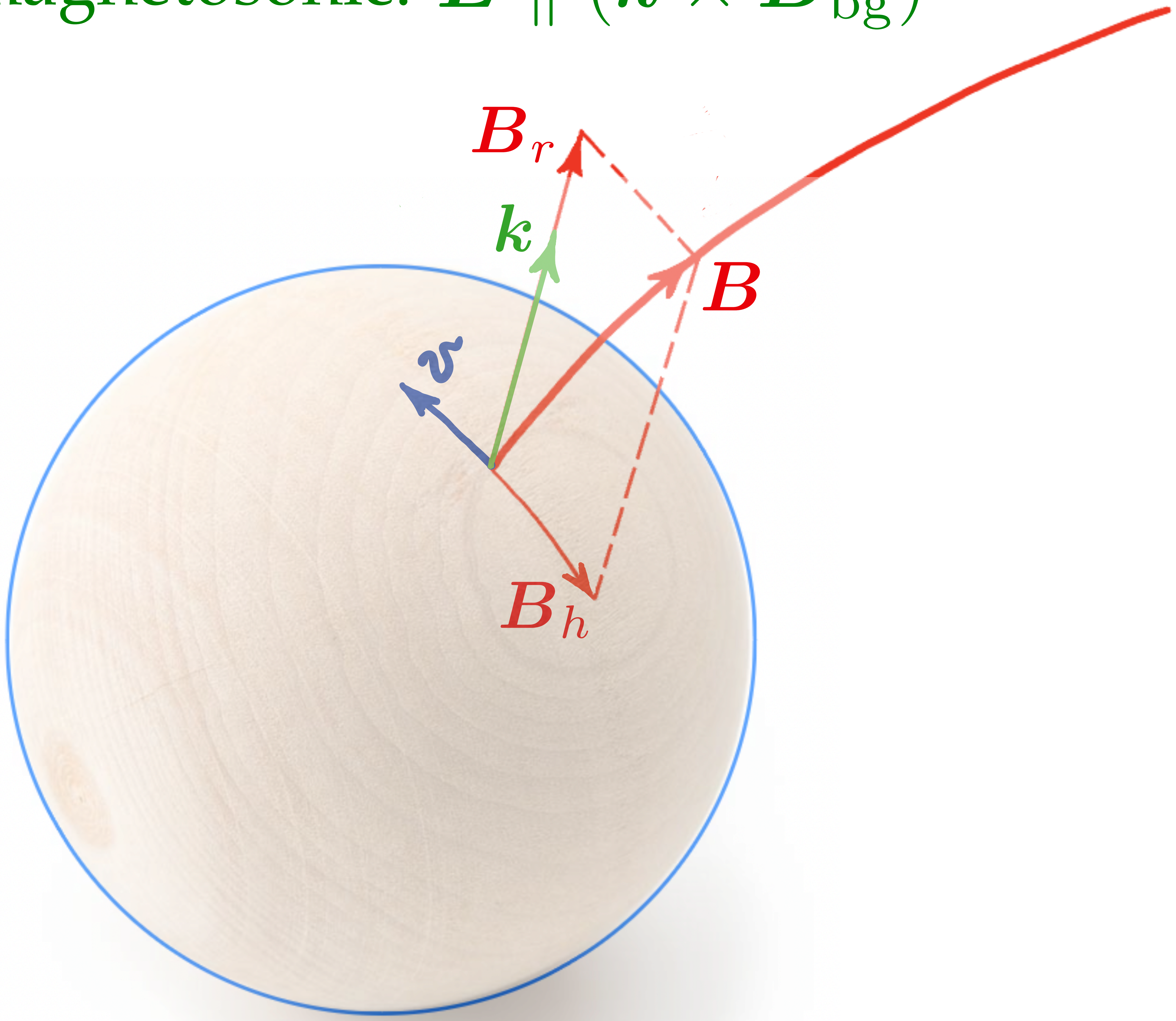
$\delta B_\star \ll B_\star$ at the star; $\delta B / B_{\rm bg}$ grows as the wave propagates outward

Wave emission by quakes (kHz)

Alfven: $\boldsymbol{E} \perp (\boldsymbol{k} \times \boldsymbol{B}_{\rm bg})$



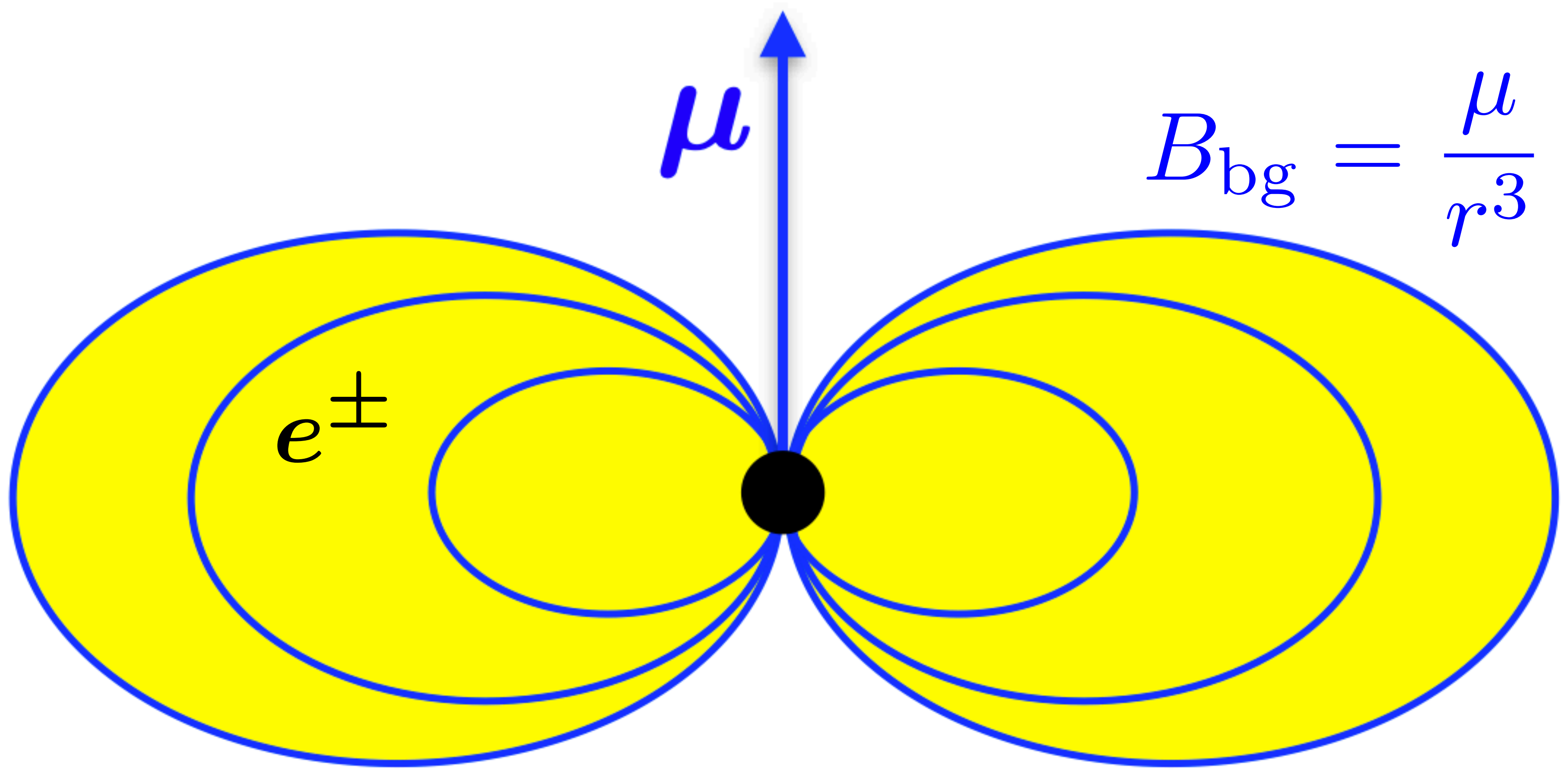
magnetosonic: $\boldsymbol{E} \parallel (\boldsymbol{k} \times \boldsymbol{B}_{\rm bg})$



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

(+ waves from instabilities in the magnetosphere itself, see Jens Mahlmann's talk)

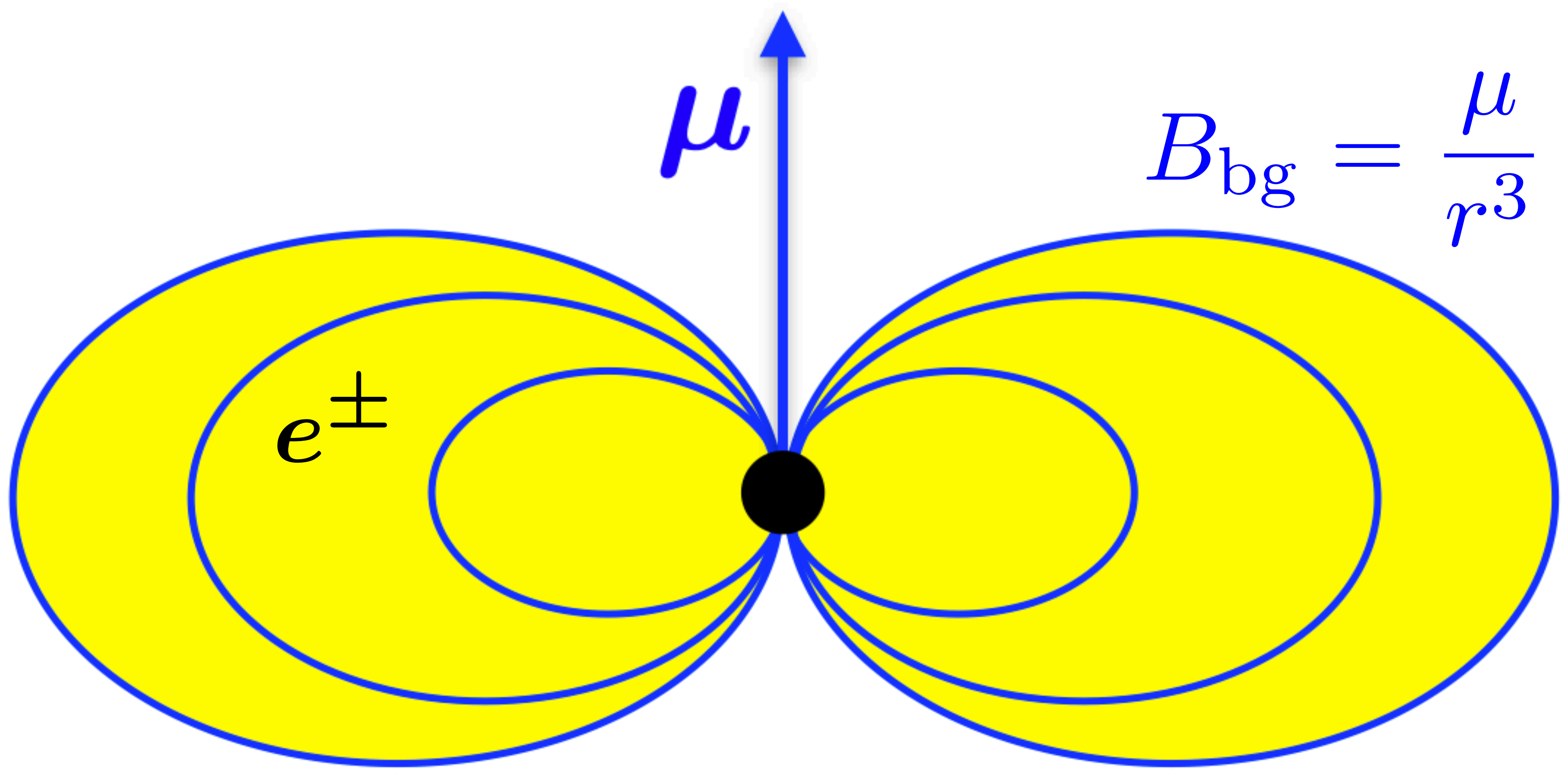
I. Magnetosonic waves



$$\sigma_{\rm bg} = \frac{B_{\rm bg}^2}{4\pi n_{\rm bg} m_e c^2} \sim 10^{10}\, r_8^{-3}$$

Magnetosonic modes (compressive waves): $\frac{v_{\rm wave}}{c} = 1 - \sigma_{\rm bg}^{-1}$

$\sigma_{\rm bg} \to \infty$: fast magnetosonic mode $\to$ vacuum electromagnetic wave (superimposed on $B_{\rm bg}$)



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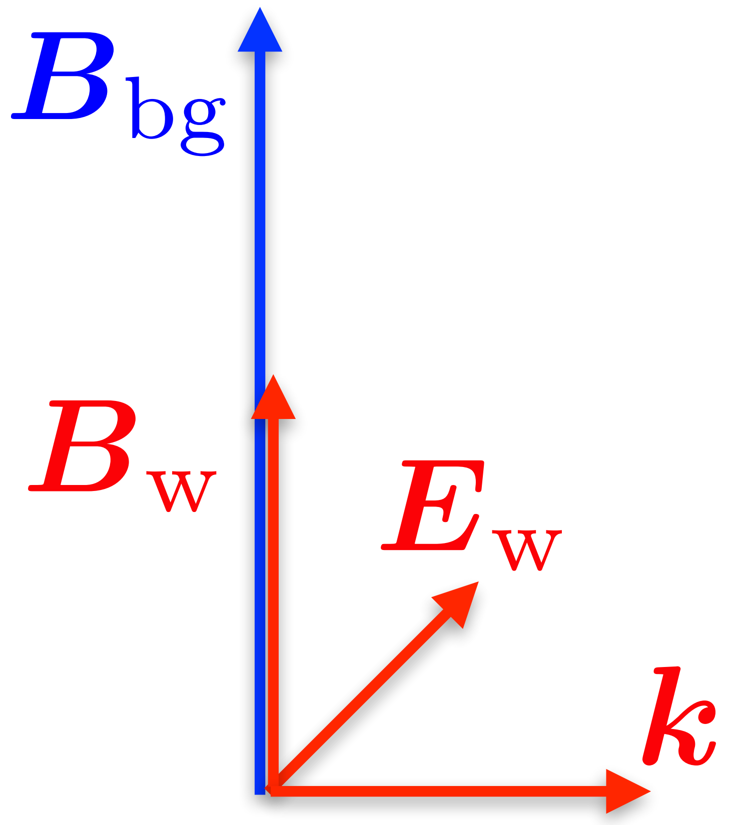
wave amplitude $E_0 \propto r^{-1}$

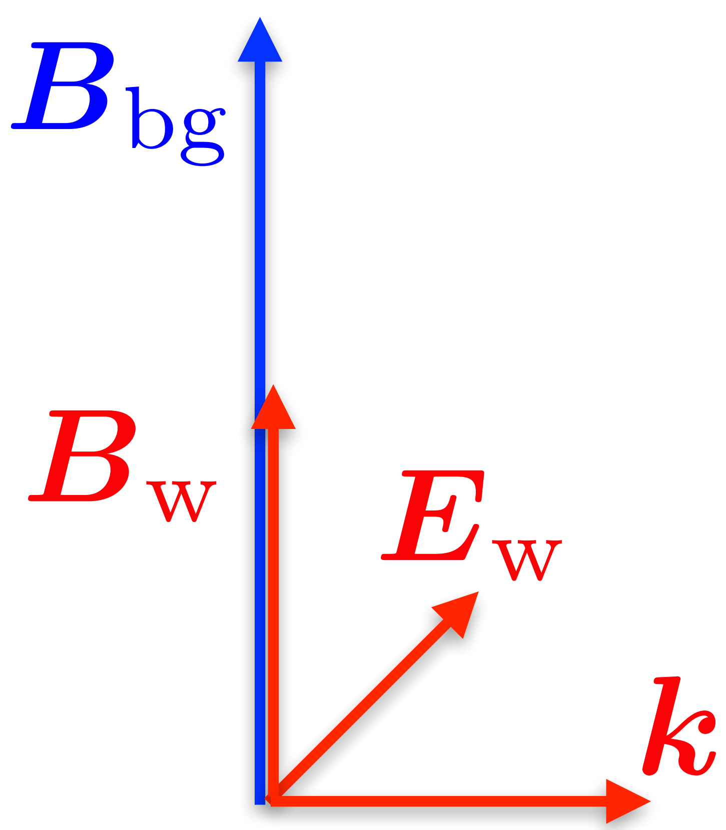
background field $B_{\rm bg} \propto r^{-3}$

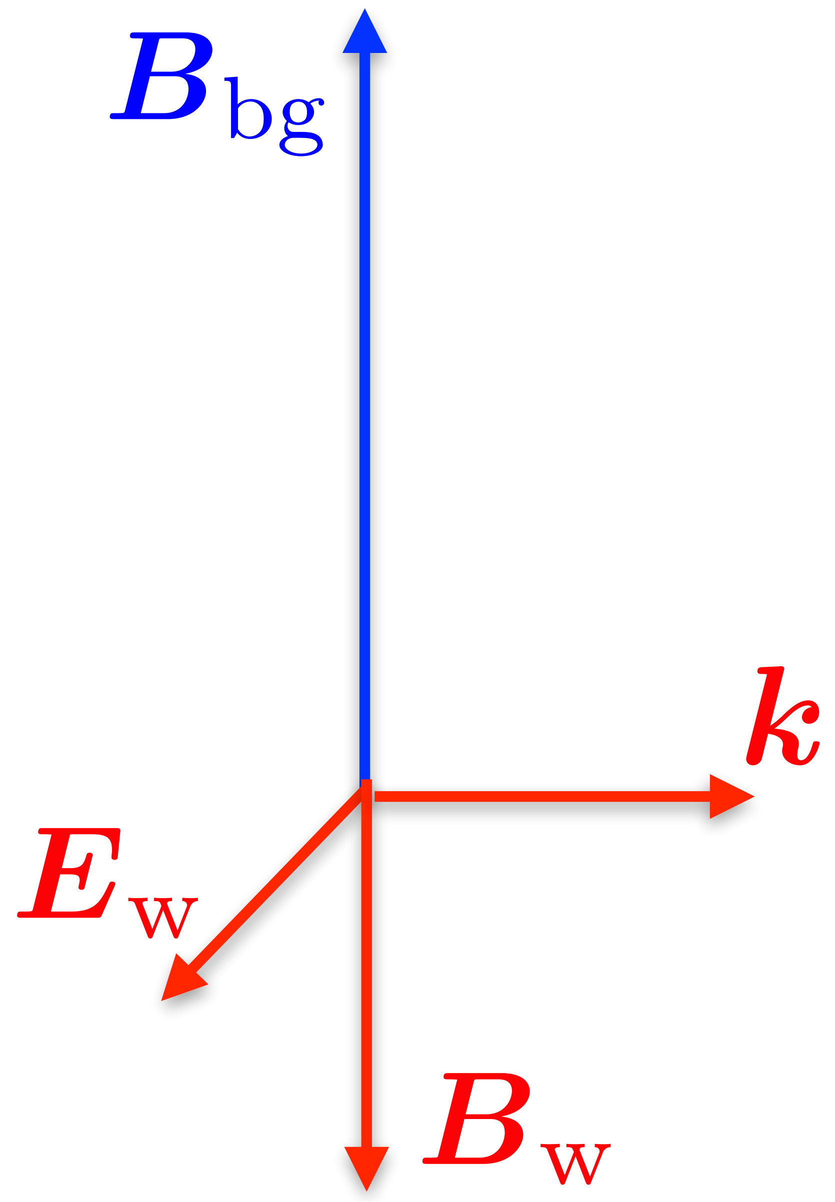
$\Rightarrow \frac{E_0}{B_{\rm bg}} \propto r^2$



$$\boldsymbol{B} = \boldsymbol{B}_{\rm bg} + \boldsymbol{B}_{\rm w}$$

$$\boldsymbol{E} = \boldsymbol{E}_{\rm w}$$



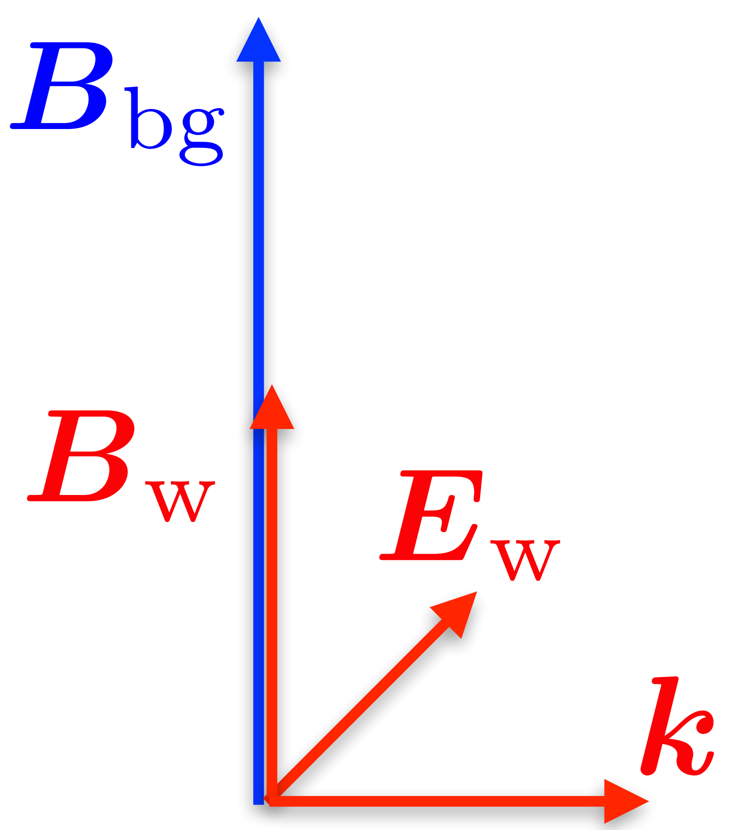


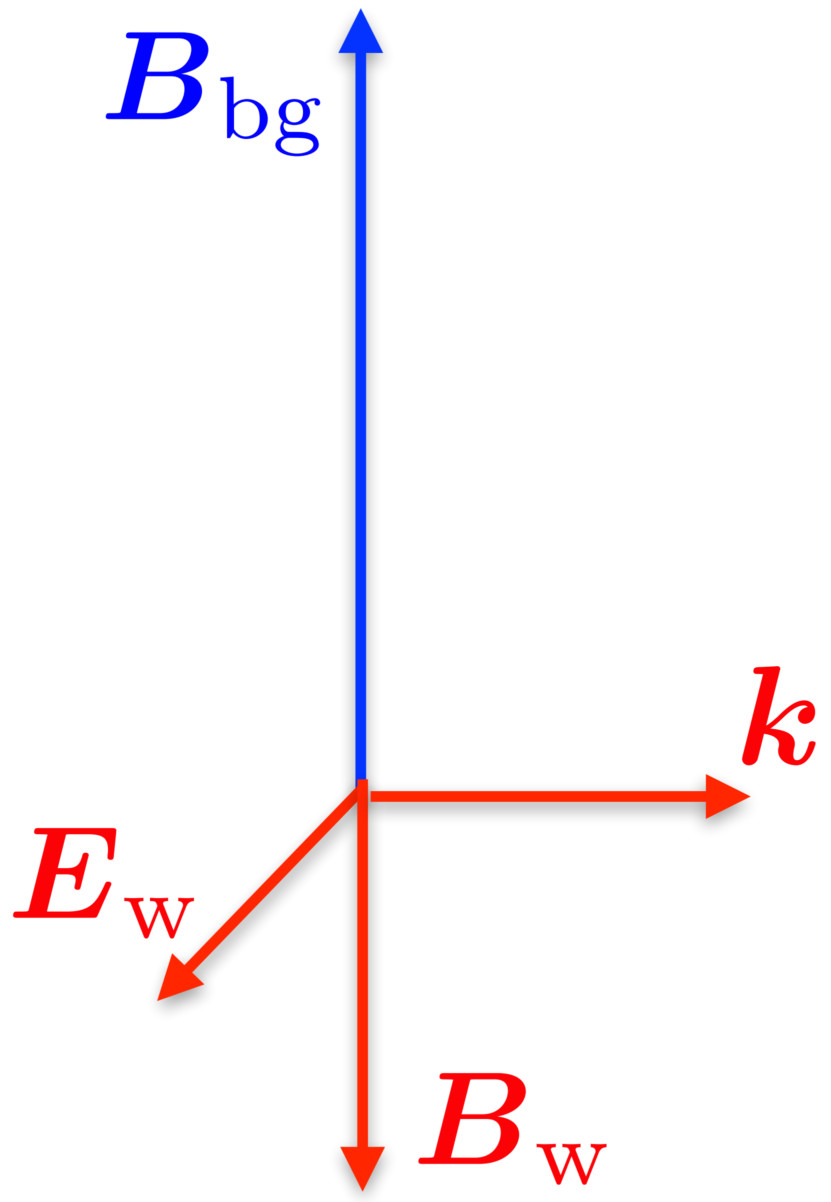
$$\boldsymbol{B} = \boldsymbol{B}_{\rm bg} + \boldsymbol{B}_{\rm w}$$

$$\boldsymbol{E} = \boldsymbol{E}_{\rm w}$$

plasma motion in the wave: $$\frac{\boldsymbol{v}_{\rm D}}{c} = \frac{\boldsymbol{E} \times \boldsymbol{B}}{B^2}$$

$$\frac{|\boldsymbol{v}_{\rm D}|}{c} = \frac{|\boldsymbol{E}|}{|\boldsymbol{B}|}$$





$$\boldsymbol{B} = \boldsymbol{B}_{\rm bg} + \boldsymbol{B}_{\rm w}$$

$$\boldsymbol{E} = \boldsymbol{E}_{\rm w}$$

wave breaks when

$$|\boldsymbol{E}| = |\boldsymbol{B}| = \frac{B_{\rm bg}}{2}$$

$$(v_{\rm D} \to -c)$$

occurs at $R_\times \sim 10^8$ cm

plasma motion in the wave: $$\frac{\boldsymbol{v}_{\rm D}}{c} = \frac{\boldsymbol{E} \times \boldsymbol{B}}{B^2}$$

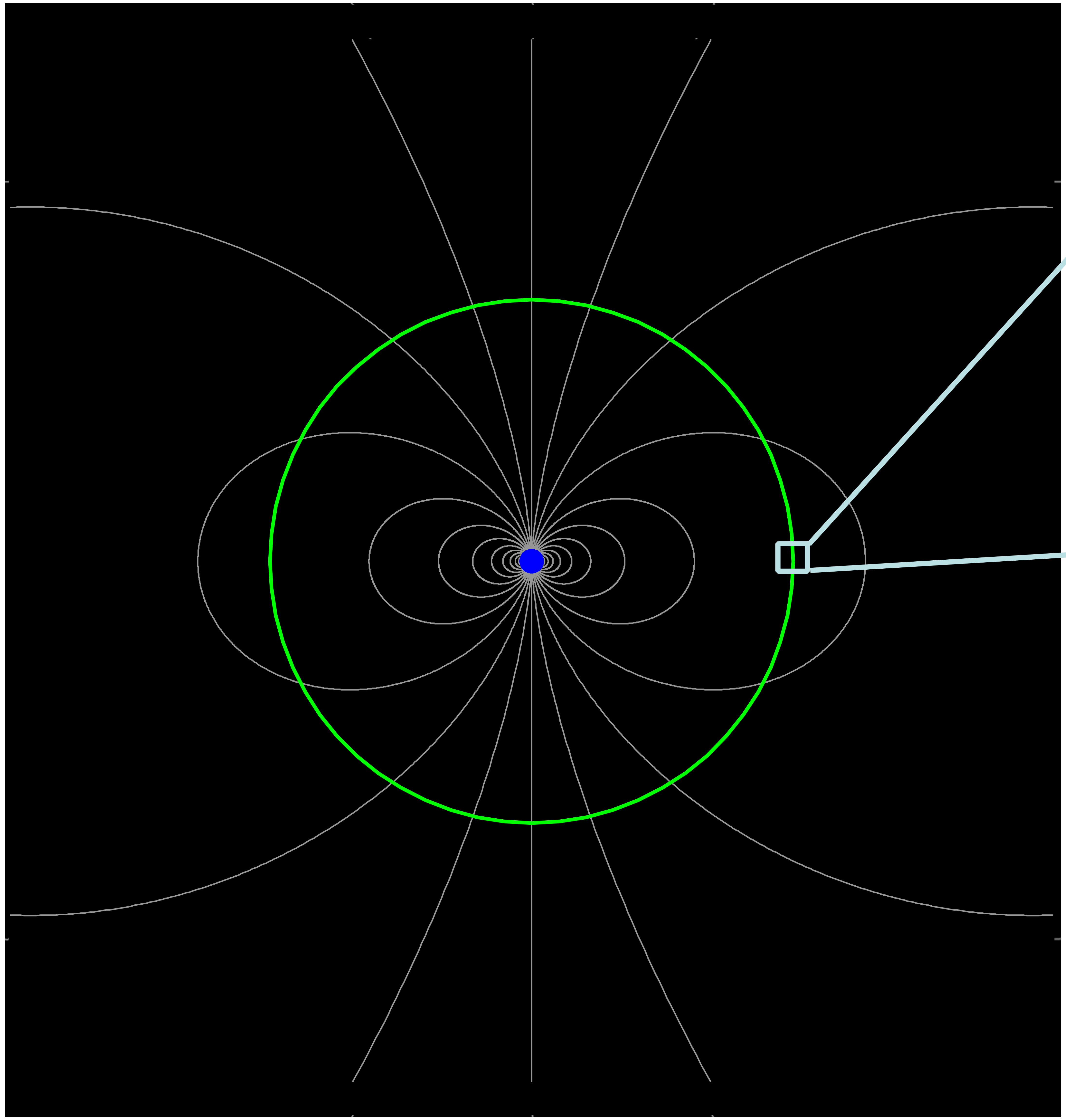
$$\frac{|\boldsymbol{v}_{\rm D}|}{c} = \frac{|\boldsymbol{E}|}{|\boldsymbol{B}|}$$

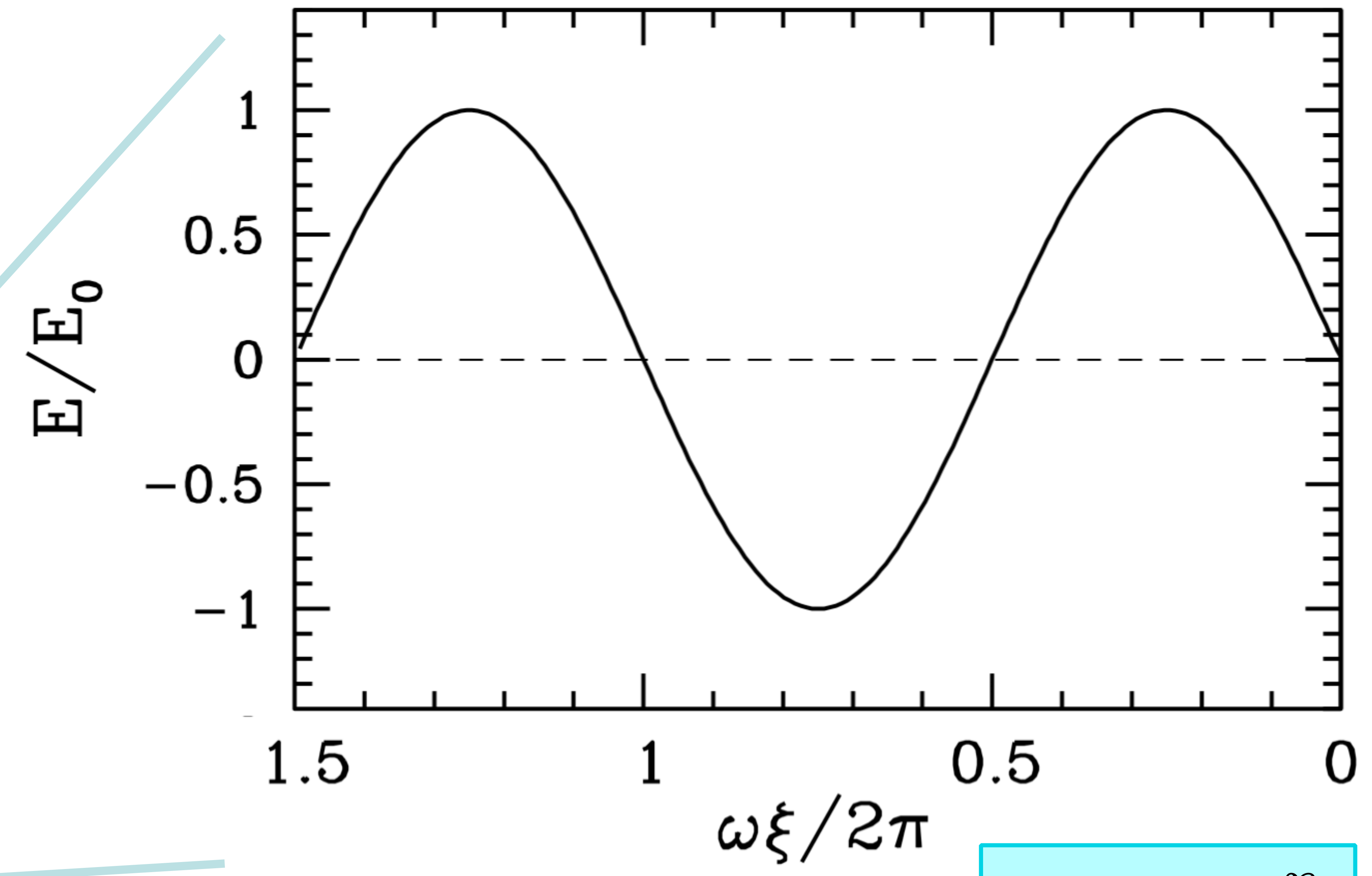
shock formation:

PIC simulation:
Chen et al. 2022

MHD:
AB 2022

an expanding EM wave packet

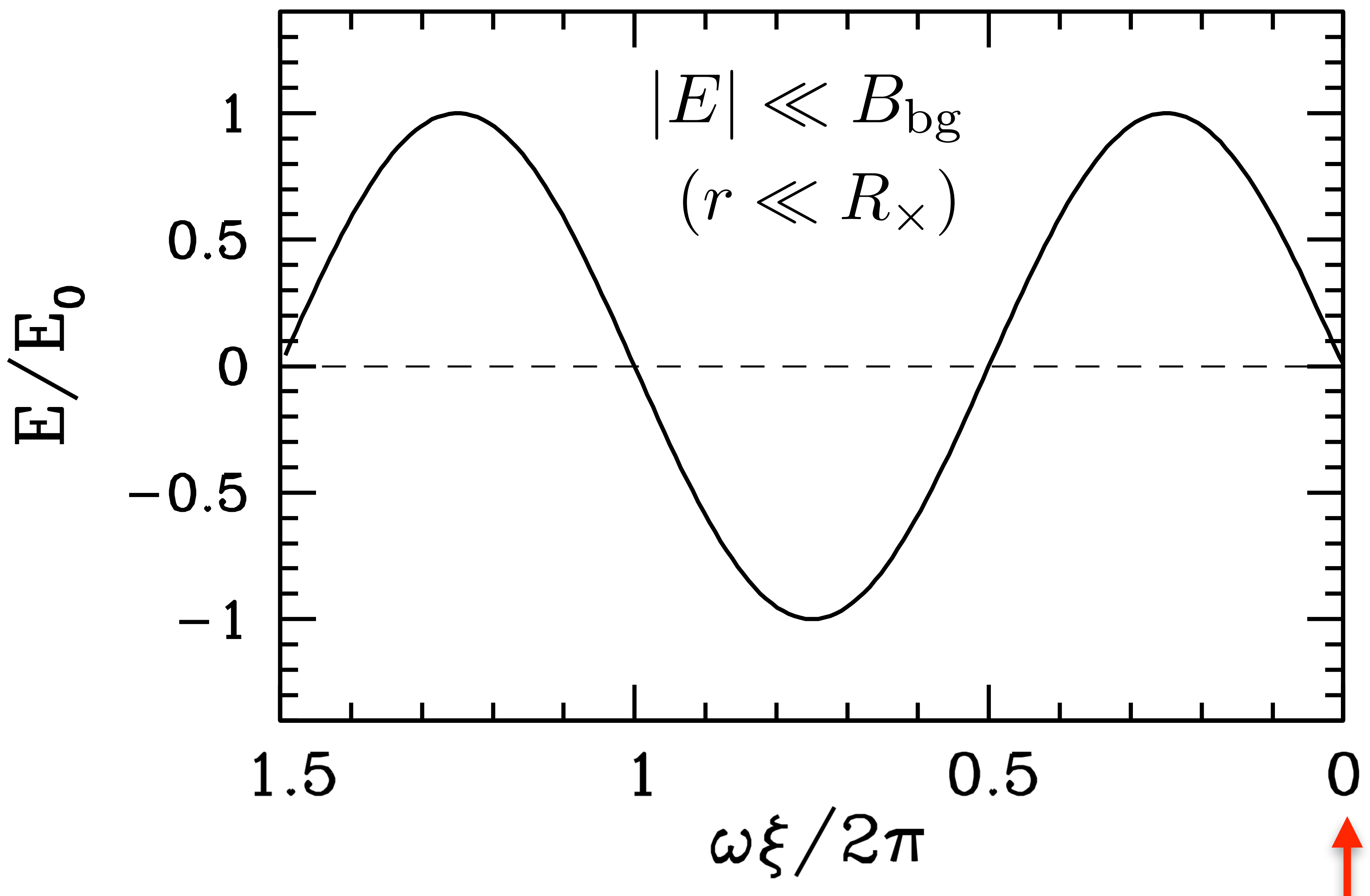




$$\xi \equiv t - \frac{r}{c}$$

- fnd the MHD solution for the wave expansion through the dipole magnetosphere

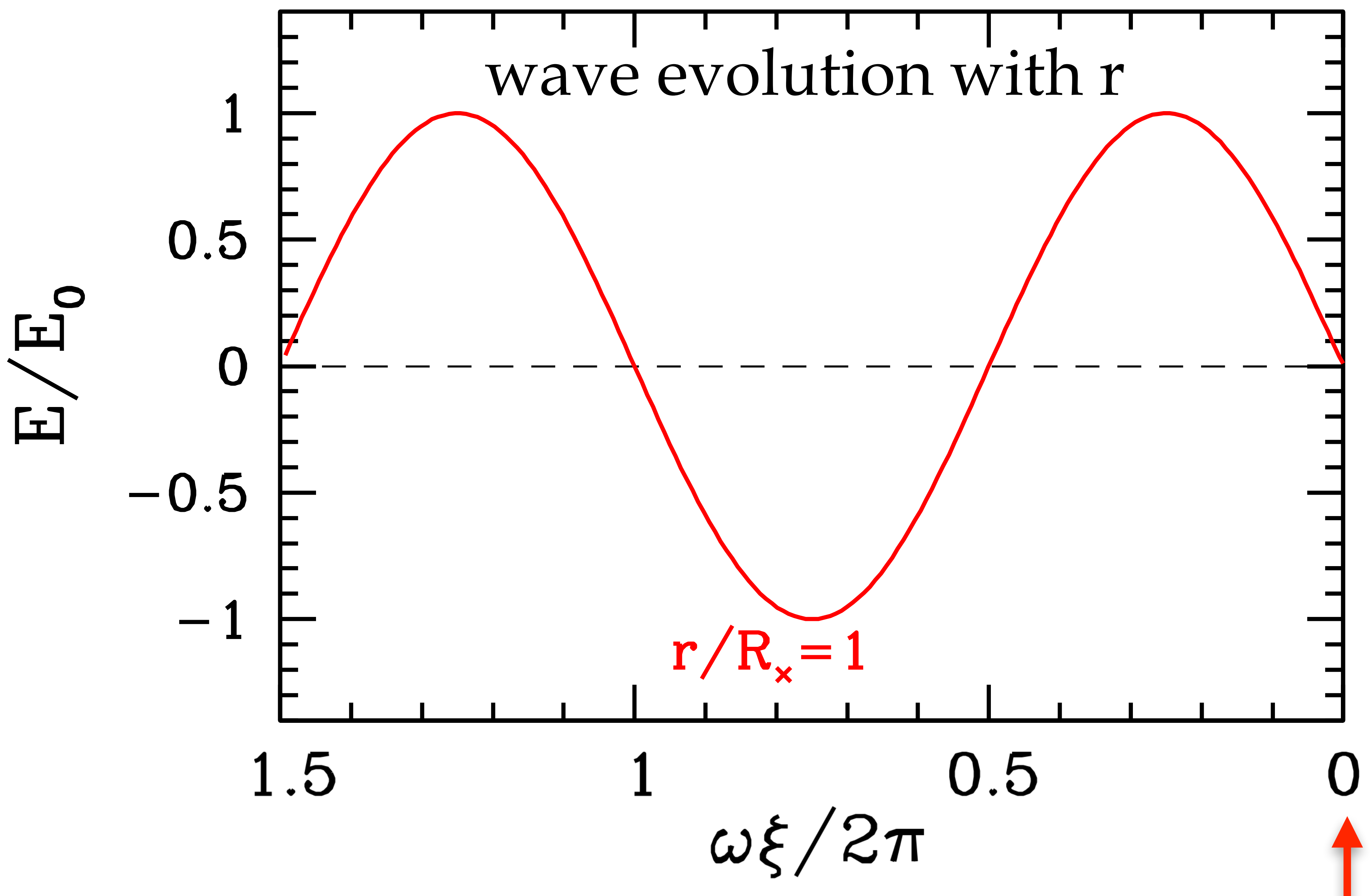
(AB, ApJ in press)



beginning of the kHz wave

initial profile: $E(\xi) = E_0 \sin(\omega\xi)$

$$\xi \equiv t - \frac{r}{c}$$



beginning of
the kHz wave

initial profile: $E(\xi) = E_0 \sin(\omega\xi)$

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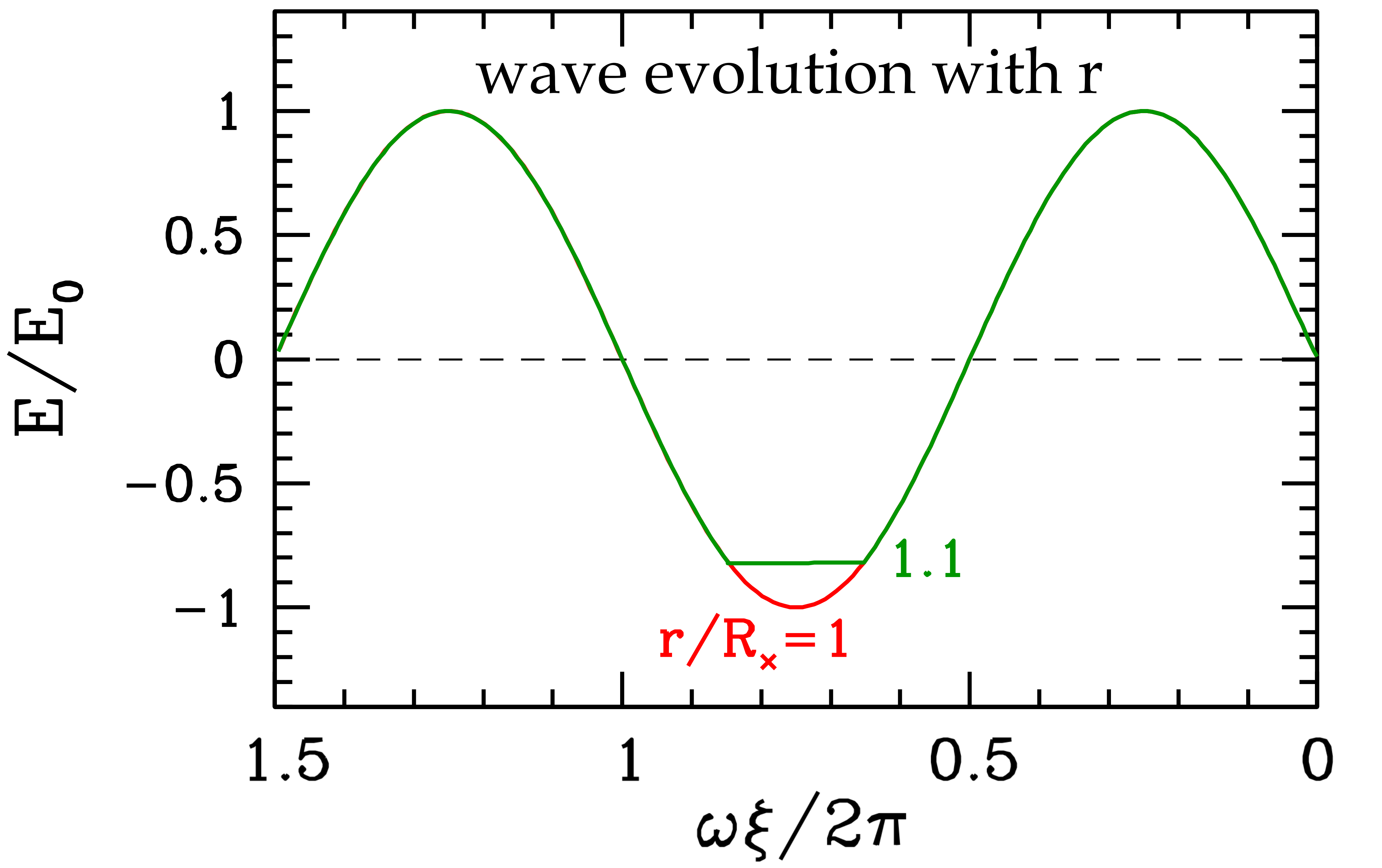
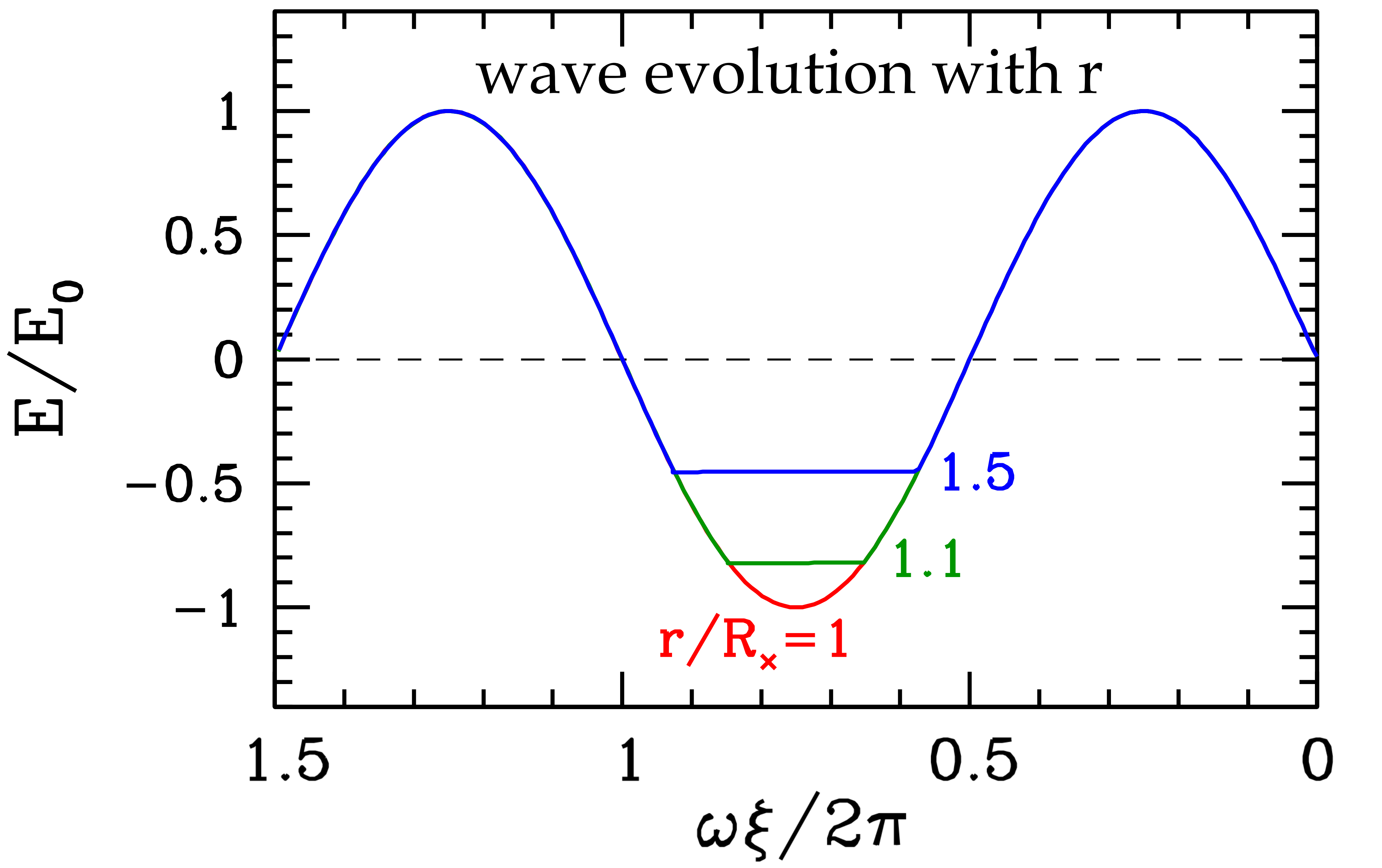


initial profile: $E(\xi) = E_0 \sin(\omega\xi)$

$$\xi \equiv t - \frac{r}{c}$$

Plateau: the ceiling of $E^2 = B^2$ corresponds to $|E_\mathrm{p}| \approx \frac{B_\mathrm{bg}}{2} \propto r^{-3}$

instead of the vacuum solution $E \propto r^{-1}$



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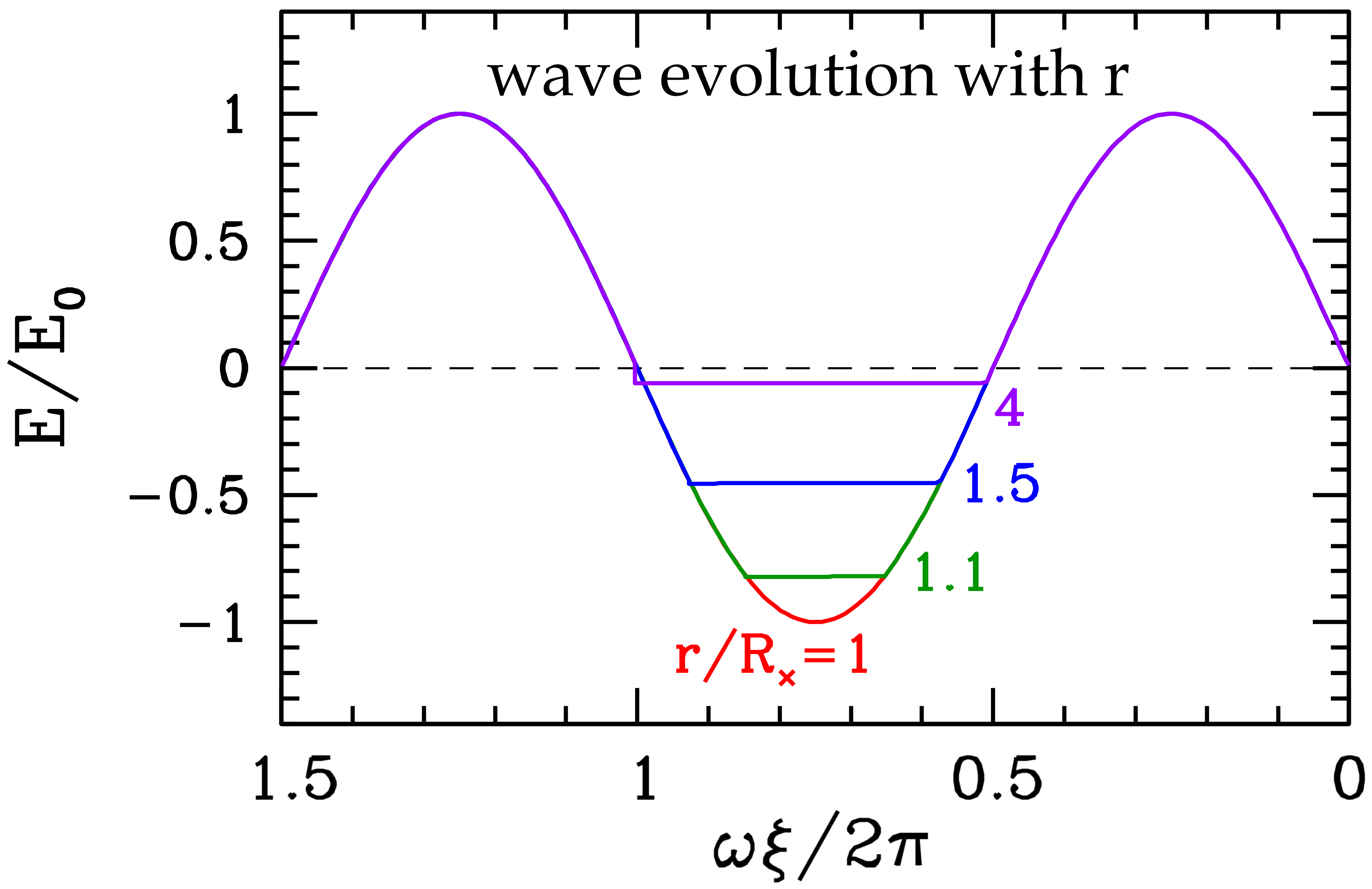

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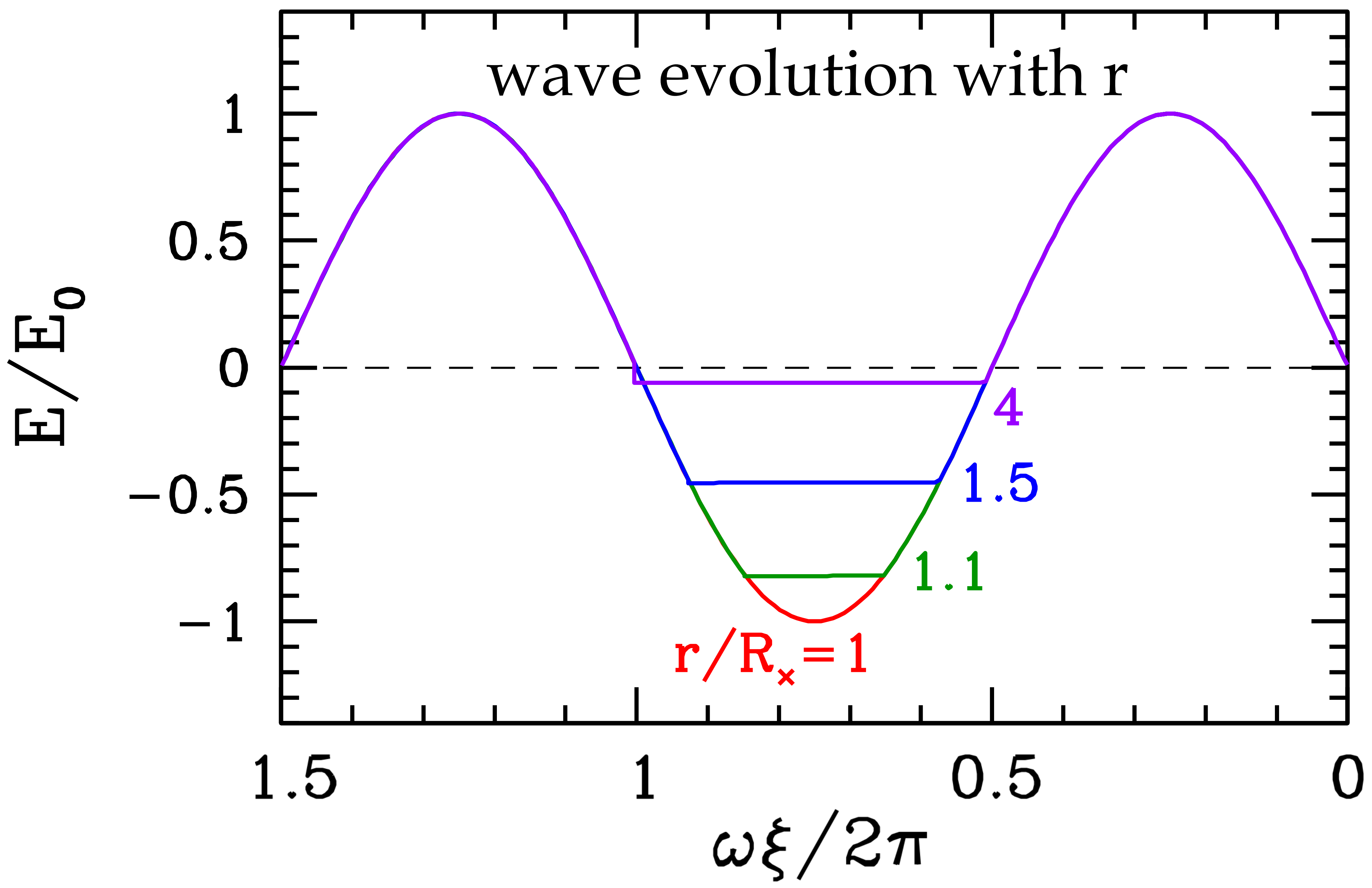

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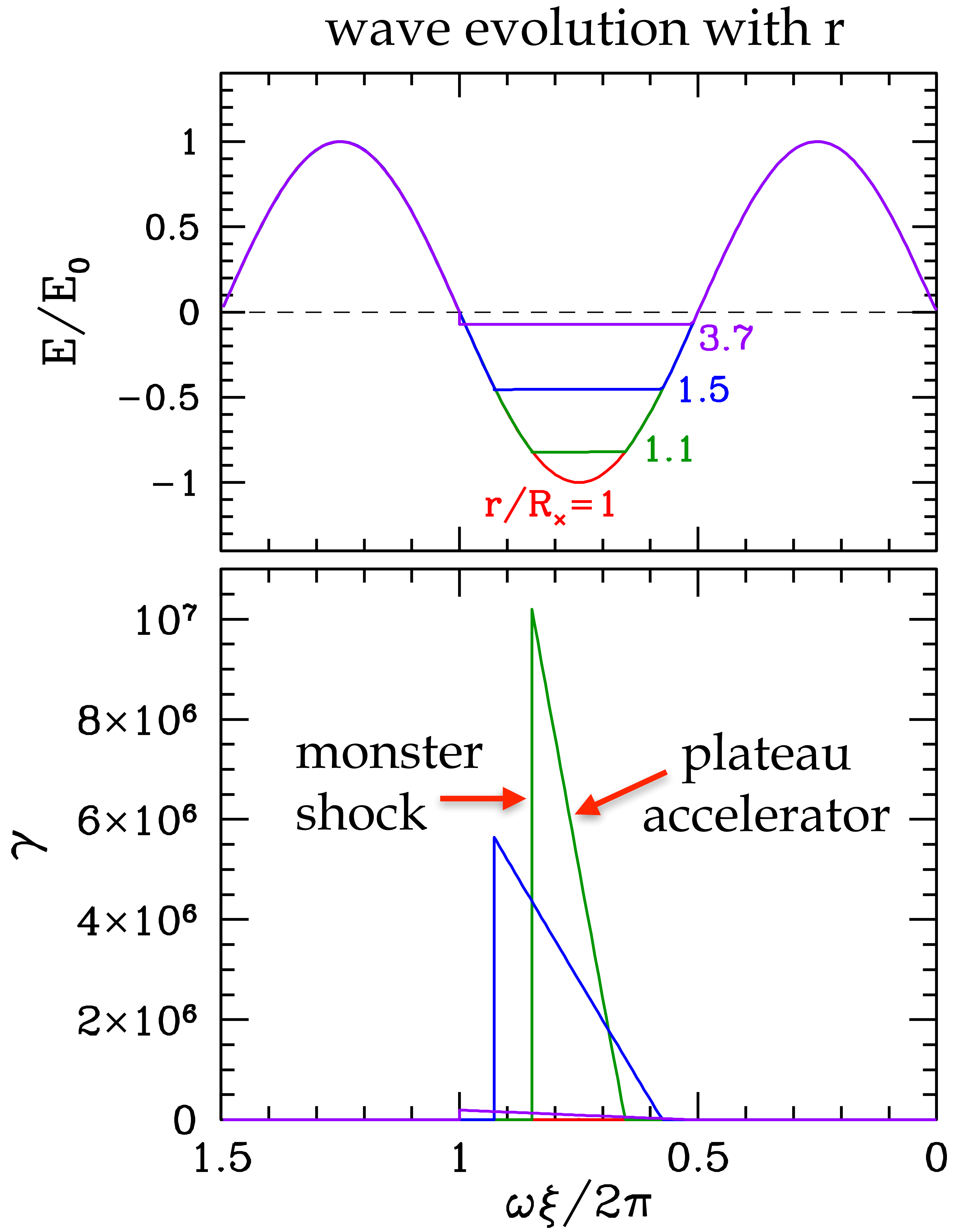
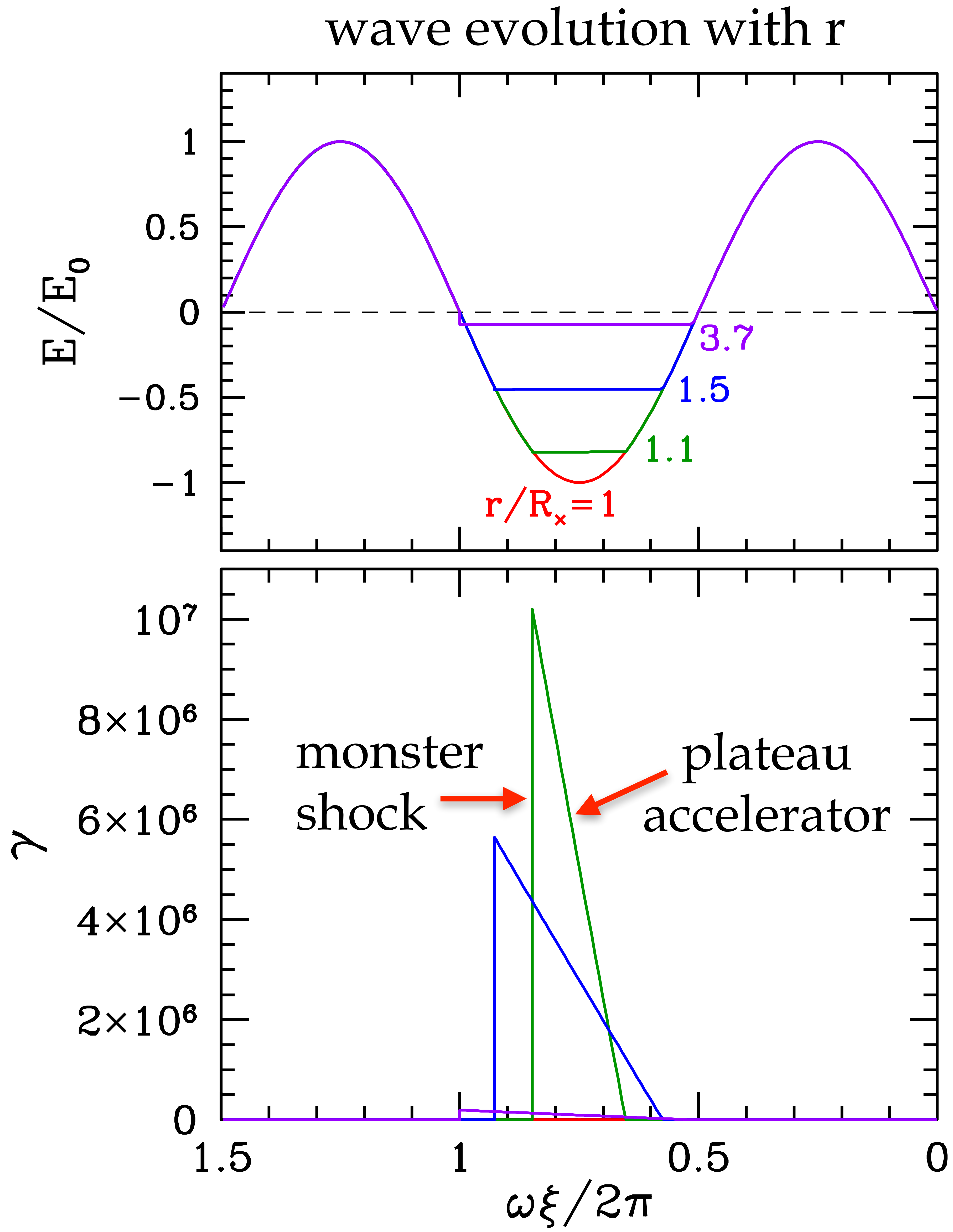
instead of the vacuum solution $E \propto r^{-1}$

where did the half-wave energy go?



$$n\,mc^2\frac{d\gamma}{dt} = \boldsymbol{E}\cdot\boldsymbol{j}$$



$$n\,mc^2\frac{d\gamma}{dt} = \boldsymbol{E}\cdot\boldsymbol{j}$$

plateau: a linear accelerator

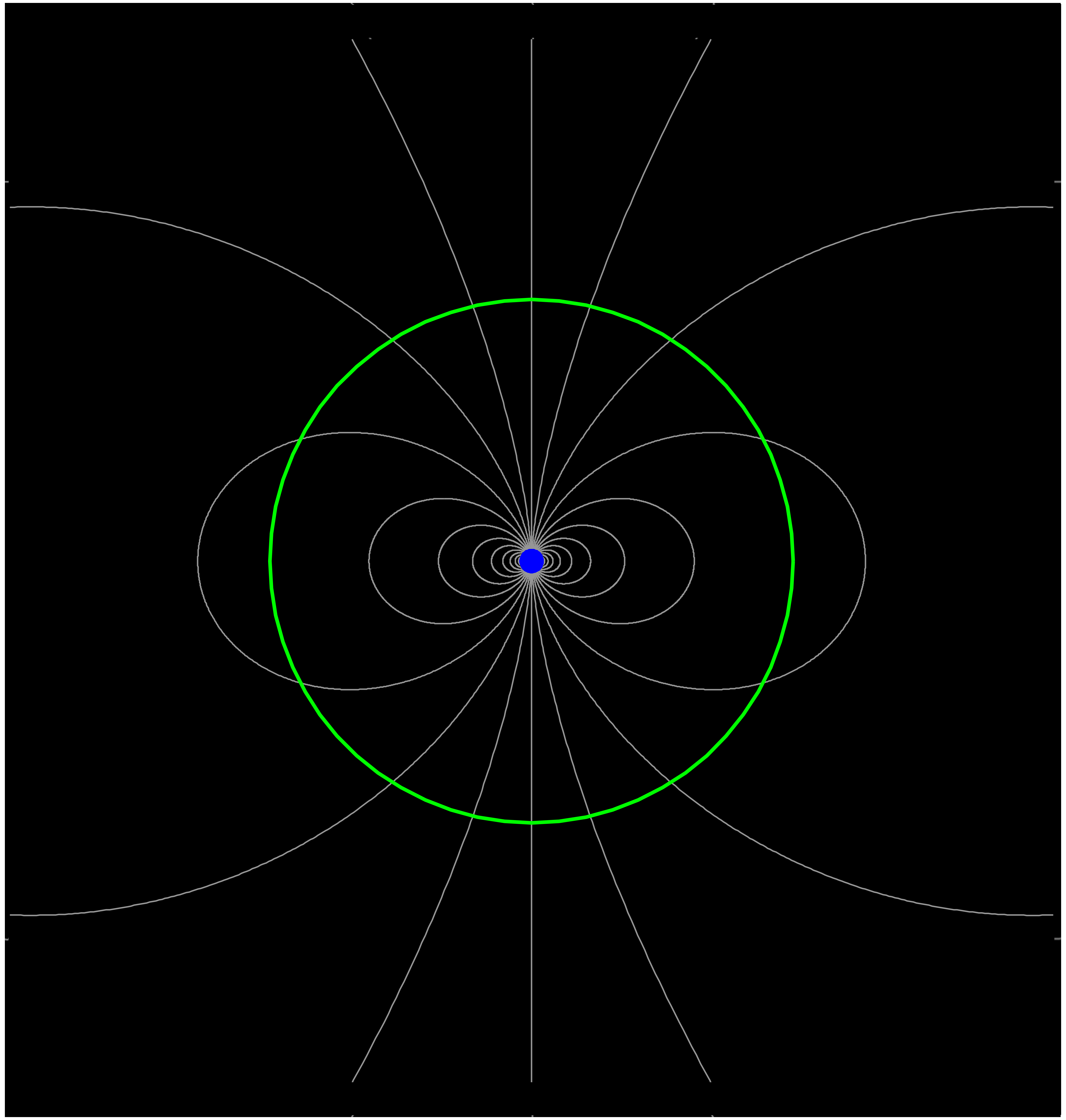
plateau width $W_{\rm p} \sim \dfrac{c}{\omega}$

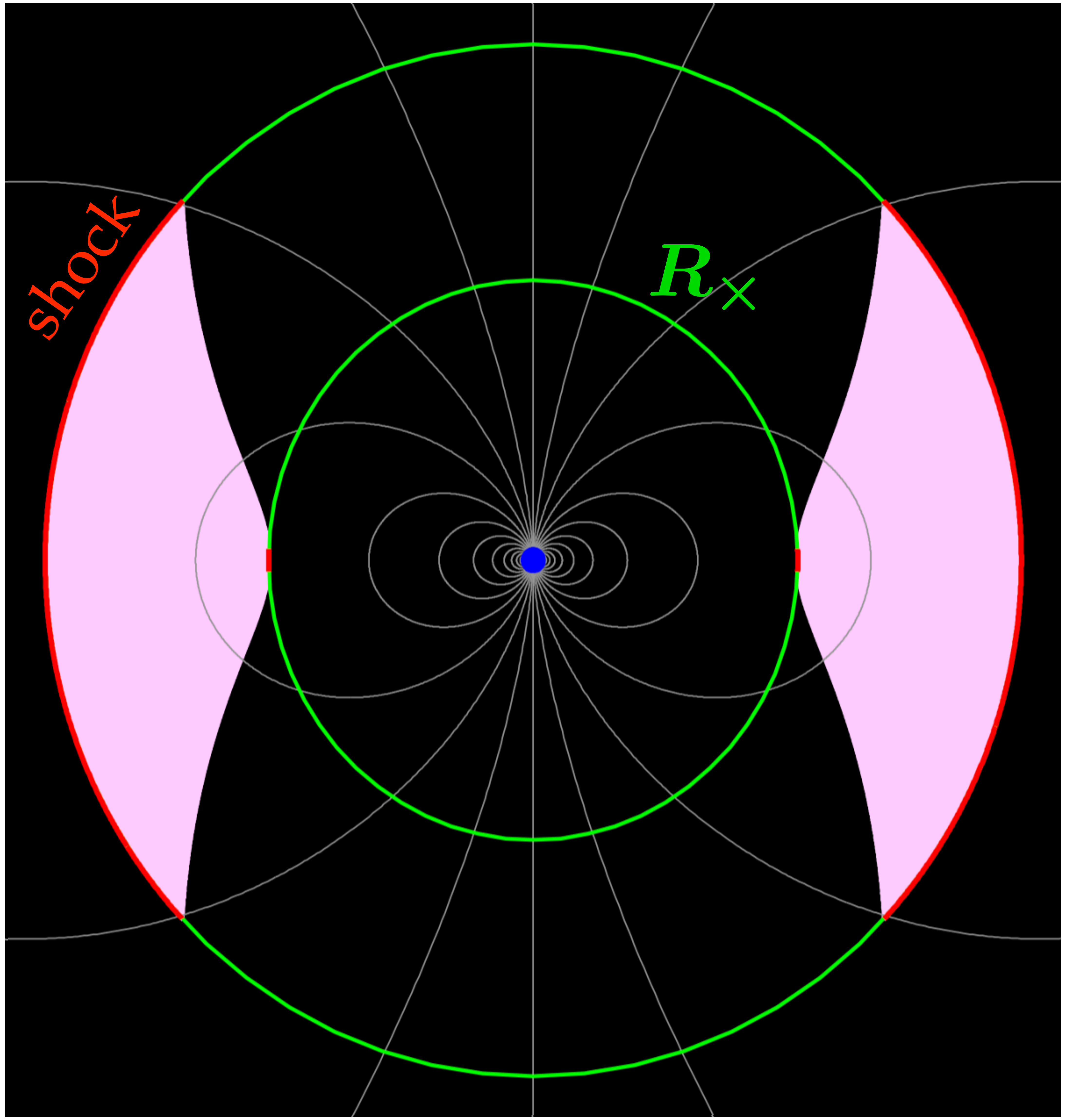
$$\gamma = \frac{W_{\rm p}}{r}\,\sigma_{\rm bg} \sim 10^7\,!$$

shock at the end of the plateau

monster shock weakens as it expands inside the magnetosphere, and again becomes strong outside.

relativistic explosion in the magnetar wind





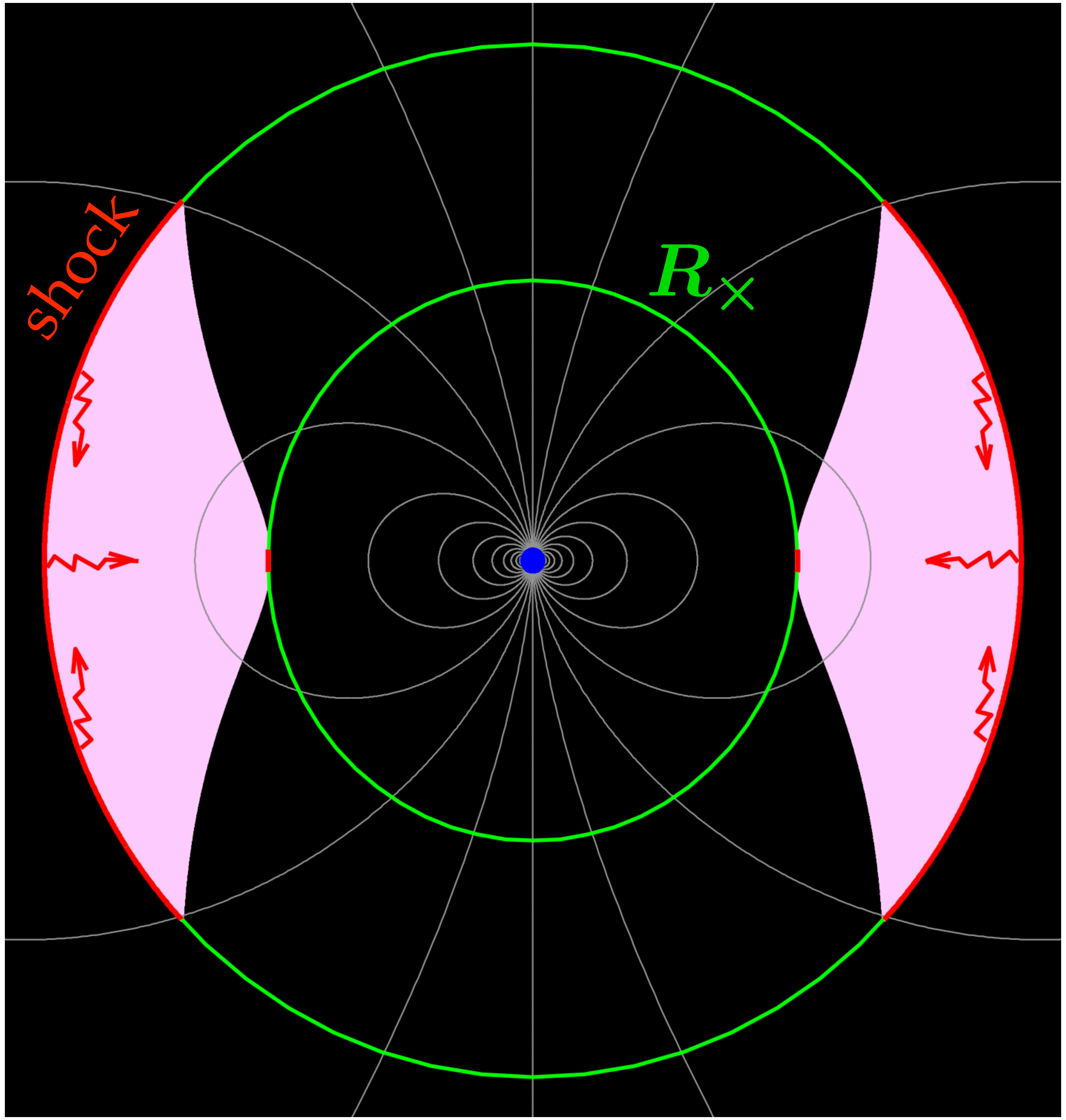
magnetic dipole moment of the star

$$R_\times = \left(\frac{c\mu^2}{8L}\right)^{1/4} \quad (E^2 = B^2)$$

wave power

Example: $L = 10^{43}\,\mathrm{erg/s}$

$$R_\times \approx 100 R_\star$$



Monster shocks are radiative

particles crossing the shock
emit curvature gamma-rays

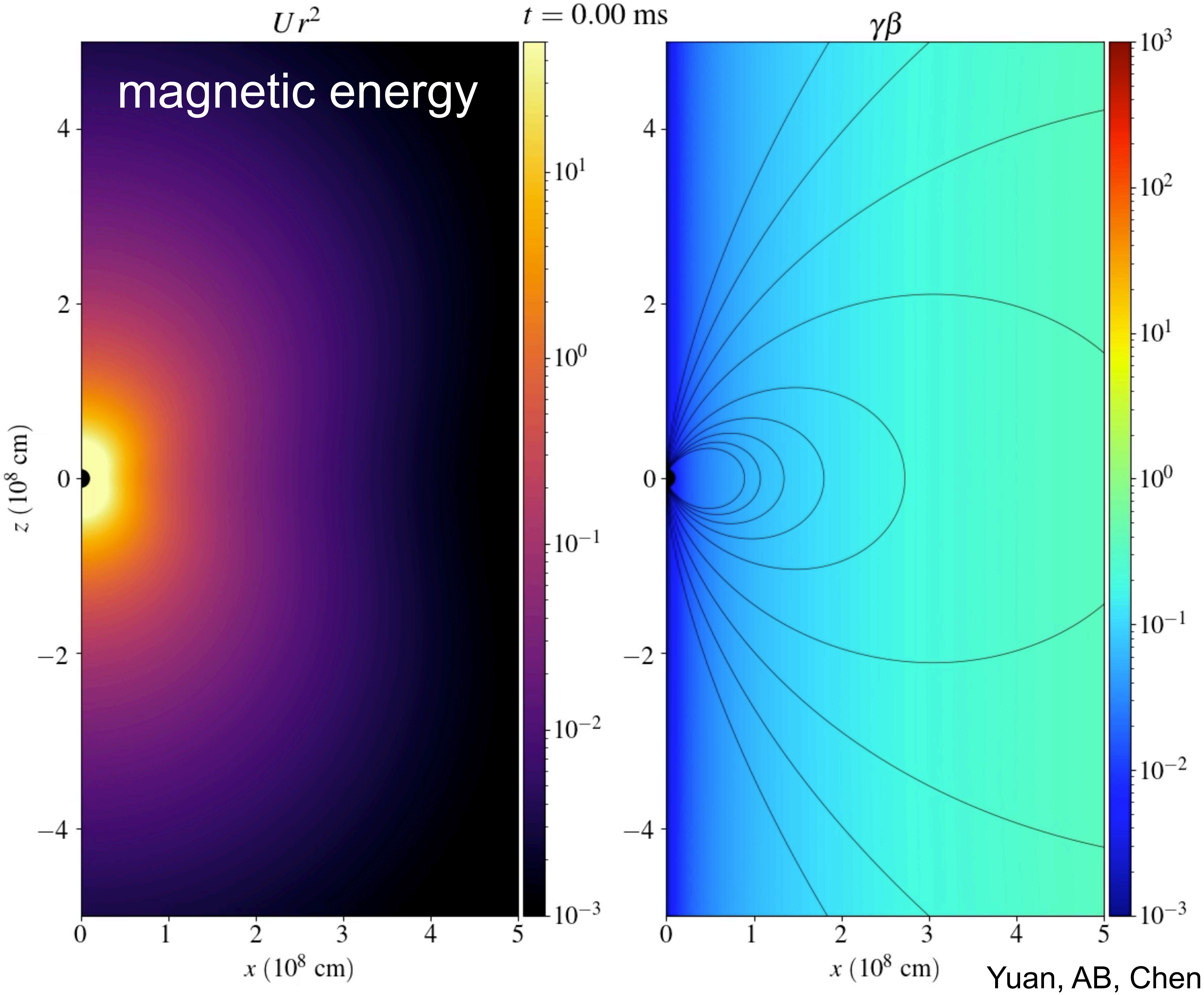
Lorentz factor $\gamma \sim \dfrac{c\,\sigma_{\rm bg}}{\omega R_\times}$

gamma-rays convert to e+- pairs:
synchrotron cascade

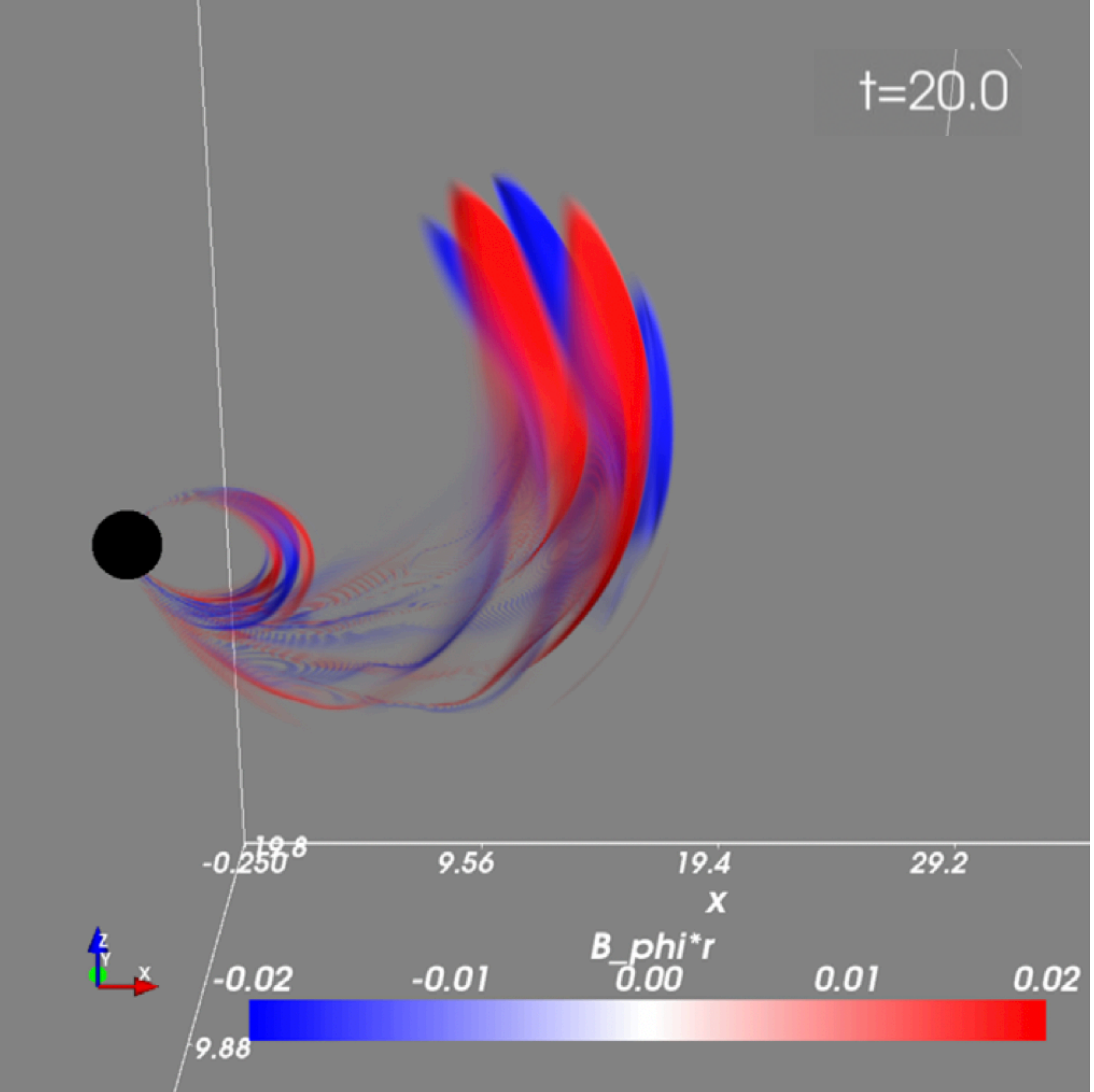
=> energy lost by the kHz wave is
radiated in the X-ray band

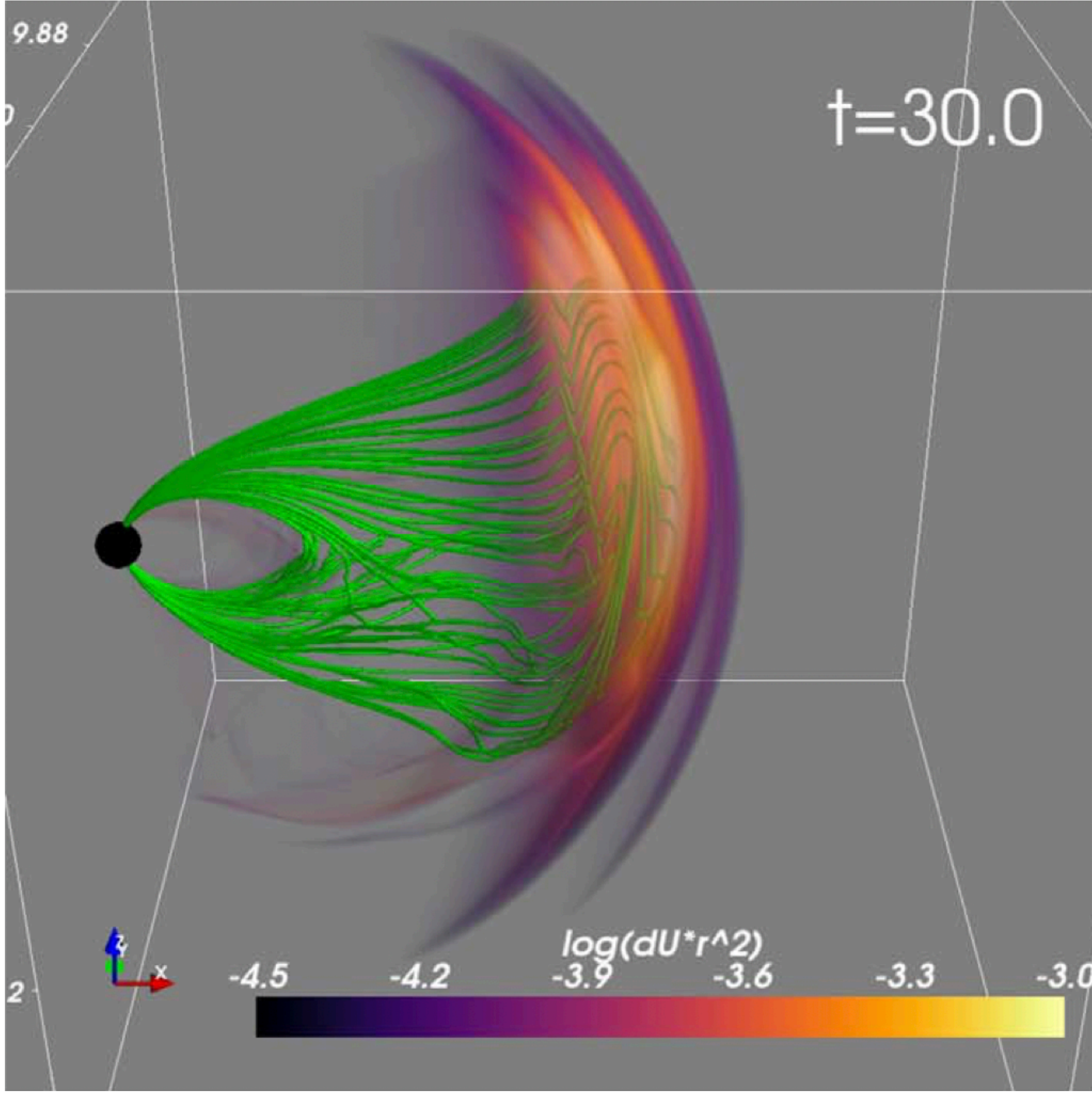
II. Alfven waves from quakes

Alfven wave from a quake



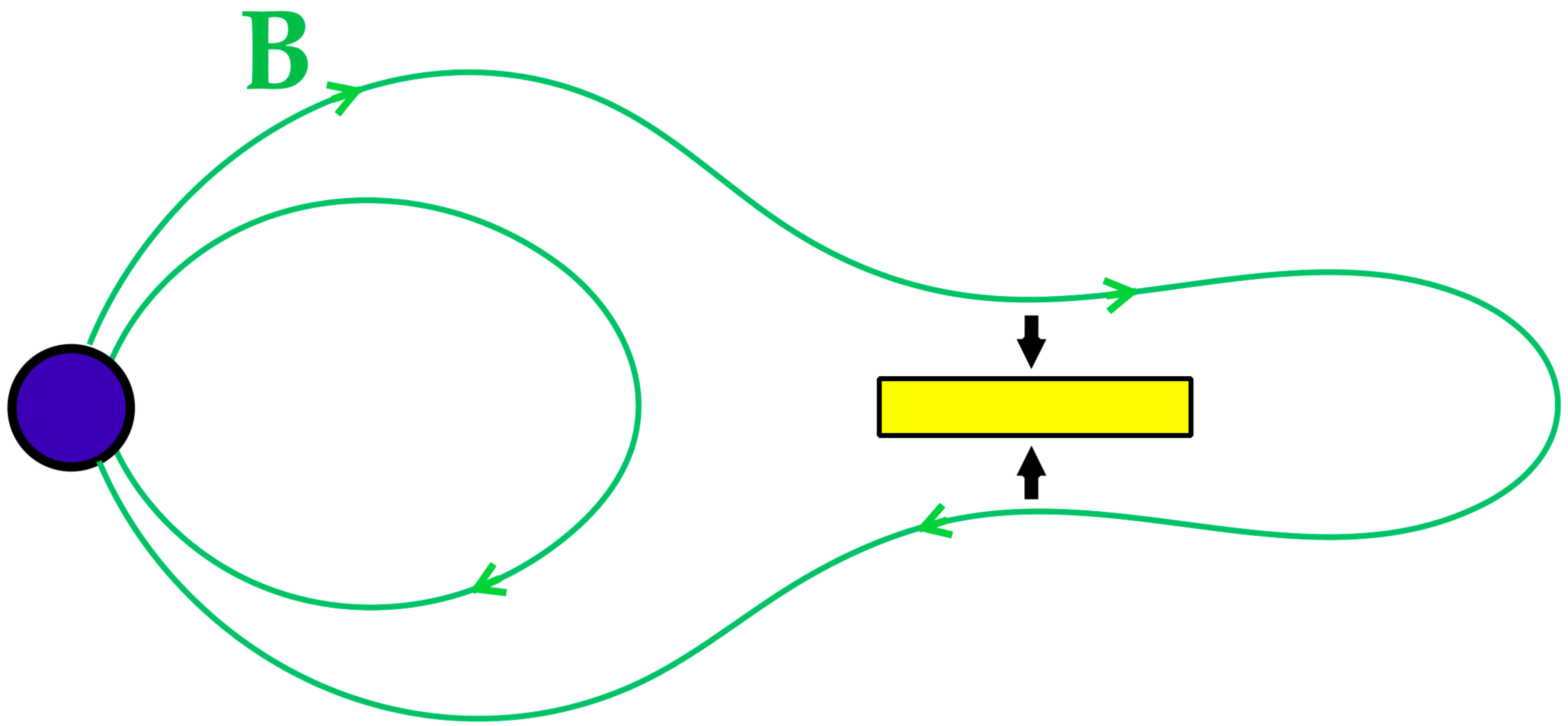
Yuan, AB, Chen, Levin 2020



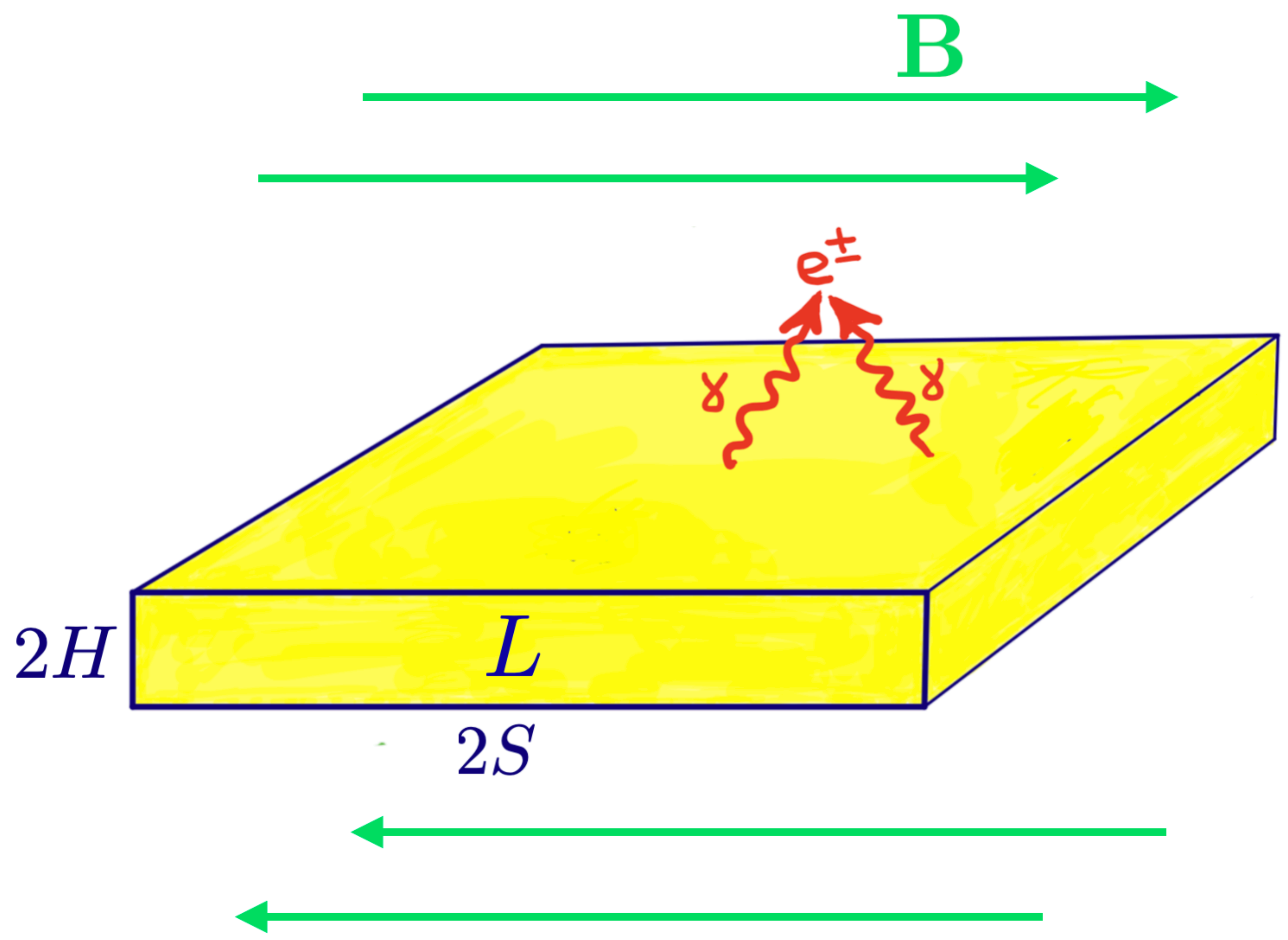


Yuan et al. 2022

Magnetic reconnection



Creation of e+- plasma and X-ray bursts



$$\ell_B \equiv \frac{U_B}{m_e c^2}\,\sigma_{\rm T} S \approx 3\times 10^5\; B_9^2\, S_7$$

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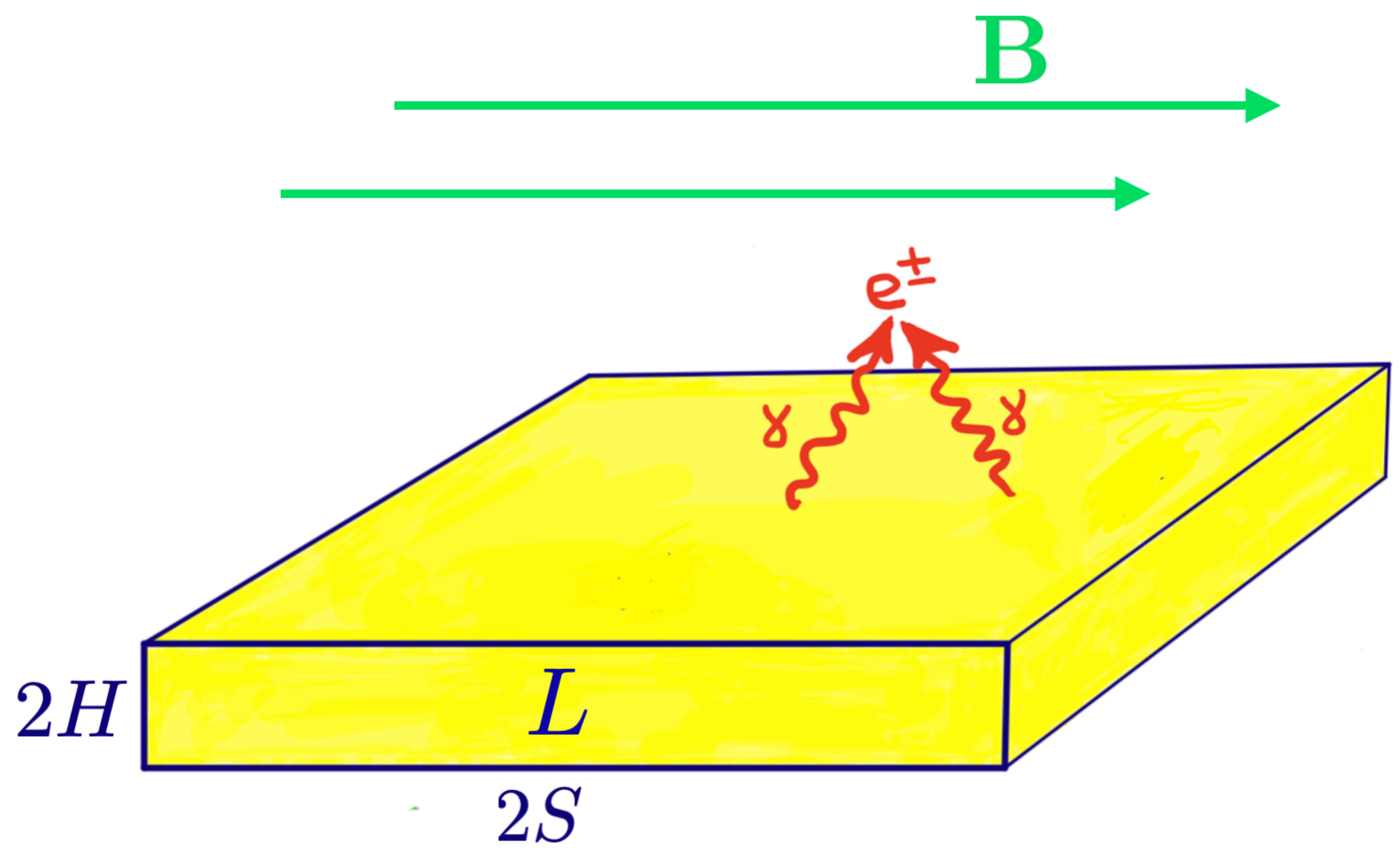
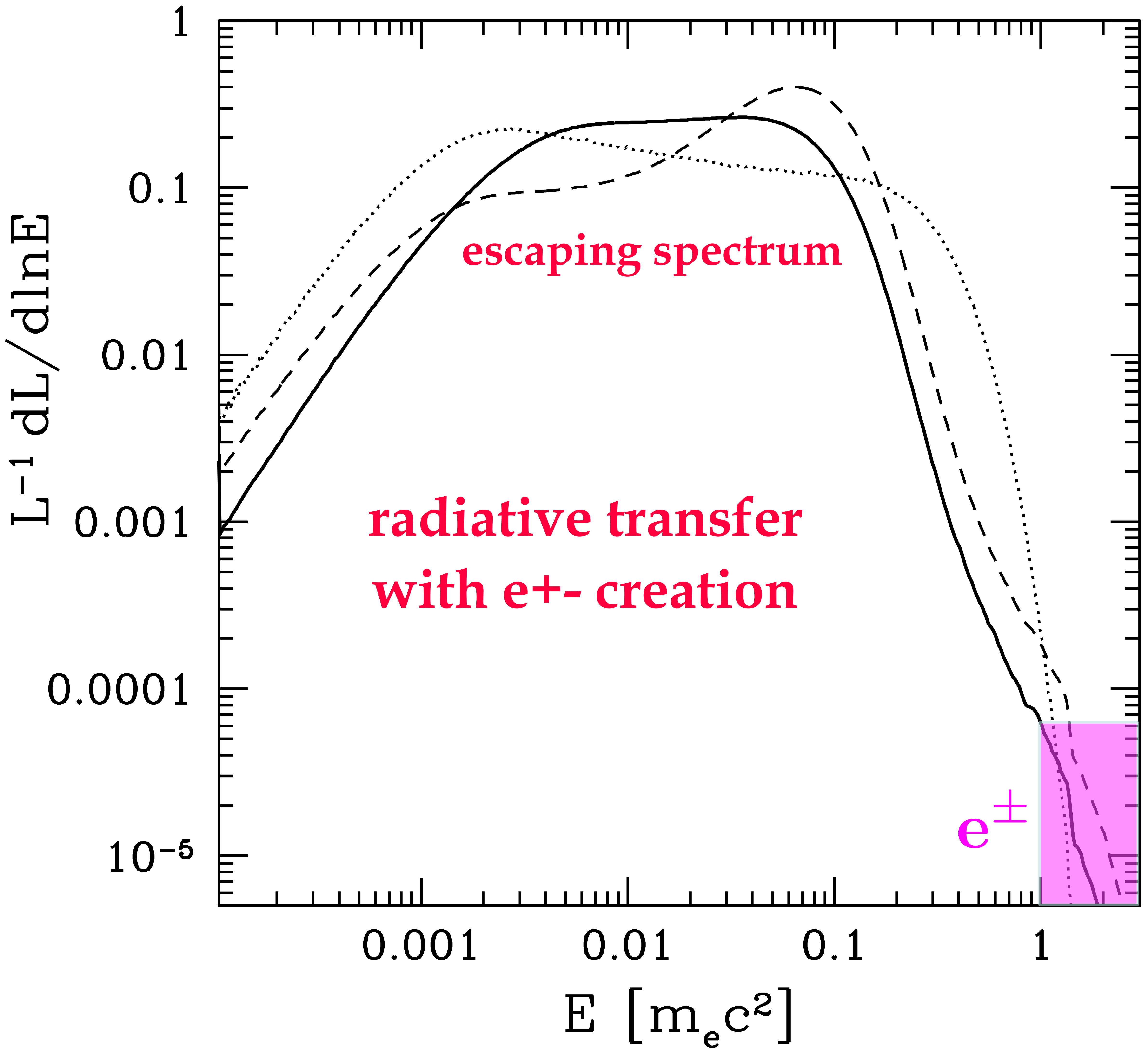


$$\ell_B \equiv \frac{U_B}{m_e c^2}\,\sigma_{\rm T} S \approx 3\times 10^5\ B_9^2\, S_7$$

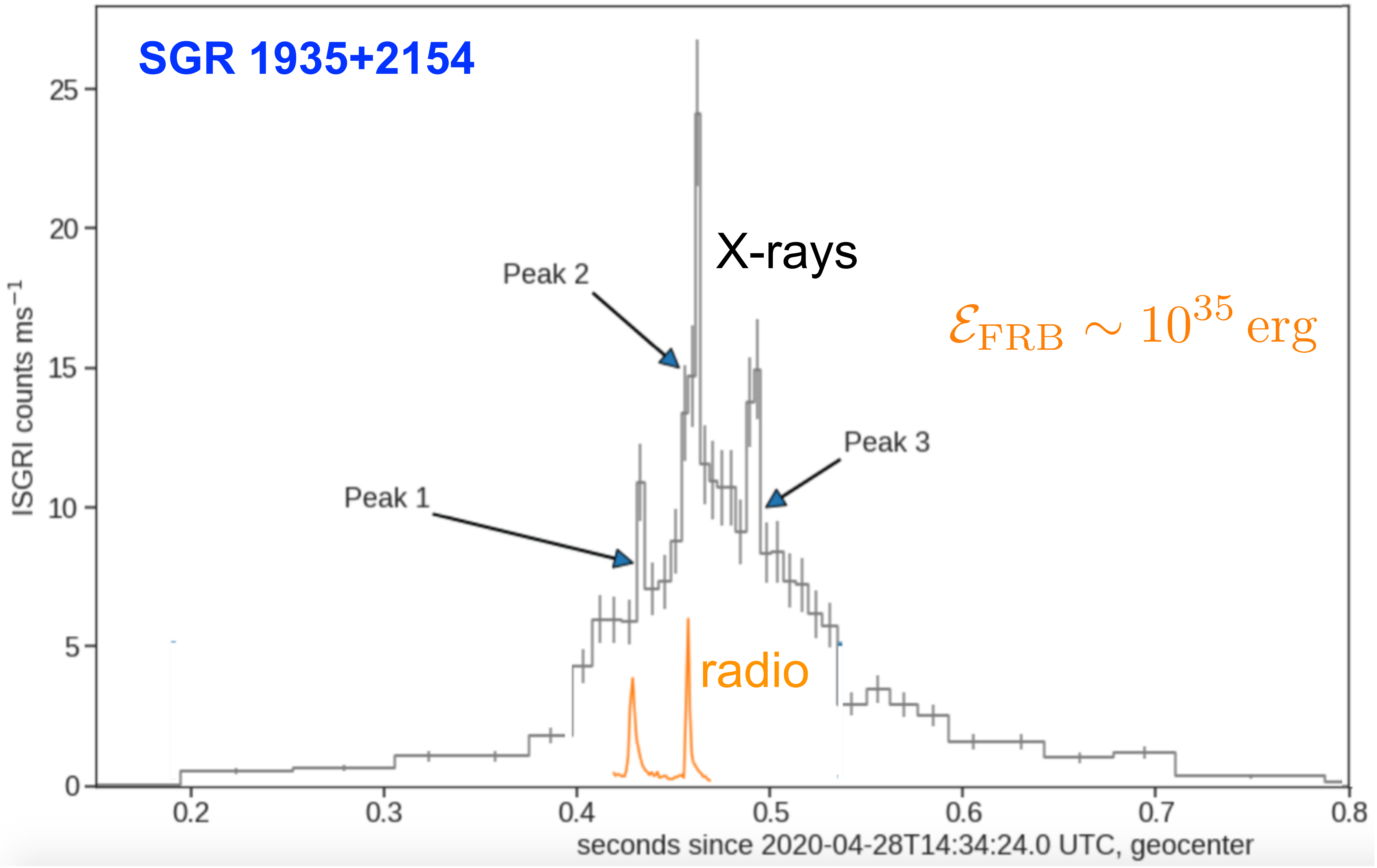


$$\frac{n_\pm}{n_\gamma} \sim 10^{-5}$$

$$\frac{kT}{m_e c^2} \sim 0.1$$

AB 2021

April 2020: FRB detection from a local magnetar



Bochenek et al. 2020; The CHIME/FRB Collaboration et al. 2020; Li et al. 2020; Mereghetti et al. 2020

FRBs:

- GHz band, ms duration
- detected in distant galaxies
- luminosities up to 10^{43} erg/s

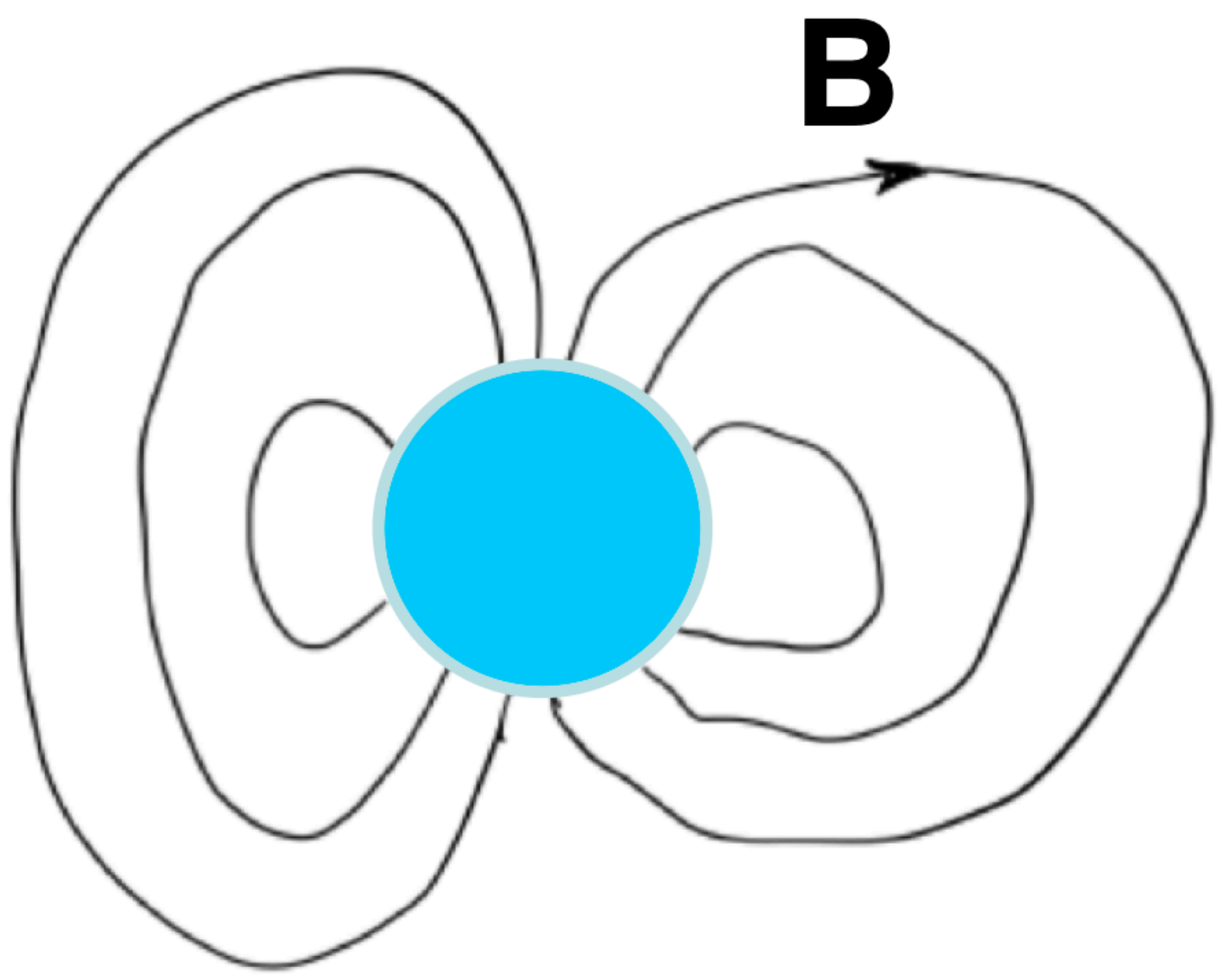
Radio bursts are damped in a static background magnetosphere

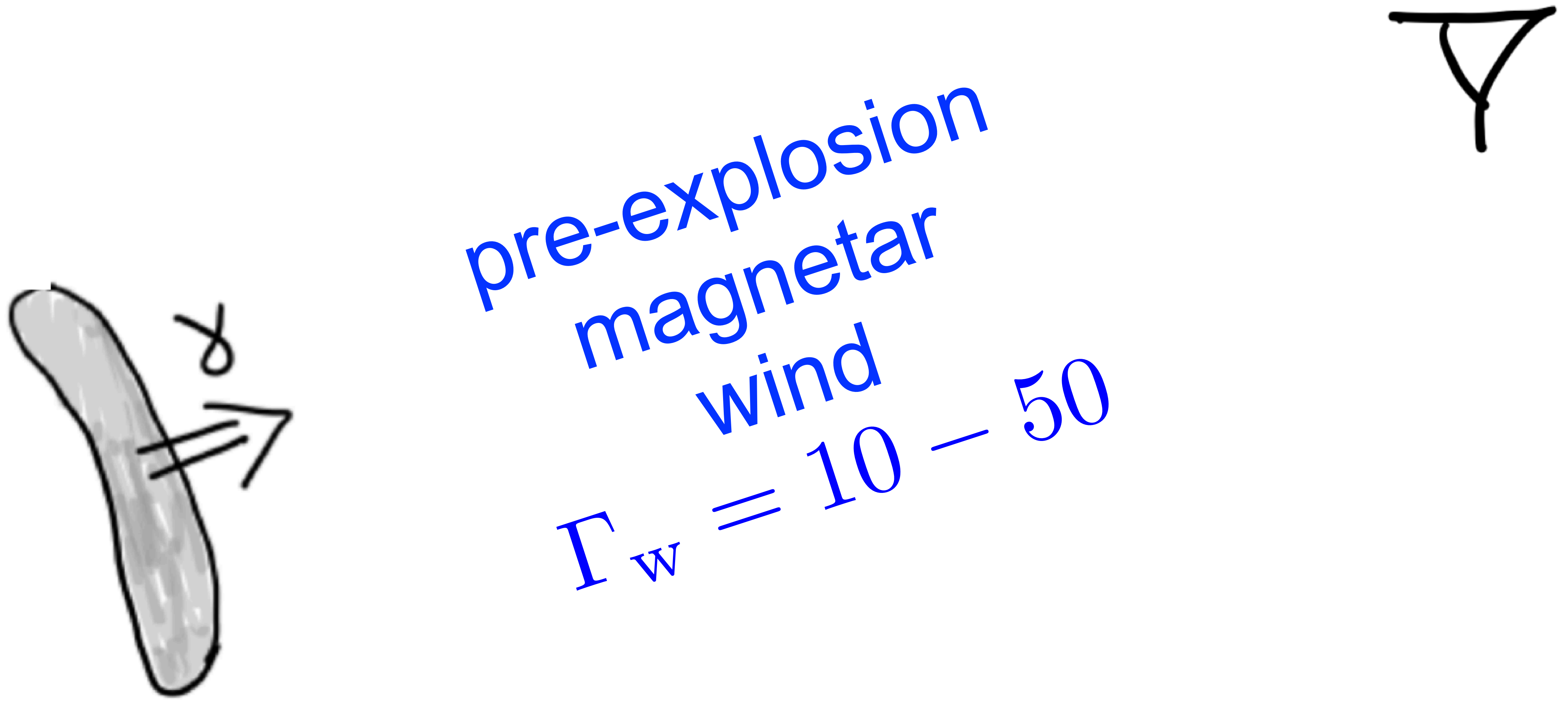
=> FRBs must be emitted by magnetic explosions
(and released far from the star, in the wind)

AB 2021, 2023
Golbreikh, Lyubarsky 2023

FRB mechanism: magnetic explosion

- shocks in the magnetar wind — AB 2017, 2020; Metzger et al. 2019
- ejecta carrying waves from magnetic reconnection — Lyubarsky 2020; Mahlmann et al. 2022





$$\Delta t \approx \frac{r}{c}\left(1 - \frac{v}{c}\right) \approx \frac{r}{2\gamma^2 c}$$

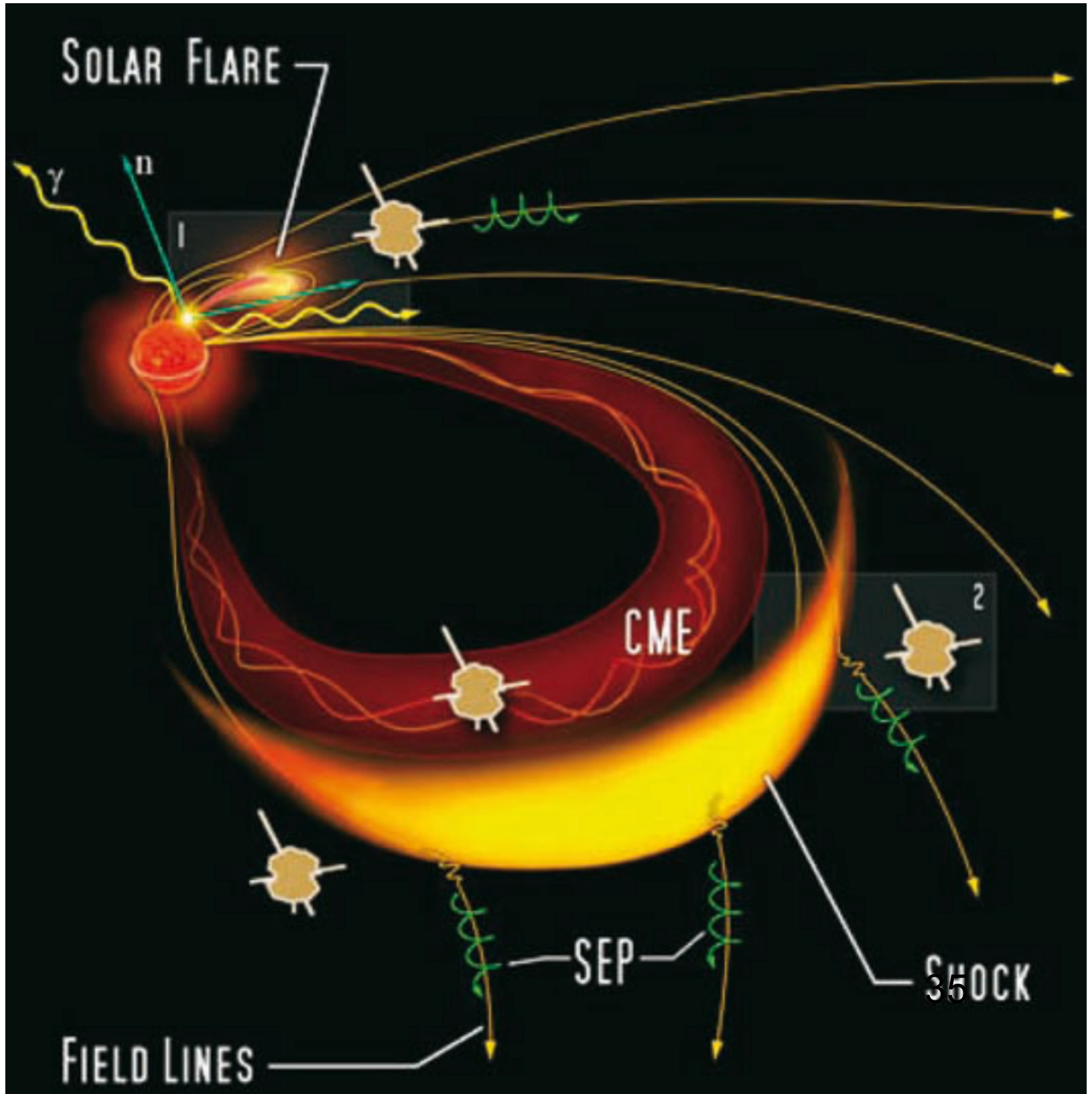
Blast waves from magnetar flares

blast Lorentz factor

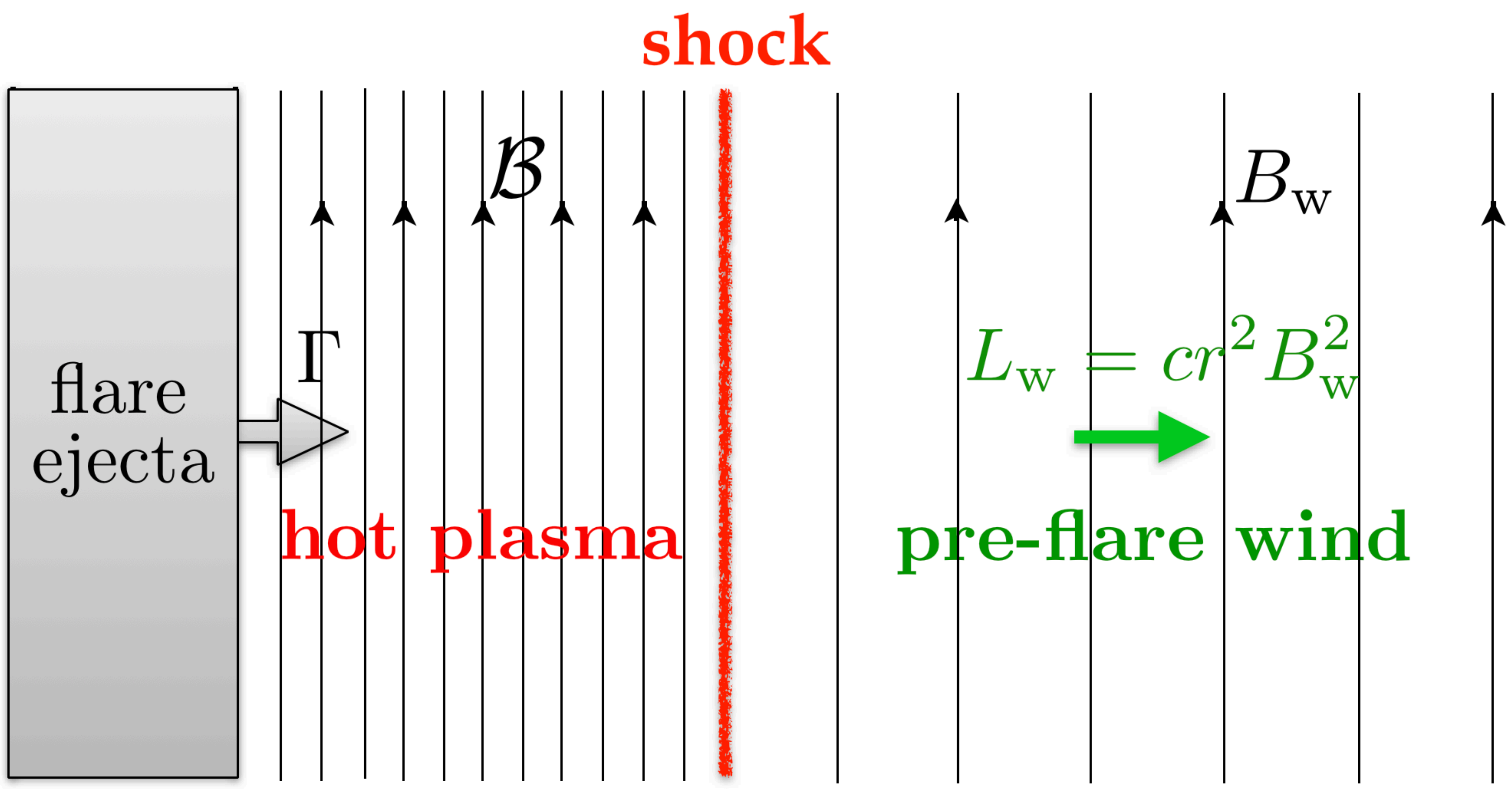
$$\frac{\Gamma}{\Gamma_{\mathrm{w}}} \approx 100 \left(\frac{L_{\mathrm{f},47}}{L_{\mathrm{w},39}} \right)^{1/4}$$

pre-shock wind Lorentz factor

(cf. solar flares)



Coherent emission mechanism: shock maser



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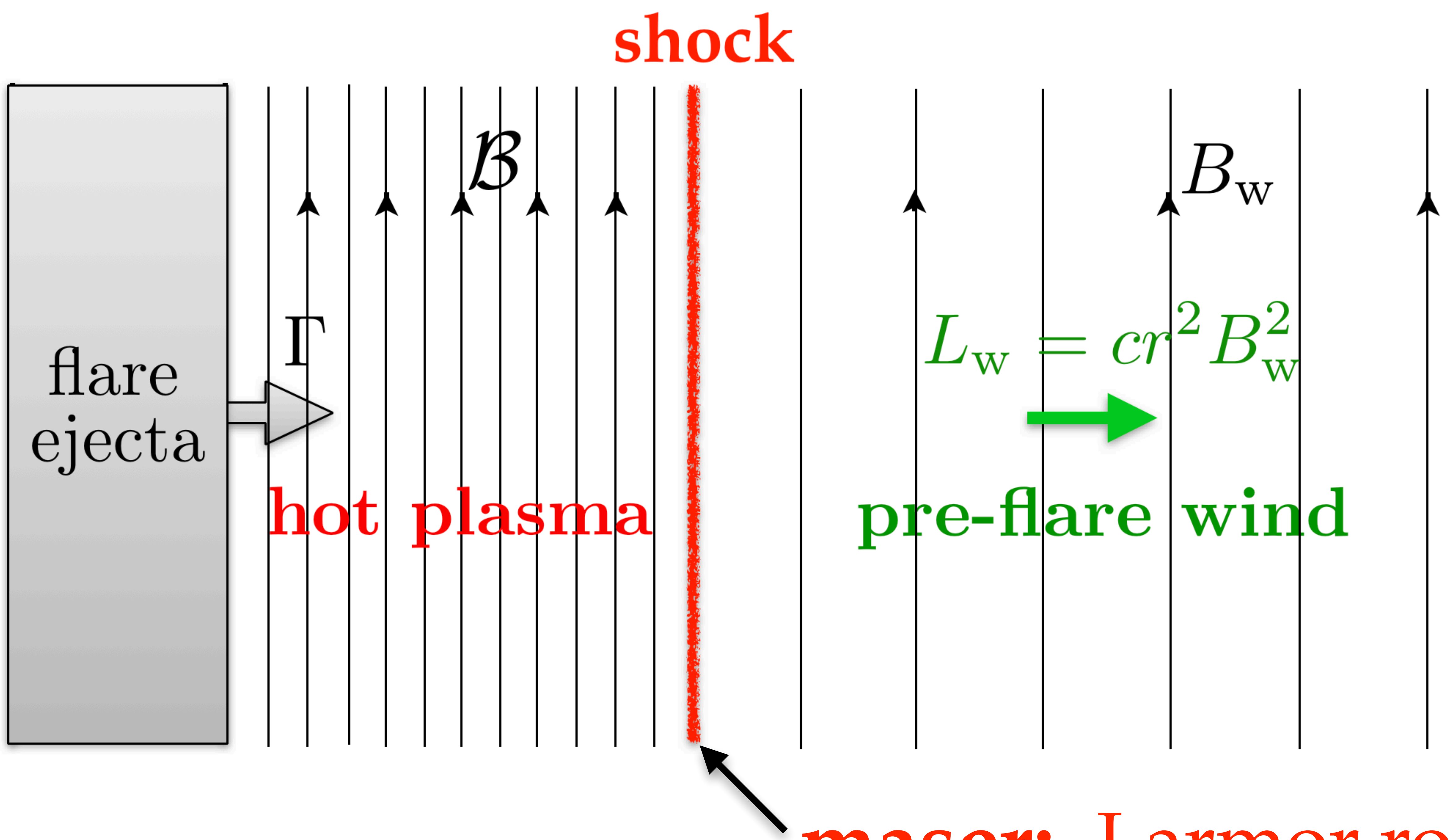
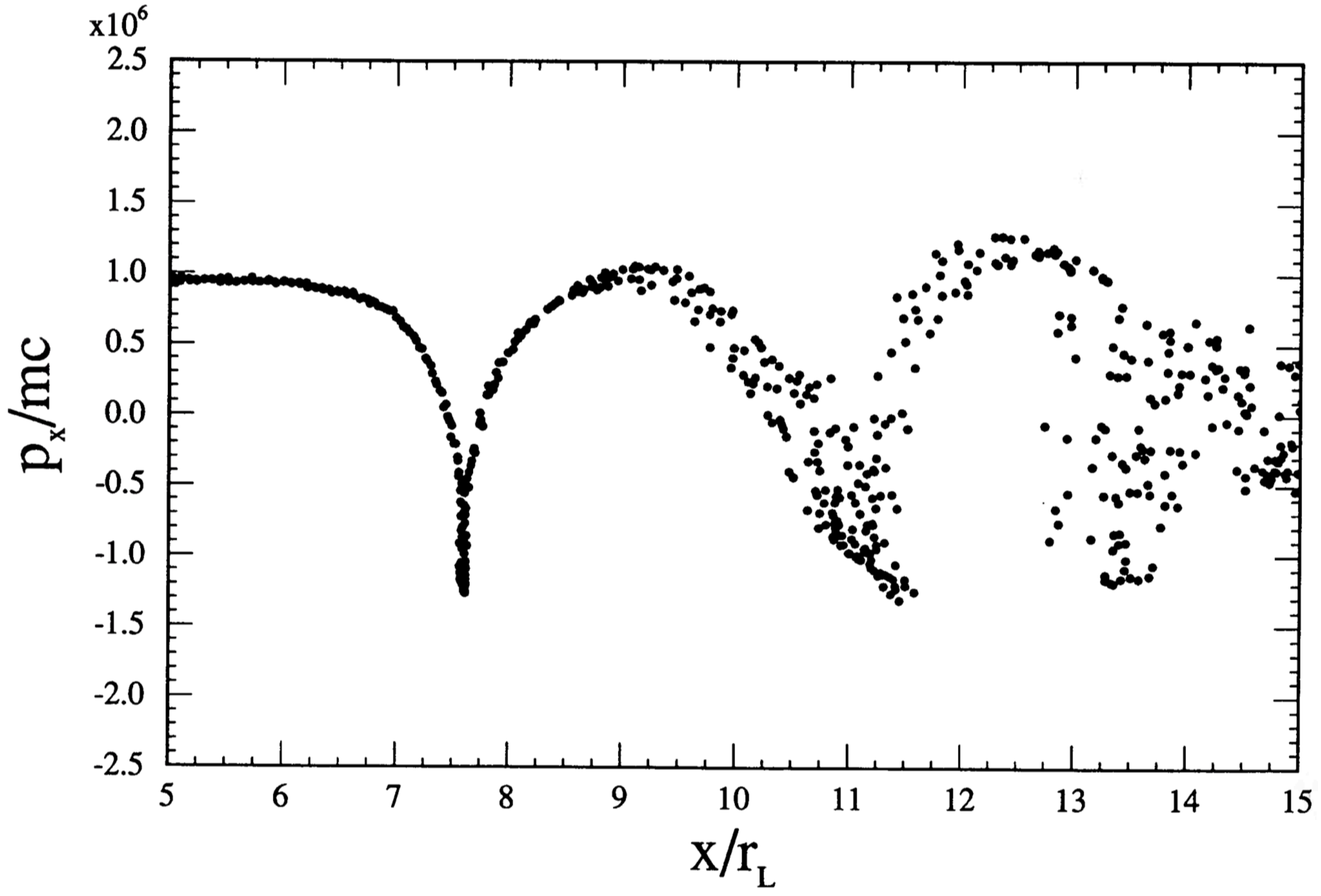


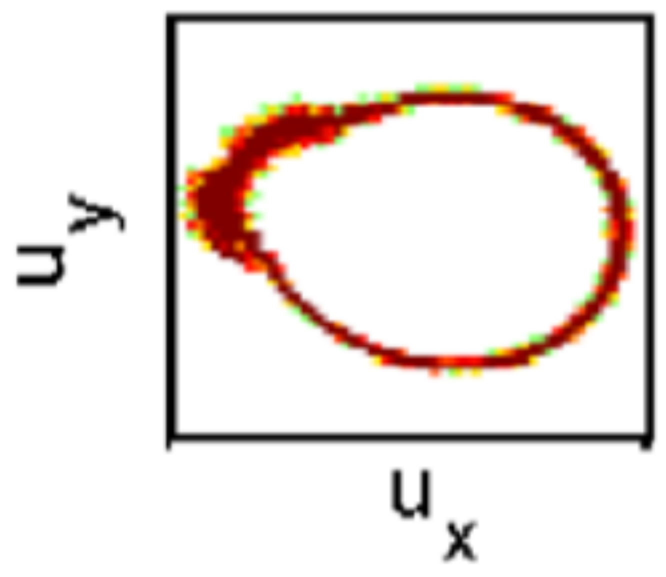
maser: Larmor rotation

$$r_{\rm L} = \frac{\Gamma_{\rm rel} m_e c^2}{e\mathcal{B}}$$

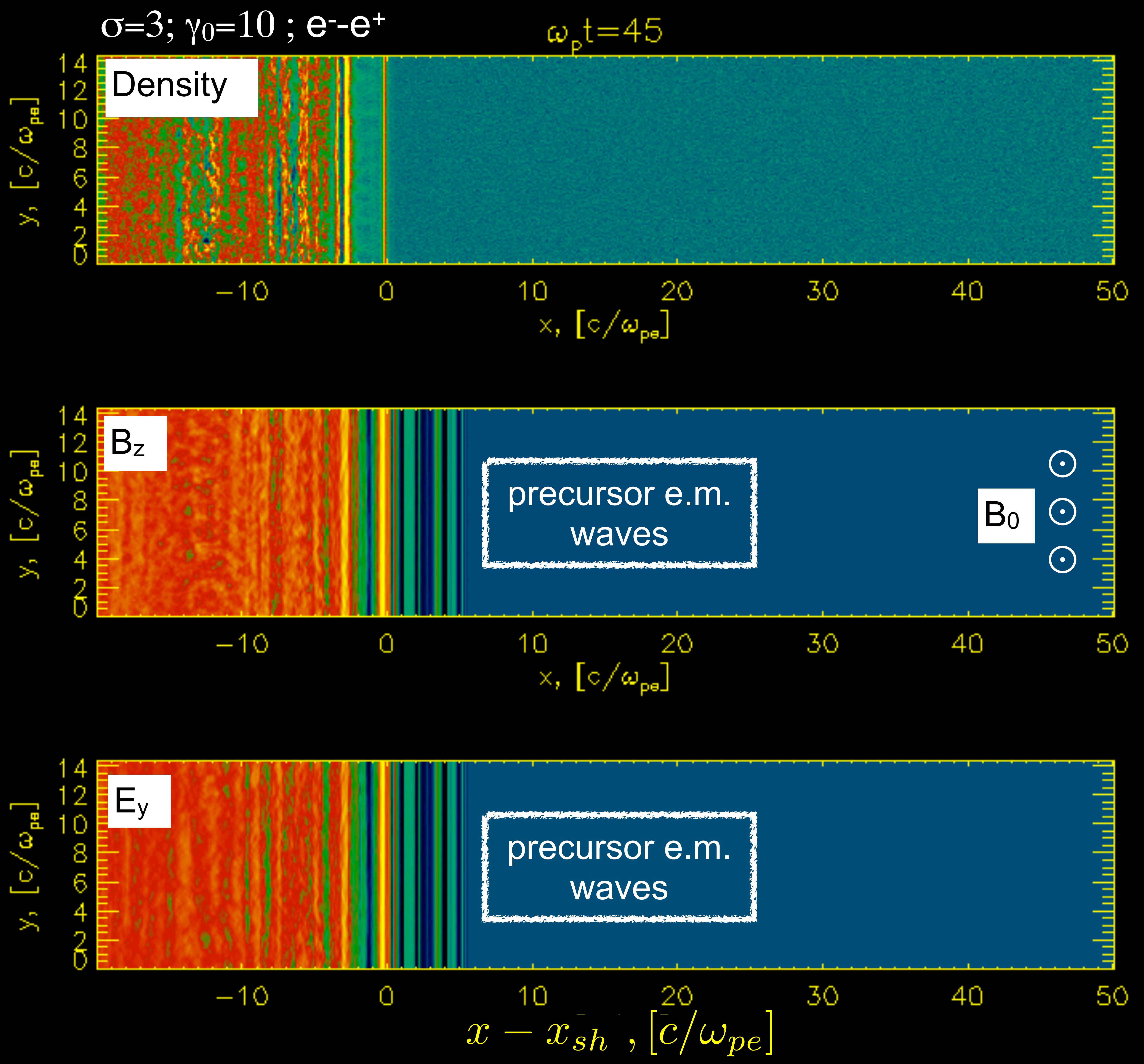


Kinetic simulations:

Gallant et al. 1992
Iwamoto et al. 2017, 2018
Plotnikov & Sironi 2019
Sironi et al. 2021

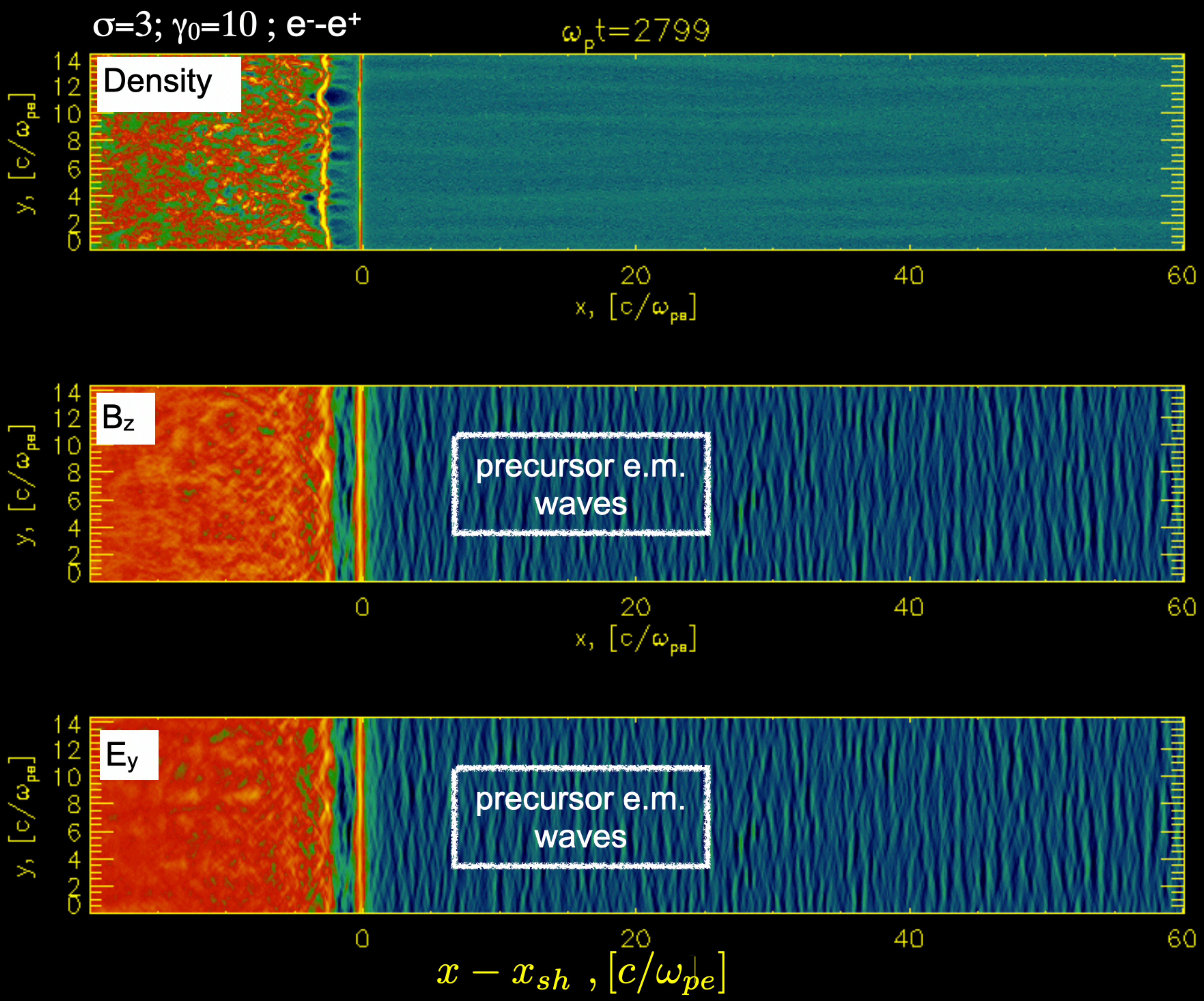


Shock-powered coherent emission



Sironi et al. 2021

Shock-powered coherent emission



Sironi et al. 2021

Summary: ejecta and bursts from magnetars

$$\begin{matrix}\text{perturbations}\\ \text{(quakes)}\end{matrix} \rightarrow \underset{(R \sim 100 R_\star)}{\begin{bmatrix}\text{monster radiative shocks}\\ \text{nonlinear Alfven waves}\end{bmatrix}} \rightarrow \begin{matrix}\text{ultra-relativistic}\\ \text{explosions}\end{matrix}$$

(plasma acceleration to Lorentz factors exceeding 10^6)

production of radiation: X-ray bursts ($R \sim 100 R_\star$)

FRBs (when ejecta expand far beyond the magnetosphere, $R \sim 1\text{AU}$)