Fast radio bursts from magnetars

Andrei Beloborodov

FRBs:

- GHz band
- ms duration
- luminosities up to 10^{43} erg/s

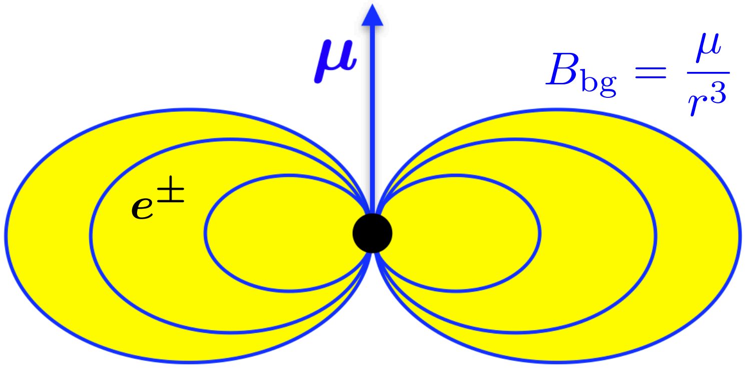
Plausible origin: magnetars (weak FRBs have been detected from a known magnetar)

Energy source: magnetic field near the neutron star $(B_{\rm bg} \gg E_{\rm wave})$:

$$r < 100 R_\star \ \text{(well inside } R_{\rm LC} \sim 10^4 R_\star\text{)}$$

Magnetosphere

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



Waves: (1) O-mode $\boldsymbol{E} \perp (\boldsymbol{k} \times \boldsymbol{B}_{\rm bg})$

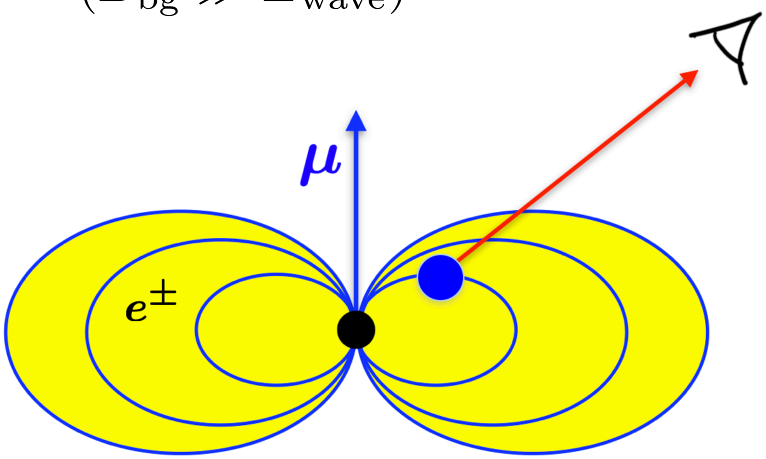
(2) X-mode $\boldsymbol{E} \parallel (\boldsymbol{k} \times \boldsymbol{B}_{\rm bg})$

MHD if Larmor radius $r_{\rm L} \ll \frac{c}{\omega}$

Damping of GHz bursts in the magnetosphere

AB 2023 (arXiv:2307.12182)

imagine a FRB source in the inner magnetosphere ($B_{\rm bg} \gg E_{\rm wave}$)



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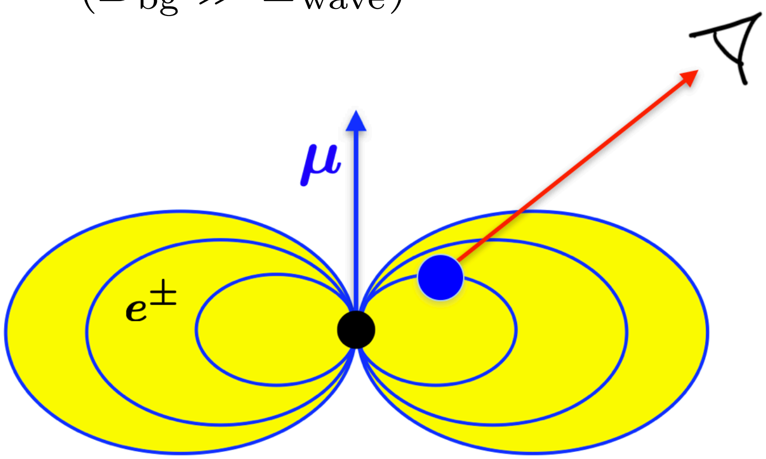
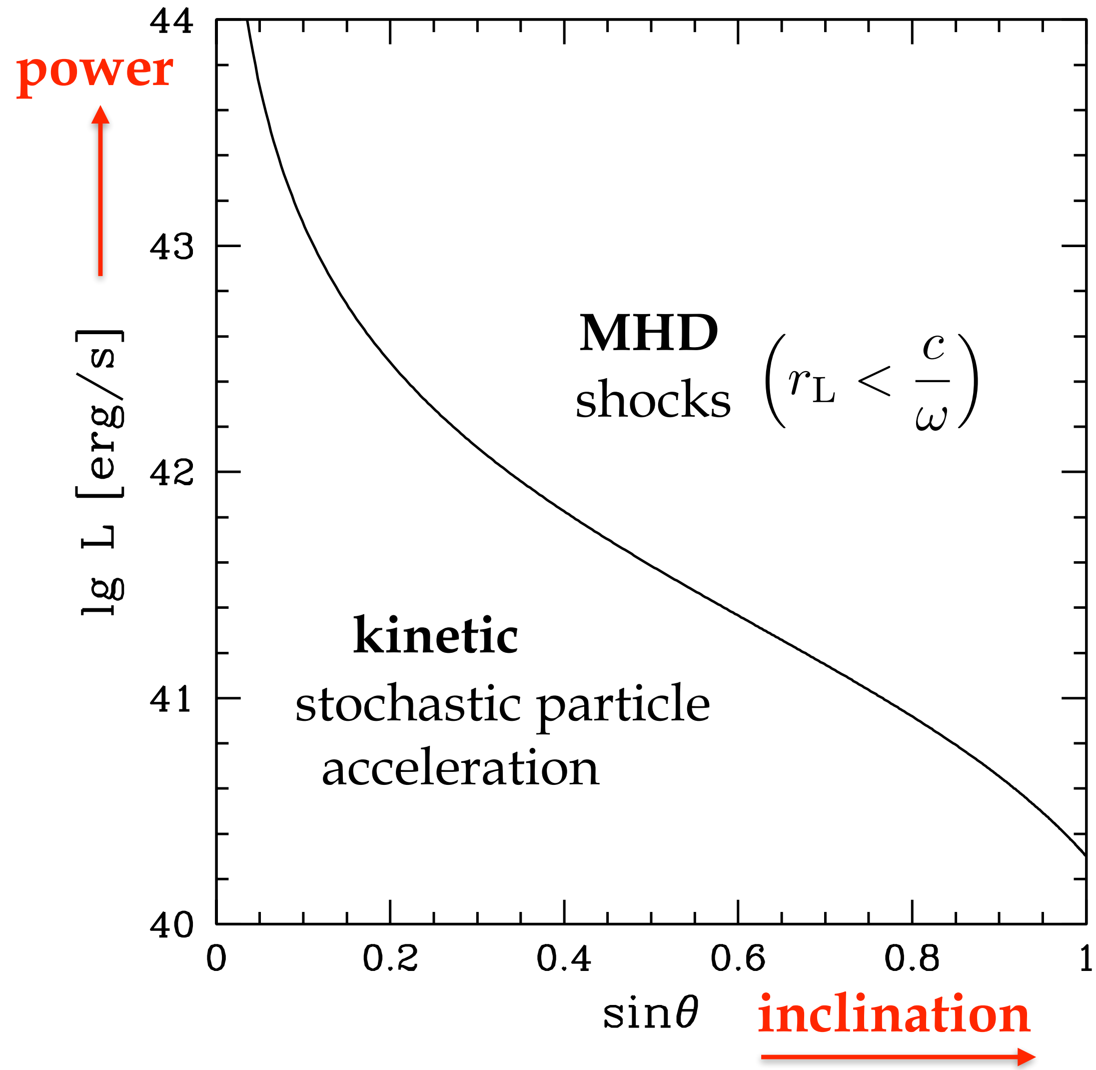




Damping occurs at radii $r > R_\times$ where $B_{\rm bg}$ drops below $B_{\rm wave} = E_{\rm wave}$

magnetic dipole moment of the star

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

wave power

PIC simulation:
Chen et al. 2022

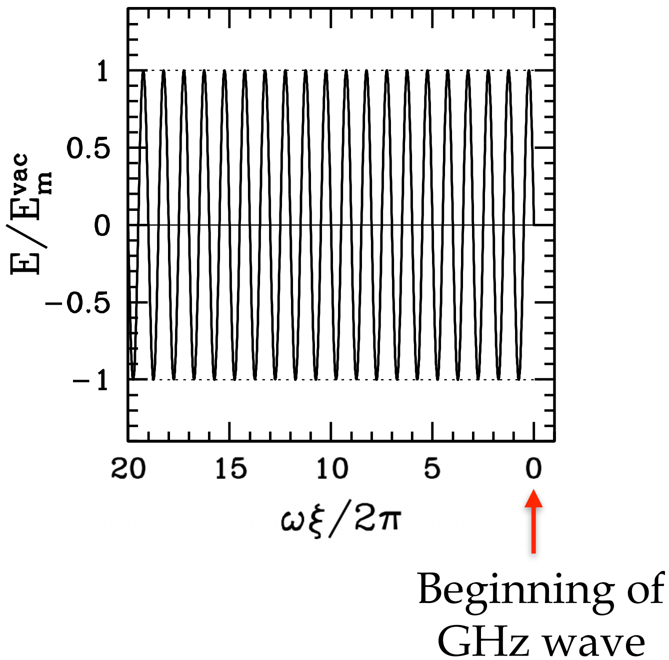
MHD:
AB 2022

MHD regime

Example:

GHz wave
with power
$L = 10^{42}$ erg/s

$R_\times = 2.5 \times 10^8$ cm
$\approx 200\, R_\star$



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

MHD regime

Example:

GHz wave
with power
$L = 10^{42}\,\mathrm{erg/s}$

$R_\times = 2.5 \times 10^8\,\mathrm{cm}$
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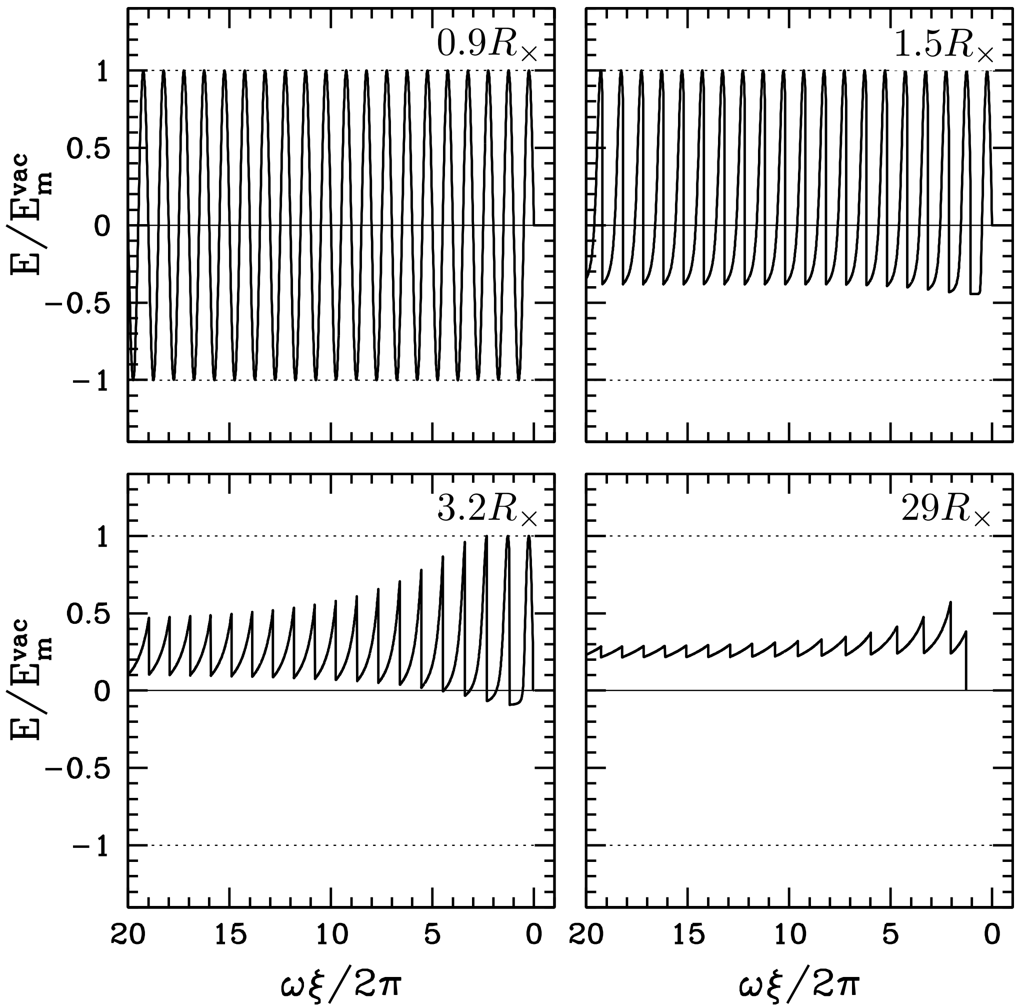
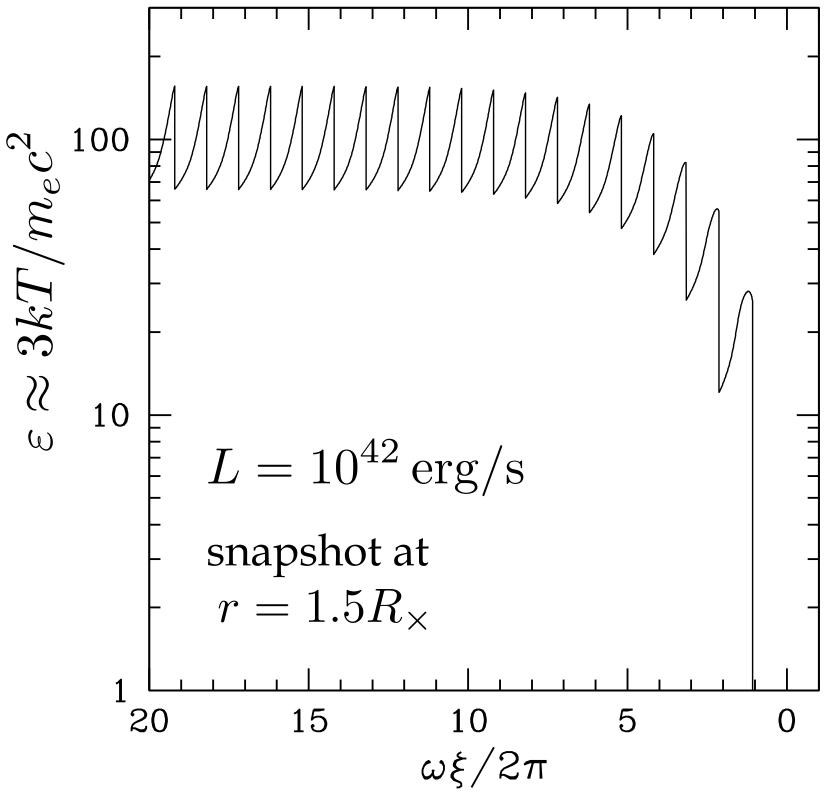
Evolution of a GHz wave train with r



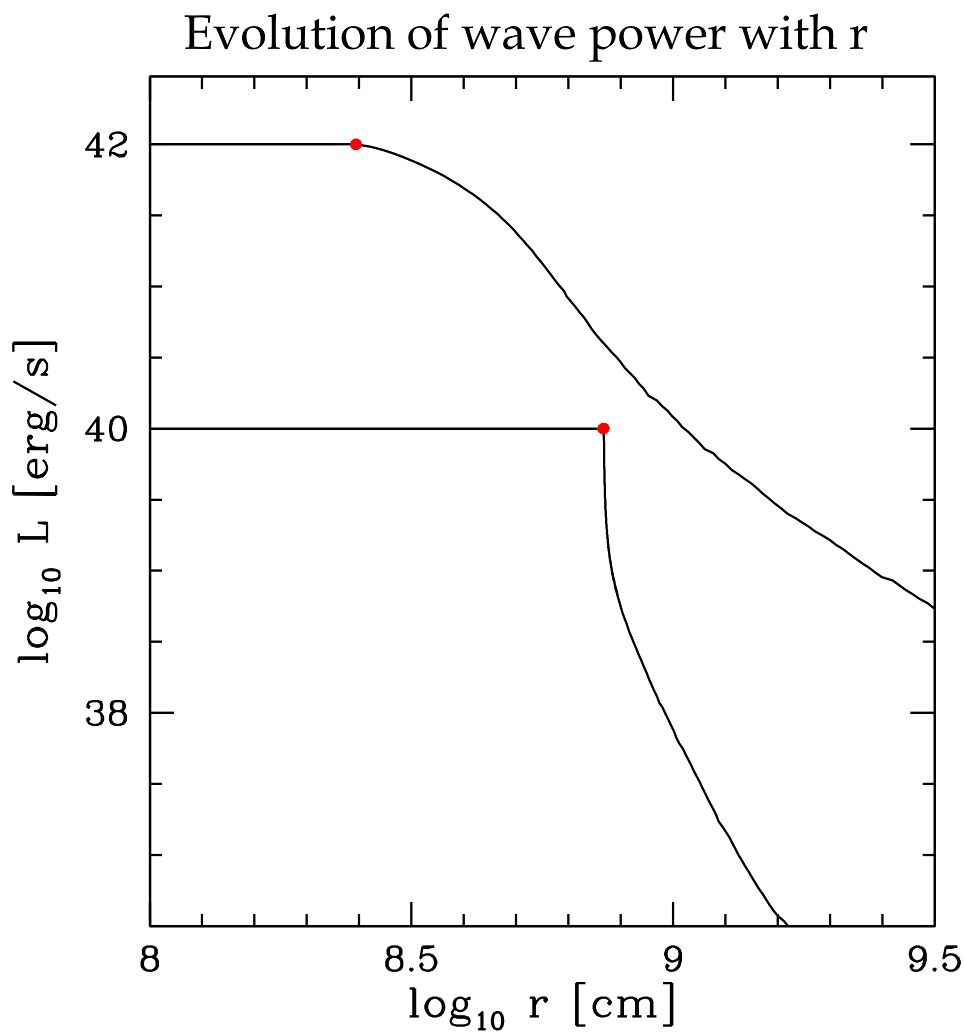
$$\xi \equiv t - \frac{r}{c}$$

Shock heating in the GHz wave train



synchrotron cooling
balances shock heating
at high temperature T

=> conversion of wave energy
to synchrotron (X-ray) emission

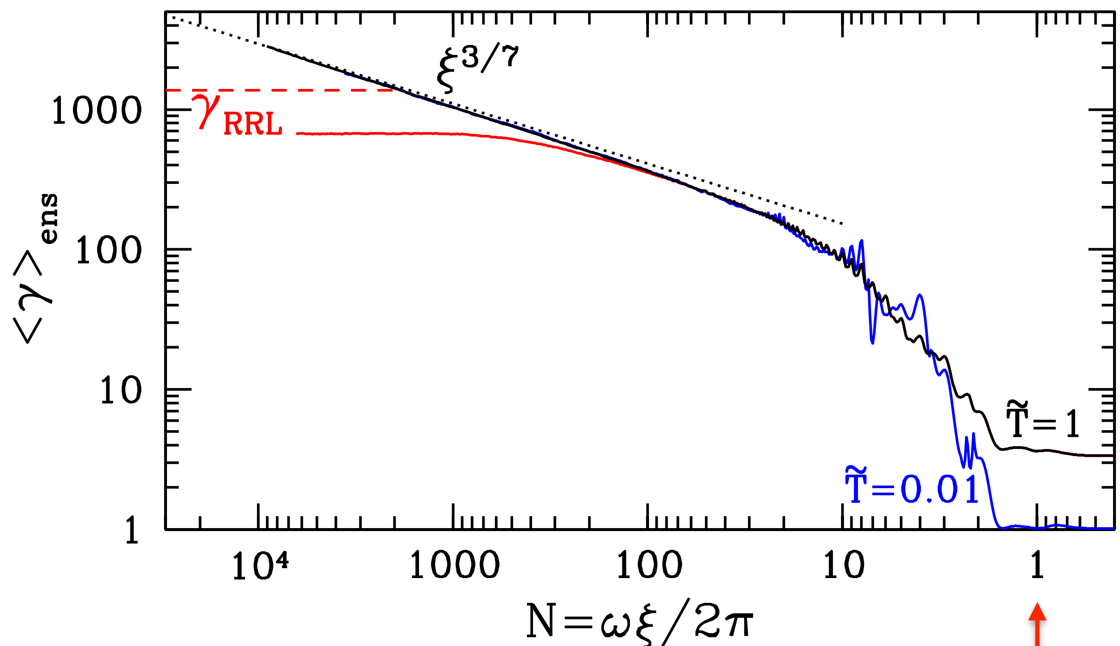

Evolution of wave power with r
42
40
38
$\log_{10}$ L [erg/s]
8
8.5
9
9.5
$\log_{10}$ r [cm]

Kinetic regime

Stochastic particle acceleration
to the radiation reaction limit

radio wave energy $\longrightarrow$ X-rays

ensemble average of particle energy



Beginning of
GHz wave

AB 2022

Radio bursts are damped in the static background magnetosphere

AB 2021, 2023
Golbreikh, Lyubarsky 2023

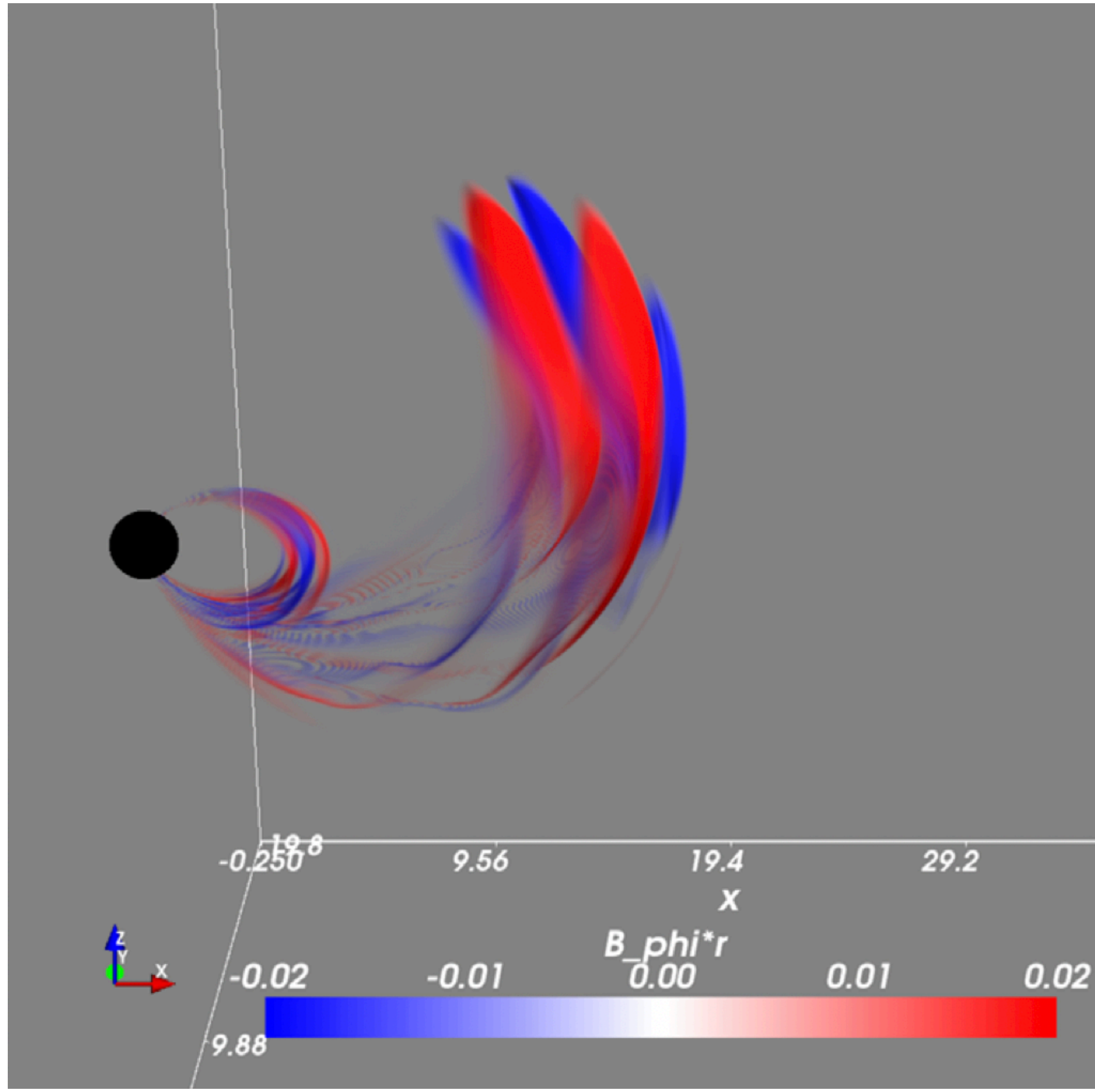
=> **FRBs must be emitted by magnetic explosions**
(and released far from the star, in the wind)

Explosions can develop from small perturbations of the magnetosphere
— a typical crustal quake (kHz) with amplitude ~0.001 is sufficient

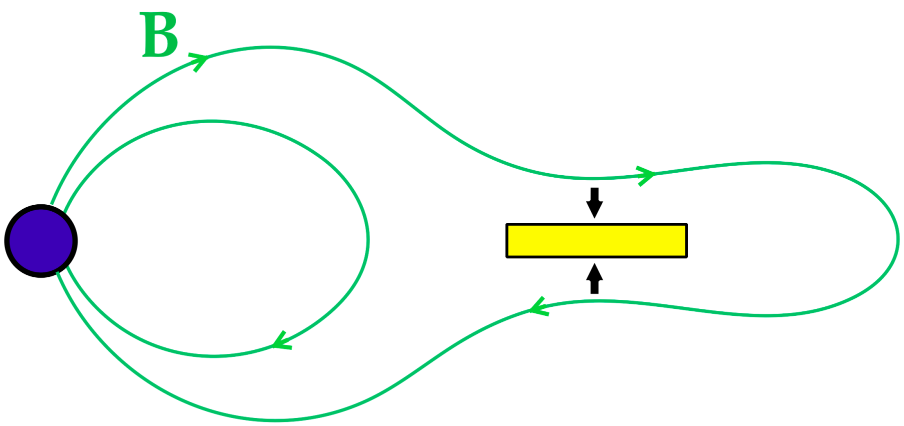
Explosions from Alfvenic perturbations

Shear (Alfven) wave is launched from the star, grows nonlinear, and launches an explosion

Yuan et al. 2022

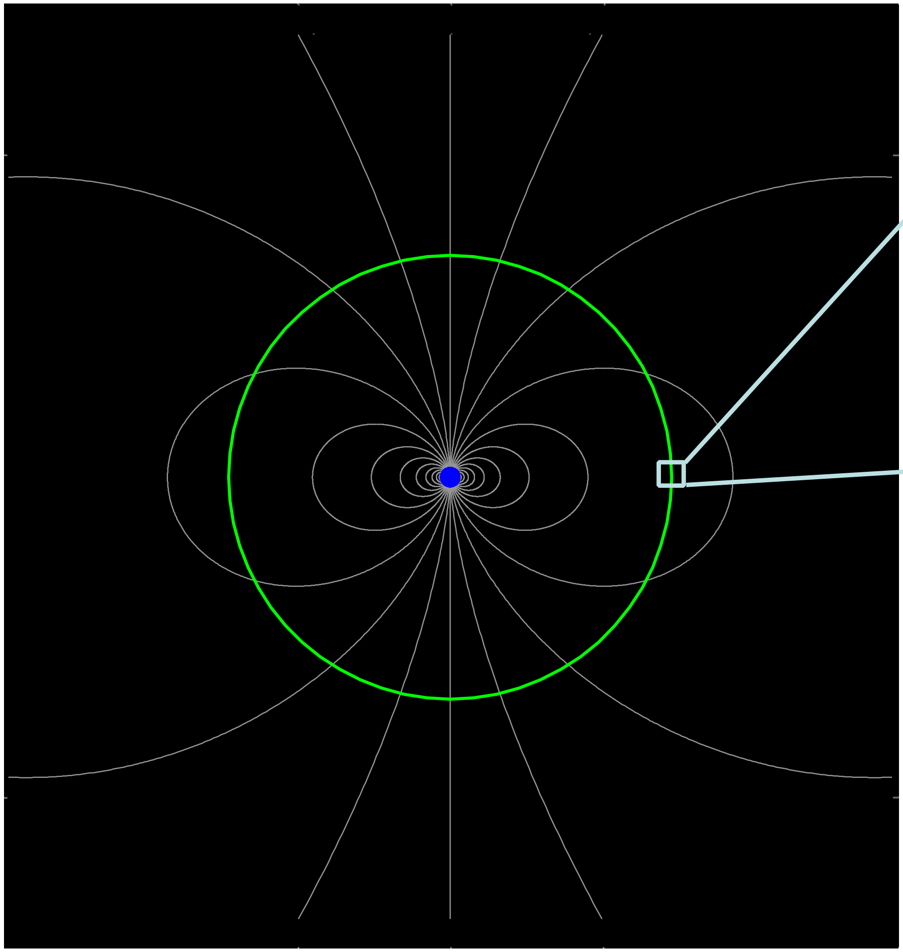


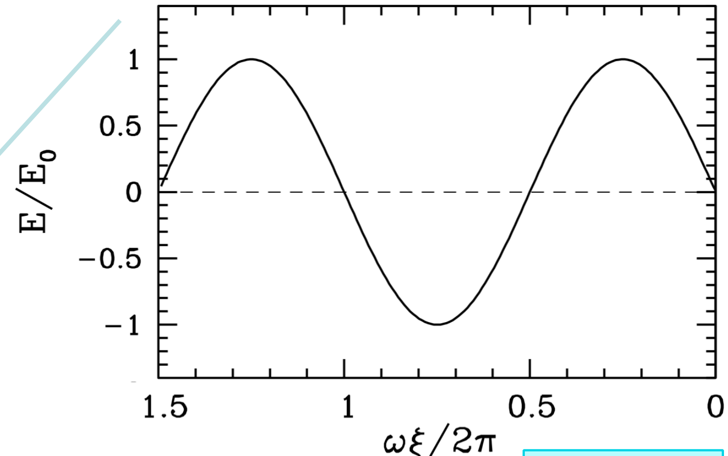
Magnetic reconnection



Explosions from magnetosonic perturbations

an expanding EM wave packet





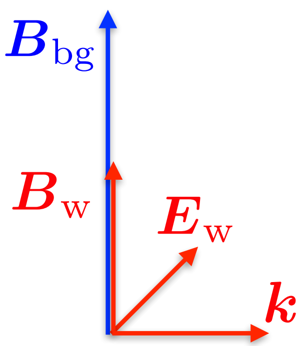
$$\xi \equiv t - \frac{r}{c}$$

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

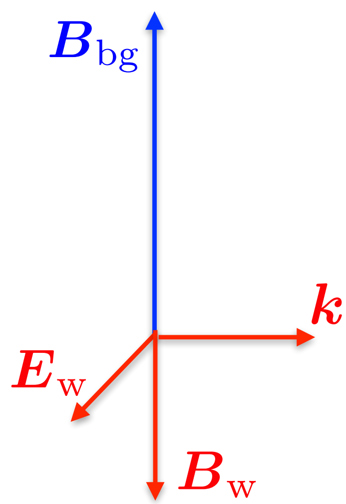
(AB, ApJ in press)

Compressive MHD wave

compression



rarefaction



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

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

$$\frac{v_{\mathrm{wave}}}{c} = 1 - \sigma_{\mathrm{bg}}^{-1}$$

Compressive MHD wave

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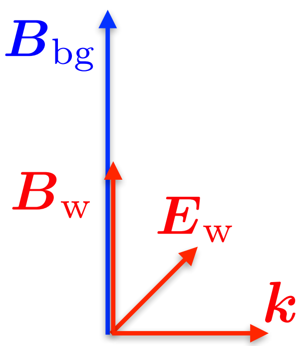

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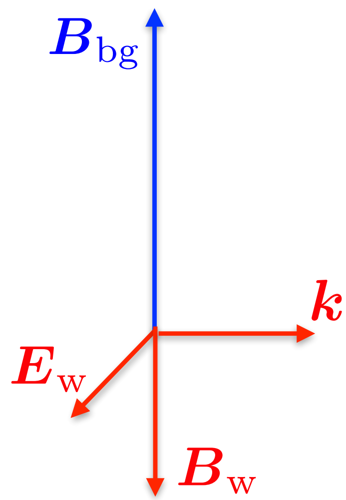


$$\boldsymbol{B} = \boldsymbol{B}_{\rm bg} + \boldsymbol{B}_{\rm w}$$

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

$$\frac{v_{\rm wave}}{c} = 1 - \sigma_{\rm bg}^{-1}$$

plasma motion in the wave:

$$\frac{\boldsymbol{v}_{\rm D}}{c} = \frac{\boldsymbol{E}\times\boldsymbol{B}}{B^2} \qquad \frac{|\boldsymbol{v}_{\rm D}|}{c} = \frac{|\boldsymbol{E}|}{|\boldsymbol{B}|}$$

wave breaks when

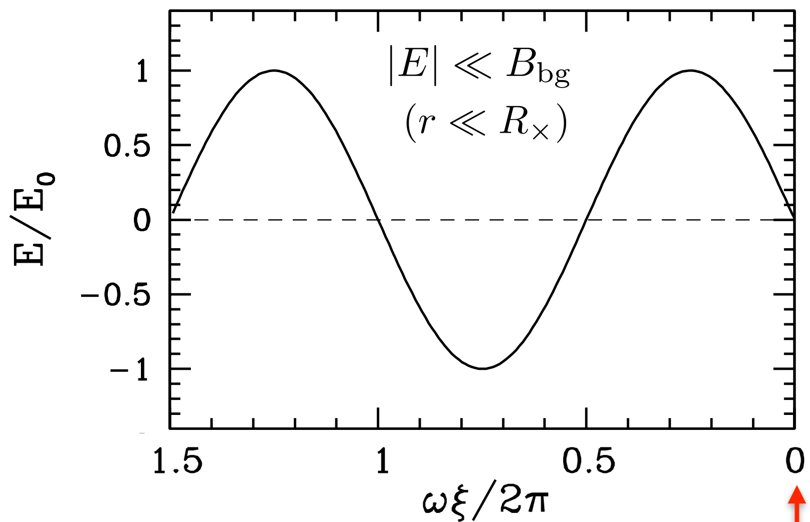
$$|\boldsymbol{E}| = |\boldsymbol{B}| = \frac{B_{\rm bg}}{2}$$

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

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

PIC simulation: Chen et al. 2022

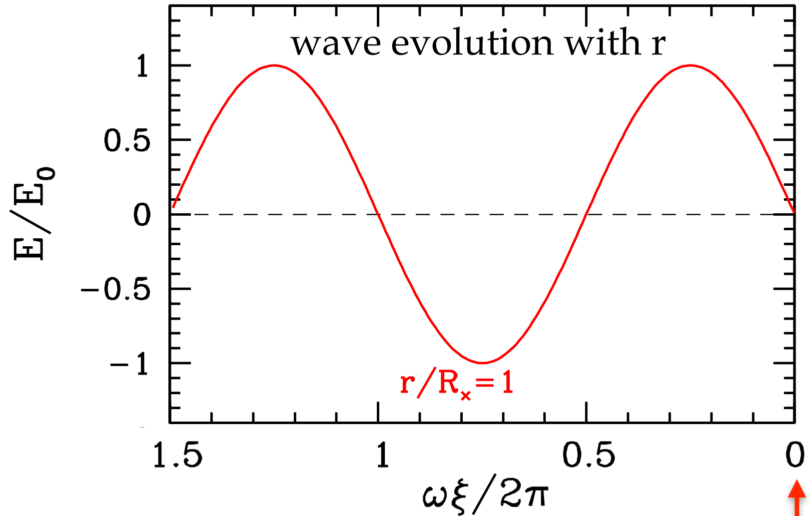
MHD: AB 2022



beginning of the kHz wave

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

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



beginning of
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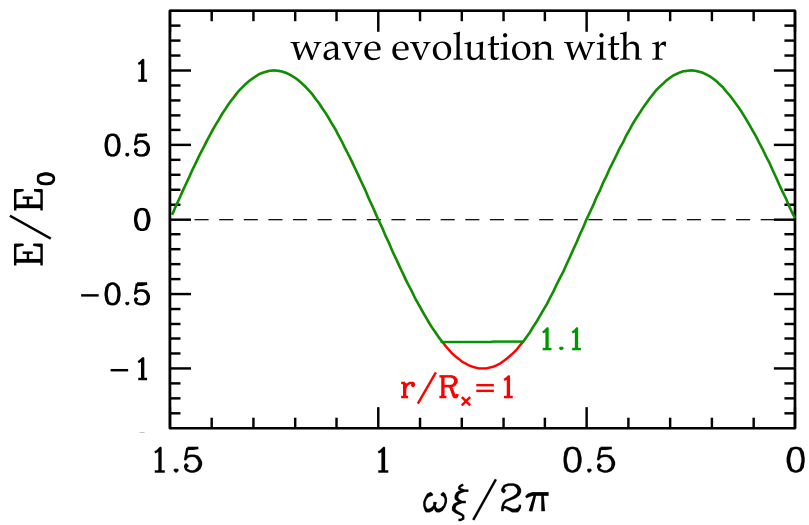

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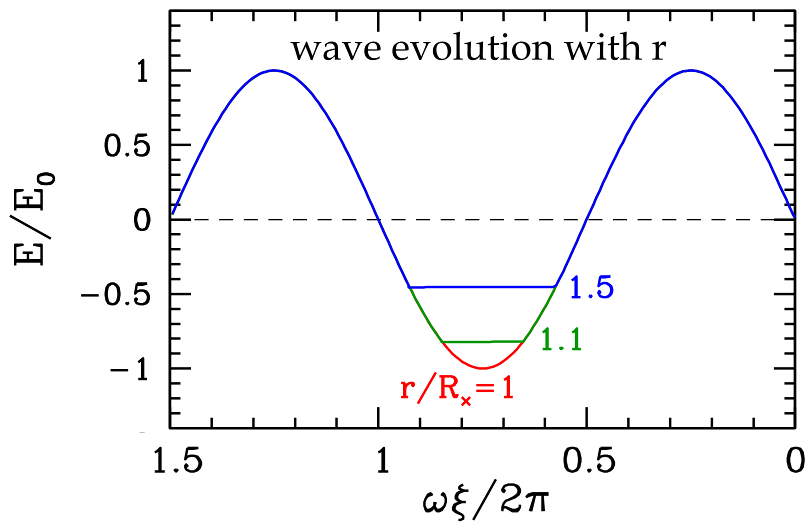
Plateau: the ceiling of $E^2 = B^2$ corresponds to $\boxed{|E_{\rm p}| \approx \frac{B_{\rm bg}}{2}} \propto r^{-3}$

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



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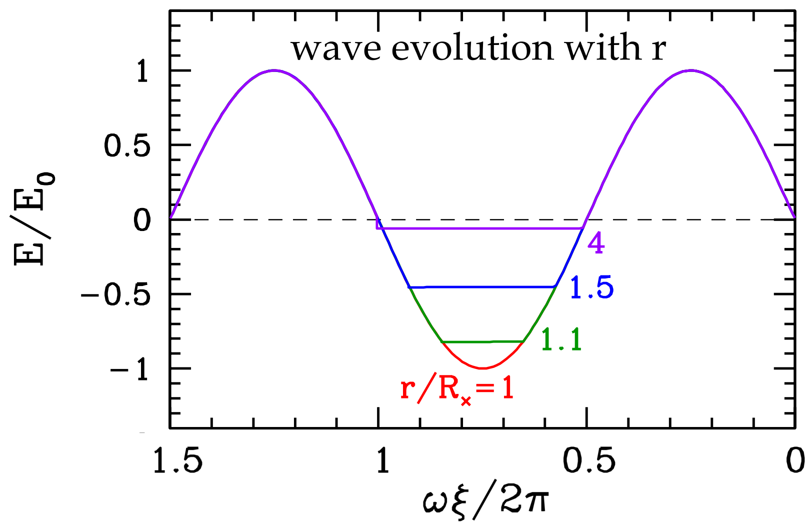

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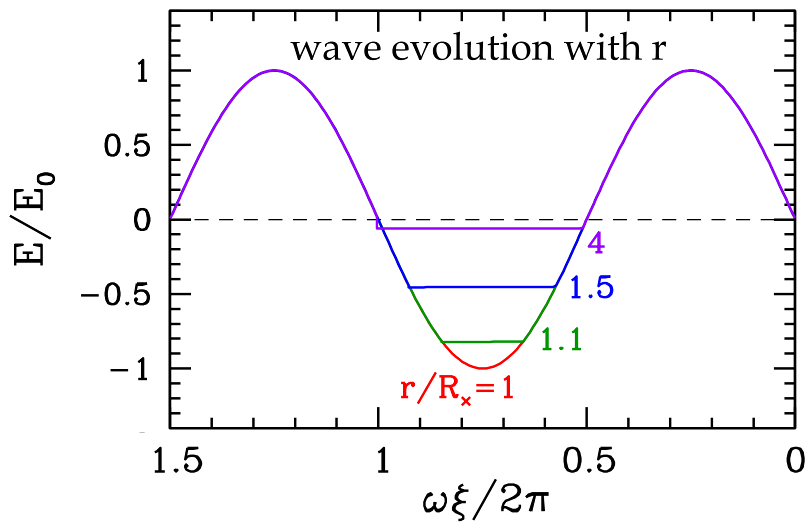

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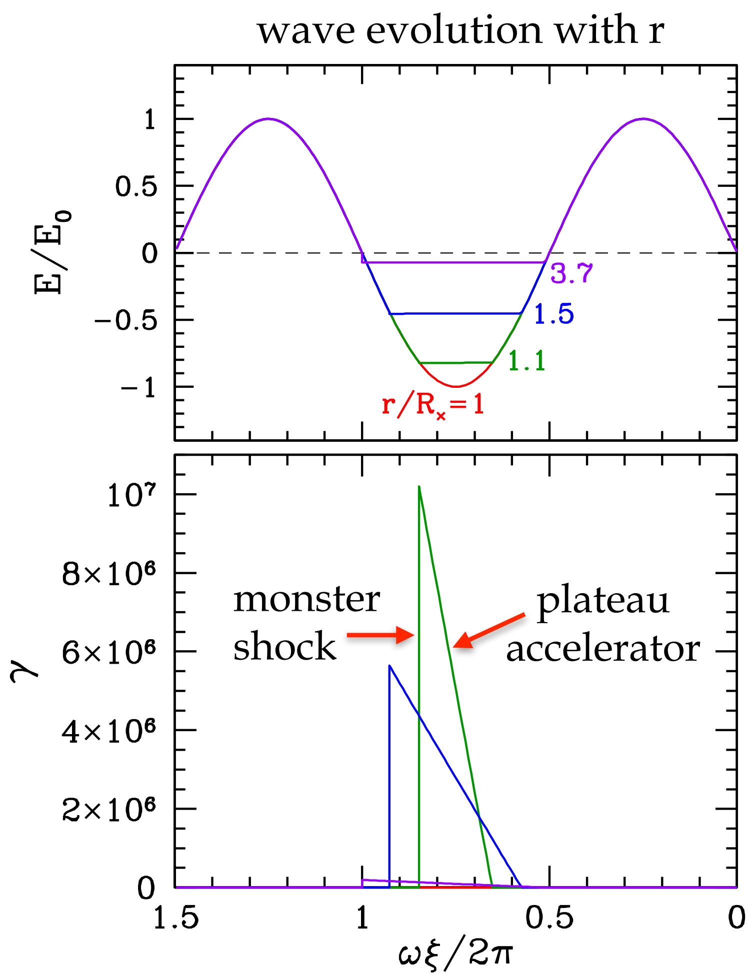
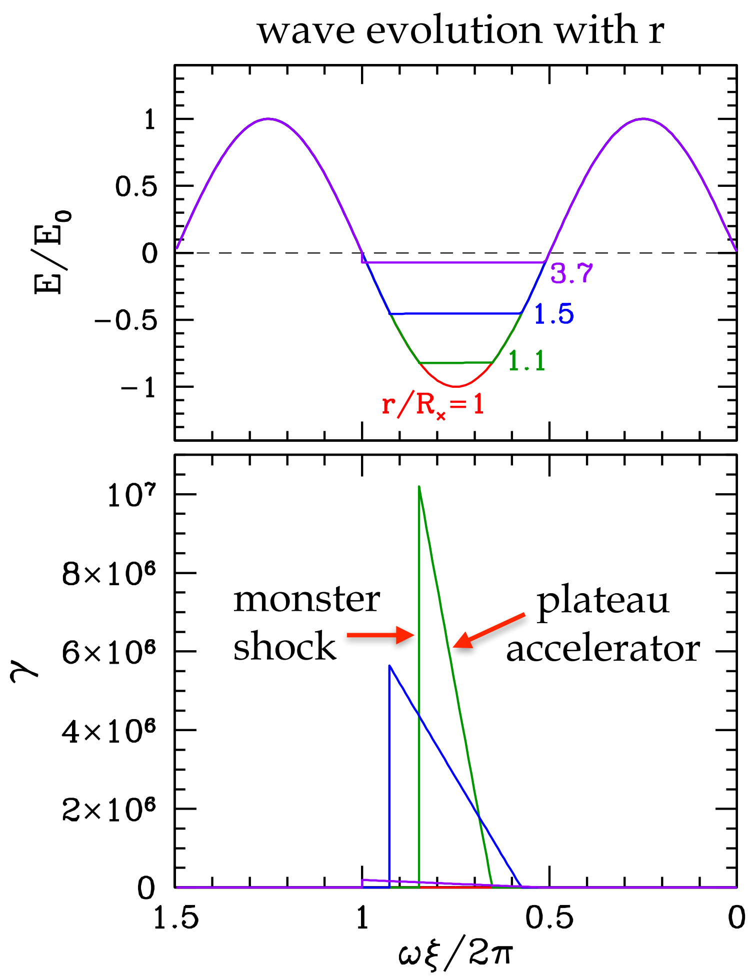
where did the half-wave energy go?



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



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

plateau: a linear accelerator

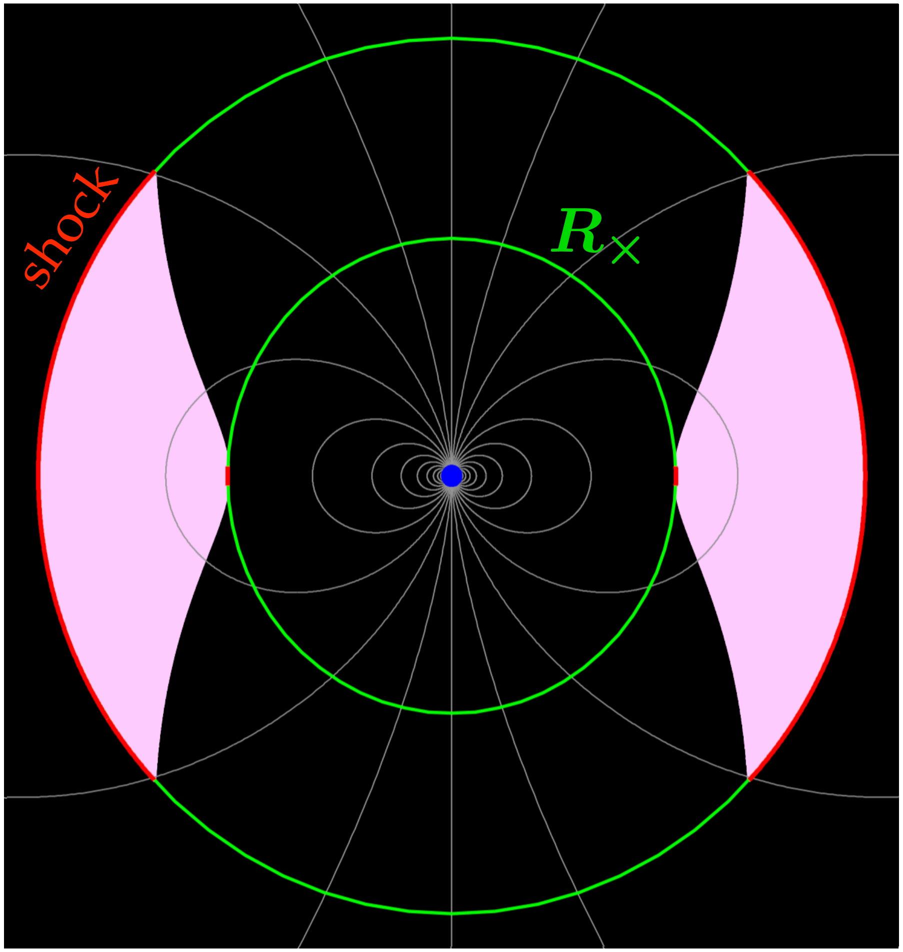
plateau width $W_{\rm p}\sim\dfrac{c}{\omega}$

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

shock at the edge of the plateau

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

relativistic explosion in the magnetar wind



Shock from a kHz magnetosonic perturbation in the magnetosphere

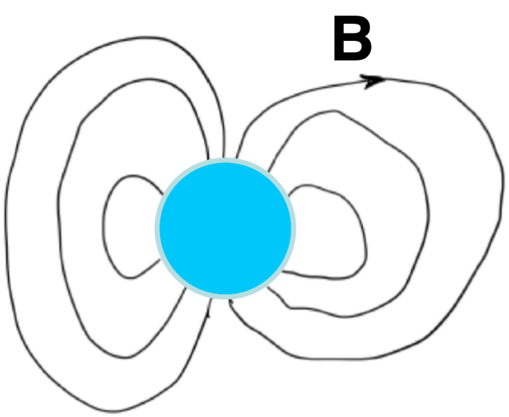
$$R_\times : \; B_{\rm bg} = 2E_{\rm wave}$$

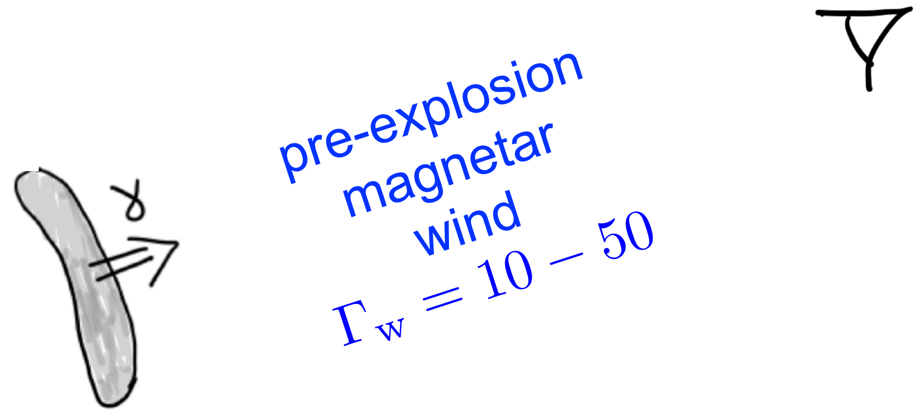
$$(E^2 = B^2)$$

FRB mechanism: magnetic explosion

– shocks in the magnetar wind — AB 2017, 2020

– ejecta carrying waves from magnetic reconnection — Lyubarsky 2020; Mahlmann et al. 2022





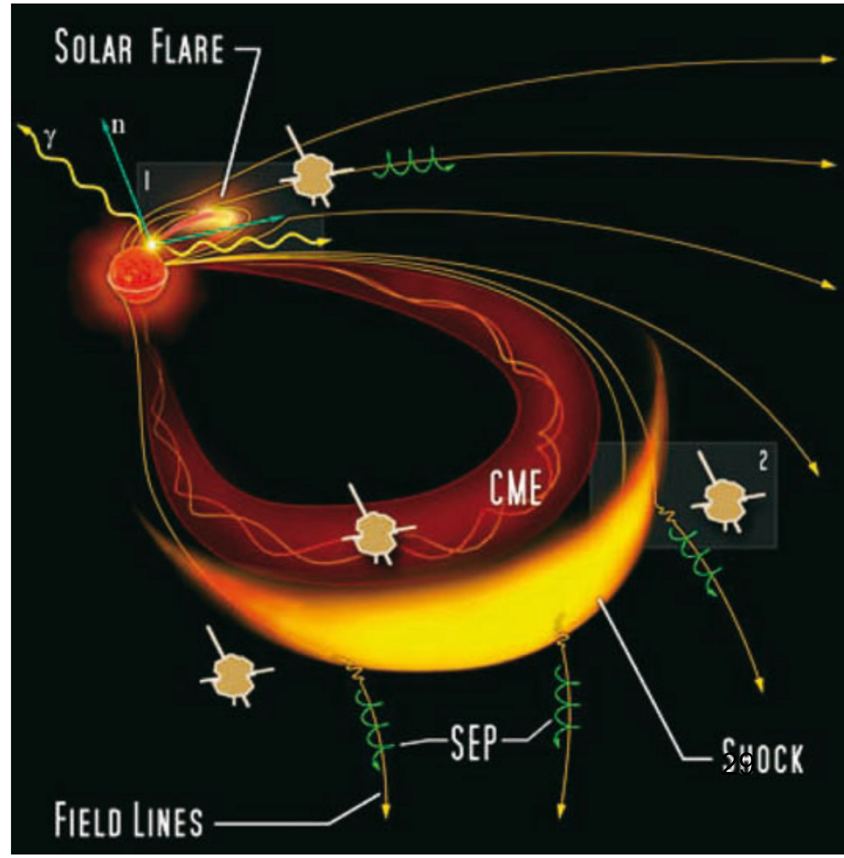
$$\Delta t \approx \frac{r}{c}\left(1 - \frac{v}{c}\right) \approx \frac{r}{2\gamma^2 c}$$

Blast waves from magnetars

blast Lorentz factor

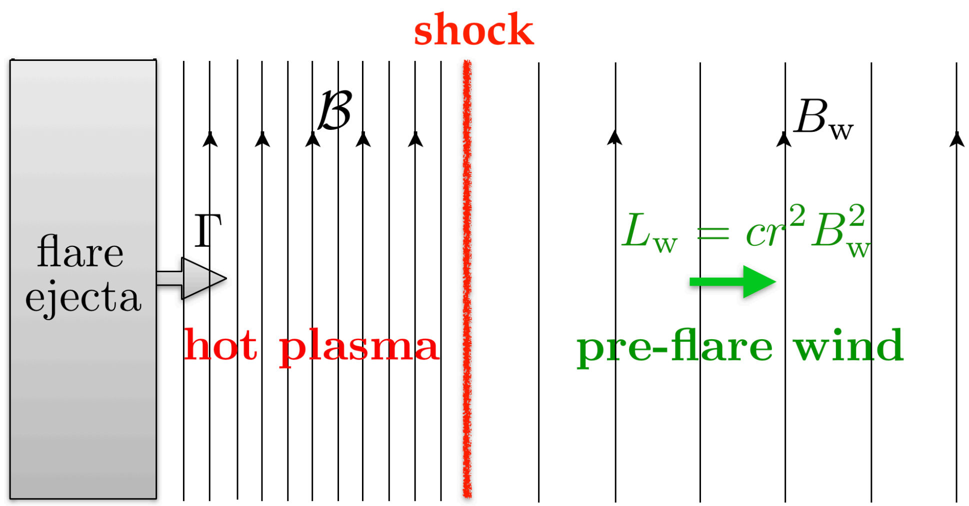
$$\frac{\Gamma}{\Gamma_{\rm w}} \approx 100 \left(\frac{L_{\rm f,47}}{L_{\rm w,39}} \right)^{1/4}$$

pre-shock wind
Lorentz factor



(cf. solar flares)

Coherent emission mechanism: shock maser



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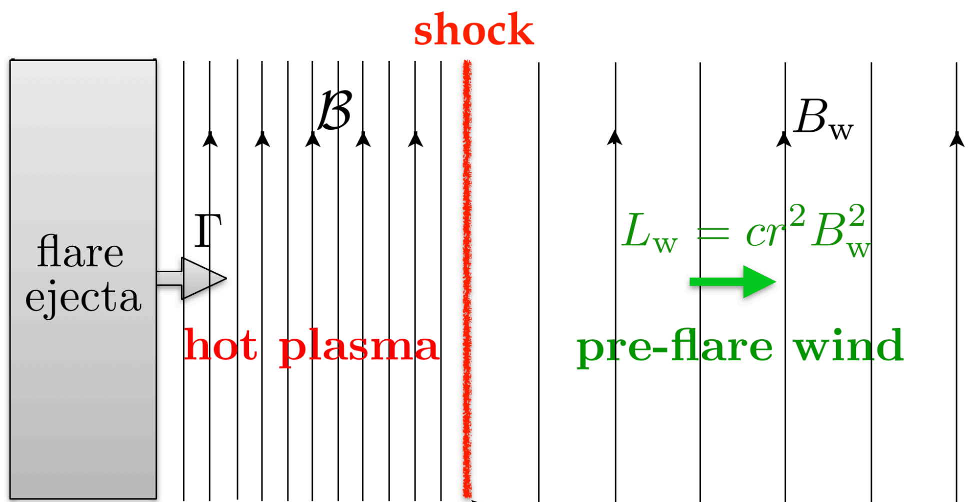
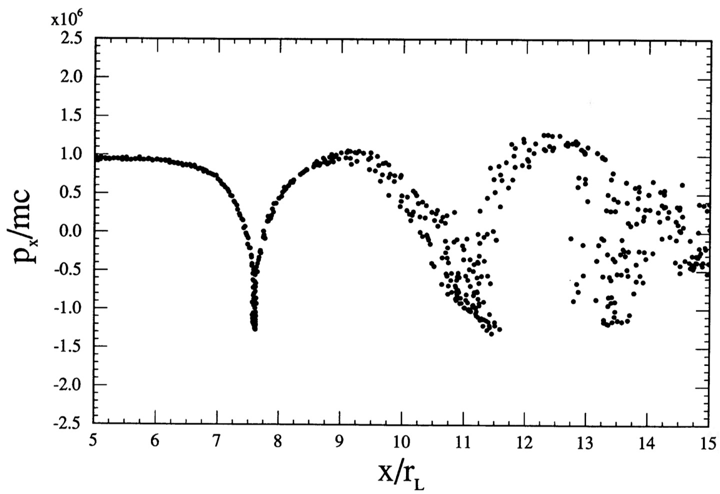


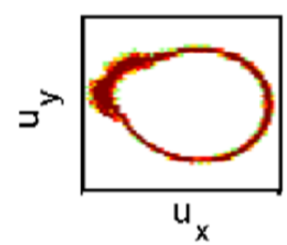
maser: Larmor rotation

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

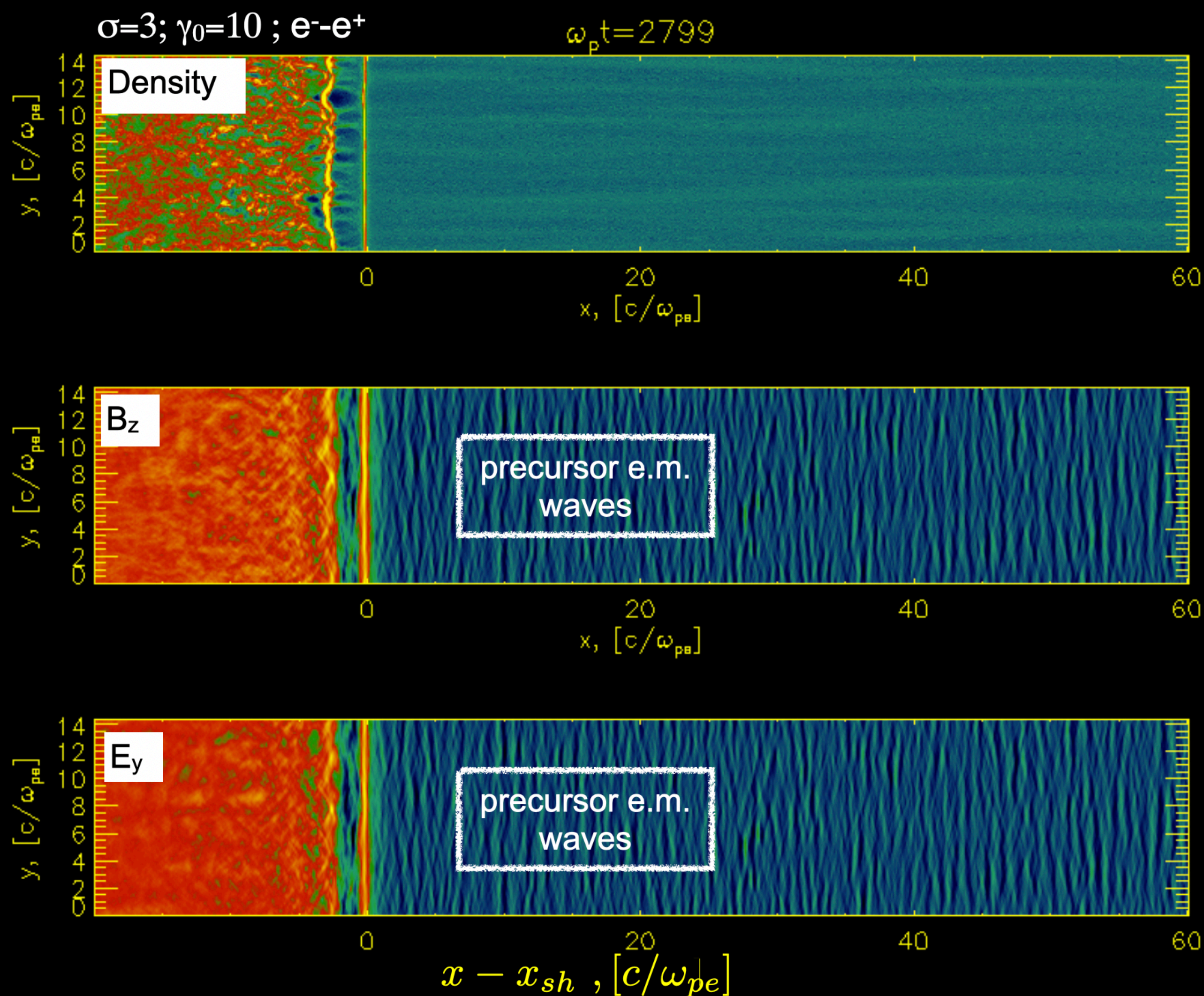


Kinetic simulations:

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



Shock-powered coherent emission



Sironi et al. 2021

FRBs from magnetars

- Required energy source: inner magnetosphere $B_{\rm bg} \gg E_{\rm burst}$

- Static outer magnetosphere acts as a pillow damping GHz waves

  => energy must be transported beyond the magnetosphere where FRBs can be released

FRBs come from powerful electromagnetic outflows/explosions

(and involve "field instability" rather than "plasma instability")

- Formation of strong shocks (now settled)

  shocks produce semi-coherent radio emission