Propagation of strong electromagnetic waves in tenuous plasmas

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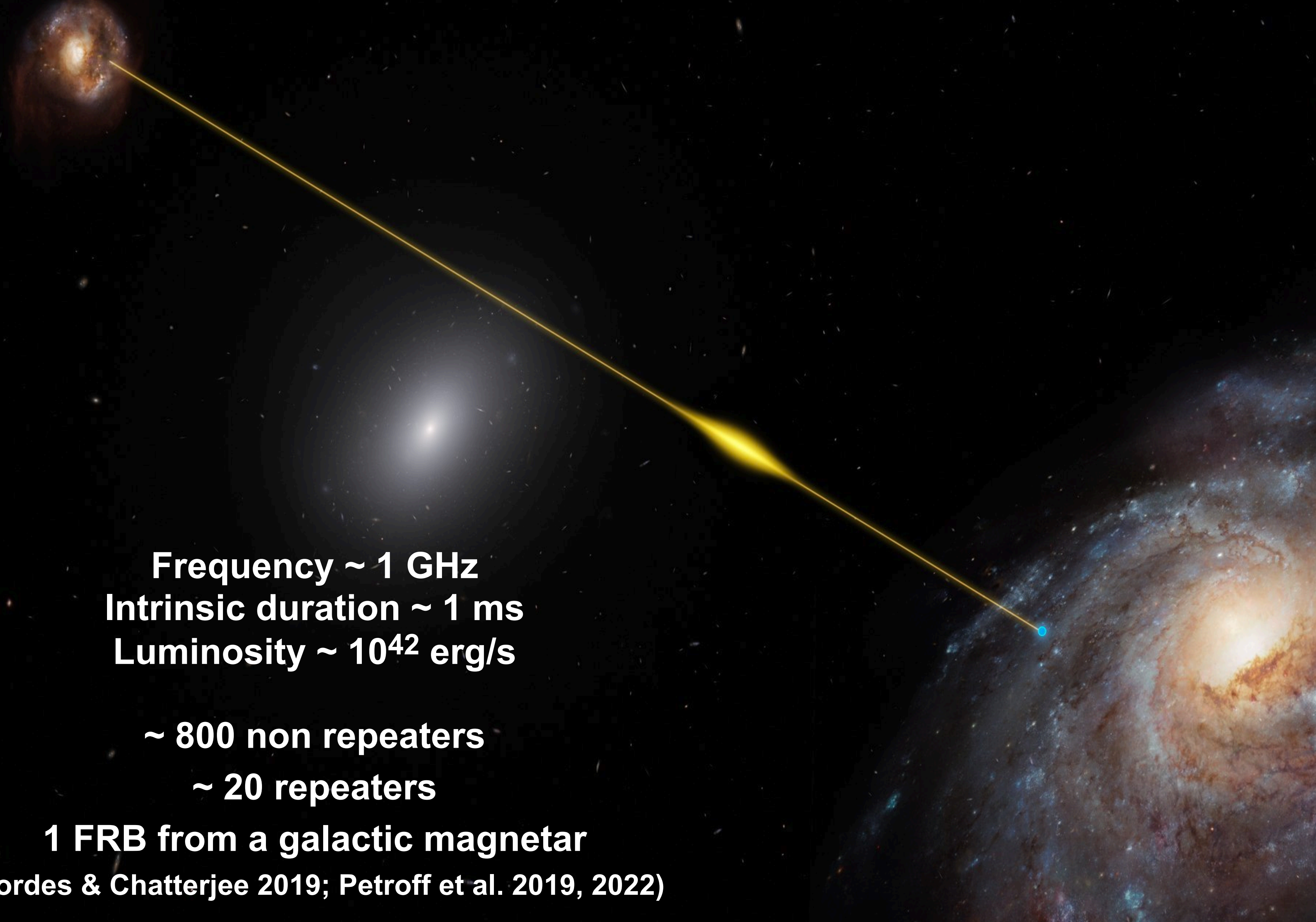
ES, Iwamoto, Sironi & Piran 2024, Phys. Rev. Research, 6, 043213

ES, Iwamoto, Sironi & Piran 2024, A&A, 690, A332

Fast Radio Bursts



Frequency ~ 1 GHz
Intrinsic duration ~ 1 ms
Luminosity ~ 10^{42} erg/s

~ 800 non repeaters

~ 20 repeaters

1 FRB from a galactic magnetar

(Cordes & Chatterjee 2019; Petroff et al. 2019, 2022)

FRB strength parameter

strength parameter $a_0 = u_\perp/c$
($u_\perp$= transverse component of the electron four-velocity)

transverse momentum = electric force * timescale

$$mca_0 = (eE_{FRB}) * (1/\nu)$$

$$a_0 = eE_{FRB}/mc\nu$$

For typical FRBs, one finds

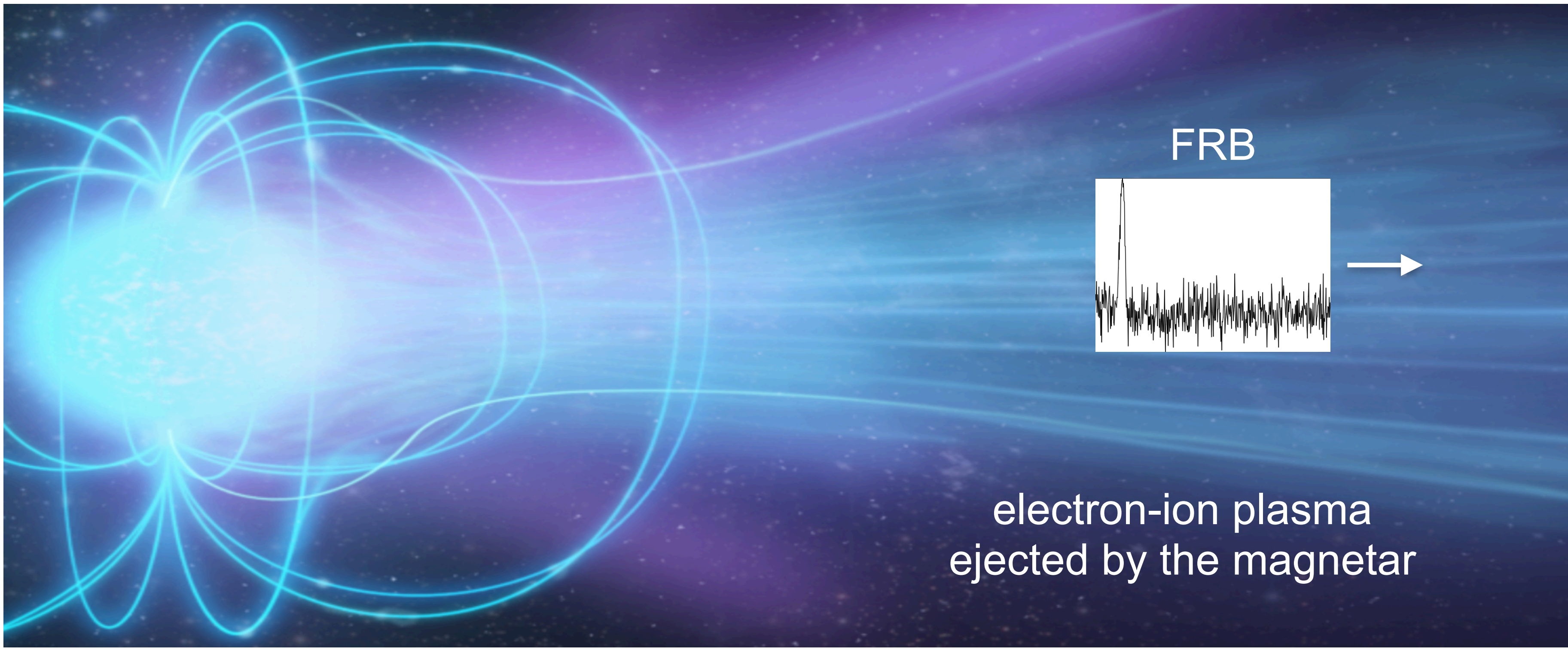
$$a_0 \sim 0.2 \left(\frac{\nu}{\mathrm{GHz}}\right)^{-1} \left(\frac{L}{10^{42}\ \mathrm{erg\ s^{-1}}}\right)^{1/2} \left(\frac{R}{10^{14}\ \mathrm{cm}}\right)^{-1}$$

frequency luminosity distance from the source

Outline of the talk

magnetar

$e^{\pm}$ wind



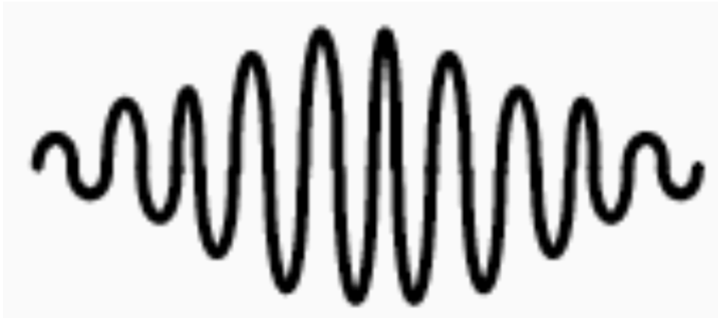
R ~ 10^{10} cm
(light cylinder)

R ~ 10^{11} cm

R ~ 10^{14} cm

$a_0 > 1$ $\omega > \omega_L, \omega_P$

Test-particle motion in strong waves



$a_0(z\text{-}ct)$

z

$e^{\pm}$ plasma

proper density n_0

$$u_\perp = a_0 \qquad u_z = a_0^2/2 \qquad \gamma = 1 + a_0^2/2$$

$$n = n_0 \qquad N = \gamma n = (1 + a_0^2/2) n_0$$

(Gunn & Ostriker 1971)

$$j_\perp = N \frac{u_\perp}{\gamma} = n u_\perp = n_0 a_0$$

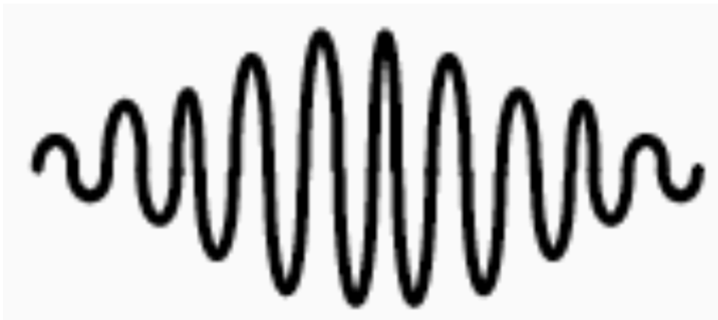
response of the plasma is linear in test-particle limit

$$\omega^2 = c^2 k^2 + \omega_P^2$$

(ES, Iwamoto, Sironi & Piran 2024)

$\omega_P = \sqrt{4\pi n_0 e^2/m}$

Unmagnetized electron-positron plasma



$a_0(z-ct)$

$\xrightarrow{z}$

$e^{\pm}$ plasma

proper density n_0

$$\frac{\textbf{particles kinetic energy}}{\textbf{wave energy}} = \left(\frac{a_0 \omega_{\rm P}}{\omega}\right)^2$$

response of the plasma is linear for

$$a_0 < \omega/\omega_{\rm P}$$

(ES, Iwamoto, Sironi & Piran 2024)

Magnetized electron-positron plasma

$a_0(z-ct)$

z

$e^{\pm}$ plasma

⊙ magnetic field B_{bg}

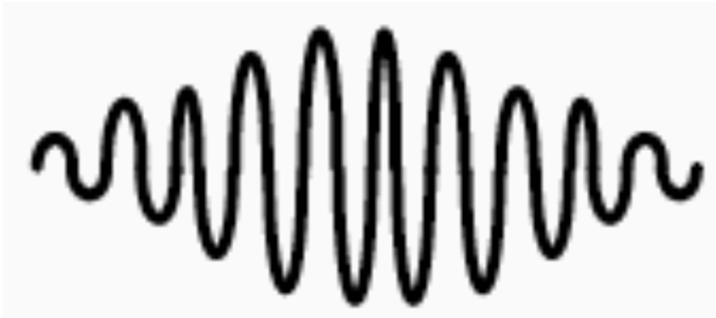
$$N = \gamma n = (1 + a_0^2/2) n_0$$

background magnetic field is frozen into the plasma

$$\langle B \rangle = (1 + a_0^2/2) B_{\rm bg} \qquad \langle E \rangle = (a_0^2/2) B_{\rm bg}$$

(ES, Iwamoto, Sironi & Piran 2024)

Magnetized electron-positron plasma



z

$e^{\pm}$ plasma

$\odot$ magnetic field B_{bg}

$a_0(z\text{-}ct)$

$$\frac{\text{background magnetic energy}}{\text{wave energy}} = \left(\frac{a_0 \omega_L}{\omega}\right)^2$$

response of the plasma is linear for

$$a_0 < \omega / \omega_L$$

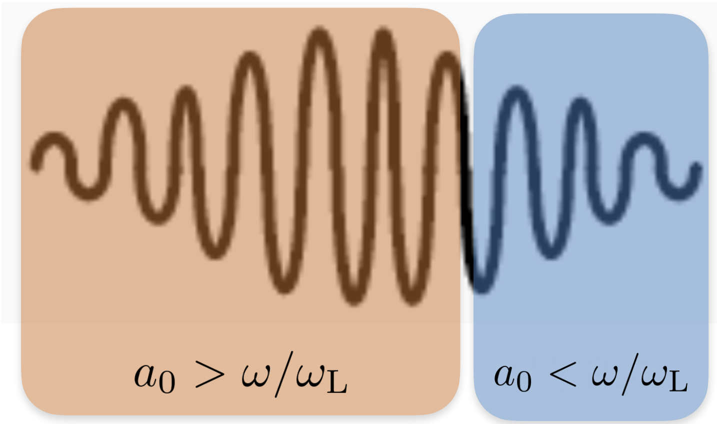
in "unperturbed" magnetar wind, this implies R>10^{12} cm

(ES, Iwamoto, Sironi & Piran 2024)

$$\omega_L = eB_{bg}/mc$$

Escape of FRBs from magnetars

10^{11} cm < R < 10^{12} cm



z

$e^{\pm}$ plasma

⊙ magnetic field B_{bg}

background magnetic energy
~ wave energy

→ FRBs produced by an "antenna" near the magnetar surface cannot escape, which challenges several models

Two alternative possibilities:

FRBs are produced at R>10^{12} cm
(Lyubarsky 2014; Beloborodov 2017, 2020; Metzger et al. 2019; Sironi et al. 2021; Iwamoto et al. 2024)

Structure of magnetar magnetosphere/wind strongly modified (explosion)
(Lyubarsky 2020; Mahlmann et al. 2022; Vanthieghem & Levinson 2025)

Comparison with other studies

$\langle B \rangle = B_{\rm bg}, \langle E \rangle = 0$

previous work: background field not modified by the wave

"stochastic heating" for $\omega_{\rm L}/a_0 < \omega < \omega_{\rm L}$

(Beloborodov 2022)

$\langle B \rangle = (1 + a_0^2/2)B_{\rm bg}, \langle E \rangle = (a_0^2/2)B_{\rm bg}$

our work: background field modified by the wave

strongly nonlinear regime for $\omega_{\rm L}/a_0 < \omega < a_0\omega_{\rm L}$

no "stochastic heating" for $\omega > a_0\omega_{\rm L}$

(ES, Iwamoto, Sironi & Piran 2024)

Comparison with other studies

$\langle B \rangle = B_{\rm bg}, \langle E \rangle = 0$

previous work: background field not modified by the wave

"stochastic heating" for $\omega_{\rm L}/a_0 < \omega < \omega_{\rm L}$

(Beloborodov 2022)

$\langle B \rangle = (1 + a_0^2/2) B_{\rm bg}, \langle E \rangle = (a_0^2/2) B_{\rm bg}$

our work: background field modified by the wave

strongly nonlinear regime for $\omega_{\rm L}/a_0 < \omega < a_0 \omega_{\rm L}$

no "stochastic heating" for $\omega > a_0 \omega_{\rm L}$

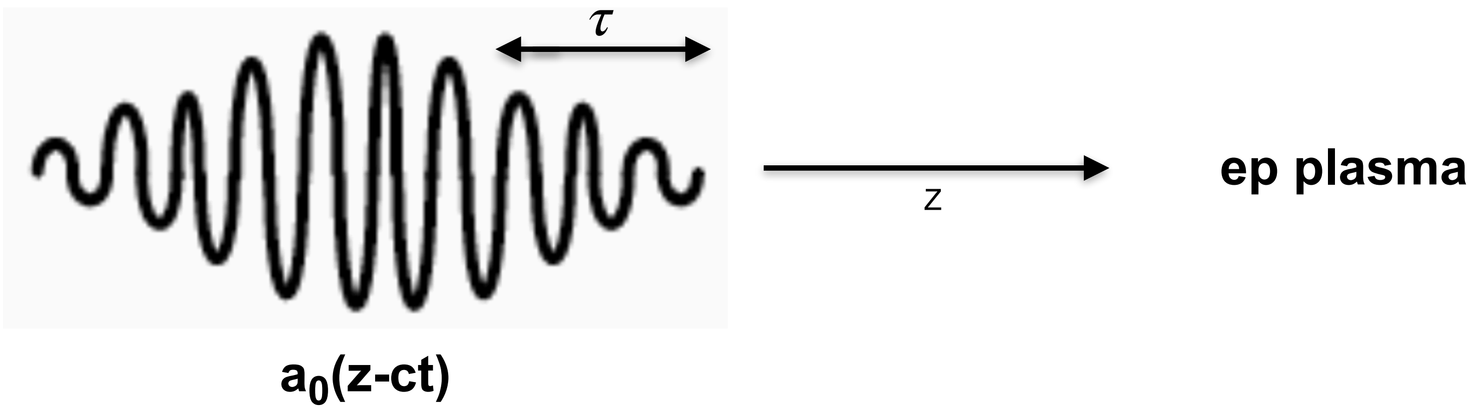
(ES, Iwamoto, Sironi & Piran 2024)

later work: background field modified by the wave

"stochastic heating" is possible for $\omega < a_0^2 \omega_{\rm L}$

(Beloborodov 2025)

Unmagnetized electron-ion plasma



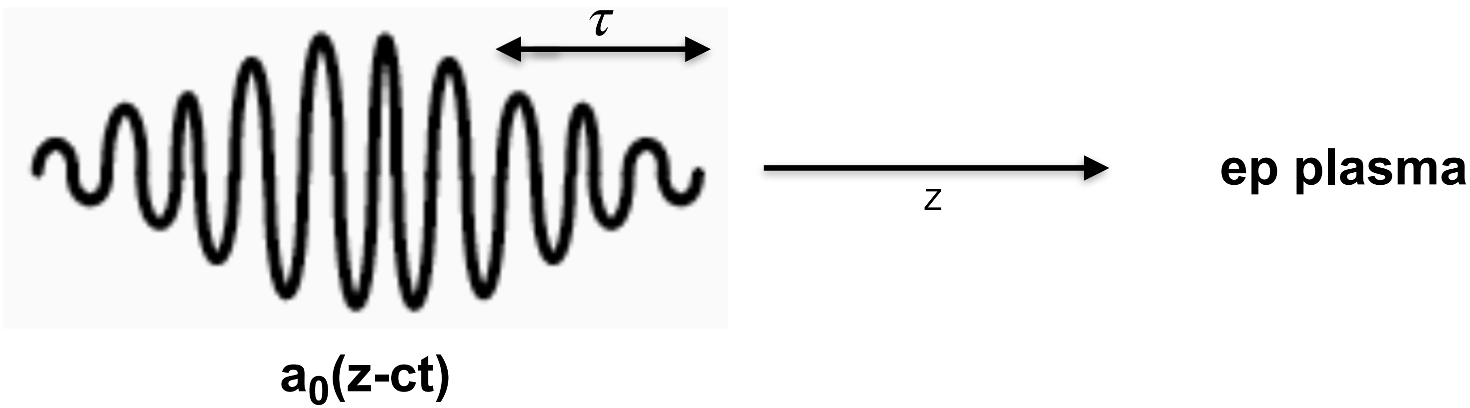
$$N_e = (1 + a_0^2/2)n_0 \qquad N_i = n_0$$

electrostatic potential is generated

$$\frac{e\phi}{m_e c^2} \sim (a_0 \omega_{\rm P} \tau)^2$$

(Sprangle, Esarey & Ting 1990; ES, Iwamoto, Sironi & Piran 2024)

Unmagnetized electron-ion plasma



response of the plasma is linear for

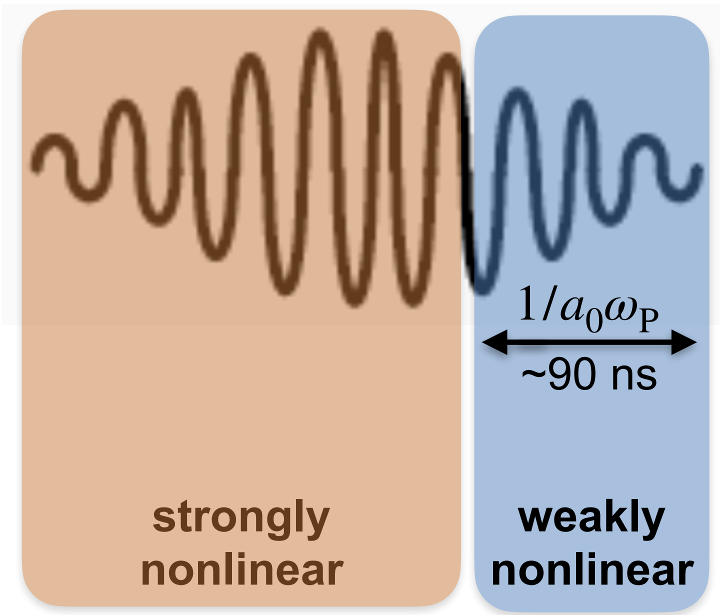
$$\frac{e\phi}{m_e c^2} \sim (a_0 \omega_{\rm P} \tau)^2 < 1$$

(Sprangle, Esarey & Ting 1990; ES, Iwamoto, Sironi & Piran 2024)

$$\tau < \frac{1}{a_0 \omega_{\rm P}} = 90 \left(\frac{n_0}{1\ {\rm cm}^{-3}} \right)^{-1/2} \left(\frac{R}{10^{11}\ {\rm cm}} \right)\ {\rm ns}$$

(never happens for the entire ~ms FRB pulse)

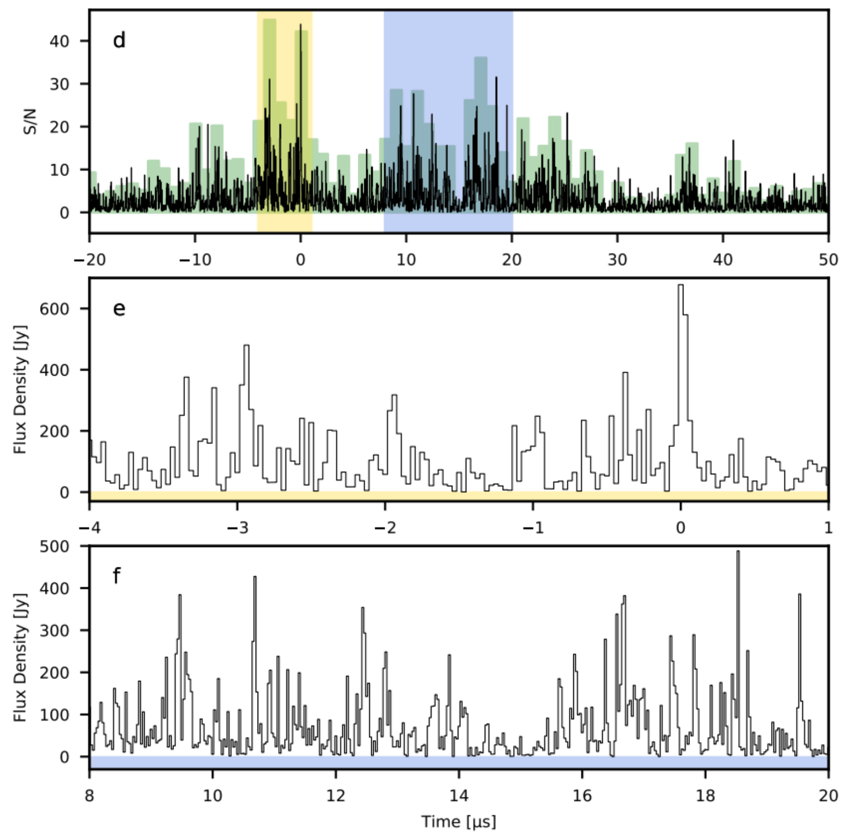
Temporal variability of FRBs



z

ep plasma

(ES, Iwamoto, Sironi & Piran 2024)



(Nimmo et al. 2022)

Summary

propagation of strong electromagnetic waves ($a_0 > 1$)
in regime of large wave frequency ($\omega > \omega_L, \omega_P$)

relevant for FRBs at radii 10^{11} cm $< R < 10^{14}$ cm

Magnetized electron-positron plasmas

response of the plasma is linear for $a_0 < \omega/\omega_L$
damping for $\omega_L < \omega < a_0\omega_L$ (i.e. 10^{11} cm $< R < 10^{12}$ cm)?

Unmagnetized electron-ion plasmas

response of the plasma is linear for $a_0 < 1/\omega_P\tau$
time variability on $\tau \sim 1/a_0\omega_P$ (i.e. sub-μs) timescales?