Induced Scattering of Strong Electromagnetic Waves in Pair Plasmas

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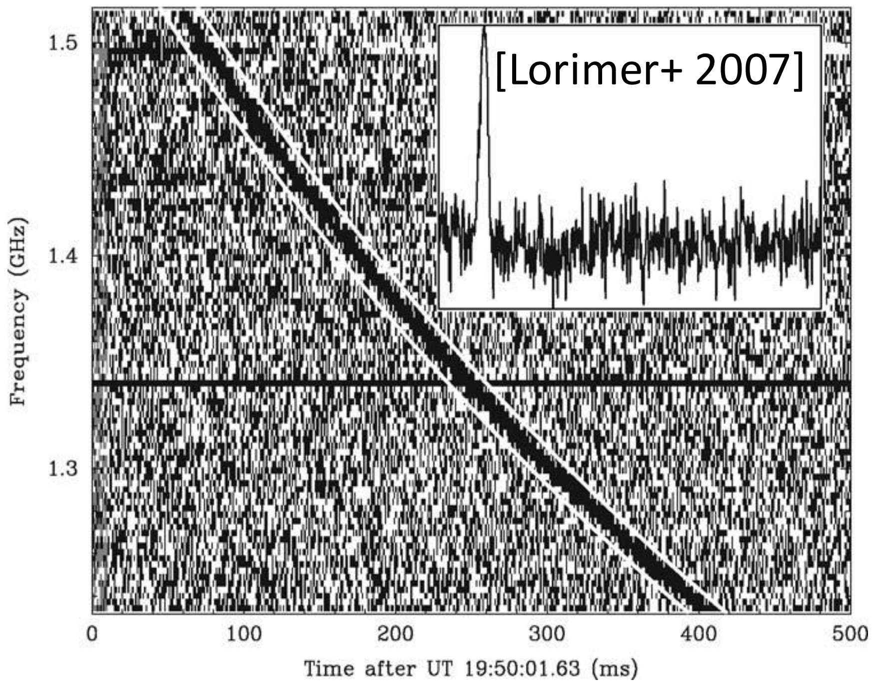
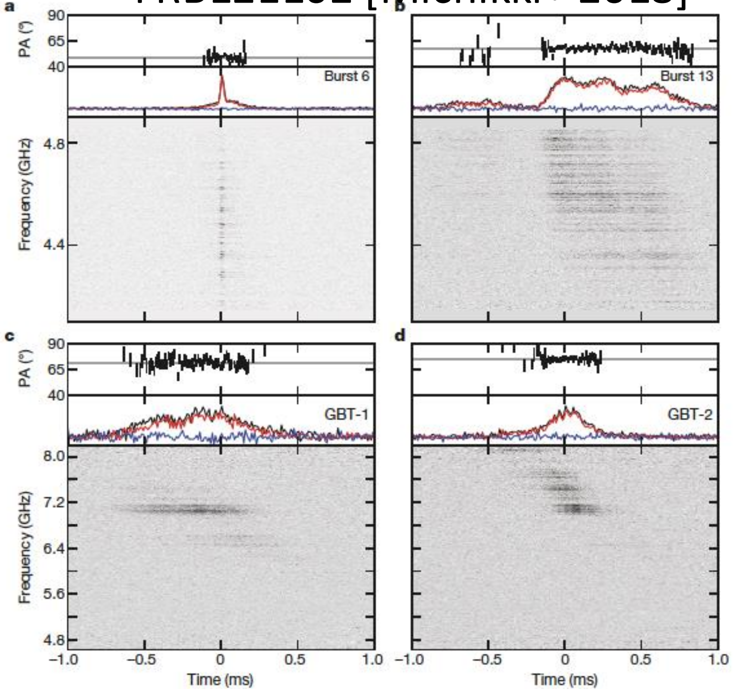
Fast Radio Bursts (FRB)

- ✓ Millisecond-duration, extremely bright radio pulses (Lorimer+ 2007)
- ✓ High brightness temperature ($\sim 10^{35} K$)→ coherent emission
- ✓ Some FRBs are known to repeat, and repeating FRBs often show high linear polarization (e.g., Michikki+ 2018)
- ✓ Magnetar origin?(Bochenek+2020; CHIME/FRB Collaboration+ 2020)



FRB121102 [Michikki+ 2018]

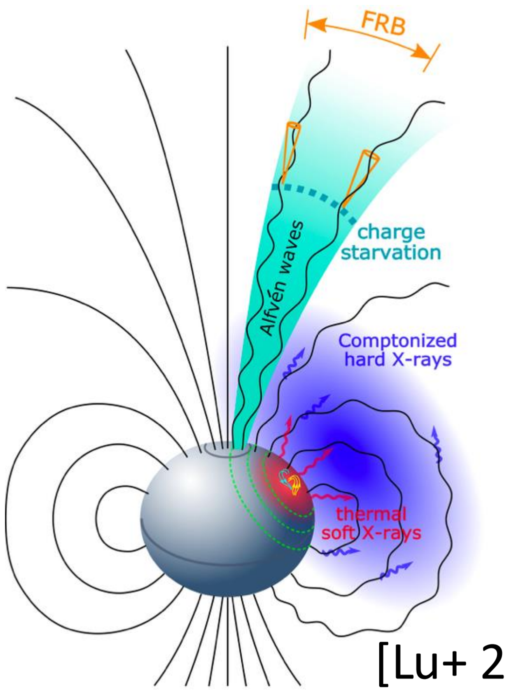


FRB Emission Model

Where is the emission region: Magnetosphere or Wind?

Magnetospheric (Pulsar-like) Model

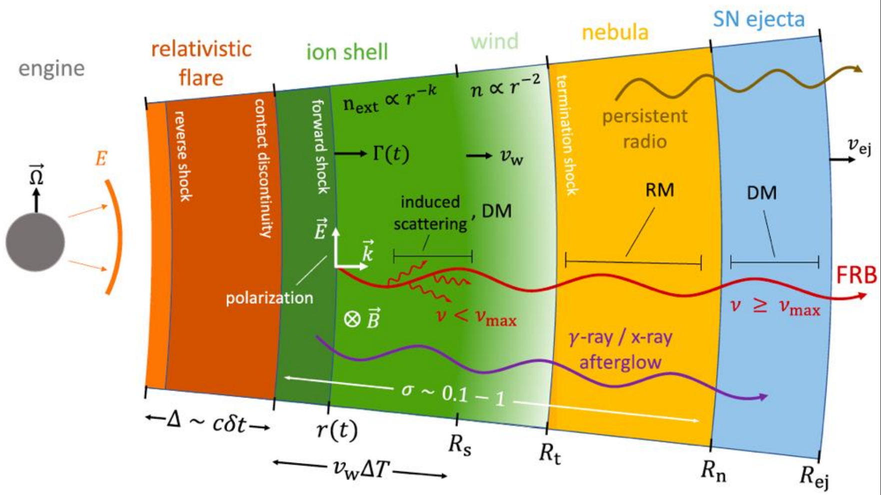
Coherent curvature radiation from charge bunches



[Lu+ 2020]

Far-away (GRB-like) model

Synchrotron maser instability in relativistic shocks



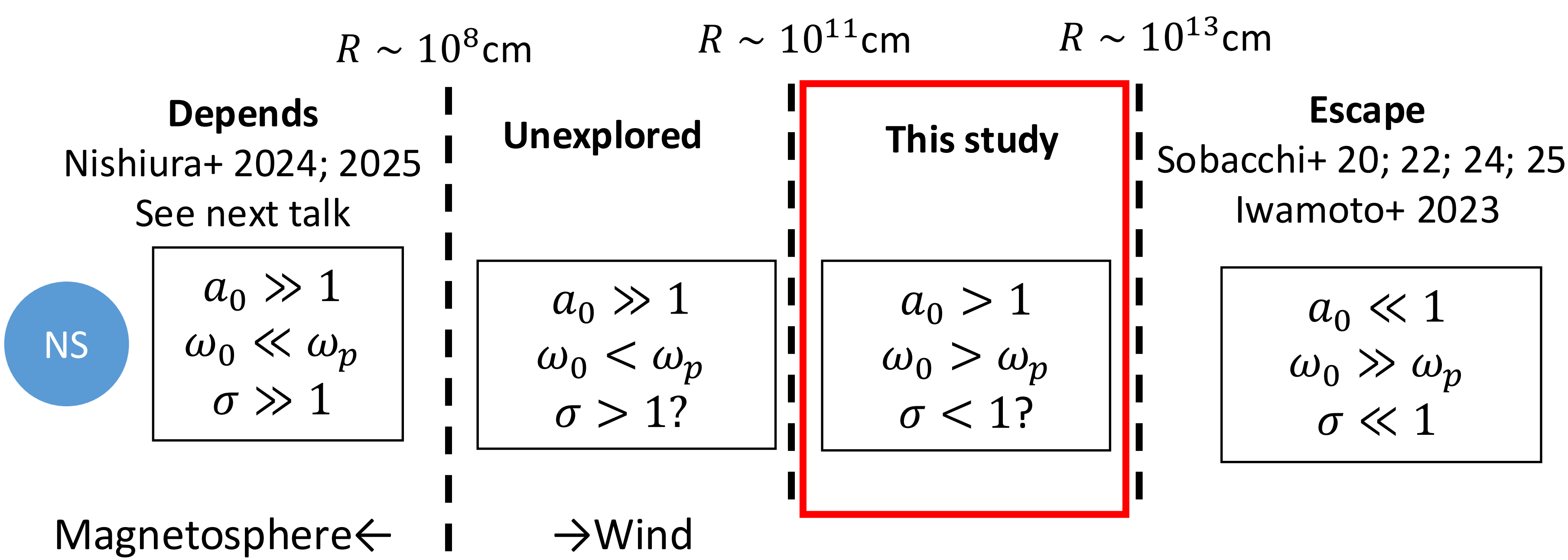
[Metzger+ 2019]

FRB Propagation

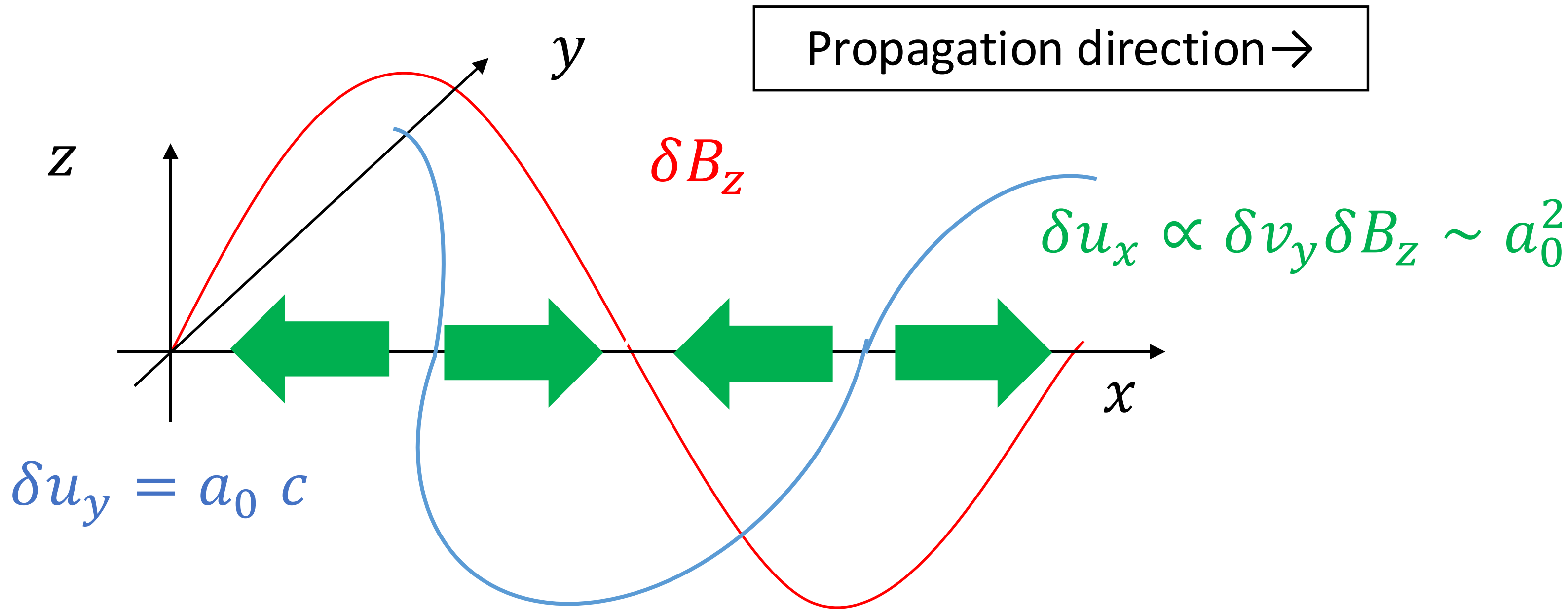
- ✓ FRBs are strong (Luan & Goldreich 2014):

$$a_0 = \frac{eE_0}{m_e c \omega_0} > 1 \text{ for } R \lesssim 10^{13}\text{cm}$$

- ✓ Such strong waves are subject to induced scattering
  → constrains the emission region
- ✓ This study focuses on $10^{11}\text{cm} \lesssim R \lesssim 10^{13}\text{cm}$



Wave Nonlinearity



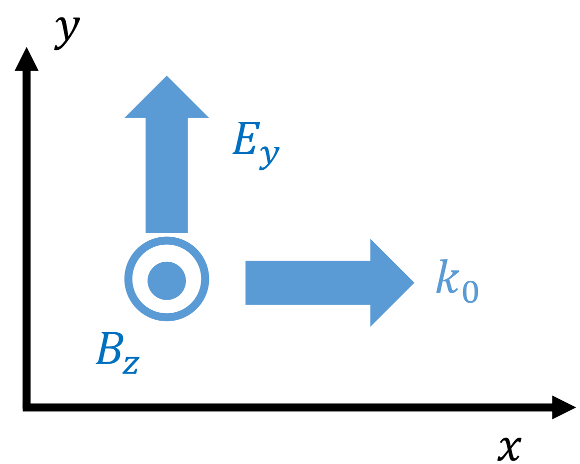
- ✓ Conservation of transverse canonical momentum →$\delta u_y = a_0 c$
- ✓ Nonlinear Lorentz force ∝ $\delta v_y \delta B_z \sim a_0^2$
  → longitudinal motion becomes dominant for $a_0 > 1$
  → strongly coupled with plasmas
- ✓ No analytic steady-state solution exists for for $a_0 > 1$

Revisit to Steady-State Solution

Akhiezer & Polovin 1954; Max 1973; Clemmow 1974; Kennel & Pellat 1976

Assumptions

- ✓ Unmagnetized, cold electron-positron fluid
- ✓ Linearly polarized, monochromatic plane wave
- ✓ All physical quantities are expressed as a function of $\phi_0 = k_0 x - \omega_0 t$



$$\frac{\alpha^2 a_0^2}{\gamma_g^2}\left(\frac{\mathrm{d}y}{\mathrm{d}\phi_0}\right)^2 = \frac{(1-y^2)(1-y^2+q)}{(1-y^2+q/2)^2}$$

$$\frac{\alpha a_0}{\gamma_g}\frac{2E(m)-(1-m)K(m)}{2\sqrt{m}} = \frac{\pi}{2}$$

$$\gamma = 1 + \frac{\alpha a_0^2}{2}(1-y^2)$$

$$u_x = \frac{\alpha \beta_g a_0^2}{2}(1-y^2)$$

$$u_y = \pm a_0 \int y \mathrm{d}\phi_0$$

Where

$$y = \frac{E_y}{E_0}, a_0 = \frac{eE_0}{mc\omega_0}, \alpha = \frac{\omega_0^2 - c^2 k_0^2}{2\omega_{pe}^2}$$

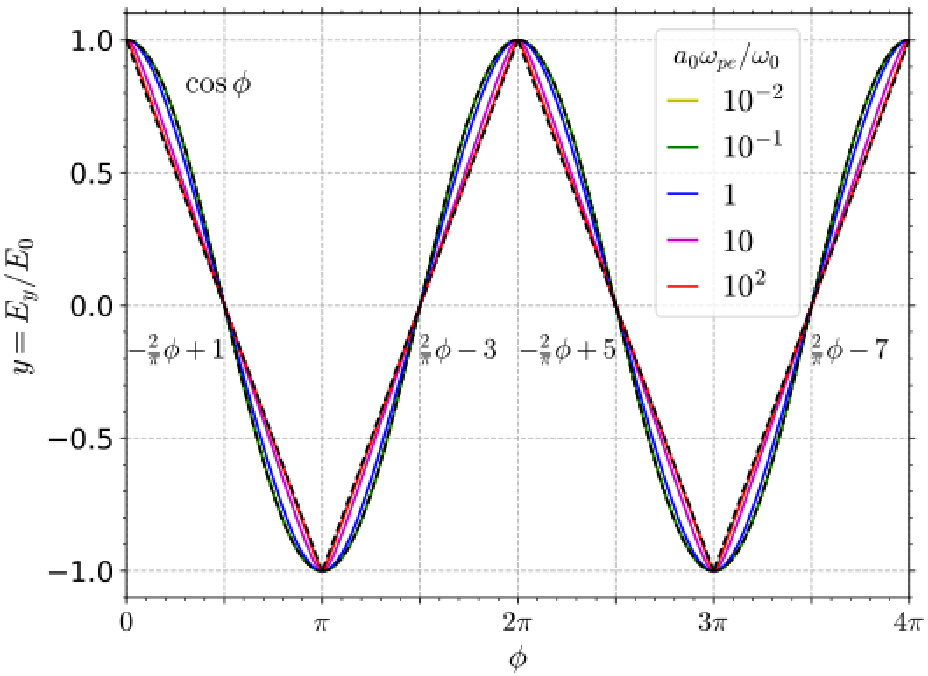
$$\beta_g = \frac{ck_0}{\omega_0}, \gamma_g = \frac{1}{\sqrt{1-\beta_g^2}},$$

$$q = \frac{8\omega_{pe}^2 \gamma_g^4}{\omega_0^2 a_0^2}, m = \frac{1}{1+q},$$

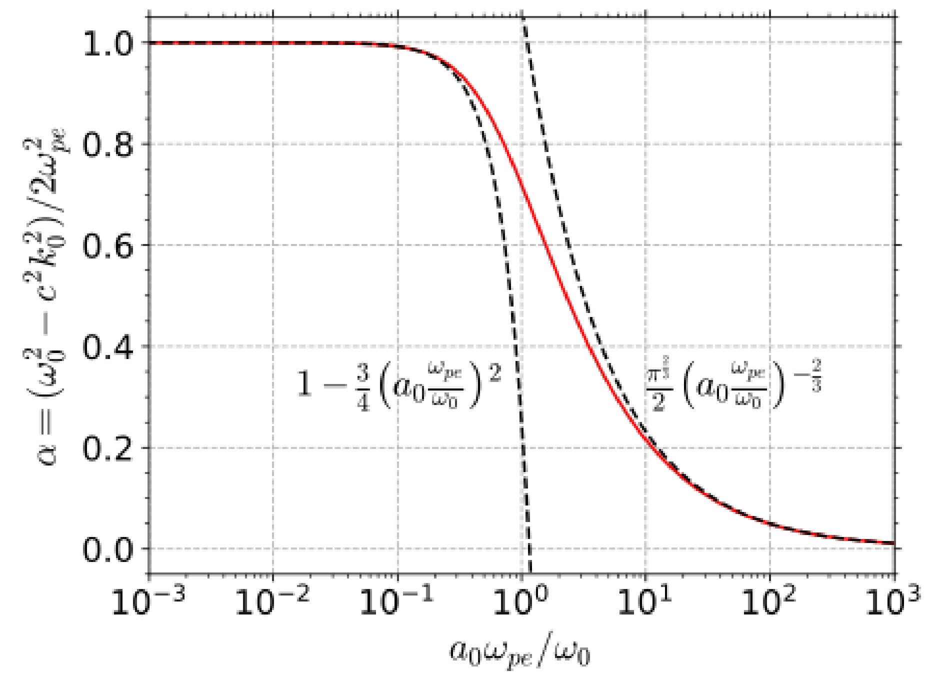
$K\&E$:Incomplete elliptic integral of the first/second kind

Parameter Dependence

Wave form



Dispersion relation



- ✓ Well-characterized by $\frac{a_0\omega_{pe}}{\omega_0}$ rather than a_0
- ✓ $\frac{a_0\omega_{pe}}{\omega_0} \ll 1$ → linear solution even if $a_0 > 1$

Linear Analysis of Stimulated Scattering

- ✓ In unmagnetized pair plasmas, linearly polarized EM waves are subject to Induced Compton Scattering (ICS)
- ✓ ICS can be interpreted as a classical plasma instability
- ✓ For $a_0 \ll 1$, the linear growth rate is (Ghosh+ 2022; Iwamoto+ 2023):

$$\frac{\Gamma_{max}^{ICS}}{\omega_0} \sim \begin{cases} \sqrt{\frac{\pi}{8e}} \frac{1}{\beta_{th0}^2} \left(a_0 \frac{\omega_{pe}}{\omega_0} \right)^2, \beta_{th0} \gg \left(a_0 \frac{\omega_{pe}}{\omega_0} \right)^{\frac{2}{3}} \\ \frac{\sqrt{3}}{2} \left(a_0 \frac{\omega_{pe}}{\omega_0} \right)^{\frac{2}{3}}, \beta_{th0} \ll \left(a_0 \frac{\omega_{pe}}{\omega_0} \right)^{\frac{2}{3}} \end{cases}$$

→characterized by $\frac{a_0 \omega_{pe}}{\omega_0}$ rather than

Can be extrapolated to the regime $a_0 > 1$ as long as $\frac{a_0 \omega_{pe}}{\omega_0} \ll 1$?

Application to FRB Propagation

$R \sim 10^{8}\mathrm{cm}$ | $R \sim 10^{11}\mathrm{cm}$ | $R \sim 10^{13}\mathrm{cm}$

NS

Depends
Nishiura+ 2024; 2025
See next talk

$a_0 \gg 1$
$\omega_0 \ll \omega_p$
$\sigma \gg 1$

No previous studies

$a_0 \gg 1$
$\omega_0 < \omega_p$
$\sigma > 1?$

This study

$a_0 > 1$
$\omega_0 > \omega_p$
$\sigma < 1?$

Escape
Sobacchi+ 20; 22; 24; 25,
Iwamoto+ 2023

$a_0 \ll 1$
$\omega_0 \gg \omega_p$
$\sigma \ll 1$

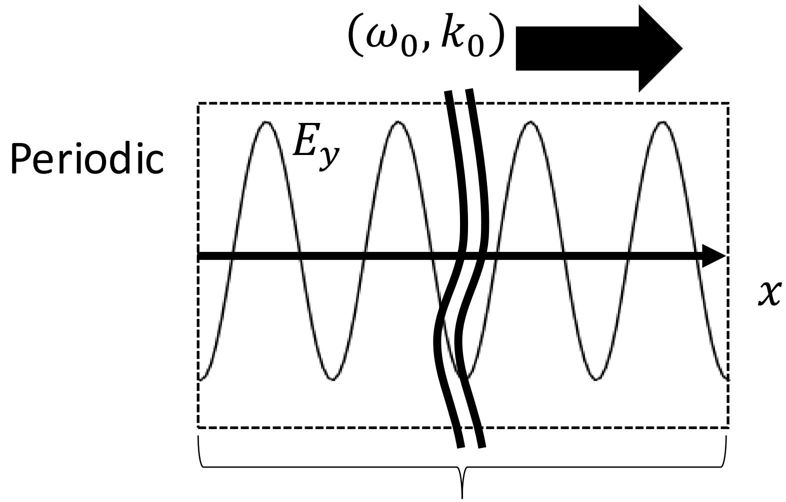
Magnetosphere← →Wind

$$a_0 \sim 2\left(\frac{10^{13}\mathrm{cm}}{R}\right), \frac{\omega_{pe}}{\omega_0} \sim 10^{-3}\left(\frac{10^{13}\mathrm{cm}}{R}\right)$$

$$\rightarrow \frac{a_0\omega_{pe}}{\omega_0} \sim 2\times10^{-3}\left(\frac{10^{13}\mathrm{cm}}{R}\right)^2 \ll 1 \text{(Beloborodov 2020)}$$

→linear regime?

Numerical Settings



$$100\lambda_0 = 20{,}000\Delta x$$
$$\Delta t = \Delta x / c$$

Parameters

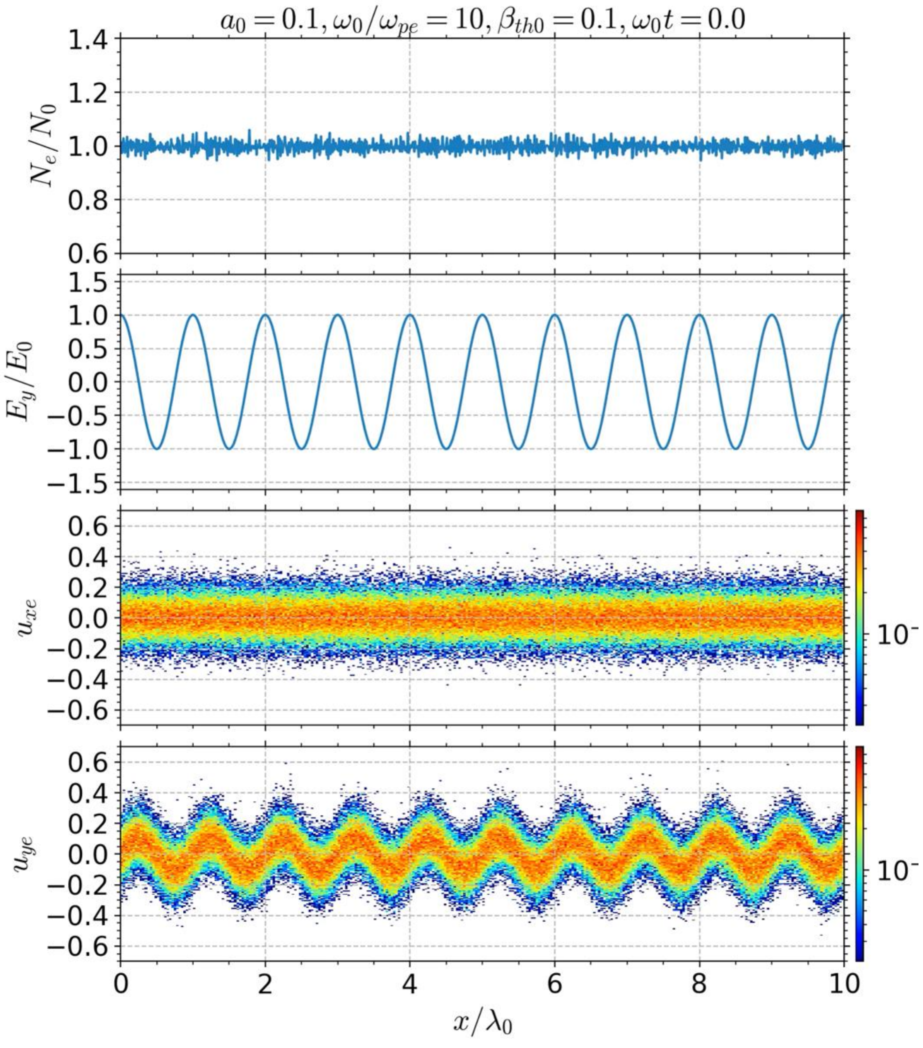
$$\left(a_0\,, \frac{\omega_0}{\omega_{pe}}\right) = (0.05{,}5), (0.1{,}10), (1{,}100), (2{,}200), (4{,}400)$$

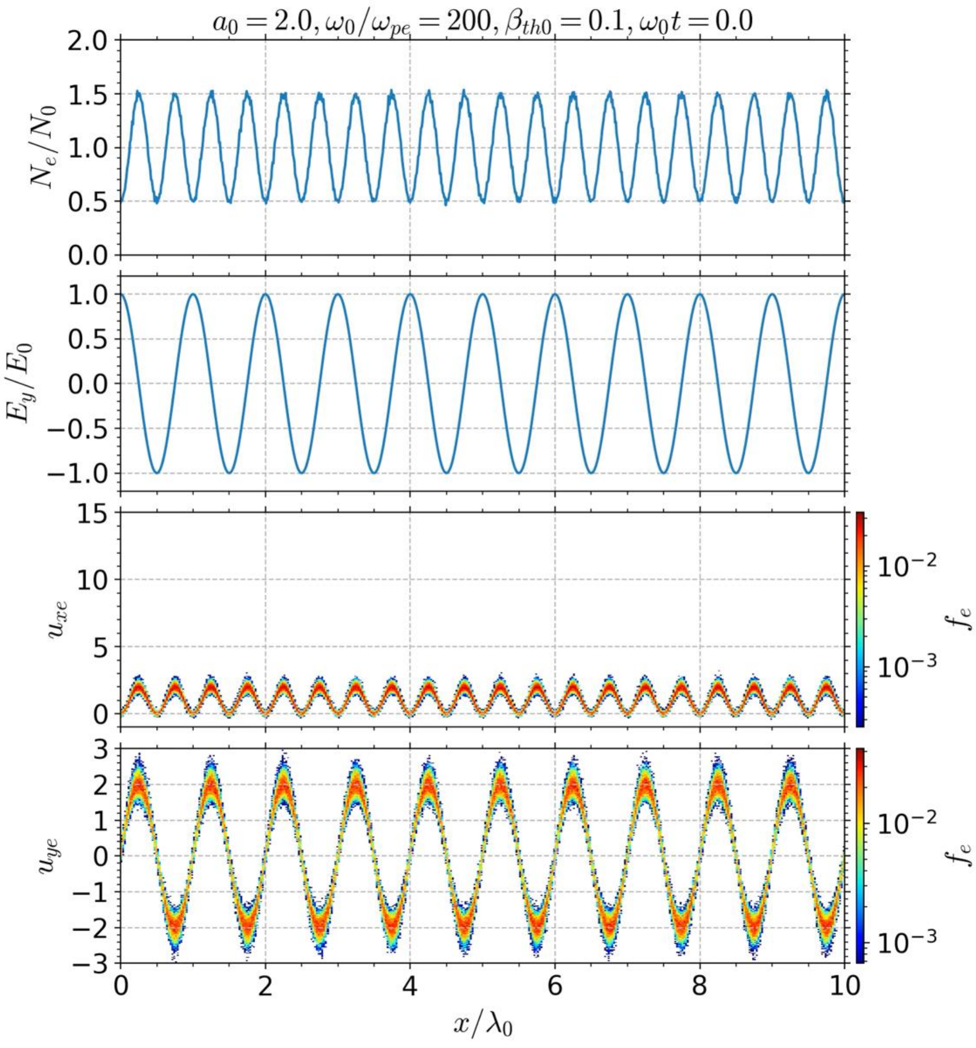
$$\left(a_0 \frac{\omega_{pe}}{\omega_0} = 0.01 \text{ is fixed}\right)$$

$$\beta_{th0} = 0.1, 0.01$$

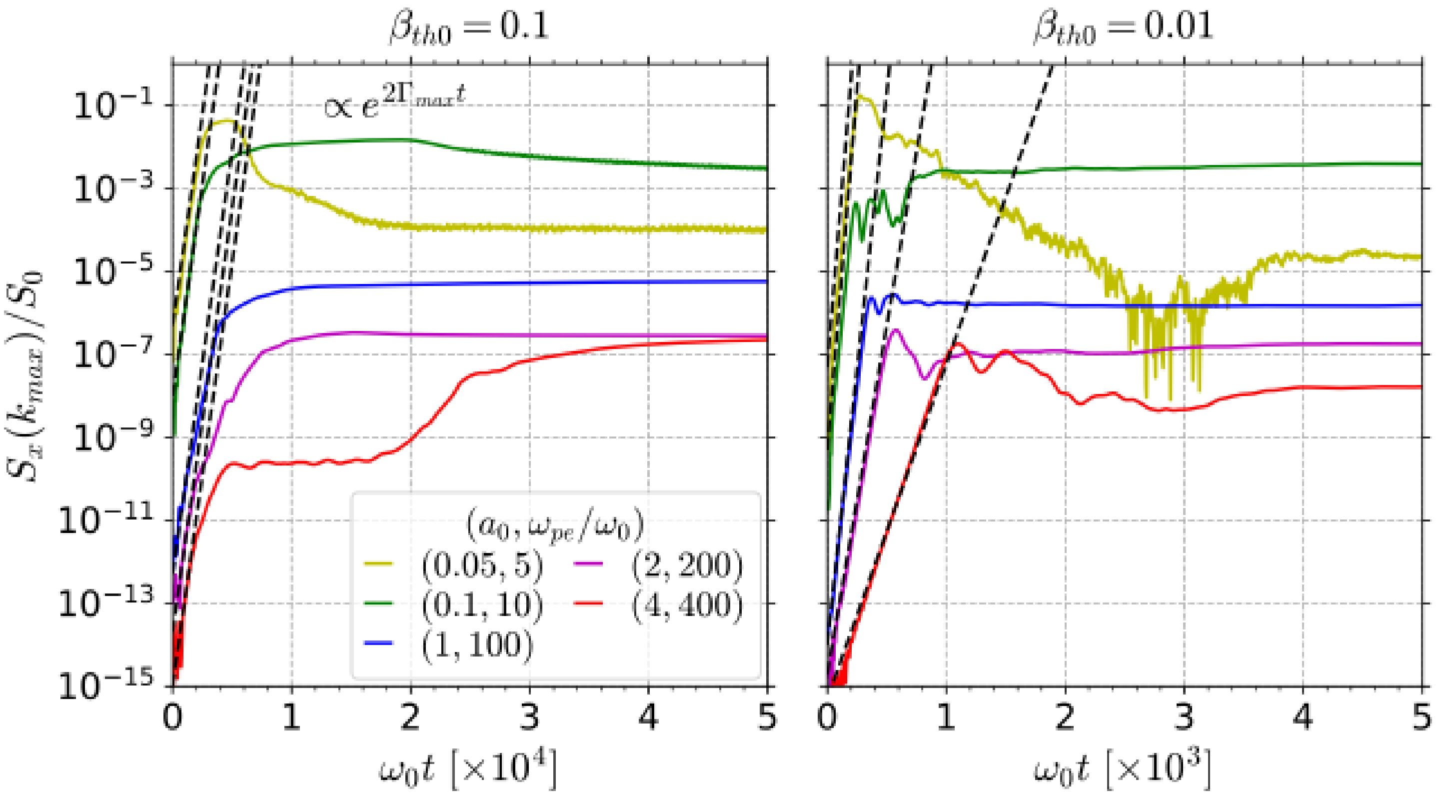
- ✓ Simulation code: Wuming (open source PIC code; Matsumoto+ 2024)
- ✓ One-dimensional systems (only induced Compton scattering works)
- ✓ k_0 is determined by dispersion relation
- ✓ Thermal velocity β_{th0} is defined in the proper (Eckart) frame

Simulation Results



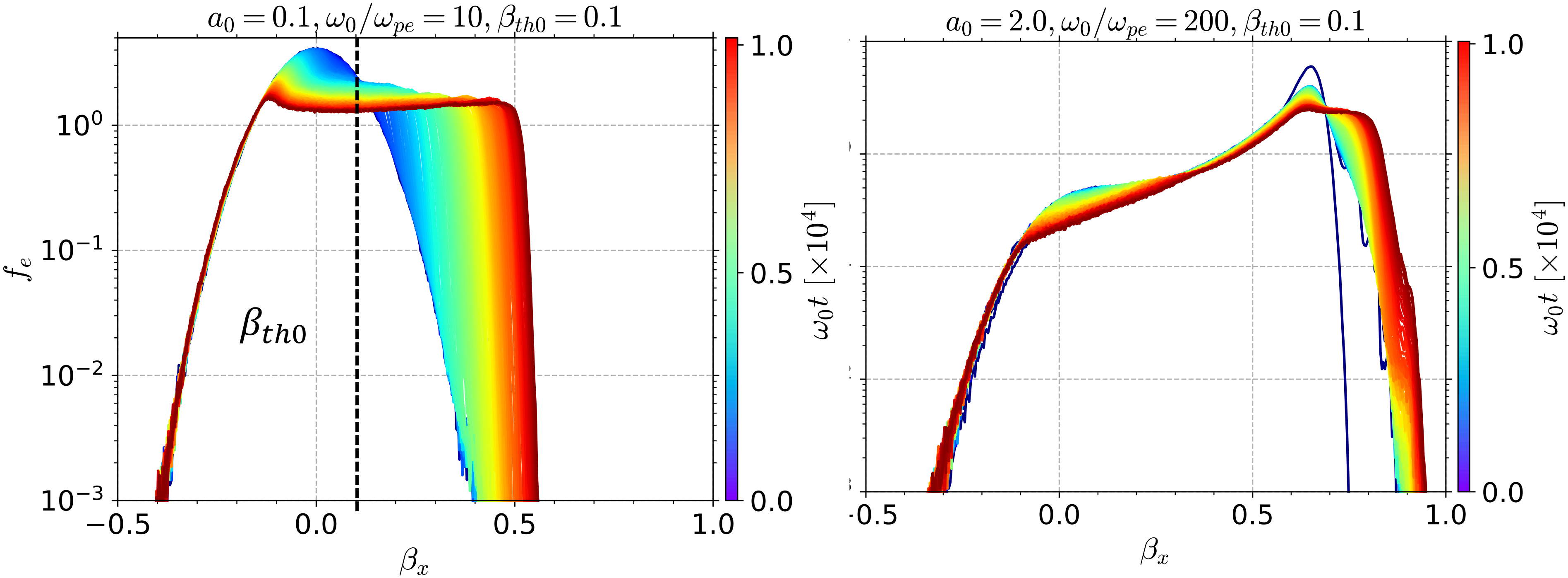


Linear Growth Rate



- ✓ FRB: $\omega_0 \delta t_{pulse} \sim (1\text{GHz}/\gamma_{wind}) \times (1\text{ms} \cdot \gamma_{wind}) = 10^6$
  → sufficiently longer than simulation time $\omega_0 t_{max} = 2 \times 10^4$
  → ICS operates
- ✓ Linear growth rates depend on both $\frac{a_0 \omega_{pe}}{\omega_0}$ and a_0
  → Lorentz boost

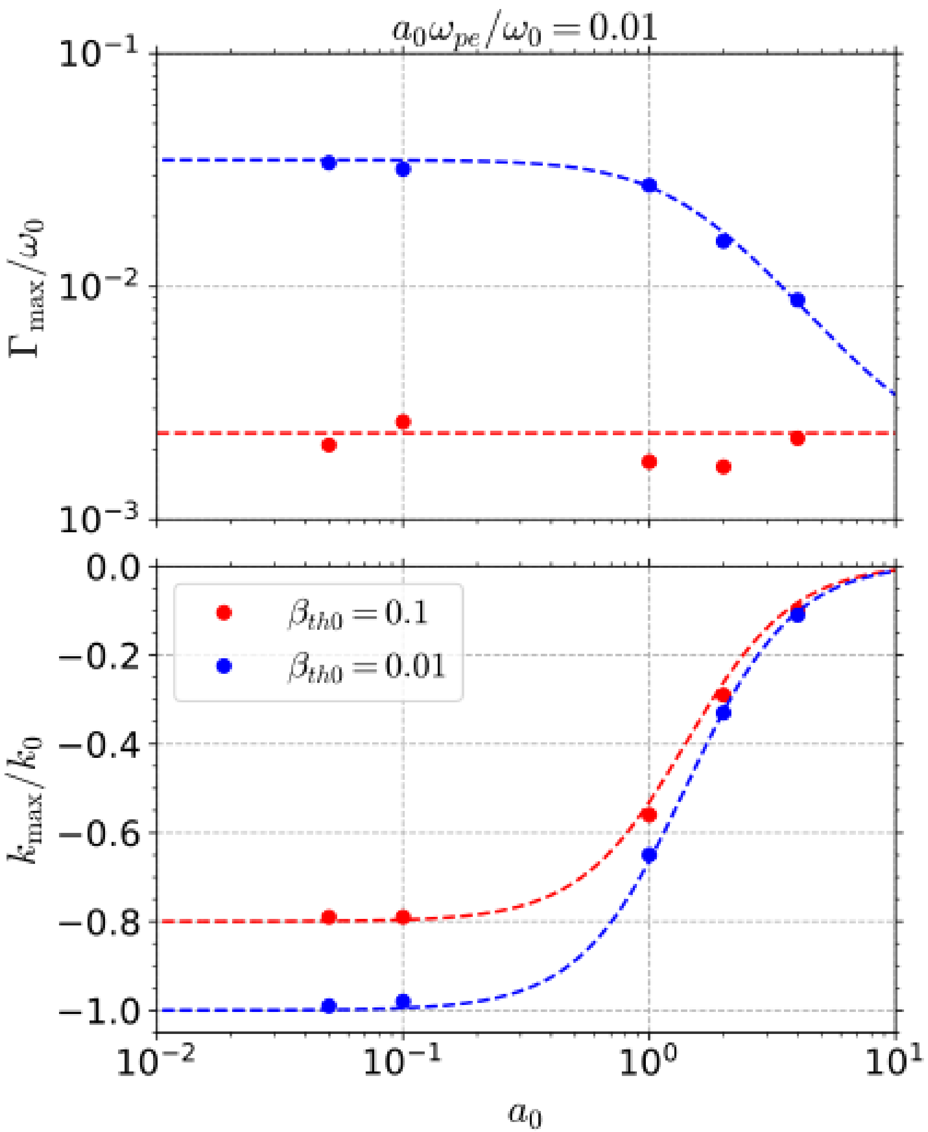
Particle Velocity Distribution



- ✓ Incident EM waves induce a longitudinal plasma drift for $a_0 > 1$
- ✓ ICS operates in the frame where the longitudinal drift vanishes?
- ✓ The drift velocity is

$$v_D = \frac{\langle u_x \rangle}{\langle \gamma \rangle} \sim \frac{a_0^2}{4 + a_0^2} c$$

Growth Rate in Simulation Frame

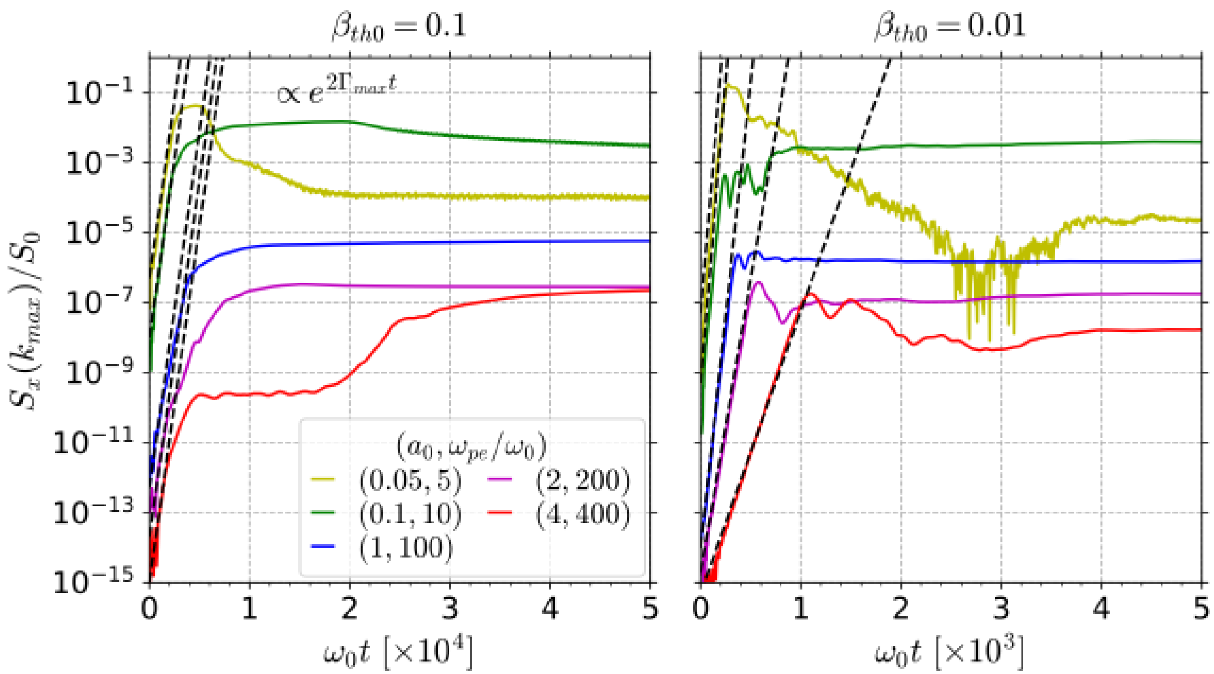


$$\frac{\Gamma_{max}}{\omega_0} \sim \begin{cases} \sqrt{\frac{\pi}{8e}} \frac{1}{\beta_{th0}^2} \left(a_0 \frac{\omega_{pe}}{\omega_0} \right)^2 \\ \frac{\sqrt{3}}{2} \left(a_0 \frac{\omega_{pe}}{\omega_0} \right)^{\frac{2}{3}} {\gamma_D}^{-\frac{4}{3}} \end{cases}$$

$$\frac{k_{max}}{k_0} \sim \begin{cases} -\frac{1}{{\gamma_D}^2} \\ -\frac{1-2\beta_{th0}}{{\gamma_D}^2} \end{cases}$$

- ✓ a_0 dependence results from Lorentz boost
- ✓ Linear treatment is valid in the frame where the longitudinal drift vanishes

Saturation Levels of Fastest-Growing Modes



$a_0\ \omega_0/\omega_{pe}$

0.25

1

100

400

1600

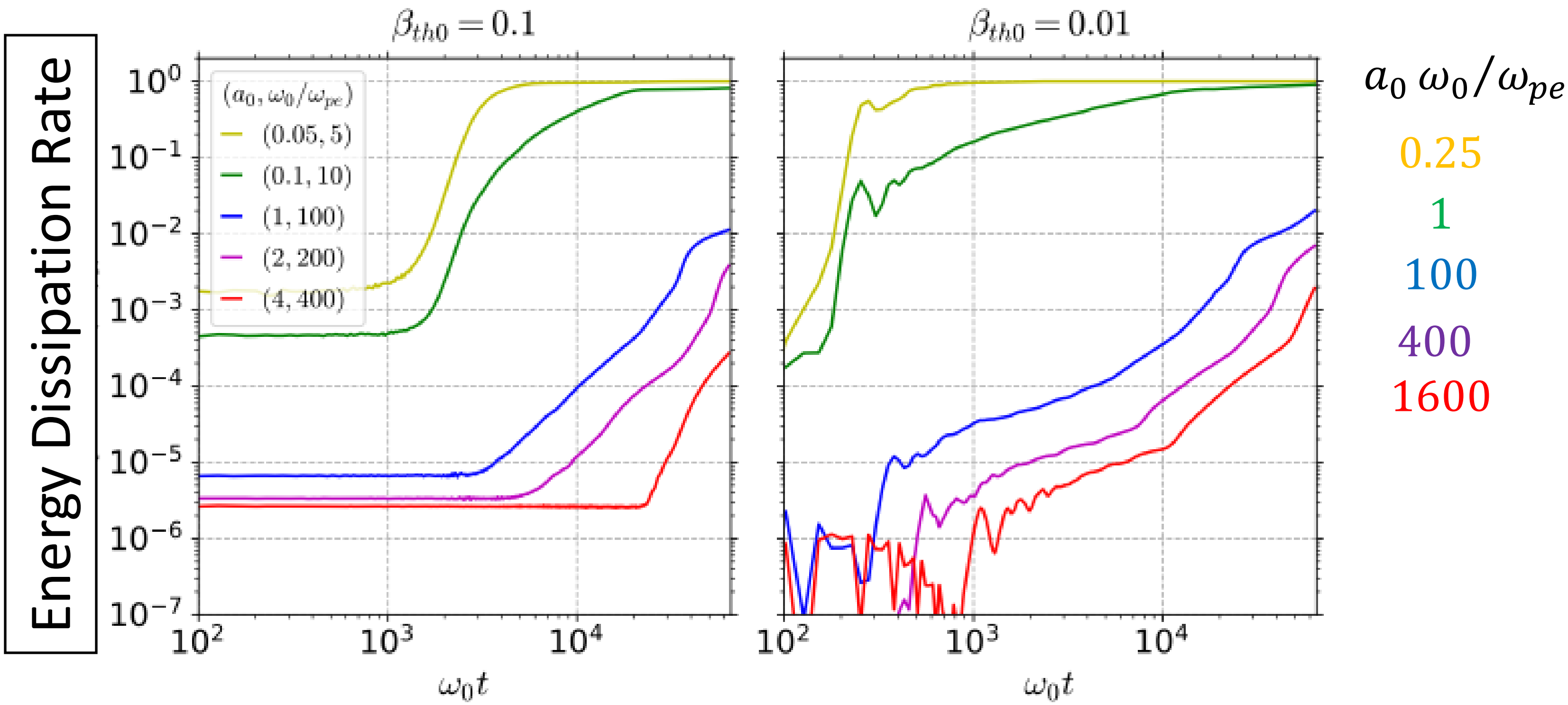
Saturation level depends on

$$\frac{a_0\omega_0}{\omega_{pe}} = \sqrt{\frac{E_0^2/4\pi}{n_0 mc^2}}$$

→Incident wave energy is dominant for $\frac{a_0\omega_0}{\omega_{pe}} \gg 1$

→Scattering is less effective

Effect on FRB Propagation



- ✓ Incident wave energy is gradually dissipated into plasmas
- ✓ $\dfrac{a_0\omega_0}{\omega_{pe}} = 1600$ → Energy loss is limited to 1% at $\omega_0 \delta t_{pulse} \sim 10^6$
- ✓ FRB: $\dfrac{a_0\omega_0}{\omega_{pe}} \sim 2 \times 10^3$ → ICS becomes negligible

Summary

$R \sim 10^8$cm | $R \sim 10^{11}$cm | $R \sim 10^{13}$cm

NS

Depends
Nishiura+ 2024; 2025
See next talk

$a_0 \gg 1$
$\omega_0 \ll \omega_p$
$\sigma \gg 1$

Unexplored

$a_0 \gg 1$
$\omega_0 < \omega_p$
σ>1?

Escape

$a_0 > 1$
$\omega_0 > \omega_p$
$\sigma < 1$?

Escape
Sobacchi+ 20; 22; 24; 25,
Iwamoto+ 2023

$a_0 \ll 1$
$\omega_0 \gg \omega_p$
$\sigma \ll 1$

Magnetosphere← →Wind

FRB propagation is controlled by $\frac{a_0 \omega_{pe}}{\omega_0}$ & $\frac{a_0 \omega_0}{\omega_{pe}}$

✓ $\frac{a_0 \omega_{pe}}{\omega_0} \ll 1$→ linear treatment is valid even for $a_0 > 1$

✓ $\frac{a_0 \omega_0}{\omega_{pe}} \gg 1$→ wave energy ≫ plasma energy

→ICS is negligible

Back up

Growth Rate in Simulation frame

Proper frame

$$\frac{\Gamma'_{max}}{\omega'_0} \sim \begin{cases} \sqrt{\frac{\pi}{8e}}\frac{1}{\beta_{th0}^2}\left(a_0\frac{\omega_{pe}}{\omega'_0}\right)^2 \\ \frac{\sqrt{3}}{2}\left(a_0\frac{\omega_{pe}}{\omega'_0}\right)^{\frac{2}{3}} \end{cases}$$

$$\frac{k'_{max}}{k'_0} \sim \begin{cases} -1 \\ -(1-2\beta_{th0}) \end{cases}$$

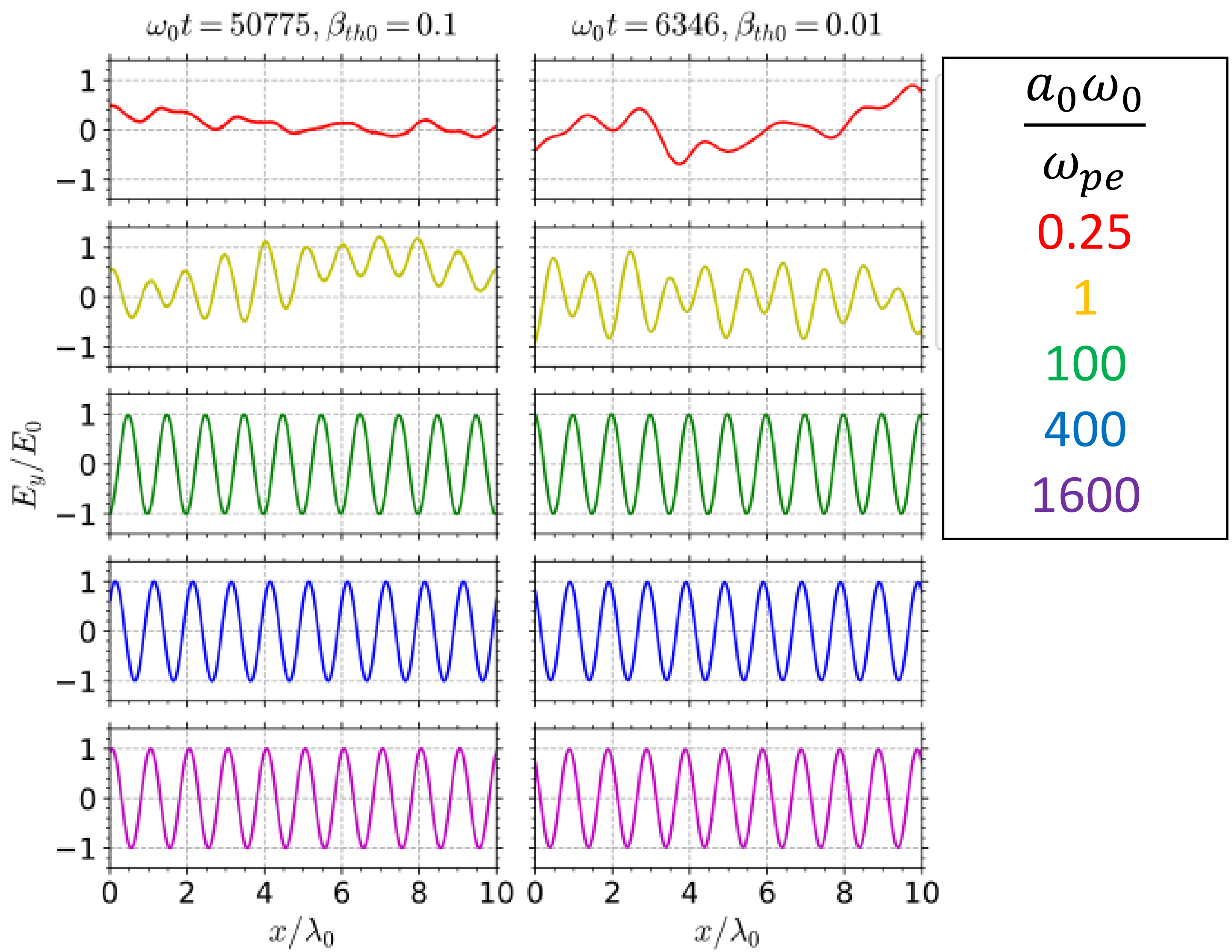
$$\Gamma'_{max} \sim \langle\gamma\rangle\Gamma_{max}, \omega'_0 \sim \frac{\omega_0}{\langle\gamma\rangle}, k'_0 \sim \frac{k_0}{\langle\gamma\rangle}, \langle\gamma\rangle \sim \sqrt{1+\frac{a_0^4}{16}}$$

Simulation frame

$$\frac{\Gamma_{max}}{\omega_0} \sim \begin{cases} \sqrt{\frac{\pi}{8e}}\frac{1}{\beta_{th0}^2}\left(a_0\frac{\omega_{pe}}{\omega_0}\right)^2 \\ \frac{\sqrt{3}}{2}\left(a_0\frac{\omega_{pe}}{\omega_0}\right)^{\frac{2}{3}}\frac{1}{\langle\gamma\rangle^{\frac{4}{3}}} \end{cases}$$

$$\frac{k_{max}}{k_0} \sim \begin{cases} -\frac{1}{\langle\gamma\rangle^2} \\ -\frac{1-2\beta_{th0}}{\langle\gamma\rangle^2} \end{cases}$$

EM Waves


$\omega_0 t = 50775, \beta_{th0} = 0.1$
$\omega_0 t = 6346, \beta_{th0} = 0.01$
E_y/E_0
x/λ_0
$\frac{a_0\omega_0}{\omega_{pe}}$
0.25
1
100
400
1600