磁化された電子陽電子プラズマ中での誘導コンプトン散乱の1次元PICシミュレーション

上島翔真（基研）

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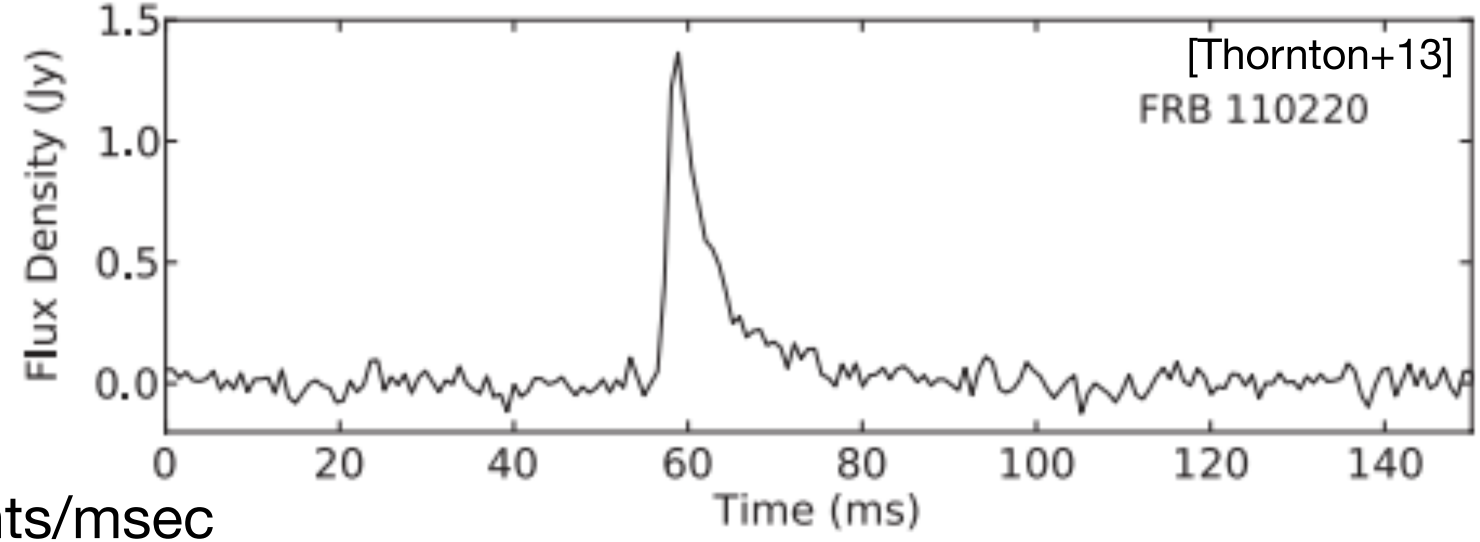
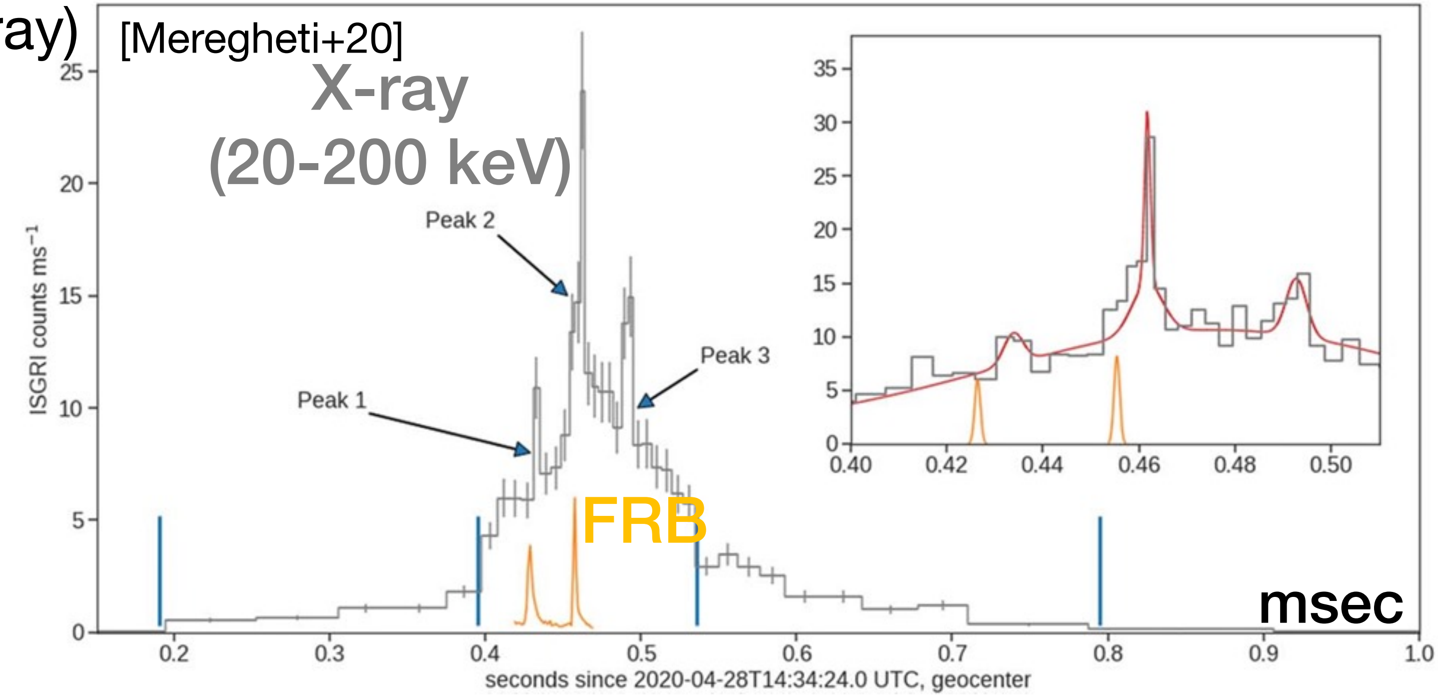
Fast Radio Burst (FRB)

- Most luminous radio transient
- Cosmological
- Frequency: $\nu \sim \mathcal{O}(\mathrm{GHz})$
- Duration: $\Delta t \sim \mathcal{O}(\mathrm{msec})$
- Flux density: $S_\nu \sim \mathcal{O}(\mathrm{Jy})$ @GHz
- High Brightness temperature: → coherent emission
- FRB from Galactic magnetar is observed in 2020.



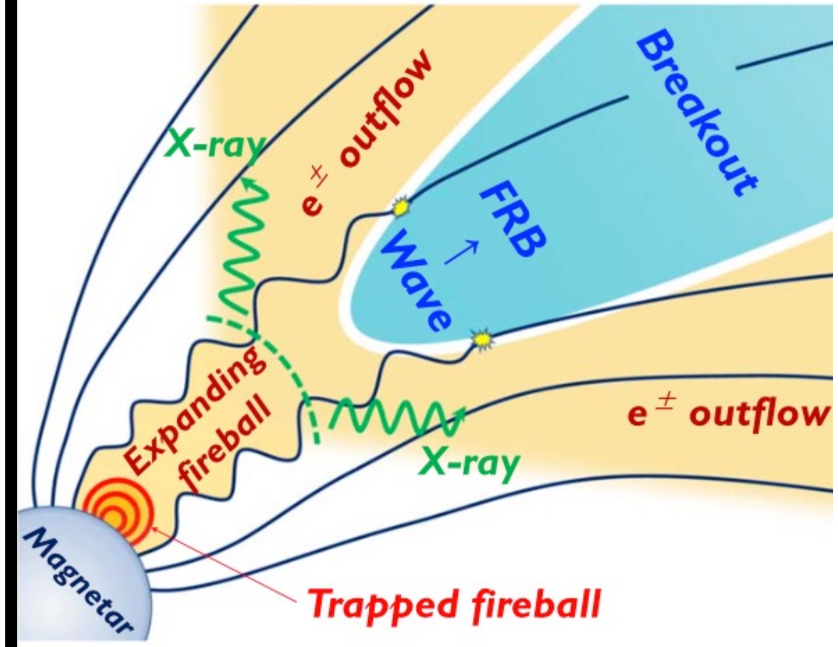


One of the origins of FRBs is a magnetar.

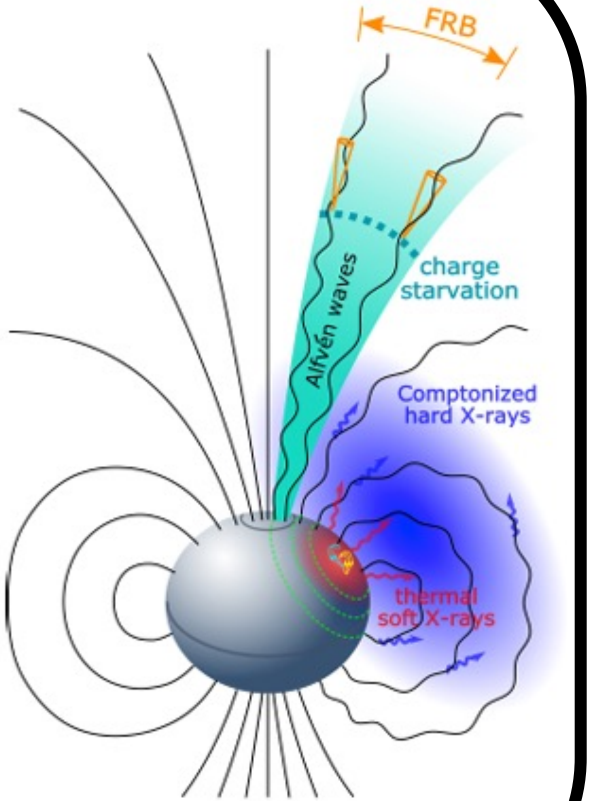
Magnetar Model

The wave propagation in magnetized plasmas is common for both models.
Parametric instabilities are important for wave propagation in plasma.

Inner Magnetosphere Model

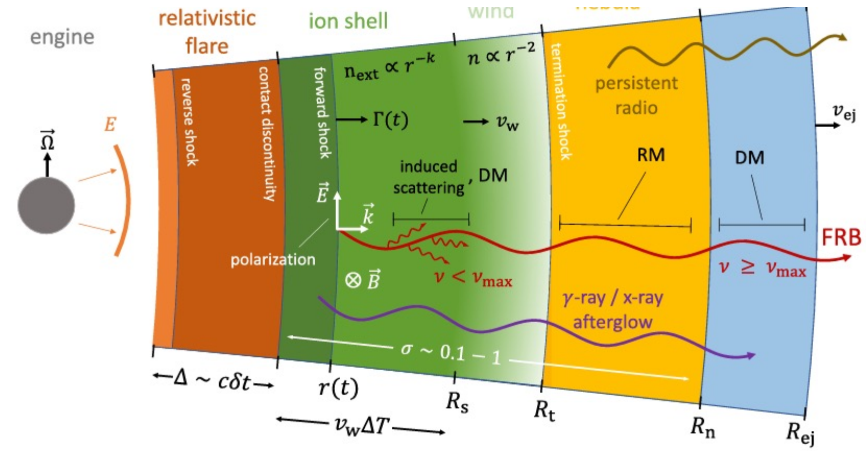


[Ioka 2020]

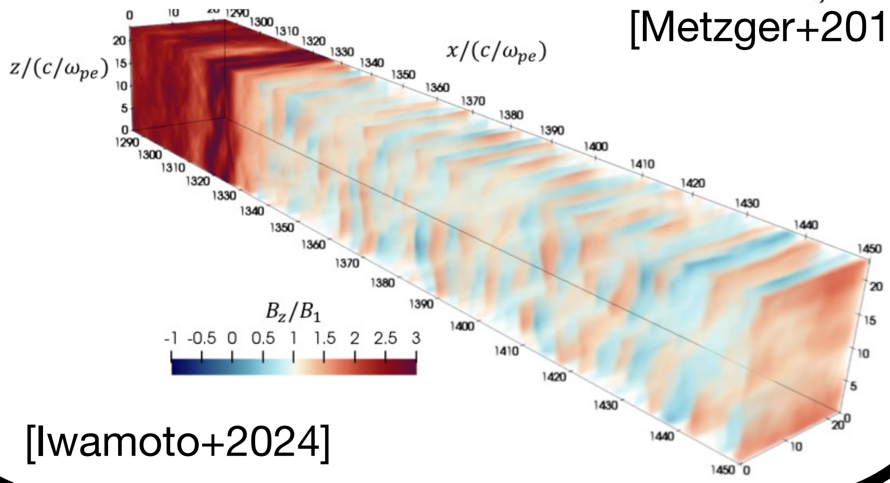


[Lu+2020]

Outer Magnetosphere Model



[Metzger+2019]



[Iwamoto+2024]

Parametric Instability in Unmagnetized Plasma

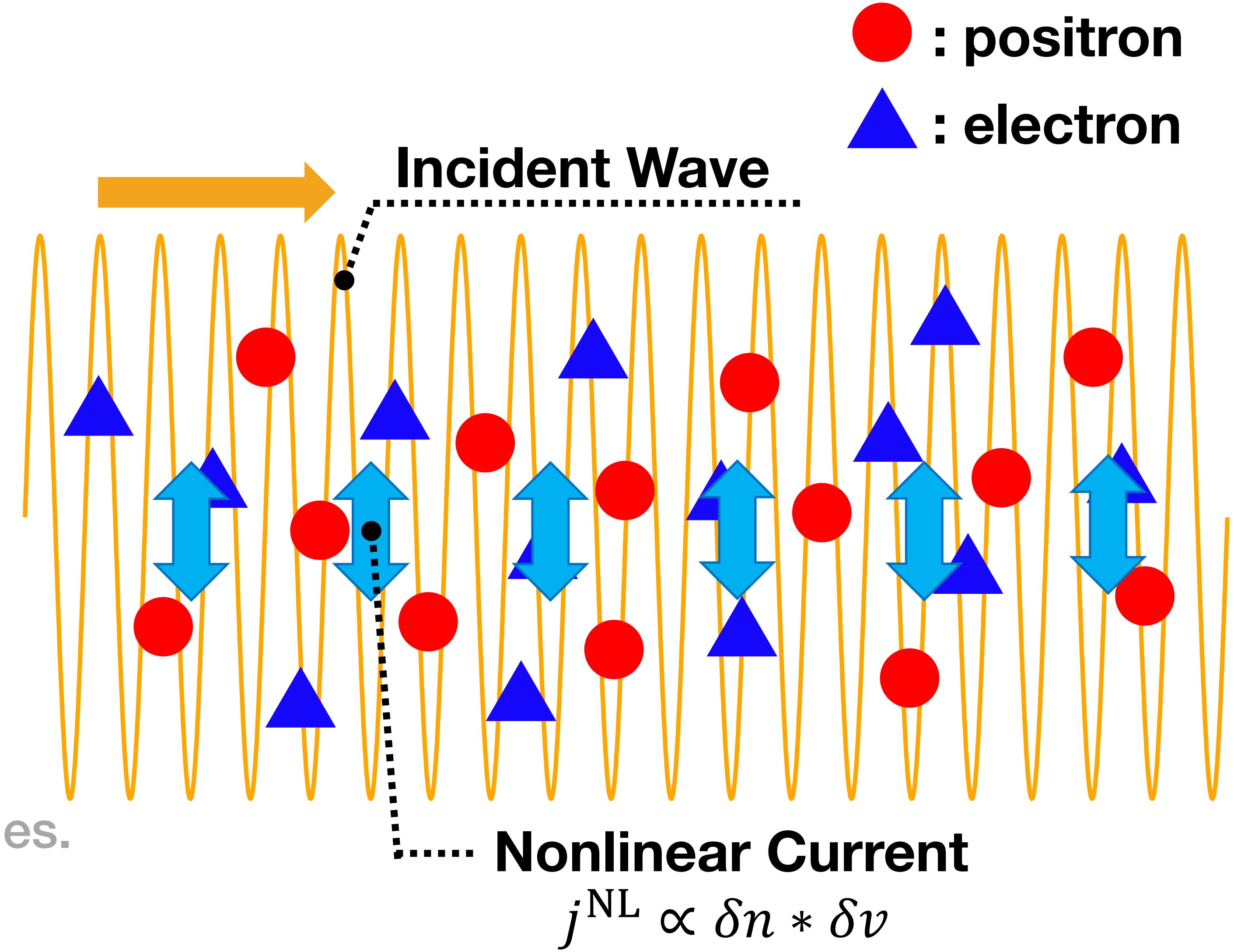
Particles oscillated by the incident wave make the nonlinear current.

The nonlinear current generates the scattered wave.

The beating wave between the incident and scattered waves is created.

The ponderomotive force acts on particles.

The density fluctuation is amplified.



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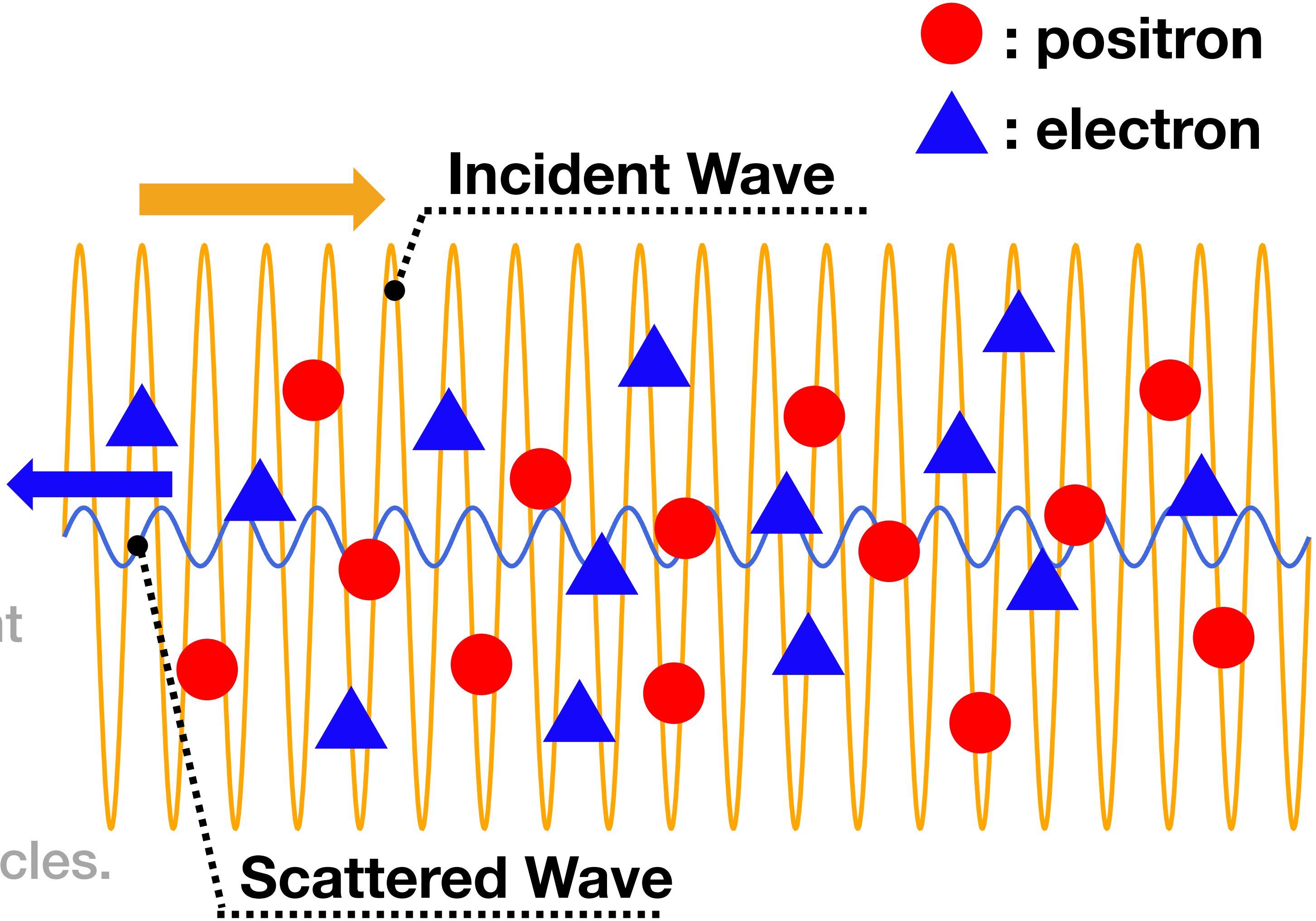

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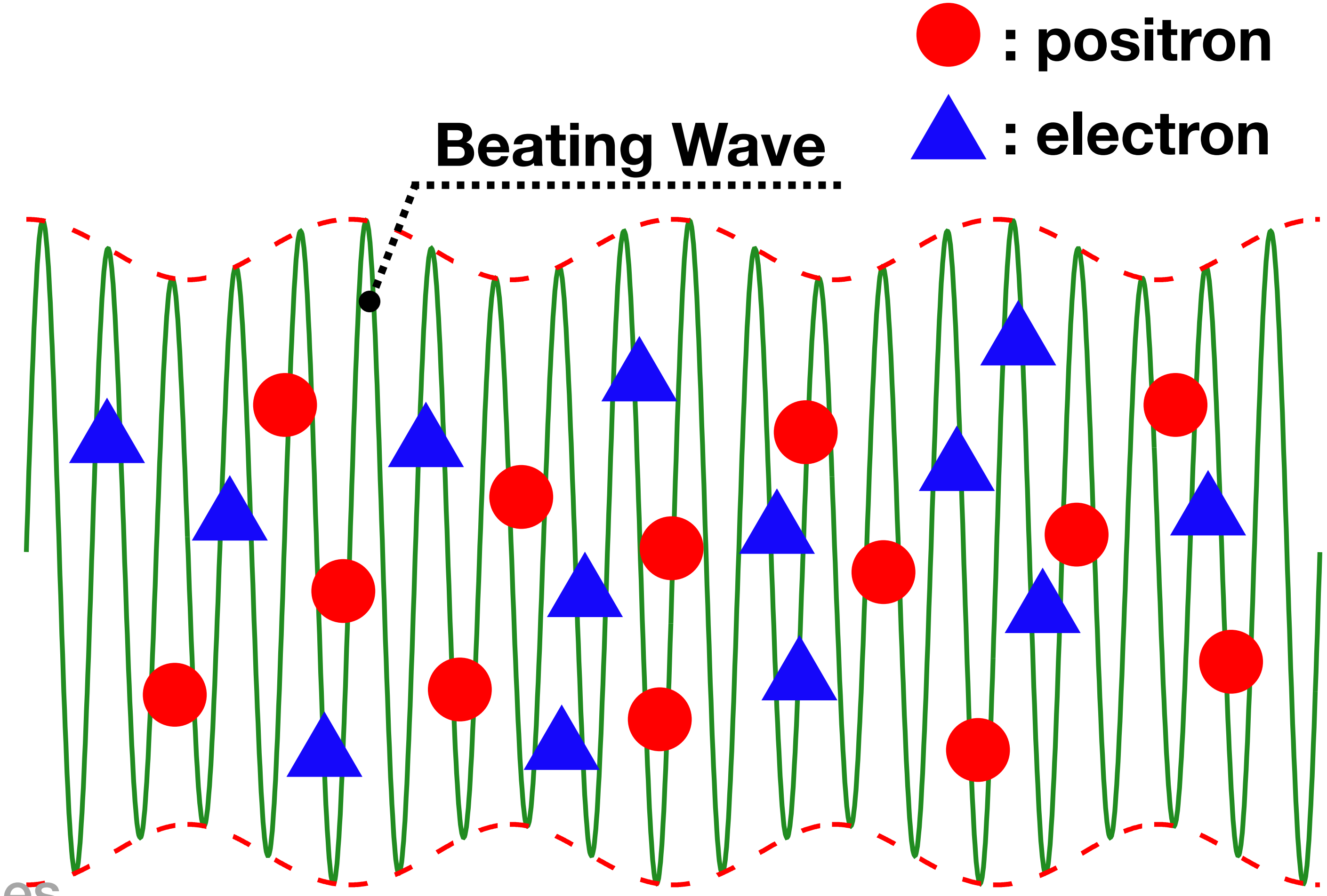

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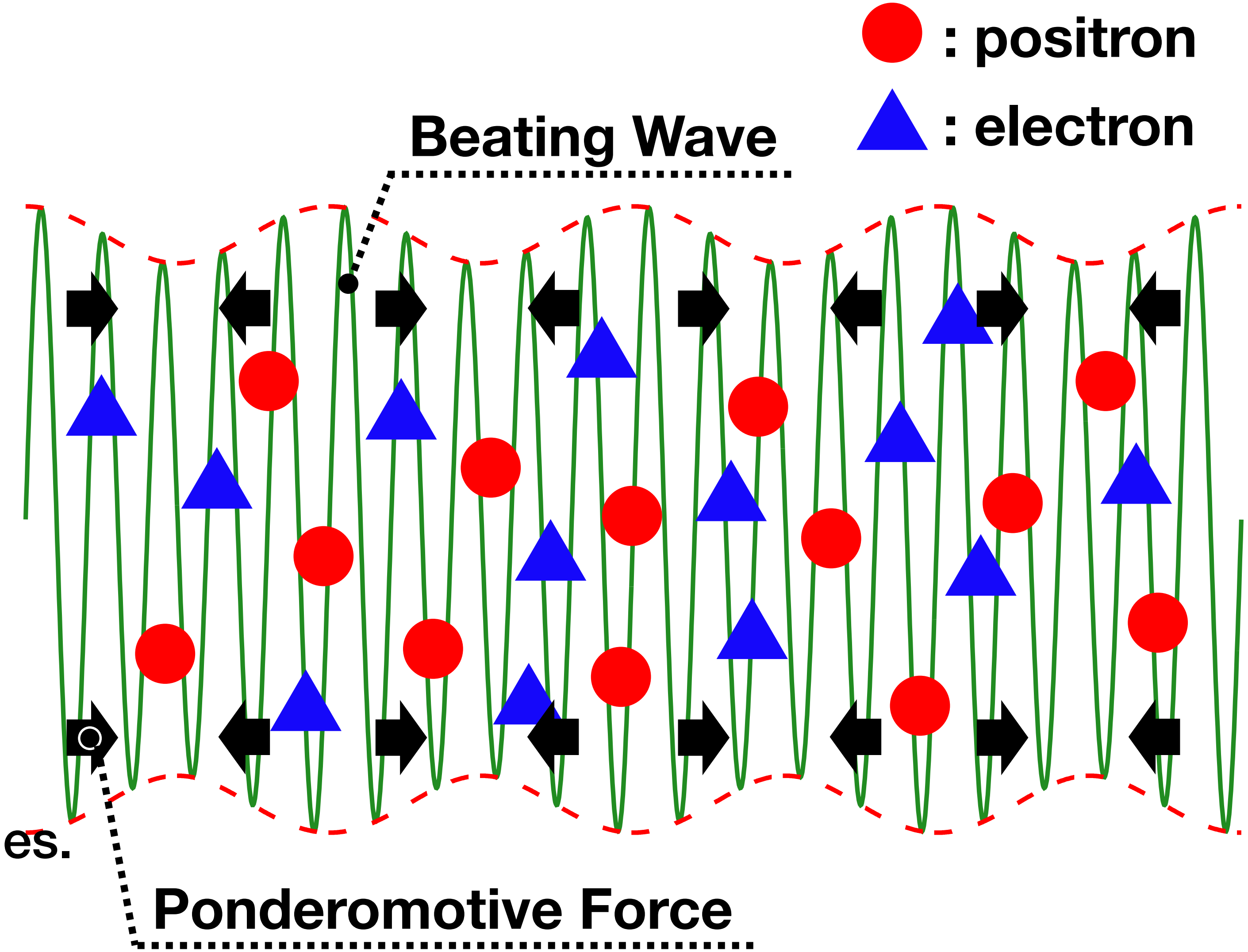

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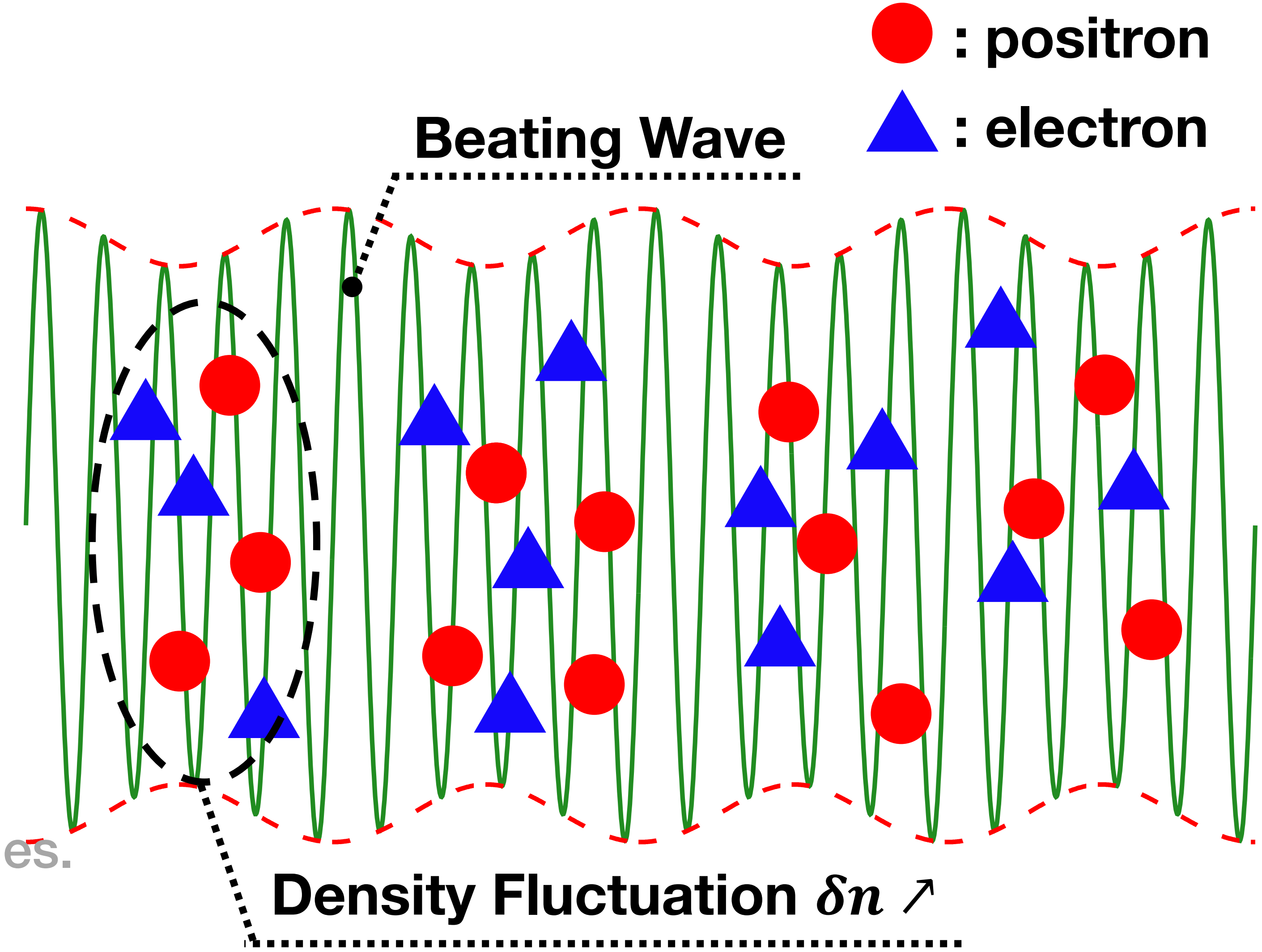

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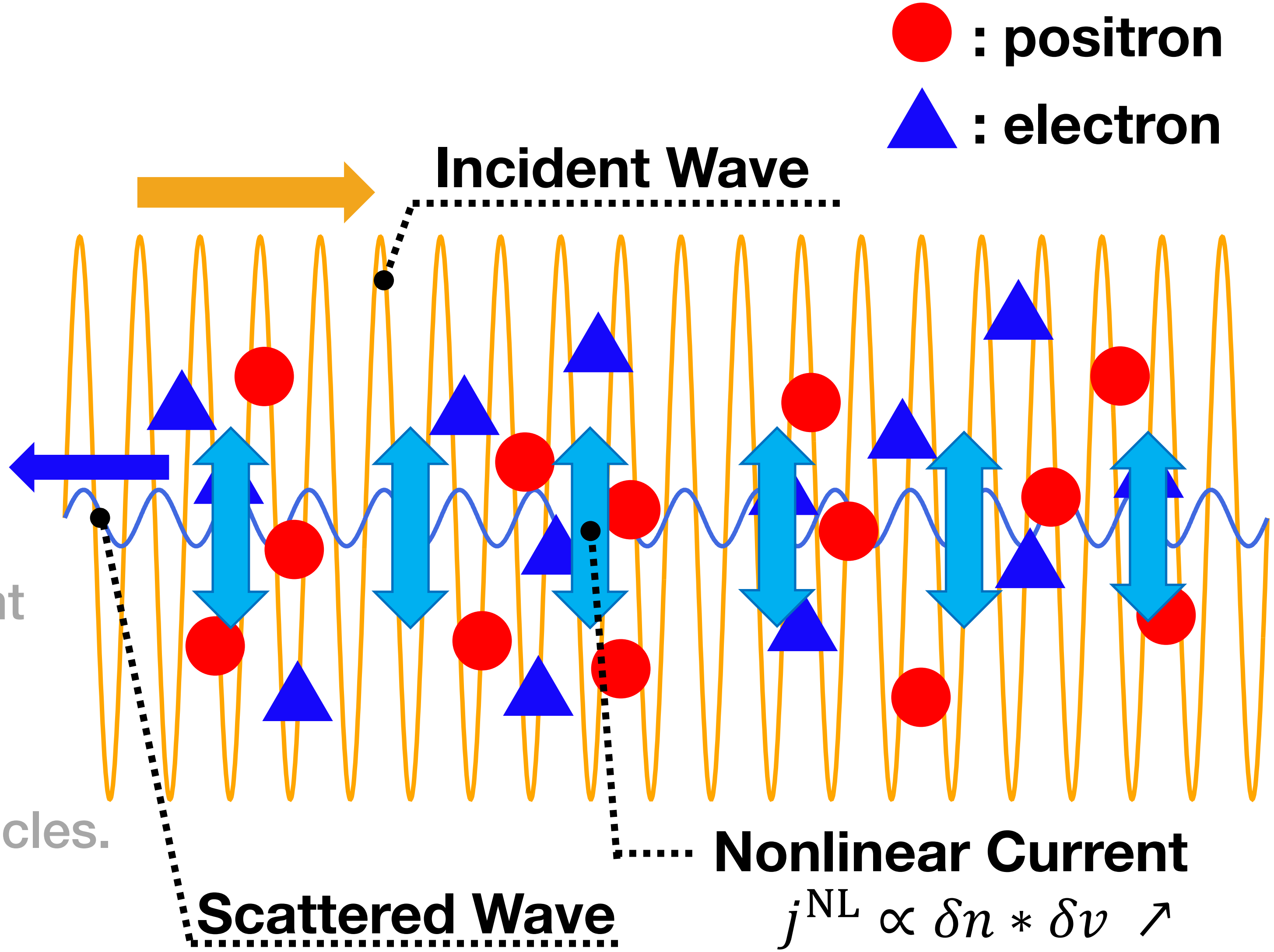

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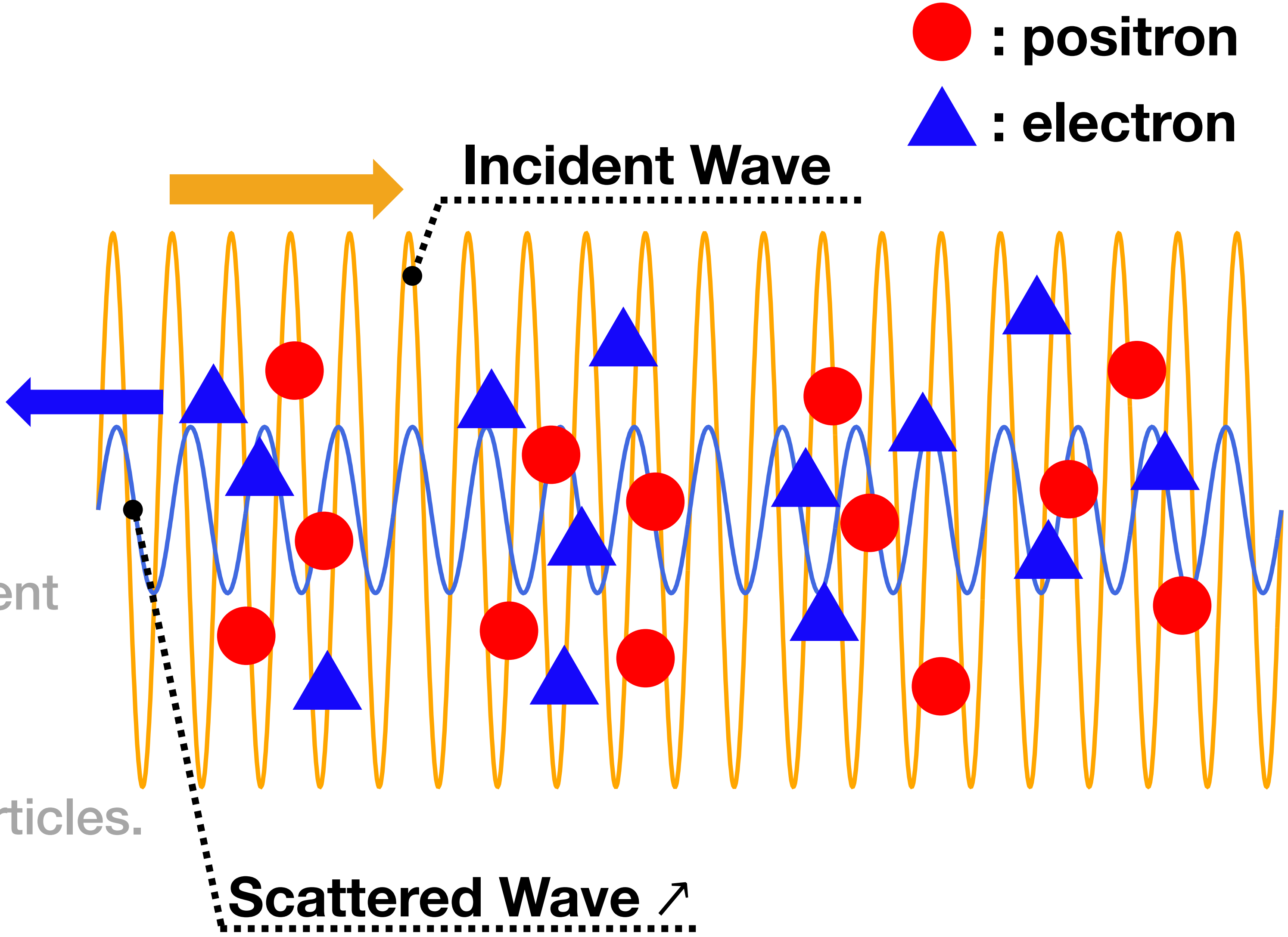

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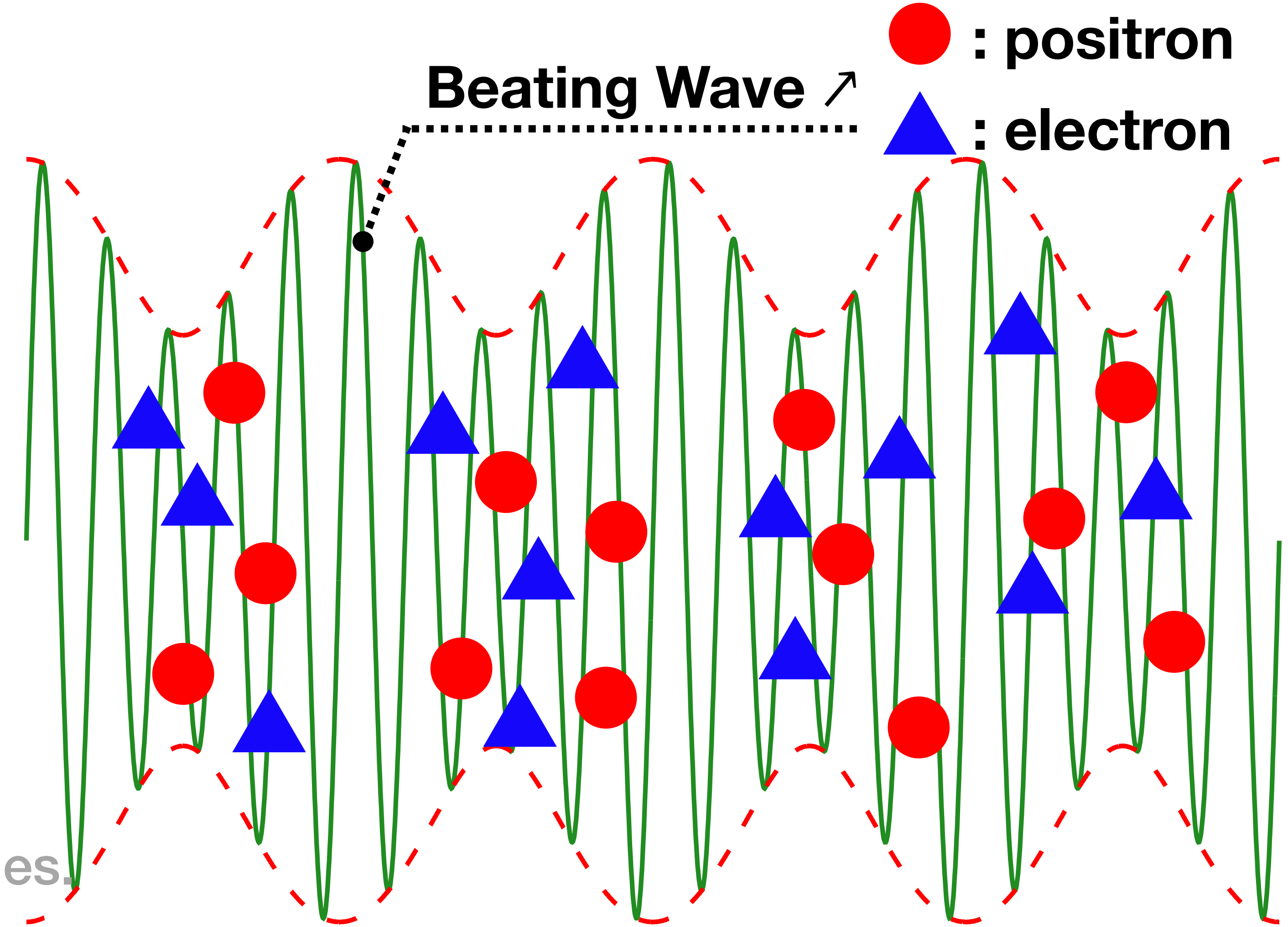

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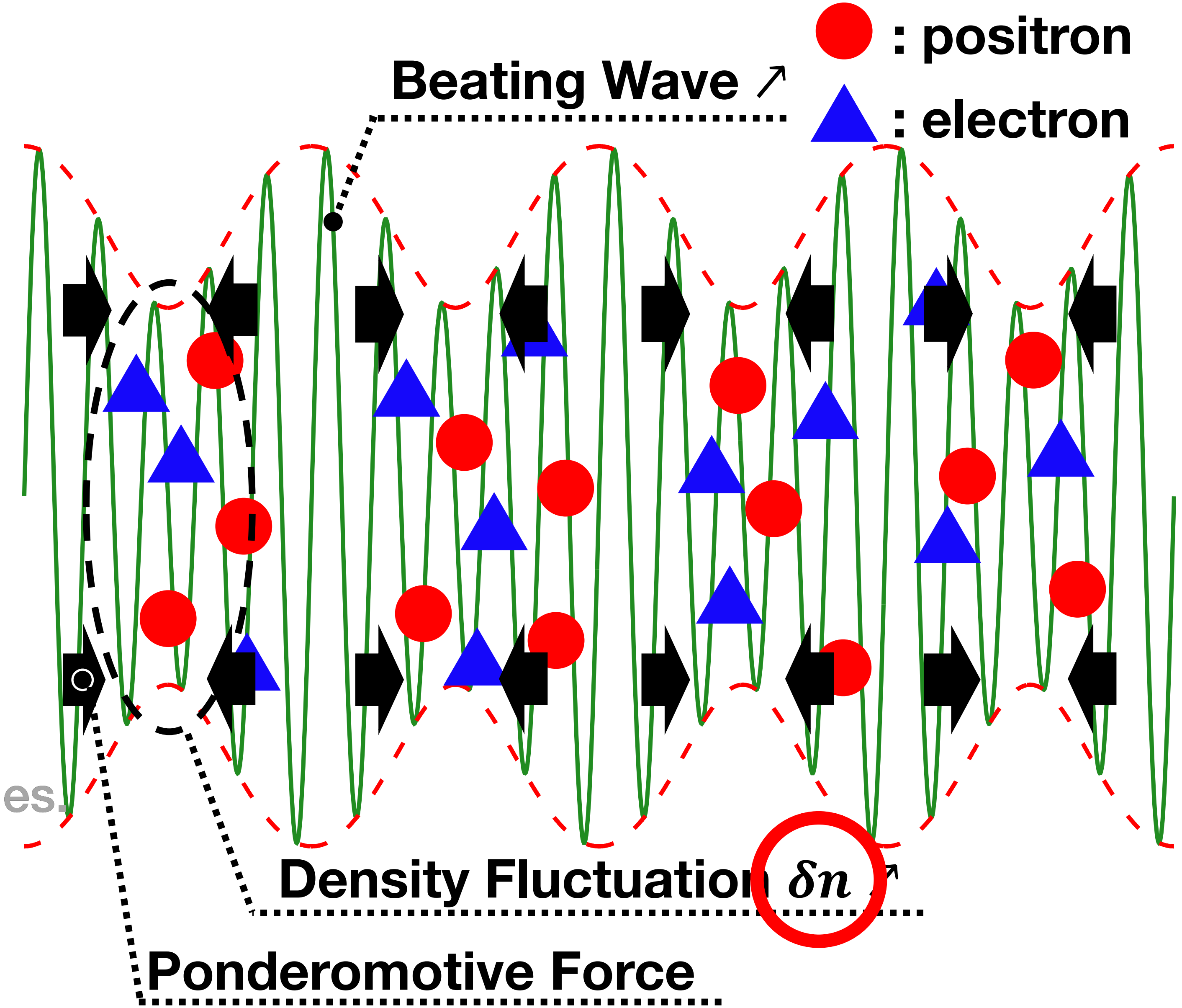


Ponderomotive Force in Magnetized Plasma

[e.g. Klima 1966, 1968, Lee & Parks 1983,1996]

$$\vec{F}_{\mathrm{pondero}} = -\frac{e^2}{4m}\nabla\left[-\frac{|E_x|^2+|E_z|^2}{\omega_c^2-\omega_0^2} \pm i\frac{\omega_c(E_z^* E_x - E_x^* E_z)}{\omega_0(\omega_c^2-\omega_0^2)}\right]$$

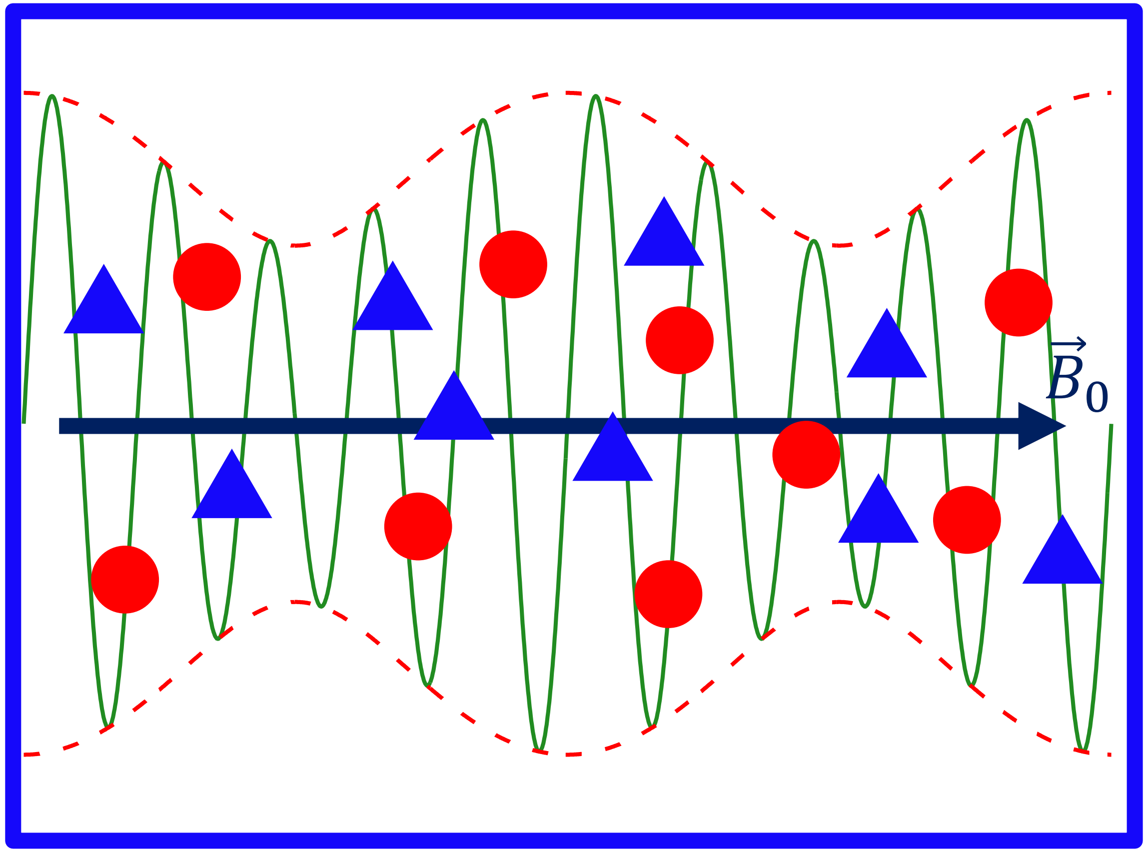
+ : positron
− : electron

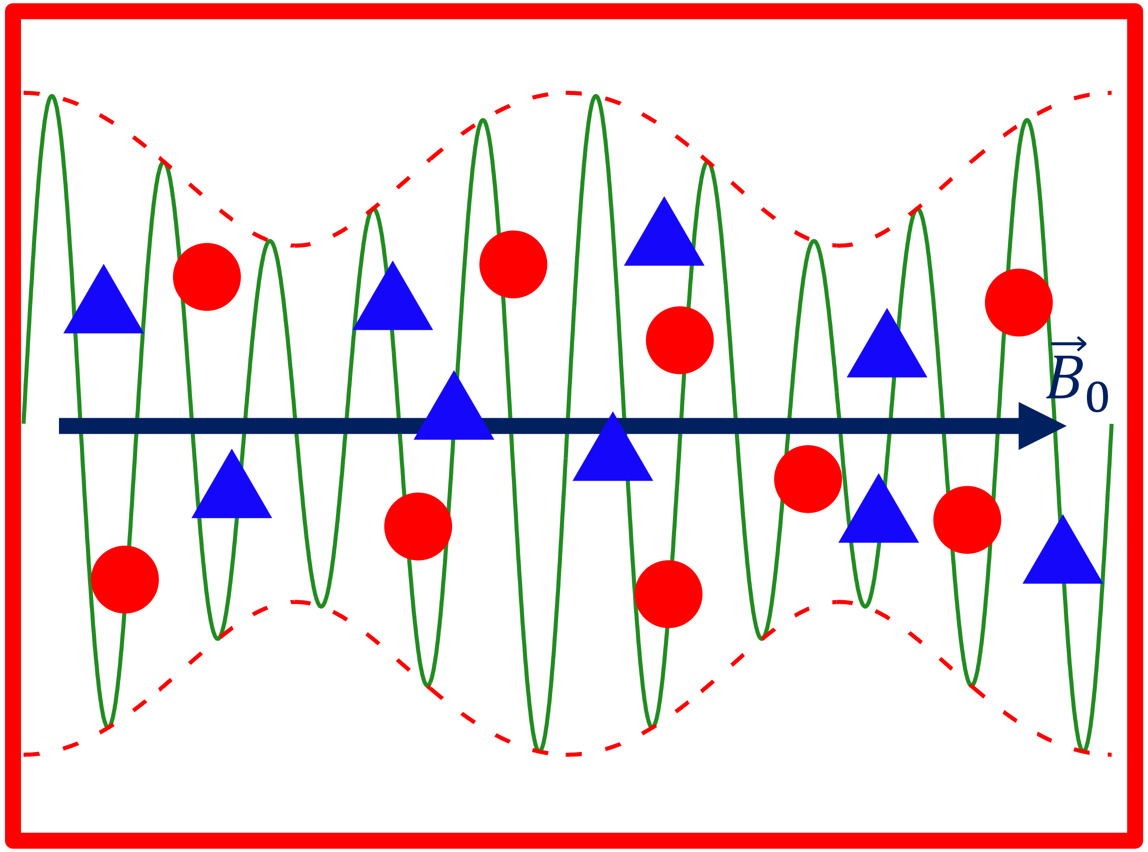
$\vec{B}_0, \vec{k}_0 \parallel y$

● : positron

▲ : electron

ω_c:cyclotron freq. > ω_0:incident wave freq.





Growth Rate in Magnetized Plasma

[Nishiura & Ioka 2024, Nishiura+ in prep.]

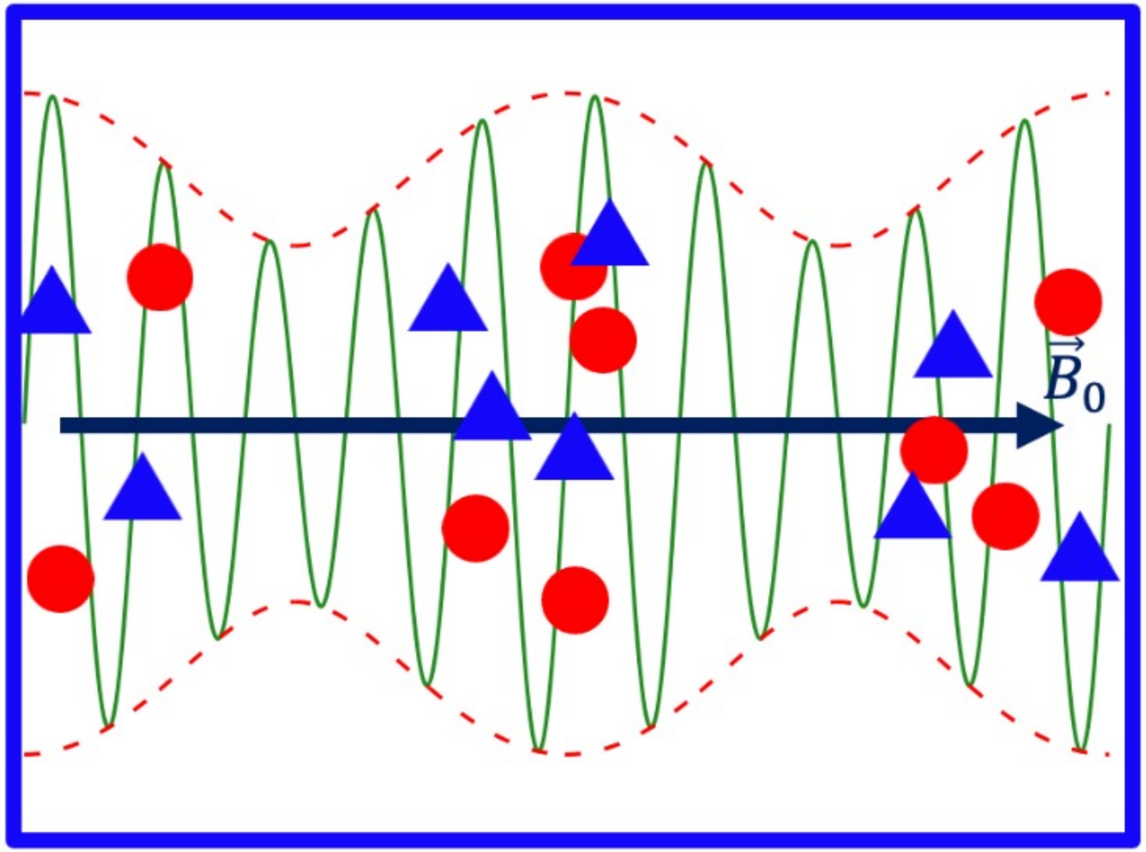
$$\Gamma^{\max}_{\mathrm{c,w/}\,B} = \Gamma^{\max}_{\mathrm{c,w/o}\,B}\ \max\left[\left(\frac{\omega_0}{\omega_c}\right)^4, \frac{32\mathrm{e}}{\pi}\left(\frac{\omega_0}{\omega_\mathrm{c}}\right)^2\left(\frac{\omega_0}{\omega_\mathrm{p}}\right)^4\left(\frac{k_\mathrm{B}T_\mathrm{e}}{m_\mathrm{e}c^2}\right)^2\right]$$

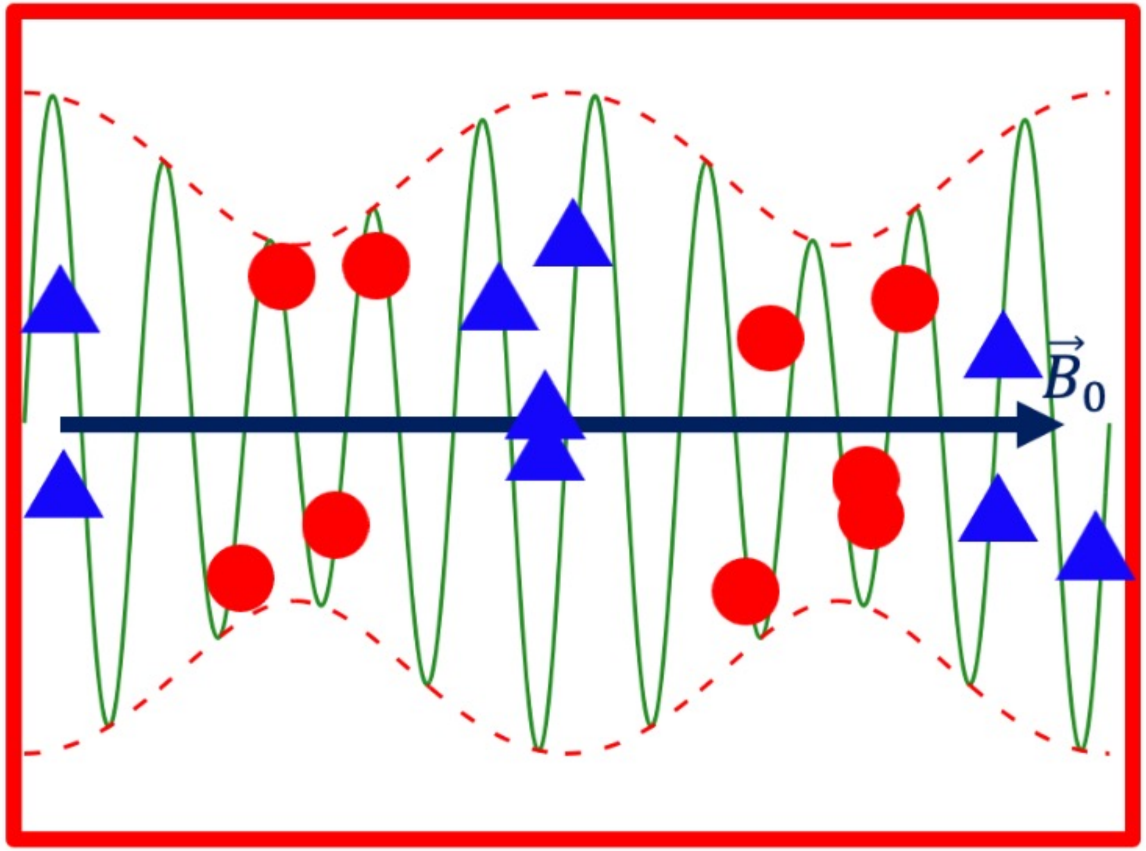
● : **Positron**

▲ : **Electron**

Neutral Mode **Charged Mode**

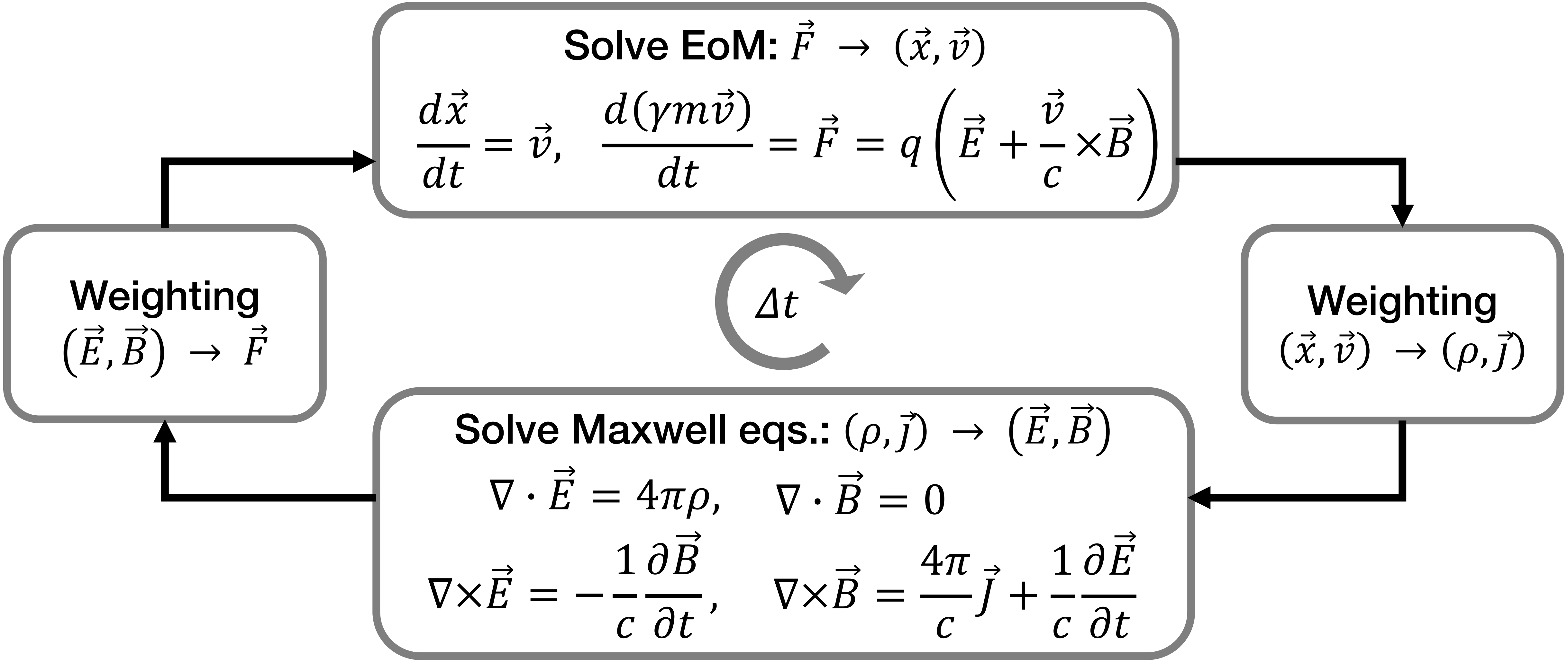
ω_c:cyclotron freq. > ω_0:incident wave freq.





Particle-in-Cell (PIC) Simulation

- WumingPIC2D [Matsumoto 2015]
- Flow (Nagoya U.), Yukawa-21 (YITP), XC50 (CfCA)



Setup

Red values are given by hands.

- mass ratio: $m_r = m_i/m_e = 1$ (e± plasma)
- ratio of plamsa freq. (ω_{pe}) & incident wave freq. (ω_0)

$$\frac{\omega_0}{\omega_{pe}} = 0.1, 0.9 \quad \left(\omega_0 \Delta t < \omega_{pe}\Delta t < \omega_c \Delta t = \sqrt{\sigma_e}\,\omega_{pe}\Delta t < 0.1\right)$$

- electron sigma parameter:

$$\sigma_e = \frac{B_0^2}{4\pi n_e m_e c^2} = 4, 100, 10000$$

- thermal velocities of e± plasma

$$\frac{v_{th,e}}{c} = \sqrt{\frac{k_B T_e}{m_e c^2}} = \frac{v_{th,i}}{c} = 0.03, 0.5$$

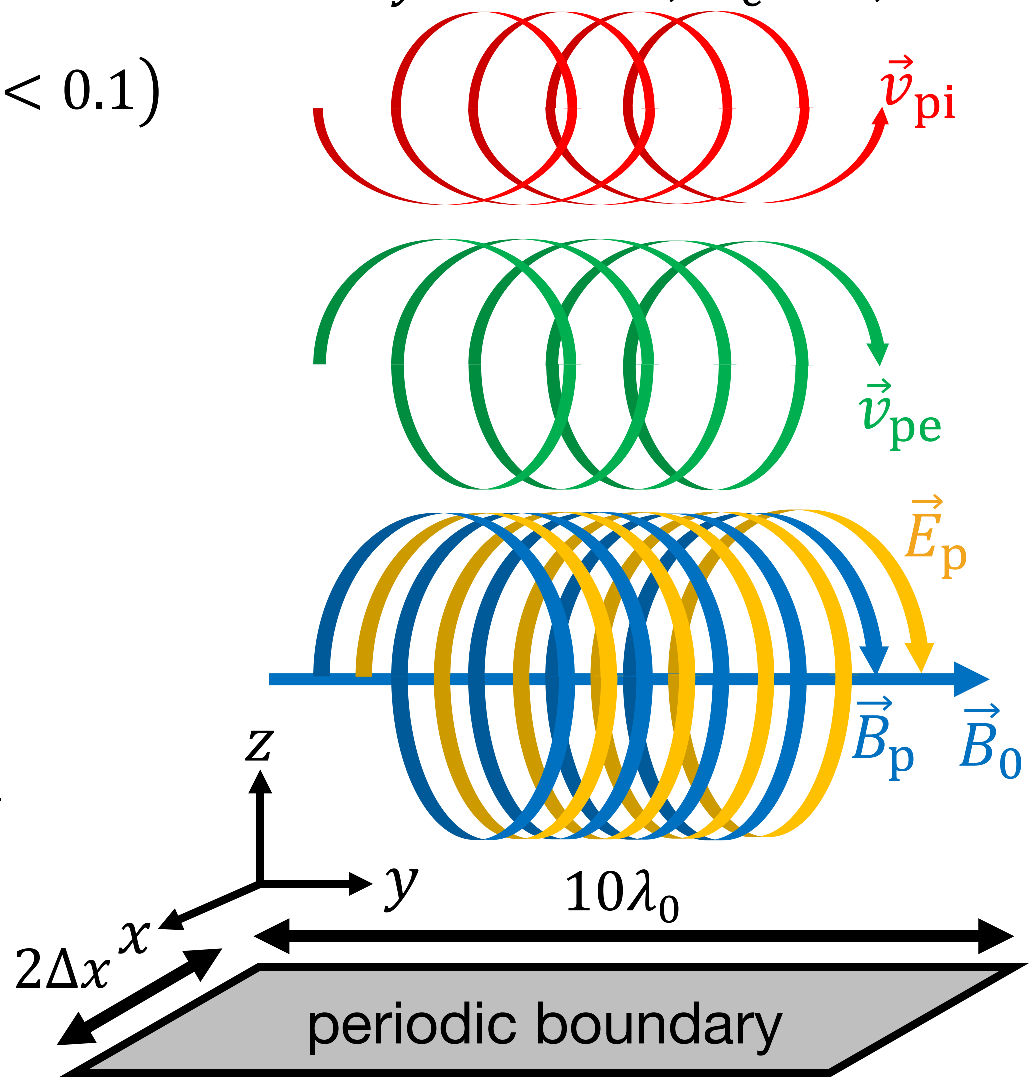
- ratio of incident wave amp.(B_p) & background B-field (B_0)

$$\eta = \frac{B_p}{B_0} \approx 0.0031 - 0.56$$

- The number of particles in each cell

$$n = 100\ /\mathrm{cell}$$

$\Delta x = \Delta y = \Delta t = 1, m_e = 1, c = 1$



Setup

Red values are given by hands.

$\Delta x = \Delta y = \Delta t = 1, m_{\mathrm{e}} = 1, c = 1$

◻ Right-handed circular pol. Alfvén wave (incident wave)

[Matsukiyo & Hada 03]

$$\vec{B}_{\mathrm{p}} = B_{\mathrm{p}}[-\sin\phi_0\,\hat{x} + \cos\phi_0\,\hat{z}], \phi_0 = k_0 y - \omega_0 t$$

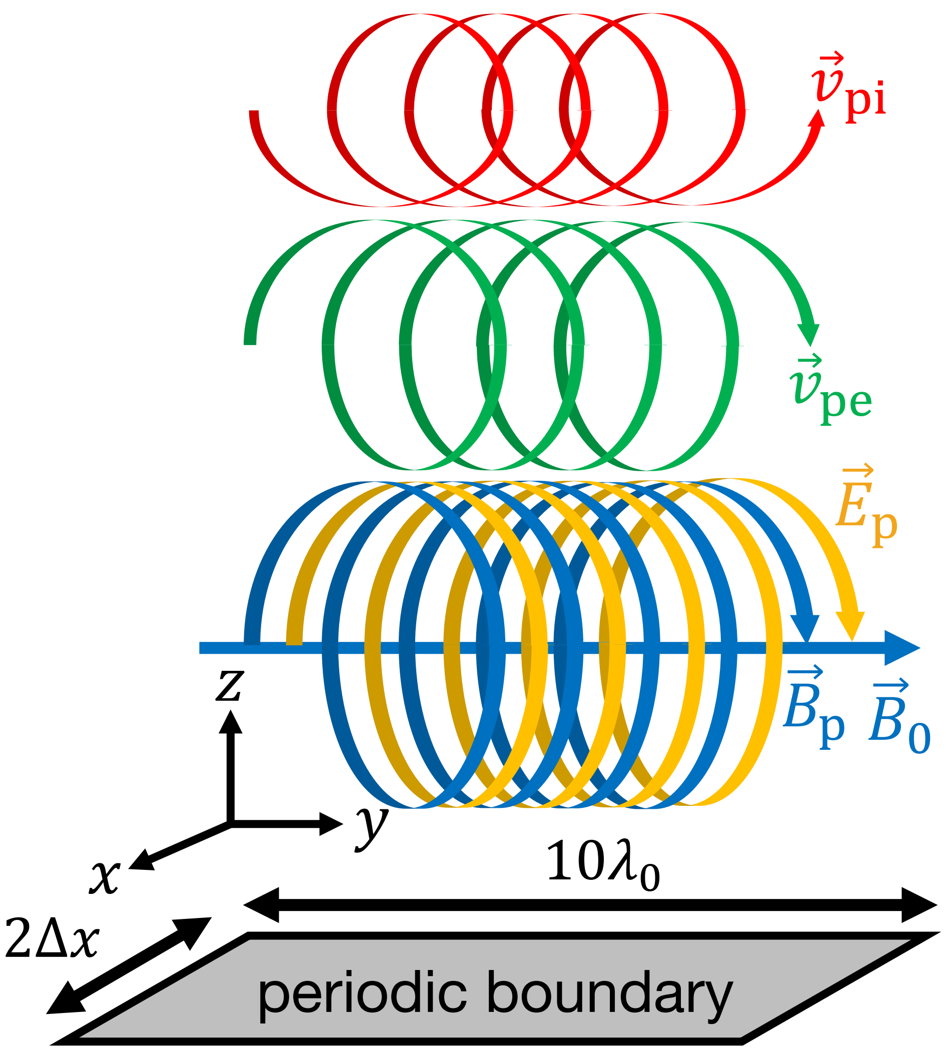
$$\vec{E}_{\mathrm{p}} = -\frac{\omega_0}{c k_0} B_{\mathrm{p}}[\cos\phi_0\,\hat{x} + \sin\phi_0\,\hat{z}] \qquad \eta = B_{\mathrm{p}}/B_0$$

$$\left(\frac{c k_0}{\omega_0}\right)^2 = 1 + \frac{\omega_{\mathrm{pe}}^2}{\omega_0(\gamma_{\mathrm{e}}\omega_0 - \omega_{\mathrm{c}})} + \frac{\omega_{\mathrm{pi}}^2}{\omega_0(\gamma_{\mathrm{i}}\omega_0 + \omega_{\mathrm{c}})}$$

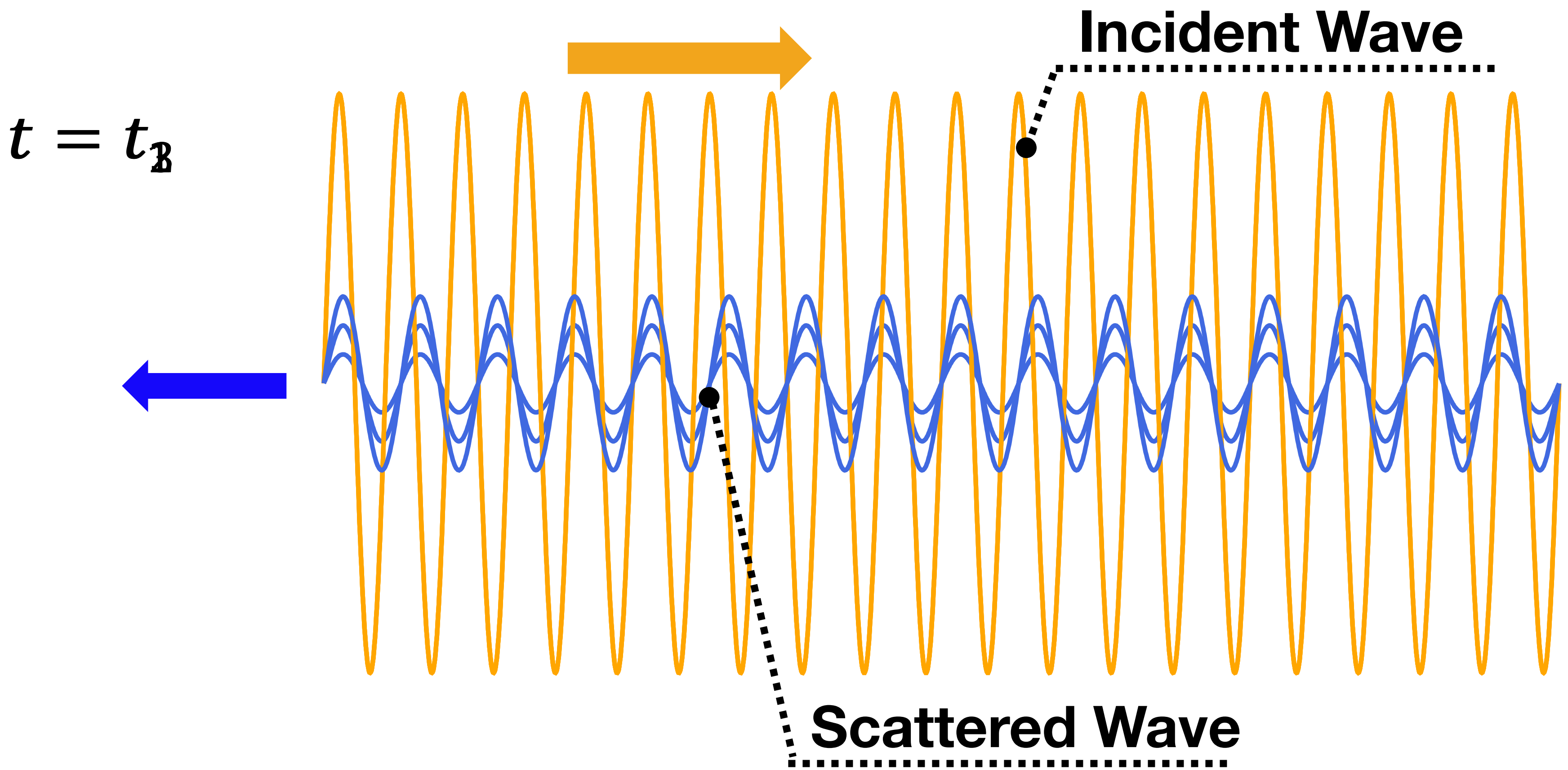
◻ initial e± plasma velocity

$$\frac{\vec{v}_{\mathrm{e}}}{c} = \frac{\omega_0}{c k_0}\frac{\eta\omega_{\mathrm{c}}}{\gamma_{\mathrm{e}}\omega_0 - \omega_{\mathrm{c}}}\frac{\vec{B}_{\mathrm{p}}}{B_{\mathrm{p}}} \qquad \frac{\vec{v}_{\mathrm{i}}}{c} = -\frac{\omega_0}{c k_0}\frac{\eta\omega_{\mathrm{c}}}{\gamma_{\mathrm{i}}\omega_0 + \omega_{\mathrm{c}}}\frac{\vec{B}_{\mathrm{p}}}{B_{\mathrm{p}}}$$

$$\gamma_{\mathrm{e(i)}} = \frac{1}{\sqrt{1 - \left(\frac{v_{\mathrm{e(i)}}}{c}\right)^2}}$$



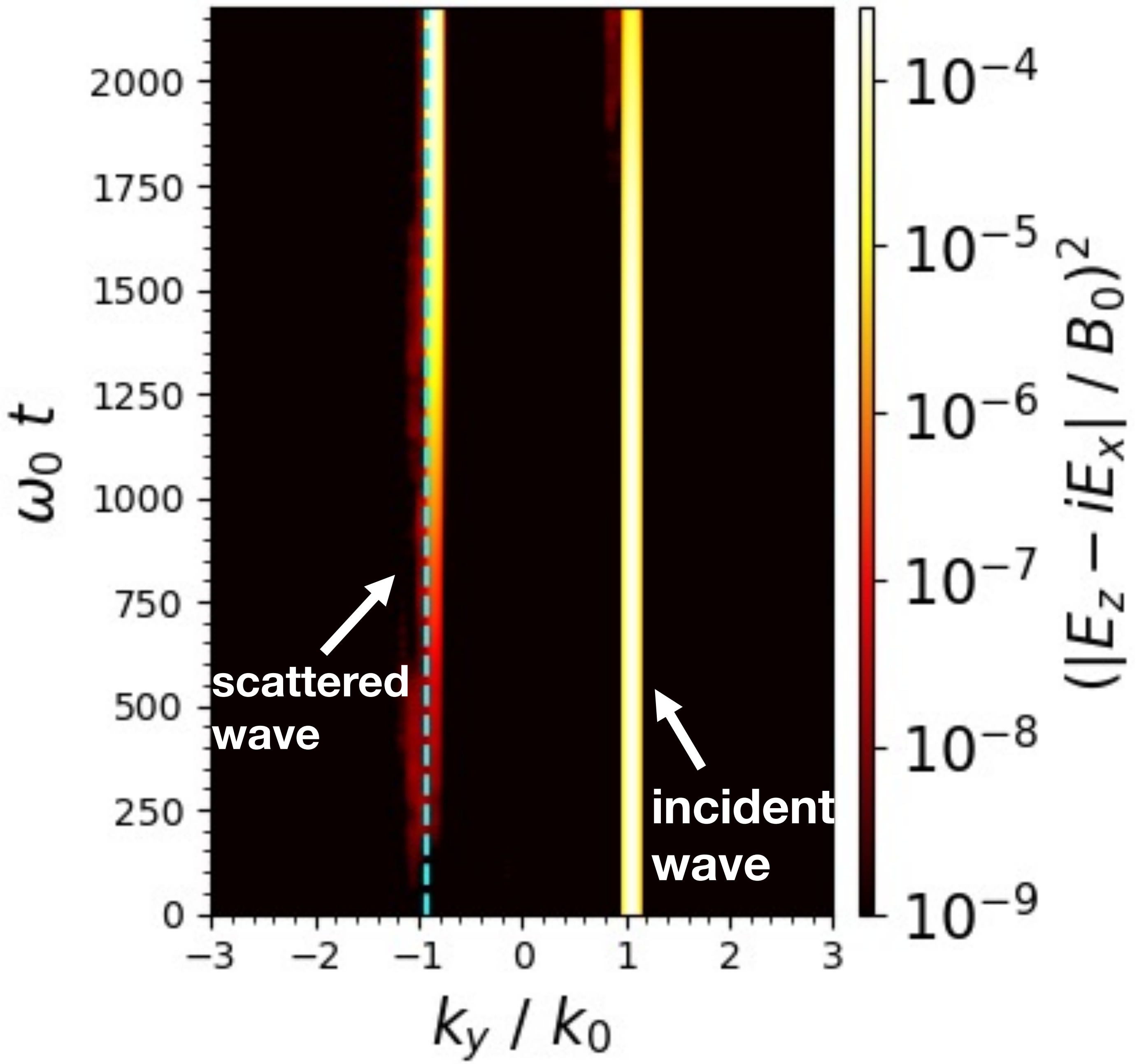
Wave Decomposition



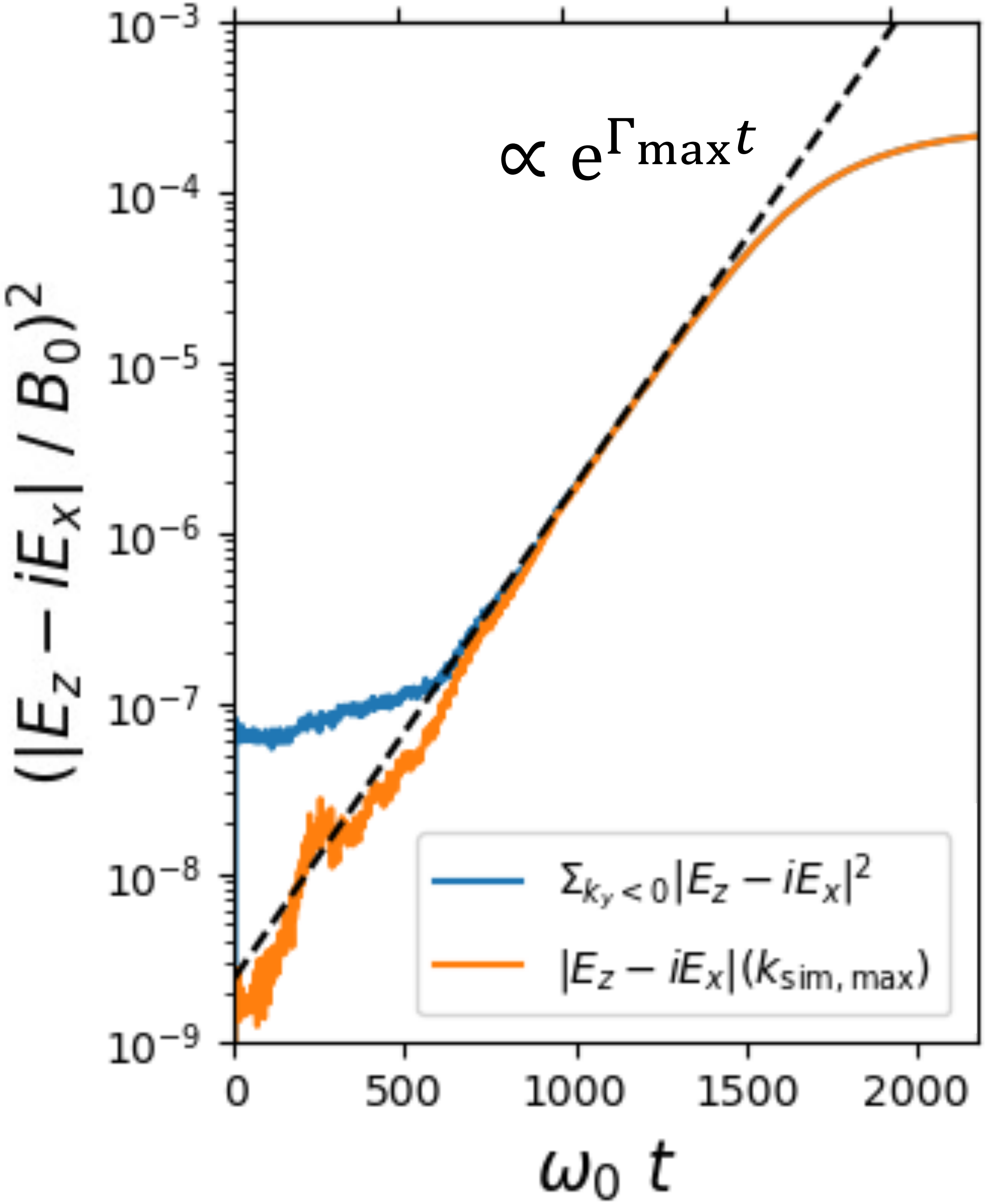
The growth rate is estimated from the time evolution of the power (or amplitude) of the scattered wave.

We decompose the forward propagating incident wave and the backward propagating scattered wave from the snapshot data.

Results



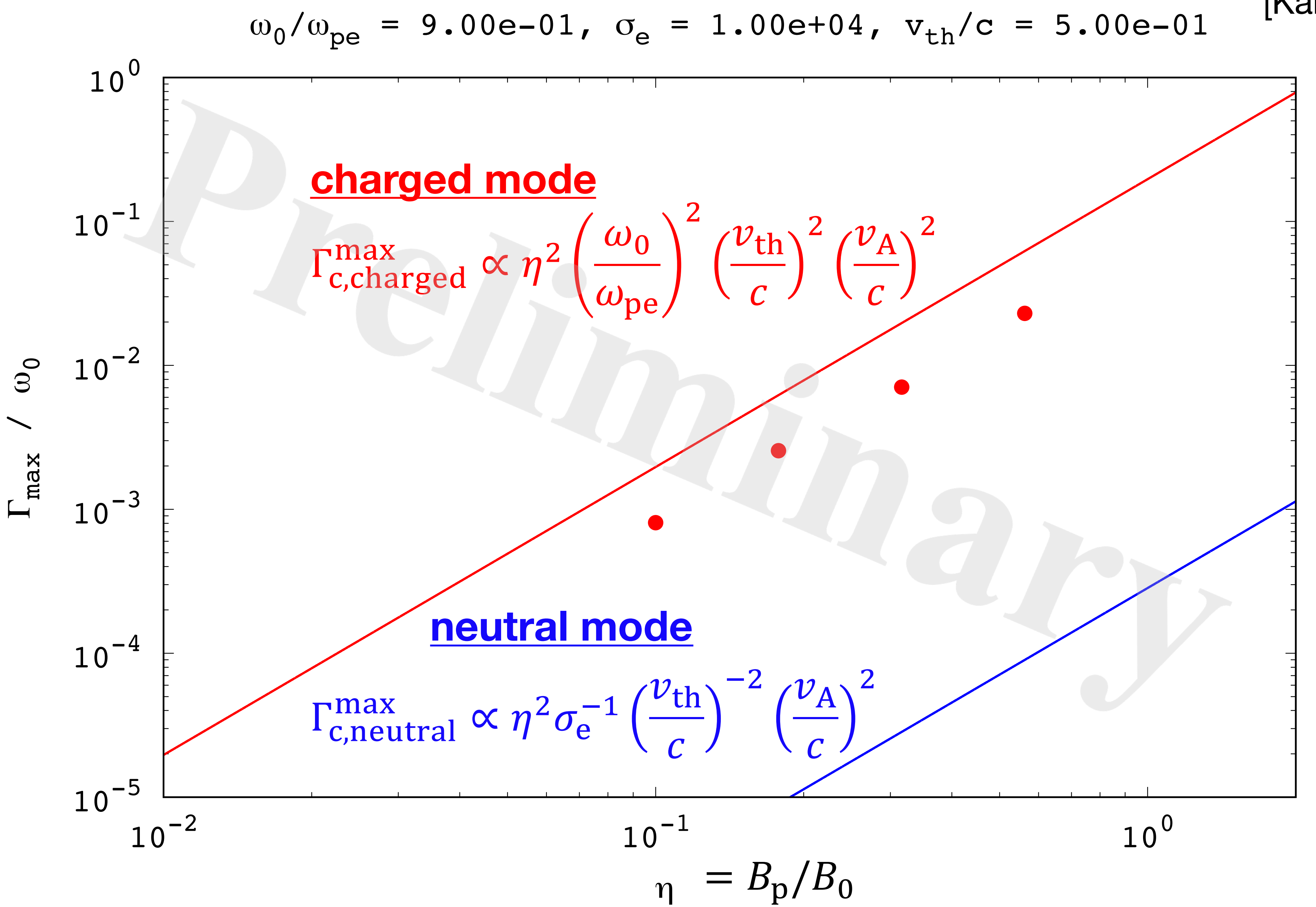
$\omega_0\, t$
scattered wave
incident wave
$k_y\, /\, k_0$
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
$(|E_z - iE_x|\, /\, B_0)^2$



$\propto e^{\Gamma_{\max} t}$
$(|E_z - iE_x|\, /\, B_0)^2$
$\Sigma_{k_y<0}|E_z - iE_x|^2$
$|E_z - iE_x|(k_{\mathrm{sim,\,max}})$
$\omega_0\, t$

Charged Mode

[Kamijima+ in perp.]



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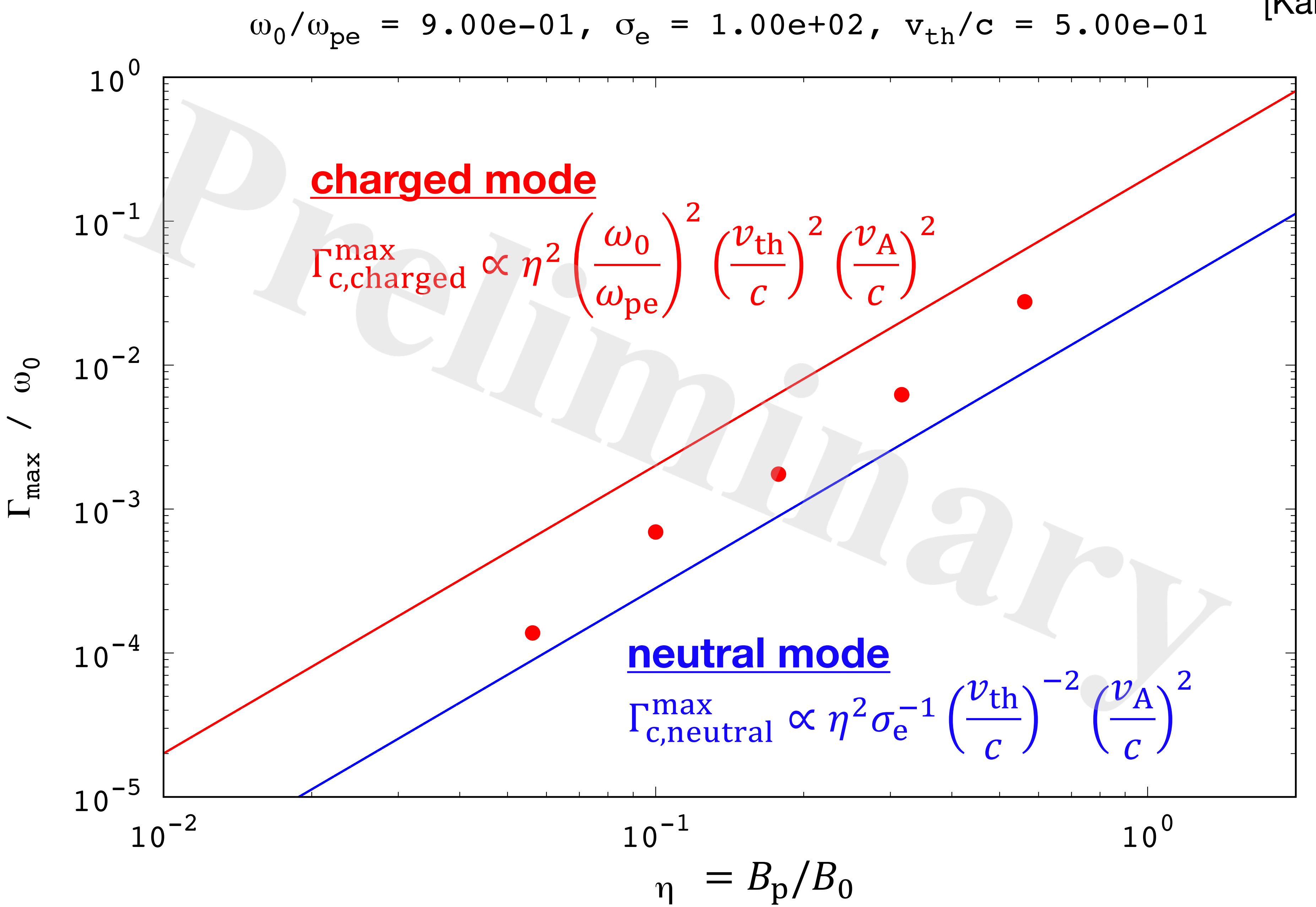
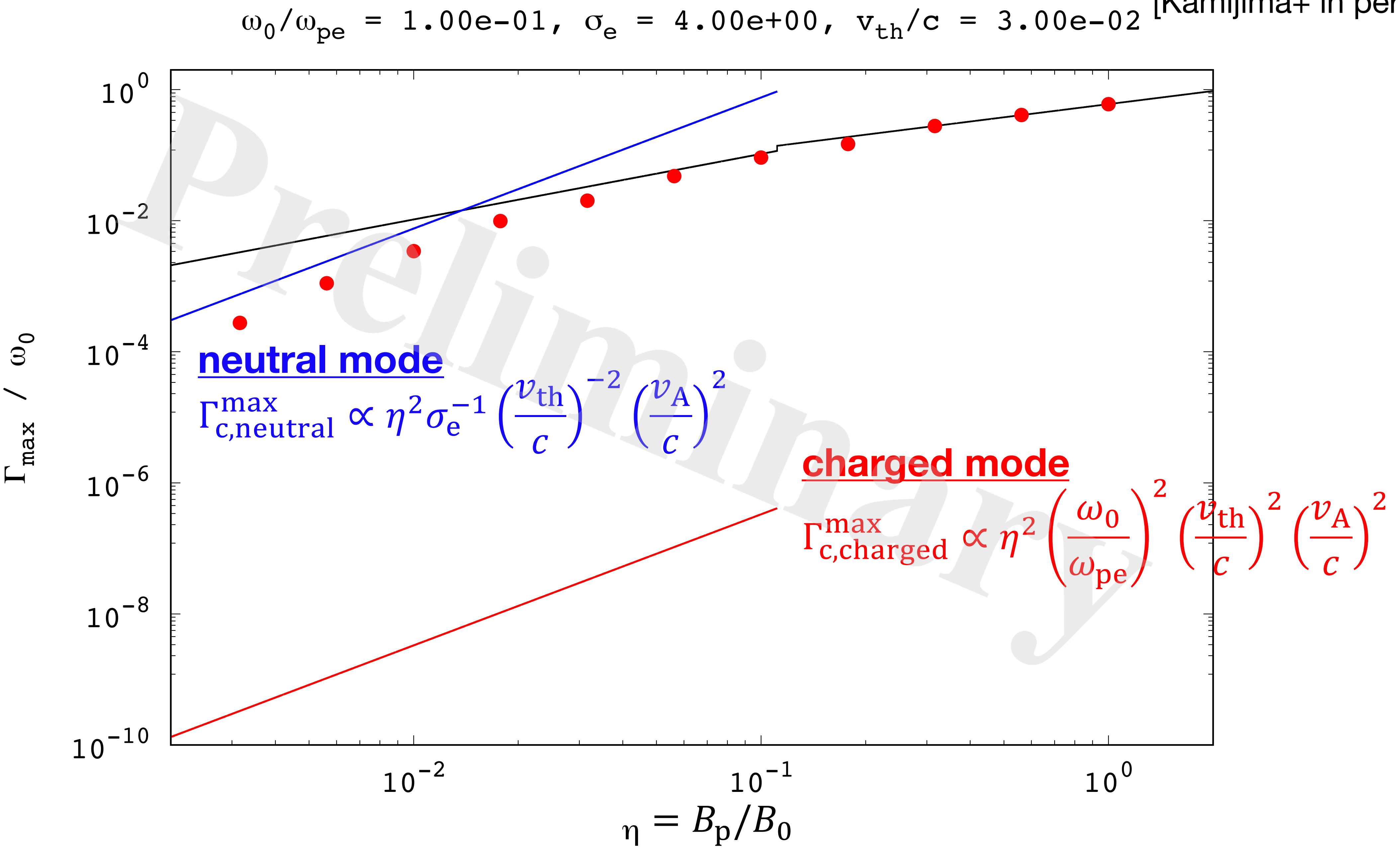


Neutral Mode

[Kamijima+ in perp.]



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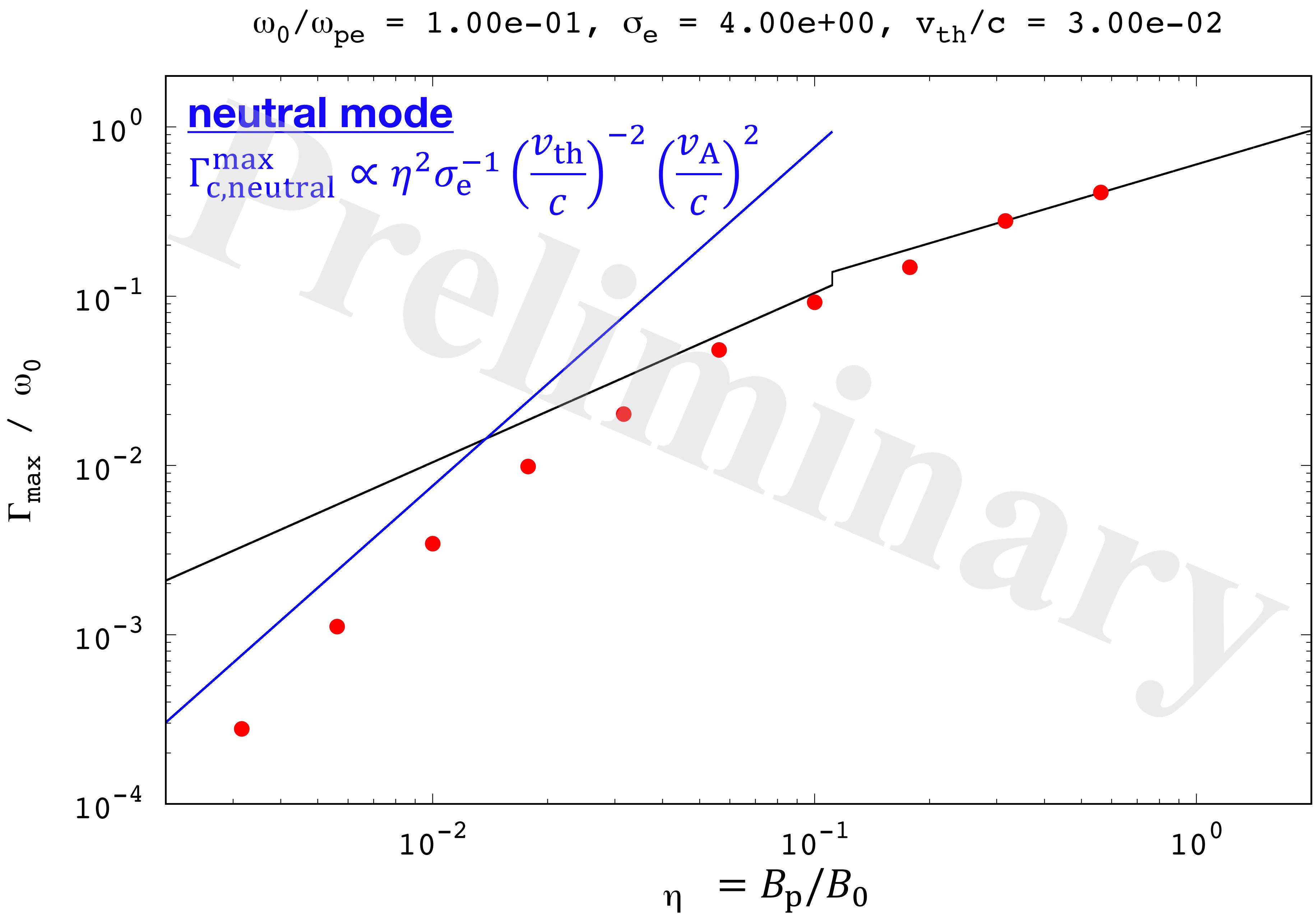
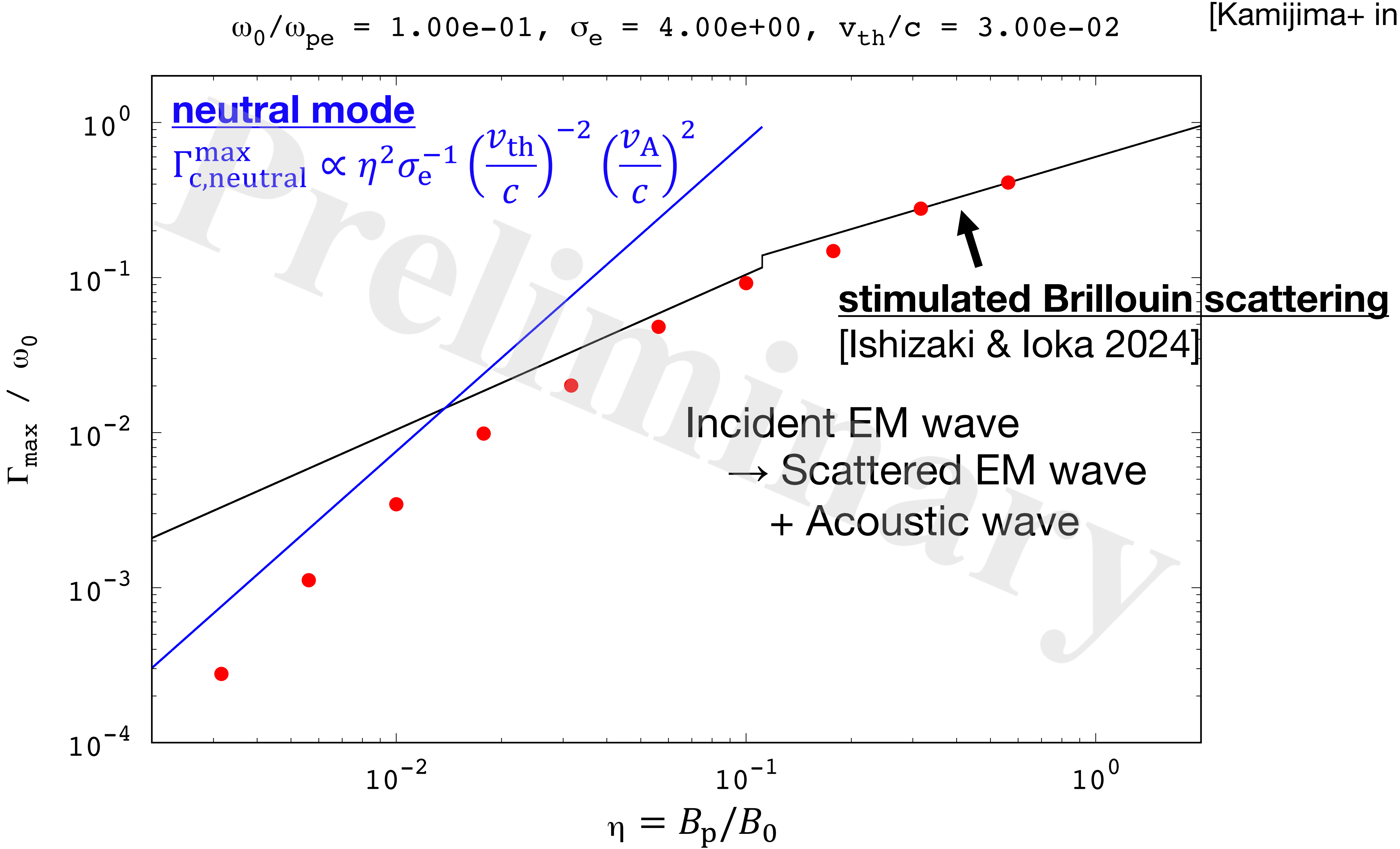


Neutral Mode vs. Stimulated Brillouin Scattering

[Kamijima+ in perp.]



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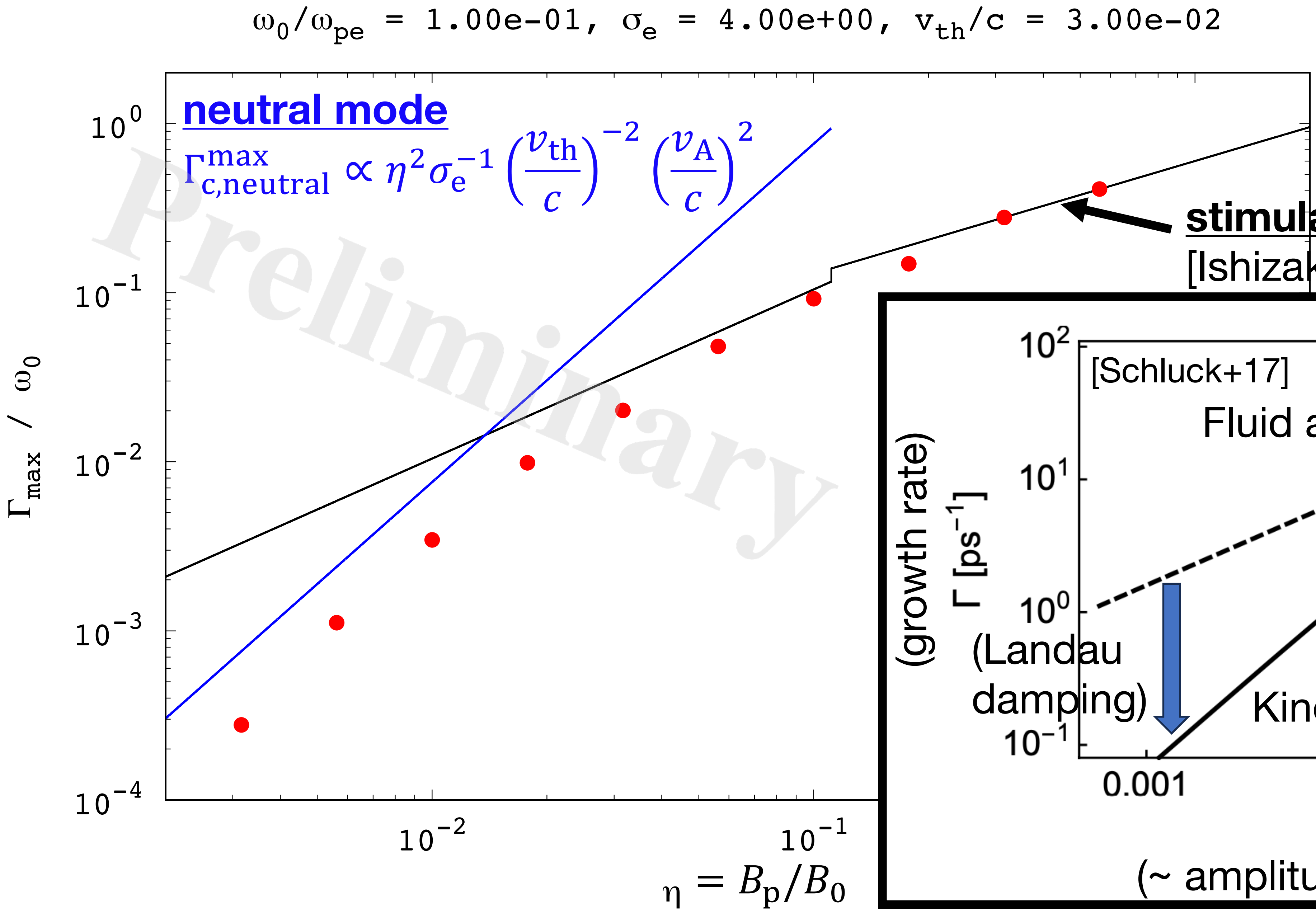
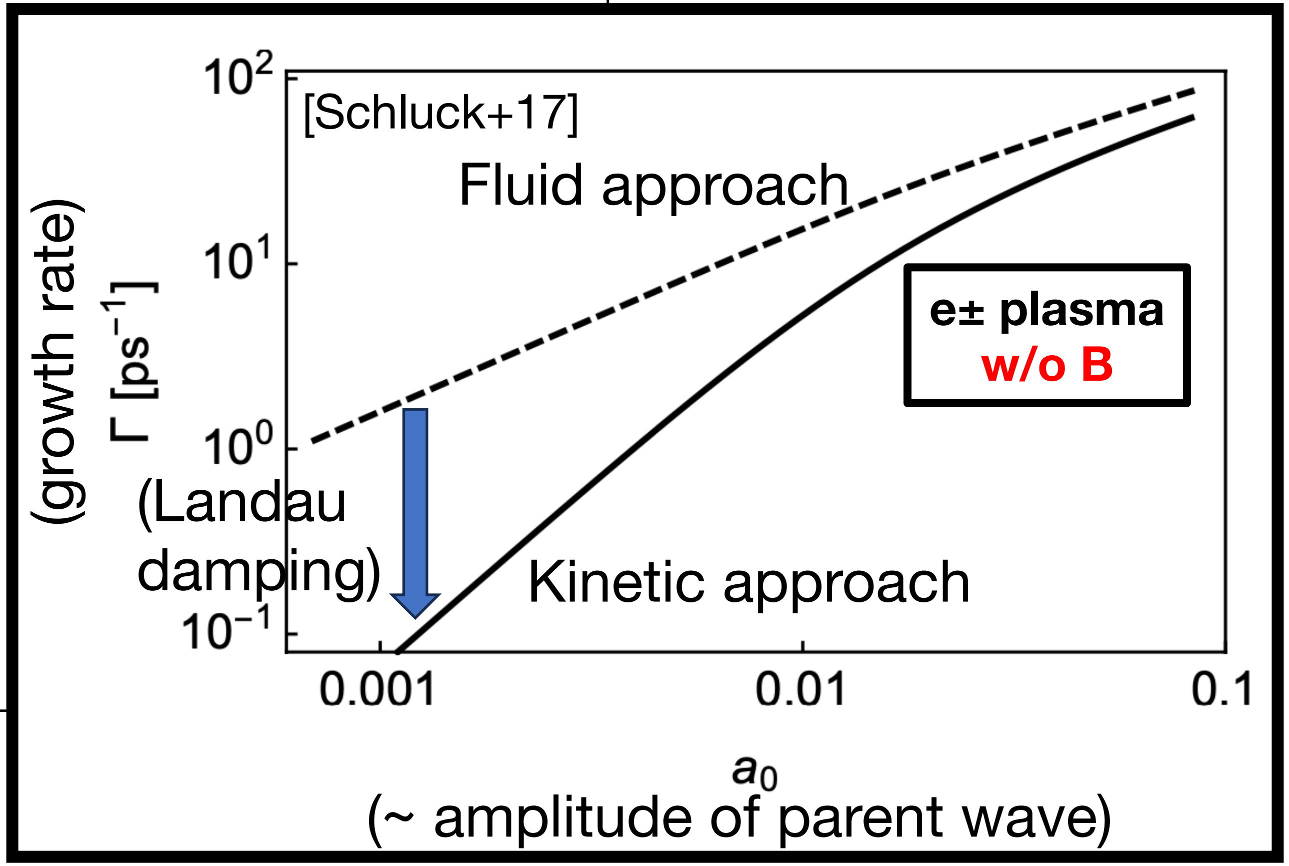


stimulated Brillouin scattering
[Ishizaki & Ioka 2024]



Summary & Future Work

- We investigate propagation of Alfvén waves in magnetized pair plasma by using Particle-in-Cell simulations.

- Simulation results are almost in good agreement with the theoretical growth rate of induced Compton scatterings and stimulated Brillouin scatterings.

- Incident wave: plane wave -> pulse, circular pol. -> linear pol.

- We will investigate the nonlinear phase.

- Dependency of other parameters.