磁化された電子陽電子プラズマ中における誘導散乱のプラズマ粒子シミュレーション

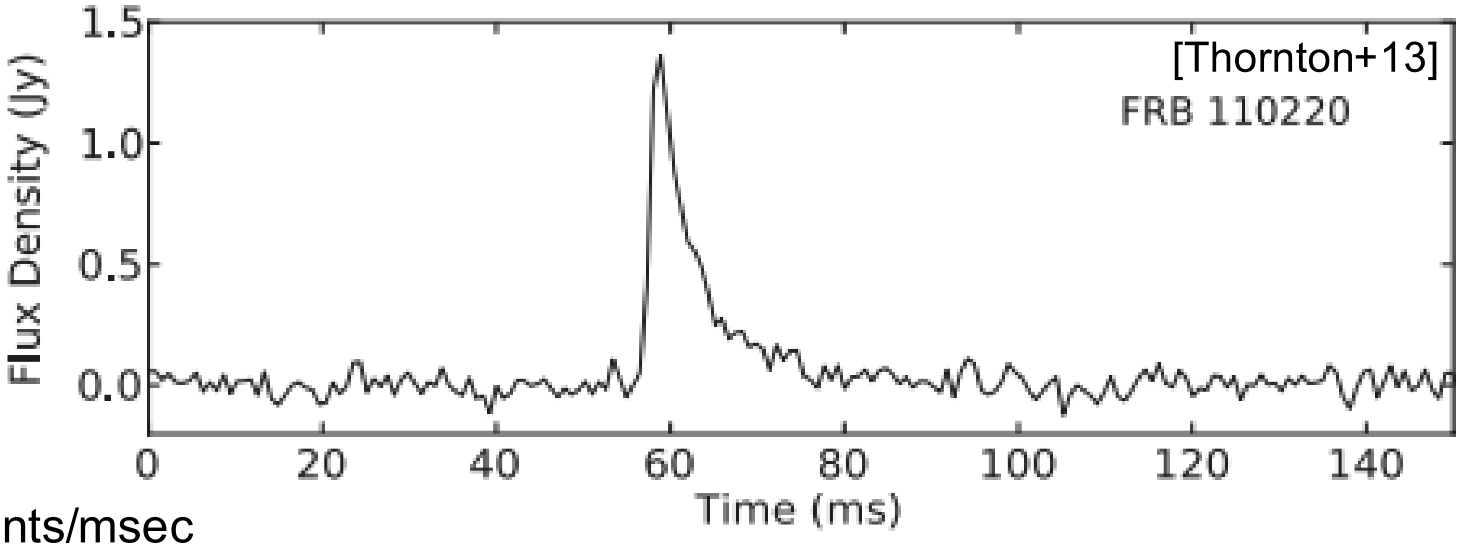
Shoma F. Kamijima（YITP）

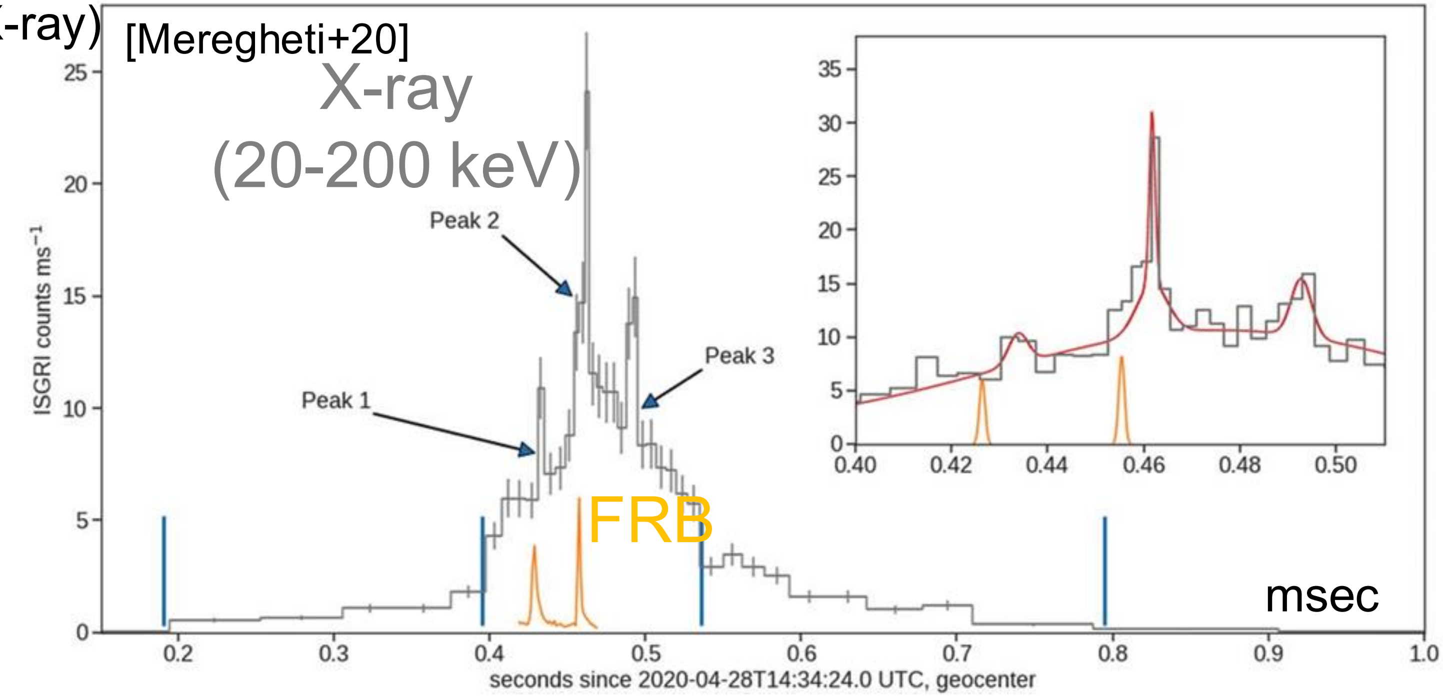
Collaborator: Rei Nishiura(Kyoto U.), Wataru Ishizaki(Tohoku U.), Masanori Iwamoto(YITP), Kunihito Ioka (YITP)

Fast Radio Burst (FRB)

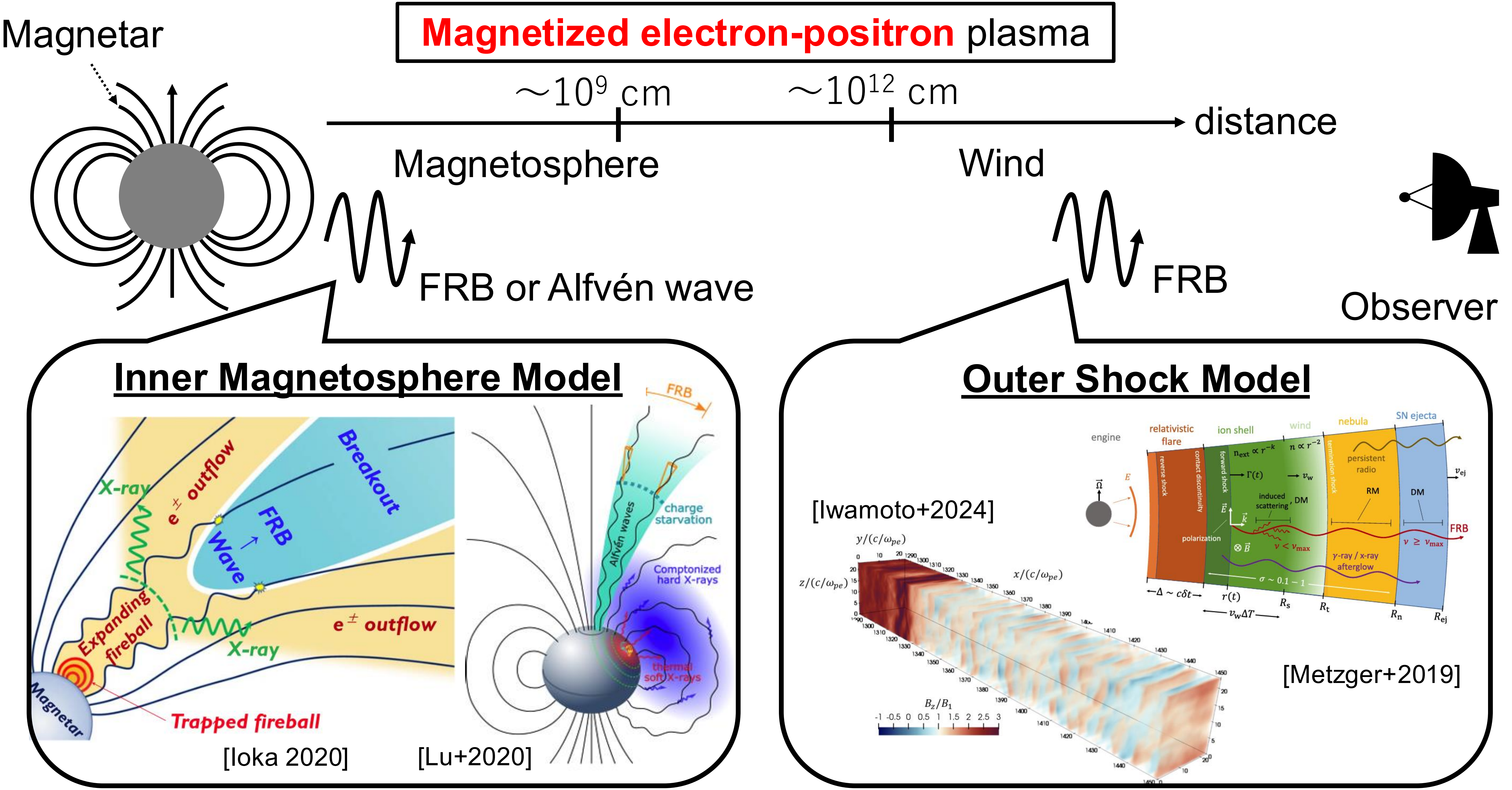
- Most luminous radio transient
- Large dispersion measure
  → Cosmological
- Frequency: $\nu \sim \mathcal{O}(\mathrm{GHz})$
- Duration: $\Delta t \sim \mathcal{O}(\mathrm{msec})$
- Flux density: $S_\nu \sim \mathcal{O}(\mathrm{Jy})$ @GHz
- High Brightness temperature:
  → Coherent emission
- FRB from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

One of the origins of FRBs is a magnetar.

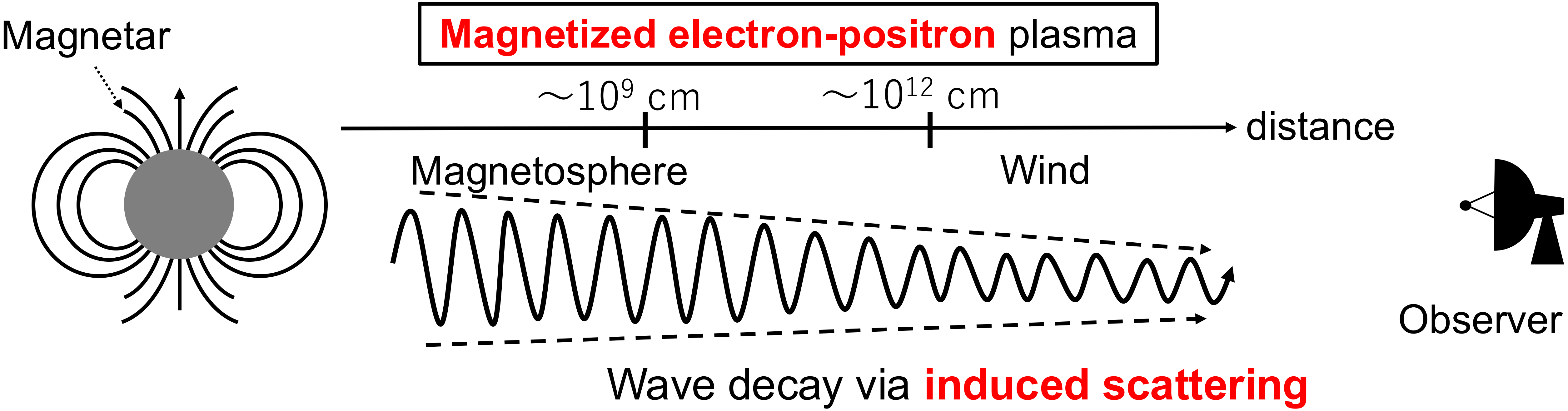




Magnetar Model



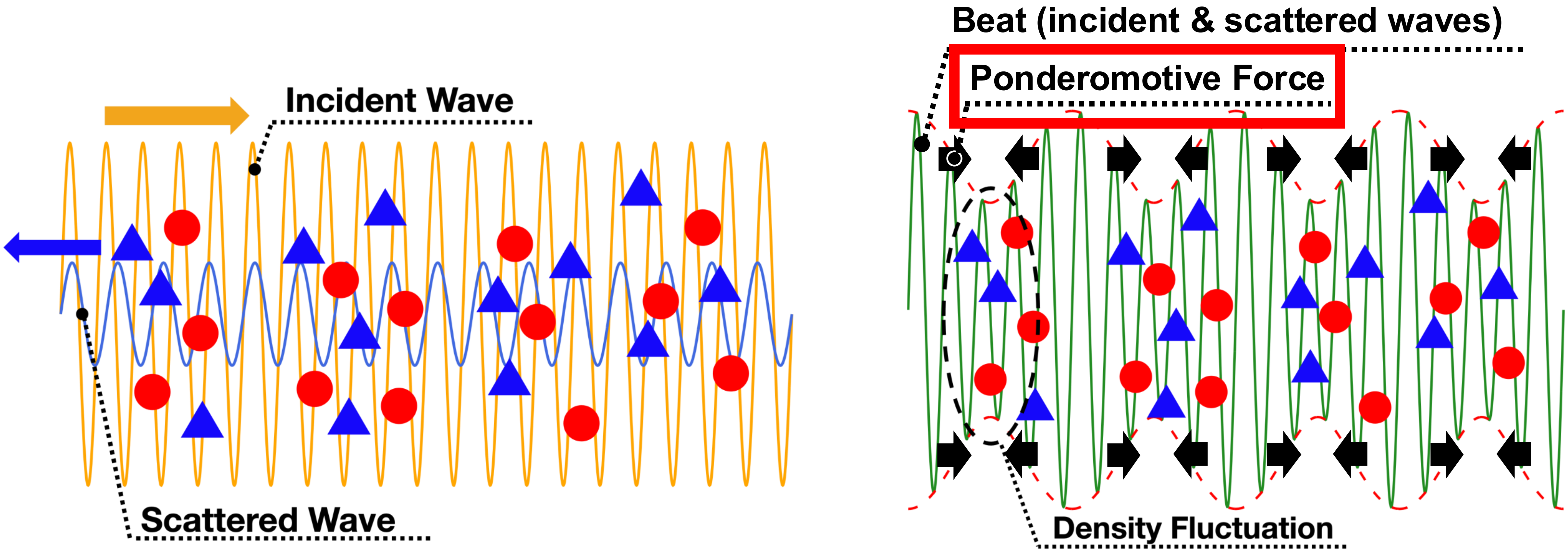
Magnetar Model



The wave propagation in magnetized plasma is common for both models.
Induced scattering (parametric instability) is important in plasma.
→ This could limit the emission region and mechanisms.

We investigate induced scattering (parametric instability) in magnetized electron-positron pair plasma.

Induced Scattering (Parametric Instability)



Incident wave (FRB) (Transverse mode)	→	Scattered wave (Transverse mode)	+	Density fluctuation (Longitudinal mode)

Incident waves (FRB) lose their energy while propagating in plasma.

Ponderomotive Force w/ Background B-field

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

$$\vec{F}_{\mathrm{pond}} = -\frac{e^2}{4m}\nabla\left[-\underbrace{\frac{|E_{\mathrm{x}}|^2 + |E_{\mathrm{z}}|^2}{\omega_{\mathrm{c}}^2 - \omega_0^2}} \pm i\underbrace{\frac{\omega_{\mathrm{c}}(E_{\mathrm{z}}^* E_{\mathrm{x}} - E_x^* E_{\mathrm{z}})}{\omega_0(\omega_{\mathrm{c}}^2 - \omega_0^2)}}\right]$$

$+$: Positron

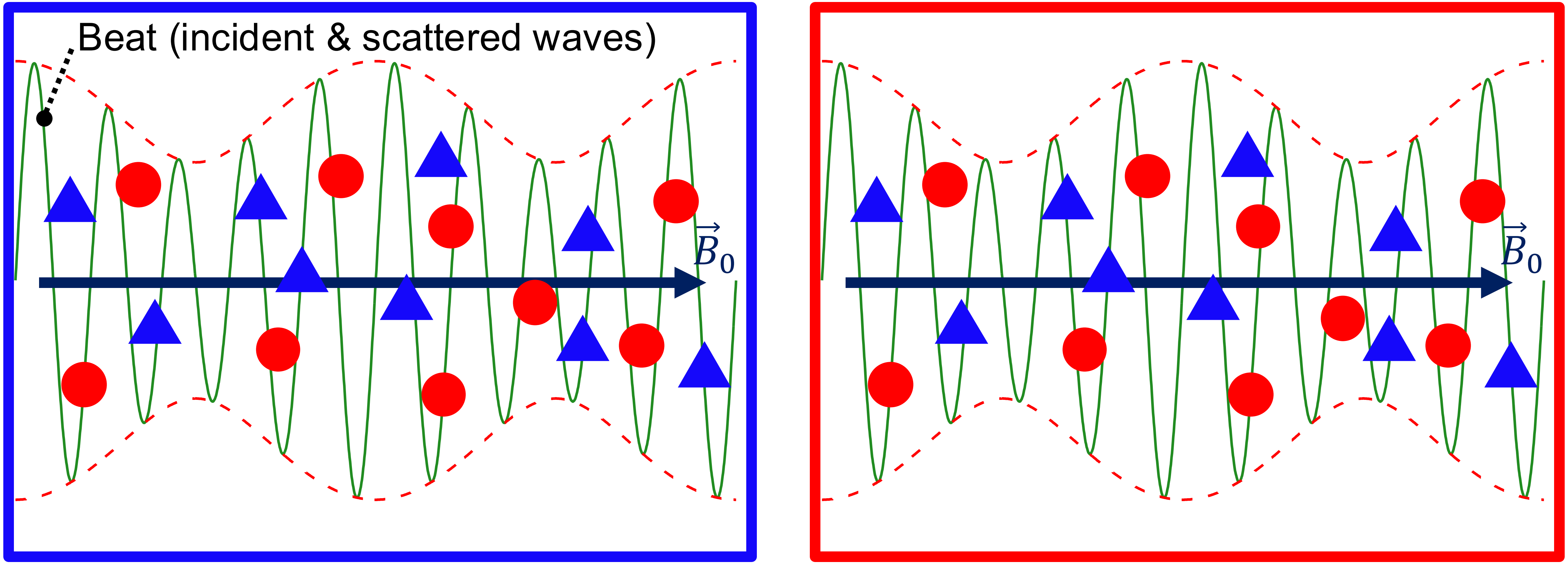
$-$: Electron

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

● : Positron

▲ : Electron

$\omega_{\mathrm{c}} = eB_0/(m_e c)$:cyclotron freq. > ω_0:incident wave freq.



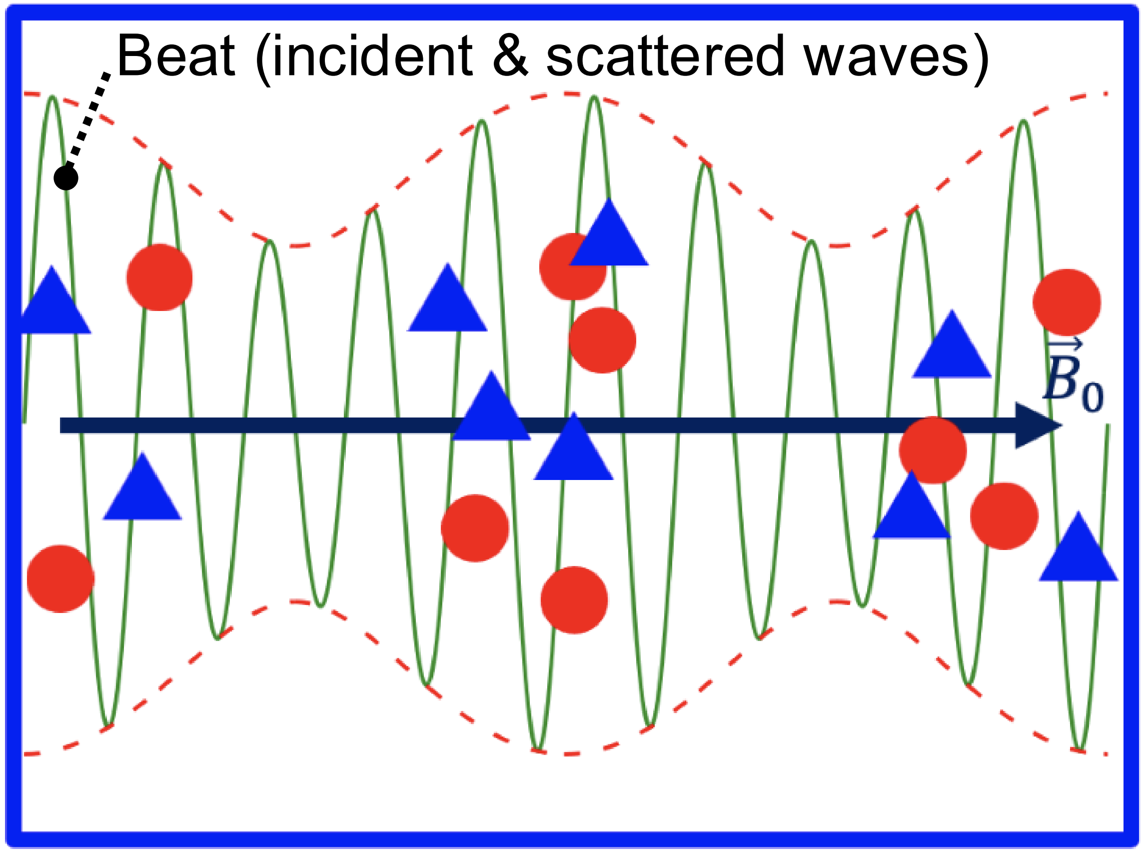
Induced Compton Scattering Rate w/ Background B-field

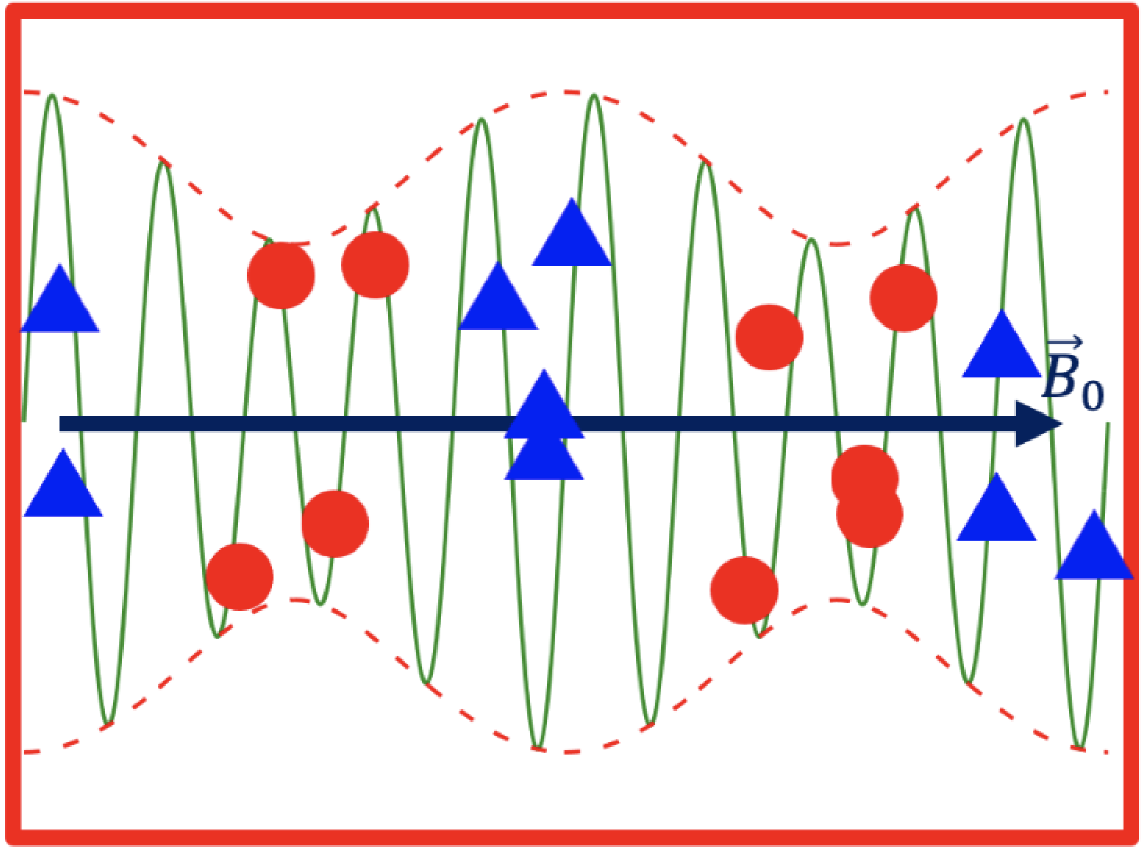
[Nishiura & Ioka 2024, Nishiura, **SFK**+2025]

$$\Gamma_{\max}^{\mathrm{w/}\,B_0} = \Gamma_{\max}^{\mathrm{w/o}B_0} \max\left[\underbrace{\left(\frac{\omega_0}{\omega_\mathrm{c}}\right)^4}_{\text{Neutral Mode}}, \underbrace{\frac{32\mathrm{e}}{\pi}\left(\frac{\omega_0}{\omega_\mathrm{c}}\right)^2 \left(\frac{\omega_0}{\omega_\mathrm{p}}\right)^4 \left(\frac{k_\mathrm{B}T_\mathrm{e}}{m_\mathrm{e}c^2}\right)^2}_{\text{Charged Mode}} \right]$$

● : **Positron**

▲ : **Electron** $\omega_\mathrm{c} = eB_0/(m_e c)$:cyclotron freq. > ω_p : plasma freq. > ω_0:incident wave freq.





Parametric Instability for FRB

Growth rate of ICS **w/ background B-field**

$$\Delta t^{-1} = 10^3\ \mathrm{s}^{-1}$$

(Inverse of the burst duration)

$$(t_{\mathrm{charged}}^{\mathrm{broad}})^{-1} = \frac{\pi}{4}\left(\frac{\omega_0}{\omega_\mathrm{c}}\right)^2 \frac{\omega_\mathrm{p}^2 a_\mathrm{e}^2}{\omega_0}\left(\frac{8k_\mathrm{B}T_\mathrm{e}}{m_\mathrm{e}c^2}\right)^2\left(\frac{\omega_0}{\omega_\mathrm{p}}\right)^4\left(\frac{\omega_0}{\Delta\omega}\right)^2$$

$$= 4.6\times 10^2\ \mathrm{s}^{-1}\,\frac{P_{\mathrm{sec}} r_8^7 B_{\mathrm{p},14} L_{38} T_{80\mathrm{keV}}^2}{\mathcal{M}_6 \nu_9^2 B_{\mathrm{p},14}^3 R_{\mathrm{NS},6}^9}\left(\frac{\Delta\nu/\nu_0}{1}\right)^{-2} \sim \Delta t^{-1}$$

$$(t_{\mathrm{neutral}}^{\mathrm{broad}})^{-1} = \pi\,\frac{\omega_\mathrm{p}^2 a_\mathrm{e}^2}{\omega_0}\left(\frac{\omega_0}{\omega_\mathrm{c}}\right)^4\left(\frac{\omega_0}{\Delta\omega}\right)^2$$

$$= 1.8\times 10^{-2}\ \mathrm{s}^{-1}\,\frac{\mathcal{M}_6 L_{38} \nu_9^2 r_8^7 T_{80\mathrm{keV}}^2}{P_{\mathrm{sec}} B_{\mathrm{p},14}^3 R_{\mathrm{NS},6}^9}\left(\frac{\Delta\nu/\nu_0}{1}\right)^{-2} \ll \Delta t^{-1}$$

Waves can escape.

Growth rate of ICS **w/o background B-field**

[Drake+1974, Ghosh+2022]

$$\left(t_{\mathrm{c,max}}^{\mathrm{w/o}\,B_0}\right)^{-1} = \sqrt{\frac{\pi}{32\mathrm{e}}\frac{\omega_\mathrm{p}^2 a_\mathrm{e}^2}{\omega_0}\frac{m_\mathrm{e}c^2}{k_\mathrm{B}T_\mathrm{e}}} \sim 10^{20}\ \mathrm{s}^{-1}\,\frac{B_{\mathrm{p},14}\mathcal{M}_6 L_{38} R_{\mathrm{NS},6}}{P_{\mathrm{sec}} r_8^5 \nu_9^3 T_{80\,\mathrm{keV}}} \gg \Delta t^{-1}$$

Growth Rate in Magnetized Plasma

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

Linear growth rate of induced Compton scattering w/ background B-field

$$\Gamma_{\max}^{\mathrm{w/}\,B} = \Gamma_{\max}^{\mathrm{w/o}\,B}\max\left[\underbrace{\left(\frac{\omega_0}{\omega_c}\right)^4}_{\text{Neutral Mode}},\ \underbrace{\frac{32\mathrm{e}}{\pi}\left(\frac{\omega_0}{\omega_c}\right)^2\left(\frac{\omega_0}{\omega_p}\right)^4\left(\frac{k_B T_e}{m_e c^2}\right)^2}_{\text{Charged Mode}}\right]$$

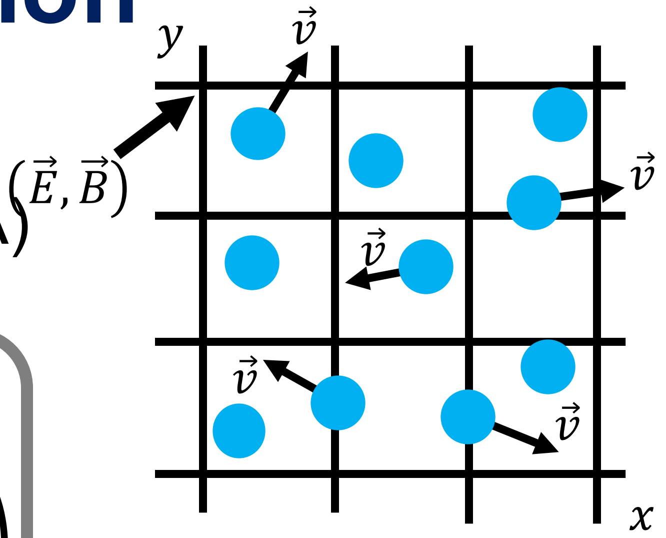
Neutral Mode　　Charged Mode

We investigate the linear and the nonlinear stages of neutral and charged modes of induced Compton scattering by using Particle-in-Cell (PIC) simulations.

$$\omega_0 < \omega_p < \omega_c$$

Particle-in-Cell (PIC) Simulation

- ☐ WumingPIC2D (public code) [Matsumoto+2024]
- ☐ Flow (Nagoya U.), Yukawa-21 (YITP), XC50, XD2000 (CfCA)



Solve EoM: $\vec{F} \rightarrow (\vec{x}, \vec{v})$

$$\frac{d\vec{x}}{dt} = \vec{v}, \quad \frac{d(\gamma m \vec{v})}{dt} = \vec{F} = q\left(\vec{E} + \frac{\vec{v}}{c} \times \vec{B}\right)$$

Weighting (Splitting)
$(\vec{x}, \vec{v}) \rightarrow (\rho, \vec{j})$

Δt

Solve Maxwell eqs.: $(\rho, \vec{j}) \rightarrow (\vec{E}, \vec{B})$

$$\nabla \cdot \vec{E} = 4\pi\rho, \quad \nabla \cdot \vec{B} = 0$$

$$\nabla \times \vec{E} = -\frac{1}{c}\frac{\partial \vec{B}}{\partial t}, \quad \nabla \times \vec{B} = \frac{4\pi}{c}\vec{j} + \frac{1}{c}\frac{\partial \vec{E}}{\partial t}$$

Weighting (Gathering)
$(\vec{E}, \vec{B}) \rightarrow \vec{F}$

Setup

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

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

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

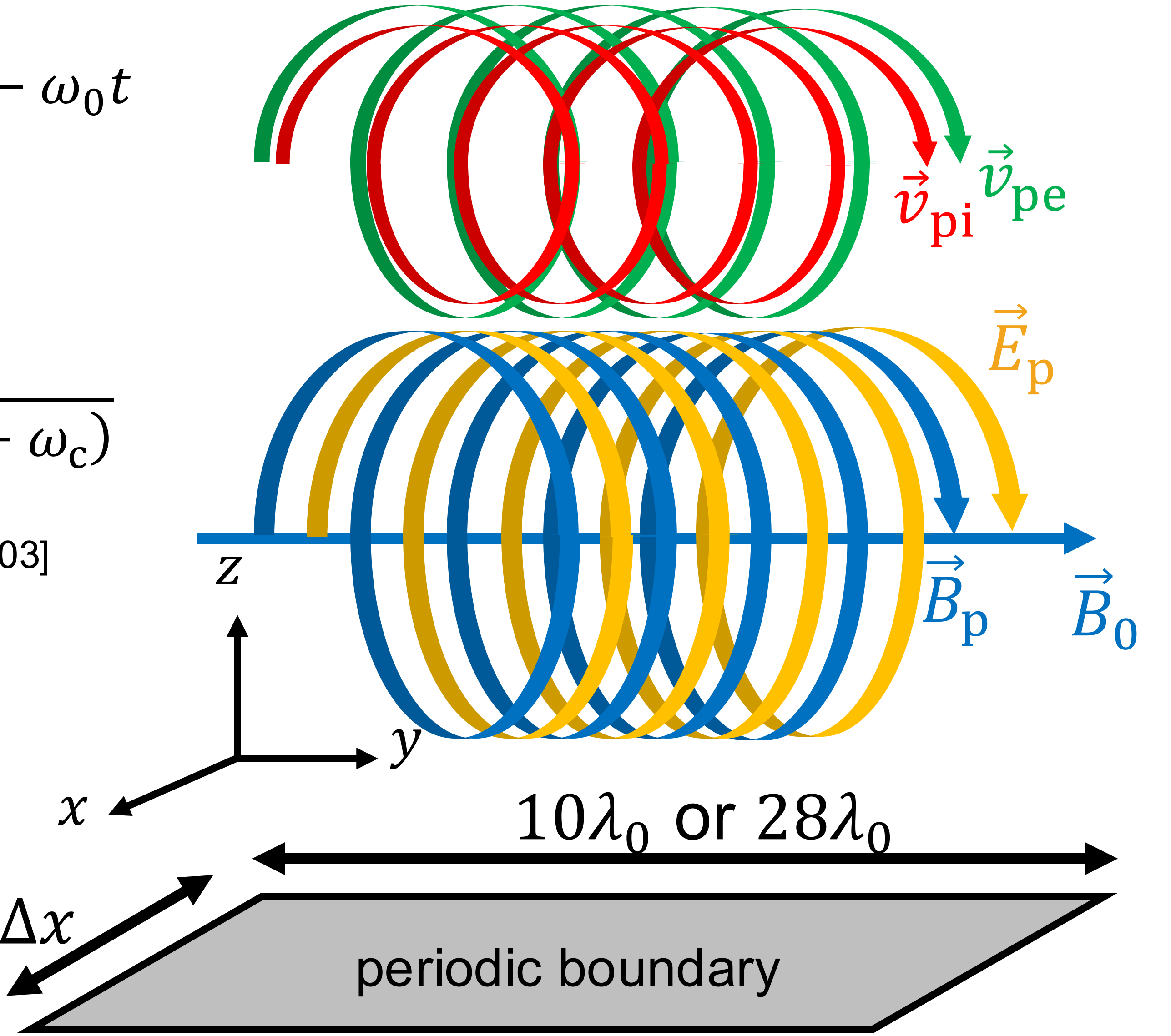
$$\vec{E}_{\mathrm{p}} = -\frac{\omega_0}{ck_0} B_{\mathrm{p}}[\cos\phi_0\,\hat{x} + \sin\phi_0\,\hat{z}]$$

$$\left(\frac{ck_0}{\omega_0}\right)^2 = 1 - \frac{\omega_{\mathrm{pe}}^2}{\omega_0(\gamma_{\mathrm{e}}\omega_0 - \omega_{\mathrm{c}})} - \frac{\omega_{\mathrm{pi}}^2}{\omega_0(\gamma_{\mathrm{i}}\omega_0 + \omega_{\mathrm{c}})}$$

☐ initial e$\pm$ plasma velocity [Matsukiyo & Hada 2003]

$$\frac{\vec{v}_{\mathrm{e(i)}}}{c} = -\frac{\omega_0}{ck_0}\frac{\eta\omega_{\mathrm{c}}}{\omega_{\mathrm{c}} \pm \gamma_{\mathrm{e(i)}}\omega_0}\frac{\vec{B}_{\mathrm{p}}}{B_{\mathrm{p}}}$$

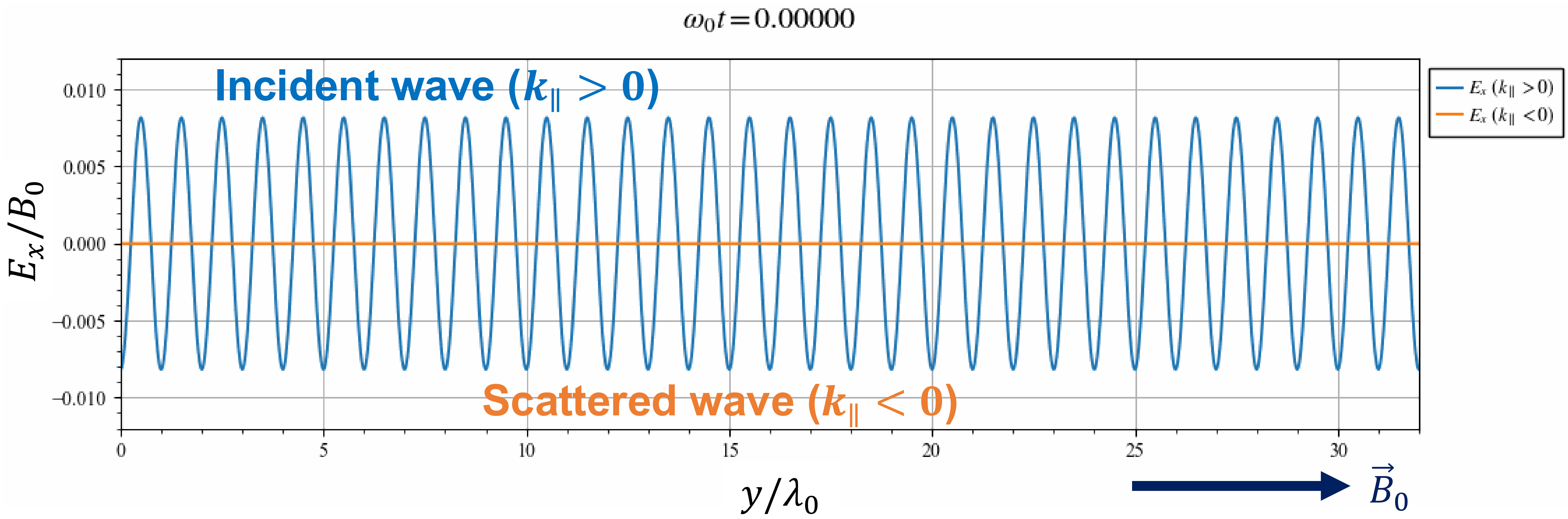
$$\gamma_{\mathrm{e(i)}} = \frac{1}{\sqrt{1 - \left(\frac{v_{\mathrm{e(i)}}}{c}\right)^2}} \qquad \eta = \frac{B_{\mathrm{p}}}{B_0} = a_0\frac{\omega_0}{\omega_{\mathrm{c}}}$$



Simulation Setup

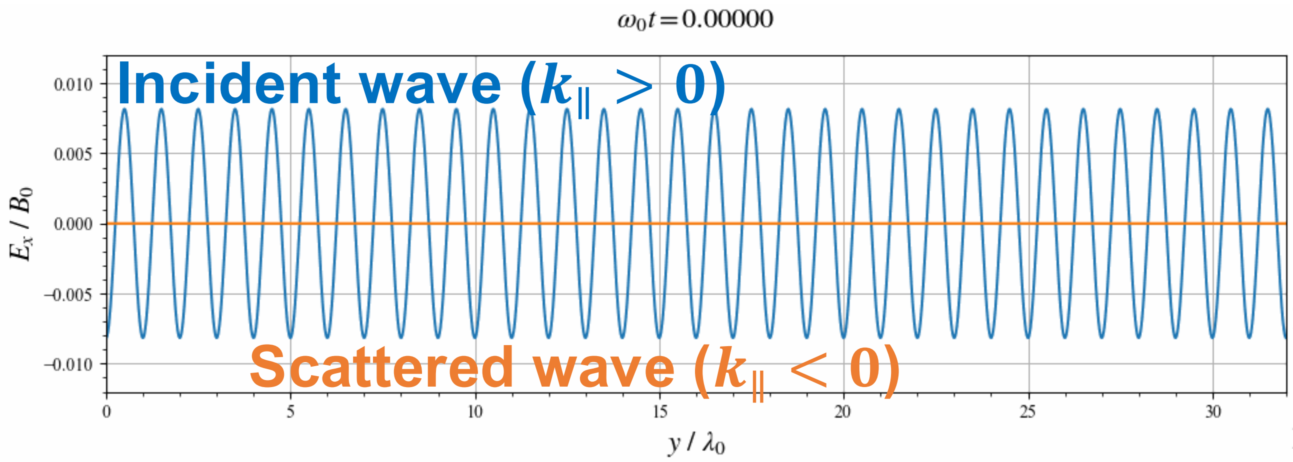
	Charged	Neutral	Neutral
mass ratio: m_{r}	1		
frequency ratio: $\frac{\omega_0}{\omega_{\mathrm{pe}}}$ $\left(\omega_0 \Delta t < \omega_{\mathrm{pe}} \Delta t < \omega_{\mathrm{c}} \Delta t = \sqrt{\sigma_{\mathrm{e}}} \omega_{\mathrm{pe}} \Delta t < 0.1\right)$	0.9		0.1
electron sigma: $\sigma_{\mathrm{e}} = \frac{B_0^2}{4\pi n m_{\mathrm{e}} c^2} = \left(\frac{\omega_{\mathrm{c}}}{\omega_{\mathrm{pe}}}\right)^2$	2500		4
thermal velocity: $\frac{v_{\mathrm{th,e}}}{c} = \sqrt{\frac{k_{\mathrm{B}} T_{\mathrm{e}}}{m_{\mathrm{e}} c^2}} = \frac{v_{\mathrm{th,i}}}{c}$	0.21	0.04	0.04
amp. of incident wave: $\frac{B_{\mathrm{p}}}{B_0}$	0.1, 0.141, 0.316, 0.562		0.01, 0.0141, 0.0316
wavelength of incident wave: $\lambda_0 / \Delta x$	3200		1200
The number of particles per cell: n [/cell]	100		
simulation box: $L_x \times L_y$	$2\Delta x \times 10\lambda_0$	$2\Delta x$	$2\Delta x \times 32\lambda_0$

Time evolution of waves



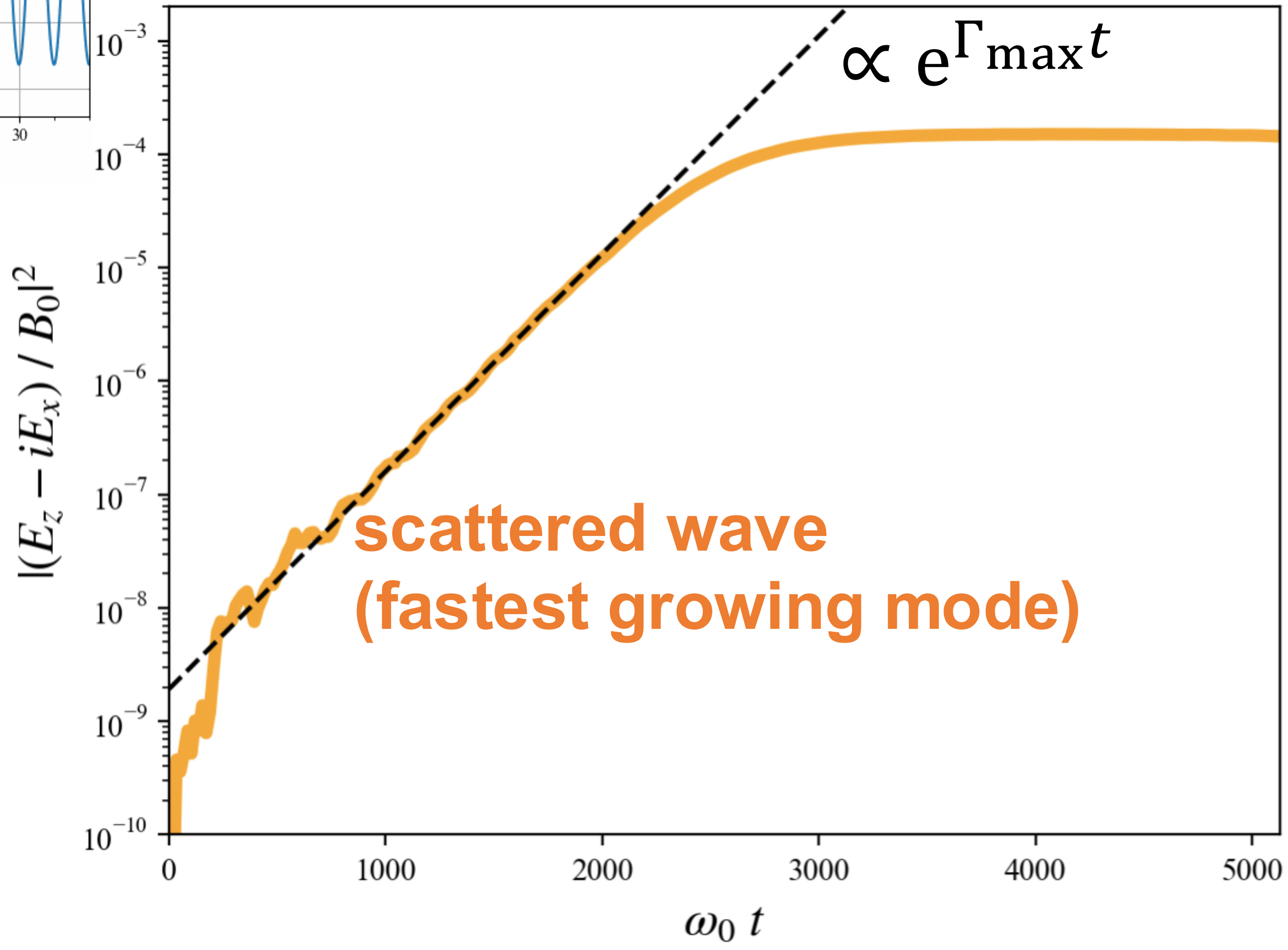
The growth rate is estimated from the time evolution of the power of the scattered wave.

growth rate from simulations

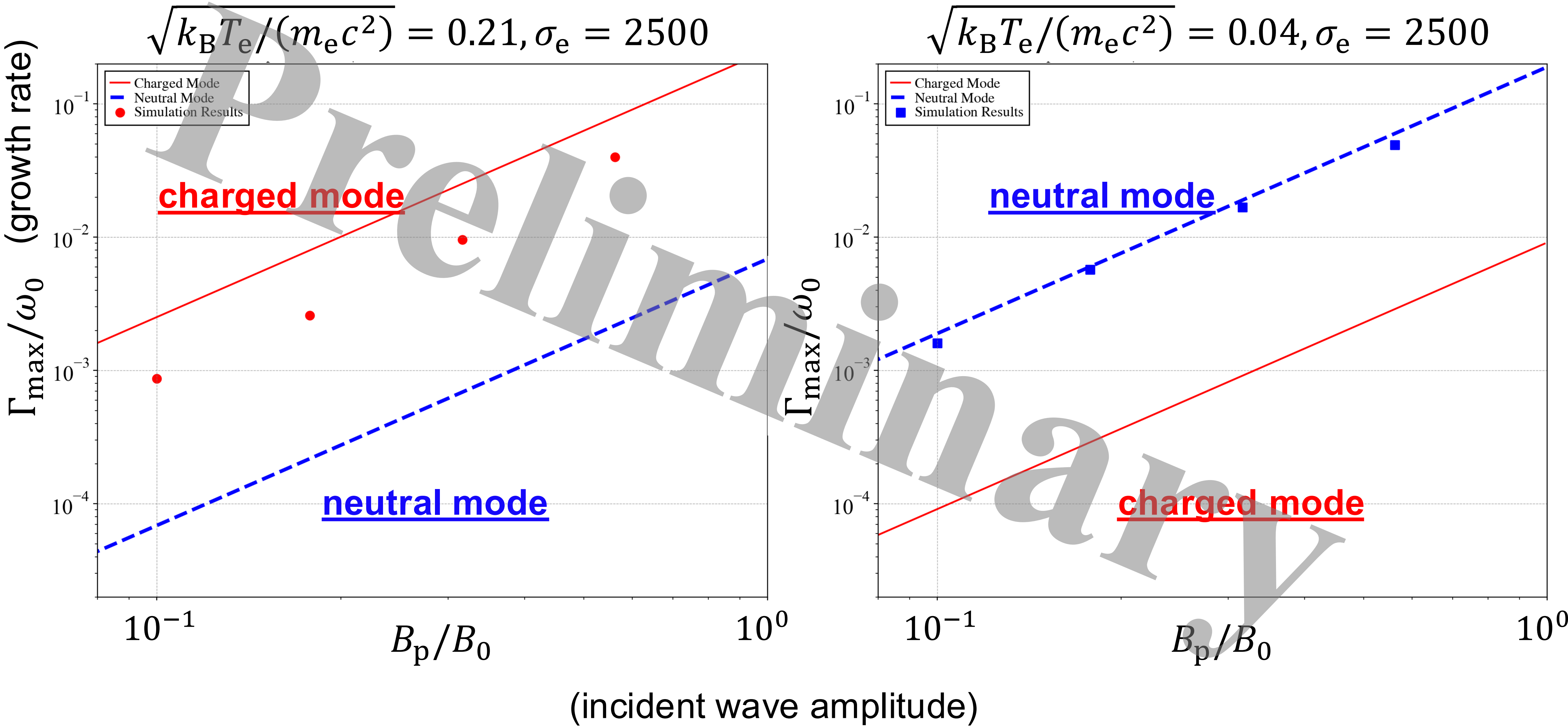


We extract the fastest growing mode of the scattered waves.

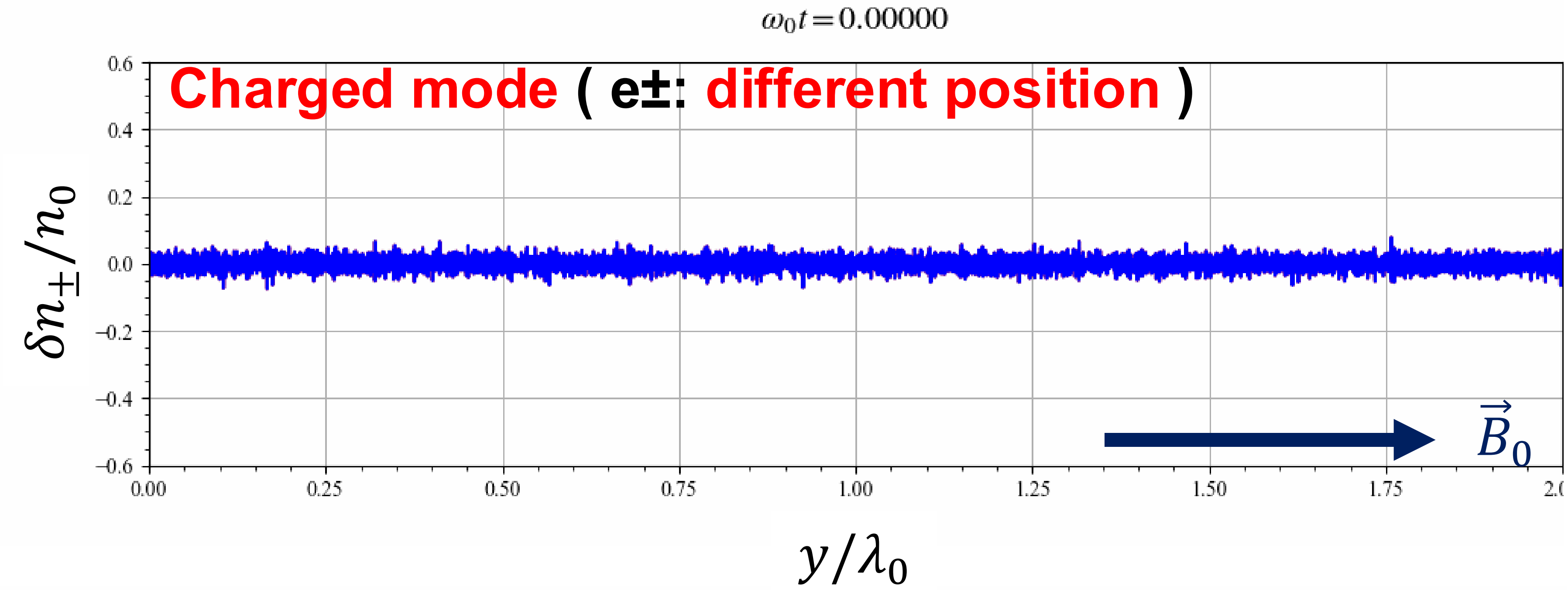
$\Gamma_{\max}$ is given from simulations.

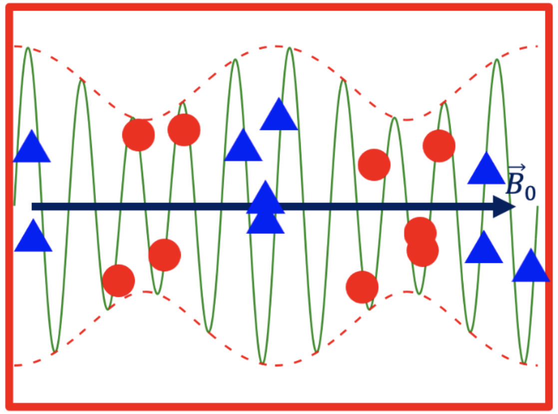


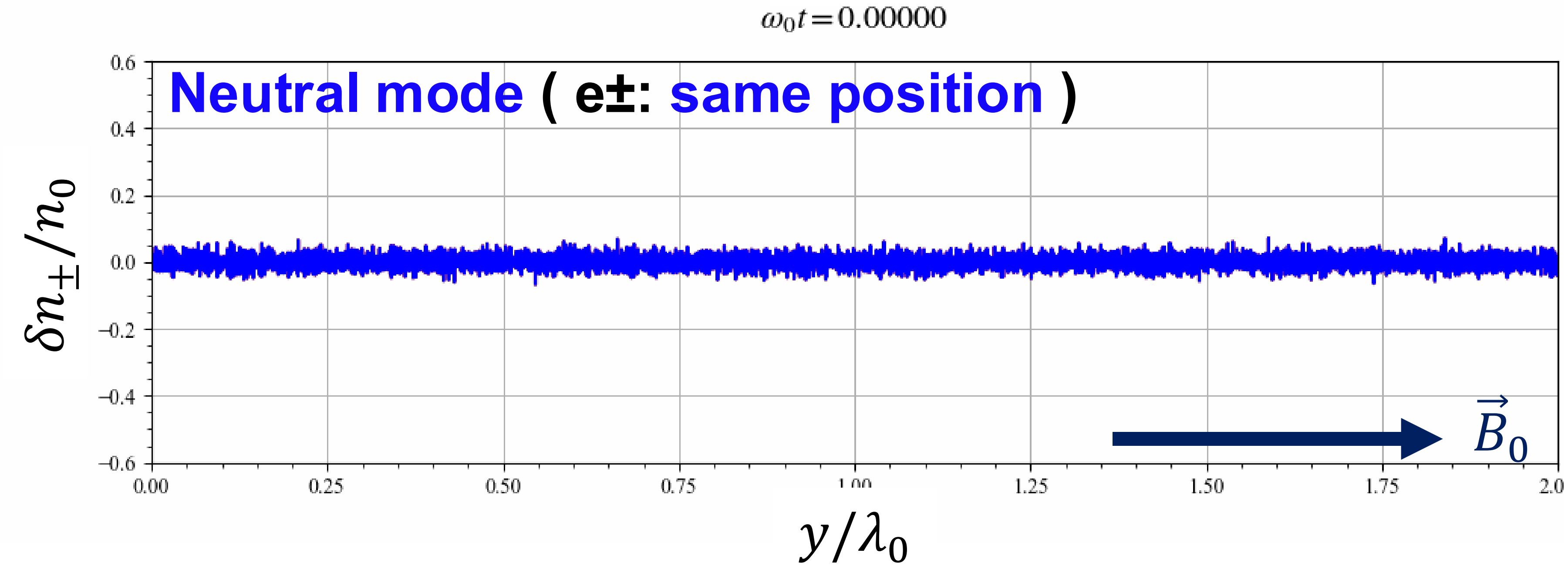
Growth rate of induced Compton scattering

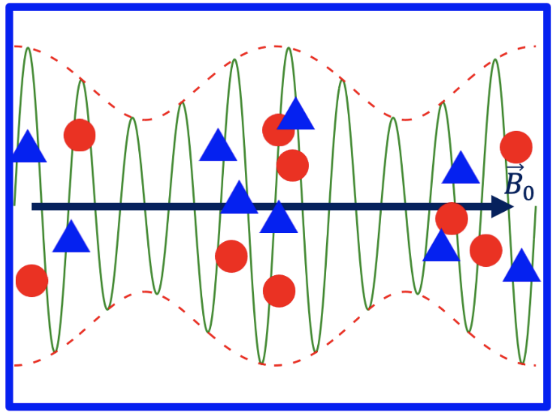


Density fluctuation









density fluctuations of electrons and positrons

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 (charged & neutral modes)

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

- Dependency of other parameters