Particle-in-Cell simulation of propagation of Alfvén waves in magnetized pair plasmas

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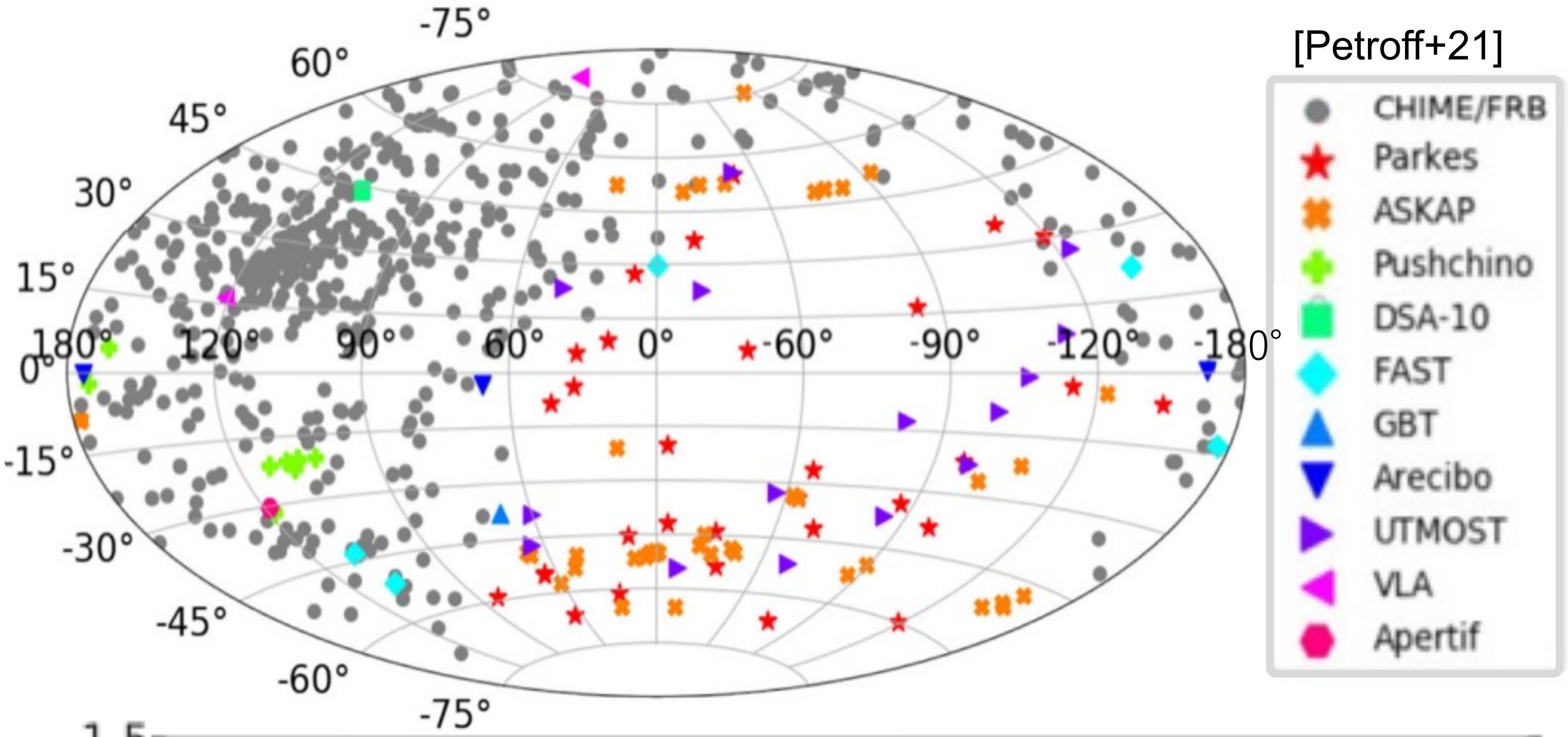
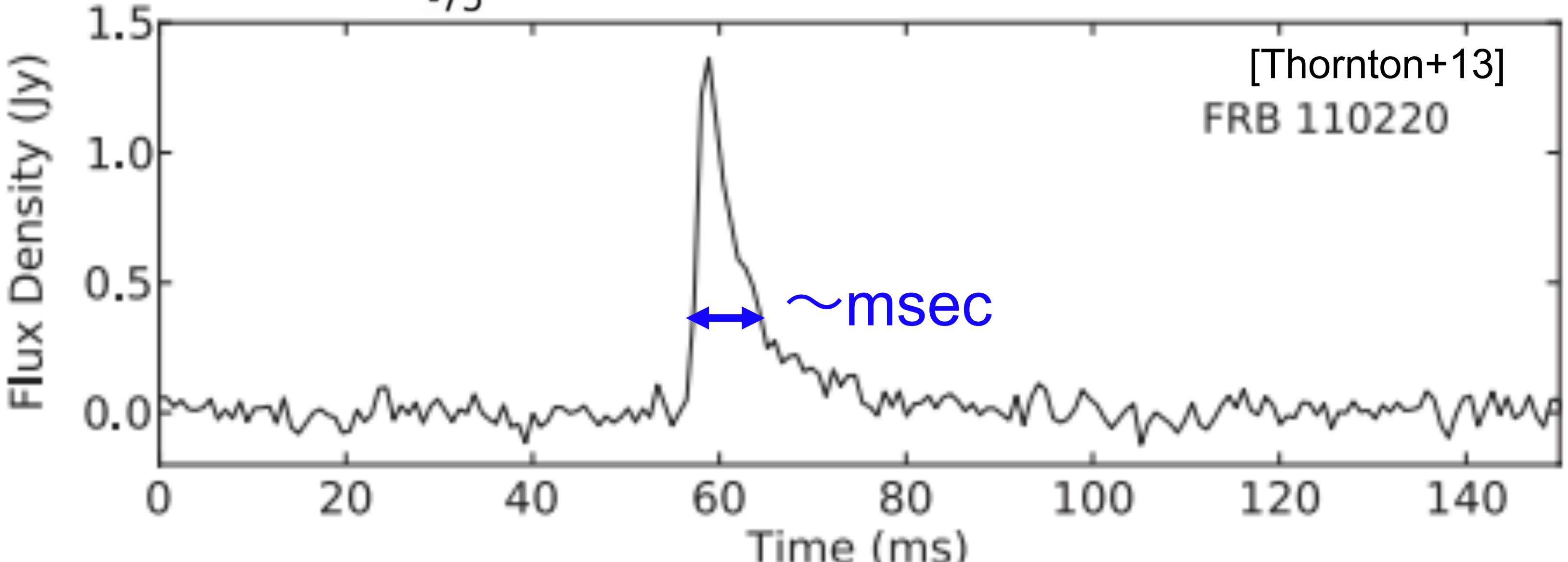
Fast Radio Bursts (FRBs)

- Bright 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 temp.
  →coherent emission

The origin and emission mechanism of FRBs are unclear.

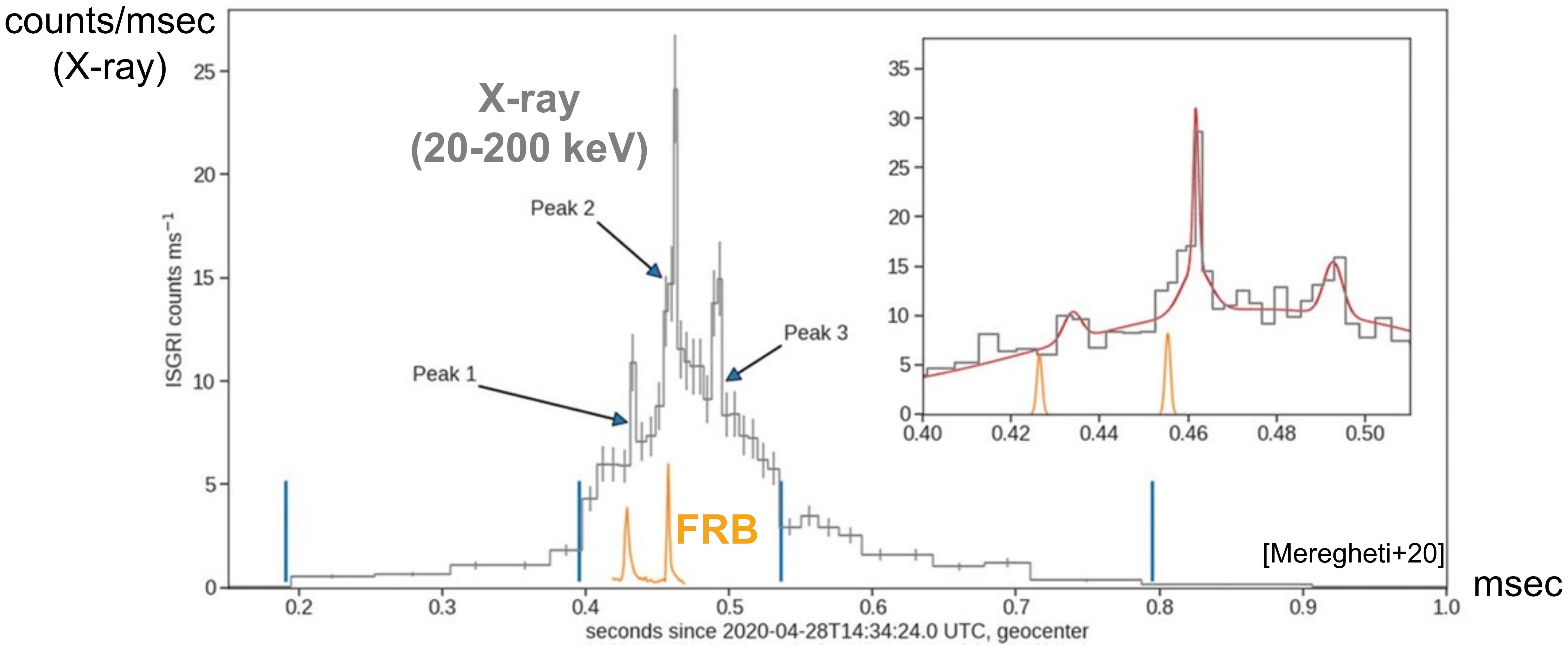




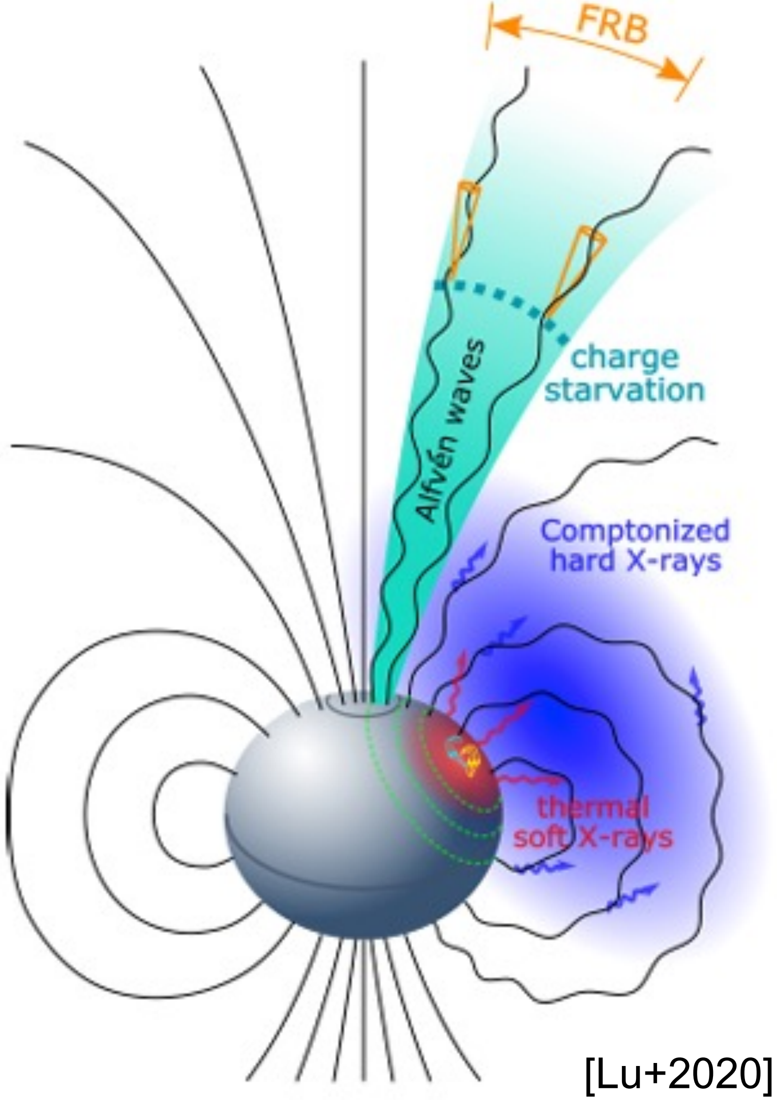
FRB 20200428A: FRB & short X-ray burst

FRB 20200428A associates with the short X-ray burst for the Galactic magnetar SGR 1935+2145.

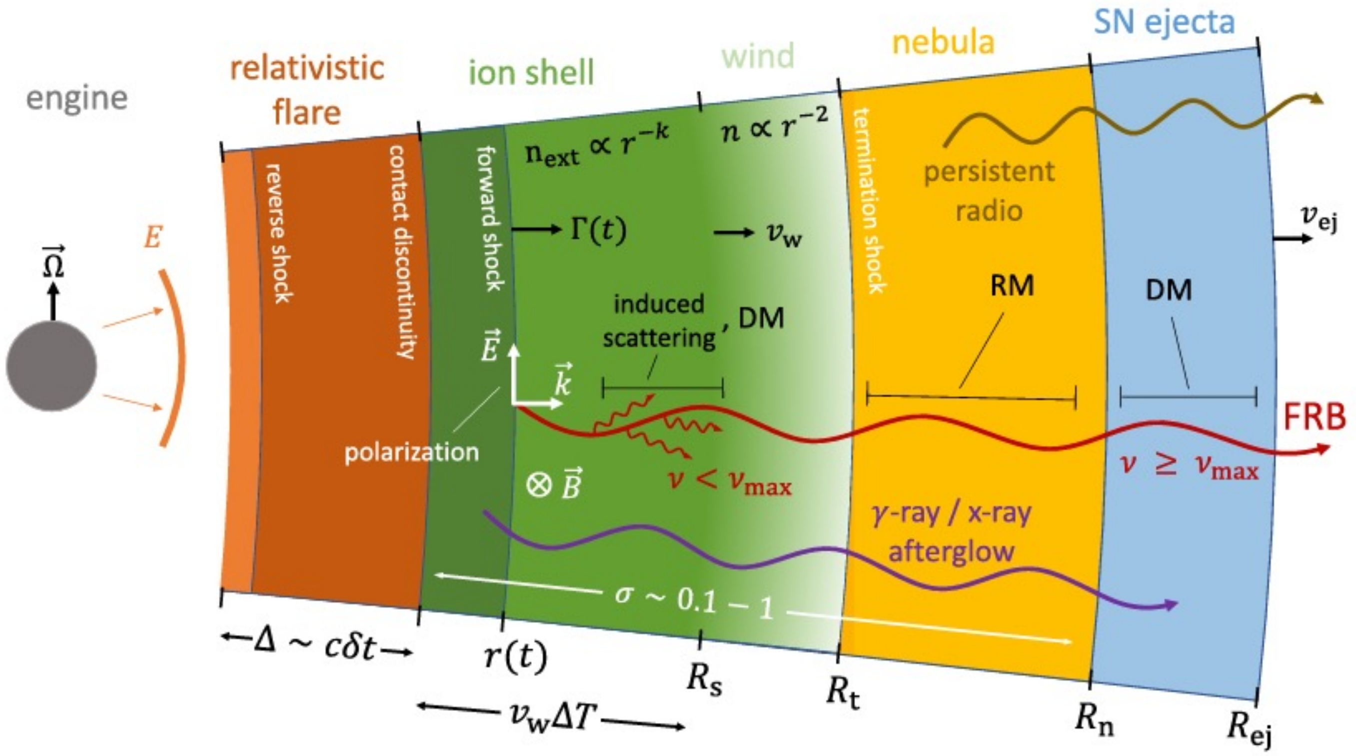
→**Magnetars are one of the plausible origin of FRBs.**



Magnetar models



[Lu+2020]



[Metzger+2019]

The wave propagation in magnetized plasmas is common for both models.

Alfvén waves in magnetized plasmas

- Many instabilities [e.g. Matsukiyo & Hada 03]

  e.g.) Parametric decay instability:

  parent wave → daughter electromagnetic wave + daughter electrostatic wave

- Particle acceleration by counter-propagating Alfvén waves [Matsukiyo & Hada 09, Isayama+23]
- Bunching of charged particles by charge-starved Alfvén wave [Kumar & Bosnjak 20, Kumar+22]
- Magnetic reconnection by the Alfvén wave-induced shear flow [Yuan+20]

We investigate the Alfvén wave propagation in the magnetized pair plasmas by using Particle-in-Cell simulations.

<u>Realistic situation</u>	**<u>Our simulation (as a first step)</u>**
e.g.) 3 dimension	1 dimension
Ambient B-field and plasma density change distant from the NS surface.	uniform B-field & plasma density
large-amplitude wave	small-amplitude wave
etc.	

Simulation setup

- Wuming (public code)

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

$n_e = 20$ /cell, $v_{th,e}/c = v_{th,i}/c = 0.02$

- e± pair plasma ($m_r = m_i/m_e = 1$)

$\omega_{pe}\Delta t = \omega_{pi}\Delta t = 0.02$ $\sigma_e = B_0^2/(4\pi n_e m_e c^2) = 25$

$\Omega_e \Delta t = (eB_0/(m_e c))\Delta t = \Omega_i \Delta t = \sqrt{\sigma_e}\,\omega_{pe}\Delta t = 0.1$

- circularly polarized Alfvén wave (parent wave)

$\vec{B}_p = B_p[-\sin\phi_0\,\hat{x} + \cos\phi_0\,\hat{z}], \phi_0 = k_0 y - \omega_0 t$ $\omega_0 \Delta t = 0.01$

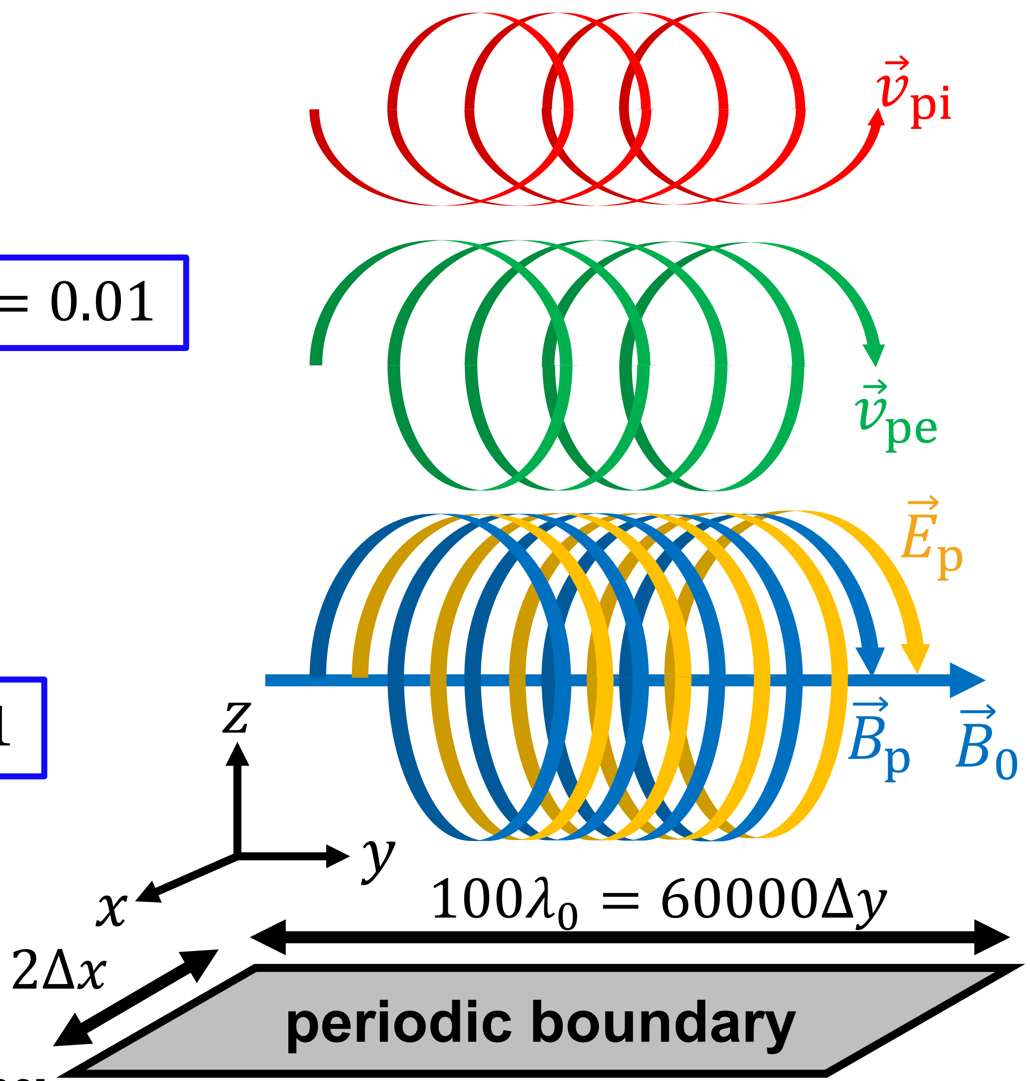
$$\vec{E}_p = -\frac{\omega_0}{ck_0} B_p[\cos\phi_0\,\hat{x} + \sin\phi_0\,\hat{z}]$$

$$1 - \left(\frac{ck_0}{\omega_0}\right)^2 - \frac{\omega_{pe}^2}{\omega_0(\gamma_e\omega_0 - \Omega_e)} - \frac{\omega_{pi}^2}{\omega_0(\gamma_i\omega_0 + \Omega_i)} = 0$$

- e± velocity $(\vec{B} = \vec{B}_0 + \vec{B}_p, \vec{E} = \vec{E}_p)$ $\eta = B_p/B_0 = 0.1$

$$\frac{\vec{v}_{pe}}{c} = \frac{\omega_0}{ck_0}\frac{\eta\Omega_e}{\gamma_e\omega_0 - \Omega_e}[-\sin\phi_0\,\hat{x} + \cos\phi_0\,\hat{z}]$$

$$\frac{\vec{v}_{pi}}{c} = -\frac{\omega_0}{ck_0}\frac{\eta\Omega_i}{\gamma_i\omega_0 + \Omega_i}[-\sin\phi_0\,\hat{x} + \cos\phi_0\,\hat{z}]$$

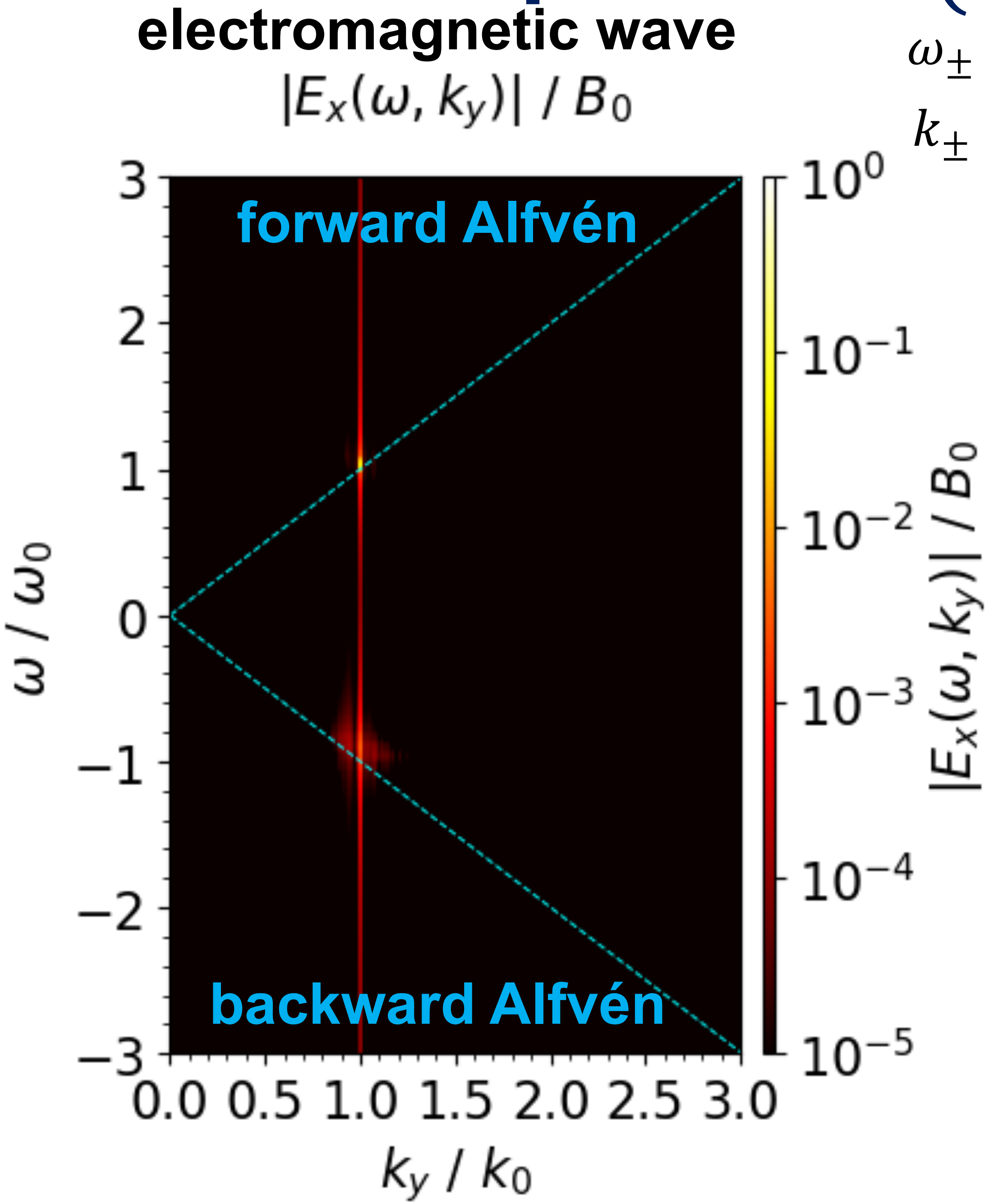


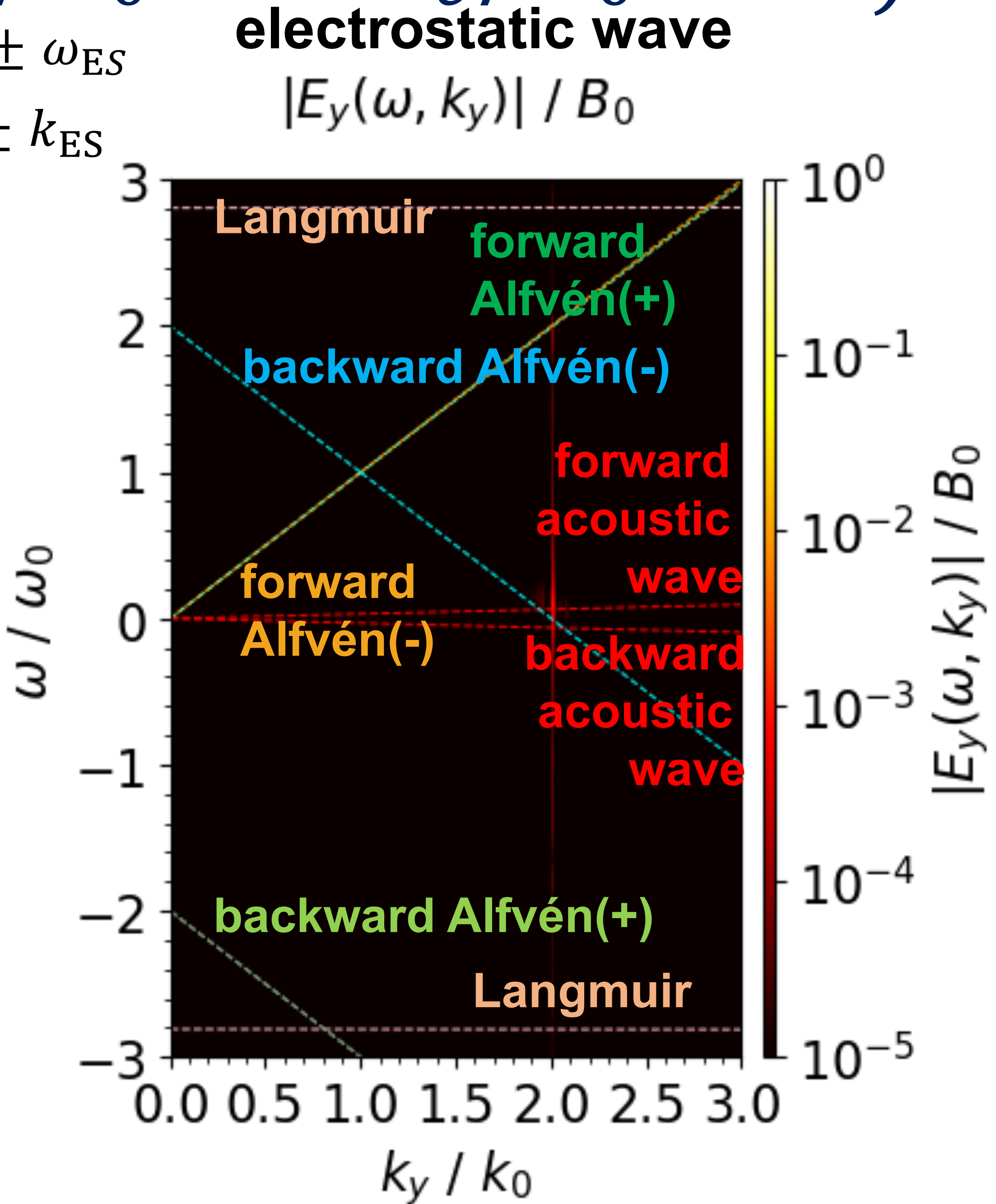
[Matsukiyo & Hada 03]

Fourier spectrum $\left(\omega_{pe}/\omega_0 = 2, \Omega_e/\omega_0 = 10\right)$

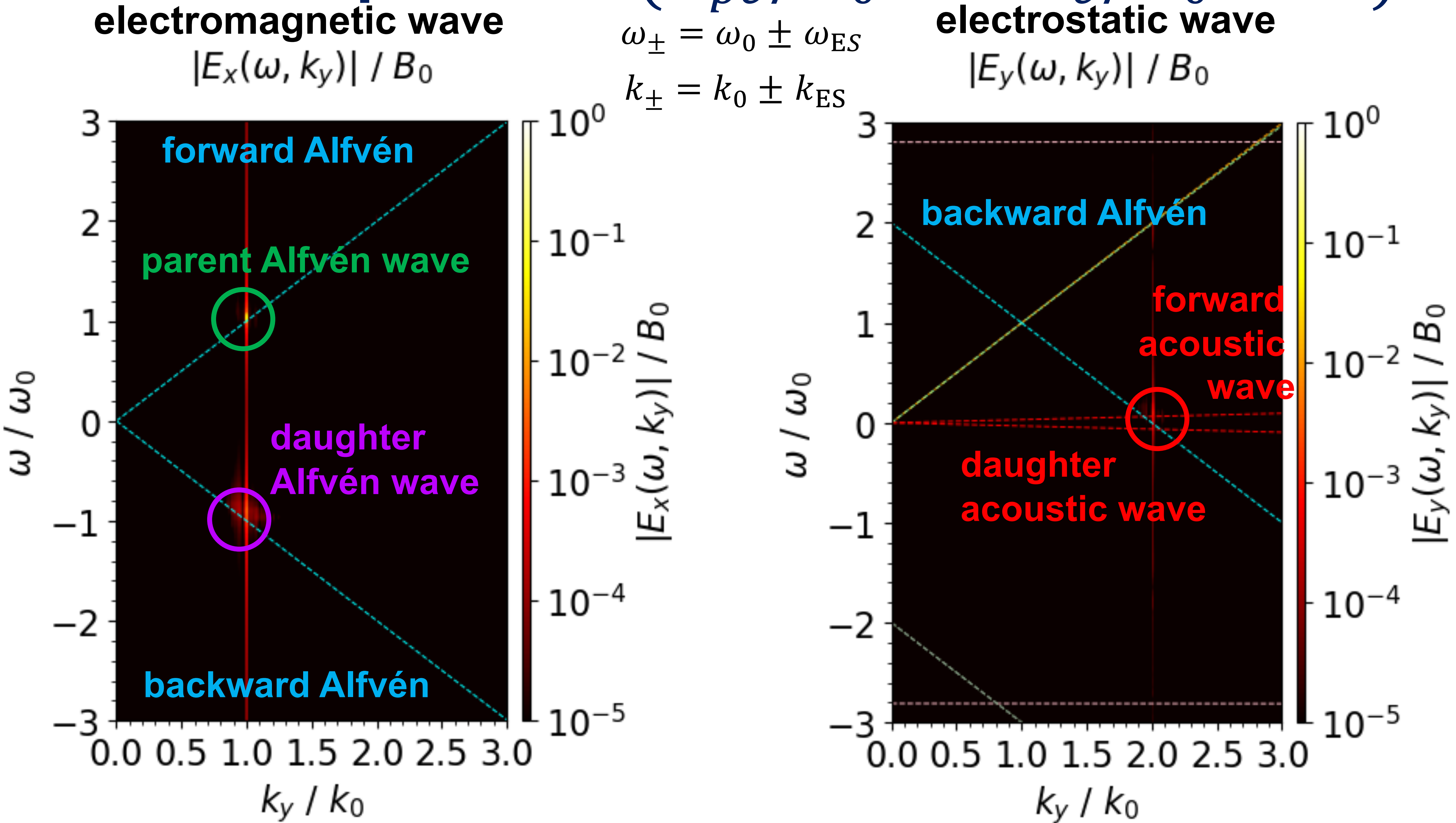
$$\omega_\pm = \omega_0 \pm \omega_{\mathrm{ES}}$$

$$k_\pm = k_0 \pm k_{\mathrm{ES}}$$



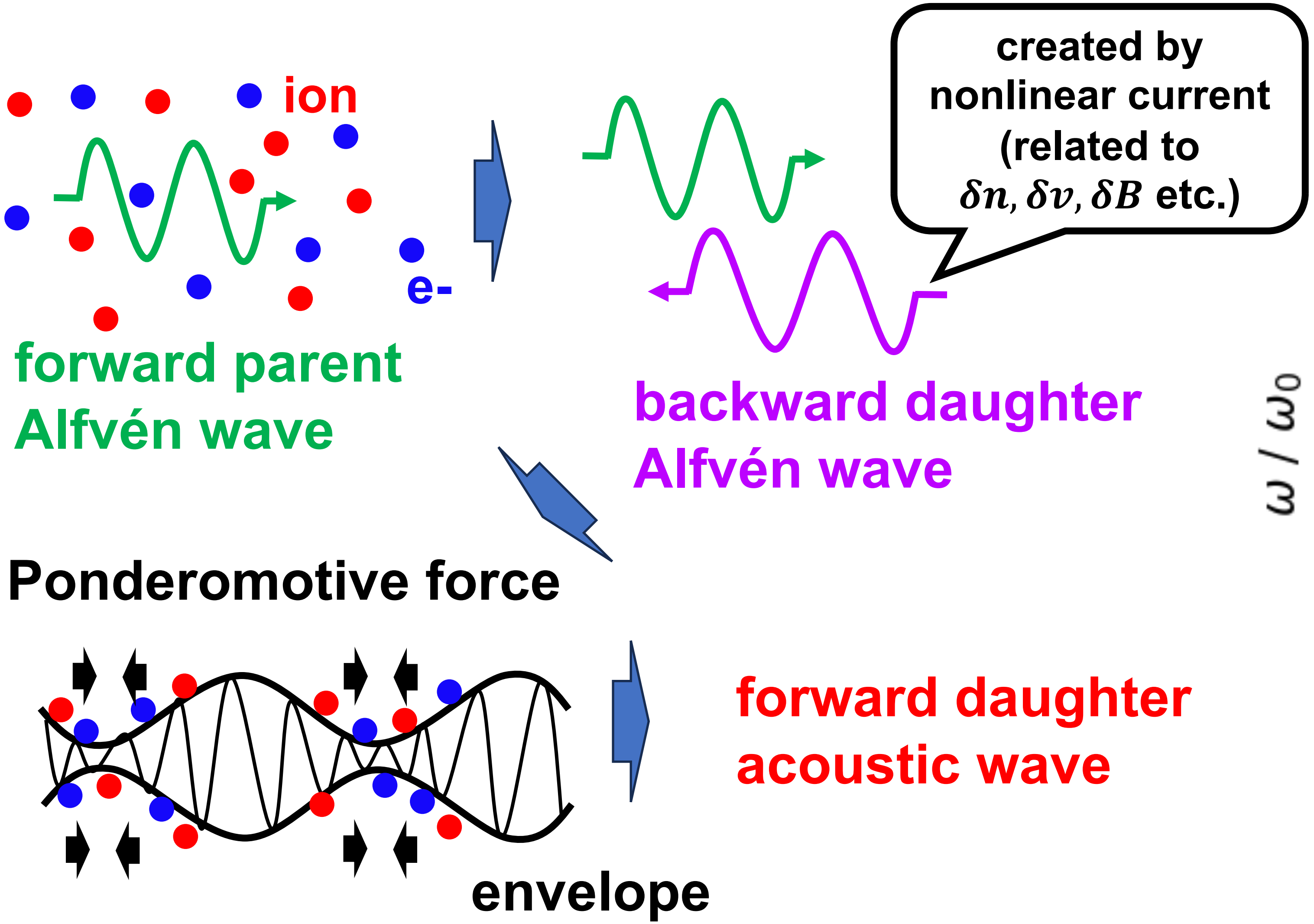


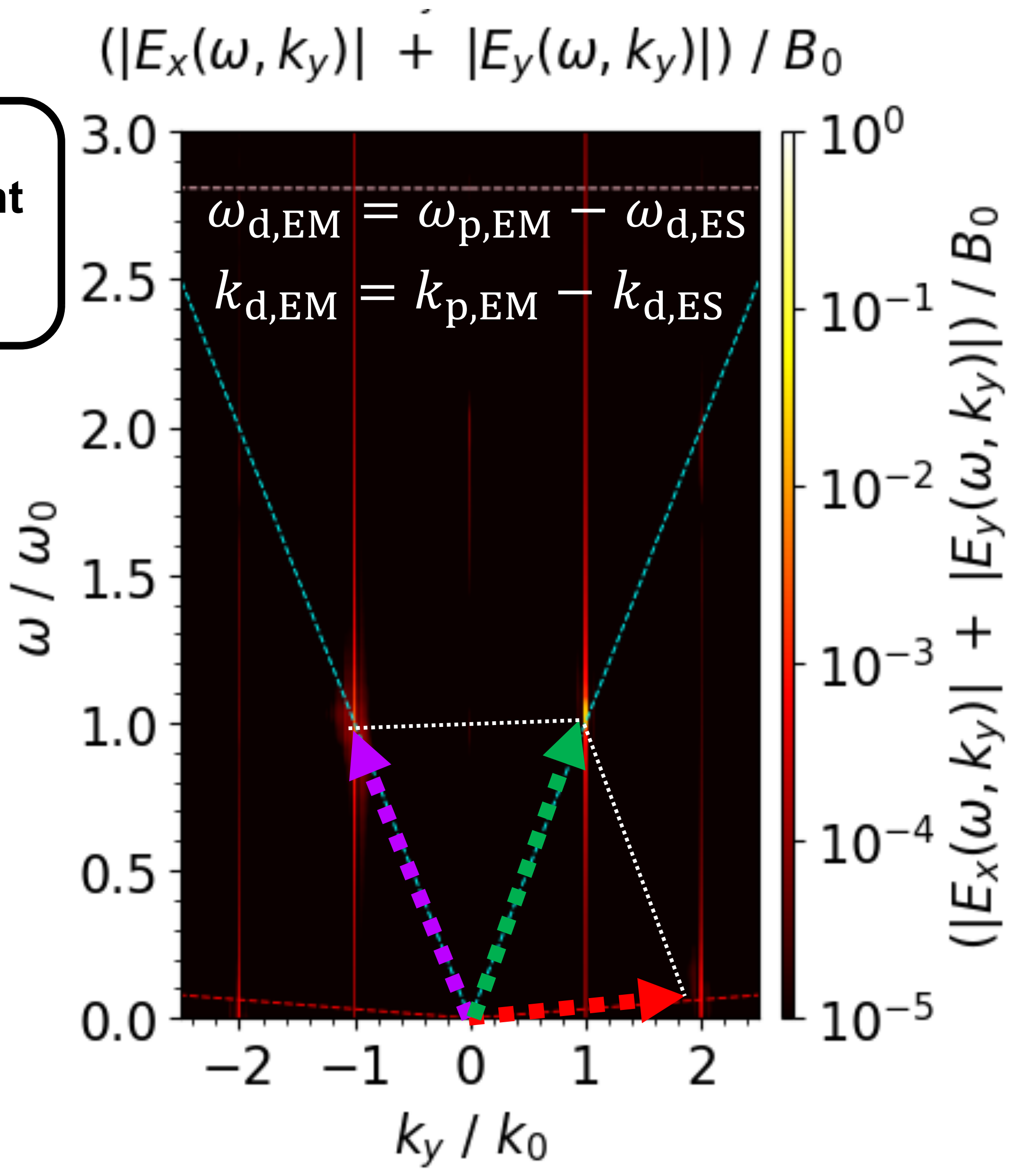
Fourier spectrum $\left(\omega_{pe}/\omega_0 = 2, \Omega_e/\omega_0 = 10\right)$



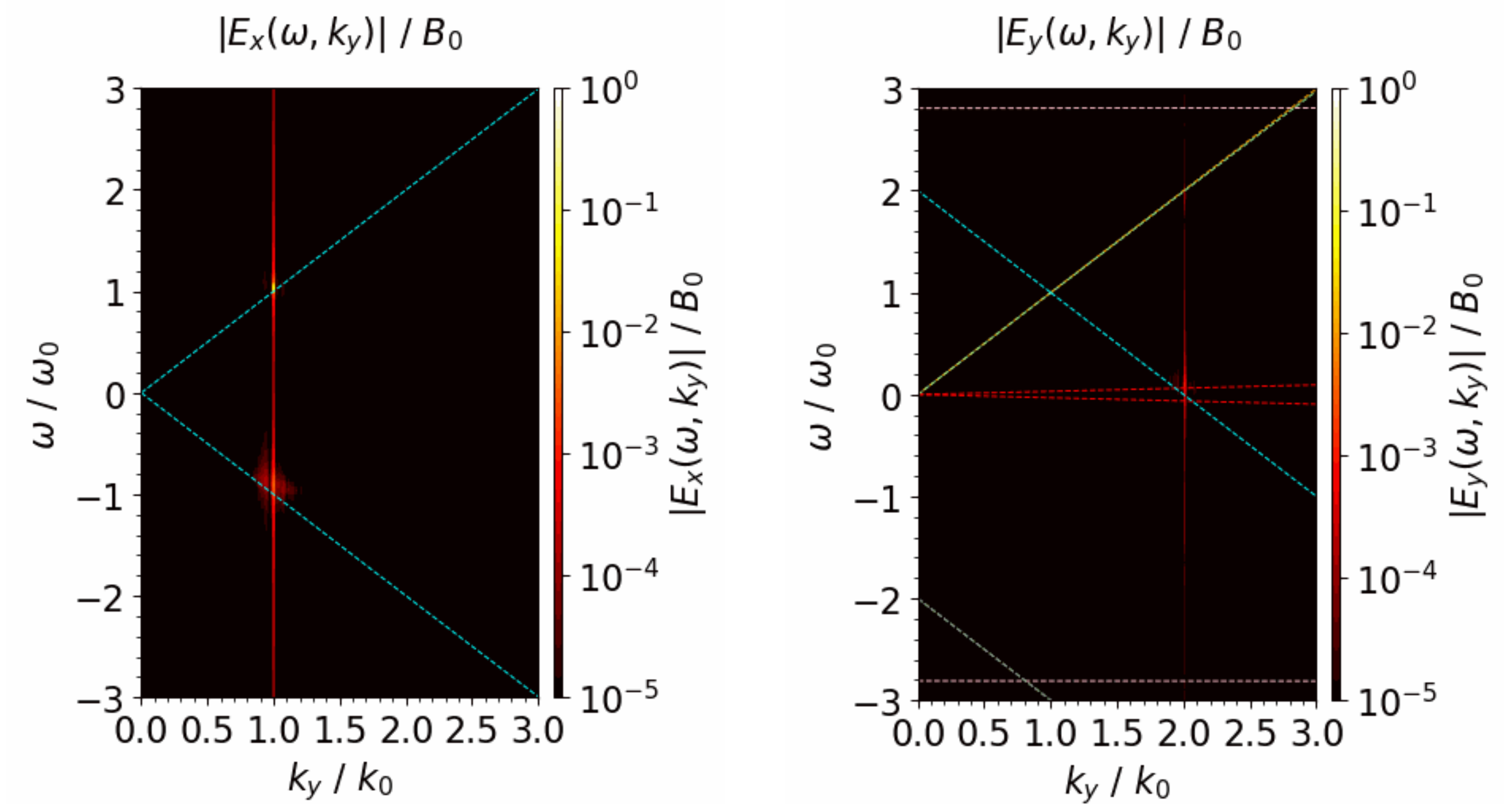
Decay instability

□(Acoustic) decay instability



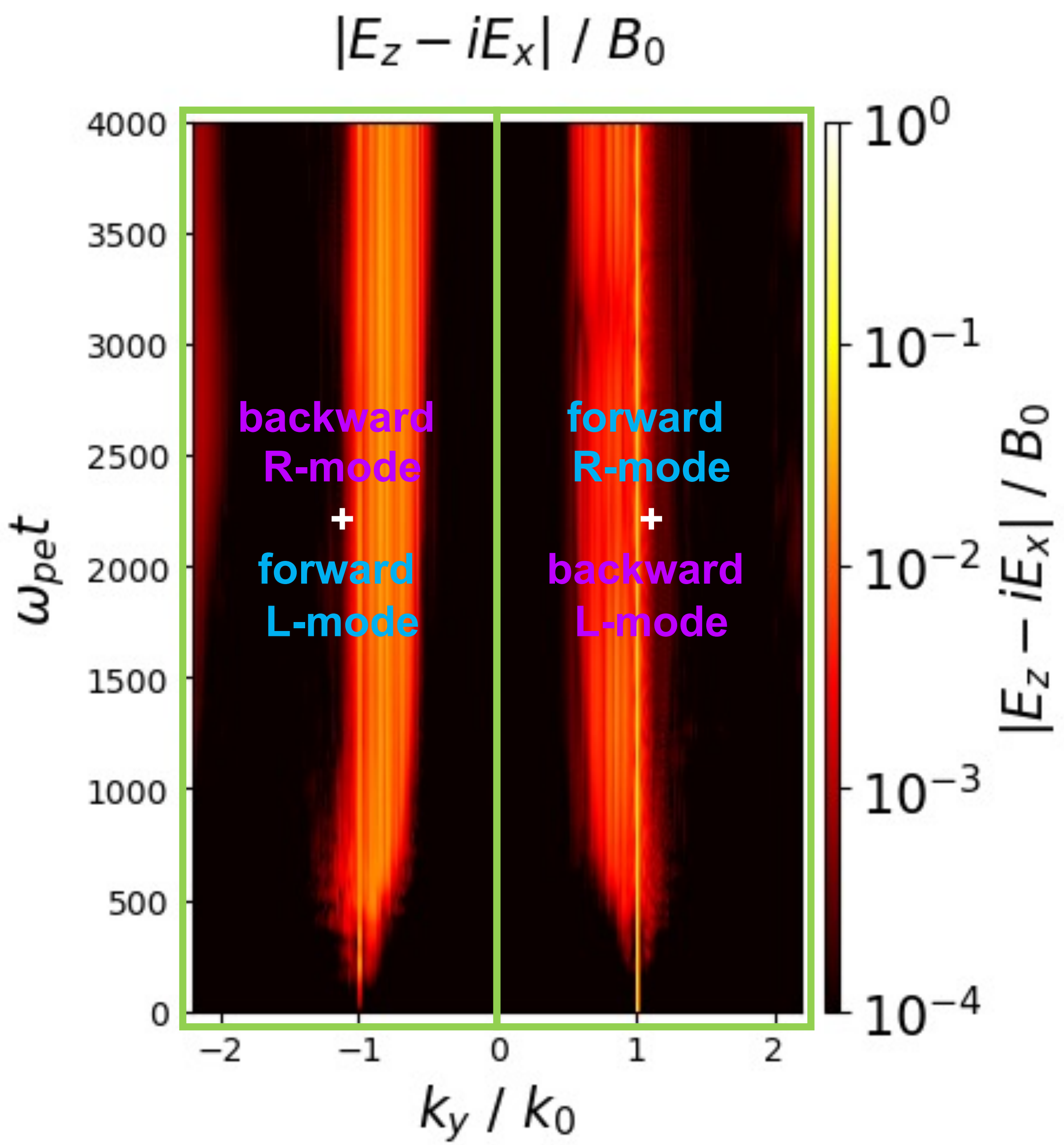


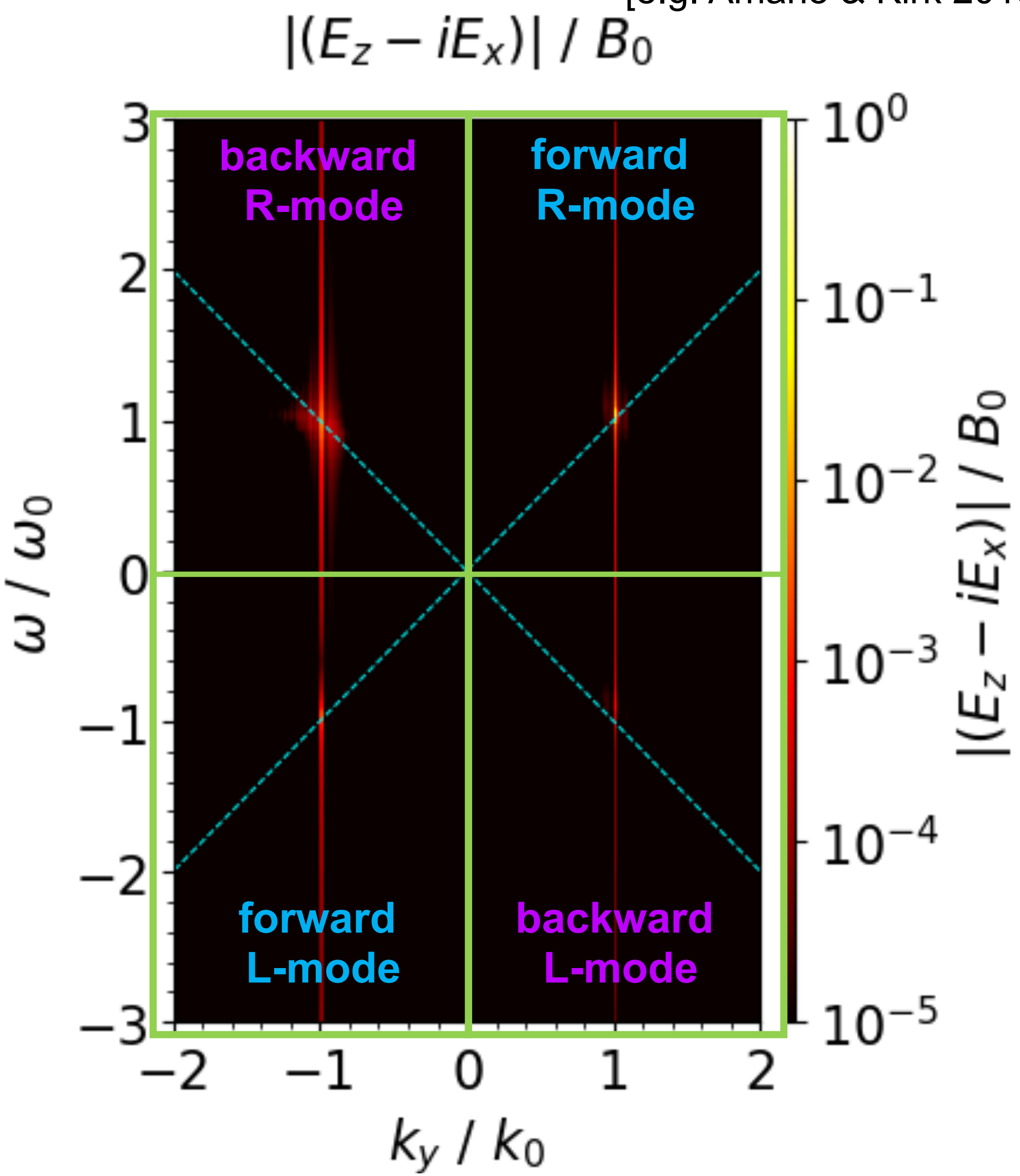
Time evolution of Fourier spectrum



Mode decomposition

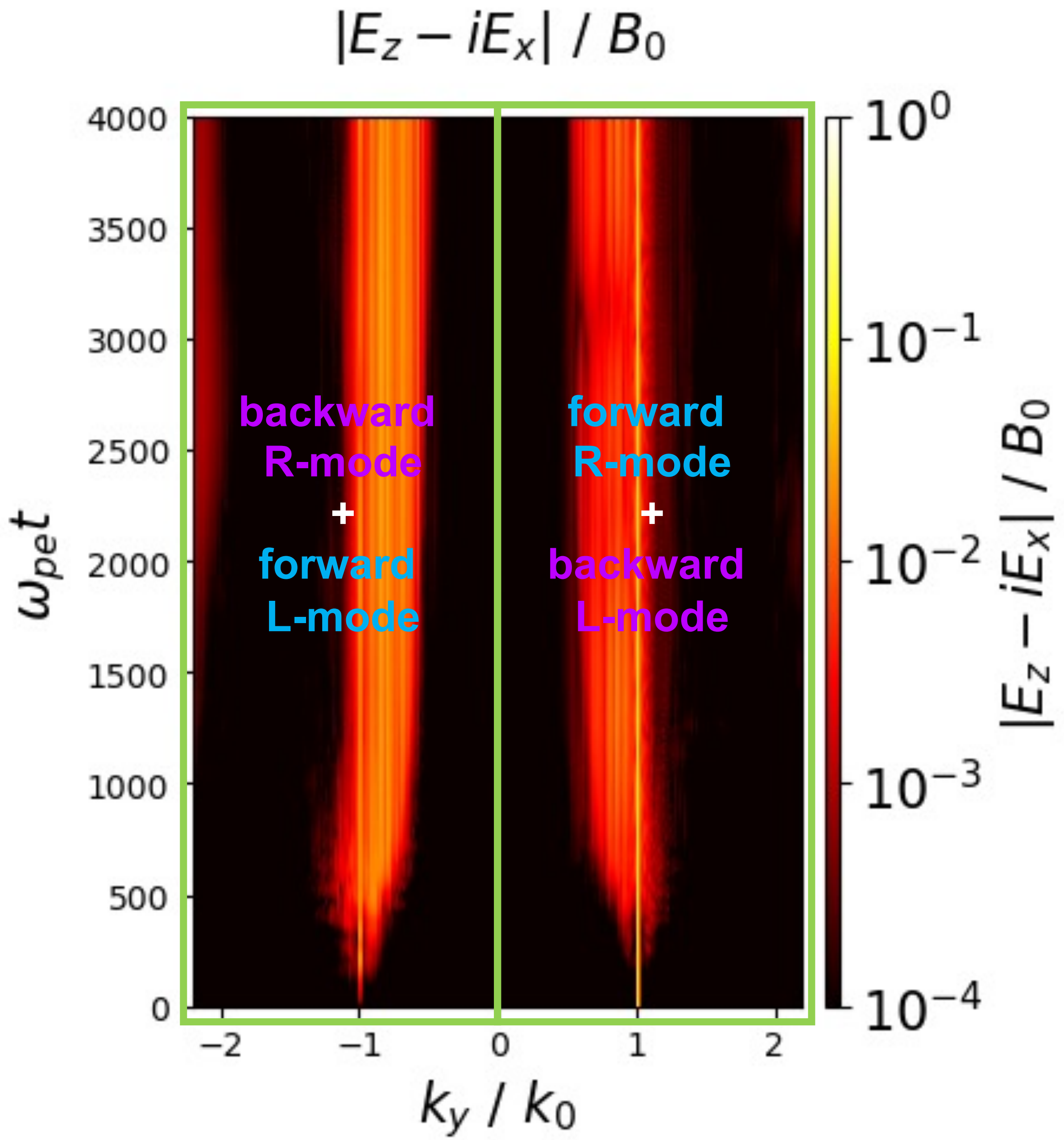
[e.g. Amano & Kirk 2013]

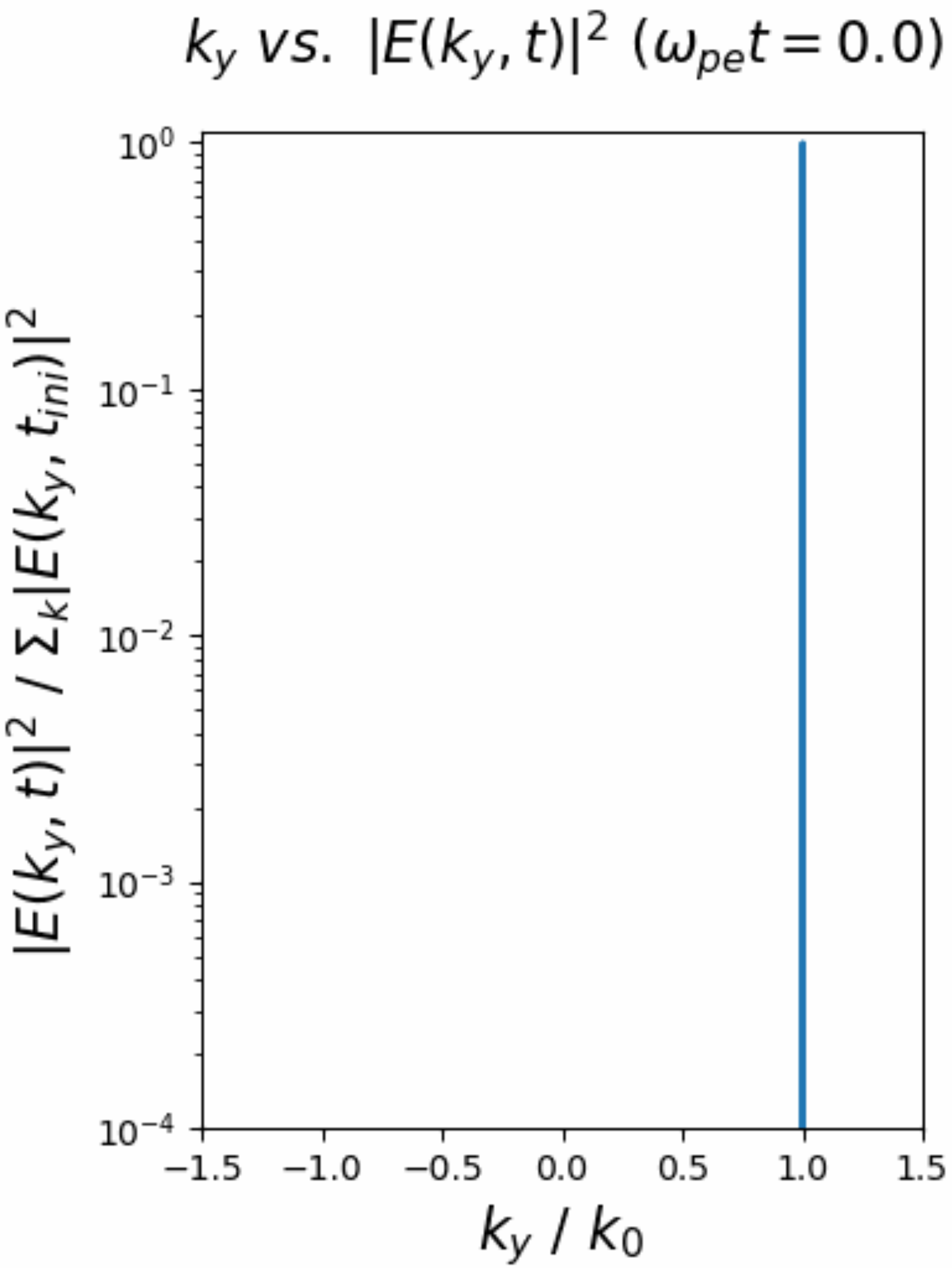




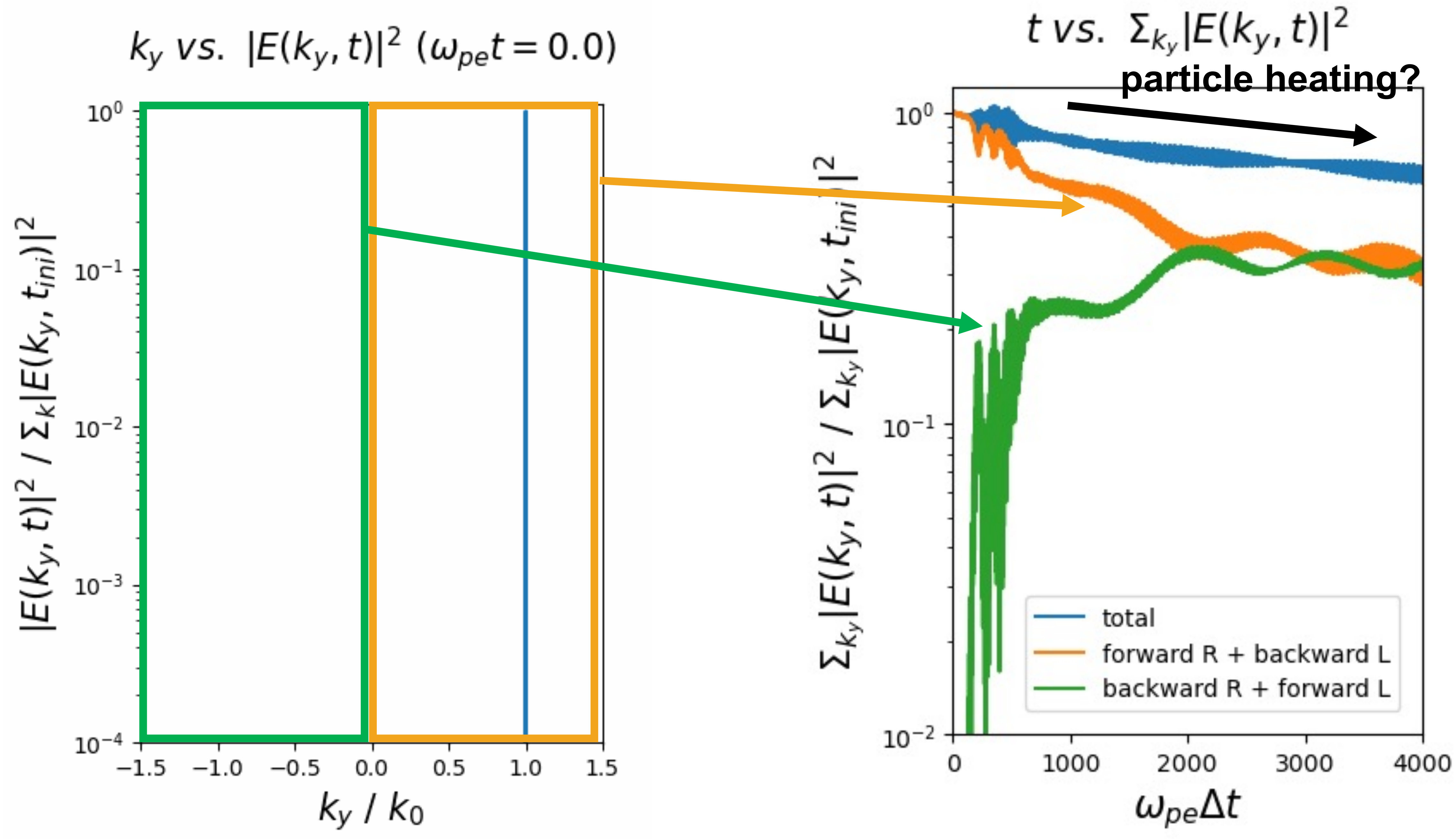
Mode decomposition

[e.g. Amano & Kirk 2013]

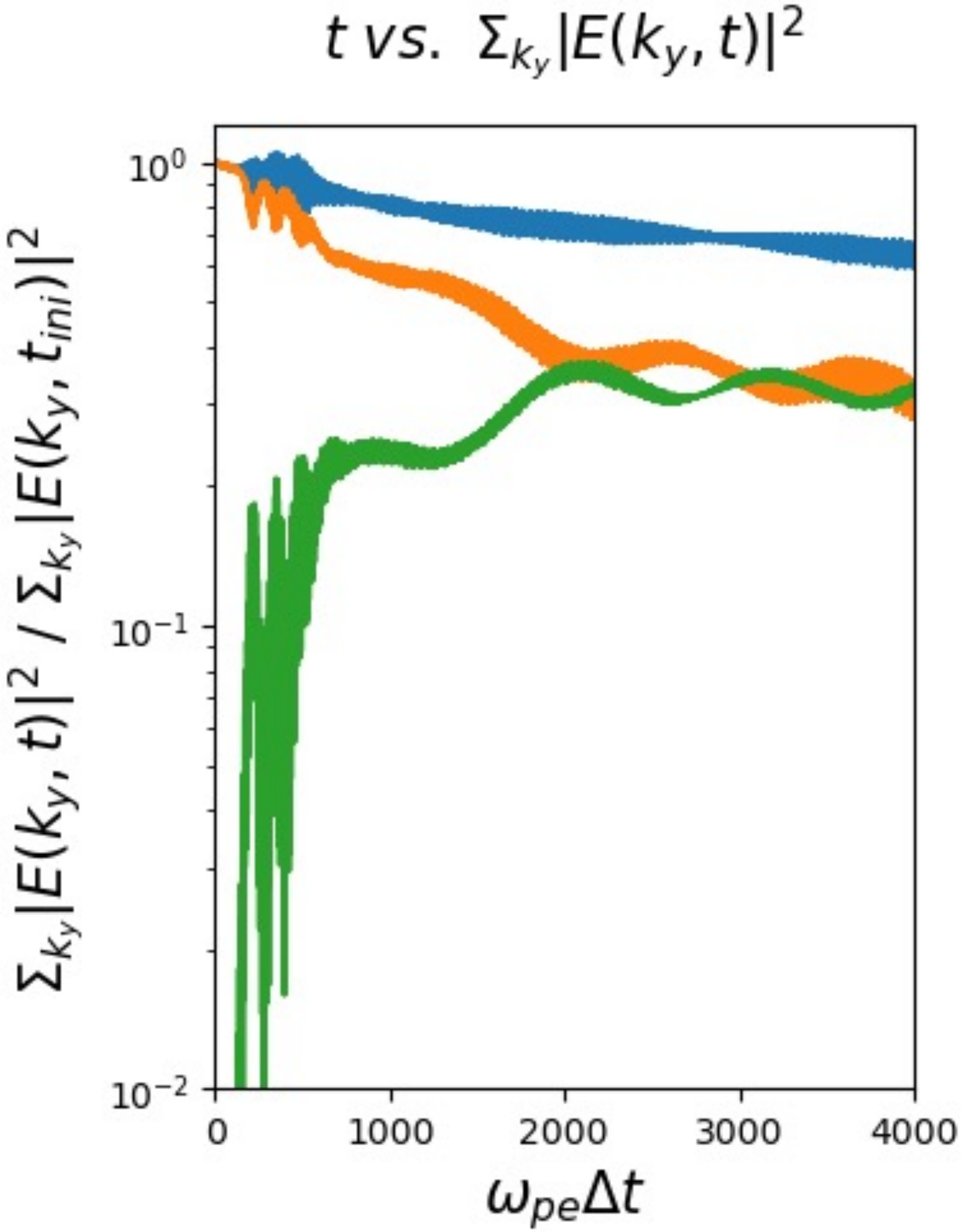




Time evolution of wave power



Time evolution of wave power



30 - 40% of the parent wave power remains. at the end of this simulation.

→ **We will perform long & multidimensional simulations.**

In 2D simulations, waves could decay rapidly compared to 1D simulations.
[Umeda, Saito, & Nariyuki 2018]

Summary & Future Work

- We investigate the Alfvén wave propagation in magnetized pair plasmas by using Particle-in-Cell simulations.
- The acoustic decay instability is confirmed in the early stage.
- Some wave-wave interactions occur, and many waves are generated as time elapses.
- The wave power of forward propagating waves remains 30 – 40 % of the wave power of the incident parent wave.
- We will analyze what wave-wave interactions occur.
- We will perform multi-dimensional PIC simulations.