Unified Kinetic Theory of Induced Scattering in Magnetized Pair Plasma

Theory & application ： Rei Nishiura (Kyoto U.)

Kunihito Ioka (YITP)

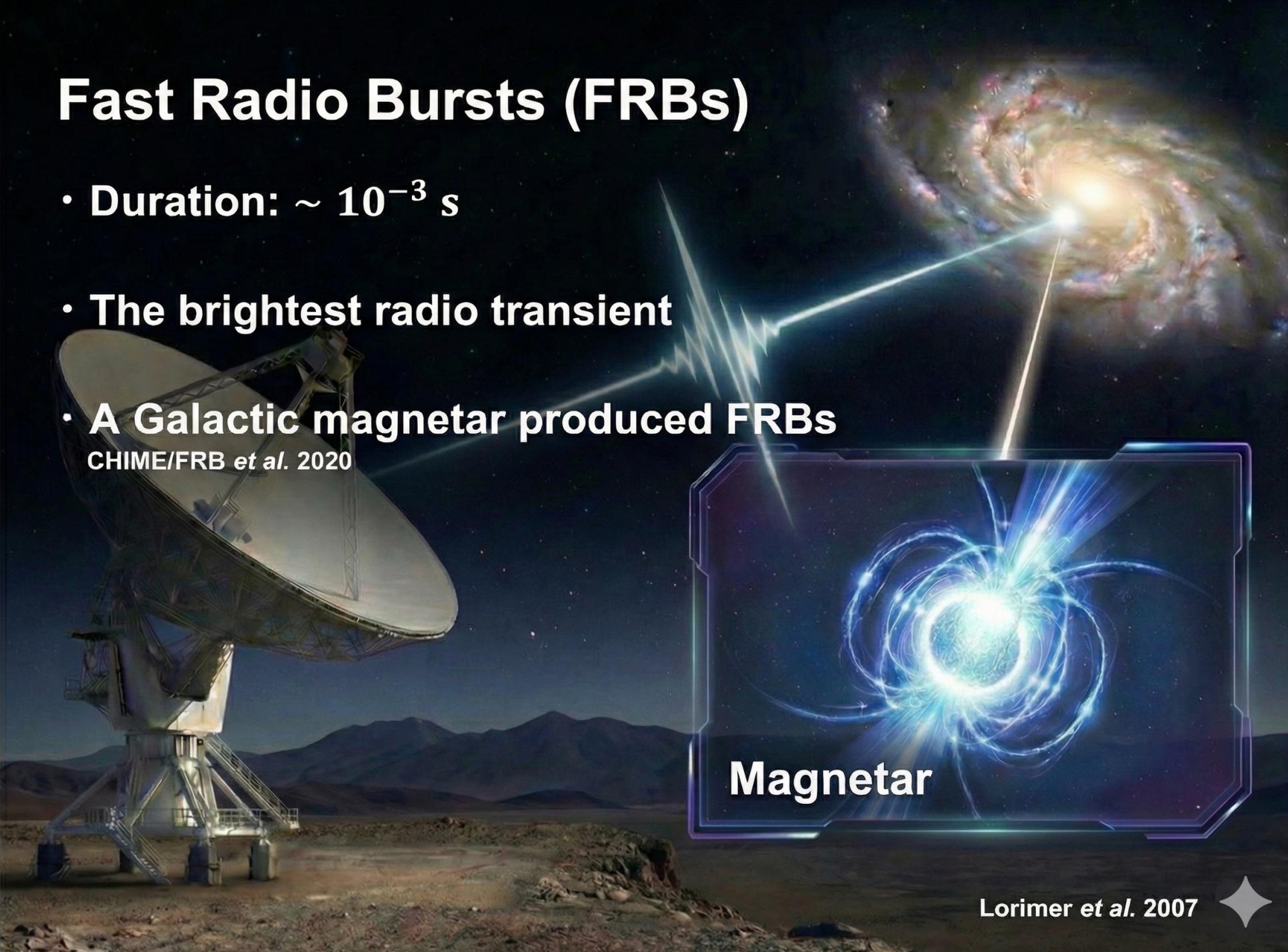PIC Simulation ： Shoma Kamijima (YITP)

Masanori Iwamoto (Kobe U.)

Fast Radio Bursts (FRBs)

- Duration: $\sim 10^{-3}$ s

- The brightest radio transient

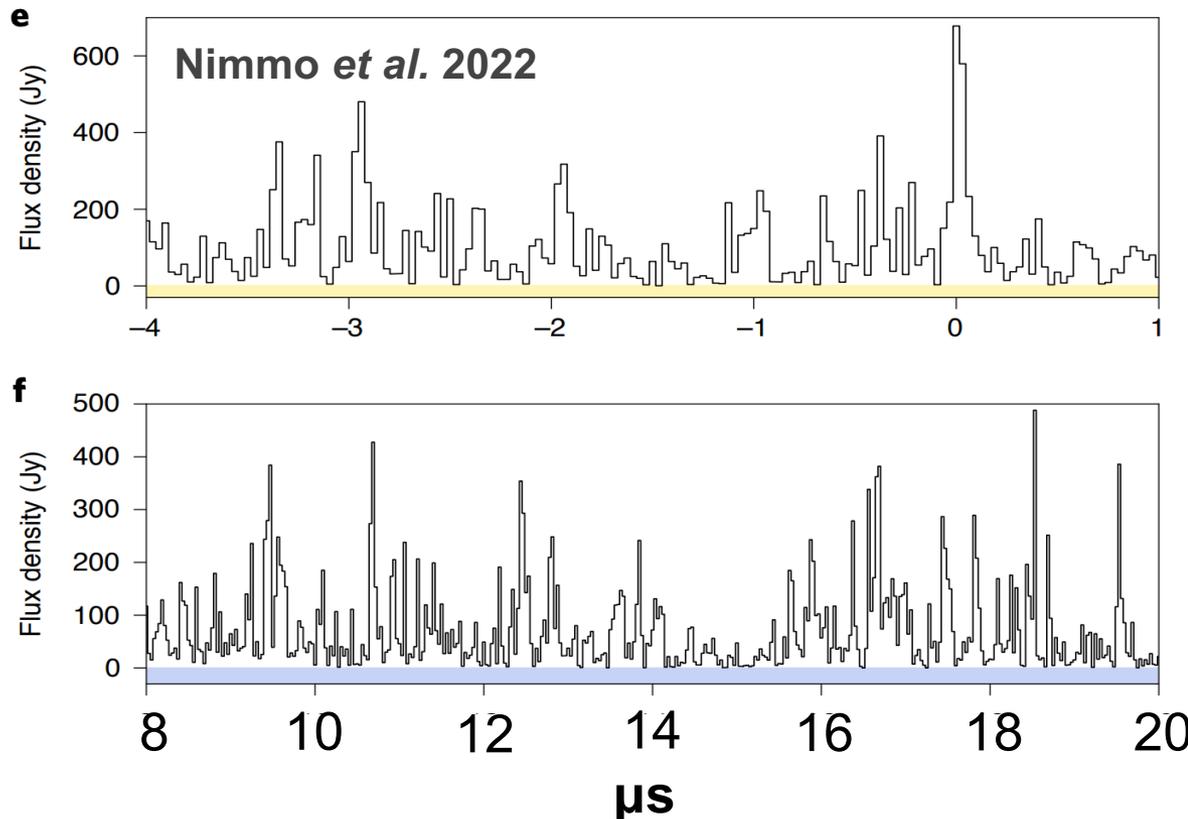- A Galactic magnetar produced FRBs
  CHIME/FRB *et al.* 2020

Magnetar

Lorimer *et al.* 2007

Some observations suggest an FRB emission region is comparable in size to the magnetar magnetosphere.

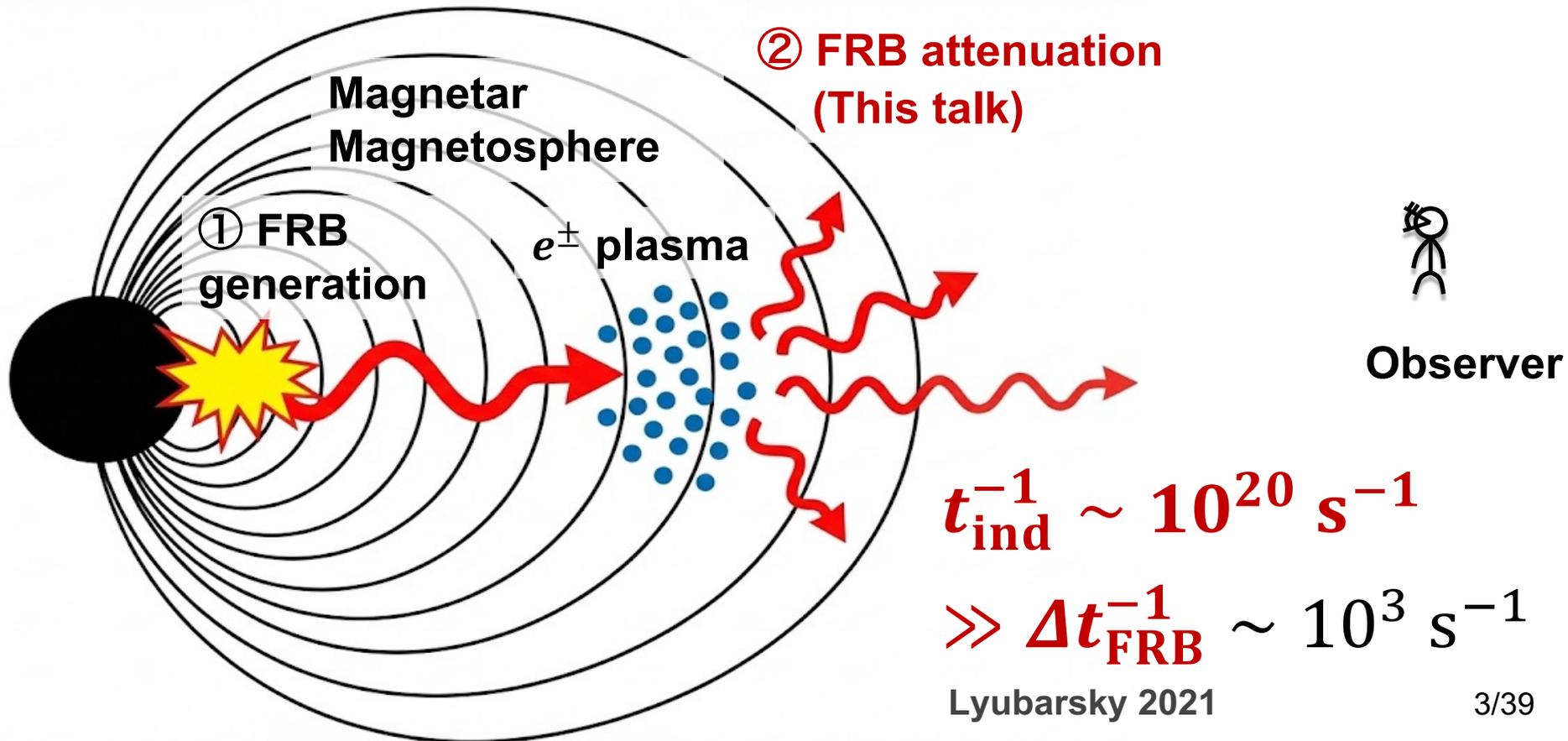- Nanosecond structure in FRBs

Nimmo *et al.* 2022

$$r_{\text{source}} < 3.6 \times 10^9 \text{ cm}$$
$$\times \Gamma_3^2 \Delta t_{60\text{ns}}$$

- FRB Scintillation
  Nimmo *et al.* 2025

- Pulsar-like short-period emission
  CHIME/FRB *et al.* 2022

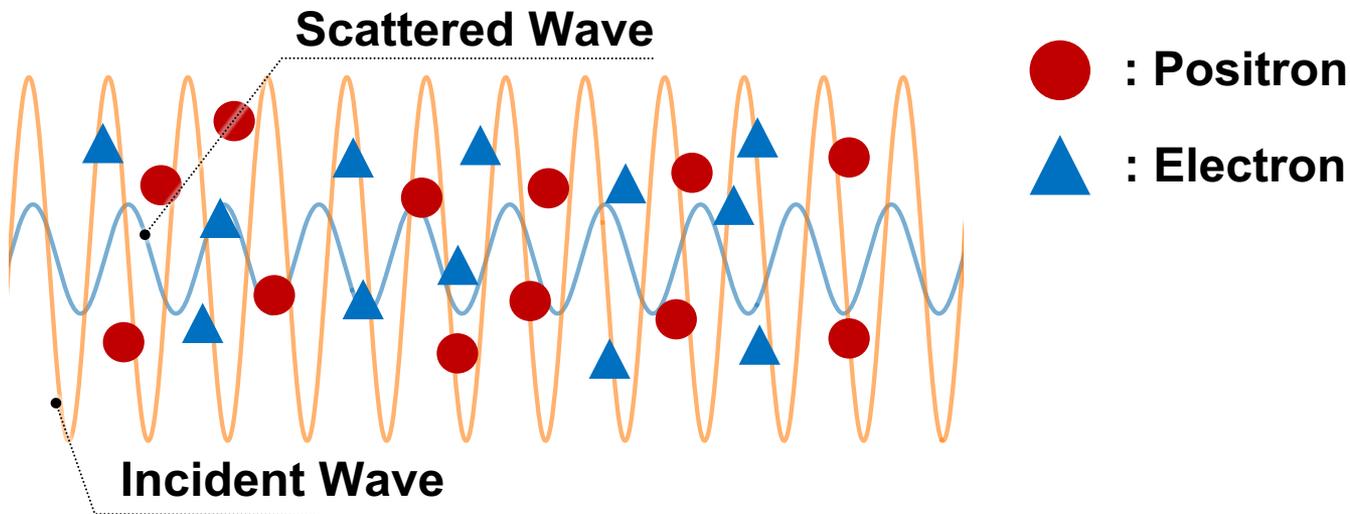**Observations : magnetospheric-size emission region**

Theory : strong induced scattering should attenuate FRBs

② **FRB attenuation (This talk)**

Magnetar Magnetosphere

① **FRB generation**

$e^{\pm}$ **plasma**

Observer

$$t_{\mathrm{ind}}^{-1} \sim 10^{20} \ \mathrm{s}^{-1}$$

$$\gg \Delta t_{\mathrm{FRB}}^{-1} \sim 10^{3} \ \mathrm{s}^{-1}$$

Lyubarsky 2021

The incident wave generates a scattered wave in $e^{\pm}$ plasma.

The incident and scattered waves interfere, producing a beat wave.

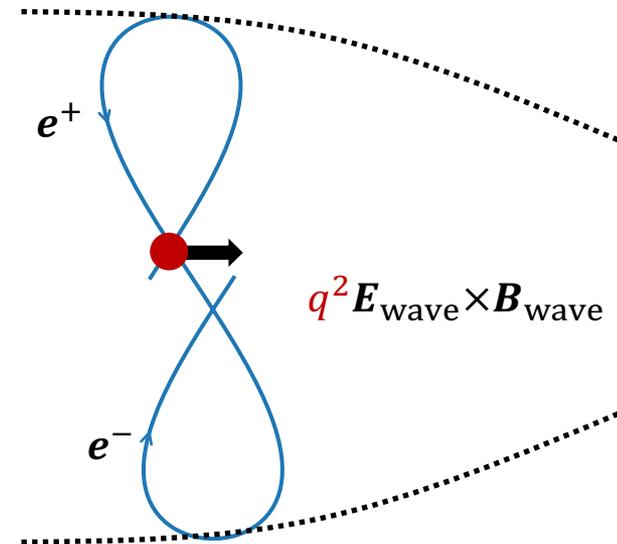Beat Wave

🔴 : Positron

🔺 : Electron
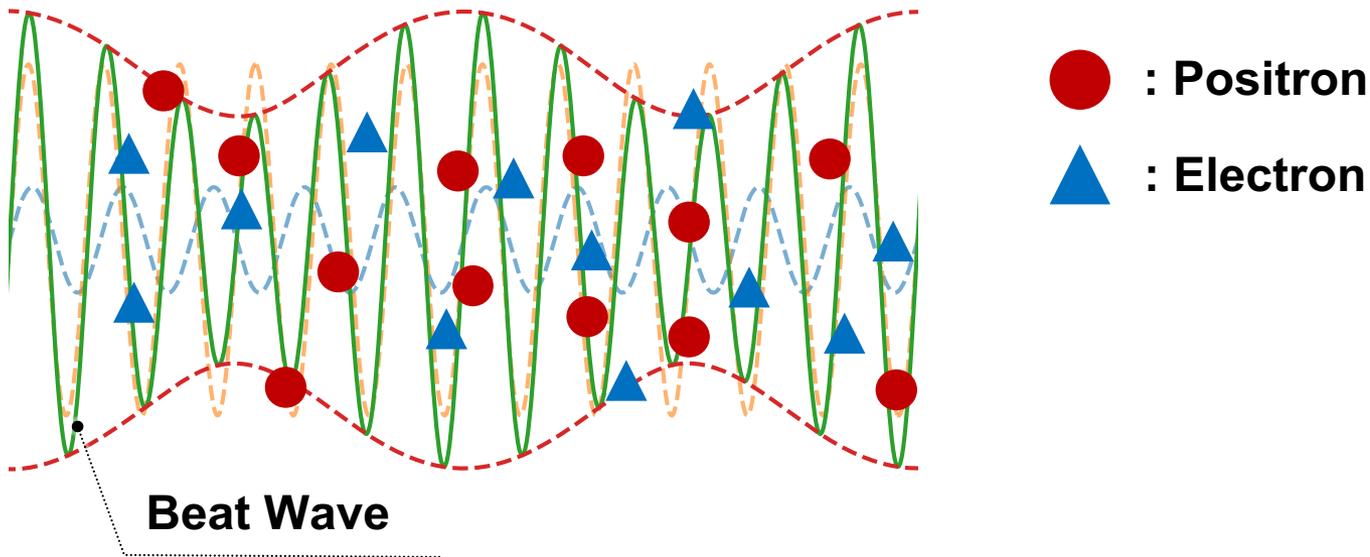
Ponderomotive Force (No Background Magnetic Field)

Charged particles experience a force toward regions of lower amplitude in a slowly varying field.

: Positron

: Electron

e^+

qE_{wave}

e^-

E_{wave}

B_{wave}

e^+

$q^2 E_{\text{wave}} \times B_{\text{wave}}$

e^-

Electromagnetic field amplitude
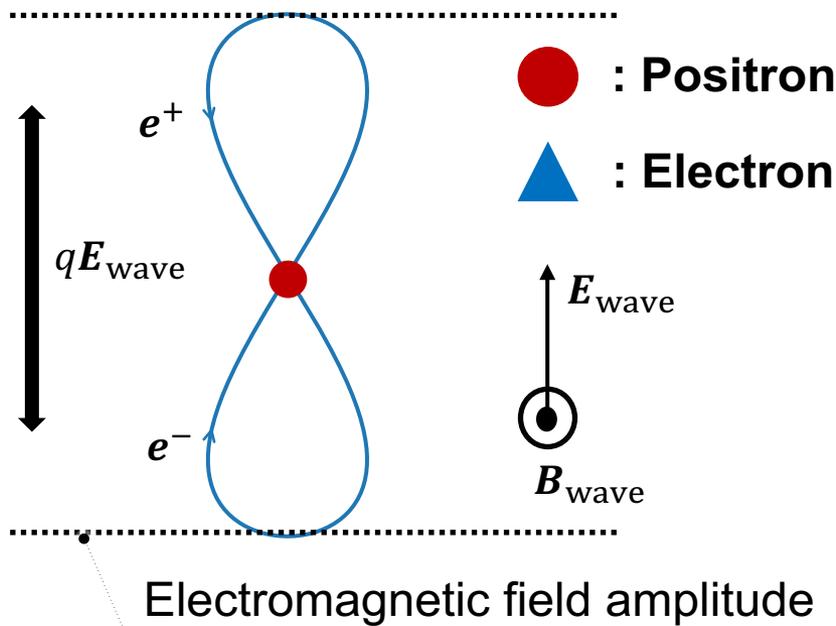
$$m_{\text{e}} \ddot{\boldsymbol{r}}_{0\pm} = -\nabla \phi_{\text{p}}$$

Oscillation Center

$$\phi_{\text{p}} = \frac{e^2}{m_{\text{e}} \omega_0^2} \left\langle \frac{\left| E(\boldsymbol{r}_{0\pm}, t) \right|^2}{2} \right\rangle_{\text{time}}$$

Ponderomotive Potential

The beat wave excites density fluctuations resonantly.

Ponderomotive Force
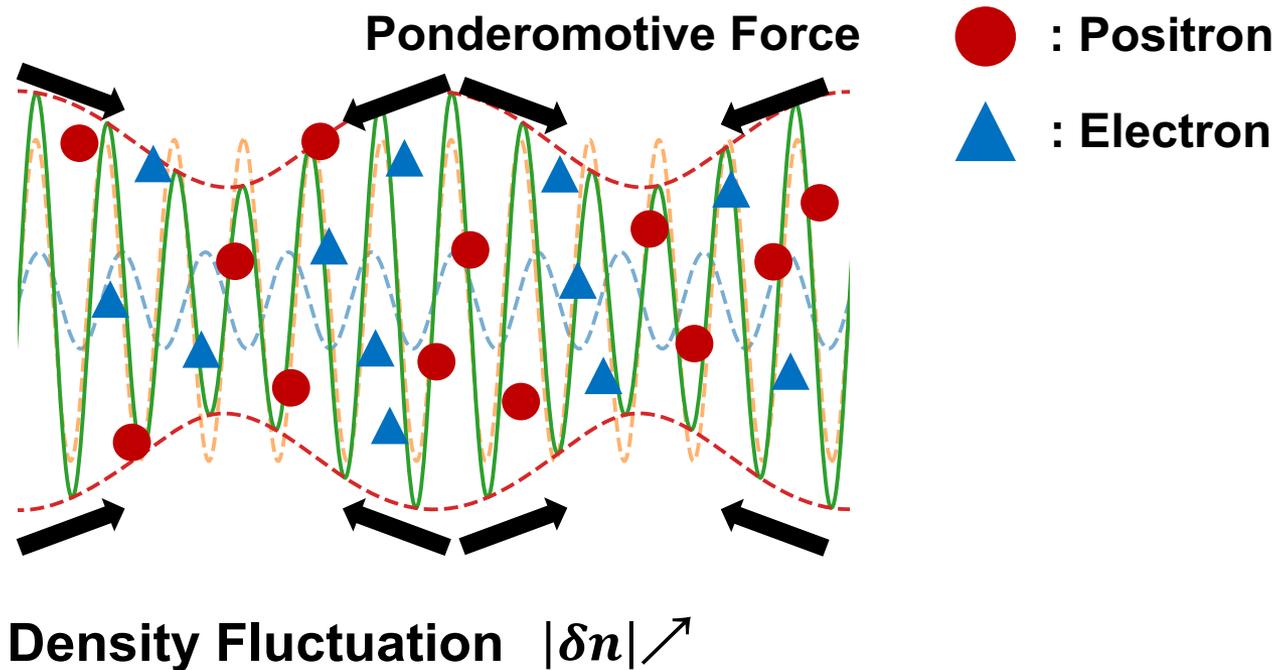
● : Positron

▲ : Electron

Density Fluctuation $|\delta n|\nearrow$

The incident wave is attenuated since it is converted into scattered waves and density fluctuations.
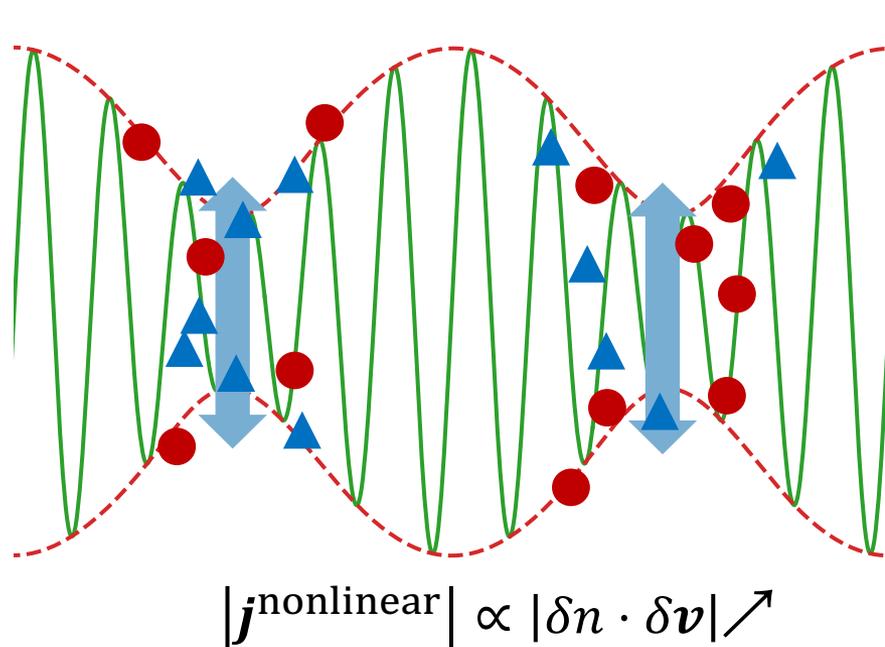
● : Positron

▲ : Electron

- Linear growth rate $[\mathrm{sec}^{-1}]$

$$t^{-1} \sim \mathbf{Im}\, \boldsymbol{\omega}\, (\boldsymbol{\delta B_{\mathrm{w}}}, \boldsymbol{n_{\mathrm{e}}}, \boldsymbol{T_{\mathrm{e}}}, \boldsymbol{\omega_0})$$

$$\left| \boldsymbol{j}^{\mathrm{nonlinear}} \right| \propto |\delta n \cdot \delta v| \nearrow$$

How does the instability behave under magnetar's strong magnetic field ?

We formulated induced scattering in magnetized $e^\pm$ plasma for the first time. Nishiura *et al.* 2025a; 2025b

$$\frac{\partial f_\pm}{\partial t} + \boldsymbol{v} \cdot \frac{\partial f_\pm}{\partial \boldsymbol{r}} + \boldsymbol{F} \cdot \frac{\partial f_\pm}{\partial \boldsymbol{p}} = 0$$

$$\omega_\mathrm{c} = \frac{eB_0}{m_\mathrm{e}c}$$

Cyclotron frequency

$$\boldsymbol{F} = \pm e \left(\boldsymbol{E} + \frac{\boldsymbol{v} \times \boldsymbol{B}_0}{c} \right) - \boldsymbol{\nabla}\phi_\mathrm{p}^\pm$$

Lorentz force   Ponderomotive force

$$\phi_\mathrm{p}^\pm = \frac{e^2}{2m_\mathrm{e}} \left\langle \frac{\left|\boldsymbol{E}_{\mathrm{w}\parallel}\right|^2}{\omega_0^2} + \frac{|\boldsymbol{E}_{\mathrm{w}\perp}|^2}{\omega_0^2 - \omega_\mathrm{c}^2} \pm \mathrm{i}\frac{\omega_\mathrm{c}\widehat{\boldsymbol{B}}_0 \cdot (\boldsymbol{E}_{\mathrm{w}\perp}^* \times \boldsymbol{E}_{\mathrm{w}\perp})}{\omega_0(\omega_0^2 - \omega_\mathrm{c}^2)} \right\rangle$$

$$f_\pm(\boldsymbol{r}, \boldsymbol{v}, t) = f_{0\pm}(\boldsymbol{v}) + \delta f_\pm(\boldsymbol{r}, \boldsymbol{v}, t) \implies$$ **Dispersion relations**

Linear growth rates

We discovered two new instability modes.

Nishiura *et al.* 2025

$$\phi_{\mathrm{p}}^{\pm} = \frac{e^2}{2m_{\mathrm{e}}} \left\langle \frac{|\boldsymbol{E}_{\mathrm{w}\perp}|^2}{\omega_0^2 - \omega_{\mathrm{c}}^2} \right. \qquad \pm\, \mathrm{i}\, \frac{\omega_{\mathrm{c}} \widehat{\boldsymbol{B}}_0 \cdot (\boldsymbol{E}_{\mathrm{w}\perp}^* \times \boldsymbol{E}_{\mathrm{w}\perp})}{\omega_0 (\omega_0^2 - \omega_{\mathrm{c}}^2)} \left. \right\rangle$$

Neutral mode   **Charged mode**
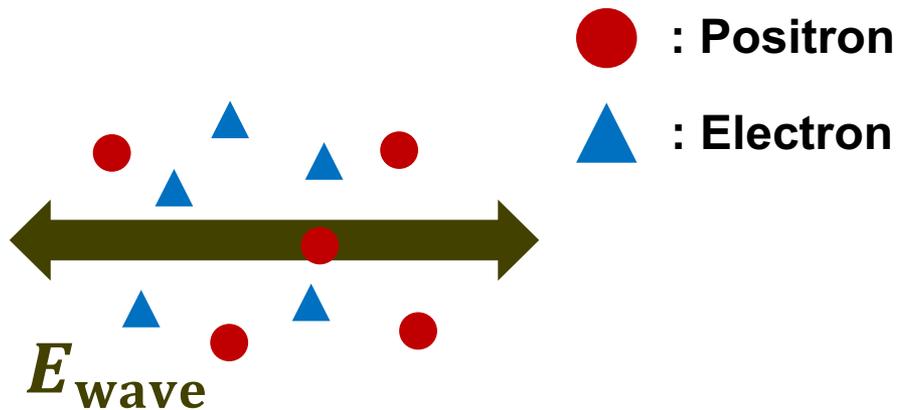
● : Positron

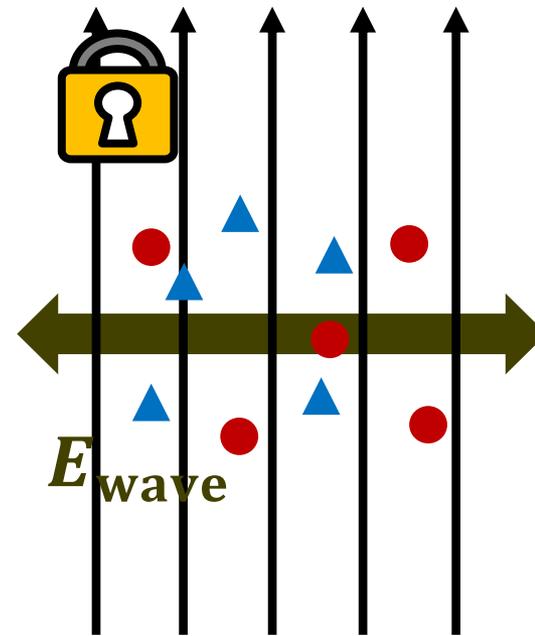▲ : Electron
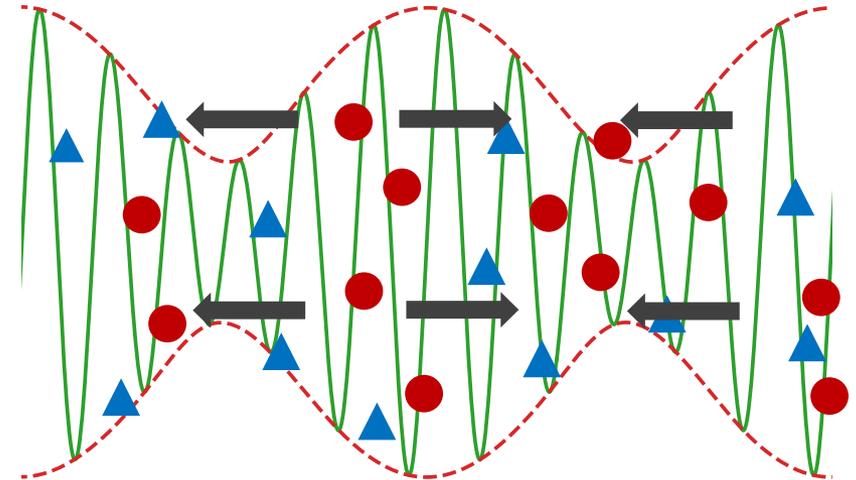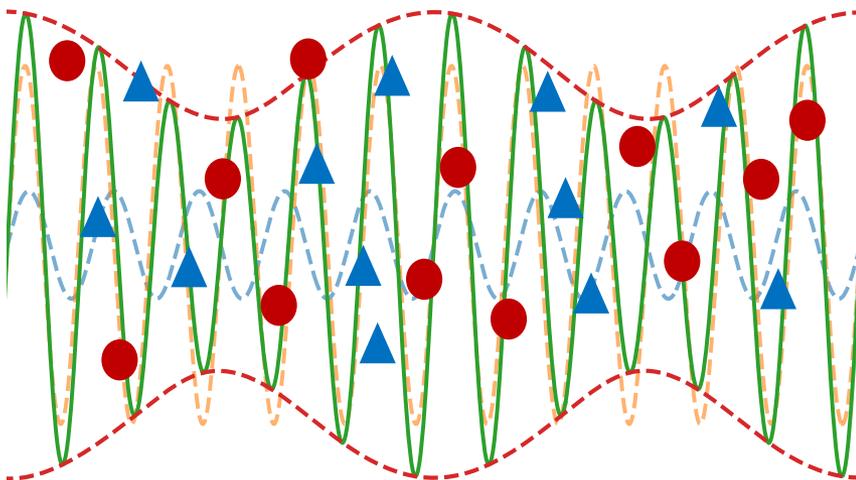
Electrostatic wave

Scattering Suppression by a Strong Magnetic Field

The linear growth rates are strongly suppressed by the background magnetic field.

$B_0 = 0$

Strong B_0

● : Positron

▲ : Electron

E_{wave}

E_{wave}

Suppression factor $\propto \left(\dfrac{\omega_0}{\omega_c}\right)^{\alpha}$

$\alpha > 0$

Even if B_0 makes the linear growth slower, we still need to consider the nonlinear evolution.
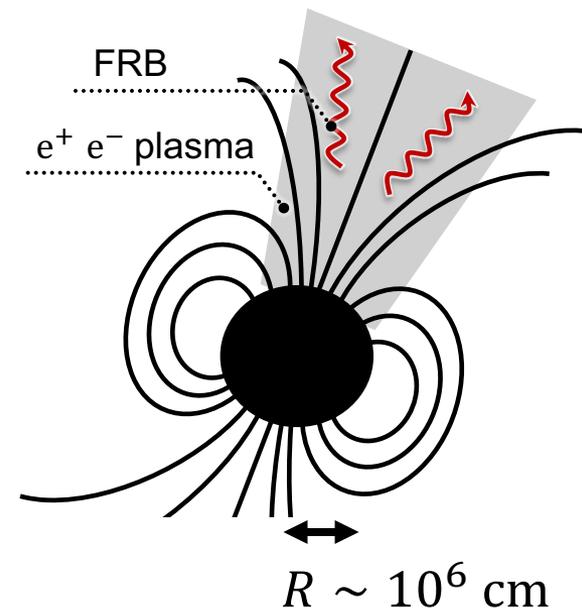
$$t_{\text{ind}}^{-1}(B_0 = 0) \sim 10^{20}\ \text{s}^{-1}$$

- Dipolar magnetic field model
  Goldreich & Julian 1969

$$t_{\text{charged}}^{-1} \sim 4.6 \times 10^2\ \text{s}^{-1}\ \frac{Pr_8^7 L_{40} \nu_9^3 T_{80\text{keV}}^2}{B_{\text{p},14}^3 \mathcal{M}_8 R_{\text{NS},6}^9}$$

$$t_{\text{neutral}}^{-1} \sim 1.9 \times 10^2\ \text{s}^{-1}\ \frac{r_8^7 \nu_9 L_{40} \mathcal{M}_8}{B_{\text{p},14}^3 P R_{\text{NS},6}^9}$$

$$\Delta t_{\text{FRB}}^{-1} = 10^3\ \text{s}^{-1} \sim t_{\text{charged}}^{-1} \sim t_{\text{neutral}}^{-1}$$

FRB

$e^+\ e^-$ plasma

$R \sim 10^6$ cm

Even if B_0 makes the linear growth slower, we still need to consider the nonlinear evolution.

$t_{\mathrm{ind}}^{-1}(B_0 = 0) \sim 10^{20} \mathrm{\ s^{-1}}$

FRB

We test using particle-in-cell (PIC) simulations:

Kamijima, Nishiura,
Iwamoto, & Ioka 2026

- Validate the analytic linear growth rates.

- Explore the evolution beyond the linear stage.

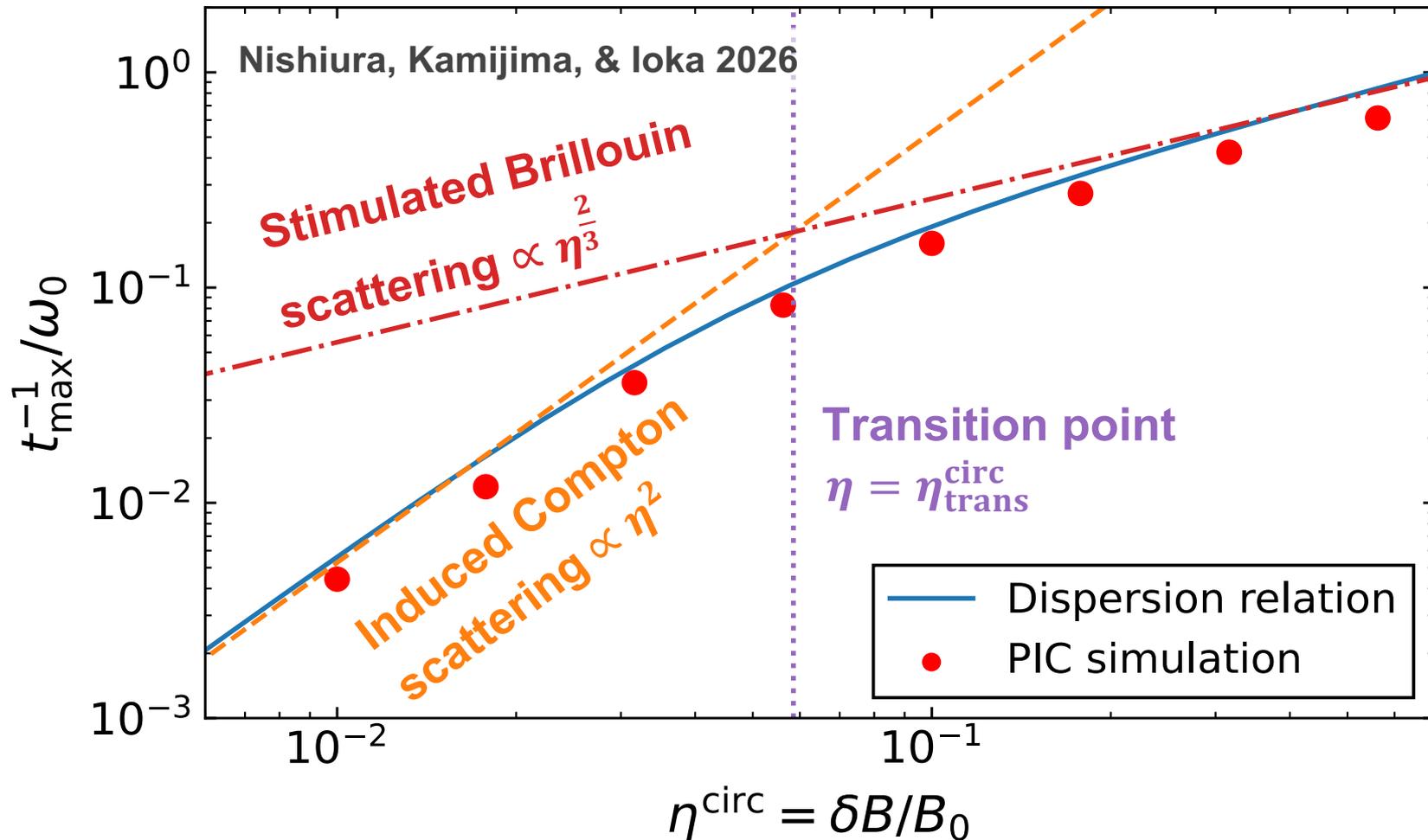- 1D $e^{\pm}$ plasma + Uniform $\boldsymbol{B_0}$ + Circular polarized Alfvén wave

$t_{\mathrm{neutral}} \sim 1.9 \times 10$ s

$\overline{B_{\mathrm{p},14}^3 P R_{\mathrm{NS},6}^9}$

$\Delta t_{\mathrm{FRB}}^{-1} = 10^3 \mathrm{\ s^{-1}} \sim t_{\mathrm{charged}}^{-1} \sim t_{\mathrm{neutral}}^{-1}$

Linear growth rates of neutral mode reproduced in PIC.

Nishiura, Kamijima, & Ioka 2026

Stimulated Brillouin scattering $\propto \eta^{\frac{2}{3}}$

Induced Compton scattering $\propto \eta^2$

Transition point
$\eta = \eta_{trans}^{circ}$

— Dispersion relation
• PIC simulation

t_{max}^{-1}/ω_0

$\eta^{circ} = \delta B/B_0$

- The errors relative to the analytic values are **within 16-28%.**

Full scattering

Low incident wave energy

Partial scattering

High incident wave energy
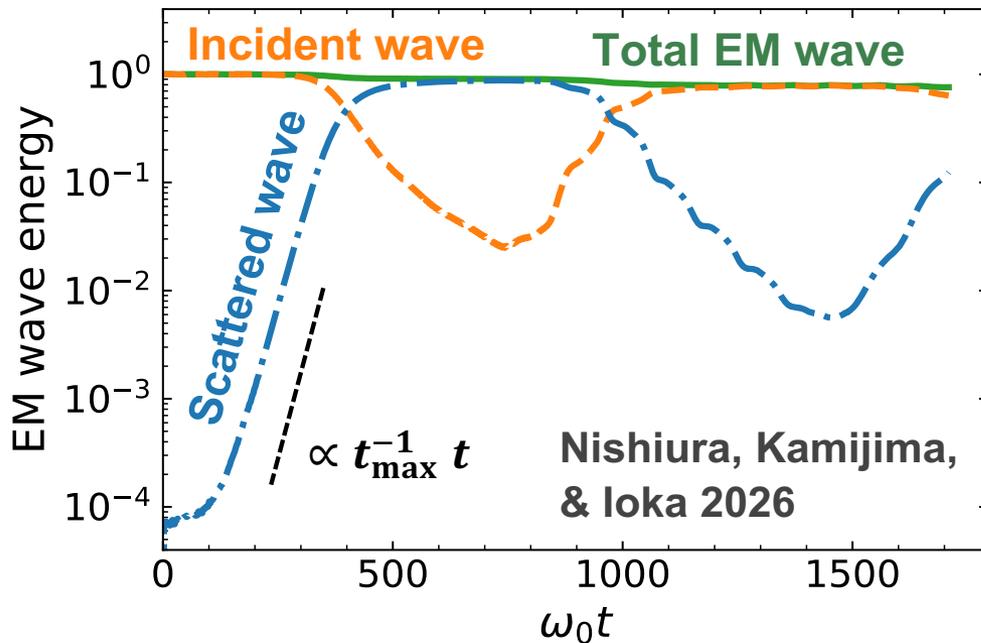
- Local energy oscillations

➡ **Effective attenuation** from
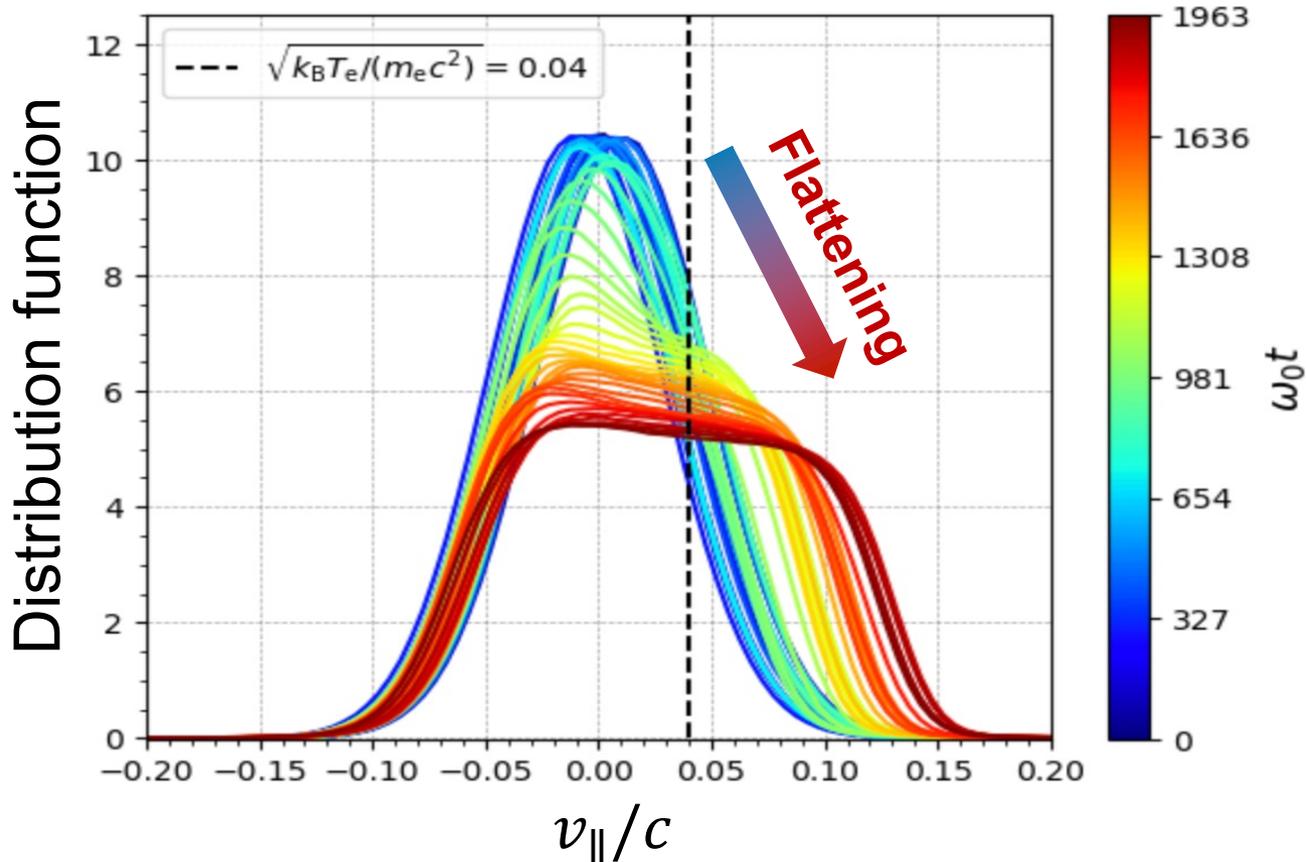
  incomplete cycles in fresh plasma.
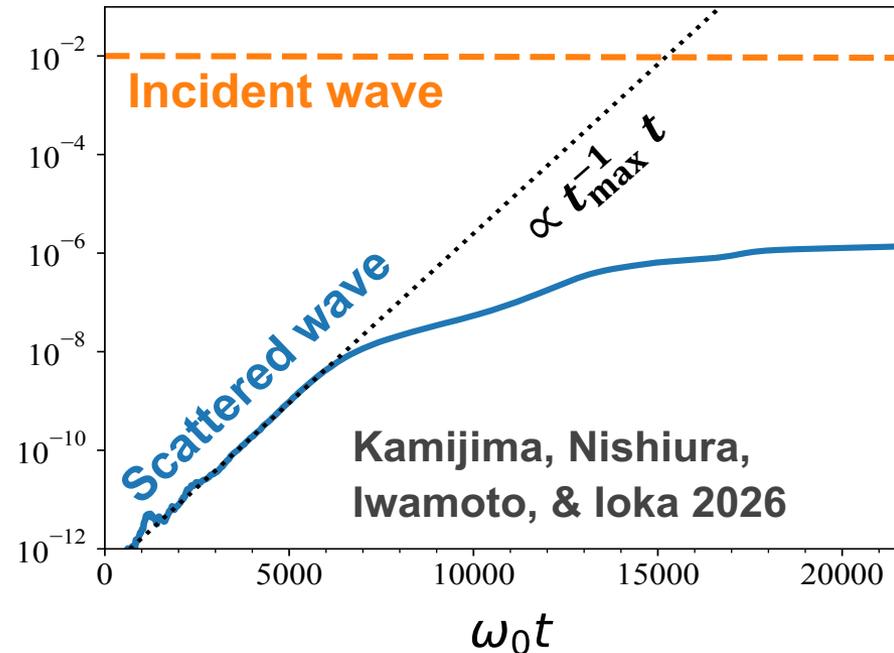
- Saturation → **little attenuation**

The instability ceases once the distribution function become flat.

(instability drive)

$$\propto -\frac{\partial f_\pm}{\partial \boldsymbol{p}} \to 0$$
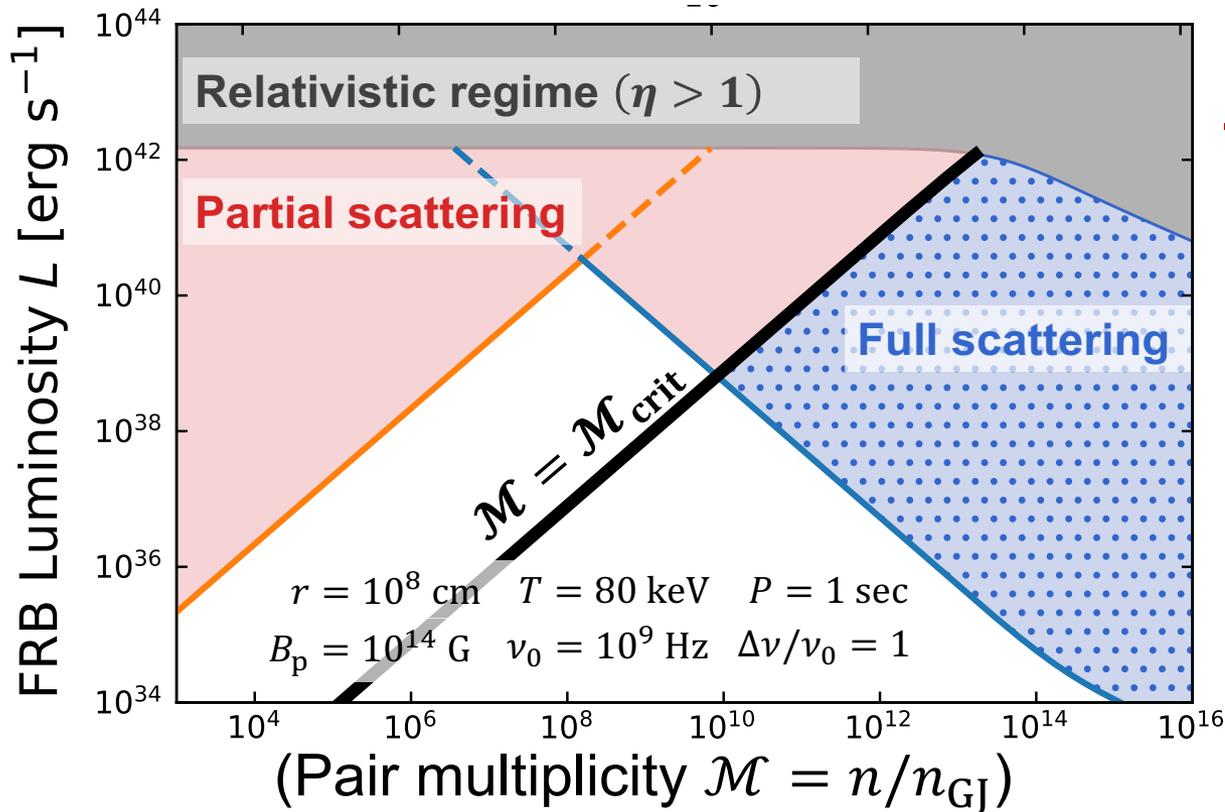
Wave energy

↓

Internal energy

↓

Flattening

Induced scattering saturates if the incident wave energy is larger than the plasma initial internal energy.

Magnetization σ_B

10^{10} $\qquad$ 10^8 $\qquad$ 10^6 $\qquad$ 10^4 $\qquad$ 10^2 $\qquad$ 10^0 $\qquad$ 10^{-2}

Nonlinear regime $(\boldsymbol{\eta > 1})$

Partial scattering

$L = L_{\text{neutral}}$

SBS

Charged ICS

Neutral ICS

Full scattering

$T = 80 \text{ keV}$

$\Delta v / v_0 = 1$

(Pair multiplicity $\mathcal{M} = n/n_{\text{GJ}}$)

No induced scattering

$L = L_{\text{charged}}$

$r = 10^8 \text{ cm}$ $\qquad$ $P = 1 \text{ sec}$

$B = 10^{14} \text{ G}$ $\qquad$ $v = 10^9 \text{ Hz}$

tion.

$< 10^{11}$

$\dfrac{\Delta t_{-3}}{T_{80\text{keV}}}$

sphere.

Partial scattering

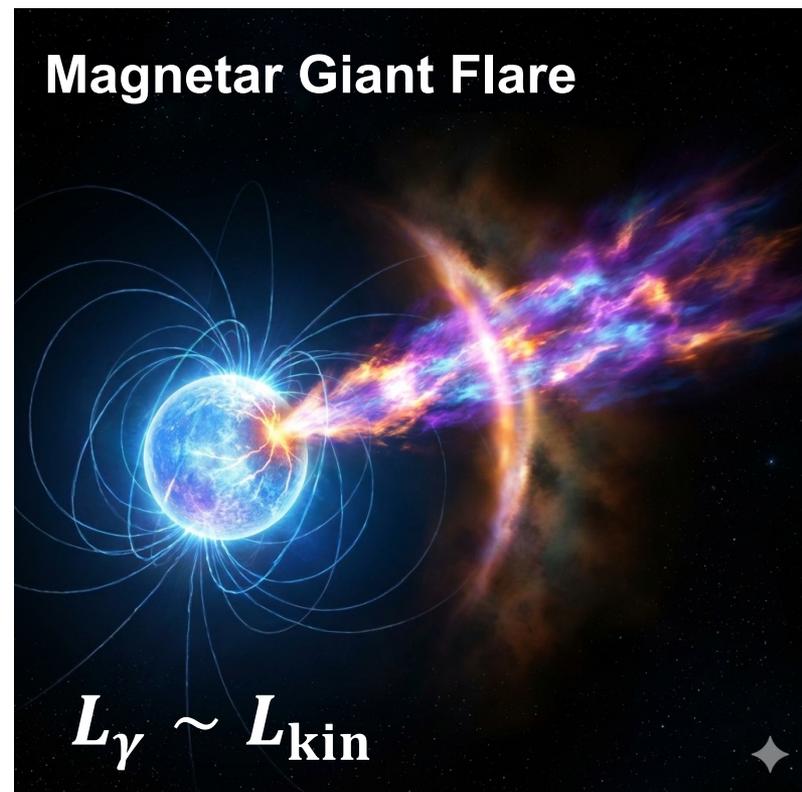$$(\mathcal{M} < \mathcal{M}_{\mathrm{crit}})$$

FRB

$e^+ e^-$ plasma
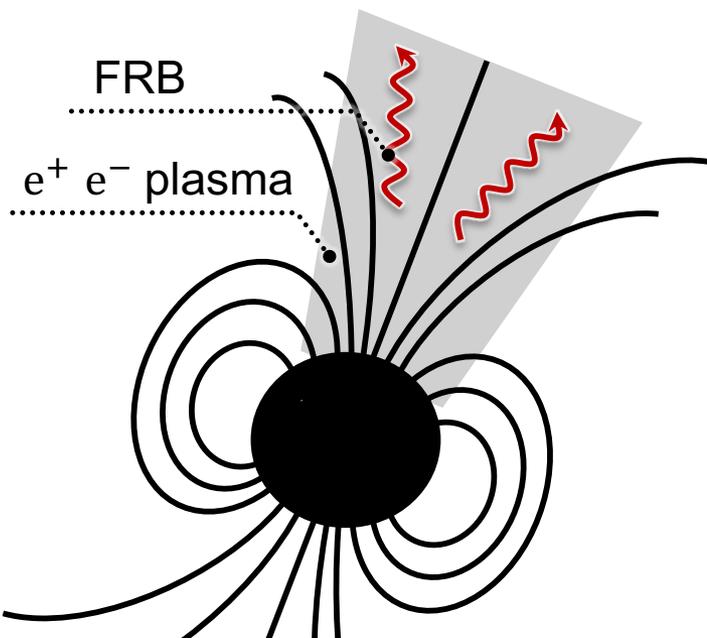
- Magnetosphere-sized

  emission region

  Nimmo *et al.* 2022; 2025; CHIME/FRB Collaboration 2022

Full scattering

$$(\mathcal{M} > \mathcal{M}_{\mathrm{crit}})$$

Magnetar Giant Flare

$$L_\gamma \sim L_{\mathrm{kin}}$$

- Non-detection of FRBs with giant flare

  Gaensler *et al.* 2005; Gelfand *et al.* 2005

Conclusion

Can FRBs survive induced scattering and escape the magnetar magnetosphere?

Yes：if the plasma is not extremely dense
(need to consider the relativistic regime)

No：if a large amount of plasma is ejected

Kamijima-san's Poster

arXiv: 2601.18865 (Today)