マルチメッセンジャー天文学の展開

相対論的イオン･電子衝撃波からのコヒーレント放射

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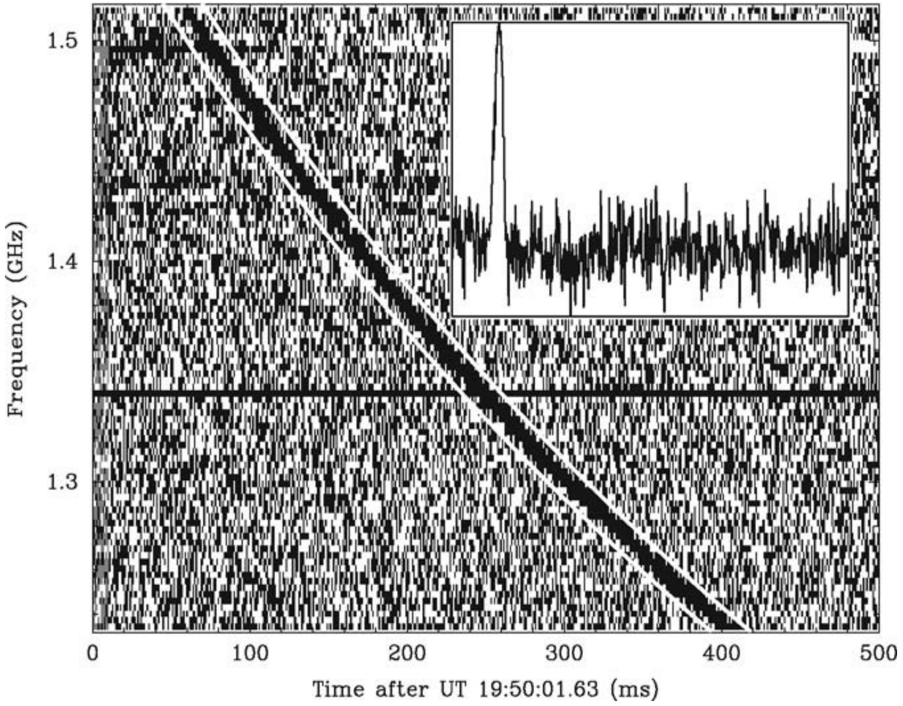
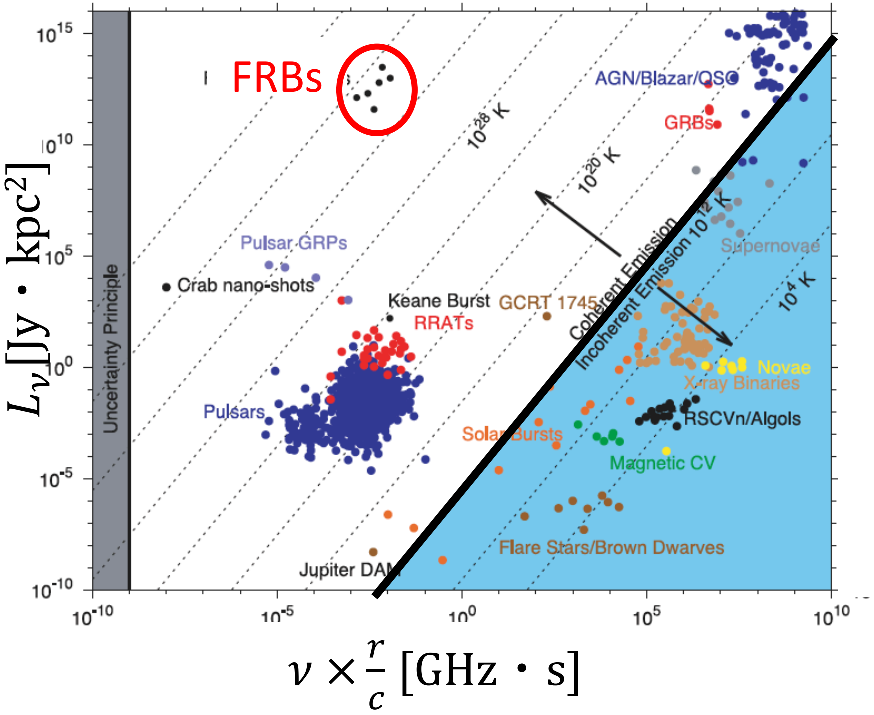
Fast Radio Bursts(FRB)

- ✓ Millisecond-duration intense pulses at radio frequency(Lorimer+ 2007)
- ✓ Extraordinarily high brightness temperature
  →coherent emission (=emission from electron bunches)

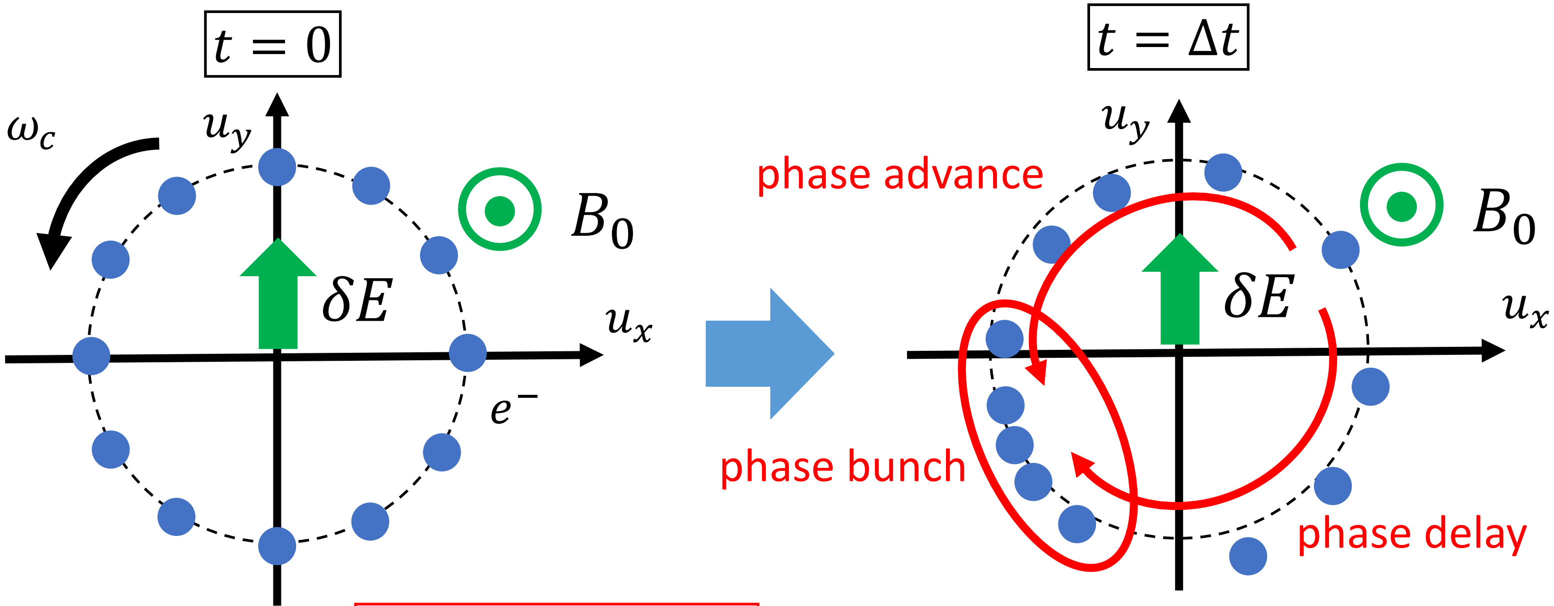
[Lorimer+ 2007]



[Pietka+ 2015]



Synchrotron Maser Instability (SMI)



$$\boxed{\omega_c = \frac{eB}{\gamma mc}}$$

Accelerated e^-→ phase delay
Decelerated e^-→ phase advance

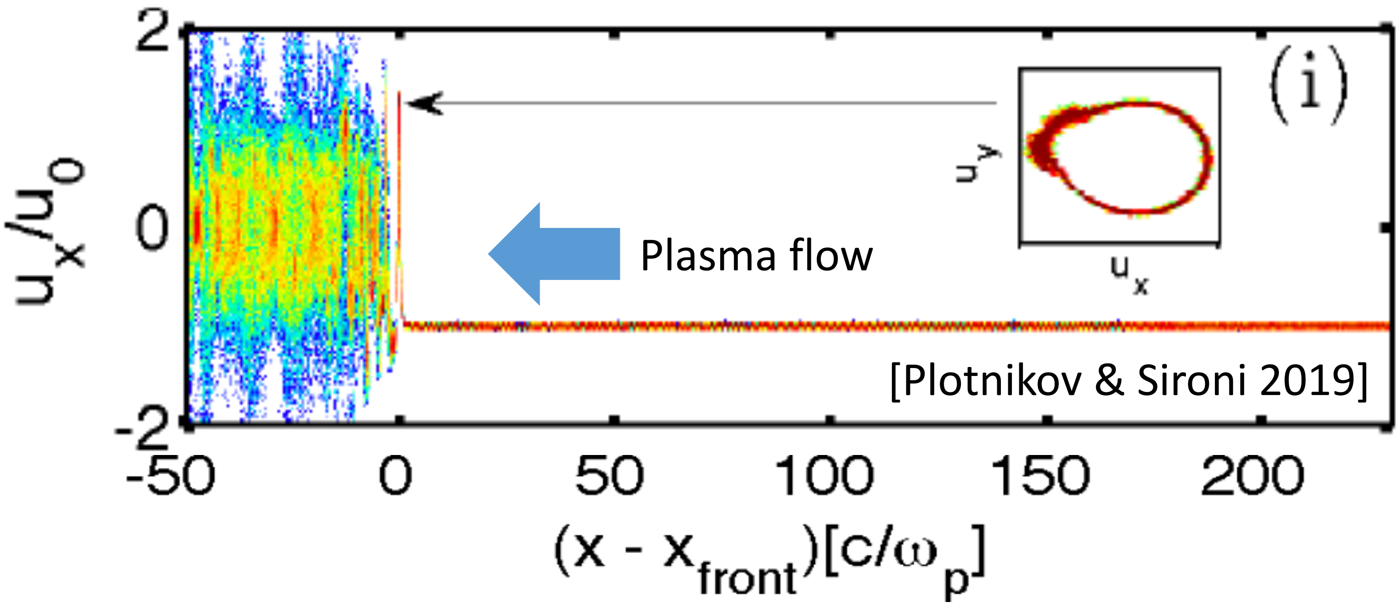
$$\Delta\theta \simeq \left(1 - \frac{\Delta\gamma}{\gamma_0}\right)\frac{eB_0}{\gamma_0 mc}\Delta t = \left(1 + \frac{e\delta E v_y \Delta t}{\gamma_0 m_e c^2}\right)\omega_{c0}\Delta t$$

SMI naturally excite coherent waves

SMI in Relativistic Magnetized Shocks

- ✓ Electrons begin to gyrate at the shock front
  →induce SMI (Hoshino & Arons 1991)
- ✓ Previous simulations demonstrated the coherent emission from relativistic magenetized shocks (e.g., Hoshino+ 1992, Iwamoto+ 2017)
  →Relativistic magnetized shocks are a natural source of coherent emission

←Downstream Shock front Upstream→

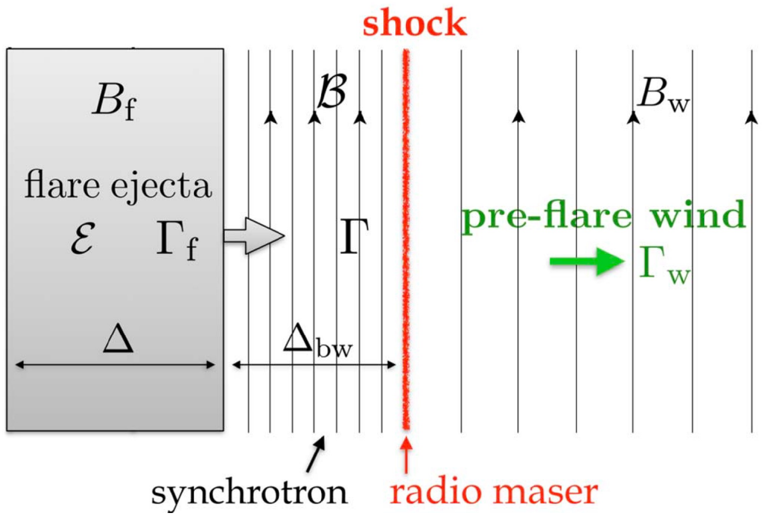


[Plotnikov & Sironi 2019]

Application for FRBs

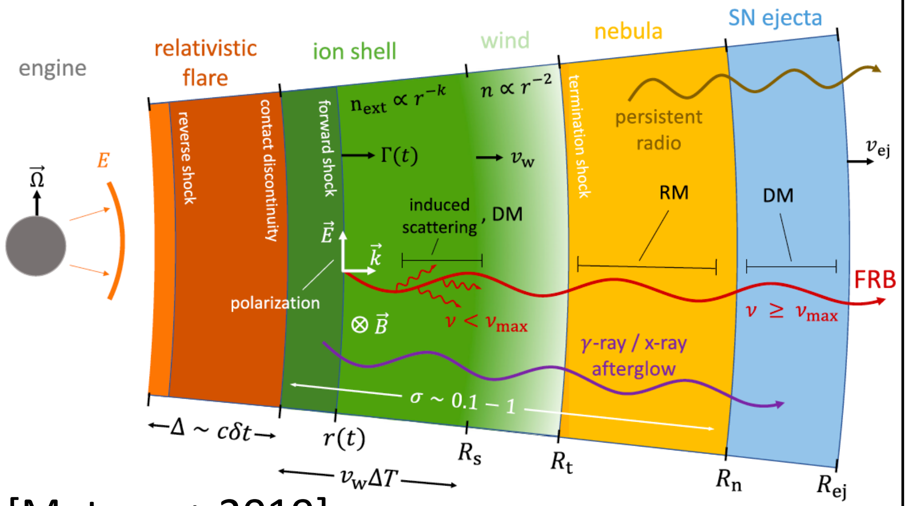
- ✓ Association with a galactic magnetar (The CHIME/FRB collaboration 2020)
  → magnetar origin?
- ✓ Magnetar flare induces relativistic shocks → SMI→ coherent emission

Pair shocks with $\sigma \gg 1$



[Beloborodov 2020]

Ion-electron shocks with $\sigma \sim 0.1 - 1$



[Metzger+ 2019]

Properties of SMI-generated waves are not clear…
Emission efficiency? Polarization? Frequency?

Problems

Emission efficiency

- ✓ How much flare energy is converted into coherent emission?
- ✓ SMI models generally assume

$$f_\xi = \frac{\text{emission efficiency}}{\text{total incoming energy}} \sim 10^{-3}$$

Polarization

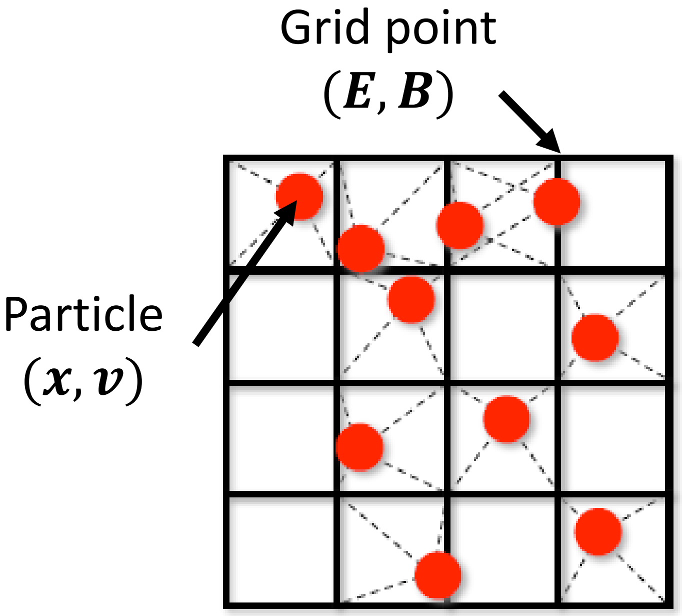
- ✓ Repeating FRBs often show high degree of linear polarization
- ✓ SMI excites linearly polarized waves (X-mode)
- ✓ O-mode as well as X-mode waves are observed in 2D simulation (Iwamoto+ 2018, Sironi+ 2021)
  → wave polarization? 3D simulations are required

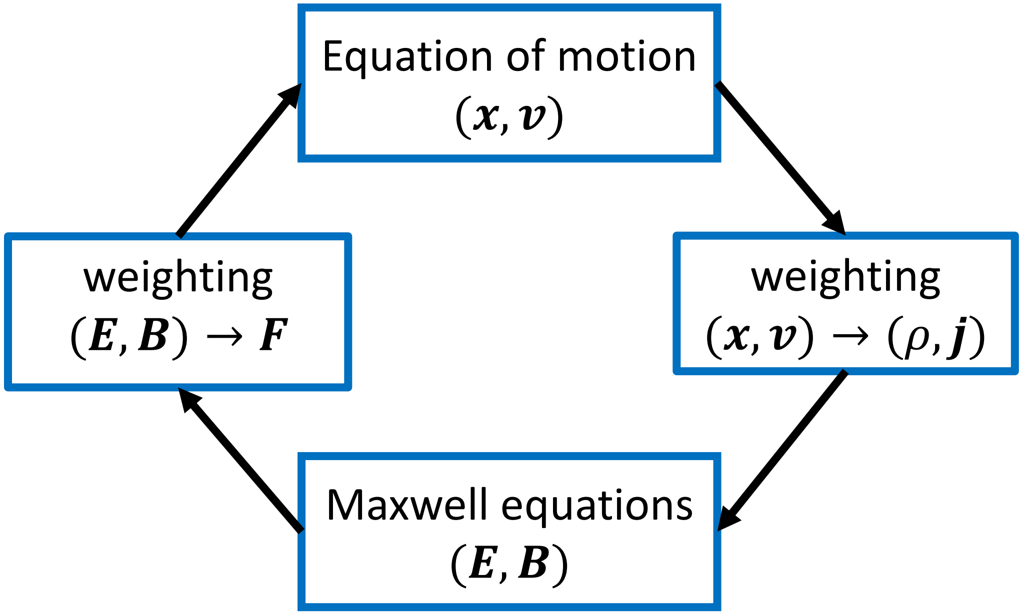
Frequency

- ✓ Coherent emission in 1GHz band?

Particle-in-Cell(PIC) Simulation

- First-principles method for collisionless plasmas
- Basic equations
  - Equation of motion (Lagrangian)
  - Maxwell equations (Eulerian)
- numerous number of charged particles→high computational costs





Equation of motion
$(\boldsymbol{x}, \boldsymbol{v})$

weighting
$(\boldsymbol{x}, \boldsymbol{v}) \rightarrow (\rho, \boldsymbol{j})$

Maxwell equations
$(\boldsymbol{E}, \boldsymbol{B})$

weighting
$(\boldsymbol{E}, \boldsymbol{B}) \rightarrow \boldsymbol{F}$

Numerical Setting

- ✓ Code: Wuming
- ✓ Number of particles: $\sim 10^{13}$
- ✓ time step: $\omega_{pe}\Delta t = 0.05$
- ✓ Grid size: $\Delta x/(c/\omega_{pe}) = 0.05$
- ✓ Upstream Lorentz factor: $\gamma_1 = 40$
- ✓ Mass ratio: $m_i/m_e = 200$
- ✓ Magnetization parameter:

$$\sigma_i \equiv \frac{B_1^2}{4\pi\gamma_1 N_1 m_i c^2} = 0.1, 0.5$$

$$\sigma_e = \frac{m_i}{m_e}\sigma_i = 20{,}100$$

- ✓ # of nodes: 13,225
- ✓ Computational costs: 2×10^6 nodehour ×2run

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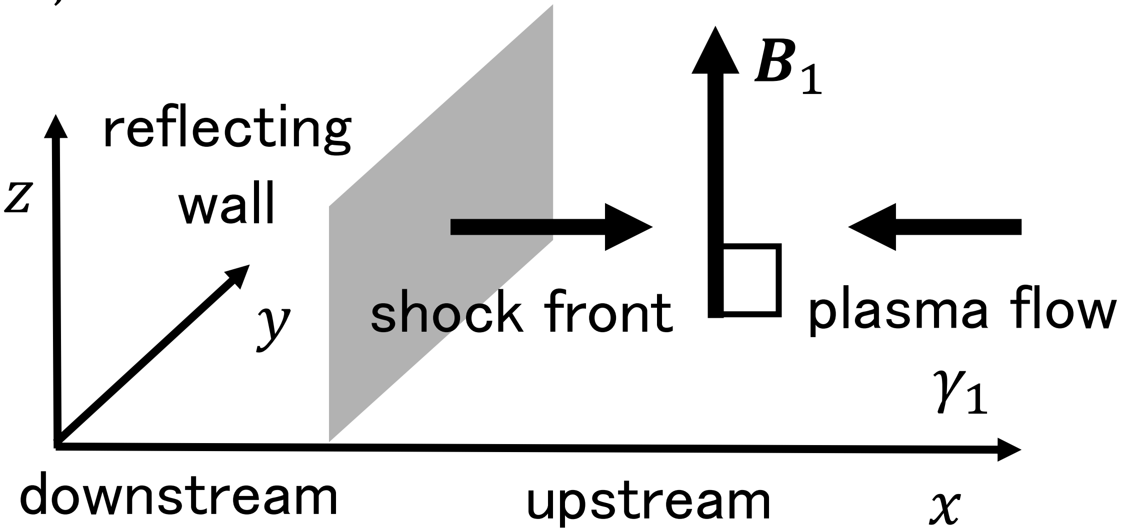
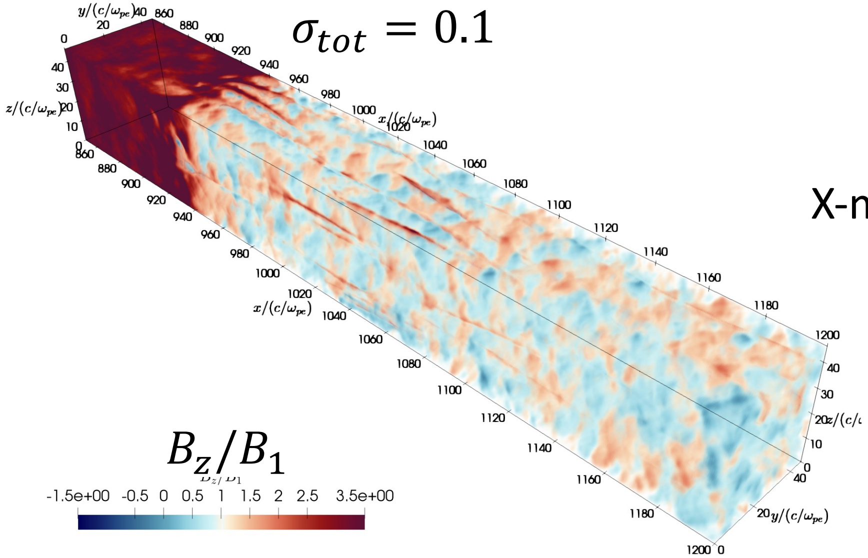


Global Shock Structures

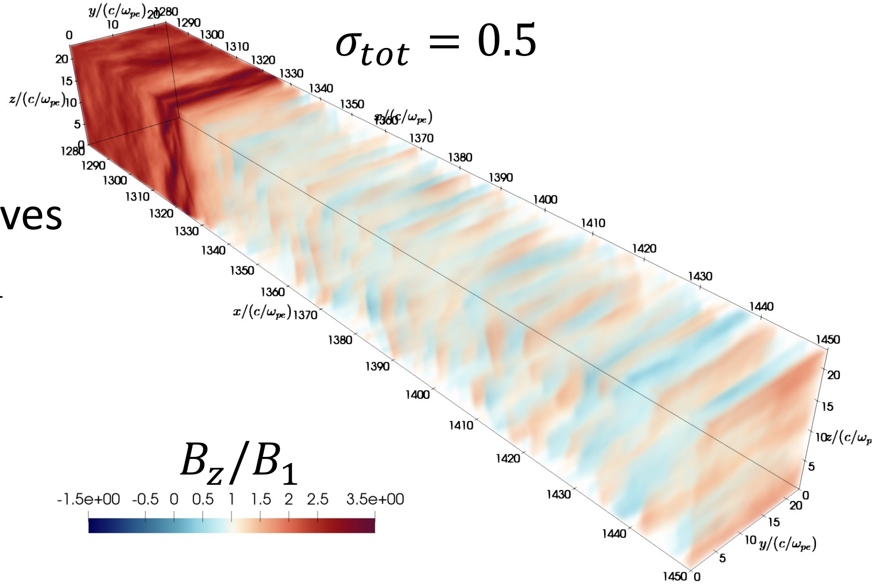
$\sigma_{tot} = 0.1$

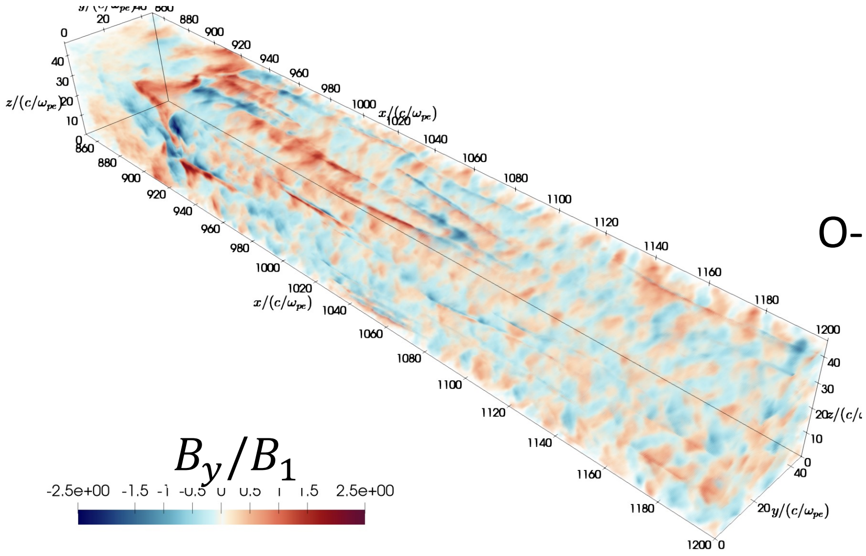


X-mode waves

$\boldsymbol{\delta B} \parallel \boldsymbol{B_1}$

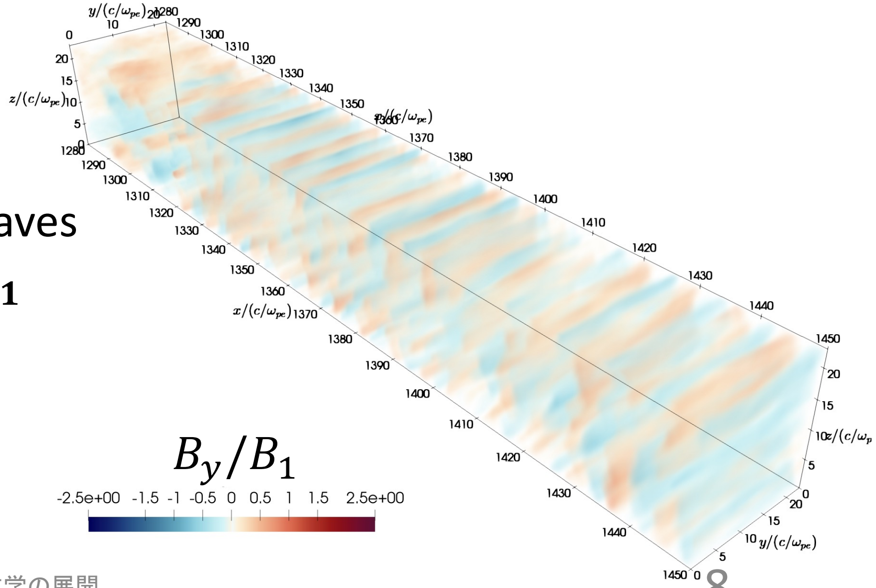
$\sigma_{tot} = 0.5$



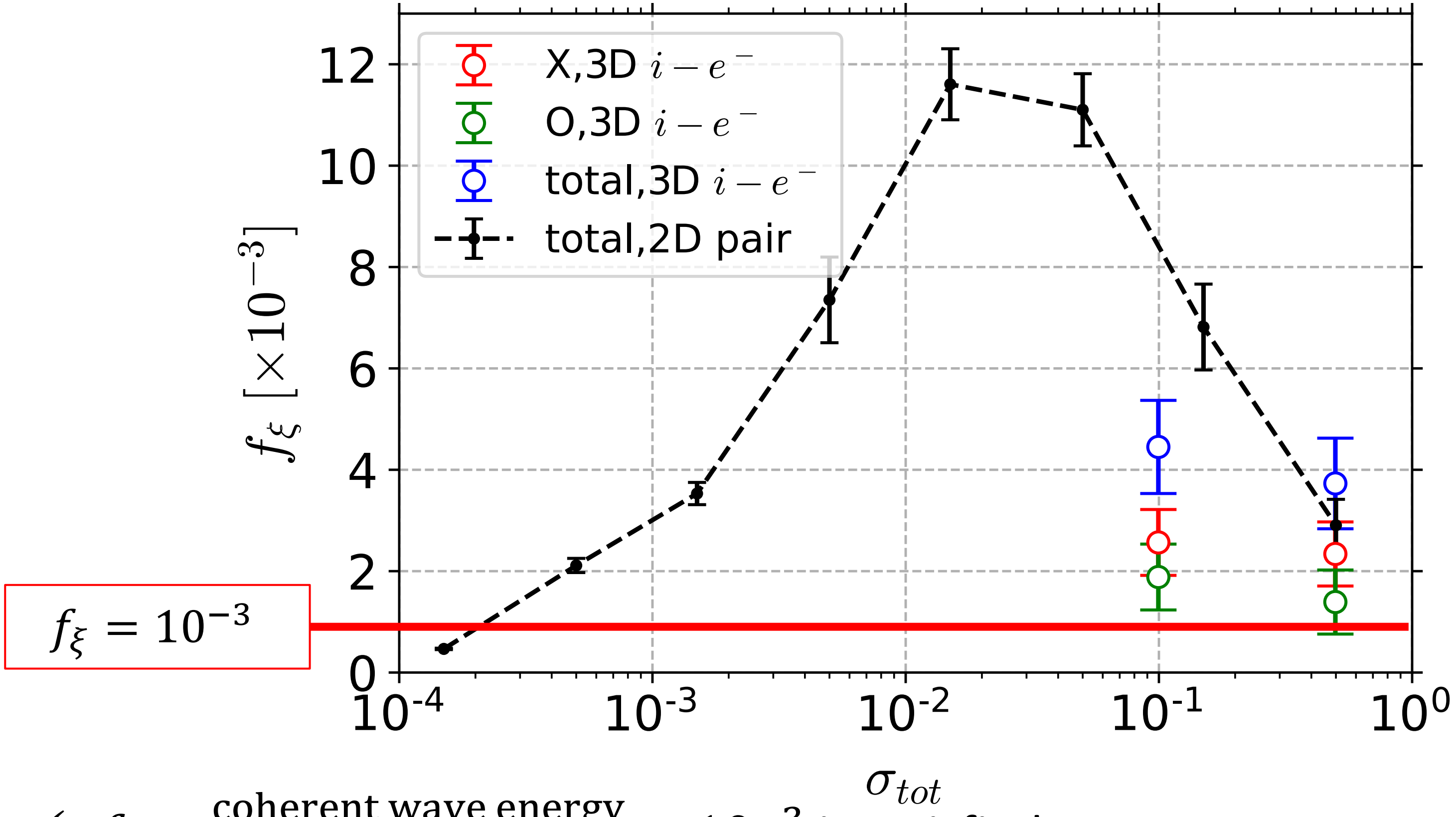


O-mode waves

$\boldsymbol{\delta B} \perp \boldsymbol{B_1}$

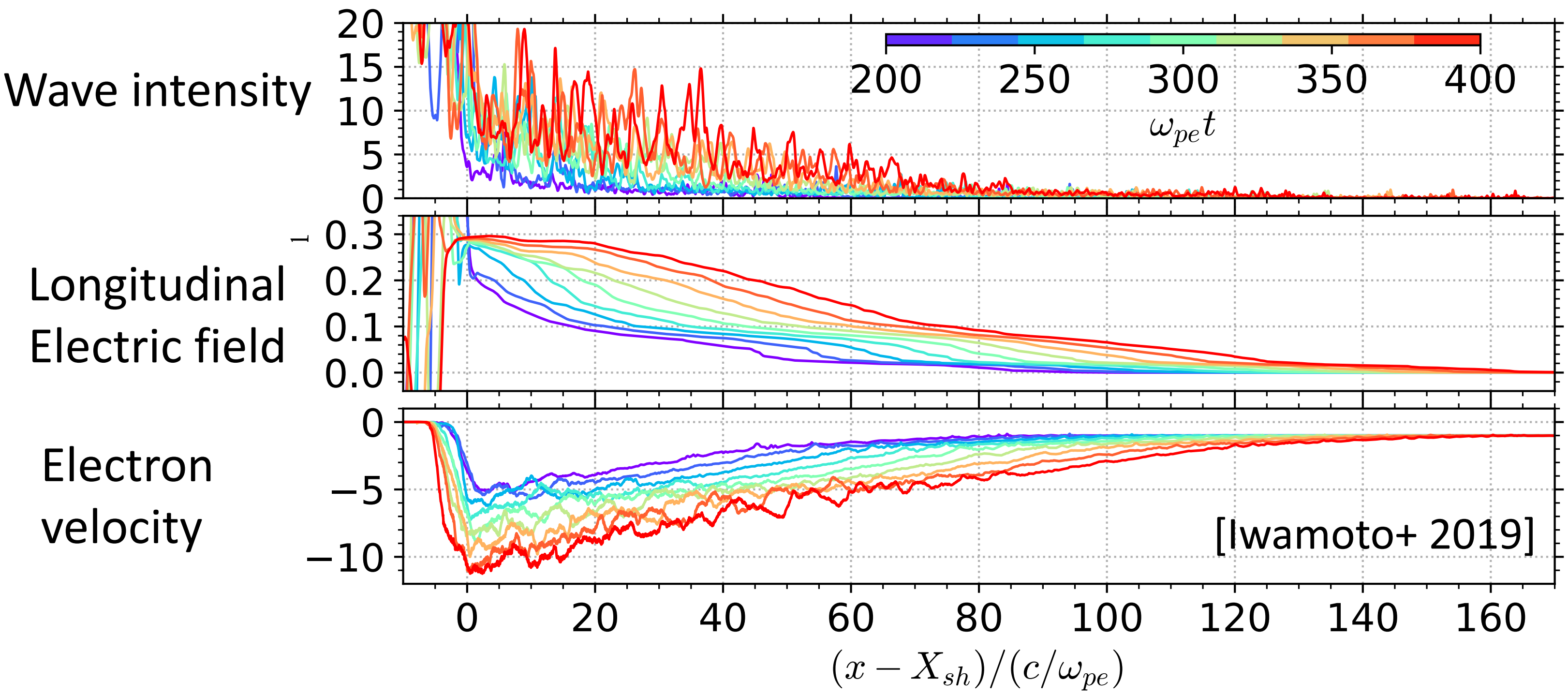


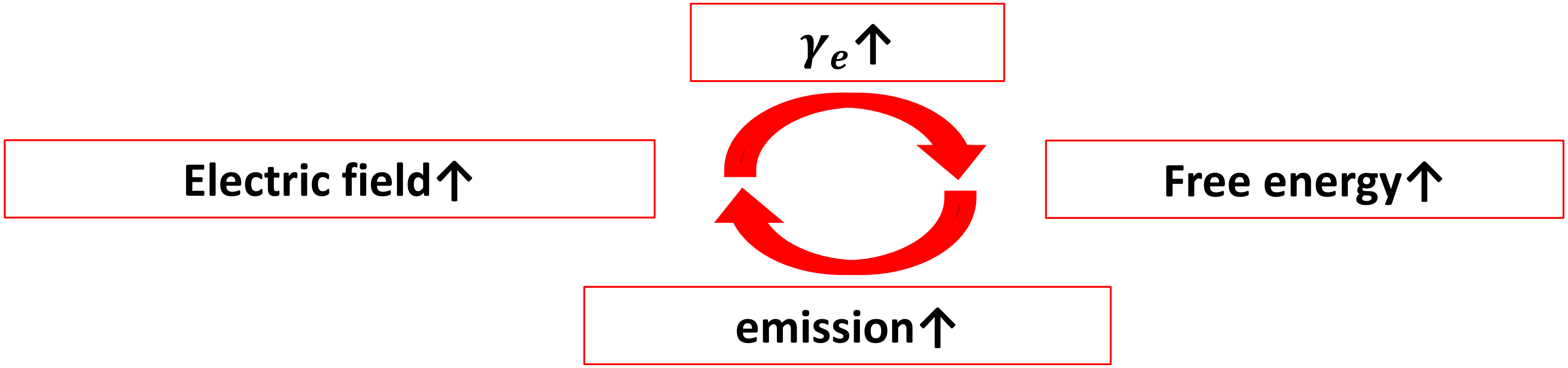
Emission Efficiency



- ✓ $f_\xi = \frac{\text{coherent wave energy}}{\text{incoming total energy}} > 10^{-3}$ is satisfied
- ✓ Ion-electron coupling→σ_{tot} controls the emission efficiency
- ✓ Low σ_{tot}→ competing with Weibel instability
- ✓ High σ_{tot}→ shock velocity is too fast

Ion-Electron Coupling in Upstream





γ_e↑

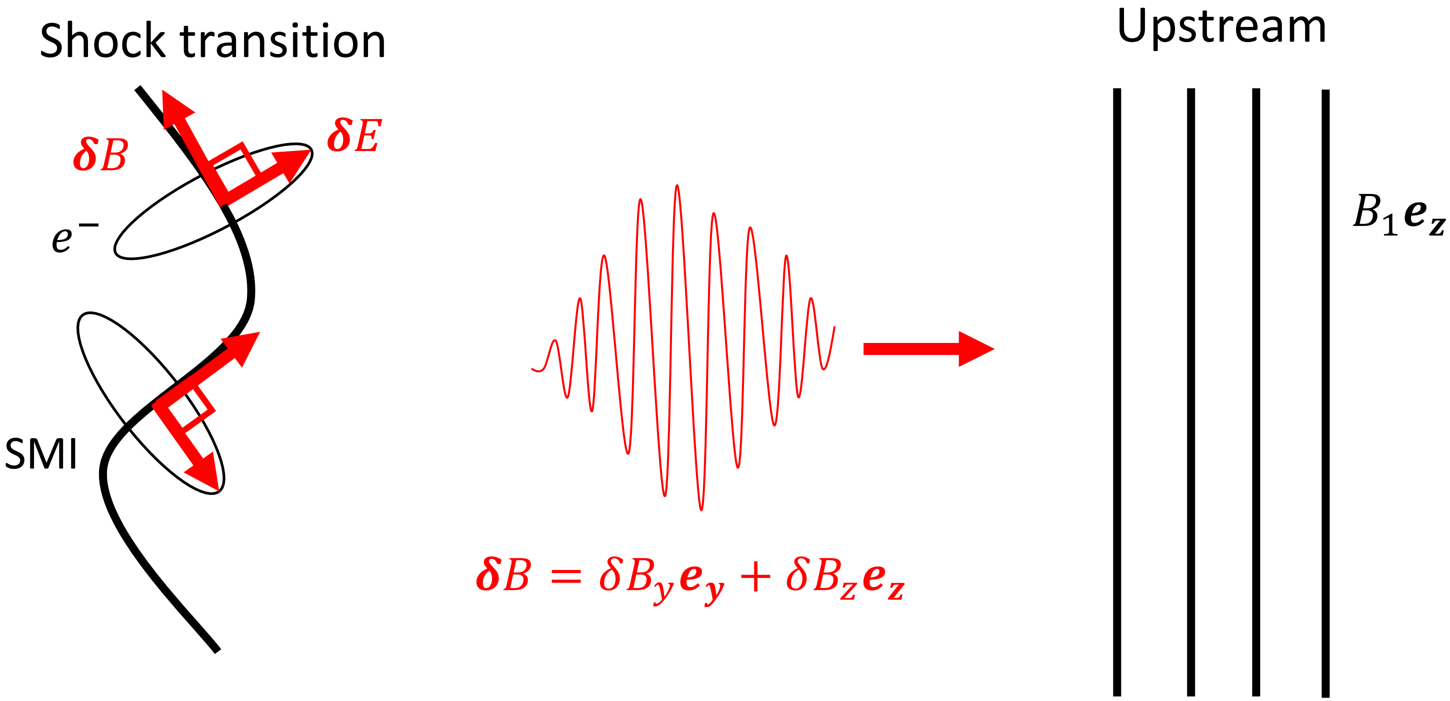
Free energy↑

emission↑

Electric field↑

O-mode Wave Excitation

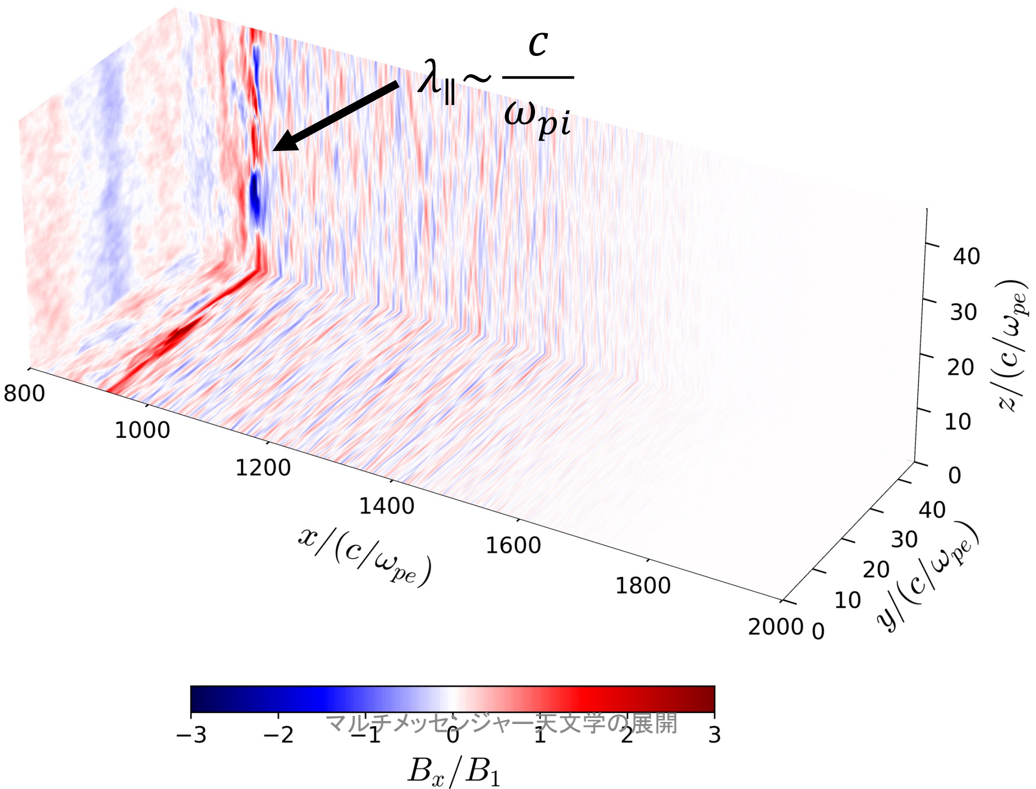
- ✓ Linear theory of SMI expects X-mode waves ($\boldsymbol{\delta B} \parallel \boldsymbol{B_1}$&$\boldsymbol{\delta E} \perp \boldsymbol{B_1}$)
- ✓ O-mode waves ($\boldsymbol{\delta B} \perp \boldsymbol{B_1}$ & $\boldsymbol{\delta E} \parallel \boldsymbol{B_1}$) are also generated in relativistic shocks due to the fluctuations along the background magnetic field



Alfven Ion Cyclotron (AIC) Instability

- ✓ Temperature anisotropy in the shock transition triggers AIC instability (Winske & Quest 1988;Umeda+ 2014)
  →background magnetic field is perturbed
- ✓ Typical wavelength: ion inertial length c/ω_{pi}
- ✓ O-mode waves are excited after AIC instability grows into an substantial amplitude

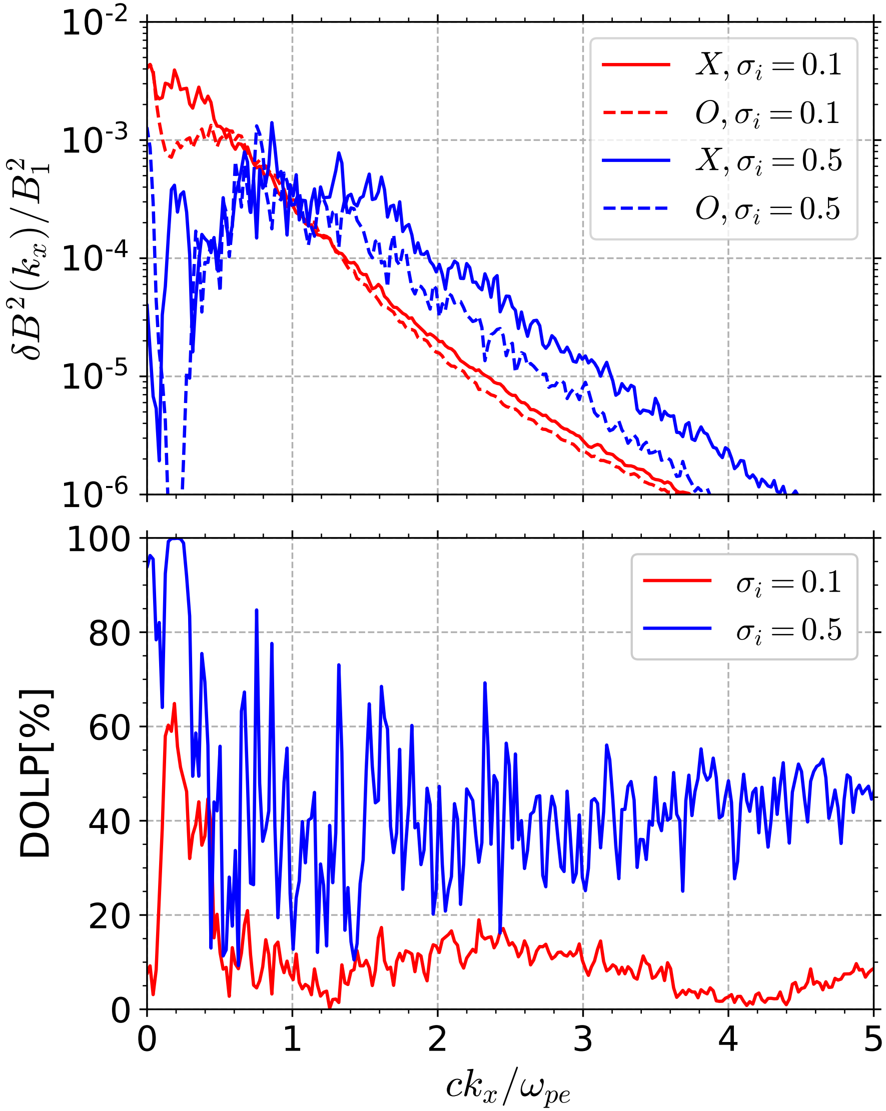
$\omega_{pe}t = 2000, \sigma_i = 0.1, m_i/m_e = 200$



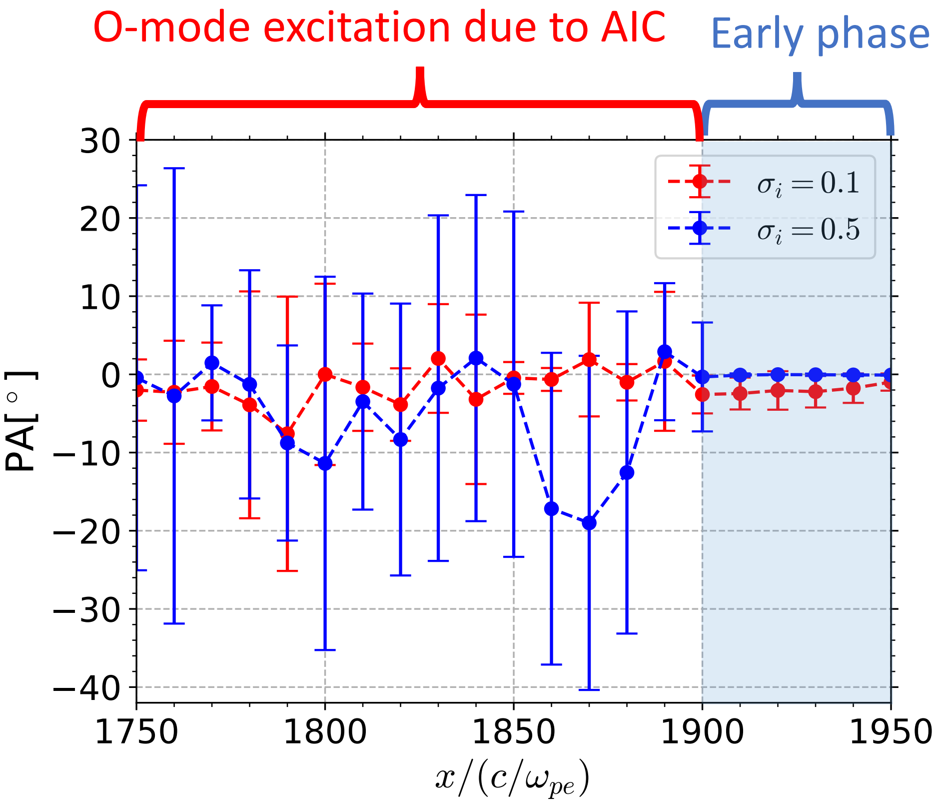
$\lambda_{\parallel} \sim \frac{c}{\omega_{pi}}$

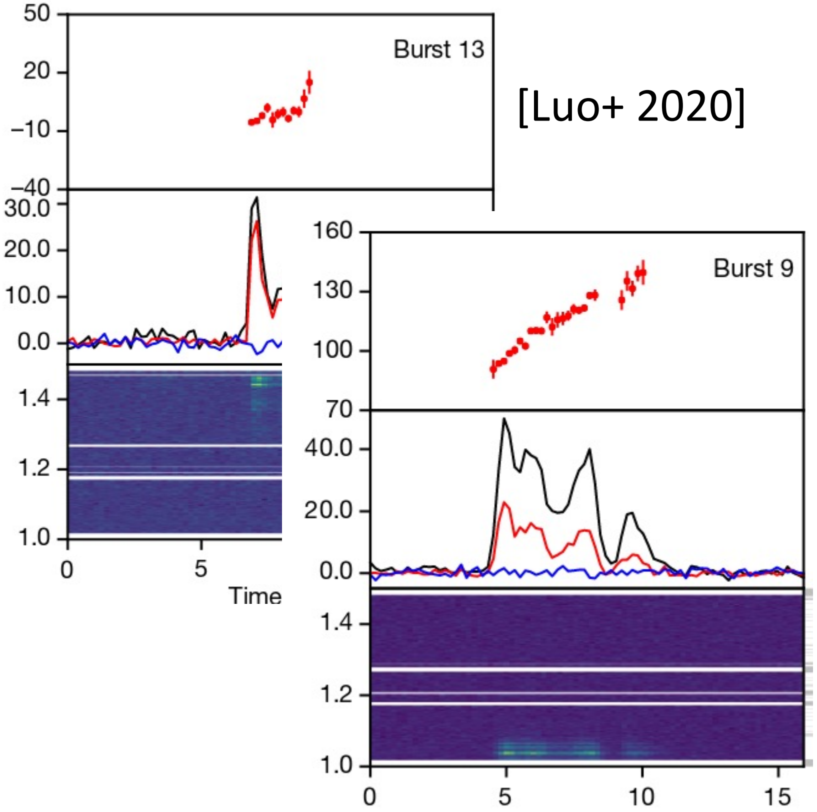
Polarization

- ✓ Fourier transformation of δB_y and δB_z along x axis
  →Stokes parameters U, Q, V, and I
  →Degree of Linear Polarization (DOLP) as a function of k_x
- ✓ almost 100% at ck_x/ω_{pe}~0.2
- ✓ The ambient magnetic field is large for high σ_i
  →unaffected by the AIC waves
  →O-mode waves are suppressed
  →DOLP for $\sigma_i = 0.5$ is higher than that for $\sigma_i = 0.1$



Fluctuations of Polarization Angle




[Luo+ 2020]

- ✓ O-mode waves are excited after the AIC instability sufficiently perturbs the ambient magnetic field
  → O-mode waves lag behind X-mode waves
- ✓ Polarization Angle (PA) fluctuates after the O-mode wave excitation
  →origin of PA swings?

Peak Frequency

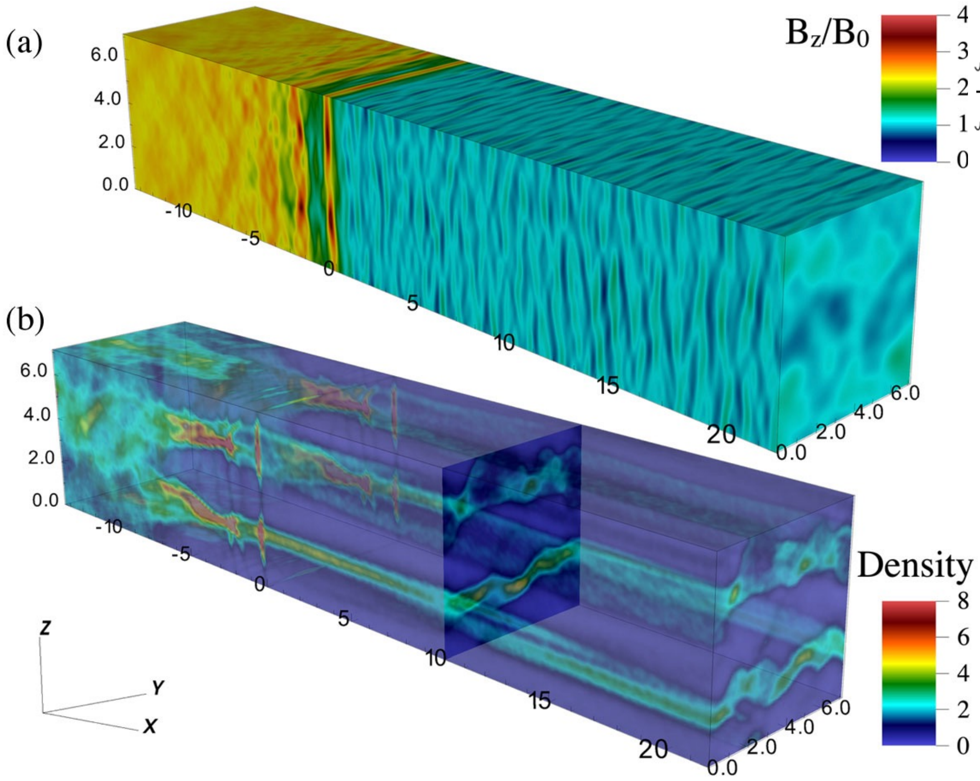
- ✓ Ion–electron coupling
  →energy equipartition
  →electron Lorentz factor: $\gamma_e \sim (m_i/2m_e)\gamma_1$
- ✓ $k_{peak} \sim \zeta\sqrt{\frac{2m_e}{m_i}}\frac{\omega_{pe}}{c}$ from simulation results (downstream-rest frame)
- ✓ Lorentz transformation to the upstream frame (observation frame) with the dispersion relation of $\omega^2 = c^2k^2 + \omega_{pe}^2$,

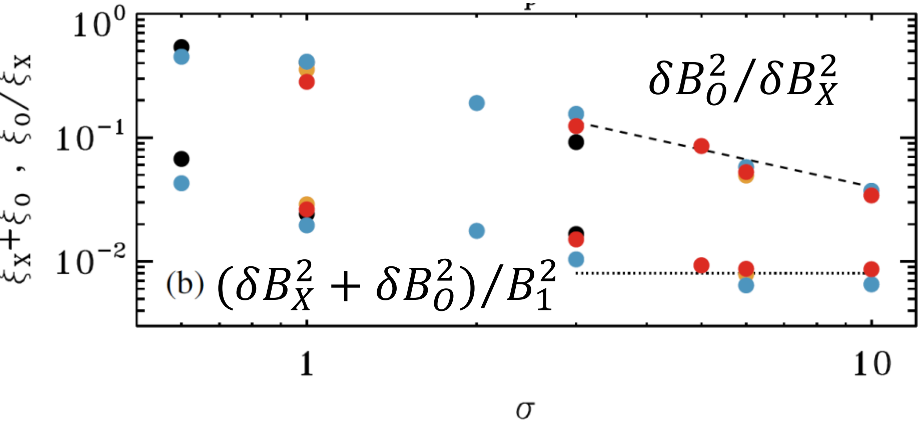
$$\nu_{peak} \sim \gamma_{sh}\sqrt{1+\zeta^2}\sqrt{\frac{2m_e}{m_i}}\frac{\omega_{pe}}{2\pi} \sim 1\mathrm{GHz}\sqrt{\frac{\gamma_{sh}^2 n_0}{10^{13}\ \mathrm{cm}^{-3}}}$$

- ✓ $\gamma_{sh}^2 n_0 \sim 10^{13}\mathrm{cm}^{-3}$ is required for GHZ band

Comparing with High σ Pair Shocks

$\sigma = 6, \gamma_1 = 10$ (Sironi+ 2021)





- ✓ $f_\xi \sim 10^{-3}\sigma^{-1}$
  →inefficient
- ✓ DOLP$= 1 - 0.8\sigma^{-1}$
  →high DOLP
- ✓ $\nu_{peak} \sim 1\mathrm{GHz}\sqrt{\frac{\gamma_{sh}^2 n_0}{10^{10}\ \mathrm{cm}^{-3}}}$
  →relatively easy

Implication for FRBs

	pair shocks with high σ (Sironi+ 2021)	ion-e^- shocks with moderate σ (this study)
Emission Efficiency	×	○
Polarization	○	○
Peak Frequency	○	△

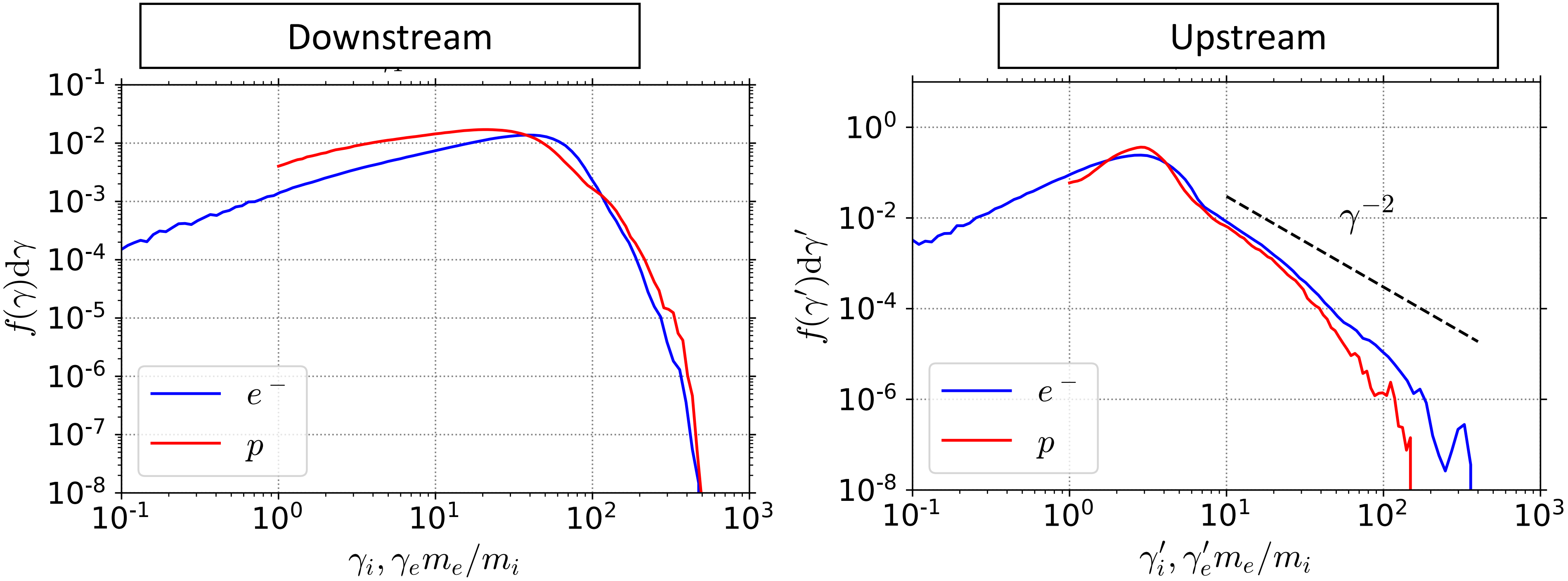
Pair shocks with high σ

- ✓ $f_\xi \sim 10^{-3}\sigma^{-1} \ll 10^{-3}$
- ✓ Solitons rather than shocks are induced in high σ plasmas (Kennel & Pellat 1976)
- ✓ Shock solution does not exist for $\sigma > (\gamma_1 - 1)/2$? (Alsop & Arons 1988)

Ion-e^- shocks with moderate σ

- ✓ Peak frequency is $\sqrt{2m_e/m_i}$ times smaller than that in pair shocks
- ✓ Can $\gamma_{sh}^2 n_0 \sim 10^{13}\mathrm{cm}^{-3}$ be satisfied? Very model dependent…

Particle Acceleration



Downstream

Upstream

- ✓ Efficient particle acceleration occurs in the near-upstream region (Hoshino 2008; Iwamoto+ 2022)
  - – No particle acceleration in high σ pair shocks
  - – Whole acceleration process is not captured…
  - – Power-law-like spectra in the downstream at a later phase?
- ✓ Nonthermal counterparts?

Summary & Future Work

Summary

- ✓ Emission efficiency $f_\xi \sim 10^{-3}$ is satisfied for $\sigma \sim 0.1 - 1$
- ✓ High DOLP
- ✓ Diversity of polarization angle due to the mixture of the two different linearly polarized waves
- ✓ Peak frequency: $\nu_{peak} \sim 1\mathrm{GHz}\sqrt{\frac{\gamma_{sh}^2 n_0}{10^{13}\ \mathrm{cm}^{-3}}}$

Future Work

- ✓ Upstream temperature dependence of f_ξ
  - – Pair plasma: detoriorates for $k_B T_e / m_e c^2 > 10^{-1.5}$ (Babul & Sironi 2020)
  - – Ion-electron plasma: remain unsolved…
- ✓ Escaping process
  - – Induced scattering (Compton, Raman, and Brillouin)
  - – Wave-wave interaction (e.g., filamentation instability)