Keihan Astrophysics Meeting 2024 fall

Kinetic Simulations of Coherent Emission from Relativistic Shocks

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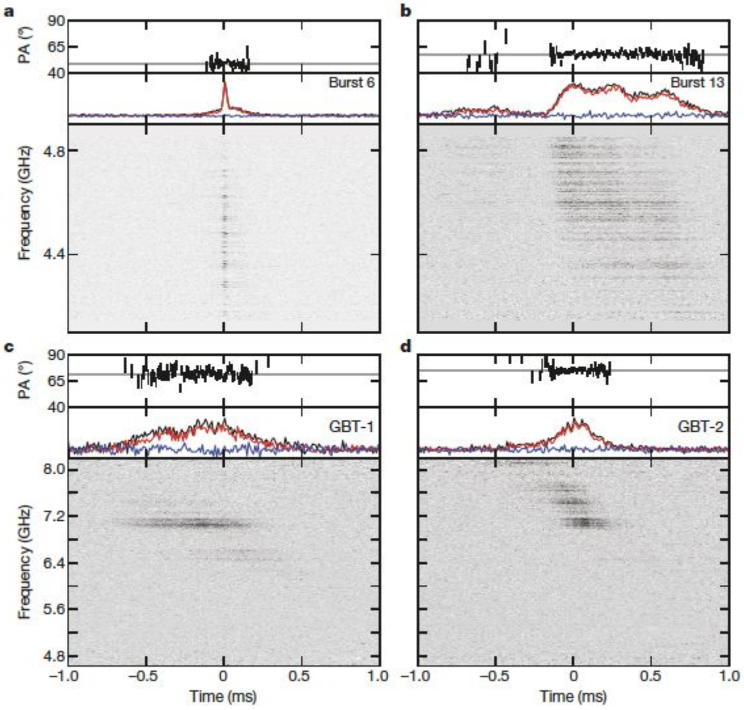
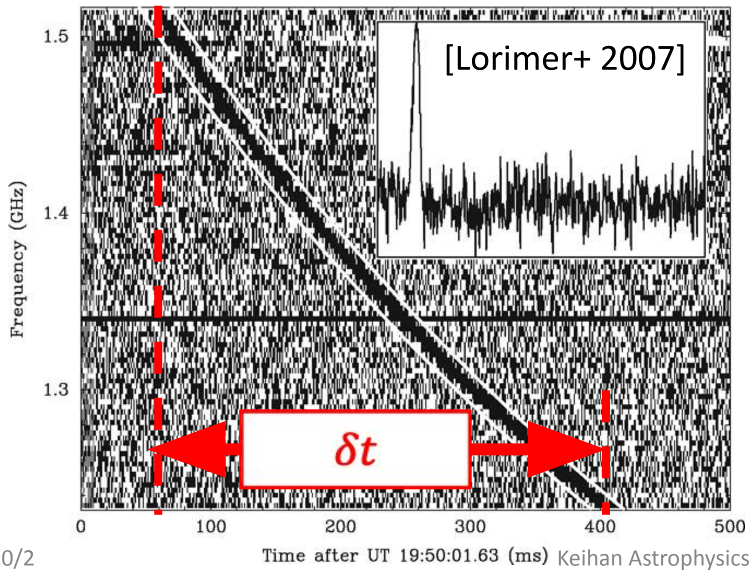
Fast Radio Burst (FRB)

- ✓ Typical frequency: ~1GHz
- ✓ Pulse duration: ~1ms
- ✓ Narrow spectra: $\frac{\Delta\nu}{\nu} < 1$
- ✓ often show high linear polarization
- ✓ High dispersion measure→ extragalactic origin
- ✓ Association with magnetar (Bochenek+ 2020)
  → Magnetar origin?



FRB121102 [Michikki+ 2018]



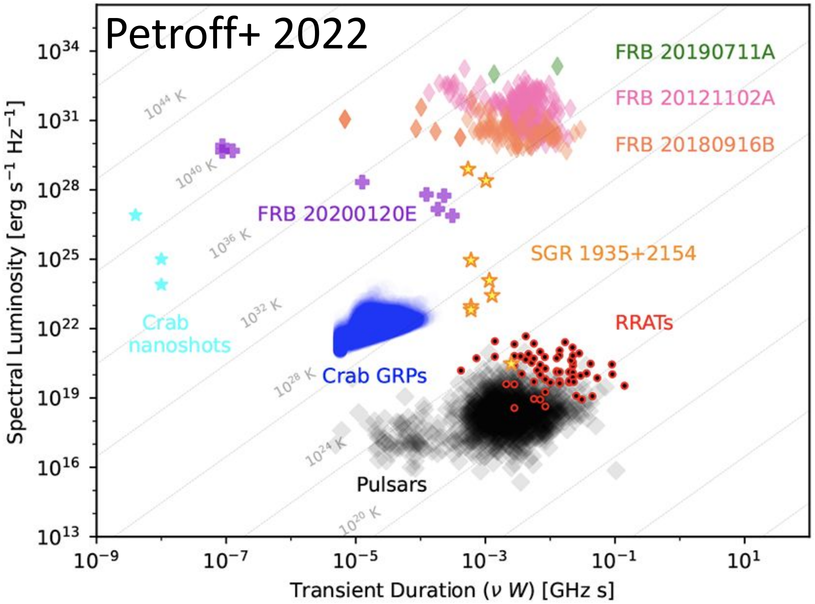
$$\delta t \sim \frac{2\pi e^2}{m_e c}\left(\frac{1}{\omega_1^2}-\frac{1}{\omega_2^2}\right)\boxed{\int_0^L n_e\, ds}$$

Dispersion Measure

Brightness Temperature

$$L_\nu = \frac{2k_B T_B \nu^2}{c^2} 4\pi r^2$$

T_B: brightness temperature



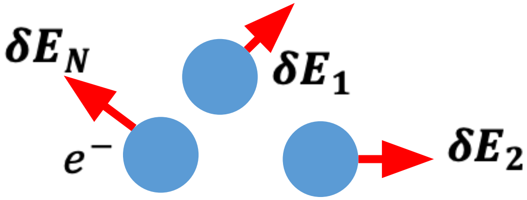
FRBs: $T_B \sim 10^{36}$K

→coherent emission (Katz 2014)

Candidates

- ✓ **Bunching**
- ✓ **Plasma instability**

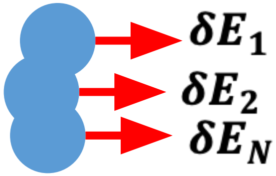
Incoherent Emission



Radiating power

$$\propto \langle(\delta E_1 + \delta E_2 + \cdots + \delta E_N)^2\rangle$$
$$\sim \langle\delta E_1^2\rangle + \langle\delta E_2^2\rangle + \cdots + \langle\delta E_N^2\rangle$$
$$= N\langle\delta E^2\rangle$$

Coherent Emission

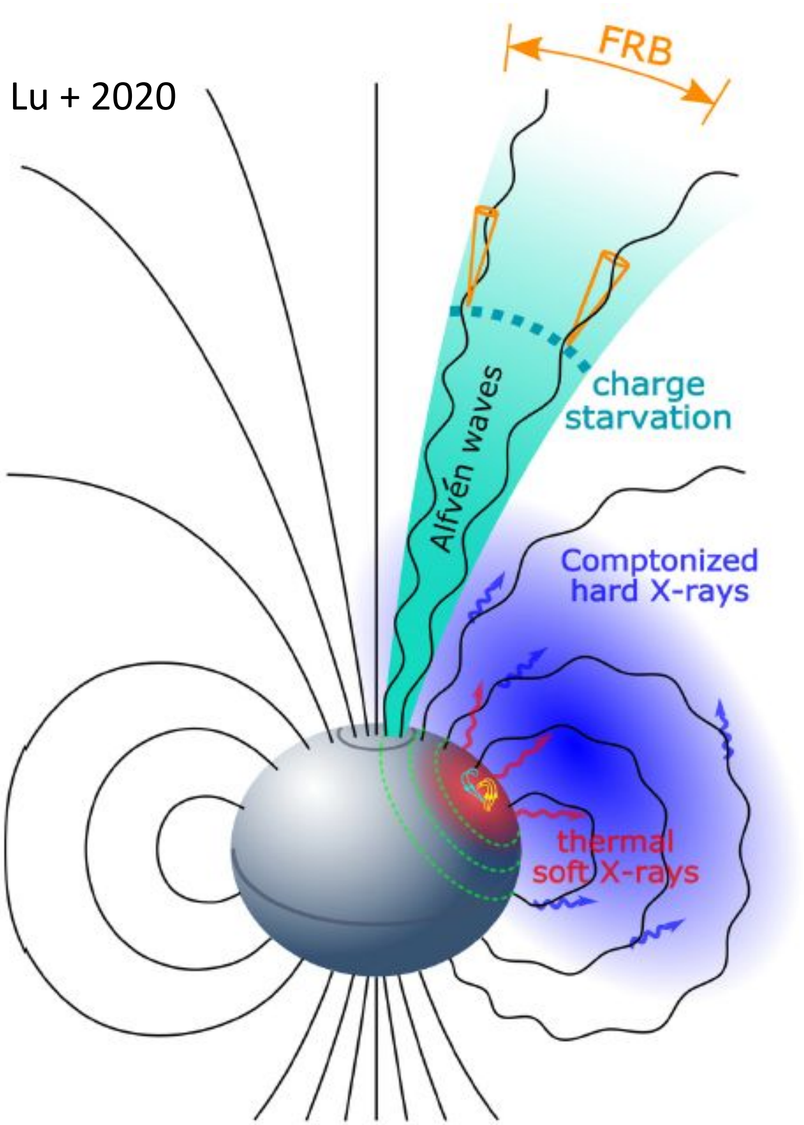


Radiating power

$$\propto \langle(\delta E_1 + \delta E_2 + \cdots + \delta E_N)^2\rangle$$
$$\sim \langle(N\delta E)^2\rangle$$
$$= N^2\langle\delta E^2\rangle$$

Magnetospheric Model

E.g., Katz 2016, Kumar+ 2017, Yang & Zhang 2018, Lu+ 2018; 2020, Wang+ 2020



Lu + 2020

- ✓ Emission by charge bunches
- ✓ Coherent curvature radiation **inside** magnetosphere (pulsar-like model)
- ✓ No plausible model for generating charge bunches

Outbursts near the magnetar surface
→Alfven waves
→Density is too low to sustain the plasma current
→$E_{\parallel}$ is induced?
→accelerating charge clumps?
→coherent emission?

Shock Model

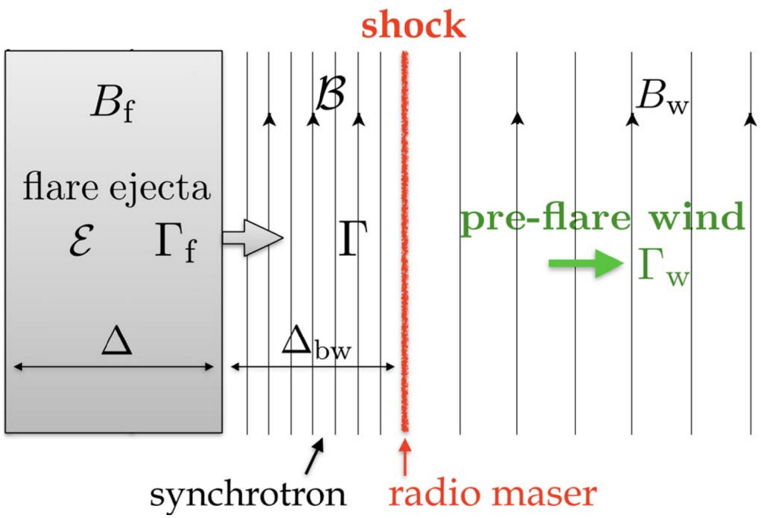
e.g., Lyubarsky 2014, Waxman 2017, Beloborodov 2017; 2020, Metzger+ 2019, Margalit+ 2020

✔ Synchrotron maser instability (SMI) in relativistic shock

✓ Magnetar flare induces relativistic shocks **far away from** magnetosphere
→ coherent emission (=GRB-like model)

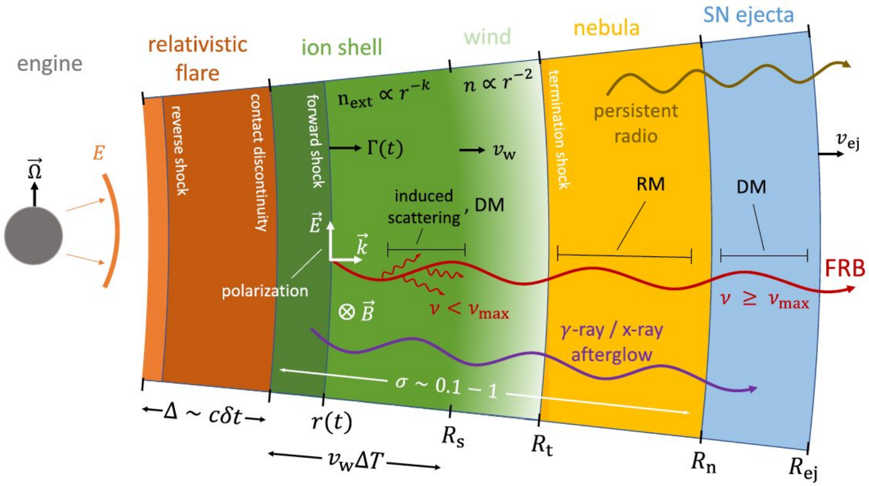
✓ Upstream environment:
Pair plasmas with high σ or Ion-electron plasmas with moderate σ
($\sigma \equiv \frac{B^2}{4\pi\gamma^2 nmc^2} = \frac{\omega_c^2}{\omega_p^2}$: magnetization parameter)

Pair plasmas, $\sigma \gg 1$



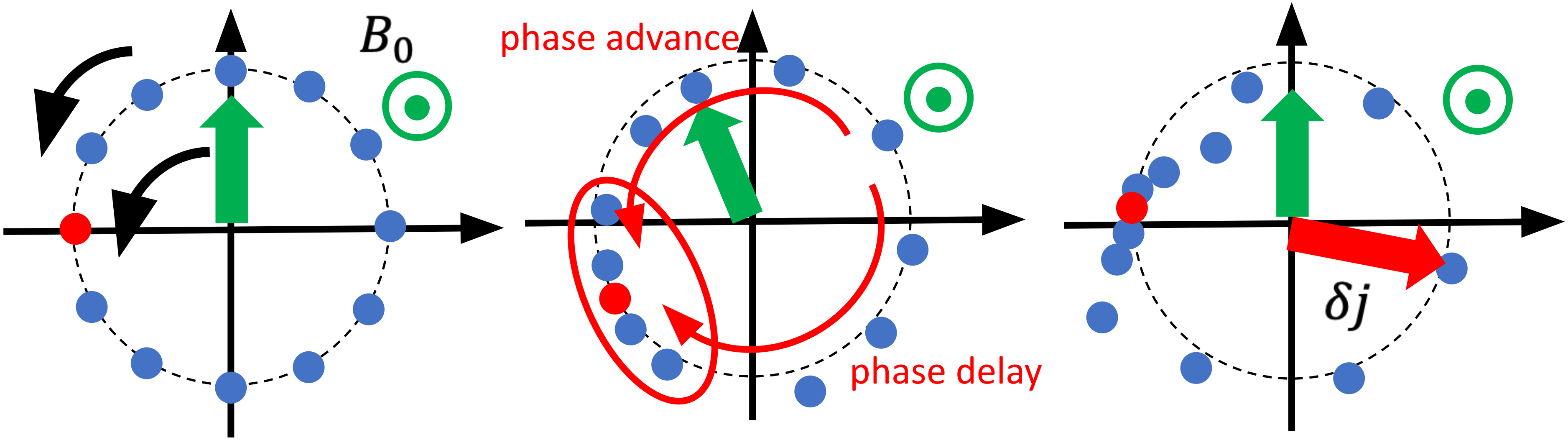
[Beloborodov 2020]

Ion-electron plasmas, $\sigma \sim 0.1 - 1$



[Metzger+ 2019]

Intuitive Explanation



$$\omega = \omega_c + \delta\omega$$
$$\delta\omega \ll \omega_c$$
$$\omega_c = \frac{eB}{\gamma mc}$$

$$\Delta\gamma = -\frac{e\boldsymbol{\delta E}\cdot\boldsymbol{v}\Delta t}{mc^2}$$
$$\Delta\gamma < 0 \rightarrow \omega_c \uparrow$$
$$\Delta\gamma > 0 \rightarrow \omega_c \downarrow$$

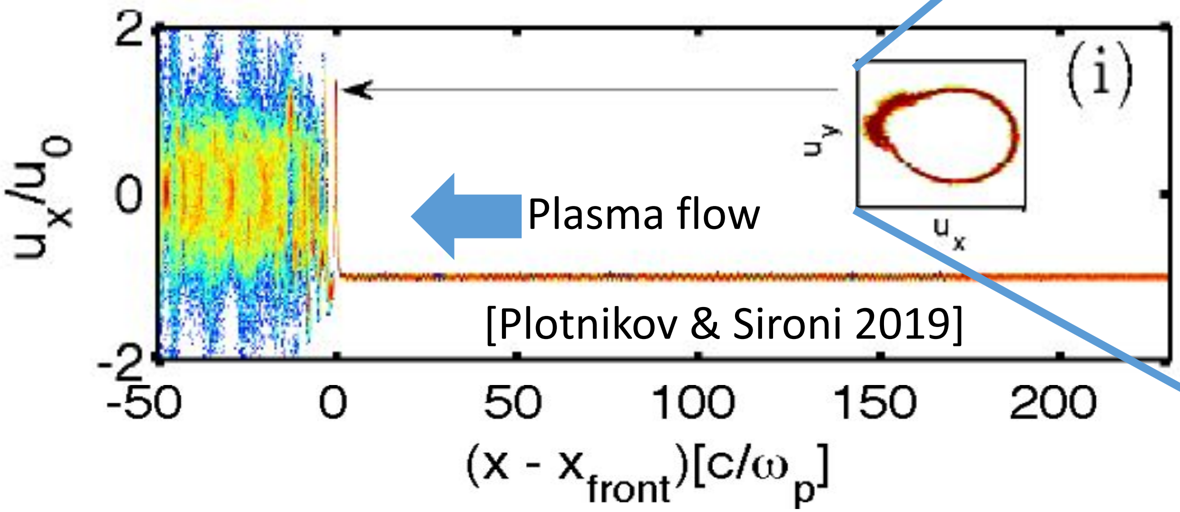
$$\langle \boldsymbol{\delta E}\cdot\boldsymbol{\delta j}\rangle < 0$$
→particle kinetic energy is transferred into wave energy
→δE can grow

- ✓ Electron bunches in momentum space are generated due to relativistic effect→ oscillating current→ electromagnetic waves
- ✓ preferentially excite X-mode waves ($\boldsymbol{\delta E} \perp \boldsymbol{B_0}$)

SMI in Relativistic Collisionless Shocks

- ✔ Electrons begin to gyrate at the shock front
  →induce SMI (Hoshino & Arons 1991)
- ✔ Many kinetic simulations demonstrate the electromagnetic wave emission via the SMI (e.g., Gallant+1991, Hoshino+ 1992)
  →Relativistic collisionless shocks are natural resources of coherent emission

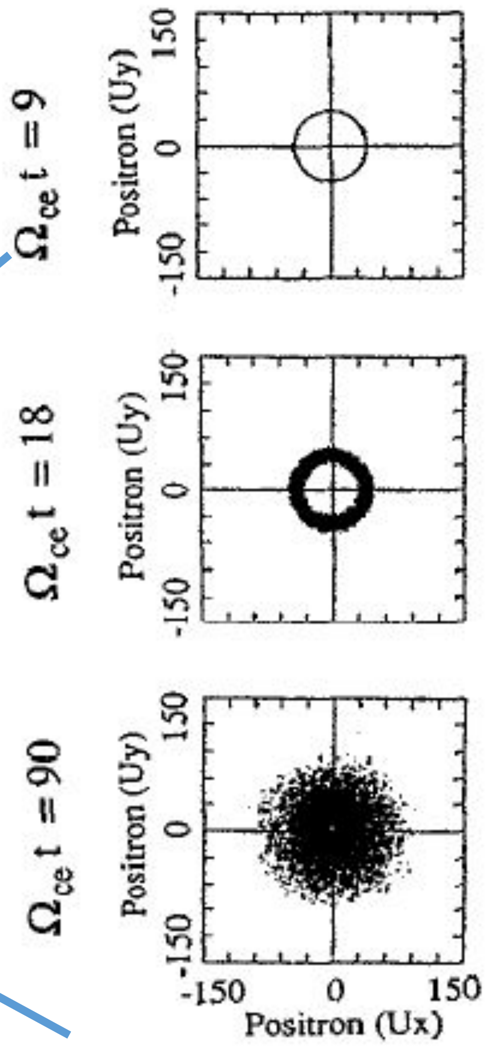
←Downstream Upstream→



Plasma flow

[Plotnikov & Sironi 2019]

[Hoshino & Arons 1991]



SMI in 1D Pair Shocks

e.g., Gallant+ 1991, Hoshino+1992,
Amato & Arons 2006, Plotnikov& Sironi 2019

- ✔ Wave emission efficiency:

$$f_\xi = \frac{\text{emission efficiency}}{\text{total incoming energy}}$$

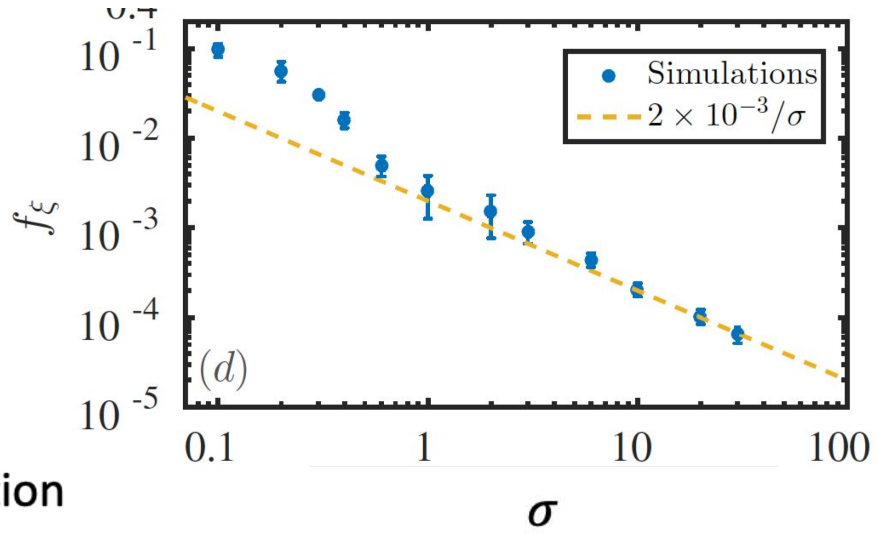
SMI models assume $f_\xi \sim 10^{-3}$
→well satisfied

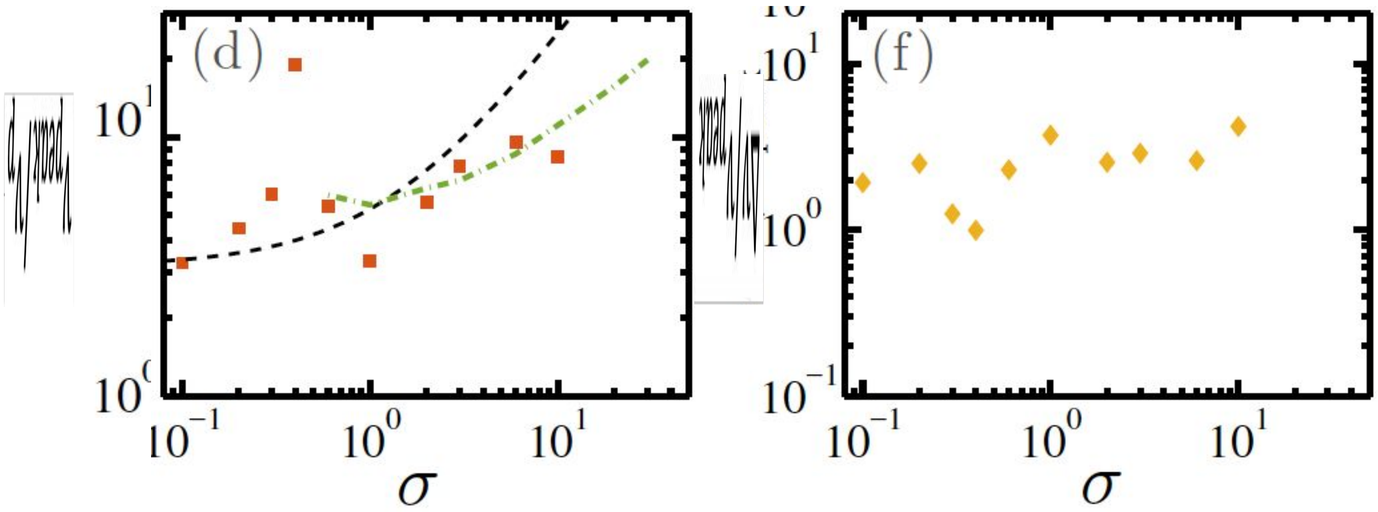
- ✓ Peak frequency in upstream rest frame:

$$\nu_{peak} \sim 1\text{GHz}\sqrt{\frac{\gamma_{sh}^2 n_0}{10^{10}\ \text{cm}^{-3}}}$$

- ✓ Only X-mode waves→100% linear polarization
- ✓ Narrow band $\Delta\nu/\nu_{peak} \sim 1$

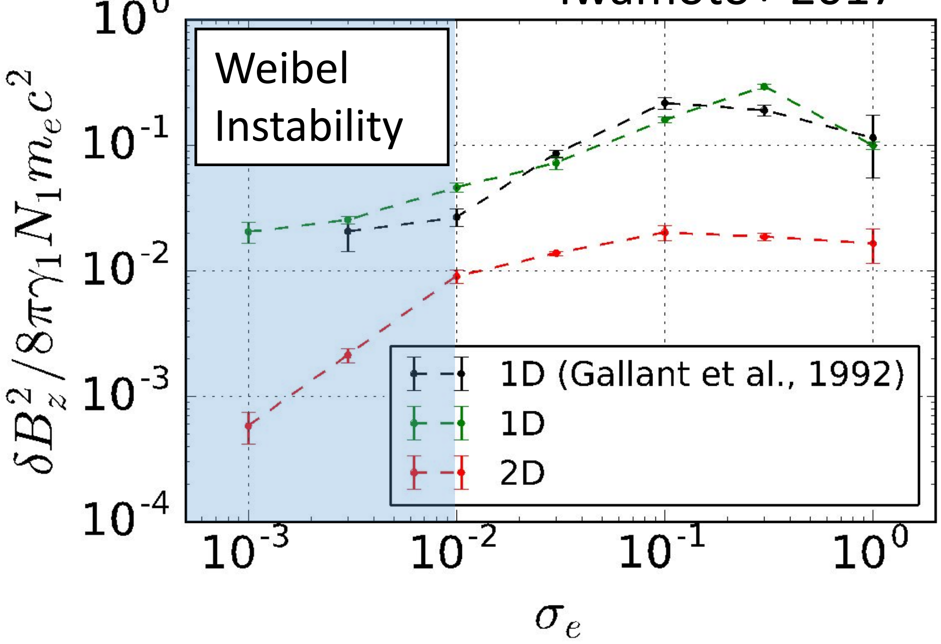
Plotnikov& Sironi 2019



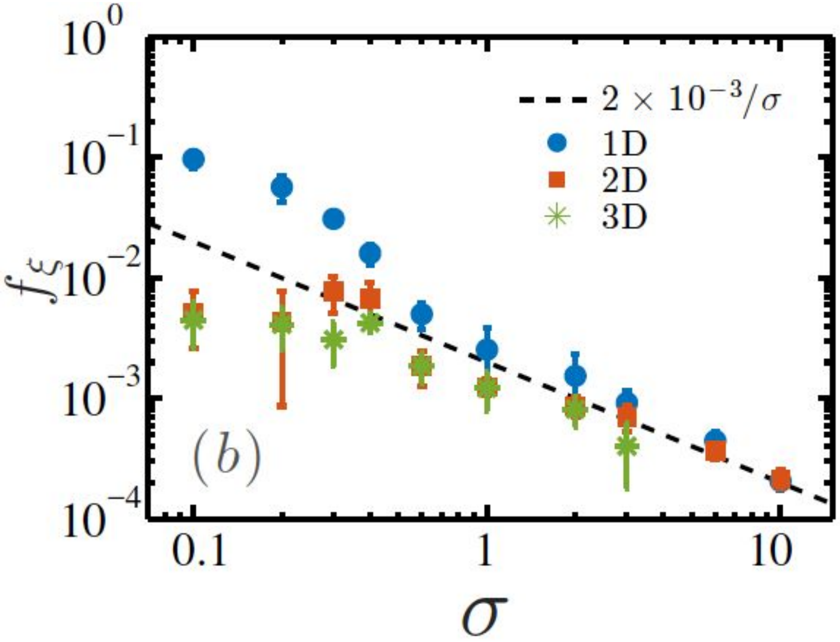


SMI in Multi-dimensional Pair Shocks

Iwamoto+ 2017



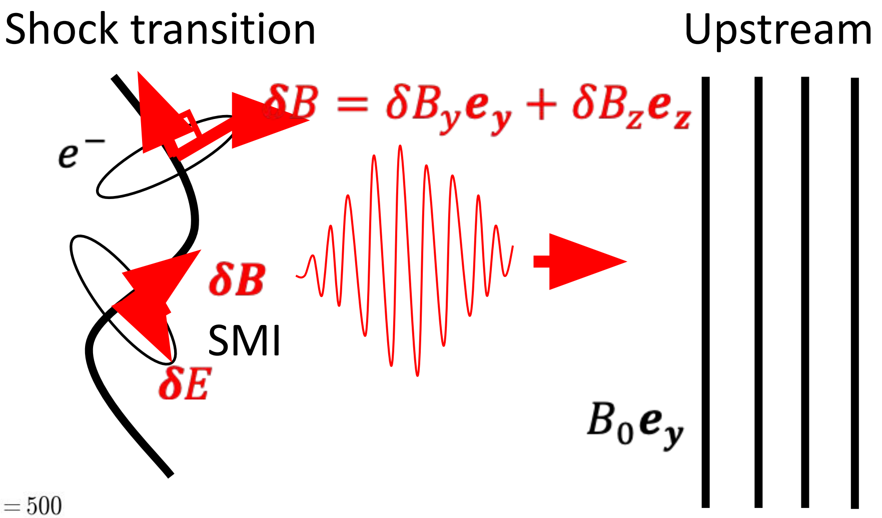
Plotnikov& Sironi 2019

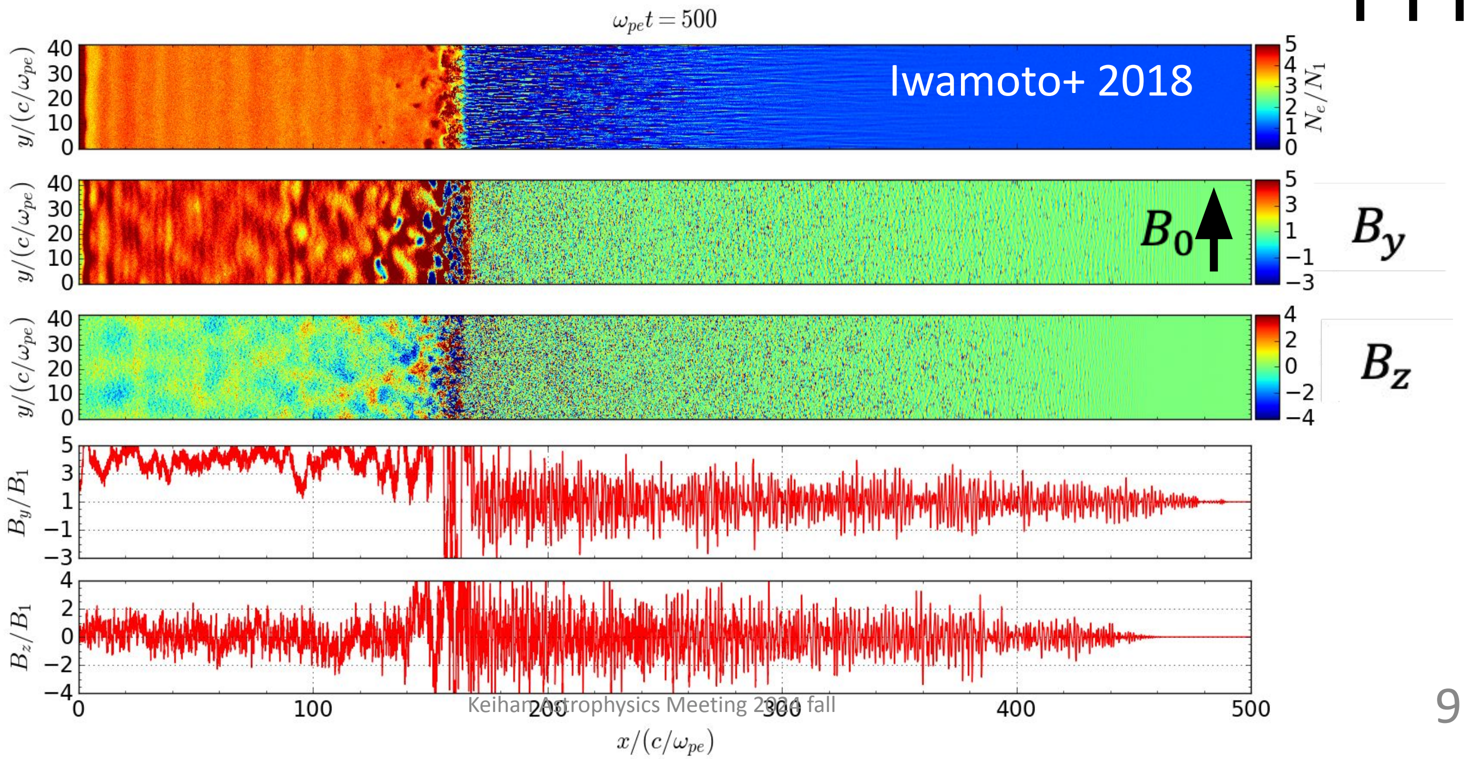


- ✓ The amplitude in 2D is systematically smaller than that in 1D
  → due to the inhomogeneity along the shock surface
- ✓ Emission Efficiency drastically decreases for $\sigma < 10^{-2}$
  → SMI competes with Weibel instability
- ✓ Multi-dimensional effects are negligible for $\sigma \gtrsim 1$ because clear ring-like distribution can be formed

O-mode Wave Excitation

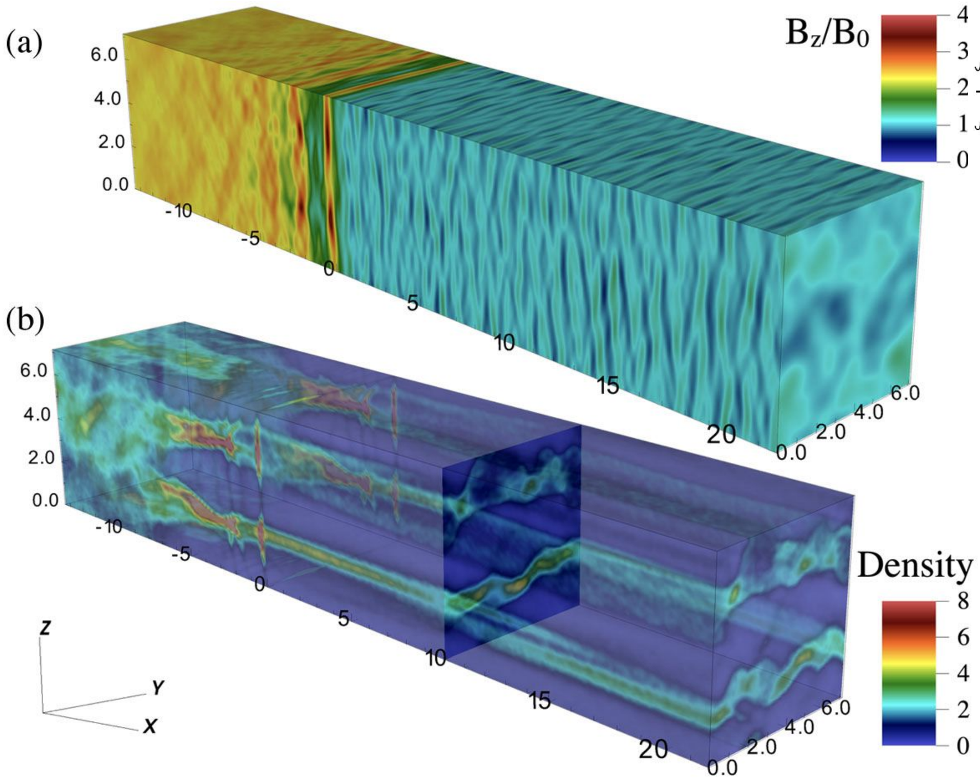
- ✔ 2D shocks with the in-plane magnetic field demonstrates O-mode waves ($\boldsymbol{\delta B} \perp \boldsymbol{B_0}$ & $\boldsymbol{\delta E} \parallel \boldsymbol{B_0}$) are excited
- ✓ Alfven ion cyclotron (AIC) instability operates (Winske & Leroy 1984)
  →Fluctuations along $\boldsymbol{B_0}$
  →O-mode wave

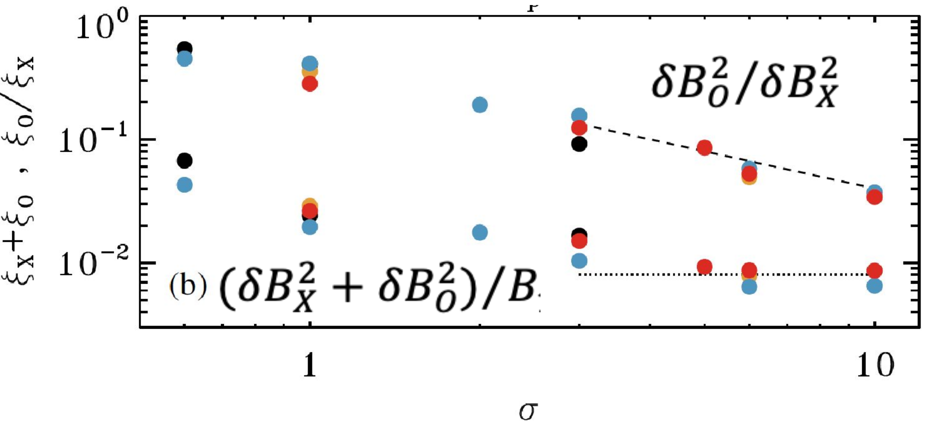




Latest 3D Simulations of Pair Shocks

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





- ✓ $f_\xi \sim 10^{-3}\sigma^{-1}$
  →inefficient for $\sigma \gg 1$
- ✓ Degree of linear polarization:
  $\mathrm{DOLP} = 1 - 0.8\sigma^{-1}$
  →high DOLP
- ✓ $\nu_{peak} \sim 1\mathrm{GHz}\sqrt{\frac{\gamma_{sh}^2 n_0}{10^{10}\ \mathrm{cm}^{-3}}}$

SMI in Ion-electron shocks

✓**Emission efficiency**

- ✓ $f_\xi \sim 10^{-3}$ is also assumed in ion-electron shocks
- ✓ SMI consumes electron kinetic energy
  →Electrons transfer only a small fraction of the upstream energy
  → f_ξ is much smaller?

Polarization

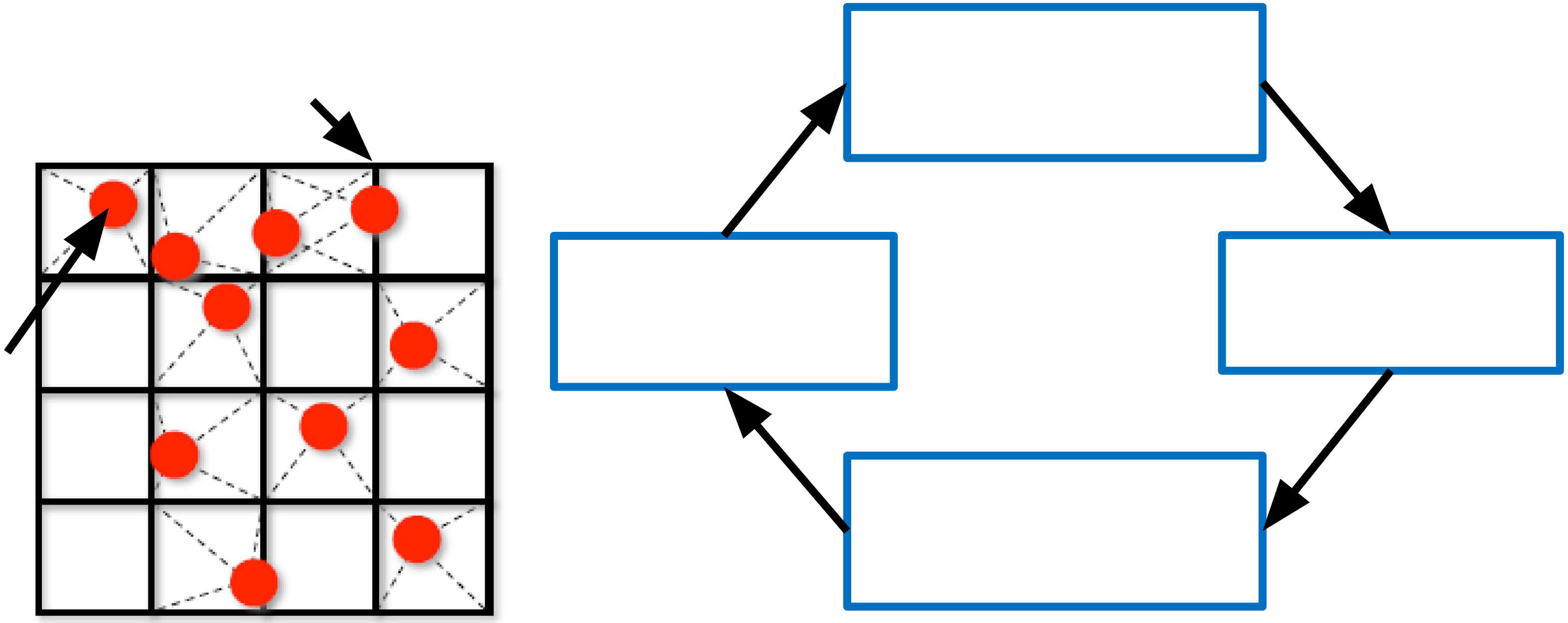
- ✓ O-mode wave excitation should be considered for $\sigma \sim 0.1 - 1$
- ✓ Only 3D simulation can provide a realistic picture of polarization

Frequency

- ✓ Coherent emission in 1GHz band?
- ✓ $\nu_{peak} \sim 1\mathrm{GHz}\sqrt{\frac{\gamma_{sh}^2 n_0}{10^{10}\ \mathrm{cm}^{-3}}}$ still holds?

Particle-in-Cell(PIC) Simulation

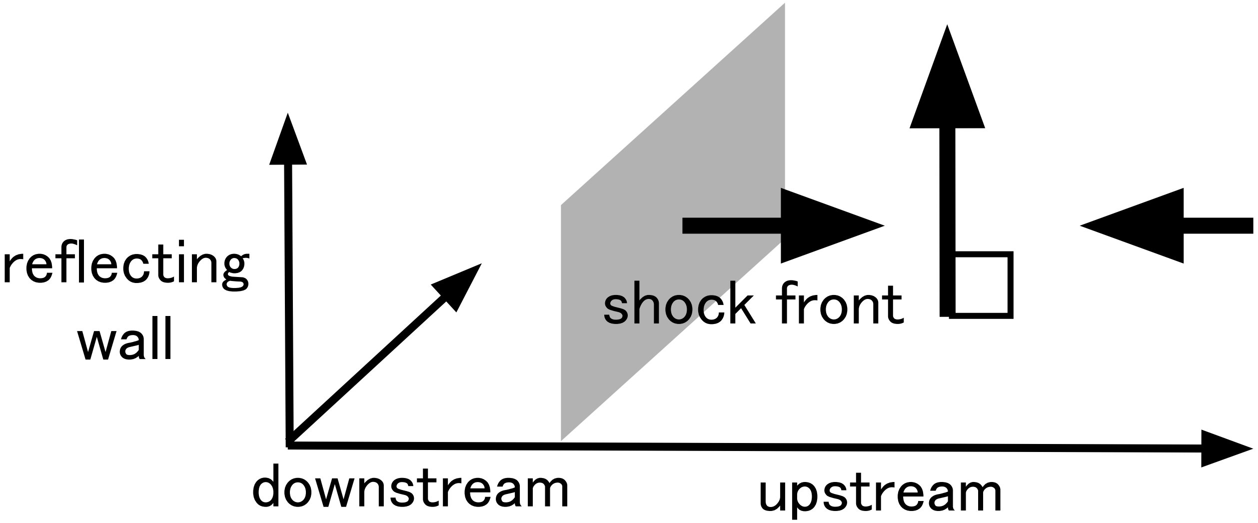
- ✔ First-principles method for collisionless plasmas
- ✔ Basic equations
  - Equation of motion (Lagrangian)
  - Maxwell equations (Eulerian)
- ✔ numerous number of charged particles→high computational costs



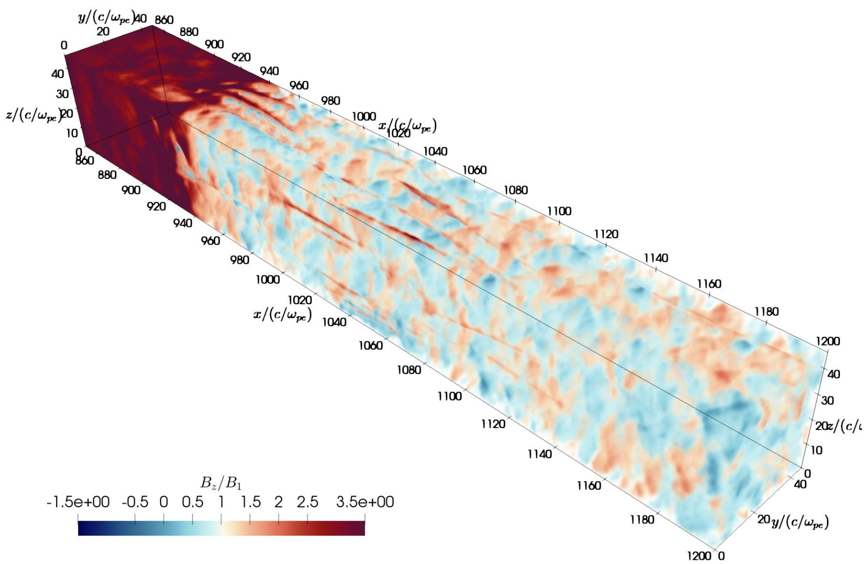
Numerical Setting

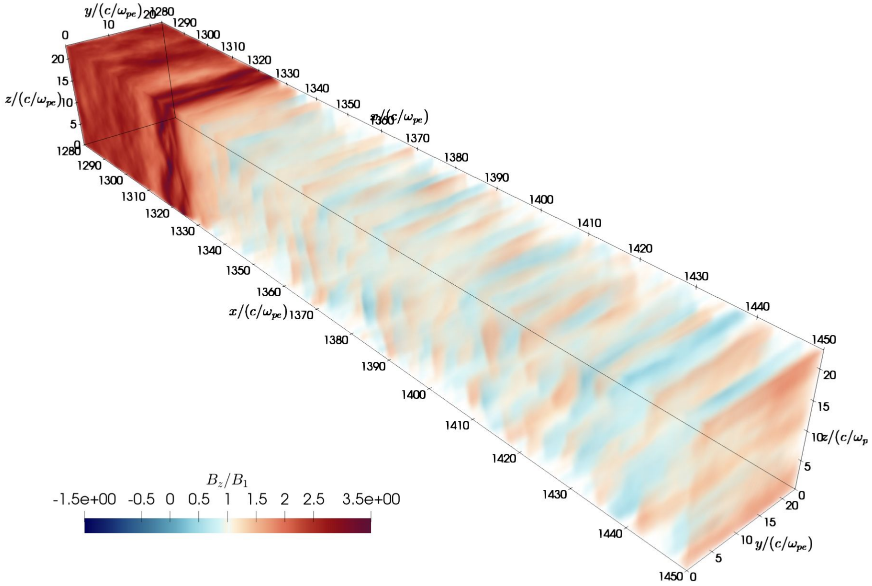
- ✓ Code: Wuming (open source PIC code)
- ✓ Number of particles: $\sim 10^{13}$
- ✓ time step: $\omega_{pe}\Delta t = 0.05$
- ✓ Grid size: $\Delta x/(c/\omega_{pe}) = 0.05$
- ✓ Upstream Lorentz factor: $\gamma_1 = 40$
- ✓ Mass ratio: $m_i/m_e = 200$
- ✓ Magnetization parameter:

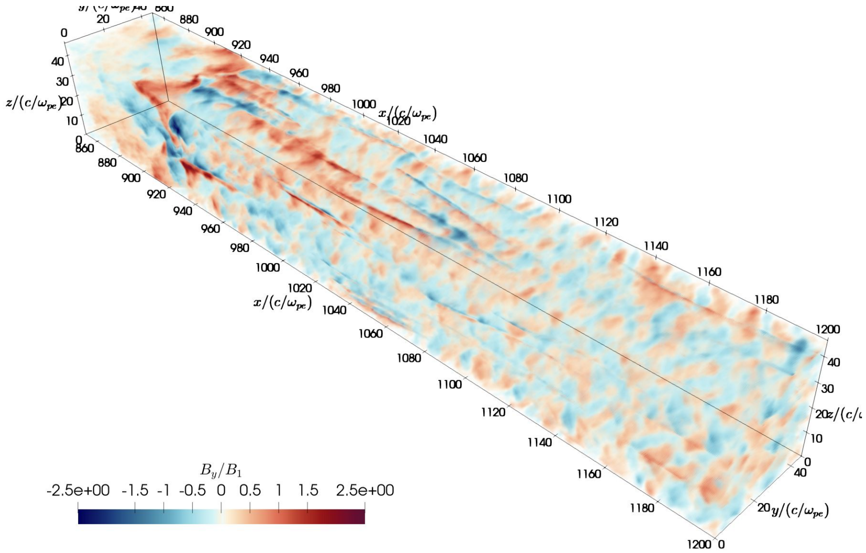
$$\sigma_i \equiv \frac{B_1^2}{4\pi\gamma_1 N_1 m_i c^2} = 0.1, 0.5\ \left(\sigma_e = \frac{m_i}{m_e}\sigma_i = 20{,}100\right)$$

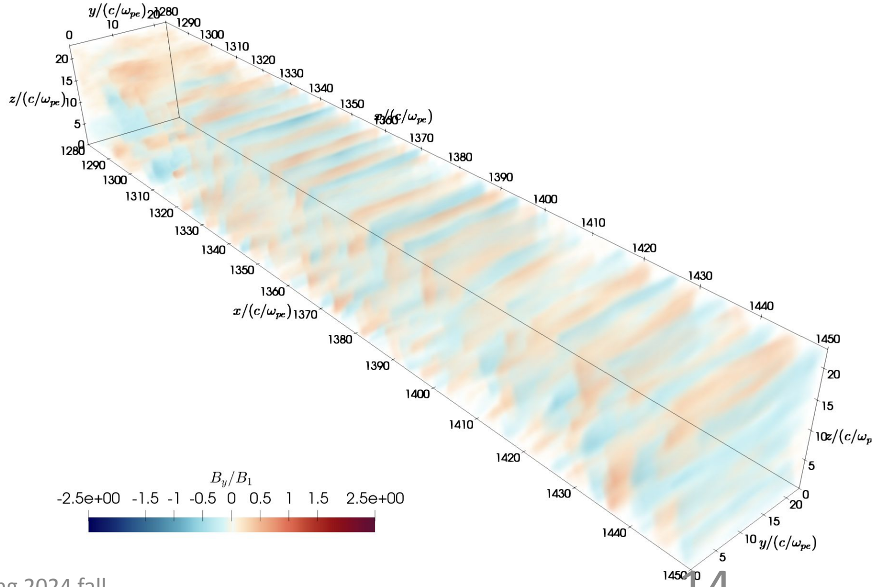


Global Shock Structures

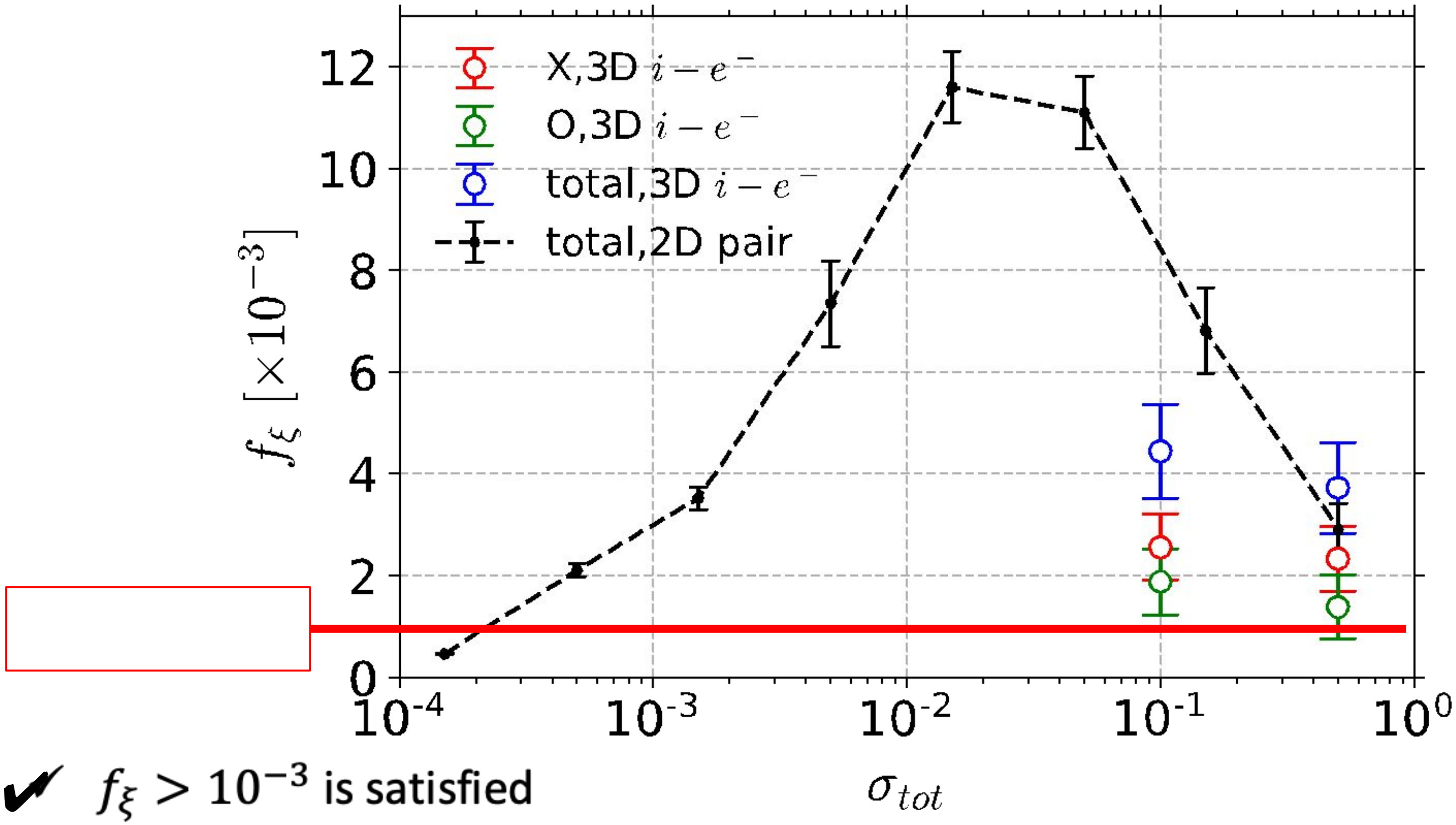








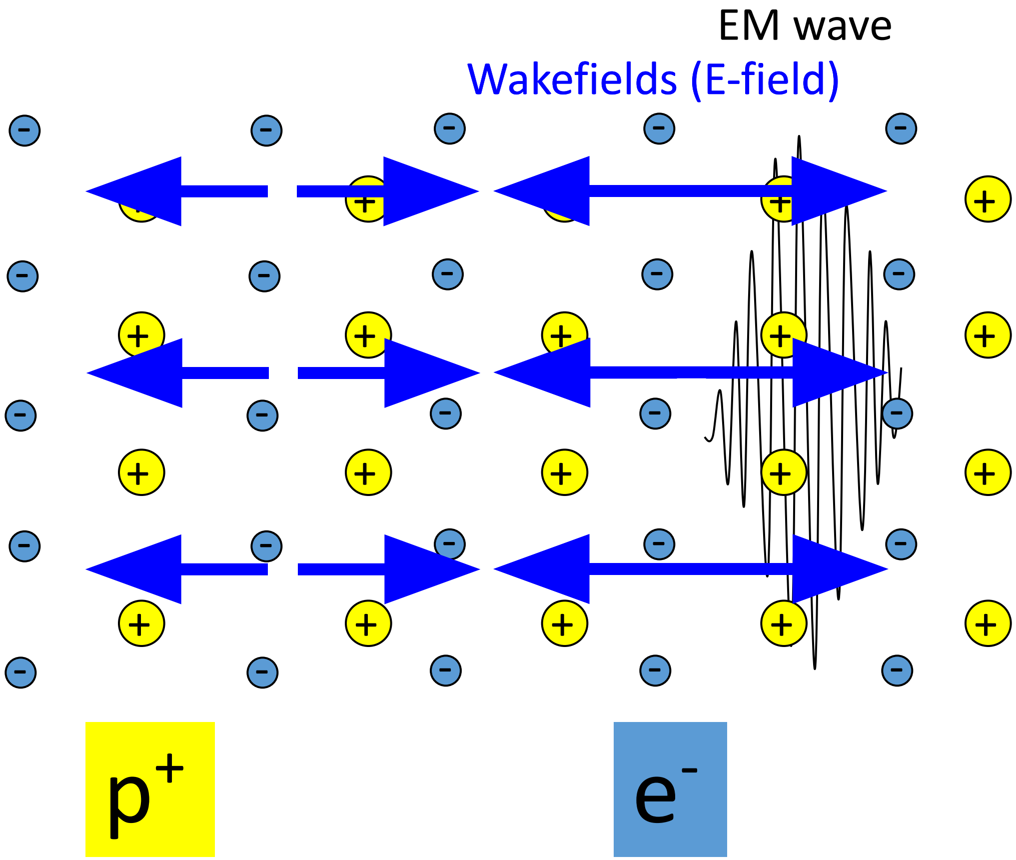
Emission Efficiency



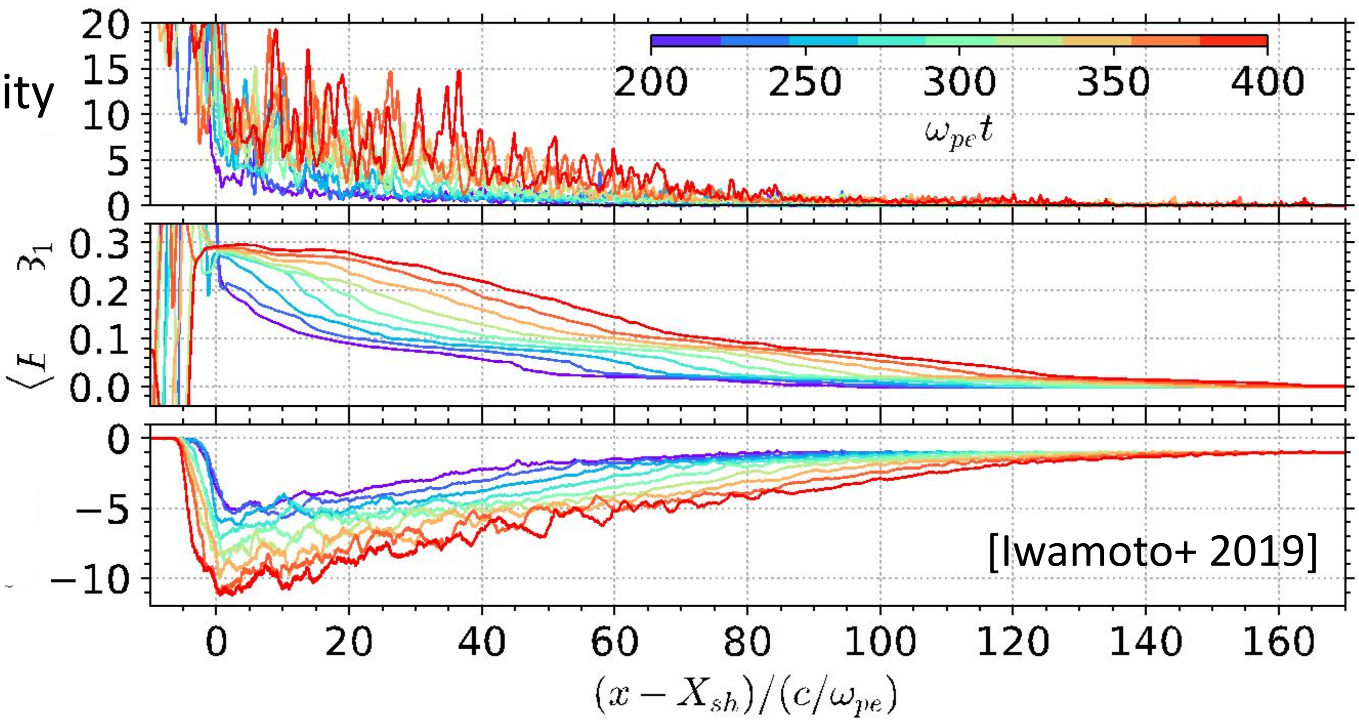
- ✓ $f_\xi > 10^{-3}$ is satisfied
- ✓ **Ion-electron coupling via wakefield**
  →characterized by $\sigma_{tot} = \frac{B_1^2}{4\pi\gamma_1 N_1 (m_i+m_e)c^2} \simeq \sigma_i$ rather than σ_e
- ✓ Low σ_{tot}→ competing with Weibel instability
- ✓ High σ_{tot}→ shock velocity is too fast

Wakefield

Stimulated/induced Raman scattering
photon → photon + plasmon
=wakefield



Ion-Electron Coupling in Upstream

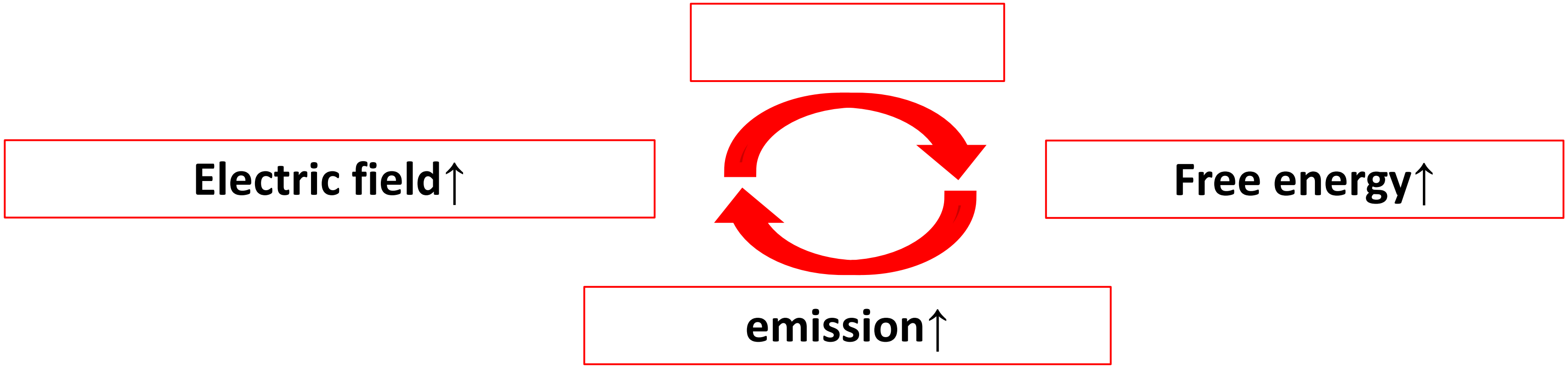


Wave intensity

Wakefield

Electron velocity

[Iwamoto+ 2019]



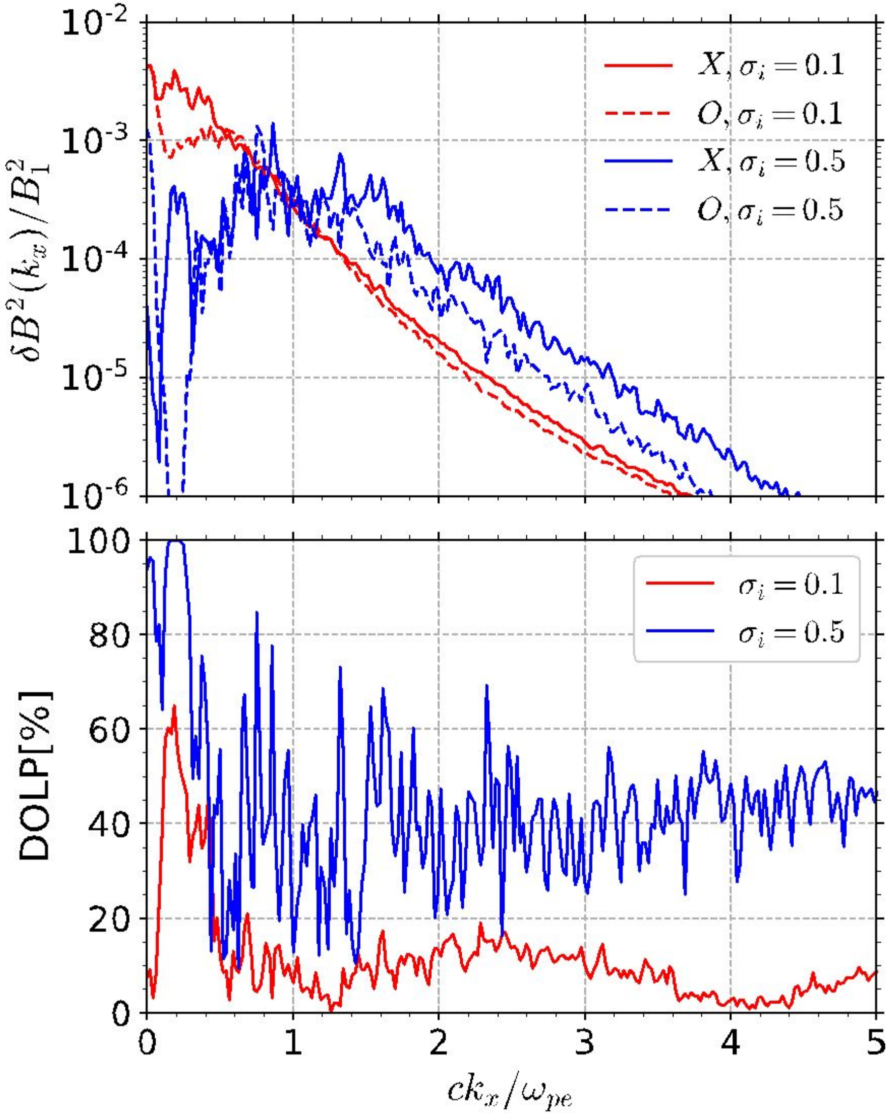
Electric field↑

Free energy↑

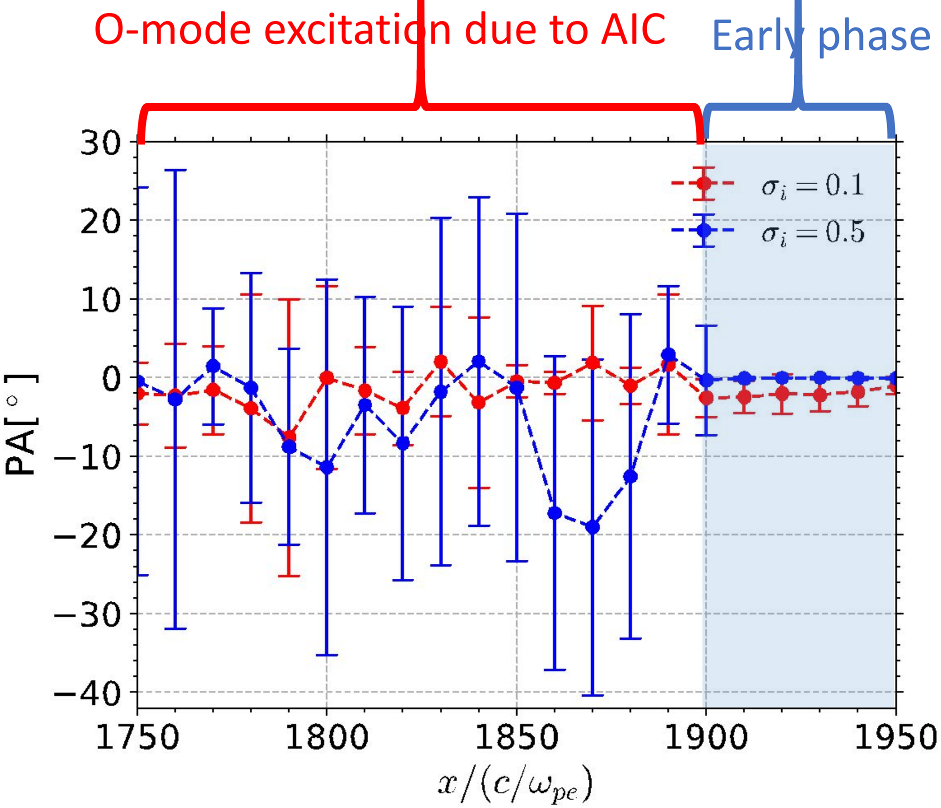
emission↑

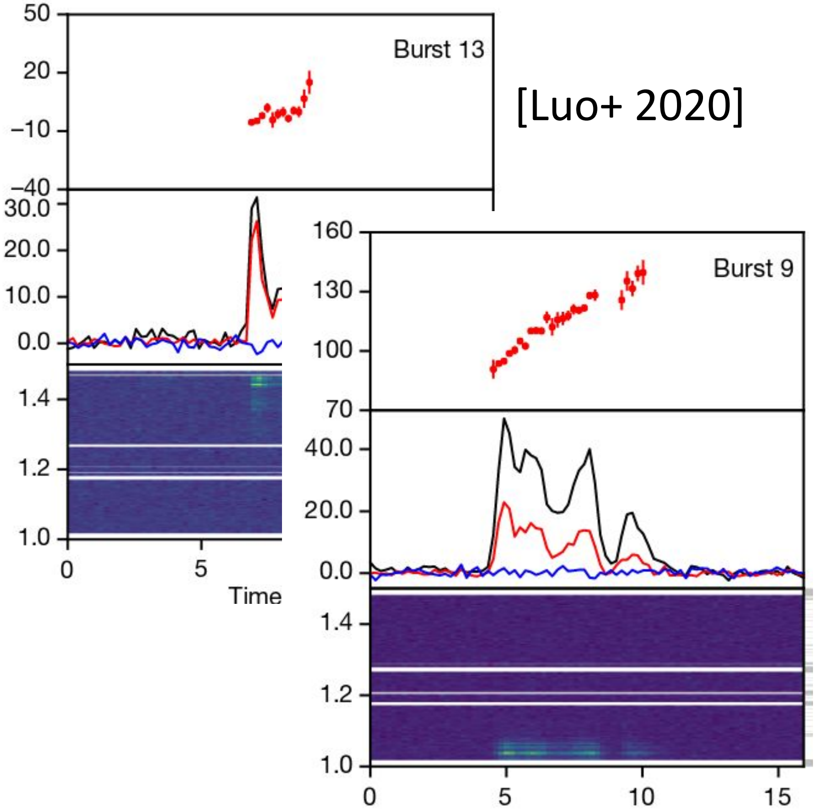
Polarization

✔



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

Implication for FRBs

Emission Efficiency	×	○
Polarization	○	○
Peak Frequency	○	△

Pair shocks with high $\boldsymbol{\sigma}$

- ✓ $f_\xi \sim 10^{-3}\sigma^{-1} \ll 10^{-3}$
- ✓ Shock solution does not exist for $\sigma > (\gamma_1 - 1)/2$? (Alsop & Arons 1988)

Ion-e^- shocks with moderate $\boldsymbol{\sigma}$

- ✓ 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…

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: $\nu_{peak} \sim 1\mathrm{GHz}\sqrt{\frac{\gamma_{sh}^2 n_0}{10^{13}\ \mathrm{cm}^{-3}}}$

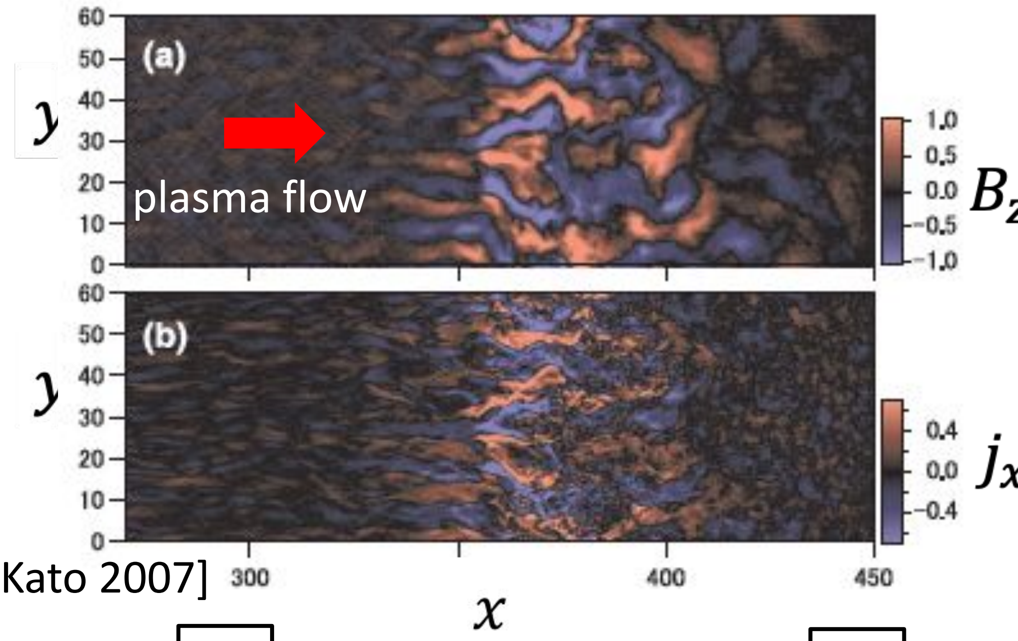
Future Work

- ✓ Upstream temperature dependence of f_ξ
  - – Pair plasma: deteriorate for $k_B T_e / m_e c^2 > 10^{-1.5}$ (Babul & Sironi 2020)
  - – Ion-electron plasma: remain unsolved…
- ✓ Escaping process
  - – Stimulated scattering (Raman, Brillouin, and Compton)
  - – Plasma instability (filamentation & modulation instability)

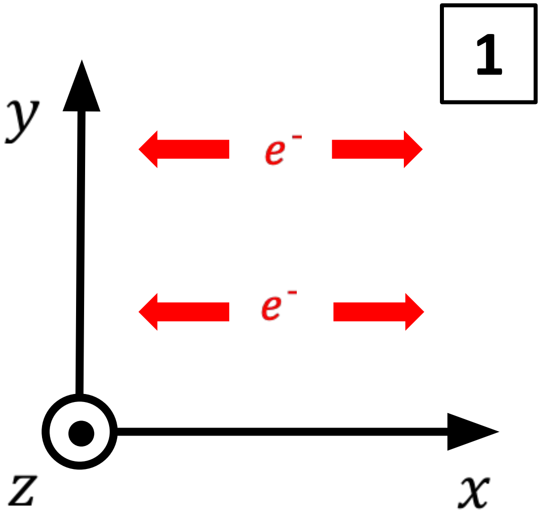
Back up

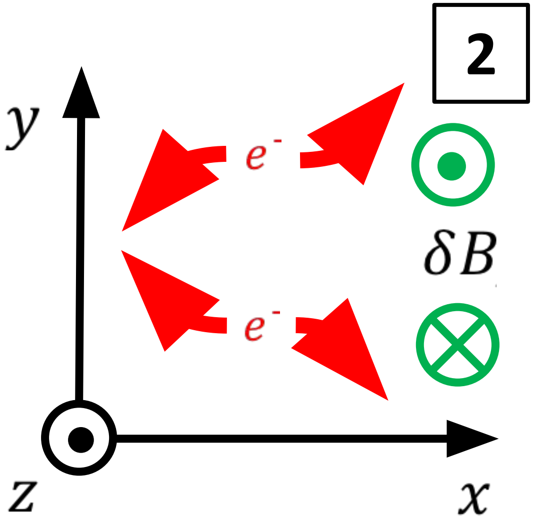
Weibel instability

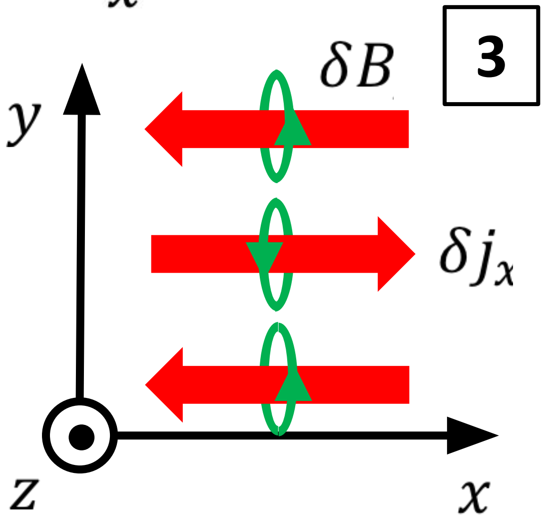
- ✓ Counter-streaming plasma flows can induce the Weibel instability (Weibel 1959, Fried 1959)
- ✓ Dominant for $\sigma \ll 1$
- ✓ Ring-like distribution is not generated
  →SMI is suppressed



[Kato 2007]

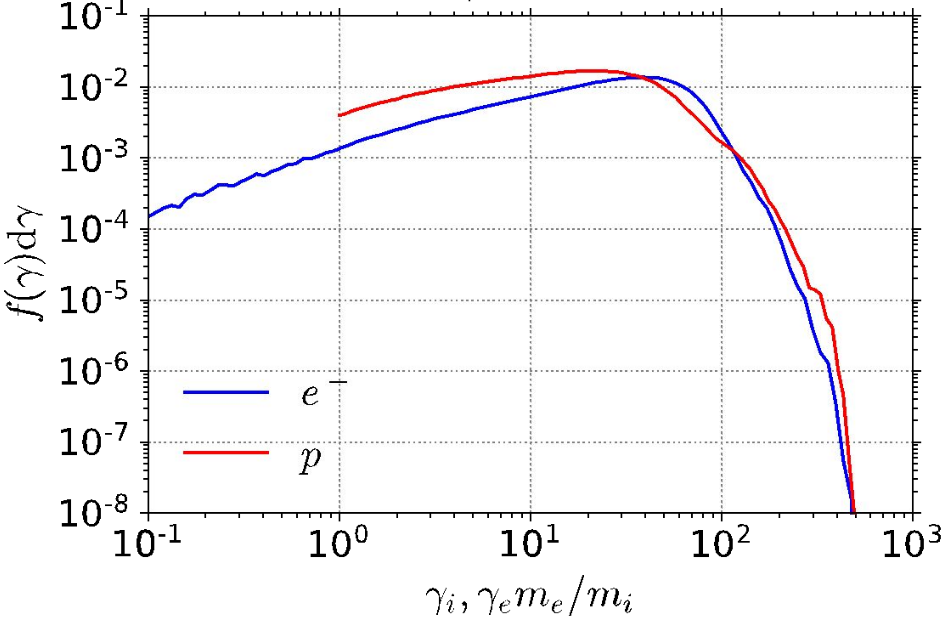




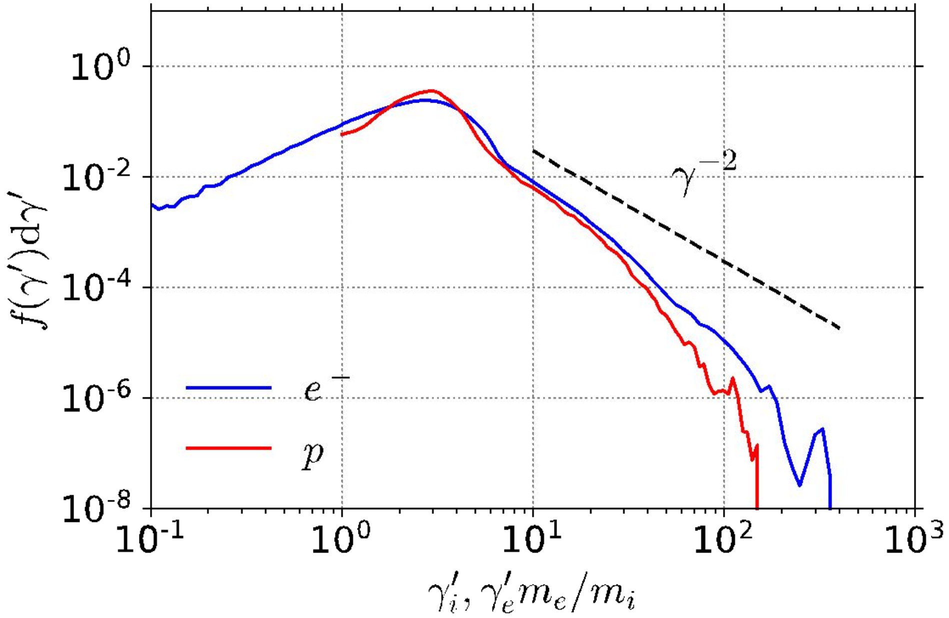


Nonthermal Particles

Downstream

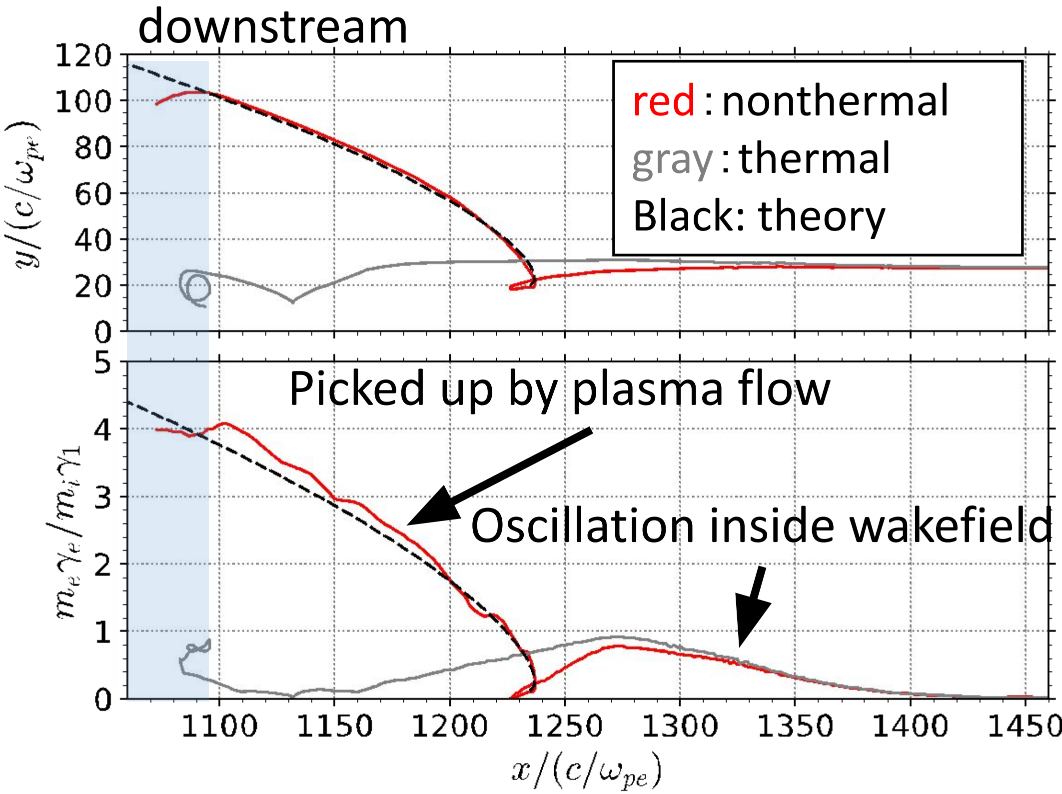


Upstream



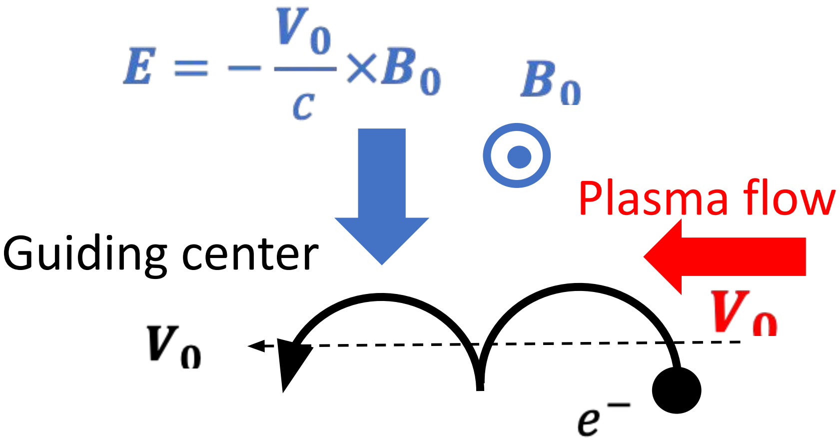
- ✔ Efficient particle acceleration occurs in the near-upstream region (Hoshino 2008; Iwamoto+ 2022)
  - No particle acceleration in high σ pair shocks
  - Power-law-like spectra in the downstream at a later phase?
- ✓ Nonthermal counterparts?

Trajectory of Nonthermal Electron



Picked up by plasma flow

Oscillation inside wakefield



$$E = -\frac{V_0}{c} \times B_0$$

Theoritical Lorentz factor

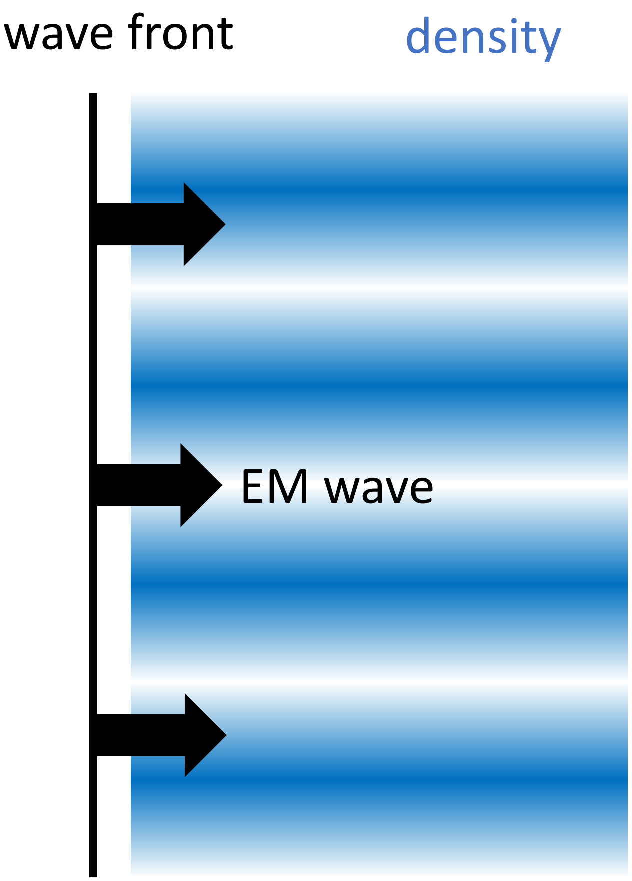
$$\gamma_s \sim \gamma_1^2 \gamma_{0s} \left[(1 + \beta_1 \beta_{0s}) - \beta_1 (\beta_1 + \beta_{0s}) \cos\left(\frac{\omega_{cs} t}{\gamma_1^2 \gamma_{0s} (1 + \beta_1 \beta_{0s})} \right) \right]$$

→Maximum Lorentz factor: $\gamma_{max} \sim \gamma_1^2 \gamma_{0s}$

Filamentation Instability

Transverse modulation instability (four-wave coupling)

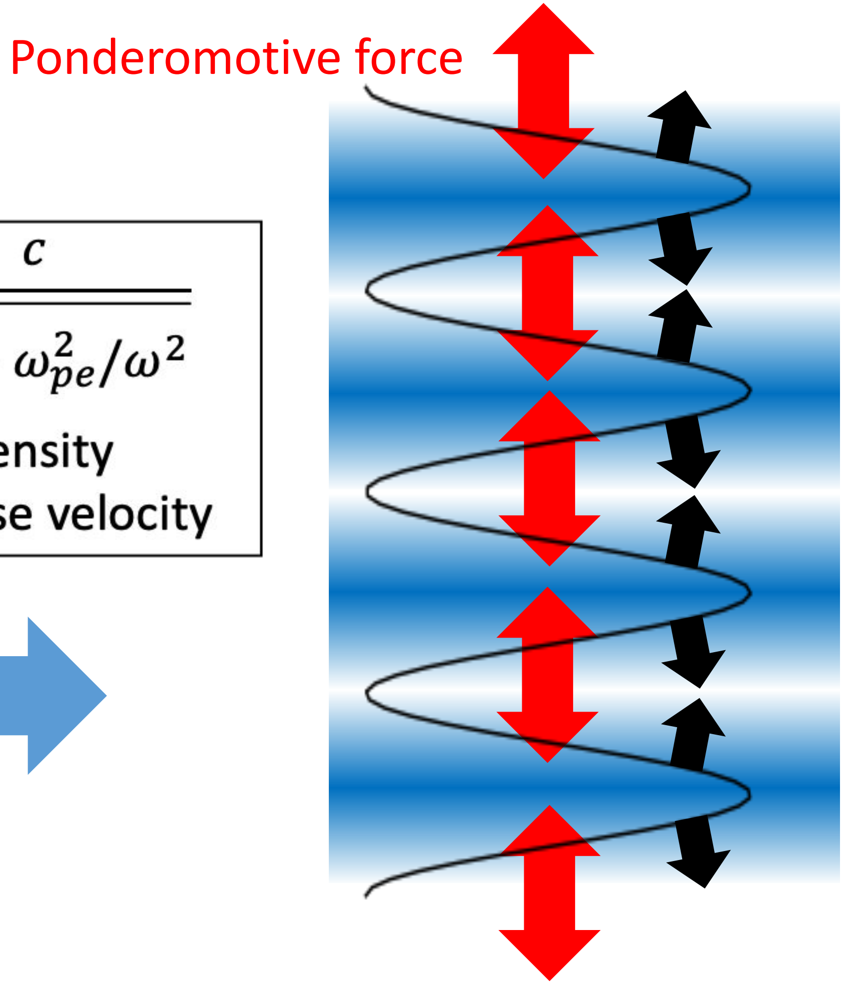
(Kaw+ 1973; Sobacchi+ 2020;2022;2023)



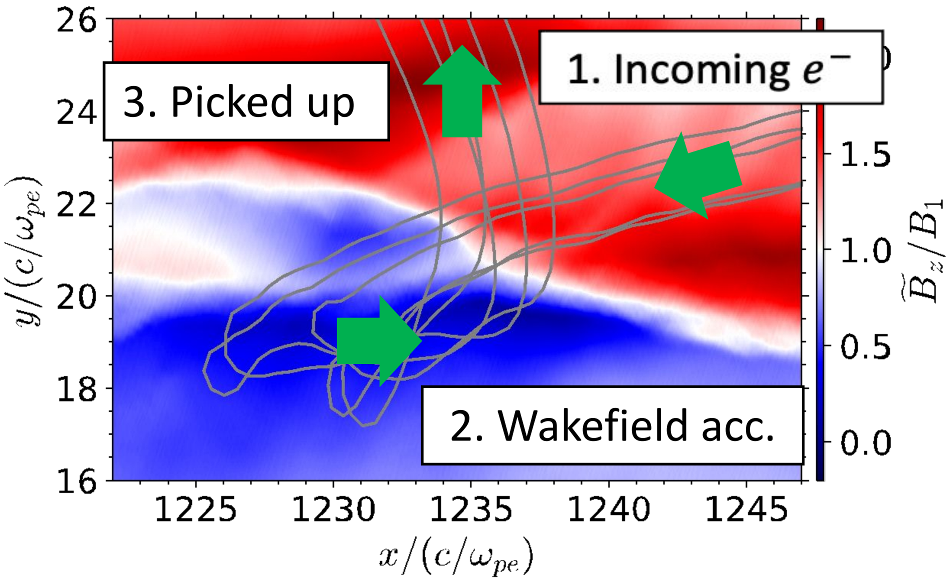
$$\frac{\omega}{k} = \frac{c}{\sqrt{1 - \omega_{pe}^2/\omega^2}}$$

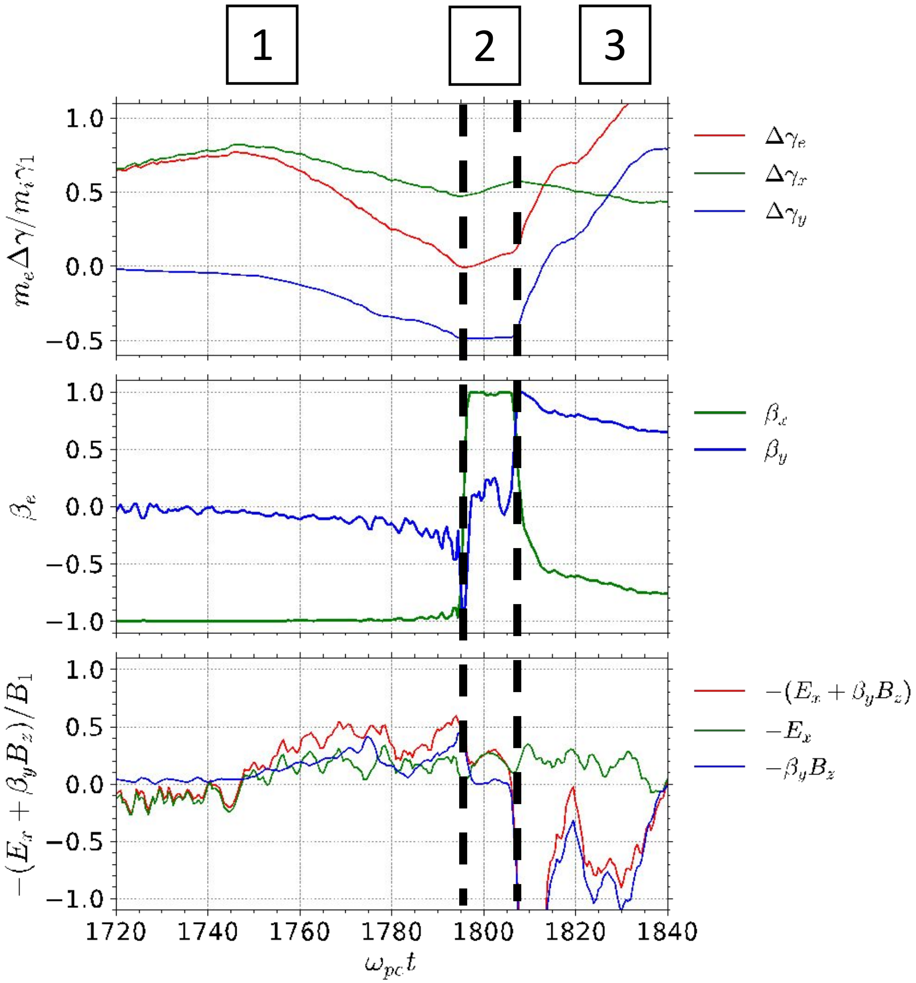
High density

→High phase velocity



Injection into Pickup Process





- ✔ $B_z \sim 0$ within filaments
  $\rightarrow qE_{wake} > q\beta_y B_z$
  $\rightarrow$trapped by wakefield
- ✓ Particles are accelerated up to γ_{0s} by wakefield and then further accelerated by the motional electric field

Maximum Attainable Energy

✔Wakefield acceleration part:

$$\gamma_{0e} = 1 + \frac{eE_{wake}L_{acc}}{m_e c^2} \sim 1 + \alpha_e \gamma_1 \sqrt{\sigma_e} \frac{E_{wake}}{B_1} \sim \alpha_e \gamma_1 \sqrt{\epsilon}$$

$$\gamma_{0i} = 1 + \frac{eE_{wake}L_{acc}}{m_i c^2} \sim 1 + \frac{m_e}{m_i} \alpha_i \gamma_1 \sqrt{\epsilon}$$

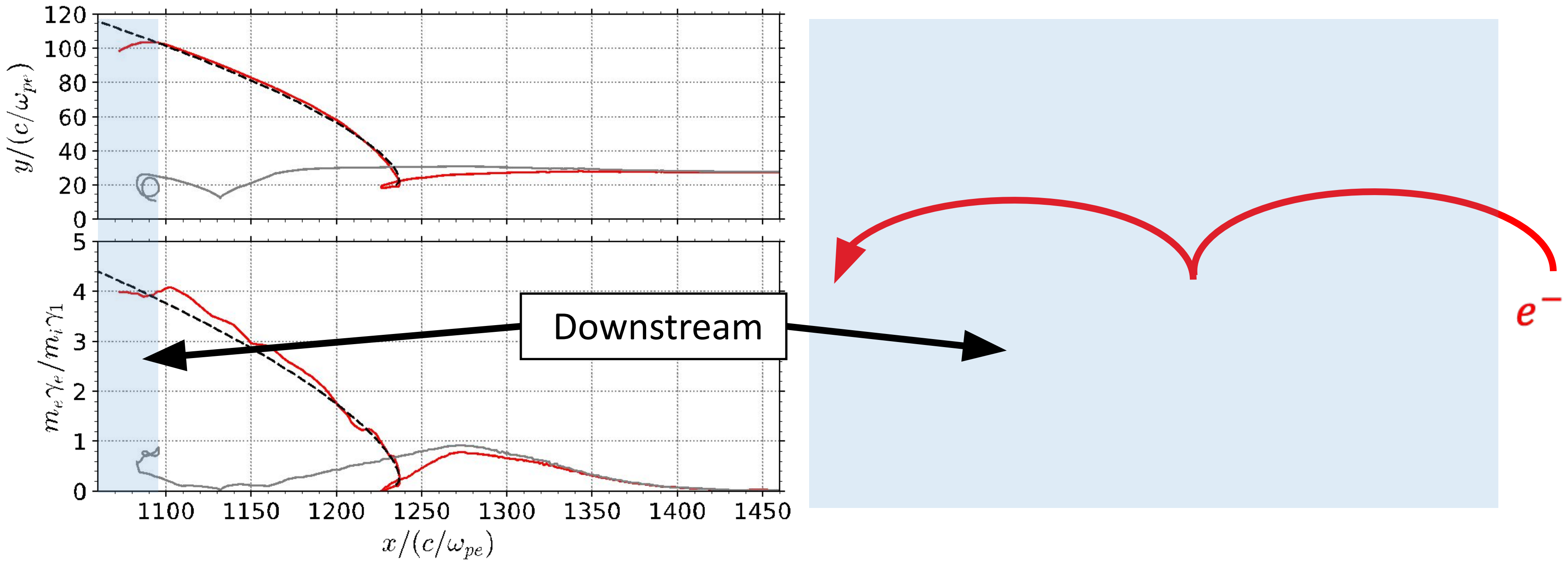
$$\alpha \equiv \frac{L_{acc}}{c/\omega_{pe}}$$

➡

$$\boxed{\begin{aligned} &\gamma_{max,e} \sim \alpha_e \gamma_1^3 \sqrt{\epsilon} \\ &\gamma_{max,i} \sim \left(1 + \frac{m_e}{m_i} \alpha_i \gamma_1\right) \gamma_1^2 \sqrt{\epsilon} \end{aligned}}$$

- ✓ Simulation → $\alpha_e \sim 10$, $\alpha_i \sim 1$, and $\epsilon \sim 1$
- ✓ The normalized wave power ϵ is independent of γ_1 as long as $\gamma_1 \gg 1$
- ✓ The maximum acceleration →wakefield wavelength: $\alpha_{max} \sim \gamma_1$

Acceleration Time



- ✓ Acceleration time scale

$$\omega_{ce}t_{acc} \sim 2\pi\gamma_1^2\gamma_0 \sim 2\pi\alpha\gamma_1^3$$

- ✓ Moving distance during the acceleration

$$\frac{\Delta x}{c/\omega_{pe}} \sim \omega_{pe}\beta_1 t_{acc} \sim \frac{2\pi\alpha\gamma_1^3}{\sqrt{\sigma_e}} \sim 10^6$$

→ Nonthermal particle enters the shock before it takes the maximum
→ need to follow the long term evolution

Summary: Particle Acceleration

✓**Thermal particles**

- ✓ Energy equipartition between ion and electron is achieved due to the ion-electron coupling via the wakefield in the upstream
- ✓ $\gamma_1 \gg 1$ is required for the strong ion-electron coupling

Nonthermal particles

- ✓ Some particles are picked up by the bulk flow and accelerated by the motional electric field
- ✓ Wakefield and filaments inject them into the pickup process
- ✓ Nonthermal particles may be observed in the downstream if we follow the long-term evolution