# Wave Activities and Their Roles in Collisionless Magnetic Reconnection

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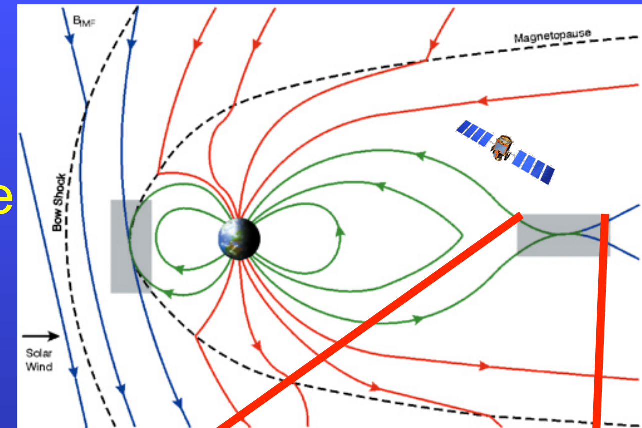
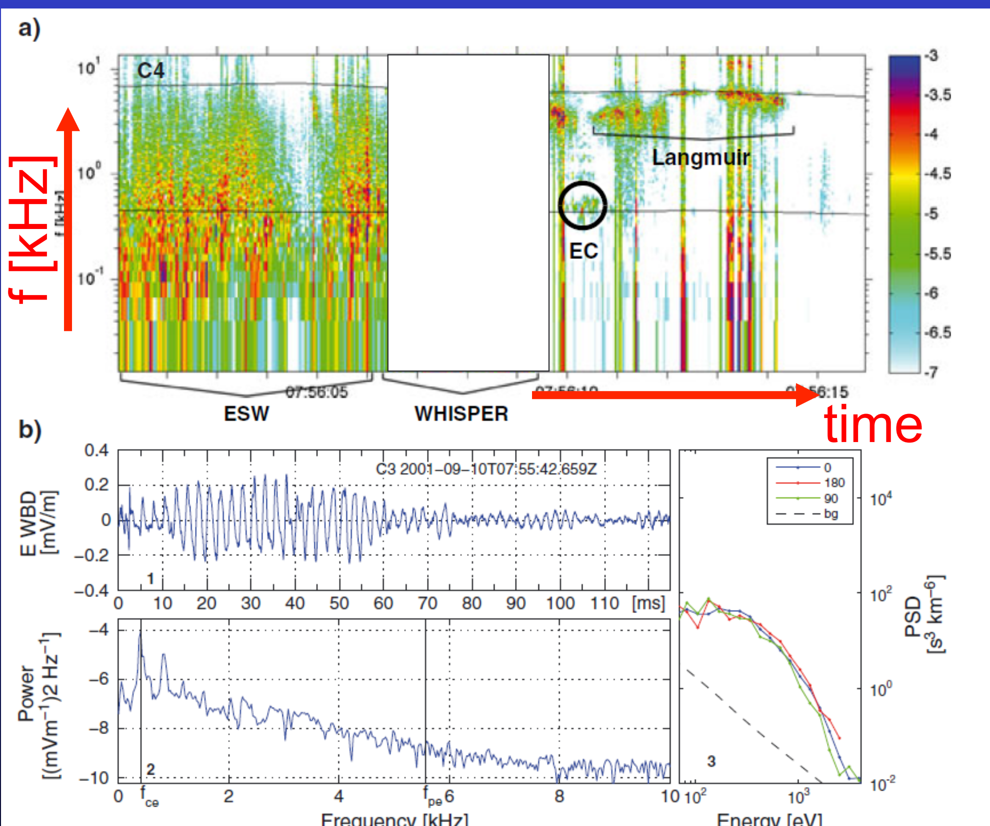
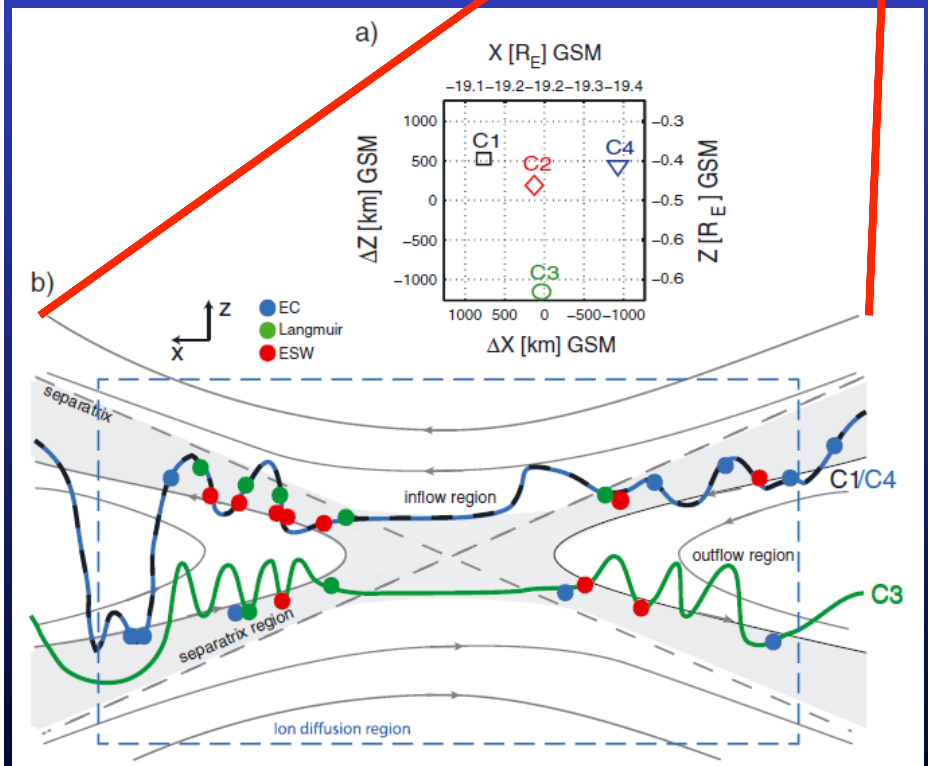
# Waves in MRX Region: Obs.

EC (Electron cyclotron: Whistler) → Electromagnetic
Langmuir (plasma oscillation)
ESW (Electrostatic Solitary Wave) → Electrostatic

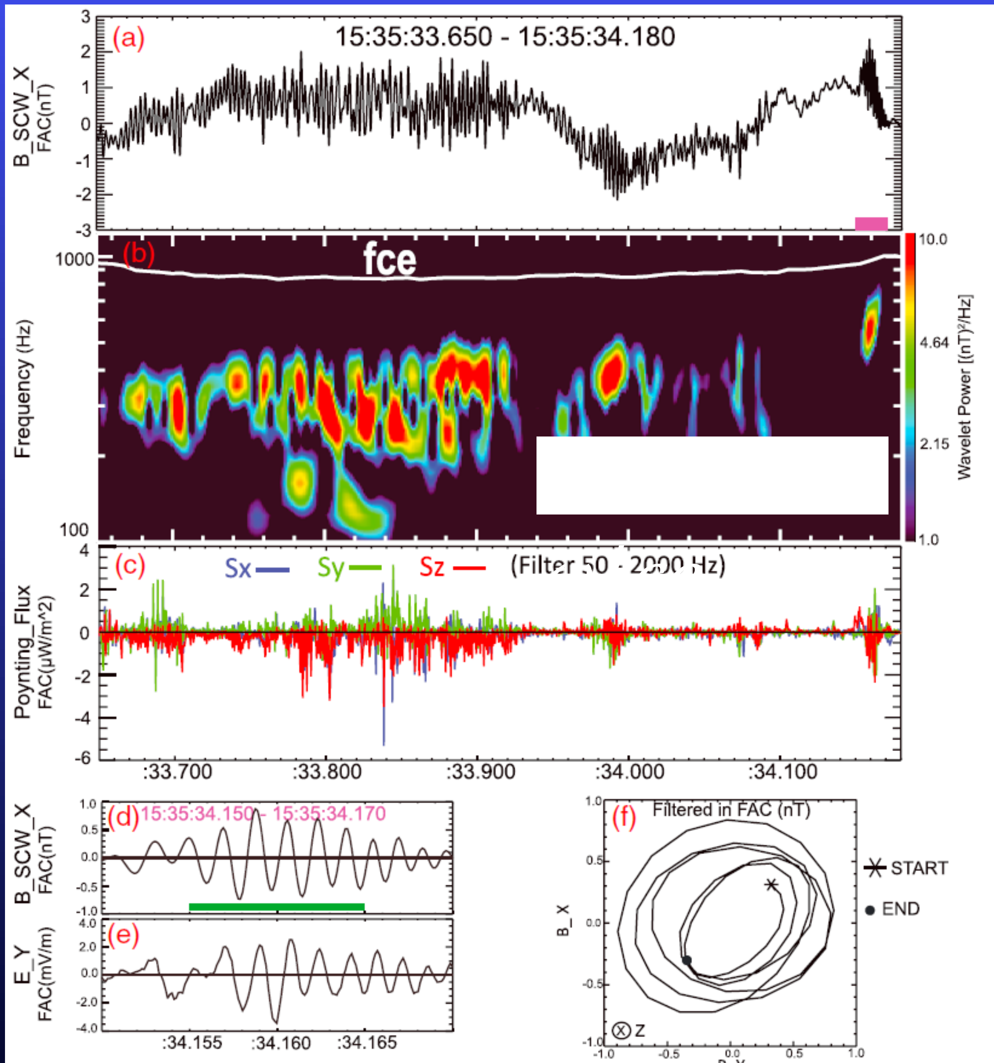


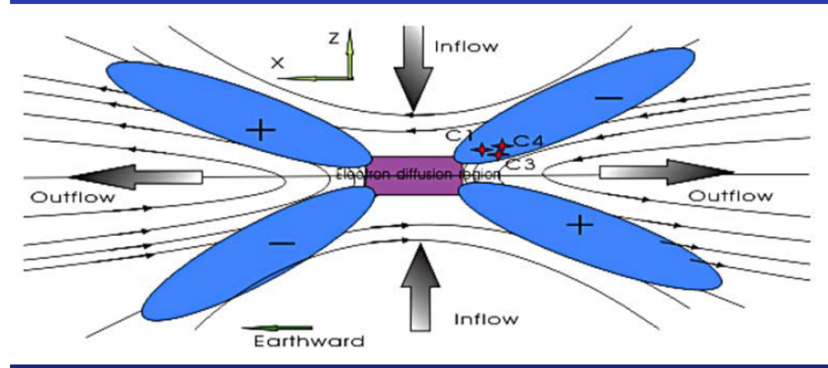

[Viberg et al., GRL, 2013]

# Waves in MRX Region: Obs. of Whistlers




Whistler waves in magnetopause

[Tang et al., GRL, 2013]



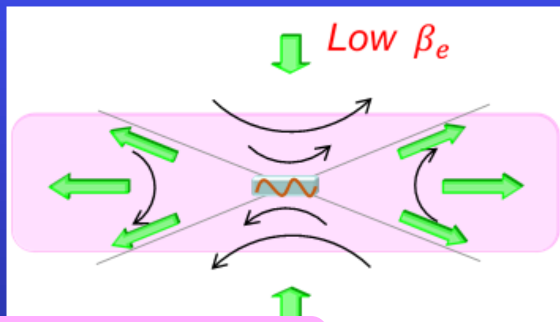

Whistler waves in magnetotail

[Wei et al., JGR, 2007]

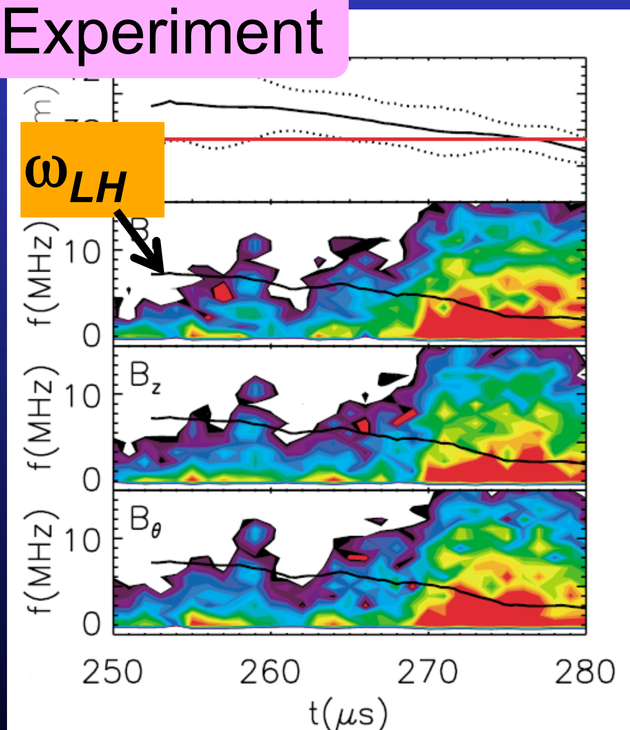
Controlling reconnection?

# Waves in MRX Region: Obs. near X-line

Lower hybrid waves are dominant.

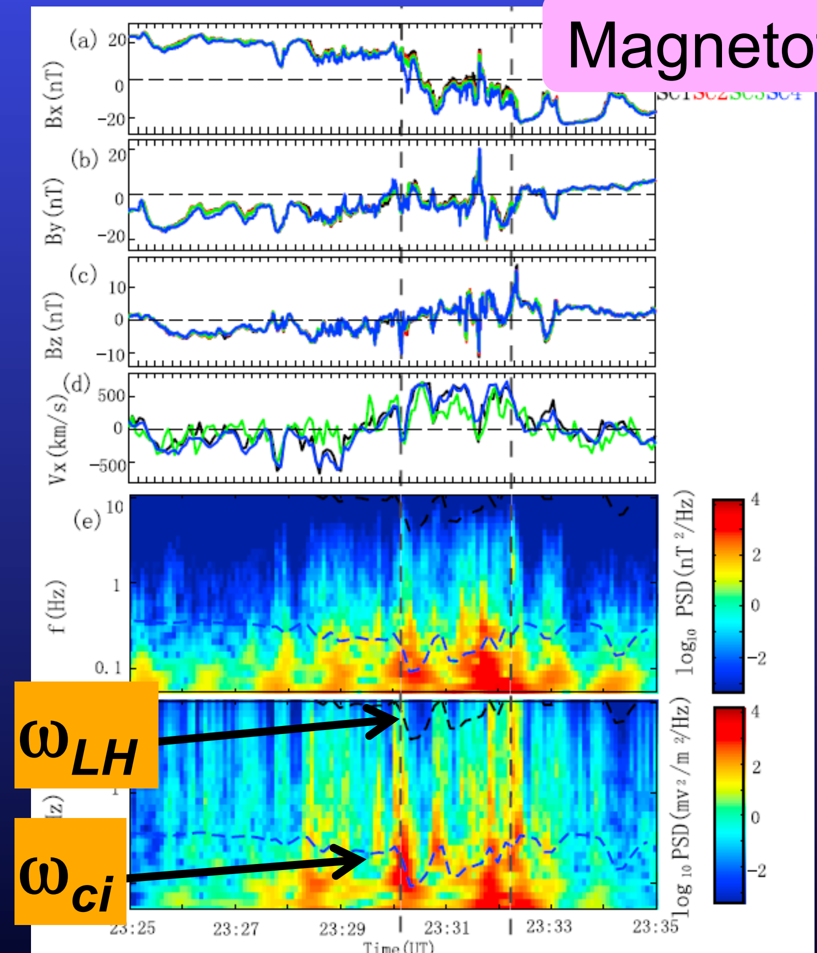



Lab Experiment




[Ji et al, PRL, 2004]

Magnetotail




[Zhou et al, JGR, 2009]

# Purpose of This Study

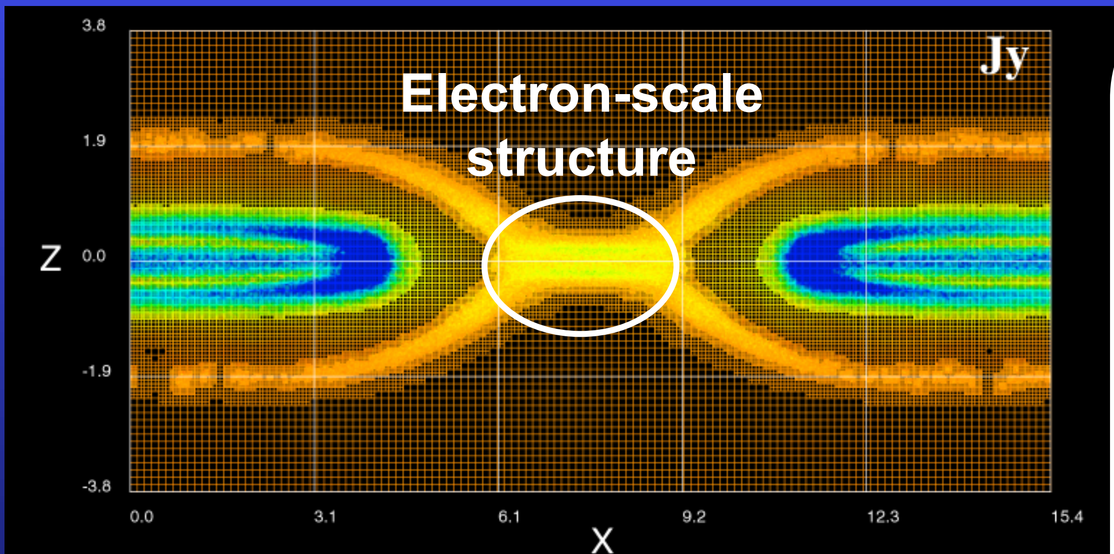
It has been difficult only from observations to identify the generation mechanisms of the waves and their roles in reconnection.

The purpose of this study is:

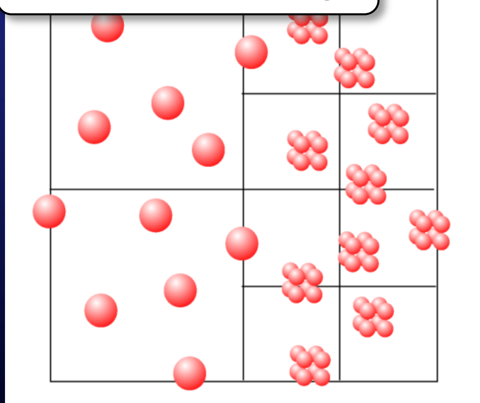
- To understand the wave generation mechanisms in the reconnection region by means of the PIC simulations and linear wave analyses, and
- To clarify the roles of the waves in reconnection.

# Simulation Model [Fujimoto, JCP, 2011]

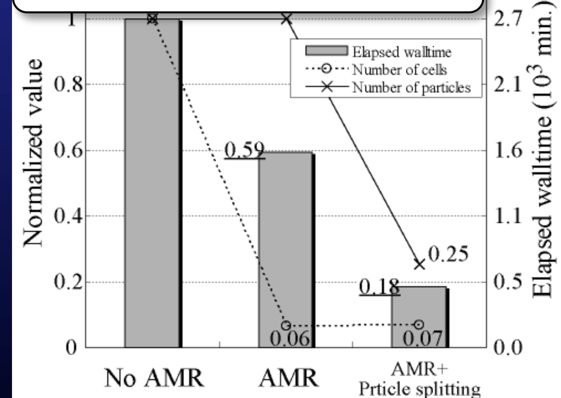
## AMR-PIC (Adaptive Mesh Refinement – Particle-in-Cell)




Particle splitting



Saving 90% memory

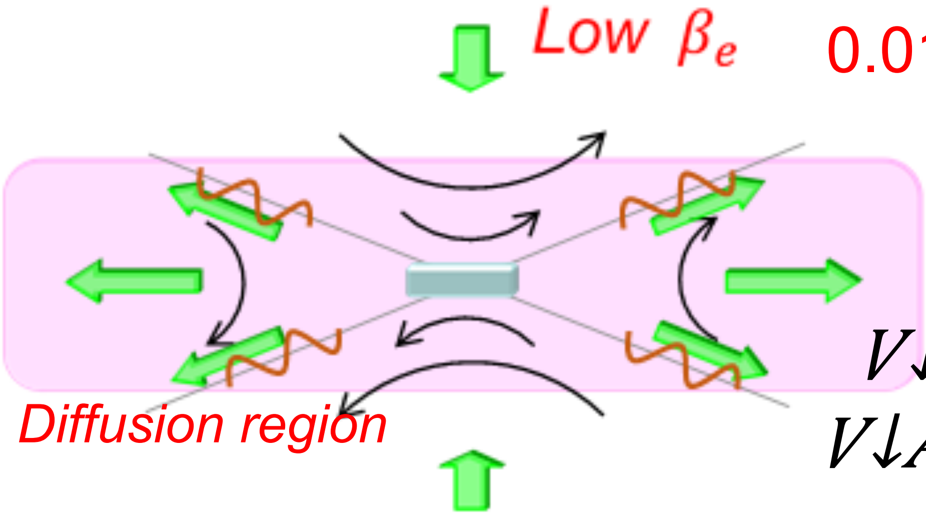



Particles

Electric and magnetic fields

Current density

# Strategy of Our PIC Simulation




0.01

for waves be active

$$\left( V_{e,out} \sim V_{Ae} = v_{th,e} / \sqrt{\beta_e} \right)$$

$$V_{e,out} \sim V_{Ae} = (m_i / m_e)^{1/2} \, (n_b / n_0)^{-1/2} \, V_{A0} = v_{th,e} / \sqrt{\beta_e}$$

More realistic parameters

$m_i/m_e$: 100 ～ 400

$n_b/n_0$: 0.04

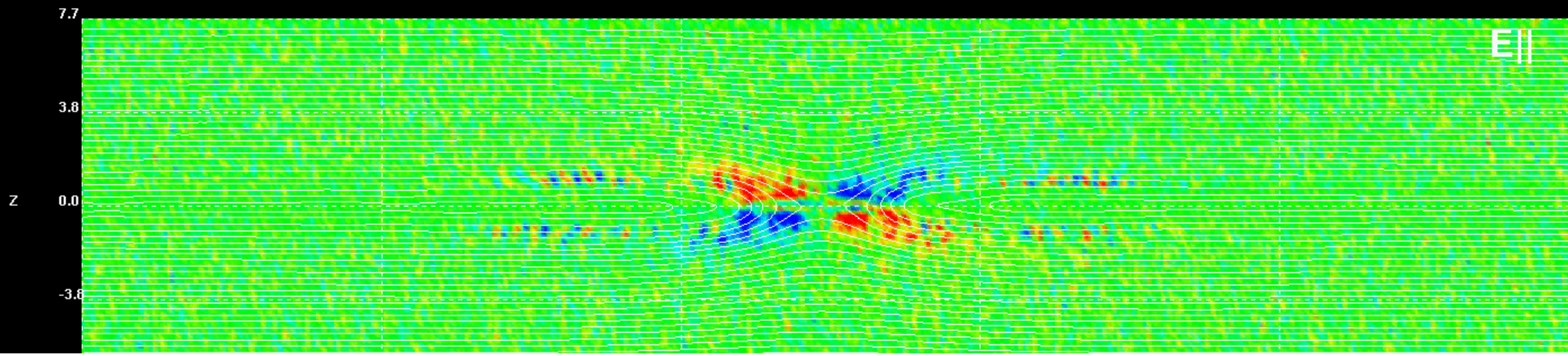
AMR-PIC code

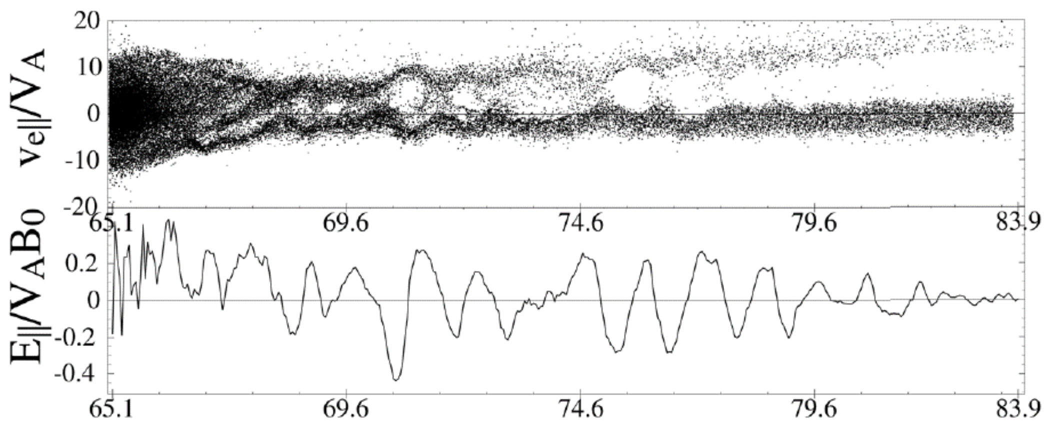
$V_{e,out} / v_{th,e} \sim$

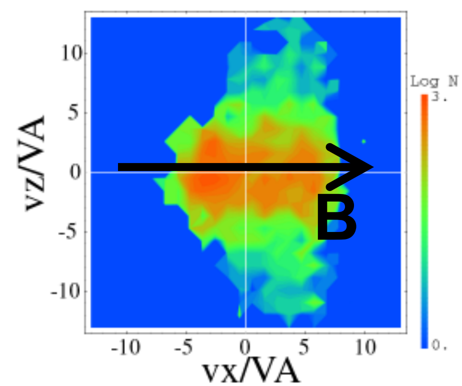
# Waves in PSBL

[Fujimoto & Machida, JGR, 2006]

For anti-parallel reconnection
Langmuir waves + Electron heating at PSBL




Flat-top electron

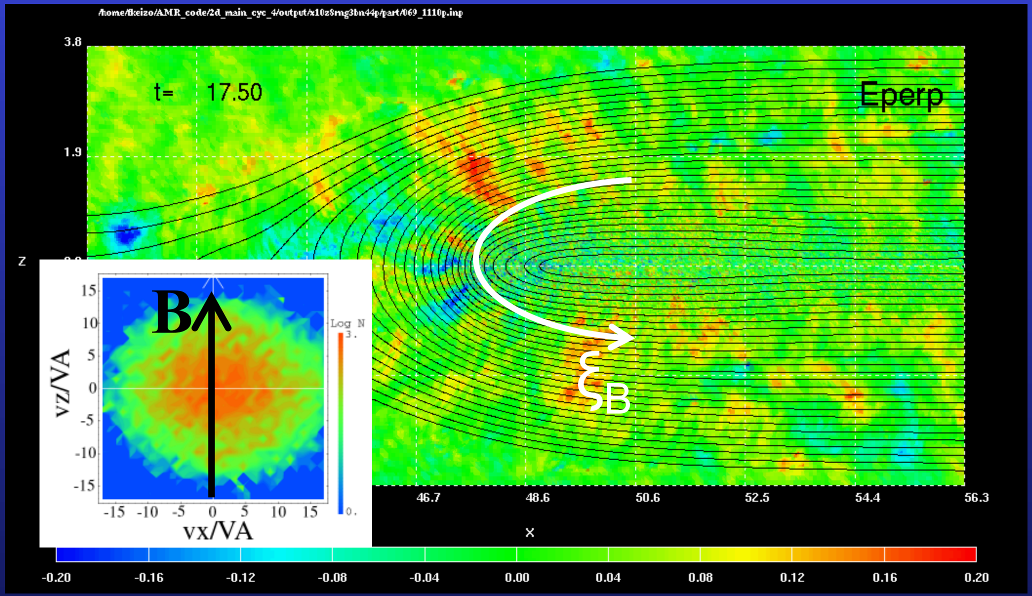
Electron 2-stream instability

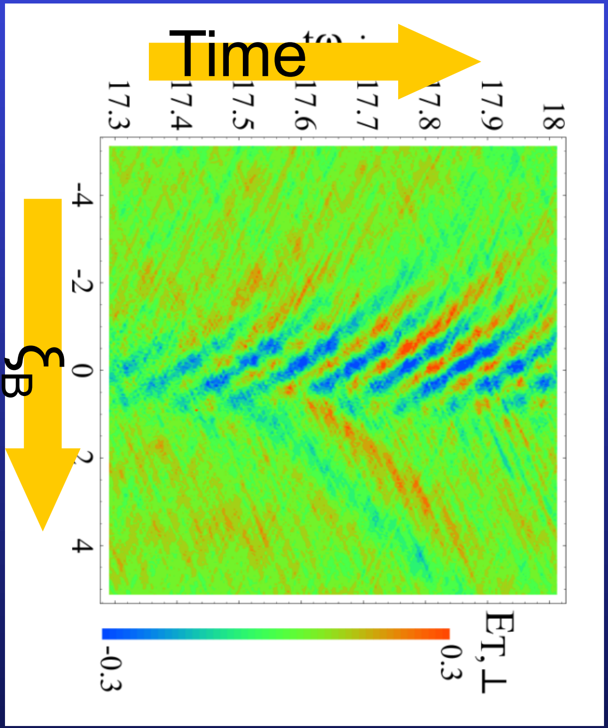
Parallel electron heating

# Waves in Pile-up Region

[Fujimoto & Sydora, GRL, 2008]

Whistler waves in the pile-up region of B-field



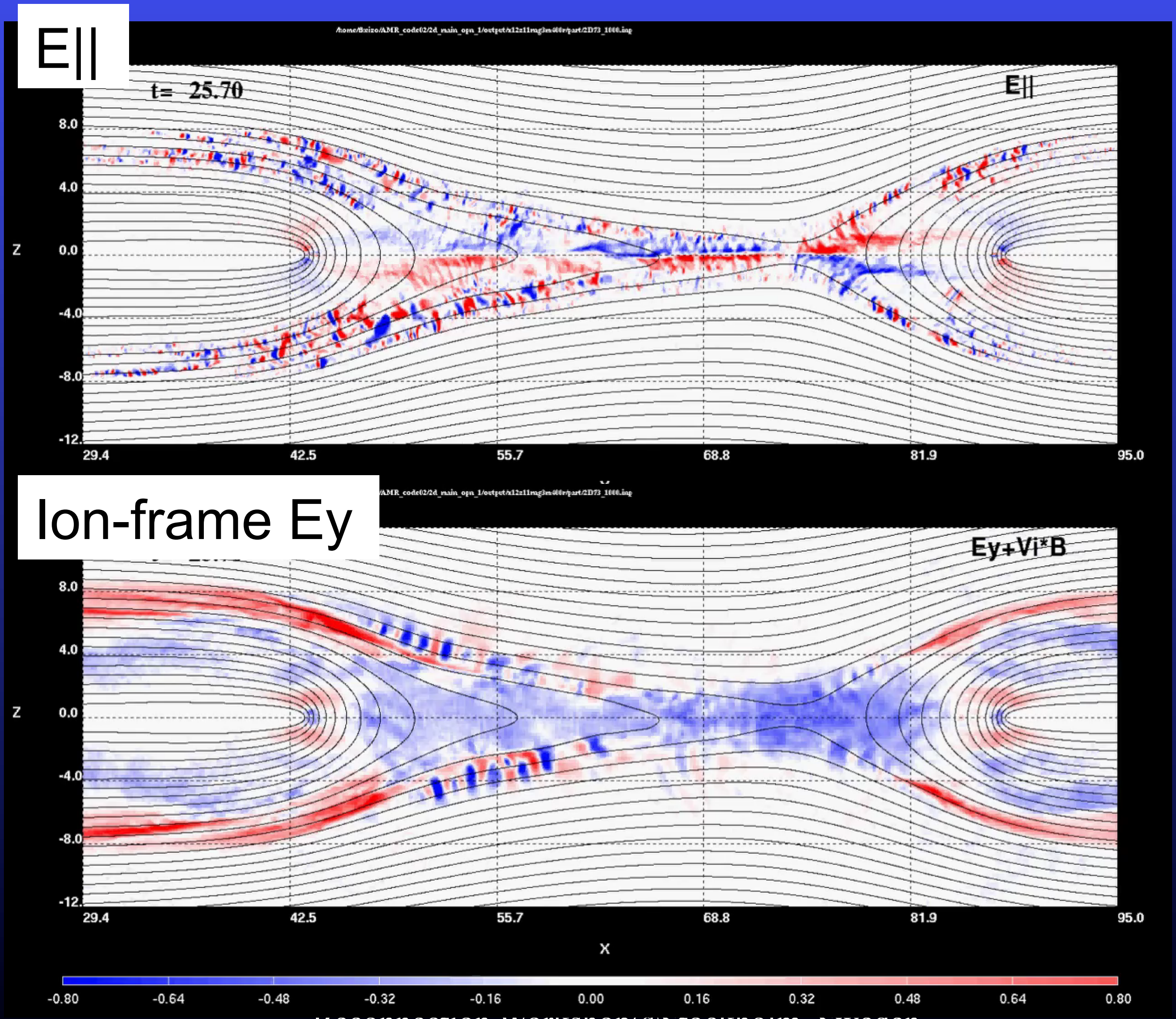




Temperature anisotropy ($T_{e\perp}/T_{e||} > 1$) generates whistlers.

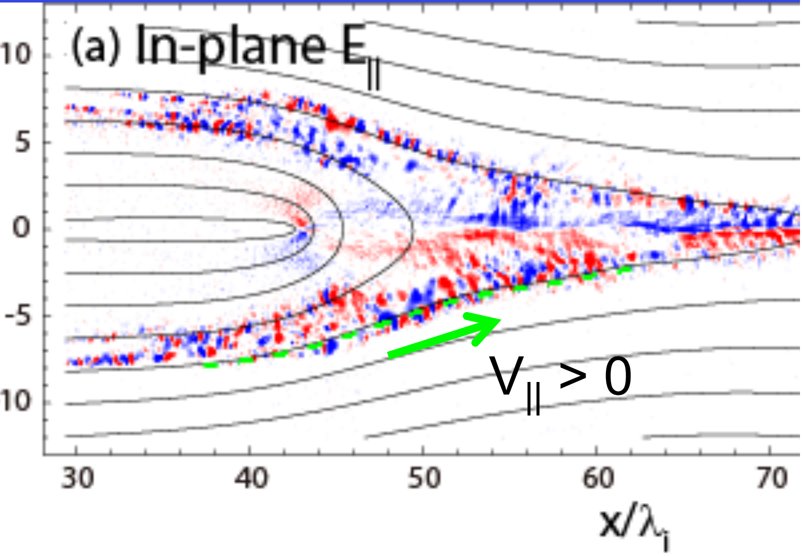
Electrons are scattered to the parallel direction.

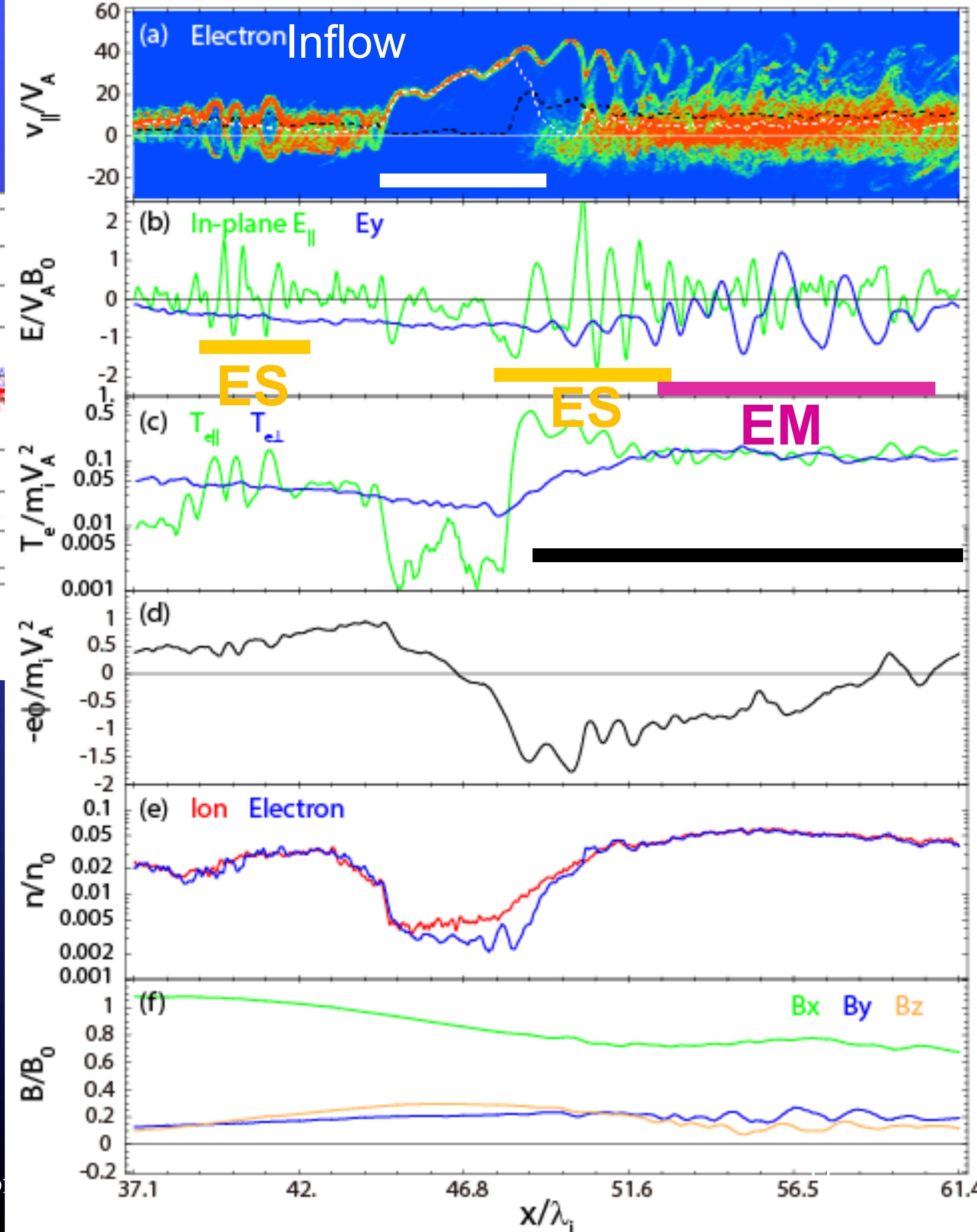
# Waves Around Separatrices

[Fujimoto, GRL, 2014]



# Wave Activities



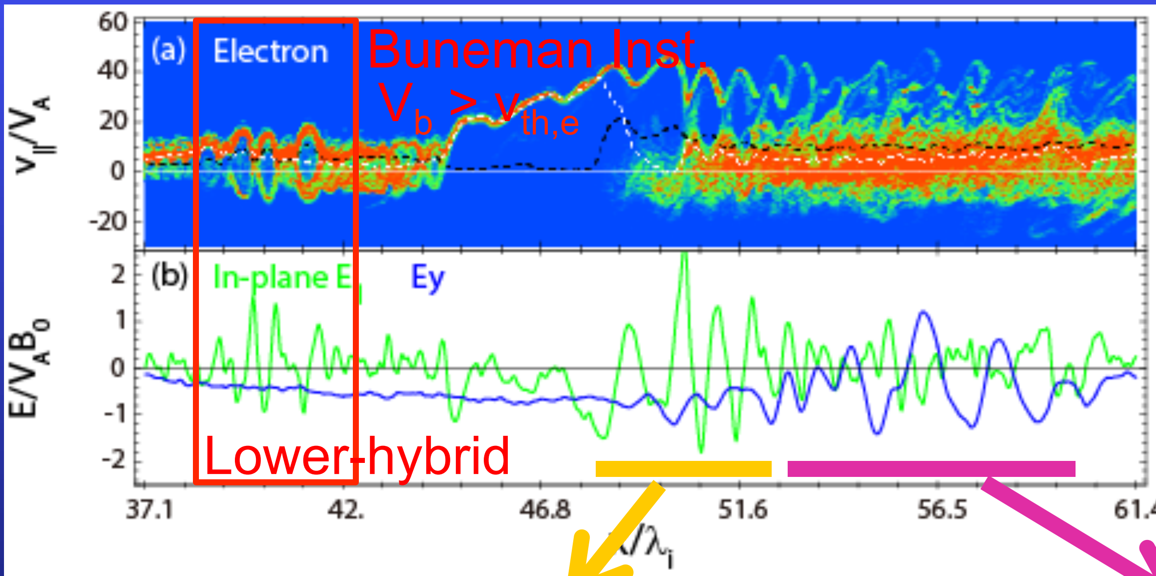



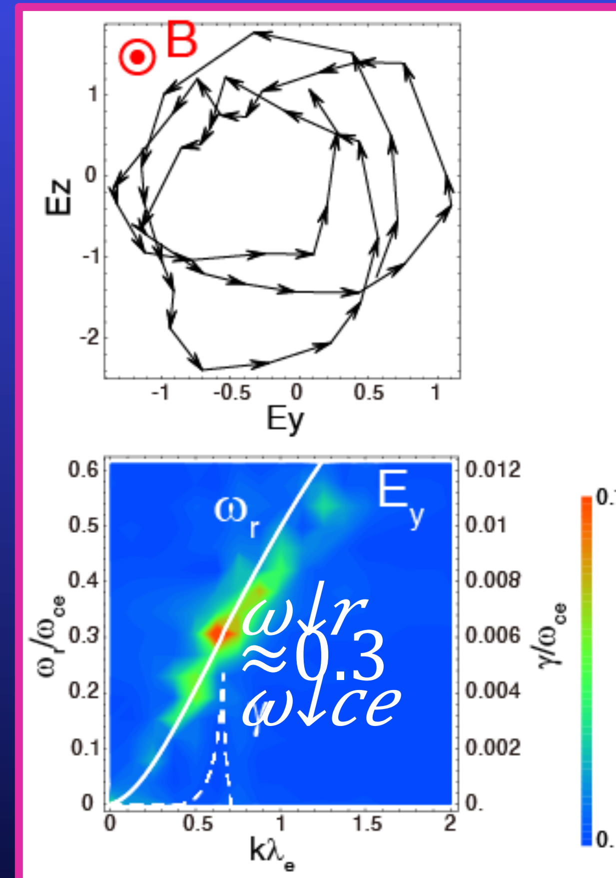

- Weak waves
- Local strong acceleration of electron
- Intense wave activities
- Electron heating

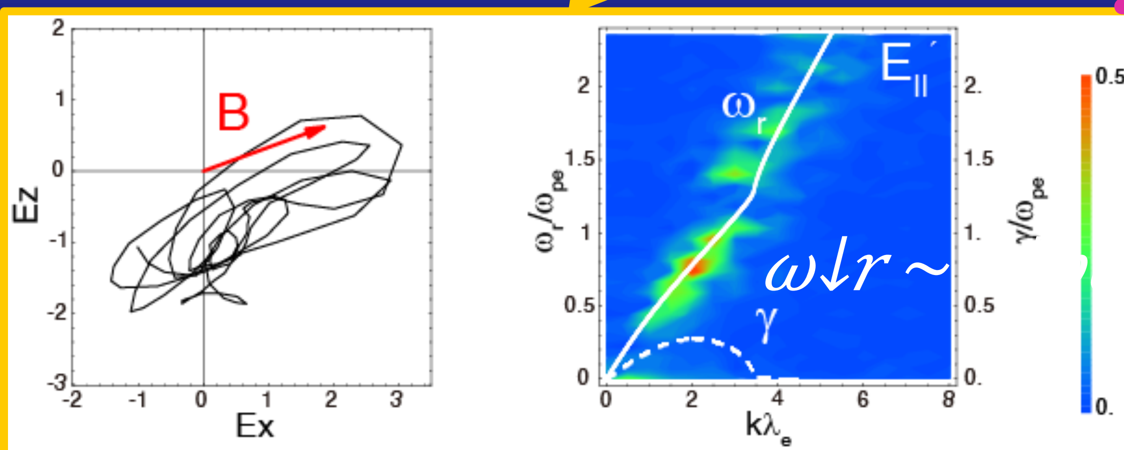
# Wave Generation Mechanisms

Linear analyses

$\omega=\omega_r+i\gamma$



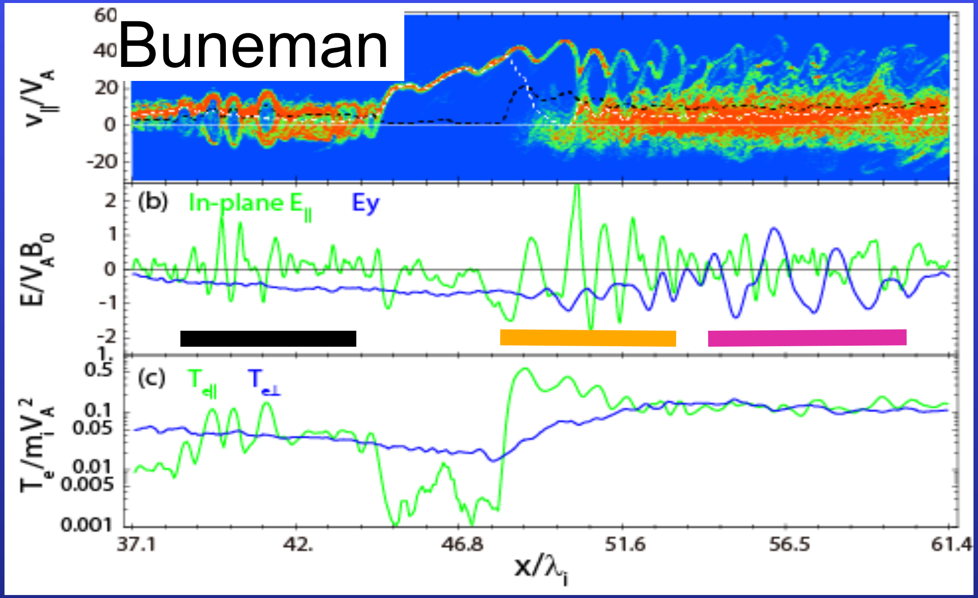




Beam-driven whistler instability

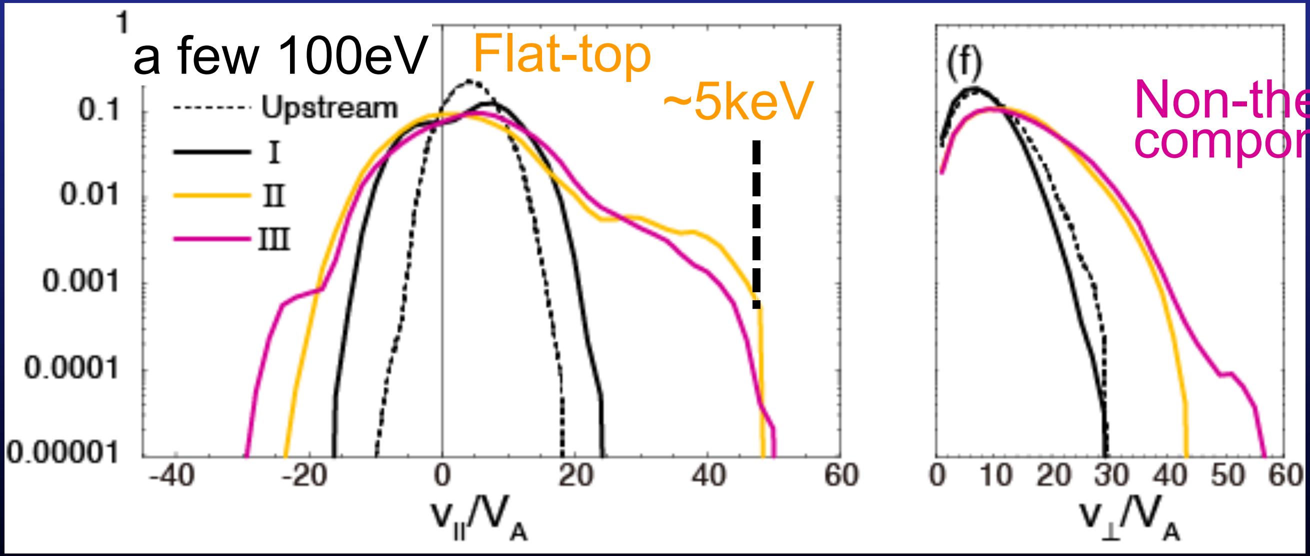
Electron-electron 2-stream instability

# Role of the Waves in Separatrices




Electron-electron 2-stream instability

Beam-driven whistler instability

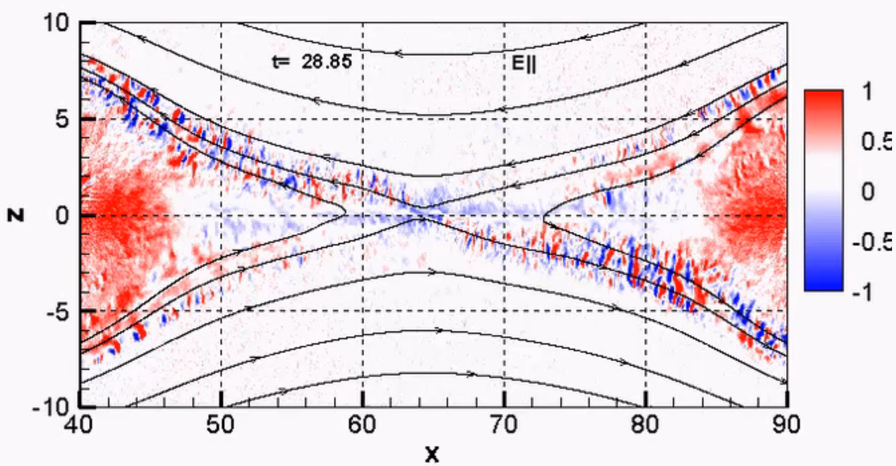


# Waves in Separatrices with $B_g$=0.3

[Chen, Fujimoto et al., JGR, 2015]

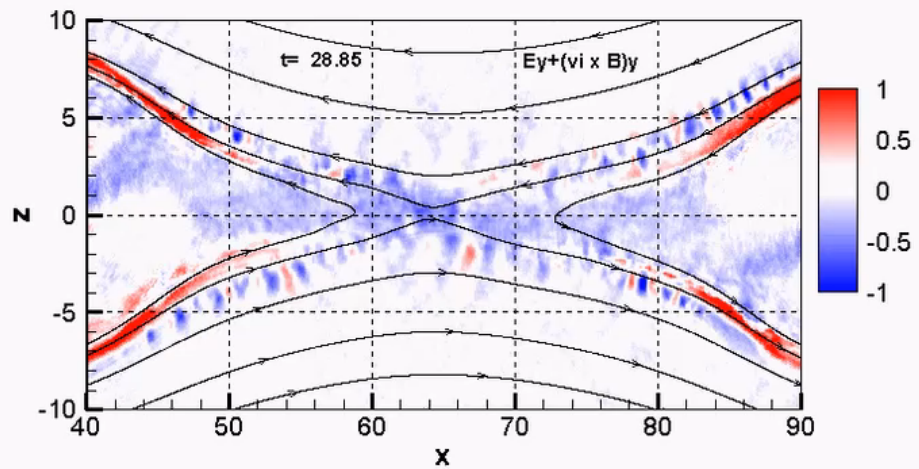
Guide field $B_g$=0.3

E||




Electron 2-stream + Buneman

Ion-frame Ey



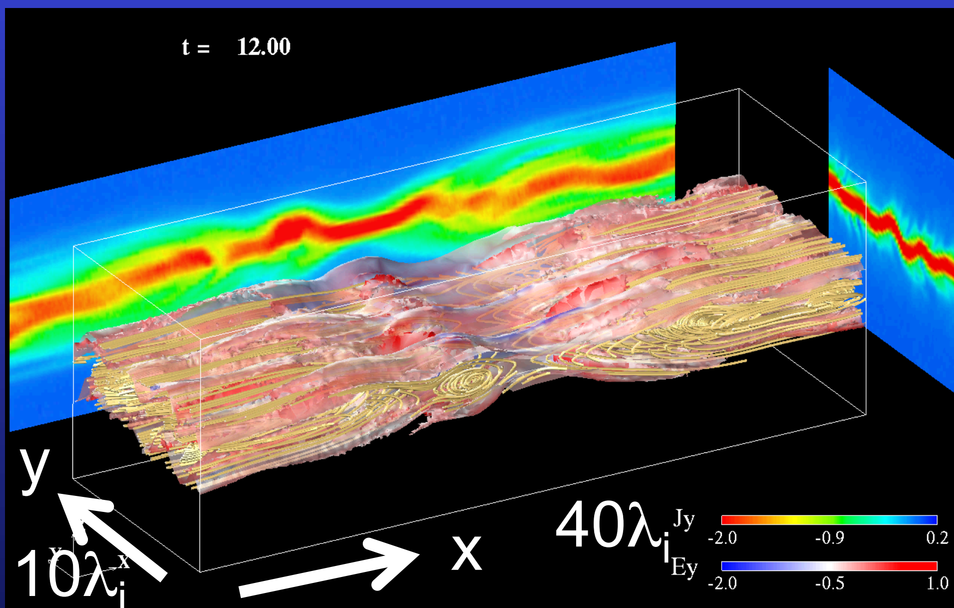

Beam-driven Whistlers

# Waves near X-line

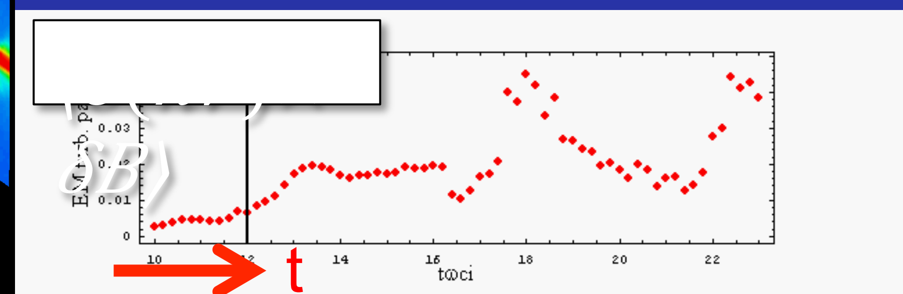
[Fujimoto & Sydora, PRL, 2012]

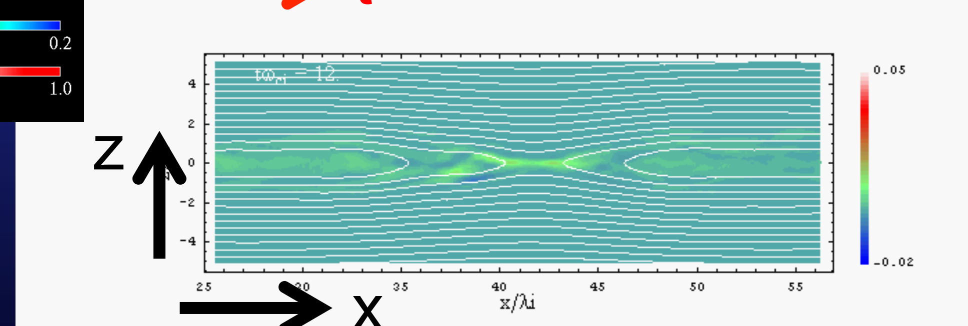
**Surface: |J|, Line: Field line**
**Color on the surface: Ey, Cut plane : Jy**

$m_i/m_e = 100$ ~ $10^{11}$ particles




- Plasmoid induces turbulence.
- A current sheet shear mode is responsible for the anomalous momentum transport.



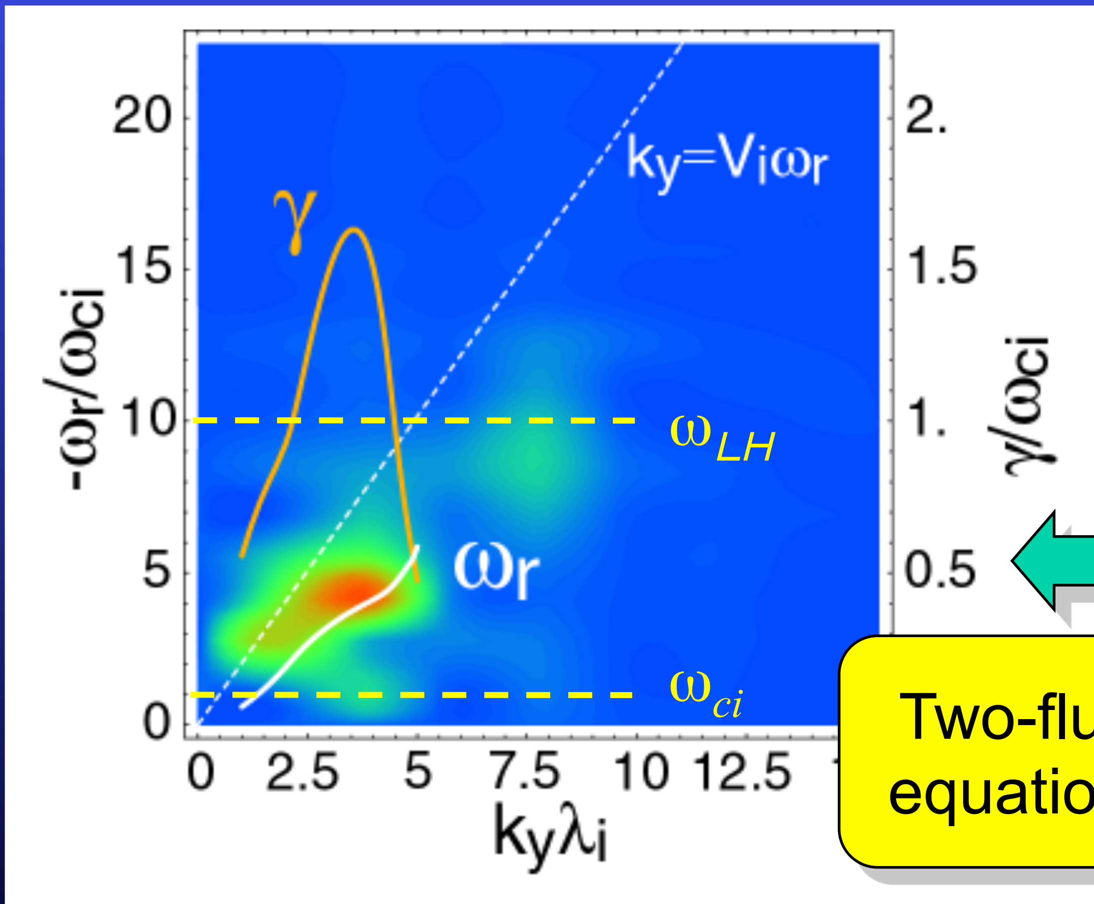




**Lx×Ly×Lz = $81\lambda_i \times 10\lambda_i \times 81\lambda_i$**

**Maximum resolution:**
**Nx×Ny×Nz = 4096×512×4096**

# Wave Properties near X-line

$\omega = \omega_r + i\gamma$




## Simulation results

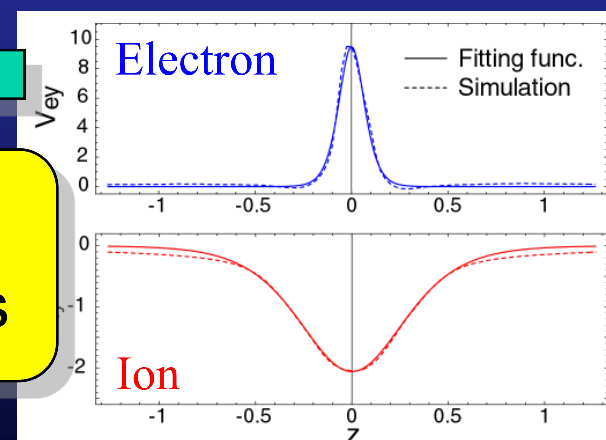
$$\omega_{ci} < |\omega_r| < \omega_{LH}$$

$$V_{ph} \approx V_A$$

## Linear analyses

Profiles taken from simulation

Two-fluid equations

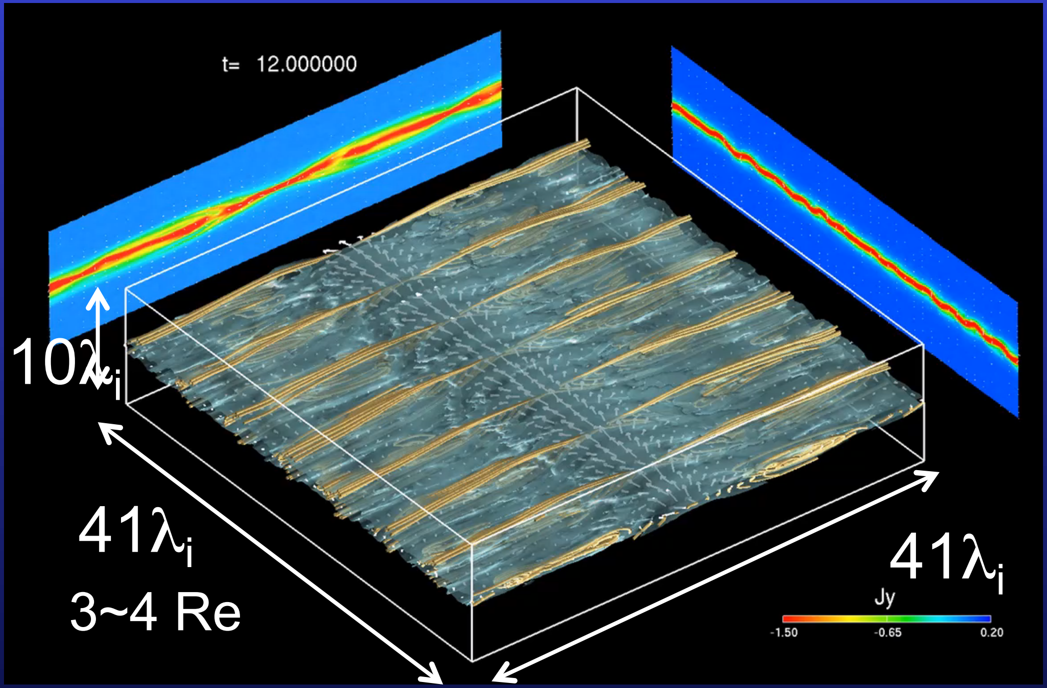


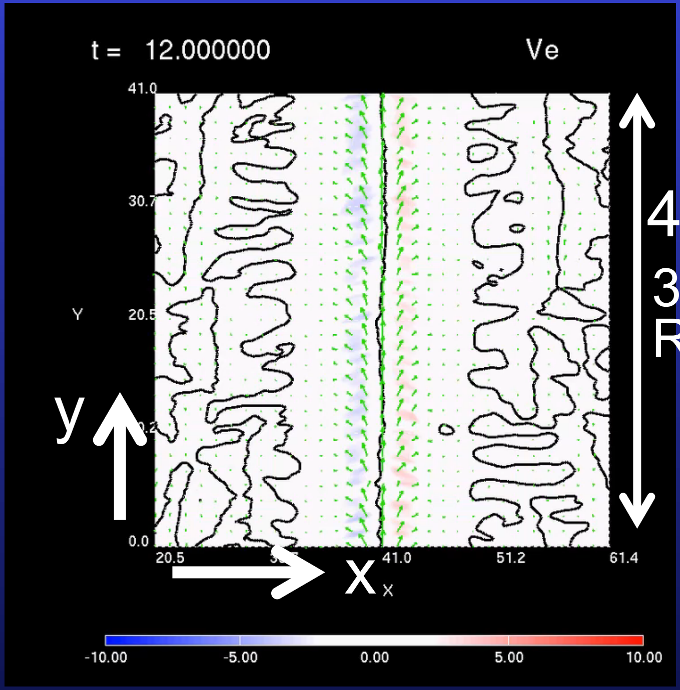
# Waves near X-line (Larger System)

**Surface: $|J_{xz}|$, Line: Field line**
**Arrow: Ve at z=0, Cut planes : Jy**

$m_i/m_e = 100$   ~ $5\times10^{11}$ particles

Electron outflow Vex and lines of Bz=0 at the equator plane



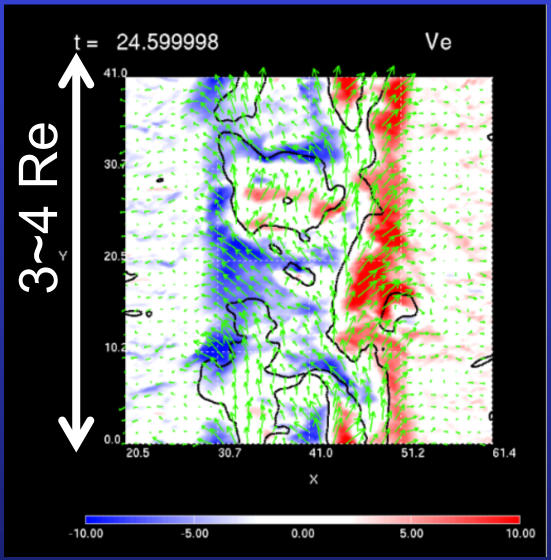




**$Lx\times Ly\times Lz = 81\lambda_i\times40\lambda_i\times81\lambda_i$**

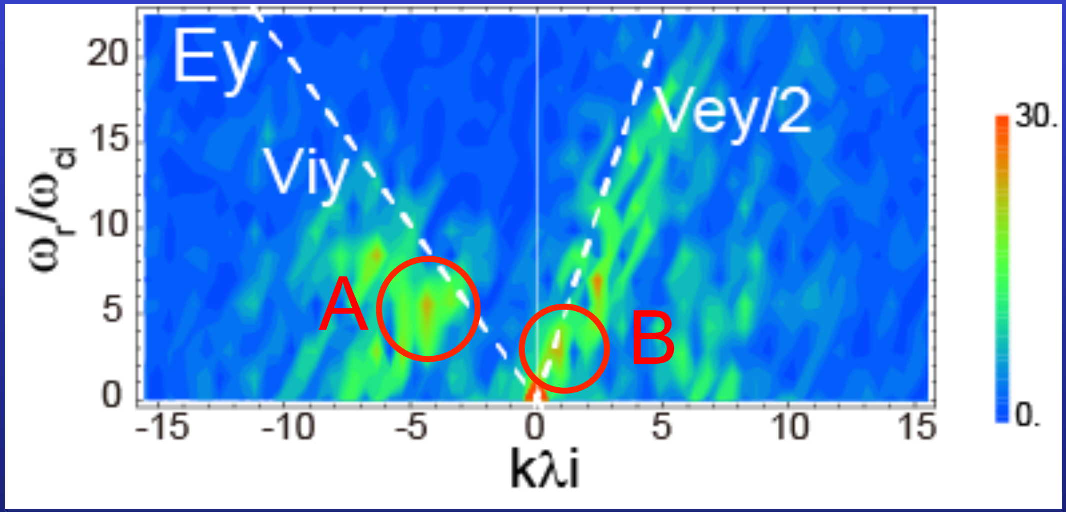
**8192 nodes (65,536 cores)**

**Maximum resolution:**
**$Nx\times Ny\times Nz = 4096\times2048\times4096 \sim 5\times10^{10}$**

# Waves near X-line (Larger System)




Wave spectrum along the current sheet



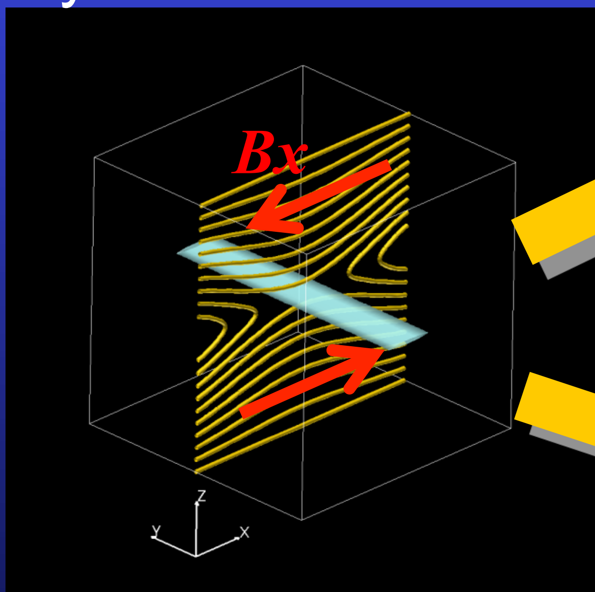

3D flux ropes &
3D outflow jets

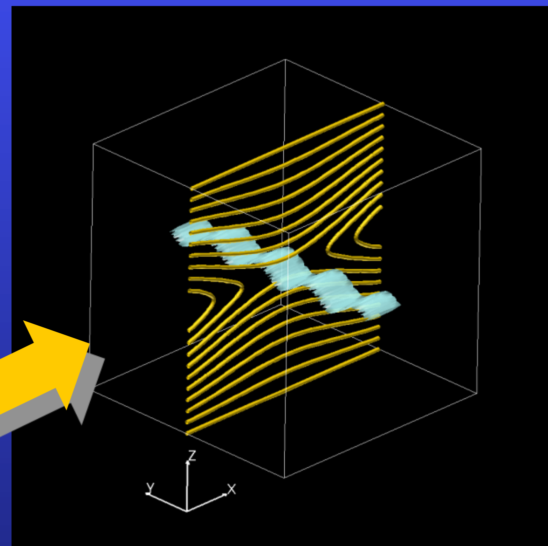
A. Current sheet shear mode
[Fujimoto & Sydora, PRL, 2012]

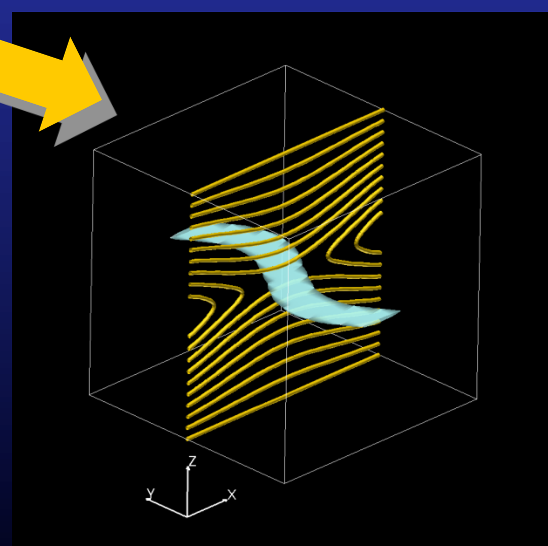
B. An electron shear mode
(responsible for the 3D flux ropes)

# Waves near X-line (Summary)

Localized current layer




## Current sheet shear mode

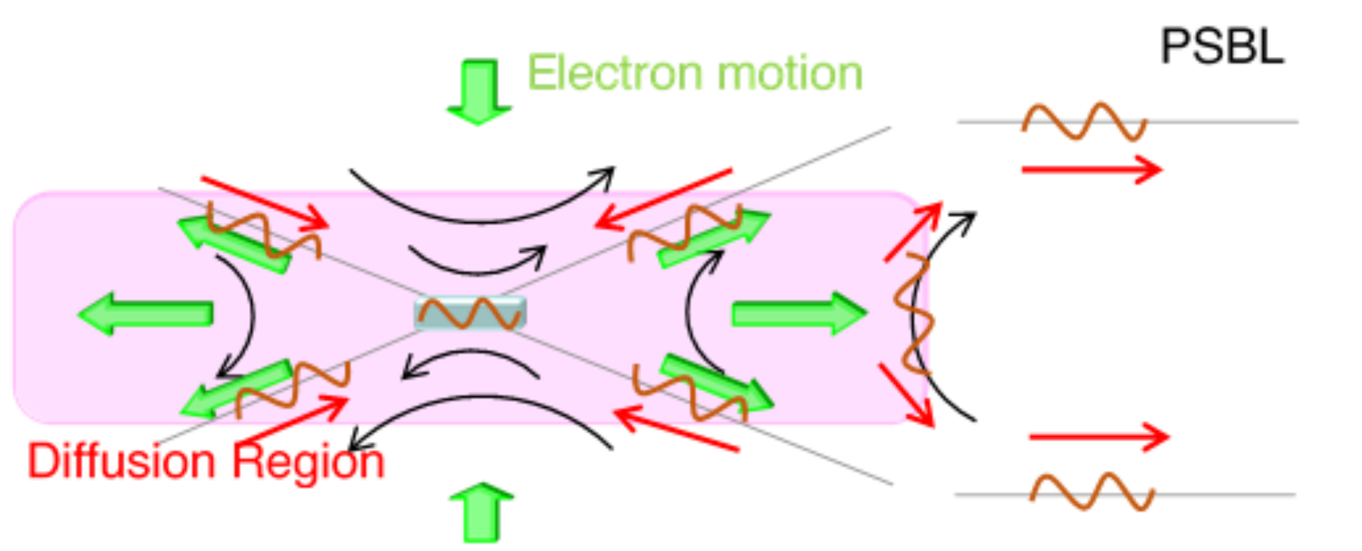
- Perturbation in the inflow direction
- Anomalous resistivity
- $\lambda \sim 2\pi\sqrt{\lambda_i \lambda_e} \propto (m_i/m_e)^{1/4}$

## Electron shear mode

- Perturbation in the outflow direction
- 3D flux ropes
- $\lambda \sim 20\pi\sqrt{\lambda_i \lambda_e}$ ~a few Re

$(\lambda_i = c/\omega_{pi}, \lambda_e = c/\omega_{pe})$

# Summary




PSBL: Langmuire & ESWs due to electron 2-stream. Flat-top electrons are formed.

Pile-up region: Whistlers due to temp anisotropy.

Separatrix: Langmuire & ESWs by electron 2-stream, LH & ESWs waves by Buneman, and beam-driven Whistlers. Flat-top and non-thermal electrons are formed.

Electron current layer: Two kinds of shear modes. Anomalous resistivity and 3D flux ropes are generated.