Wave Activities and Electron Acceleration near the Separatrices of Magnetic Reconnection

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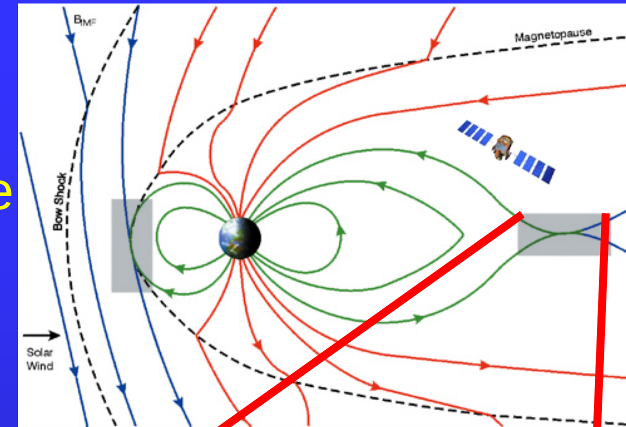
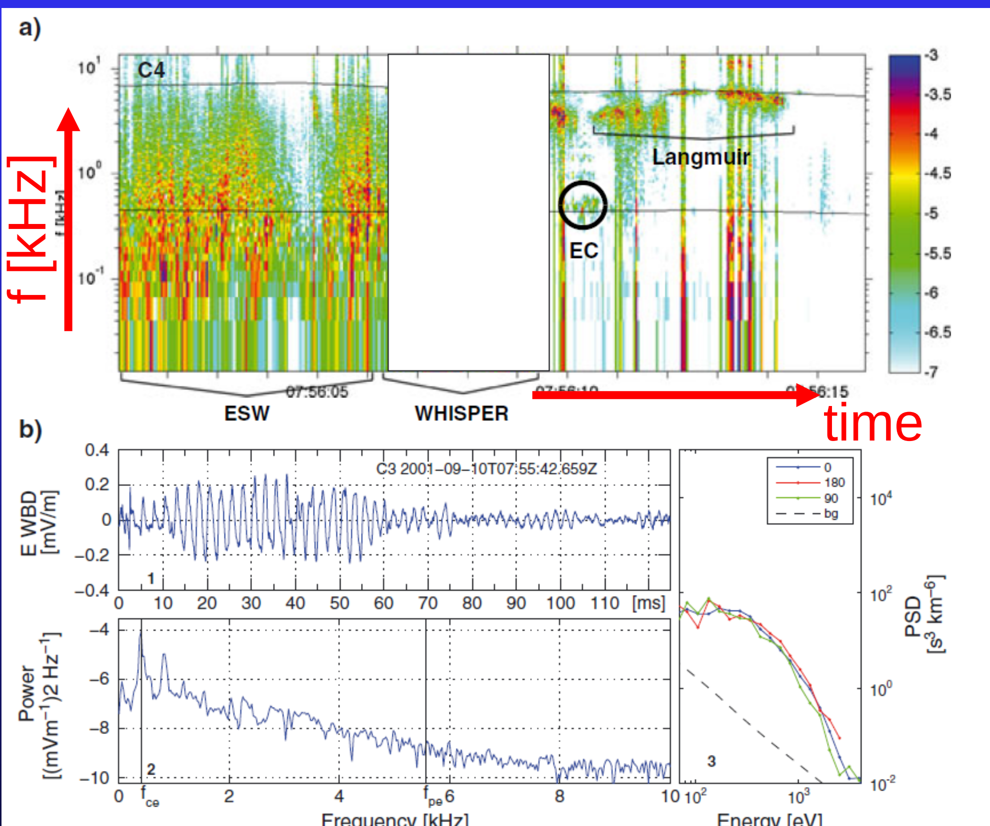
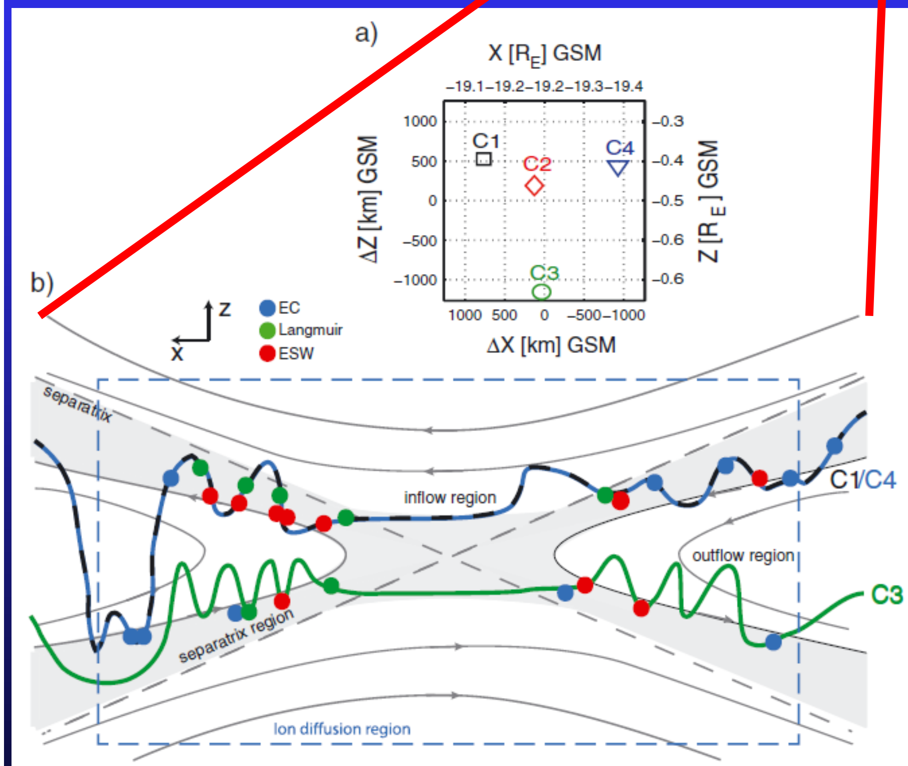
Waves in MRX Region: Obs.

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

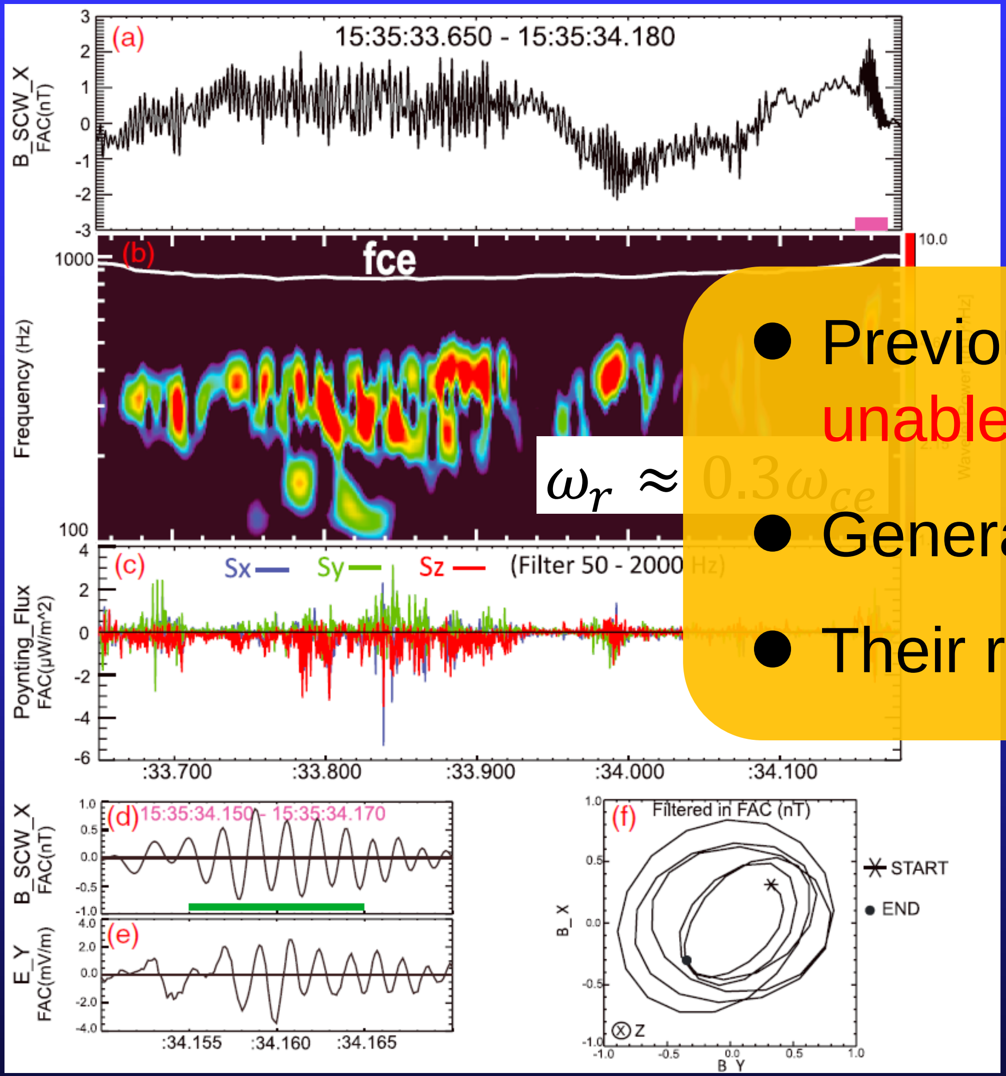






[Viberg et al., GRL, 2013]

Waves in MRX Region: Observations

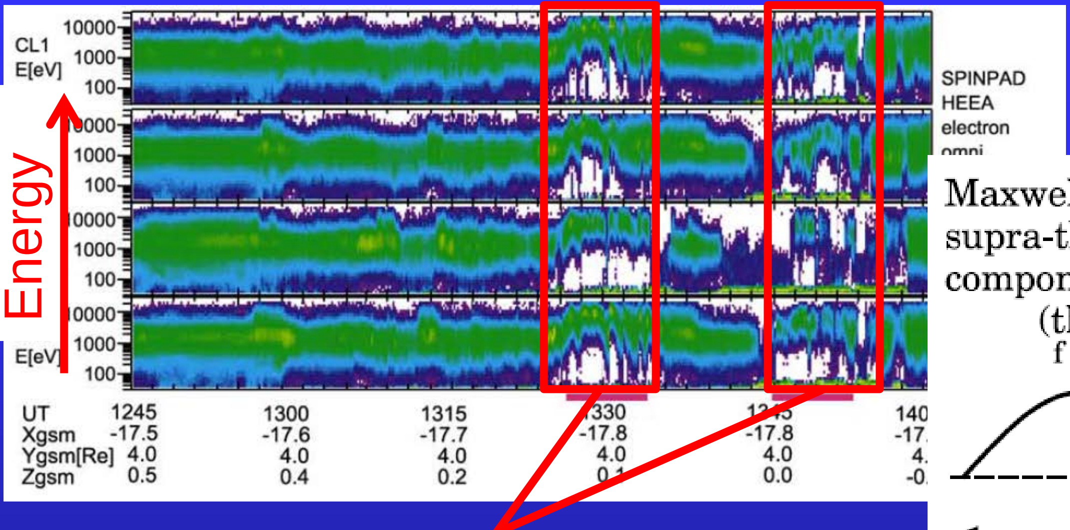


Whistler waves

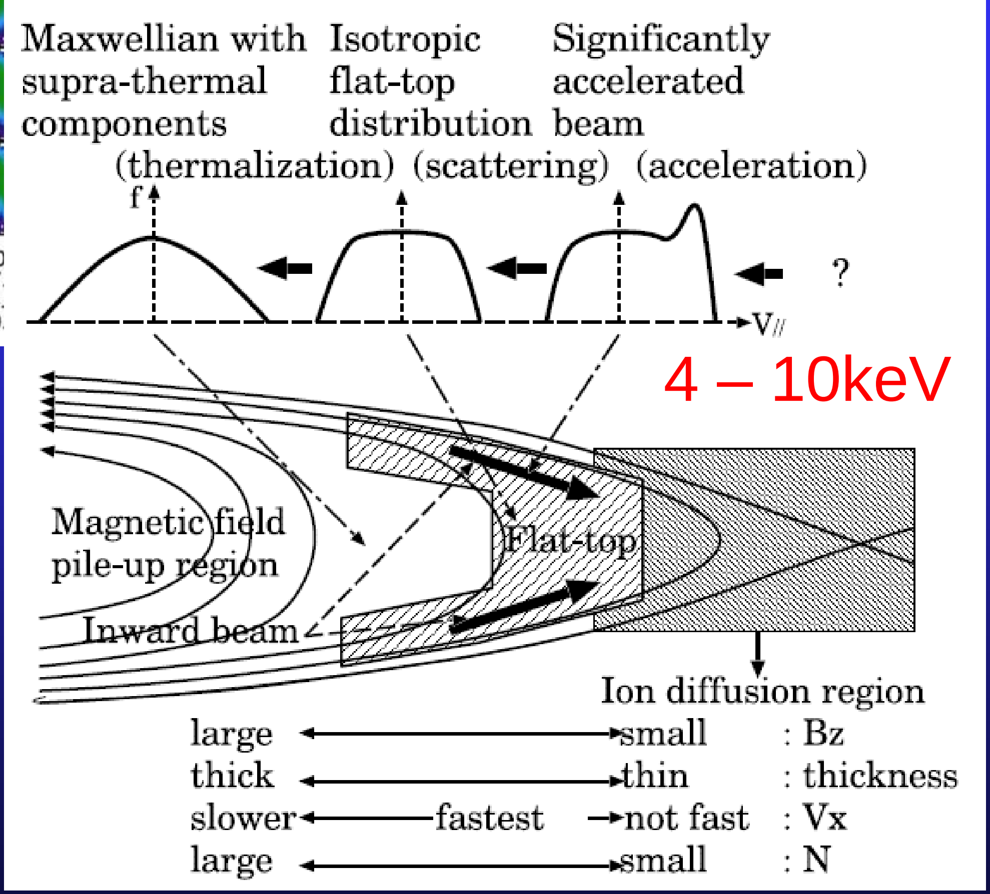
[Tang et al., GRL, 2013]

- Previous simulations were unable to reproduce them.
- Generation mechanisms?
- Their roles in reconnection？

Electron Energetics: Observations



[Asano et al, JGR, 2008]



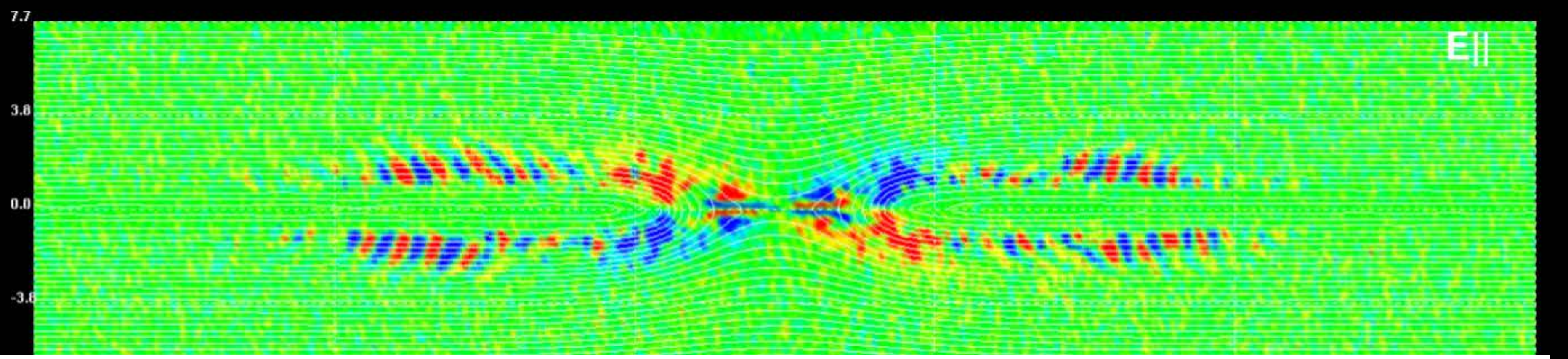
Reconnection region

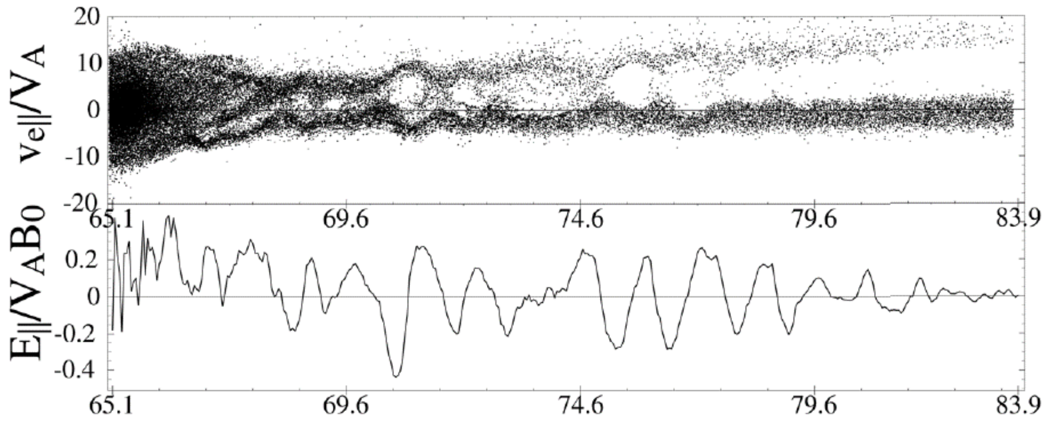
- High energy electrons around separatrices
- "Flat-top" electrons

Previous Simulation of Waves in MRX

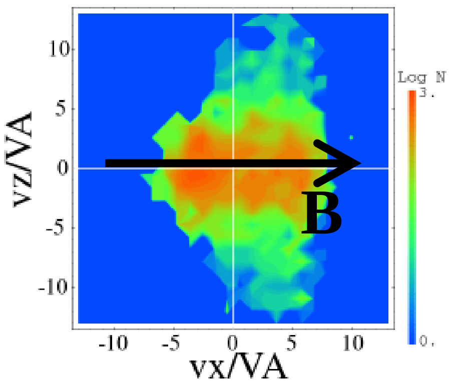
[Fujimoto & Machida, JGR, 2006]

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





Electron 2-stream instability

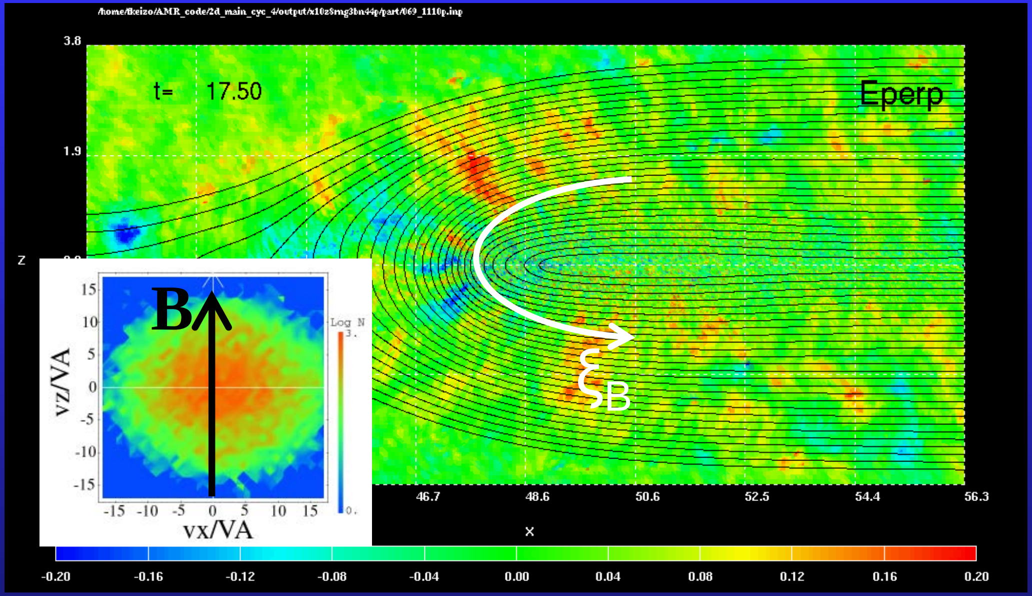


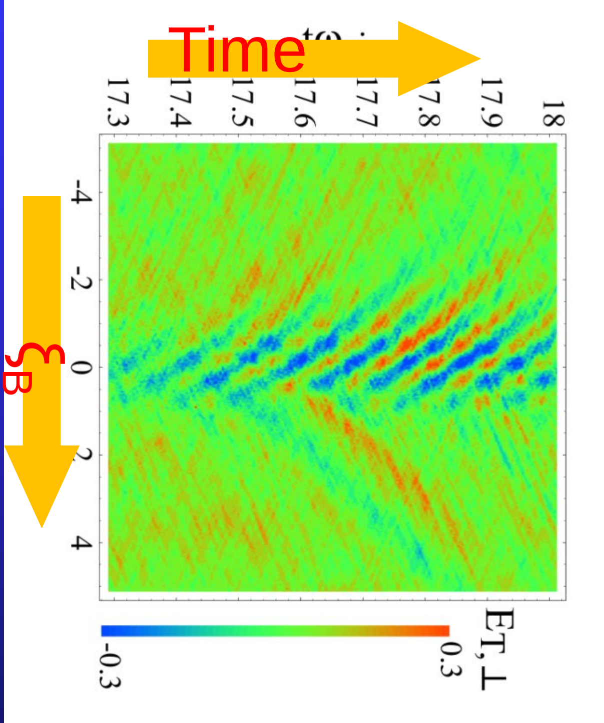
Parallel electron heating

Previous Simulation of Waves in MRX

[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.

Purpose of This Study

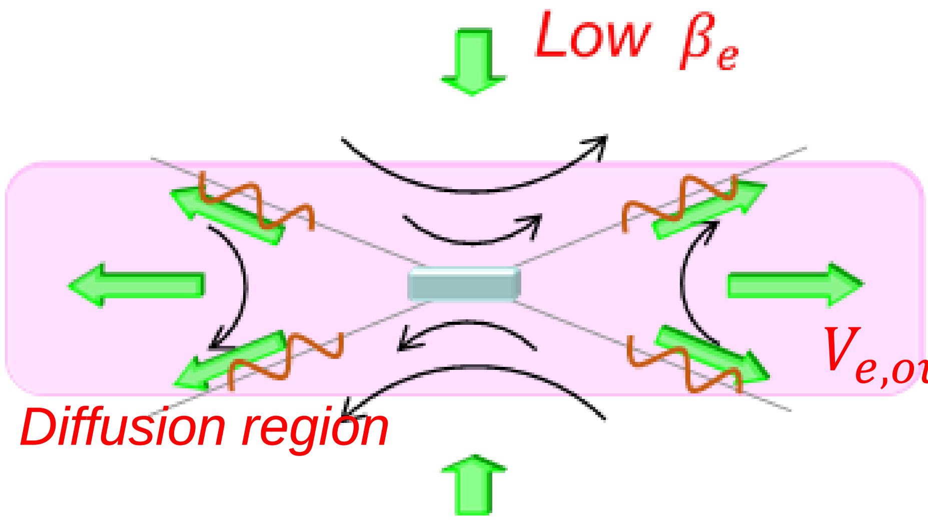
- To understand the generation mechanisms of the waves around the separatrices of anti-parallel reconnection, and
- To clarify the roles of the waves in reconnection, in particular, in electron acceleration.

Recent PIC simulations have shown the signature of electrostatic waves in the separatrix region.

[Lapenta+, GRL, 2011; Egedal+, Nat. Phys., 2012]

However, the corresponding instabilities have not been identified clearly.

Strategy of Our PIC Simulation



$v_{th,e} \ll V_{e,out}$
for waves be active

$(v_{th,e} \equiv \sqrt{2T_e/m_e})$

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

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

More realistic parameters

m_i/m_e: 100 → 400

n_b/n_0: 0.2〜0.3 → 0.04 AMR-PIC

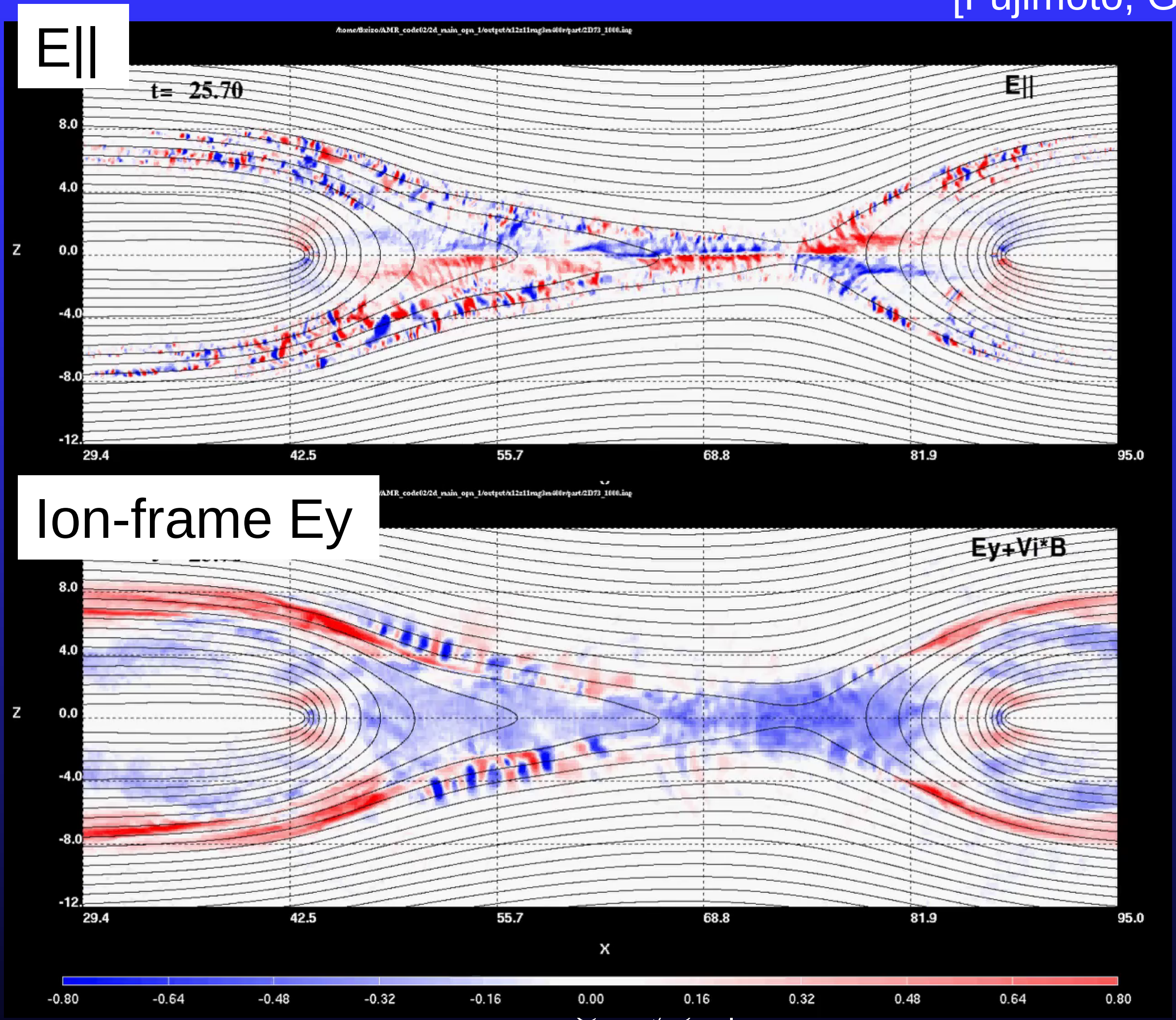
Long-time evolution :
Periodic → Open boundary

N_p : ~ 10^{10}

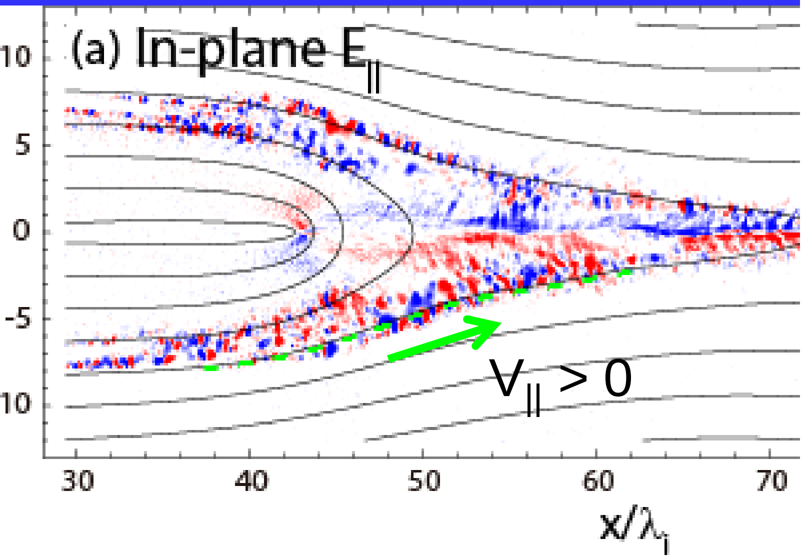
Memory : ~ 1TB

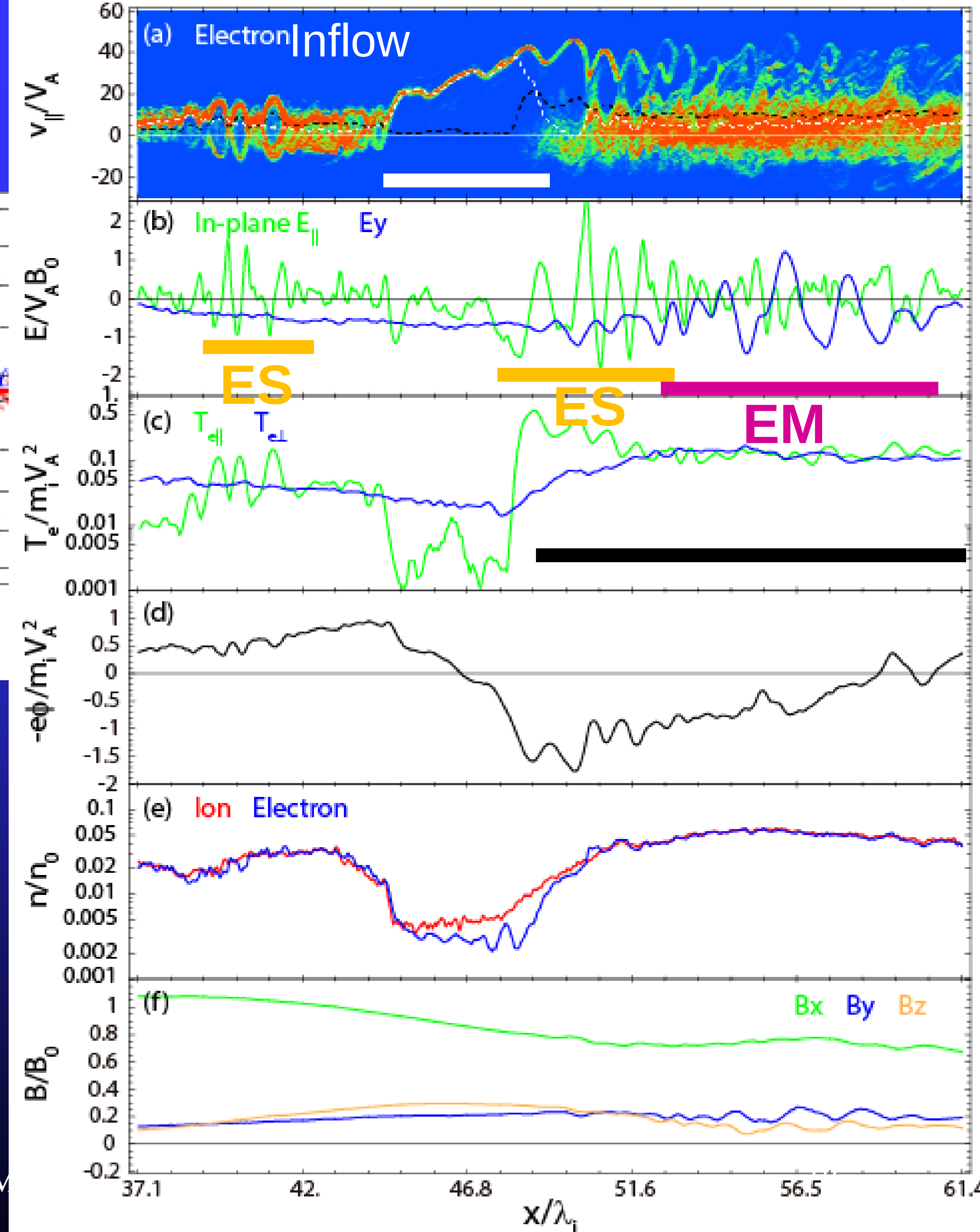
Wave Activities Around Separatrices

[Fujimoto, GRL, 2014]



Wave Activities



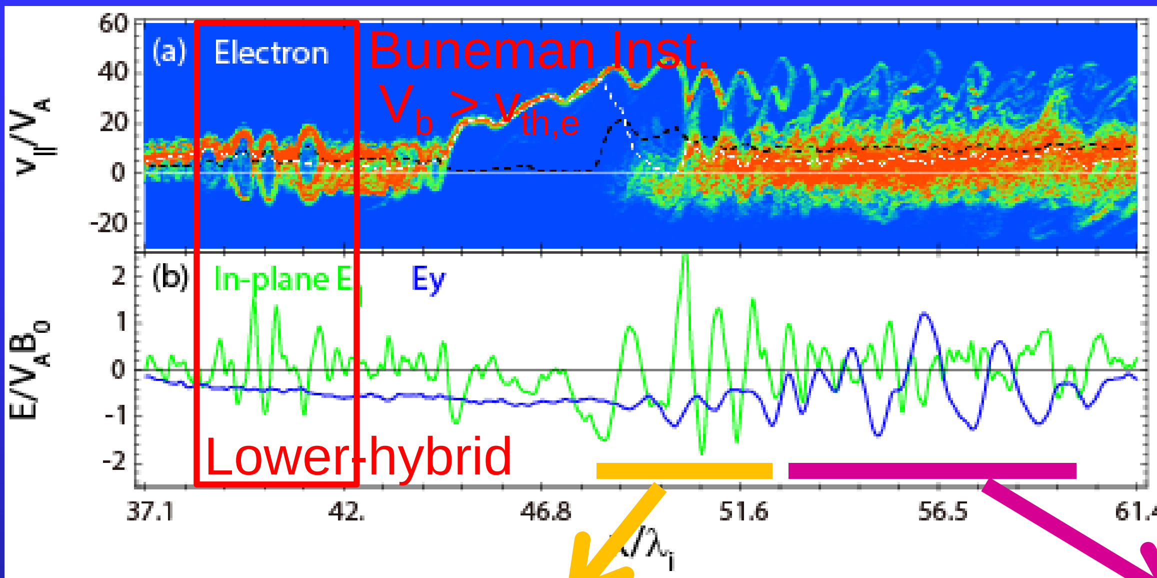


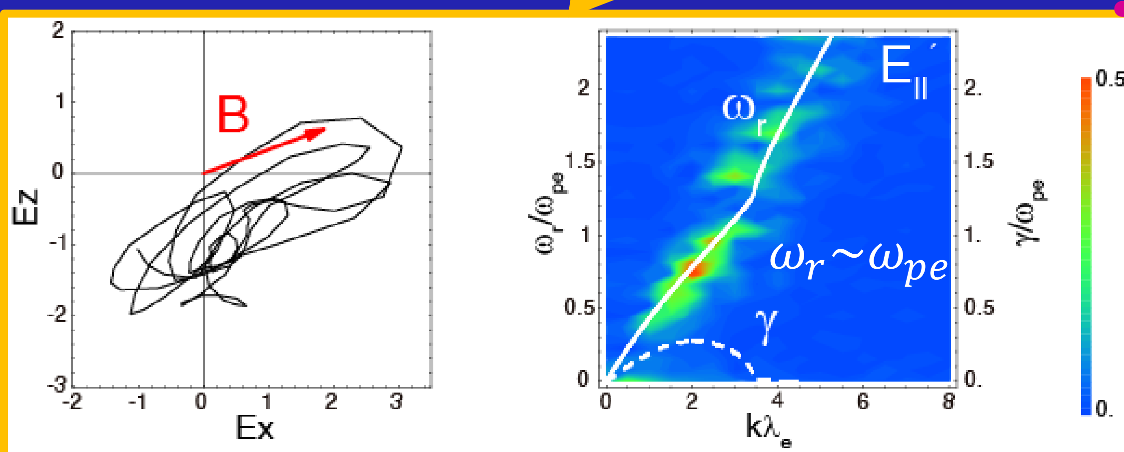
- Weak waves
- Local strong acceleration of electron
- Intense wave activities
- Electron heating

Wave Generation Mechanisms

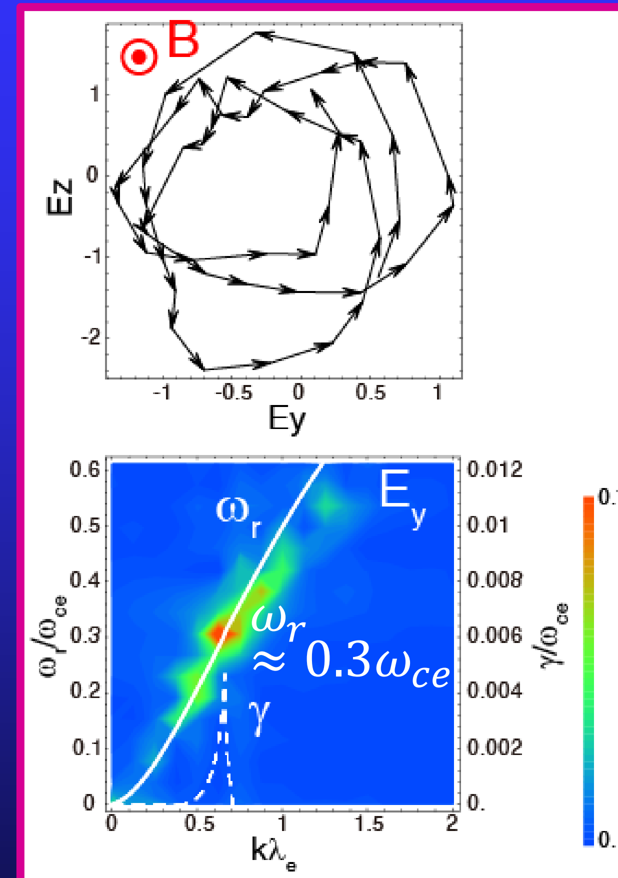
Linear analyses

$$\omega = \omega_r + i\gamma$$



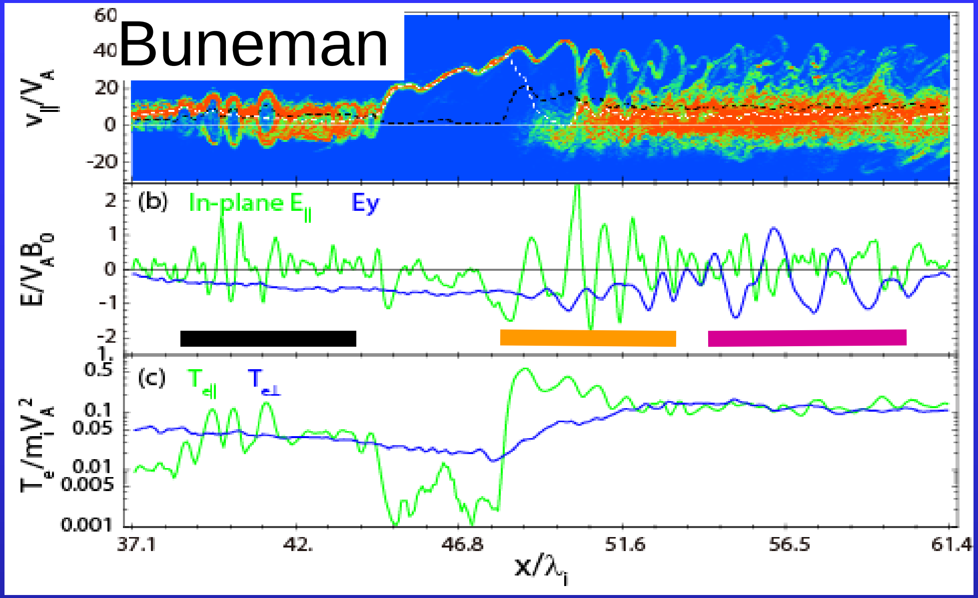


Electron-electron 2-stream instability



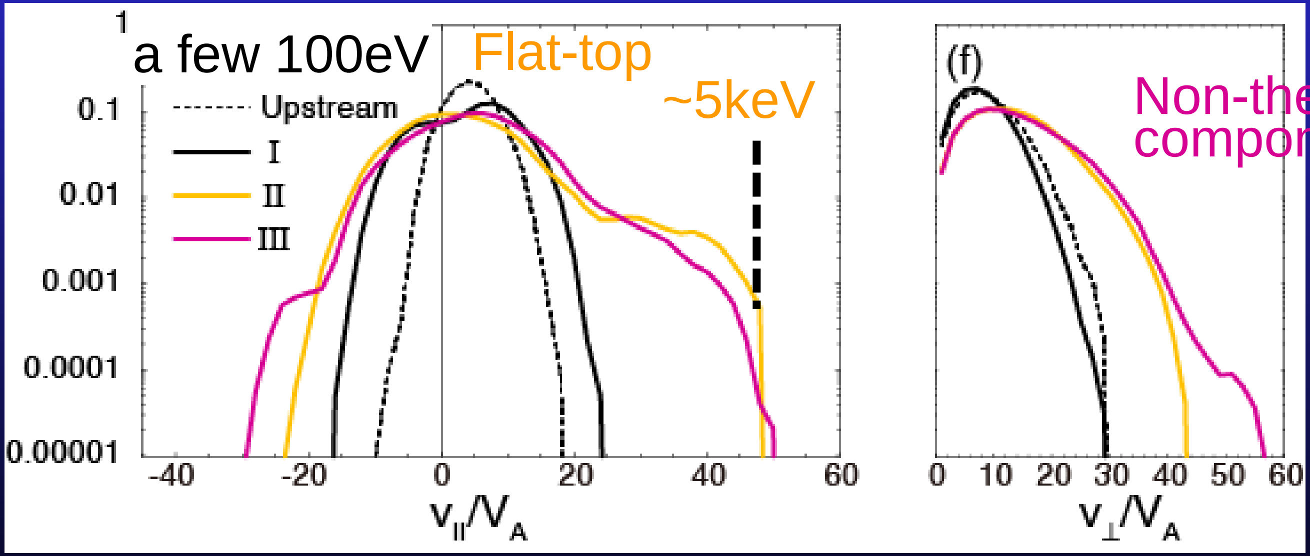
Beam-driven whistler instability

Role of the Waves



Electron-electron 2-stream instability

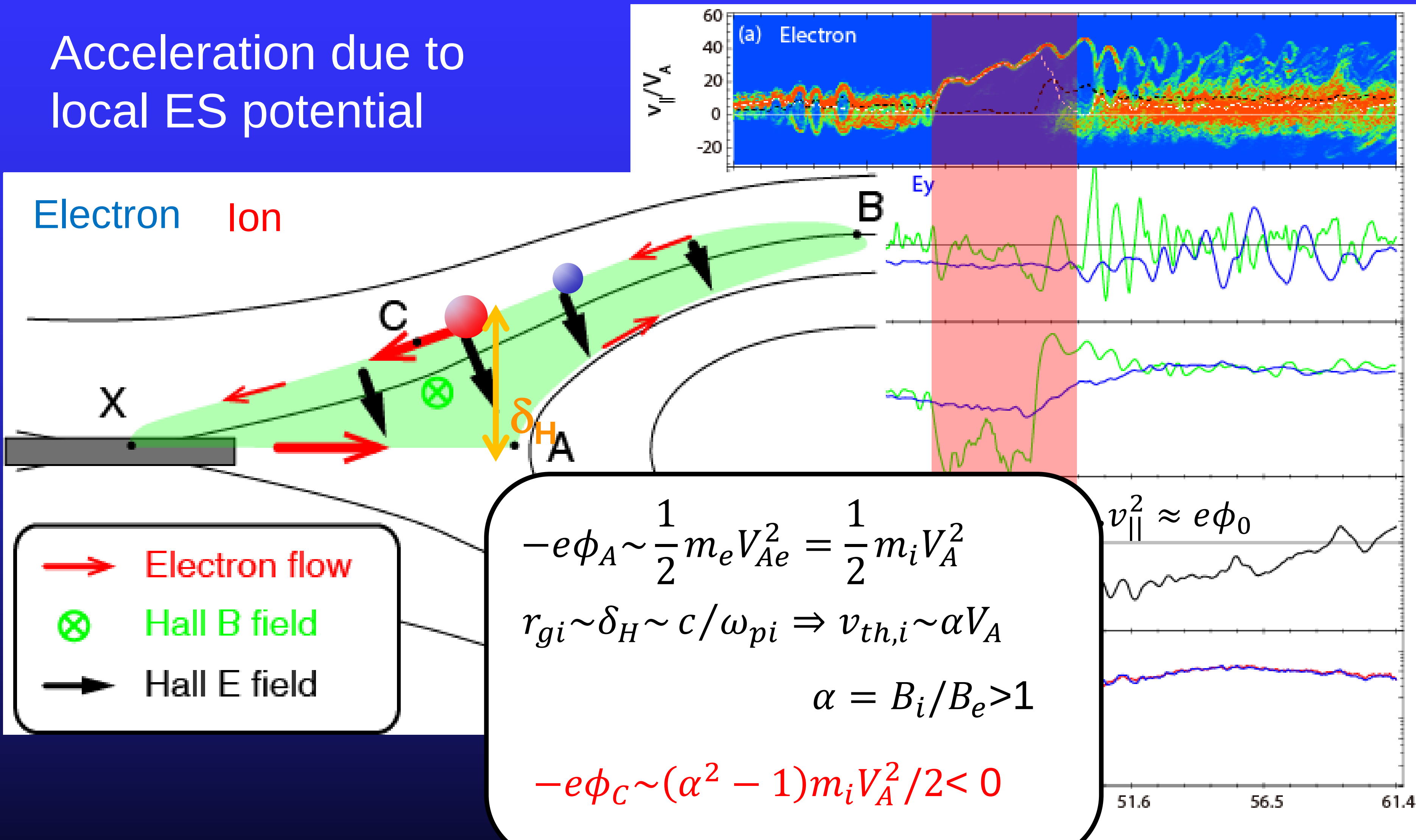
Beam-driven whistler instability



Non-thermal component

Electron Acceleration Mechanism

Acceleration due to local ES potential



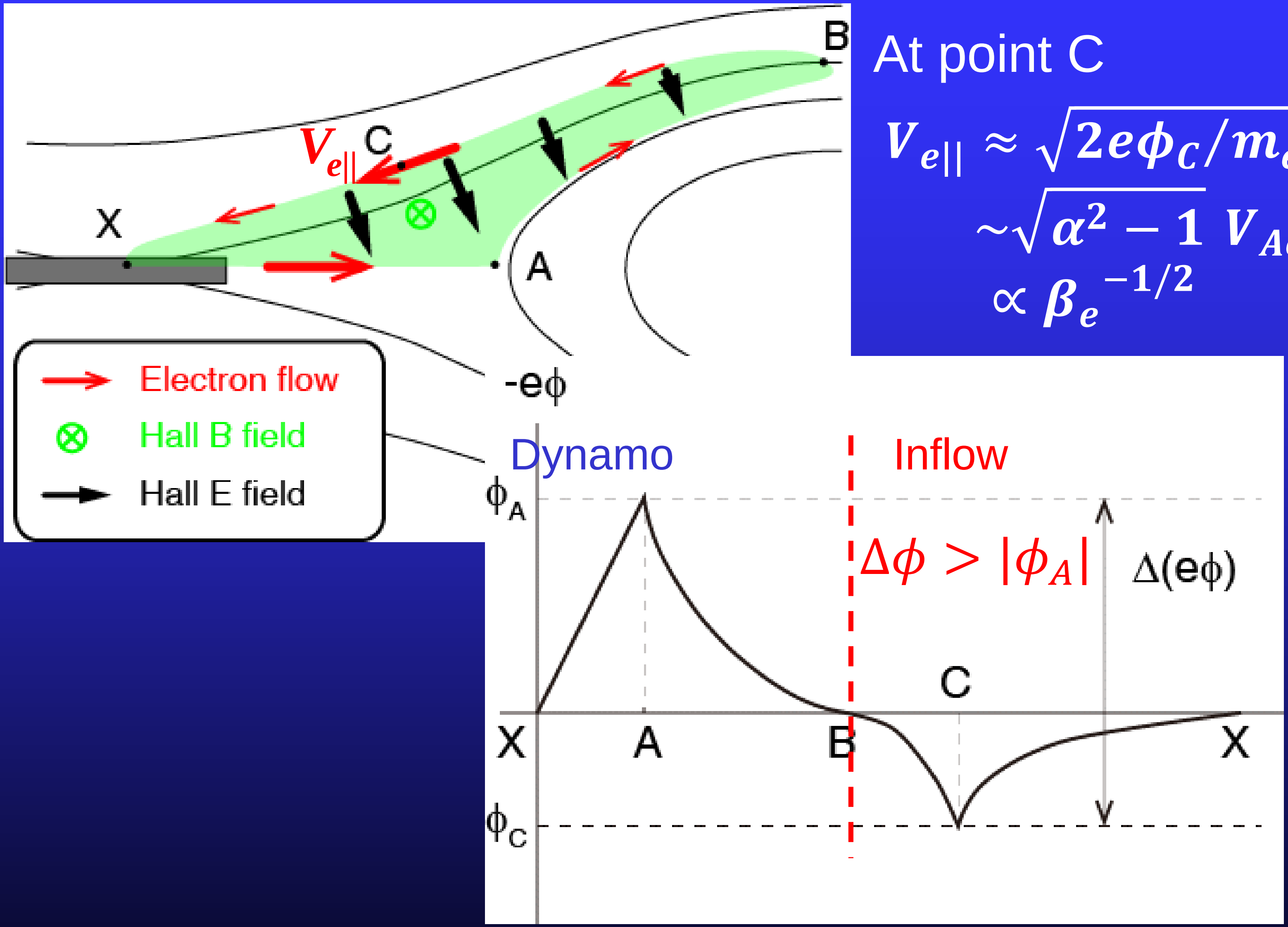
$$-e\phi_A \sim \frac{1}{2} m_e V_{Ae}^2 = \frac{1}{2} m_i V_A^2$$

$$r_{gi} \sim \delta_H \sim c/\omega_{pi} \Rightarrow v_{th,i} \sim \alpha V_A$$

$$\alpha = B_i/B_e > 1$$

$$-e\phi_C \sim (\alpha^2 - 1) m_i V_A^2/2 < 0$$

Electron Acceleration Mechanism

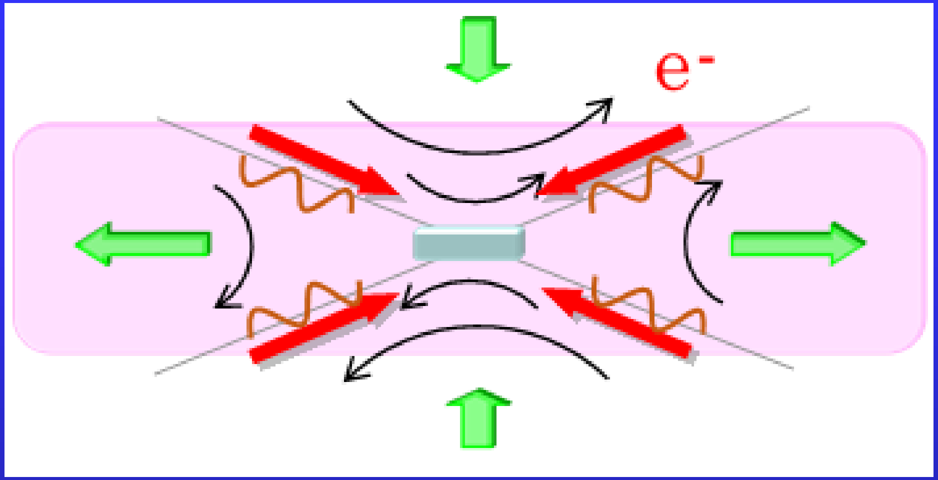


At point C

$$V_{e||} \approx \sqrt{2e\phi_C/m_e}$$
$$\sim\sqrt{\alpha^2 - 1}\, V_{Ae}$$
$$\propto \beta_e^{-1/2}$$

Summary [Fujimoto, GRL, 2014]

The generation mechanisms of the waves in the separatrix regions have been identified for anti-parallel reconnection.



Key parameters are realistically low plasma beta.

The waves are responsible for "flat-top" and non-thermal electrons.

The waves are useful to diagnose the electron dynamics in the reconnection region by means of on-going and/or up-coming satellite observations.

Guide-field cases will be investigated as a next step.