Reconnection and waves

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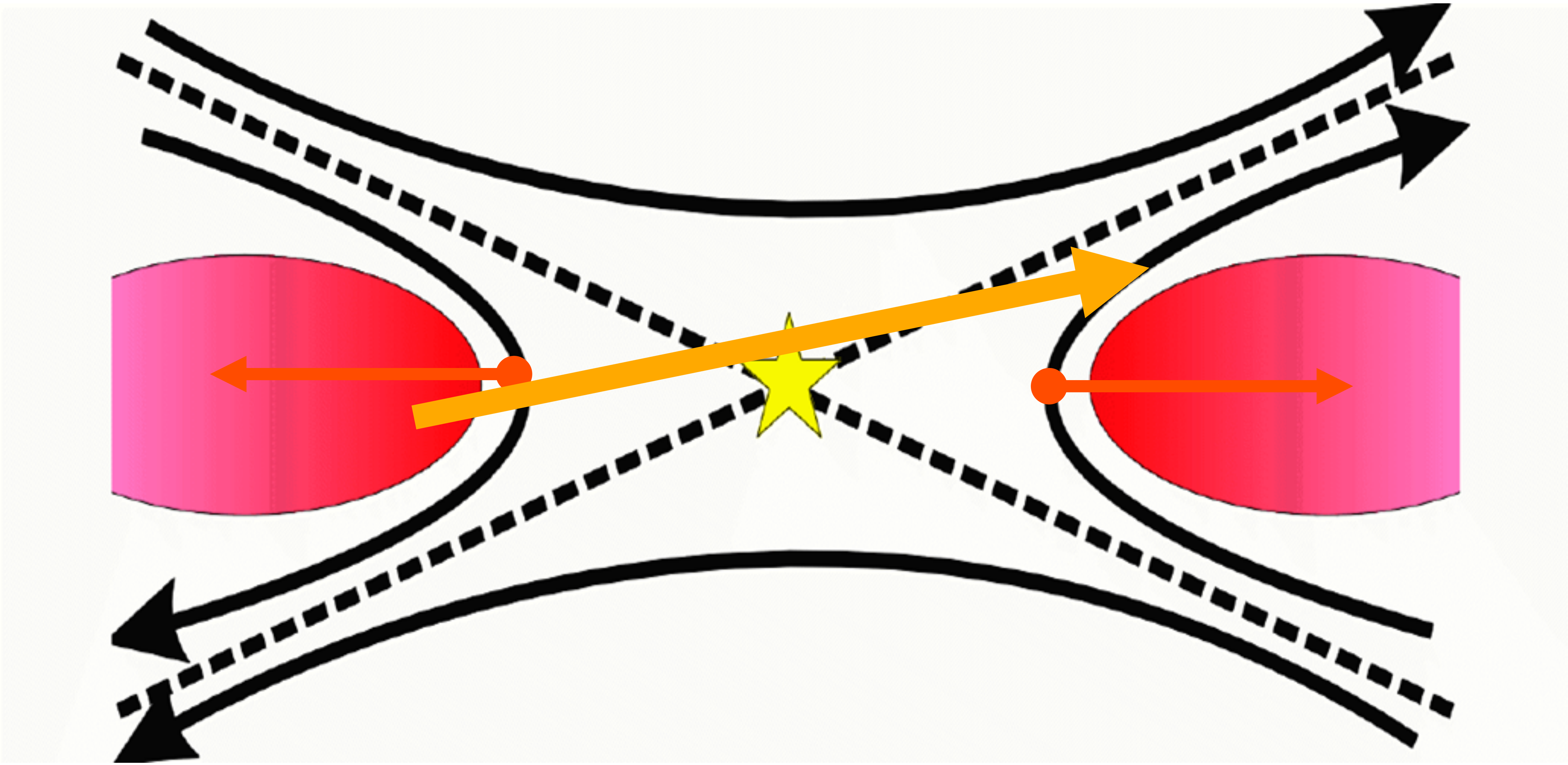
ISAS,JAXA

With so much input from so many friends

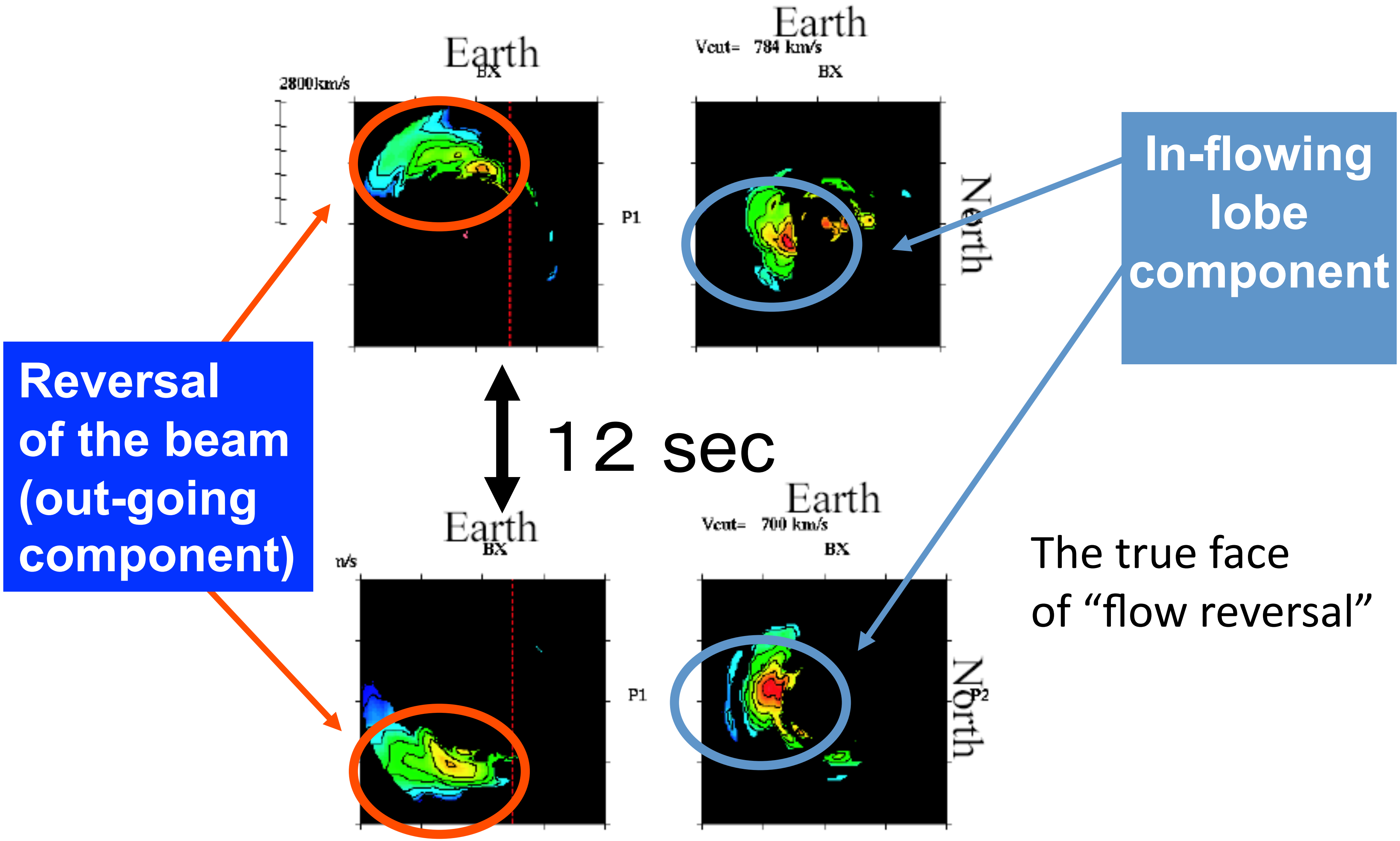
Wave data in the context of reconnection research: How useful?

- Waves at electron scales: probes for electron dynamics that particle data cannot resolve yet as of today
- Waves at ion-electron hybrid scales: enables ion-electron coupling, agent for dissipation
- Waves at ion-scales and at lower frequency: not negligible in the energy budget argument, enables remote effects to emerge

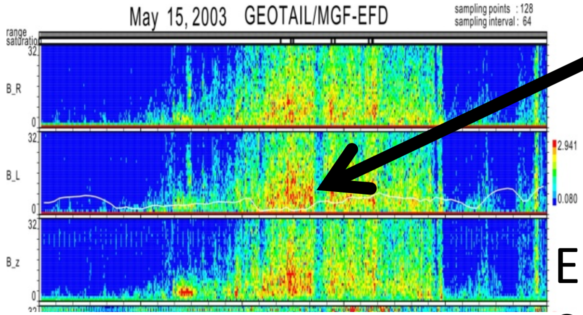
The best event in the magnetotail [Nagai, in prep]



Ion distribution function data:
Superposition of in-coming and out-going ions

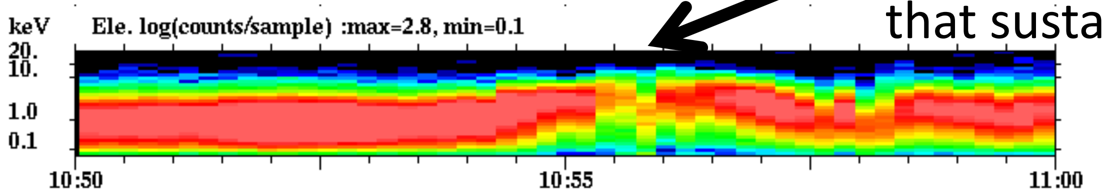


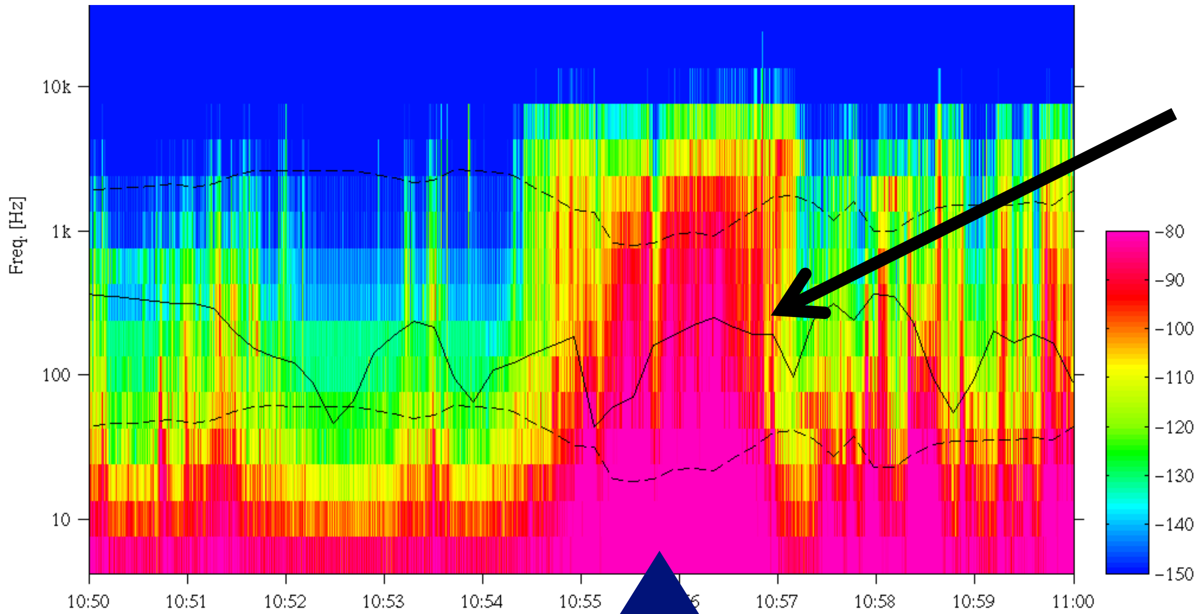
Electron-scale dynamics



Intense EM fluctuations
in the LH frequency range

Electron heating
Super Alfveic cross-tail electron bulk flow (Vey)
that sustains the intense current density





Broadband Electrostatic Noise
(BEN)

The most intense BEN
in the Geotail PWI's history

Flow reversal

Wave observation at an X-line in the real space:

Makes you excited

- Waves at electron scales: dynamic electrons
- Waves at ion-electron hybrid scales: smoking-gun evidence for dissipation?

A similar event seen by WIND [Farell02]

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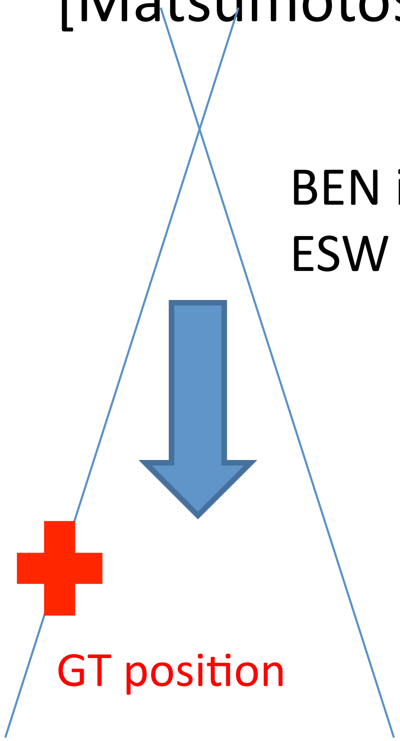
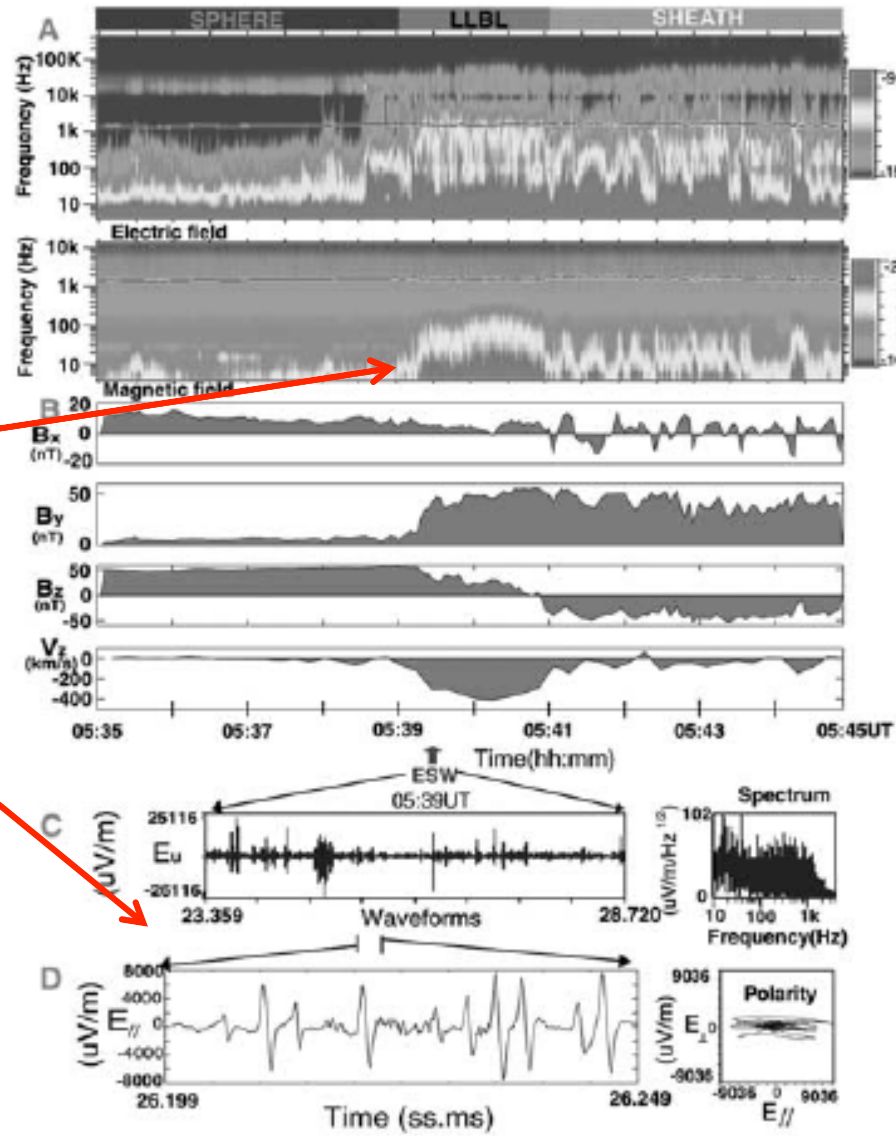
ESW: Electrostatic Solitary Waves

- Seen by Geotail PWI thanks to the “wave form capture” capability

[Matsumoto93, Kojima94]

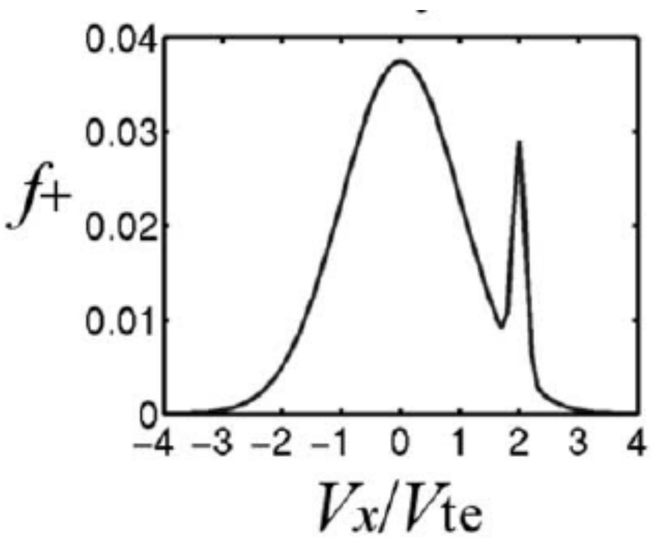
BEN in the f-t diagram
ESW in the waveform data

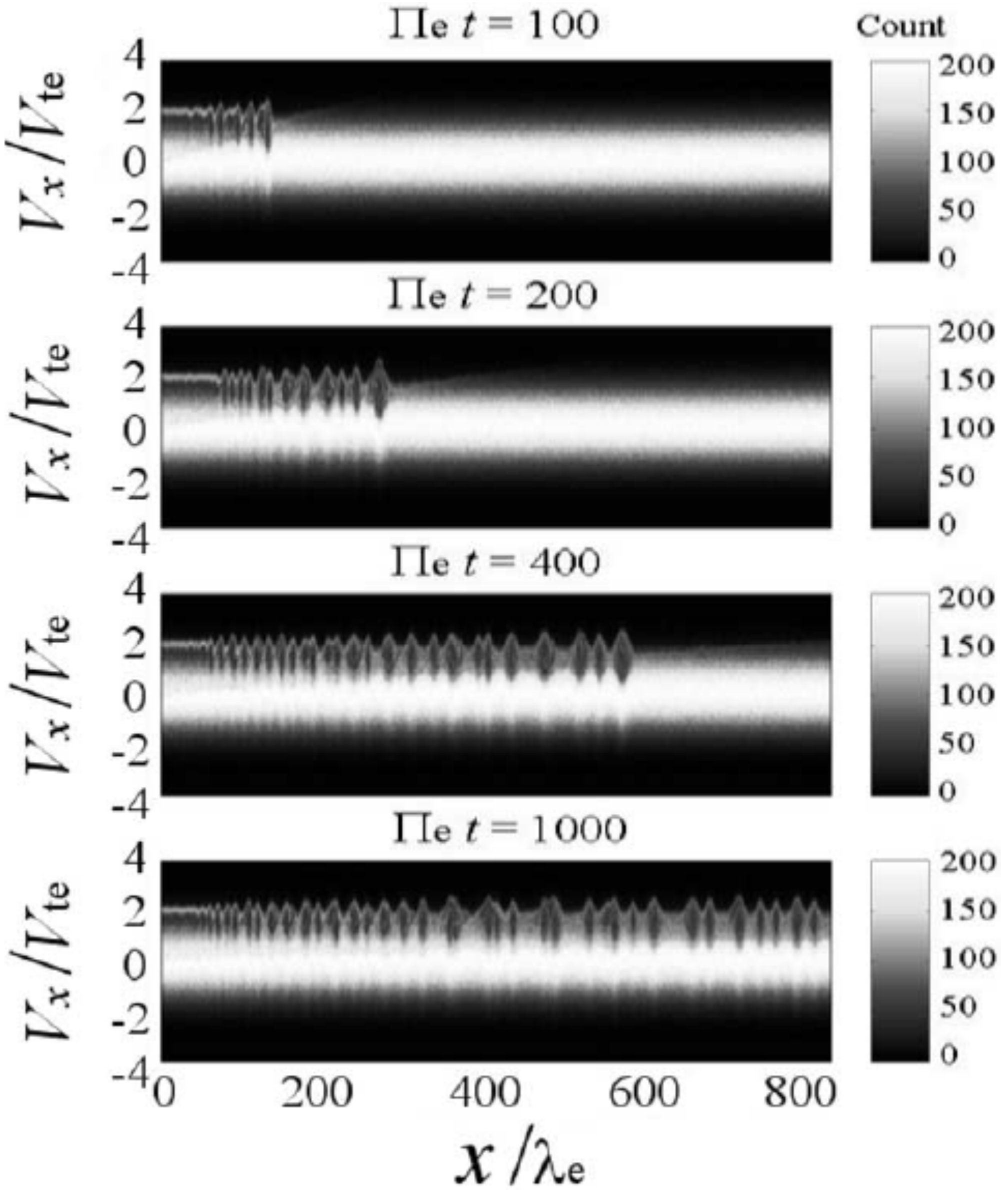




Interpretation: Ele two-stream/bump-in-tail

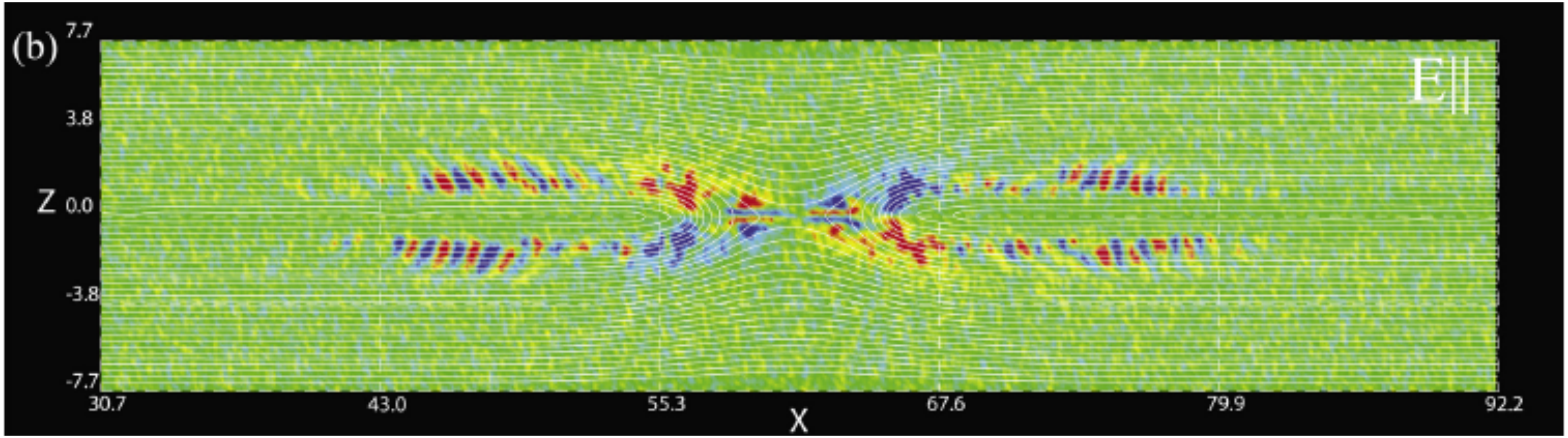
[Umeda02]

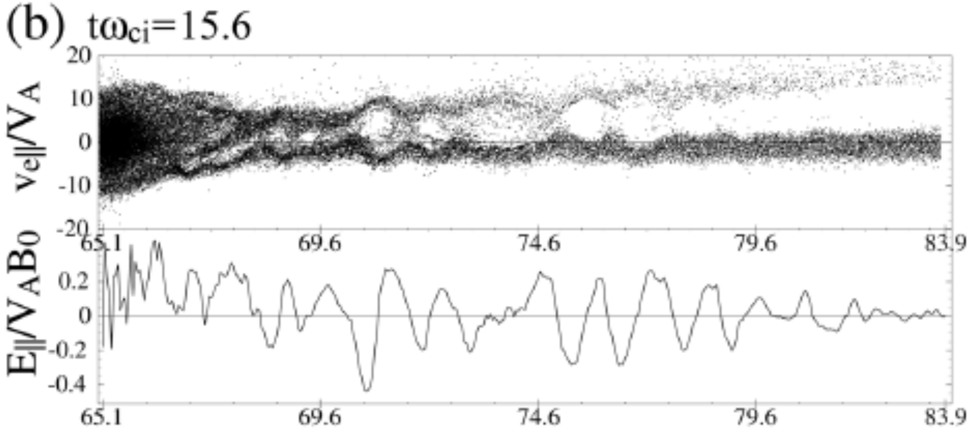




1D/2D ES simulation
B-field along the x-axis

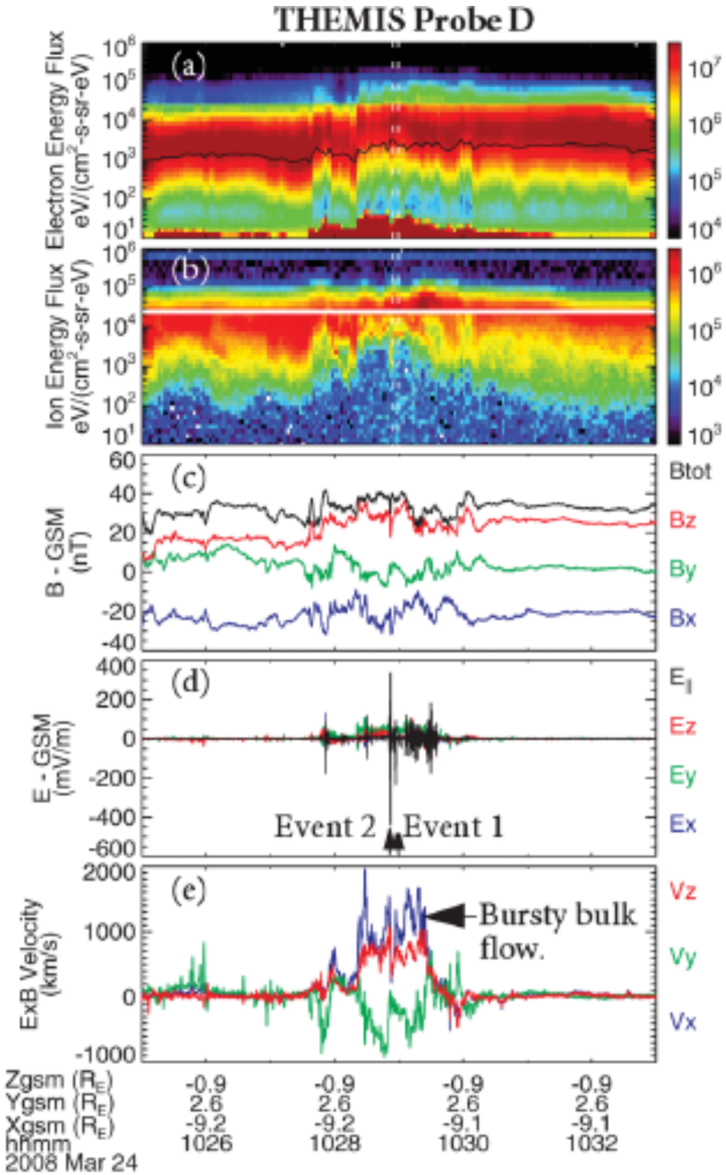
In 2D RX simualtion

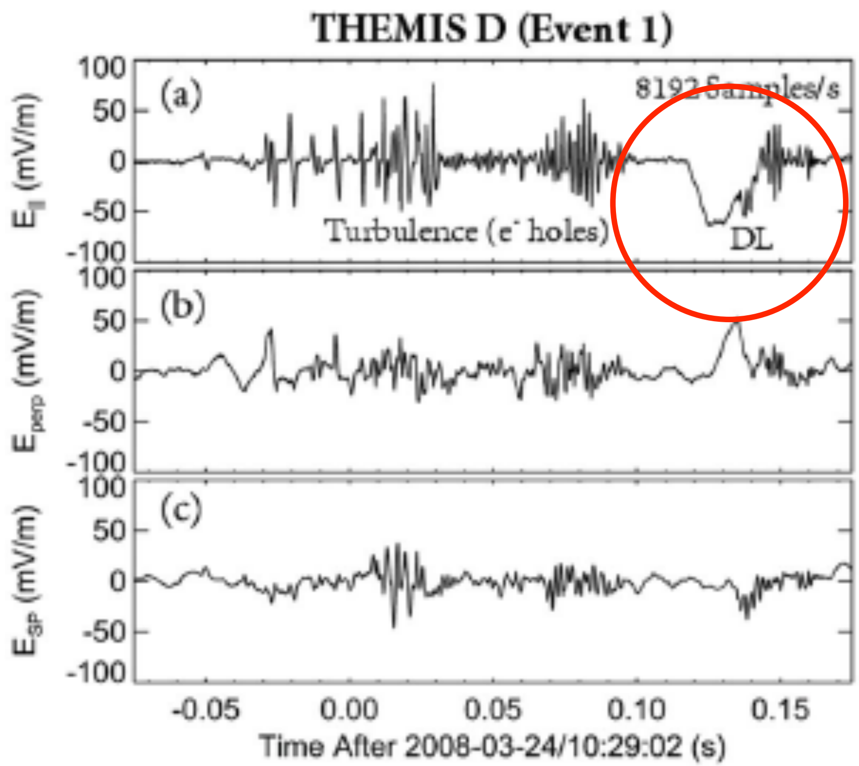




[Fujimoto06]

Double layers, too.



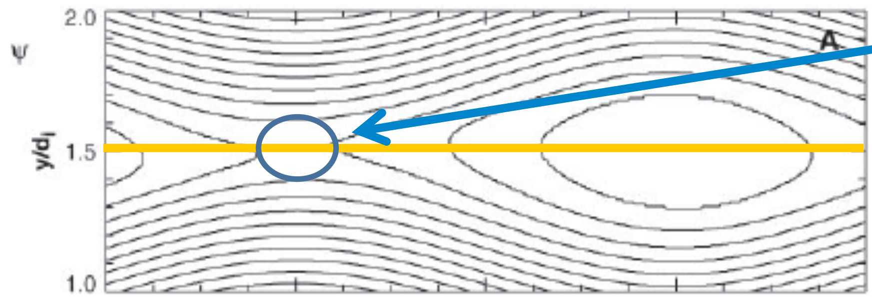


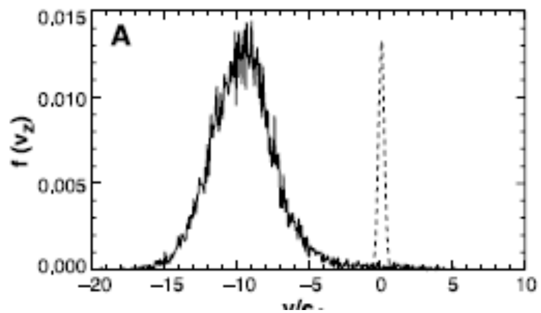
[Ergun09]

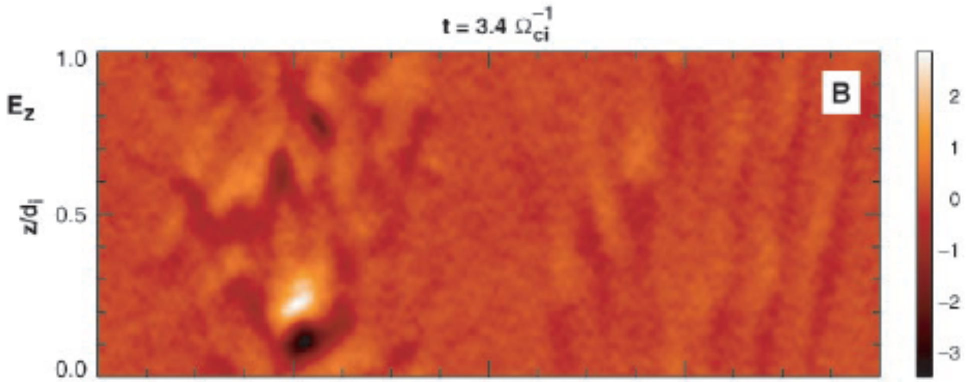
ESW: Scene changes

- ESW by Buneman inst. Seen in 3D simulation of RX with strong guide field

ele ion







ESW decays via coupling to LH wave

[Drake03] Stimulated by Polar obs

Scene changes: Buneman inst

- Waves at electron scales: probes for electron dynamics that particle data cannot resolve yet as of today
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Buneman instability…

- Unstable condition looks so tough.
- Can it really be excited in the magnetosphere?

The simulation had large guide field.

ESW: Bump-in-tail vs Buneman

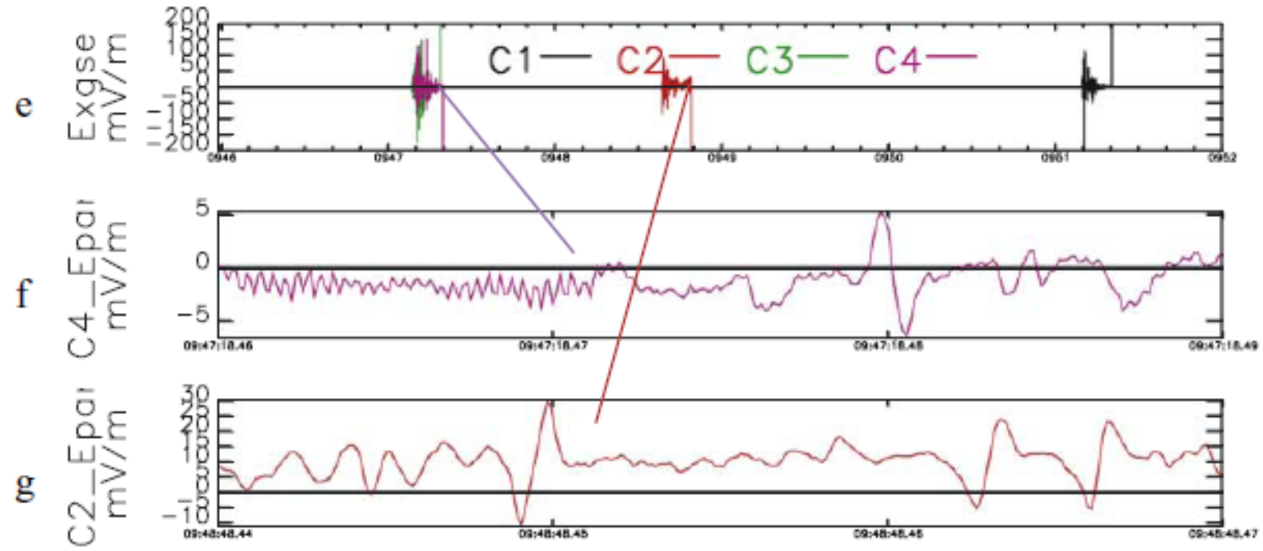
- Totally different phase velocity

  → Easily discernible in observations

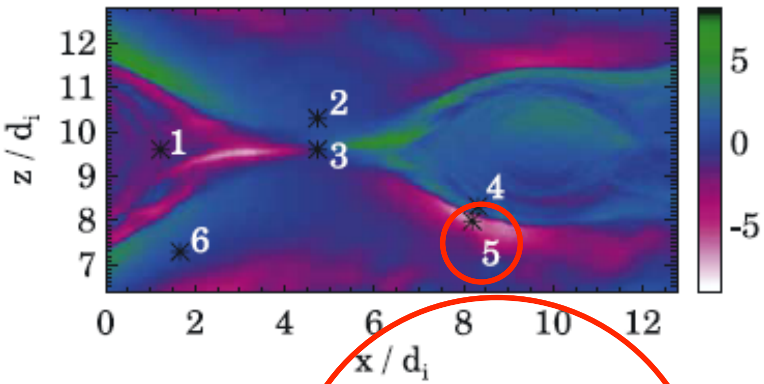
Actually, Cluster does not have the capability (high-cadence sampling) to catch the faster ESW due to bump-in-tail electrons.

Cluster obs

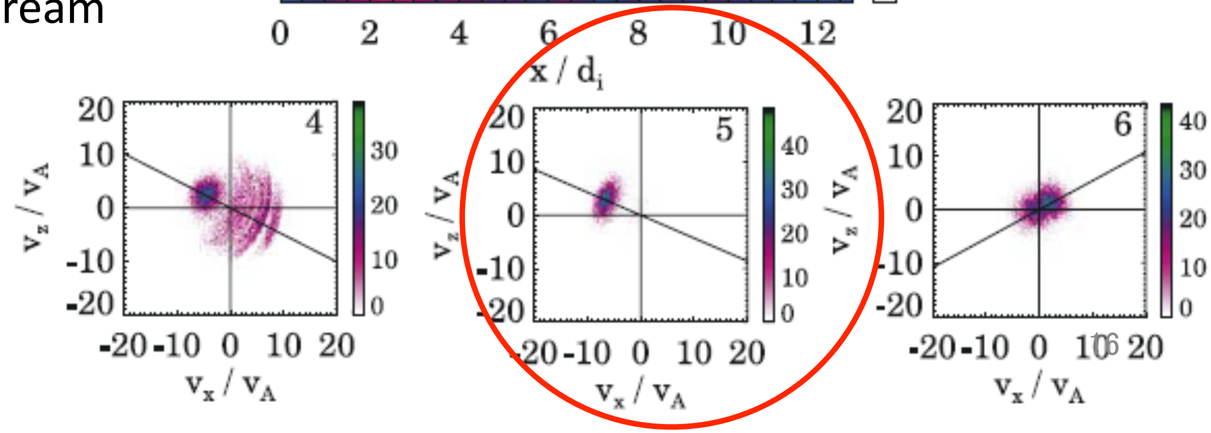
[Cattell05]



ESW at the sepratrix
at the position #5



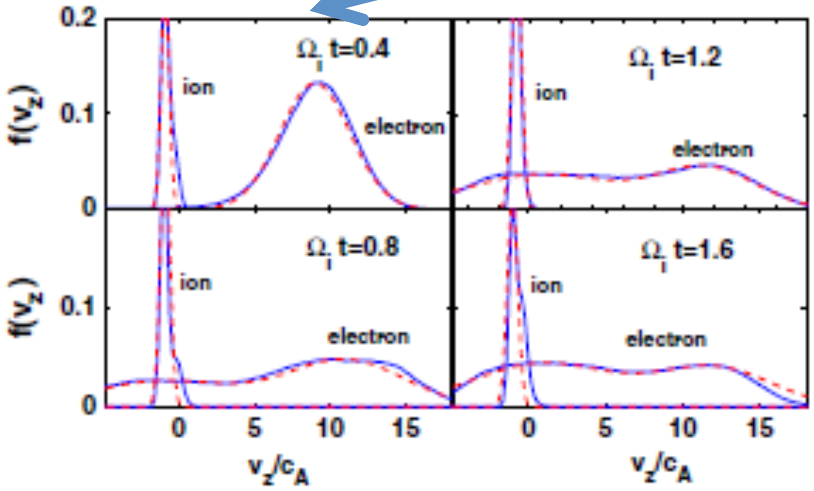
How about ESW due to two-stream
at the Position #4?:
Cluster is **not** capable
of detecting
this higher frequency
component

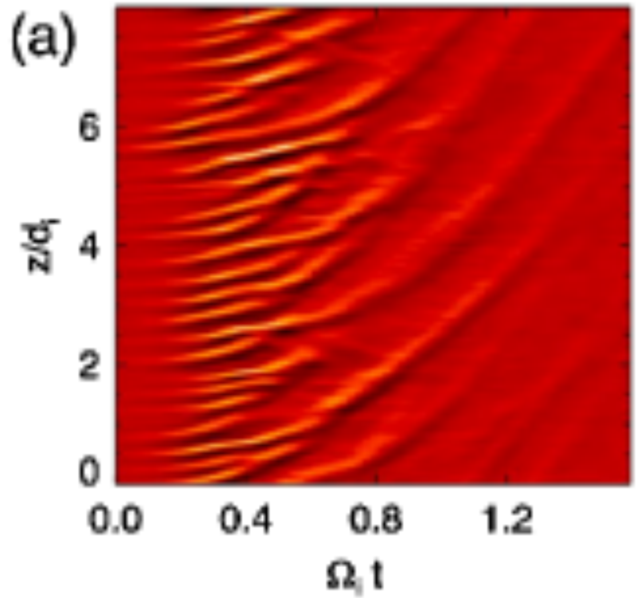


Another twist in the tale?

- Slow ESW (Buneman type) can be seen only in a limited time interval? [Che09]

Only during this interval, ESW is Buneman-like





How can spacecraft obs catch such a short-lived phenomena?!

- Waves at electron scales: probes for electron dynamics that particle data cannot resolve yet as of today
- Waves at ion-electron hybrid scales: enables ion-electron coupling, agent for dissipation
- Waves at ion-scales and at lower frequency: not negligible in the energy budget argument, enables remote effects to emerge

In this area of interest, traditionally

- Buneman instability
- Lower hybrid wave

are the focus of interest

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- Buneman instability
- Lower hybrid wave

are the focus of interest

Observations in the tail: ISEE1/Geotail

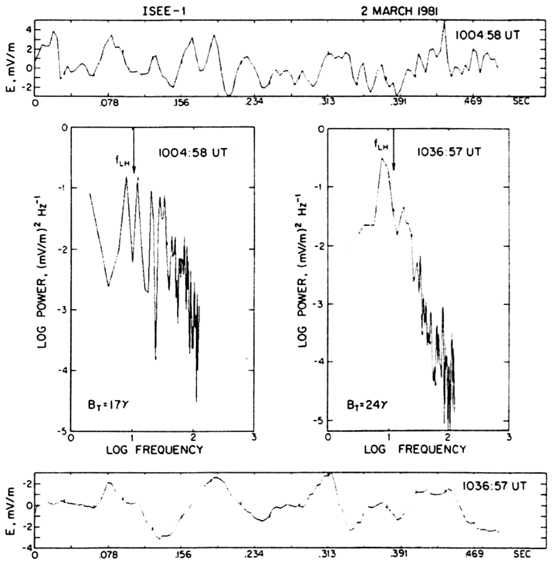


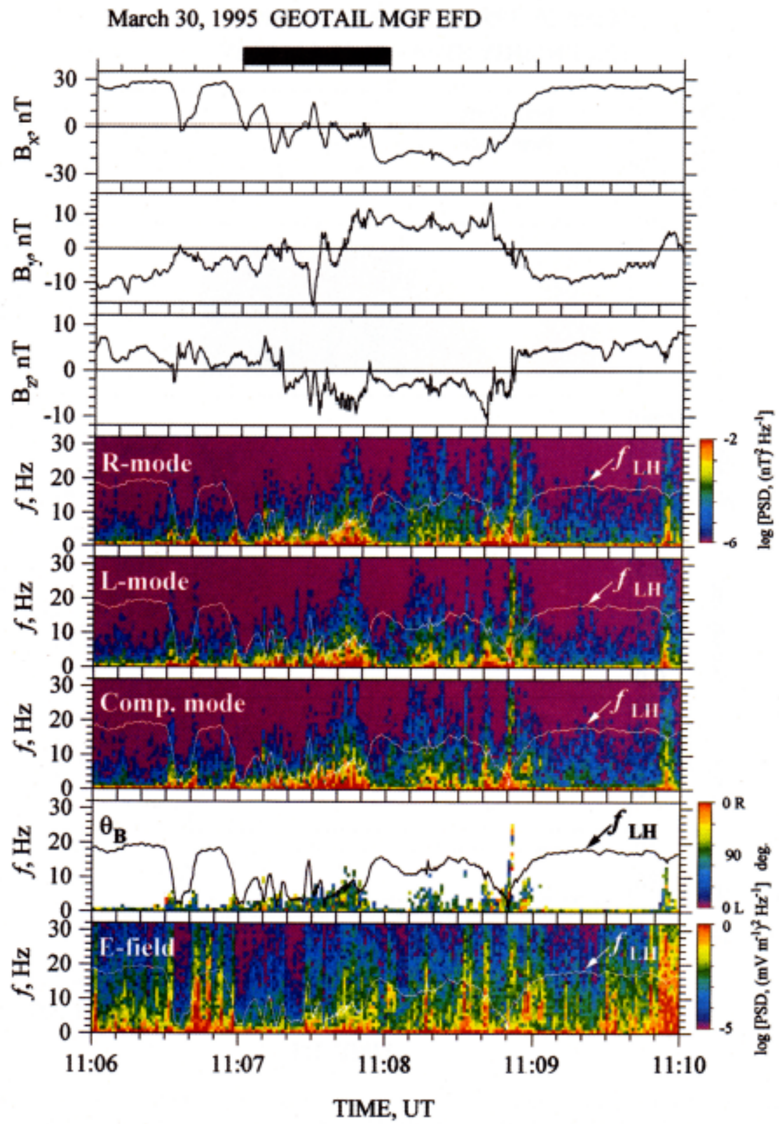
Figure 3—Two 0.5-s electric field waveforms and the associated power spectra. The lower hybrid frequency (assuming 100% H +) is indicated.

ISEE1 data
Cattell and Mozer (1987)

- Geotail frequently observes lower hybrid waves <u>in the plasma sheet boundary</u> [Okada94, Cattell94]

- And subsequently <u>in the center</u> [Shinohara98]

- In low β region (PSBL), strong LH wave is observed and the equivalent Reynolds number is as low as $R_M \sim O(100)$.
- In High β region, LH wave power is 1~2 orders below what can supply the required anomalous resistivity.



Observations in the close proximity of an X-line

[Shinohara98]

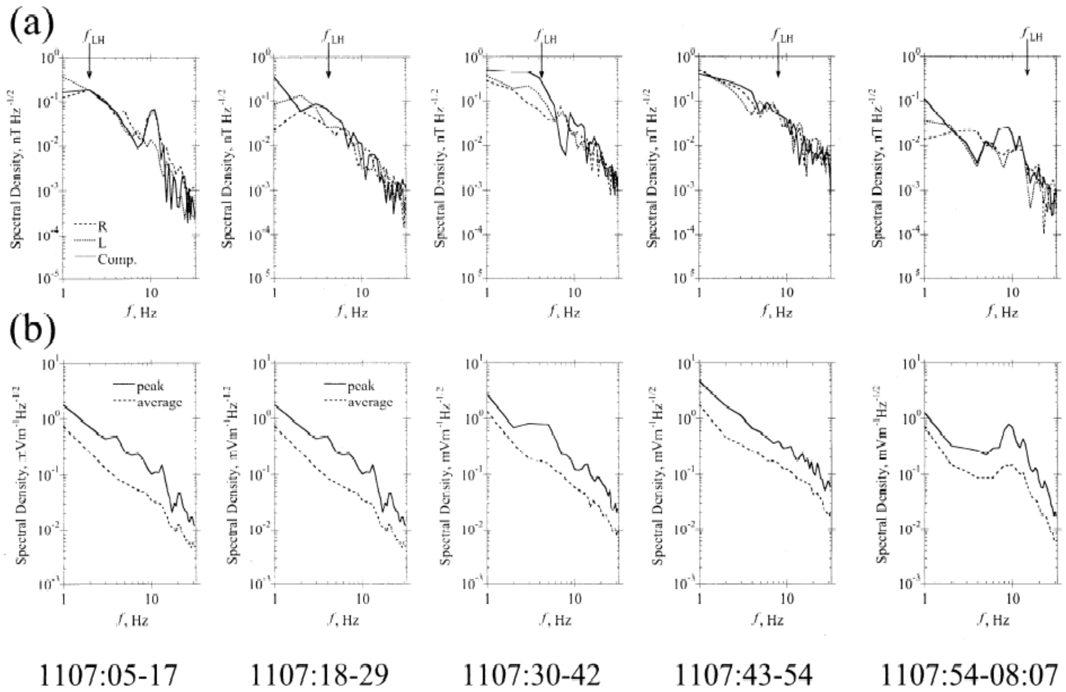
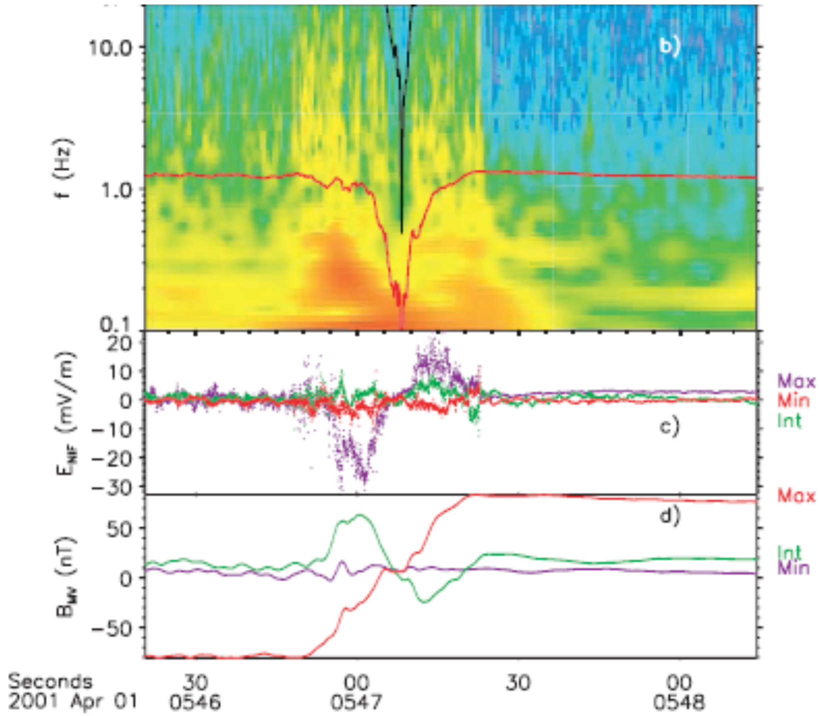


Figure 4. The individual wave spectra of both the magnetic and the electric wave components obtained for 1107:05–1107:55 UT. Each Fourier spectrum is calculated in every 12 s corresponding to the plasma observations shown in Plate 1. (a) The Fourier spectra for the magnetic field are presented, and the dashed, dotted, and solid lines indicate the spectra of the right-handed, left-handed, and compressional components, respectively. (b) The Fourier spectra for the electric field, and the solid and dotted lines represent the average and peak spectral density within each 12 s, respectively.

- Observed frequency is close to the local lower hybrid frequency.
- Calcluated $c|B|/|E|$ is consistent with the LH wave.
- Observed propagation angle is perpendicular to the ambient field.

LHDI effects confined to the edges

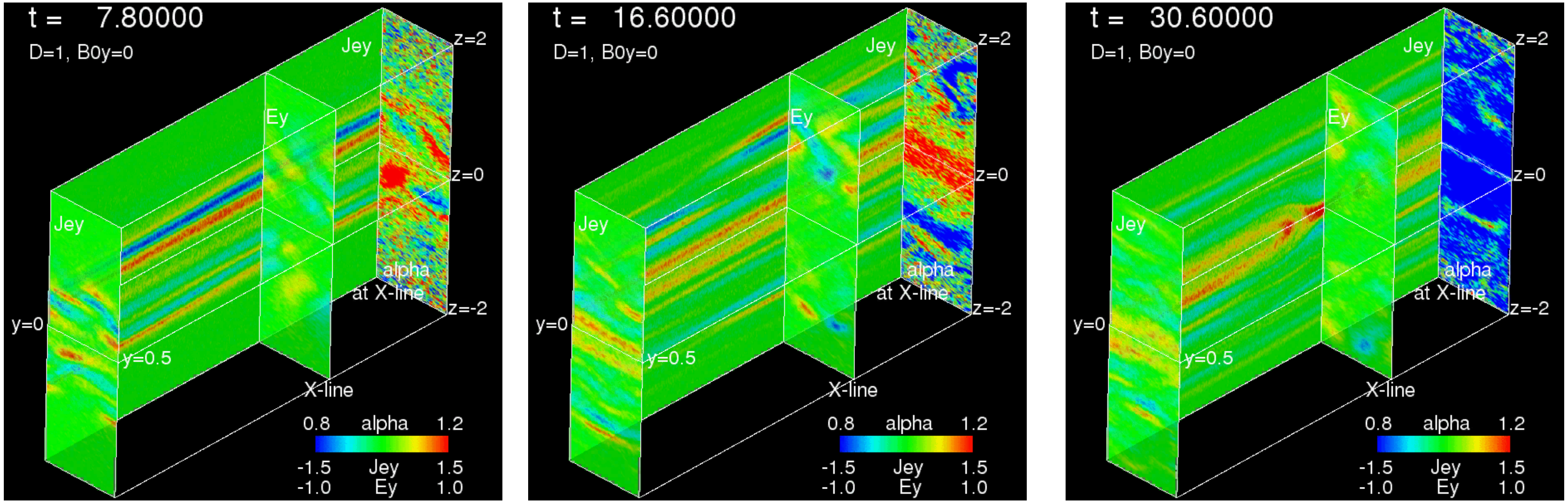
Excited by the density gradient at the current sheet edges but is damped in the center where the plasma beta is high



[Bale02]

[Carter02] for lab experiment

LHDI only at the edges: useless? ...NO!



LHDI only at the edges: useless? ...NO!

- LHDI at the edges
  → local current density reduction at the edges
  → non-local current density re-distribution
  → current density enhancement at the center
- Overall consequences
  = Formation of thin-embedded current sheet at the center:

Either

intense enough current density

or

anisotropically (Tperp>Tpara) heated electrons at the current sheet center

triggers RX

[Scholer03, Tanaka04, Daughton04, Ricci04, Tanaka05, Shinohara05, Fujimoto05, Tanaka09]

Yet, the quest for the waves
and the associated dissipation
at the current sheet center continues:

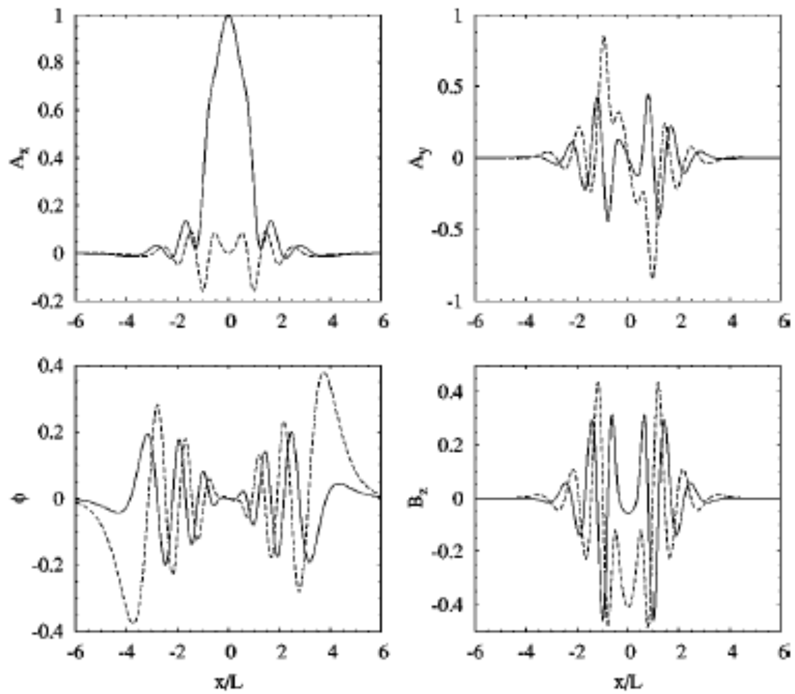
Stability of a current sheet

EM waves of w ~ w_lh at the current sheet center

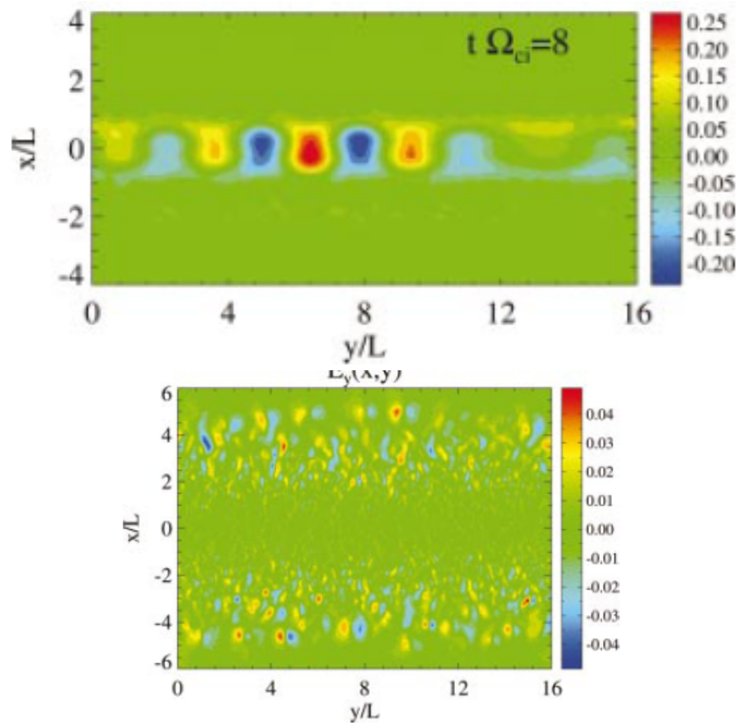
- Lab experiment [Ji2004]
- Oblique whistler waves

Global analysis of Harris current sheet

- Long wavelength mode with substantial EM component at the current sheet center



Eigen mode analysis

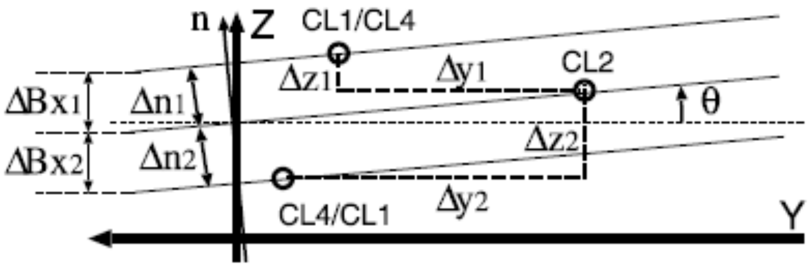


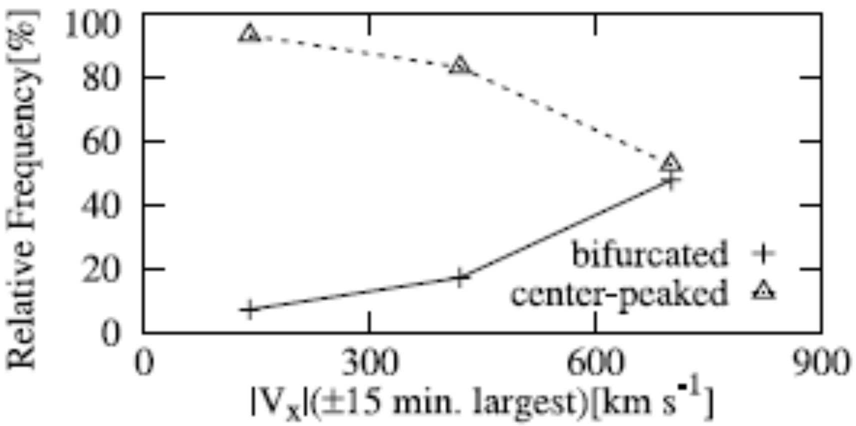
2D simulation

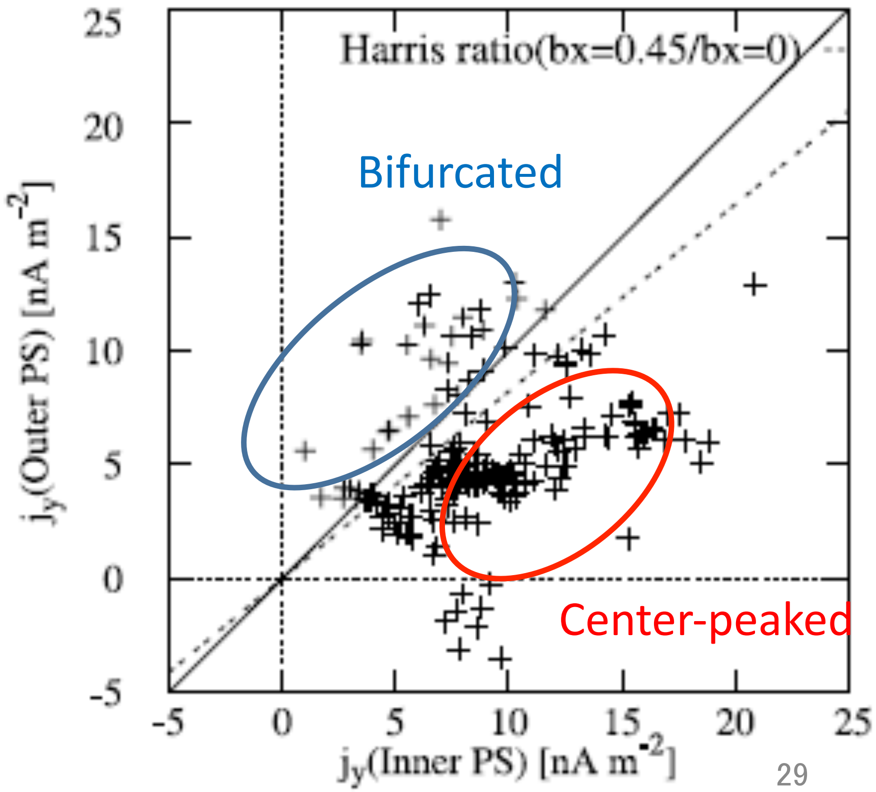
[Daughton03]

Growing interest in the properties of <u>Non-Harris</u> current sheet: Cluster obs of the current density profile

Four CL spacecraft formation not regarded as
a tetrahedron but as two-pairs of s/c
→ Current density at two locations within a current sheet [Asano05]







The Harris current sheet

- These two invariants of motion are linearly combined together in the model, and an exponential form is assumed:

$$f_\alpha \propto \exp\left[-\left(W_\alpha - V_{D\alpha} P_{y\alpha}\right)/T_\alpha\right] \qquad \alpha = e, i$$

$$\propto \exp\left[-q\left(\phi + V_{D\alpha} A\right)/T_\alpha\right] \cdot \exp\left[-m\left(V - V_{D\alpha}\right)^2 / 2T_\alpha\right]$$

- The particle distribution functions can thus be substituted into the Maxwell equation:

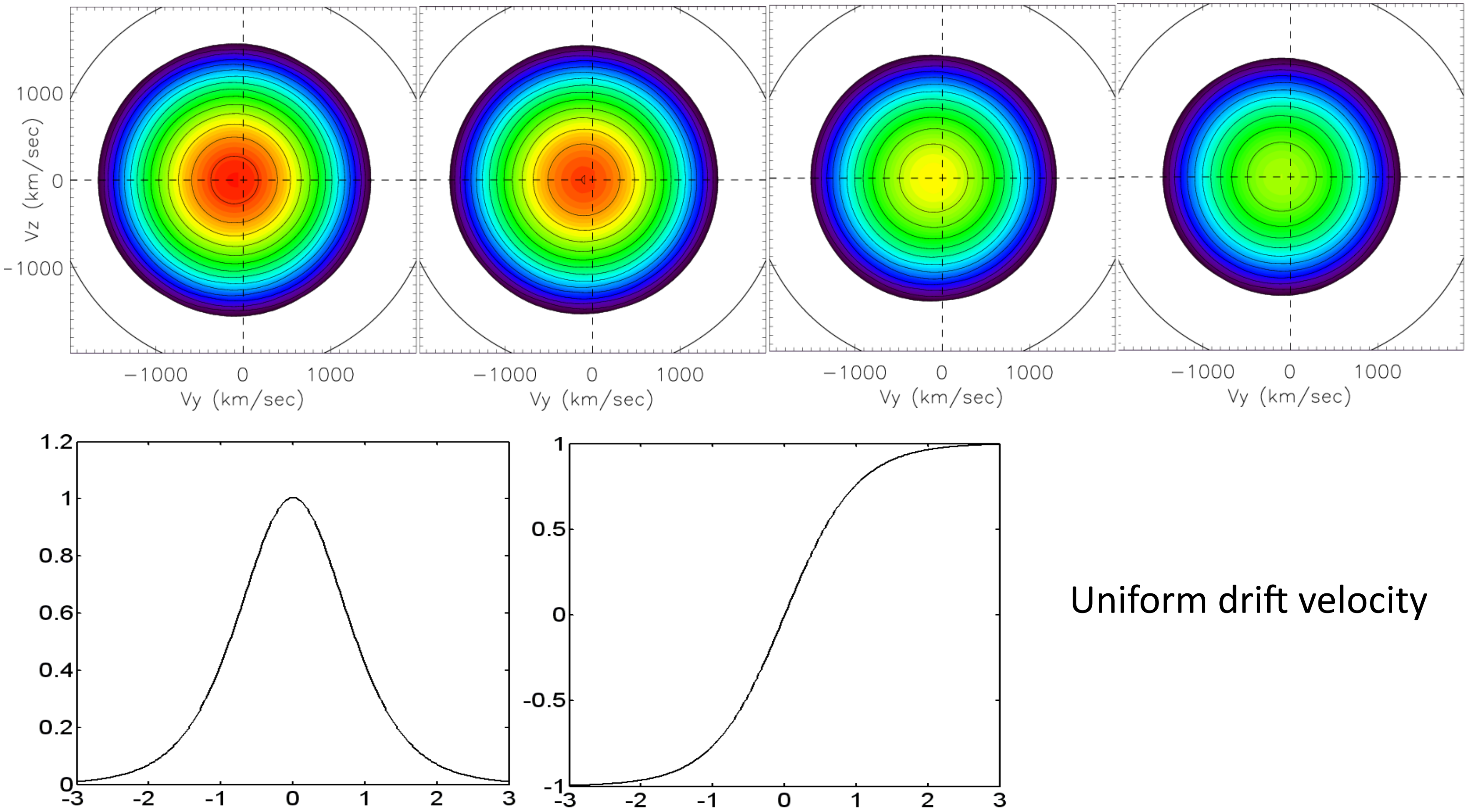
$$\nabla \cdot E = 4\pi \sum q_\alpha \int f_\alpha d^3 V_\alpha$$

$$\nabla \times B = 4\pi / c \sum q_\alpha \int f_\alpha V_\alpha d^3 V_\alpha$$

and a self-consistent current sheet solution can be obtained.

Ion distributions within the Harris sheet

B=0 B=0.5B_L B=0.9B_L B=0.95B_L



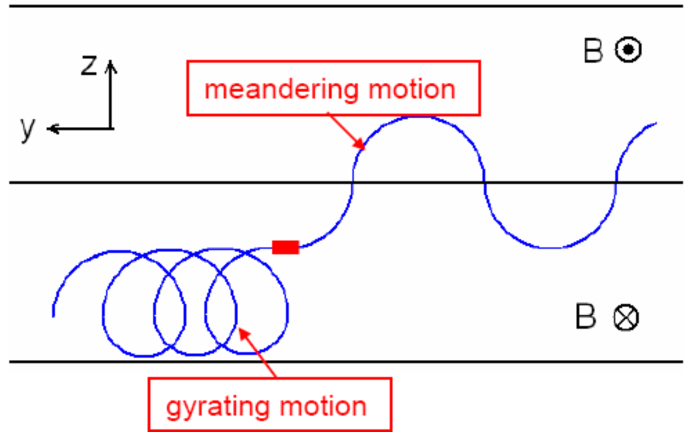
Density & Current Profiles

Magnetic Field Profile

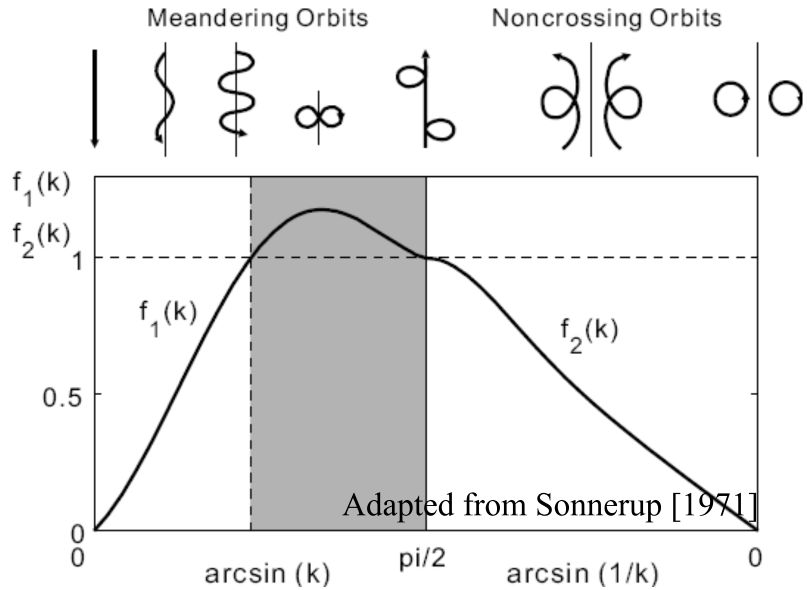
Uniform drift velocity

A non-Harris model: The SGS model

- Another invariant of motion, say, the sheet invariant $I = 1/2\pi \cdot \oint m V_z dz$ is used to construct the distribution function (Sitnov et al., 2003, 2006).



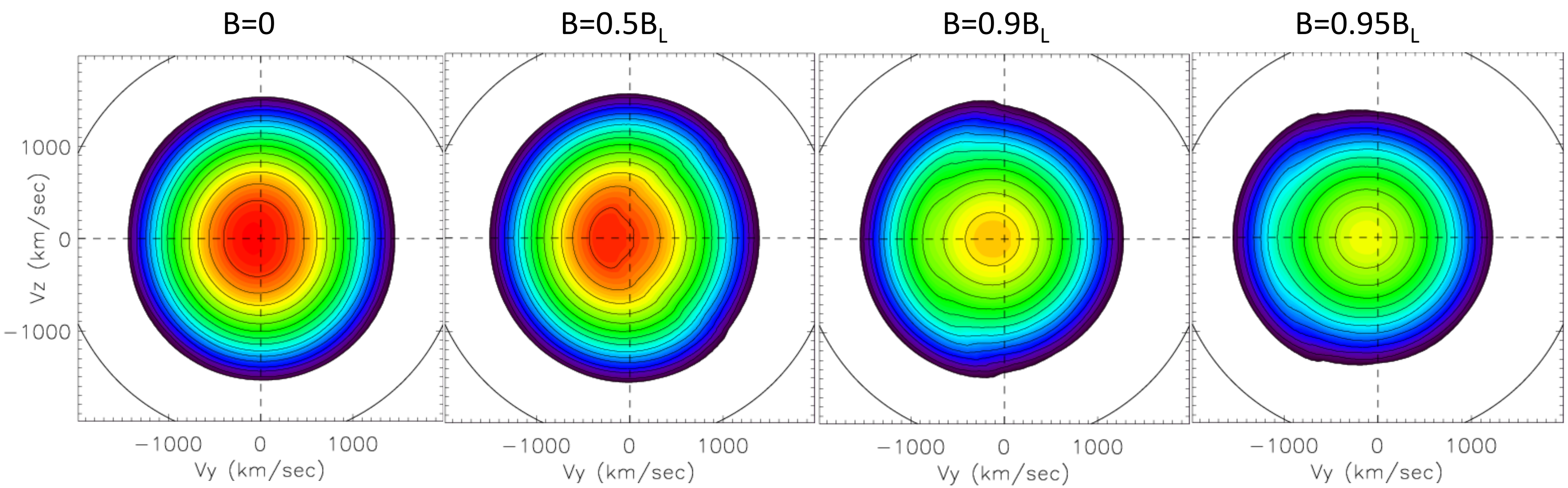
Particles with the same energy but moving in different directions are following distinct orbits, and thus have very different I values.

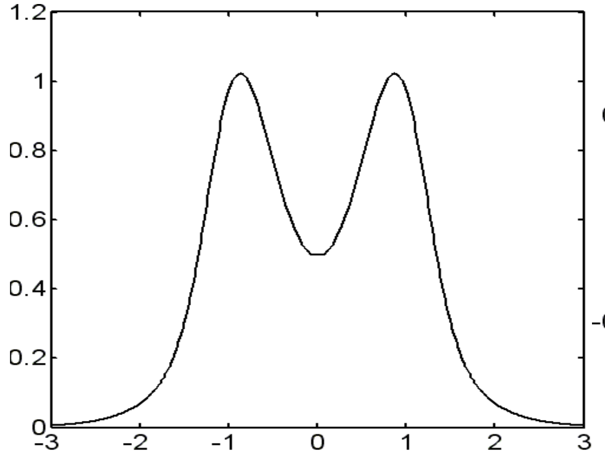


- Now the distribution function becomes:

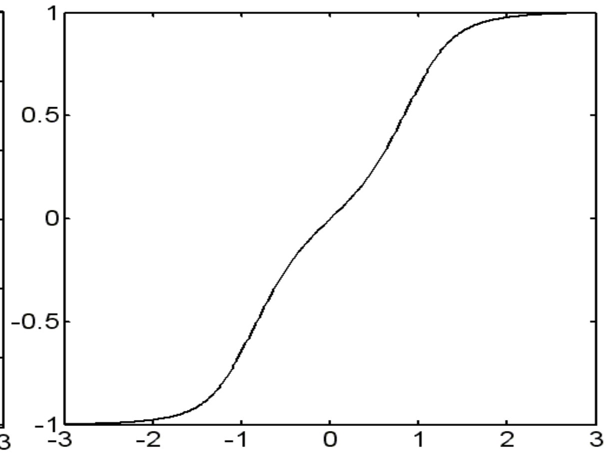
$$f_\alpha \propto \exp\left[-\left(W_\alpha - V_{D\alpha} P_{y\alpha}\right)/T_{//\alpha} + I_\alpha\left(T_{//\alpha}^{-1} - T_{\perp\alpha}^{-1}\right)\omega_\alpha/2\right]$$

Ion distributions within the SGS sheet





Current Profiles



Magnetic Field Profile

The meandering ions sustain the bifurcated structure.

The overall current sheet is bifurcated in this original form where meandering ions dominate as current carriers.

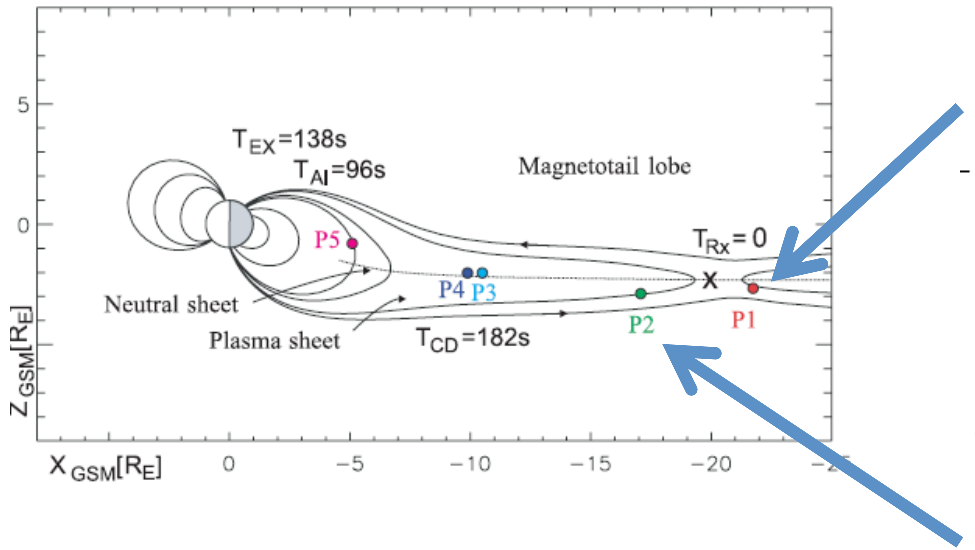
Stability?

- Is a bifurcated current sheet more unstable?

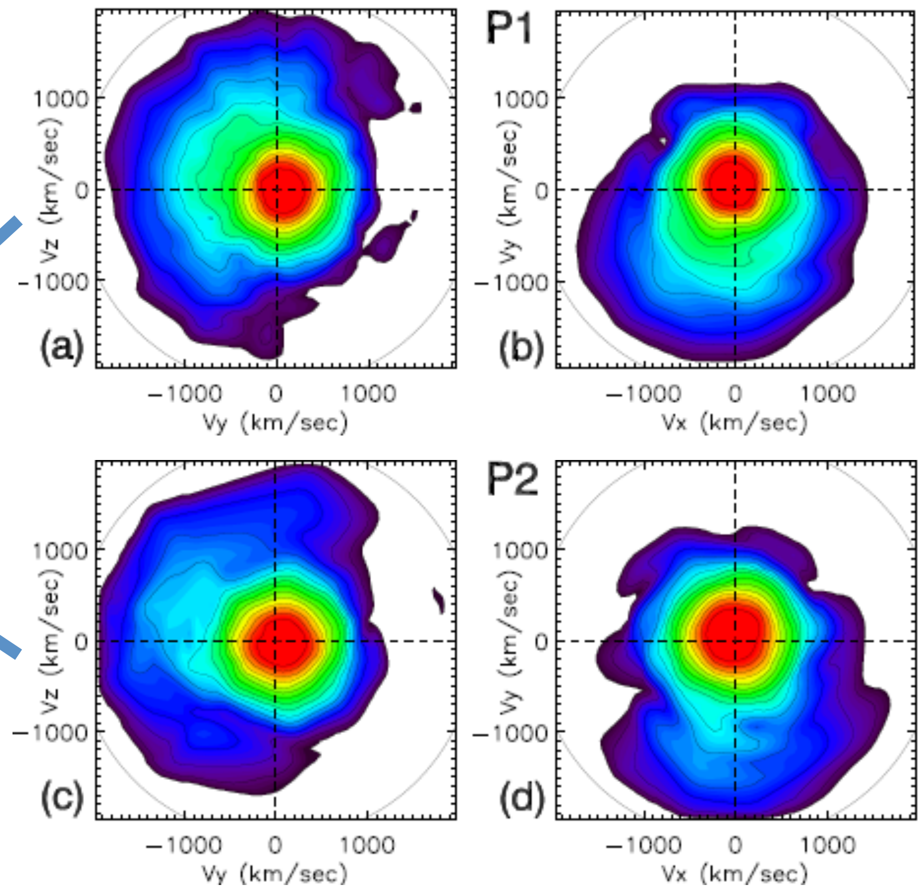
- Unlikely.
- But I still stick to this because of the nice work by Zhou09.

Recent results from THEMIS

[Zhou09]

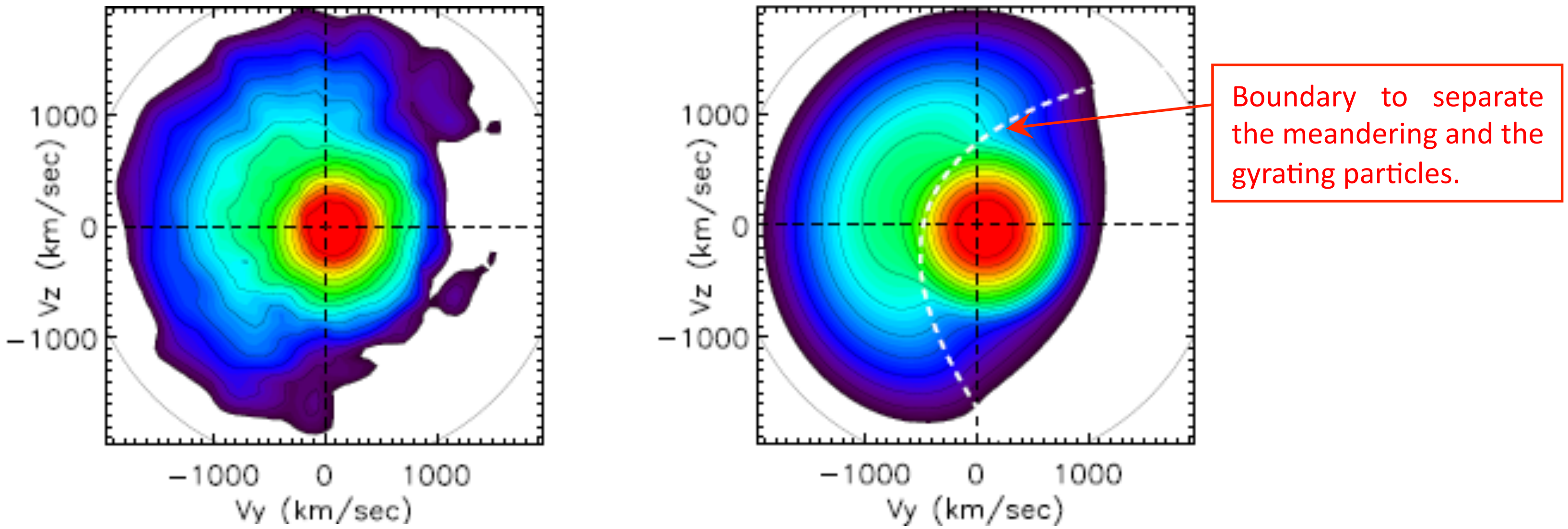


Ions in a thin current sheet that is about to host an X-line



Mushroom-shape
In the plane perp to B-field

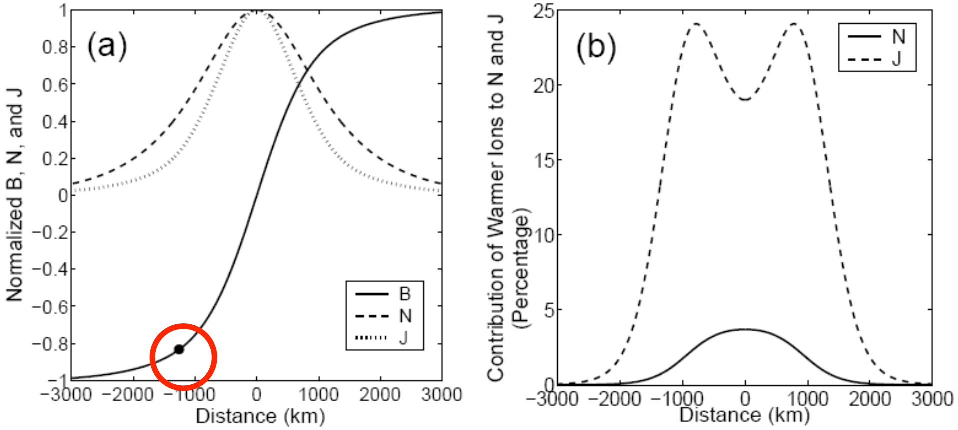
Model Validation with observations



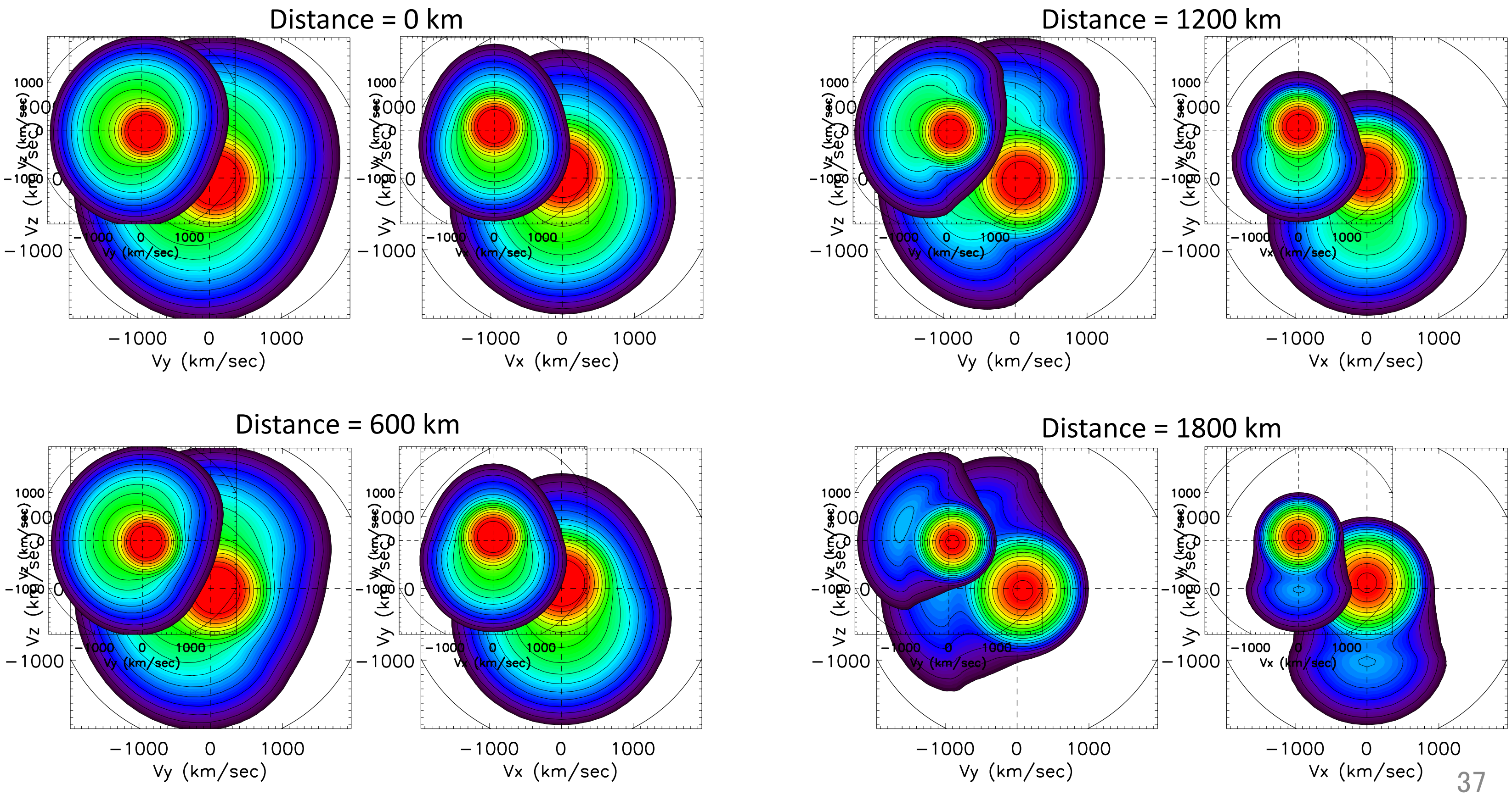
- The SGS model is slightly modified, with the distribution function of:

$$f_\alpha = A\exp\left[-\left(W_\alpha - V_{D\alpha w}P_{y\alpha}\right)/T_{//\alpha w} + I_\alpha\left(T_{//\alpha w}{}^{-1} - T_{\perp\alpha w}{}^{-1}\right)\omega_\alpha/2\right]$$
$$+ B\exp\left[-\left(W_\alpha - V_{D\alpha c}P_{y\alpha}\right)/T_{//\alpha c}\right]$$

as a superposition of a Harris-type function (for colder component) and a SGS-type function (for warmer component).



Meandering ions do not dominate:
Center-peaked current profile.



They are indeed precious dataset.
It is indeed a nice work, however

- "Cold" component is locally gyrating at the site of the observations
- Its spatial distribution within the current sheet was modeled rather than measured: It is not clear whether there is this much "cold" component at the current sheet center

 # The effort of trying to get best info out of the distribution function data should be highly acknowledged.

Non-Harris current sheet:

With enhanced ion-electron velocity difference at the center

- Enhanced velocity difference can lead to modified two-stream instability [Yoon04]

Meandering ions and the stability of a current sheet:

- Meandering ions → current density bifurcation → more stable current sheet? … Then, why did THEMIS see the current sheet to undergo reconnection soon after seeing the meandering ions?

 # Meandering ions and bifurcated current sheet are NOT necessarily one-to-one correspondence. Producing more meandering ions may lead to enhanced current density at the center carried by electrons. [Fujimoto, in progress]

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- Waves at ion-electron hybrid scales: enables ion-electron coupling, agent for dissipation
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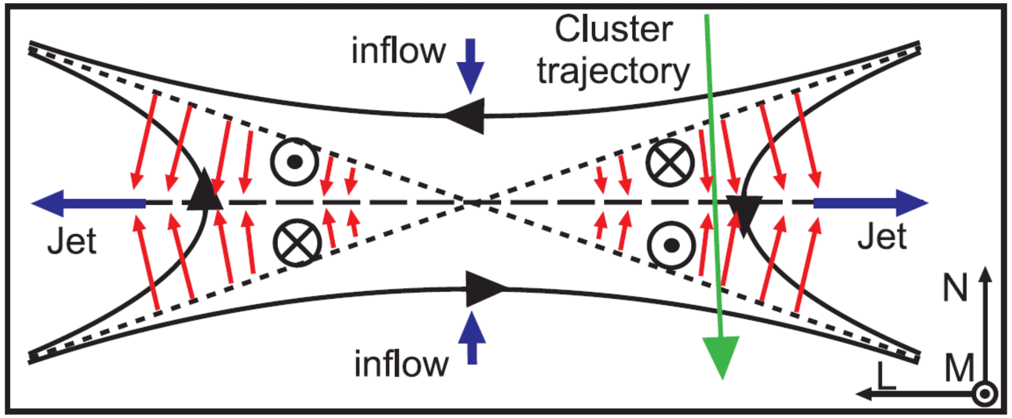
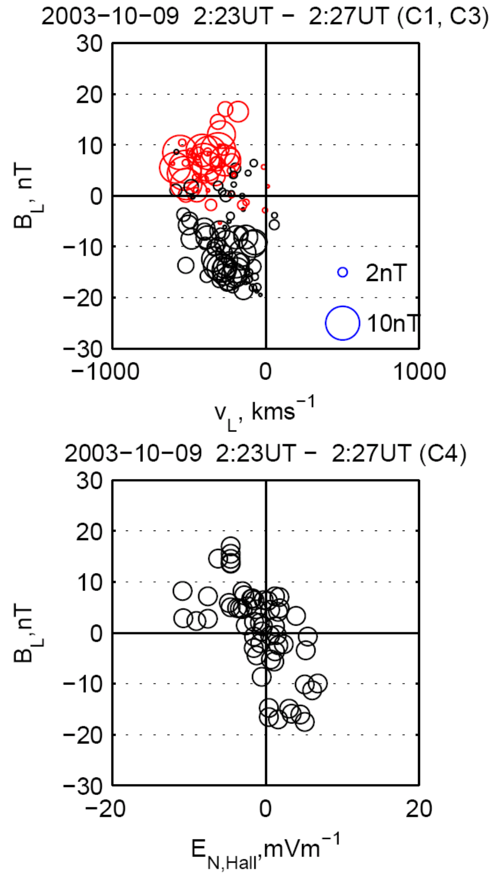
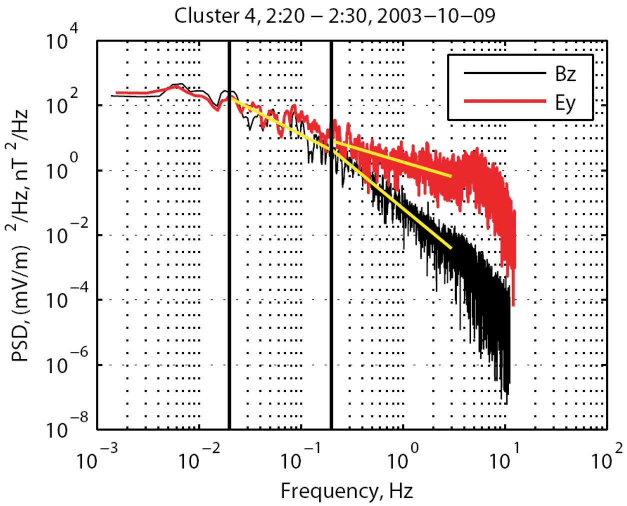
One case: zero guide-field
[Eastwood09]

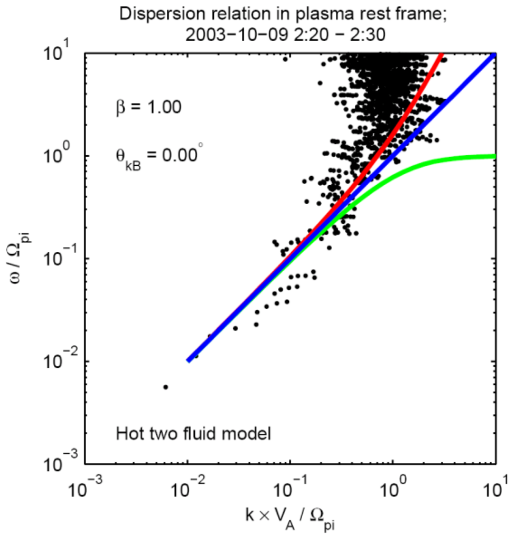


At large scale, quadrupolar By: Hall effects



Wave filtering technique

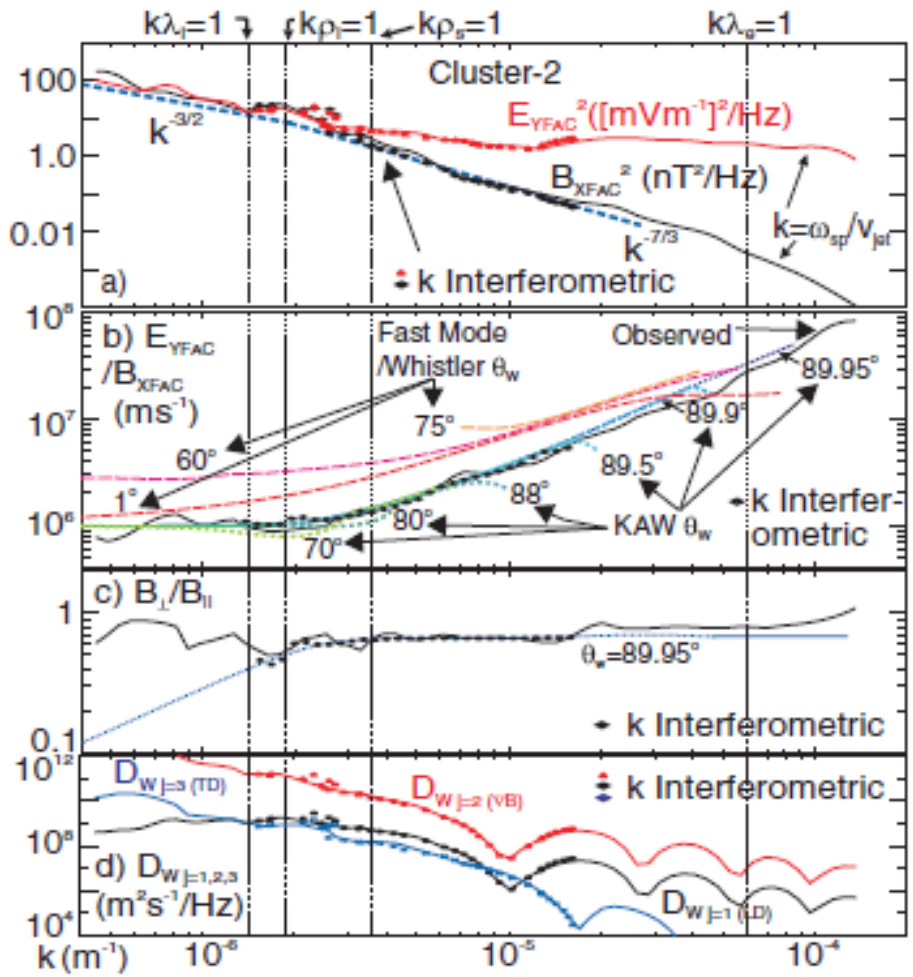




Alfven mode,
with Hall term correction,
k **parallel** to B,
as the nature of turbulence in the jets

Another case in the tail: with guide-field (0.3)

[Chaston09]



KAW identified : k perp to B

Agent for diffusive transport along the current sheet normal at the X-line

Significant contribution to the energy budget:
Substantial part of the energy outflow carried by the outgoing waves

Analogy to dissipation-fluctuation theorem

- In 3-D with guide-field,

  - RX rate at a certain level gives rise to KAW fluctuation

  - The KAW fluctuation provides the dissipation needed to keep the RX rate

Dissipation agent

Traditionally

- Buneman instability
- Lower hybrid wave

Also

- Whistler wave, Modified two-stream instability

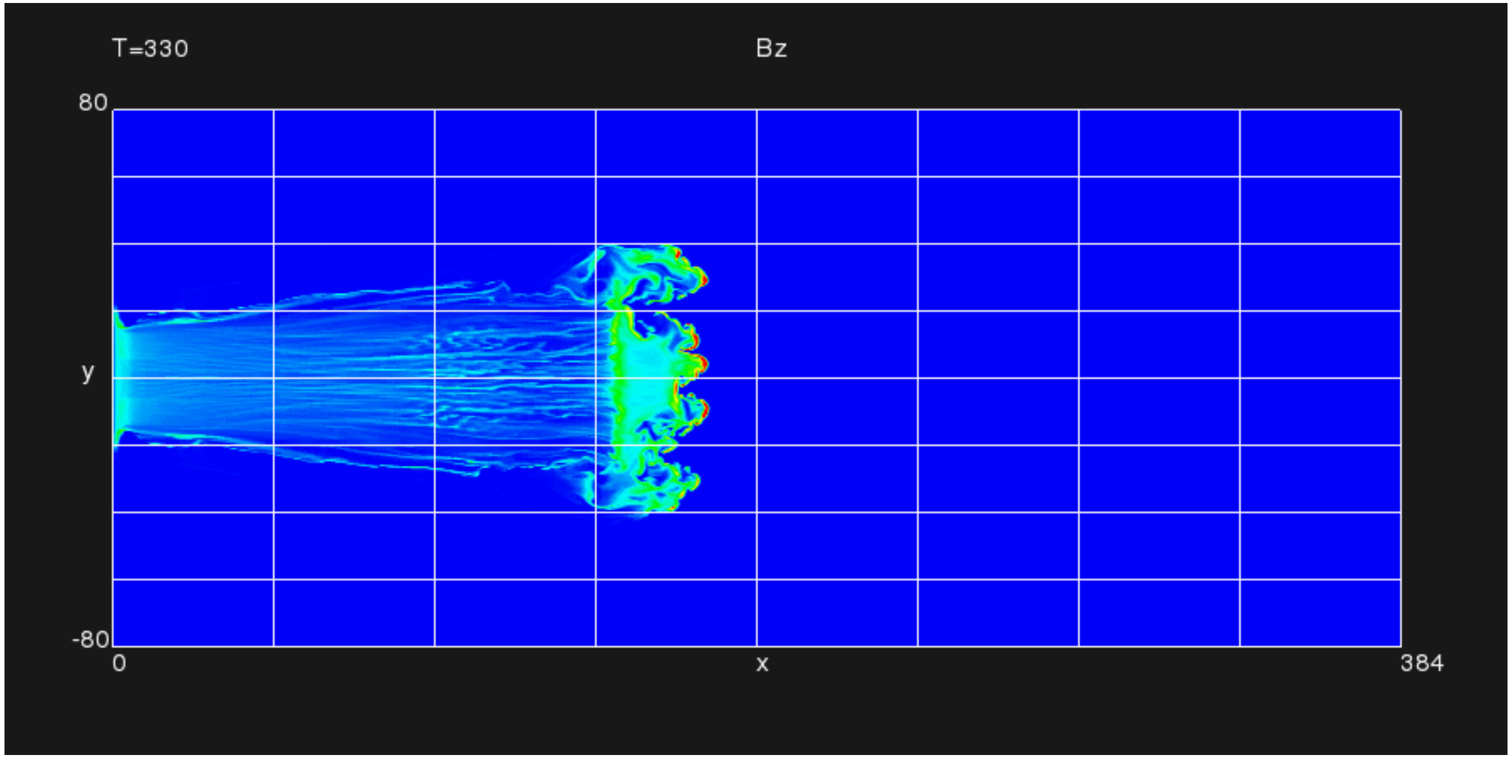
In addition,

- Kinetic Alfven wave

#More work in progress [Eastwood]

At the leading-edge of a jet

- Ballooning instability triggers multi-scale turbulence
- One of the Focal points of recent interest (Cluster, THEMIS)



Wave data in the context of *reconnection* research: How useful?

- Waves at electron scales: probes for electron dynamics that particle data cannot resolve yet as of today
- Waves at ion-electron hybrid scales: enables ion-electron coupling, agent for dissipation
- Waves at ion-scales and at lower frequency: not negligible in the energy budget argument, enables remote effects to emerge
- *Islands*

Magnetic islands

- Plasmoid instability
- Secondary islands
- Coalescence
- Particle acceleration

Magnetic islands

- Plasmoid instability
- Secondary islands
- Coalescence
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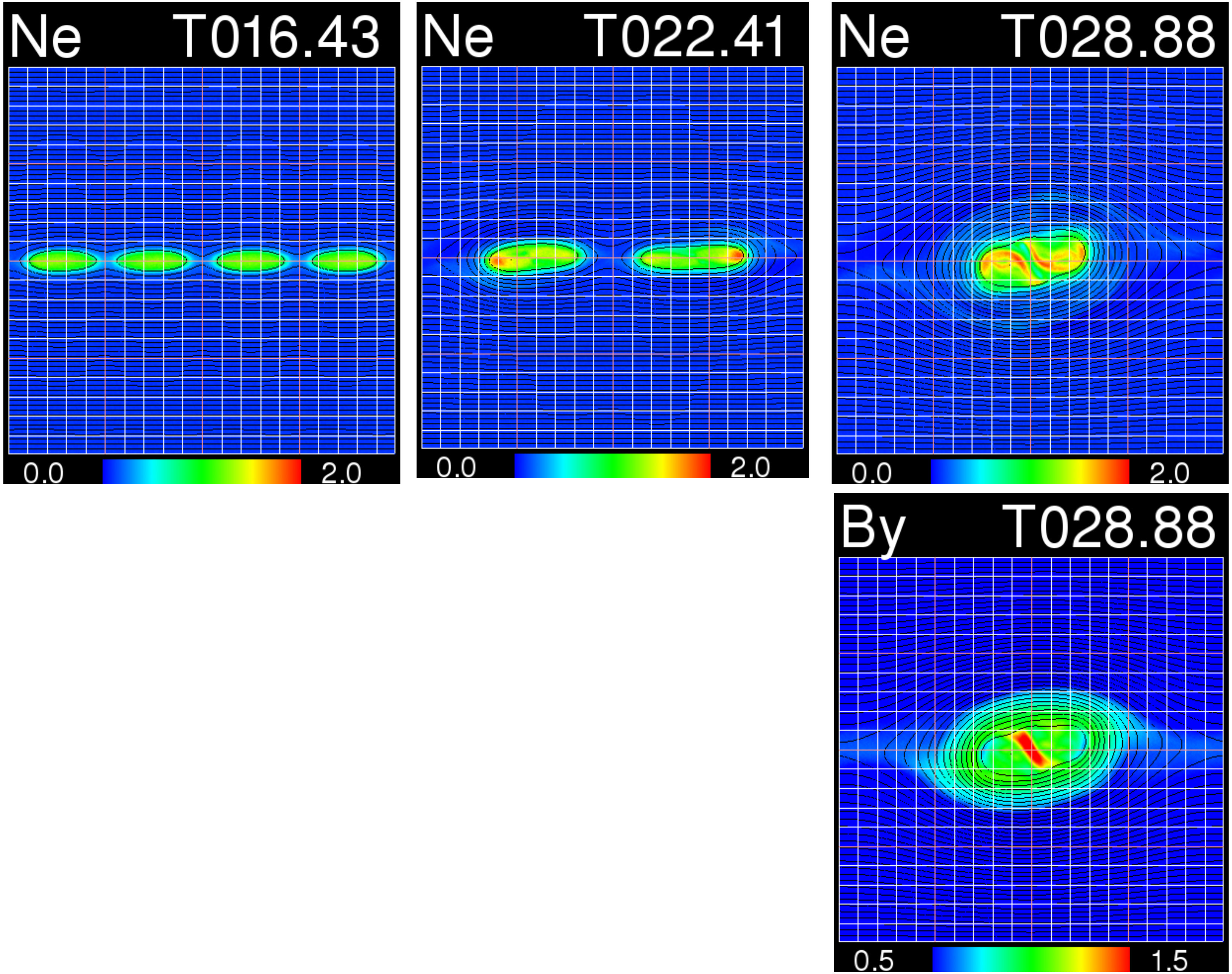
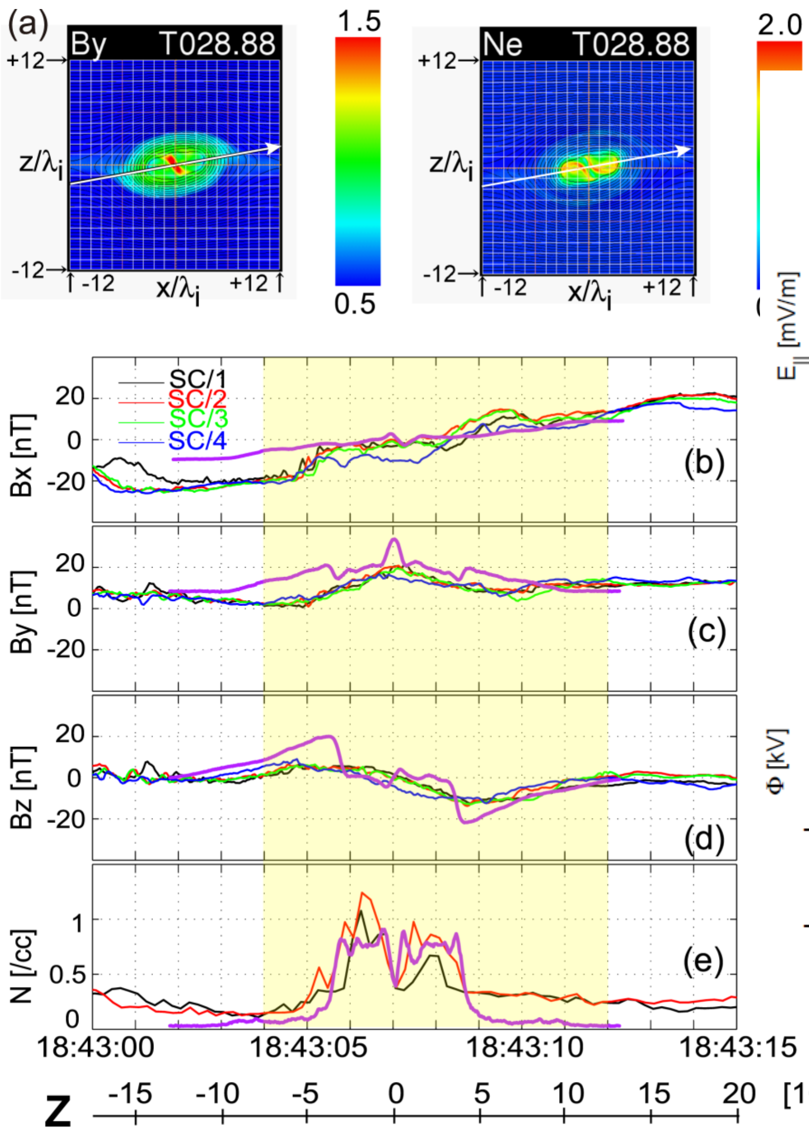
Features at the center of an island formed by coalescence, and that right after the coalescence

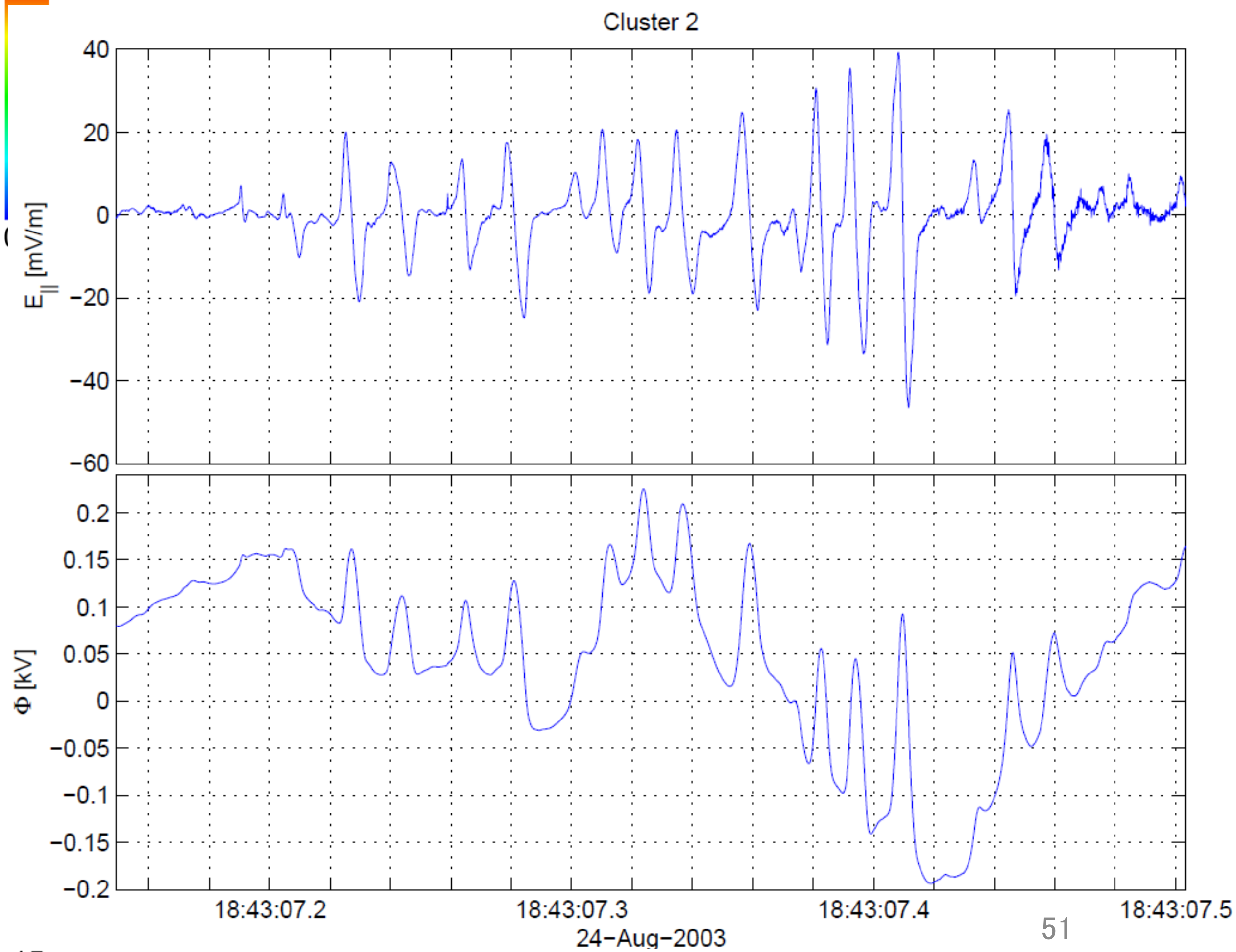


Cluster obs of an island:

- Size ~ 20 ion inertial length
- Density dip & guide-field peak at the center

- Comparison with 2D PIC simulations
- Best agreement when N dip and By max in the center of flux rope corresponding to final coalescence stage (from t=20 to t=30)
- **Cluster might have crossed flux rope right after coalescence**





Slow ESW (Buneman type) at an O-line

- Another item to suggest that this site for the O-line would have been that for an X-line facilitated the coalescence which formed the island! [Yuri Khotyaintsev, in preparation]

- Smoking gun evidence for coalescence (?)

Reconnection and waves: The framework

- So far, typically, dynamics in a 2-D picture plus 3-D freedom for the waves

- Are we ready for full 3-D consideration?