Multi-Scale Investigations of Flux transfer events (FTEs) and Kelvin-Helmholtz waves/vortices (KHWs/KHVs)

Kyoung-Joo ('Joo') Hwang (1)

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Acknowledgements: MMS FPI, Fields, EPD, and Theory/Modeling teams

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Outline

1. **FTE: general knowns**
2. **Reconnection-based FTE models**
3. **New findings on FTE after MMS**
4. **Velocity-shear-induced FTE**

Outline

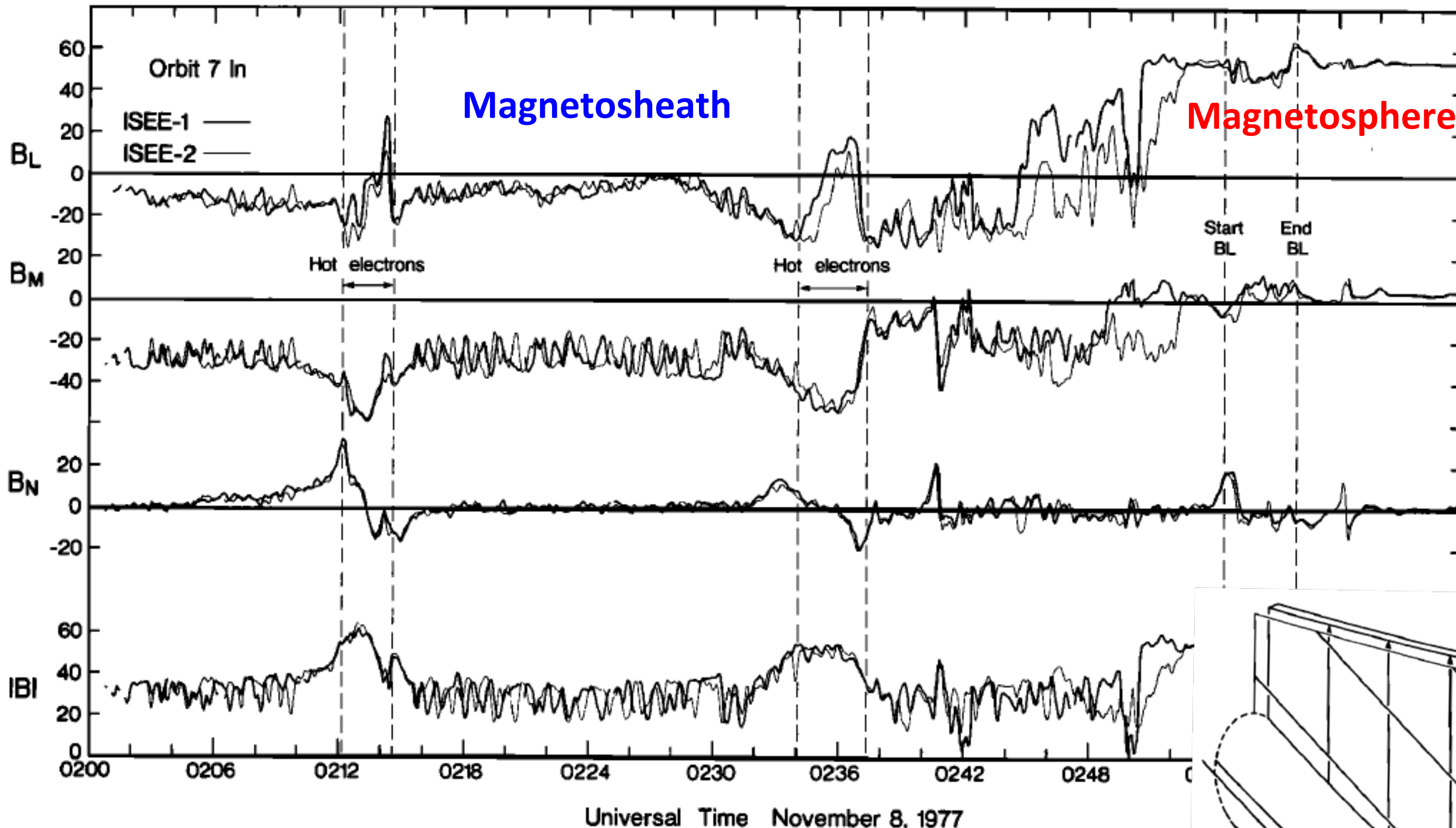
1. FTE: general knowns

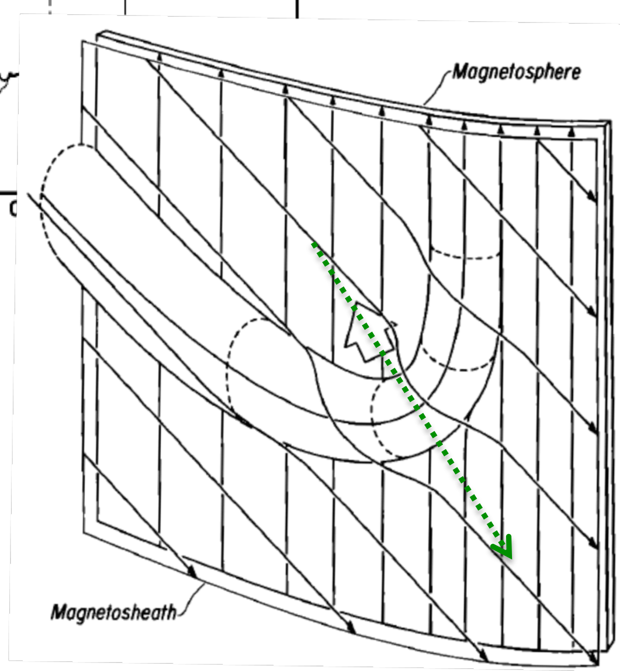
2. Reconnection-based FTE models

3. New findings of FTE after MMS

4. Velocity-shear-induced FTE

FTE: Initial In-situ Observation

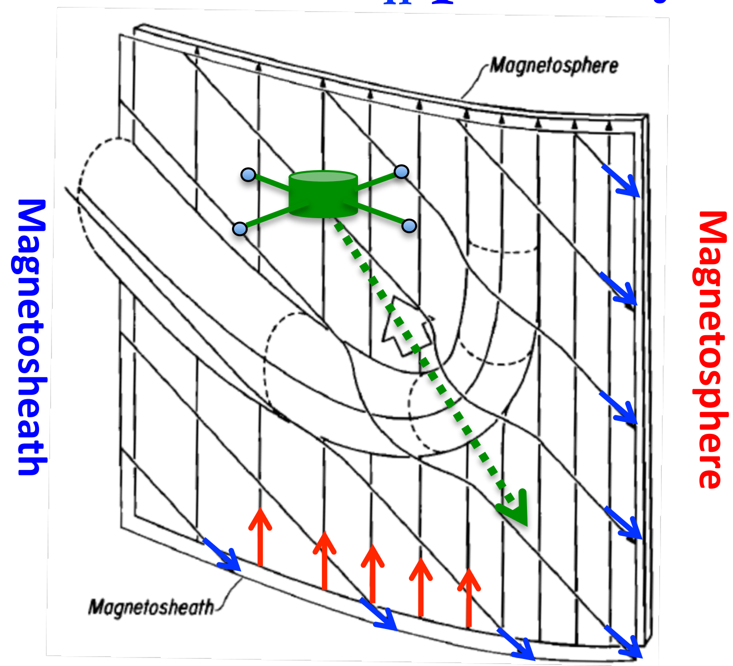




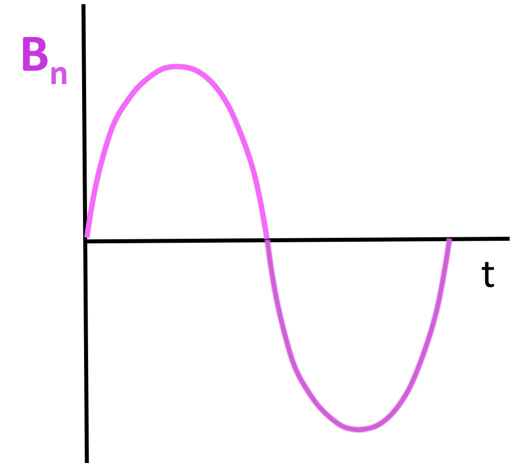
Russell & Elphic [1978; 1979]

- Introduced boundary normal coordinate system (LMN)
- Identified bipolar B_n signature & |B| enhancement
- Interpreted as signature of localized flux ropes, 'flux transfer events'

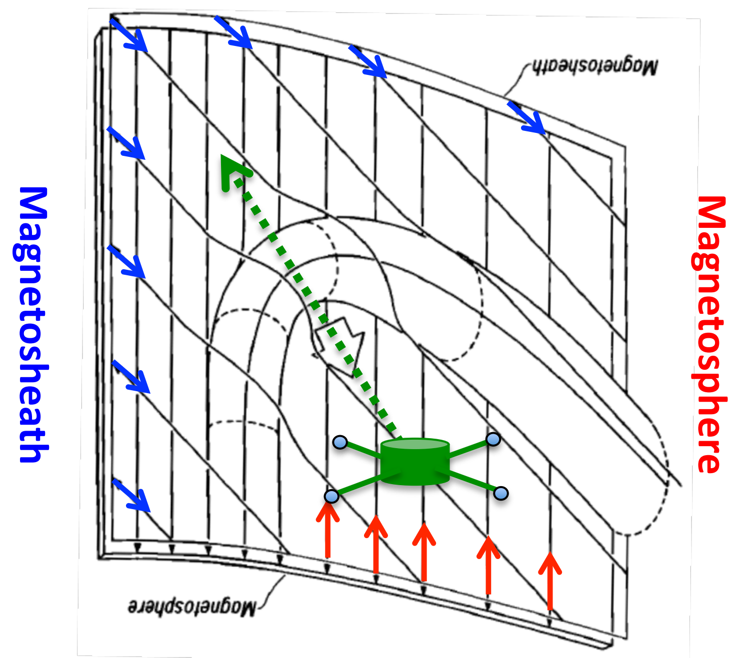
FTE: B_n polarity representing a motion - 1



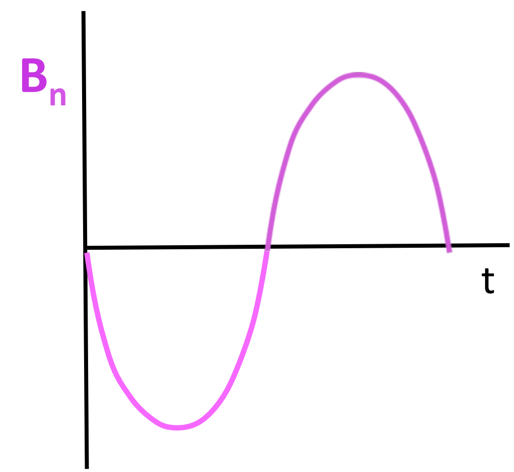
Northward motion (standard polarity):



Russell & Elphic [1978]

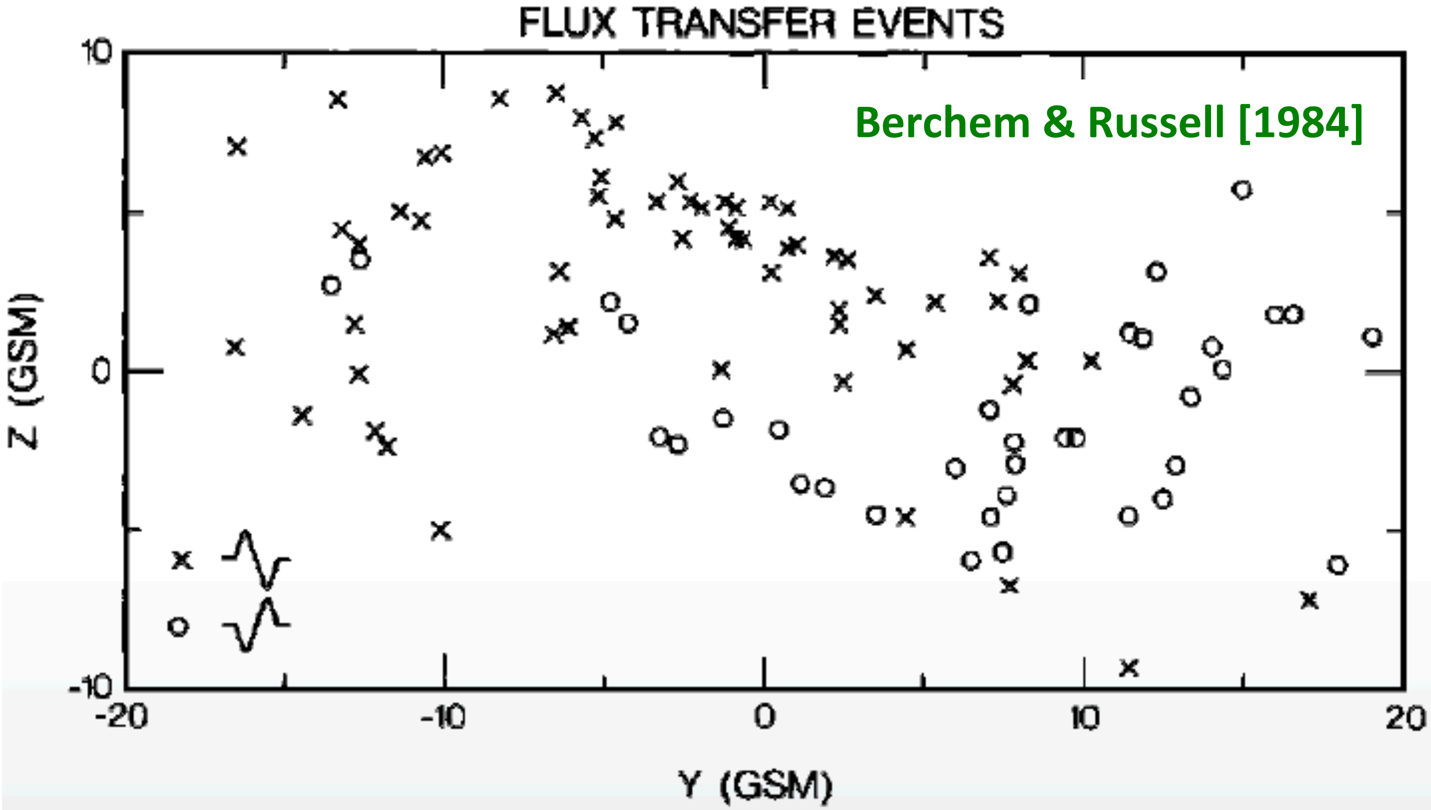


Southward motion (reverse polarity):



Rijnbeek et al. [1982]

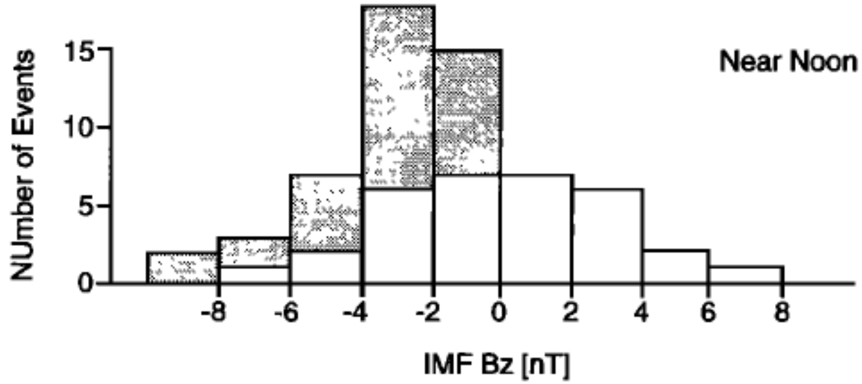
FTE: B_n polarity representing a motion - 2

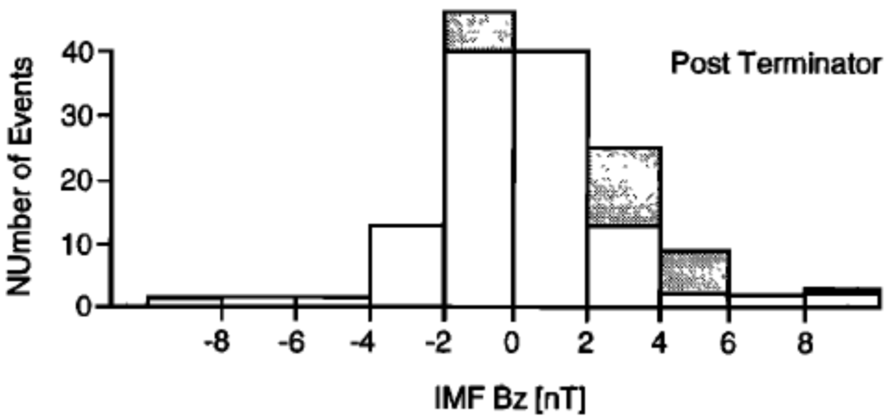


- Standard polarity (positive => negative; **X**): predominantly in the northern hemisphere
- Reverse polarity (negative => positive; **O**): predominantly in the souhern hemisphere
- Indicative of subsolar reconnection as a generation mechanism (even when there is a dominant IMF By condition, leading to guide-field reconnection [Russell+, 1985])

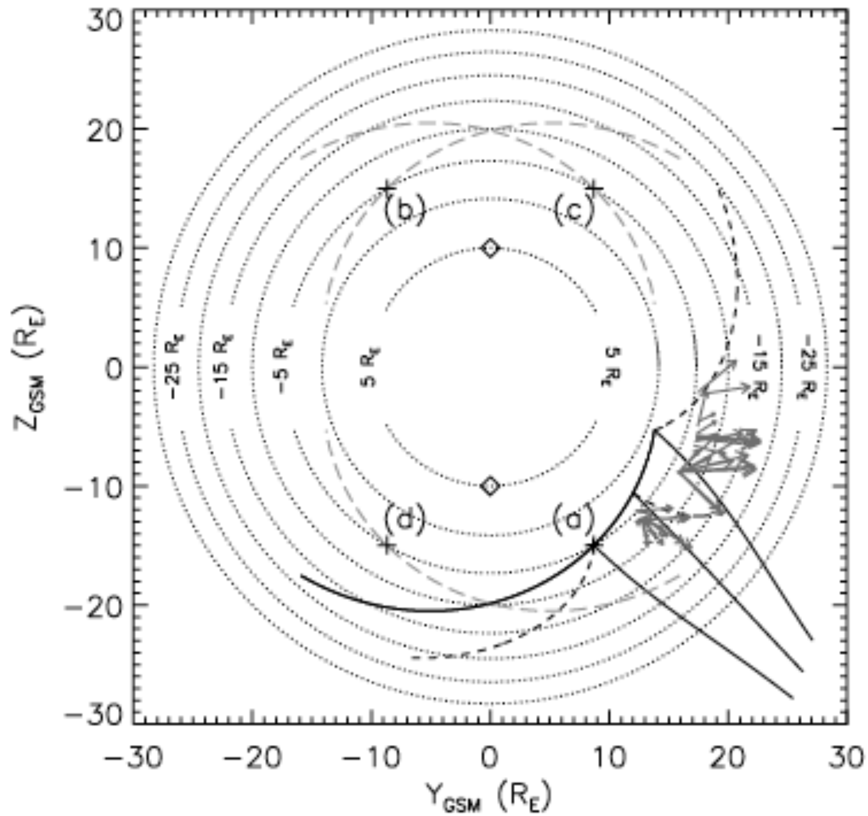
FTE: IMF Bz dependence

340 FTEs from ISEE 1 [Kawano & Russell, 1997a]



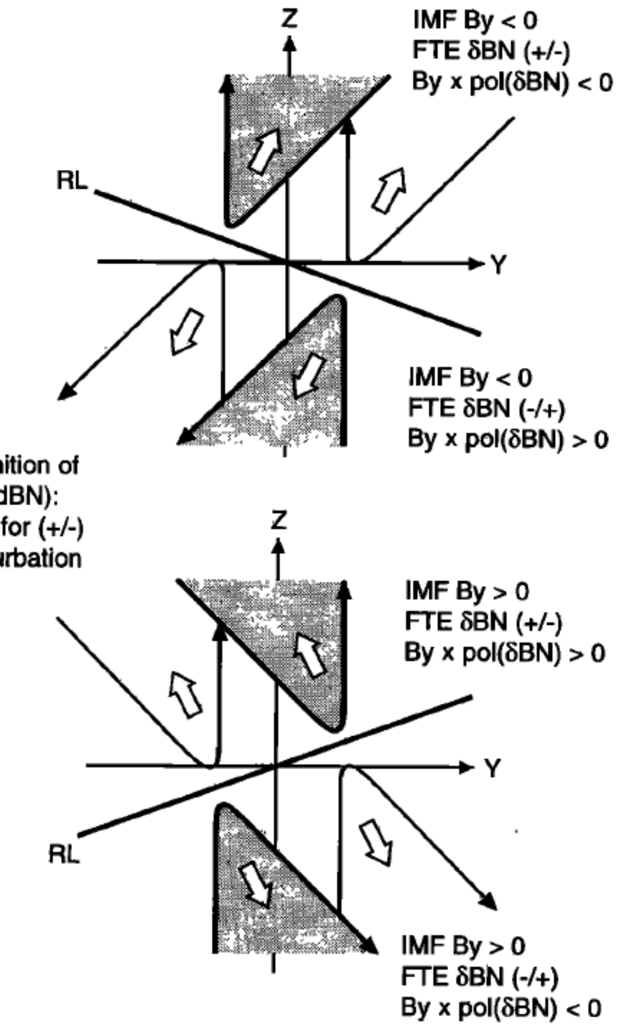


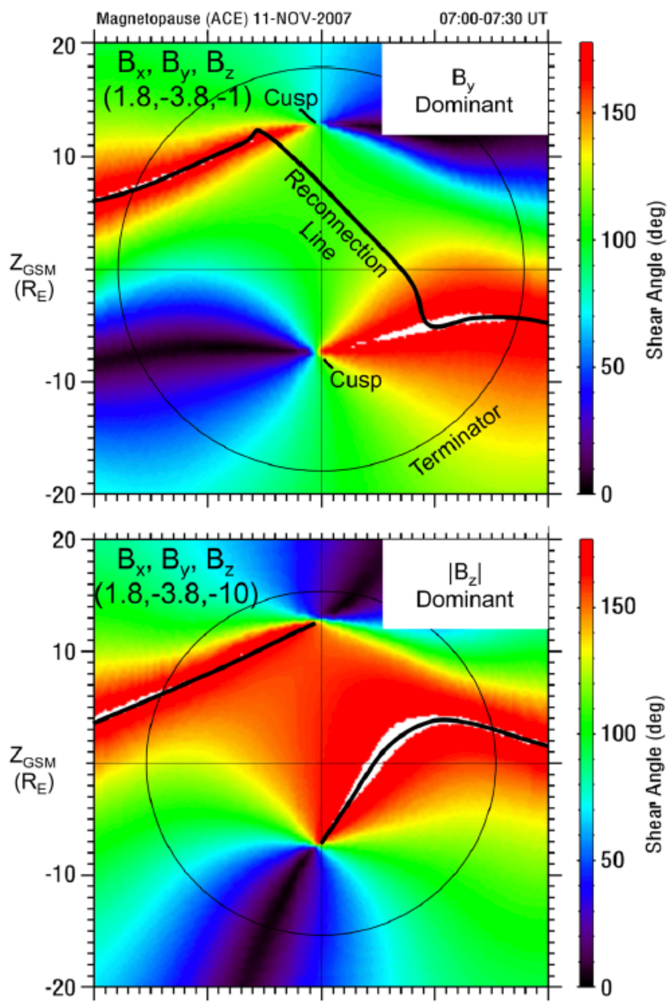
FTEs from Cluster during IMF +Bz[Fear+, 2005]

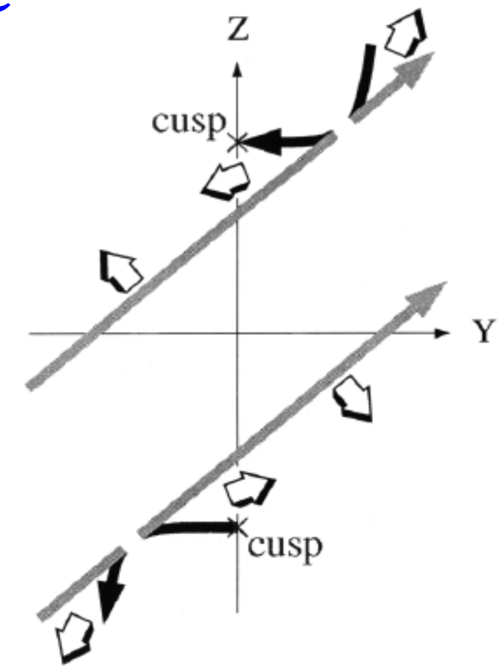


- Subsolar and pre/post-noon FTEs are observed mainly during southward IMF [Kuo+ 1995; Kawano & Russell, 1997a,b]
- Post-terminator FTEs are associated with strongly northward IMF [Kawano & Russell, 1997a,b] <= high-latitude reconnection for IMF +Bz
- FTE event from Cluster shows an tailward/equatorward motion during IMF +Bz

FTE: IMF By dependence





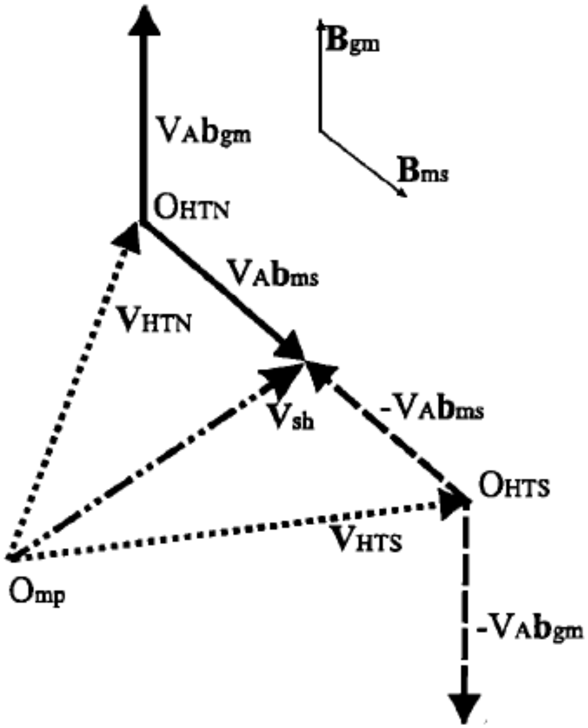


B_y dependence for strong IMF +Bz
[Kawano & Russell, 1997b]

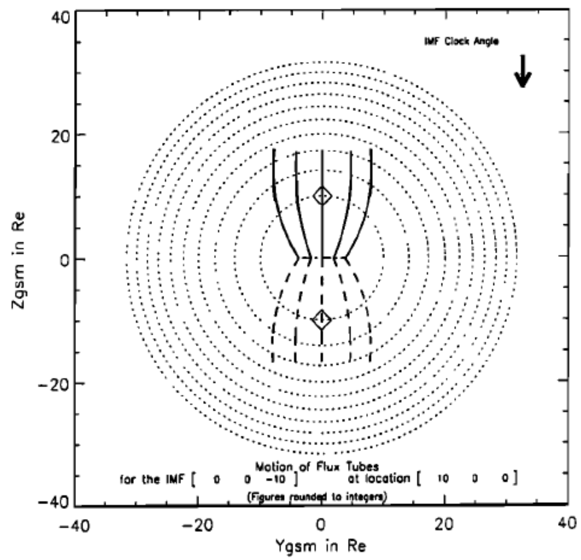
- Southward and slightly northward IMF: Most of events are explained by a tilted subsolar component RX
- More northward IMF: Cusp reconnection explains polarities and IMF By dependence.

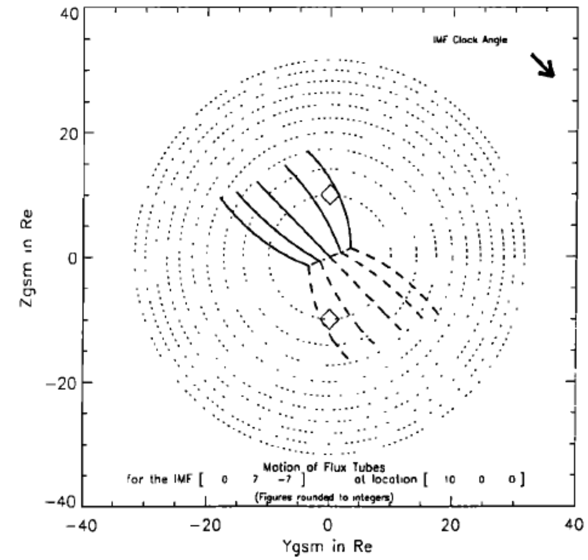
B_y dependence during IMF −Bz
[Kawano & Russell, 1997a; left]
[Fuselier+, 2016; right]

FTE: Motion – Magnetosheath Flow Effect



Motion of FTEs [Cooling+, 2001]



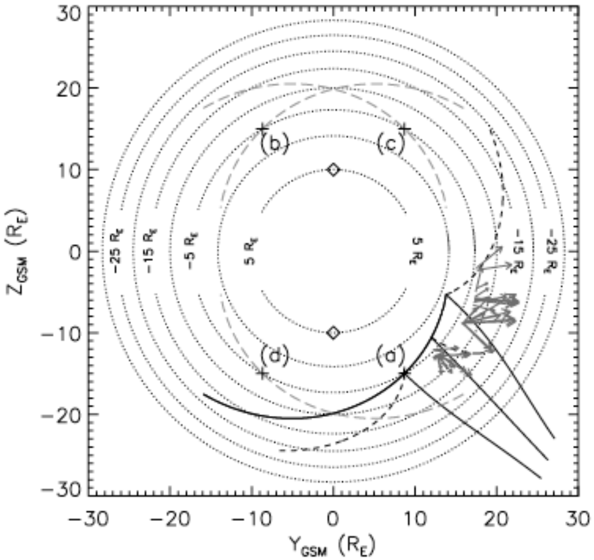


$$V_{HTN} = V_{SH} - V_A \hat{b}_{SH}$$

$$V_{HTS} = V_{SH} + V_A \hat{b}_{SH}$$

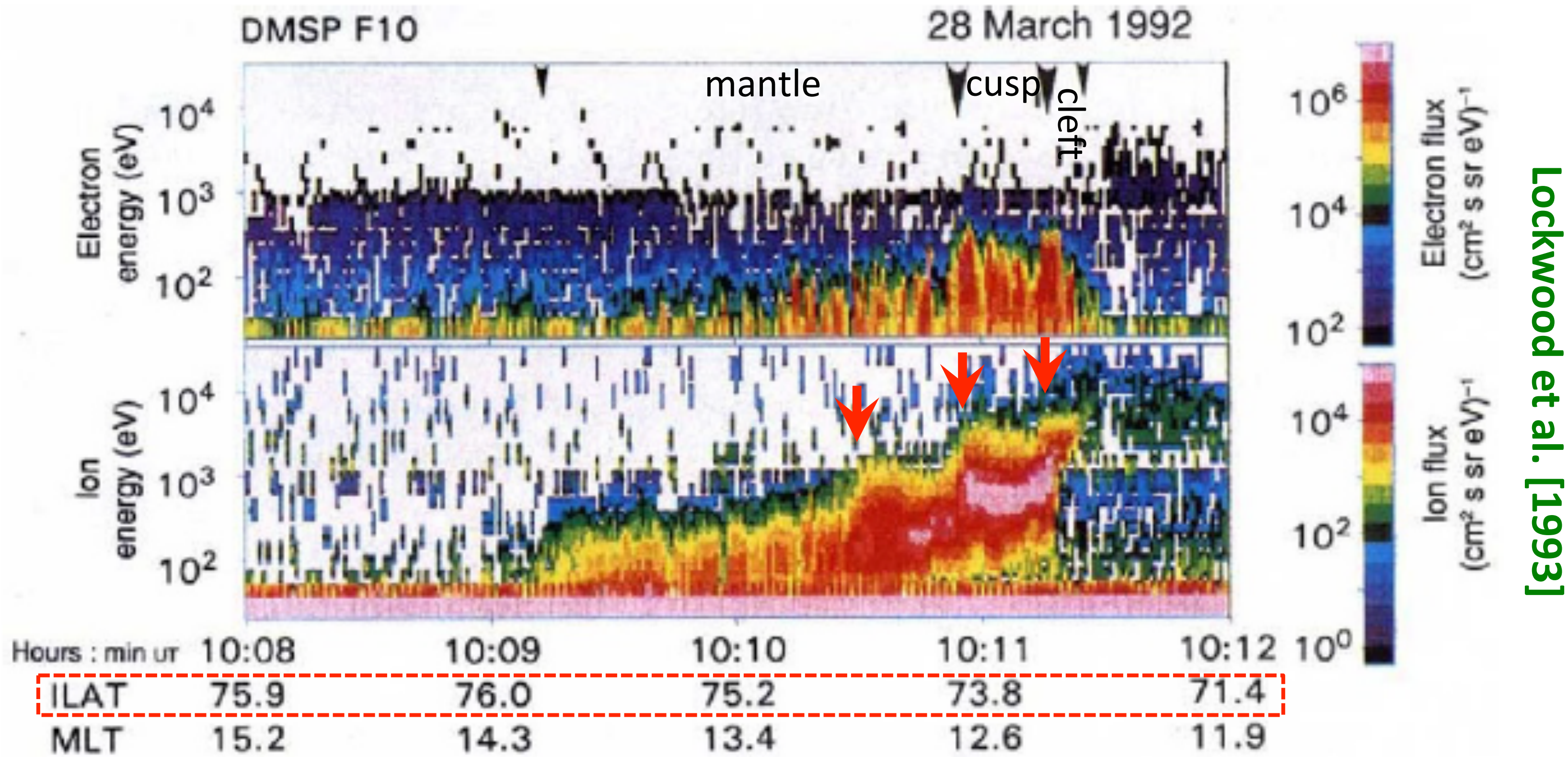
[Cowley & Owen, 1989]

Motion of FTEs for IMF +Bz [Fear+, 2005]



- 118 FTE statistics from Cluster show consistency in both direction and speed with either V_{HTN} or V_{HTS} calculated from the Cooling model [Fear+, 2007]

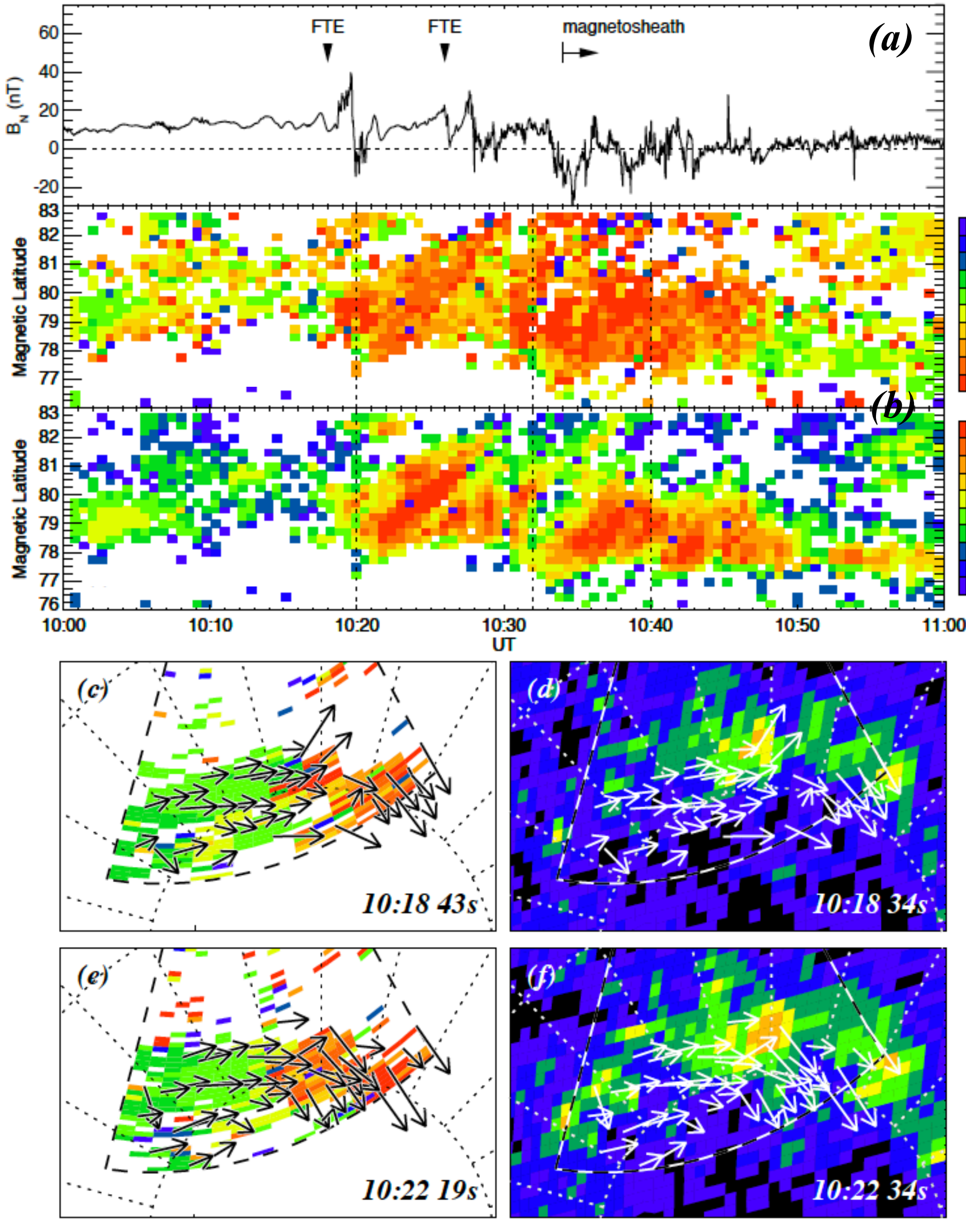
FTE: Cusp responses



- Steady-state reconnection leads to dispersion pattern of precipitating ions in the cusp region **(lowest time of flight from X, for highest energy ions)**: For subsolar RX, decrease in ion energies with latitude
- Pulses in reconnection cause discrete steps (red arrows) in ion dispersion
- Evidence for the fact that reconnection takes place in a series of bursts, therefore, producing FTEs

[Courtesy to R. Fear]

FTE: Ionospheric Responses



Neudegg et al. [2001]

- At the footprints of newly opened magnetic field lines
- Optically, as Poleward Moving Auroral Forms (PMAF) [Sandholt+ 1986; 1992]
- In radar, as Pulsed Ionospheric Flows or Poleward Moving Radar Auroral Forms [Provan+ 1998; McWiliams+, 2000]
- Conjugate studies between In-situ and ground-based observations [Elphic+ 1990; Amm+, 2005; Wild+ 2005; 2007]
- **Neudegg+ [2001]: In-situ (a) + Radar (b) + Optical (c-f) conjunctions**

[Courtesy to R. Fear]

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1. FTE: general knowns
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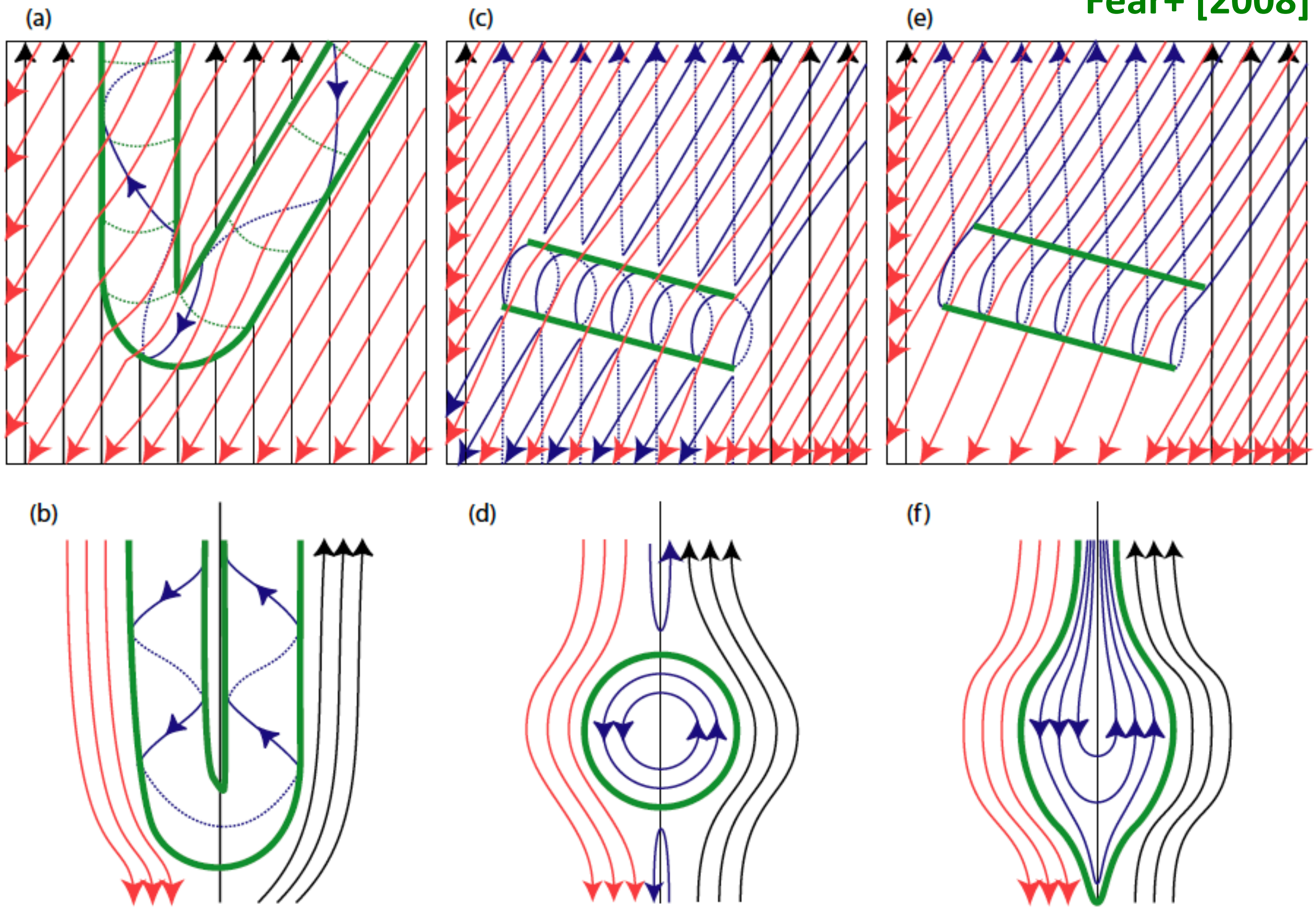
FTE: Other Reconnection-based Models

Fear+ [2008]

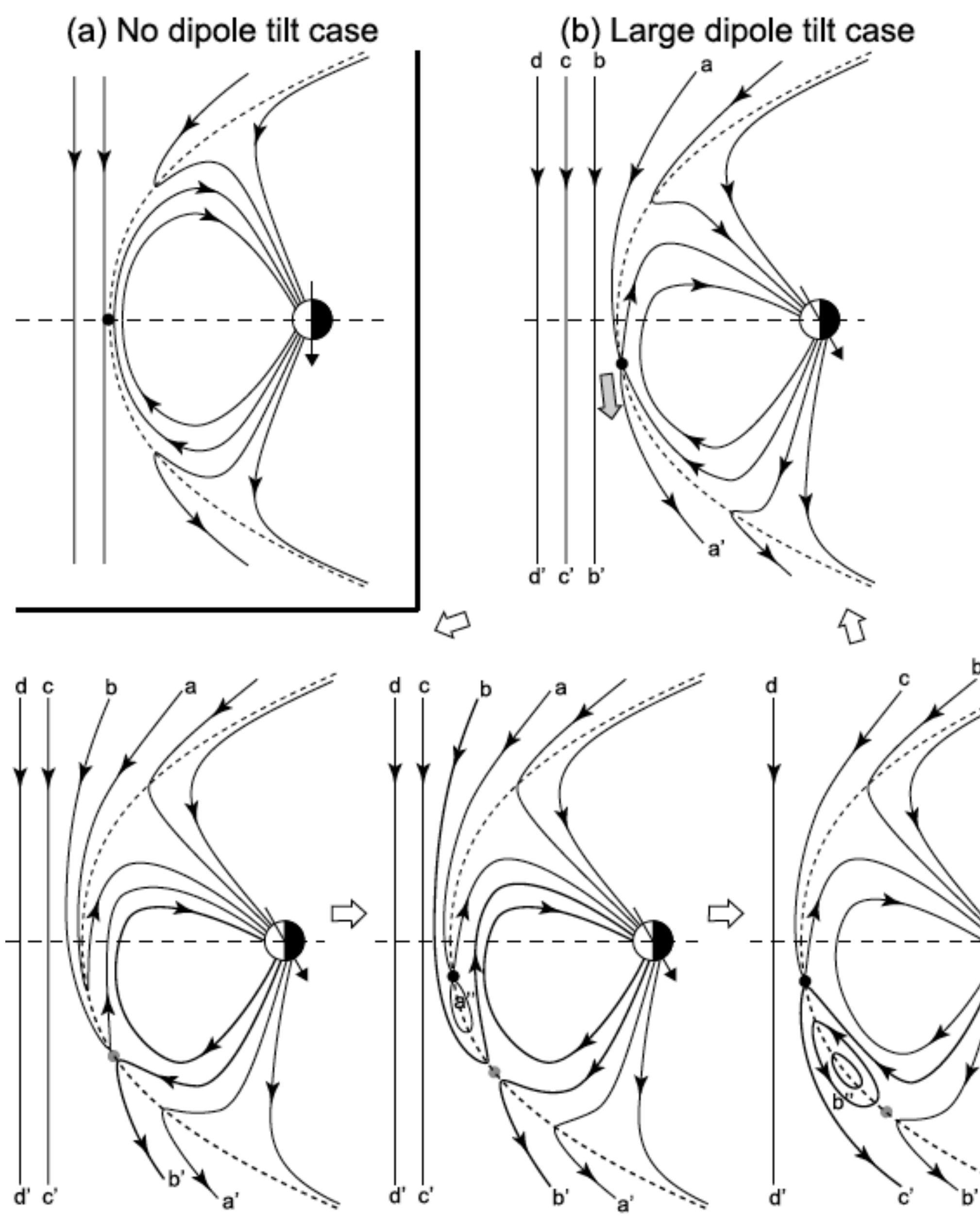


Elbow-shaped flux bundle FTEs
Russell & Elphic [1979]

Multiple X-line FTEs
Lee & Fu [1985]

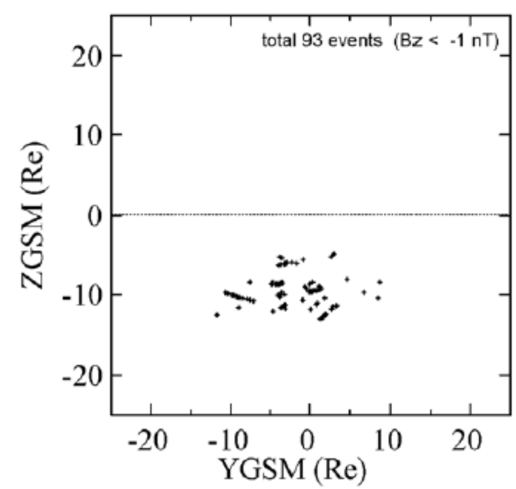
Single X-line FTEs
Southwood [1988]
Scholer [1988]

FTE: Seasonal dependence (SMXR model)

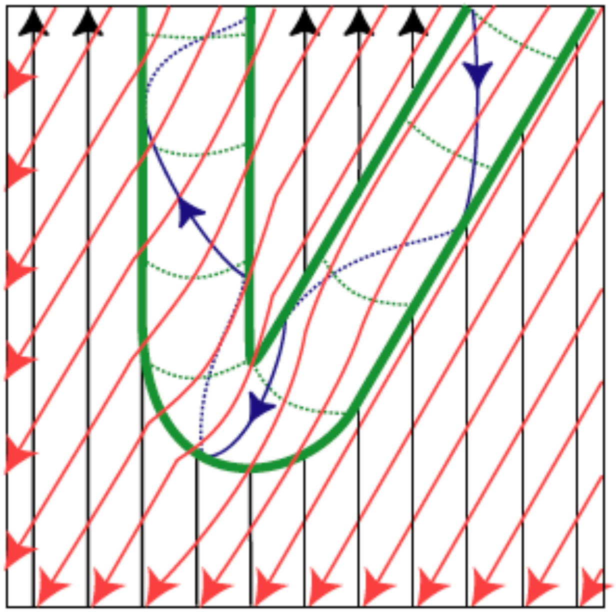


[Raedar 2006; Hasegawa+ 2010]

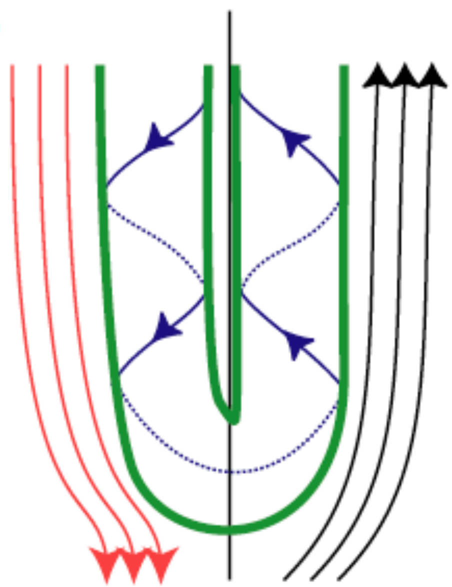
- In presence of dipolar tilt, FTEs are formed by sequential multiple X-line reconnection (SMXR)
- FTEs move preferentially to the **winter** hemisphere
- SMXR: not present in all related simulation works
- Korotova+ [2008] showed FTEs detected by Interball-1 around June solstice in 1996-1999 are found exclusively in winter hemisphere



FTE: Signatures of Elbow-shaped flux-bundle FTEs



(b)



Formed by localized patchy reconnection

B topology:

- Topologically open
- The spiral magnetic field lines connect the magnetosheath magnetic field to either the northern or southern high-latitude ionosphere
- Their magnetosheath and magnetospheric ends connect through a circular hole (with a diameter of ~1 R_E) on the magnetopause

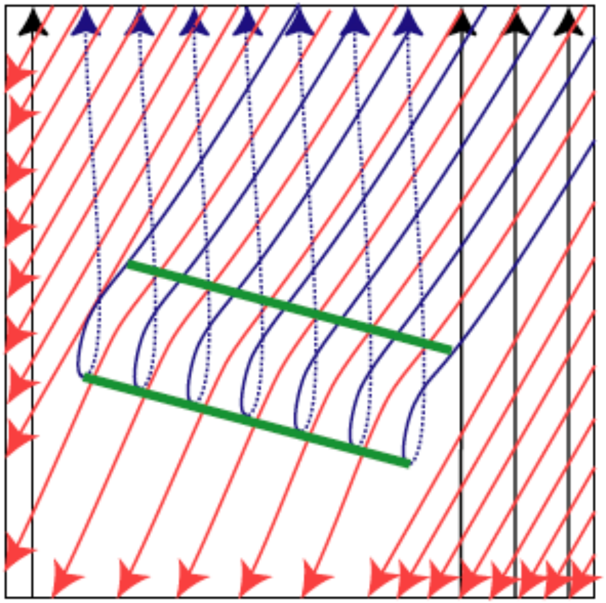
Extent:

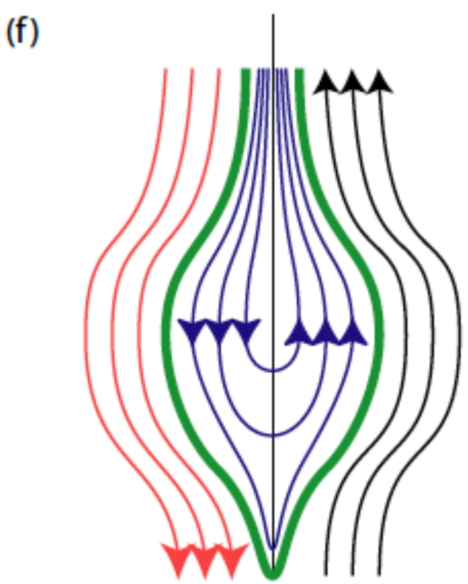
- Having narrow azimuthal (dawn-dusk) extents

Particle signature:

- Bidirectional electrons at the edge of FTEs
- Mostly unidirectional ions in the rearward edge of the FTE [Varsani+, 2014]
- Hot and more isotropic electrons in the FTE core

FTE: Signatures of Single X-line Model





Via transient increases in the reconnection rate

B topology:

- Topologically open; no helical flux rope
- May contain a core guide field
- The newly reconnected magnetic field lines simply connect the magnetosheath to either the northern or southern hemisphere.

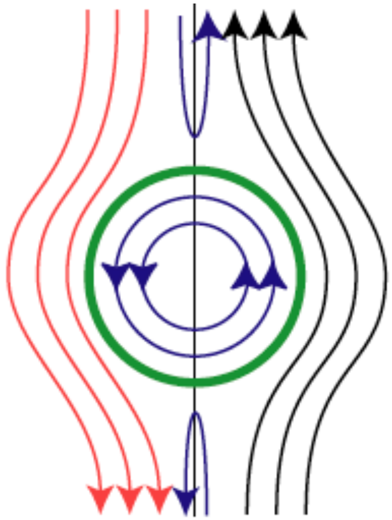
Extent:

- Can extend azimuthally over many R_E

Particle signature:

- Reconnection jets flow away from the X-line on the edges of FTEs
- Thermalized plasma populate within the core
- The particle signatures similar to Elbow-shaped FTEs
- Lockwood and Hapgood [1998]: continuous variation in the ion distribution function between the event core (reconnected earlier) and the draped field lines (reconnected later)

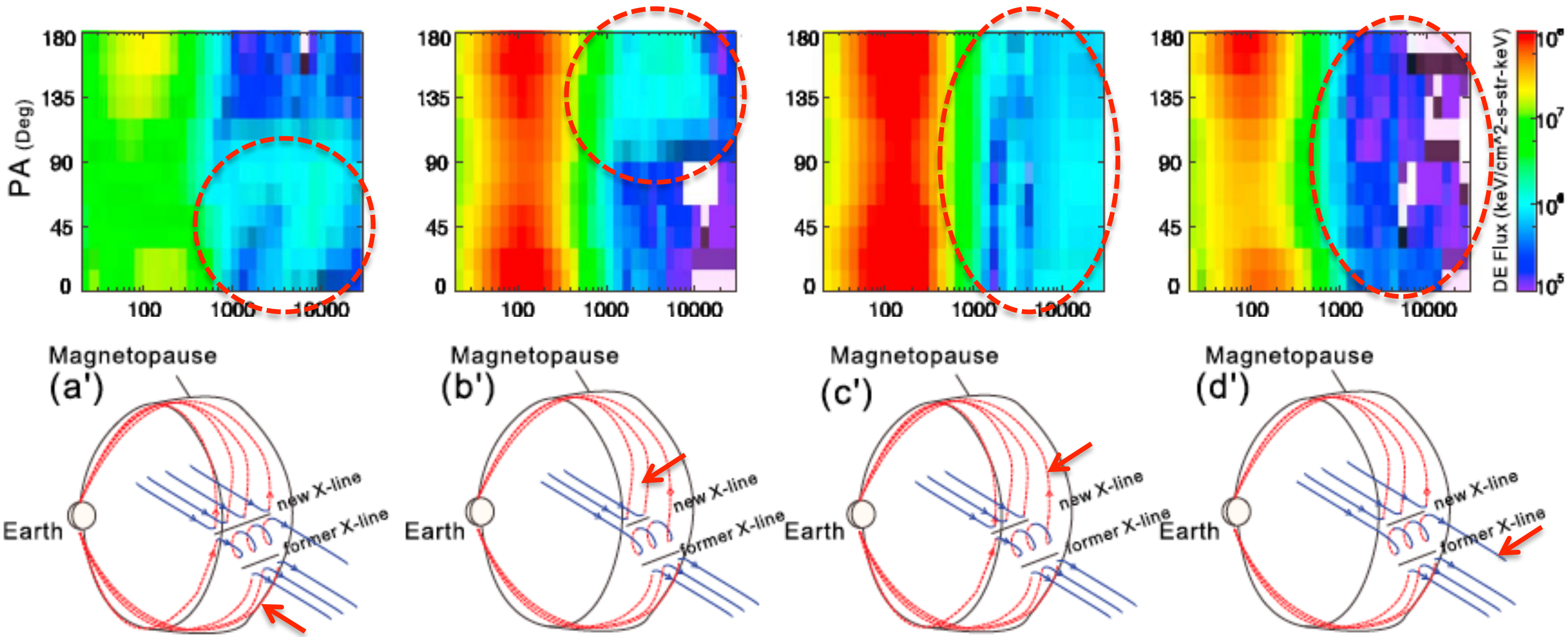
FTE: Signatures of Multiple X-line Model - 1



<u>Via simultaneous or sequential multiple X-lines</u>

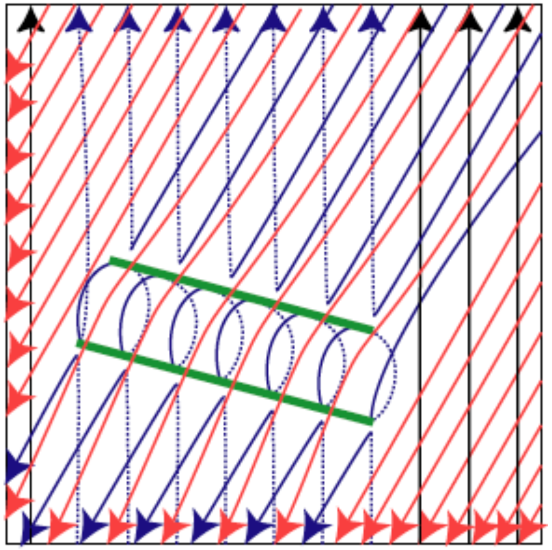
B topology:

- Possibly topologically closed
- Mixed magnetic field topologies, *e.g.*, open field lines connecting the northern or southern hemisphere to the magnetosheath, closed field lines connecting both hemispheres, and purely magnetosheath fields [Pu+ 2013; Zhong+, 2013]



[Pu+ 2013]

FTE: Signatures of Multiple X-line Model - 2



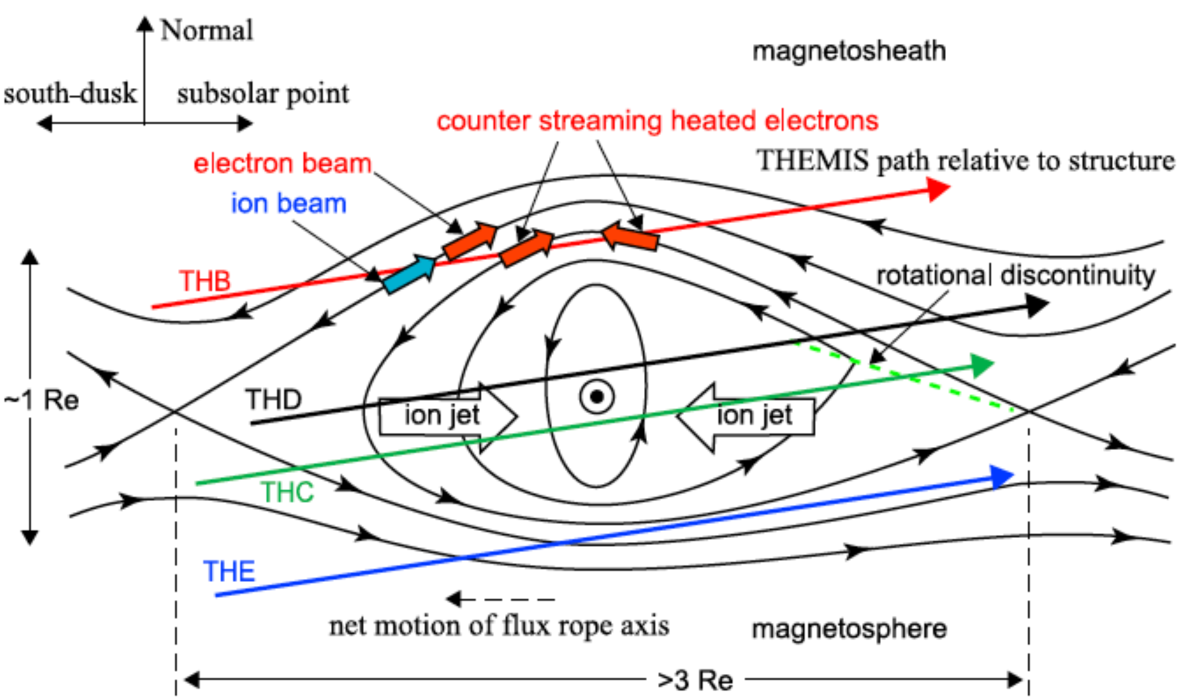
Via simultaneous or sequential multiple X-lines

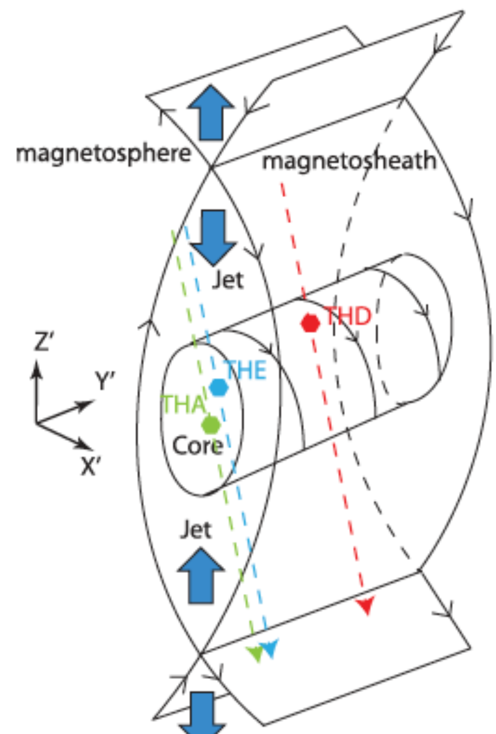
Extent:

- Can extend azimuthally over many R_E

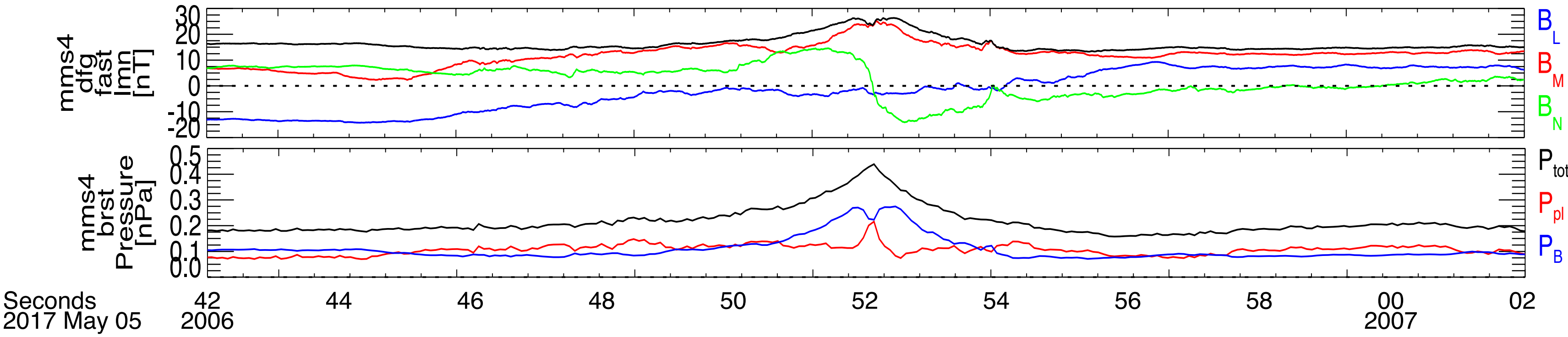
Particle signature:

- Two ion jets converging toward the center of such FTEs [Hasegawa+, 2010; Øieroset+, 2011]
- Heated magnetosheath electrons flowing both parallel and antiparallel to B [Hasegawa+, 2010]





FTE: Crater FTEs



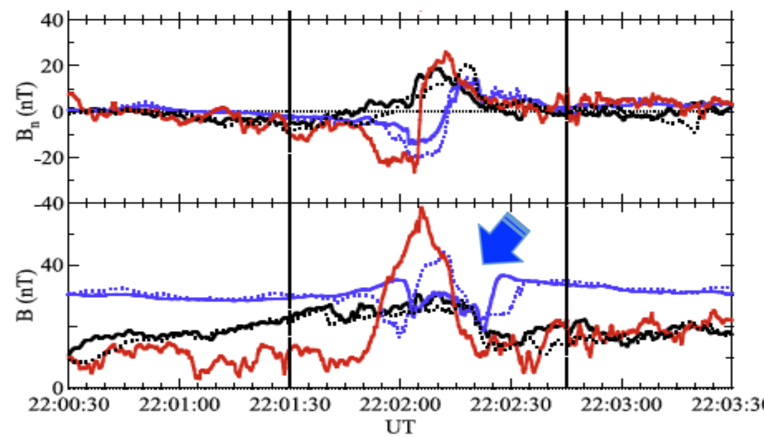
[Hwang+ in prep]

More complex shape in |B| enhancement:

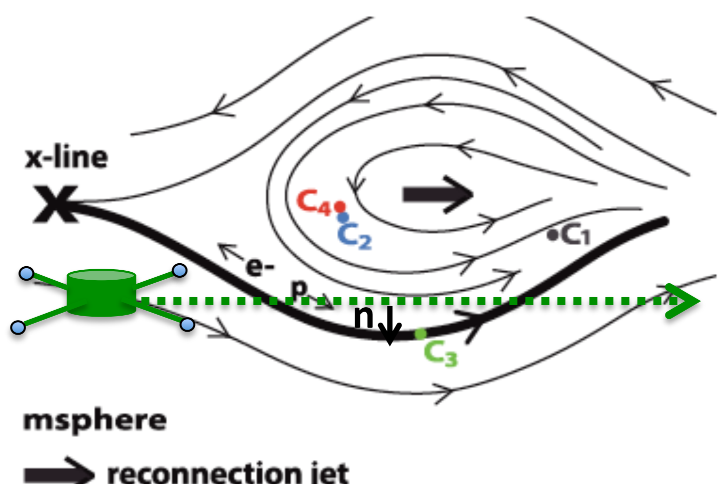
- **'M'- shaped:** central depression in |B|
- **'W'-shaped**: strong core bounded by weak |B|

Scenarios:

- Pressure pulses-causing transient relocation of the spacecraft across the boundary layer with respect to an FTE [Sibeck & Smith, 1992; Owen+, 2008]
- Encounters with the separatrix resulting in the crater-like B variations with bipolar B_n across the event [Farrugia+, 2011]



[Sibeck+, 2008]



[Farrugia+, 2011]

FTE: Multi-spacecraft observations before MMS

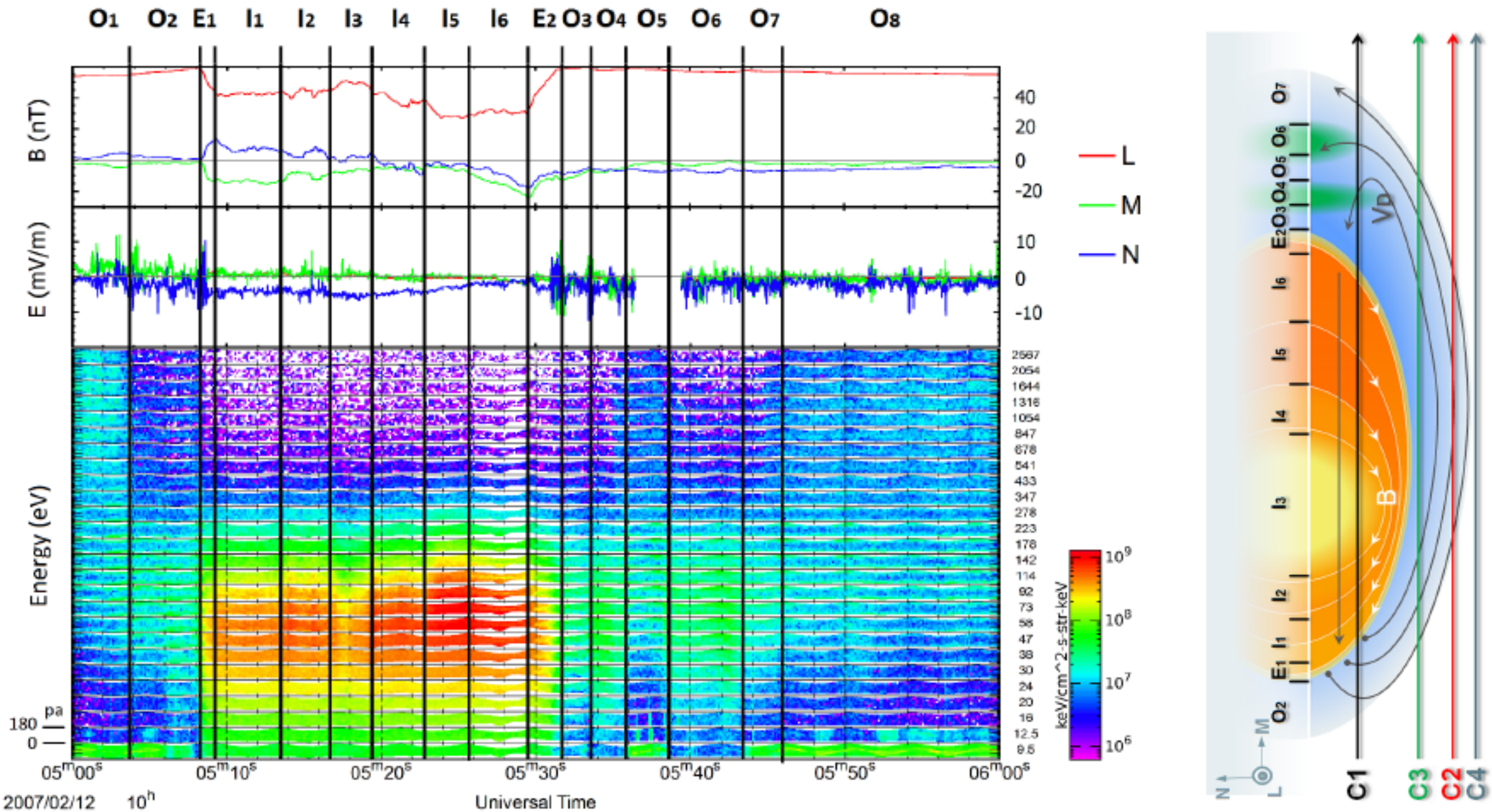
Distinguishing among different models:

- **Fear et al. [2008]** used tetrahedral **Cluster** observations to describe an FTE with a much larger azimuthal than north-south extent, which is inconsistent with the elbow-shaped flux tube model.
- **Dunlop et al. [2005]** presented **Cluster** and **TC-1** observations of a pair of FTEs propagating northward and southward away from the reconnection site, consistent with single X-line model.
- **Hasegawa et al. [2010]** reported **THEMIS** observation of an FTE between two converging jets, and therefore suggested multiple X-line model (**Grad-Shafranov reconstruction** using **multi-s/c measurements**).
- **Farrugia et al. [2011]** reported a single X-line crater FTE with multiple layers on the basis of their magnetic, electric, and plasma signatures from the four **Cluster** spacecraft.

Magnetic topology using B-field and electron measurements on improved temporal resolution:

- **Owen et al. [2001]** used Cluster-FGM/PEACE observations to define the magnetic field connectivity of the substructure of FTEs inferred from the magnetic field and electron signatures.
- **Øieroset et al. [2011]** presented observations of electrons that were not trapped within the FTE, demonstrating that the event was three-dimensional and had an open magnetic field topology.
- **Pu et al. [2013], Zhong et al. [2013]** used energy-dependent electron pitch angle distributions to show mixed magnetic field topologies of a multiple X-line FTE.
- **Varsani et al. [2014]** identified the multi-layer interior and surrounding structures of a crater FTE based on the electron pitch angles using 125 ms observations of Cluster-PEACE measurements assuming that the electrons were gyrotropic.

FTE: Multi-spacecraft observations before MMS



Magnetic topology using B-field and electron measurements on high time resolution:

- Varsani et al. [2014] identified the multi-layer interior and surrounding structures of a crater FTE based on the electron pitch angles using 125-ms observations of Cluster-PEACE measurements assuming that the electrons were gyrotropic.

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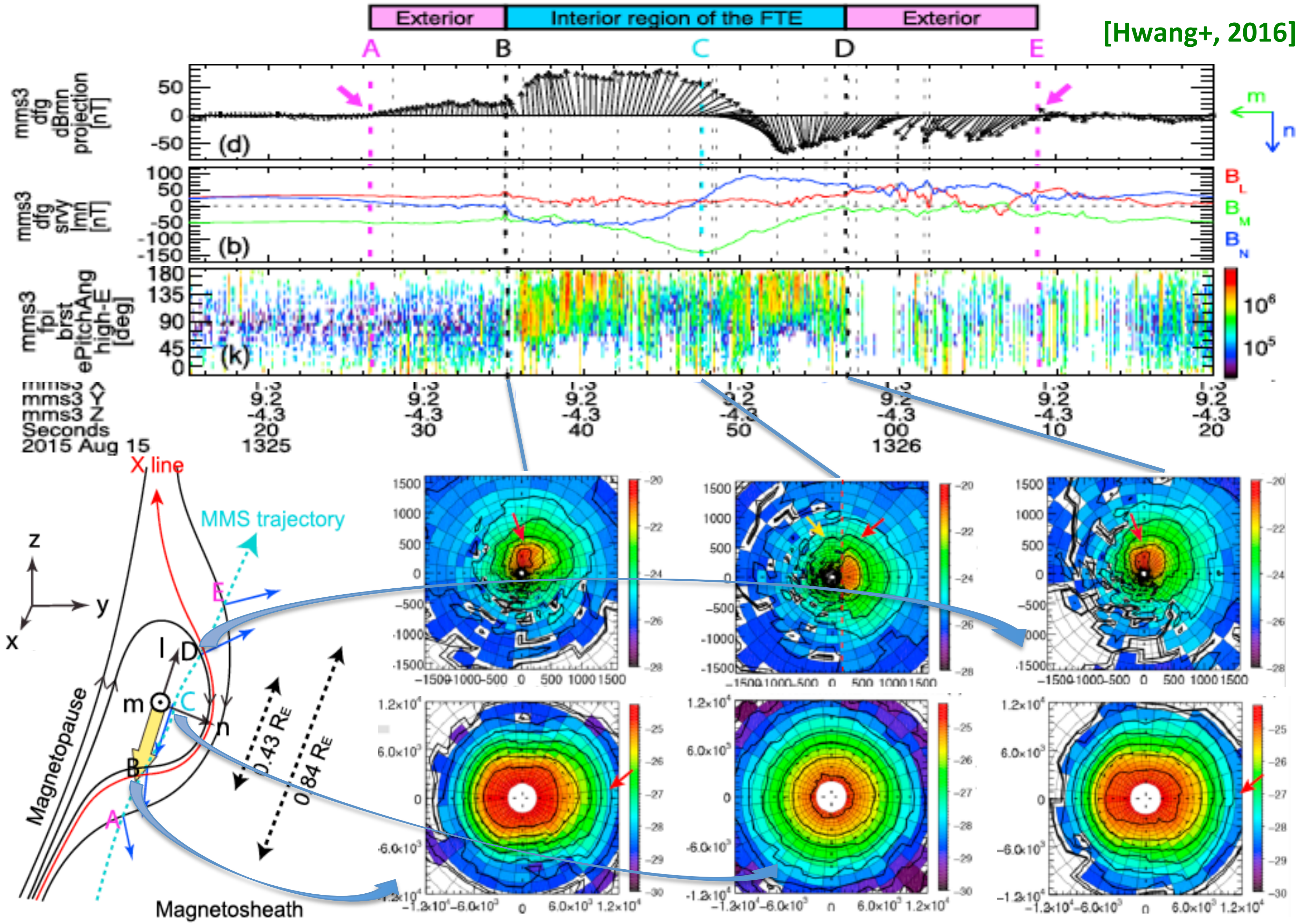
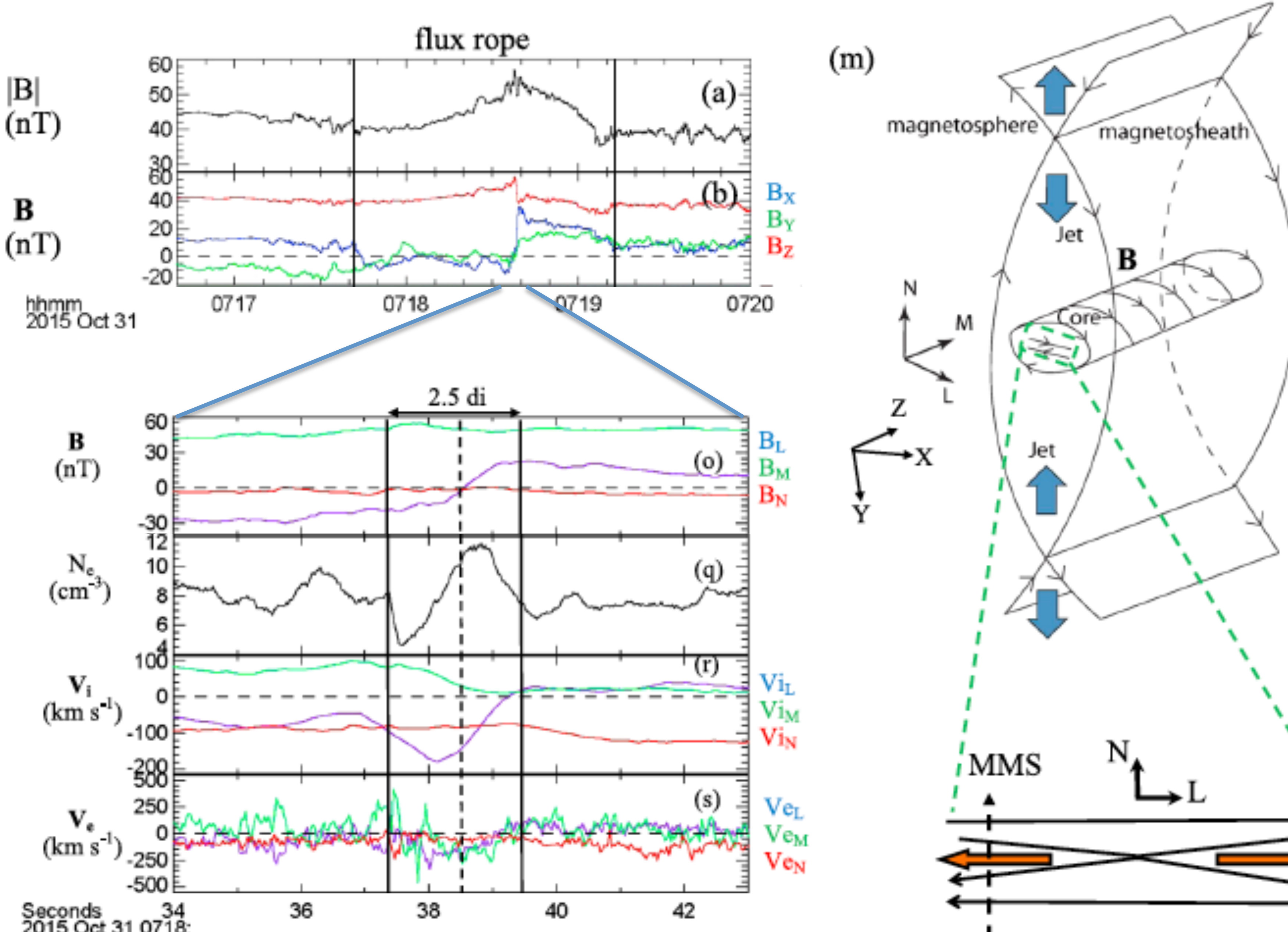
FTE: After MMS - 1. Substructure

[Hwang+, 2016]

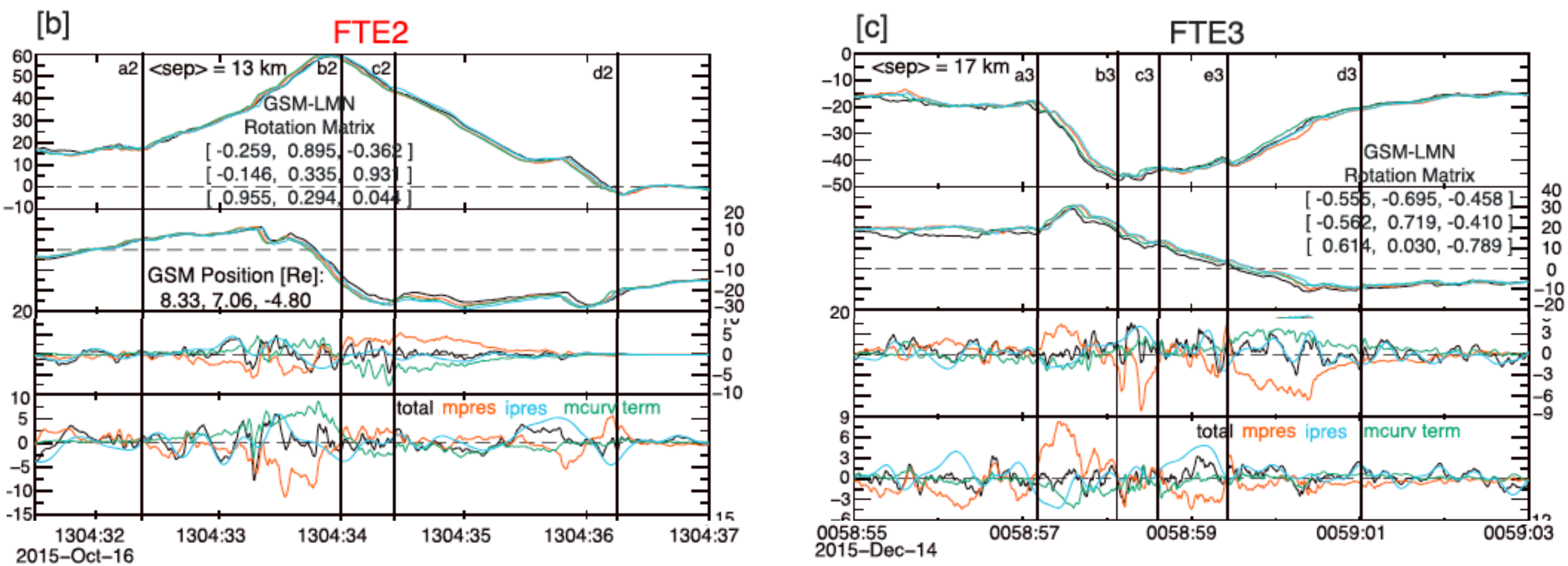


FTE: After MMS - 1. Substructure



Øieroset et al. [2016]

FTE: After MMS - 2. Force balance



[Zhao et al., 2016]

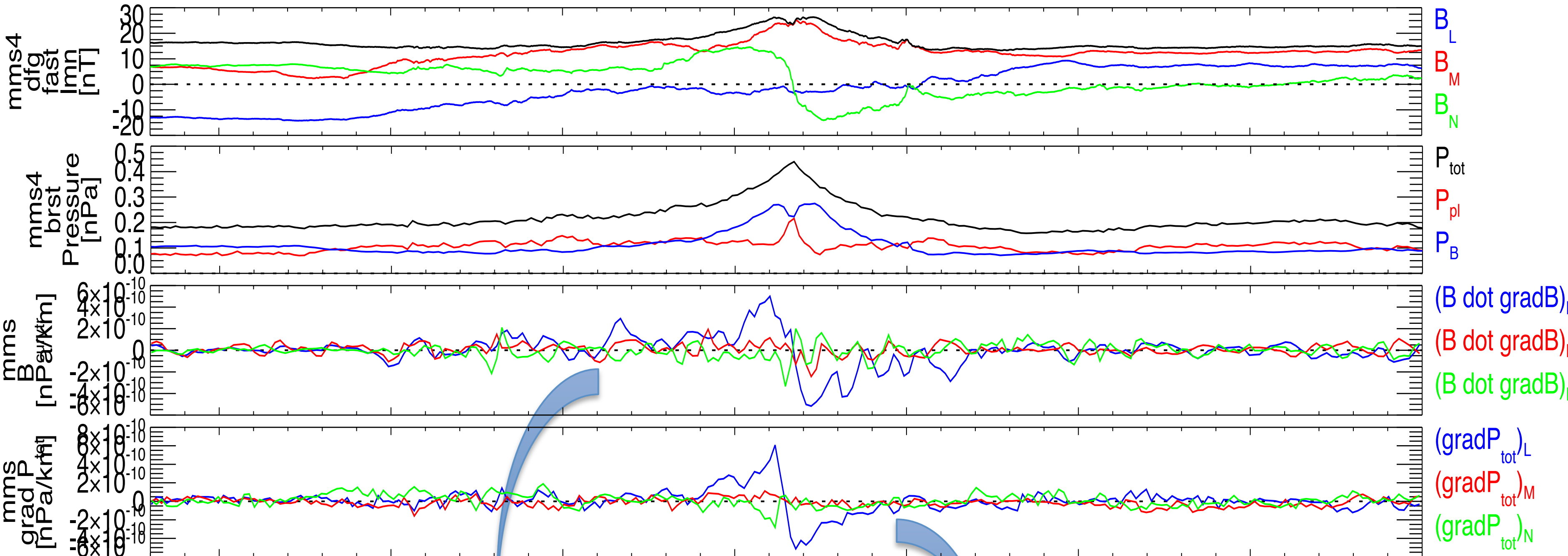
Force-free flux rope [Lundquist, 1950]: **J x B = 0, i.e., J parallel to B**

⟹ B curvature (green) is balanced by B pressure force (orange)

- **FTE2 (left)**
  - ➢ **B curvature is balanced by B pressure force**
- **FTE3 (right)**
  - ➢ **B curvature is NOT balanced by B pressure force**
  - ➢ **Ion pressure force (cyan) is dominant**
  - ➢ **Force balanced between J x B and $\nabla \cdot \boldsymbol{P}$**

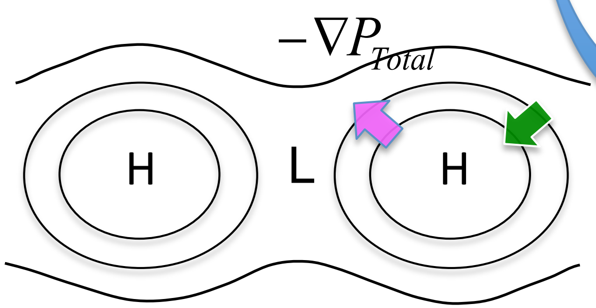
$$\rho \frac{\mathrm{D}\boldsymbol{u}}{\mathrm{D}t} = \boldsymbol{j} \times \boldsymbol{B} - \nabla \cdot \boldsymbol{P}$$

FTE: After MMS - 2. Force Balance



[Hwang+, in prep.]

Force balance around FTEs:



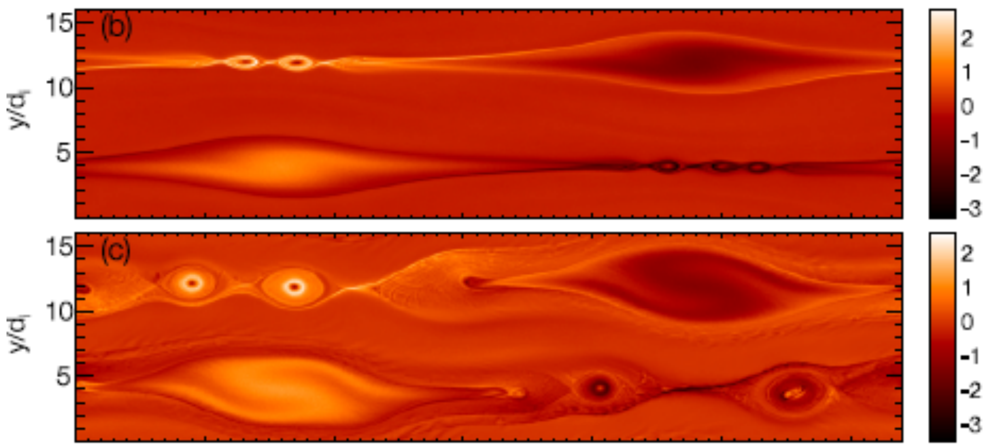
$$-\frac{(\vec{B}\cdot\nabla)\vec{B}}{\mu_0} = -\nabla P_{Total}$$

- **Steady-state FTEs:**

✓ Magnetic curvature force is balanced by the pressure force [**Elphic, 1998**; **Ieda+, 1998**]

✓ Not perfectly force-balanced

FTE: After MMS - 3. Small scale FTEs



[Drake+, 2006]

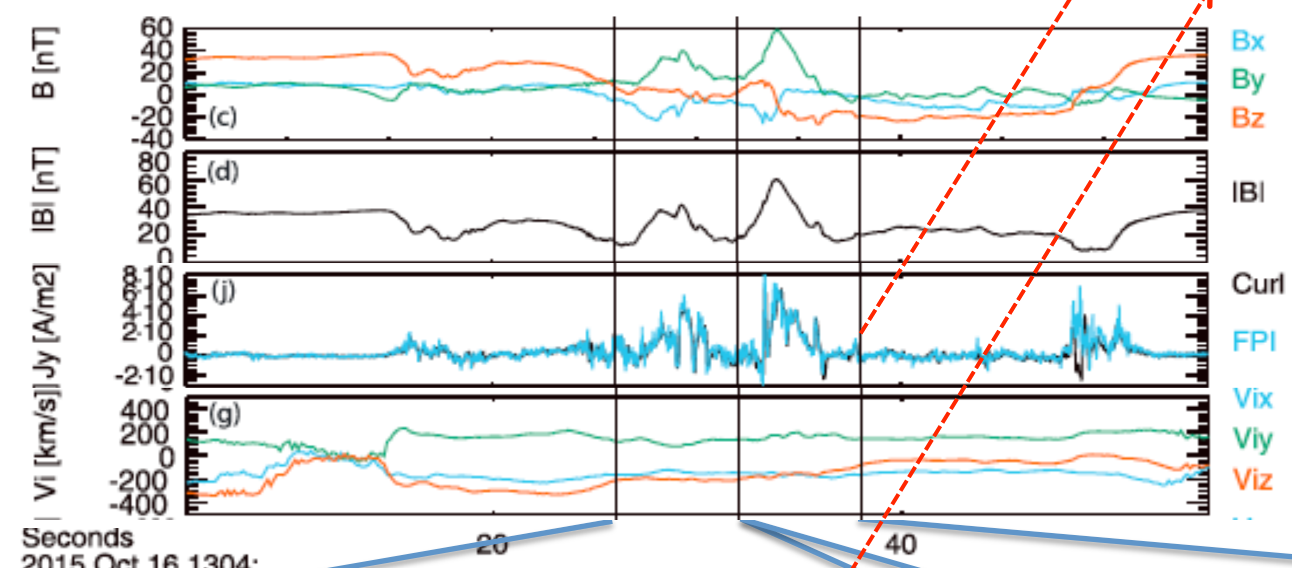
- During B_g-reconnection, the electron current layers near the magnetic x-line are long => unstable to the formation of secondary magnetic islands.

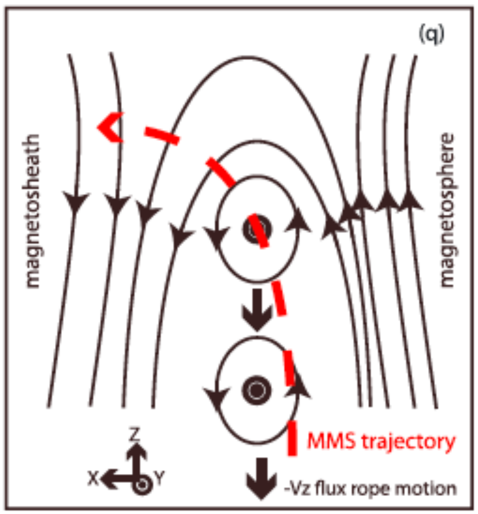
- Ion-scale (~7 d_i; >1000 km) FTEs:

✓ Most likely generated by secondary reconnection

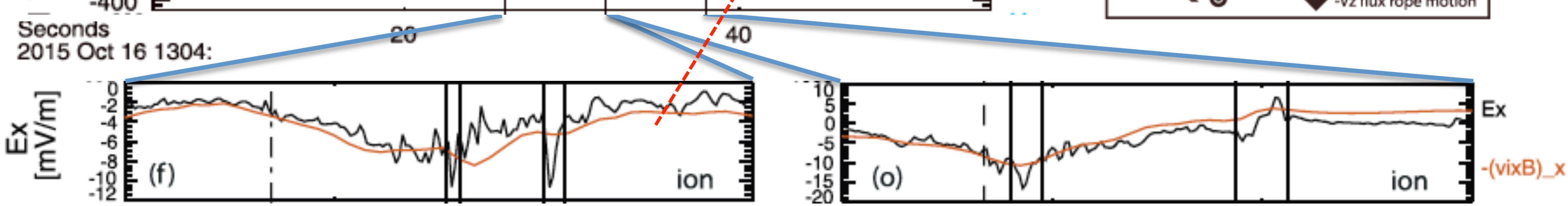
✓ Filamentary current density

✓ Demagnetized ions

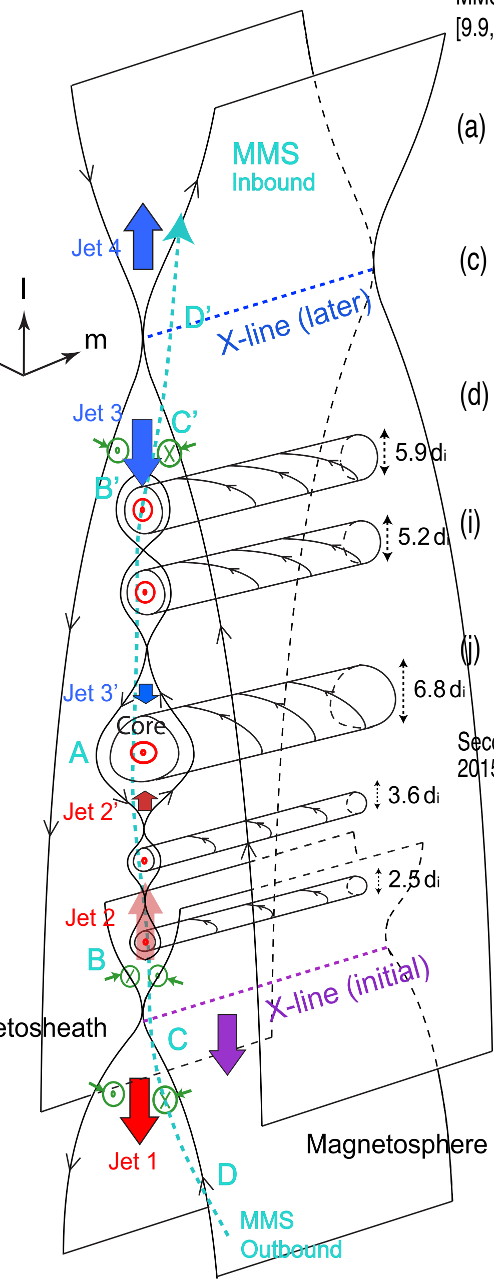




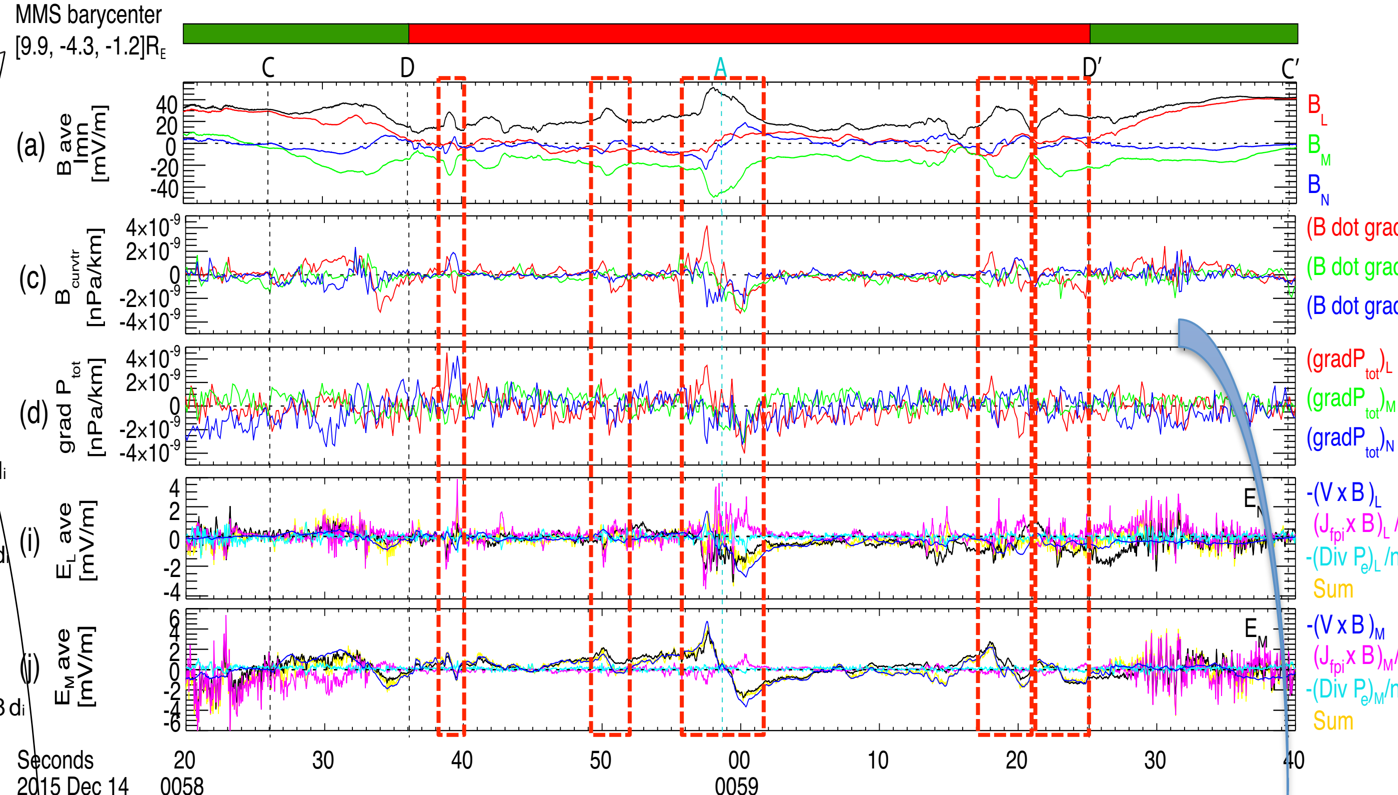
[Eastwood+, 2016]



FTE: After MMS - 3. Small-scale FTEs



[Hwang+, 2018]



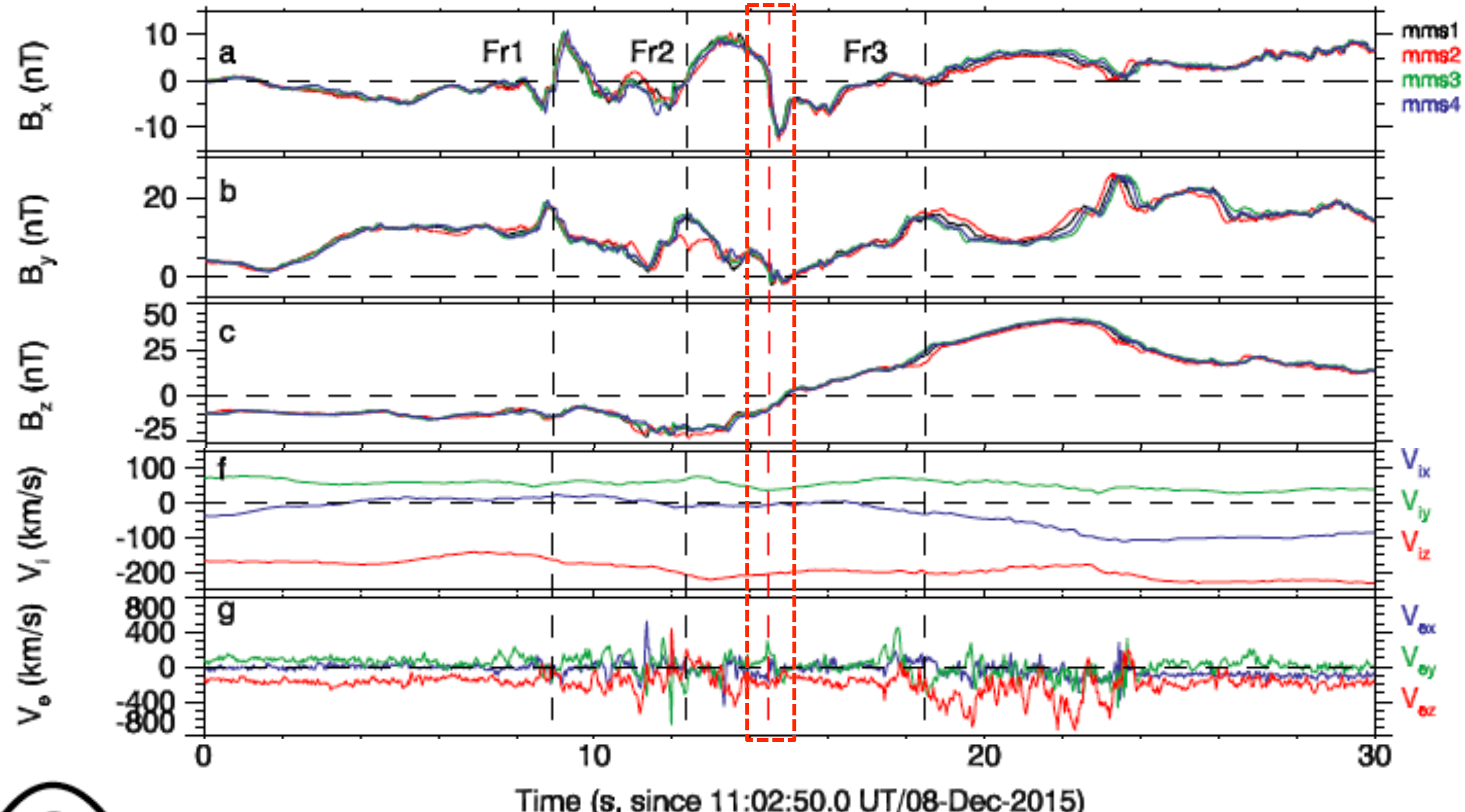
✓ The current sheet between the two X-lines is elongated => **unstable to tearing mode**

Scale sizes: 2.5–6.8 d_i (> 187.5 km)

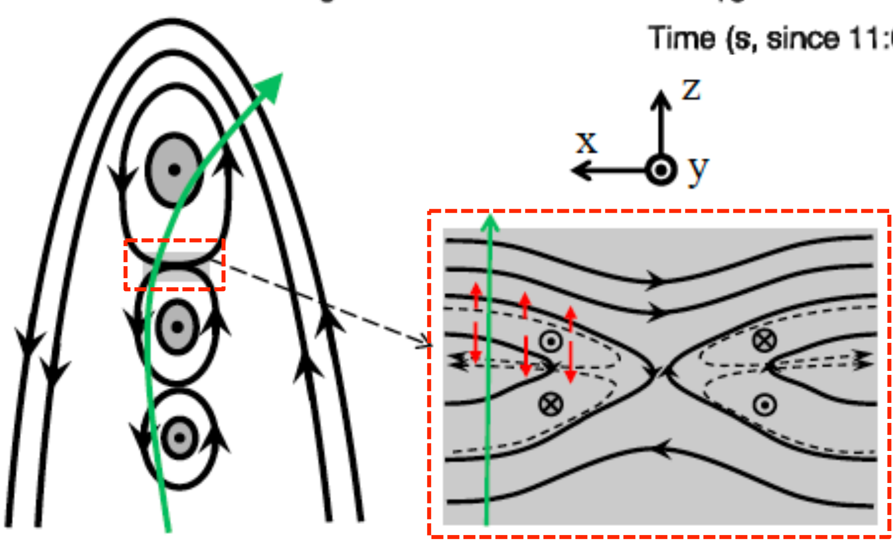
Supporting observations:

- Converging ion jets toward the FTE center.
- Co-existence of mixed magnetic topology
- Localized $B_{curvature}$ mainly balanced by Grad_P

FTE: After MMS - 4. Coalescence of small-scale FTEs



[Wang+, 2017]



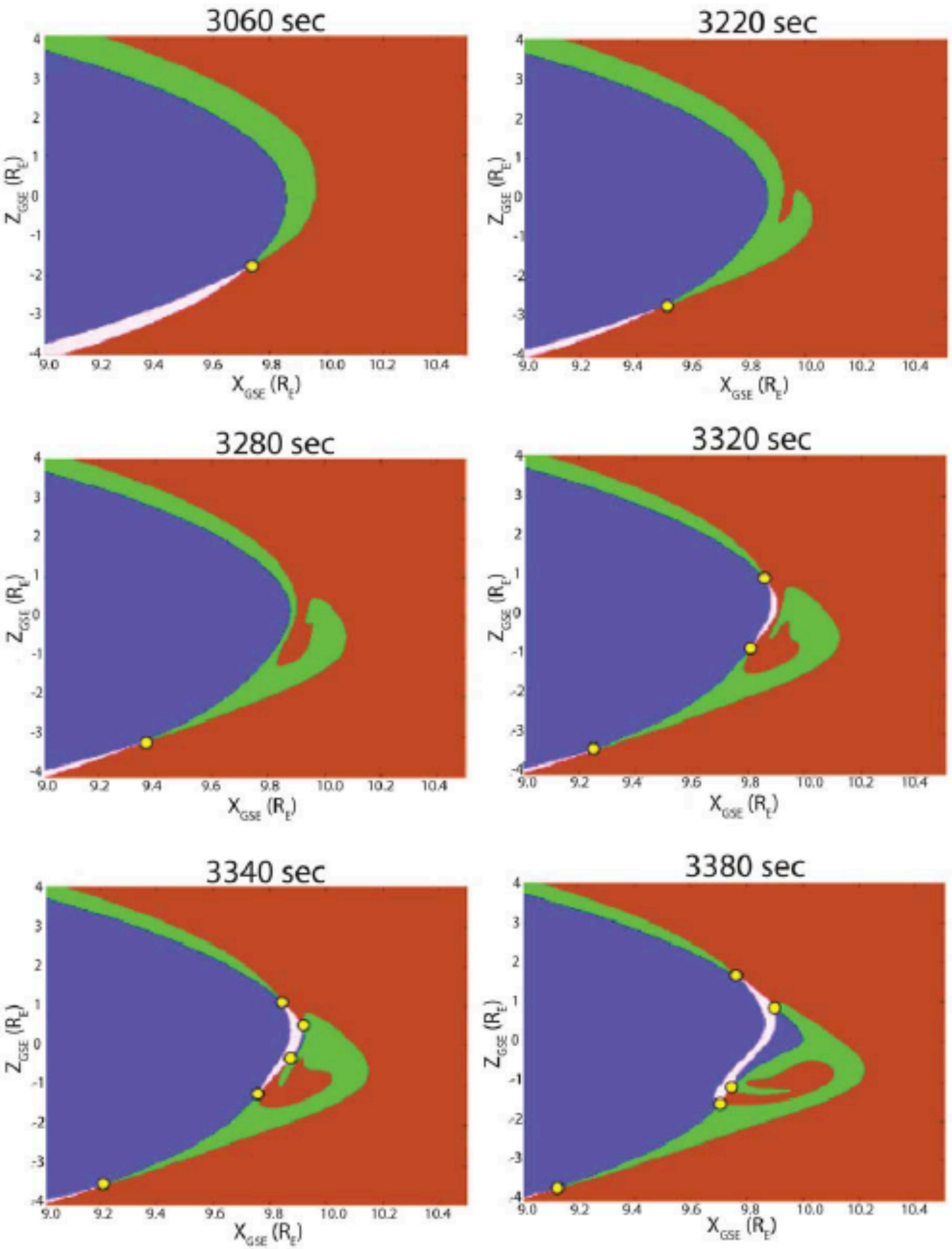
- **Scale sizes:** 1.3–8.6 d_i; 91–609 km
- **Induced current layer between Fr2 and Fr3:**
  - Carried by electrons
  - ~1 d_i thickness

Also, Zhou+ [2017]: an electron-scale current layer at the interface of two coalescing macroscopic (with sizes of ~1 R_E) flux ropes.

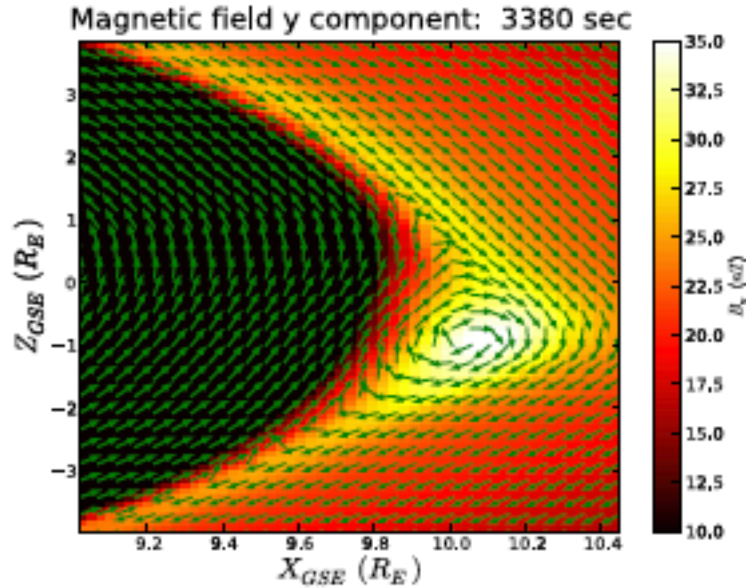
Outline

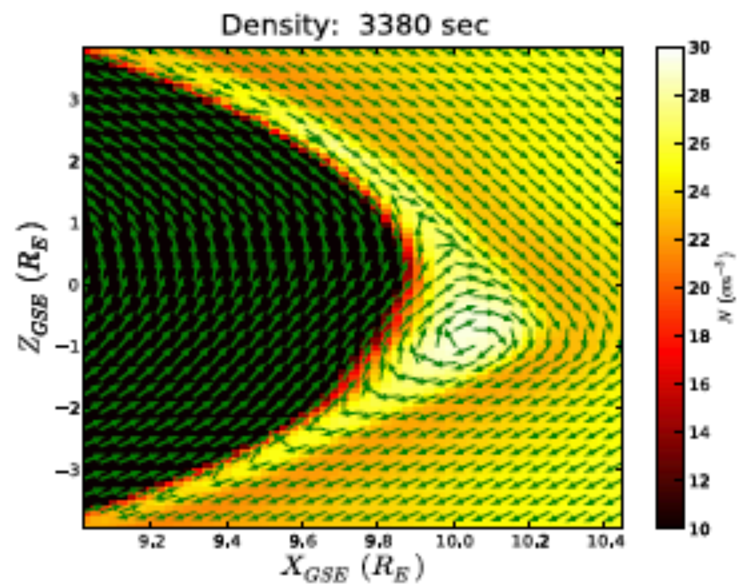
1. FTE: general knowns
2. Reconnection-based FTE models
3. New findings on FTE after MMS
4. Velocity-shear-induced FTE

Velocity-shear induced FTE

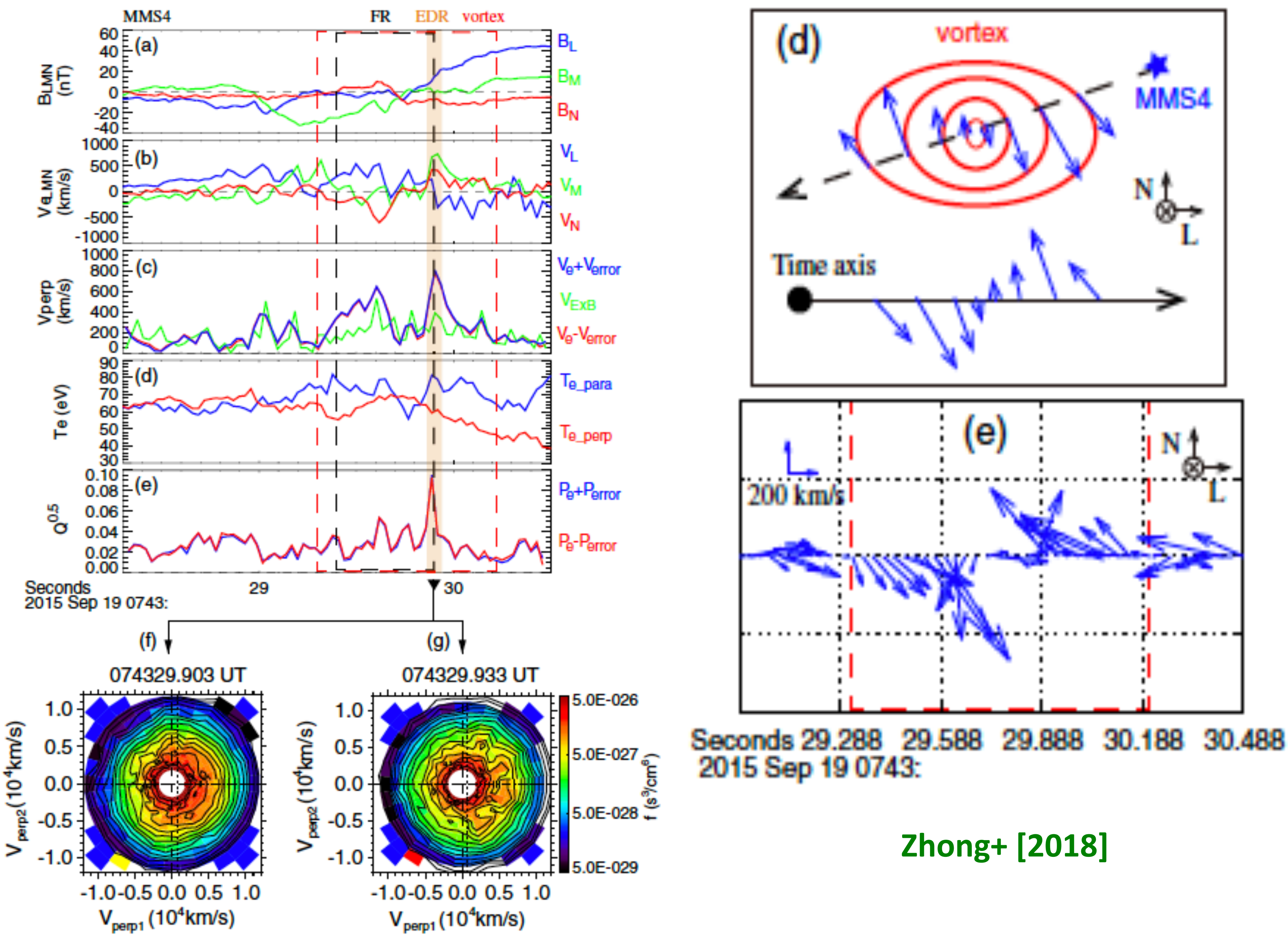


Dorelli & Bhattacharjee [2009]





Velocity-shear induced FTE: electron-vortex induced FTE



Zhong+ [2018]

Velocity-shear induced FTE: 3-D PIC simulation

Lx x Ly x Lz

= 100di x 50di x 150 di

= 2048 x 1024 x 3072 grids

→ 1.2 x 10^{12} total particles

X: k-vector of KHI

Y: boundary normal

Z: **X** x **Y**

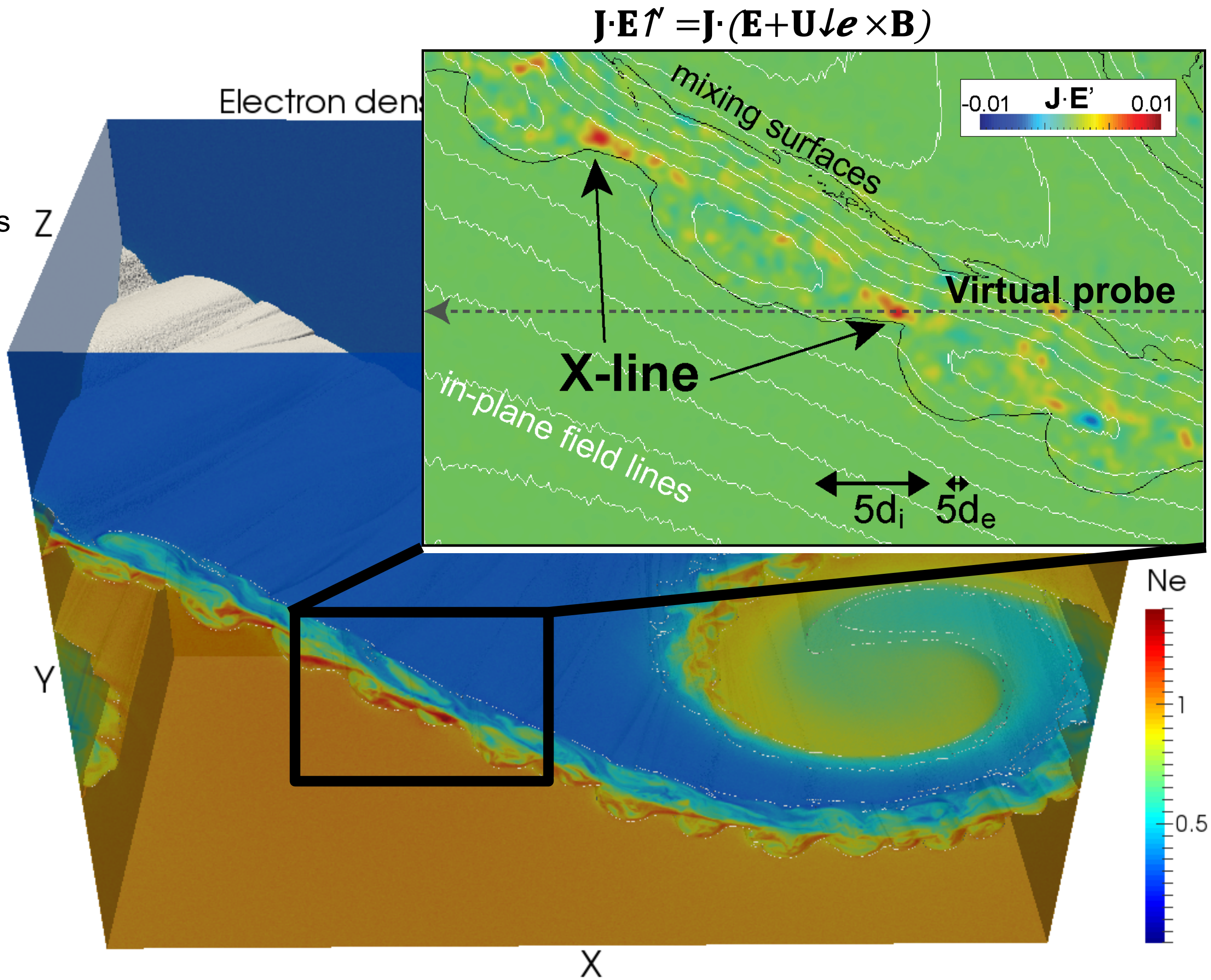
Mixing surfaces:

F_e=-0.99, 0.99

Mixing fraction:

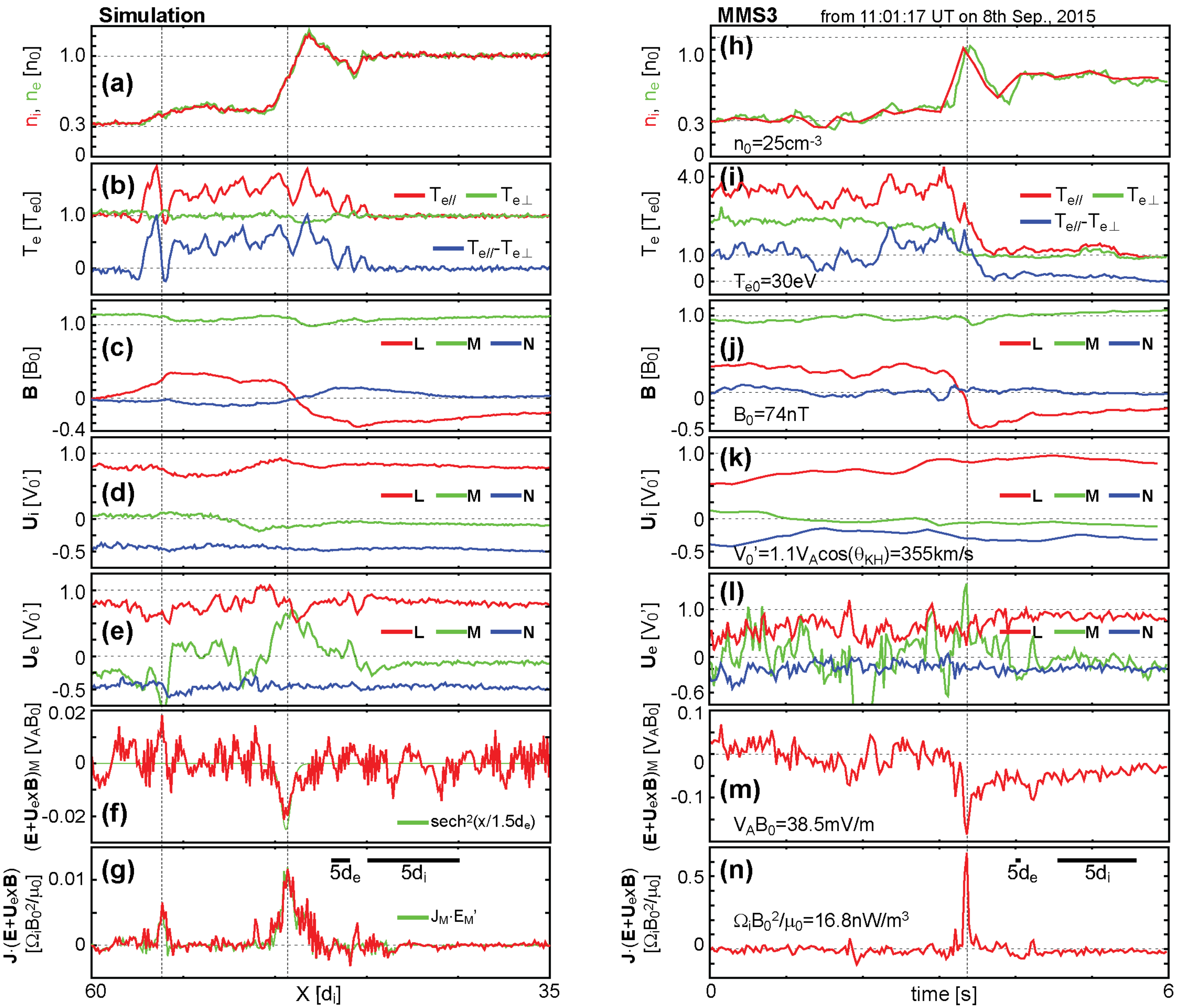
$$F \equiv \frac{N_1 - N_2}{N_1 + N_2}$$

F=1: Magnetosheath
F=-1: Magnetosphere
|F|<1: Mixing



[Nakamura+, 2017; Courtesy to T.K.M Nakamura]

Velocity-shear induced FTE: Comparison with Obs.



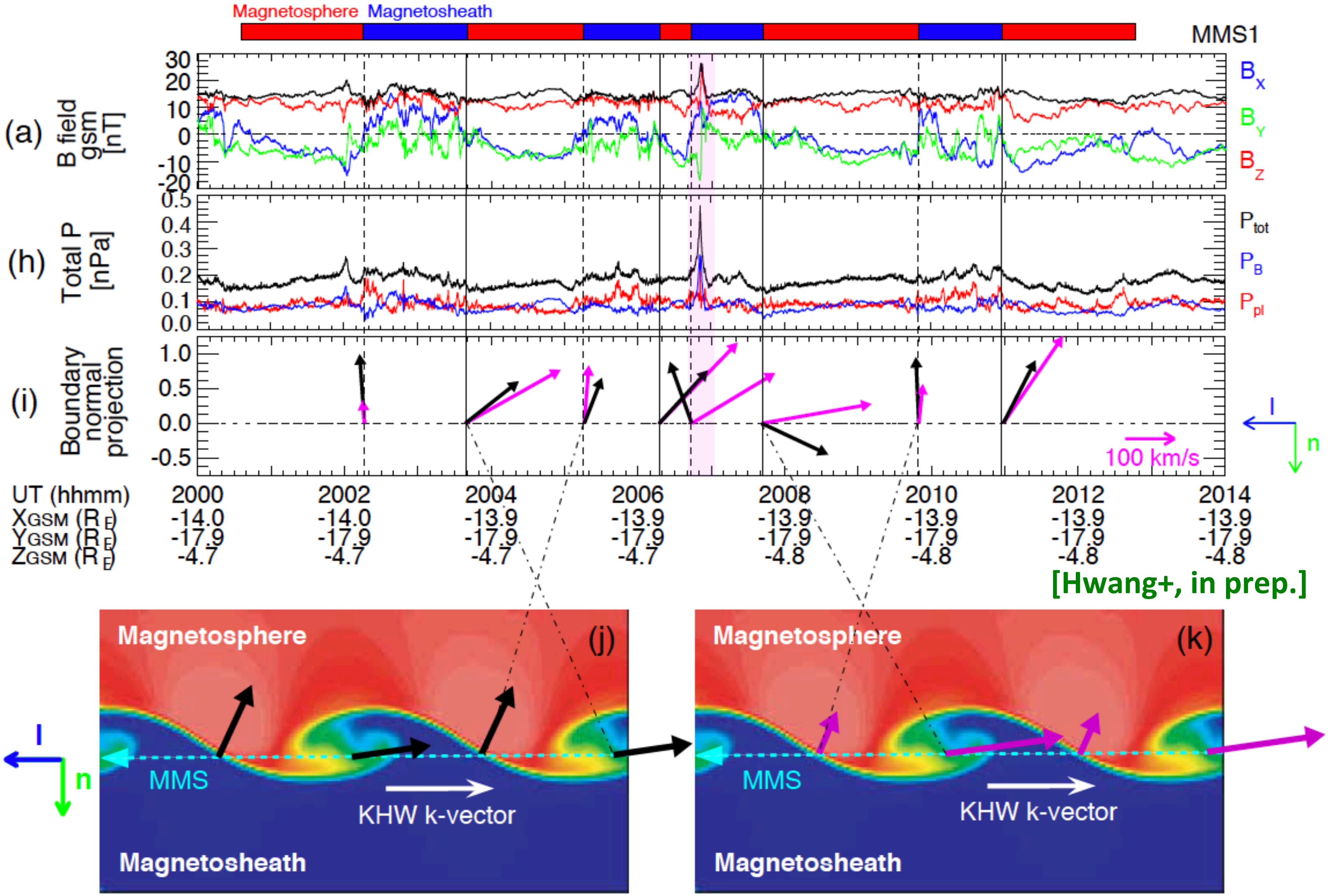
[Nakamura+, 2017]

[Eriksson+, 2016]

- Para electron heating
- Thin current sheet
- No ion jet
- No ele. Jet
- Current sustained by electorn flow
- Strong E_M` (more than 5 times larger than 0.1 rate)
- d_e-scale strong

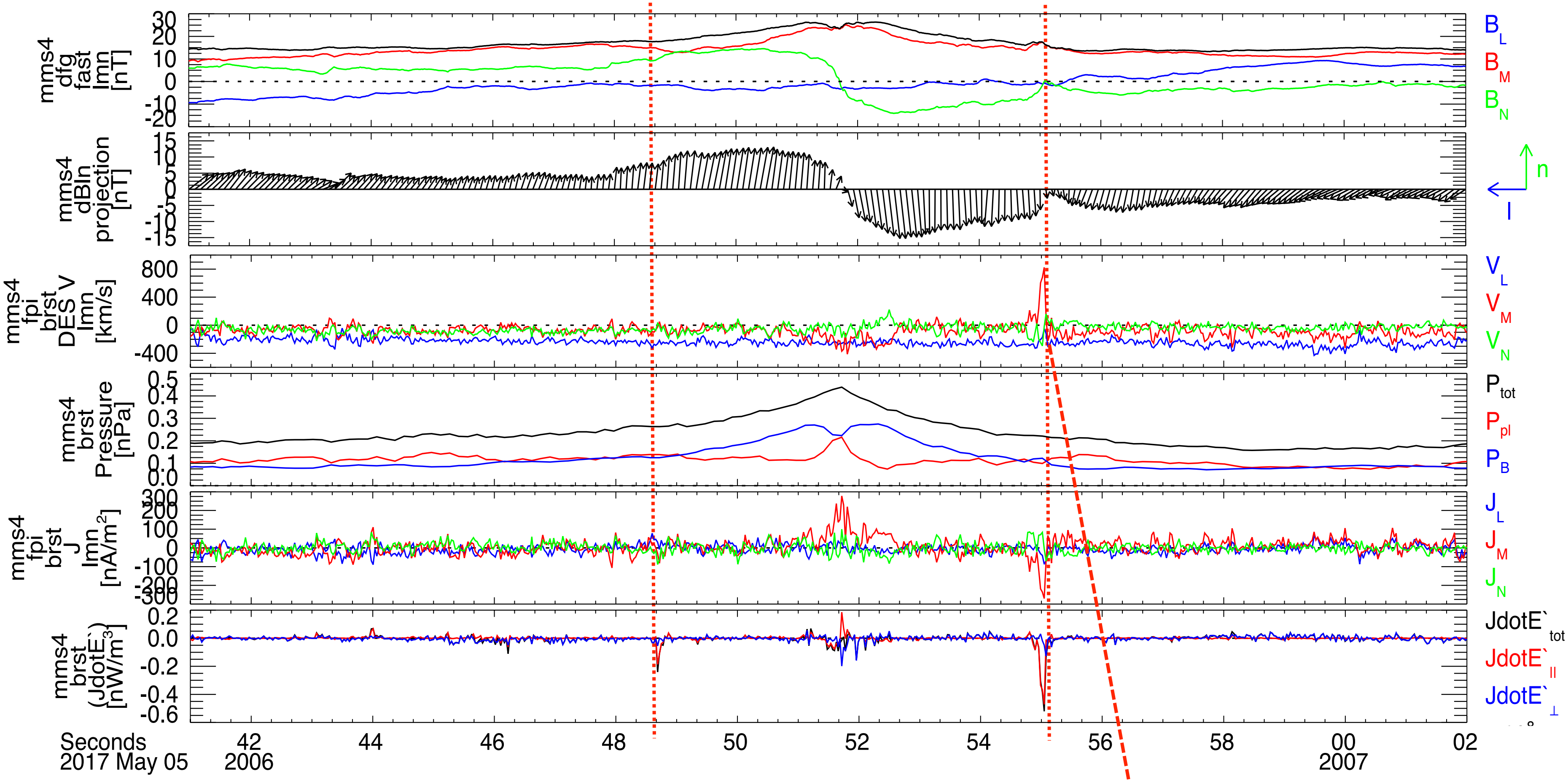
[Courtesy to T.K.M Nakamura]

KHV+FTE: FTE detected at the KHV boundary



[Hwang+, in prep.]

KHV+FTE: FTE detected at the KHV boundary

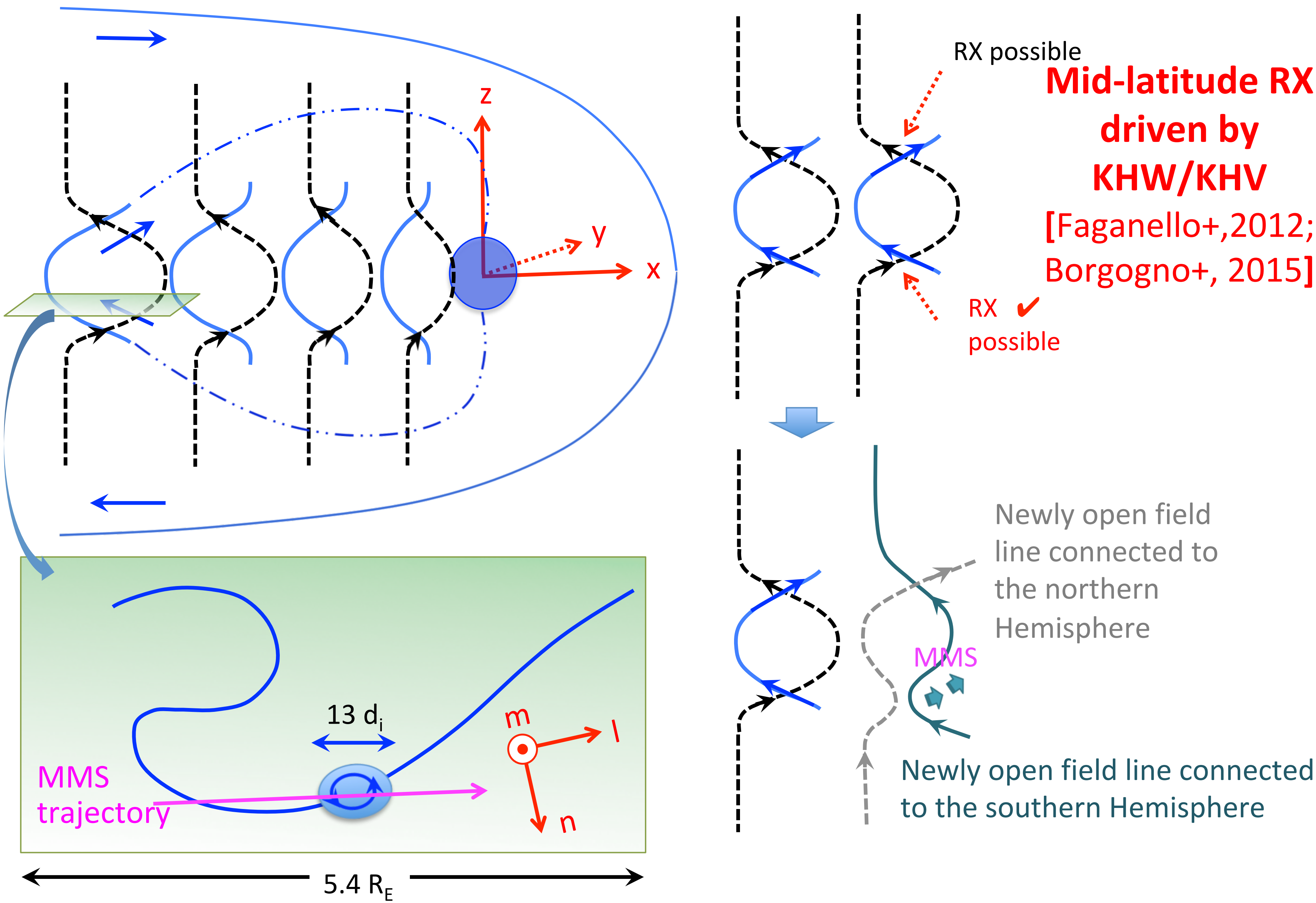


Similar to Nakamura+ [2017] and Eriksson+ [2016]…

- Parallel electron heating
- no ion/electron in-plane jets
- Current carried by electrons
- Non-zero J dot E'

"Strong northward electron jets"

KHV+FTE: FTE detected at the KHV boundary



Summary

FTE

Knowns

- General structure, motion, and extent
- IMF dependence
- Different models leading to different topology
- Substructure (partly)

Unknowns

- Substructure (further details, variations)
- Energy conversion (partly answered by MMS)
- What regulates the contraction or expansion of FTEs? (related to force balance?)
- The relationship with ion/electron flow vortex

Outline

1. FTE: general knowns
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4. Velocity-shear-induced FTE

Thank you!