Tracing the flow of energy through magnetotail reconnection

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Nordita reconnection workshop

Introduction

- Magnetotail reconnection can be divided into three interacting regions:
  - the diffusion region in the vicinity of the X-line
  - the exhaust (see talk by Hietala this morning)
  - the dipolarization front, where the exhaust leading edge interacts with the pre-existing plasma

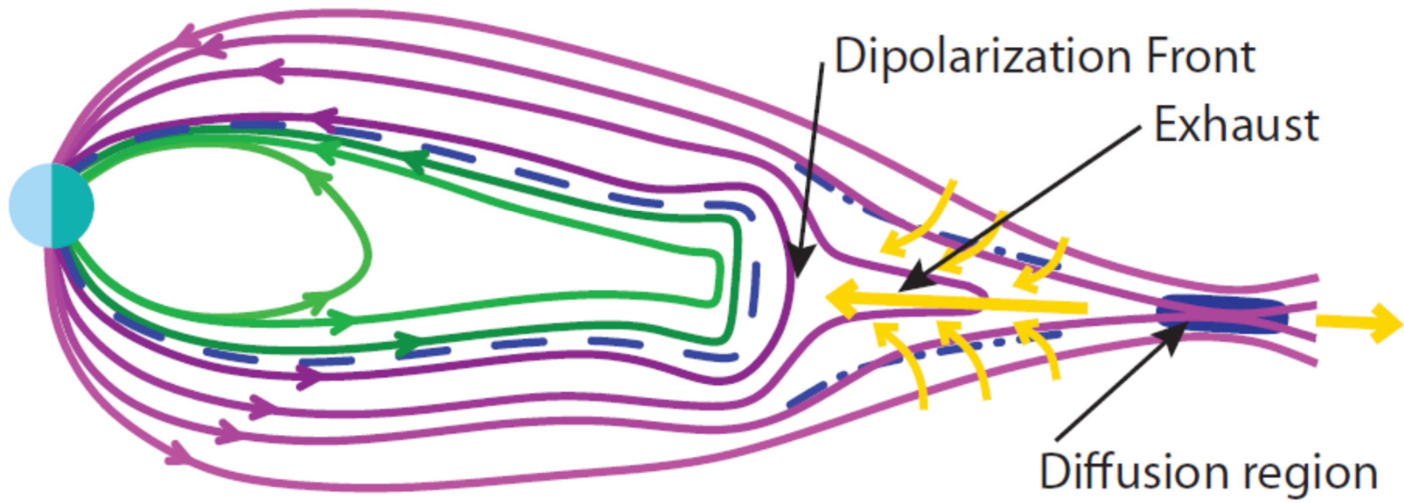

Image credit: Heli Hietala

How does reconnection partition energy?

- Energy partition
  - A basic problem in plasma physics.
  - Relevant for observations which rely on only one component of the plasma.

- MHD scaling and resistive MHD simulations show equipartion between kinetic energy flux and enthalpy flux in the outflow ($\beta_{inflow} \rightarrow 0$) [*Priest & Forbes*, 2000; *Birn et al.*, 2005, 2009].

- More generally, enthalpy flux exceeds kinetic energy flux (hybrid simulations) [*Aunai et al.*, 2011].

- The outward Poynting flux is considered negligible, in part because scaling arguments lead to the conclusion that the magnetic field in the outflow is small.

- But the Poynting flux is quite large?

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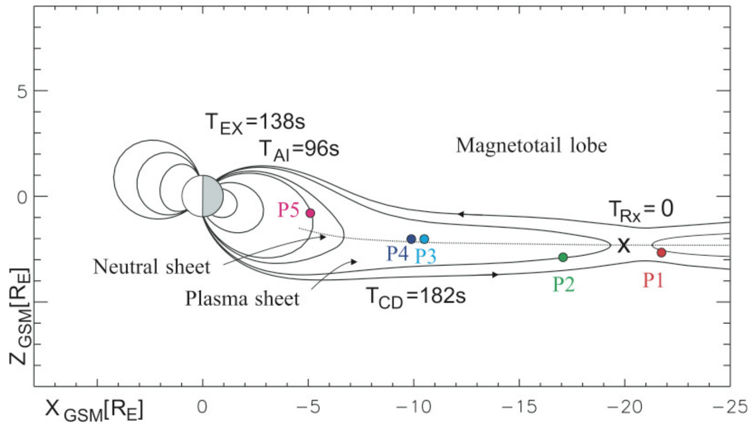
THEMIS substorm timing results



26 February Substorm

- *Angelopoulos et al.*, 2008
- *Lui et al.*, 2009

An interesting point

- c_A ~ 500 km/sec
- 20 R_e => 200-300 sec transit time
- Reconnection onset to Auroral Intensification took 96 sec.

How is this possible?

- Angelopoulos et al. mention kinetic Alfven waves.
- Lui et al.: current disruption

Further studies [*Lin et al.*, 2009; *Kepko et al.*, 2009; *Nishimura et al.*, 2010] not conclusive

Event	Observed time (UT)	Inferred delay (seconds since 04:50:03 UT)
Reconnection onset	04:50:03 (inferred)	T_{Rx} = 0
Reconnection effects at P1	04:50:28	25
Reconnection effects at P2	04:50:38	35
Auroral intensification	04:51:39	T_{AI} = 96
High-latitude Pi2 onset	04:52:00	117
Substorm expansion onset	04:52:21	T_{EX} = 138
Earthward flow onset at P3	04:52:27	144
Mid-latitude Pi2 onset	04:53:05	182
Dipolarization at P3	04:53:05	T_{CD} = 182
Auroral electroject increase	04:54:00	237

Angelopoulos et al., Science, 2008.

[Shay et al., Phys. Rev. Lett., **107**, 065001, 2011]

Two Reconnection 'Signals'

Reconnection starts in the middle of the frame; two jets (related to the Alfvén wave signal) develop and propagate to the left and right. This starts at t = 100 and grows to fill the box by the end of the animation.

Close examination reveals an earlier signal (see for example at t = 90): pairs of thin light-blue lines extending from the reconnection site to the left and right edges of the box.

Enhanced Poynting flux near the edge of the jet associated with KAW-like signature

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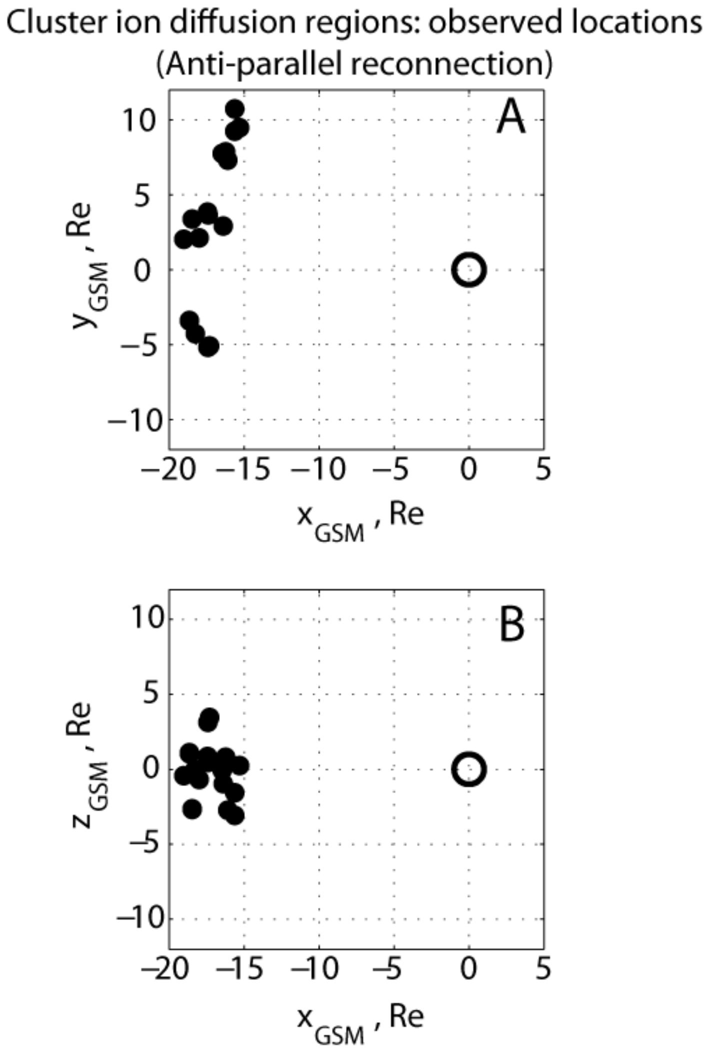
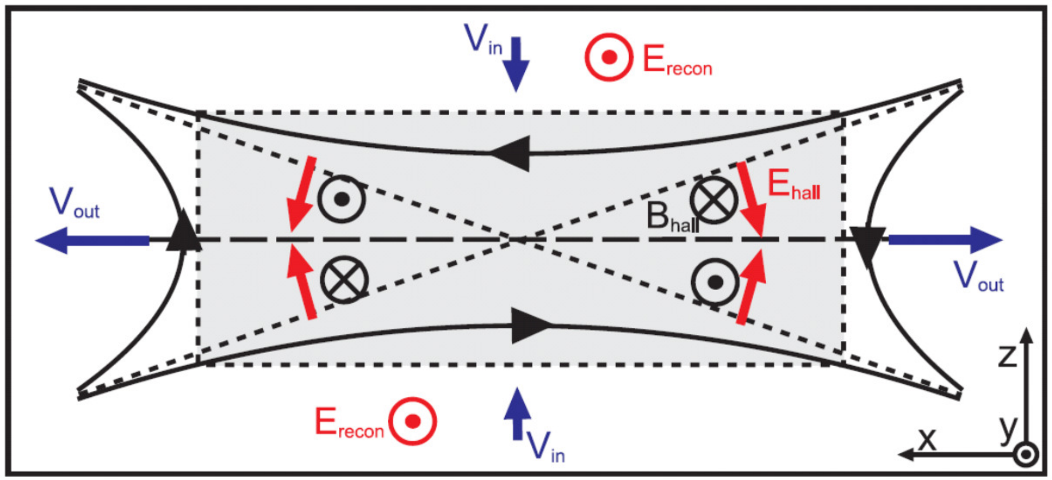
Ion diffusion region: Cluster observations

- Survey the Cluster dataset from 2001-2005 for diffusion region encounters
- Identified 18 anti-parallel diffusion regions
- During each encounter the spacecraft crossed the region in a different way
- Can piece them all together to get overall picture





[Eastwood et al., J. Geophys. Res., 115, A08215, 2010]

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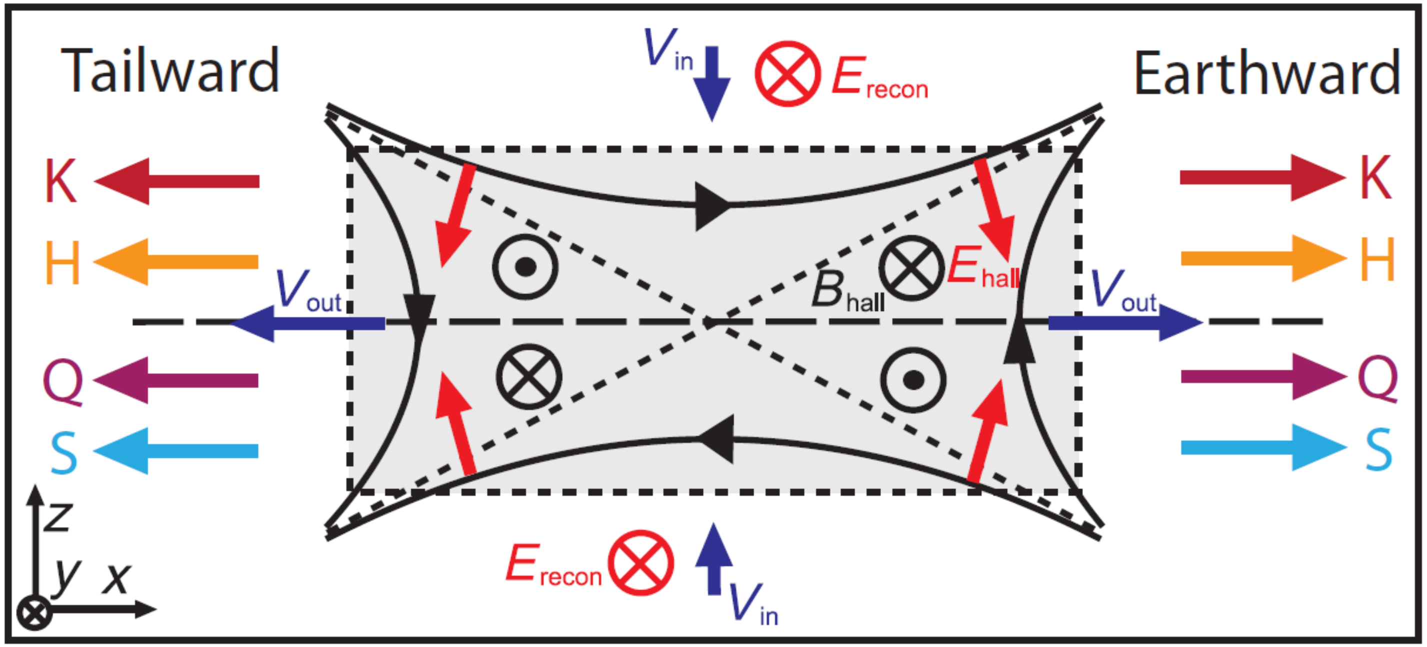
Geometry



$$H_{s,x} = (U_s + P_s)\, v_{x,s} = \frac{\gamma}{\gamma - 1} P_s v_{x,s}$$

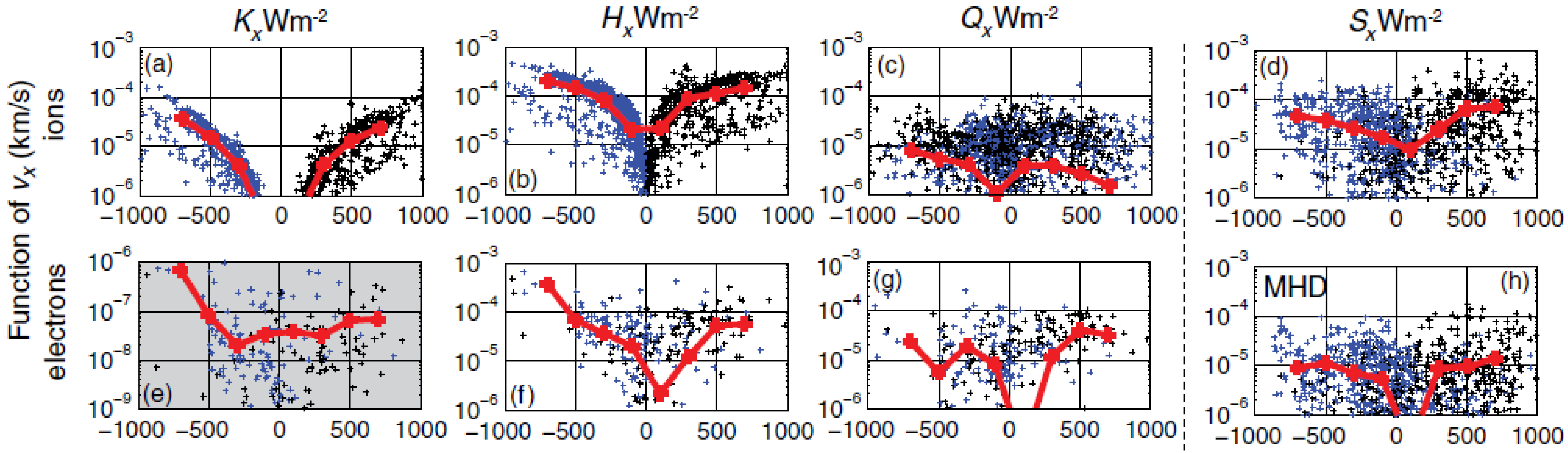
$$K_{x,s} = \left(\frac{1}{2} m_s n_s v_{x,s}^2\right) v_{x,s}$$

$$S_x = \frac{(\mathbf{E} \times \mathbf{B})_x}{\mu_0} = \frac{E_y B_z - E_z B_y}{\mu_0}$$

Non-thermal components in the magnetotail diffusion region are negligible compared to the ion kinetic energy [*Oieroset et al.*, PRL, 2002], and so this is neglected in the present calculations.

$$S_x^{MHD} = E_y B_z / \mu_0$$

Energy partition



$v_{i,x} < 0$ = tailward position, $v_{i,x} > 0$ = Earthward position

$|K_{i,x}|$ and $|H_{i,x}|$ rise with $|v_{i,x}|$. $|H_{e,x}|$ smaller than $|H_{i,x}|$

$|S_x| > |S^{MHD}{}_x|$

$|K_{e,x}|$ is 10^2 smaller than any of the other energy fluxes

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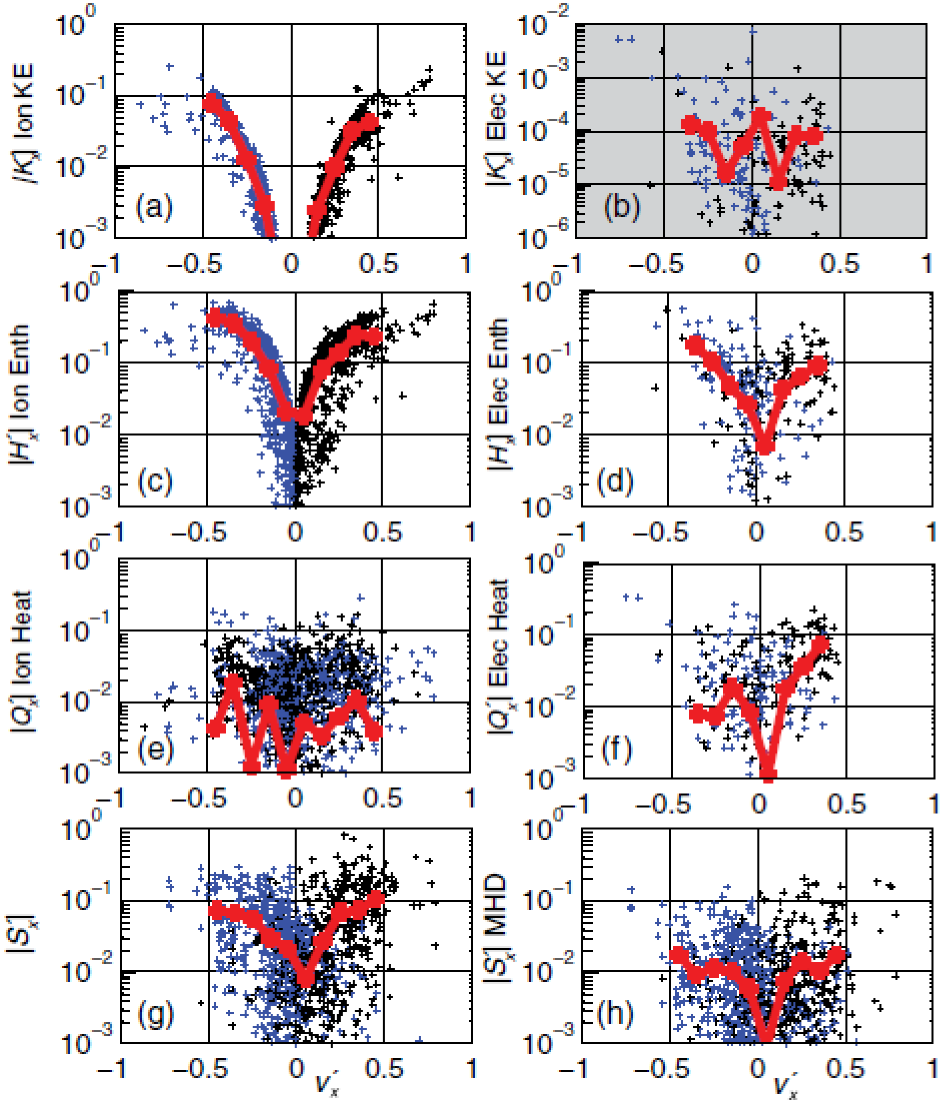
Energy partition (scaled)



$v'_{i,x}$ [a]	$K'_{i,x}$	$H'_{i,x}$	$H'_{e,x}$	$Q'_{e,x}$	S'_x
0.45	0.04	0.24	0.09	0.09	0.10
−0.45	−0.08	−0.43	−0.18	−0.01	−0.07

$$\mathbf{B}' = \mathbf{B}/B_L$$

$$n' = n/n_c$$

$$\mathbf{v}' = \mathbf{v}/v_A(B_L, n_c)$$

$$\mathbf{E}' = \mathbf{E}/(B_L V_A)$$

$$m' = m/m_i$$

$$E'_F = (\mu_0/V_A B_0^2) E_F$$

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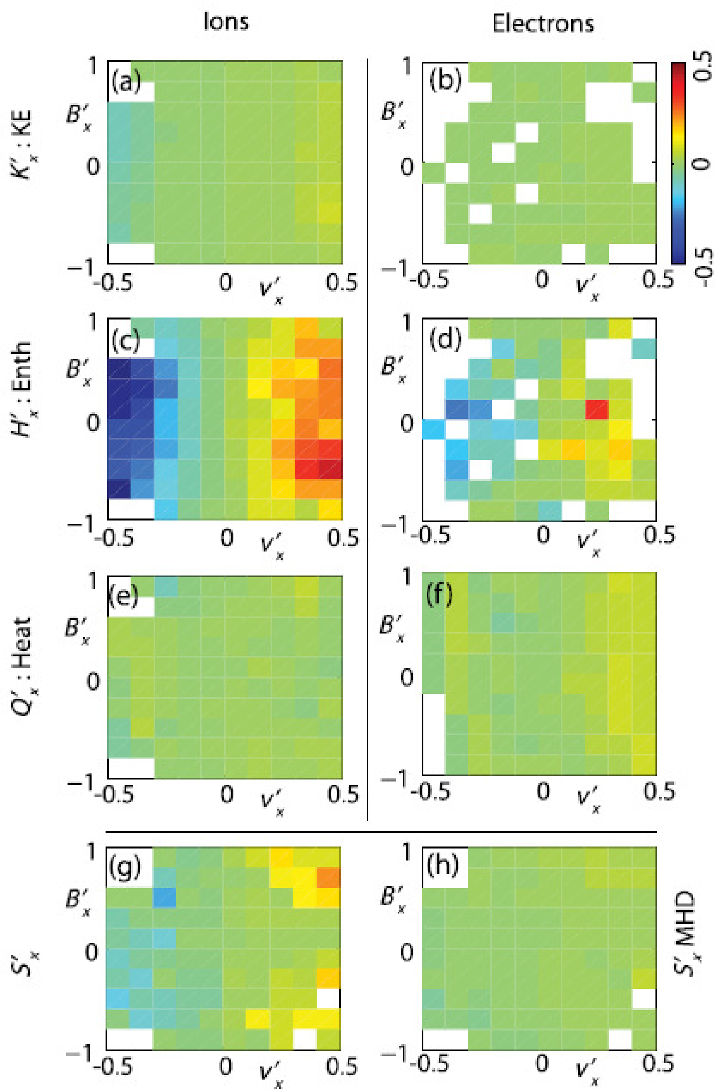
doi:10.1103/PhysRevLett.110.225001

Energy partition (scaled) – 2 dimensional maps



- $H'_{i,x} > H'_{e,x}$
- $H'_{e,x} > K'_{i,x}$

- Poynting flux
  - Hall effects increase the size of S'_x and make it an important component of the outflow.
  - Clear bifurcation in the Earthward S'_x
  - In localized regions, S'_x is comparable to $H'_{i,x}$ and greater than $K'_{i,x}$, dominating certain regions of the jet.

[*Eastwood et al., Phys. Rev. Lett.*, **110**, 225001, 2013]

The dipolarization front (Earthward propagating)

- Rapid increase in B_z GSM
  - Separates pre-existing plasma sheet from the fast, rarefied, heated BBF
  - Propagates coherently
  - Wave-particle interactions
  - Electron acceleration and heating
- Ion physics – ions have the energy!
  - DFs reflect ions back into the high-density pre-existing plasma sheet [e.g. Zhou et al.]
  - Theoretical studies: test particle [Zhou et al.], MHD [Birn et al.], Ion kinetics [Nakamura], PIC [Wu & Shay]
- Compare multipoint experimental observations of a DF with a PIC simulation of reconnection onset

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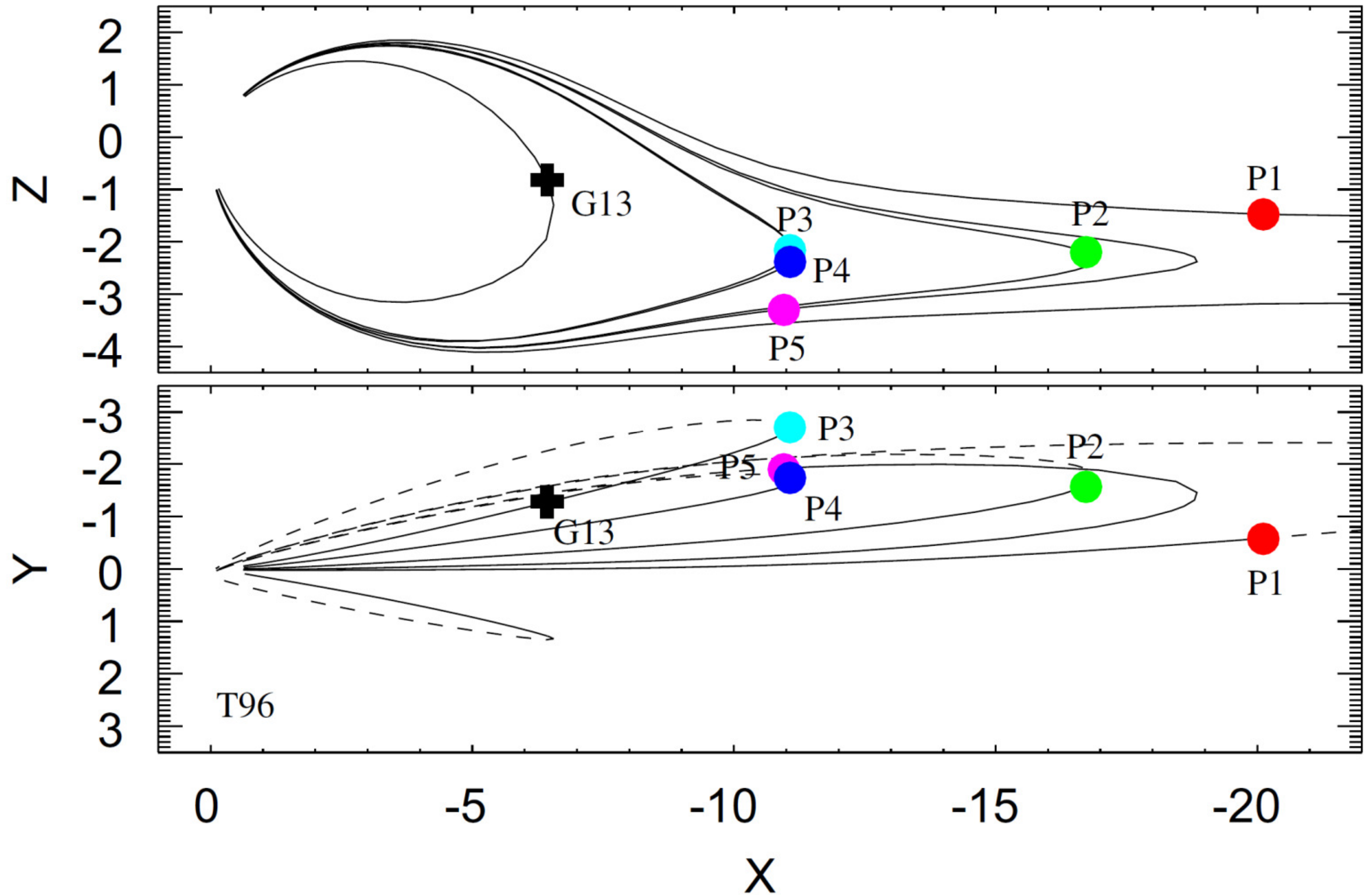
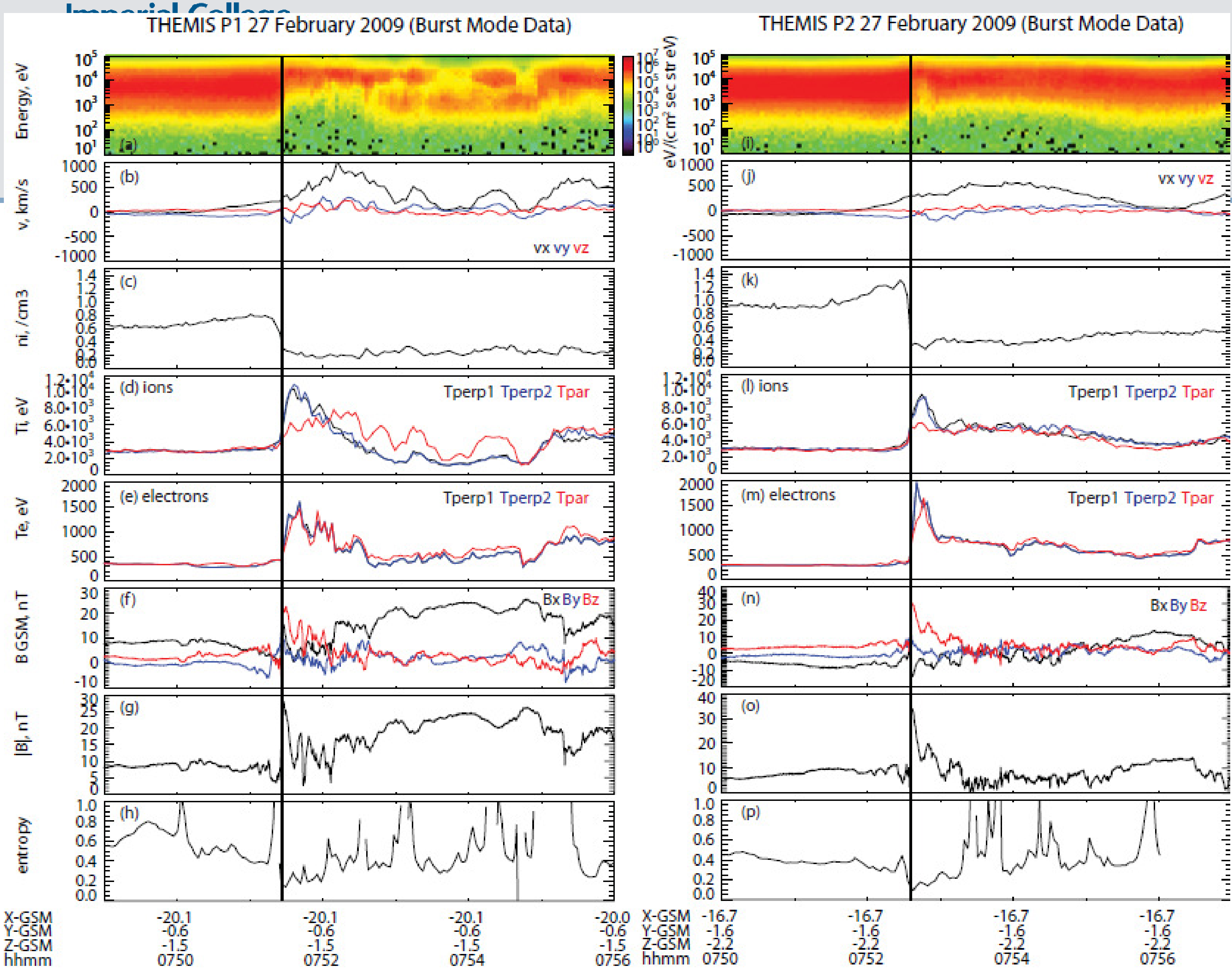
Observations: 27 February 2009 – Runov et al. 2009

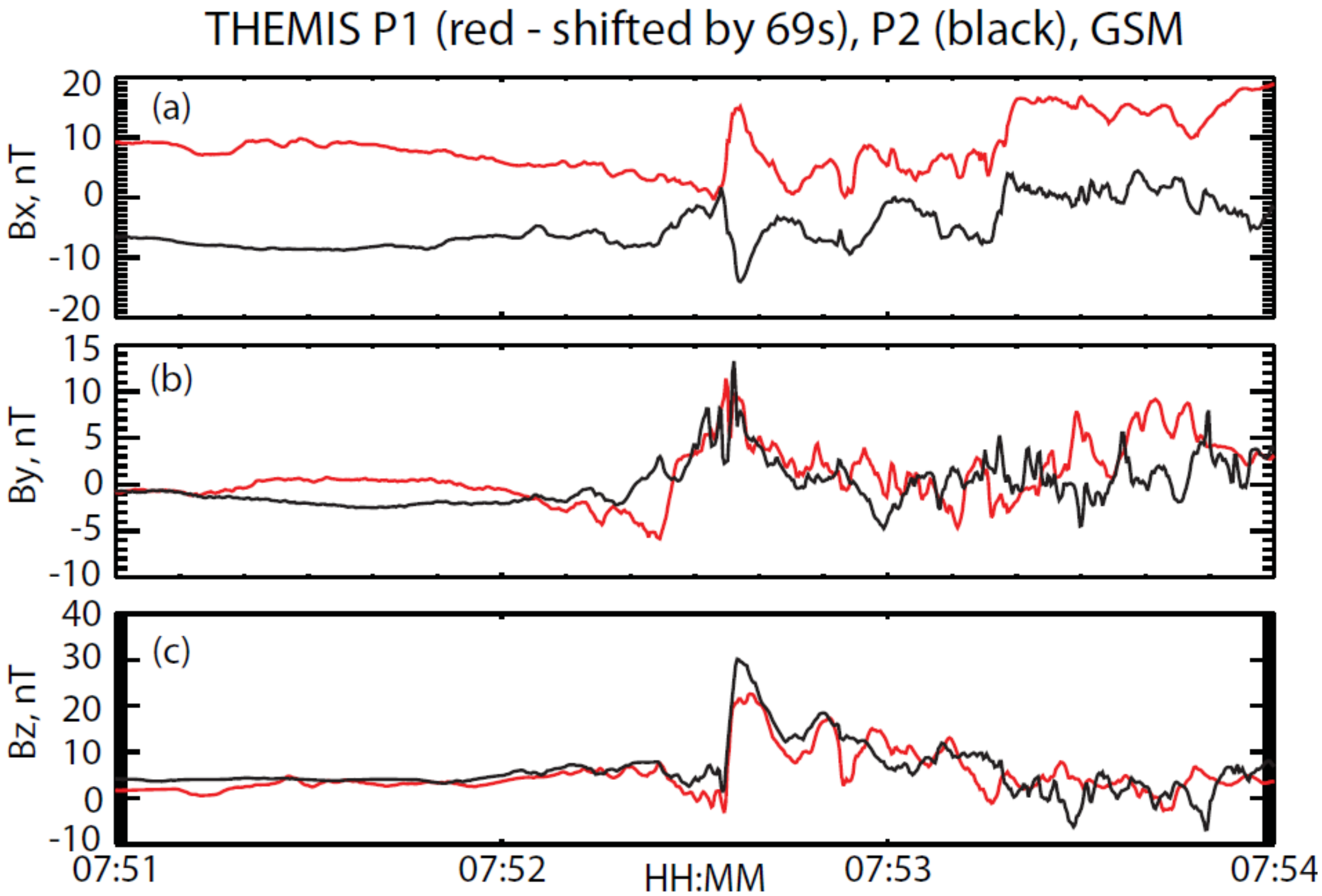


Clean and uncontroversial DF event



THEMIS P1 27 February 2009 (Burst Mode Data)
THEMIS P2 27 February 2009 (Burst Mode Data)
Energy, eV
eV/(cm² sec str eV)
v, km/s
vx vy vz
ni, /cm3
Ti, eV
(d) ions
(l) ions
Tperp1 Tperp2 Tpar
Te, eV
(e) electrons
(m) electrons
B GSM, nT
Bx By Bz
|B|, nT
entropy
X-GSM -20.1 -20.1 -20.1 -20.0
Y-GSM -0.6 -0.6 -0.6 -0.6
Z-GSM -1.5 -1.5 -1.5 -1.5
hhmm 0750 0752 0754 0756
X-GSM -16.7 -16.7 -16.7 -16.7
Y-GSM -1.6 -1.6 -1.6 -1.6
Z-GSM -2.2 -2.2 -2.2 -2.2
hhmm 0750 0752 0754 0756

P1 and P2 magnetic field timeseries



- $|B_{xGSM}|$ similar: equal distance from $B_{xGSM} = 0$ plane
- Lobe field strength
  - B_L~25–30 nT,
  - f_{ci} = 0.42 Hz
- Current sheet density
  - n~0.8 /cm^3
  - d_i~255 km
- Characteristic Alfvén speed ~670 km s^{-1}.
  - v_{DF}~314 km s^{-1}
- s/c separation
  - Δx ~3.4 RE ~85 d_i
  - Δt ~69 s ~29 f_{ci}^{-1}

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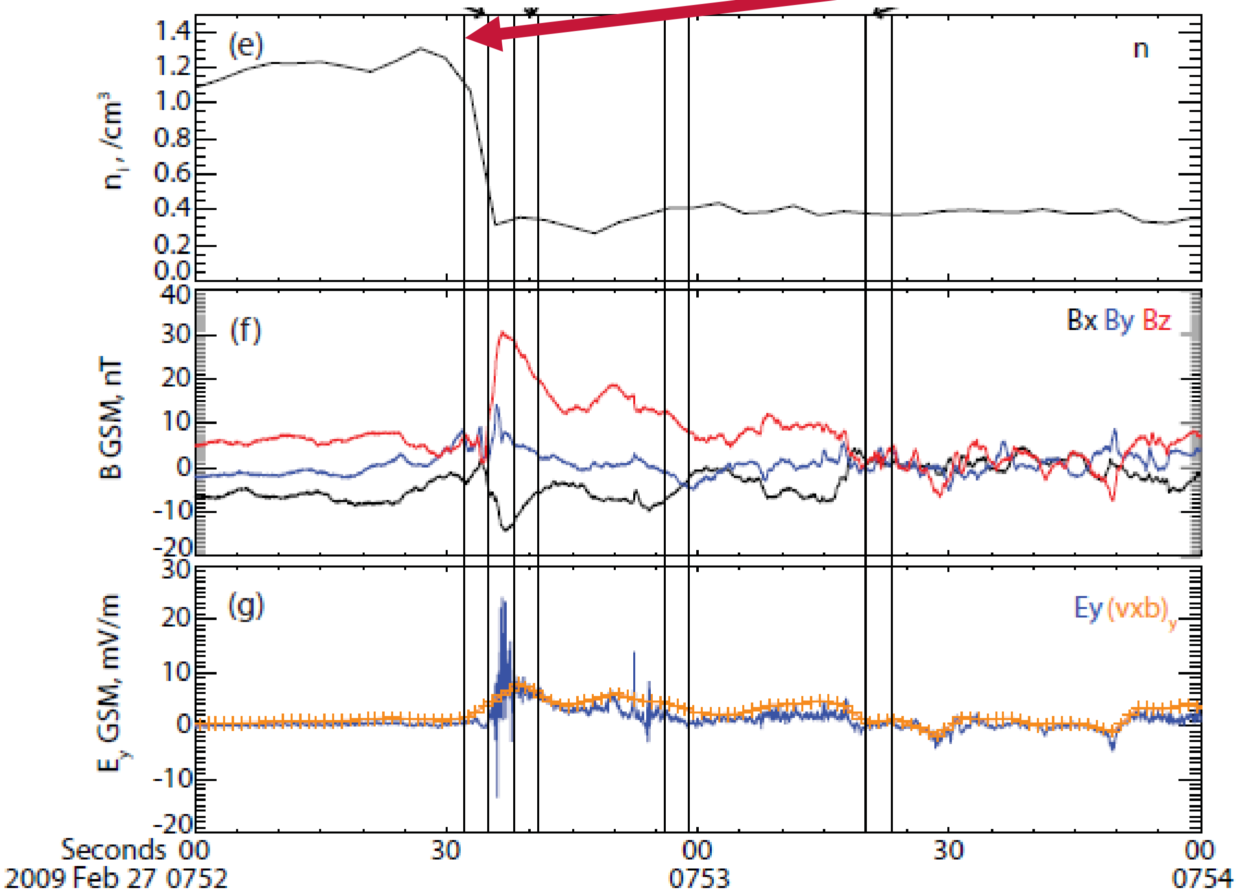
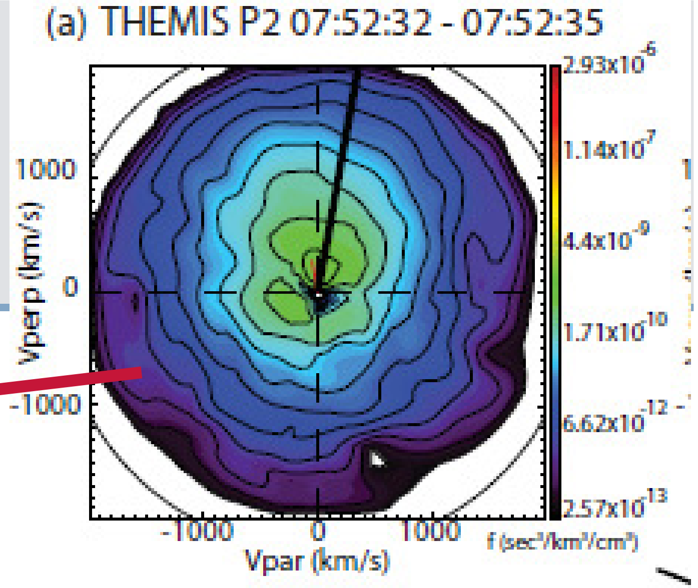
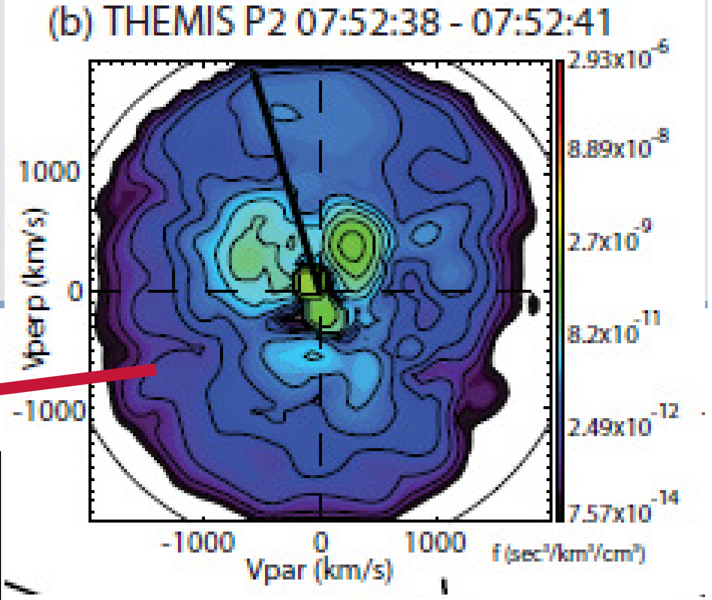
P2 ion distributions and electric field

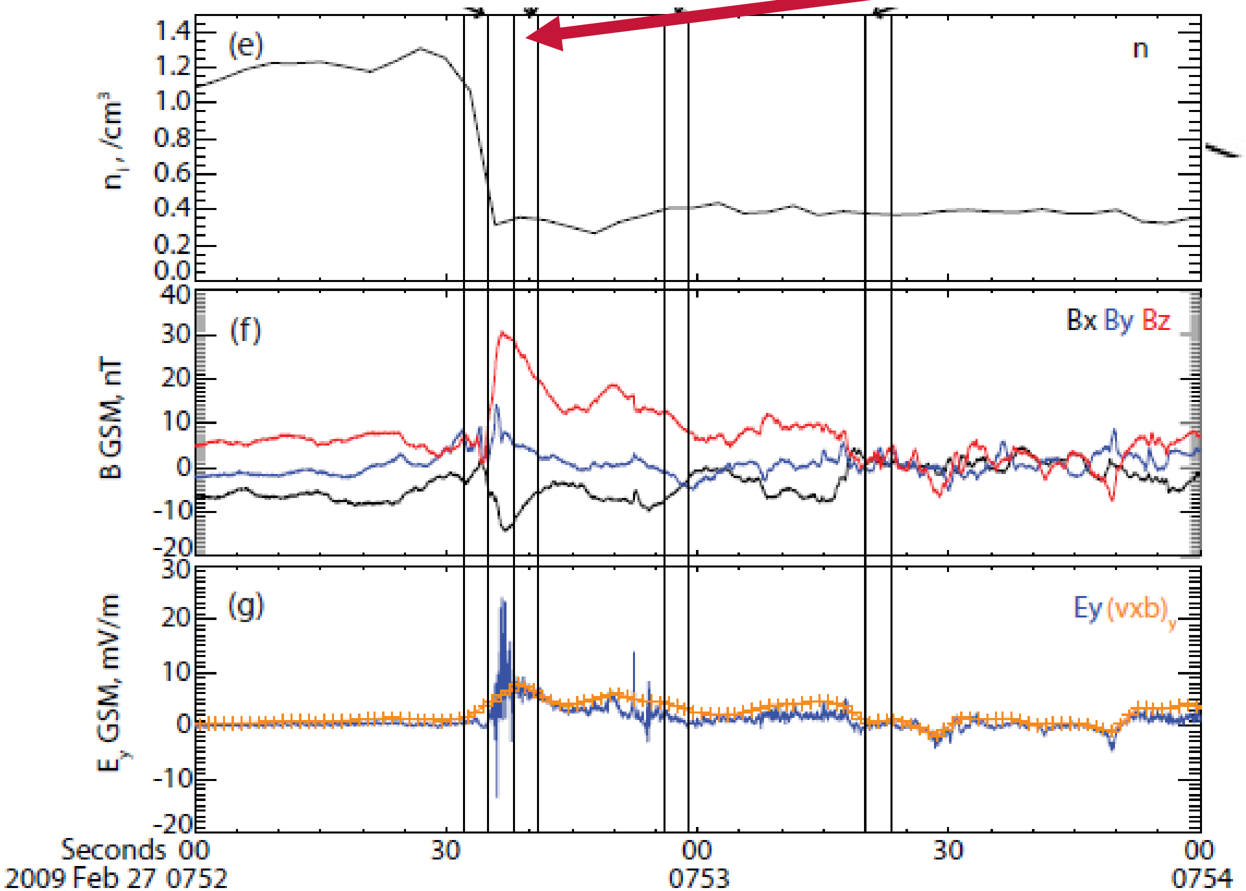




- High-density stagnant current sheet
- Immediately prior to DF arrival
- Single ion population asymmetric
  - Net flux in the $+x_{GSM}$ direction
  - High-energy ions moving earthward from the DF

P2 ion distributions and electric field





- Immediately adjacent to the DF
- Two distinct populations
  - separated in ±vpar
  - displaced in +vperp
- Black line = x_{GSM}
- Parallel ~ $+z_{GSM}$
- Perpendicular ~ $+x_{GSM}$

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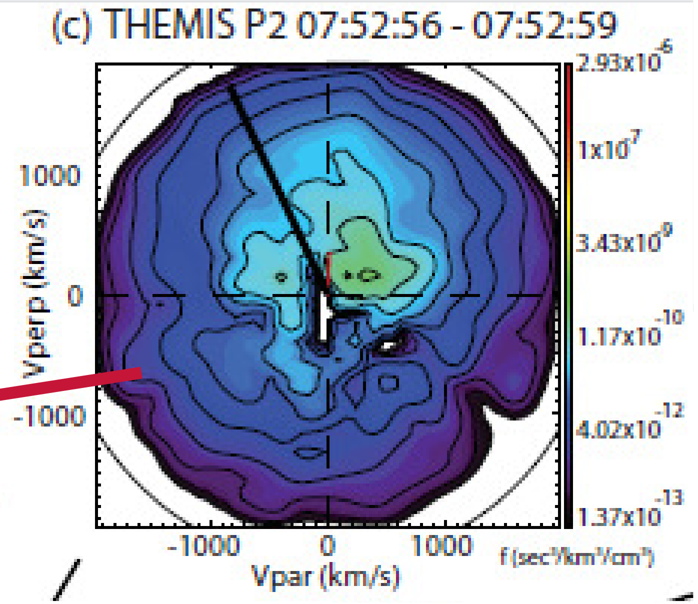
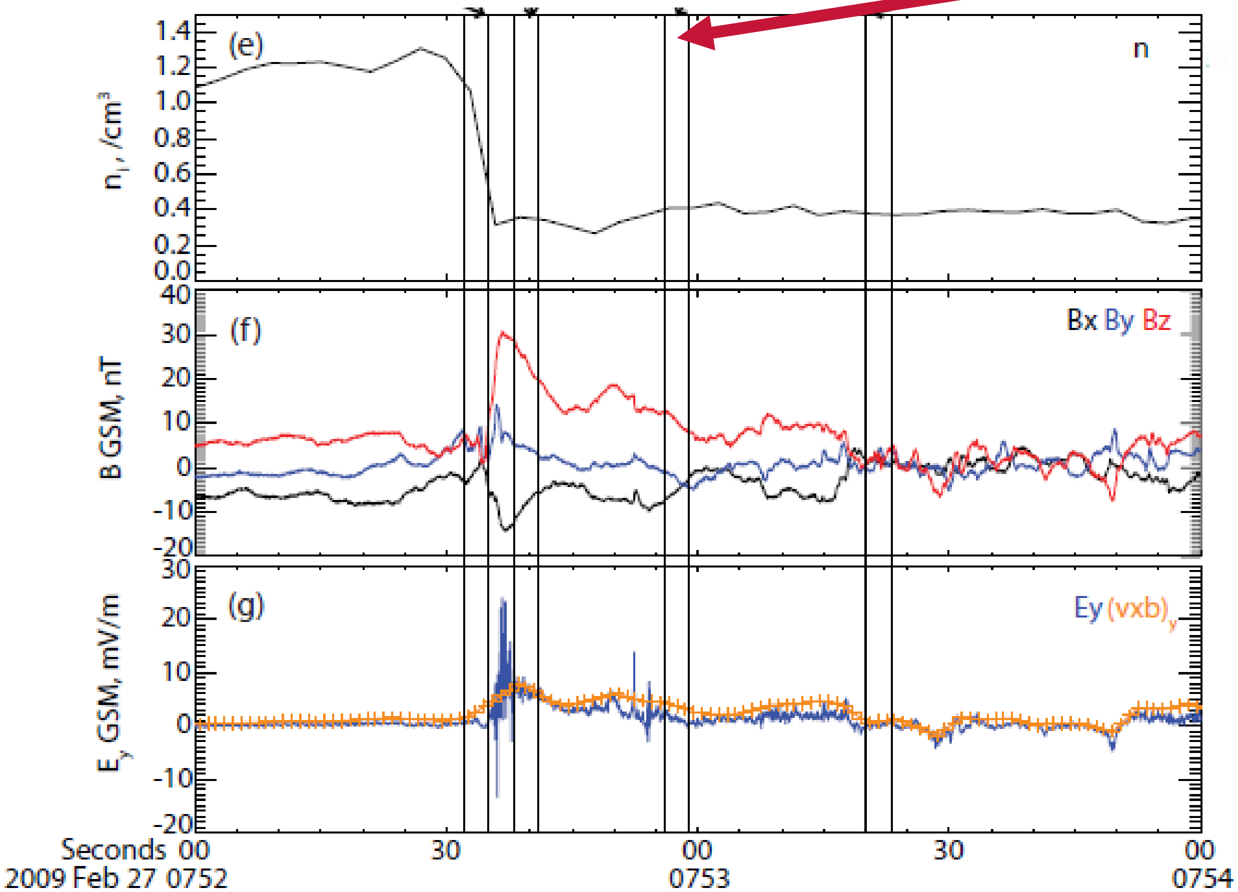
P2 ion distributions and electric field





- Counterstreaming beams
- Persistent feature
- Observed for 10s of seconds after the passage of the DF,
- (distribution midway through the interval)

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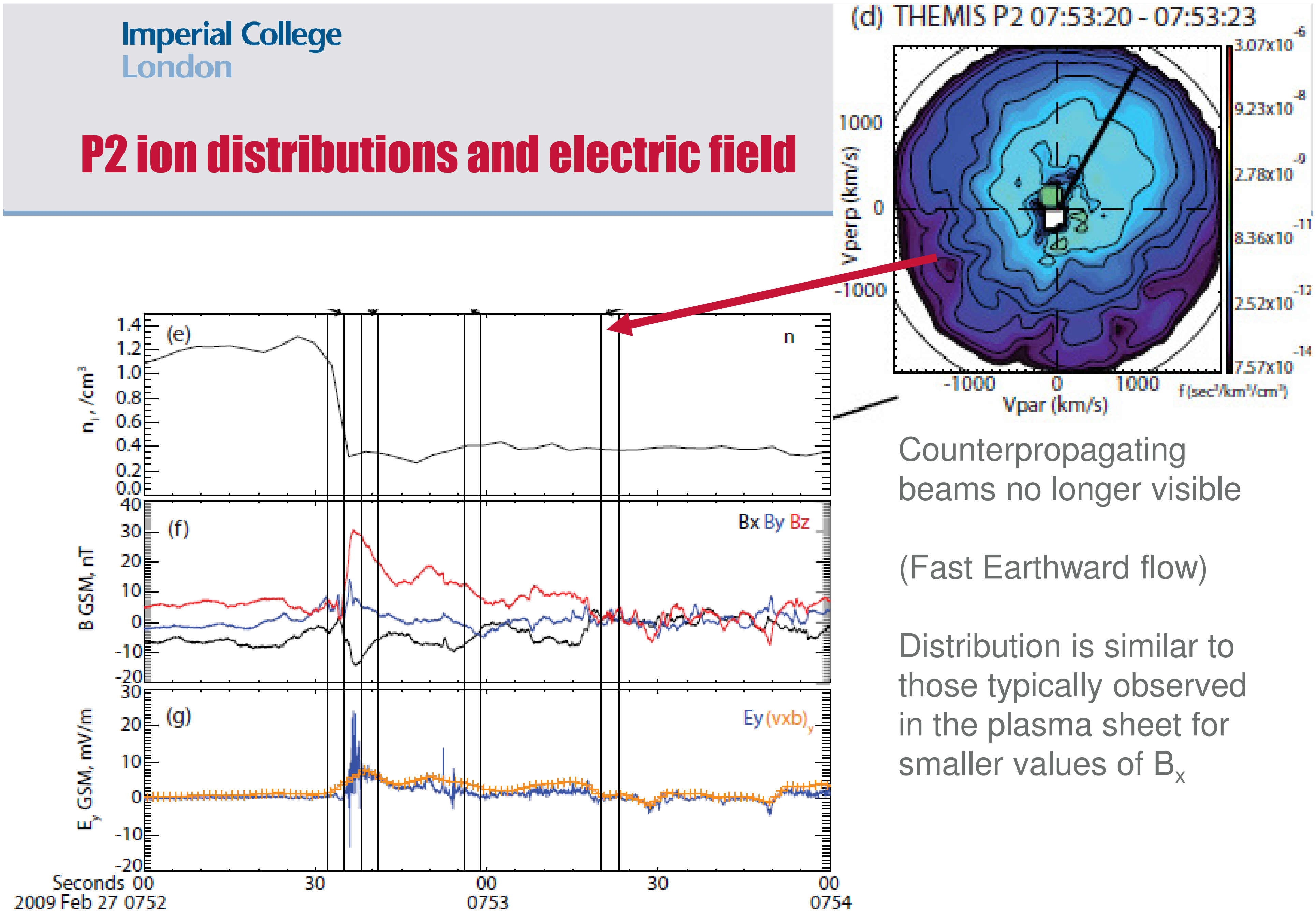
P2 ion distributions and electric field



Counterpropagating beams no longer visible

(Fast Earthward flow)

Distribution is similar to those typically observed in the plasma sheet for smaller values of B_x

Comments on spacecraft data

- Similar features observed by THEMIS P1.
  - NB Temperature anisotropy does not reflect the existence of the counterpropagating beams

- Size:
  - Durations correspond to a spatial scale of ~2.1–2.4 RE or ~52–60 di in xGSM
  - Direct confirmation that this is a discrete region (P1 exits before the DF reaches P2)
  - Counterpropagating beam region changes little in size from P1 to P2
  - Survives in quasi-dynamic equilibrium for tens of ion gyroperiods

- Electric field
  - Strong short-period fluctuations at the DF itself
  - Otherwise appears to be largely frozen-in
  - No obvious hint of the underlying structure in the ion plasma

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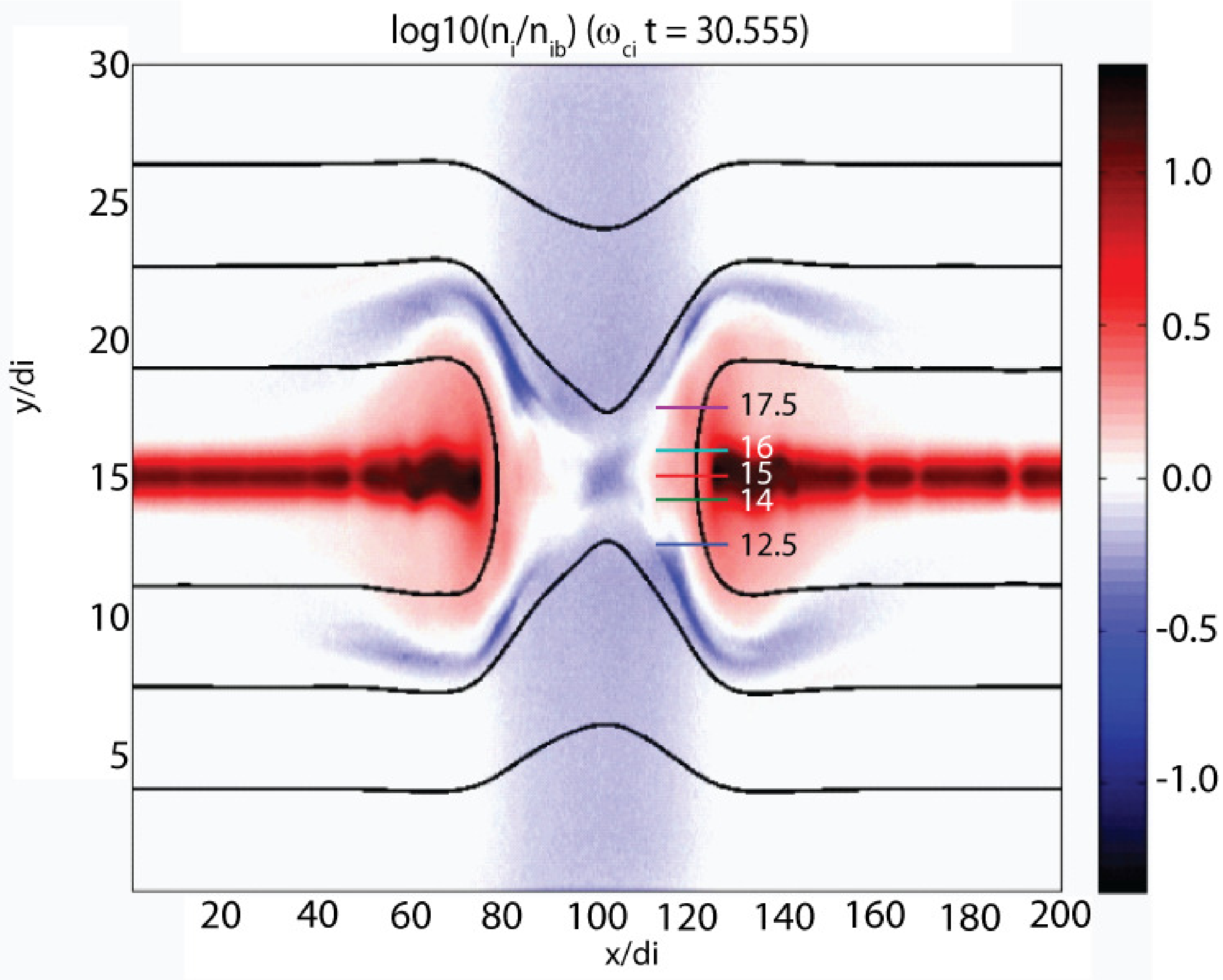
Reconnection simulation



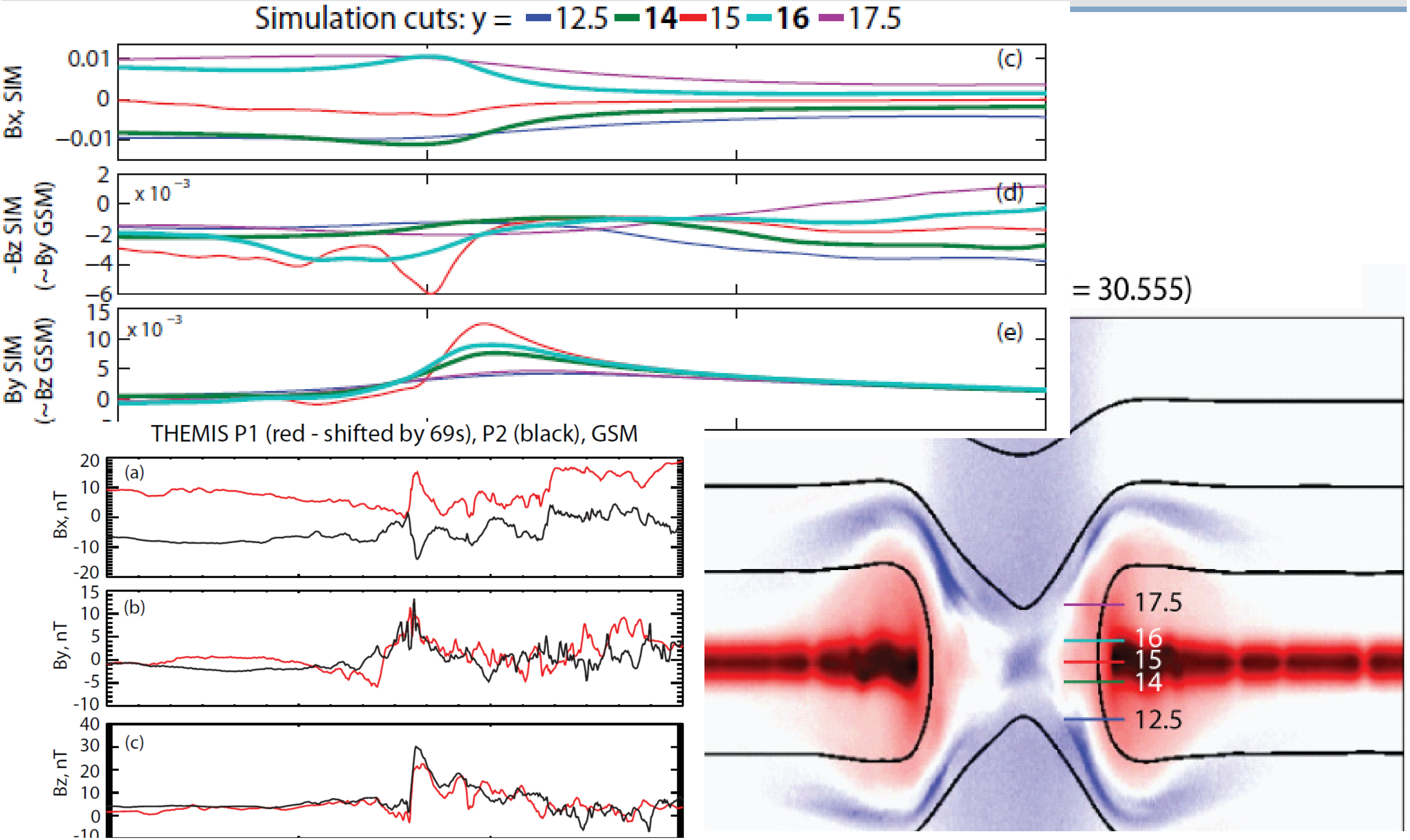
- Parsek2d implicit PIC code

- $\partial/\partial z_{SIM} = 0$
- $x_{SIM} : y_{SIM} = 200 : 30$ di
- $B_{zSIM} = B_g = 0.1$
- mi/me = 256
- Te~1 keV and Ti~5 keV (for physical electrons)
- Initial Harris sheet eqn

- Conversion
- between GSM and SIM:
  $x_{GSM} = \quad x_{SIM}$
- $y_{GSM} = - z_{SIM}$
- $z_{GSM} = \quad y_{SIM}$

Cuts through the DF

y = 14 and y = 16 compare best with data



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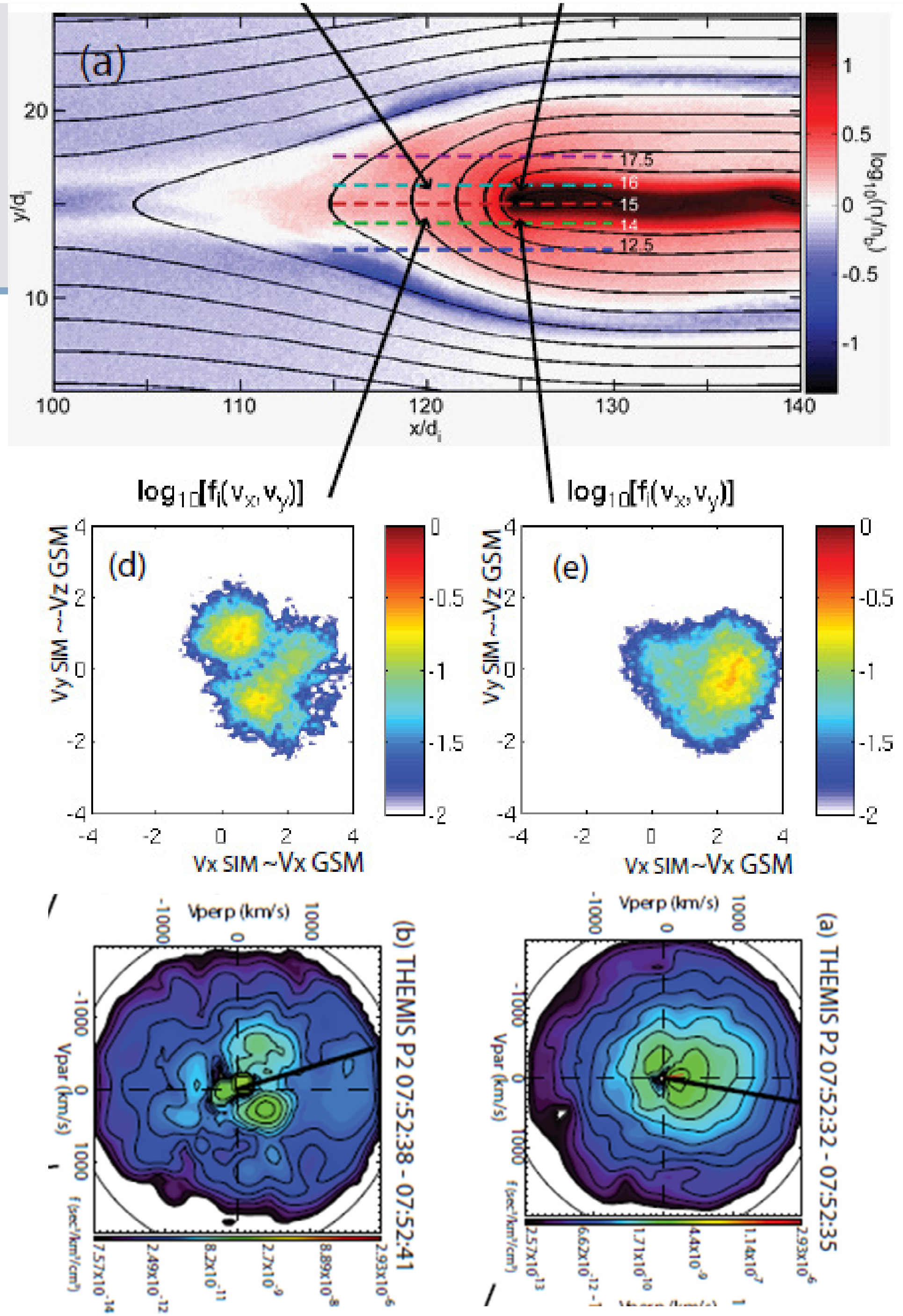
Dist. function comparison

- Distributions:
  - *Comparing simulation + expt. is not trivial*
  - Simulation: instantaneous & integrated
  - Experimental: accumulated & cuts
  - Different coordinate systems
  - these formats reveal the structure most cleanly
- Low density side:
  - peaks at $+v_{xSIM}/+v_{ySIM}$ and $+v_{xSIM}/v_{ySIM}$
  - speeds ~ Alfvén speed
  - magnetic field is dominated by B_{ySIM}
  - separated in velocity space ~along the magnetic field.
- Consistent with experimental data
  - Same found for THEMIS P1



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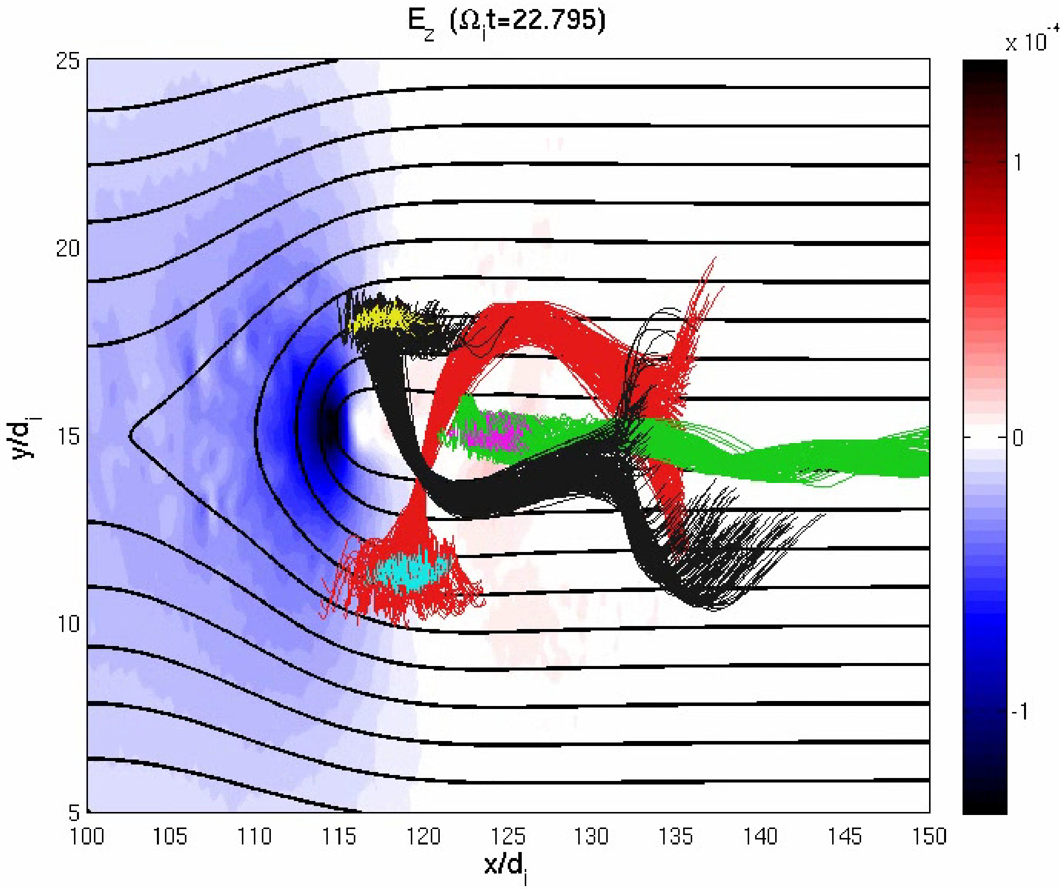
Ion dynamics



Back- and forward tracing of ion trajectories passing through cross-over point at t = 30

Reconnection electric field also shown

Black & Red ion beam:

- Initially part of the unperturbed thermal population on the flanks of the Harris sheet
- Accelerated in z_{SIM} by reconnection E field (into board)
- Driven toward the midplane of the current sheet by the Lorentz force associated with
- B_{xSIM}, creates v_{ySIM}
- Closer to the midplane, B_{ySIM} enhanced
  - Ion beam velocity rotates to the $+x_{SIM}$ direction by the $v_{zSIM} \times B_{ySIM}$

Ions not frozen in.

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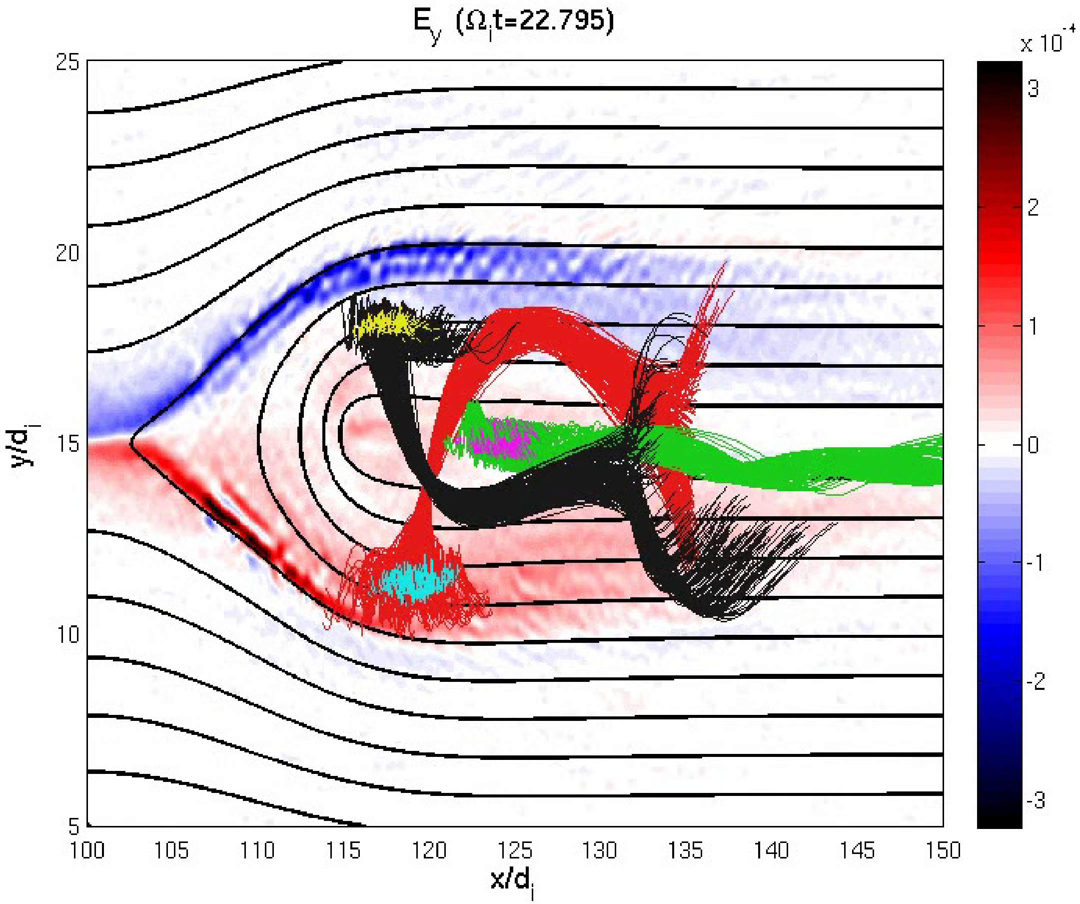
Ion dynamics



- **Green** ion beam
  - Adjacent to the DF at $t \approx 30$ (when black and red beams cross)
  - Undergoes 'standard' reflection

- "Hall" electric field (E_{ySIM}) extends well past the front
- The counterpropagating ion beams don't cross the separatrices from the inflow region
- Come from the preexisting plasma sheet
- The limited DF extent perp. to jet means that in fact the two plasmas can mix.

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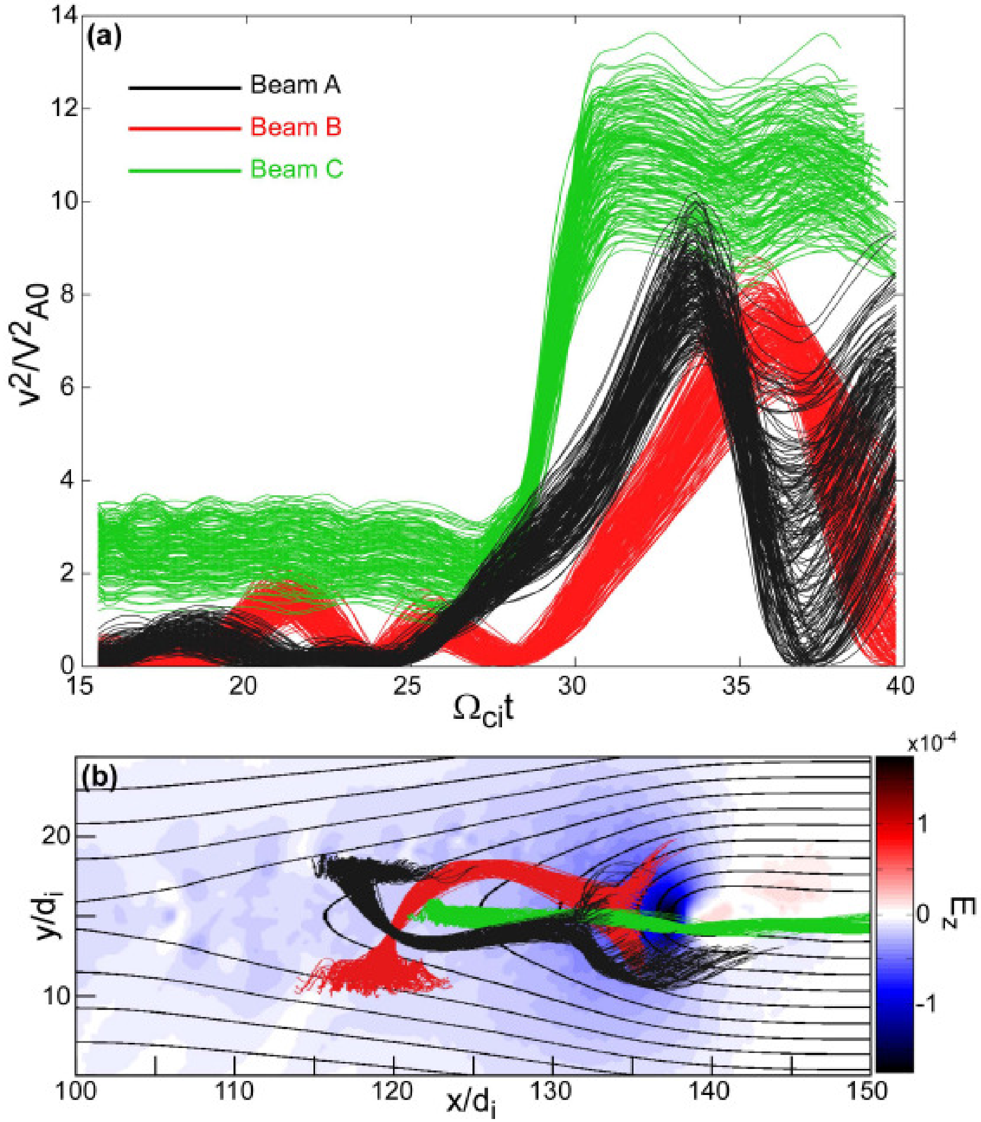
Ion kinetic energy time history



- When black and red beams cross at t ≈ 30, both have gained significant energy and continue to gain energy
- By t ≈ 40:
- **Black** beam has been rapidly thermalized, energetic particles ahead of DF
- **Red** beam particles on low-density side of the DF, forms part of the reconnection jet
- **Green** beam particles more energetic, but black beam more dispersed in energy. Energies comparable to previous observations [Zhou et al., 2010]

Eastwood et al., JGR, 2015, **doi:10.1002/2014JA020516**

Conclusions

- Counter-propagating ion beams exist in a macroscopic volume (52 – 60 di) in the jet leading edge
  - Observed at P1 and P2 (separation 69 s = 29 ion gyroperiods, 3.4 Re = 85 di)
  - Not reflected in the ion moments
  - Observed at other DF events reported in the literature
- Very good agreement between spacecraft data and simulations
- Beams sourced from pre-existing plasma sheet
  - Ions accelerated by reconnection electric field, gyrate around the edge of the DF into the jet. Do not cross the separatrices
  - May subsequently overtake the DF
- The jet entrains the pre-existing plasmasheet
- BBF not an isolated bubble of separate low-entropy plasma propagating earthward