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CICART
Center for Integrated Computation and Analysis of Reconnection and Turbulence

Magnetic Reconnection: Recent Developments and Future Challenges

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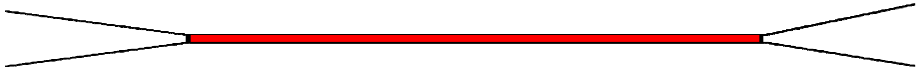
Outline

- Brief history

  From Sweet-Parker to Petschek to Hall Models
- Key questions, with emphasis on what are some of the new things we have learned since the design of Cluster, Themis, and MMS.
- Some future challenges?

Classical (2D) Steady-State Models of Reconnection

Sweet-Parker [Sweet 1958, Parker 1957]



Geometry of reconnection layer : Y-points [Syrovatskii 1971]

Length of the reconnection layer is of the order of the system size >> width Δ

Reconnection time scale

$$\tau_{SP} = (\tau_A \tau_R)^{1/2} = S^{1/2} \tau_A$$

Solar flares: $S \sim 10^{12}, \quad \tau_A \sim 1s$

$\Rightarrow \tau_{SP} \sim 10^6 s$ Too long to account for solar flares!

Q. Why is Sweet-Parker reconnection so slow?

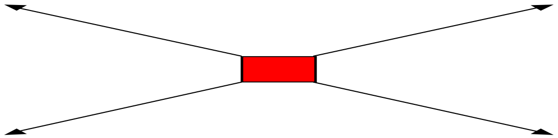
A. Geometry

Conservation relations of mass, energy, and flux

$$V_{in} L = V_{out}\delta, \quad V_{out} = V_A$$

$$V_{in} = \frac{\delta}{L} V_A, \quad \frac{\delta}{L} = S^{-1/2}$$

Petschek [1964]



Geometry of reconnection layer: X-point

Length Δ ($<< L$) is of the order of the width δ

$$\tau_{PK} = \tau_A \ln S$$

Solar flares: $\tau_{PK} \sim 10^2 s$

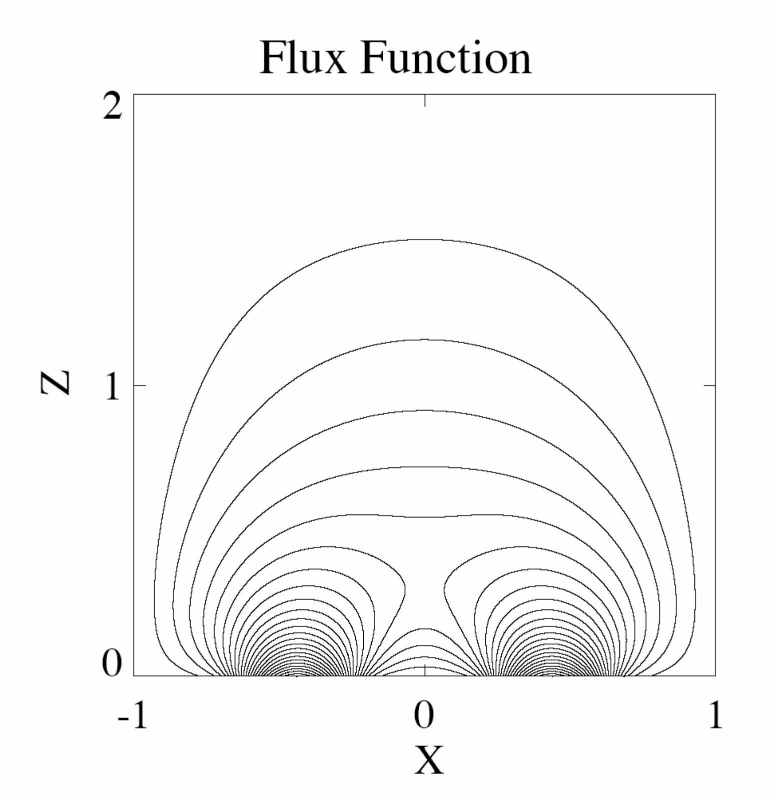
Computational Tests of the Petschek Model

[Sato and Hayashi 1979, Ugai 1984, Biskamp 1986, Forbes and Priest 1987, Scholer 1989, Yan, Lee and Priest 1993, Ma et al. 1995, Uzdensky and Kulsrud 2000, Breslau and Jardin 2003, Malyshkin, Linde and Kulsrud 2005]

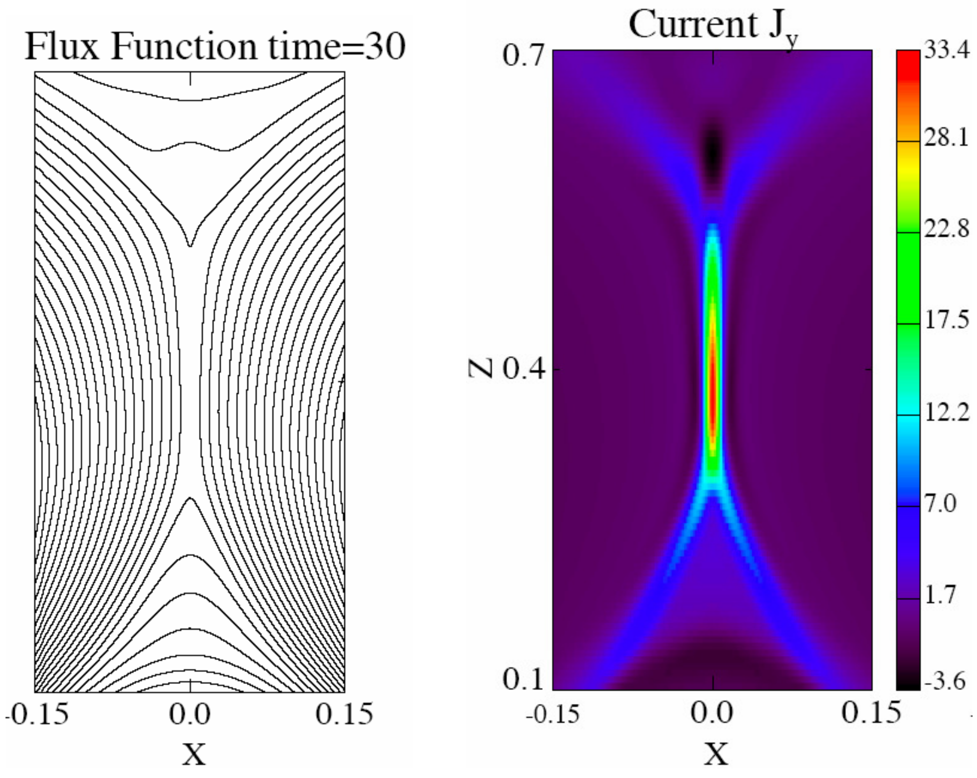
Conclusions

- Petschek model is not realizable in high-S plasmas, unless the resistivity is locally strongly enhanced at the X-point.
- In the absence of such anomalous enhancement, the reconnection layer evolves dynamically to form Y-points and realize a Sweet-Parker regime.

2D coronal loop : high-Lundquist number resistive MHD simulation



T = 0



T = 30

[Ma, Ng, Wang, and Bhattacharjee 1995]

Hall MHD (or Extended MHD) Model and the Generalized Ohm's Law

In high-S plasmas, when the width of the thin current sheet (Δ_η) satisfies

$$\Delta_\eta < c/\omega_{pi} \qquad \text{(or } \sqrt{\beta}c/\omega_{pi} \text{ if there is a guide field)}$$

"collisionless" terms in the generalized Ohm's law cannot be ignored.

Generalized Ohm's law (dimensionless form)

$$\mathbf{E} + \mathbf{v} \times \mathbf{B} = \frac{1}{S}\mathbf{J} + d_e{}^2 \frac{d\mathbf{J}}{dt} + \frac{d_i}{n}\left(\mathbf{J} \times \mathbf{B} - \nabla \bullet \overset{\leftrightarrow}{p}_e\right)$$

Electron skin depth $d_e \equiv L^{-1}\left(c/\omega_{pe}\right)$

Ion skin depth $d_i \equiv L^{-1}\left(c/\omega_{pi}\right)$

Electron beta β_e

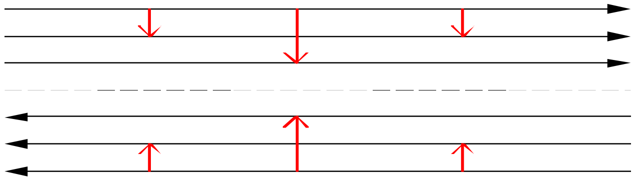
Onset of fast Hall reconnection in high-Lundquist-number systems: standard view

- As the original current sheet thins down, it will inevitably reach kinetic scales, described by a generalized Ohm's law (including Hall current and electron pressure gradient).
- A criterion has emerged from Hall MHD (or two-fluid) models, and has been tested carefully in laboratory experiments (MRX at PPPL). The criterion is:

  $\delta_{SP} < d_i$ (Ma and Bhattacharjee 1996, Cassak et al. 2005)

Forced Magnetic Reconnection Due to Inward Boundary Flows

Magnetic field

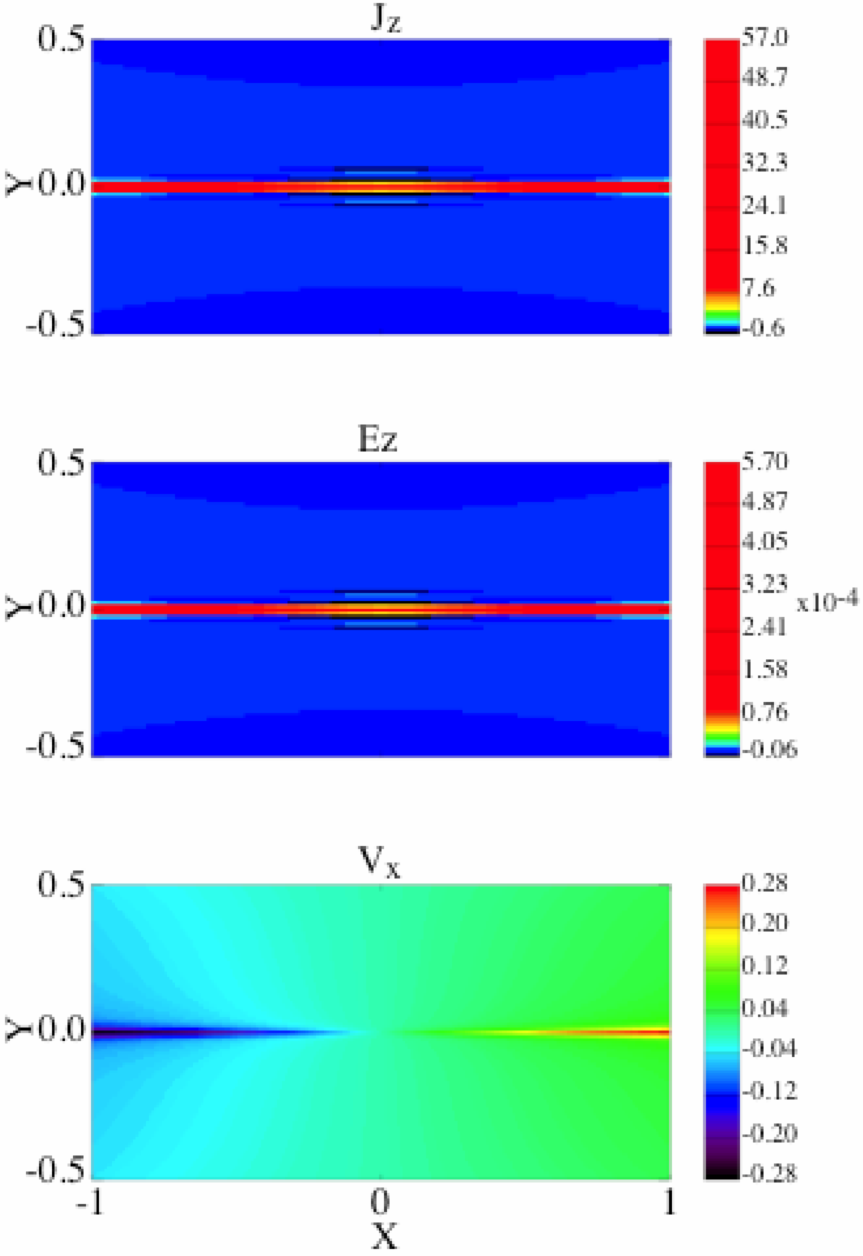


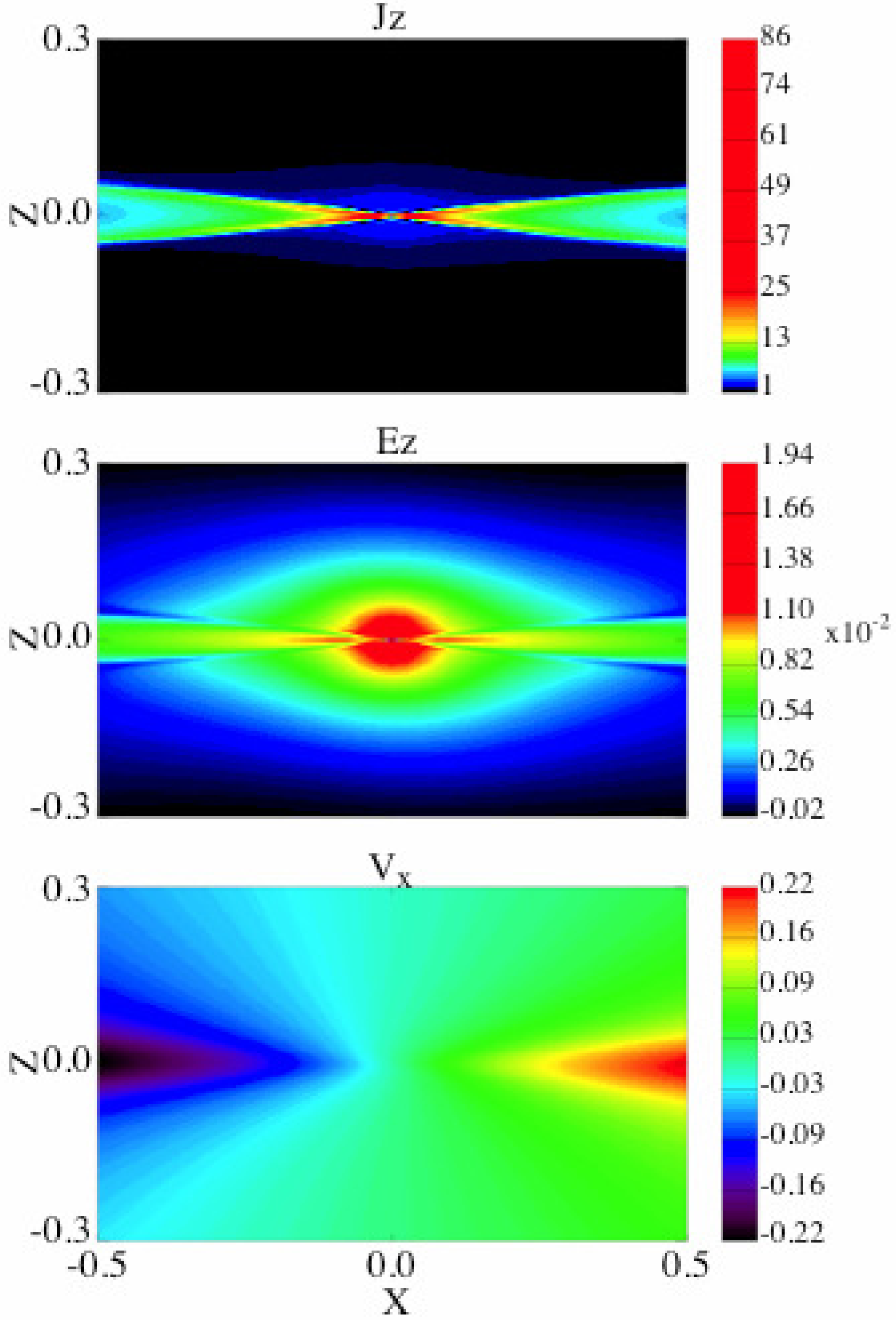
$$\mathbf{B} = \hat{\mathbf{x}} B_P \tanh z/a + \hat{\mathbf{z}} B_T$$

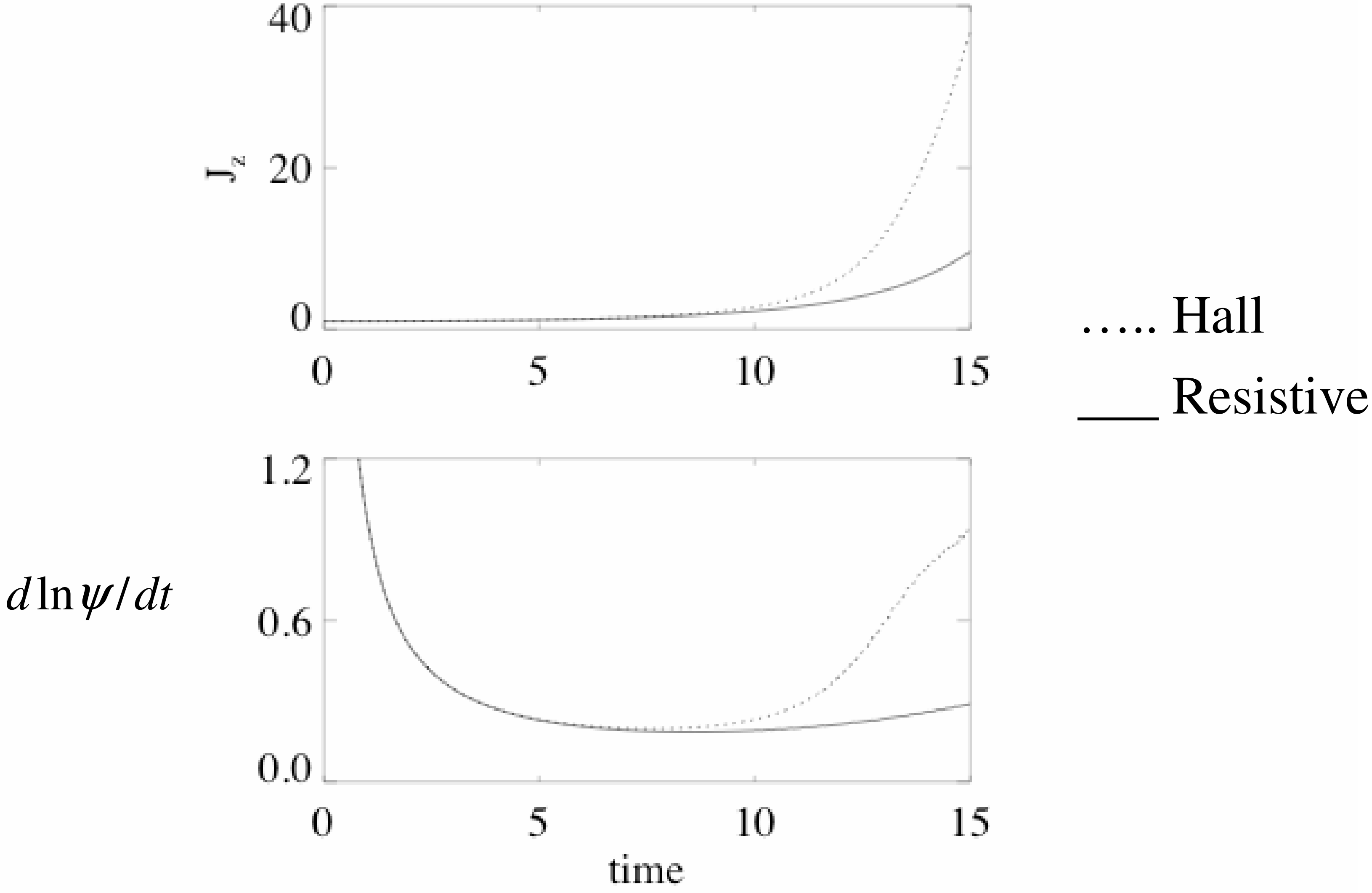
Inward flows at the boundaries

$$\mathbf{v} = \mp V_0 (1 + \cos kx)\hat{\mathbf{y}} \quad , \quad \Delta' < 0$$

Two simulations: Resistive MHD versus Hall MHD [Ma and Bhattacharjee 1996]


Jz
0.5
Y 0.0
-0.5
57.0
48.7
40.5
32.3
24.1
15.8
7.6
-0.6
Ez
0.5
Y 0.0
-0.5
5.70
4.87
4.05
3.23
2.41
1.58
0.76
-0.06
x10-4
Vx
0.5
Y 0.0
-0.5
-1
0
1
X
0.28
0.20
0.12
0.04
-0.04
-0.12
-0.20
-0.28


Jz
0.3
Z0.0
-0.3
86
74
61
49
37
25
13
1
Ez
0.3
Z0.0
-0.3
1.94
1.66
1.38
1.10
0.82
0.54
0.26
-0.02
x10^{-2}
V$_x$
0.3
Z0.0
-0.3
0.22
0.16
0.09
0.03
-0.03
-0.09
-0.16
-0.22
-0.5
0.0
0.5
X


40
20
0
J_z
0
5
10
15
….. Hall
___ Resistive
1.2
0.6
0.0
$d \ln \psi / dt$
0
5
10
15
time

Transition from Collisional to Collisionless Regimes in MRX

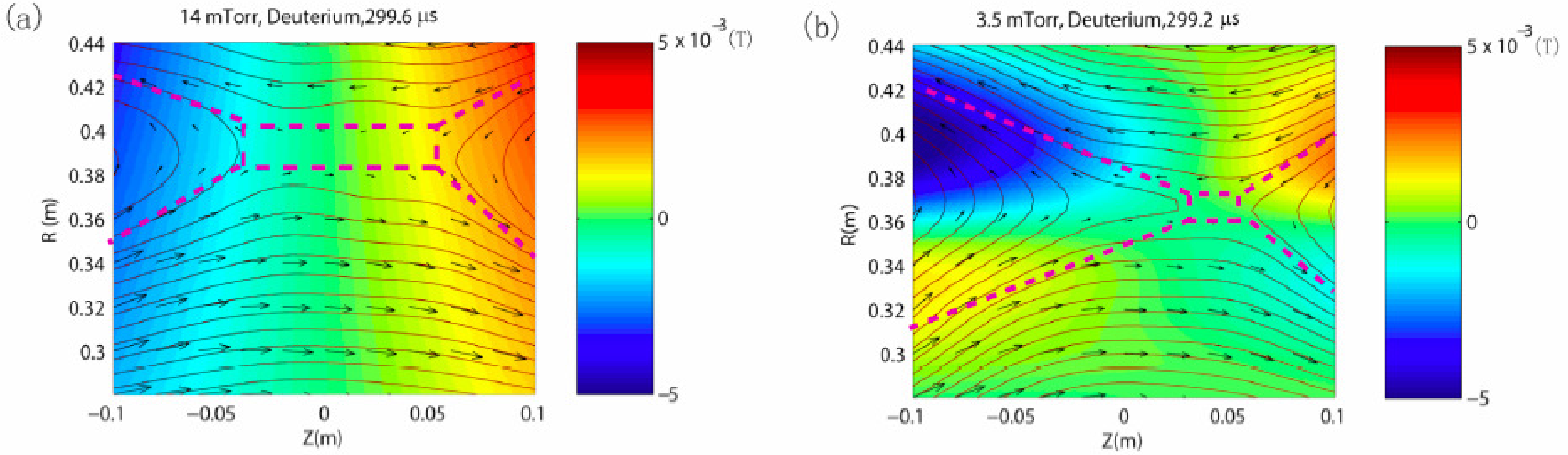
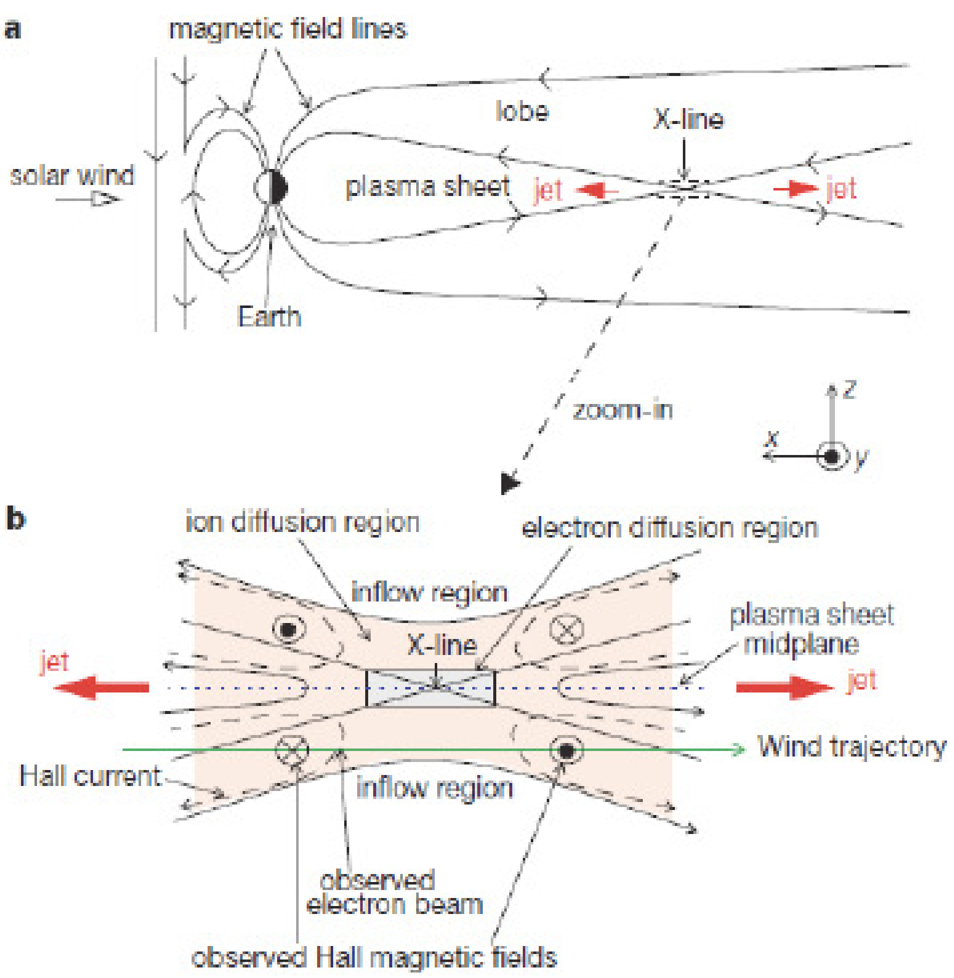
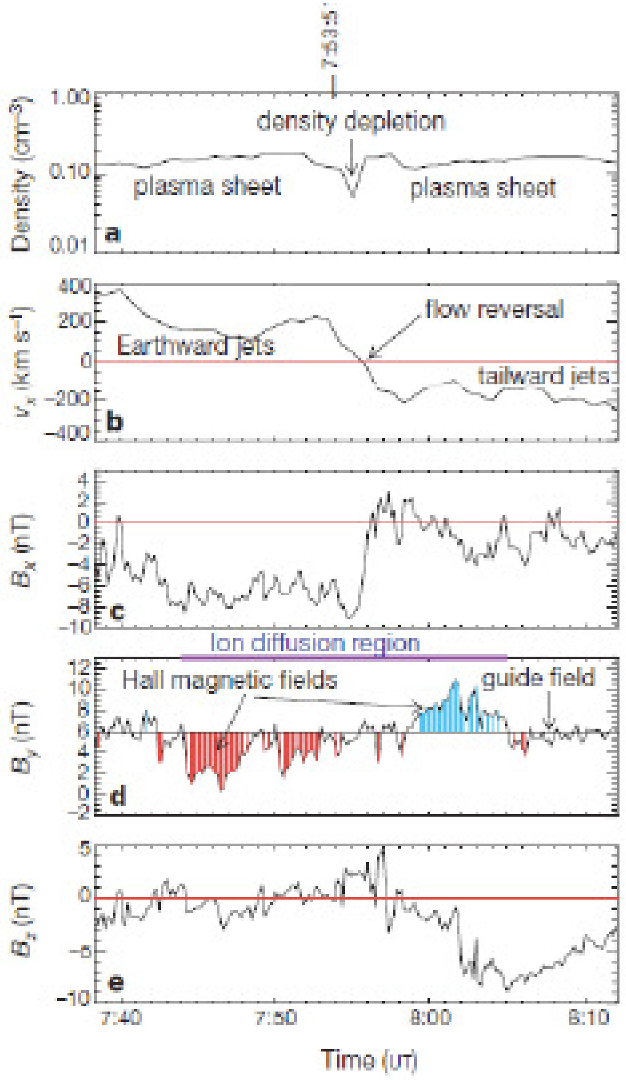


Fig.2; *Comparison of neutral sheet configuration described by measured magnetic field vectors and flux counters for high (collisional) and low density cases; (a) Collisional regime (λ_{mfp} ~1mm << δ)); (b) Nearly collisionless regime (λ_{mfp} ~1cm ~ δ). Out-of plane fields are depicted by the color codes ranged -50 G <Bt <50 G.*

Similar results from VTF (Egedal et al. 2006)





[Øieroset et al., 2001]

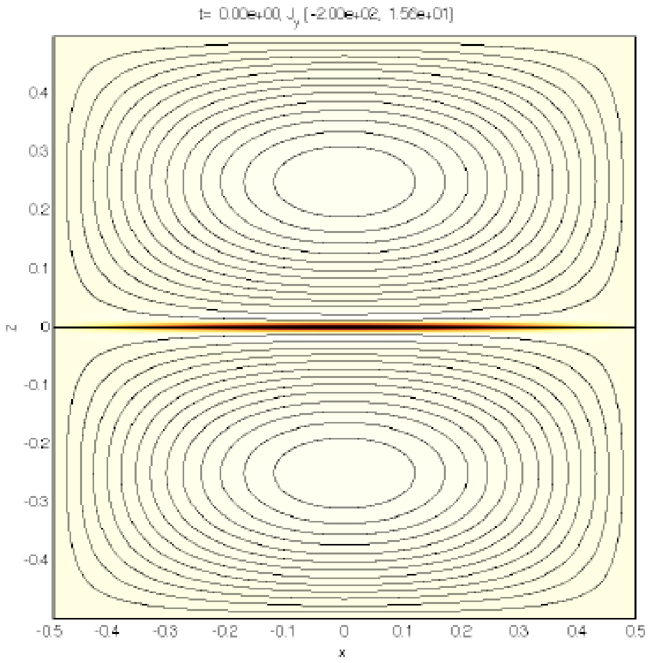
Some key questions

- What is the structure of the electron diffusion region?
- How extended are thin current sheets? Are they stable? If they are unstable, how do they break up?
- What role does reconnection play in accelerating particles? Are enough particles accelerated (the problem of numbers)?
- What is the nature of 3D reconnection?

Instability of Extended Thin Current Sheets for Large Systems

- Extended thin current sheets of high Lundquist number are unstable to a super-Alfvenic tearing instability----the "plasmoid instability". Although the instability has been known for some time, its scaling properties have been worked out fairly recently. Recent theory (Loureiro et al. 2007, Bhattacharjee et al. 2009) predicts $\gamma\tau_A \sim S^{1/4}$ and number of plasmoids $\sim S^{3/8}$
- In the nonlinear regime, the reconnection rate becomes nearly independent of the Lundquist number, and is much larger than the Sweet-Parker rate.

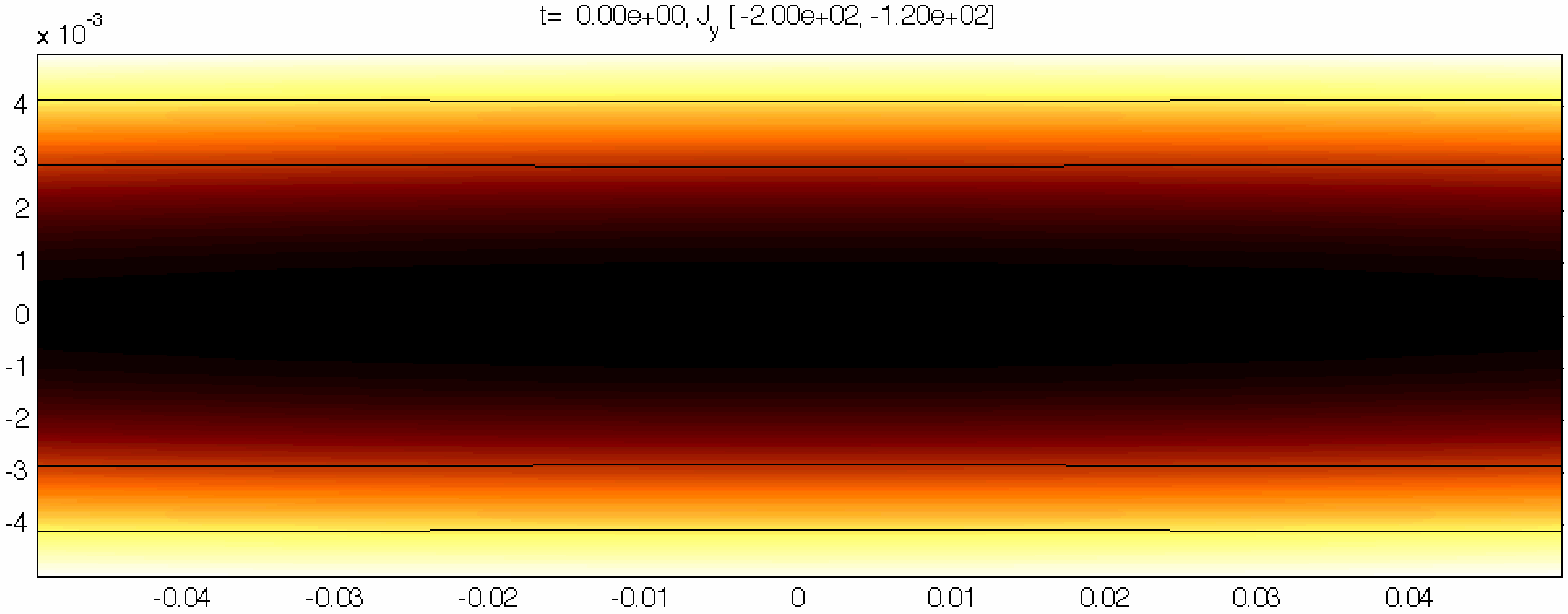
Simulation Setup



A Low Amplitude Random Forcing is Added

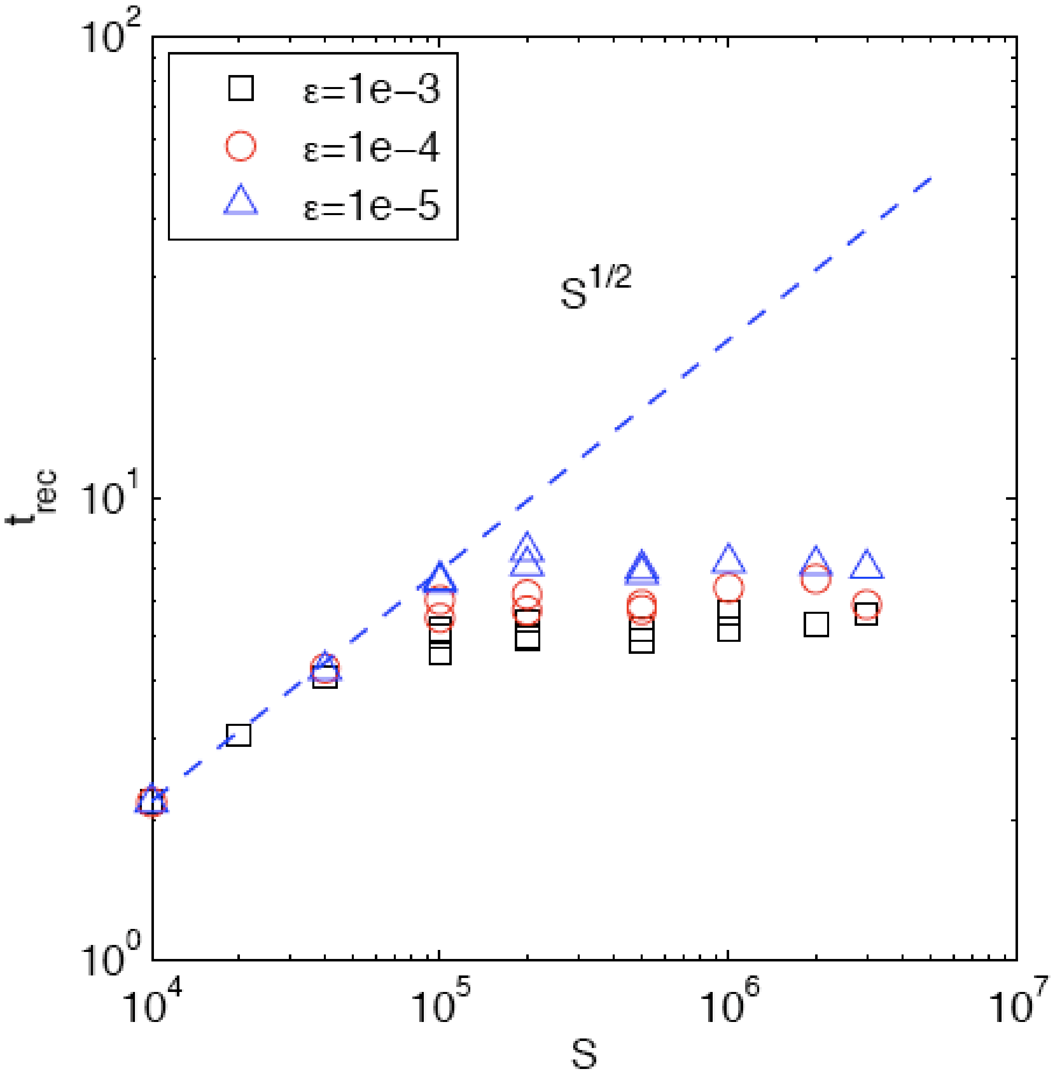
$$\partial_t(\rho \mathbf{v}) + \nabla \cdot (\rho \mathbf{v}\mathbf{v}) = -\nabla p - \nabla\psi\nabla^2\psi + \epsilon \mathbf{f}(\mathbf{x}, t)$$

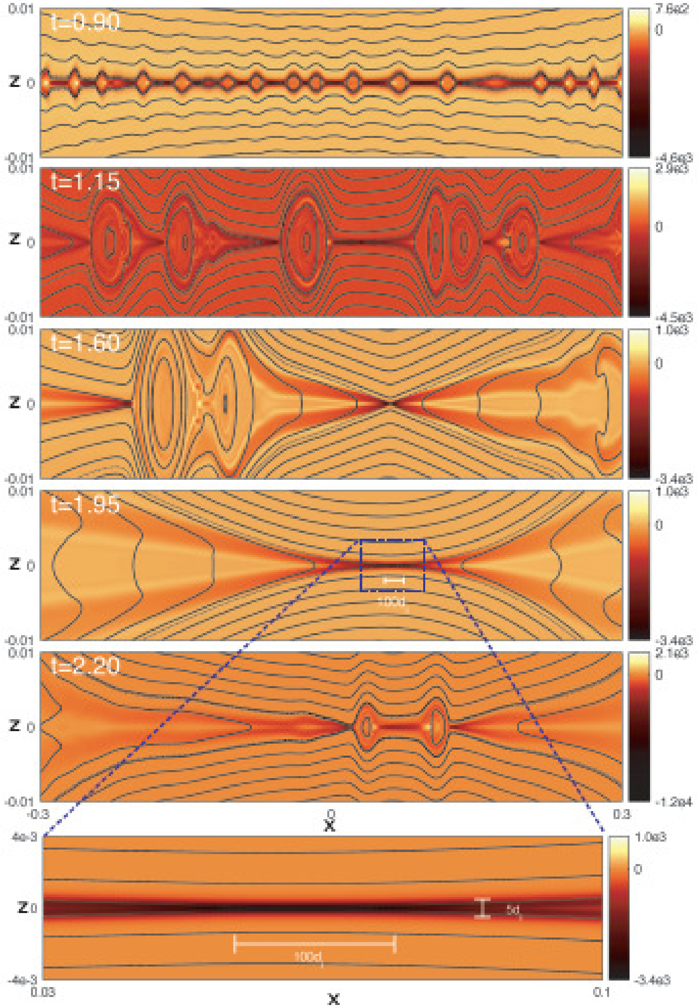
$$\langle f_i(\mathbf{x}, t) f_j(\mathbf{x}', t')\rangle \sim \delta_{ij}\delta(\mathbf{x} - \mathbf{x}')\delta(t - t')$$



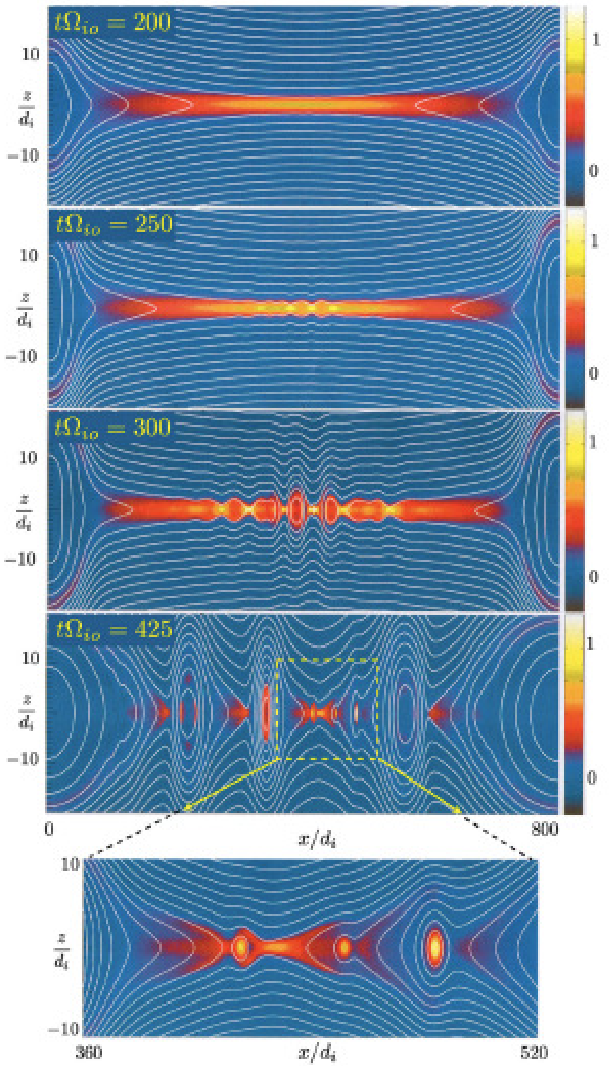
Bhattacharjee et al. 2009

Reconnection Time of 25% of Initial Flux





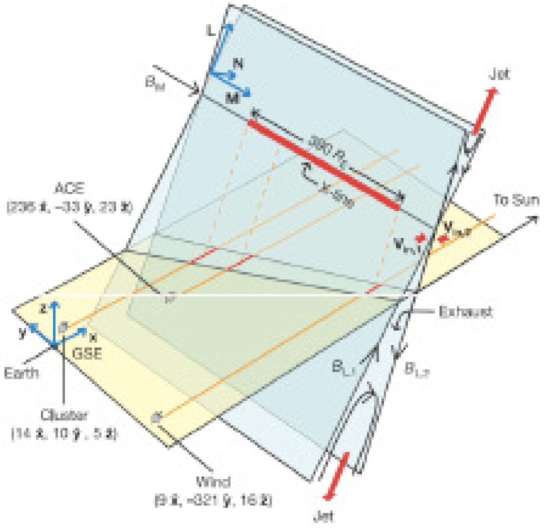
Run B, resistive Hall



Daughton et al. (2009), PIC

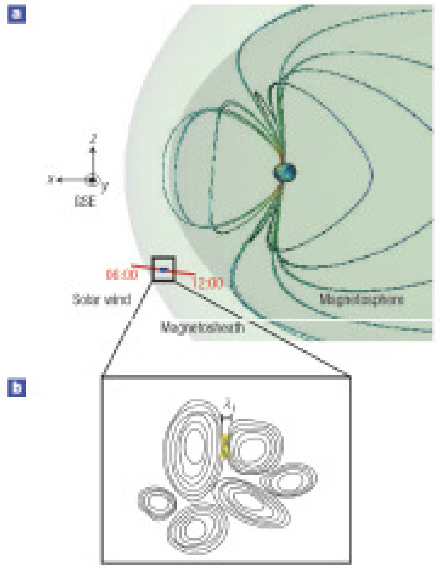
Largest 2D Hall MHD simulation: Huang, Bhattacharjee, and Sullivan, 2010

Solar Wind



- Reconnection observed across current sheets in solar wind
- Also observed in magnetosheath (triggered by shock crossing)
- [Phan et al., 2006]

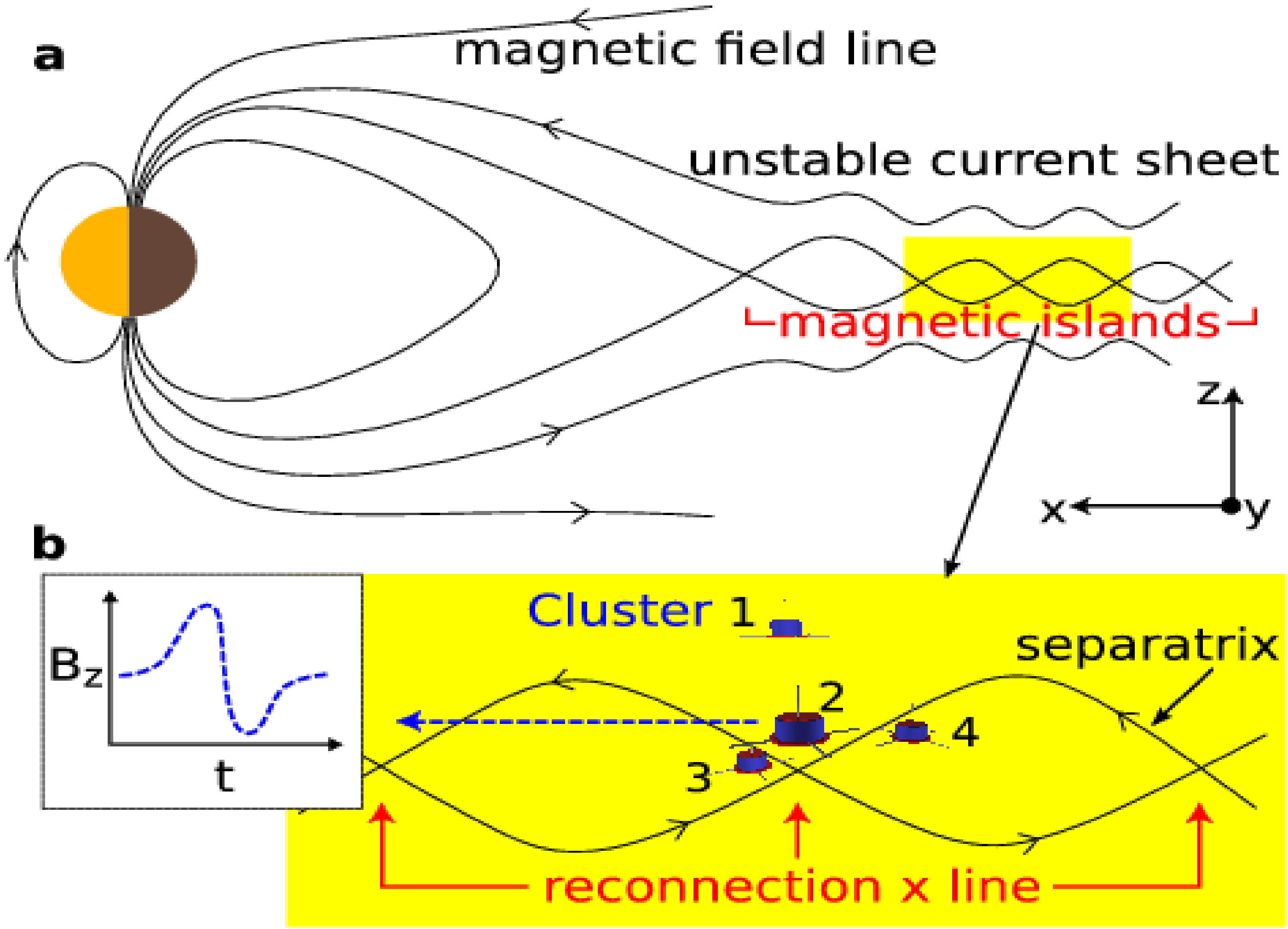
Magnetosheath



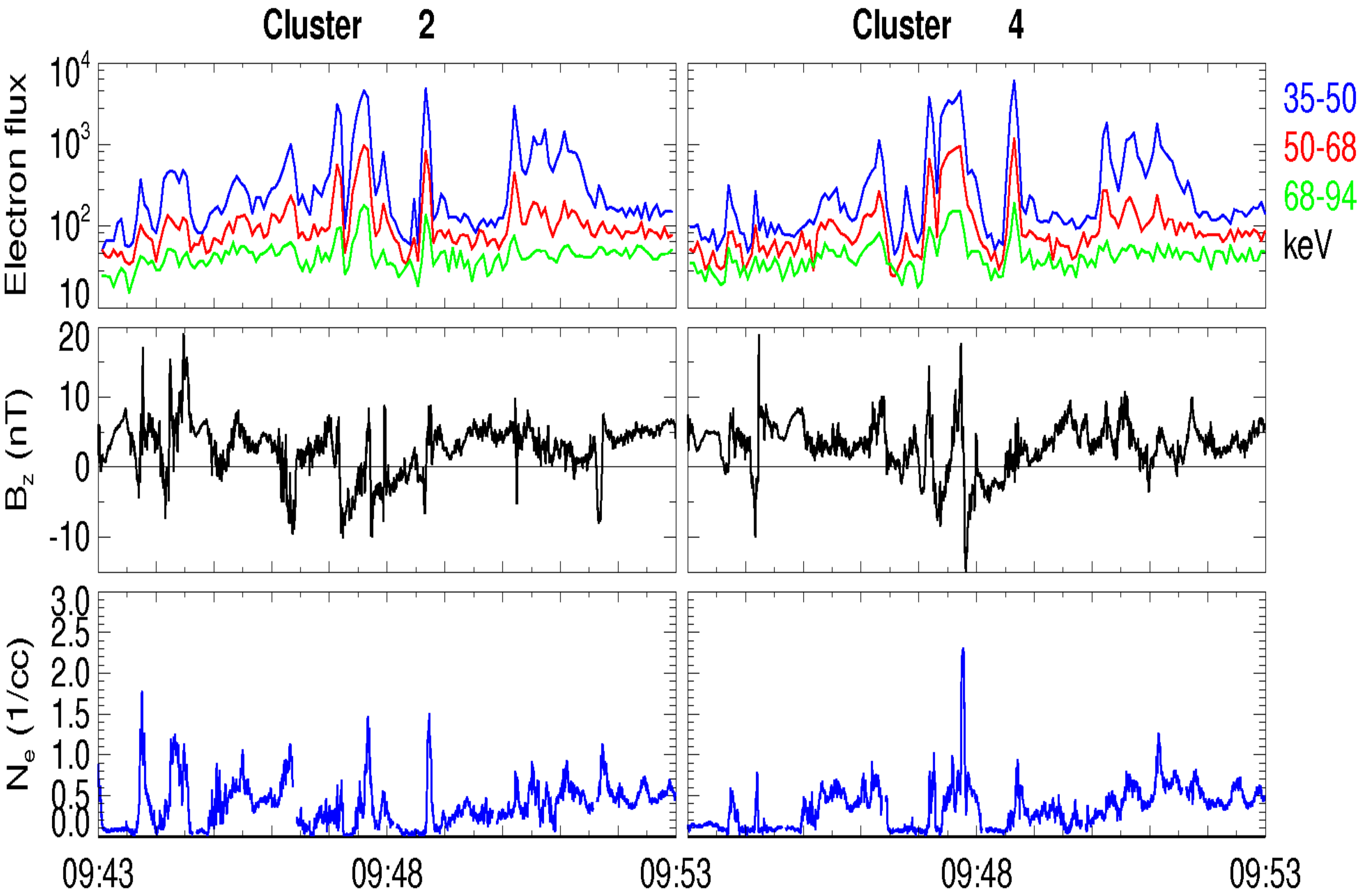
- Small scale reconnection between current sheets in the turbulent magnetosheath plasma
- [Retinò et al., 2007]

Fluxes of energetic electrons peak within magnetic islands

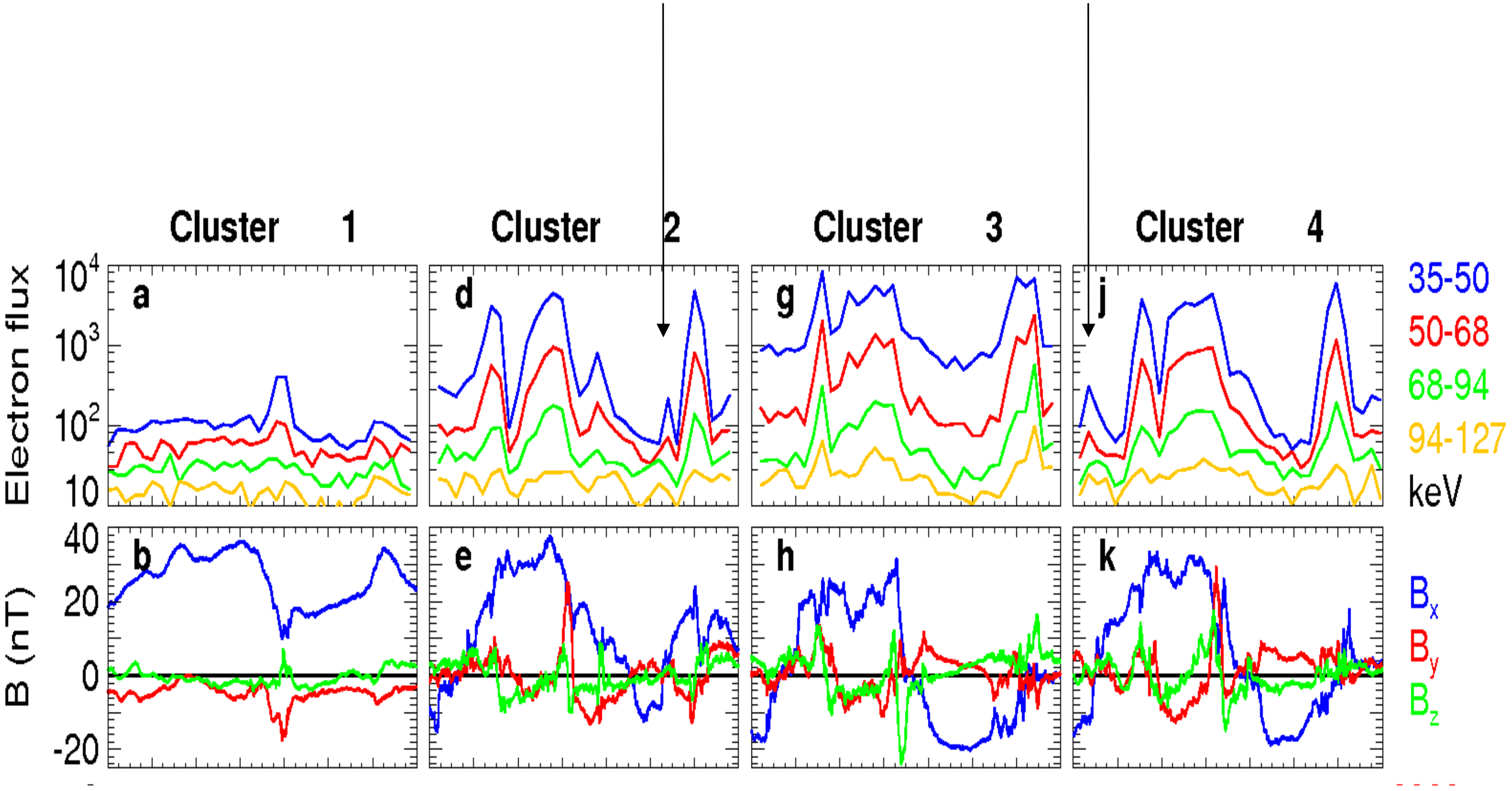
[Chen et al., Nature Phys., 2008]



e bursts & bipolar Bz & Ne peaks
~10 islands within 10 minutes



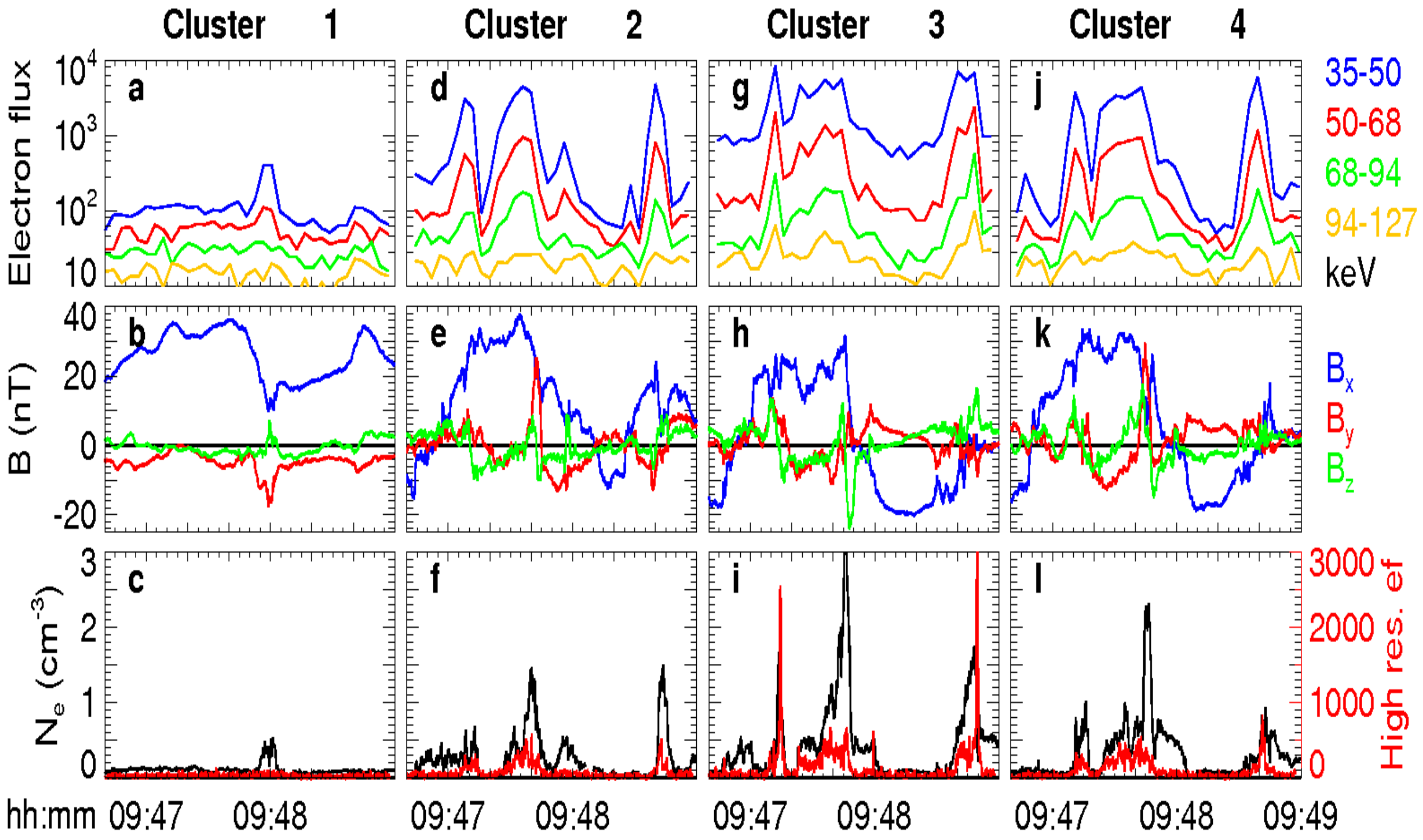
At a reconnection layer (r) and a separatrix (s), energetic electrons with much lower energy and flux are observed.



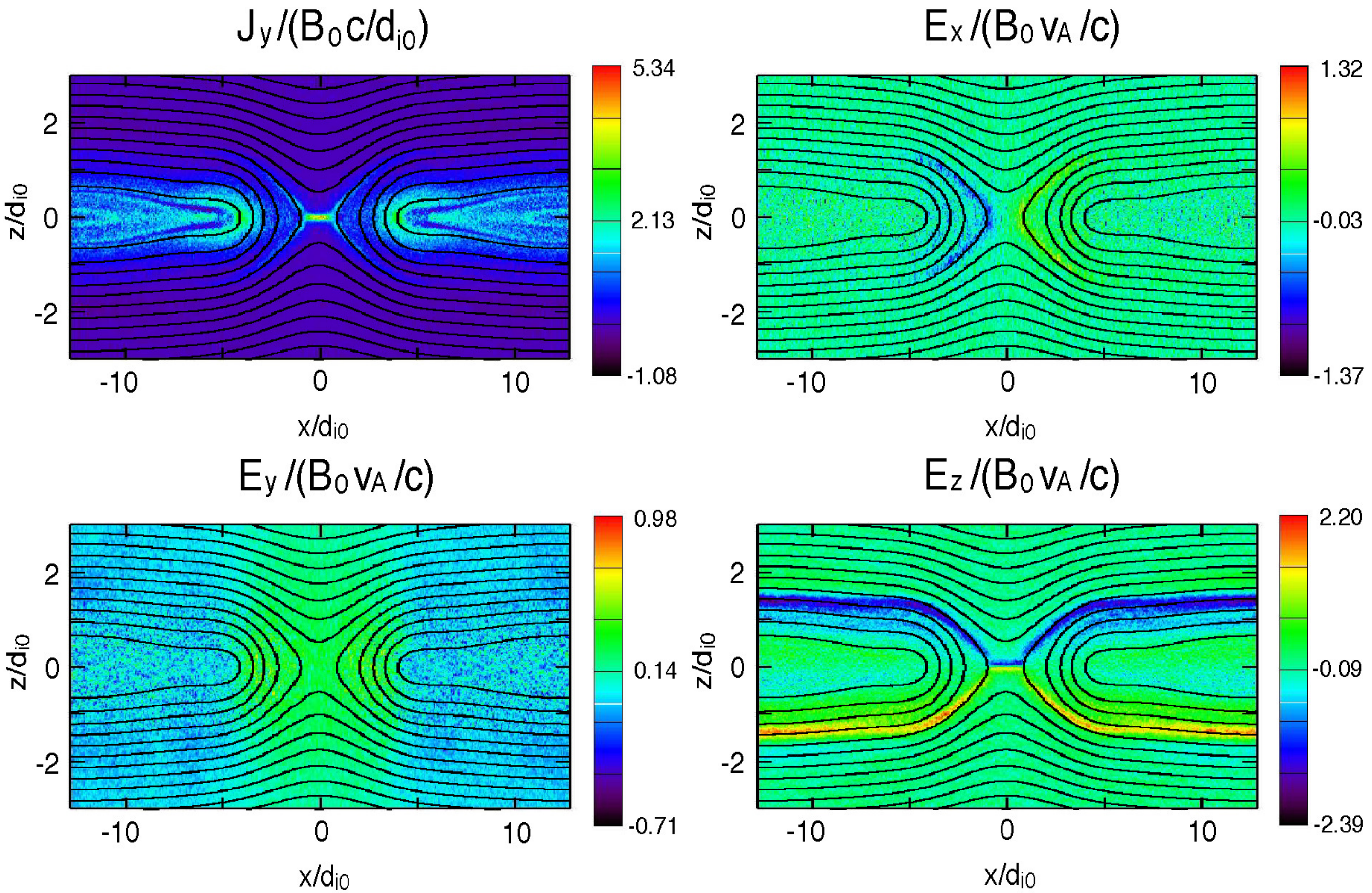
r

s

Energetic electron fluxes peak at density compression within islands



E-normal (Ez) >> Ex, Ey

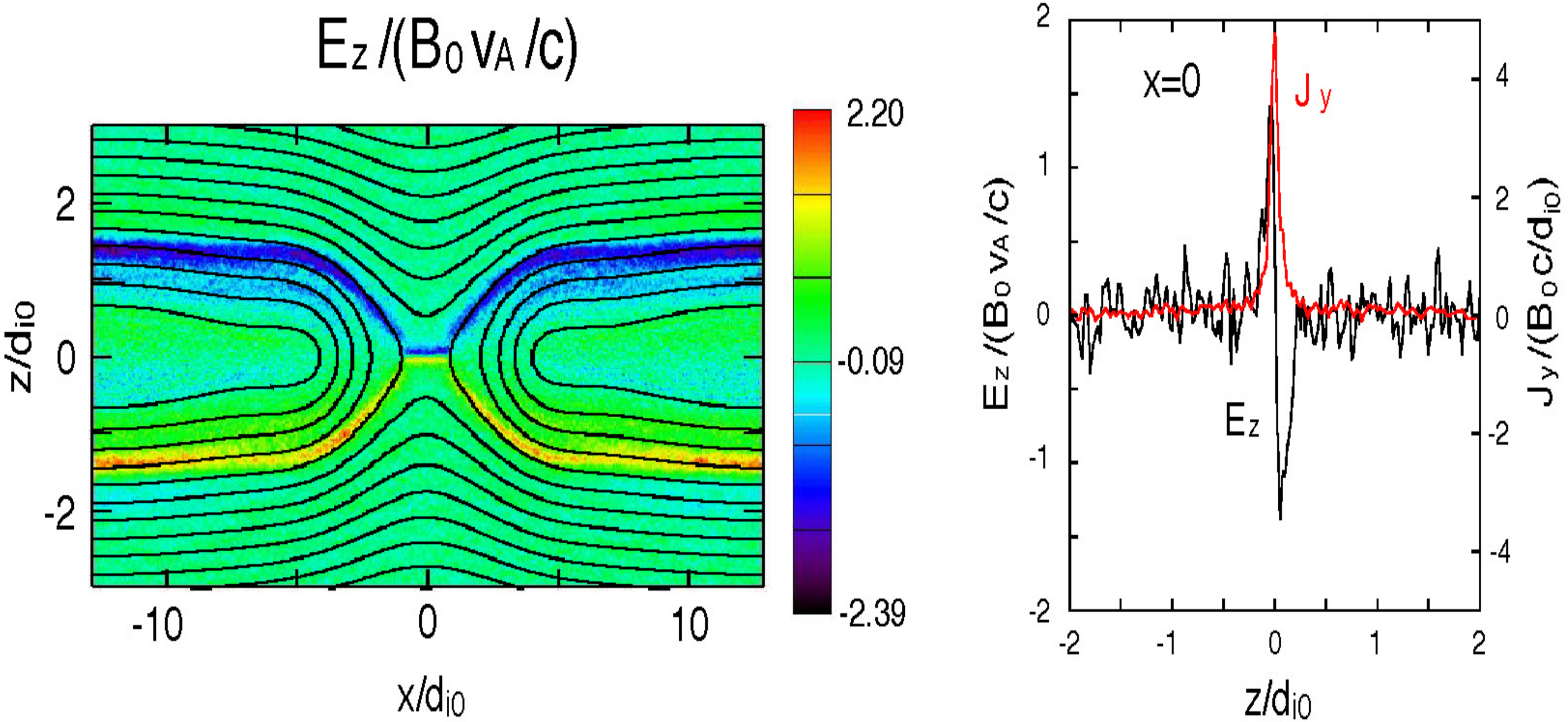


$$L_x \times L_z = 1024 \times 512 \ (25.6 \times 12.8 d_i)$$

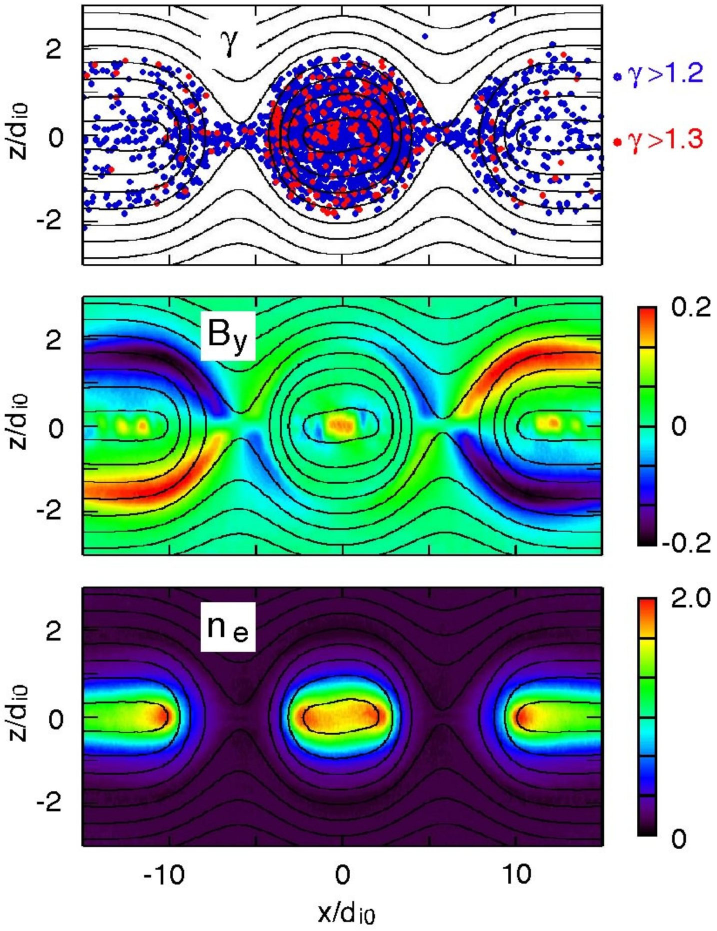
$$m_i / m_e = 800 ; T_i = 5T_e ; B_{y0} = 0$$

[2D PIC,
Naoki Bessho]

Co-location of the electron current sheet (ECS) and the Ez layer at x~0

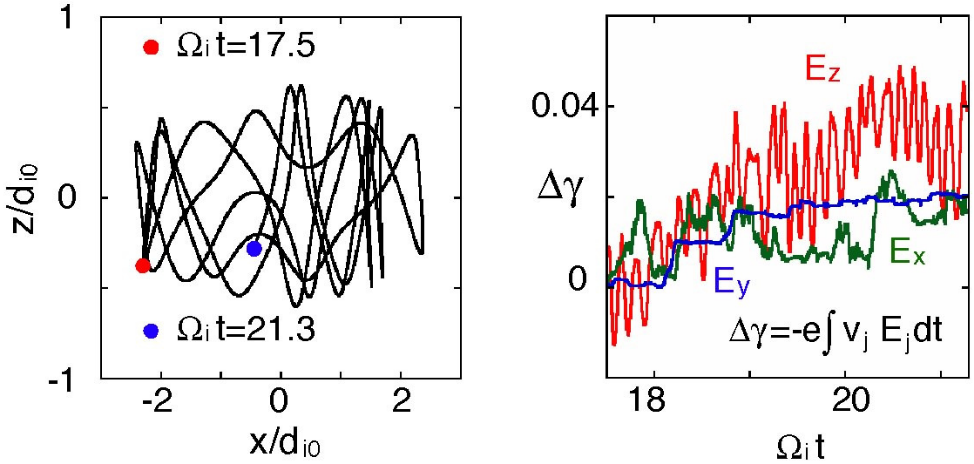


Electron acceleration in magnetic islands

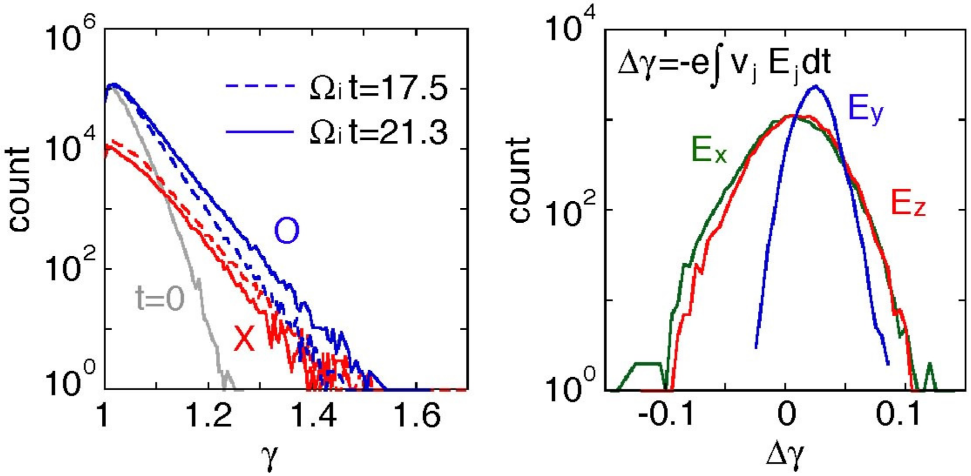


Energetic electrons are produced in a magnetic island between two X-lines.

[Bessho et al., 2008]



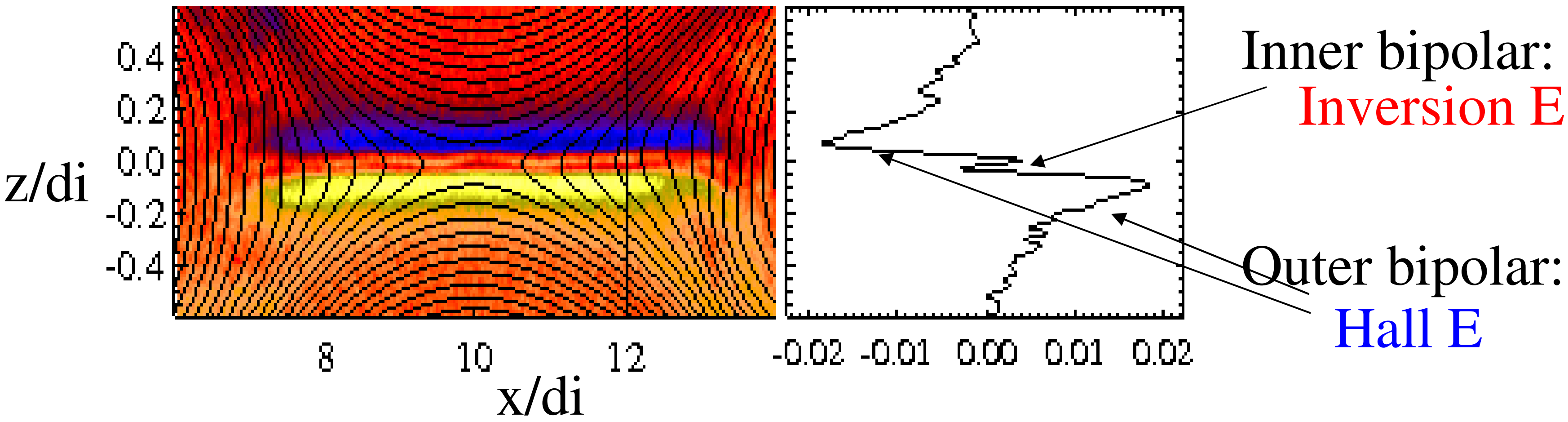
Electrons are accelerated by the in-plane electric field through wave particle interaction.



$\gamma > 1.2$, $17.5 < \Omega_i t < 21.3$, at O point

The most energetic particles are generated in the magnetic island by the in-plane electric fields.

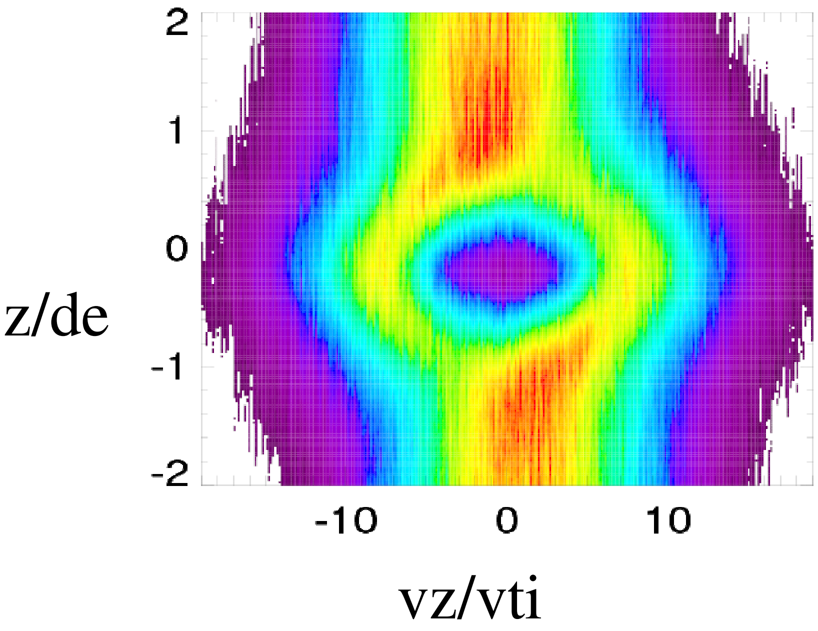
At even finer scales than the width of the electron current sheet:
The layer of inversion E and electron phase-space hole



Inner bipolar:
Inversion E

Outer bipolar:
Hall E

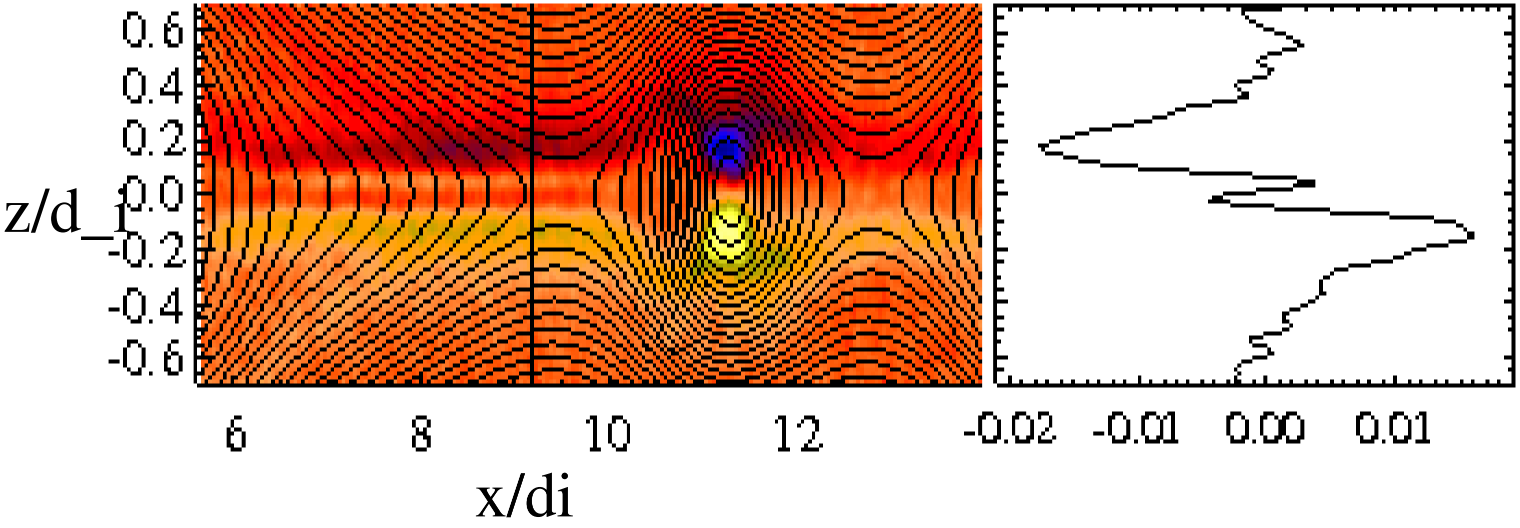
Spatial width of the hole and inversion E layer is about 1 initial de, less than a local de.



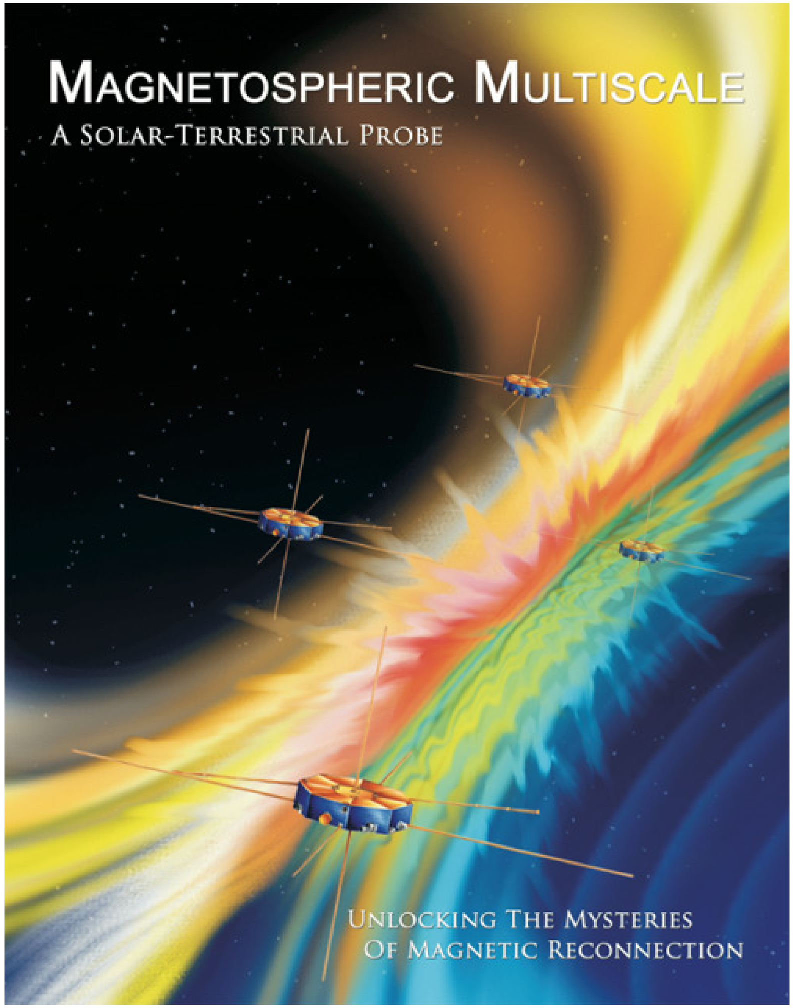
[Chen et al., Phys. Plasmas, submitted]

The layer of inversion E and electron phase-space hole

Shortly after a secondary island is formed at the ECS...



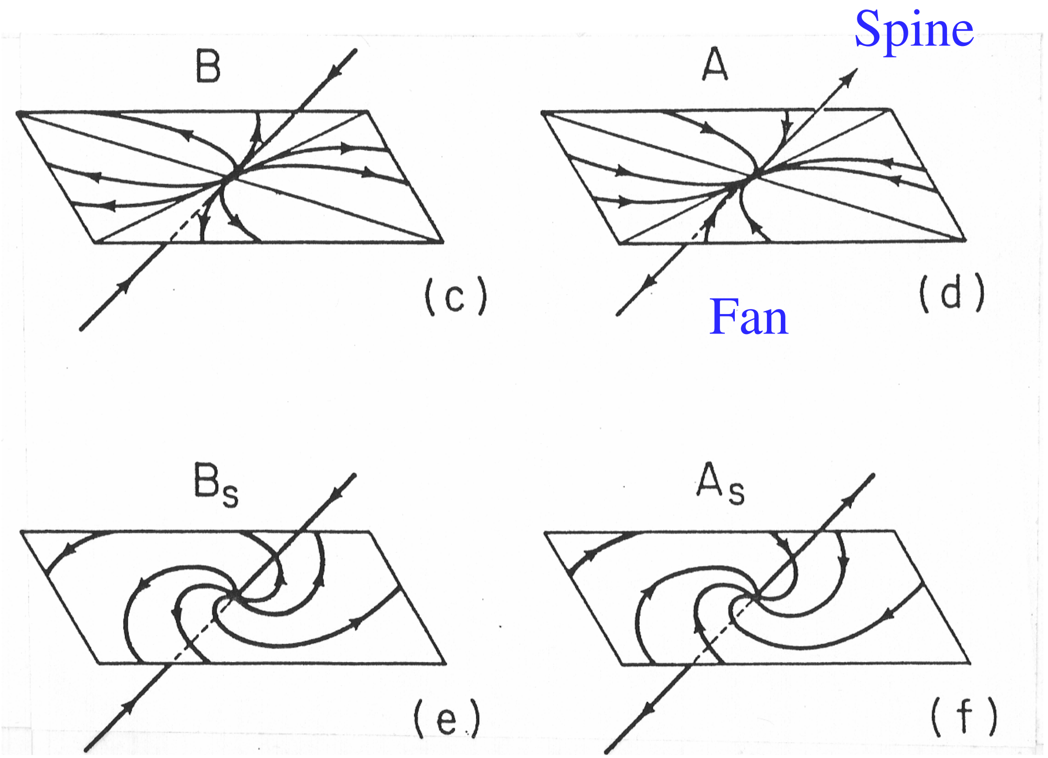
MMS will be able to resolve the inversion E and e-hole.



3D E field:
time resolution ~1ms
→ 0.01 de (1 de~10 km in the ECS),
assuming 100 km/s
boundary motion

Full electron distribution:
Time resolution ~ 30 ms
→ 0.3 de

Magnetic nulls in 3D play the role of X-points in 2D



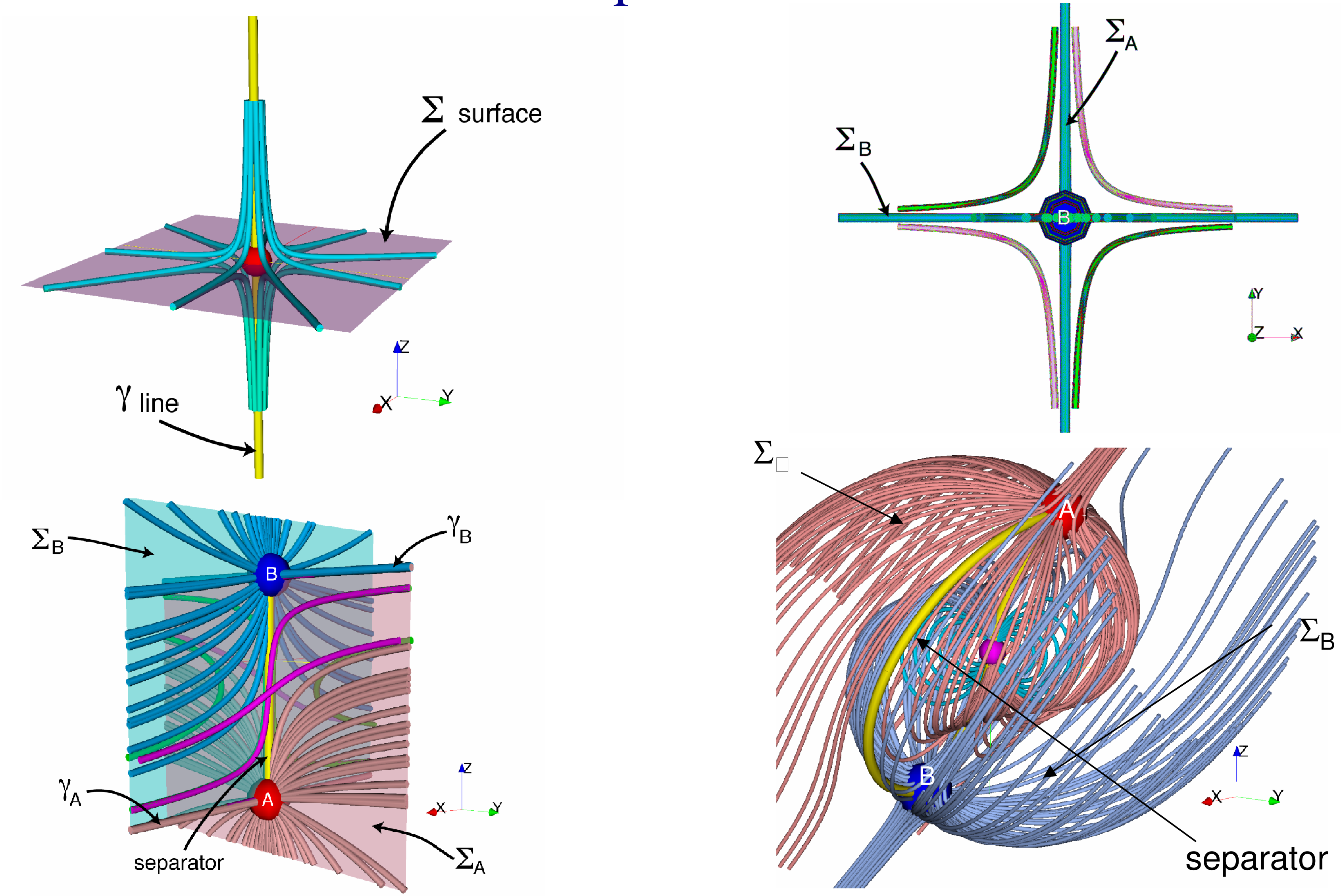
[Greene 1988, Lau and Finn 1990]

Towards a fully 3D model of reconnection

- Greene (1988) and Lau and Finn (1990): in 3D, a topological configuration of great interest is one that has magnetic nulls with loops composed of field lines connecting the nulls.

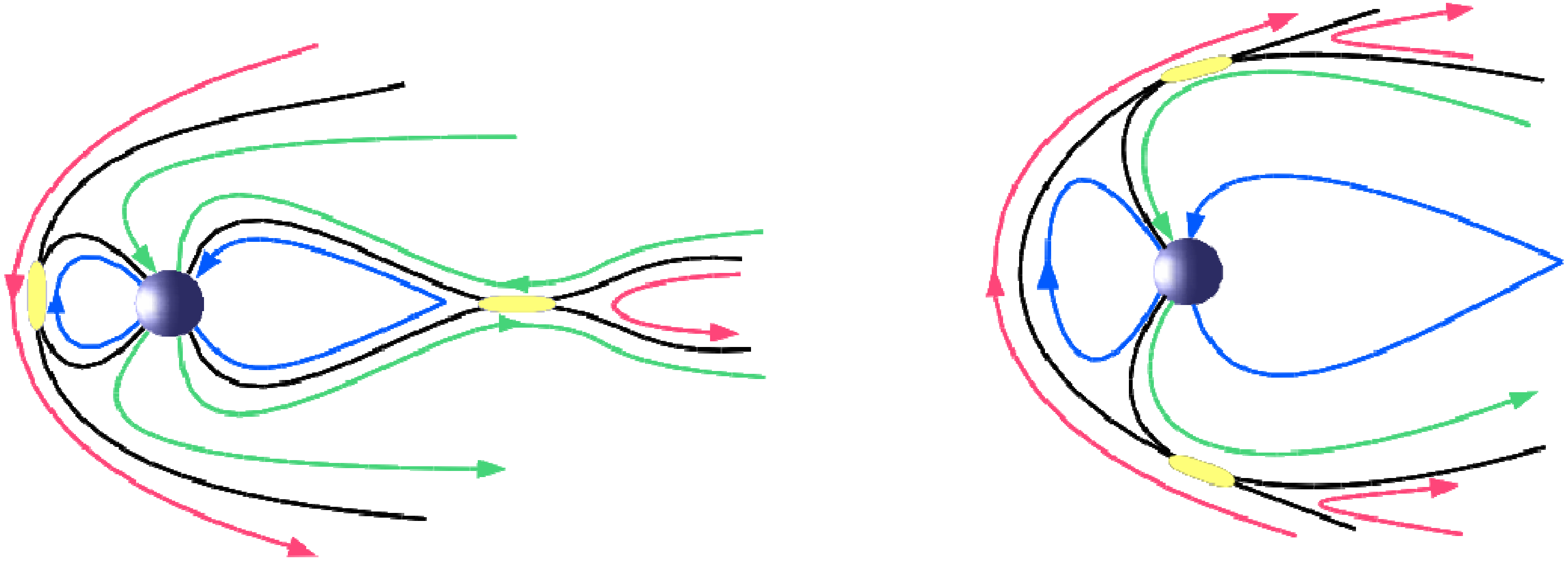
- The null-null lines are called separators, and the “spines” and “fans” associated with them are the *global* 3D separatrices where reconnection occurs.

3D Separatrices



Lau, Y.-T. and J. M. Finn, Three-dimensional kinematic reconnection in the presence of field nulls and closed field lines, Ap. J., 350, 672, 1990.

Dungey's Model for Southward and Northward IMF

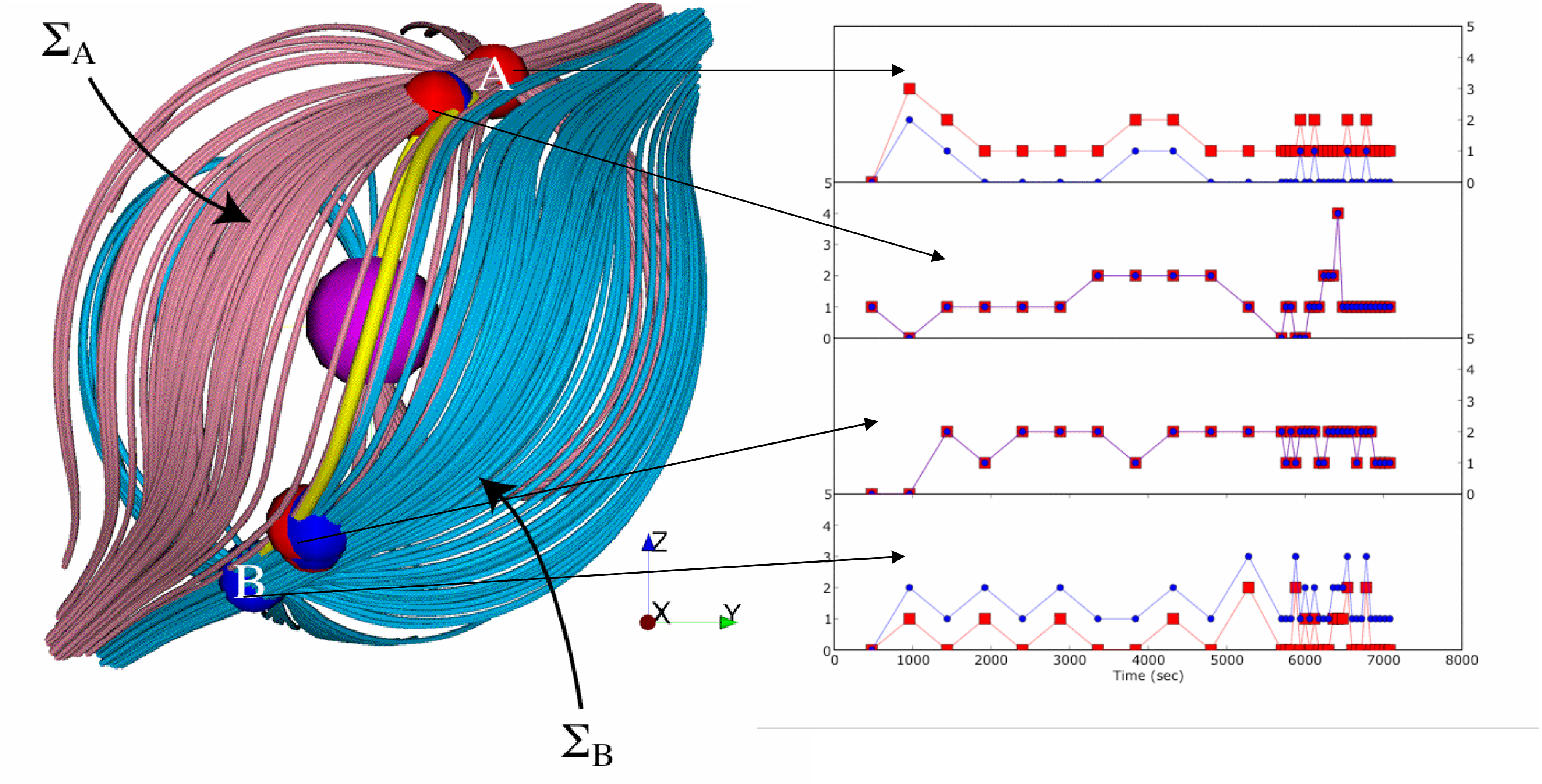


"Magnetopause phenomena are more complicated as a result of merging. This is why I no longer work on the magnetopause." -- *J. W. Dungey*

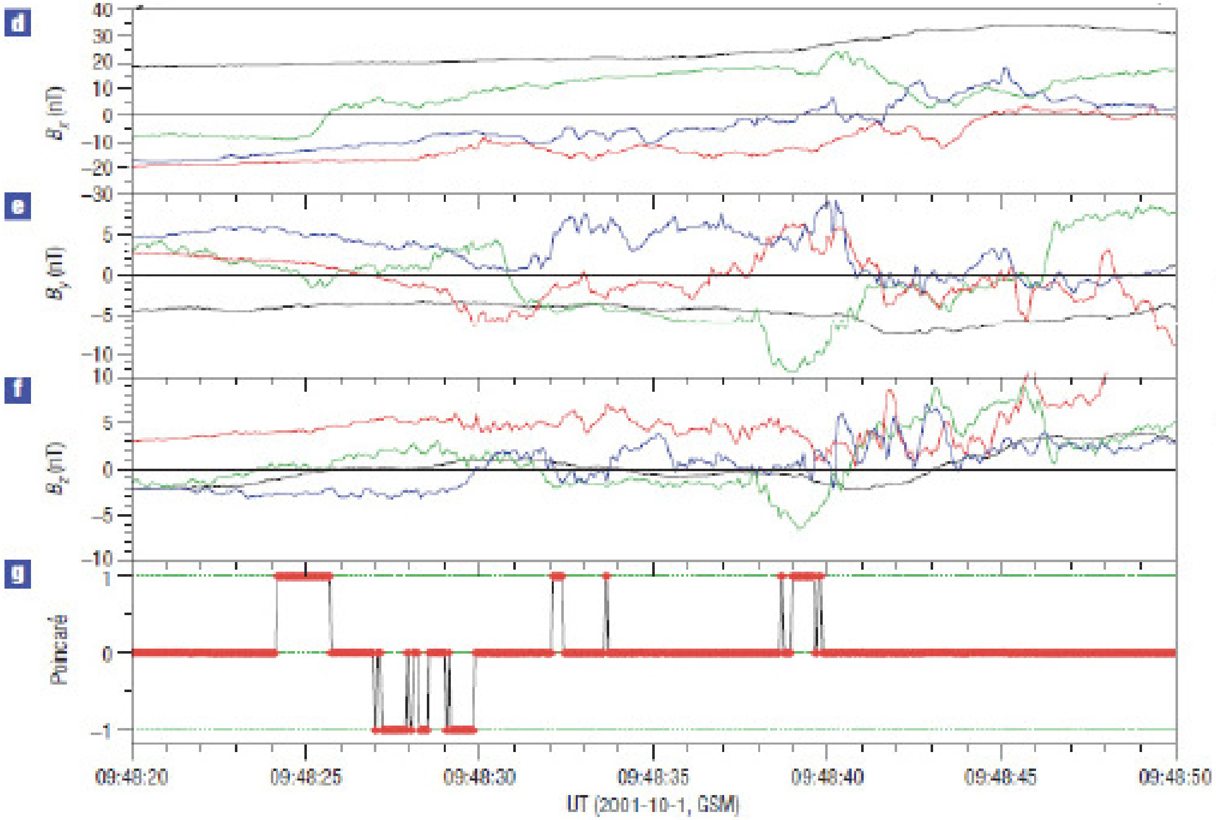
[Dungey 1961, 1963]

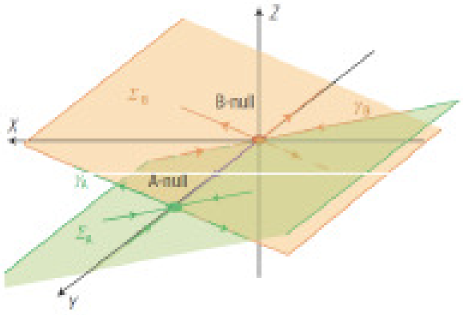
Tracking Magnetic Nulls in OpenGGCM Simulations

Greene, J., Locating three-dimensional roots by a bisection method, J. Comp. Phys., 98, 191-198, 1992.



Detection of magnetic nulls





[Xiao et al., 2007]

Anti-parallel versus component reconnection: a selection effect?

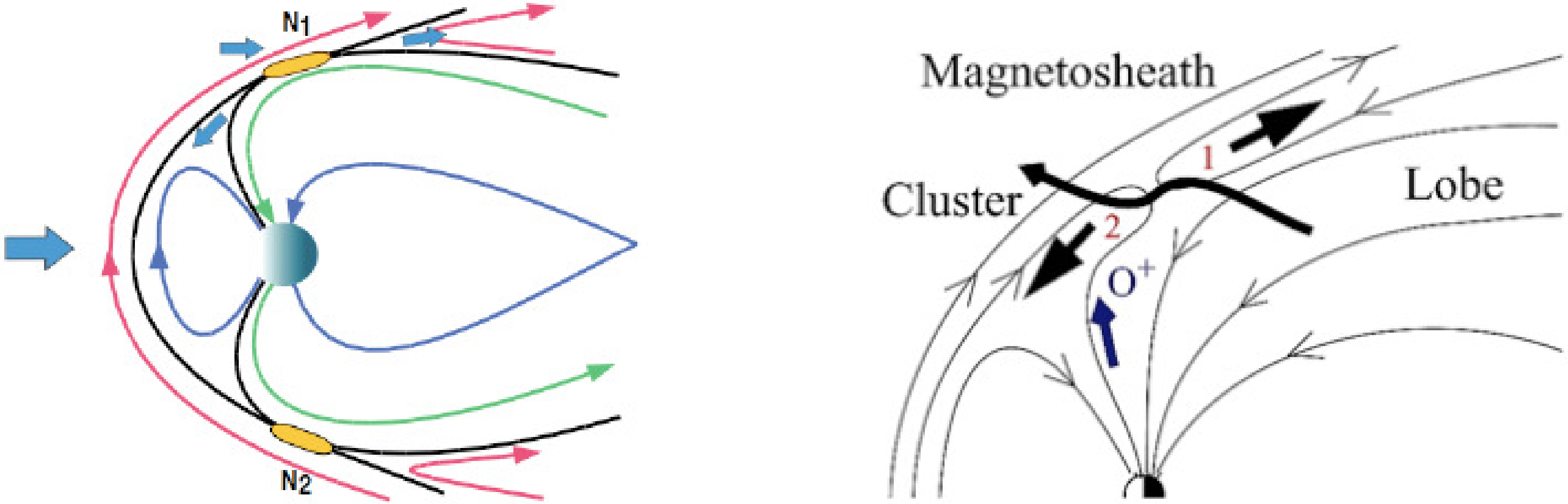
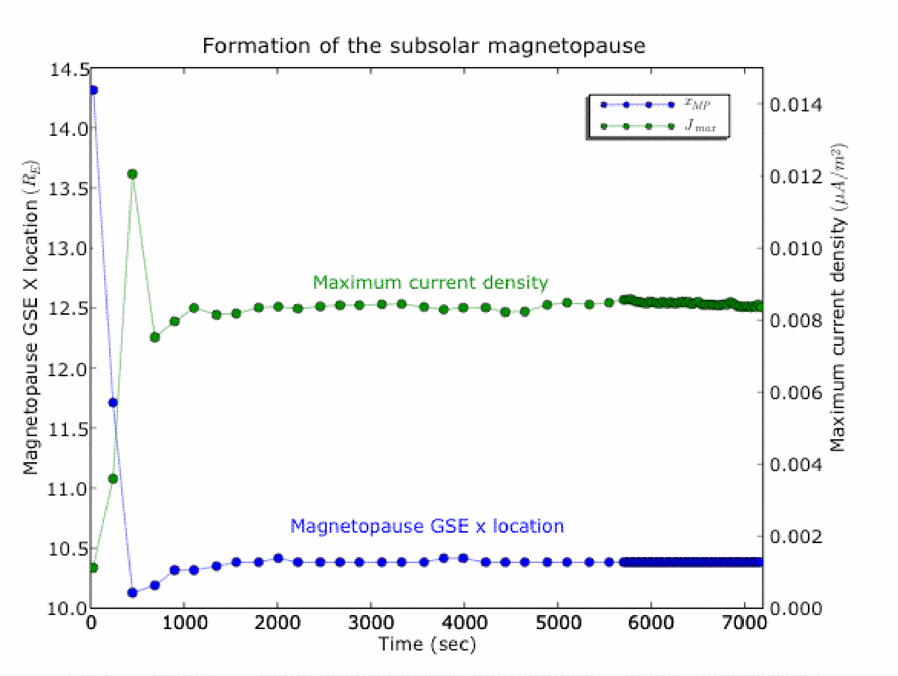
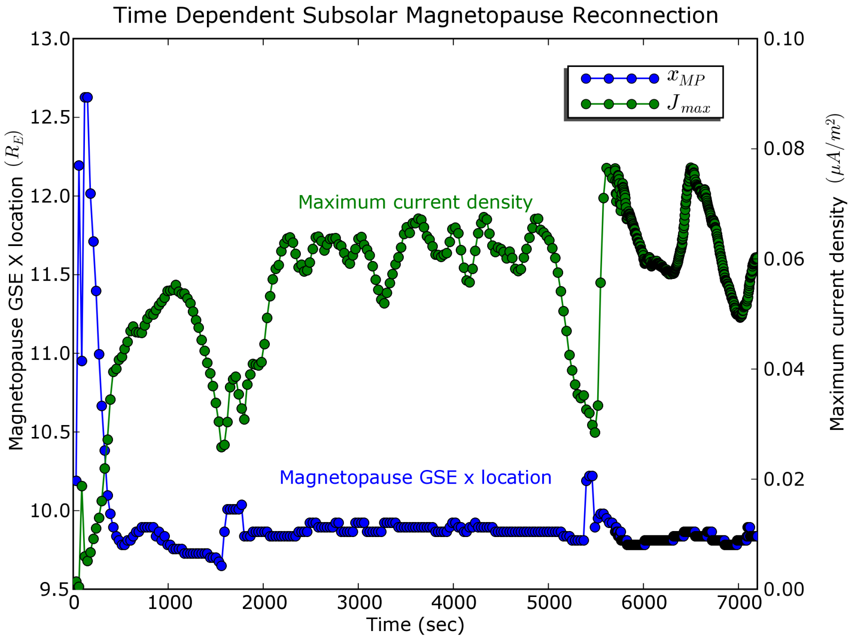


Figure 1. Spacecraft data are often interpreted in the context of the 2D version of Dungey's [1963] reconnecting magnetosphere model (left panel). For example, the right panel (taken from Phan et al. [2003]) shows how Cluster observations of bipolar flows near magnetopause rotational discontinuities are interpreted as signatures of reconnection localized at an X-type null poleward of the cusp.

Northward vs. Southward

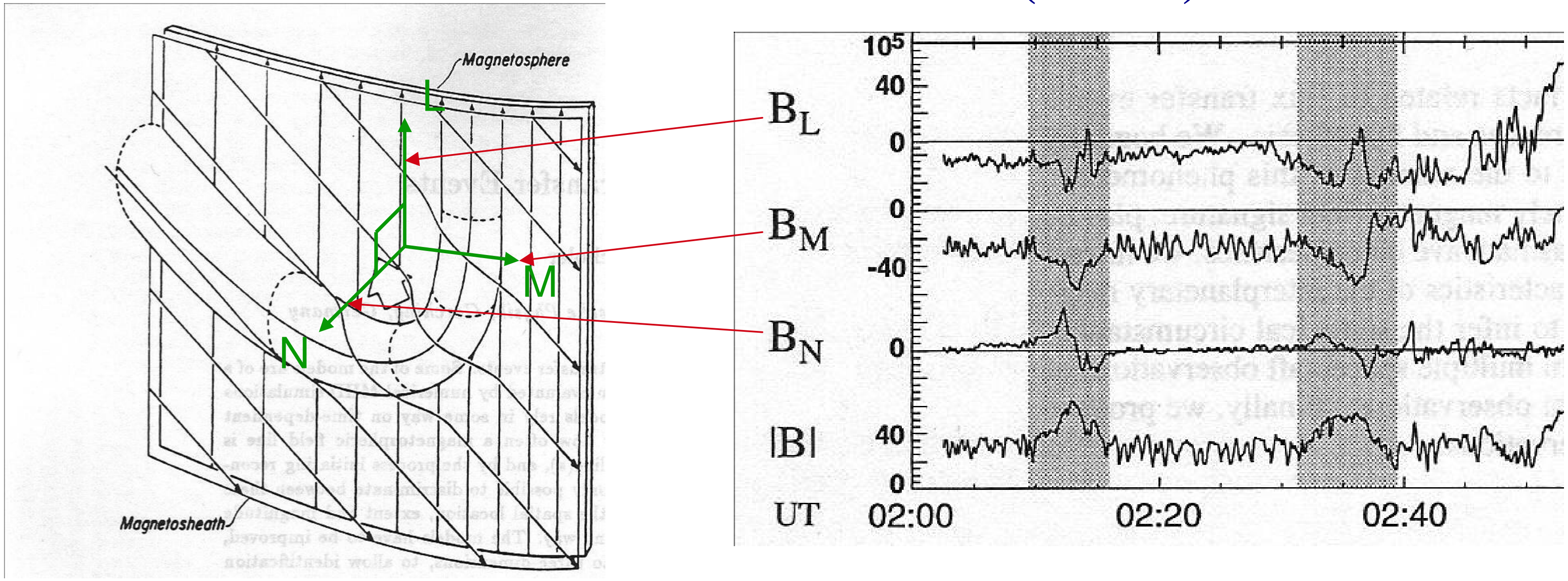




Clock angle = 45 degrees

Clock angle = 135 degrees

Flux Transfer Events (FTEs)

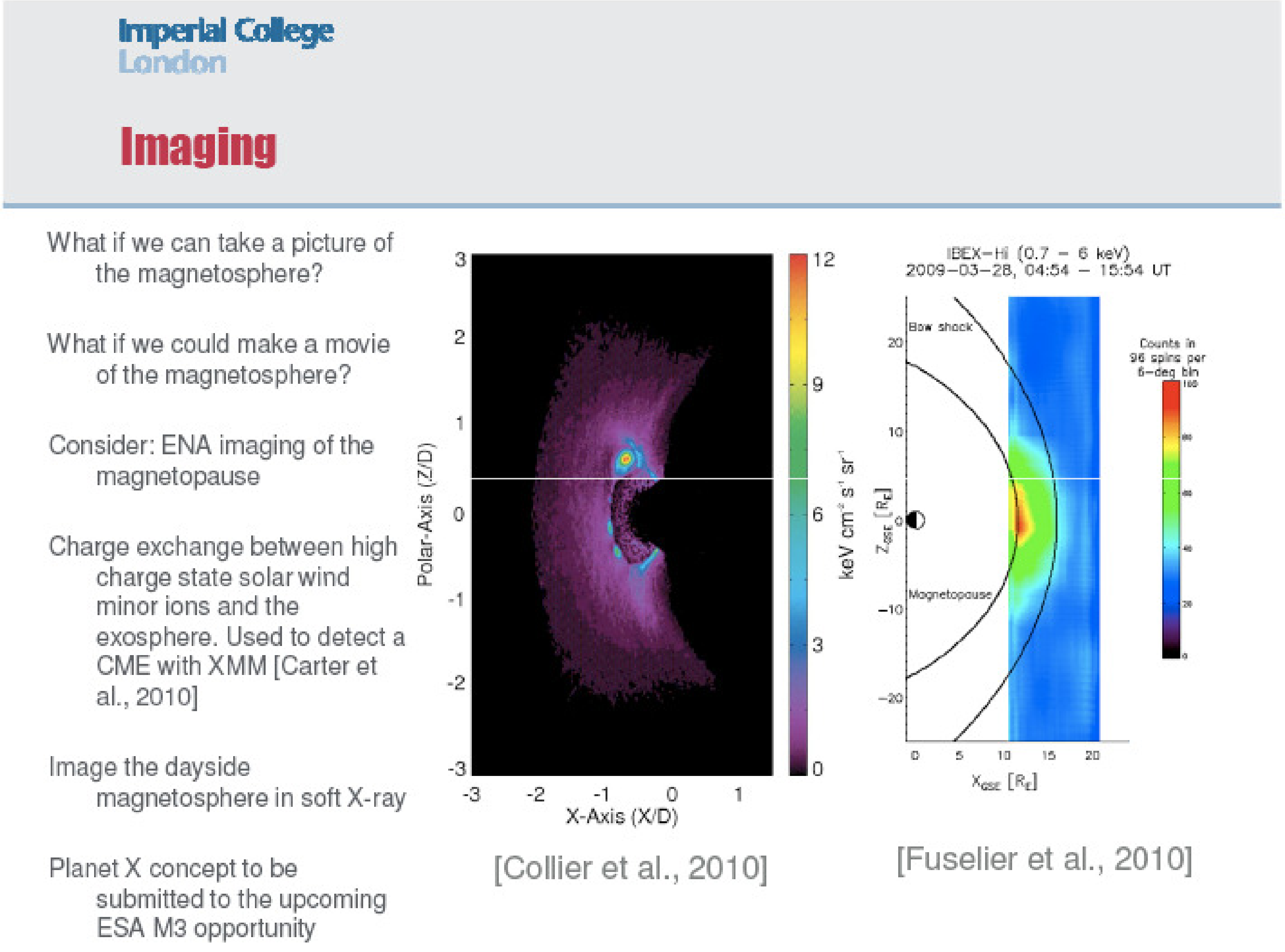


Russell, C. T. and R. C. Elphic, ISEE Observations of Flux Transfer Events at the Dayside Magnetopause, Geophys. Res. Lett., 6, 33, 1979.

The Future?

- Multi-satellite observations have been critical, but space is still severely under-sampled. We need many more micro-satellites to understand the properties of extended thin current sheets, their instabilities, and the possible turbulence they might lead to.
- Particle acceleration in the presence of multiple islands is an important cross-cutting challenge.
- Understanding 3D topology of reconnection is a grand magnetospheric physics challenge. Solar physicists are using imaging to try and address this issue. Can magnetospheric physicists image the magnetosphere?

J. Eastwood talk at the Cluster 10th Meeting (Courtesy: M. Taylor)



Imperial College London

Imaging

- What if we can take a picture of the magnetosphere?
- What if we could make a movie of the magnetosphere?
- Consider: ENA imaging of the magnetopause
- Charge exchange between high charge state solar wind minor ions and the exosphere. Used to detect a CME with XMM [Carter et al., 2010]
- Image the dayside magnetosphere in soft X-ray
- Planet X concept to be submitted to the upcoming ESA M3 opportunity

[Collier et al., 2010]

[Fuselier et al., 2010]