Magnetic Reconnection at the Dawn of the MMS Era

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Outline

- Primer on Reconnection
- Observing Electron Scales: MMS Mission
- “Simple” Electron Diffusion Regions
- Magnetic Islands and Self-Generated Turbulence
- Externally Imposed Turbulence
- Conclusions

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MHD - Magnetohydrodynamics

- Fluid Equations
  - Slow Timescales
  - Large length scales
- Key Physics
  - Plasma "Frozen-in" to the magnetic field
    - Magnetic Topology is conserved:
    - No magnetic reconnection

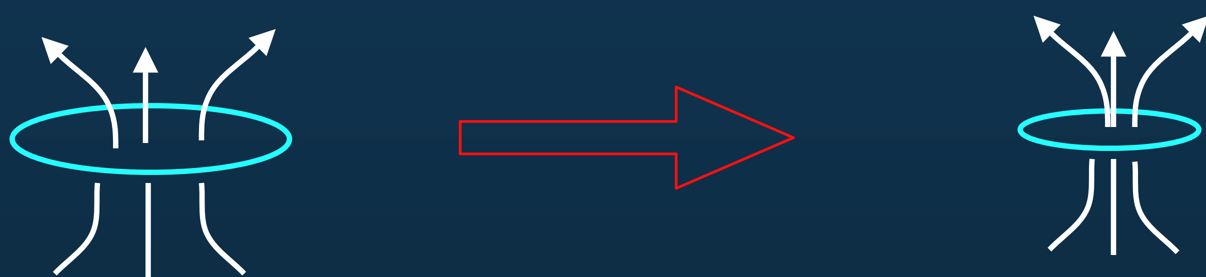
$$m_i n \frac{d}{dt}\mathbf{V} = \frac{\mathbf{B}\bullet\nabla\mathbf{B}}{4\pi} - \nabla\left(nT + \frac{\mathbf{B}^2}{8\pi}\right)$$

$$\frac{\partial}{\partial t}\mathbf{B} = -c\,\nabla\times\mathbf{E}$$

$$\frac{\partial}{\partial t}n = -\nabla\bullet n\mathbf{V}$$

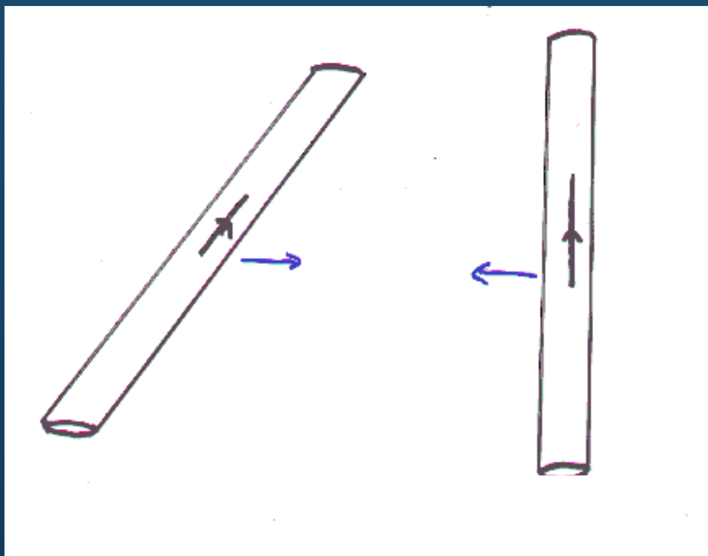
Ohm's Law

$$\mathbf{E} = -\frac{\mathbf{V}}{c}\times\mathbf{B}$$



Magnetic Topology is Conserved

Magnetic field lines can't be cut.



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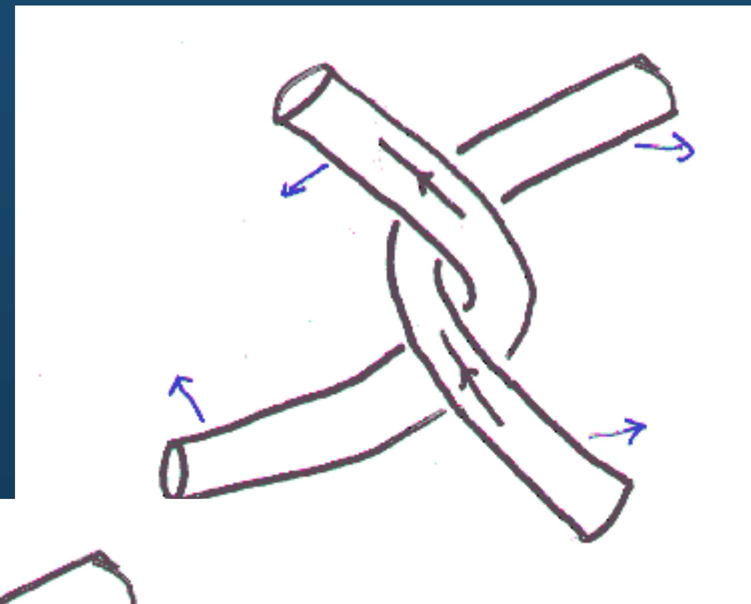
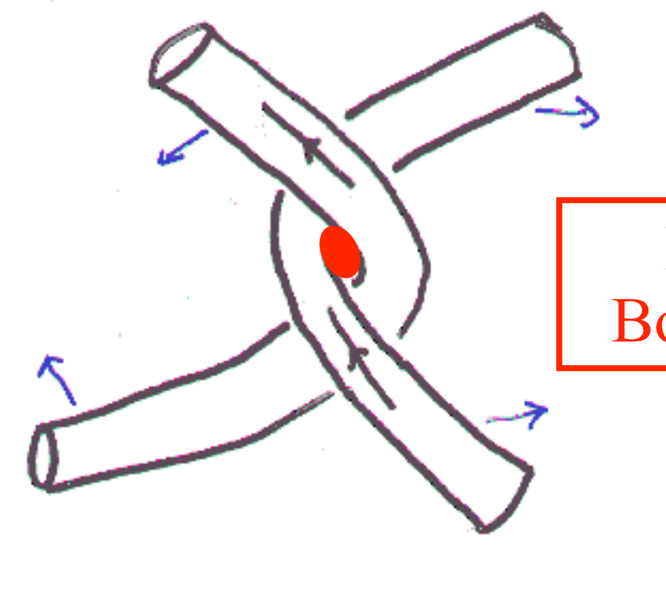
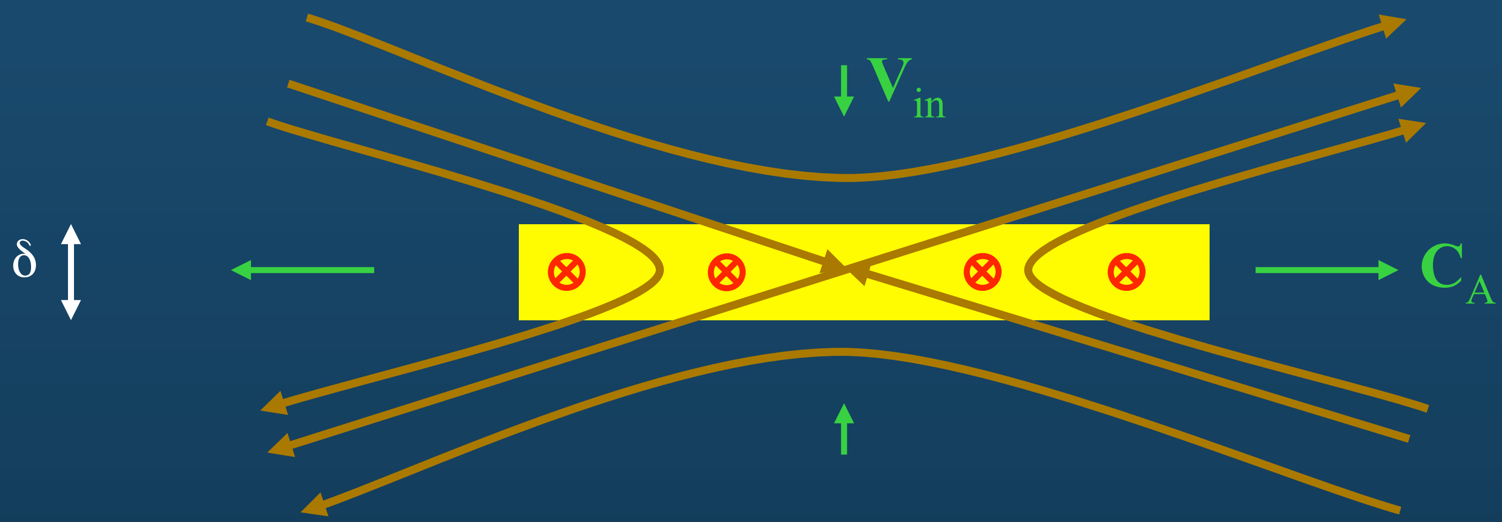


Everything Breaks Eventually



Formation of Boundary Layers

Magnetic Reconnection

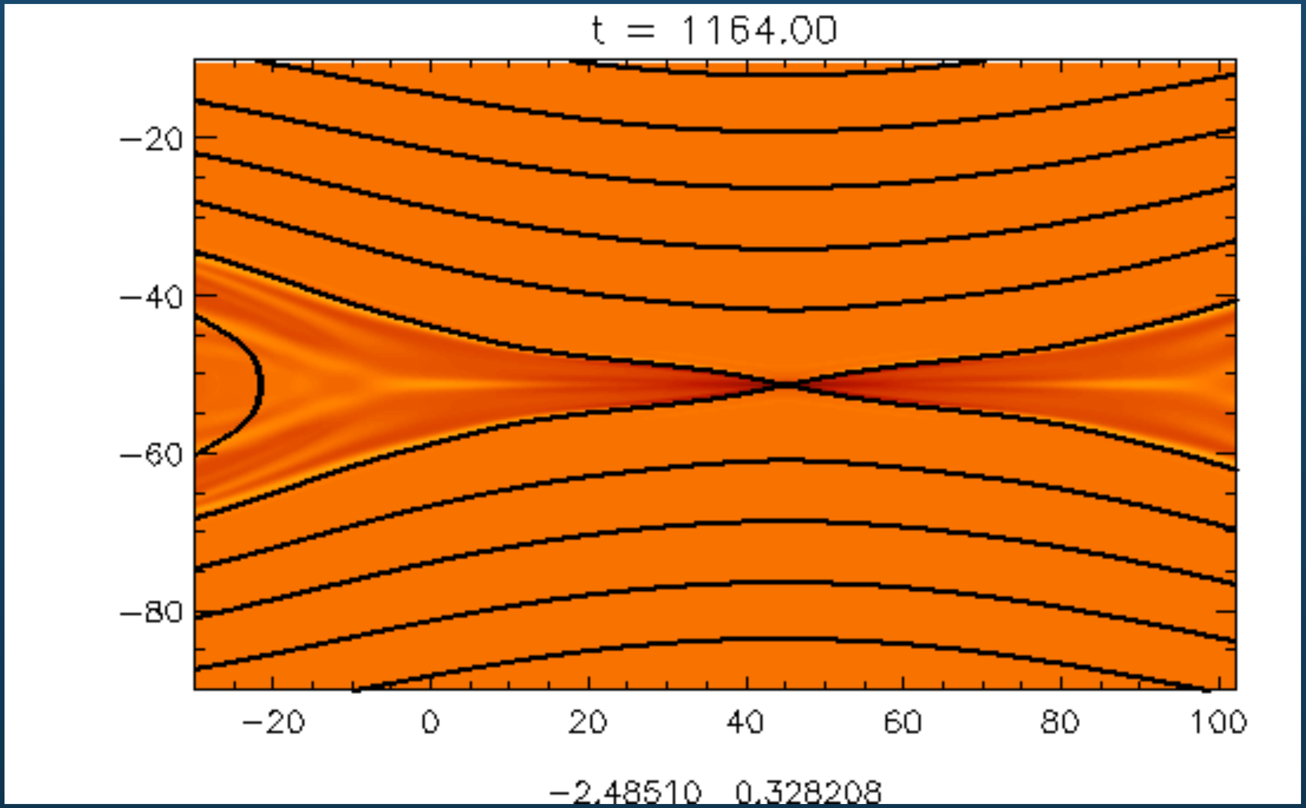


- Simplistic 2D picture
  – Tiny "Diffusion Region"
- Change of magnetic topology
  – Releases magnetic energy
- Important:
  - "Diffusion" not necessarily "Dissipation"

Diffusion Region
Boundary Layer
MHD not valid

Magnetic Reconnection

J_z and Magnetic Field Lines



- X-line region has very intense currents
    - Useful for finding likely reconnection sites

Ohm's Law

$$\mathbf{E} = \frac{-1}{c}\mathbf{V}_{ion} \times \mathbf{B} + \frac{1}{nec}\mathbf{J} \times \mathbf{B} - \frac{1}{ne}\nabla \bullet \vec{\mathbf{P}}_e - \frac{nm_e}{e}\frac{d\mathbf{V}_e}{dt} + \eta \mathbf{J}$$

Hall

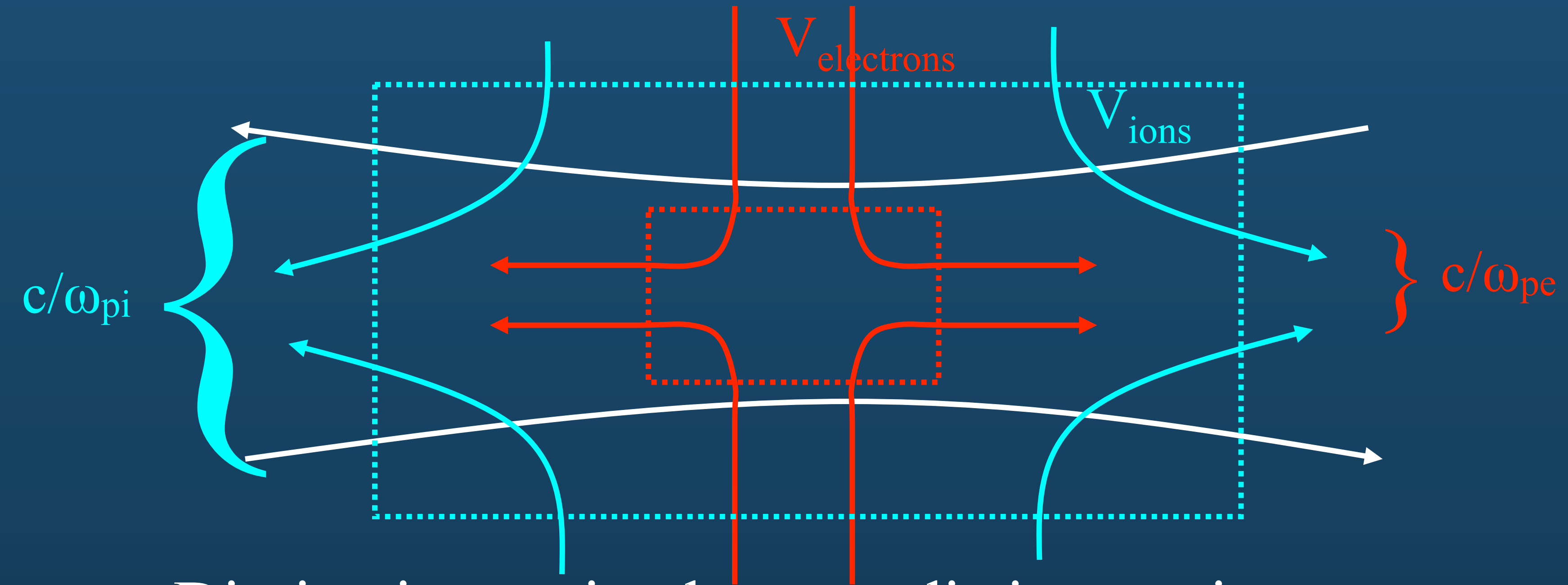
Finite electron mass

Electron-ion Collisions

c/ω_{pi}, ρ_s ρ_e c/ω_{pe}

- Diffusion region has electron and ion scales.
  - Effective electron and ion Larmor radii

Two-Scale Diffusion Region: 10 Years Ago



- Dissipation region has two distinct regions:
  1. $c/\omega_{pe} <$ length scale $< c/\omega_{pi}$, ρ_s

     Hall physics: Electron frozen-in, Ions not frozen-in

  2. length scale $< c/\omega_{pe}$

     Frozen-in totally broken: Magnetic topology can change

Electron Region Microscopic: $\ll c/\omega_{pi}$

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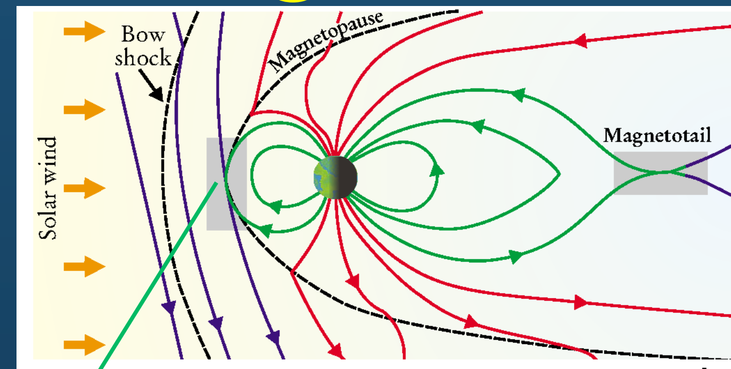
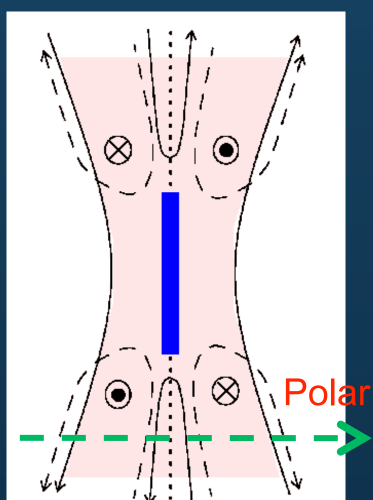
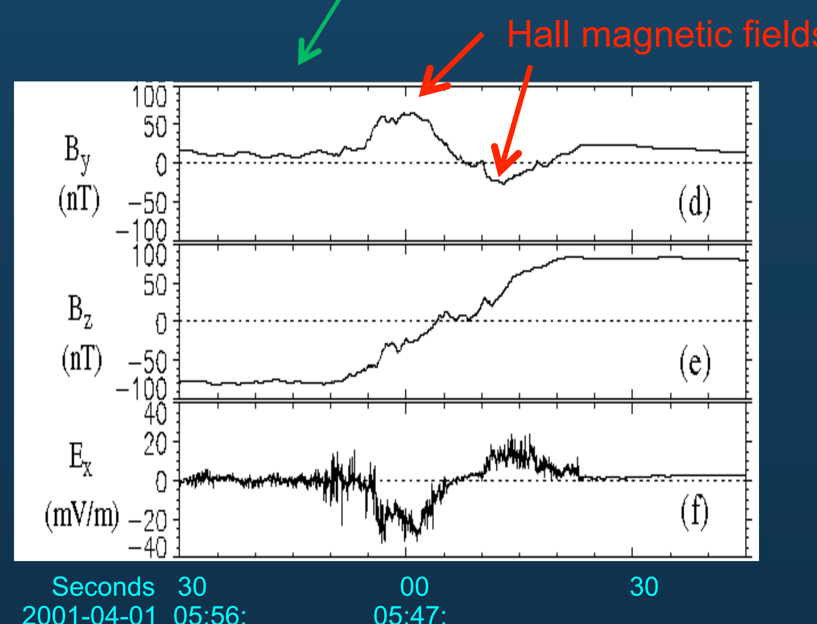
Ion Scale Diffusion Region

- Electron Diffusion Region Crossing Time is 0.1 sec!







Mozer et al., 2002

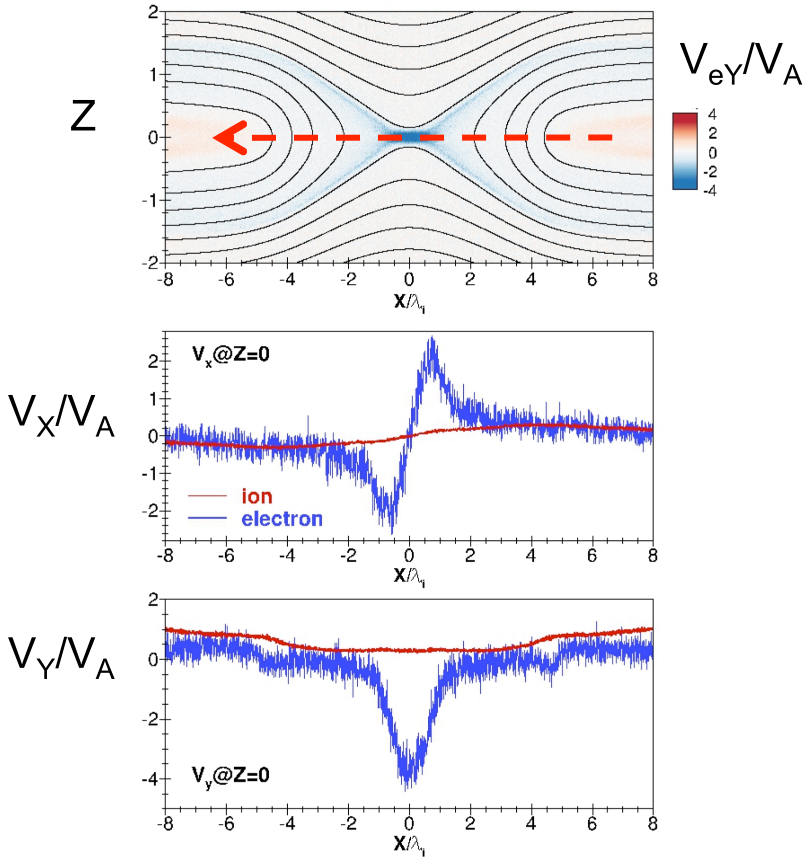
30 seconds

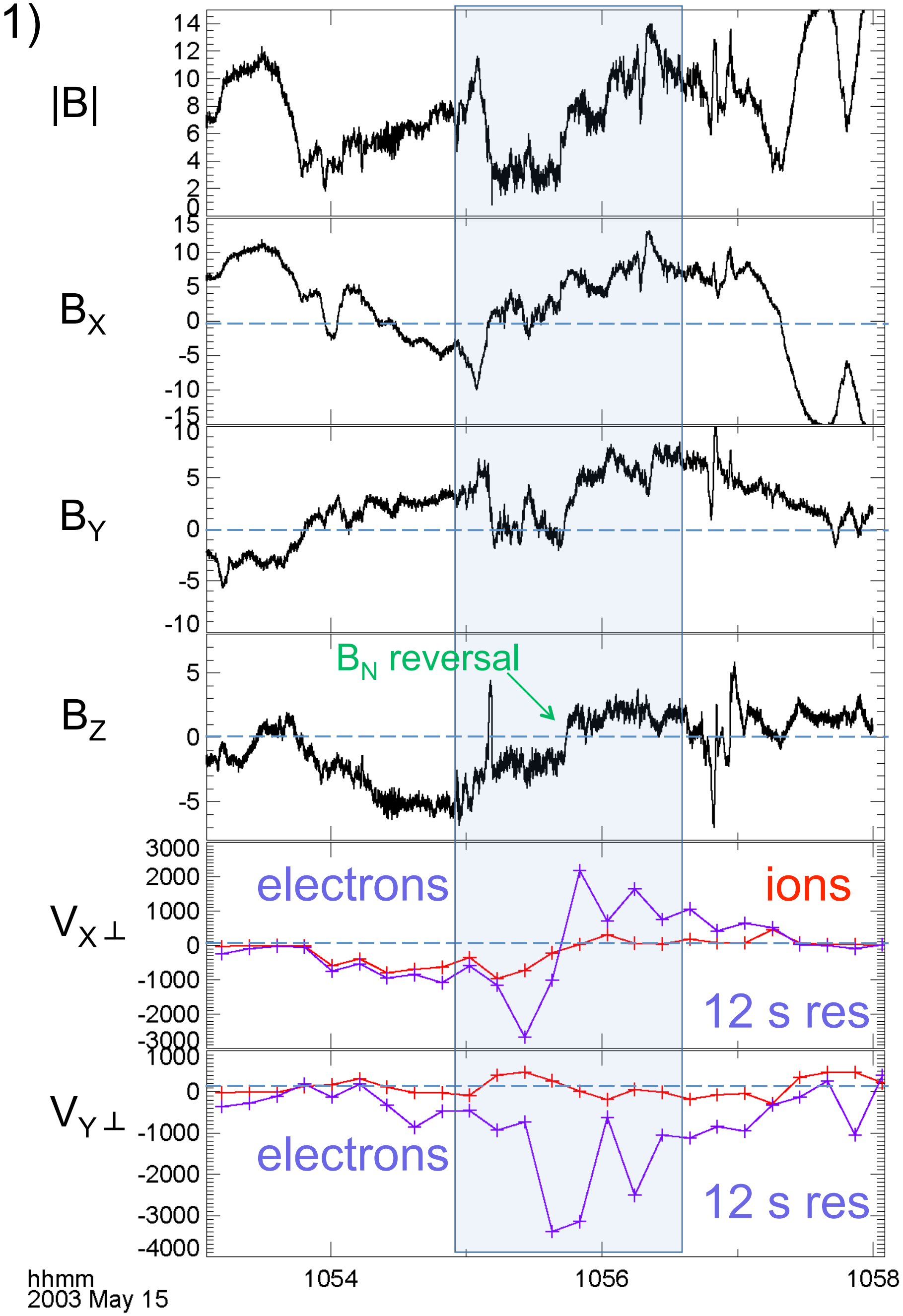
Slide Courtesy of Tai Phan

Geotail crossing through the electron diffusion region

(Nagai, Shinohara, Fujimoto et al., JGR, 2011)

Slide Courtesy of Tai Phan

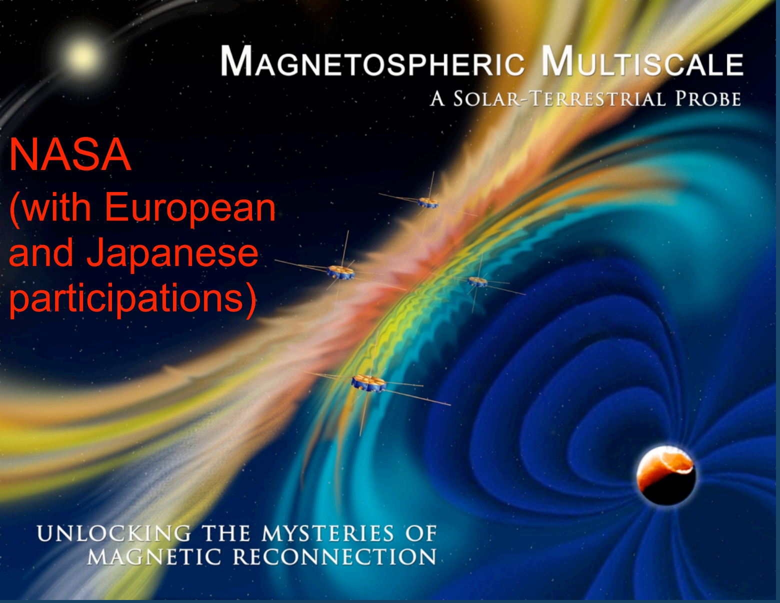




$V_{i\perp} << V_{e\perp}$ ion-electron decoupling

$V_{e\perp}$ super-ion-Alfvenic

Large cross-tail V_{eY} (strong current)
→ Electron diffusion region



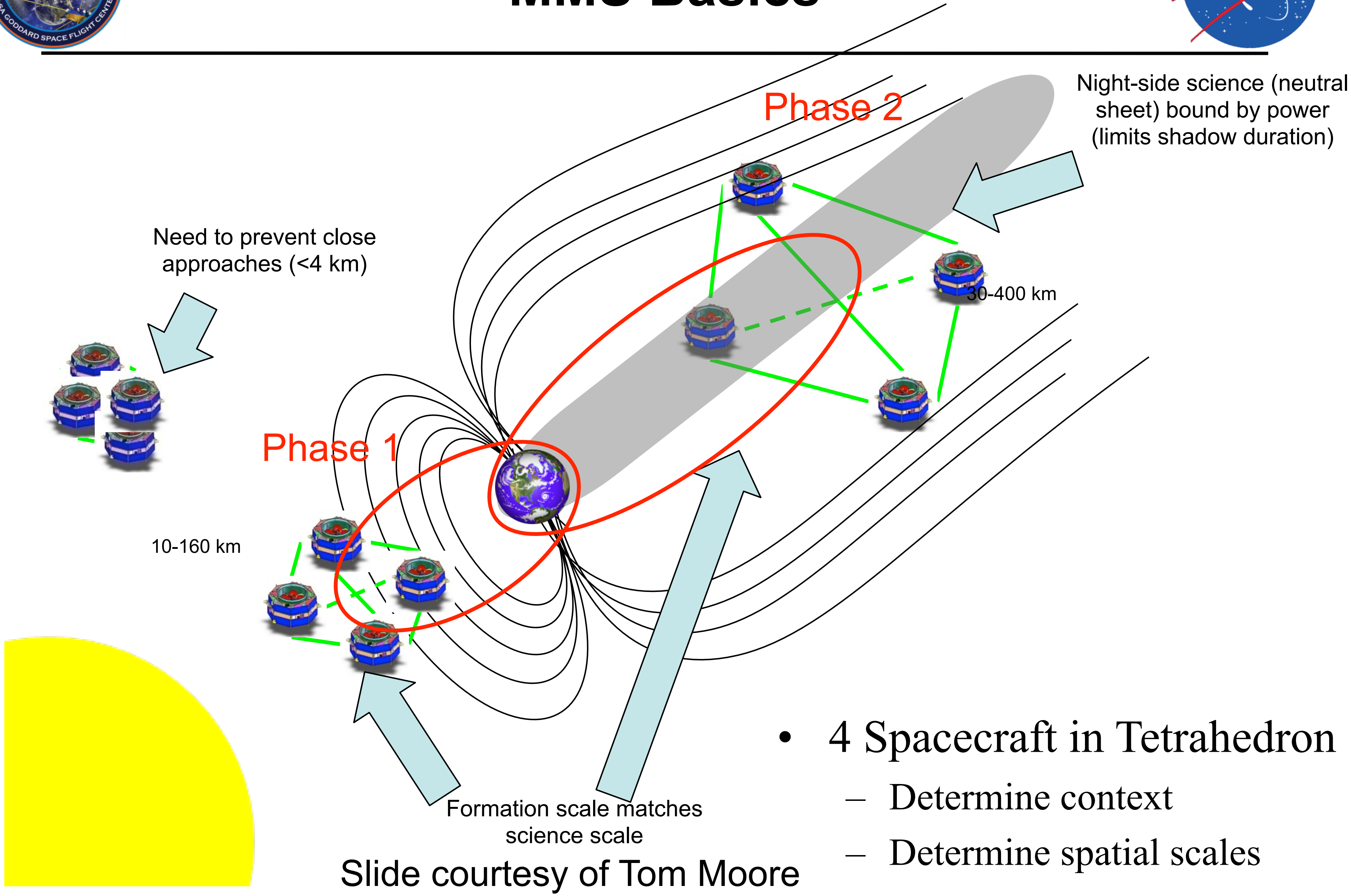
Launch: Late 2014

- Mission dedicated to reconnection
- Crucial data collected in burst mode

	Current best measurements	MMS	MMS - Dayside	MMS - Nightside
ions	3 sec	0.1 sec		
electrons	3 sec	0.008 sec	1/8 c/ω_{pe}	1/50 c/ω_{pe}
Spacecraft separation	100 km	10 km		

Slide Courtesy of Tai Phan

MMS Basics



- 4 Spacecraft in Tetrahedron
  - Determine context
  - Determine spatial scales

Slide courtesy of Tom Moore

MMS: Testbed for Magnetic Reconnection Experiments

- The magnetosphere provides a unique opportunity to study magnetic reconnection
- MMS: Unique opportunity to study electron scale physics
- Knowledge learned has broad application throughout the heliosphere
  - Sun-Magnetosphere Space Weather
  - Solar Flares
  - Outer heliosphere

Electron Scale Questions

- Where is the electron frozen-in constraint broken?
  - What allows magnetic topology to change?
- Is reconnection turbulent or laminar?
  - Effect of intrinsic instabilities?
  - Effect of external turbulence
- How is magnetic energy dissipated?
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- How are electrons energized and heated?

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Simulating Electron Diffusion Regions

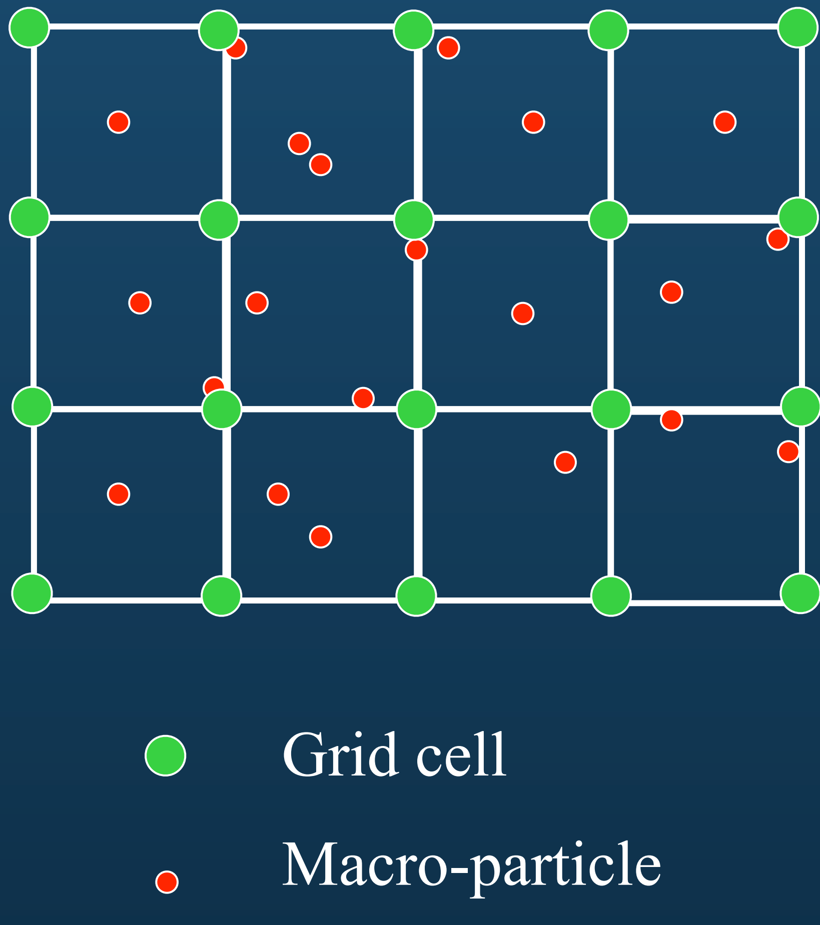
- Fluid Description not adequate
- Kinetic representation: Boltzmann Equation

$$\frac{\partial f}{\partial t} + \mathbf{v} \cdot \nabla f + \frac{e}{m_i} \left(\mathbf{E} + \frac{\mathbf{v}}{c} \times \mathbf{B} \right) \cdot \nabla_v f = 0$$

- f (x,v)
- Two options
  - Discretize x and v
    - 5 dimensions - Expensive!
  - Random particles: Follow trajectories

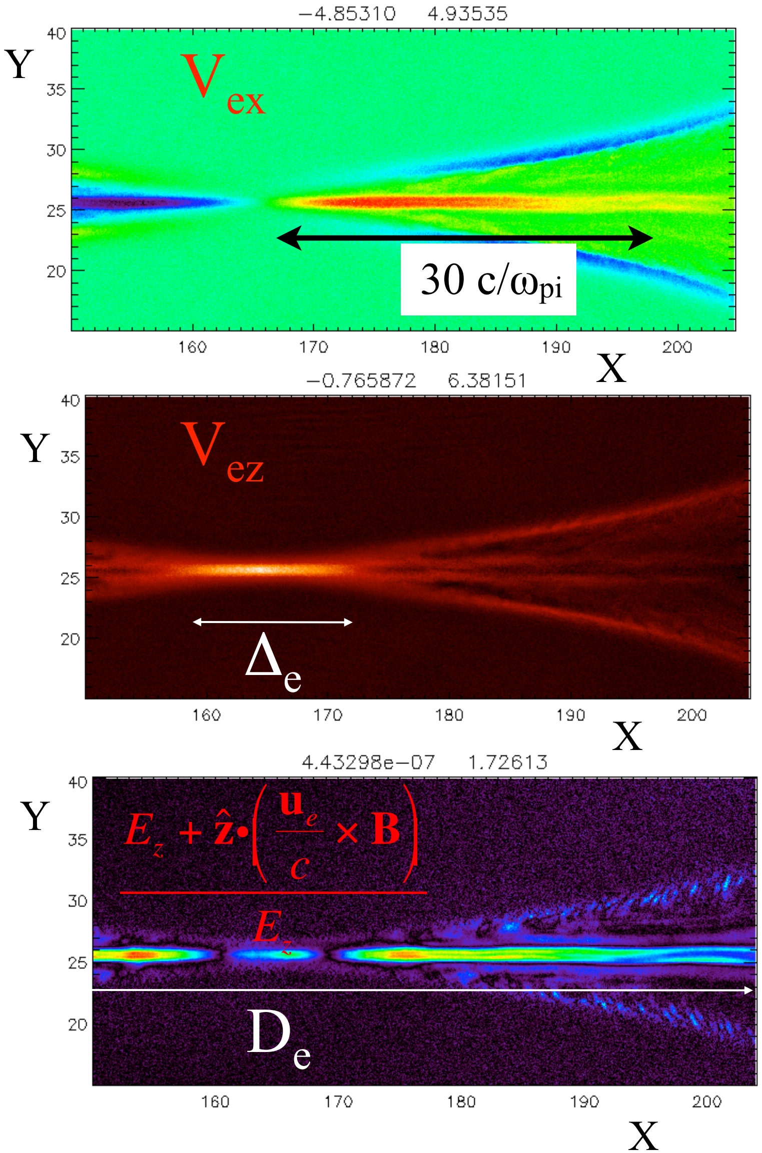
Simulating Kinetic Reconnection

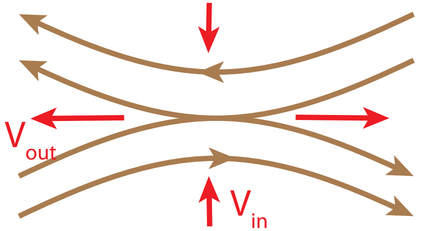
- Finite Difference
  - Fluid quantities exist at grid points.
- E,B treated as fluids always
  - Maxwell's equations
- Kinetic Particle in Cell
  - E,B fluids
  - Ions and electrons are particles.
  - Stepping fluids: particle quantities averaged to grid.
  - Stepping particles: Fluids interpolated to particle position.

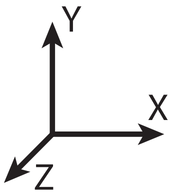


2D Simulations: Where Does Electron Frozen-In Break?

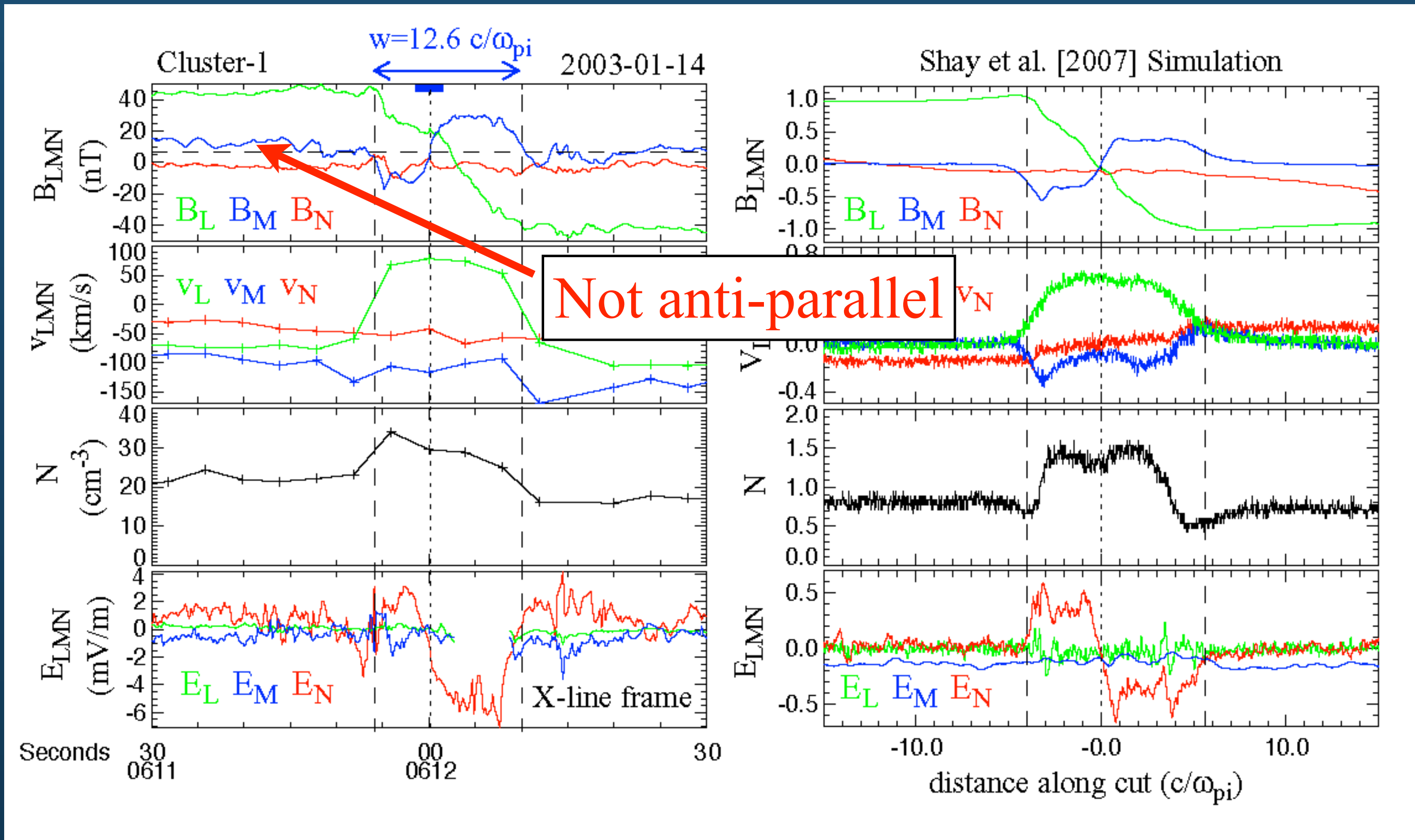
- Not a microscopic region near x-line
  - 10s of Ion Inertial Lengths!
  - Associated with large scale super-Alfvenic electron jet
    - Super-alfvenic electron outflow jet not frozen-in
  - Karimabadi et al., 2007
  - Shay et al., 2007
- Outer region not associated with dissipation.
  - Hesse et al., 2008
  - Zenitani et al., 2011







Comparison: Observations and PIC



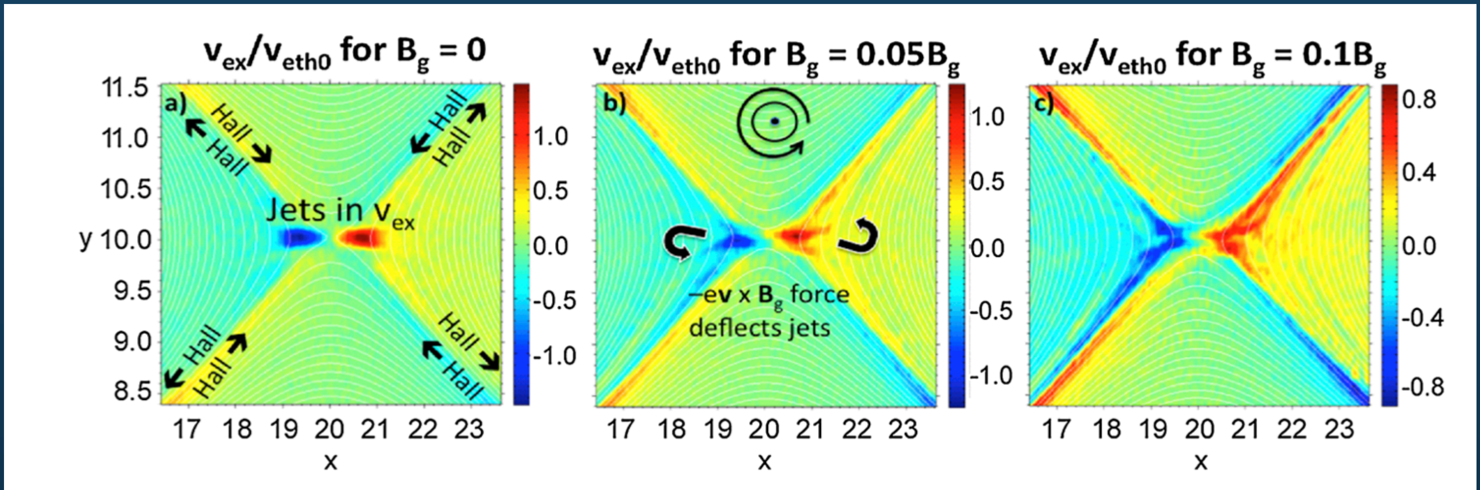
- 2D compares well with observations

Phan et al., 2007

- Observations not anti-parallel reconnection

Small Guide Field Deflects Jet?

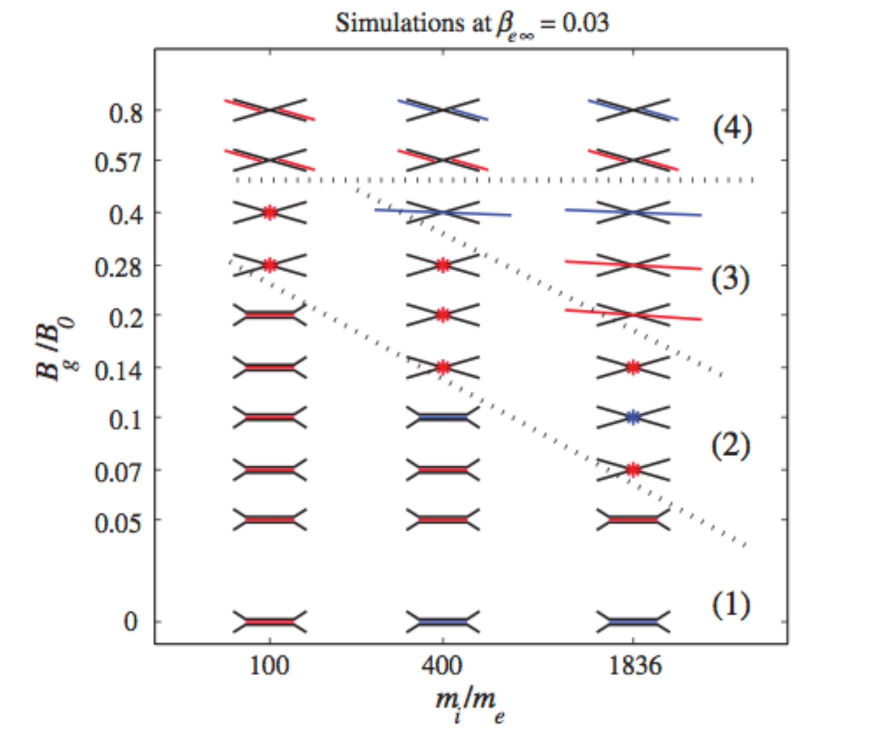
- Guide Field means not anti-parallel magnetic field lines.
  - Component Reconnection
- For realistic mass ratios, even a small guide field deflects the jet



Goldman et al., 2011

Strong Beta Dependence: Multitude of Diffusion Regions

- 4 distinct structures of the electron diffusion region depending on parameters.
  - Temperature anisotropy, $T_{e\perp}/T_{e||}$ important
- Mozer et al argues that diffusion region uninteresting.
  - Frozen-in broken all over the place



Le, Egedal et al., 2013

"Simple" Electron Diffusion Regions and MMS

- MMS Observations will be critical for understanding these basic questions
  - Where is the electron frozen-in constraint broken?
  - What breaks the electron frozen-in constraint?
  - Where does dissipation occur?

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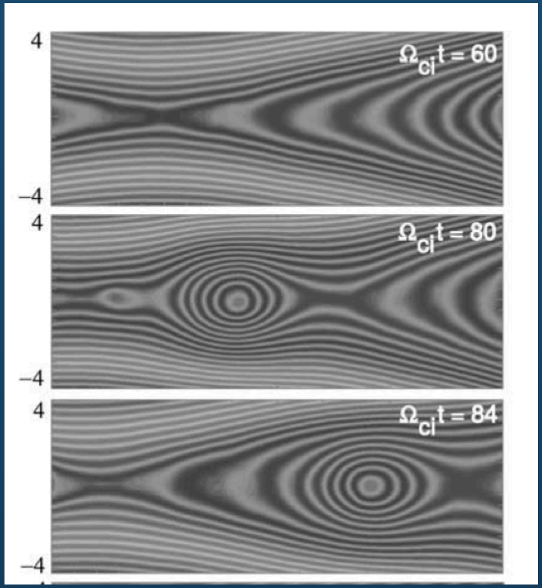
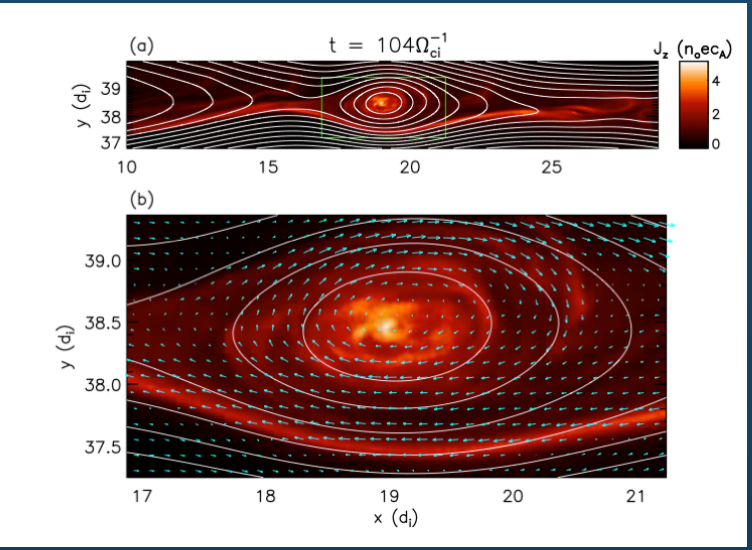
Self Generated Turbulence

Secondary Tearing Mode



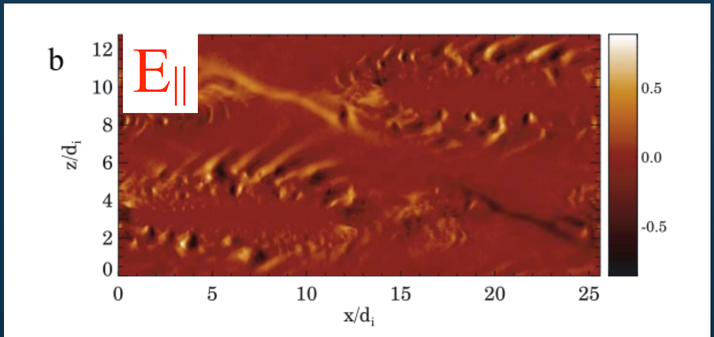
e.g., Karimabadi et al., 2005

Electron Kelvin Helmholtz



e.g., Fermo et al., 2012

Unstable Beams: Electron Holes

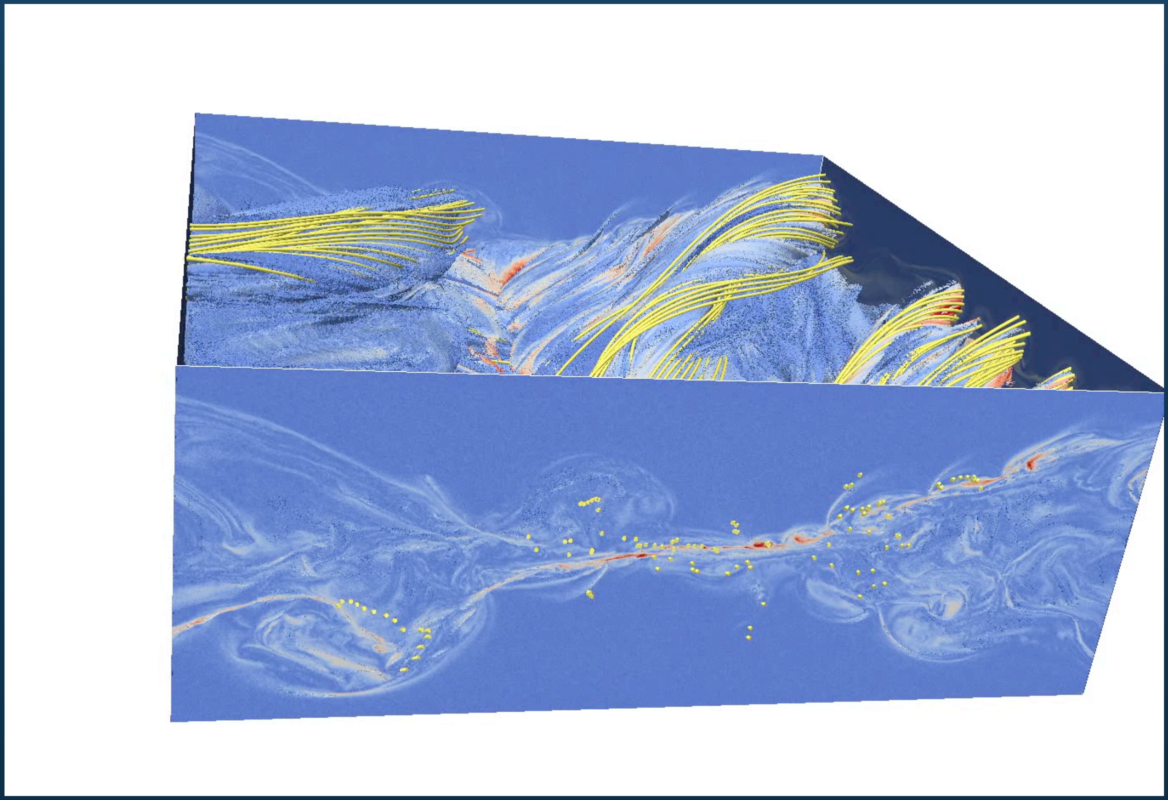


e.g., Drake et al., 2003

- Initially laminar system goes unstable.
- And many more instabilities
  - Especially in 3D

Self Generated Turbulence: 3D PIC

- Initially laminar state
- Self-generated turbulence
  - Current density with yellow magnetic field lines.



Daughton et al., 2011

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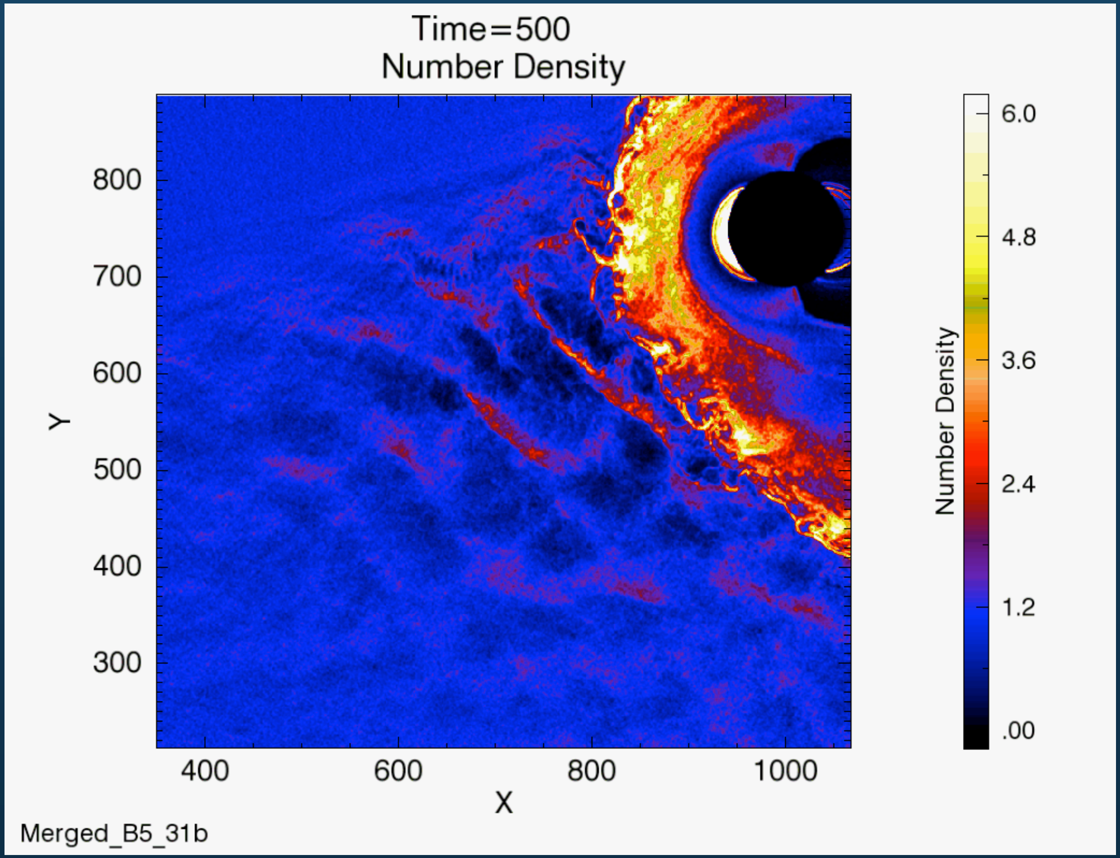
Simulations: Magnetosheath Turbulence

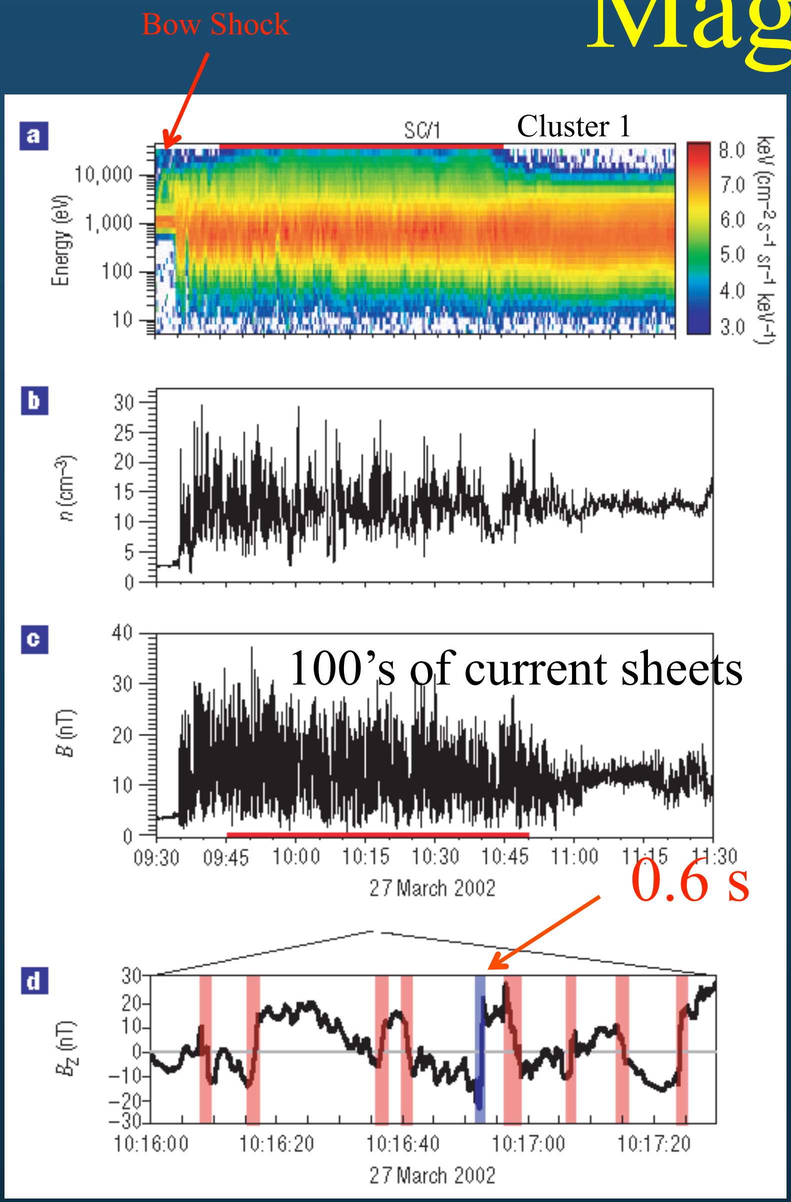
- Global Hybrid Simulations of the Earth's Magnetosphere
  - Turbulent magnetosheath
  - Especially where quasi-parallel shock

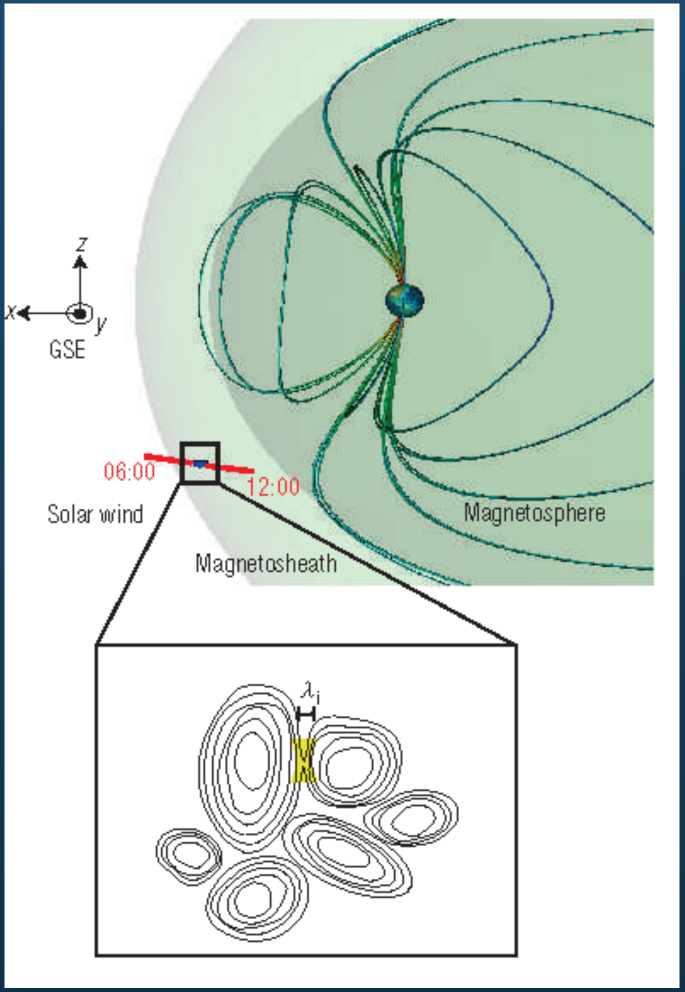


- Turbulence all over the heliosphere
  - Solar Wind
  - Corona

Omidi et al., 2013

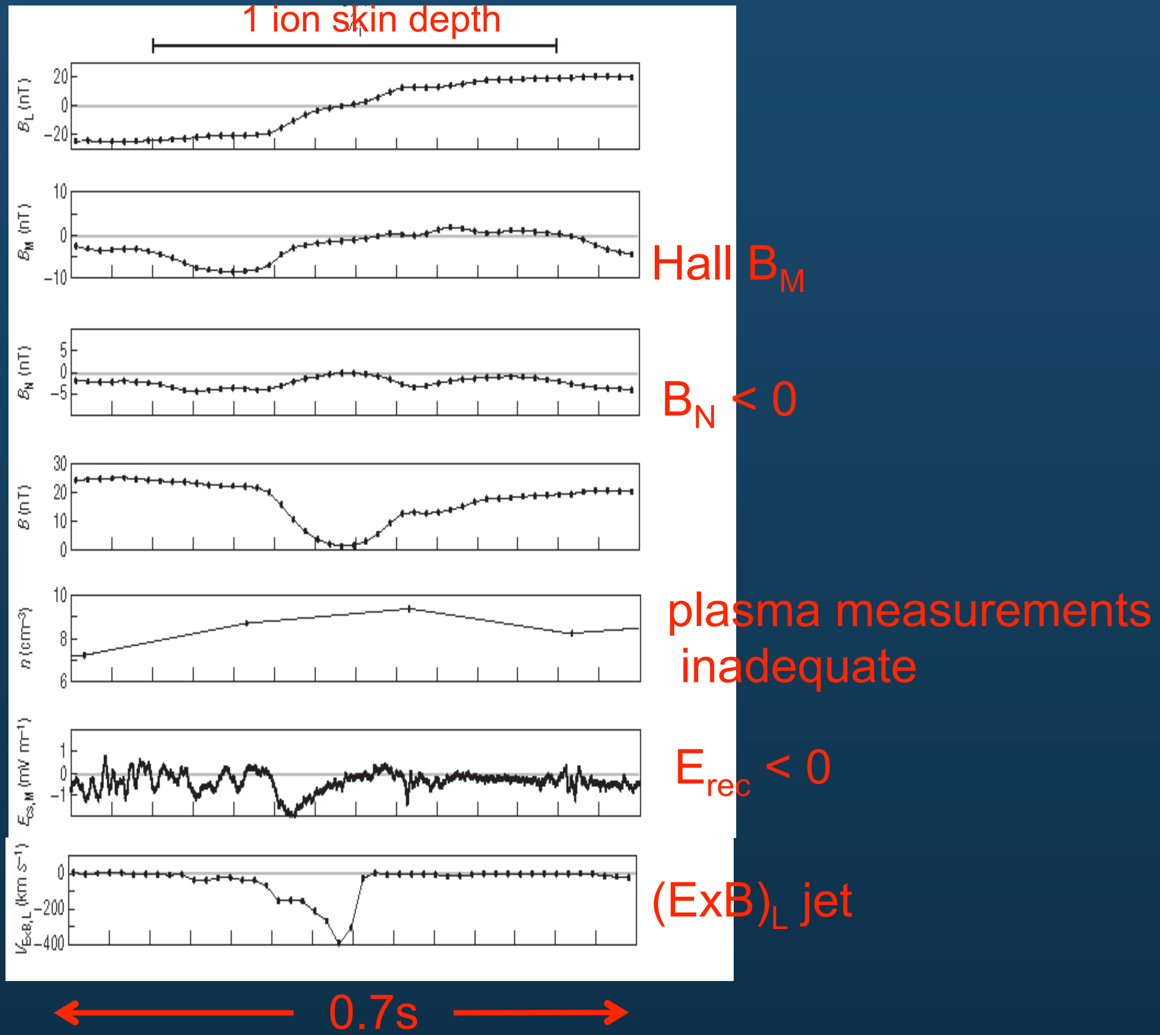
Observations: Turbulent Magnetosheath

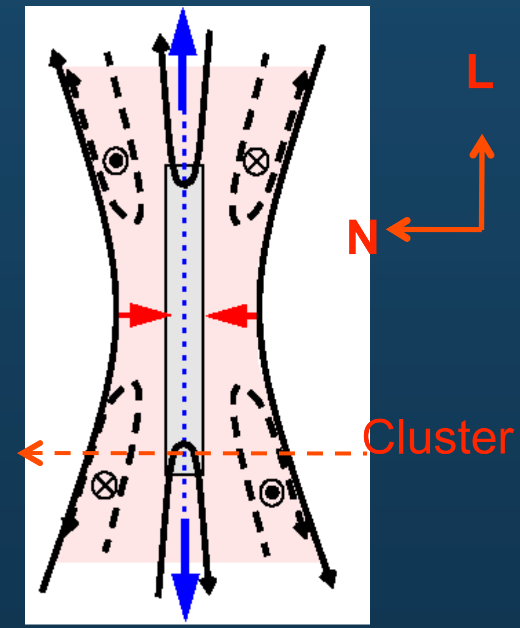




Retino et al., 2007

Observations: Turbulent Magnetosheath: Single Crossing

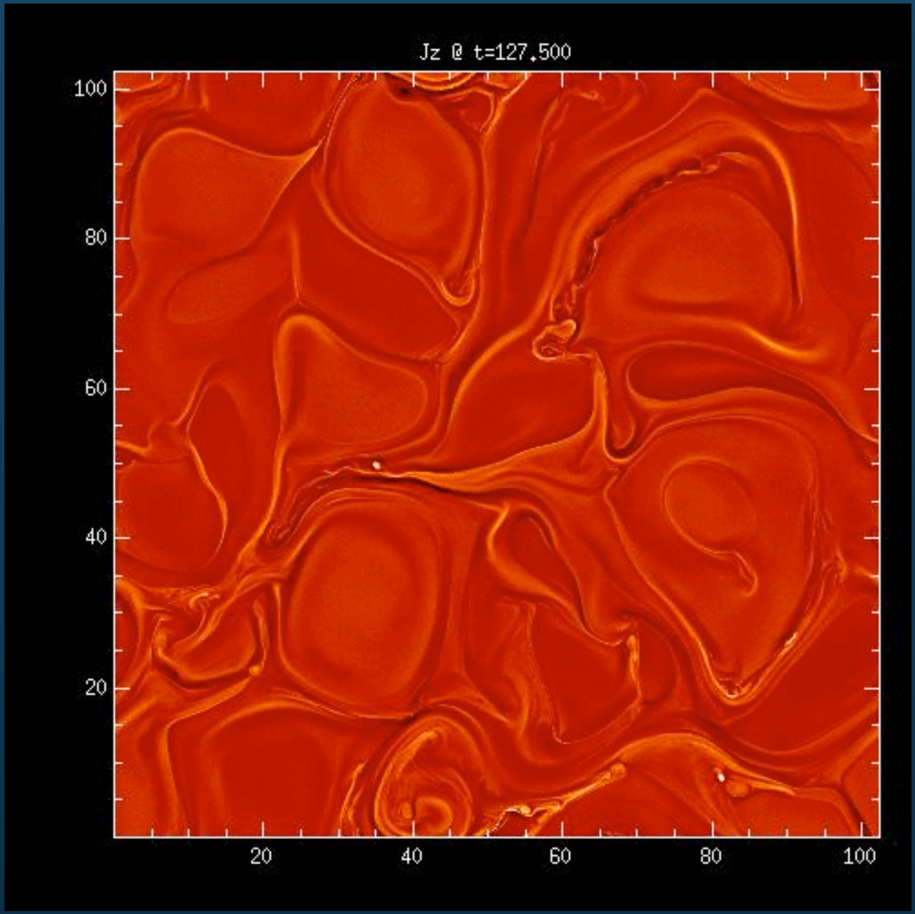




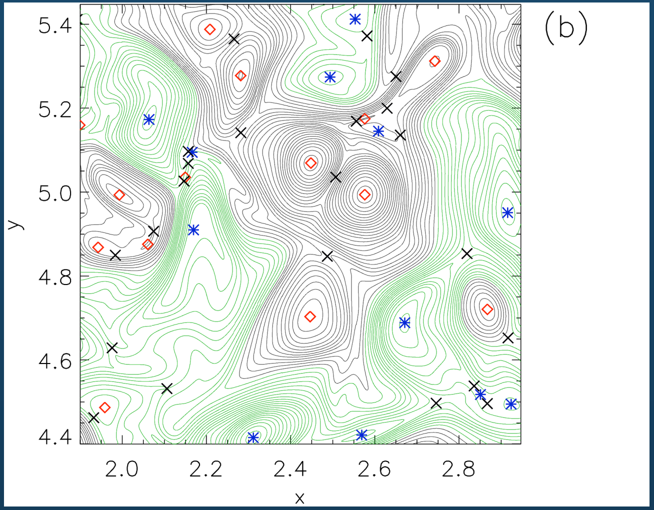
- Plasma Measurements Inadequate

Current Sheets and Reconnection in Turbulence

- 2D Kinetic-PIC Simulation
  - Wu et al., 2013

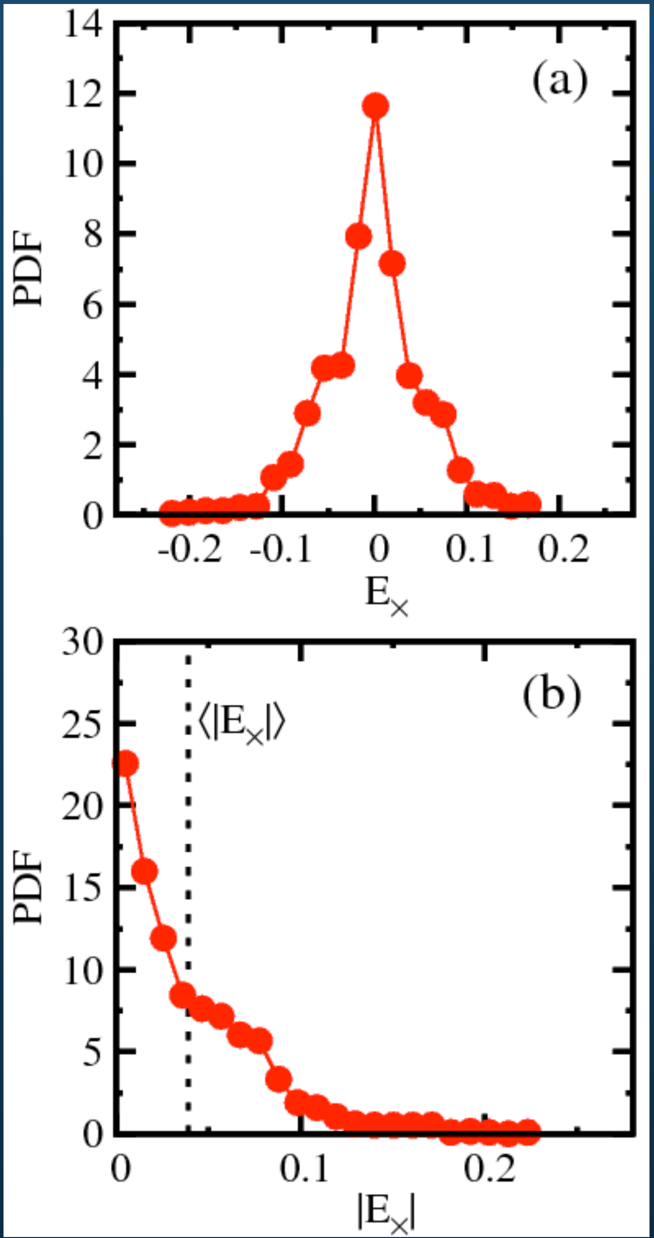


Distribution of Reconnection Rates



- MHD Simulations of Basic Turbulence
- Turbulence can be viewed as a sea of reconnecting islands with different reconnection rates.

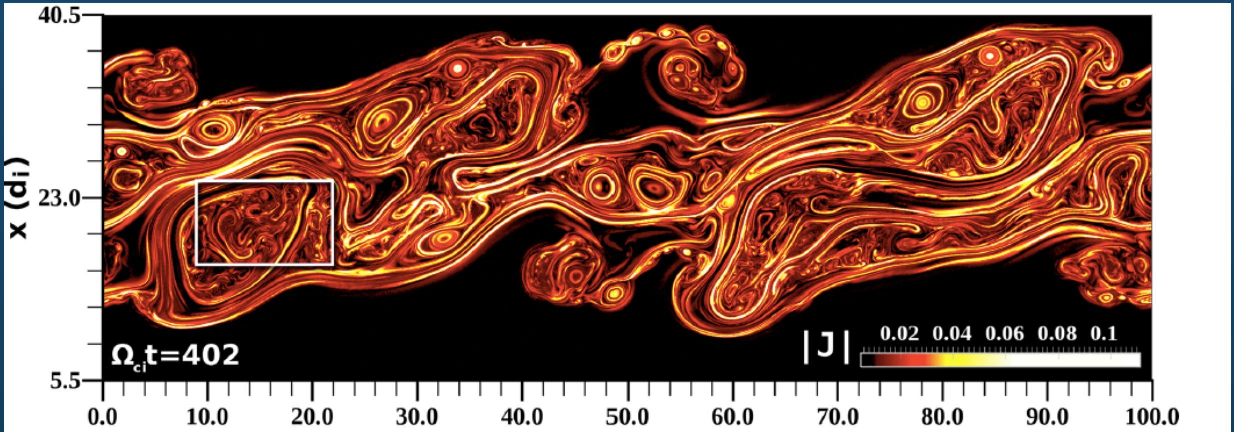
Servidio et al., 2009

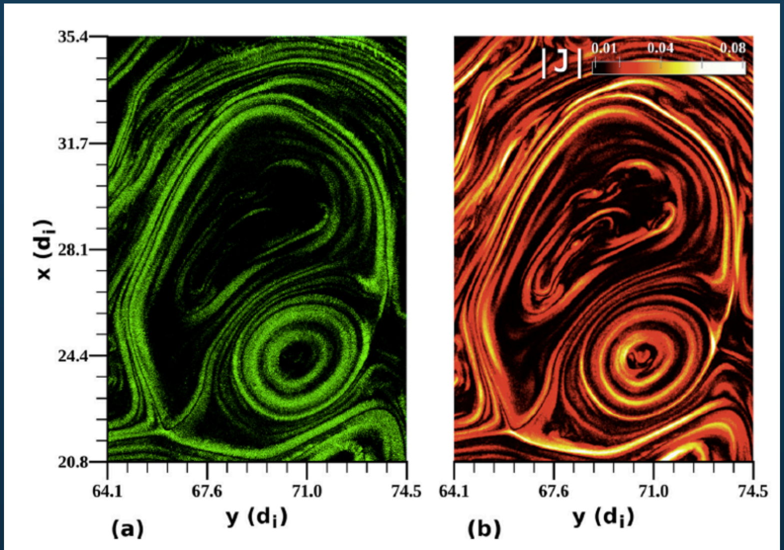


Dissipation in Turbulence: Role of Current Sheets

Karimabadi et al, 2013

- 2D Kelvin-Holmholtz Kinetic PIC simulations
- Electron Scale Current Sheets may be important sites for Dissipation.





Turbulent Systems: Questions

- Any Reconnection at All?
- Distribution of Reconnection Rates
  - Are most current sheets reconnecting or not?
- Properties of the Reconnection
  - Similar to larger scale reconnection?
  - Or, completely different?
- Dissipation in the Current Sheets
  - Important for understanding properties of the magnetosheath?
  - Energetically important for plasmas in general?

Conclusions

- Electron Scales Play a Critical Role in Reconnection Dynamics
- MMS will provide the first chance to fully resolve these regions.
  - Laboratory for electron scale physics
  - Knowledge gained applicable throughout the heliosphere
- Where is the electron frozen-in constraint broken?
- Is reconnection turbulent or laminar?
- How is magnetic energy dissipated?
- How are electrons energized and heated?