

# **Magnetic Reconnection:**

## **Open Questions that Require Multi-Scale Observations**

*Tai Phan (UC Berkeley)*

- What controls the occurrence of magnetic reconnection?
- Time variability of reconnection: What controls it?
- Spatial extent of reconnection: What controls it?
- Role of reconnection in turbulence
- Role of reconnection in Kelvin-Helmholtz waves at the magnetopause

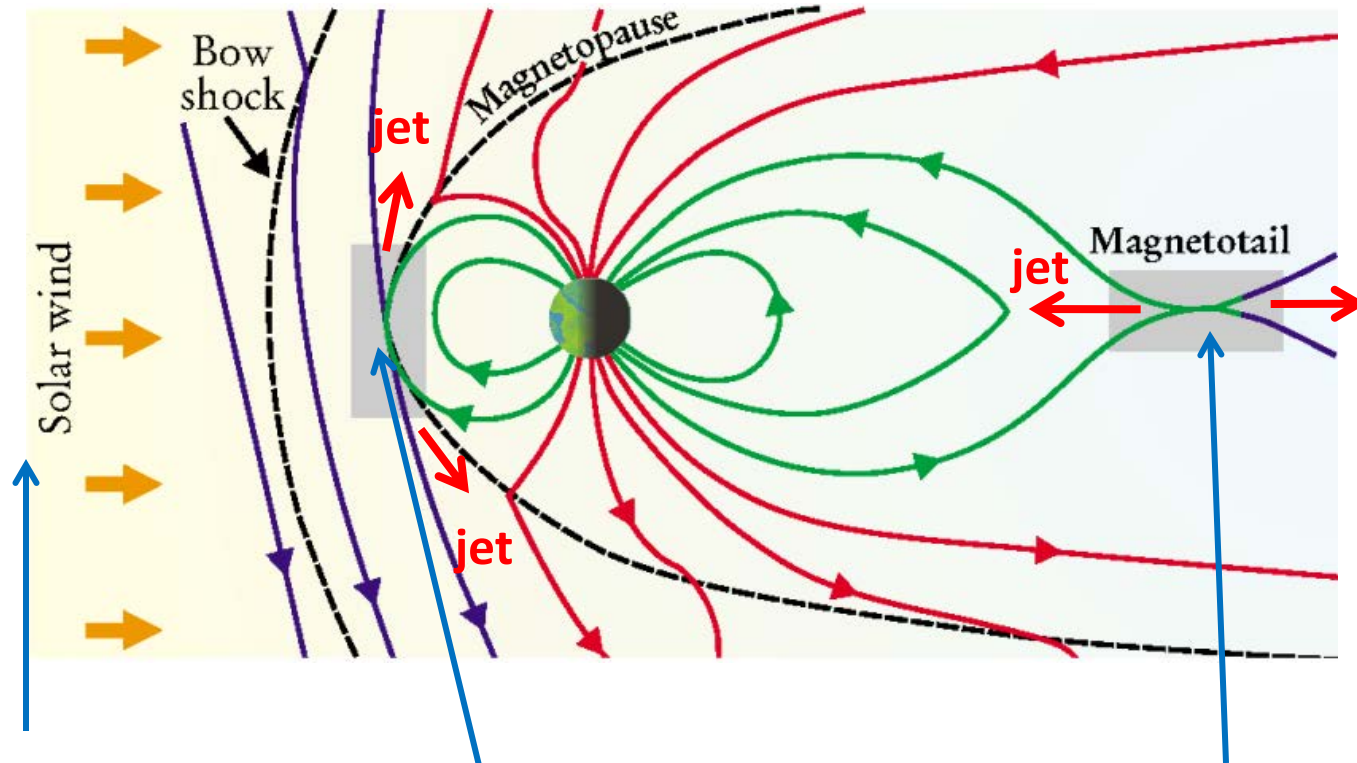
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How often does reconnection occur in current sheets in the magnetosphere and solar wind?



Solar Wind:  
occurrence rate < 1%  
(Gosling, 2011)

Magnetopause:  
occurrence rate ~ 50%  
(Phan et al., 1996)

Magnetotail:  
occurrence rate < 5%  
(Angelopoulos, 1994)

## What dictates the occurrence of reconnection: Global boundary conditions or microphysics in current sheet?

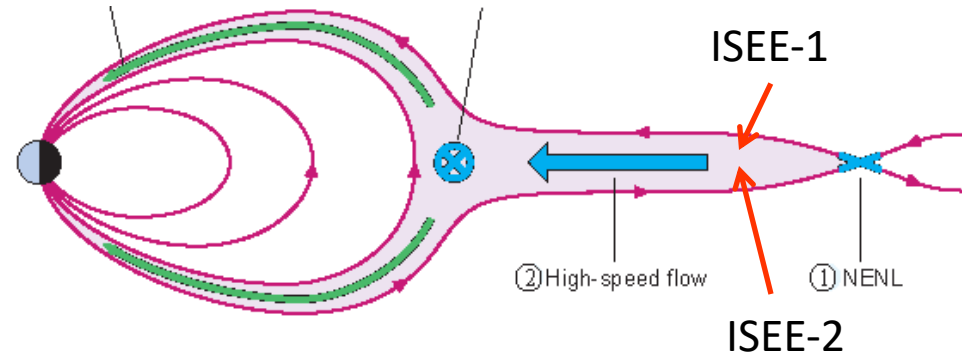
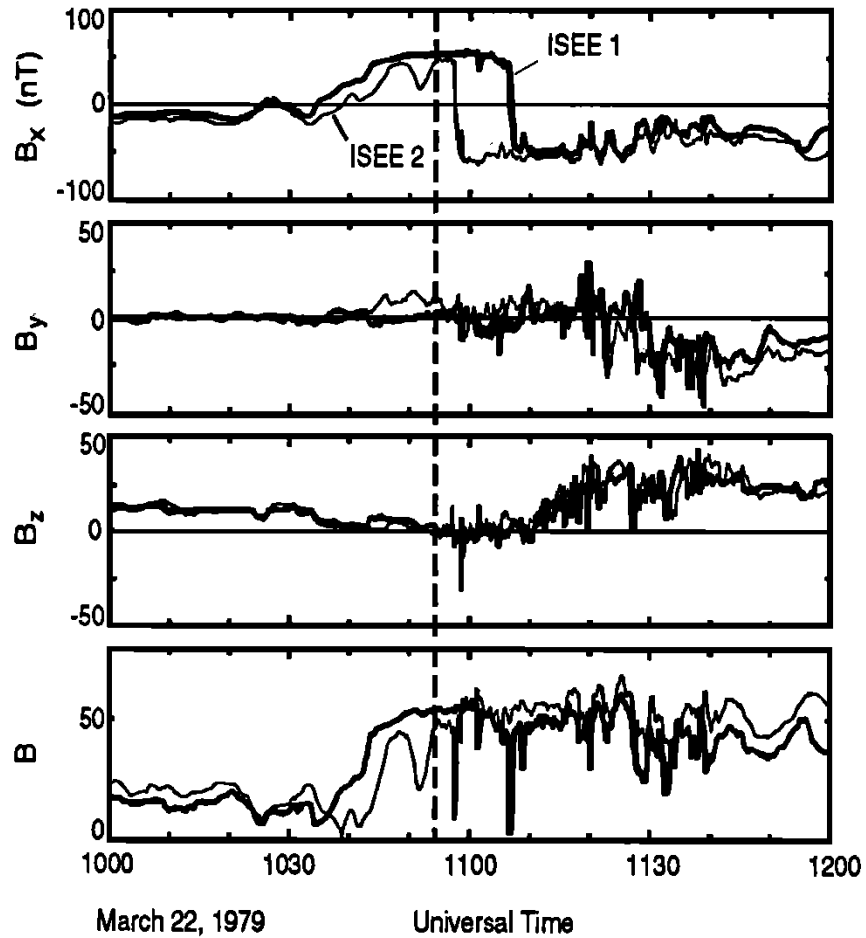
Probably both, therefore need to measure both to address the onset problem

### Known conditions for the onset of collisionless reconnection:

- Thin current sheet ( $\leq 1$  ion skin depth)
- Low plasma  $\beta$  and large magnetic shear favor reconnection
- Velocity shear can not be too large ( $< V_A$ )

# Current sheet thins to 1 ion skin depth before reconnection onset

Sanny et al. [1994]



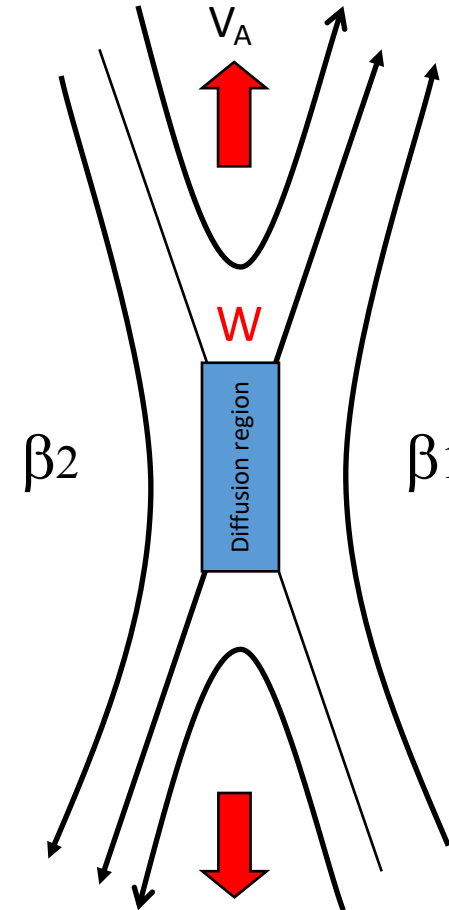
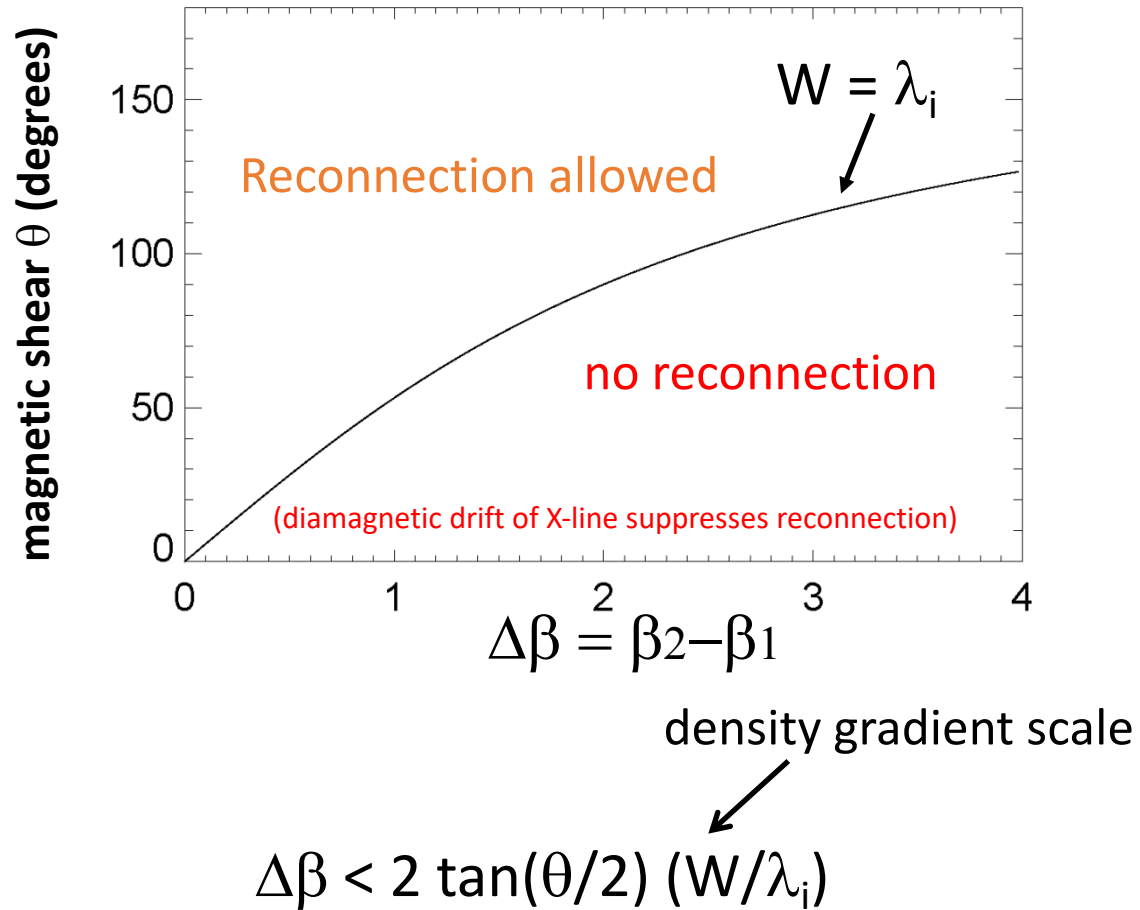
ISEE1 and ISEE2 spacecraft:

- current sheet speed: 7 km/s
- current sheet crossing time: 80s
- thickness = 560 km/s  $\sim$  1 ion skin depth

# Reconnection occurrence depends on $\beta$ and magnetic shear

Swisdak et al. [2003, 2010]

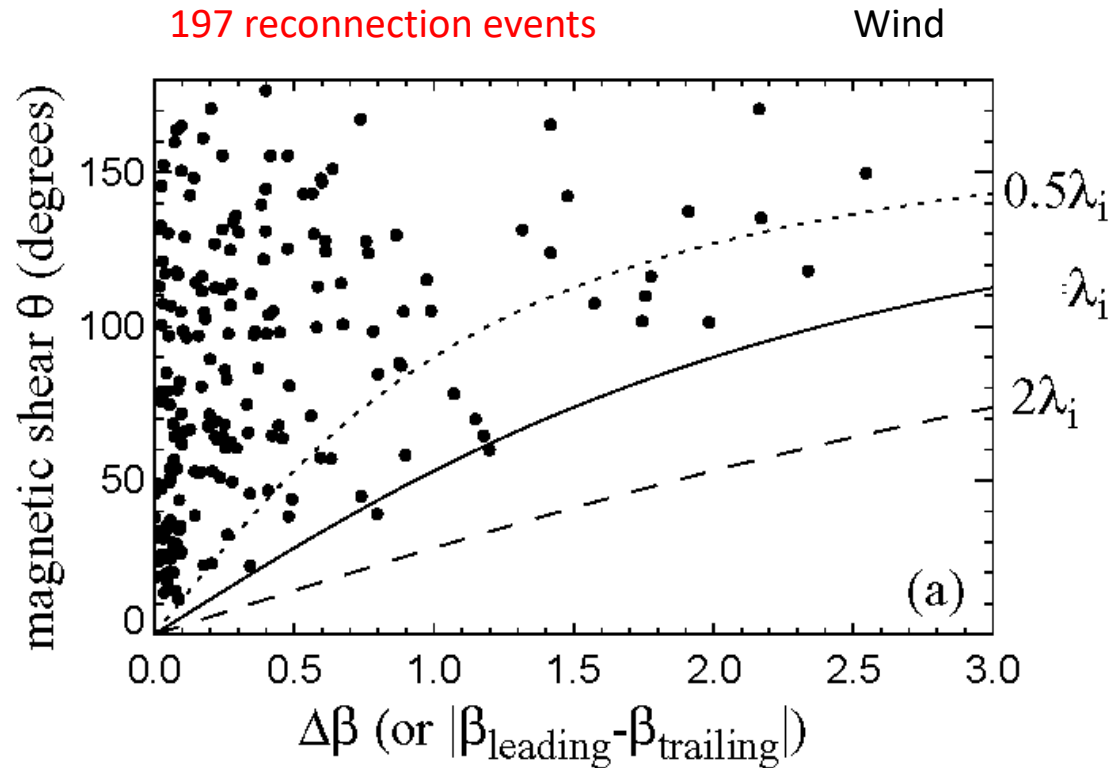
See Y. Liu and Hesse[2016]  
for a more precise prediction that  
depends on N and T, not just  $\beta$



Physics: Diamagnetic drift of X-line prevents reconnection if drift speed  $> V_A$

# Occurrence of solar wind reconnection vs. $\Delta\beta$ and magnetic shear

Phan, Gosling, et al. [ApJL, 2010]



density gradient scale

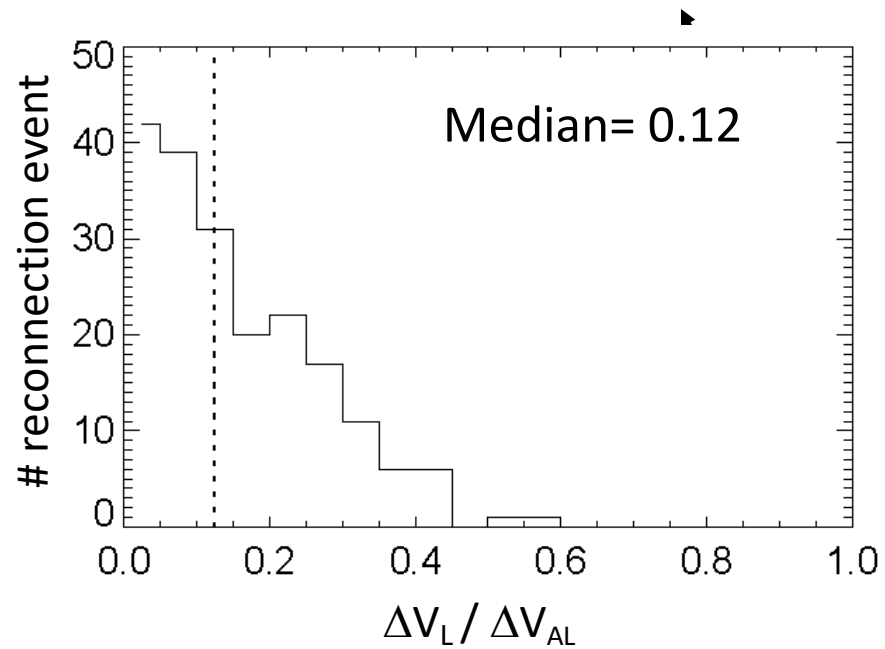
$\Delta\beta < 2 \tan(\theta/2) (W/\lambda_i)$

- At  $\Delta\beta=0.1$ , reconnection can occur for magnetic shear down to  $10^\circ$ !
- At  $\Delta\beta=2$ , reconnection requires magnetic shear  $>100^\circ$

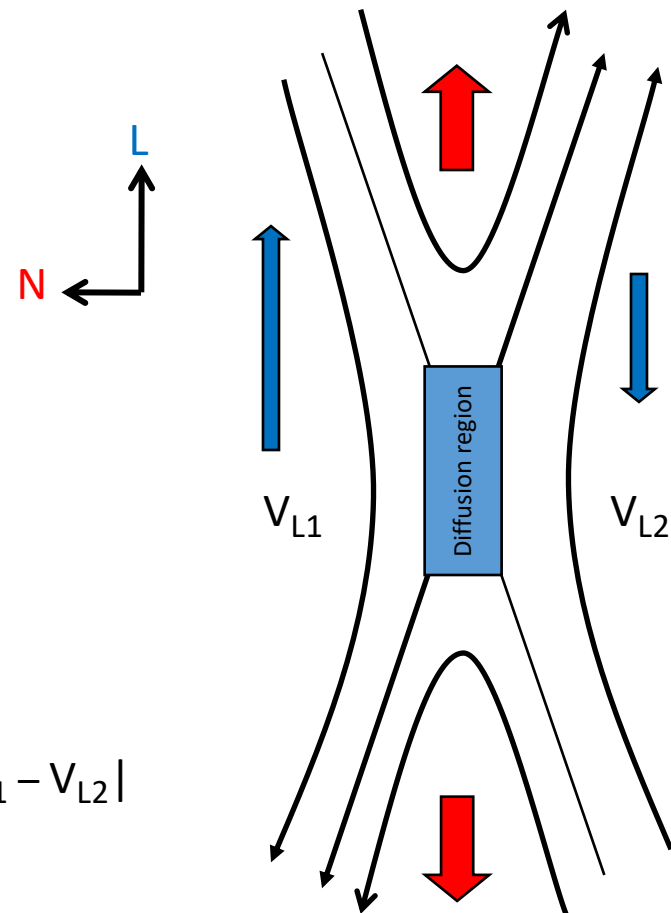
## Reconnection can only occur if the velocity shear < Alfvén speed

**Expectation:** Reconnection suppressed if Velocity Shear  $\Delta V_L > \Delta V_A$  [Cowley and Owen, 1989]

**Observed:** Velocity shear  $\Delta V_L \ll \Delta V_A$  in all solar wind reconnection events



$$\Delta V_L = |V_{L1} - V_{L2}|$$





## Summary of conditions for the onset of Reconnection

- Thin current sheet ( $\leq 1$  ion skin depth)
- Low plasma  $\beta$  and high magnetic shear
- Velocity shear  $< V_A$
- ..... other requirements?

Need multi-scale observations to understand why reconnection is triggered in a particular current sheet

## Magnetic Reconnection:

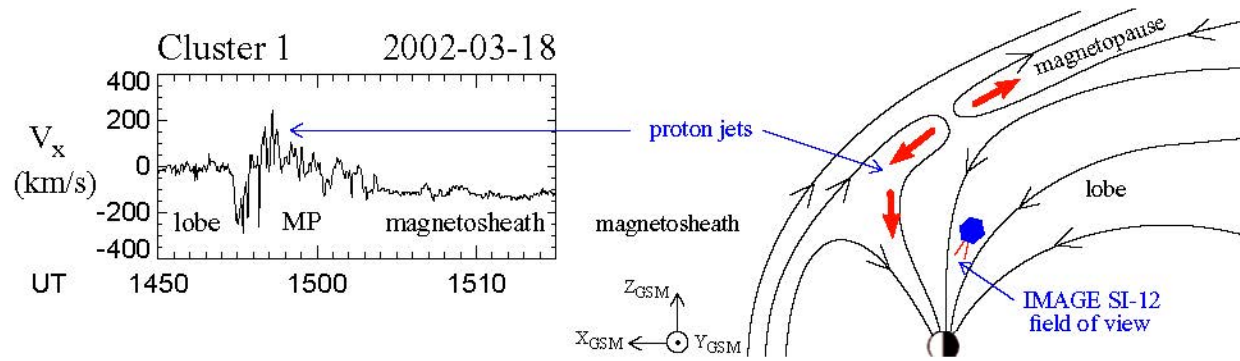
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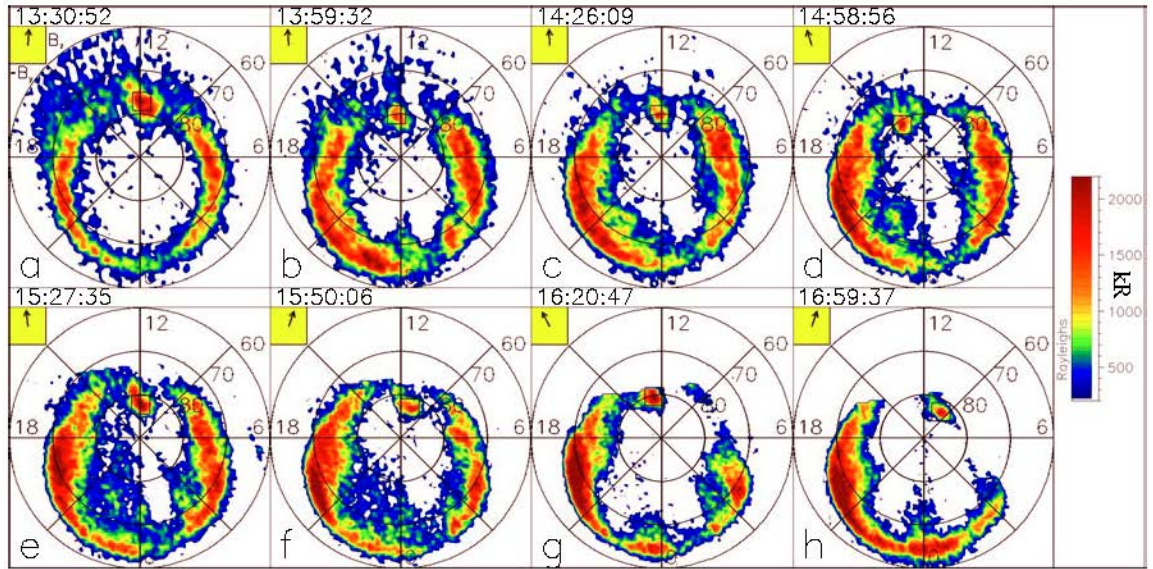
## Time variability of reconnection: What controls it?

- Both continuous reconnection and intermittent reconnection are observed in space
- What dictates the time variability of reconnection?

**Evidence for continuous reconnection at the magnetopause during northward IMF:  
proton aurora observations**  
[Frey et al., *Nature*, 2003]

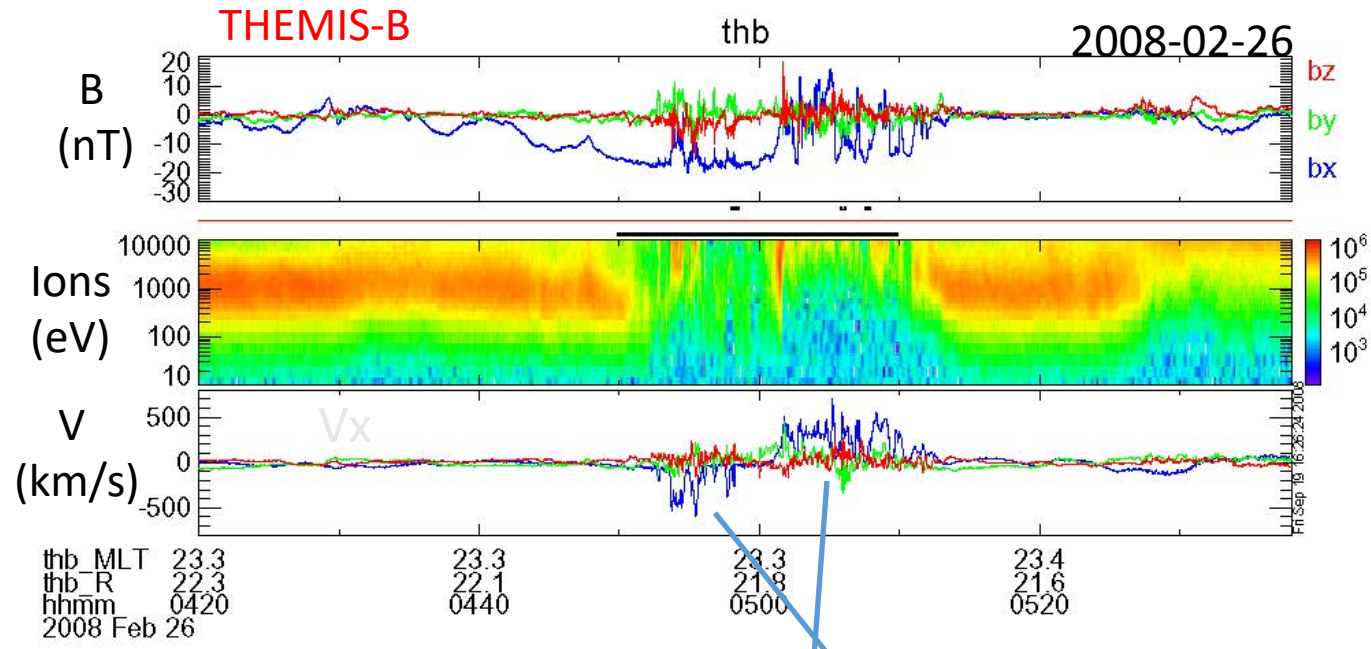


**In-situ (Cluster)  
auroral footprint  
(IMAGE)**

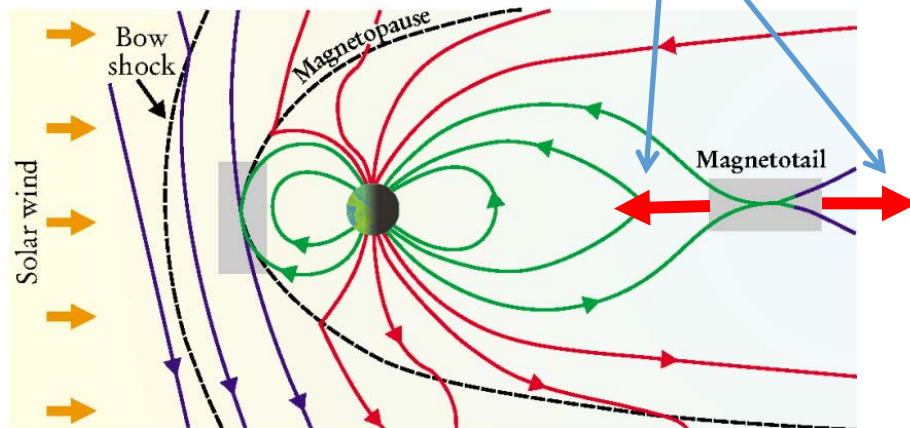


**Auroral footprint of reconnection seen for many hours -> reconnection is continuous**

# Bursty (Intermittent) Reconnection in the Magnetotail



Bursty reconnection



Angelopoulos et al. [*Science*, 2008]

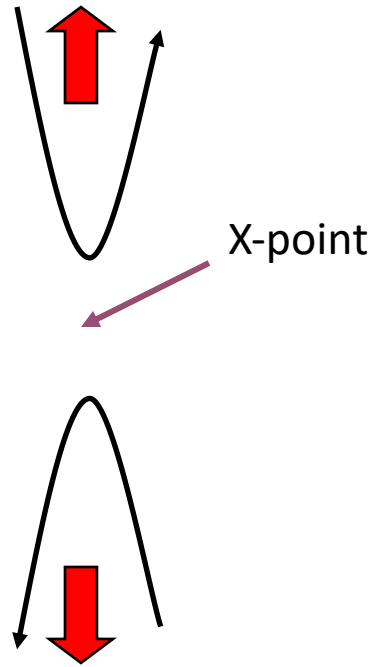
# Magnetic Reconnection:

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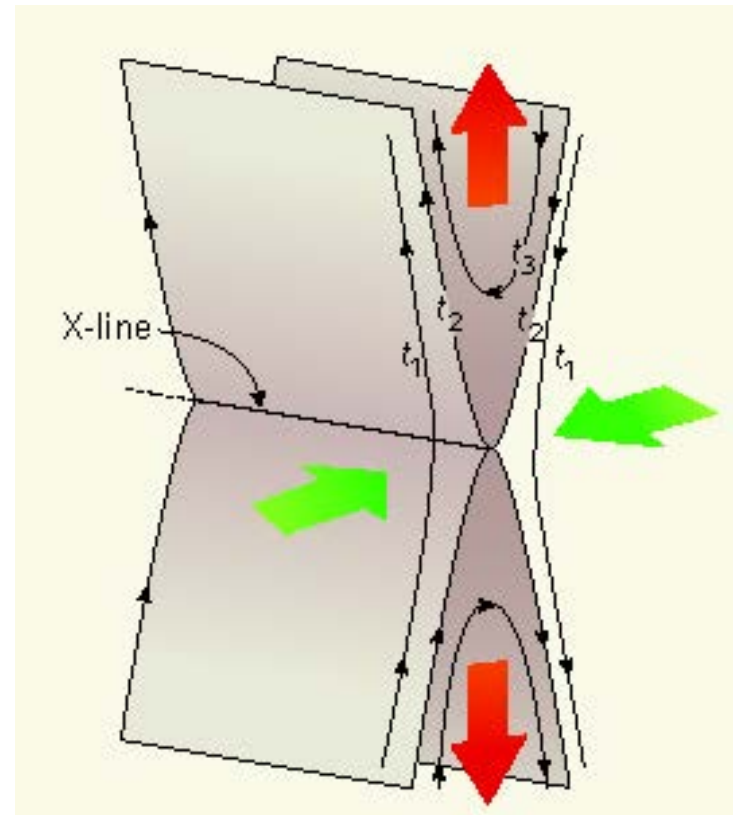
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Is reconnection patchy or extended? Both have been seen, but what controls it?

2-D



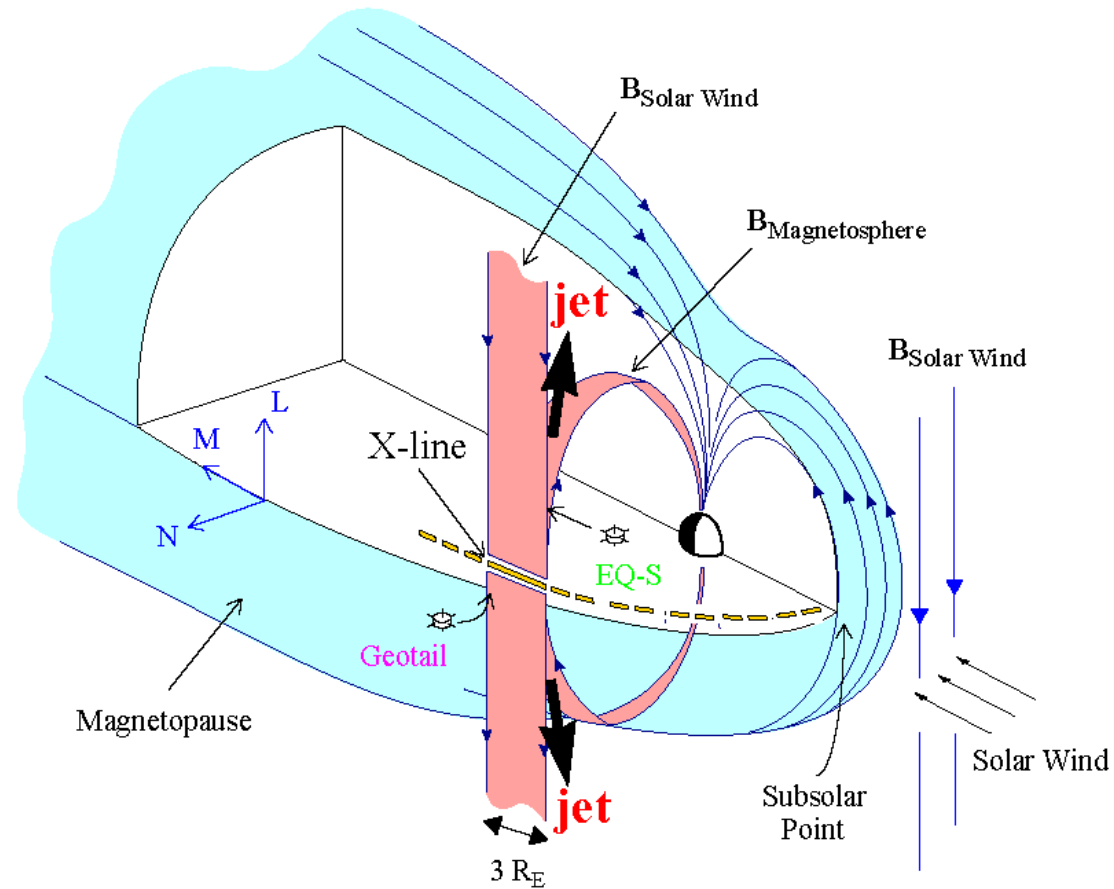
3-D



Extended: more magnetic energy release

## Patchy or Extended?

difficult to answer with observations at the magnetopause because it requires simultaneous observations at many local times

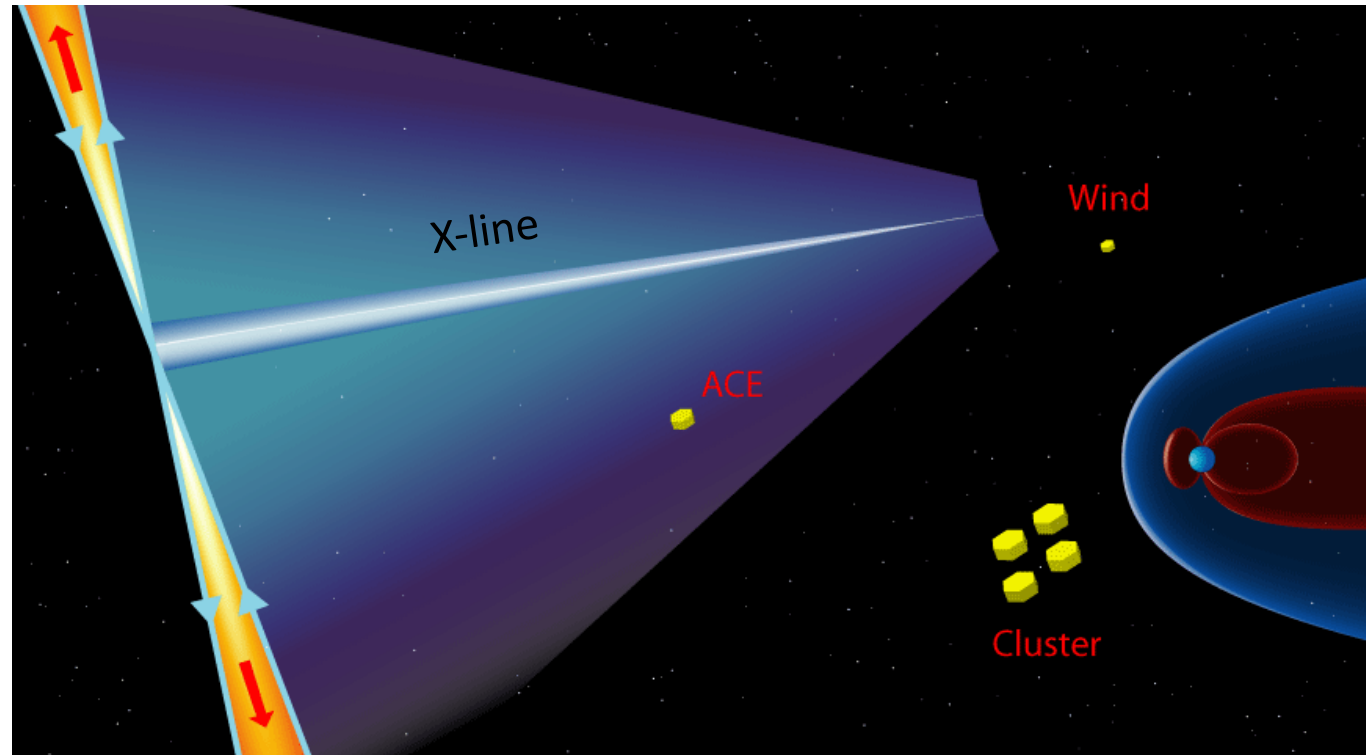


Phan et al. [2000]



# Extended (hundreds of $R_E$ long) reconnection X-line seen in solar wind current sheets

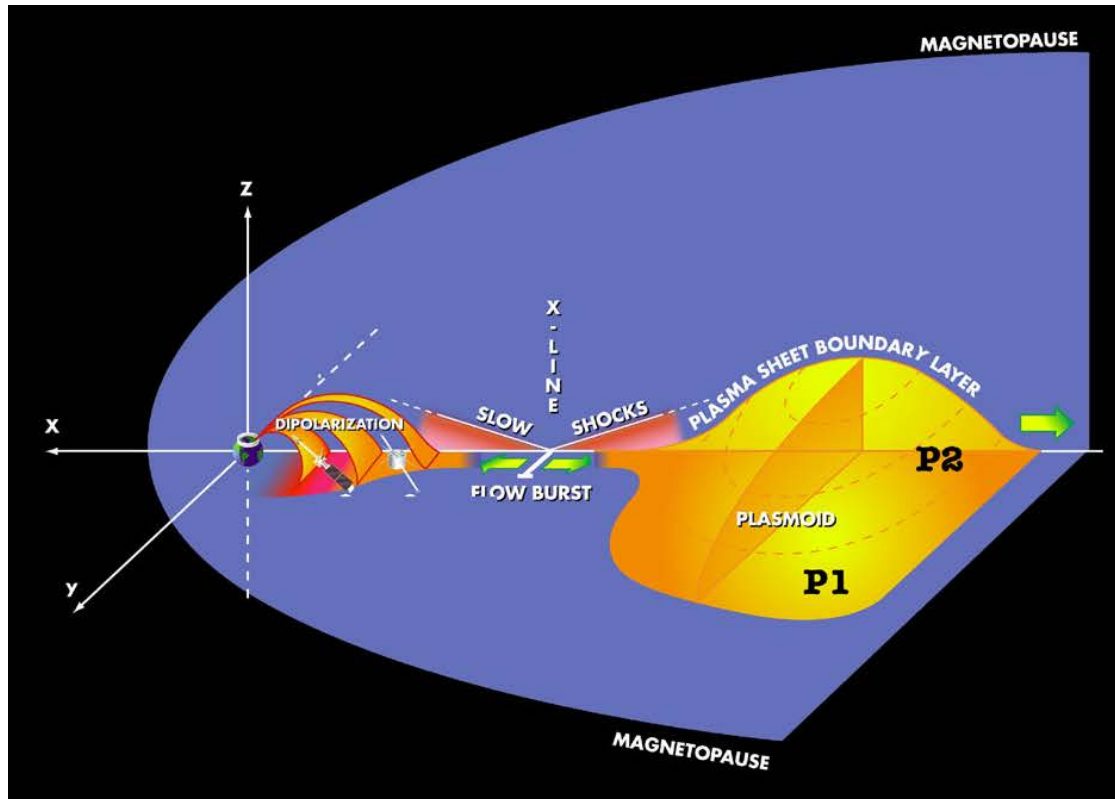
[Gosling et al., 2007; Phan et al., 2006,....]



Wind, ACE, and Cluster detected the same reconnection event

## Magnetotail Reconnection:

- Near-Earth ( $x_{\text{GSE}} = -20$  to  $-30 R_E$ ): Patchy,  $2-3 R_E$  X-line (even though the cross-tail current sheet dimension is  $30 R_E$ )  
[e.g., Nakamura et al., 2004]
- Distant Tail: X-line much more elongated



Sibeck et al. [2011]

What is the difference between near-Earth and distant tail?

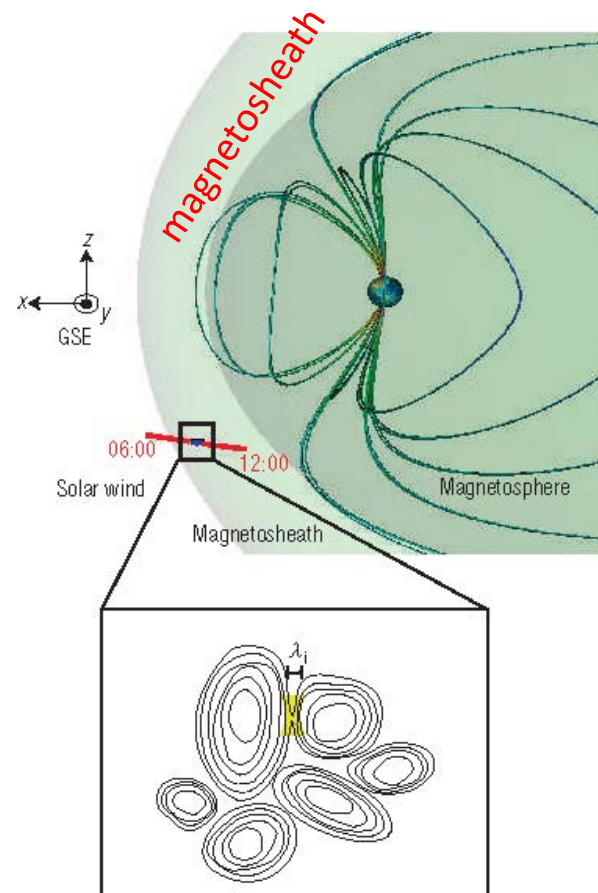
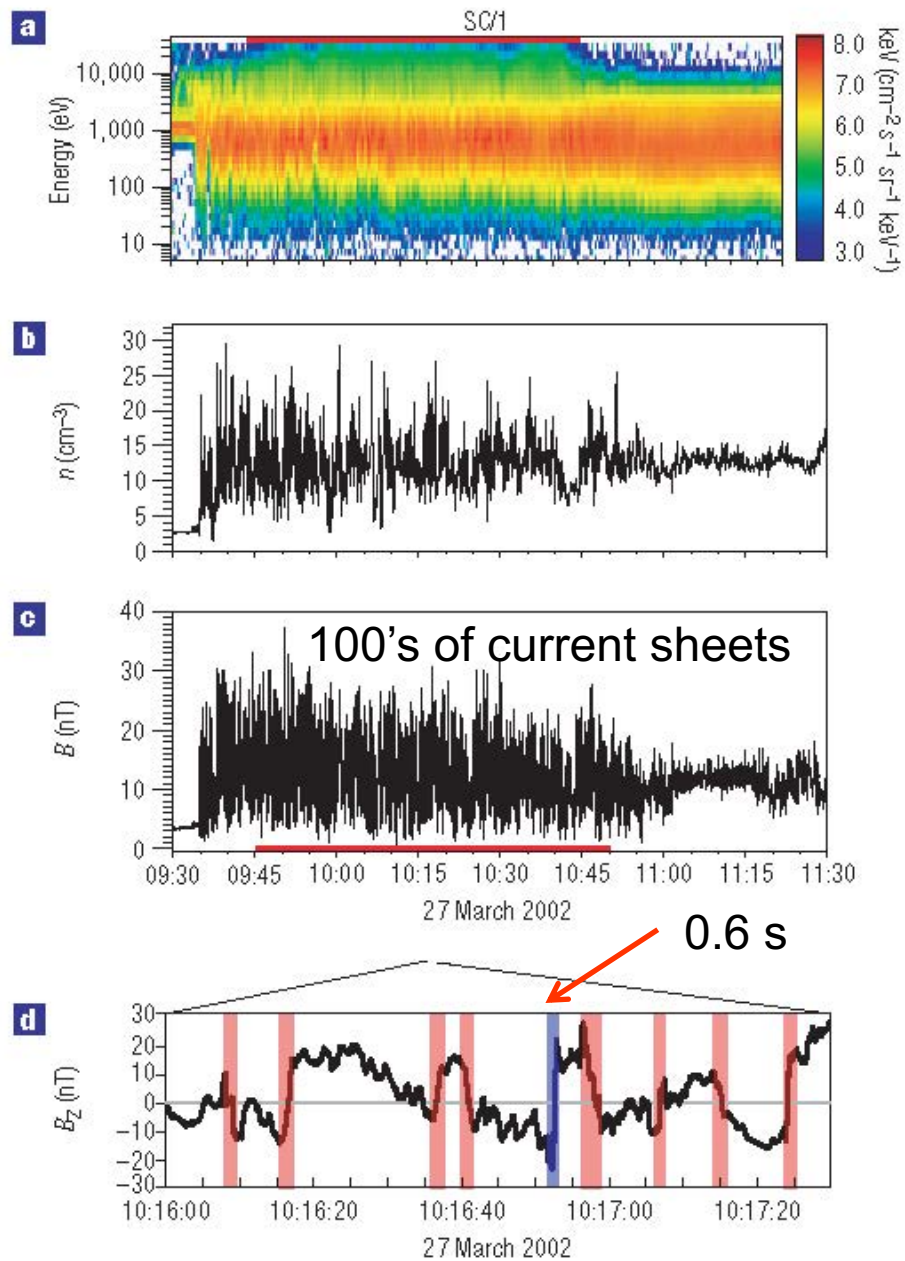
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# What is the Role of Reconnection in Turbulence?

Cluster



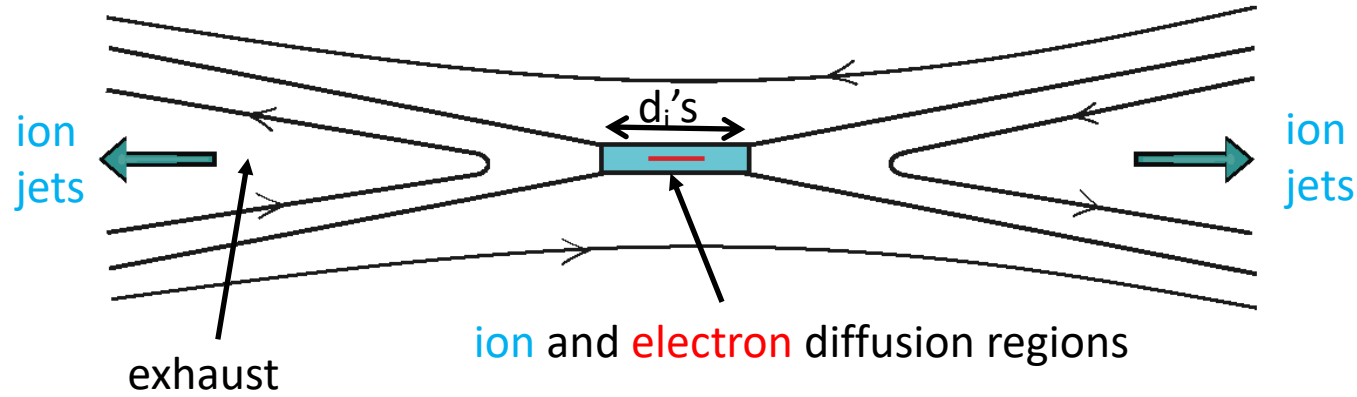
Retino et al., 2007  
Sundqvist et al. 2007

Hall B and E consistent with standard reconnection were observed

# MMS Observations of Electron Reconnection without Ion Coupling in Turbulence in Magnetosheath and Shock

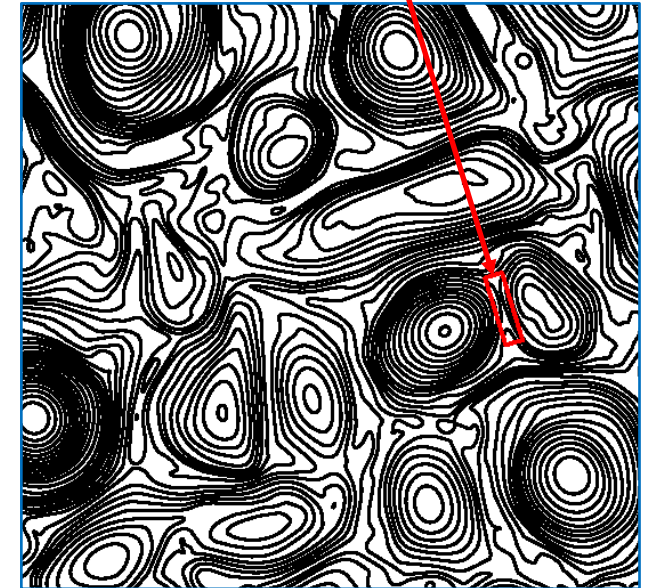
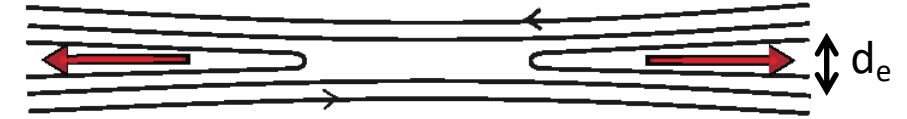
[Phan et al., 2018; Imogen et al., 2019; Wang et al., 2019; Bessho et al., 2019]

## Standard Reconnection



- Standard reconnection observed at magnetopause, magnetotail, solar wind, laminar magnetosheath, etc...
- Most observations are of the extended (MHD-scale) exhausts

## Electron Reconnection



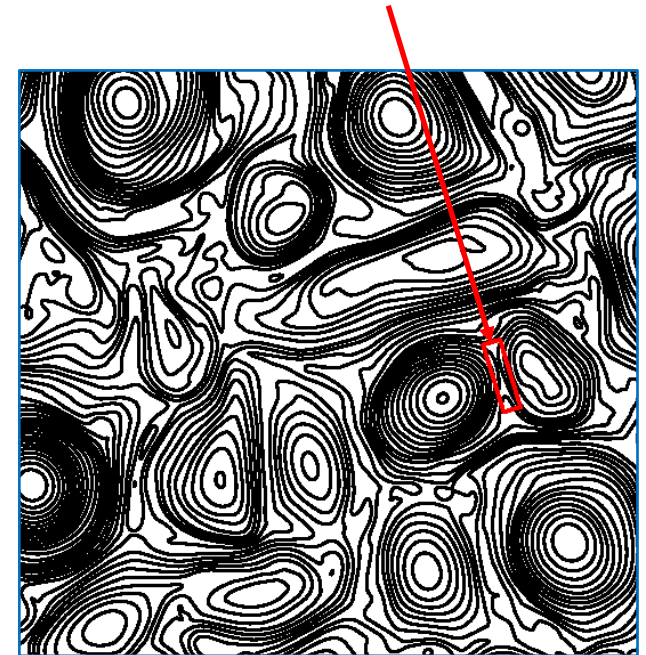
No ion exhausts

Magnetic energy converted into electrons only

# Is reconnection important in dissipating turbulence energy? How can one tell?

## Unanswered questions:

- What is the occurrence rate of reconnection in the turbulent current sheets?
- How short-lived is reconnection?
- When does one get electron-only reconnection versus standard reconnection?
- What is the distribution of scale sizes of current sheets, in 3D?

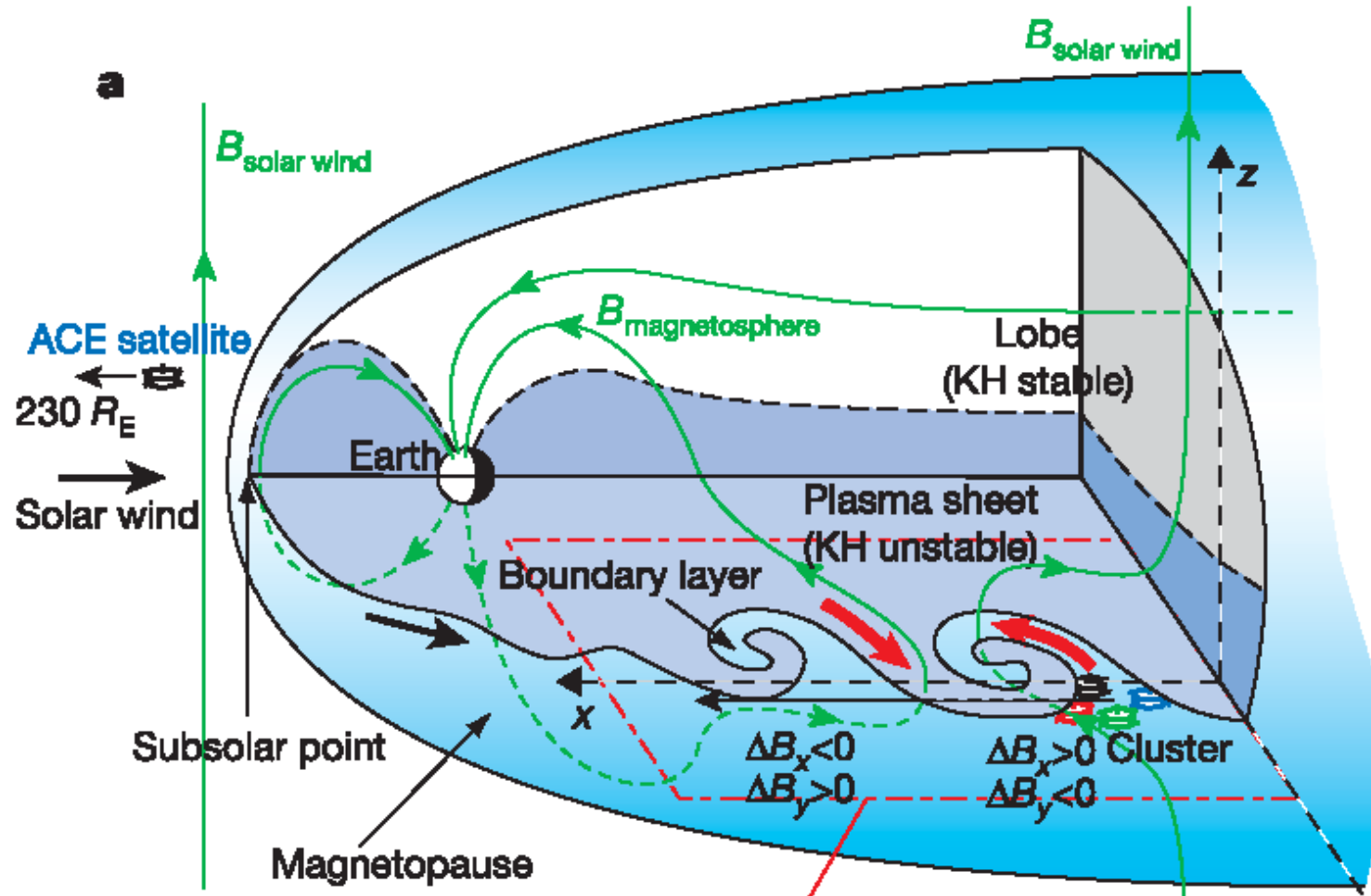


Need multi-scale observations to answer these questions

## Magnetic Reconnection:

### Open Questions that Require Multi-Scale Observations

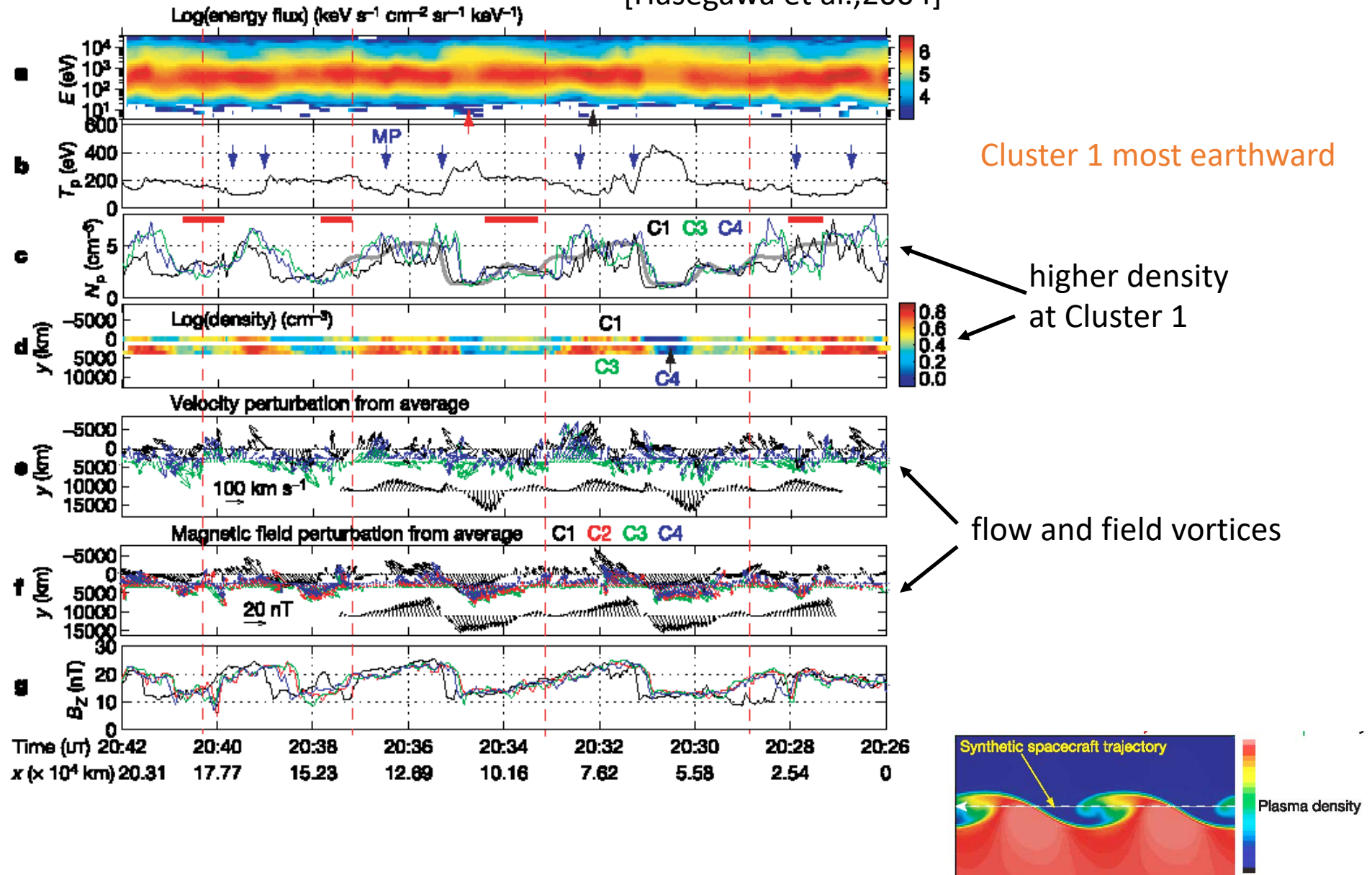
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# Evidence for Kelvin-Helmholtz Rolled-Up Vortices

[Hasegawa et al., 2004]



## **MMS detected reconnection in some K-H current sheets [Eriksson et al., 2016; Li et al., 2016]**

To understand the interplay of K-H and reconnection requires multi-scale observations:

- What is the occurrence rate of reconnection?
- How long-lived is reconnection?
- Does reconnection play a significant role in cross-field plasma transport?

## Conclusions

- Simultaneous multi-scale observations are required to answer key questions in reconnection physics
- Need strong theory/simulation component to support the interpretations of multi-point, multi-scale observations