# Magnetic reconnection and the structure of the magnetopause

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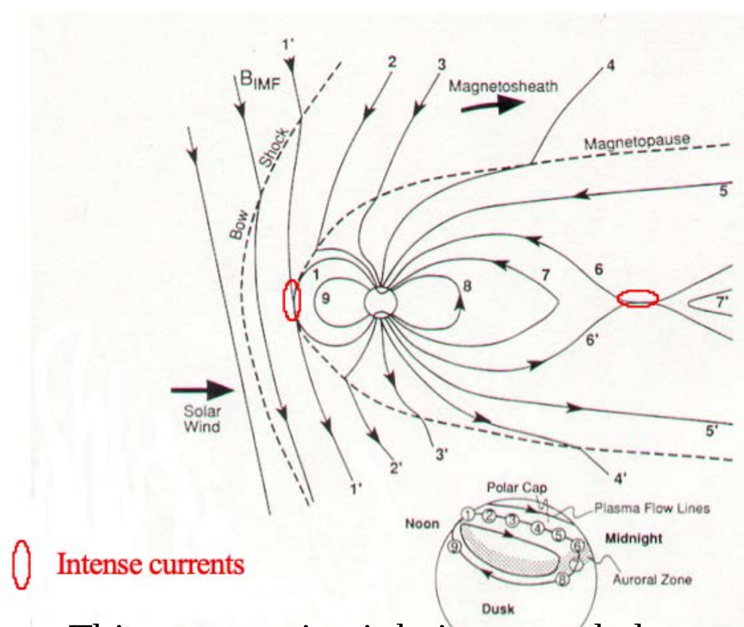
Ack: many collaborators

# Magnetic reconnection and the dynamics of the magnetosphere

- Magnetic reconnection between the solar wind and the Earth's magnetic field is a fundamental driver of the dynamics of the magnetosphere
  - Sentinel paper by Dungey in 1961 met with skepticism by many at the time
  - Reconnection at the magnetopause leads to magnetic flux transfer and formation of the extended magnetotail
    - Production of energetic particles in magnetotail reconnection events
    - Injection of energetic plasma into the inner magnetosphere – generation of the radiation belts
  - Convective transfer of flux back to the front side

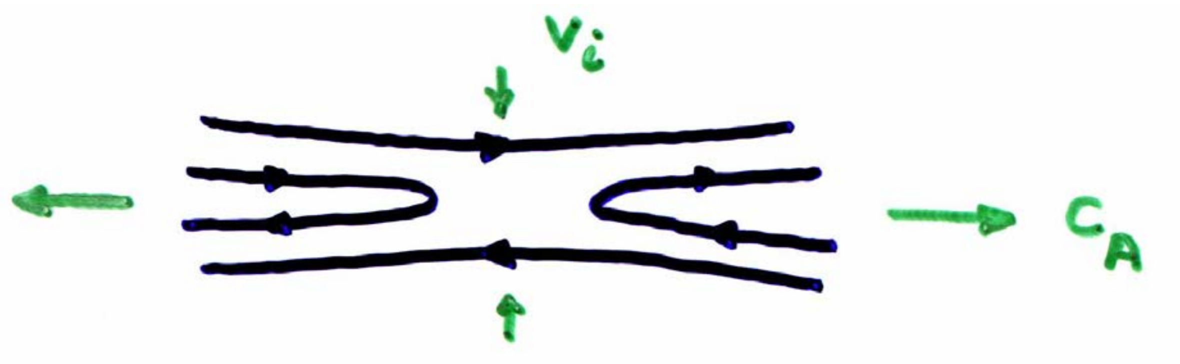



Kivelson et al., 1995

# Outline of the talk

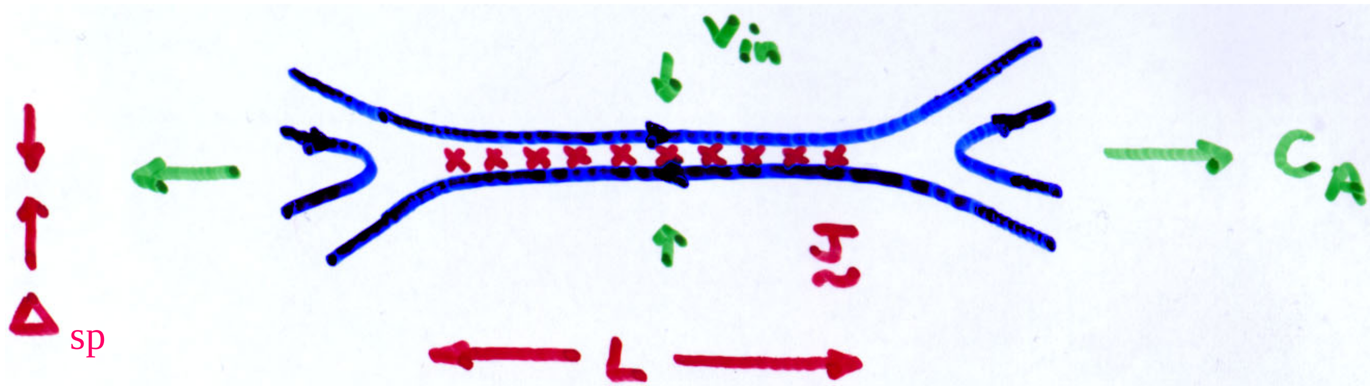
- Physics basis of magnetic reconnection (pre MMS)
  - Rate of reconnection and fundamental dynamics
  - Multiscale structure of the diffusion region
    - Ion versus electron scales
  - Asymmetric reconnection relevant to the magnetopause
- Electron scale dynamics of reconnection at the magnetopause and in the magnetosheath in the MMS era
  - Structure of the electron diffusion region
  - Reversibility of energy transfer
  - Direct measurements of electron-scale flows and the rate of reconnection
- Turbulent transport at the magnetopause
  - Implications of frozen-in electrons for transport at the magnetopause

# Magnetic Reconnection Basics




- Reconnection is driven by the magnetic tension in newly reconnected field lines
  - Drives outflow at the Alfven speed $c_A$
  - Pressure drop around the x-line pulls in upstream plasma
- Dissipation required to break field lines
  - At small spatial scales since dissipation is weak
- Reconnection is self-driven
  - No external forcing is required

# Classic Resistive MHD Description



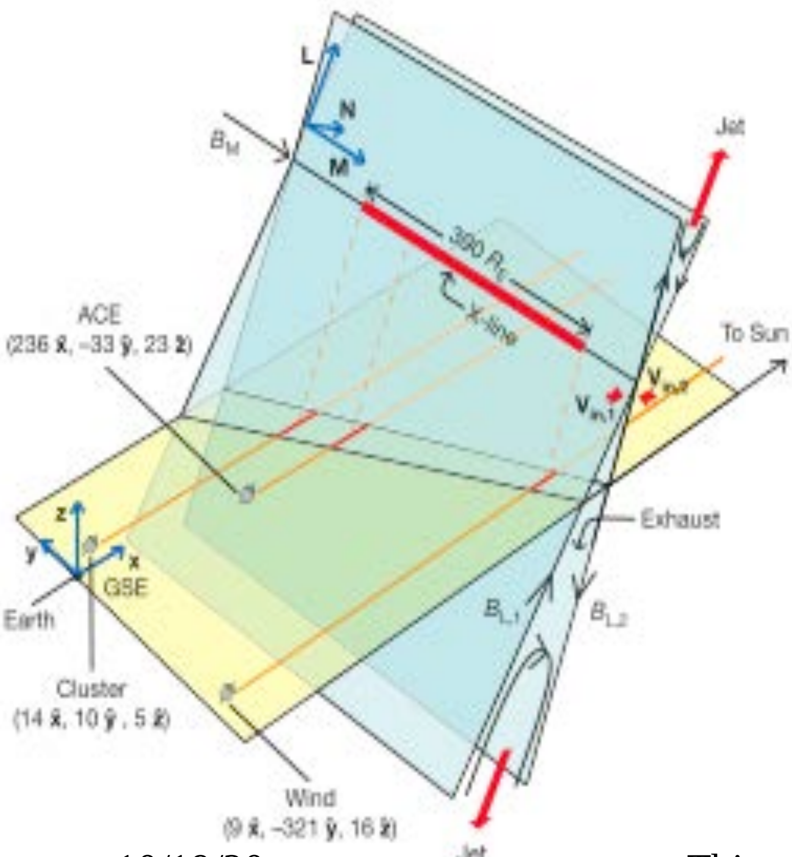

- Formation of macroscopic Sweet-Parker layer

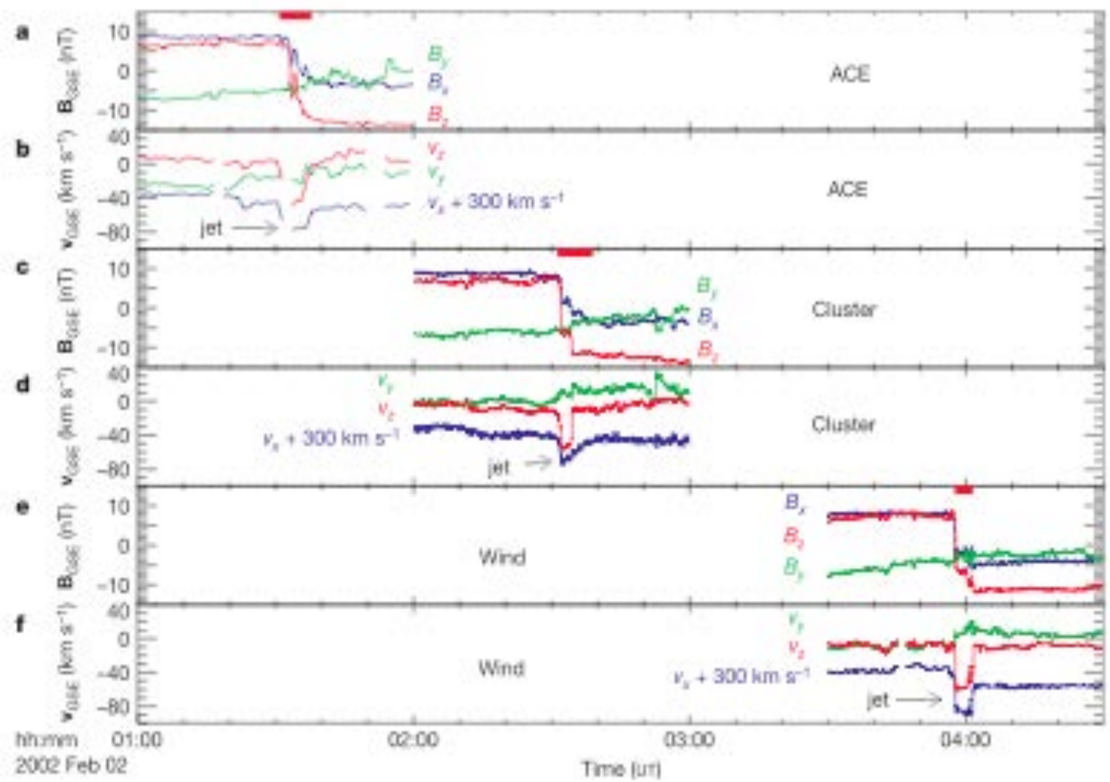
$$\mathbf{V_{in} \sim (\Delta_{sp}/L)\, C_A \sim (\tau_A/\tau_r)^{1/2}\, C_A << C_A}$$

- Slow reconnection
  - not consistent with observations
- Macroscopic nozzle
- Sensitive to resistivity

# Direct measurement of reconnection in the Earth's space environment

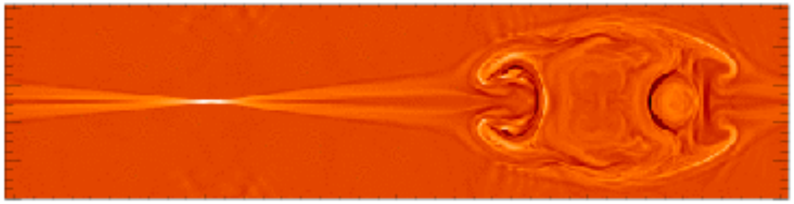
- Solar wind reconnection event
  - 390 $R_E$ reconnection encounter (Phan et al 2006)
  - Established that reconnection could release energy in a macroscale system



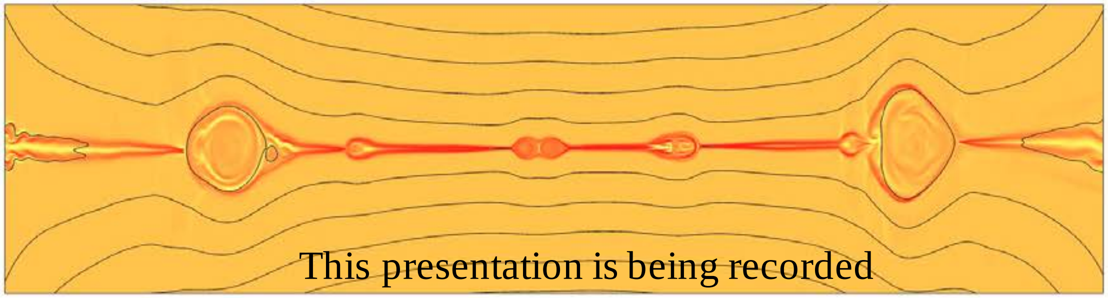



# Mechanisms for the fast release of magnetic energy: insensitive to dissipation

- Hall reconnection: an open Petschek-like outflow exhaust produces fast reconnection (Aydemir '90, Mandt et al '94, Shay et al '99, Birn et al '01)

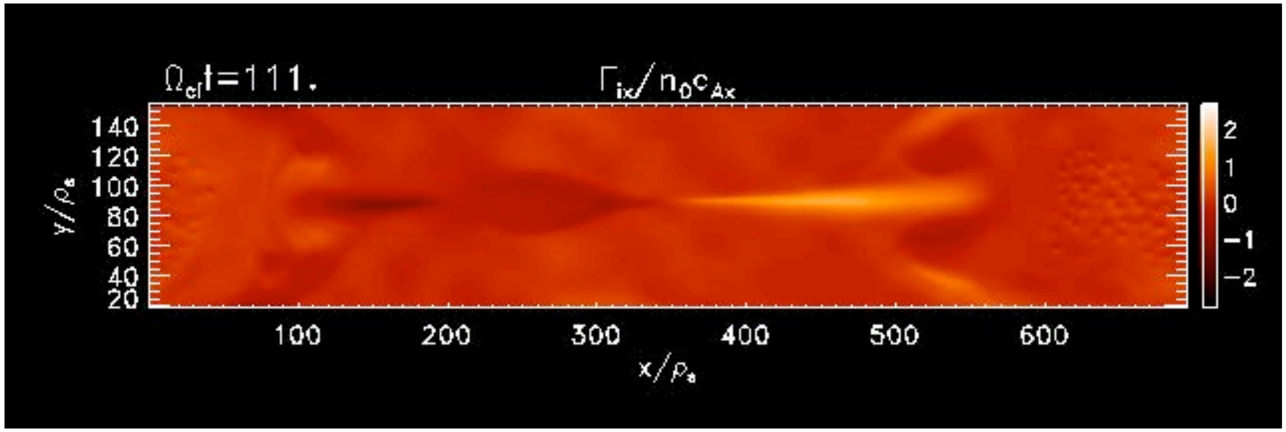


- Multi-island reconnection (Daughton et al '09, Bhattacharjee et al '09, Cassak et al '09)
  - Large-scale current layers break up into secondary islands

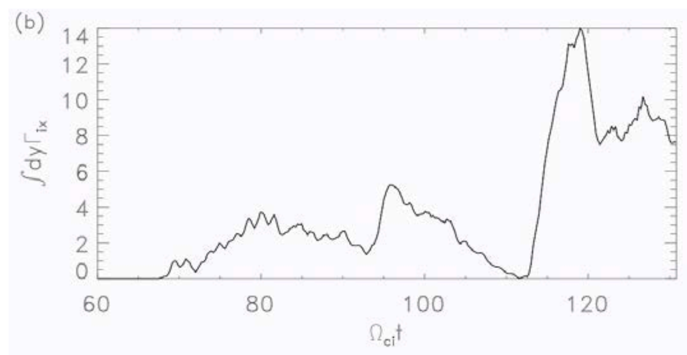


# Multi-island reconnection

- Large-scale current layers break up into secondary islands



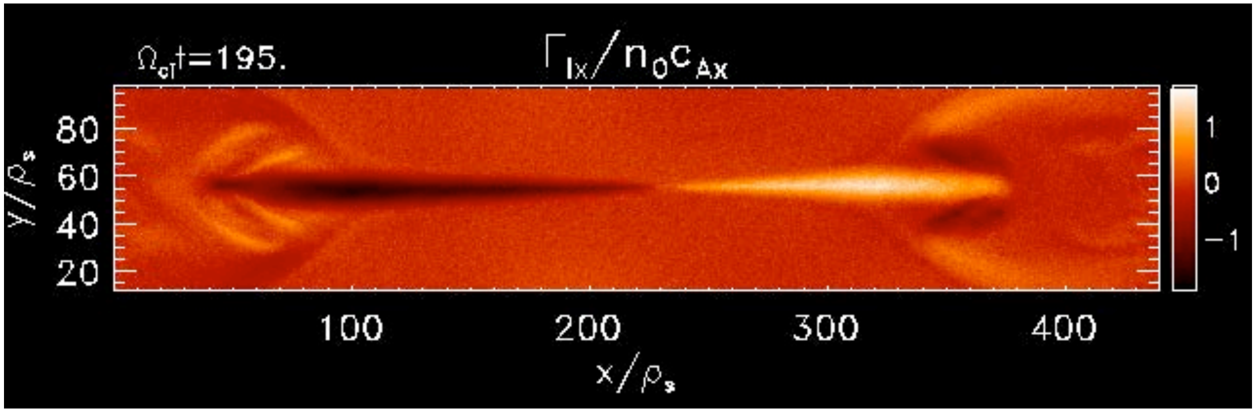

- Secondary islands carry particles out of the current layer
  - Bursty reconnection



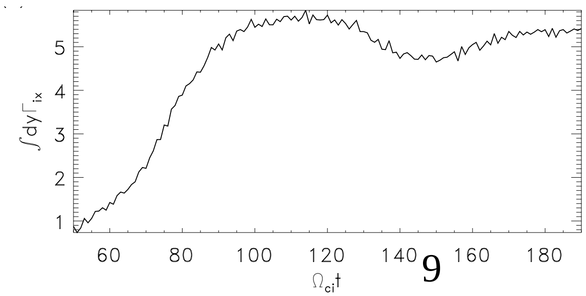

- Where?
  - Low resistivity MHD: $S = \tau_r/\tau_A > 10^4$ – solar corona?
  - Collisionless: strong guide magnetic field at low $\beta$ – solar corona?

# Hall Reconnection

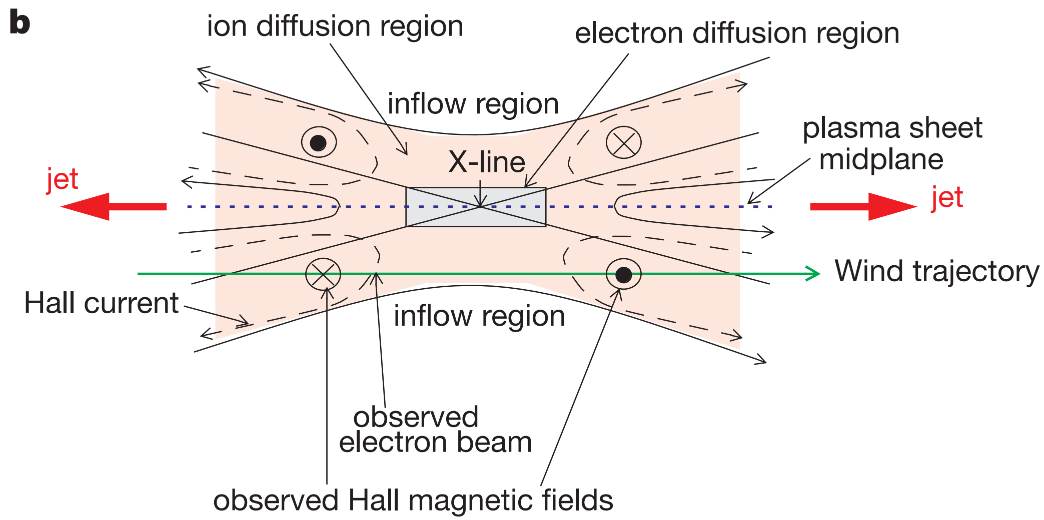
- Any system with dispersive waves at small scales produces an open exhaust and fast reconnection independent of dissipation (Birn et al ’01, Rogers et al ’01)
  - Whistler or kinetic Alfven waves
  - Signature quadrupolar Hall magnetic field has been documented in the magnetosphere and laboratory




- Particle flux from the current layer is steady
- Collisionless regime except high guide field and low β
  - Most relevant to Earth’s magnetosphere



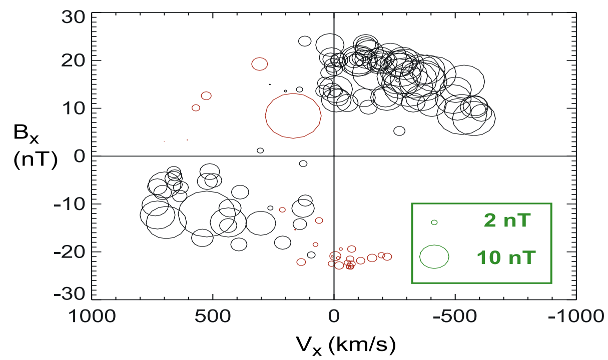
# Decoupling of electron and ion motion in collisionless reconnection




- Ion motion decouples from that of electrons at a distance $c/\omega_{pi}$ from the x-line
  - Ion outflow width $c/\omega_{pi}$ with velocity $C_A$
- Electron inflow diverted at a scale $c/\omega_{pe}$ from the x-line
  - Electron outflow width $c/\omega_{pe}$
  - The whistler wave drives the electron outflow at the electron Alfven speed $C_{ae}$
- The Hall current produce the quadrupole out-of-plane magnetic field

# Observations of the Hall magnetic field in space and the laboratory

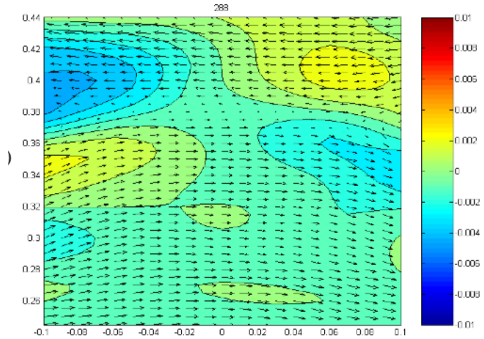
- Magnetotail (Oieroset et al ’01, Borg et al ‘05)



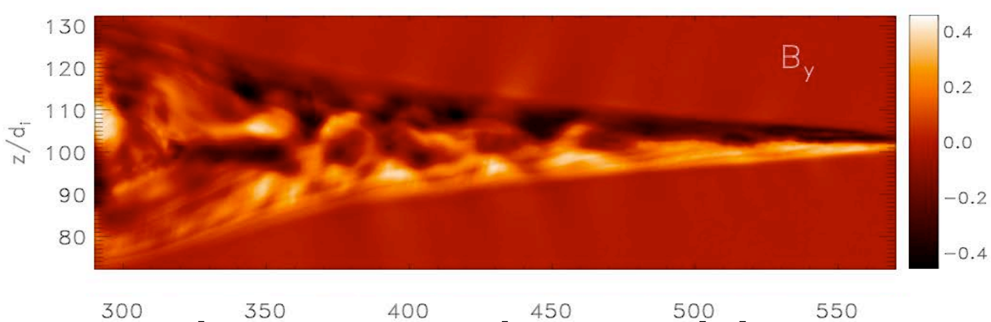

$B_y>0$

$B_y<0$

- MRX experiment



- Simulation





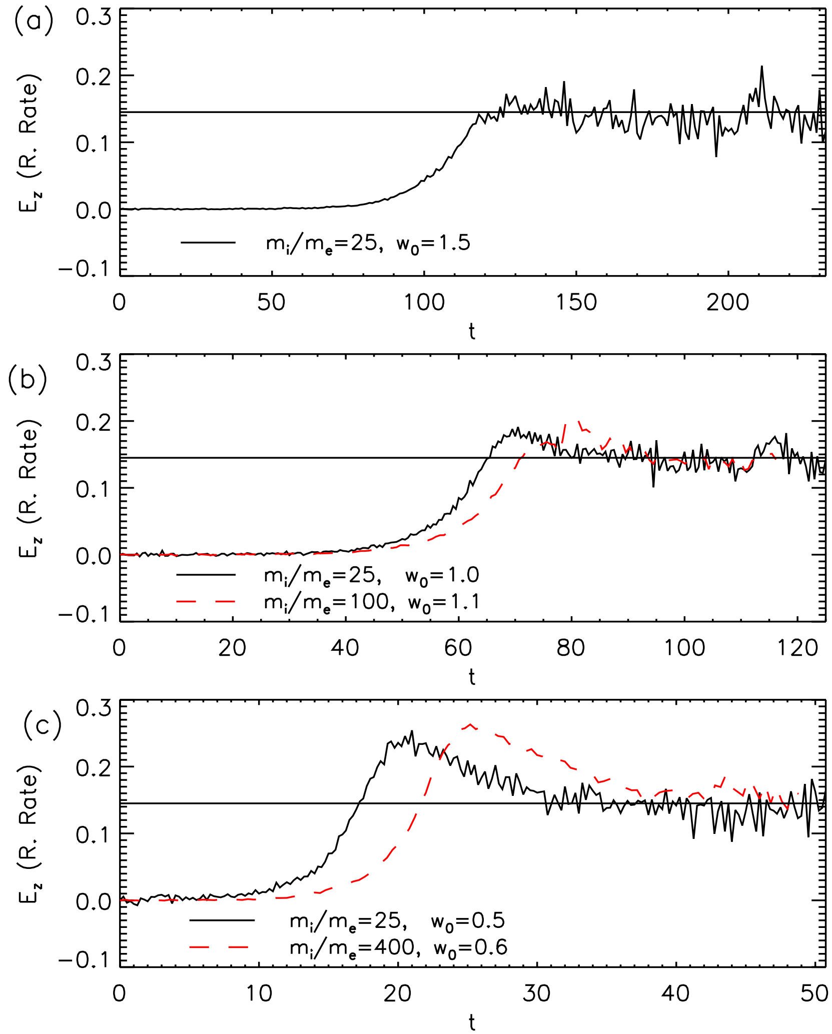

– Hall field extends 10s of $R_E$ from x-line

# Rate of reconnection: simulations

- Direct measure of the rate of reconnection from PIC simulations

$$V_{in} \sim 0.1 C_A$$

  - Fast reconnection independent of the electron-ion mass ratio and domain size (Shay+ '98, Hesse+ '99, Shay+ '07, Karimabadi+ '07)
    - Important for establishing rate of energy release in real systems




- Pre-MMS observations challenging
  - low inflow speeds
  - Dominance of the Hall electric field compared with the reconnection electric field

# What breaks magnetic field lines in collisionless reconnection?

- Electron momentum transport associated with thermal motion can break magnetic field lines during reconnection
  - Described by the off-diagonal pressure tensor (Hesse+ ‘99, Hesse+ ’02)

$$< E_y > = -\frac{\vec{\nabla} \bullet < \vec{P}_{ey} >}{< n_e > e}$$

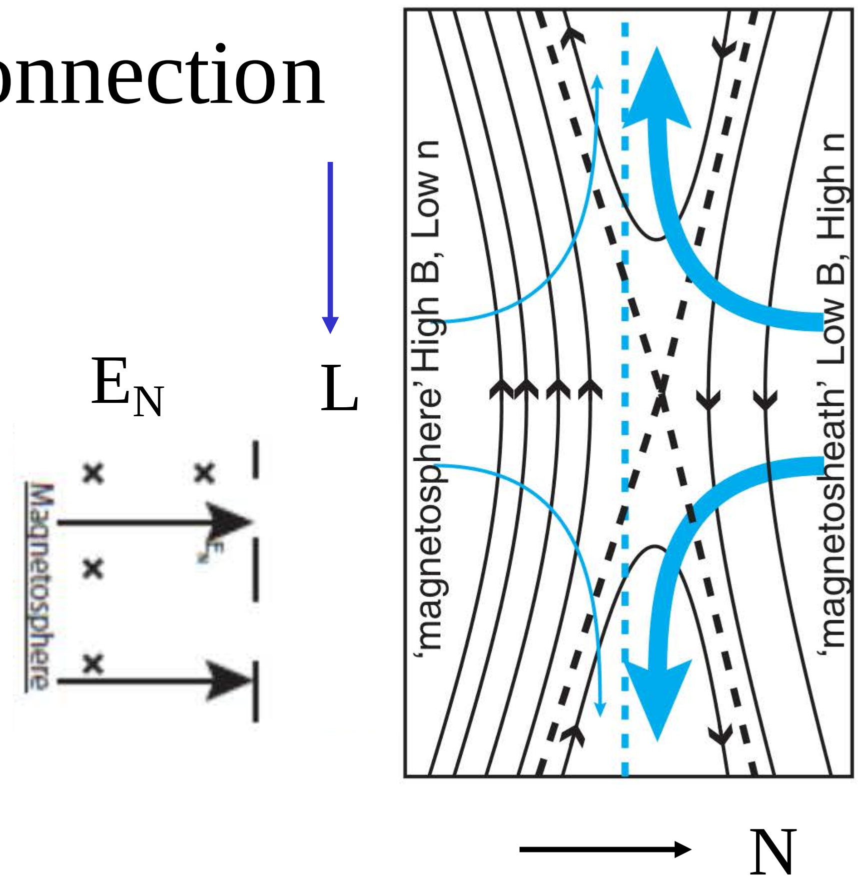
- Some form of anomalous resistivity is also often invoked to break field lines (Che+ ‘11)
  - Strong electron-ion streaming near x-line drives turbulence and associated enhanced electron-ion drag
    - Most important in low $\beta$ where electron streaming velocity dominates the thermal speed
  - Importance an open question

# MMS observations at the magnetopause

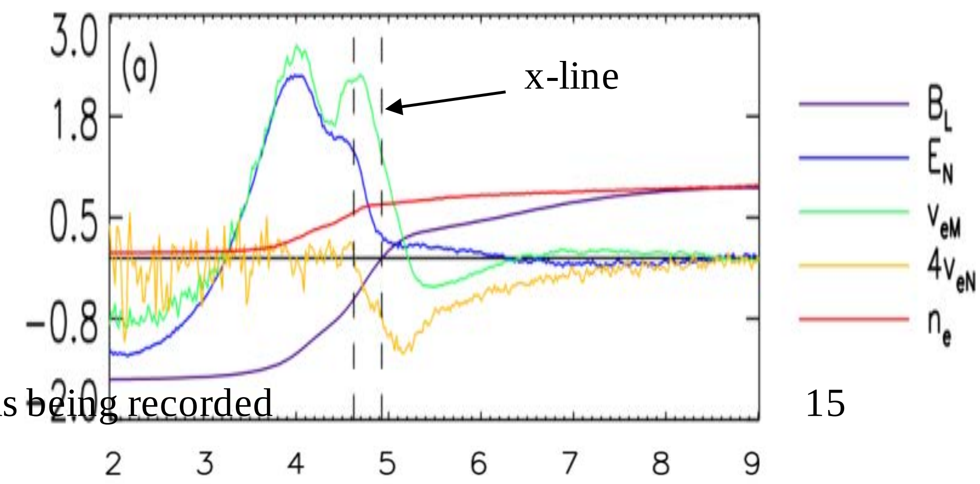
- MMS has made thousands of crossings of the magnetopause
  - Magnetic reconnection has been documented in hundreds of these events in phase 1 of the mission (Trattner+ '17, Fuselier+ 17)
  - The x-line location is generally consistent with the "maximum shear" model
    - Reconnection takes place where the rotation angle between the magnetospheric and drapped magnetosheath fields is greatest
- Crossings of the electron diffusion region are rare because this region has electron scale
  - Focus here on the diffusion region crossings

# Basics of asymmetric reconnection

- Stagnation point of reconnection inflow and current displaced toward the magnetosphere (Cassak & Shay '07)
  - High momentum of inflowing magnetosheath ions carries them past the x-line
- Large $E_N$ on the magnetosphere side of the x-line holds back the high pressure sheath ions
  - Ions nearly unmagnetized
  - Large $E_N$ is generic to asymmetric reconnection
- Dominant current $J_{eM} \sim E_N/B_L$
  - Not localized where $B_L = 0$




PIC simulation



# October 16, 2015, event

- Simulations of the MMS encounter with a magnetopause reconnection event (Burch et al 2016)
- Basic parameters

  $B_{Lsh} \sim 23nT$, $B_{Lms} \sim 39nT$

  $n_{sh} \sim 11.3/cm^3$, $n_{ms} \sim 0.7/cm^3$

  $c_{Ash} \sim 150km/s$

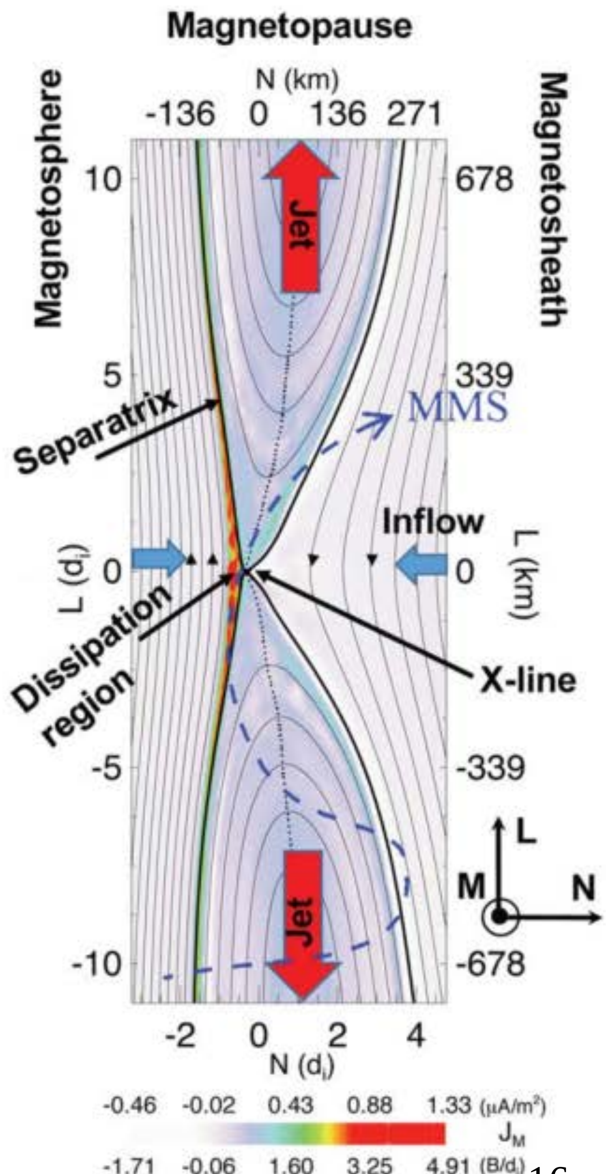
  – Nearly anti-parallel reconnection since $B_{Msh}$ is small

- Rate of large-scale reconnection and dissipation rates based on traditional reconnection simulations

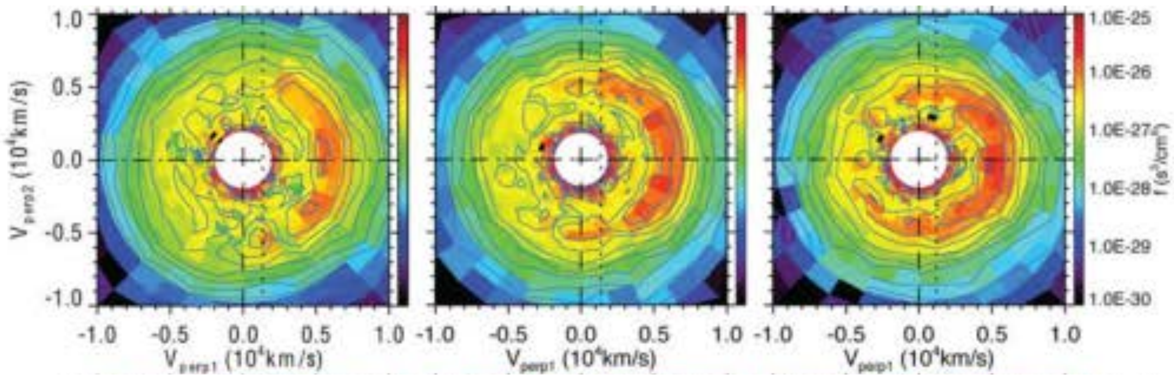
  $E_M \sim 0.2mV/m$

  $J_M \sim 0.6\ \mu A/m^2$

  $J_M E_M \sim 0.12nW/m^3$



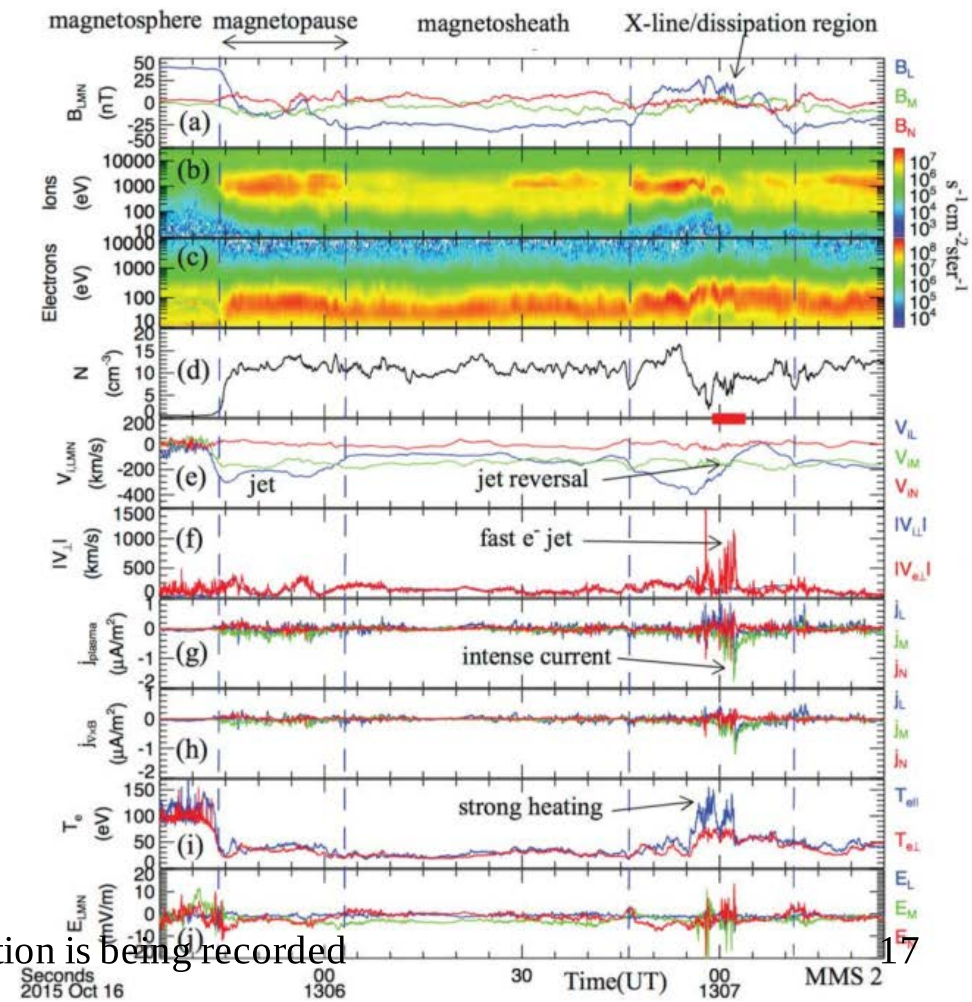
# MMS observations in the electron diffusion region




- Measurement of intense current $J_{eM}$
- Measurement of a bursty electric field with

  $E_M \sim 10$mV/m

  – Much larger than expected reconnection electric field
- Measurement of electron crescent distributions. Why?

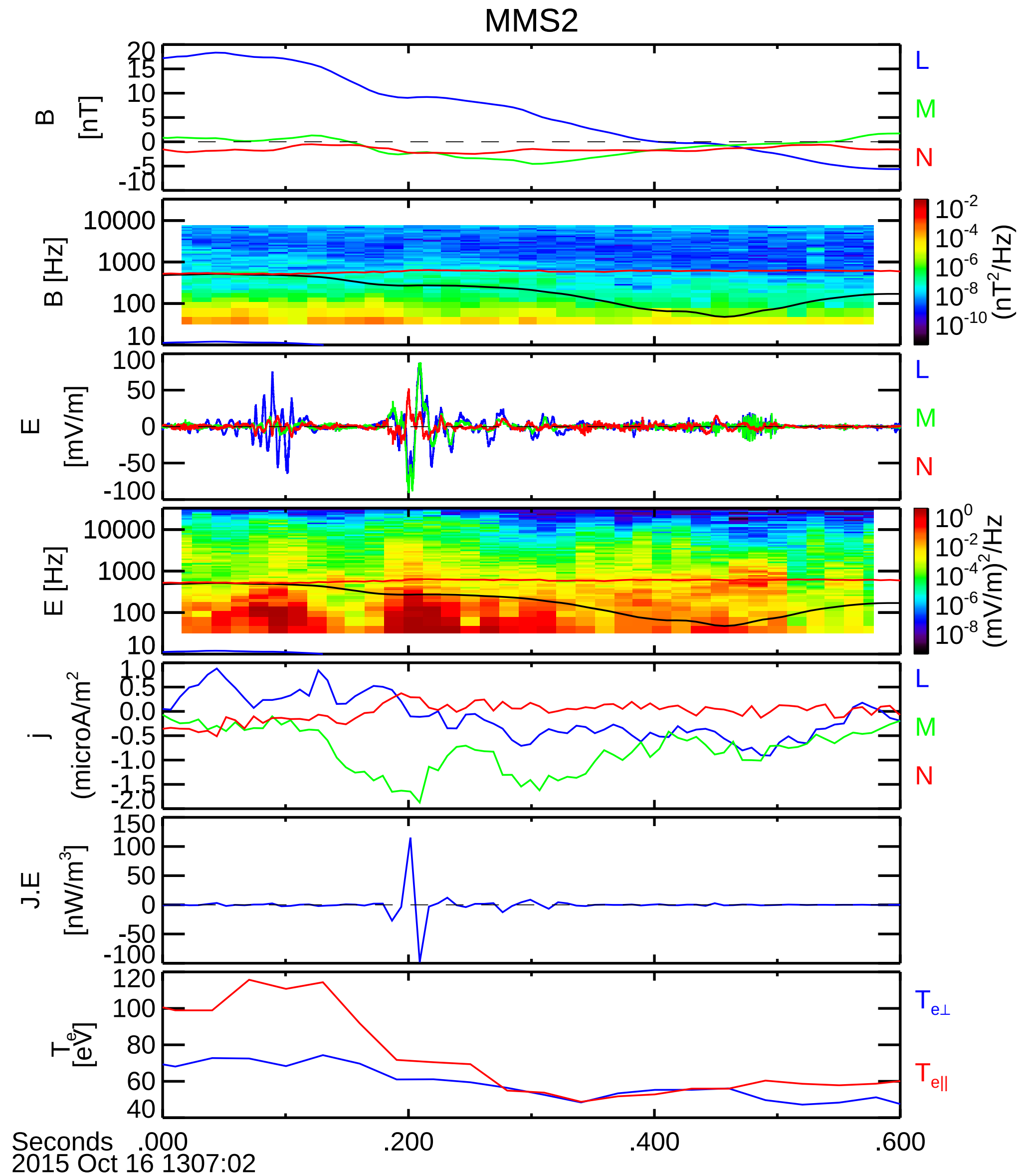


# Blowup around the electron diffusion region

- $J_{eM}$ peaked well away from the magnetic null
  - Why?
- Intense and bursty electric fields in region of strong $J_{eM}$
  - Suggests a turbulent dissipation mechanism
- Extremely intense values of

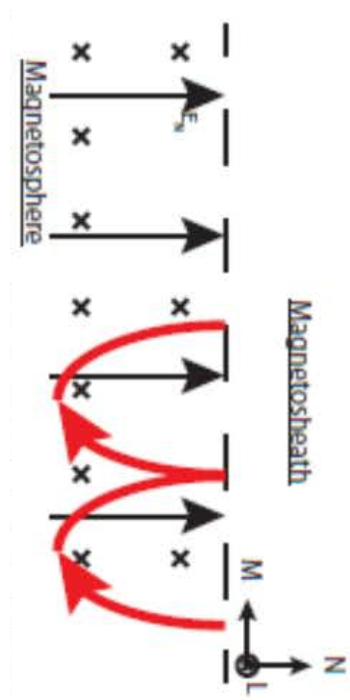
$$\vec{J} \bullet \vec{E} \sim 50nW / m^3$$

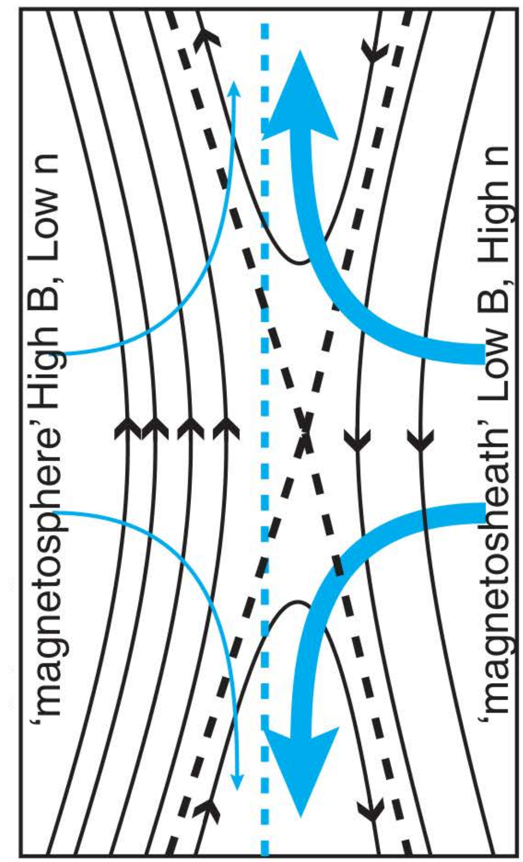
  - More than two orders of magnitude greater than expected
  - Why?
  - Why positive and negative values?



# Electron cusp orbits in asymmetric reconnection

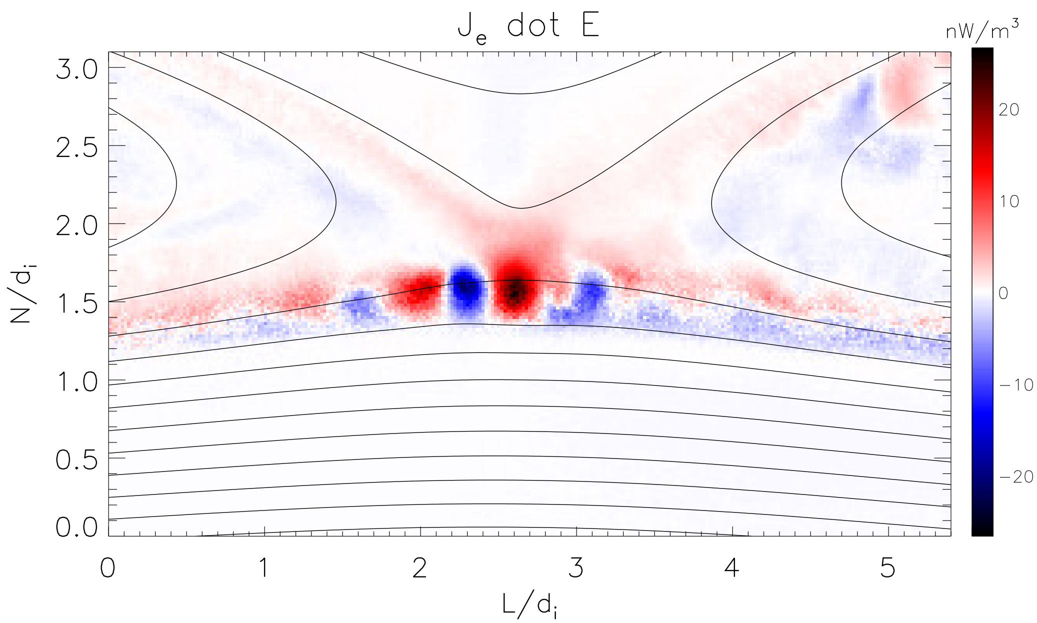
- Crescents first seen in simulations by Hesse+ '14
- $E_N$ accelerates electrons away from the x-line, forming the cusp-like orbits and the crescent distributions (Burch+ '16, Bessho+ '16, Shay+ '16)
- Why are the crescents important?
  - $E_N$ sweeps the electrons away from the x-line
  - Therefore limits the current at the x-line and facilitates reconnection
  - Crescents are the evidence of electrons being swept out of the diffusion region by $E_N$



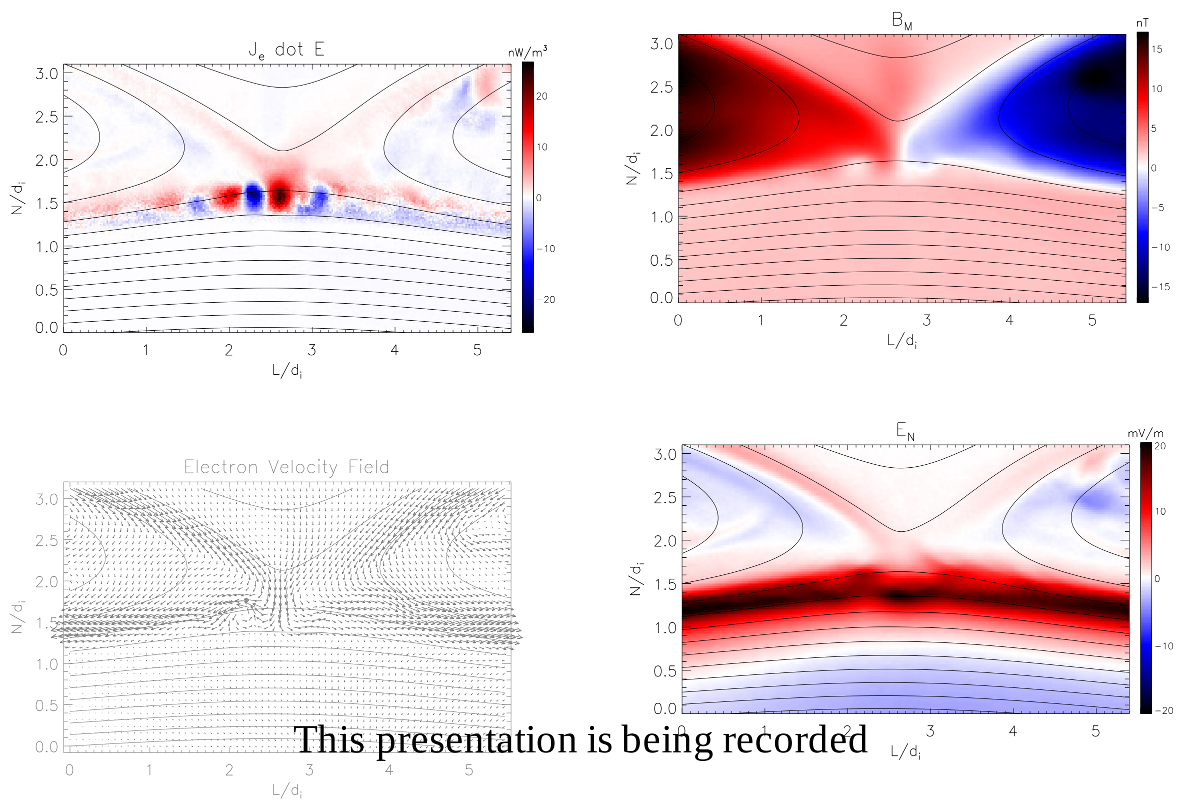
# Oscillatory energy conversion in asymmetric reconnection

- PIC simulations of the Oct 16, 2015, event (Swisdak+ ’18)
- Highly structured electron dissipation region in asymmetric system
  - Small scale standing structure at sub $d_i$ scale – not turbulence
  - Positive and negative values of $\vec{J} \bullet \vec{E}$



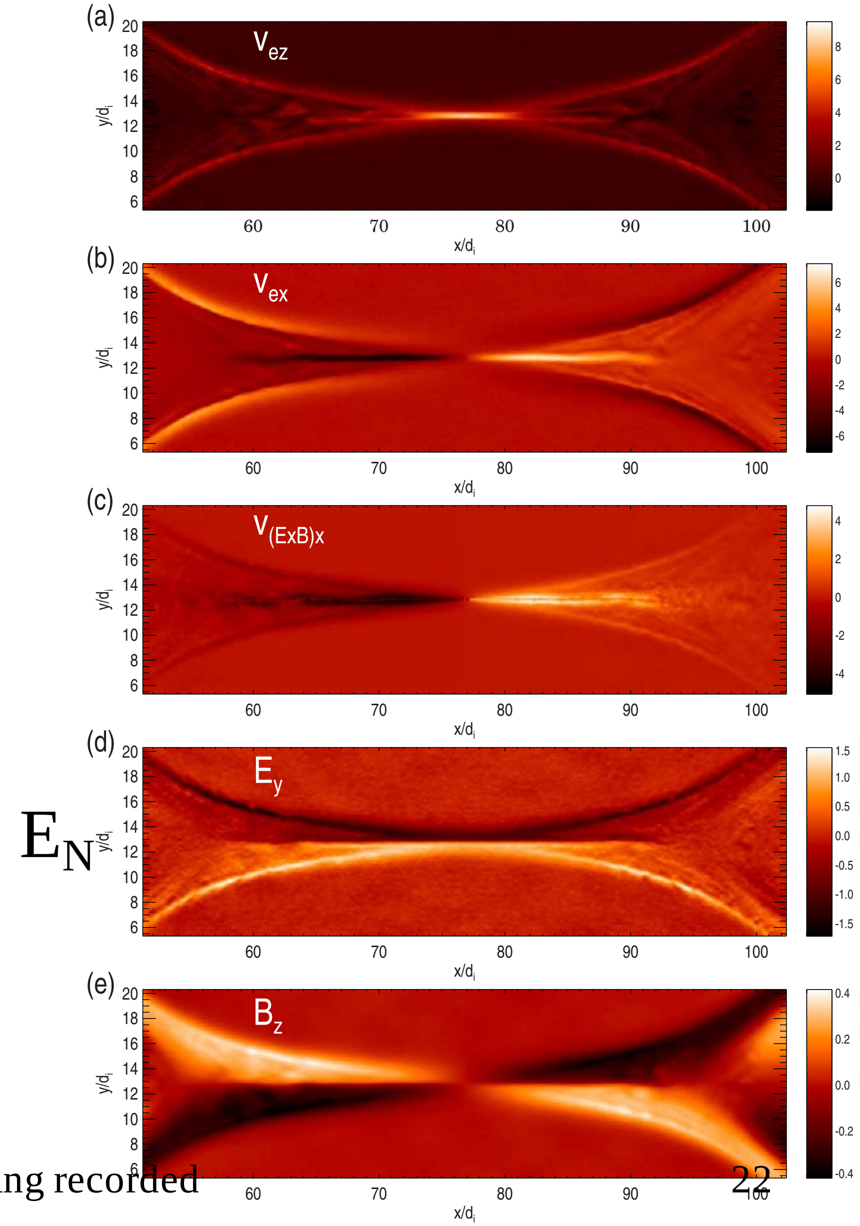
# Generation of standing oblique whistler

- Beams of electrons flowing along the magnetospheric separatrices converge and jet across the x-line
- Electrons bounce in coherent oscillations across the magnetopause and associated $E_N$
- Large, oscillatory values of $J_N E_N$ as seen in MMS data
  - Dissipation of the Hall magnetic field $B_M$



# Challenges facing direct measurements of the rate of reconnection

- Measurement of the rate of reconnection through direct observations has been a challenge
  - The reconnection electric field $E_M$ is small compared with the Hall electric field $E_N$
  - Ion inflow velocities upstream of the diffusion region are small compared with characteristic thermal speeds
  - Small errors in the minimum variance analysis mixes $E_M$ and $E_N$ and prevents an accurate measure of $E_M$ (Genestreti+ '18)

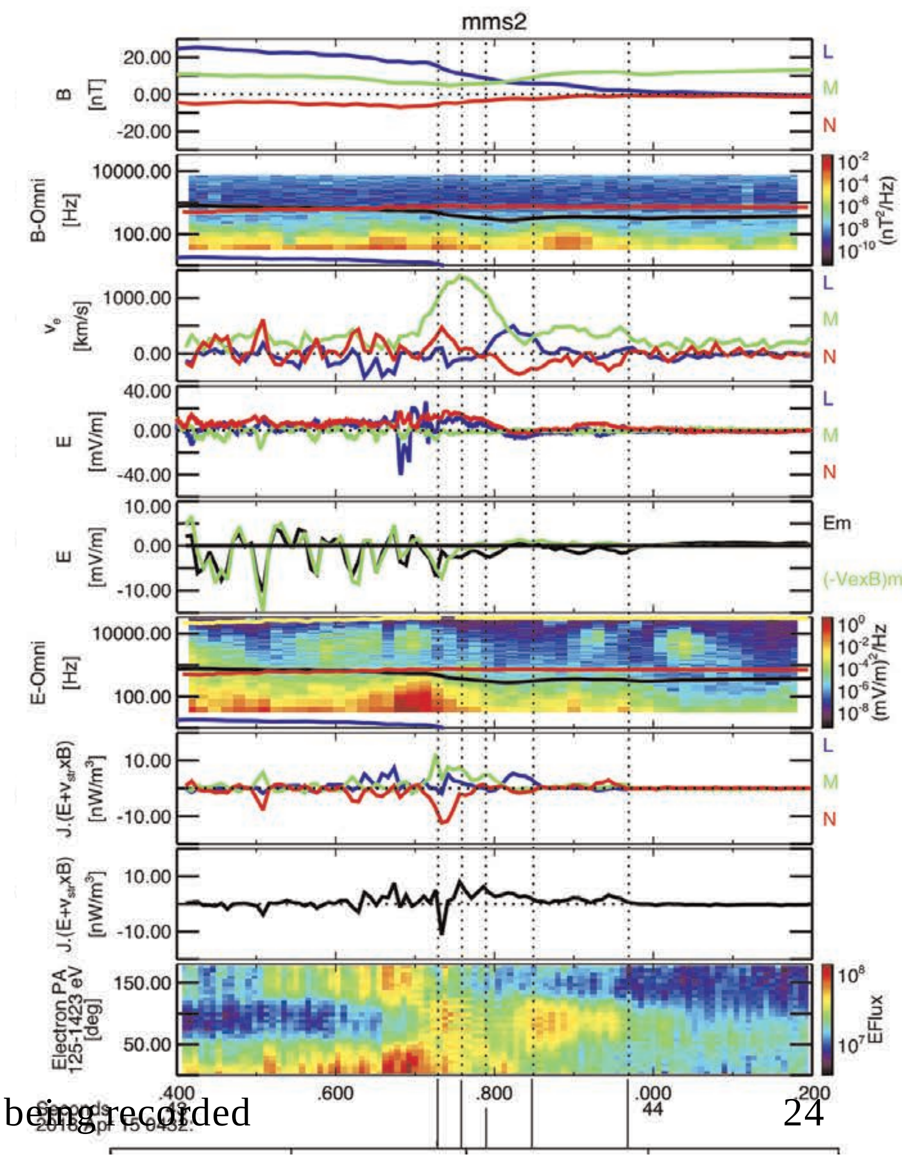


# The structure of the electron diffusion region has produced direct measurements of the reconnection rate

- Electron inflow and outflow velocities in the electron diffusion region are large
  - They scale with the electron Alfven speed $C_{Ae}$ because the dynamics is controlled by the whistler rather than the Alfven wave
- Direct measurements of these high-speed electron flows and associated strong electric fields has been carried out with MMS at the magnetopause and magnetosheath to directly measure the rate of reconnection (Burch+ ‘20)

# Electron scale structure of the April 15, 2018, event

- Direct measurements of high-speed electron flows and associated strong electric fields has been carried out with MMS at the magnetopause (Burch+ '20)
- Note the bipolar velocity $V_N$ of electrons
  - On the magnetosphere side of the null of $B_L$
- Velocities must be normalized to $C_{AeL}$ just upstream of the electron diffusion region (Drake+ '08)
  - Left-most vertical dashed line



# Normalized rate of reconnection

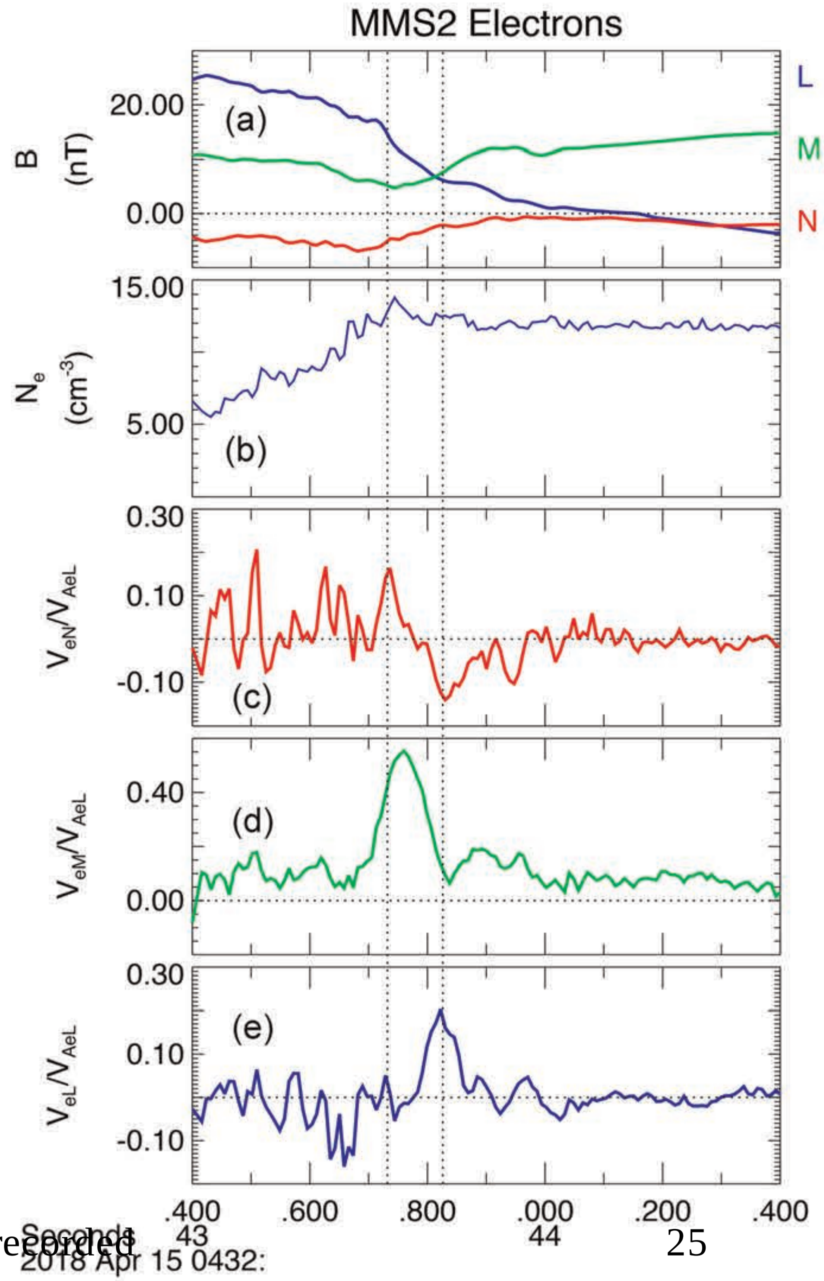
- Upstream Alfven speed ~ 2497km/s
- Normalized rate of reconnection based on the electron inflow velocity

$$V_{eN} \sim 0.14 C_{AeL}$$

- Comparable peak outflow velocity
  - Too close to the x-line to measure the peak outflow speed?
- Normalized $E_M$ (around 1.2mV/m)

$$cE_M / B_L \sim 0.04 C_{AeL}$$

- Both measurements have uncertainties that require further exploration



# Electron only reconnection

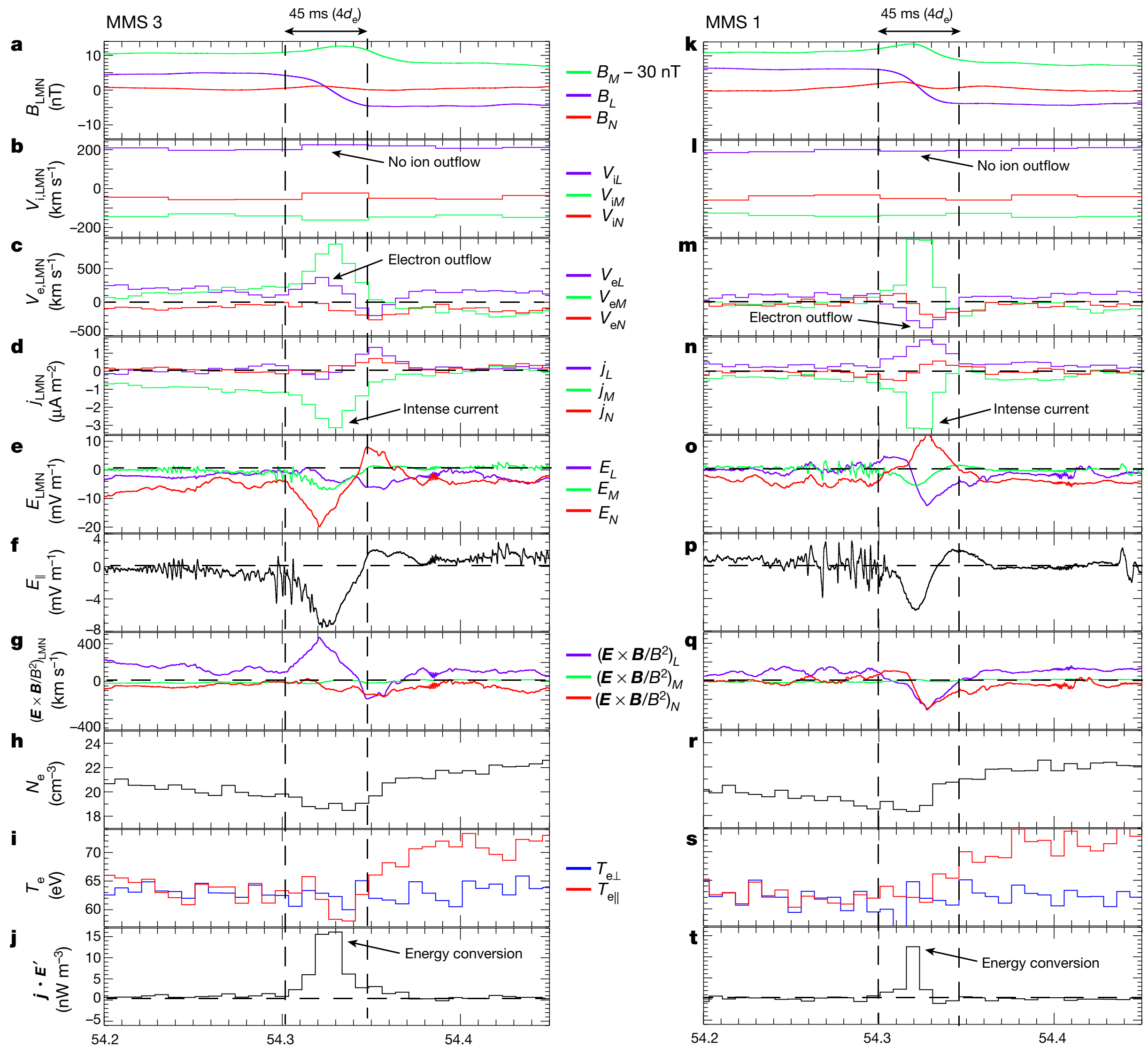
- An important question is whether magnetic reconnection plays a role in the dissipation of turbulent cascades that exist throughout the universe
  - This would require that reconnection take place at scales where ions, because of their much mass, could not respond
  - This is electron-only reconnection
- Electron-only reconnection has been documented in the turbulent magnetosheath downstream of the Earth's bow shock (Phan+ '18)
  - MMS1 and MMS3 were on opposite sides of a reconnecting x-line and measured oppositely directed outflows
  - No reconnection-driven ion flows accompanied the event
  - Strong guide field event
  - Such reconnection was explored for anti-parallel reconnection (Mandt+ '94) but only recently with a strong guide field (Pyakurel+ '19)

# December 9, 2016, magnetosheath event

- Data from MMS1 and MMS3
- Strong guide field
- $C_{AeL}$ ~ 946km/s
- Normalized reconnection rate

$$V_{eN} \sim 0.25 C_{AeL}$$

  – Why so large?






This presentation is being recorded

# Conclusions

- Satellite measurements of reconnection in the Earth space environment and PIC simulations are revealing the mechanisms of magnetic reconnection
  - Multiscale structure
  - The surprisingly important role that $E_N$ plays in ejecting electrons from the diffusion region in asymmetric reconnection
  - The unexpected dynamics of electrons within the diffusion region leading to oscillatory energy exchange
  - The first observations of electron-only reconnection
  - The first direct measurements of the rate of magnetic reconnection, a long-sought goal
- Many issues remain unresolved
  - Can turbulence break the frozen-in condition to facilitate reconnection or does the electron diffusion region always remain laminar?
  - What are the mechanisms that control the extreme reconnection events and energetic particle acceleration that have been documented in the magnetotail?
  - Why do some observations reveal rates of reconnection are faster than those seen in 2D kinetic models?