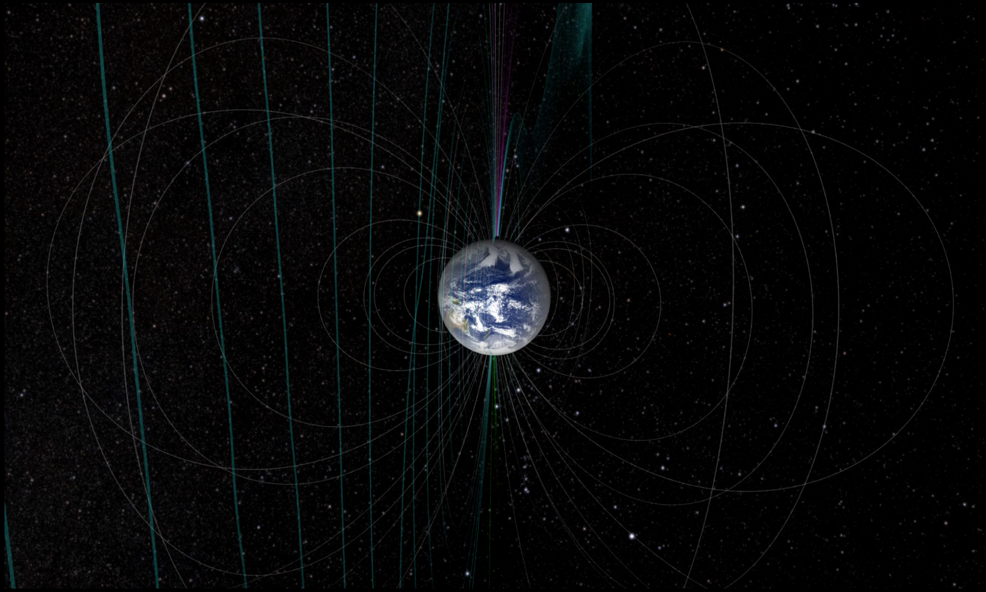
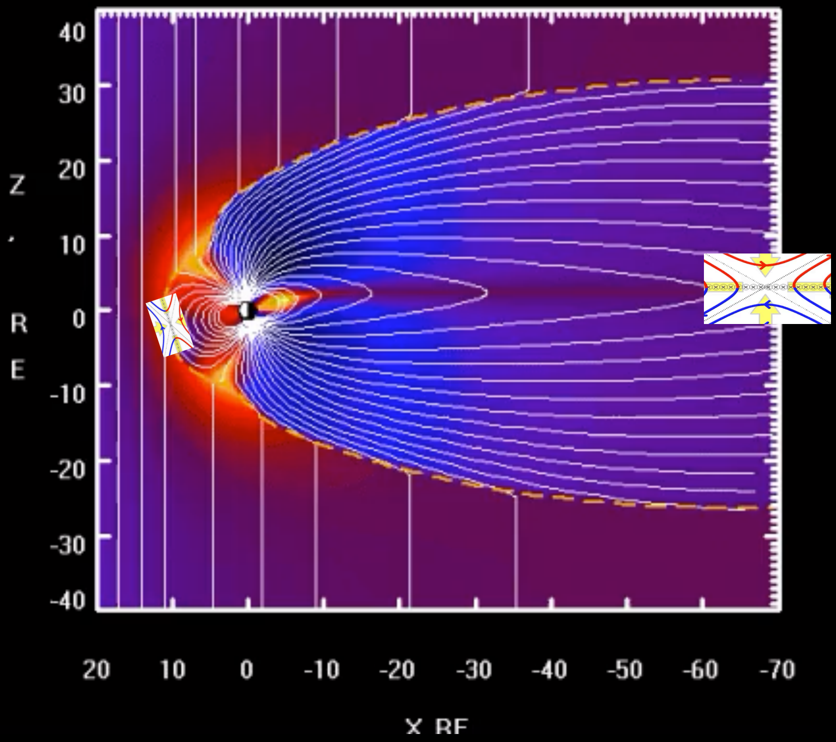
Magnetic Reconnection and MMS

GEM Workshop
Santa Fe, NM
June 26, 2019

Jim Burch

The primary objective of MMS is to solve the electron physics of magnetic reconnection in the boundary regions of the Earth's magnetosphere



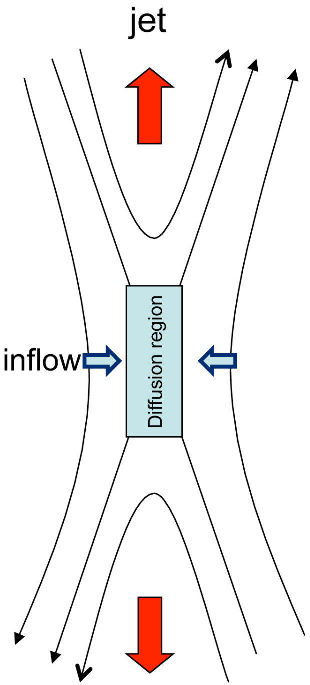


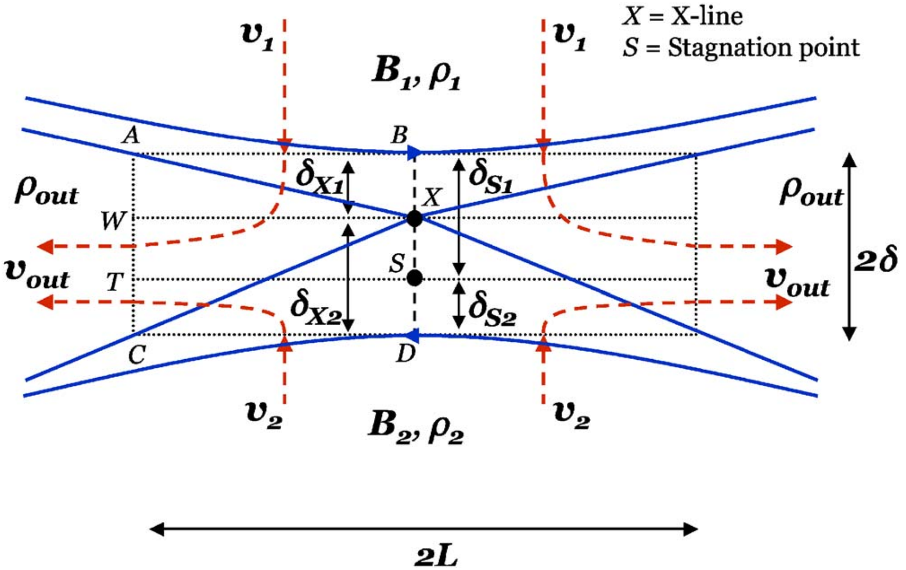
Outline

- What we’ve learned about magnetopause reconnection
- What we’ve learned about magnetotail reconnection
- Wave phenomena in reconnection
- Ubiquity of reconnection
- Particle acceleration
- Prospects for the future

Reconnection Geometry

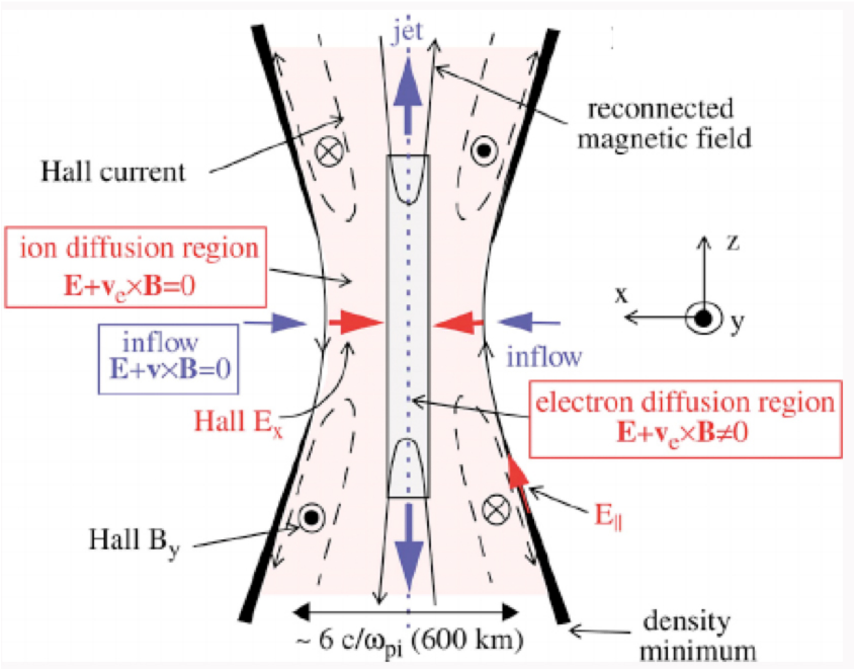
Symmetric: B, Ne and Te same in both inflow regions. Nearly true in tail. Electron inflow stagnation point and X line coincide at center of diffusion region (From Phan)



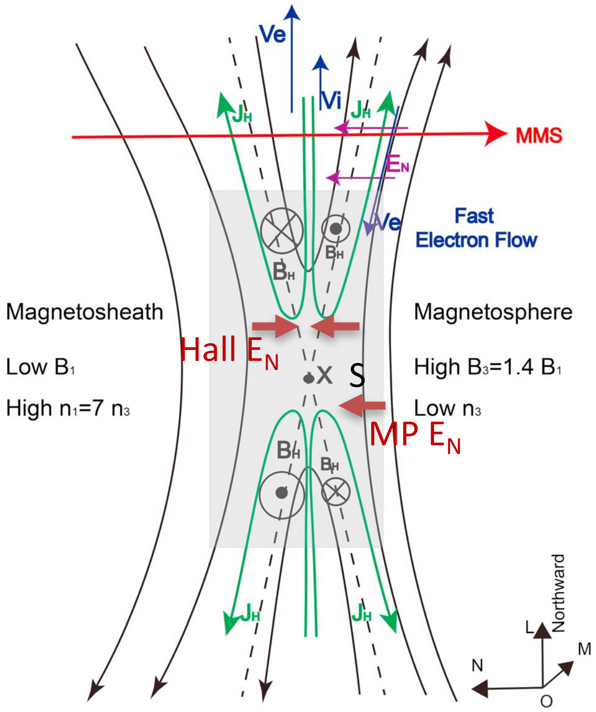


Asymmetric: Magnetosheath (top) has lower B, higher Ne, and lower Te than magnetosphere (bottom). Stagnation point (S) predicted to be displaced toward magnetosphere by Cassak and Shay (2007). Plasma flows through the X line.

Elements of Hall Reconnection



Symmetric

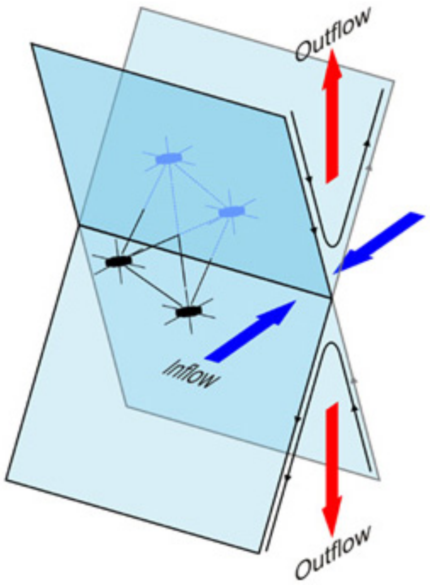


Asymmetric

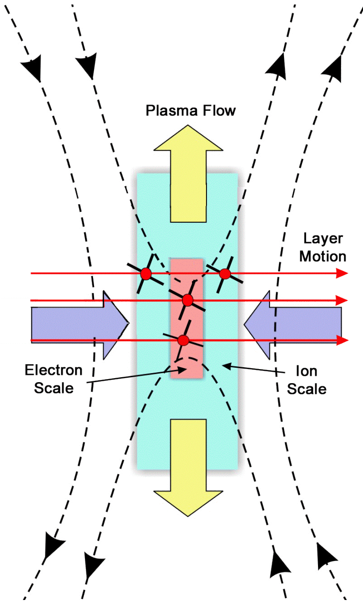
Ambipolar E_N adds to Hall E-field at MP

Need for 4 Spacecraft

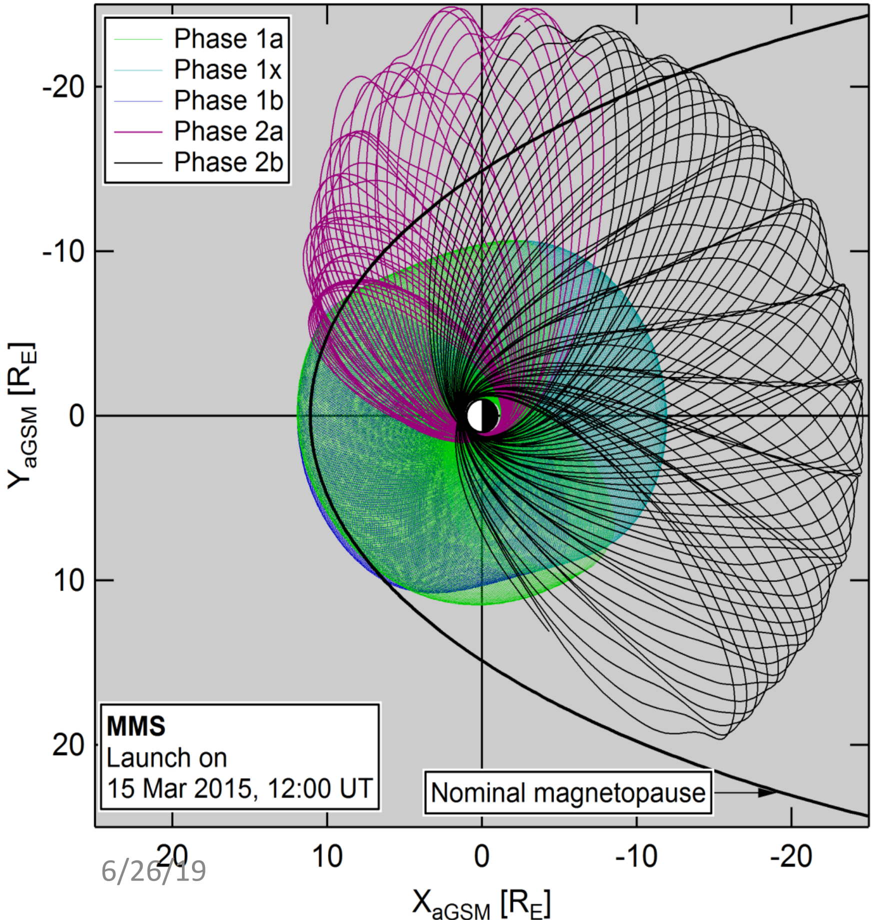
- To identify reconnection events we have separations up to 160 km with spacecraft in the two inflow regions and in the two outflow regions (blue and red arrows).

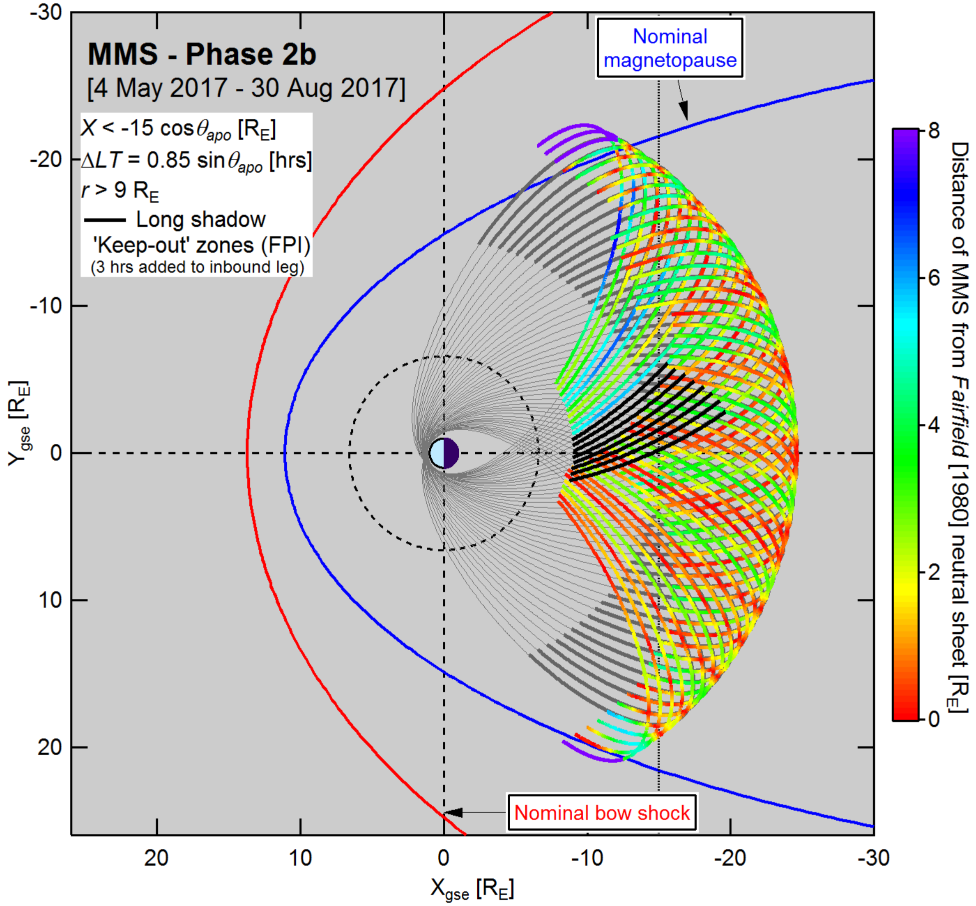


- To determine processes driving reconnection we have smaller separations (down to 7 km) with spacecraft within the diffusion region (as shown).

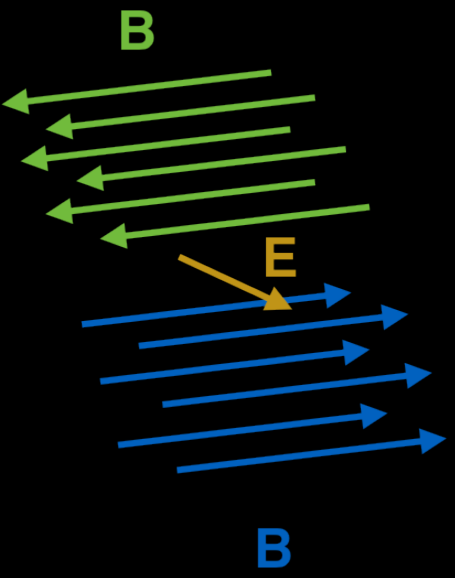


MMS Prime Mission Phases

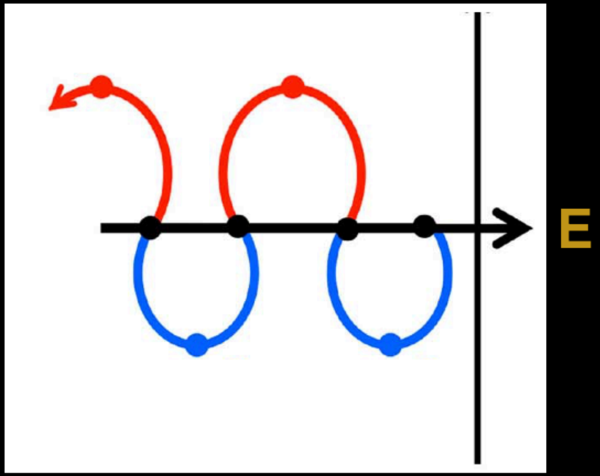




A current along an electric field describes conversion of energy; simulations predicted the current comes from meandering electrons



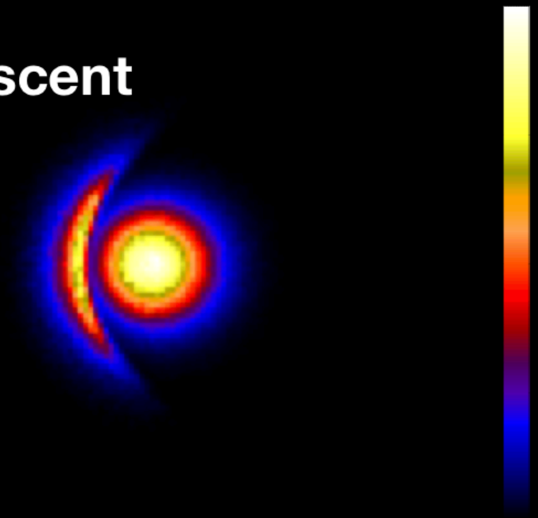
B: out-of-plane



B: in-to-plane

Bessho et al. 2016

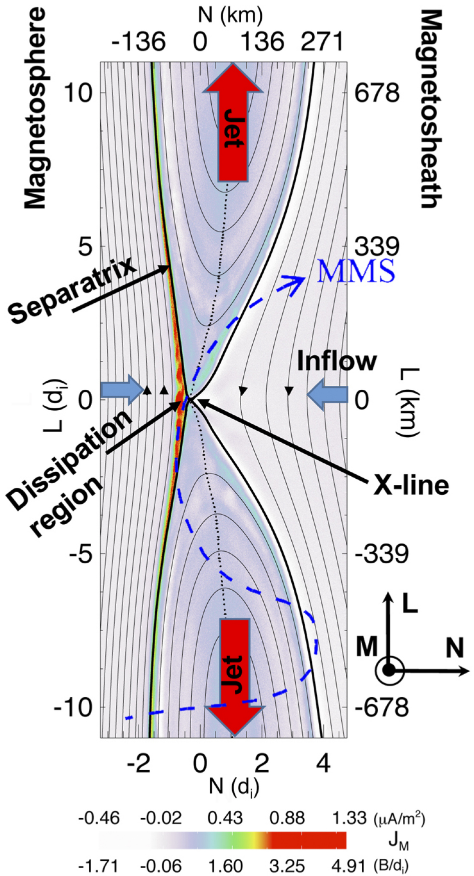
Crescent



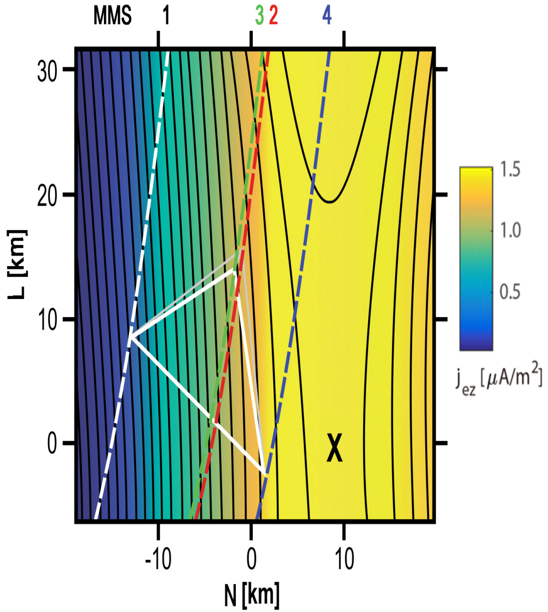
Hesse et al. 2014

EDR on October 16, 2015

Burch+, Science [2016]



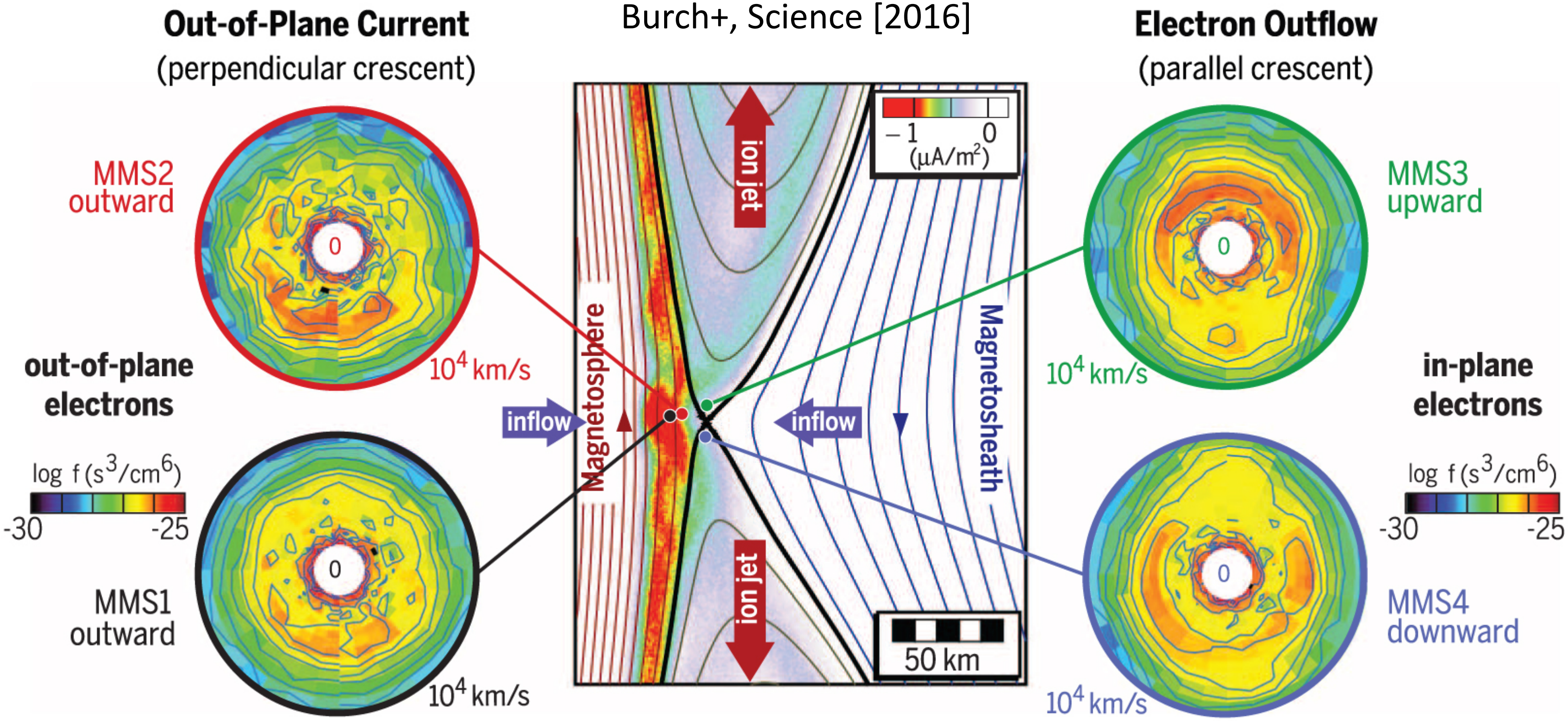
Simulation by Paul Cassak



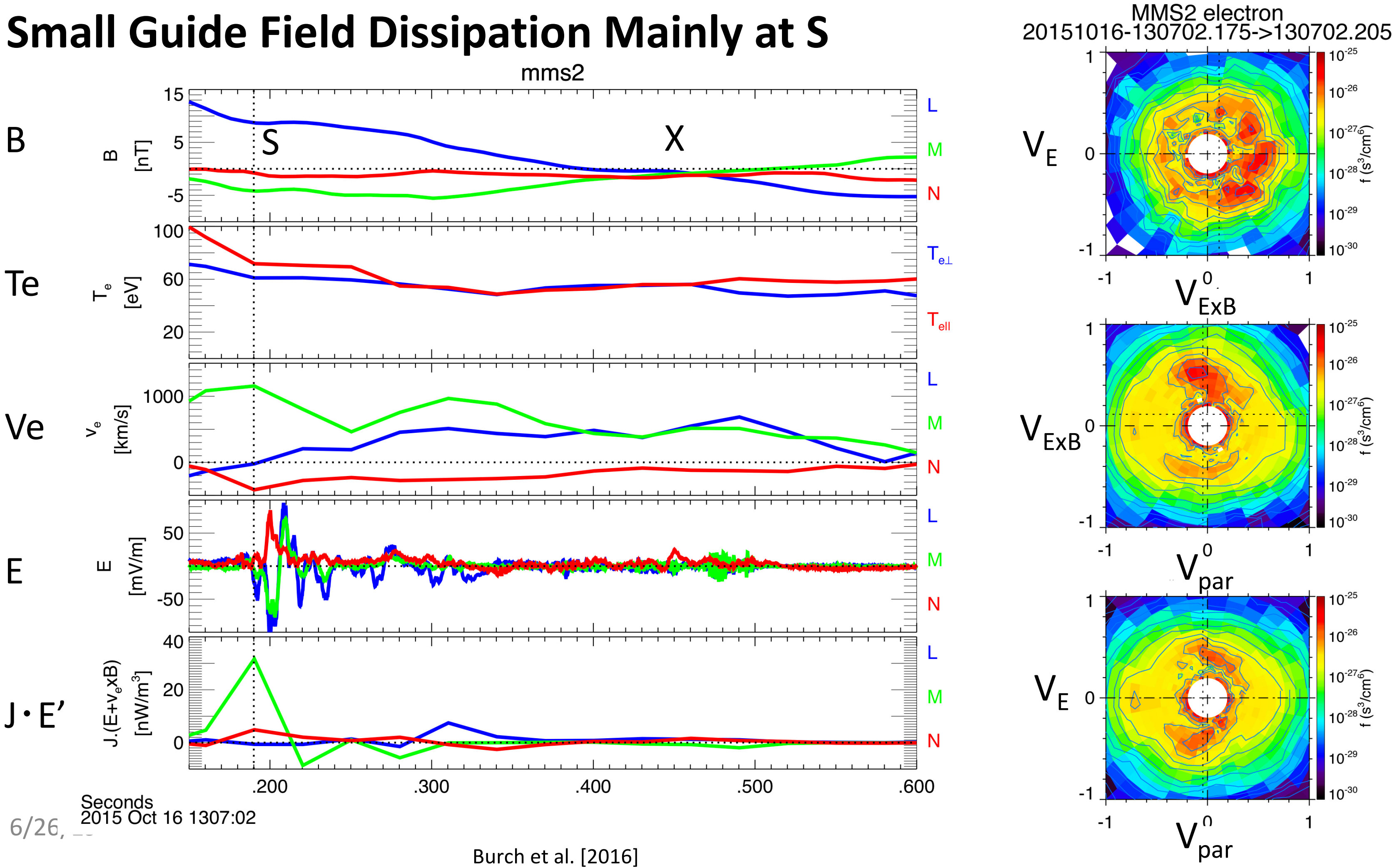
Adapted from Hiroshi Hasegawa+ [2017] and Richard Denton+ [2016]

Electron Crescent Distribution in Reconnection Diffusion Region

Burch+, Science [2016]



For Small Guide Field Dissipation Mainly at S

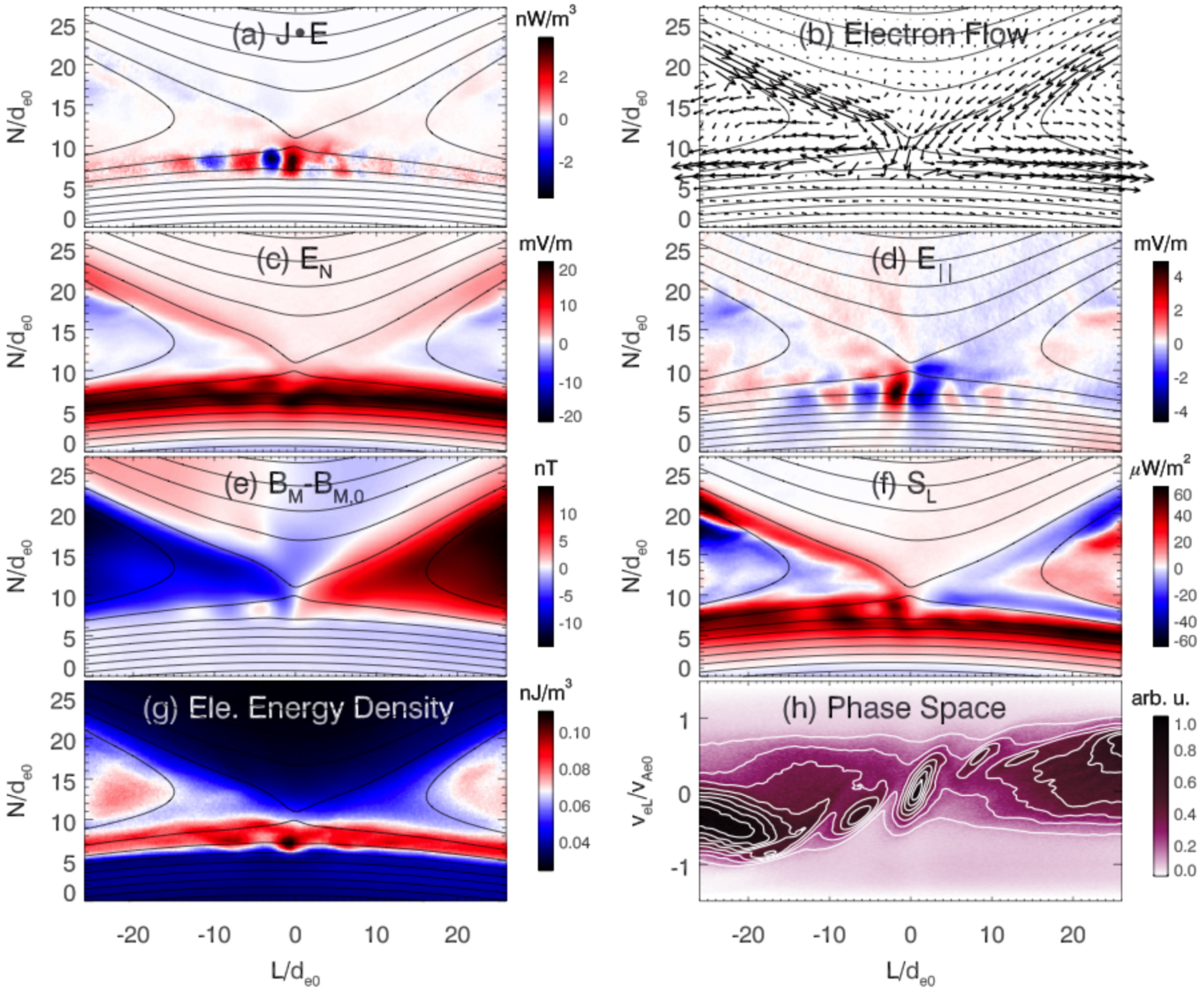


Burch et al. [2016]

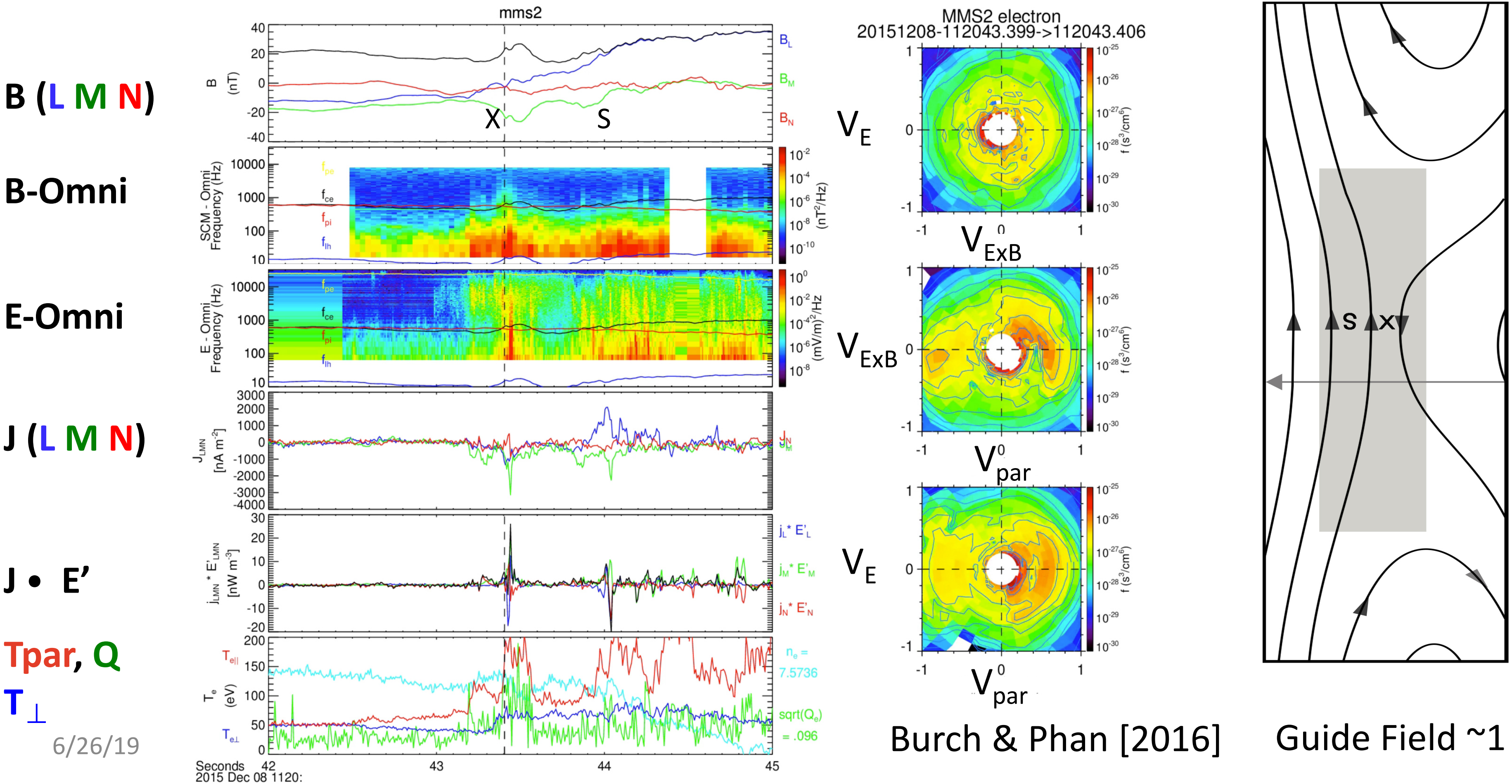
PIC simulation showing localized intense energy conversion as observed by MMS

Marc Swisdak+, GRL [2018]

- (a) Intense localized bipolar energy conversion
- (b) Electrons flow along separatrices, accelerated through X line by E_{normal}
- (d) $E_{parallel}$ ejects electrons from EDR along **B**
- (f) Poynting flux
- (h) PSD shows spatially oscillating electron energization (V_{eL}/V_{ae})



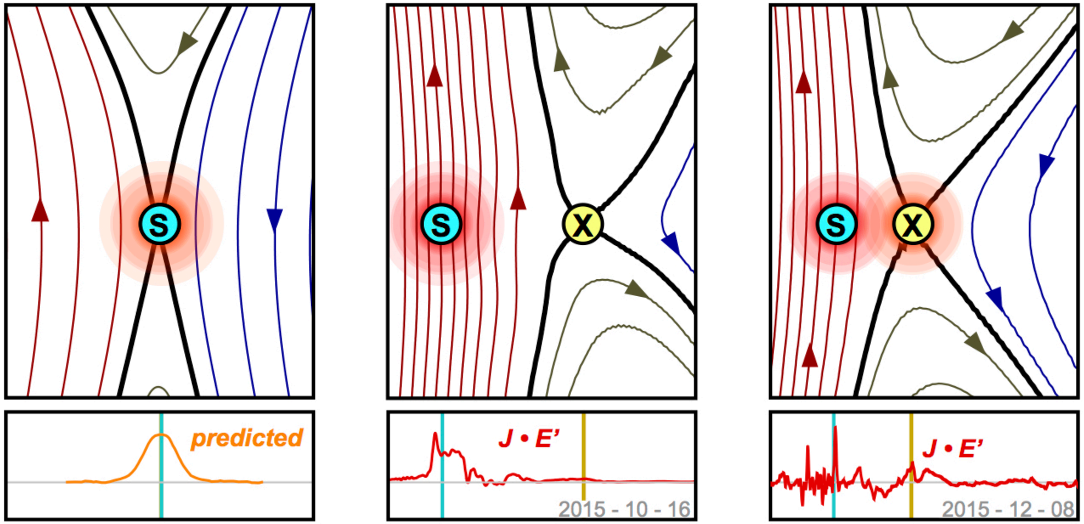
For Guide Field ~1 Dissipation Near X-Line and at Stagnation Point



Burch & Phan [2016]

Guide Field ~1

Role of Guide Field in Reconnection Dissipation



Symmetric:	Asymmetric, No Guide Field:	Asymmetric, Guide Field:
Dissipation at X-Line	Dissipation at Stagnation Point	Dissipation at *Both* X-Line and Stagnation Point
[*Zenitani et al.*, 2011]	[*Burch et al.*, 2016; *Genestreti et al.*, 2017; *Cassak et al.*, 2017]	[*Burch and Phan*, 2016; *Genestreti et al.*, 2017; *Cassak et al.*, 2017]

Generalized Ohm’s Law

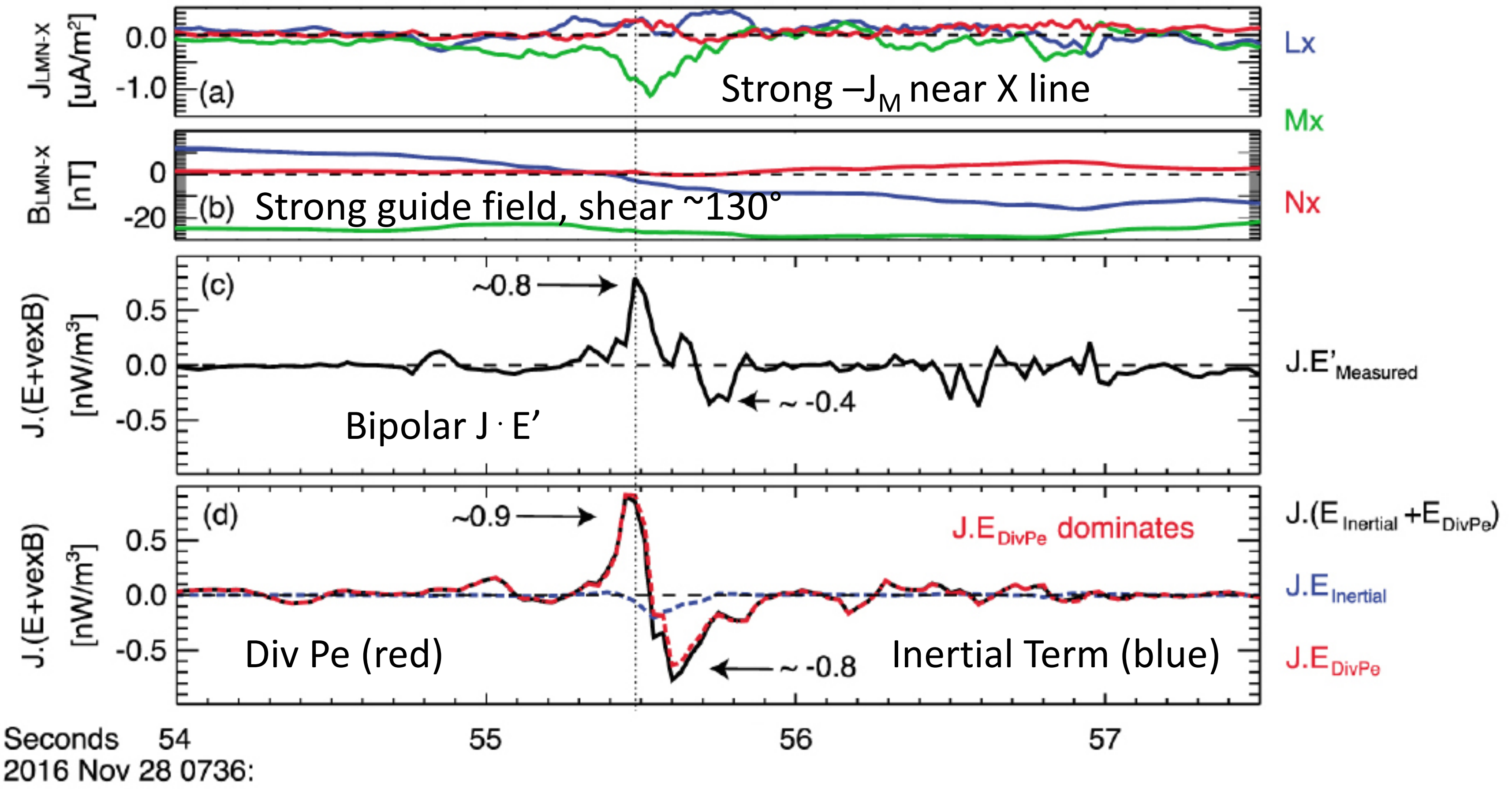
- Electron momentum equation (or generalized Ohm’s Law):

$$E + v \times B = \frac{m_e}{e}\frac{dv_e}{dt} - \frac{\nabla \cdot \overleftrightarrow{P}_e}{en} + \frac{J \times B}{en} + \eta J$$

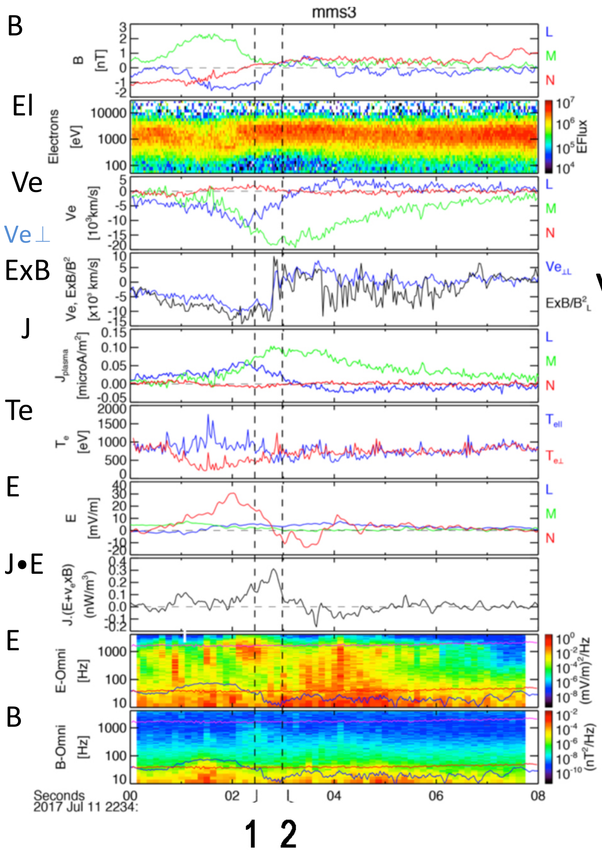
E′	Electron Inertia	Pressure Gradient	Hall MHD	Resistive MHD

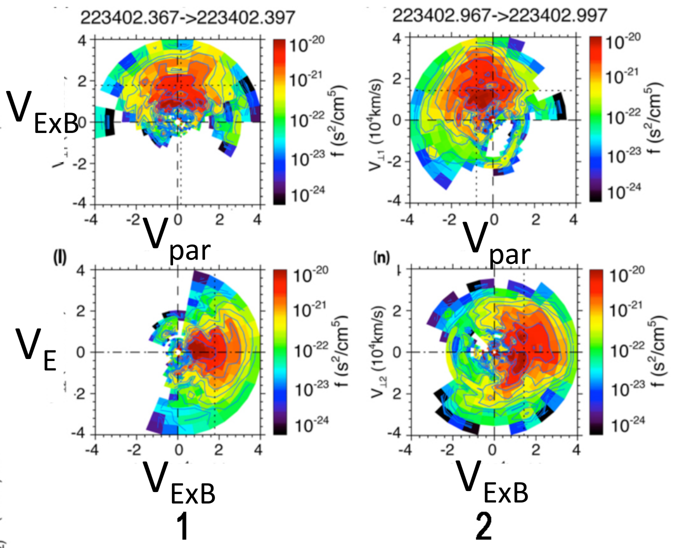
- With no reconnection the right-hand side is zero (MHD).
- In the ion diffusion region the *J* x *B* term will be most important (Hall MHD).
- In the electron diffusion region the first two terms can cause the reconnection E field in the electron diffusion region.

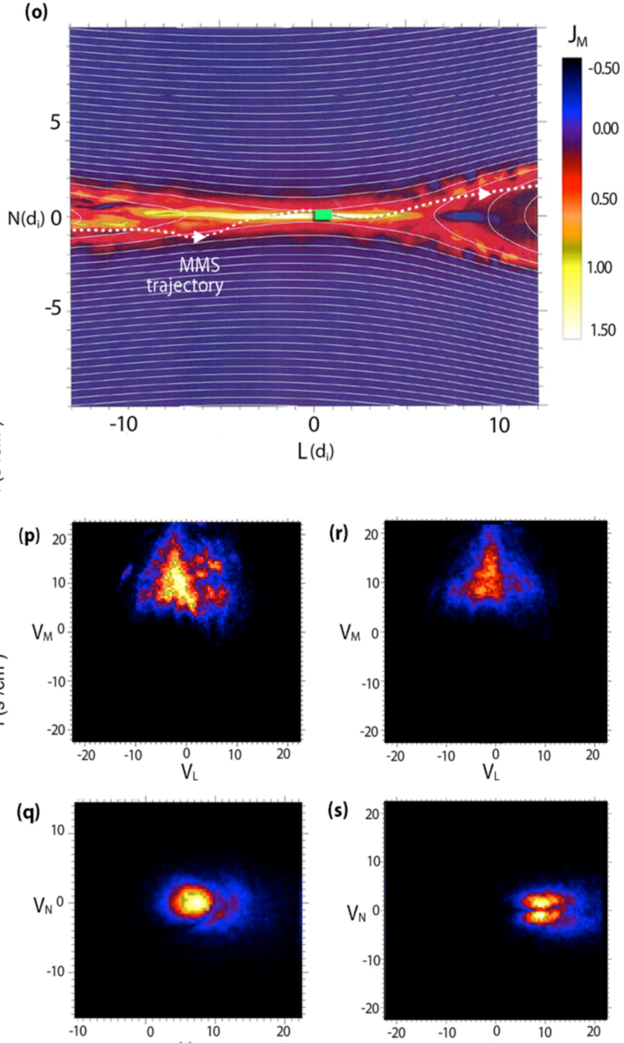
Generalized Ohm's Law Analysis for Event with Smallest S/C Separation (~6.4 km)



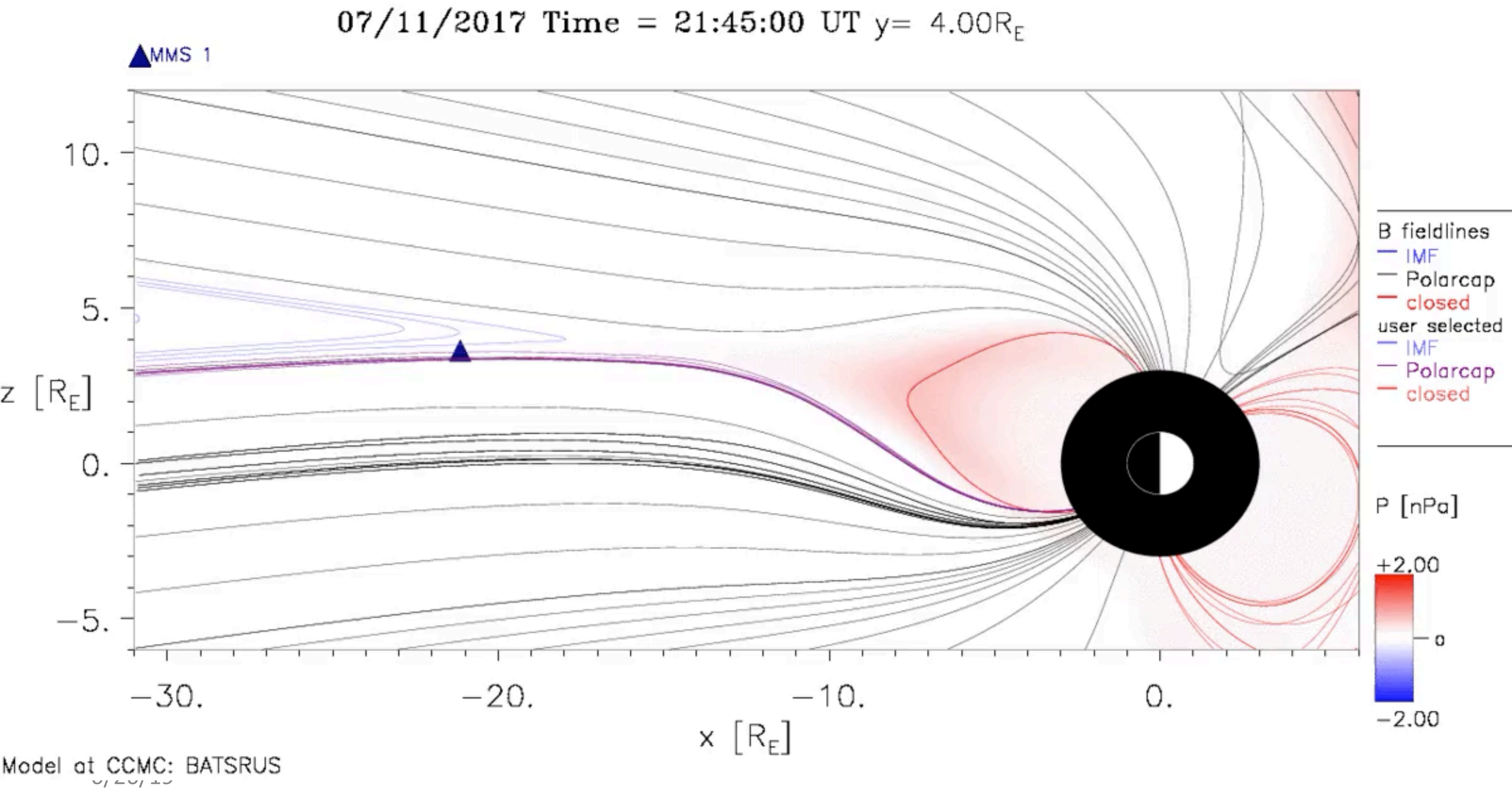
July 11, 2017
Tail Reconnection Event

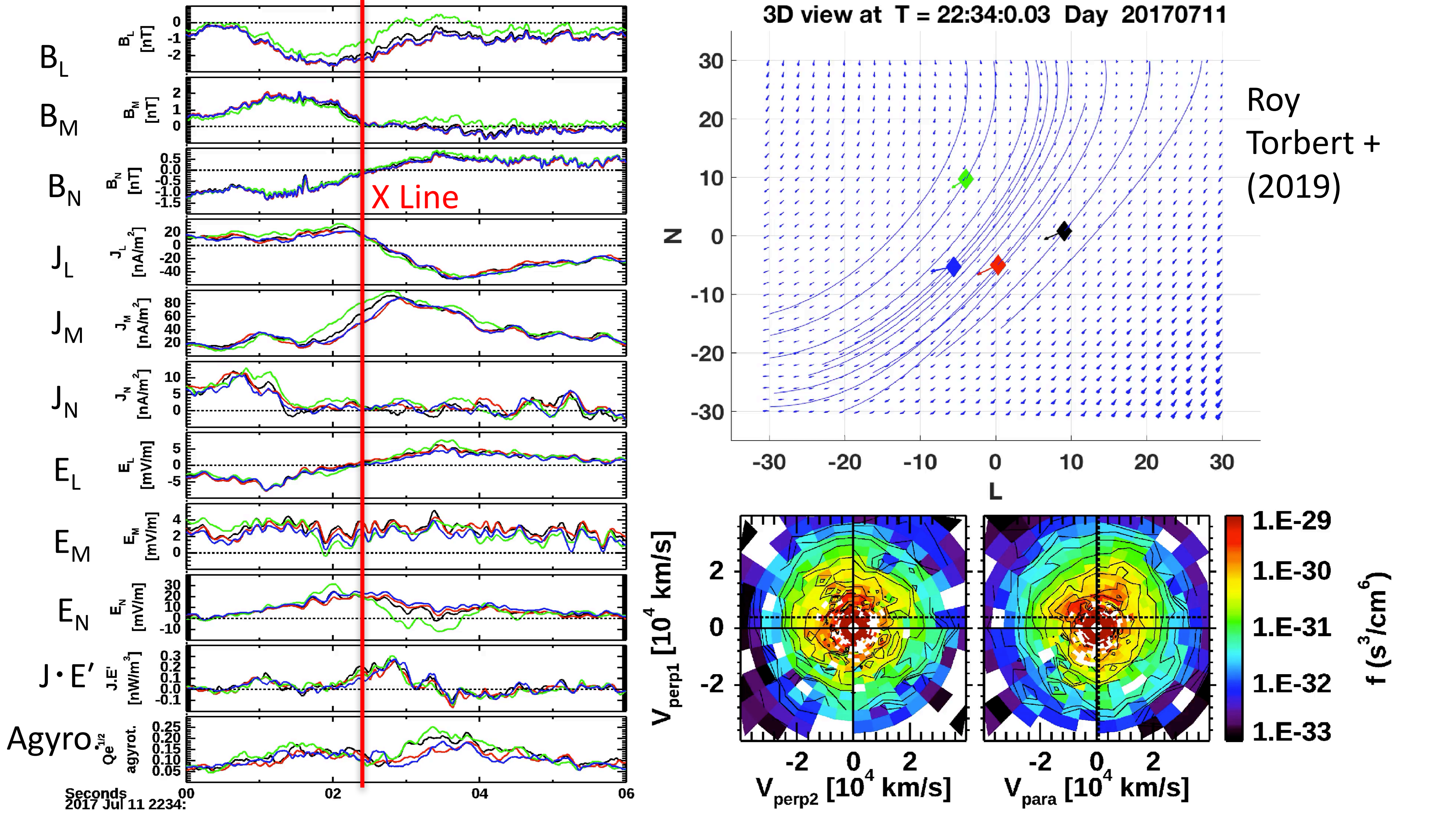






Torbert et al. [2018]


07/11/2017 Time = 21:45:00 UT y= 4.00R_E
MMS 1
10.
5.
0.
−5.
z [R_E]
−30.
−20.
−10.
0.
x [R_E]
B fieldlines
IMF
Polarcap
closed
user selected
IMF
Polarcap
closed
P [nPa]
+2.00
0
−2.00
Model at CCMC: BATSRUS



B_L
B_M
B_N
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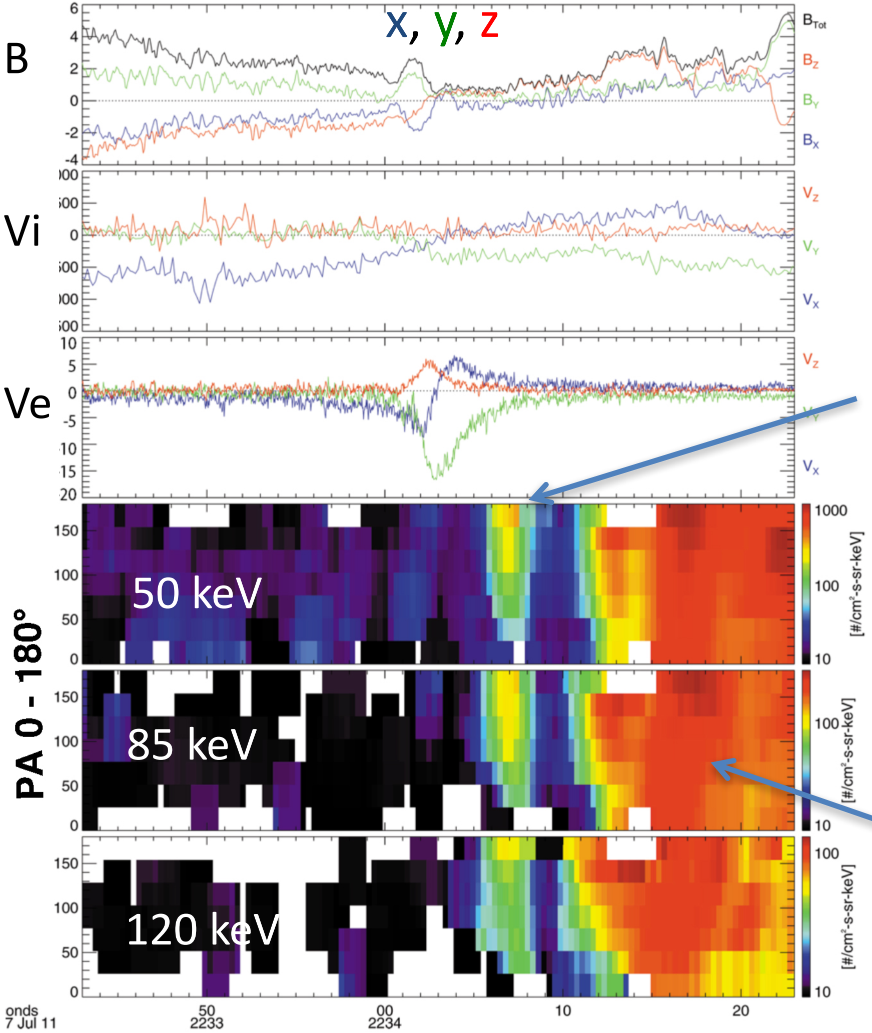
X Line
Seconds
2017 Jul 11 2234:
3D view at T = 22:34:0.03 Day 20170711
N
L
Roy
Torbert +
(2019)
V_perp1 [10^4 km/s]
V_perp2 [10^4 km/s]
V_para [10^4 km/s]
1.E-29
1.E-30
1.E-31
1.E-32
1.E-33
f (s^3/cm^6)

Energetic electrons in reconnection structure

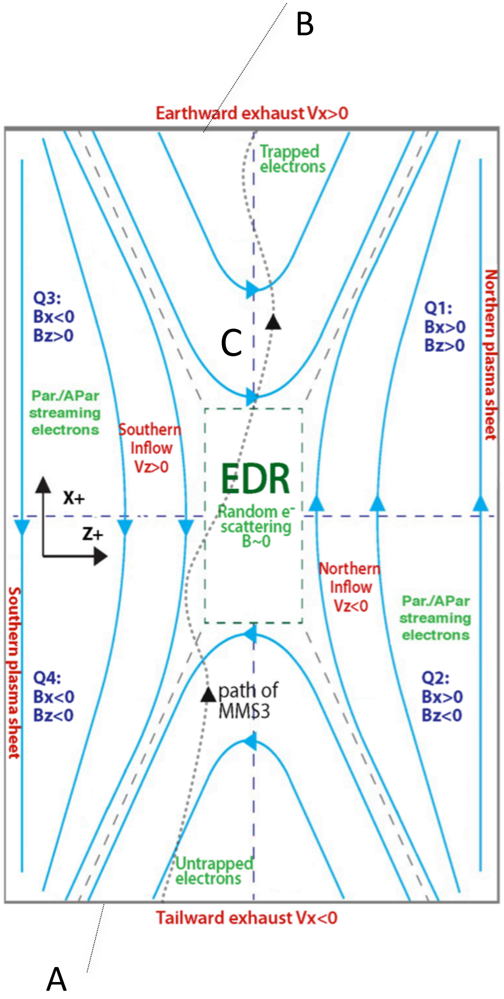
Roy Torbert+ [2018]

>100 keV electrons streaming along separatrix



Electron jet along separatrix (C)

Electrons Trapped (B)

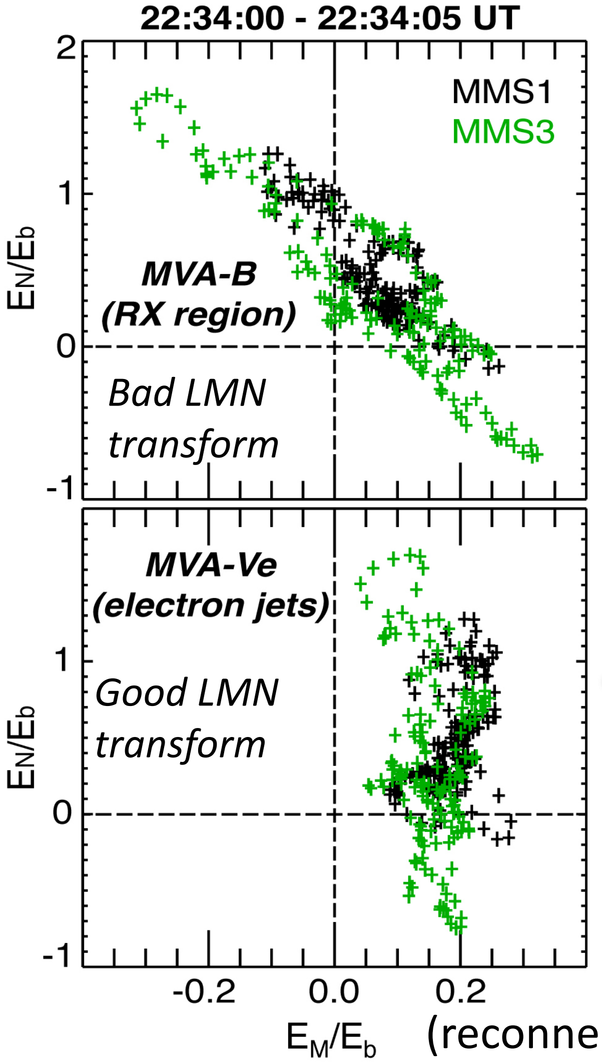


What is the Reconnection Rate?

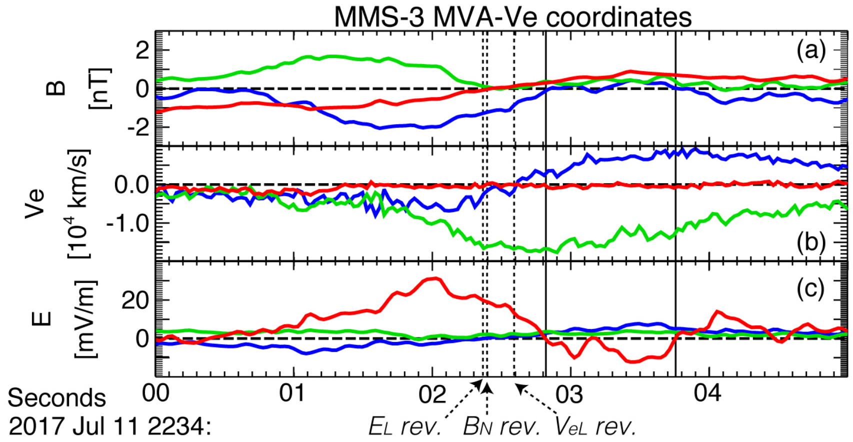
- Simulations show "canonical rate" of $0.1V_A$
- Ways to measure reconnection rate:
  - Measure ion inflow rate
  - Aspect ratio of diffusion region
  - Exhaust angle of outflow
  - Reconnection electric field
- With Cluster, Phan et al. (2007) used V_i inflow/V_{iA} ~0.07
- With MMS we can measure electron inflow rate, aspect ratio of electron diffusion region, exhaust angle of electron diffusion region, reconnection electric field in the EDR
- Results for tail reconnection shown next

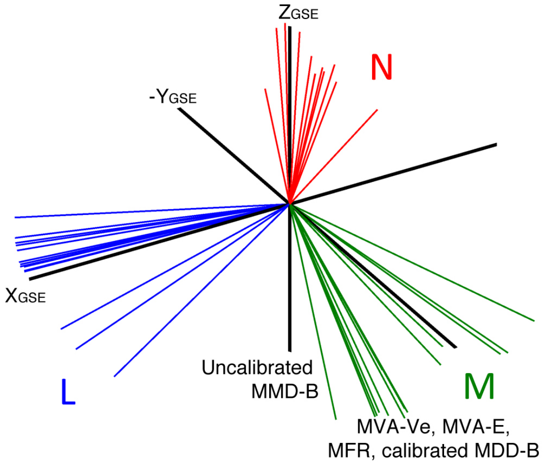
Reconnection Rate Results from Genestreti+ [2018]

Since $E_N >> E_M$ and $B_N << B_L$ LMN transform is largest error in reconnection rate.



(reconnection rate)

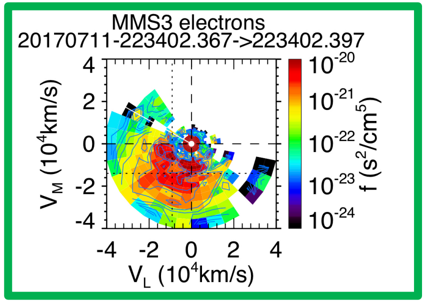




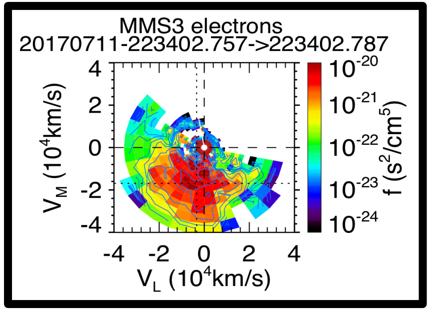
Boundary Normal Coordinates

LN = reconnection plane

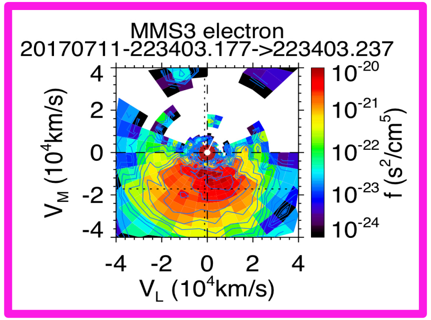
Reconnection Rate for July 11, 2017 Tail Reconnection



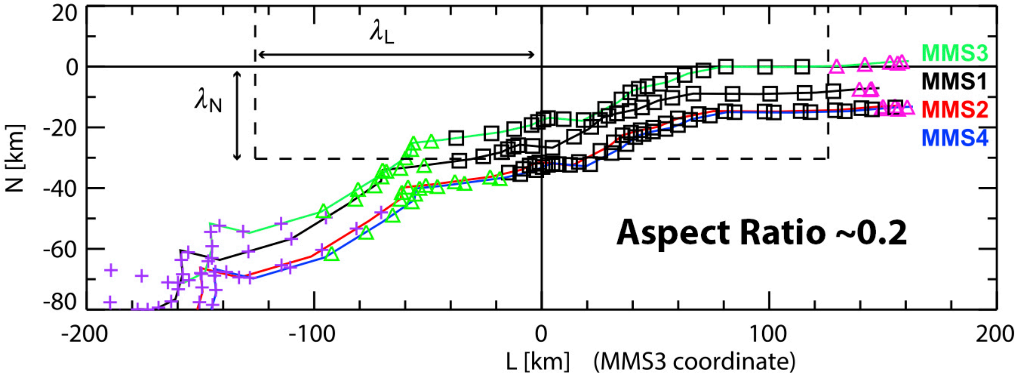
Tailward
($V_L < 0$)



X Line
($V_L \sim 0$)



Earthward
($V_L > 0$)

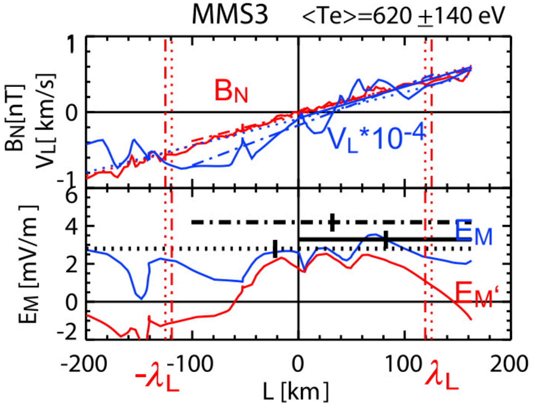


Outside Separatrix **Tailward Outflow** **Multiple Perpendicular Crescents** **Earthward Outflow Parallel Crescents**

Electron Jet Reversal

Pressure Gradient (black bar) predicts E_M

$E_M \sim E_M'$ near X line implies non-gyro-tropic pressure tensor.



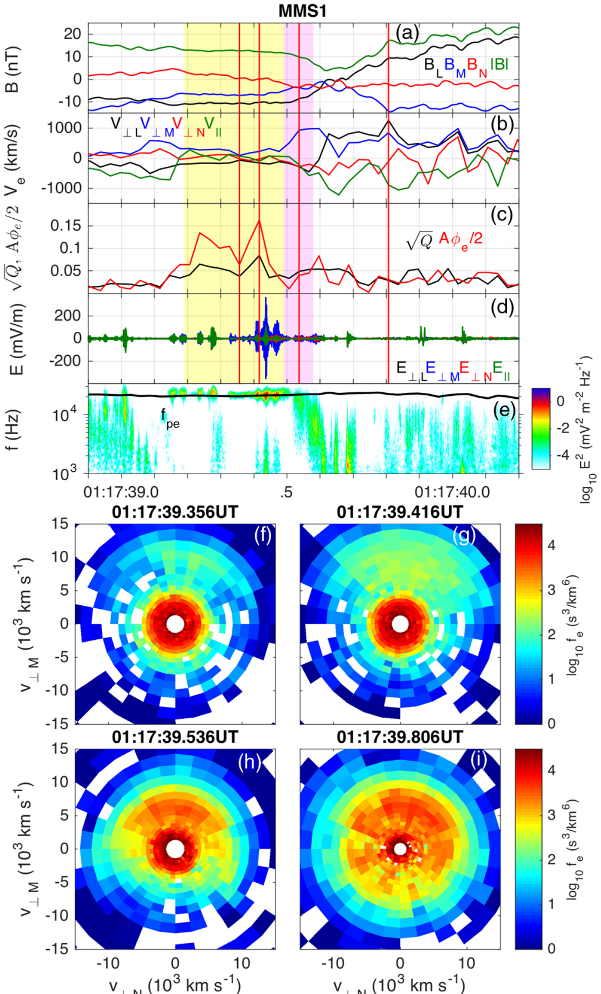
$E_M/E_O \sim 0.18$

Rumi Nakamura + 2019

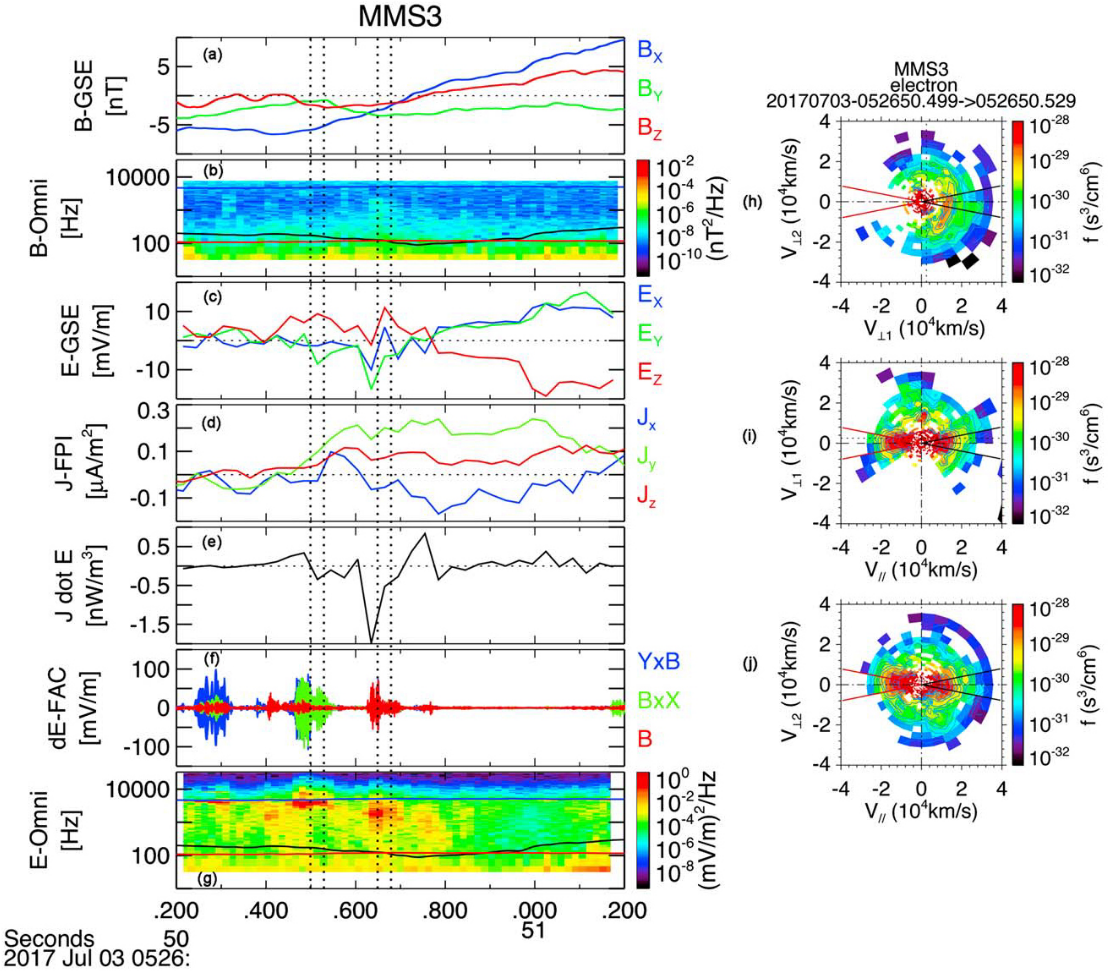
High Frequency Waves in the Reconnection Region

Upper hybrid waves caused by electron crescents at magnetopause and tail reconnection regions

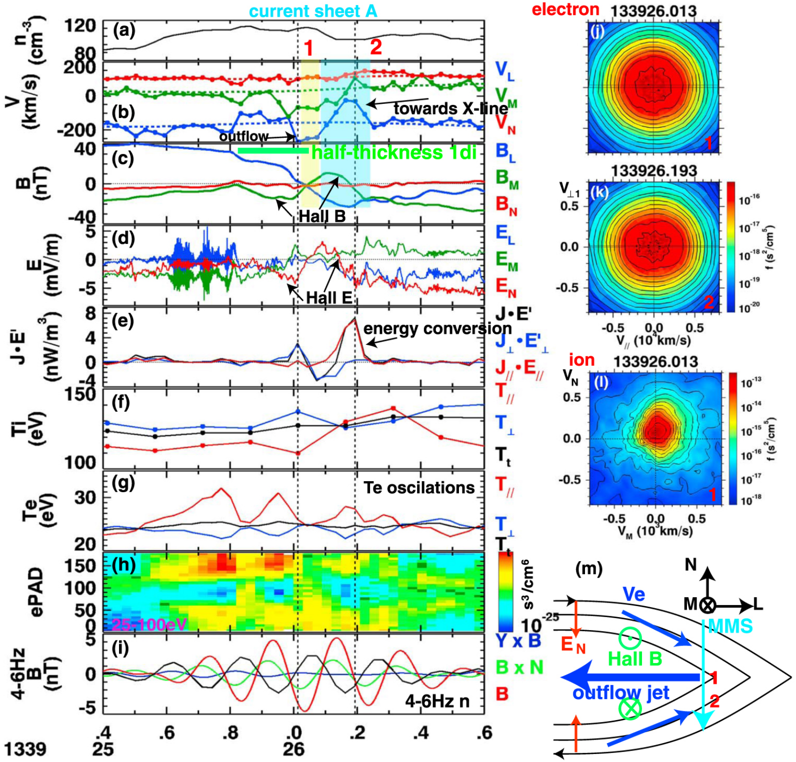
Magnetopause, Graham+ (2017)



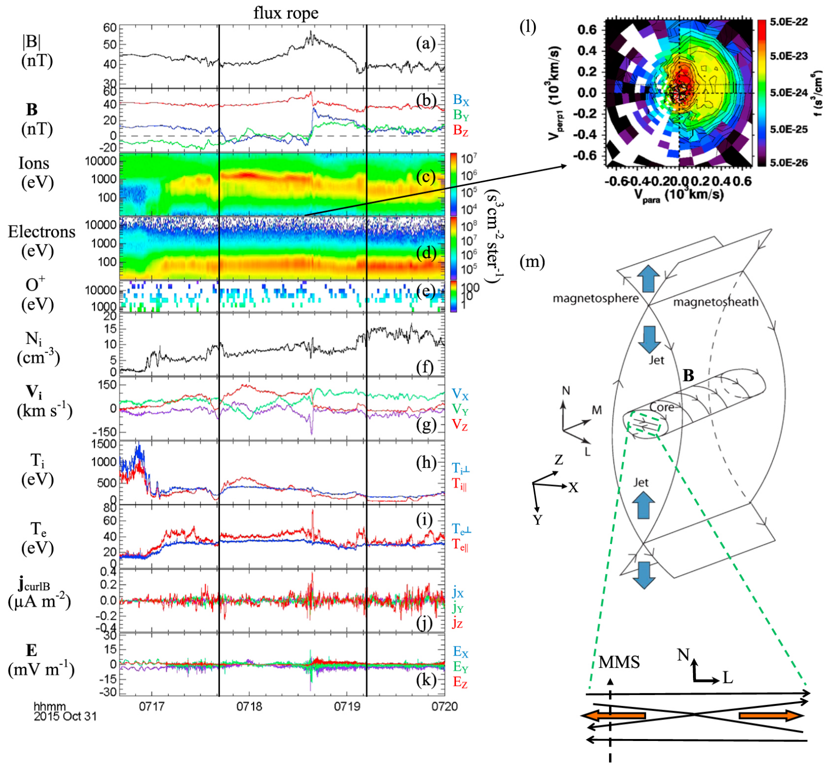
Tail, Burch+ (2019)



Ubiquity of Reconnection

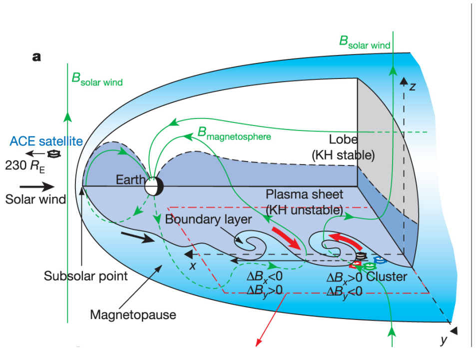


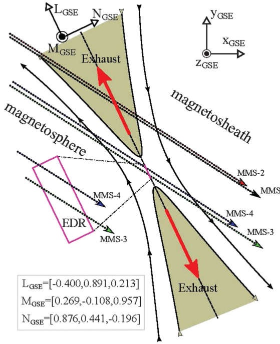
Shock transition region, Wang et al. (2018)

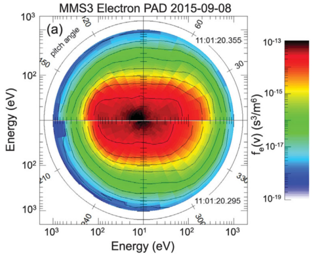


FTE, Øieroset et al. (2016)

Ubiquity of Reconnection







Kelvin Helmholtz Reconnection (Eriksson et al, 2016)

Importance of Epar for high guide field MS reconnection (Wilder et al., 2018)

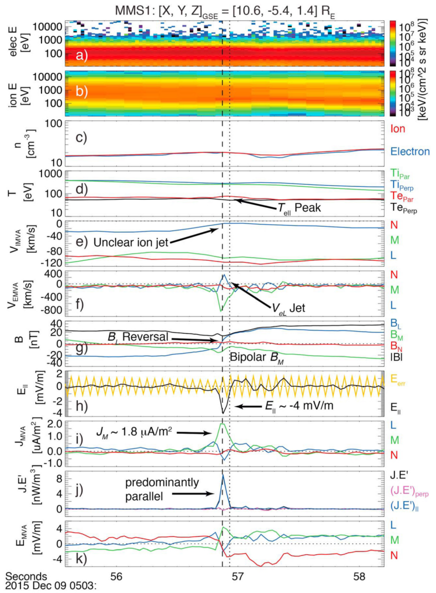


Figure 4. Overview of the magnetosheath reconnection event on 9 December 2015, given in the same format as Figure 1. GSE = geocentric solar equatorial; MMS = Magnetospheric Multiscale; MVA = minimum variance analysis.

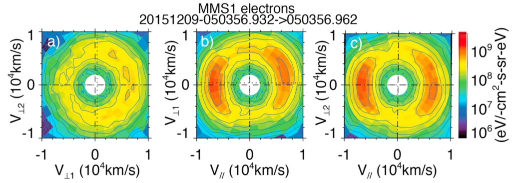
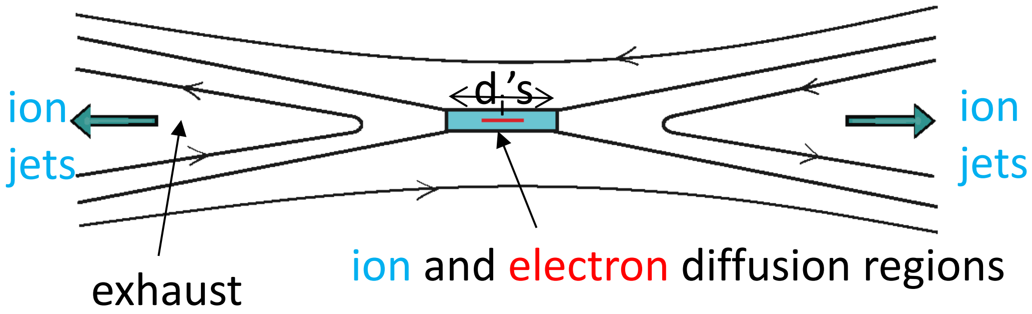
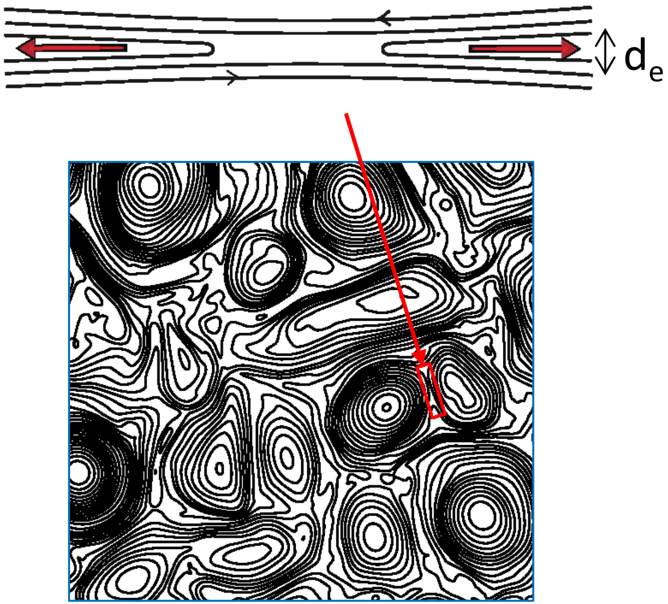


Figure 5. Cut of the most agyrotropic distribution observed by MMS1 during the 9 December 2015 reconnection event. Given in the same format as Figure 3. MMS = Magnetospheric Multiscale.

MMS Observations of Electron Reconnection without Ion Coupling in Turbulence

Tai Phan +, Nature [2018]





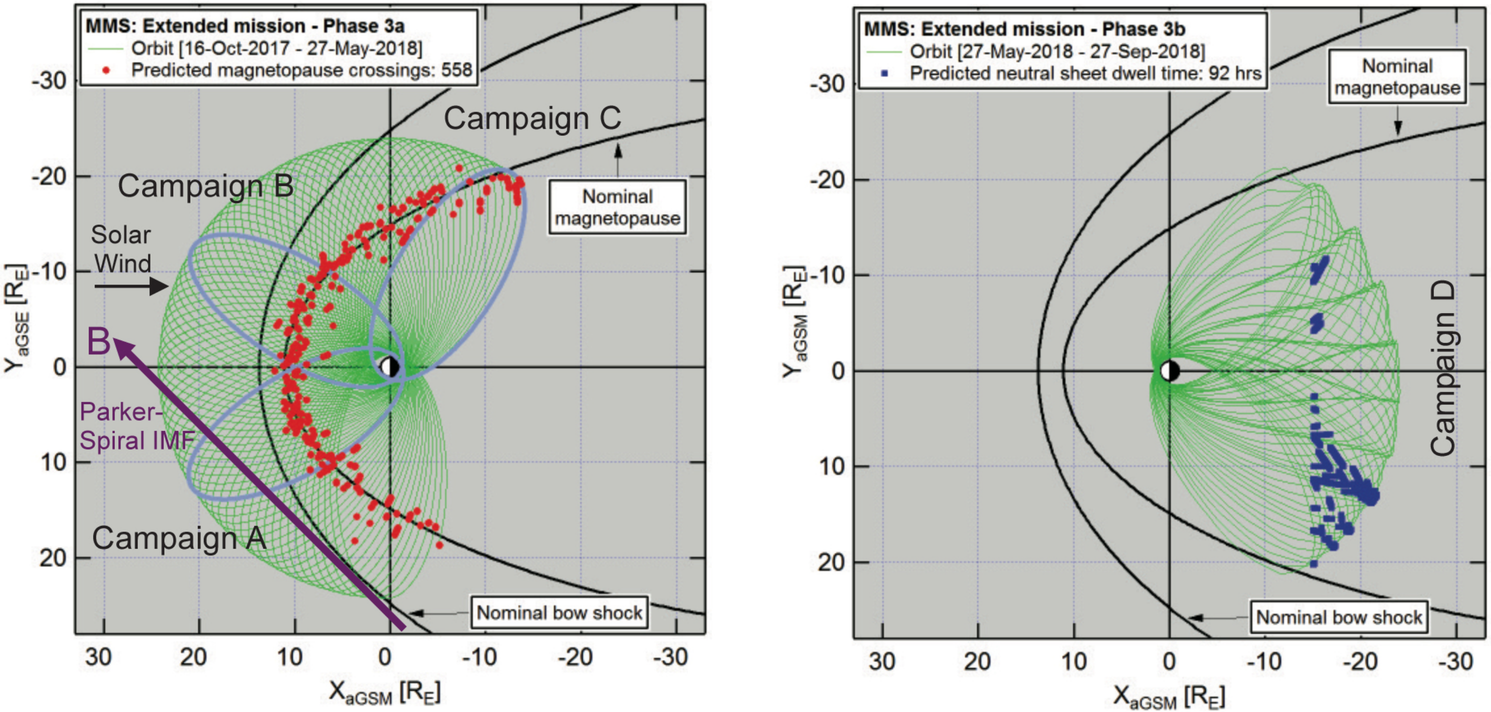
- Standard reconnection observed at magnetopause, magnetotail, solar wind, laminar magnetosheath, etc...

- Most observations are of the extended (MHD-scale) exhausts

No ion exhausts

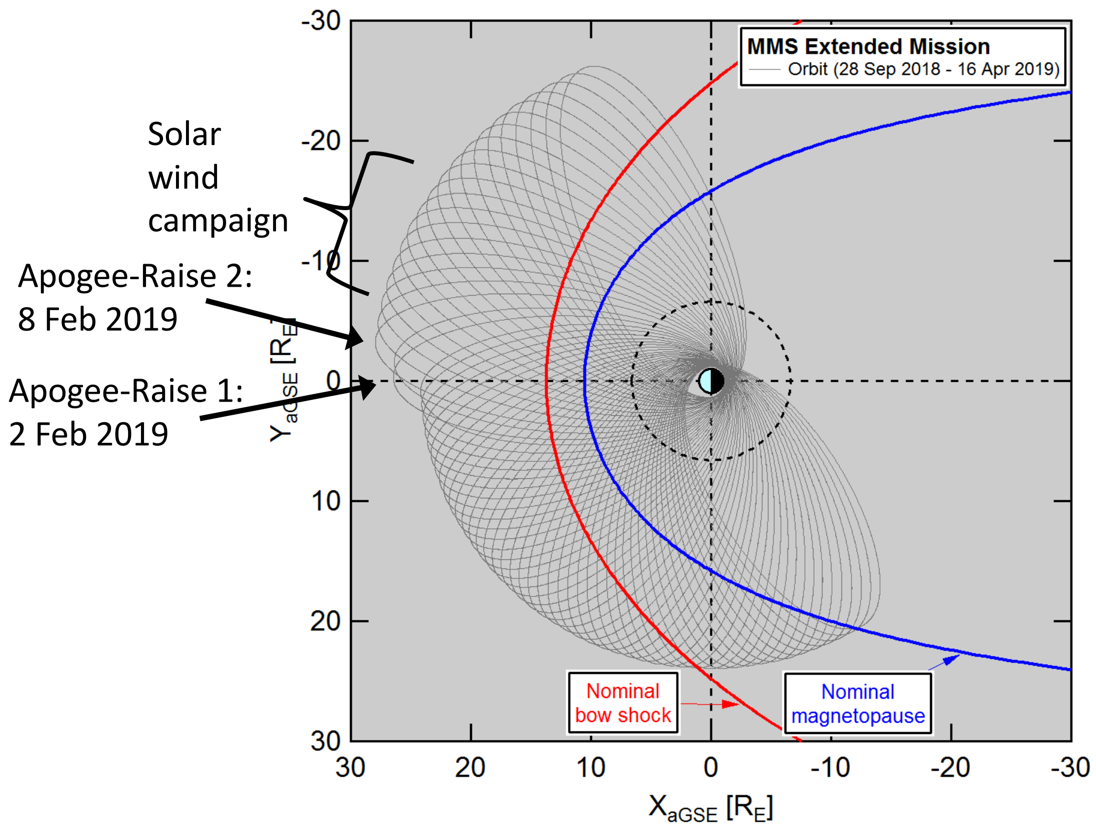
Magnetic energy converted into elec

Extended Mission Campaigns



Campaign	**A**	**B**	**C**	**D**
	Dusk to Noon MP	Noon to Dawn MP	Dawn Flank MP	Tail Reconnection
	Quasi-perp Shock	Quasi-parallel Shock	Magnetosheath	
	Pristine Solar Wind	Foreshock		

MMS Phases 4A+4B (incl orbit raise)



Summary

- MMS has solved most of the outstanding problems of magnetic reconnection in space, including guide field effects, cause of reconnection electric field, reconnection rate.
- Computer simulations provided important predictions about reconnection that MMS has confirmed.
- Computer simulations are limited with respect to MMS in their ability to access electron time scales, including turbulence and waves.
- MMS has found reconnection to be far more ubiquitous than imagined.
- Full data set available at Level 2 30 days after acquisition at:

https://lasp.colorado.edu/mms/sdc/public/