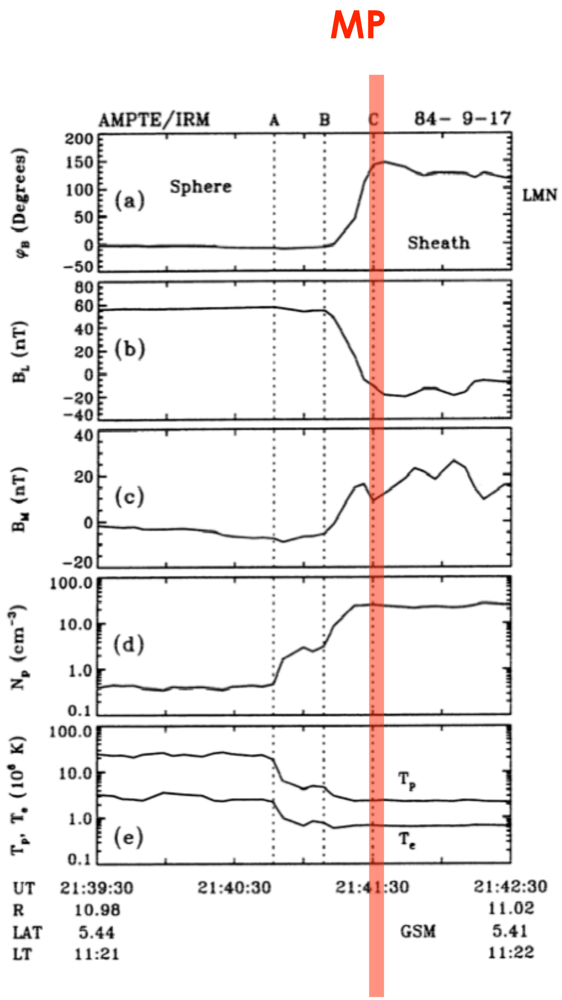
Asymmetric reconnection

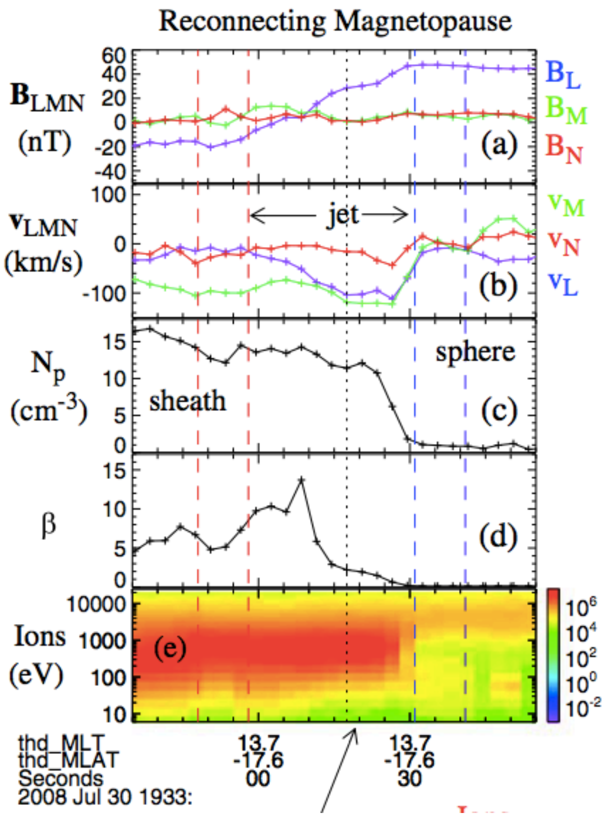
不揃いなリコネクション

Seiji Zenitani

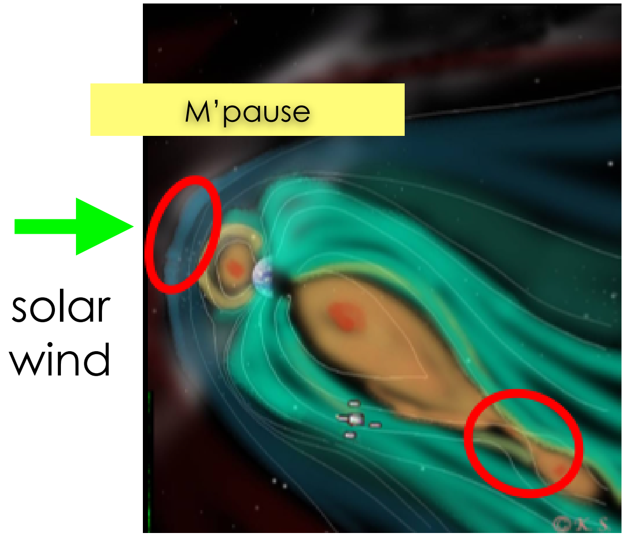
M'pause reconnection: asymmetry



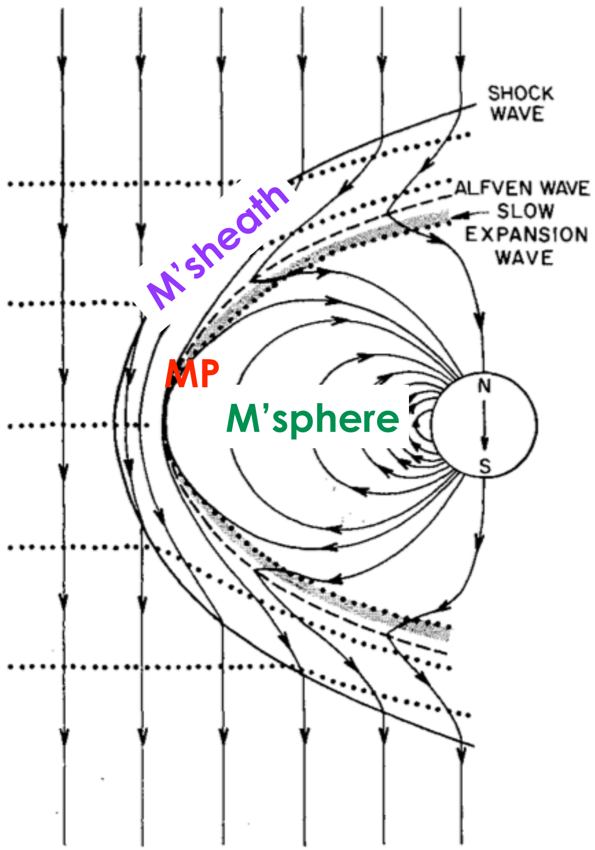
Phan & Paschmann 1996



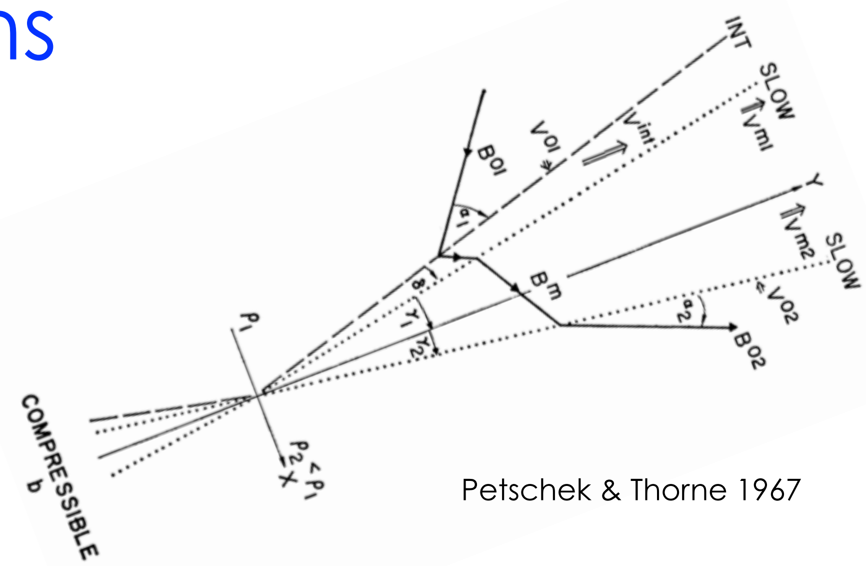
Phan+ 2013



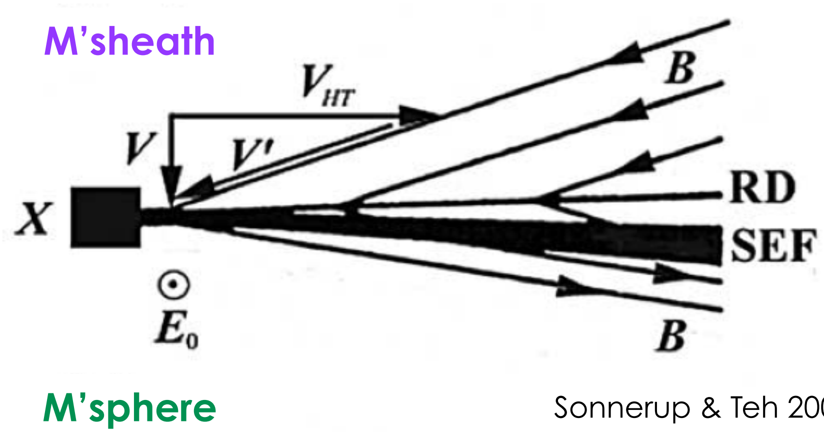
Early predictions



Levy+ 1964



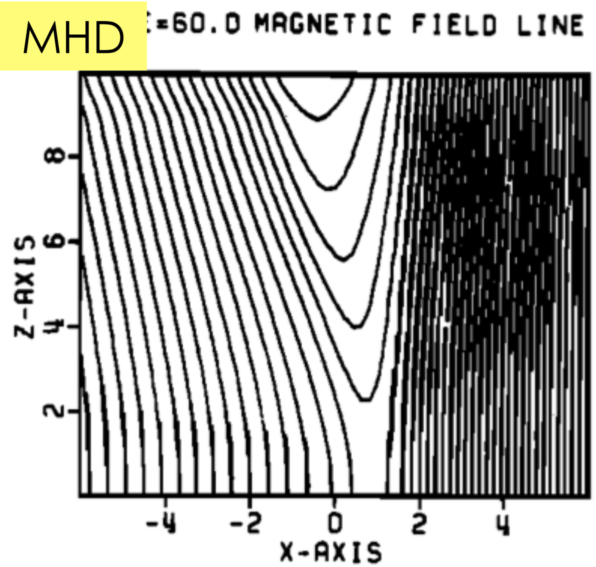
Petschek & Thorne 1967



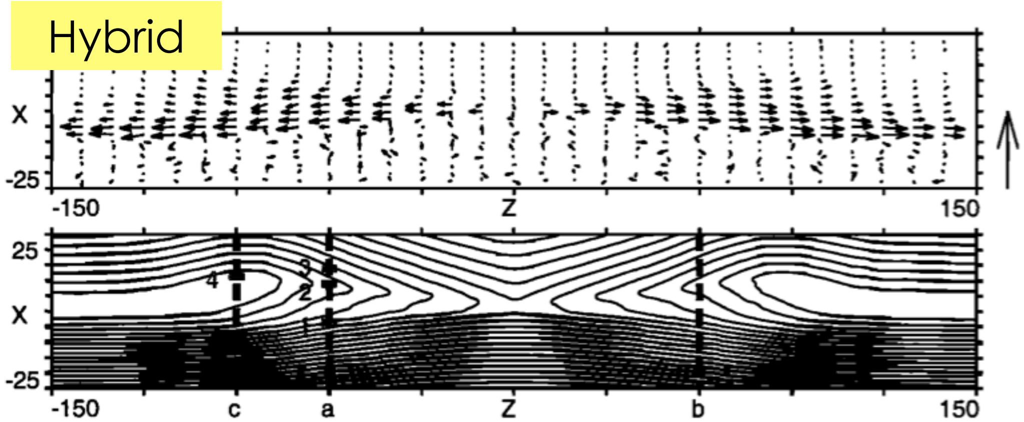
Sonnerup & Teh 2008

- Rotational discontinuity (RD) and slow-mode expansion fan (SEF) are expected
- See Lin & Lee 1993 for detail.

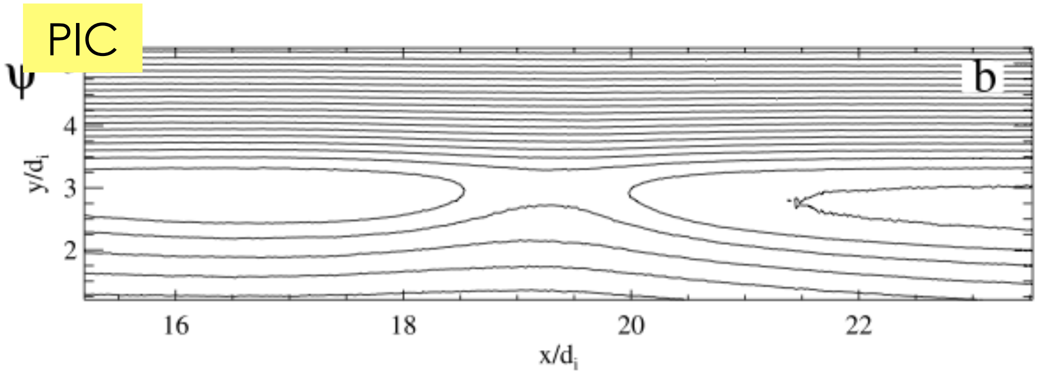
Numerical development



Hoshino & Nishida 1983



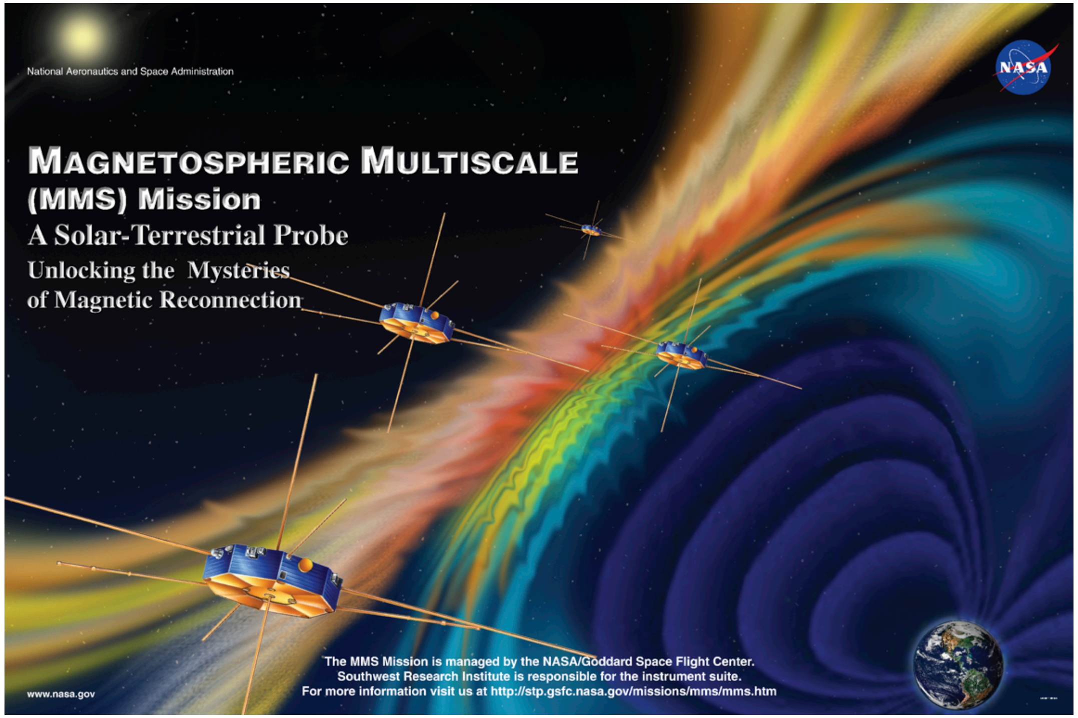
Nakamura & Scholer 2000



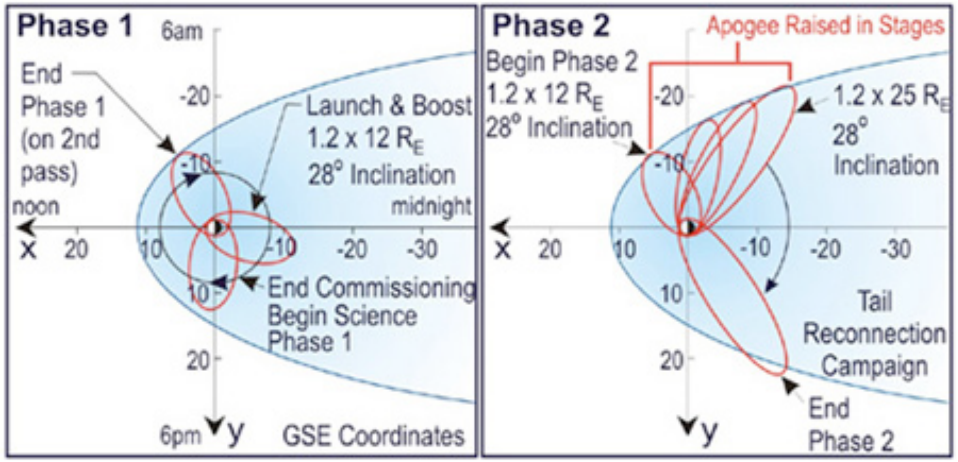
Swisdak+ 2003

- Shock structures are roughly confirmed
  - Minor details were difficult to tell: schemes, limited domain, and kinetic effects
- Steep RD and downstream bulge on the M'sheath side

Renewed attention in late 00's

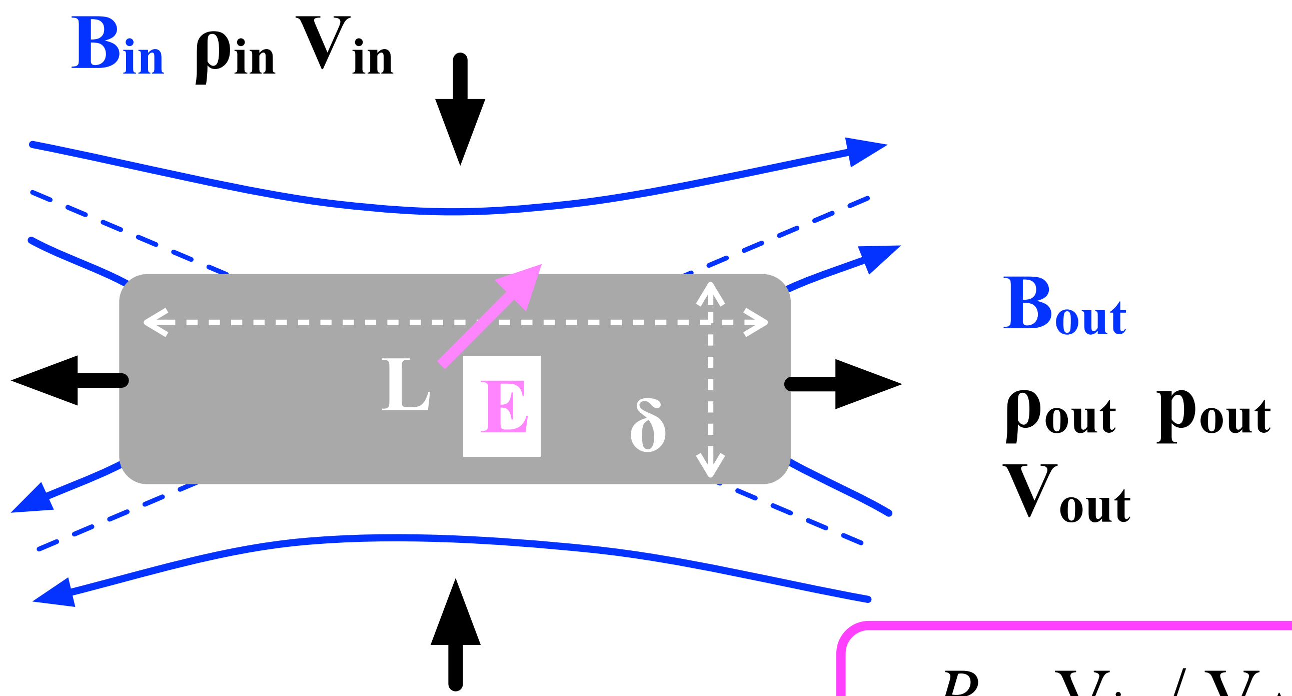


- NASA MMS mission
  - 4 satellites
  - Extremely high resolution



  - Everything is **ON SCHEDULE**
  - Launch for Oct 2014
  - During Phase 1 (2015-2016), MMS will probe RX sites at the M'pause

Basics properties in symmetric RX



$R \sim V_{in} / V_{A,in} \sim 0.1$
$E \sim 0.1 V_{A,in} B_{in}$

Energy conservation

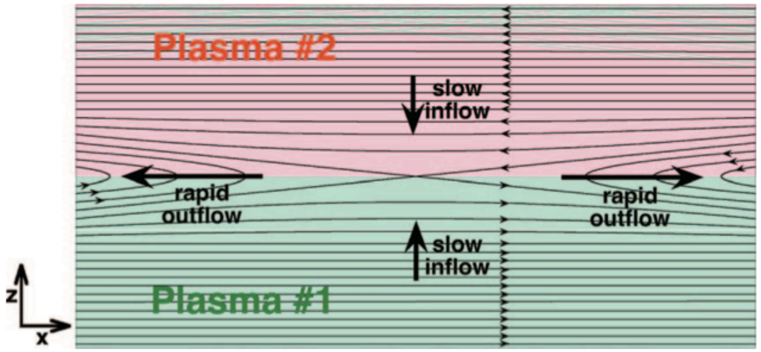
$$\frac{B_{in}^2}{4\pi} L v_{in} \sim \left(\rho_{out} v_{out}^2\right) \delta v_{out}$$

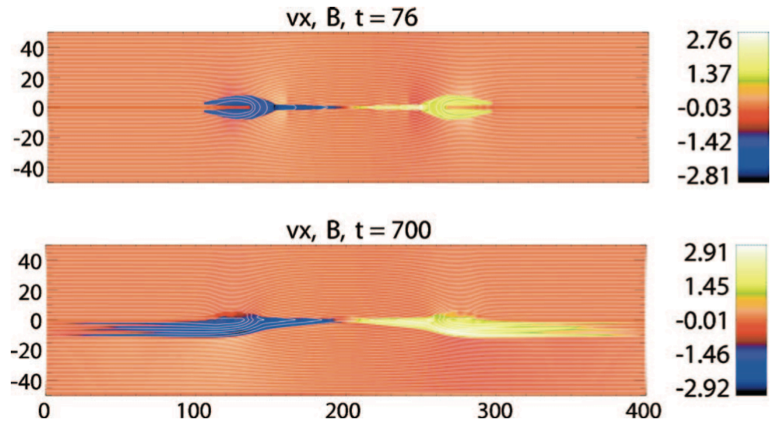
Continuity

$$\rho_{in} L v_{in} = \rho_{out} \delta v_{out}$$

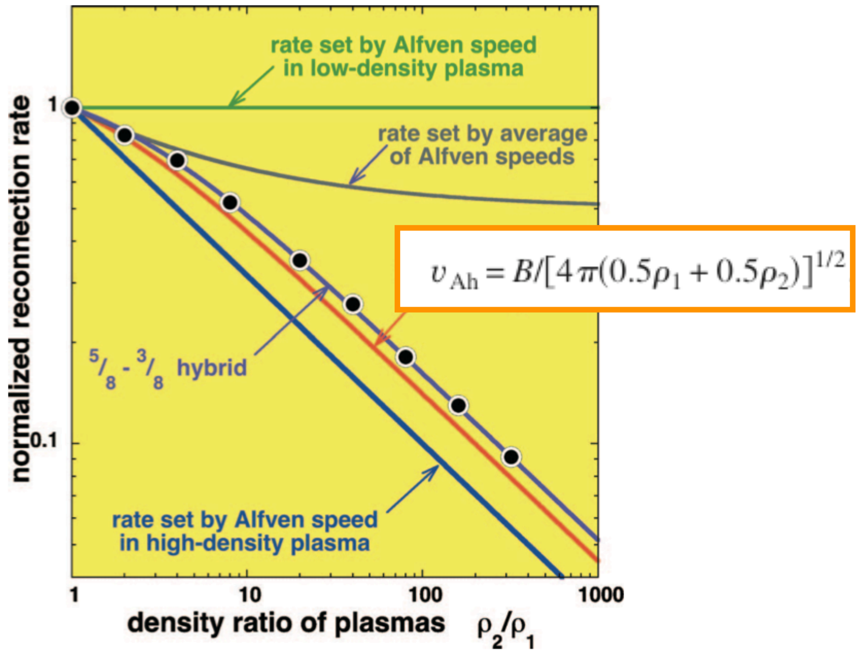
$$\frac{B_{in}^2}{4\pi\rho_{in}} \sim v_{out}^2 \qquad V_{out} \sim V_{A,in}$$

Dawn of the new MHD theory



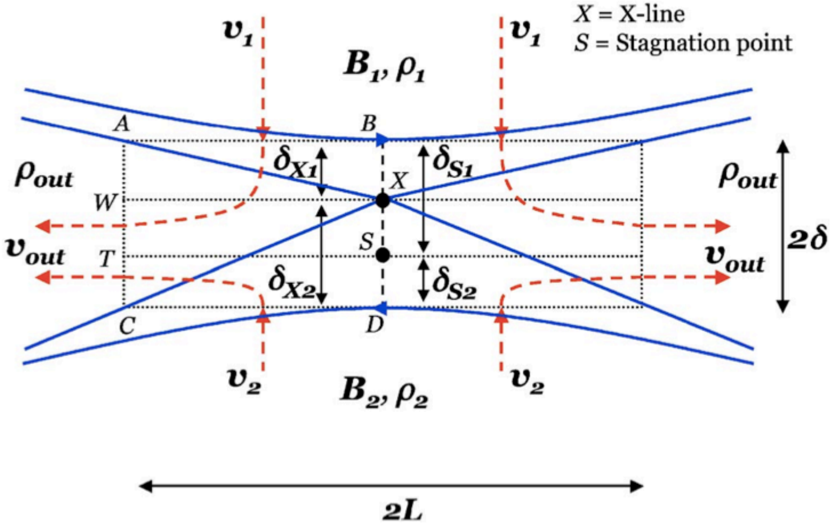


- Scaling analysis of different upstream densities
- *Empirical* hybrid relations



Borovsky+ 2007

Cassak=Shay model (1/2)



Cassak & Shay 2007

- Immediate success
- Full asymmetry
- Conservation analysis
- Useful hybrid relations

$E \sim 0.1\, v_A B_0$

$v_{out} \sim v_A$

$$\oint_S d\mathbf{S} \cdot (\rho \mathbf{v}) = 0,$$

$$\oint_S d\mathbf{S} \cdot \left[\rho \mathbf{v}\mathbf{v} + \left(P + \frac{B^2}{8\pi} \right) \mathbf{I} - \frac{\mathbf{B}\mathbf{B}}{4\pi} \right] = 0,$$

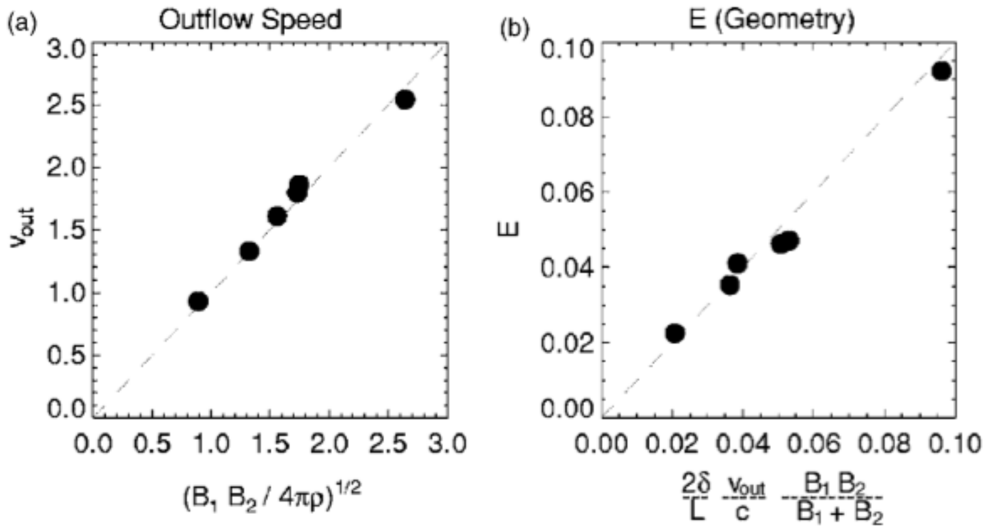
$$\oint_S d\mathbf{S} \cdot \left[\left(\mathcal{E} + P + \frac{B^2}{8\pi} \right) \mathbf{v} - \frac{(\mathbf{v} \cdot \mathbf{B})}{4\pi} \mathbf{B} \right] = 0,$$

$$E \sim \left(\frac{\delta}{L} \right) \left(\frac{v_{out}}{c} \right) \left(\frac{2 B_1 B_2}{B_1 + B_2} \right)$$

$$v_{out}^2 \sim \frac{B_1 B_2}{4\pi} \frac{B_1 + B_2}{\rho_1 B_2 + \rho_2 B_1}$$

Cassak=Shay model (2/2)

- Too good to be true?
- Minor differences aside, the results were verified by many simulation works (Cassak & Shay 2007-2009, Malakit+ 2010)



Physical quantity	Result
Density of outflow, Eq. (17)	$\rho_{out} \sim (\rho_1 B_2 + \rho_2 B_1)/(B_1 + B_2)$
Outflow speed, Eq. (13)	$v_{out}^2 \sim [(B_1 B_2)/(4\pi)][(B_1 + B_2)/(\rho_1 B_2 + \rho_2 B_1)]$
Reconnection rate, Eq. (19)	$E \sim [(B_1 B_2)/(B_1 + B_2)](v_{out}/c)(2\delta/L)$
Location of X-line, Eq. (26)	$(\delta_{X2}/\delta_{X1}) \sim (B_2/B_1)$
Location of stagnation point, Eq. (27)	$(\delta_{S2}/\delta_{S1}) \sim (\rho_2 B_1/\rho_1 B_2)$

Compressibility debate

- Cassak=Shay balances

$$L\left(\frac{B_1^2}{8\pi}v_1 + \frac{B_2^2}{8\pi}v_2\right) \sim 2\delta\left(\frac{1}{2}\rho_{\rm out}v_{out}^2\right)v_{\rm out}$$

- We became aware of the roles of
  - Compressibility
  - Enthalpy flux
  - ==> Missing pieces in Sweet-Parker theories.

- Theory (Birn+ 2010, 2011, Hesse+2011)
- Simulation (Birn+ 2008, Aunai+ 2011)
- Observation (Eastwood+ 2013)

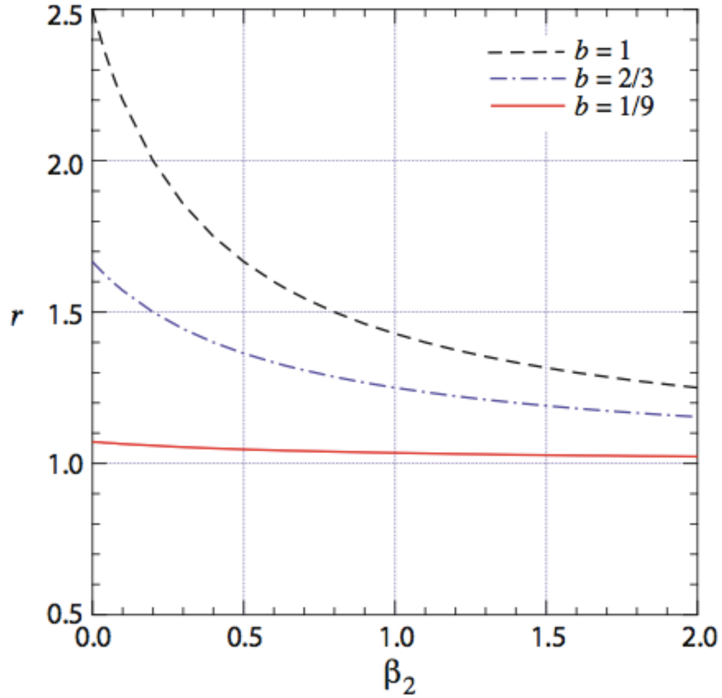
Birn+ (2010) model

- Consider the full balance equations, including the compressibility
- Near-equipartition

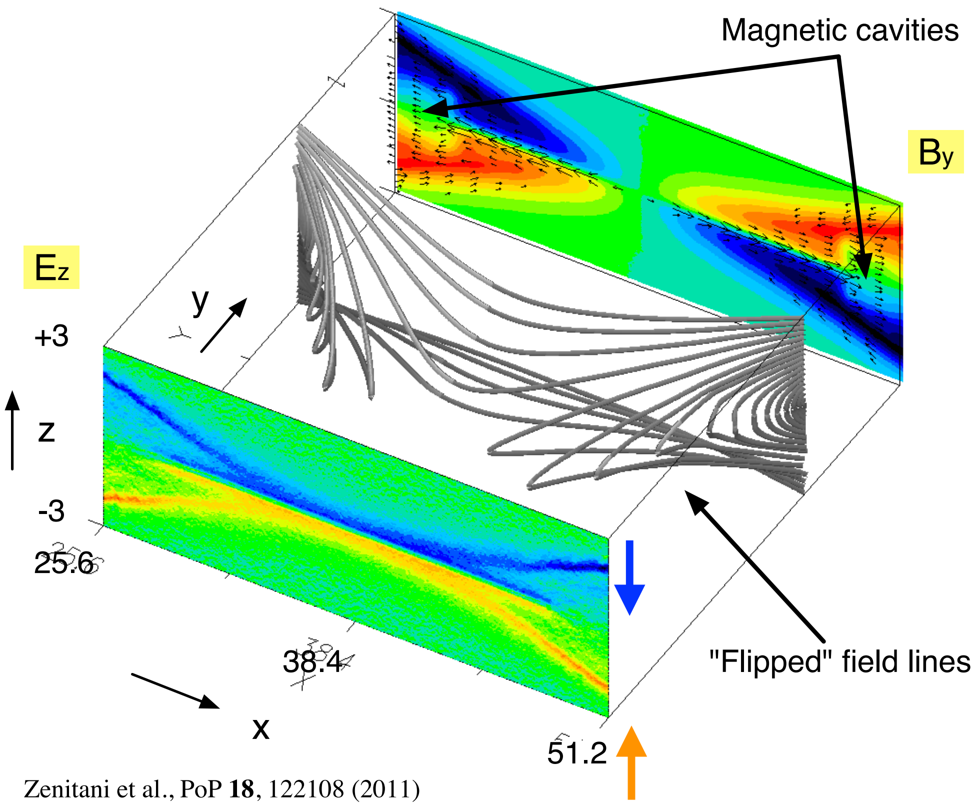
- Compression factor

$$r \equiv \frac{\rho_o}{\bar{\rho}} = \frac{\Gamma(B_1 + B_2)}{\lambda_1 B_2 + \lambda_2 B_1}$$

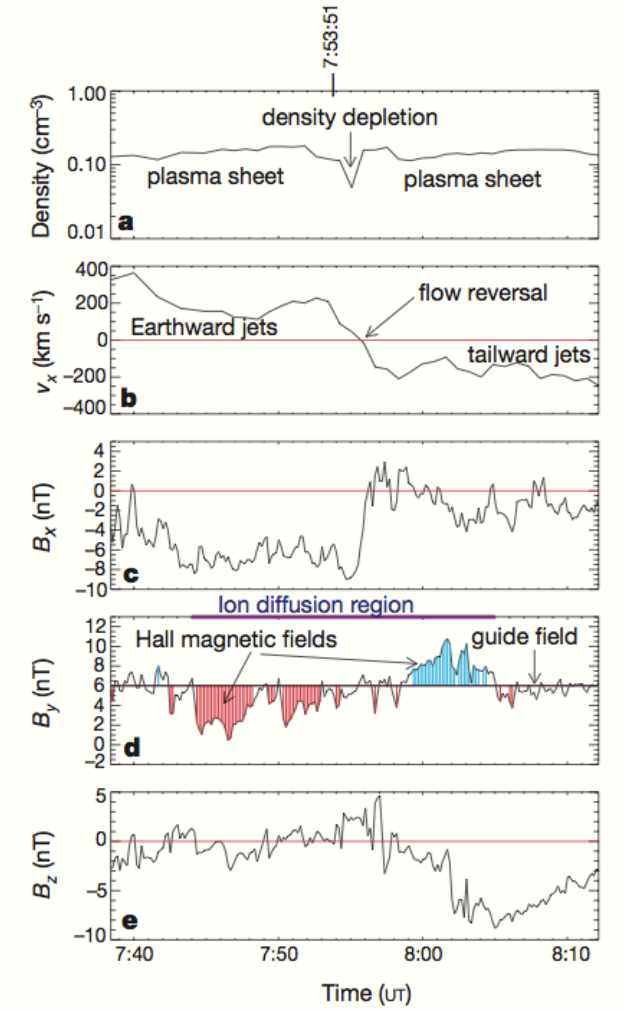
$$E \sim \frac{\Gamma(B_1 + B_2)}{\lambda_1 B_1 + \lambda_2 B_2} \left(\frac{2 B_1 B_2}{B_1 + B_2} \right) \frac{v_{out}}{c} \frac{\delta}{L}$$



Kinetic signatures in symmetric RX



Zenitani et al., PoP **18**, 122108 (2011)



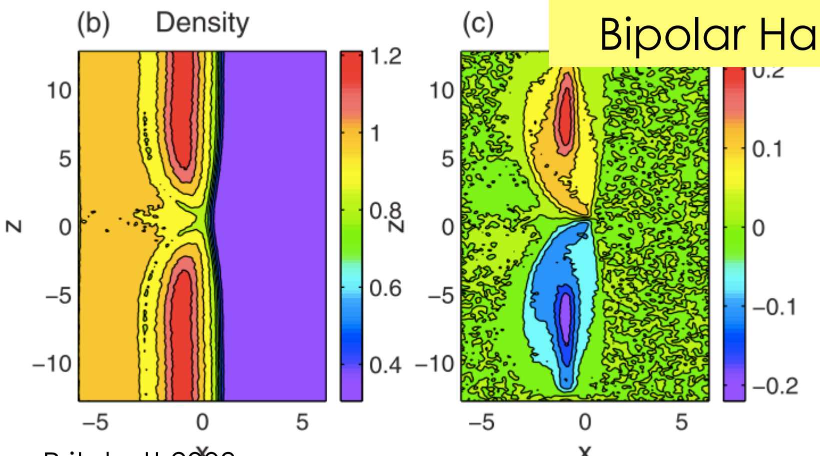
Øerosat+ 2001 Nature
See also Nagai+ 2001 JGR

- Flipping of the filed lines (Sonnerup 1979)
- Higher beta, stronger modulation

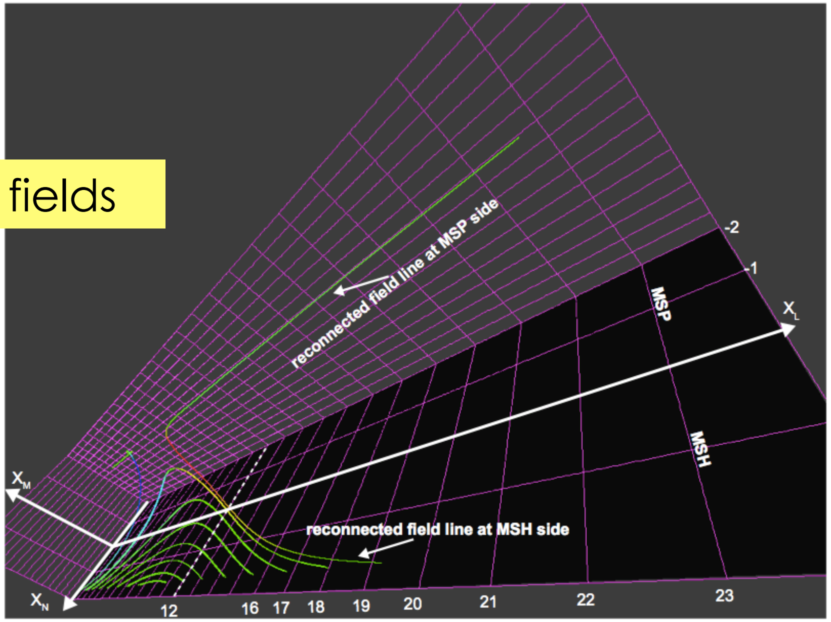
Kinetic signatures

- Many asymmetric signatures
- Few impacts to the global evolution

Bipolar Hall fields

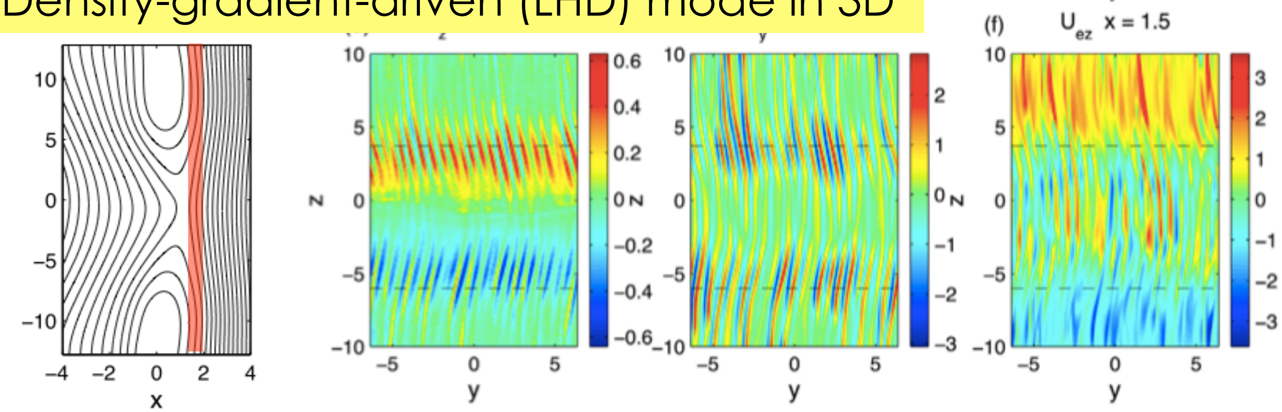


Pritchett 2008



Tanaka+ 2008

Density-gradient-driven (LHD) mode in 3D



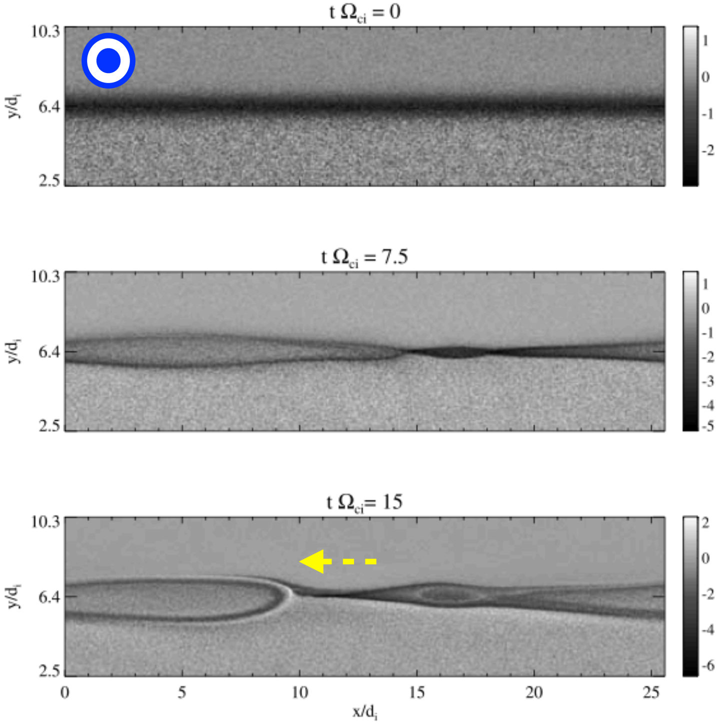
Pritchett+ 2011, 2012

Kinetic feedback 1 - diamagnetic suppression

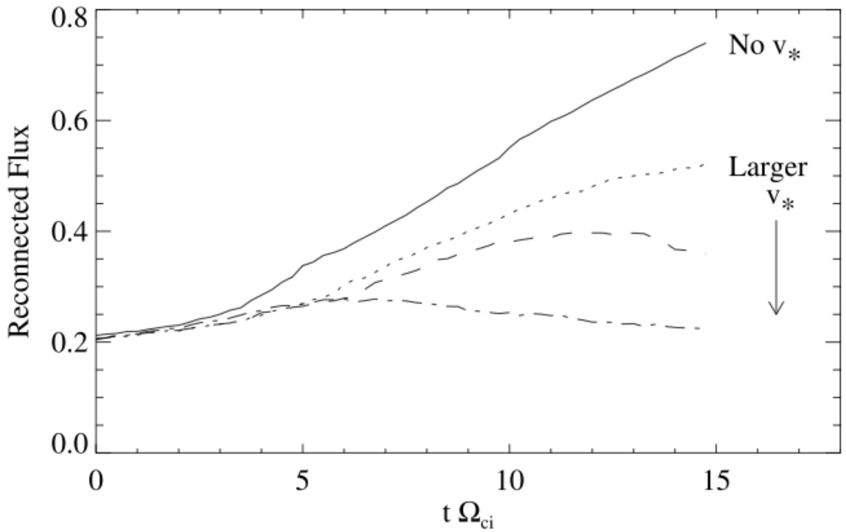
- Diamagnetic effect may suppress reconnection (Swisdak+ 2003, 2010)
- Derived a criteria

$$\Delta\beta > 2(L/\lambda_i)\tan(\theta/2)$$

- This remains controversial
  - Unclear theory: diamagnetic flow does not carry magnetic flux
  - No confirmation by other groups (i.e., Aunai+ 2013)

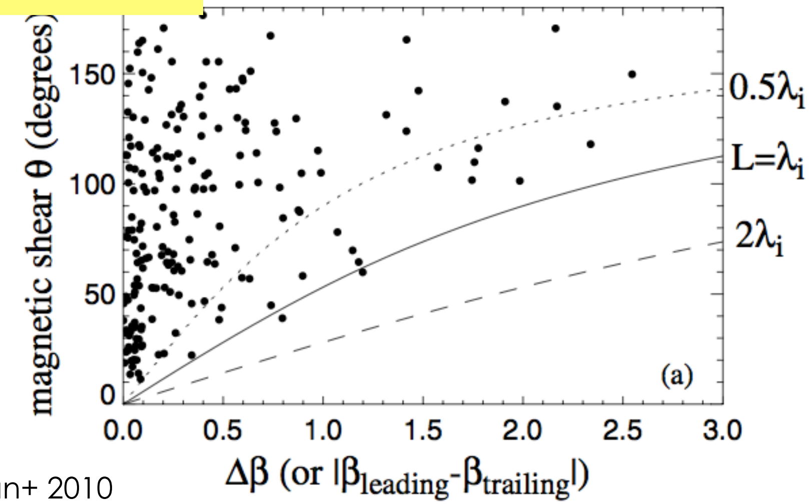


Swisdak+ 2003



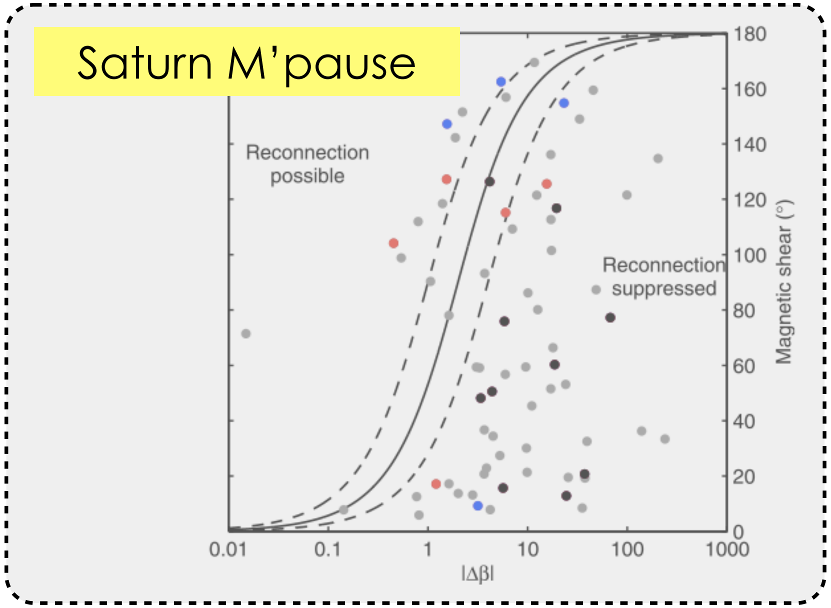
Observational support

Solar wind



Phan+ 2010

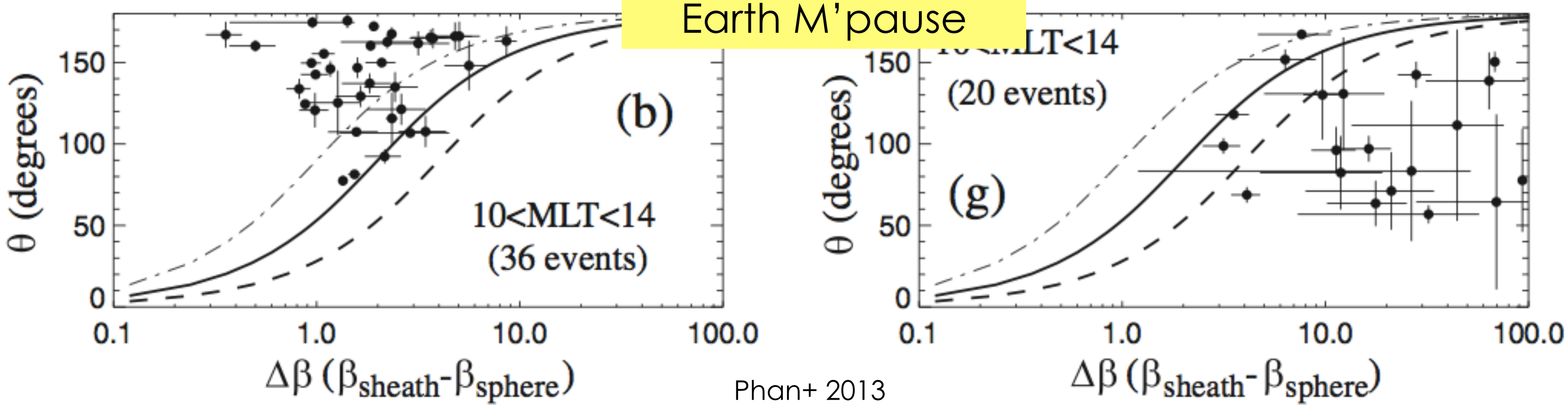
Saturn M'pause



Masters+ 2012

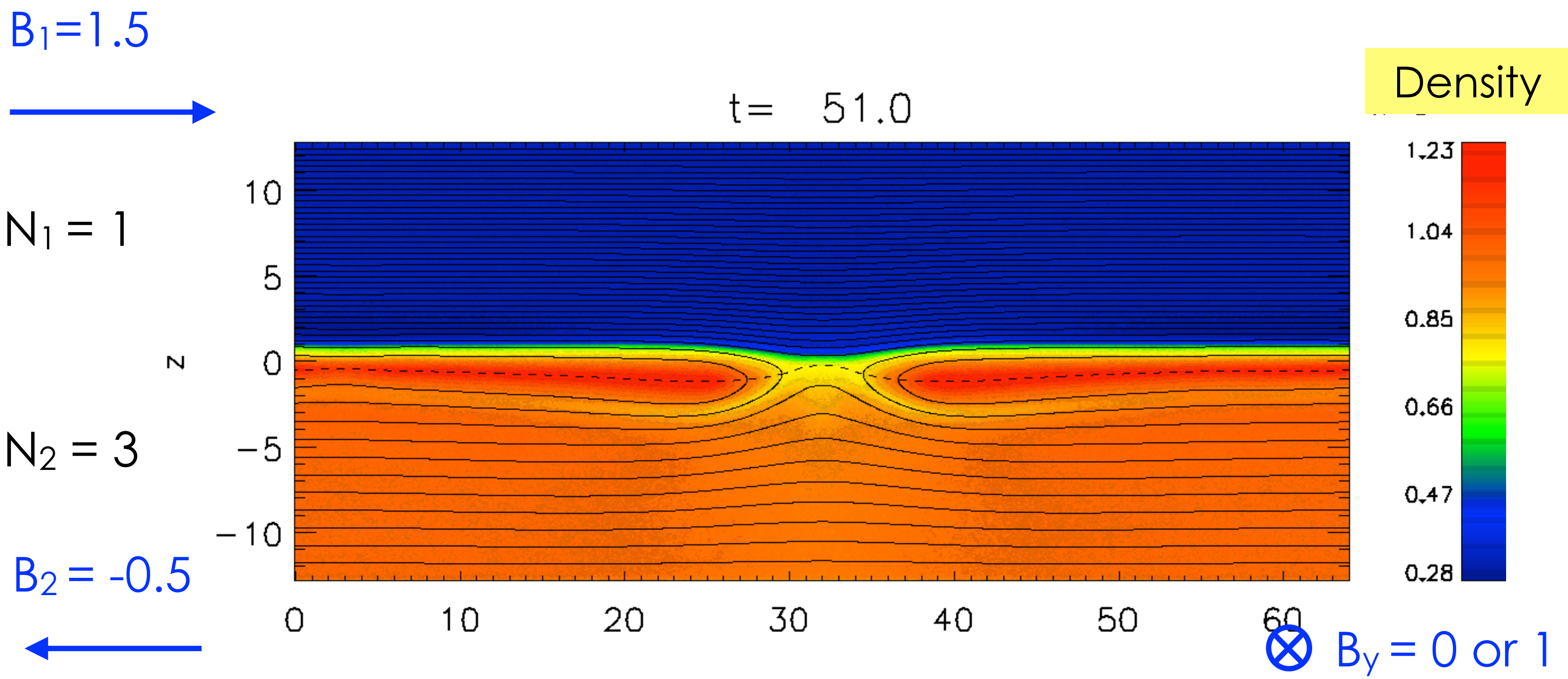
The Swisdak criteria: $\Delta\beta > 2(L/\lambda_i)\tan(\theta/2)$

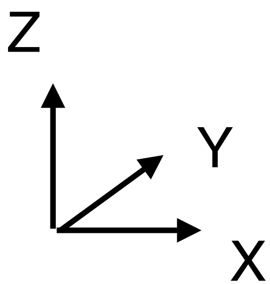
Earth M'pause



Phan+ 2013

Kinetic feedback 2 - anomalous slow down

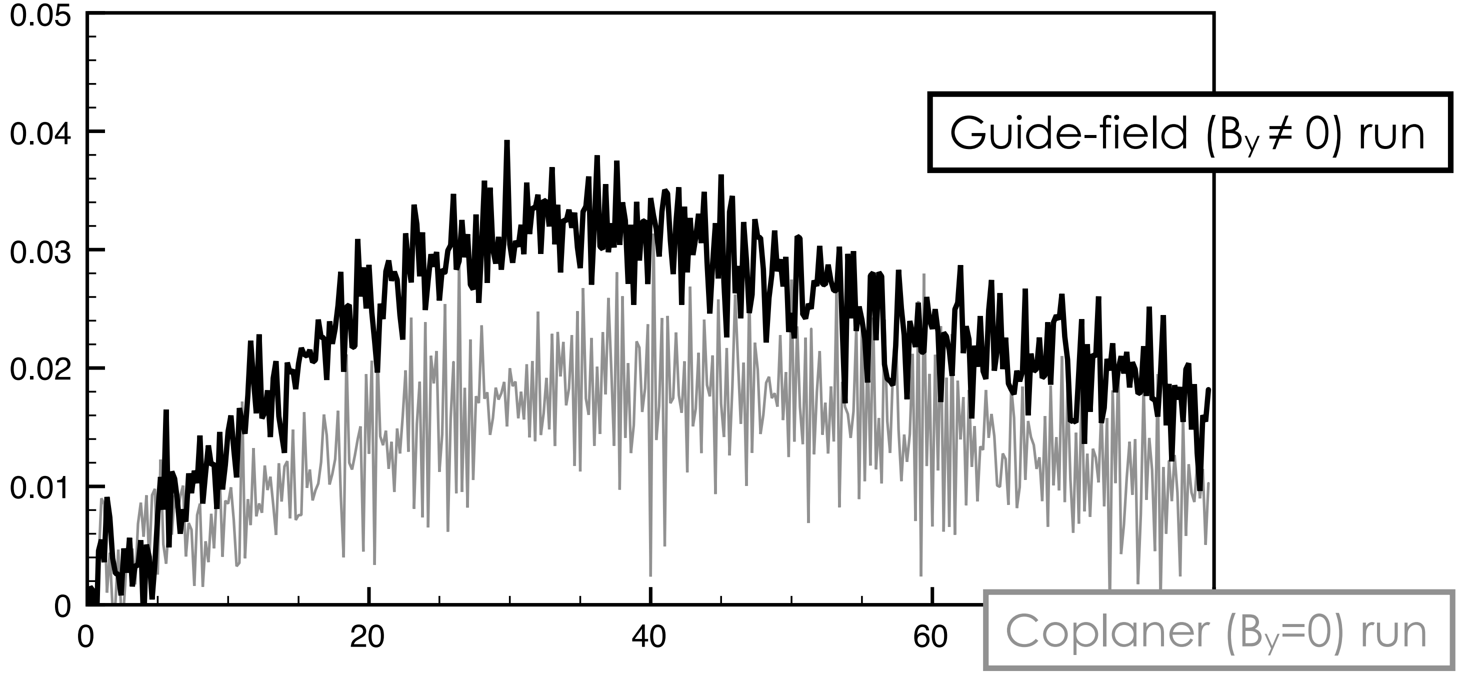




- 64.0 d_i x 25.6 d_i, periodic in x, reflecting in z
- $m_i : m_e = 25 : 1$
- Two runs: Coplaner (B_y=0) vs Guide-field ($B_y \neq 0$)

Coplaner reconnection is slow!!

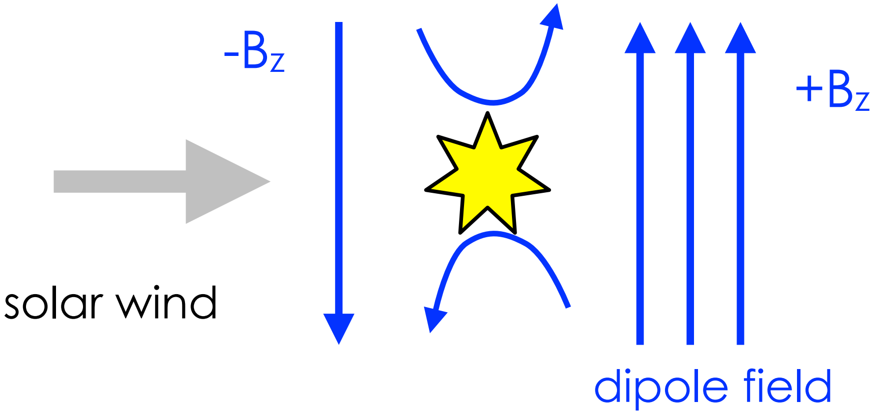
$$E \sim \left(\frac{\delta}{L}\right)\sqrt{\frac{B_1 B_2}{\mu_0}\frac{B_1+B_2}{\rho_1 B_2+\rho_2 B_1}}\left(\frac{2B_1B_2}{B_1+B_2}\right)$$

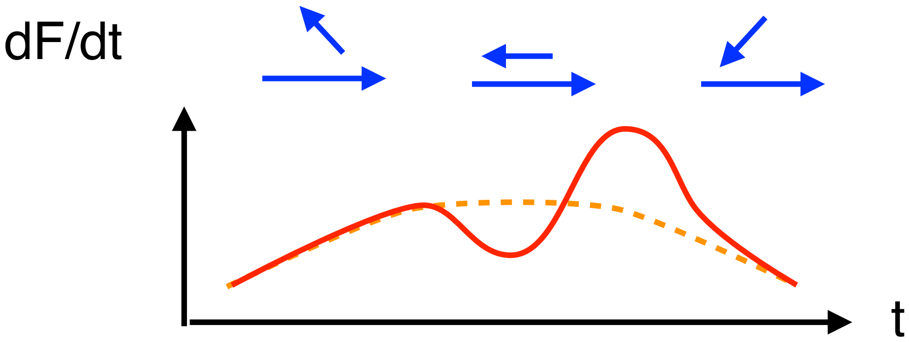


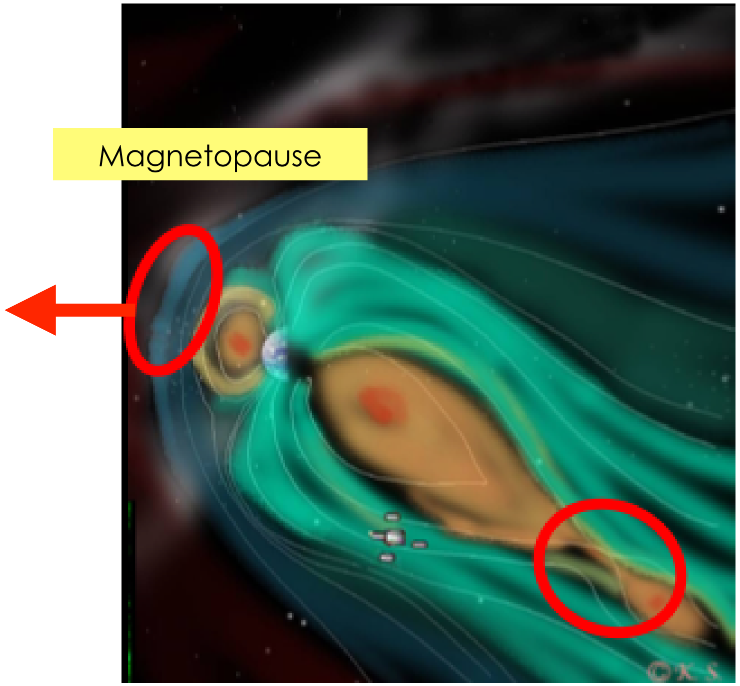
Zenitani+ 2010 unpublished
Hesse+ 2013, Aunai+ 2013

- Guide-field usually makes RX slow
- Coplaner (B_y=0) run is anomalously slow
- Consistent with previous work by Pritchett 2008

Implications

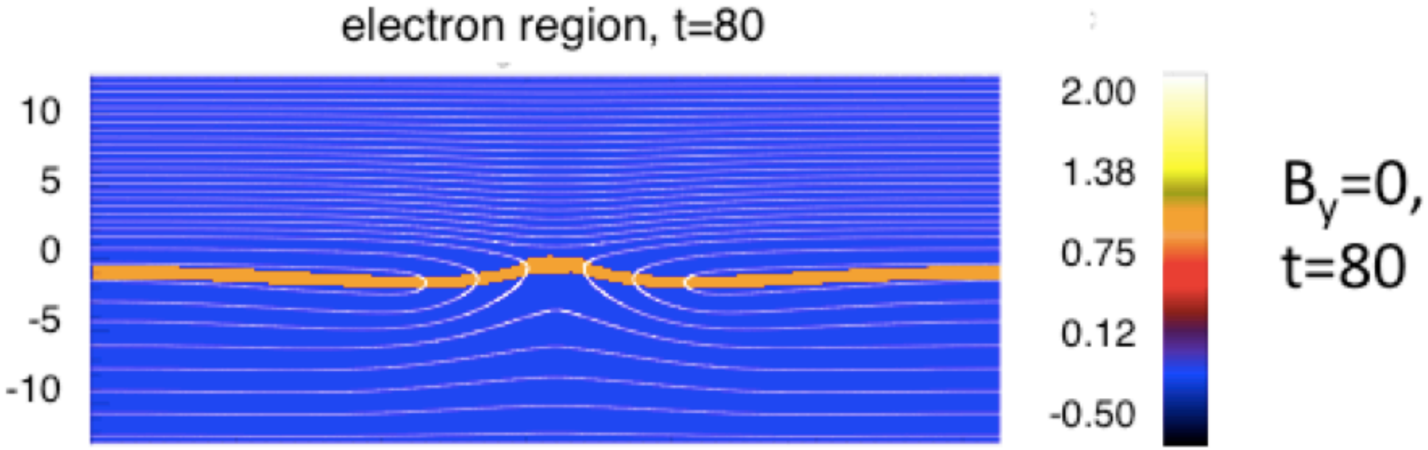






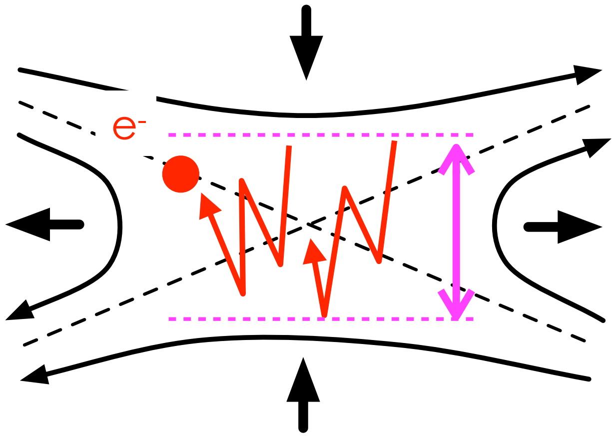
- Flux/energy/mass transfer by magnetopause reconnection can be intermittent

Particle confinement?



Hesse+ 2013

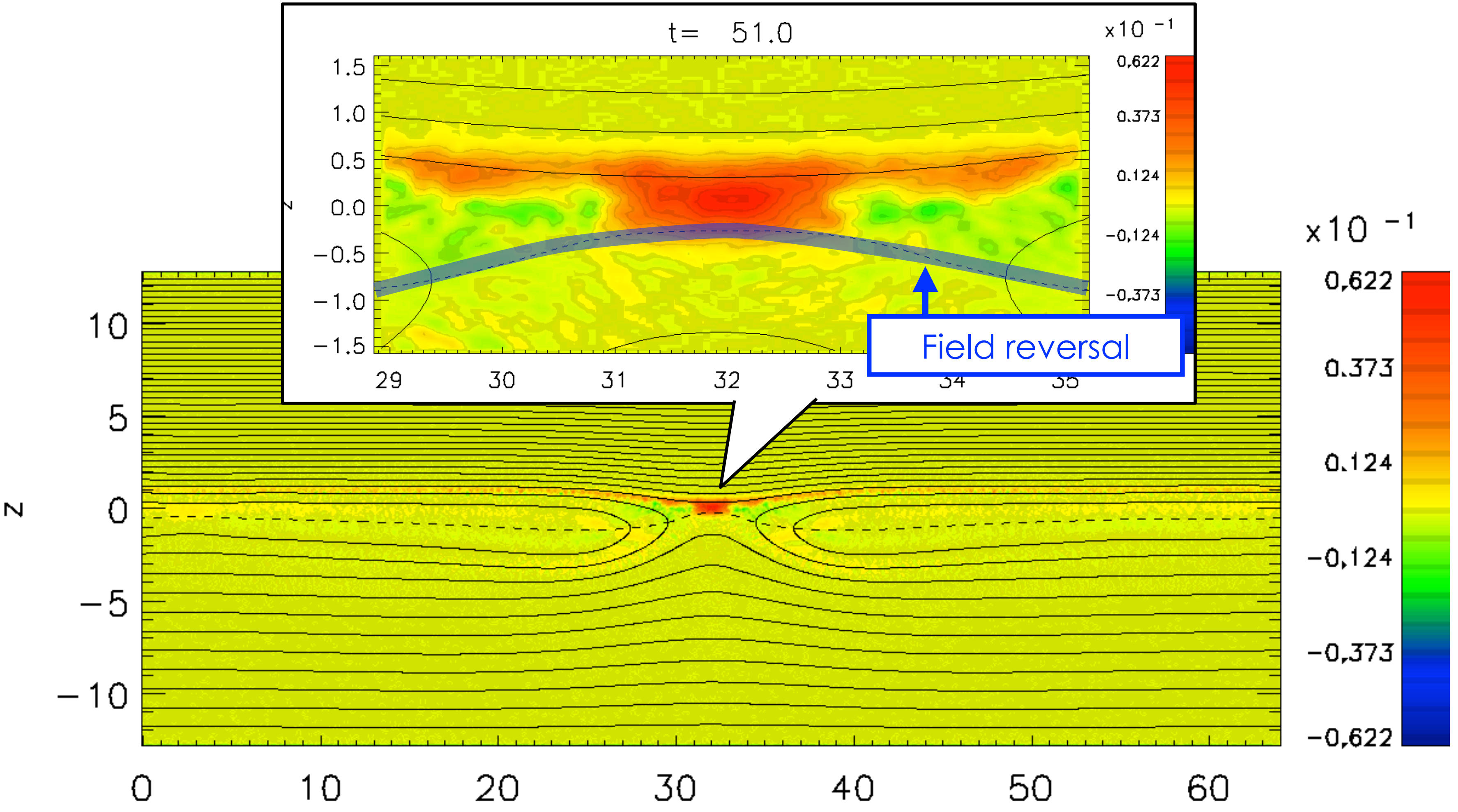
- Larger bounce width
- Wider current channel ==> Weaker E can drive the current



Dissipation region

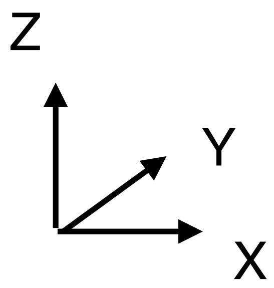
Nonideal energy dissipation

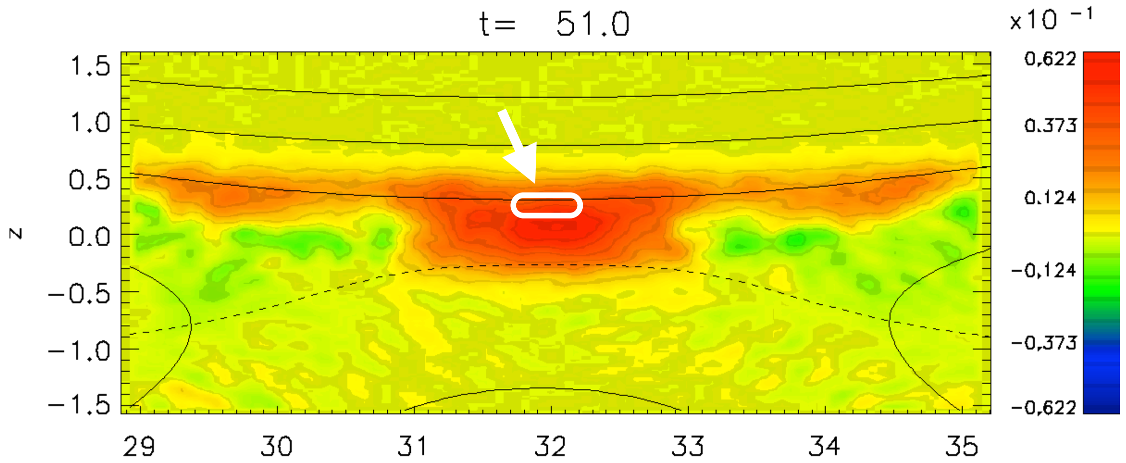
$$D_e = j_\mu e^\mu = \gamma_e\big[\boldsymbol{j}\cdot(\boldsymbol{E}+\boldsymbol{v}_e\times\boldsymbol{B}) - \rho_c(\boldsymbol{v}_e\cdot\boldsymbol{E})\big]$$

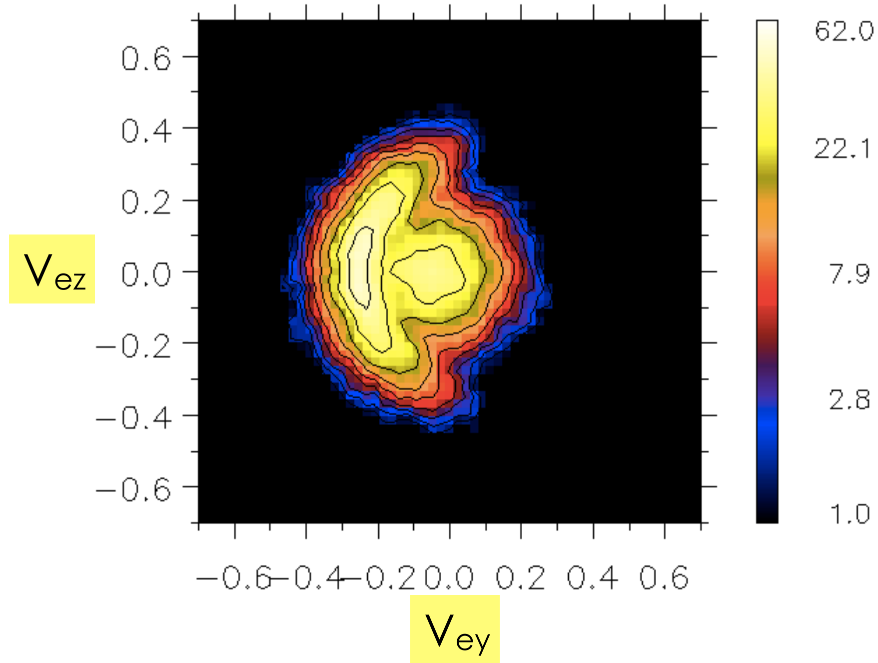


Zenitani+ 2011

Electron distribution function

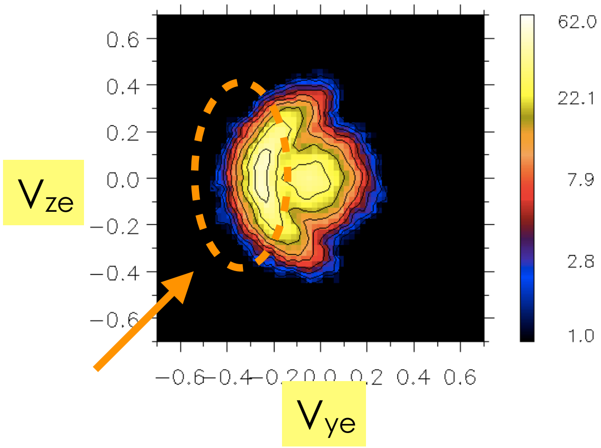


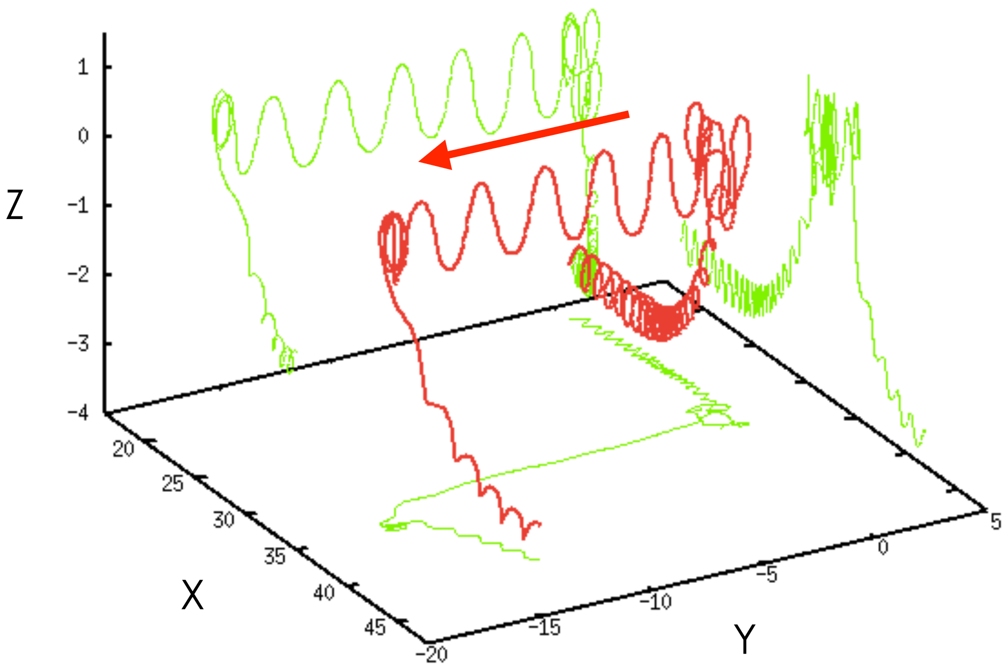


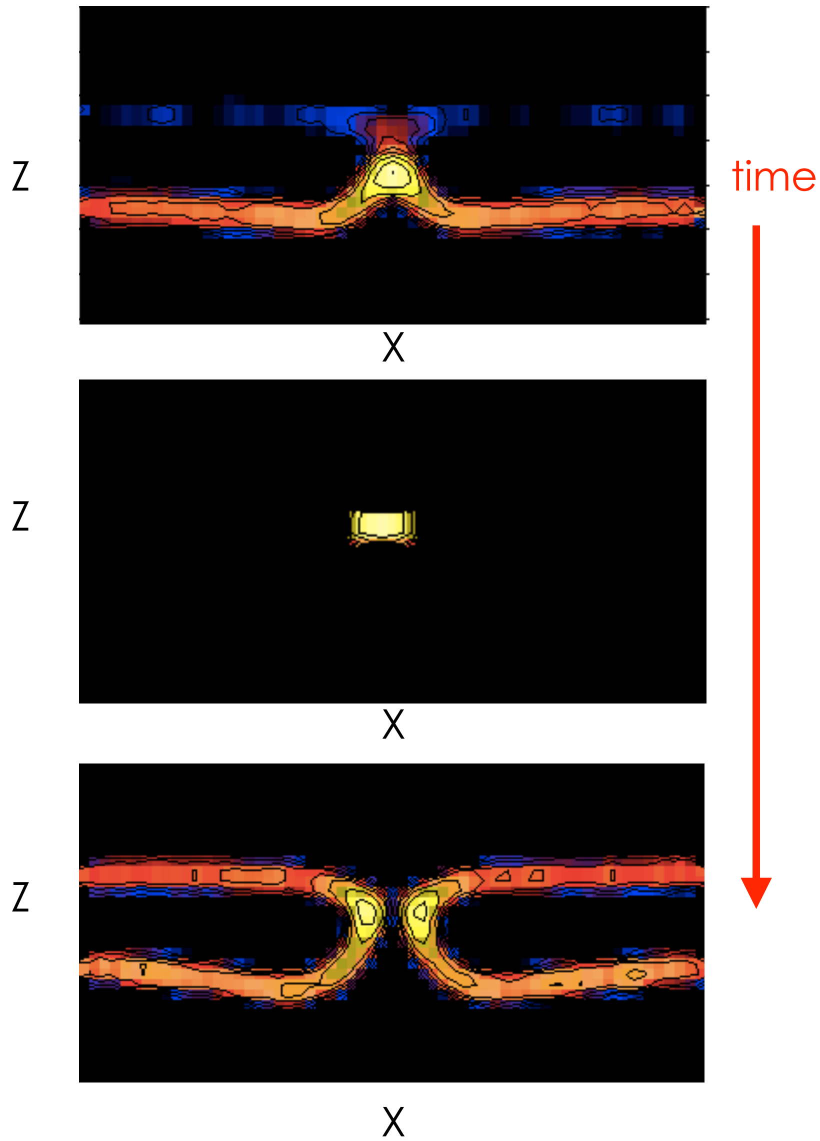


- Highly anisotropic, structured distribution
- The “half-ring” population is responsible for the energy dissipation

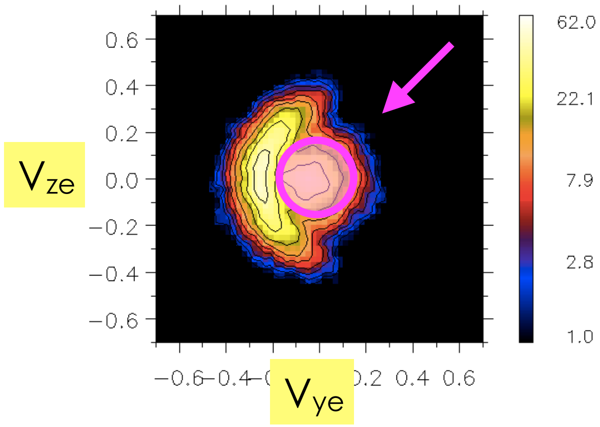
Lower-origin meandering electrons

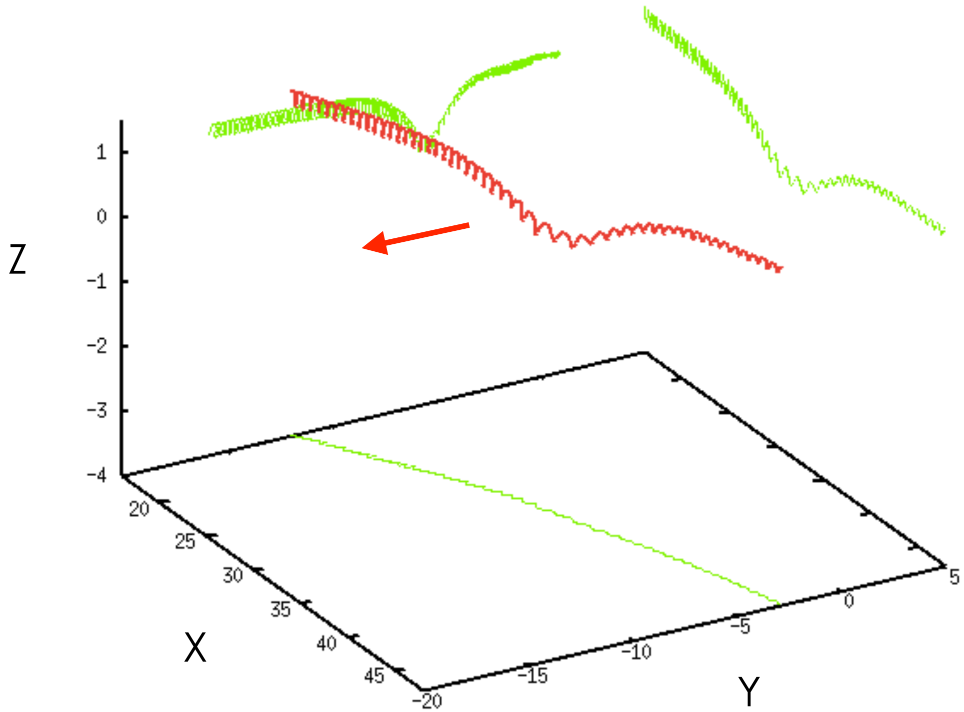


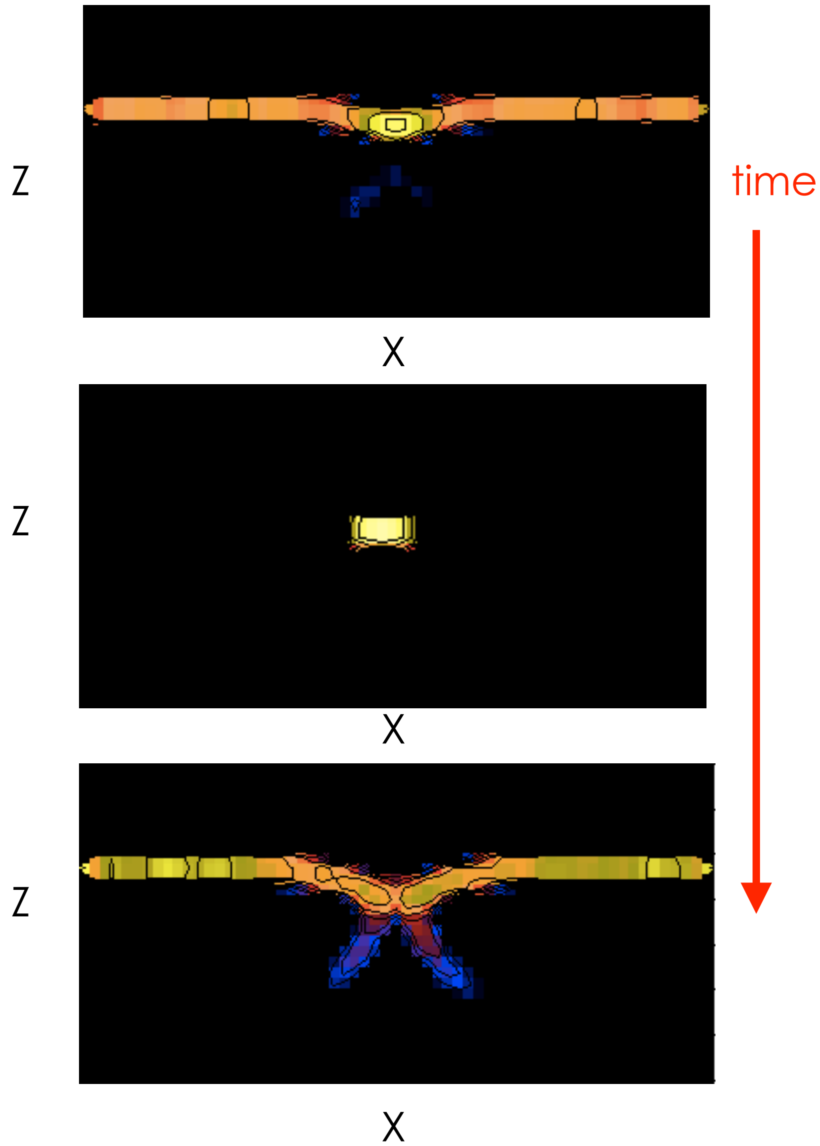




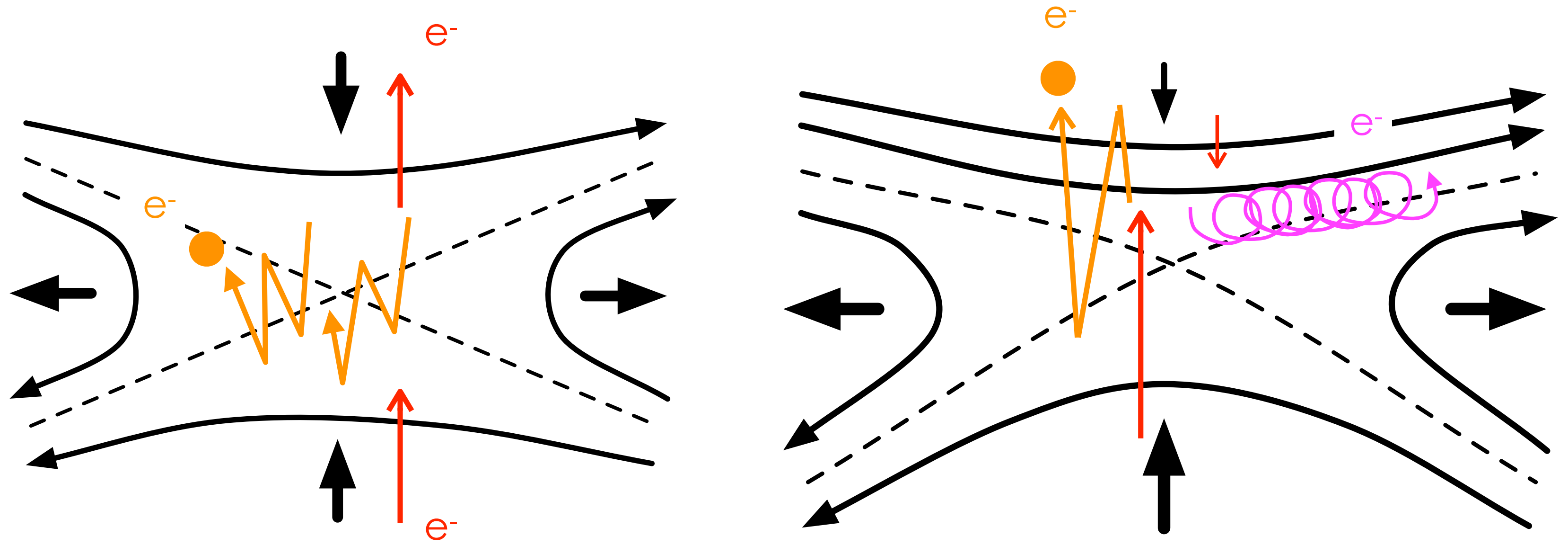
Drifting electrons on the upper side



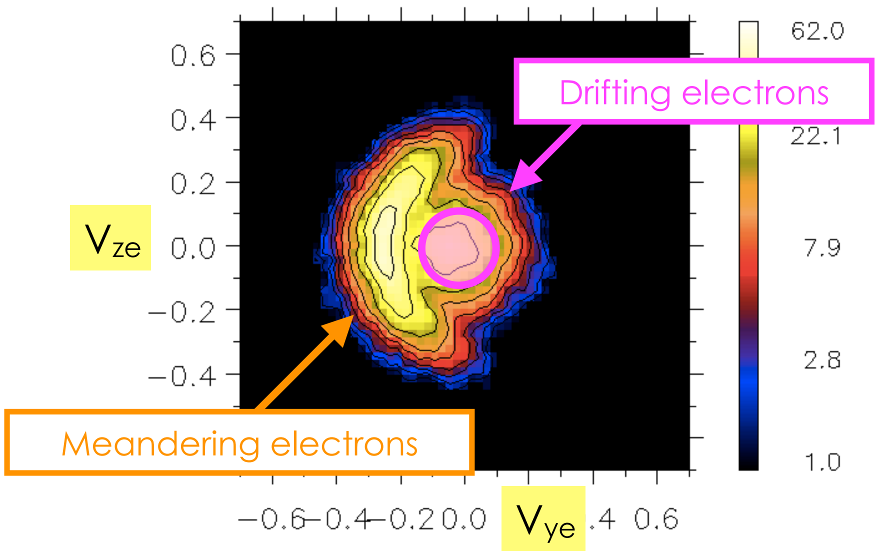




Electron particle picture



- Two current-carrying electrons
  - Meandering electrons (unconfined, dissipative)
  - drifting electrons (confined, non-dissipative)
- We are still trying to understand
  - How do they mix each other?
  - How to dissipate the energy?



Summary

- MHD properties
  - Shock structures
  - Cassak=Shay=Birn (CSB) model is successful

- Kinetic signatures
  - Bipolar Hall field, density-gradient mode etc.
  - Few impacts to global evolution

- Major unsolved issues - kinetic effects, related to $\Delta\beta$
  - Diamagnetic suppression (Swisdak+ 2003)
  - Anomalous slow down (Hesse+ 2013)

- More simulations needed, using realistic parameters
- Next-generation observations will come in 2015