Magnetic Reconnection

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What is Magnetic Reconnection?

If a plasma is perfectly conducting, that is, it obeys the ideal Ohm's law,

$$\mathbf{E} + \mathbf{v} \times \mathbf{B}/c = 0$$

B-lines are frozen in the plasma, and no reconnection occurs.

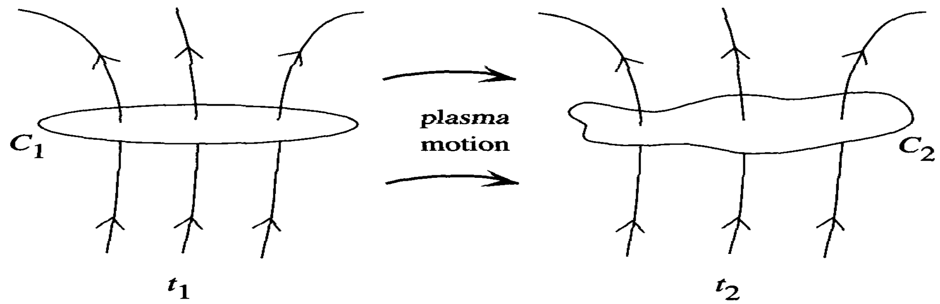


Fig. 1.6. Magnetic flux conservation: if a curve C_1 is distorted into C_2 by plasma motion, the flux through C_1 at t_1 equals the flux through C_2 at t_2.

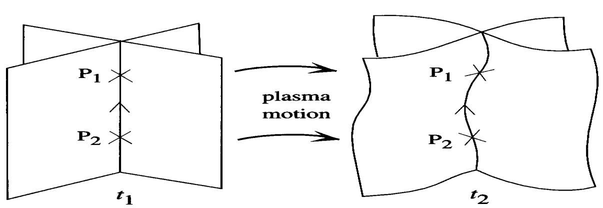


Fig. 1.7. Magnetic field-line conservation: if plasma elements P_1 and P_2 lie on a field line at time t_1, then they will lie on the same line at a later time t_2.

Magnetic Reconnection: Working Definition

Departures from ideal behavior, represented by

$$\mathbf{E} + \mathbf{v} \times \mathbf{B} / c = \mathbf{R}, \quad \nabla \times \mathbf{R} \neq \mathbf{0}$$

break ideal topological invariants, allowing field lines to break and reconnect.

In the generalized Ohm's law for weakly collisional or collisionless plasmas, **R** contains resistivity, Hall current, electron inertia and pressure.

Example of Topological Change: Magnetic Island Formation

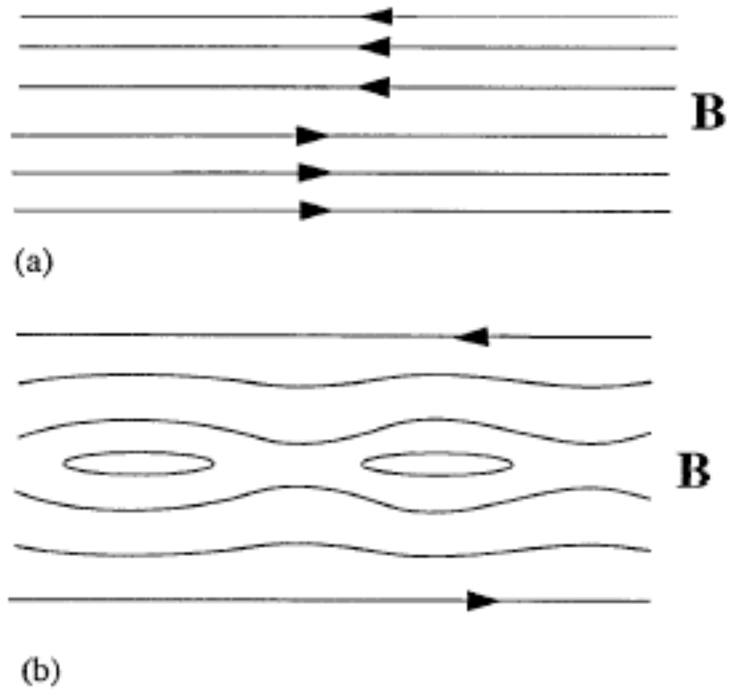


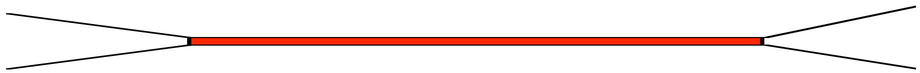
FIG. 1. (a) The topology of field lines in the Harris equilibrium $\mathbf{B}=B_0 \tanh(z/a)\hat{\mathbf{x}}$. (b) The topology of field lines when the perturbation $\mathbf{b}=b \sin(kx)\hat{\mathbf{z}}$ is imposed on the Harris equilibrium.

Why is magnetic reconnection important?

- Magnetic reconnection enables a system to access states of lower energy by topological relaxation of the magnetic field. The energy thus liberated can be converted to the kinetic energy of particles and heat. Since the Universe is permeated by magnetic fields (in Nature and the laboratory), magnetic reconnection is a ubiquitous mechanism wherever such phenomena occur, including eruptive stellar/solar flares, magnetospheric storms, and disruptions in fusion plasmas.
- By allowing small-scale, tangled fields to reconnect and forming larger-scale fields, reconnection plays a critical role in the "dynamo effect"----the mechanism most widely invoked on how large-scale magnetic fields in the Universe are spontaneously generated from various types of plasma turbulence. Understanding of fast reconnection is central to the question: "Why is the Universe magnetized?"

Classical (2D) Steady-State Models of Reconnection

Sweet-Parker [Sweet 1958, Parker 1957]



Geometry of reconnection layer : Y-points [Syrovatskii 1971]

Length of the reconnection layer is of the order of the system size >> width Δ

Reconnection time scale

$$\tau_{SP} = \left(\tau_A \tau_R\right)^{1/2} = S^{1/2} \tau_A$$

Solar flares: $S \sim 10^{12}, \quad \tau_A \sim 1s$

$$\Rightarrow \tau_{SP} \sim 10^6 s$$

Too long to account for solar flares!

Q. Why is Sweet-Parker reconnection so slow?

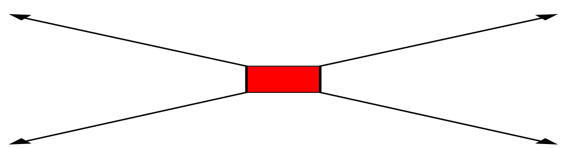
A. Geometry

Conservation relations of mass, energy, and flux

$$V_{in} L = V_{out} \delta, \quad V_{out} = V_A$$

$$V_{in} = \frac{\delta}{L} V_A, \quad \frac{\delta}{L} = S^{-1/2}$$

Petschek [1964]



Geometry of reconnection layer: X-point

Length Δ (<< L) is of the order of the width δ

$$\tau_{PK} = \tau_A \ln S$$

Solar flares: $\tau_{PK} \sim 10^2 s$

Computational Tests of the Petschek Model

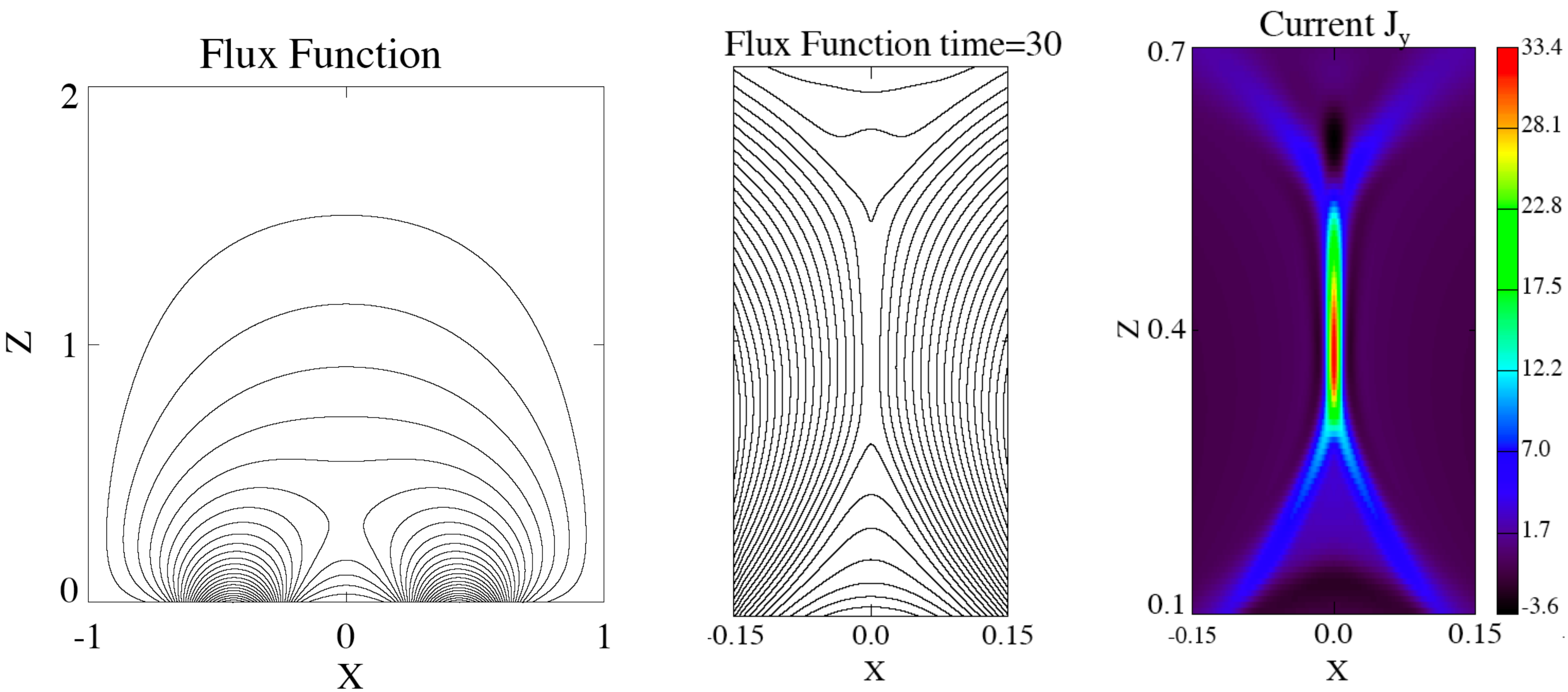
[Sato and Hayashi 1979, Ugai 1984, Biskamp 1986, Forbes and Priest 1987, Scholer 1989, Yan, Lee and Priest 1993, Ma et al. 1995, Uzdensky and Kulsrud 2000, Breslau and Jardin 2003, Malyshkin, Linde and Kulsrud 2005]

Conclusions

• Petschek model is not realizable in high-S plasmas, unless the resistivity is locally strongly enhanced at the X-point.

• In the absence of such anomalous enhancement, the reconnection layer evolves dynamically to form Y-points and realize a Sweet-Parker regime.

2D coronal loop : high-Lundquist number resistive MHD simulation



T = 0

T = 30

[Ma, Ng, Wang, and Bhattacharjee 1995]

Impulsive Reconnection: The Onset/Trigger Problem

Dynamics exhibits an impulsiveness, that is, a sudden change in the time-derivative of the reconnection rate.

The magnetic configuration evolves slowly for a long period of time, only to undergo a sudden dynamical change over a much shorter period of time.

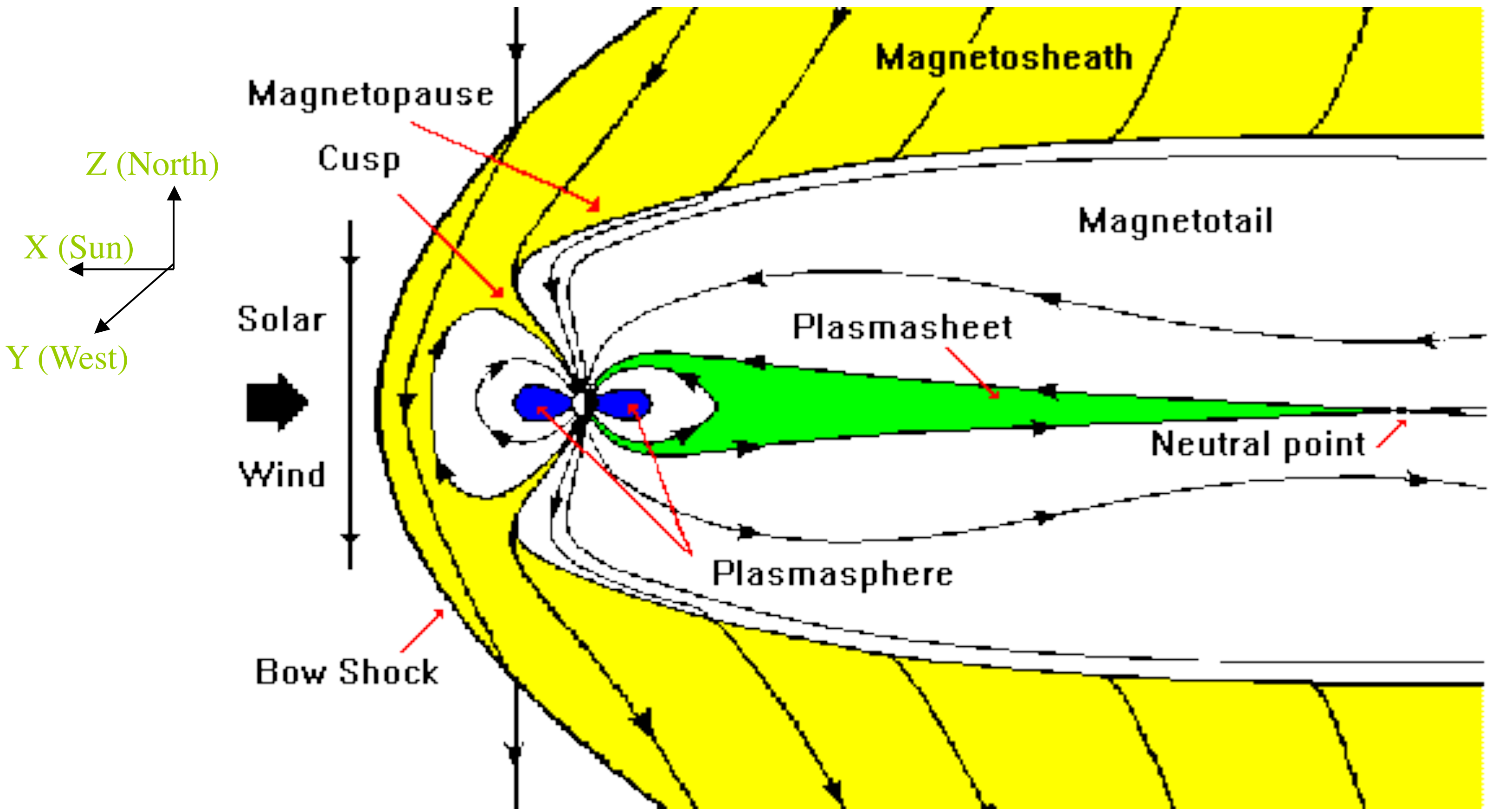
Dynamics is characterized by the formation of near-singular current sheets which need to be resolved in computer simulations: a classic multi-scale problem coupling large scales to small.

Examples

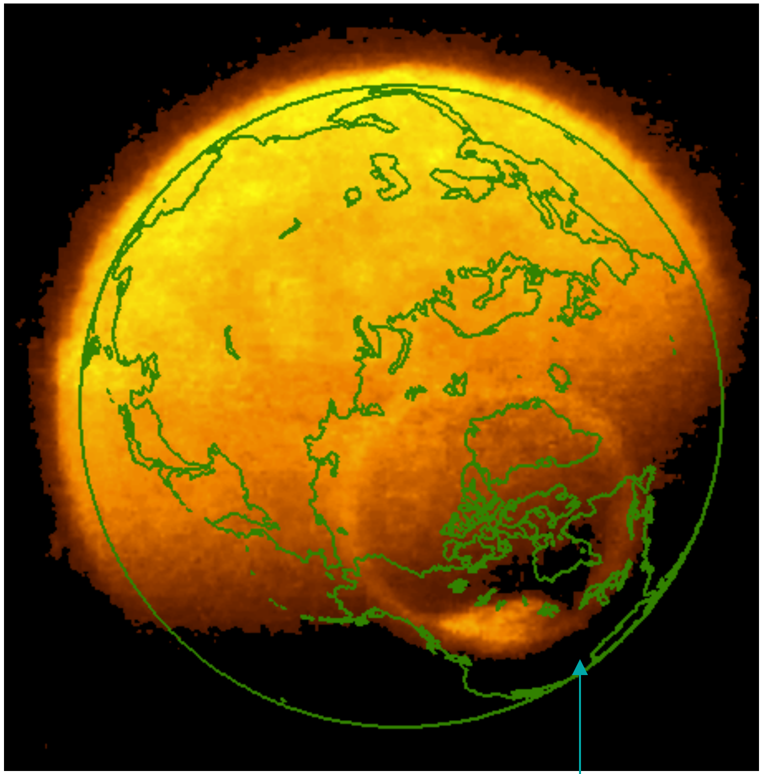
Magnetospheric substorms

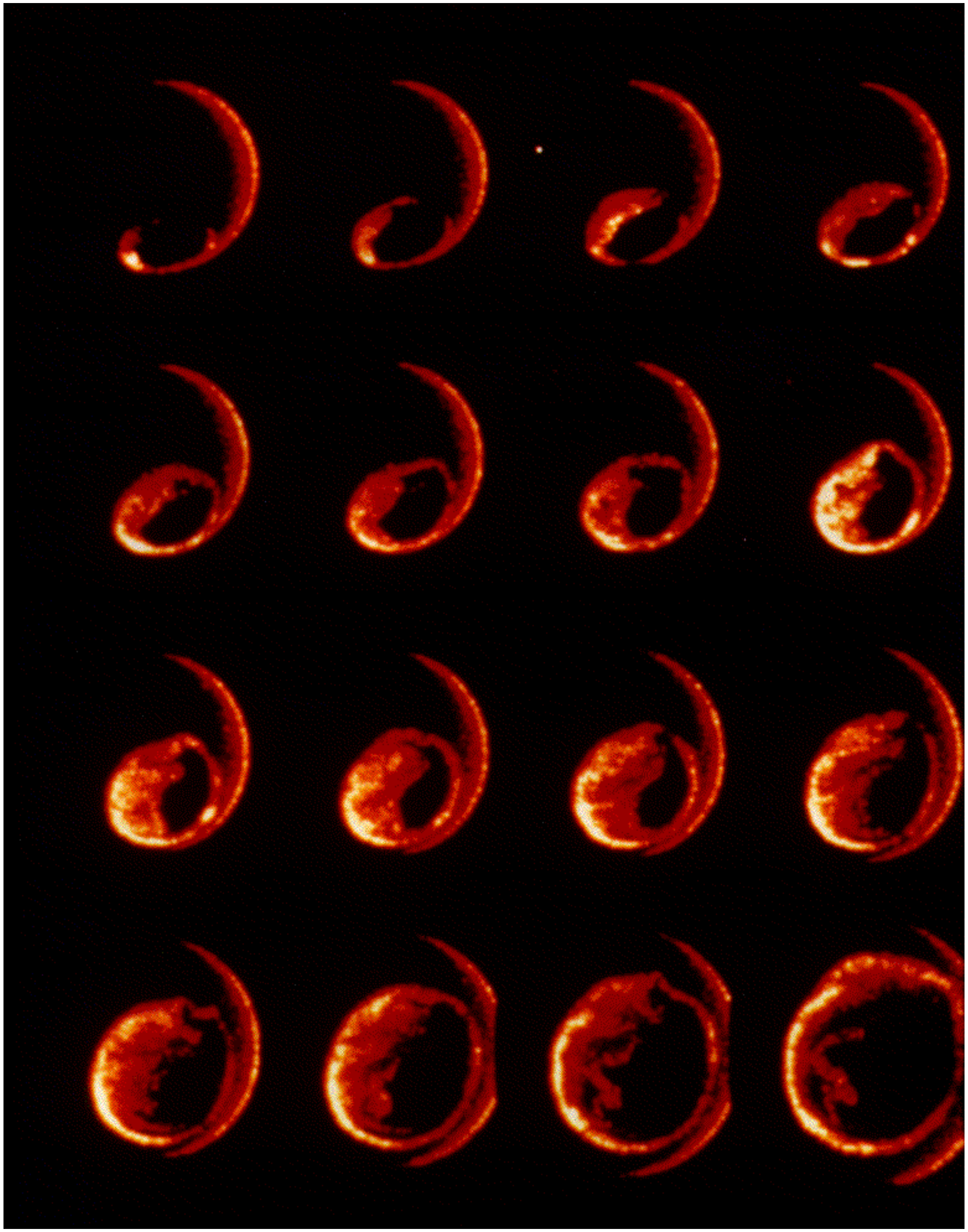
Impulsive solar/stellar flares

Substorm Onset:
Where does it occur?



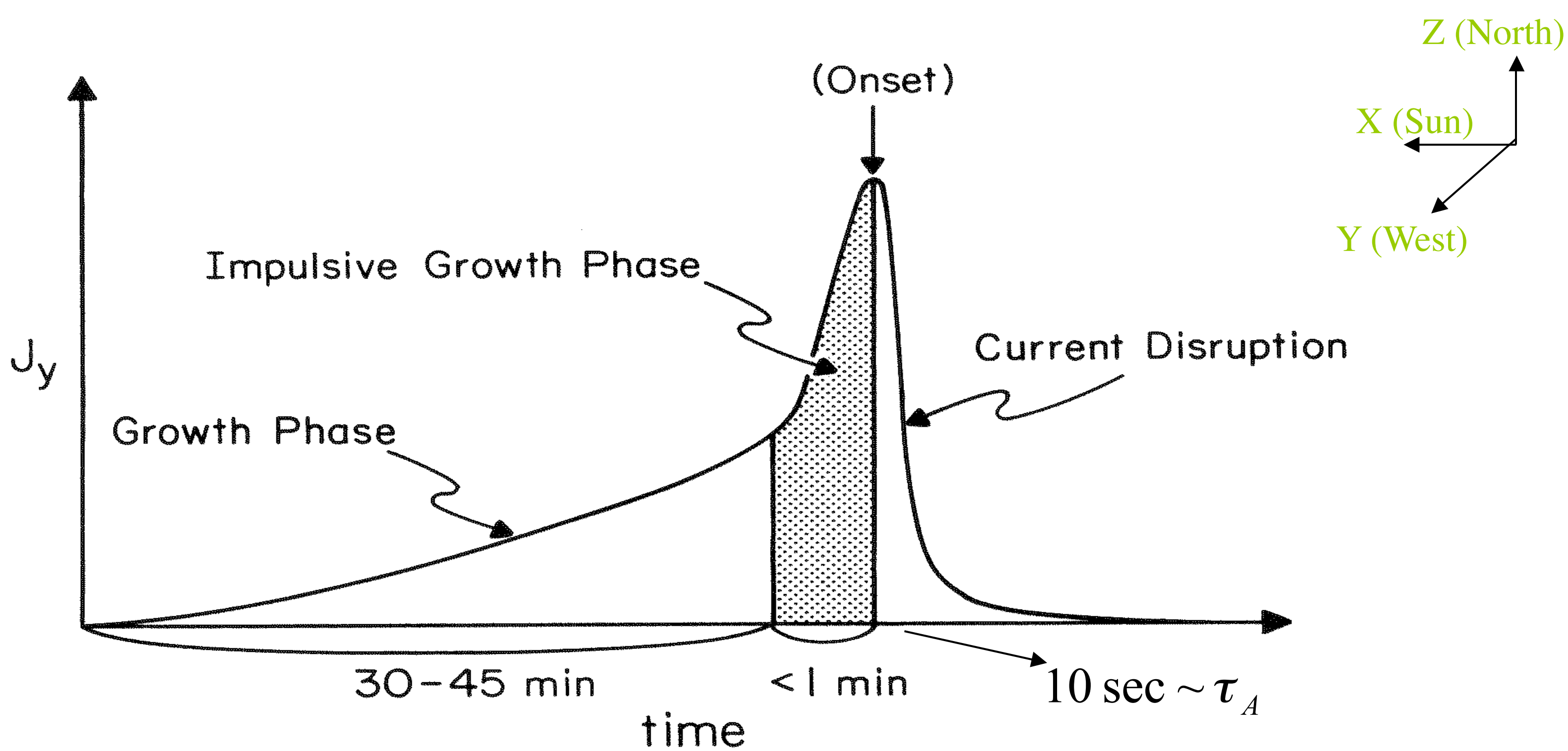
Substorm Onset:





Auroral bulge

Substorm Onset:
When does it occur?



(Ohtani et al., 1992)

Growth Expansion Recovery

Hall MHD (or Extended MHD) Model and the Generalized Ohm's Law

In high-S plasmas, when the width of the thin current sheet (Δ_η) satisfies

$\Delta_\eta < c / \omega_{pi}$ (or $\rho_s \equiv \sqrt{\beta} c / \omega_{pi}$ if there is a guide field)

"collisionless" terms in the generalized Ohm's law cannot be ignored.

Generalized Ohm's law (dimensionless form)

$$\mathbf{E} + \mathbf{v} \times \mathbf{B} = \frac{1}{S}\mathbf{J} + d_e^2 \frac{d\mathbf{J}}{dt} + \frac{d_i}{n}\left(\mathbf{J} \times \mathbf{B} - \nabla p_e\right)$$

Electron skin depth $d_e \equiv L^{-1}\left(c / \omega_{pe}\right)$

Ion skin depth $d_i \equiv L^{-1}\left(c / \omega_{pi}\right)$

Electron beta β_e

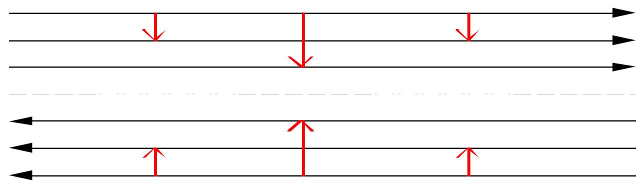
Onset of fast reconnection in large, high-Lundquist-number systems

- As the original current sheet thins down, it will inevitably reach kinetic scales, described by a generalized Ohm's law (including Hall current and electron pressure gradient).
- A criterion has emerged from Hall MHD (or two-fluid) models, and has been tested carefully in laboratory experiments (MRX at PPPL, VTF at MIT). The criterion is:

  $\delta_{SP} < d_i$ (Ma and Bhattacharjee 1996, Cassak et al. 2005) or $\delta_{SP} < \rho_s$ in the presence of a guide field (Aydemir 1992; Wang and Bhattacharjee 1993; Kleva, Drake and Waelbroeck 1995)

Forced Magnetic Reconnection Due to Inward Boundary Flows

Magnetic field



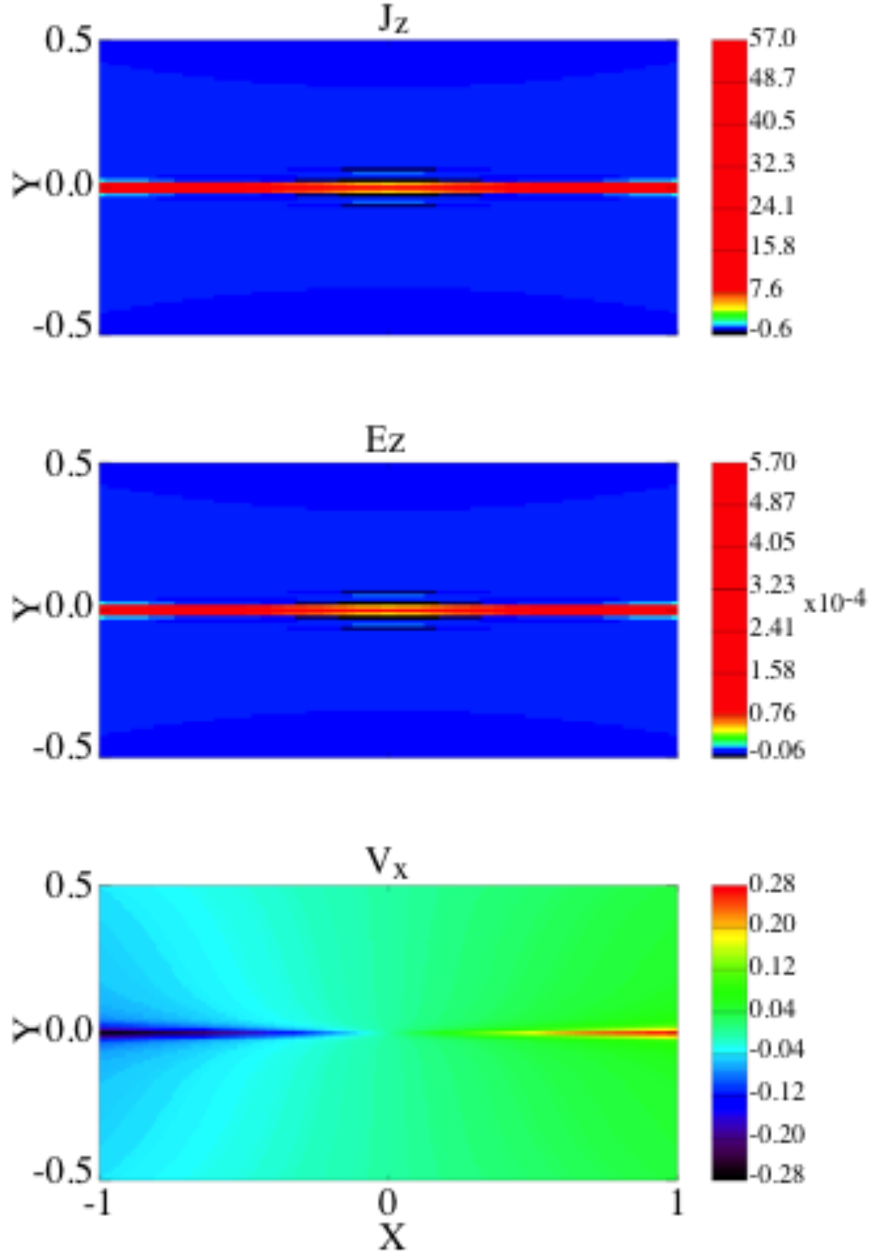
$$\mathbf{B} = \hat{\mathbf{x}} B_P \tanh z/a + \hat{\mathbf{z}} B_T$$

Inward flows at the boundaries

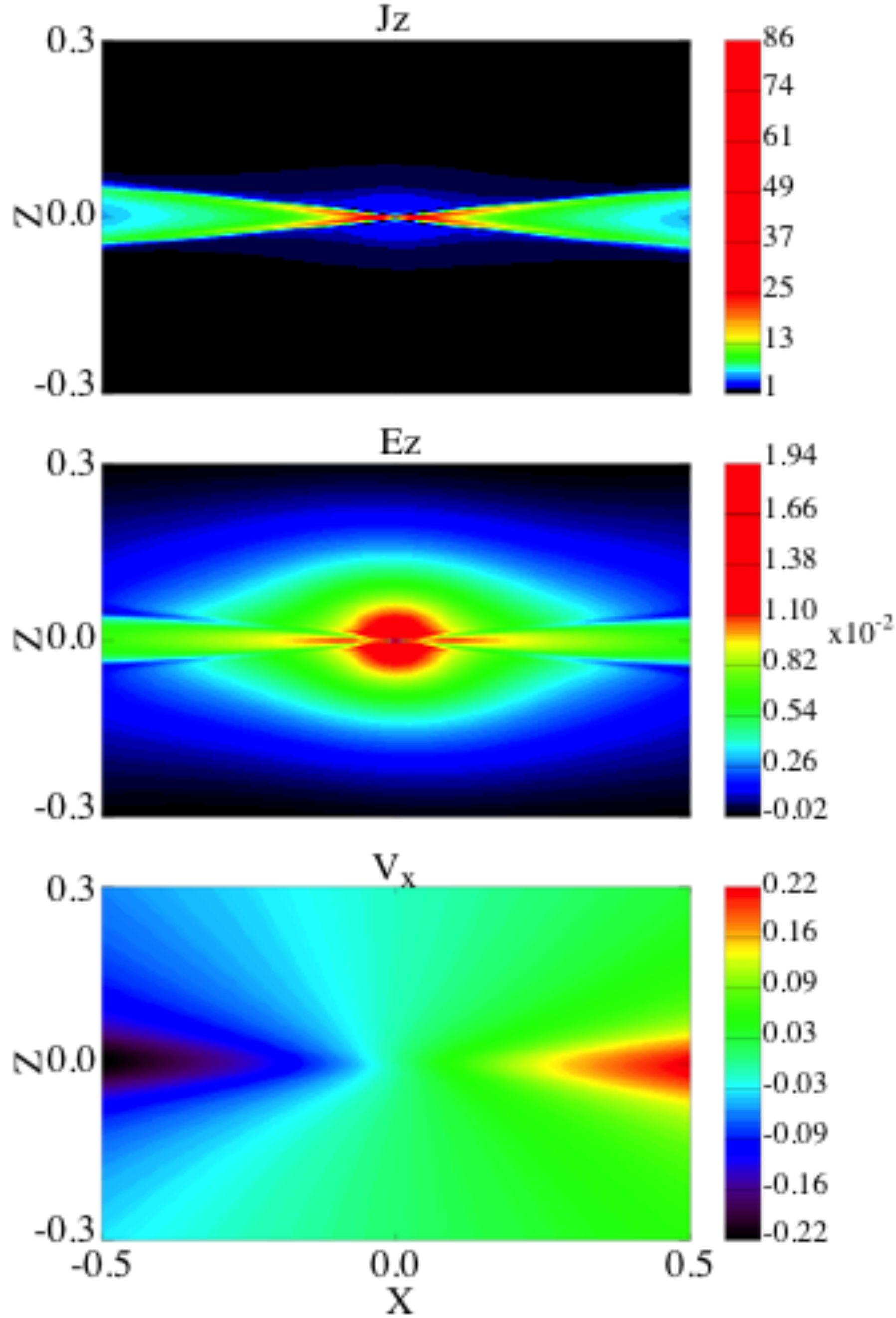
$$\mathbf{v} = \mp V_0 (1 + \cos kx)\hat{\mathbf{y}} \quad , \quad \Delta' < 0$$

Two simulations: Resistive MHD versus Hall MHD [Ma and Bhattacharjee 1996]

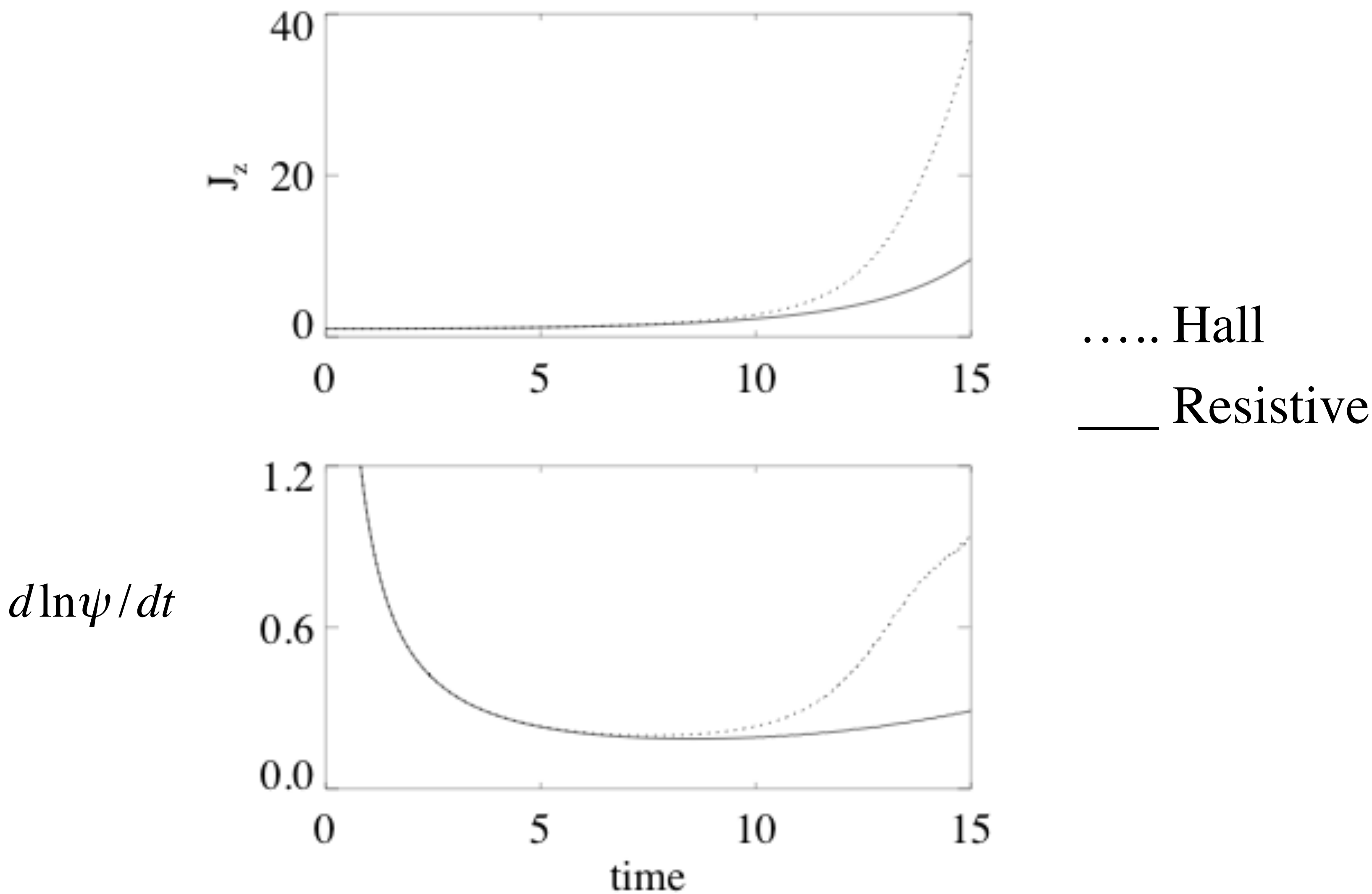
For other perspectives, with similar conclusions, see Grasso et al. (1999) Dorelli and Birn (2003), Fitzpatrick (2004), Cassak et al. (2005), Simakov and Chacon (2008), Malyshkin (2008)



J_z
0.5
Y 0.0
-0.5
57.0
48.7
40.5
32.3
24.1
15.8
7.6
-0.6
Ez
0.5
Y 0.0
-0.5
5.70
4.87
4.05
3.23
2.41
1.58
0.76
-0.06
x10-4
V_x
0.5
Y 0.0
-0.5
0.28
0.20
0.12
0.04
-0.04
-0.12
-0.20
-0.28
-1
0
1
X



Jz
0.3
Z 0.0
-0.3
86
74
61
49
37
25
13
1
Ez
0.3
Z 0.0
-0.3
1.94
1.66
1.38
1.10
0.82
0.54
0.26
-0.02
x10-2
Vx
0.3
Z 0.0
-0.3
0.22
0.16
0.09
0.03
-0.03
-0.09
-0.16
-0.22
-0.5
0.0
0.5
X



40
20
0
J_z
0
5
10
15
1.2
0.6
0.0
$d\ln\psi/dt$
time
….. Hall
___ Resistive

Transition from Collisional to Collisionless Regimes in MRX

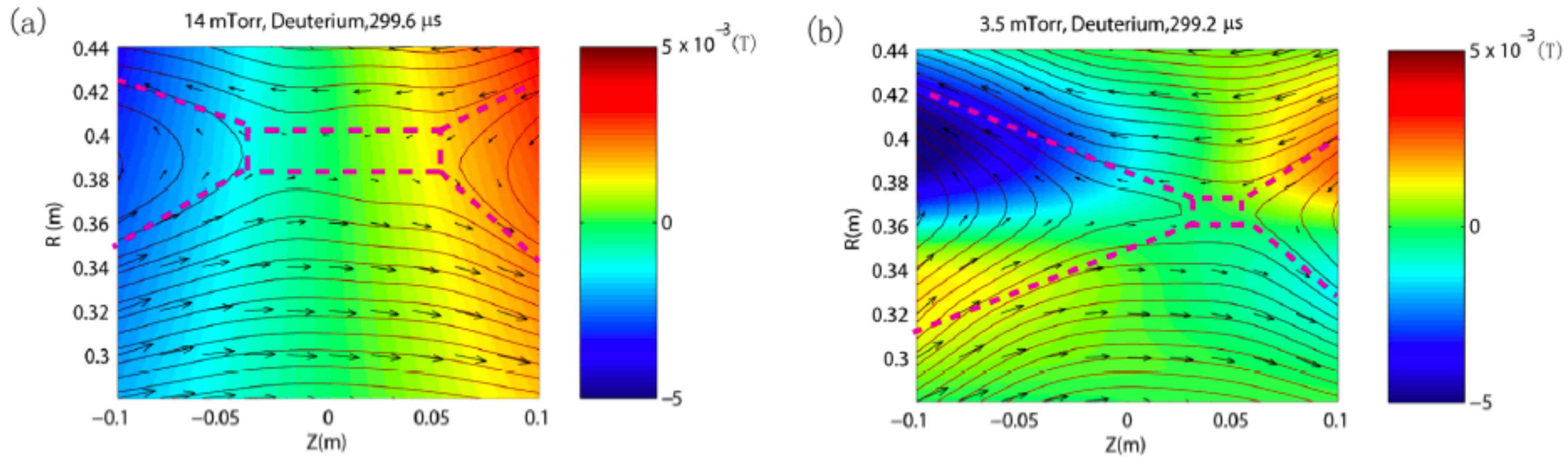
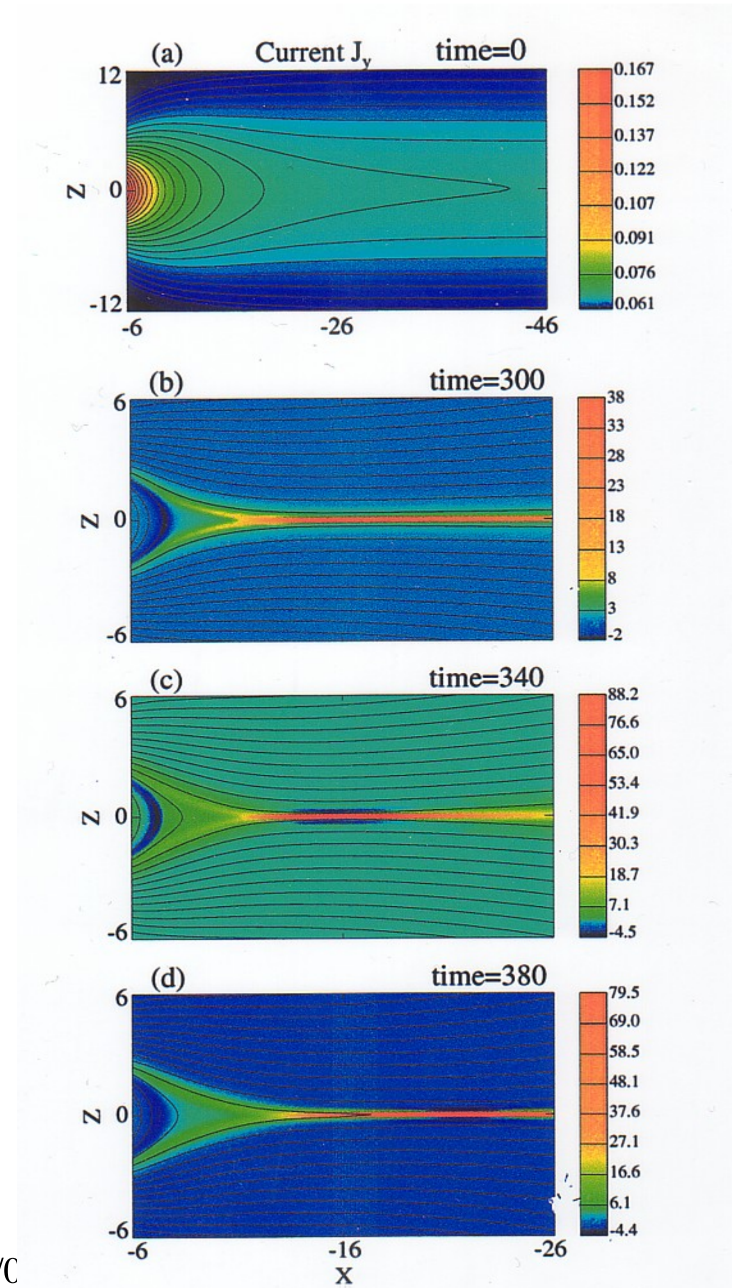
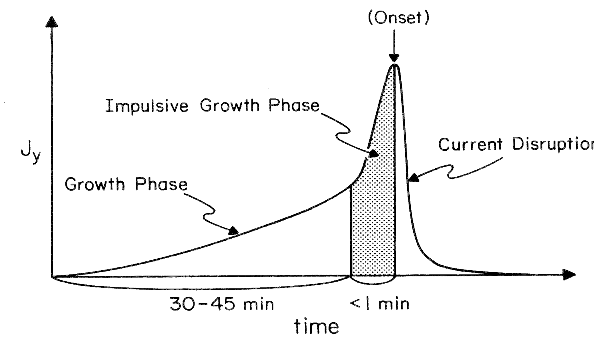
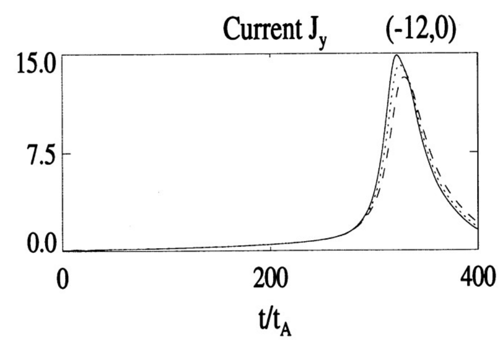


Fig.2; *Comparison of neutral sheet configuration described by measured magnetic field vectors and flux counters for high (collisional) and low density cases; (a) Collisional regime (λ_{mfp} ~1mm << δ)); (b) Nearly collisionless regime (λ_{mfp} ~1cm ~ δ). Out-of plane fields are depicted by the color codes ranged -50 G <Bt < 50 G.*







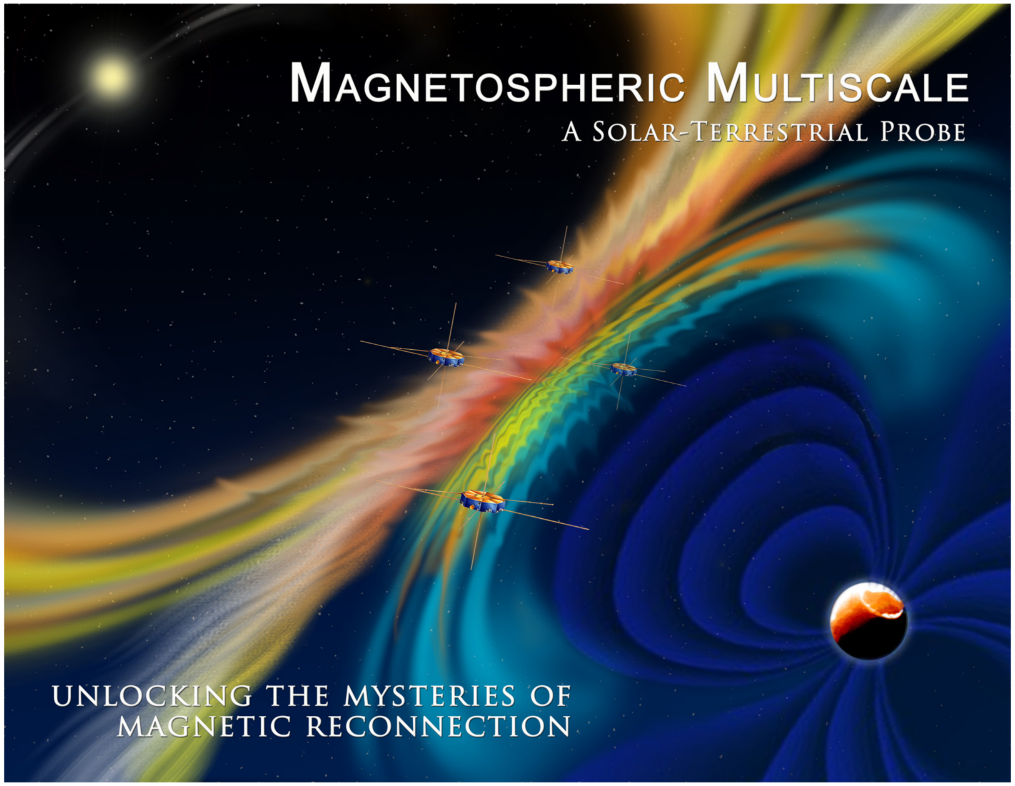
2D Hall-MHD Simulation

(Ma and Bhattacharjee, 1998)

Magnetospheric Multiscale Mission

- The MMS Mission science will be conducted by the SMART (Solving Magnetospheric Acceleration, Reconnection and Turbulence) Instrument Suite Science Team and a group of three Interdiscliplinary Science (IDS) teams.
- Launch is scheduled for October 2014.

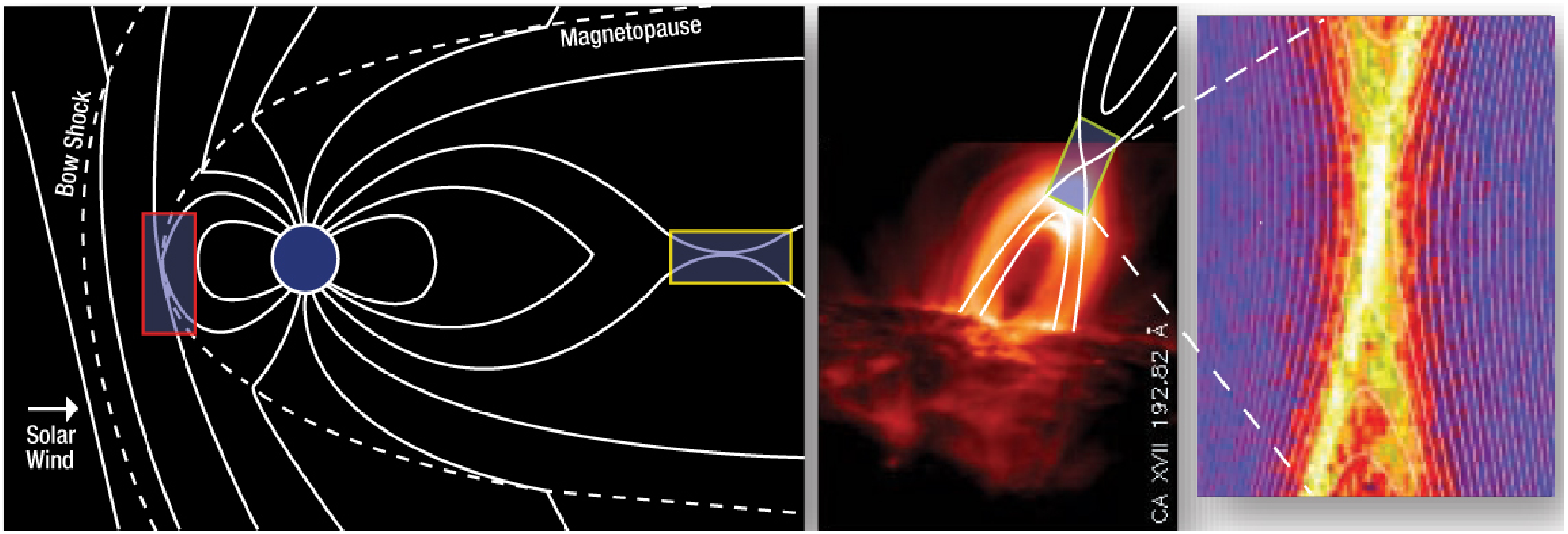
http://mms.space.swri.edu



(Courtesy: J. Burch, SWRI)

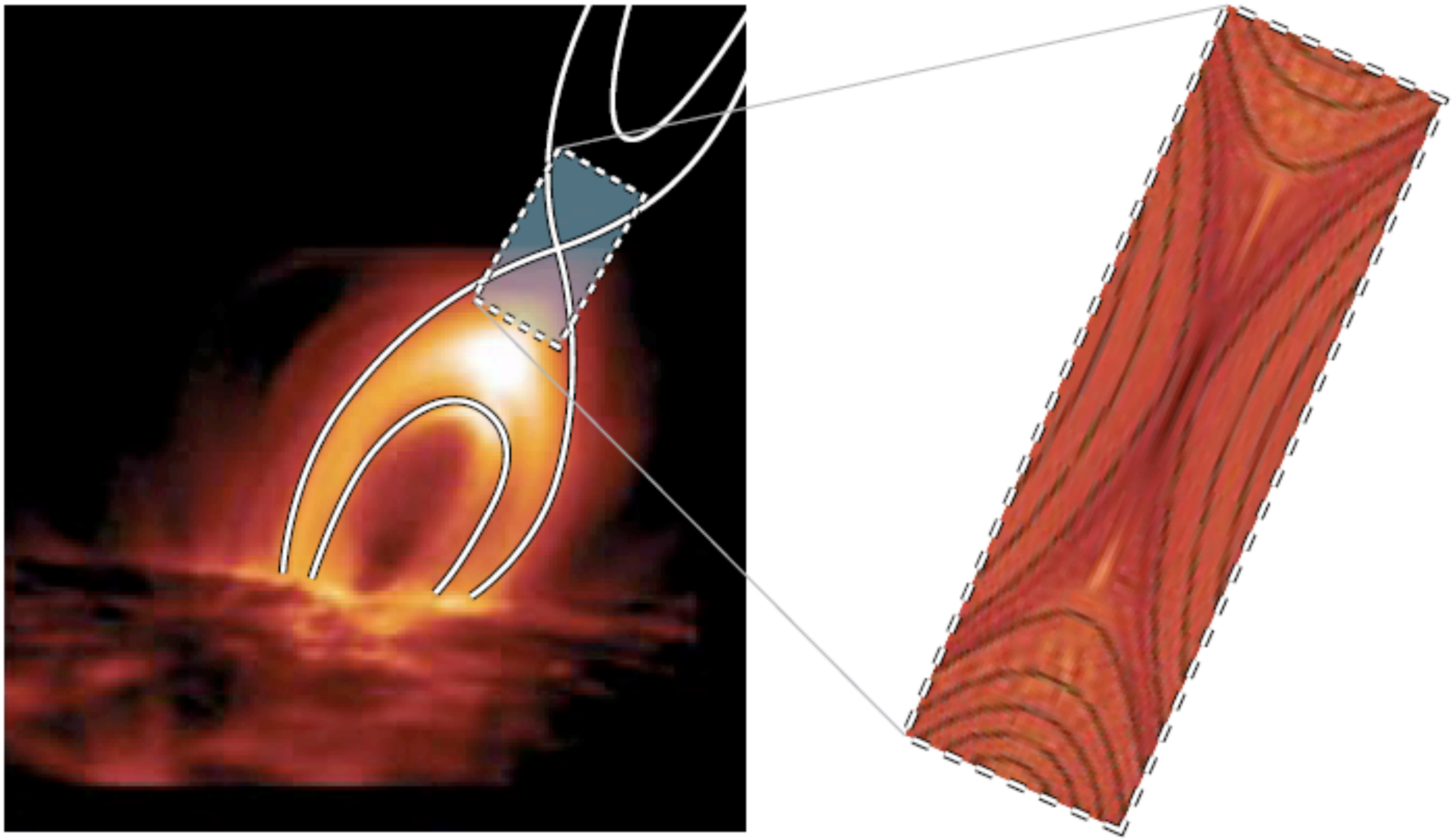
A Fundamental Universal Process

(a) (b) (c)



Magnetic reconnection is important in the (a) Earth's magnetosphere, (b) in the solar corona (solar flares and CMEs) and throughout the universe (high energy particle acceleration). Simulations (c) guide the MMS measurement strategy.

(Courtesy: J. Burch, SWRI)



Courtesy: J. Burch and J. Drake, MMS Mission

A Coronal Mass Ejection

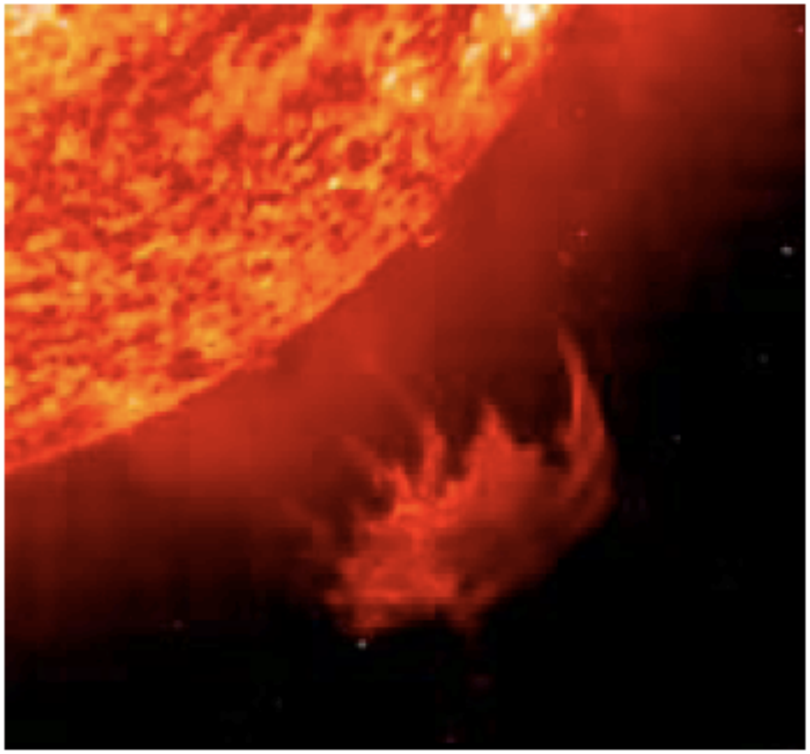
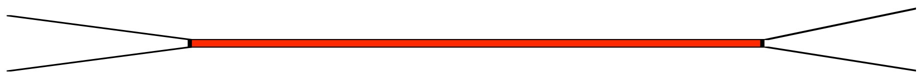


Image of a large eruption from the Sun when a large clump of solar mass is ejected into space, viewed from the satellite SOHO. On the scale of the image to the right, the Earth is the size of this blue sphere .

Image courtesy of SOHO.

Plasmoid Instability of *Large-Scale* Current Sheets

Sweet-Parker (Sweet 1958, Parker 1957)



Geometry of reconnection layer : Y-points (Syrovatsky 1971)

Length of the reconnection layer is of the order of the system size >> width Δ

Reconnection time scale

$$\tau_{SP} = \left(\tau_A \tau_R\right)^{1/2} = S^{1/2} \tau_A$$

Solar flares: $S \sim 10^{12}, \quad \tau_A \sim 1s$

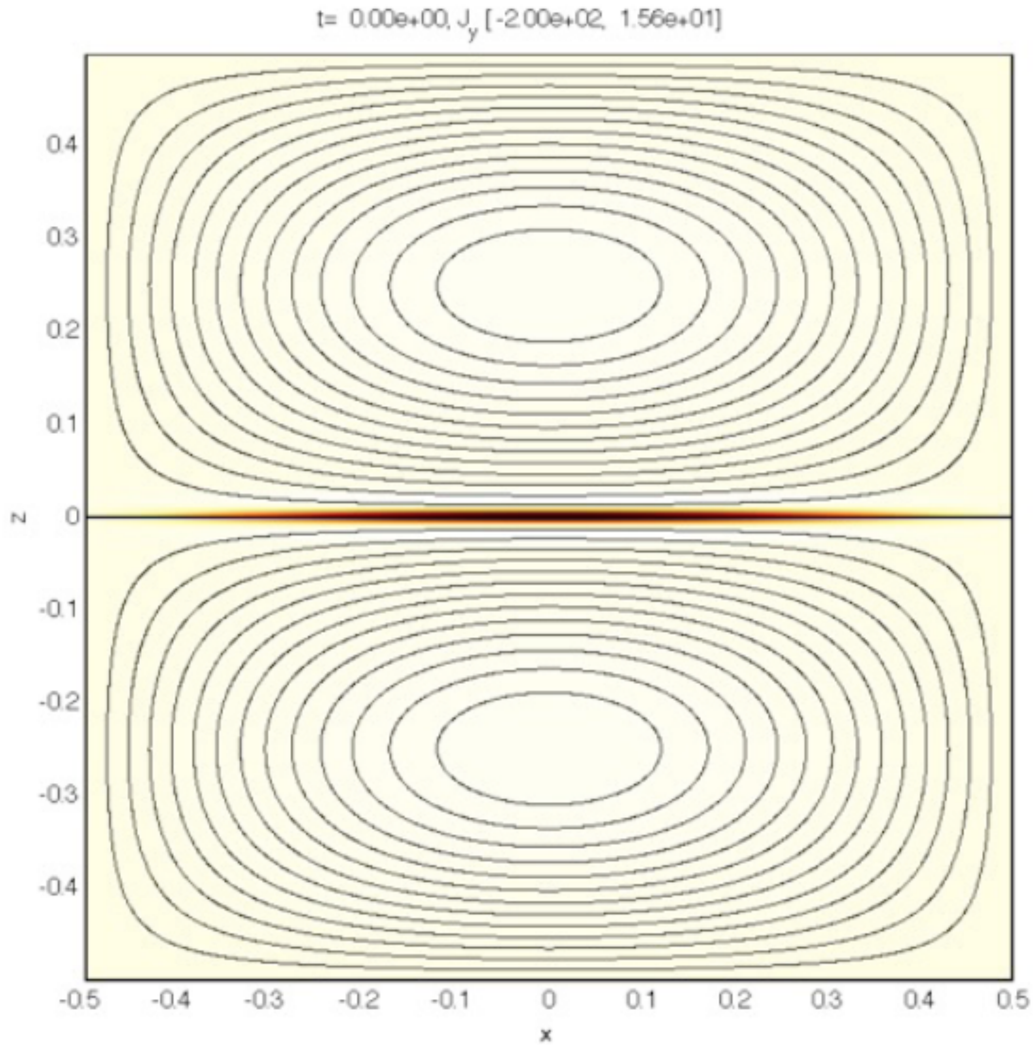
$$\Rightarrow \tau_{SP} \sim 10^6 s$$ Too long!

Fast Reconnection in Large Systems

- Extended thin current sheets of high Lundquist number are unstable to a super-Alfvenic tearing instability (Loureiro et al. 2007), which we call the "plasmoid instability," because it generates a large number of plasmoids.
- In the nonlinear regime, the reconnection rate becomes nearly independent of the Lundquist number, and is much larger than the Sweet-Parker rate.

A little history

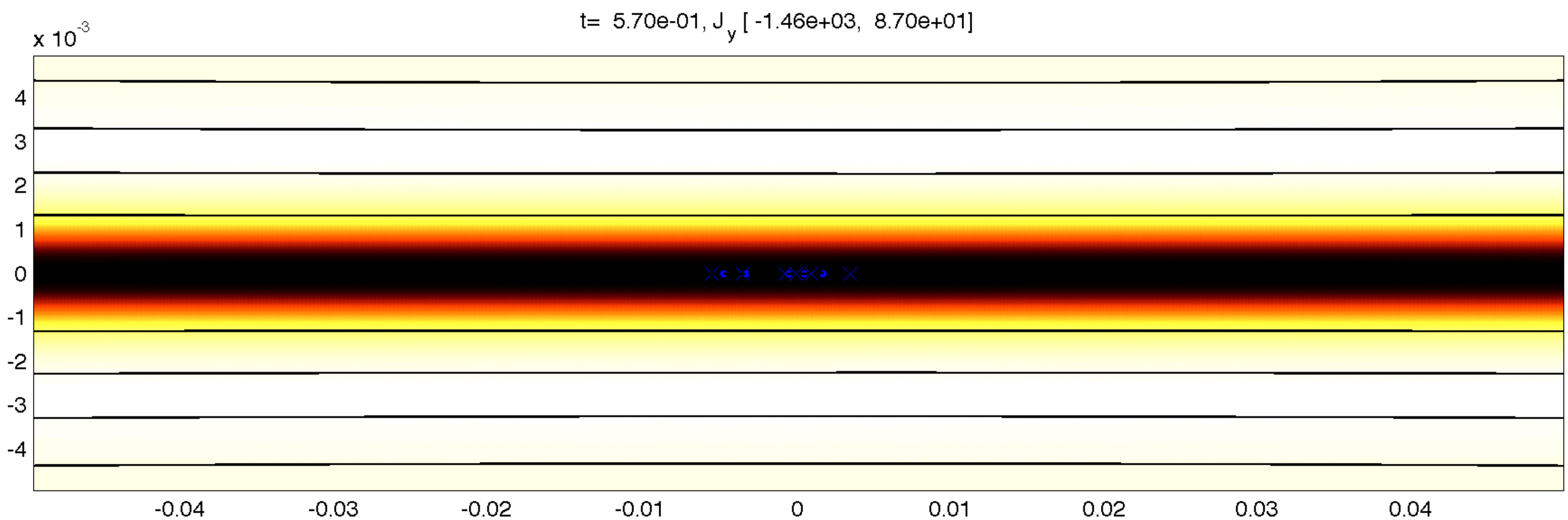
- Secondary tearing instability of high-S current sheet has been known for some time (Bulanov et al. 1979, Lee and Fu 1986, Biskamp 1986, Matthaeus and Lamkin 1986, Yan et al. 1992, Shibata and Tanuma 2001), but its precise scaling properties were determined only recently.
- The instability has been studied recently nonlinearly in fluid (Lapenta 2008, Cassak et al. 2009; Samtaney et al. 2009) as well as fully kinetic studies with a collision operator (Daughton et al. 2009).



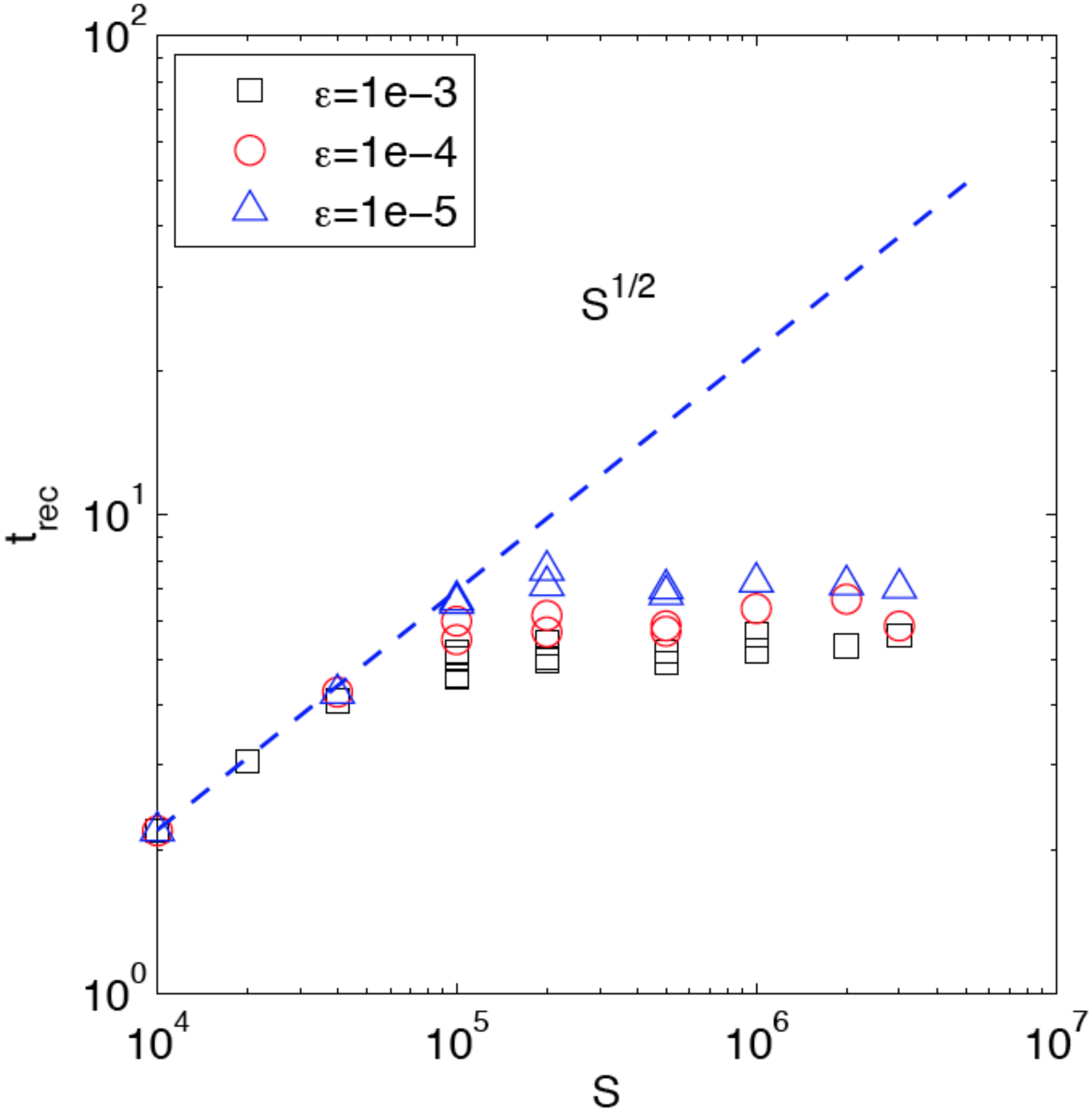
A Low Amplitude Random Forcing is Added

$$\partial_t(\rho\mathbf{v}) + \nabla\cdot(\rho\mathbf{v}\mathbf{v}) = -\nabla p - \nabla\psi\nabla^2\psi + \epsilon\mathbf{f}(\mathbf{x},t)$$

$$\langle f_i(\mathbf{x},t)f_j(\mathbf{x}',t')\rangle \sim \delta_{ij}\delta(\mathbf{x}-\mathbf{x}')\delta(t-t')$$


t= 5.70e-01, J_y [-1.46e+03, 8.70e+01]
x 10^{-3}
4
3
2
1
0
-1
-2
-3
-4
-0.04
-0.03
-0.02
-0.01
0
0.01
0.02
0.03
0.04

Reconnection Time of 25% of Initial Flux



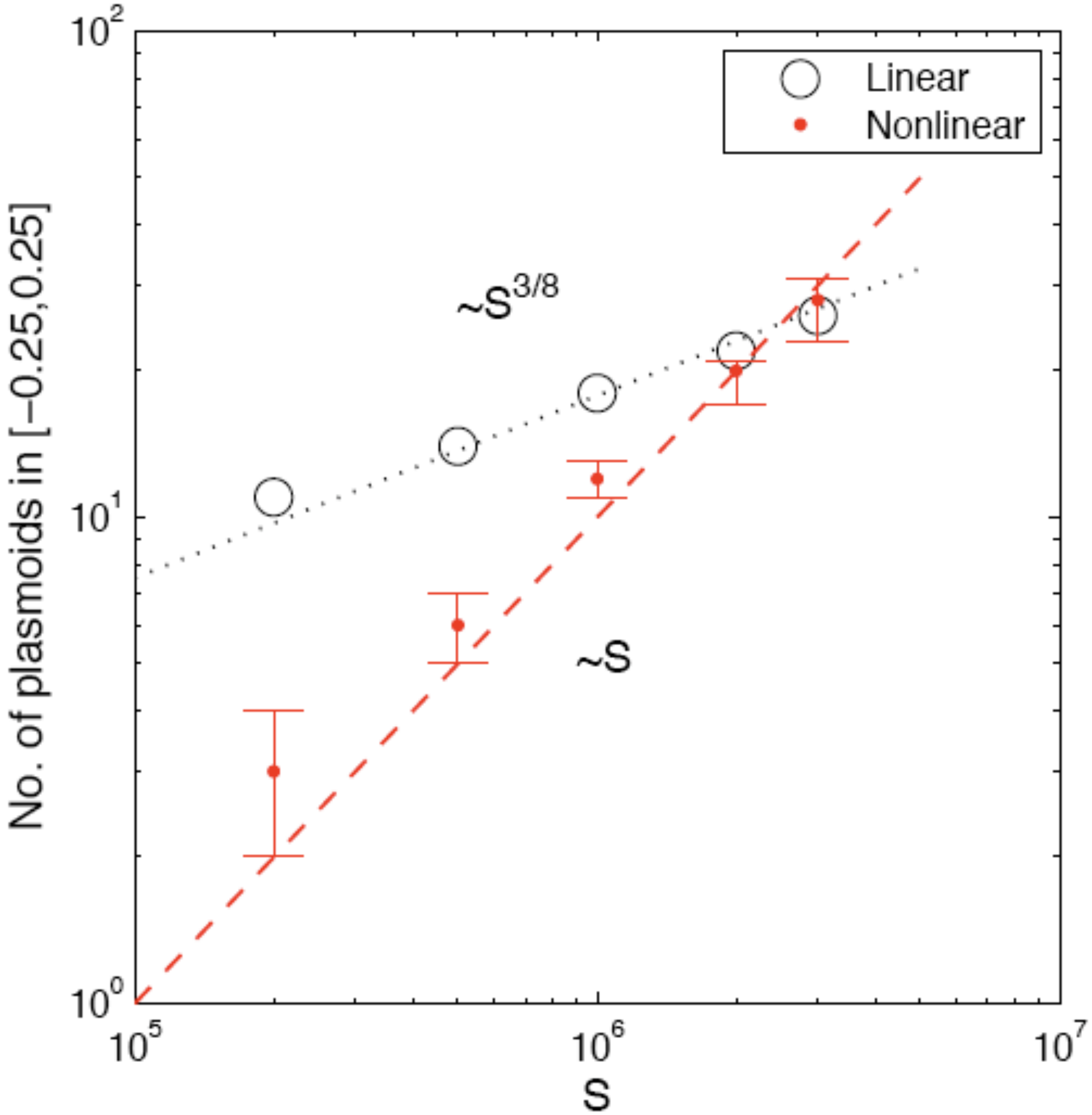
$$< \frac{1}{V_A B}\frac{d\psi}{dt} >\sim 0.01$$

$$< u_i >\sim 0.01 V_A$$

Scaling: heuristic arguments

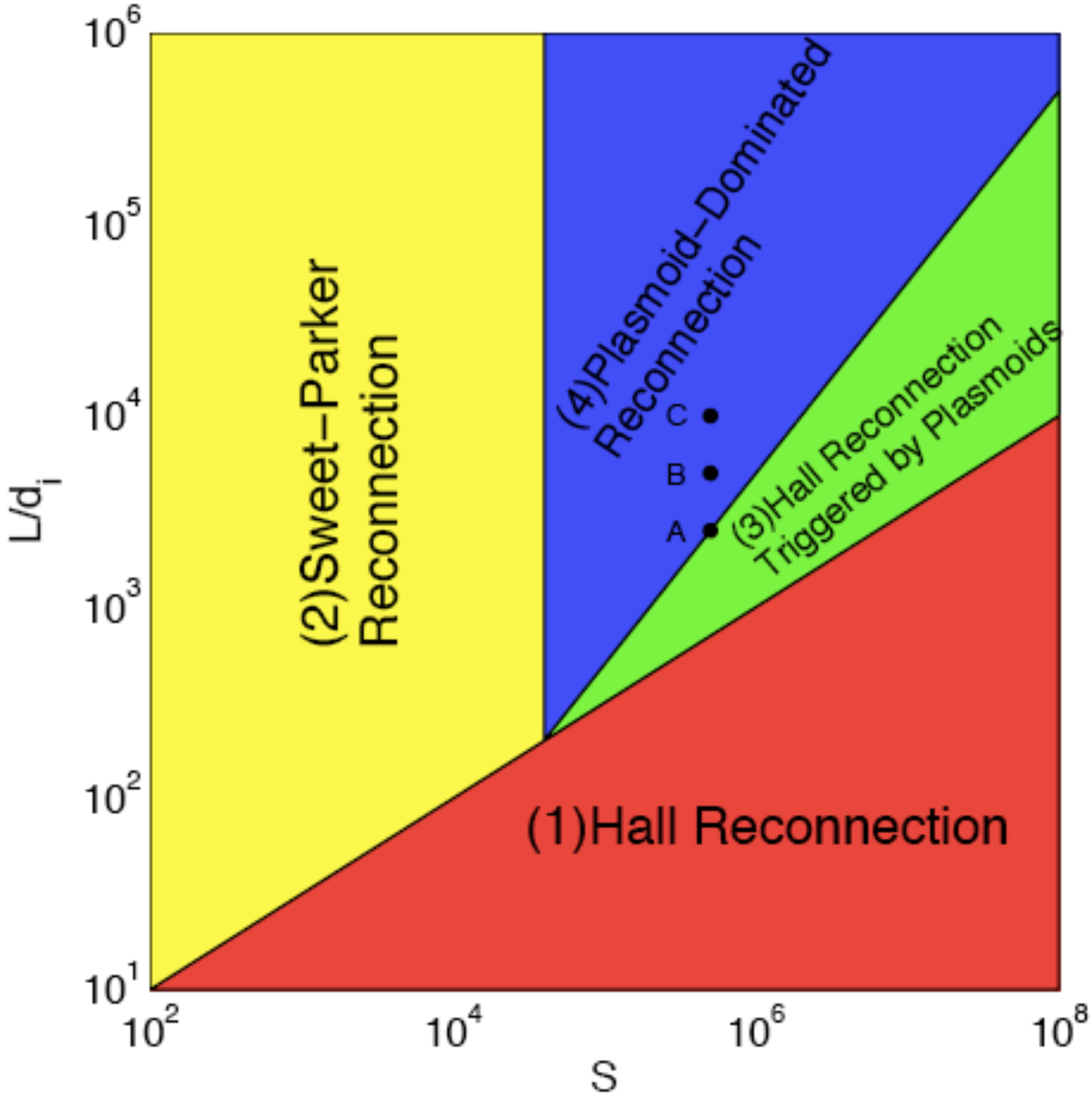
- Critical Lundquist number for instability $S = LV_A/\eta > S_c$
- Each current sheet segment undergoes a hierarchy of instabilities until it is marginally stable, i.e.,

  $L_c = S_c \eta / V_A$
- Assuming each step of the hierarchy is Sweet-Parker-like, the thickness is $\delta_c = L_c/\sqrt{S_c} = \sqrt{S_c}\eta/V_A$
- Reconnection rate, independent of resistivity ~ $V_A/\sqrt{S_c}$
- Number of plasmoids scales as $L/L_c \sim S/S_c$



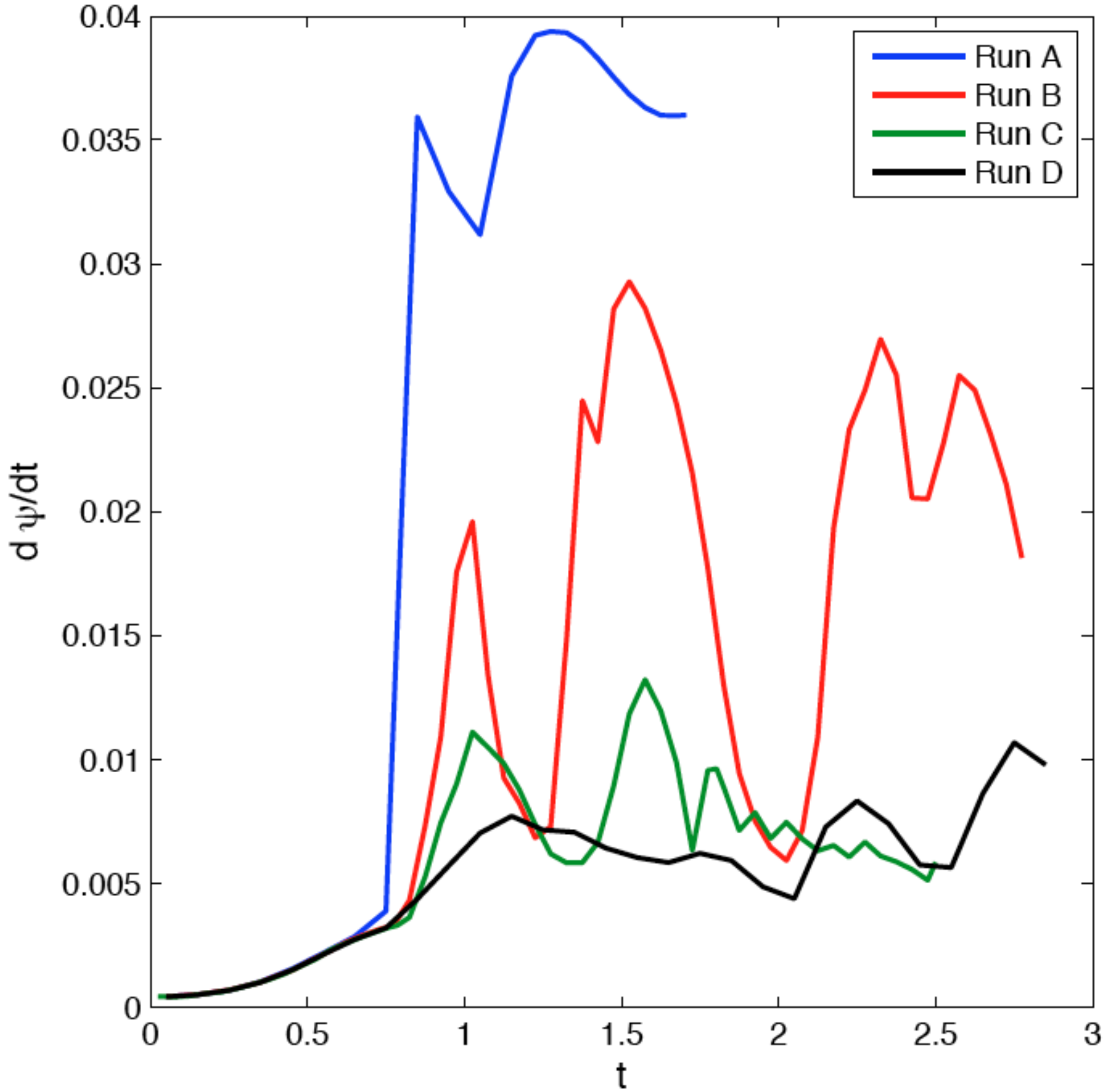
Linear
Nonlinear
~S^3/8
~S
No. of plasmoids in [−0.25,0.25]
S

Parameter Space

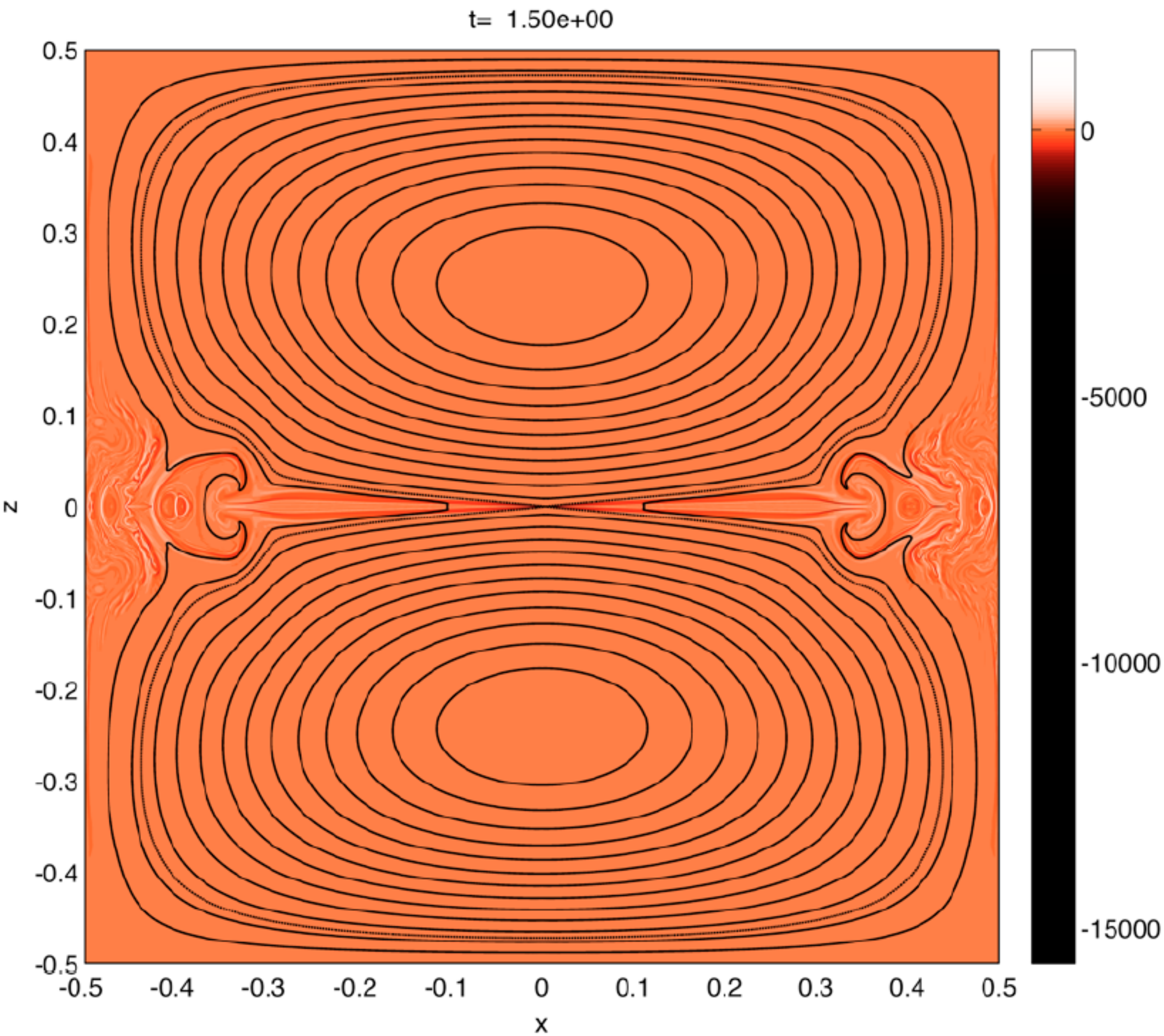


A: $S = 5 \times 10^5, d_i = 4 \times 10^{-4}$
B: $S = 5 \times 10^5, d_i = 2 \times 10^{-4}$
C: $S = 5 \times 10^5, d_i = 10^{-4}$
D: $S = 5 \times 10^5, d_i = 0$

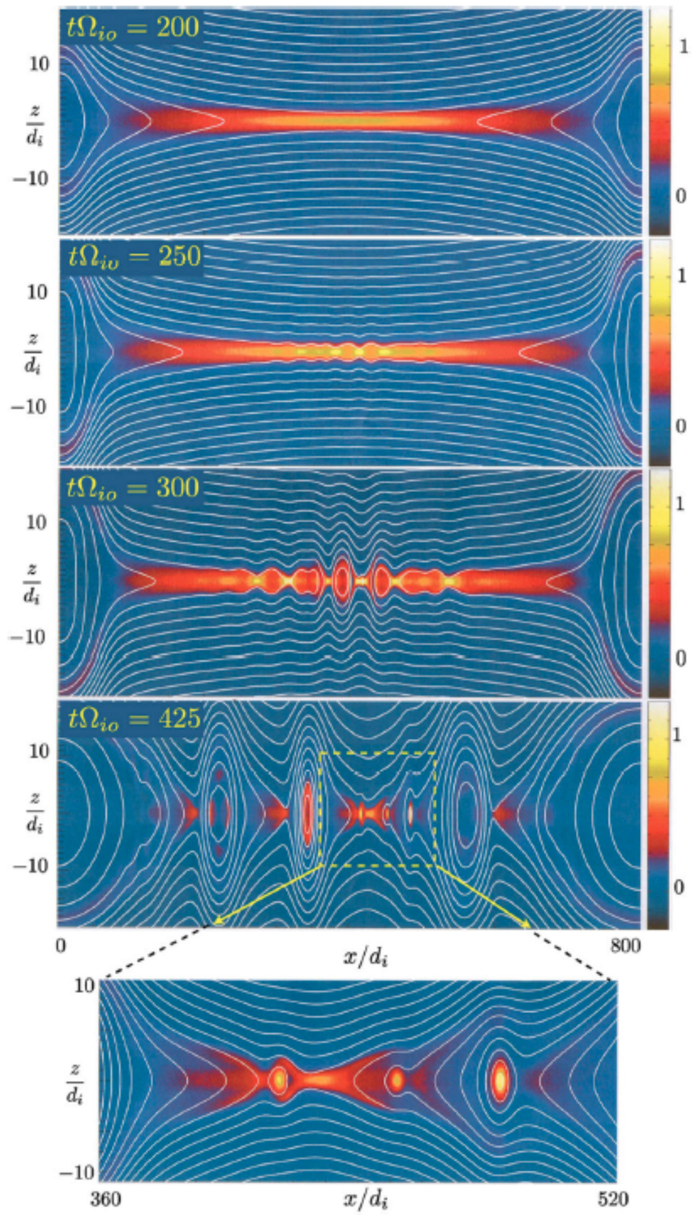
Reconnection Rate



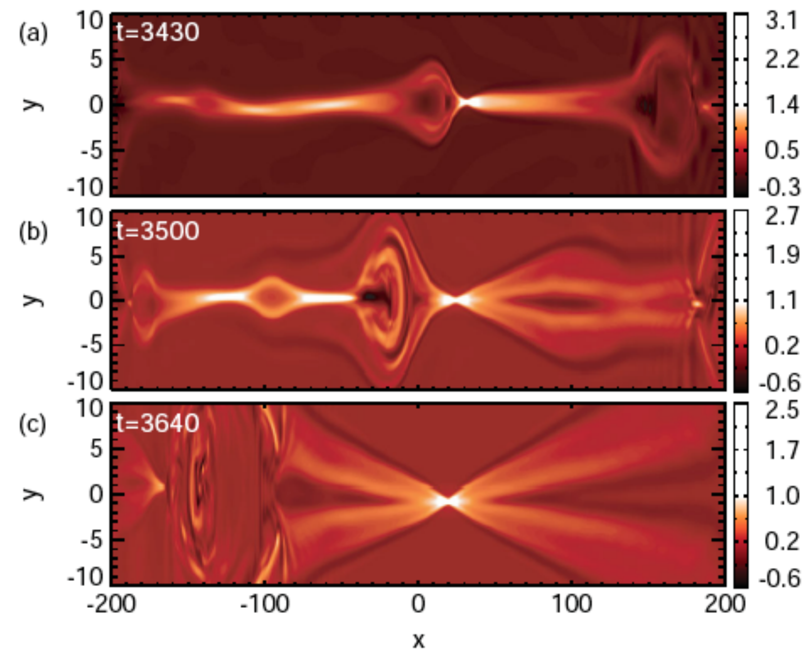
Run A, global configuration at late time



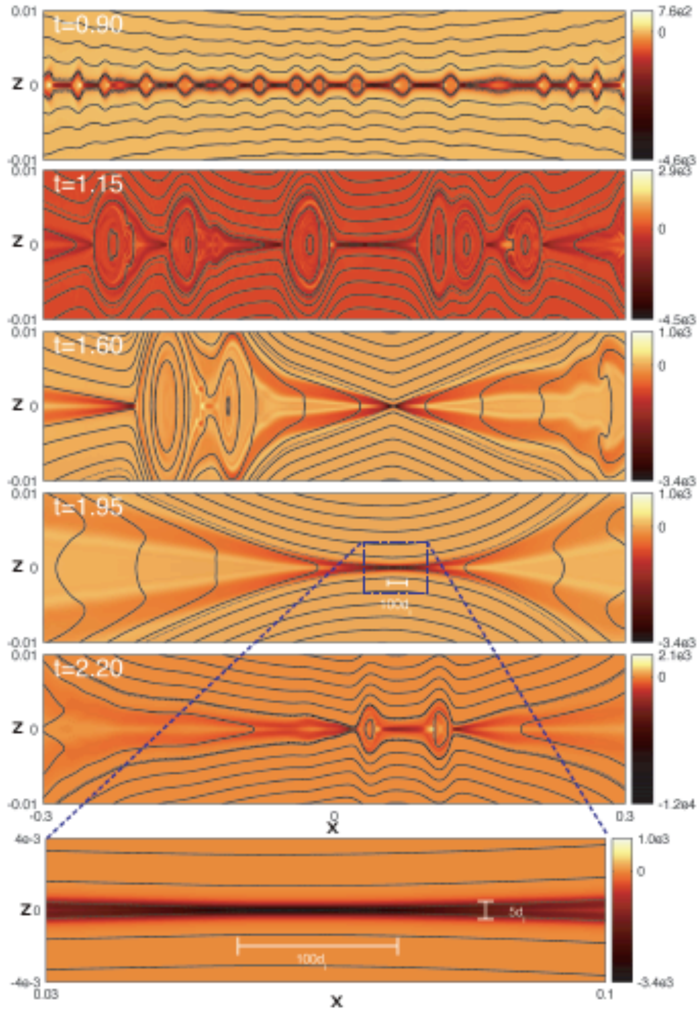
PIC and Hall MHD Simulations are Qualitatively Different



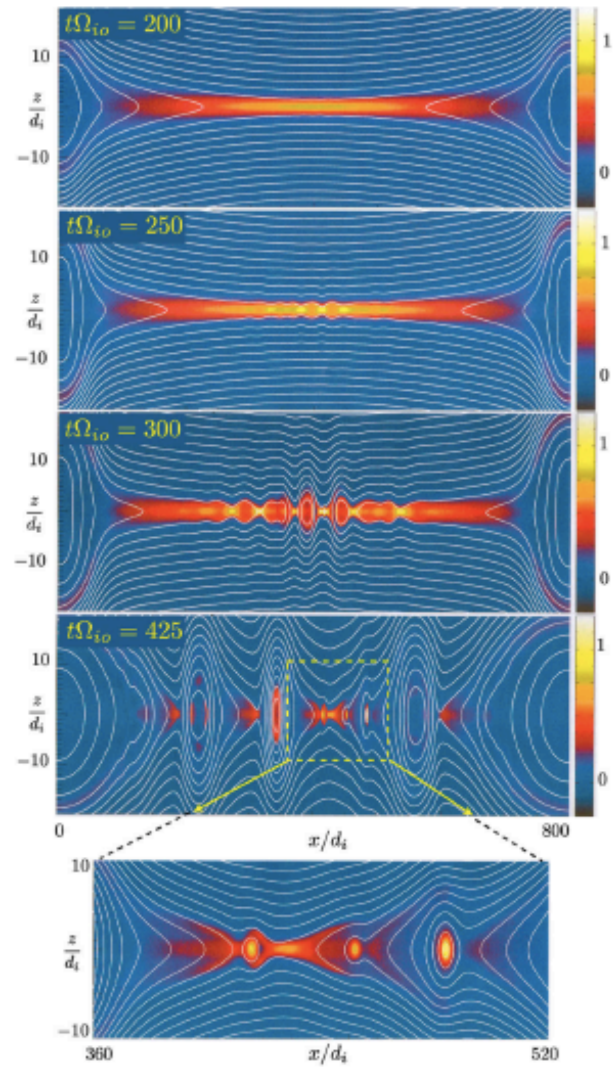
Daughton et al. (2009), PIC



Shepherd and Cassak (2010)
Resistive Hall MHD



Run B, resistive Hall

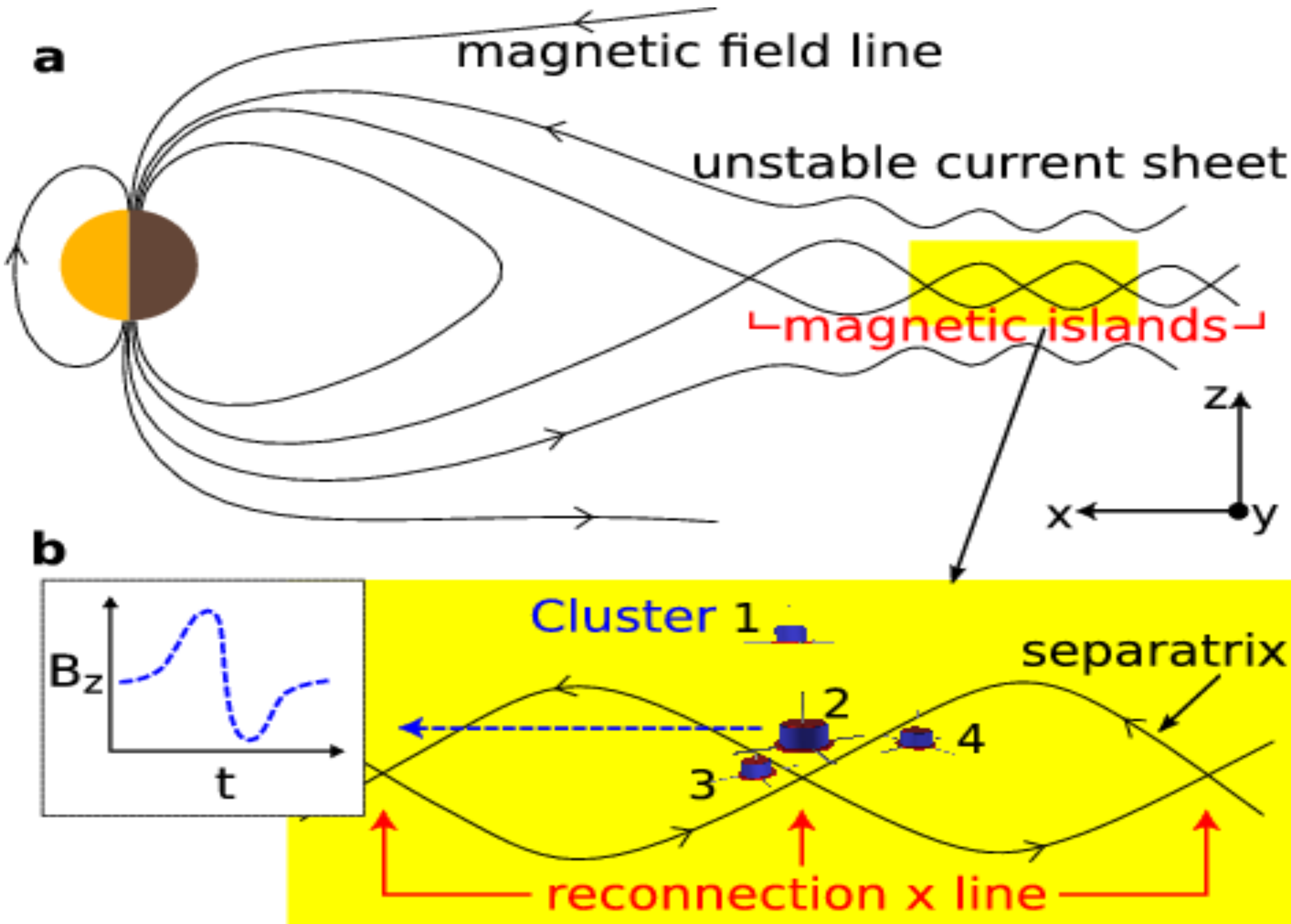


Daughton et al. (2009), PIC

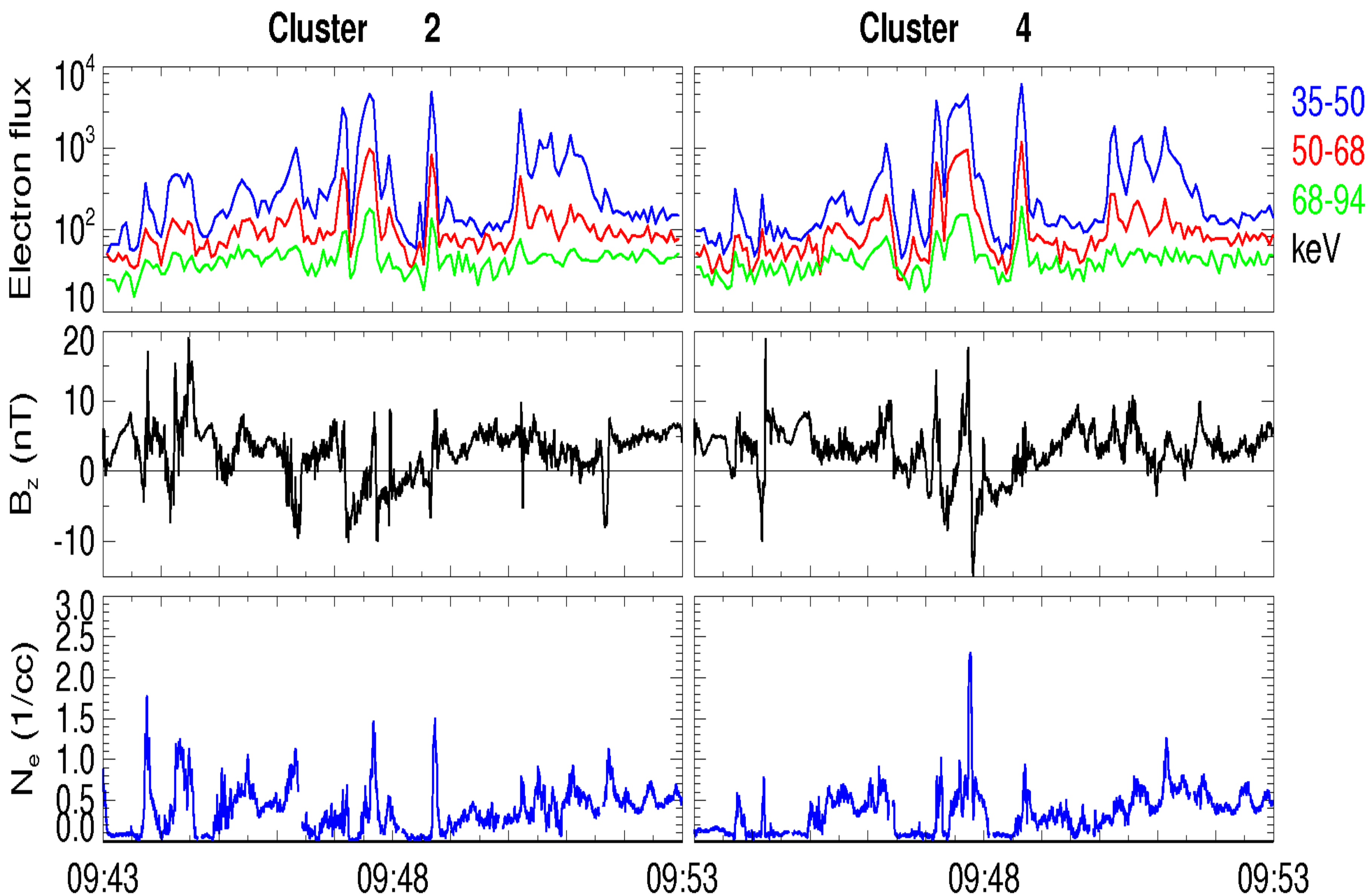
Largest 2D Hall MHD simulation to date

Observations of energetic electrons within magnetic islands

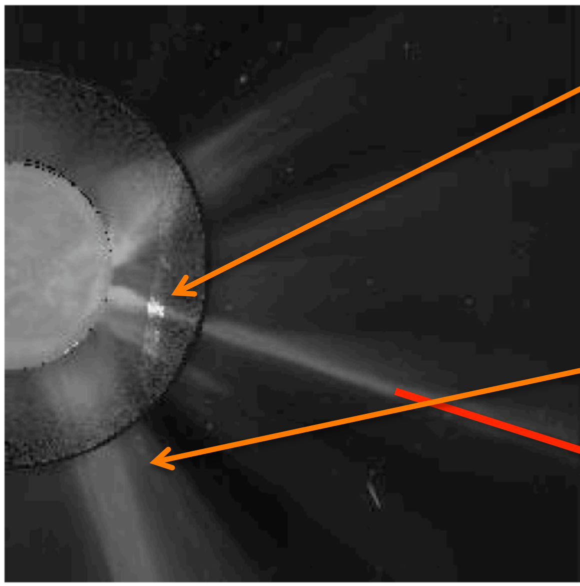
[Chen et al., Nature Phys., 2008, PoP 2009]



e bursts & bipolar Bz & Ne peaks
~10 islands within 10 minutes



Vertically-extended current sheets?

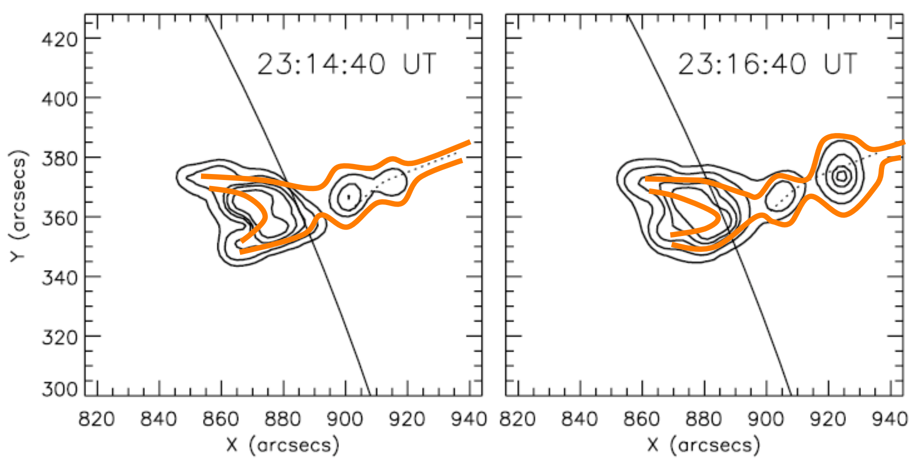


Fe XVII emission -> hot, turbulent, narrow, bright structure.

Extended post-CME current sheet?

Departed CME, plus several plasmoids

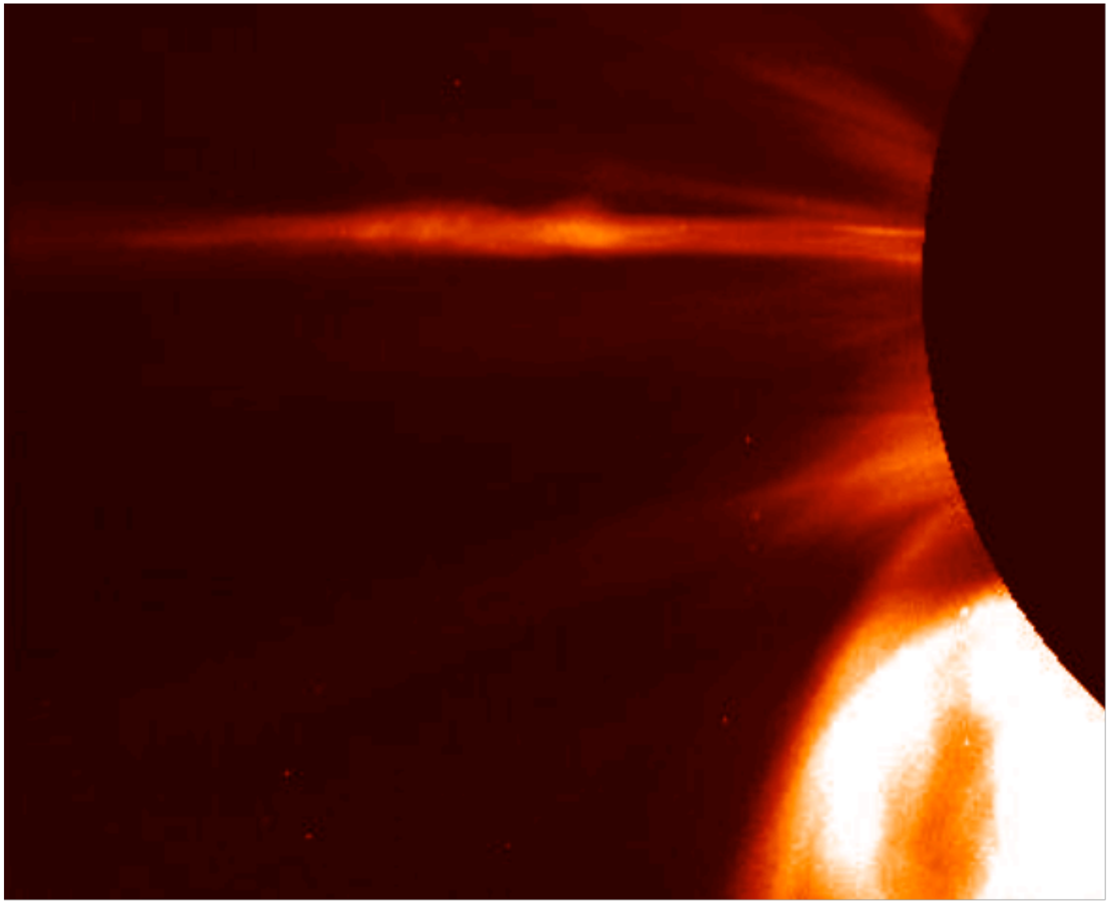
Ciaravella & Raymond 2008



Closer to the Sun - HXR evidence for extended flare current sheet, but with multiple plasmoids – tearing instability?

Sui et al (2005)

Post CME Current Sheet



Courtesy: Lijia Guo

Summary

Onset of fast reconnection, mediated by the dynamics of thin current sheets, in high-Lundquist-number laboratory and space plasmas. Two mechanisms:

- Hall MHD, seen in theory and laboratory experiments of *moderate size*, when the Sweet-Parker width falls below the ion skin depth.
- Fast plasmoid instability of thin current sheets in *large systems*, substantially exceeding Sweet-Parker rates within the realm of resistive MHD, without invoking Hall current and/or electron pressure tensor effects, or 2D/3D turbulence (Matthaeus and Lamkin 1986, Loureiro et al. 2009, Lazarian and Vishniac 1999, Kowal et al. 2009). The peak reconnection rate ~ $0.01V_{A.}$

Summary (continued)

- Hall MHD effects can enhance the peak reconnection rate an order of magnitude higher ~0 $.1V_A$.
- Hall MHD does not inevitably produce a single X-point. In an intermediate regime of fast reconnection, the system can alternate between a single X-point state and a state with multiple X-points produced by the plasmoid instability.
- In geometries such as the tokamak or the Earth's magnetotail, secondary ballooning instabilities can also halt or quench reconnecting instabilities. In these cases, the further evolution of the system may be controlled by ideal instabilities.
- 3D evolution of such systems, especially in the presence of line-tied magnetic fields, is a subject of great future interest.

Magnetic Reconnection: Sisyphus of the Plasma Universe

Titian, 1549

"The struggle itself …is enough to fill a man's heart. One must imagine Sisyphus happy."
---Albert Camus in *The Myth of Sisyphus (Le Myth de Sisyphe, 1942)*