Study of Magnetic Reconnection in Laboratory Experiments

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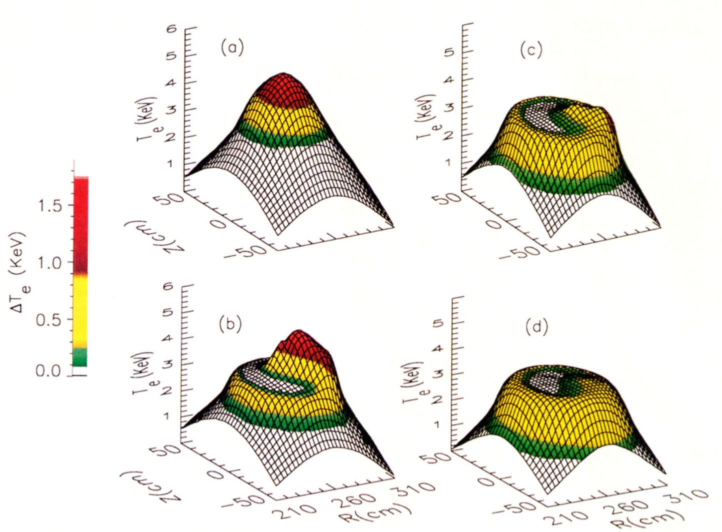
Magnetic Reconnection As A Plasma Physics Problem

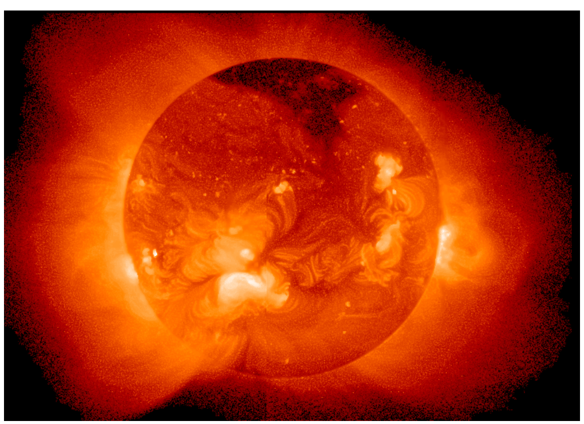
- Strongly nonlinear, therefore interesting
  - Singularity
- Ubiquitous, therefore fundamental
  - Fusion, space, solar, and astrophysical plasmas
- All aspects of plasma physics (multi-scale and multi-physics)
  - MHD, kinetic, anything within, and anything between
- Difficult, but rapid progress in recent years
  - Modern technologies and powerful simulations

Magnetic Reconnection Occurs in Nearly All Natural and Fusion Plasmas

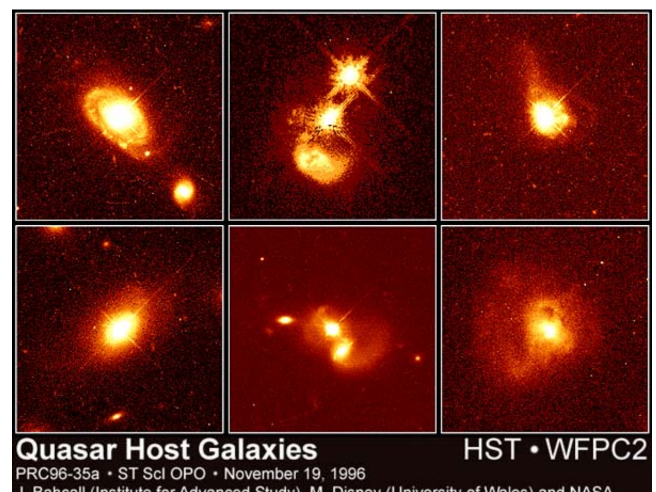


Laboratory fusion plasmas

Magnetospheric plasma

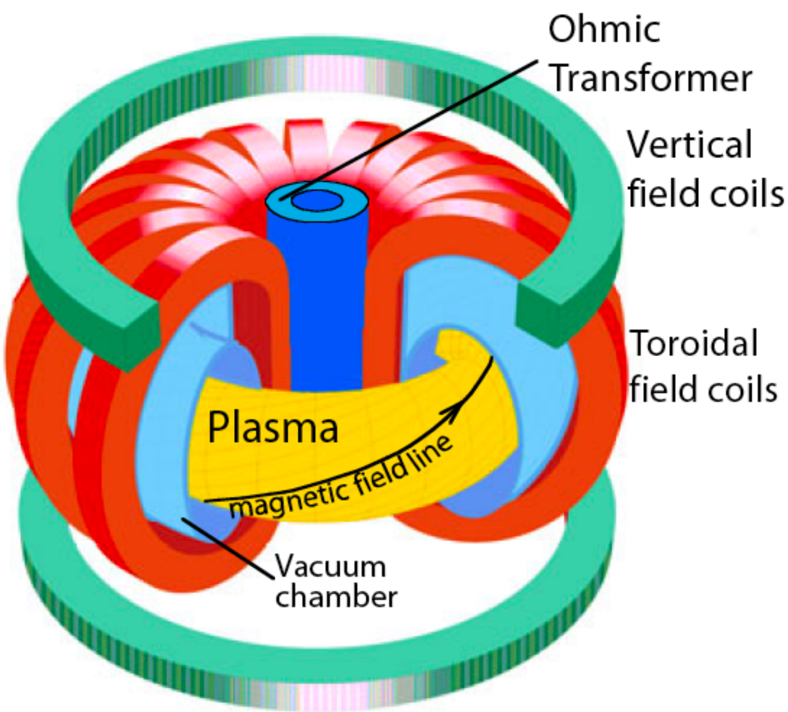


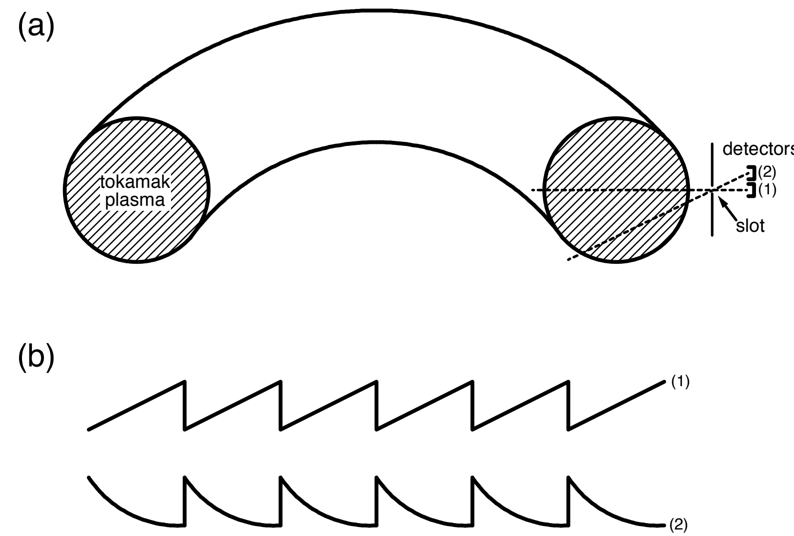
Solar plasma

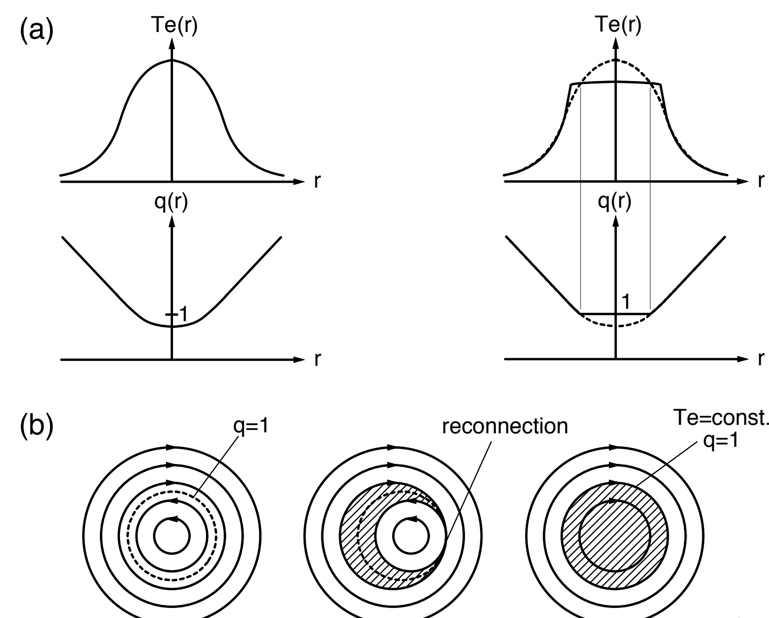


More distant astrophysical plasmas

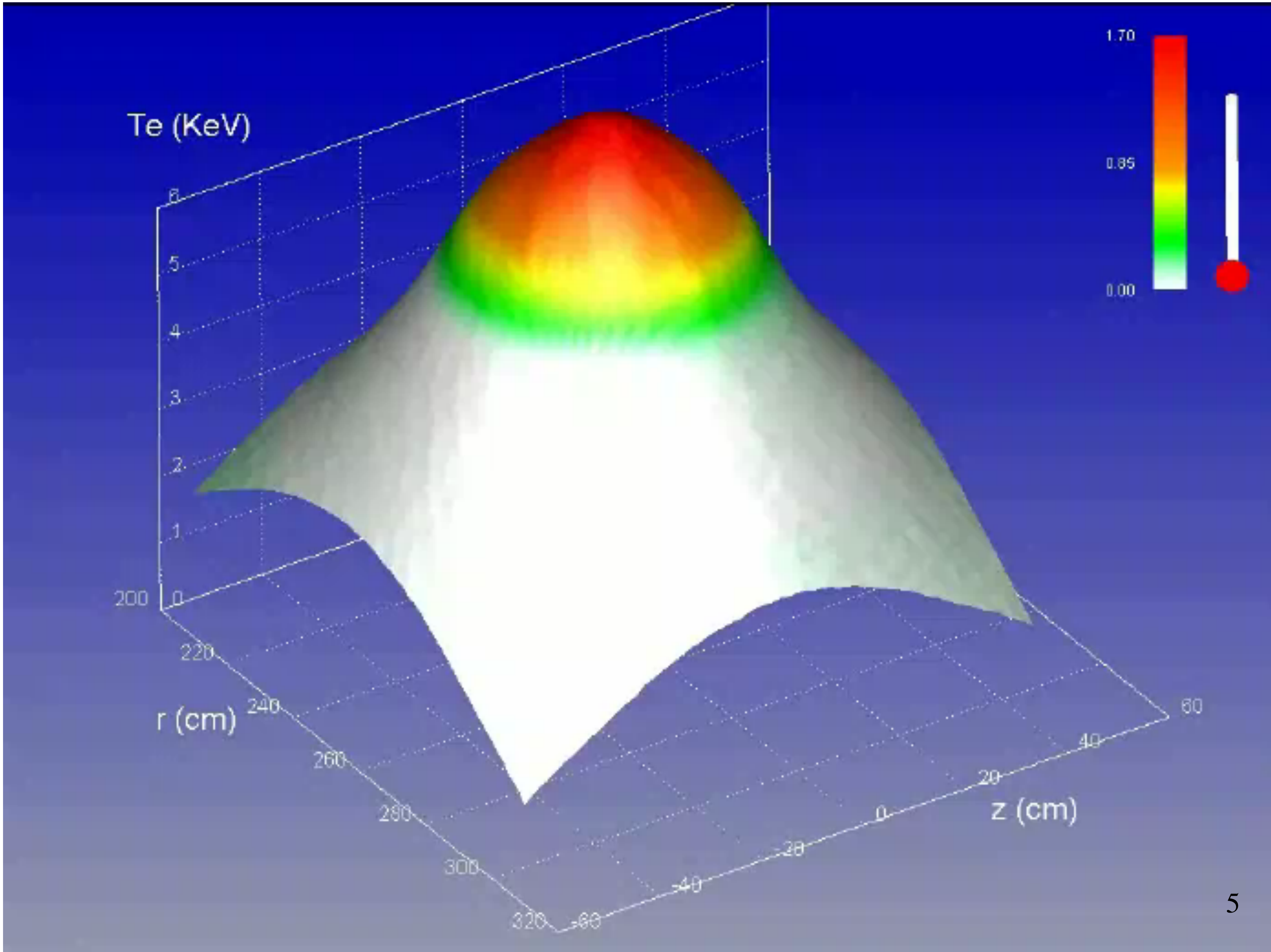
“Sawtooth Oscillation” in Tokamaks





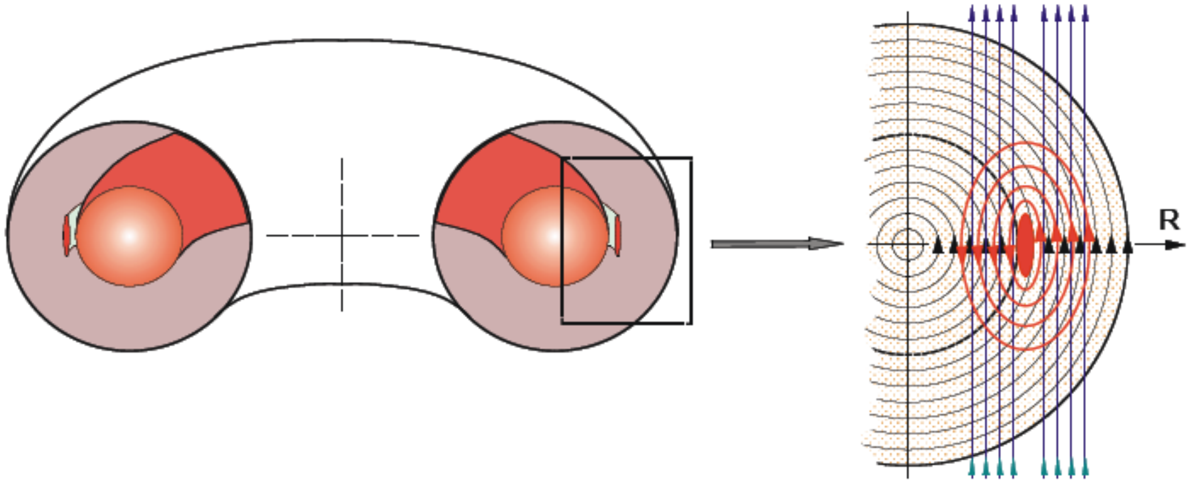


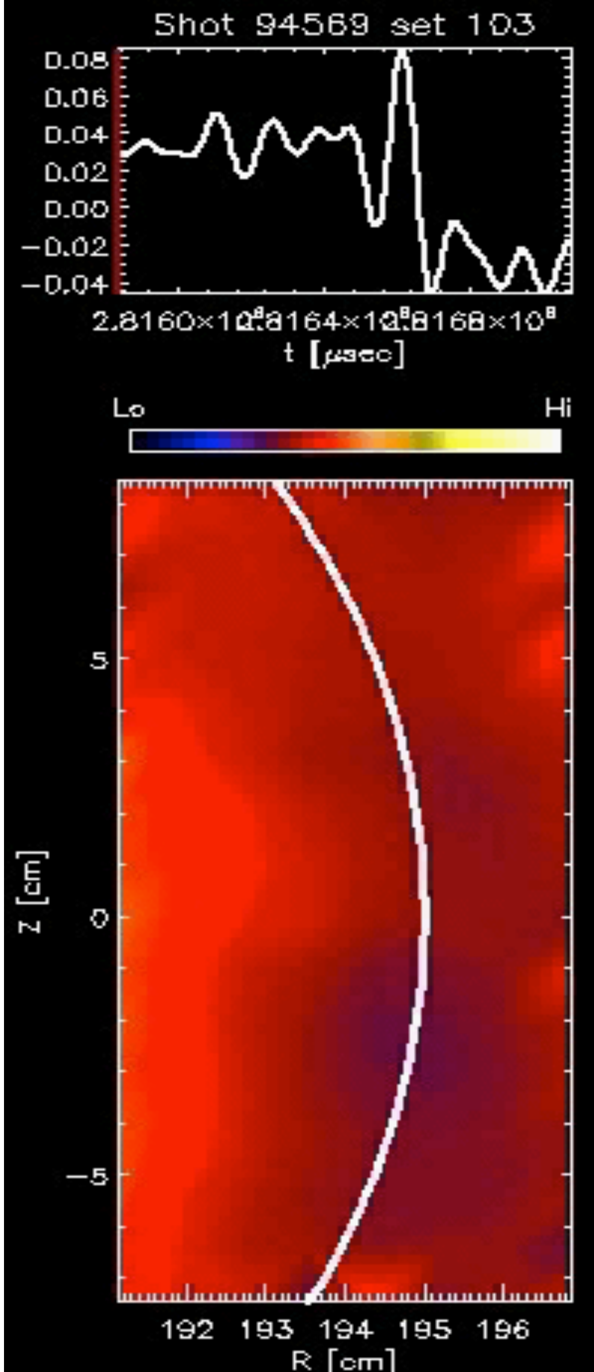
Tokamak Sawtooth Oscillations (TFTR)



2-D T_e profiles by ECE (electron cyclotron emission) measurements, **representing magnetic fluxes**

ΔT/T =>



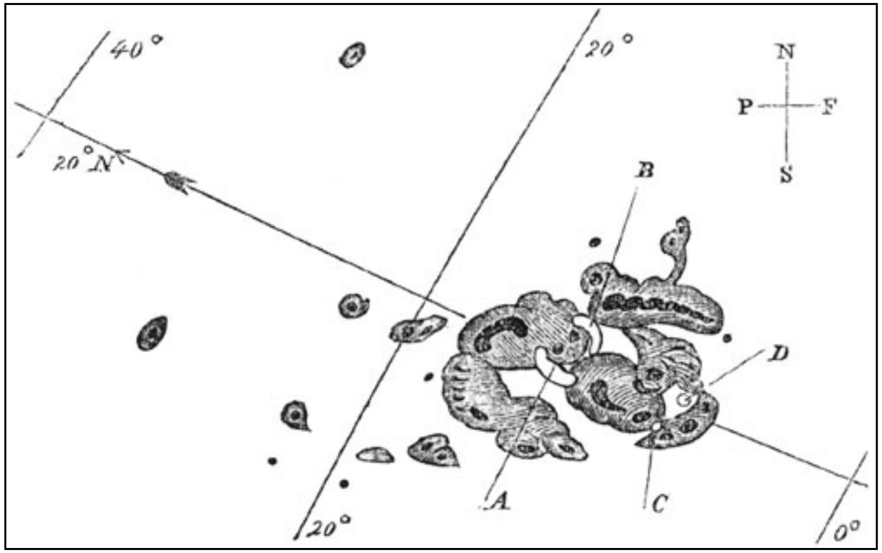


H. Park et al. (2006)

Carrington flare
(1859, Sep 1, am 11:18）

- Observed by Richard Carrington and Richard Hodgson (England)
  - White flare for 5 minutes
  - Very bright aurora appeared next day at many places on Earth, e.g. Cuba, the Bahamas, Jamaica, El Salvador, and Hawaii.

- Largest magnetic storm (>1000 nT) in recent 200 yrs.



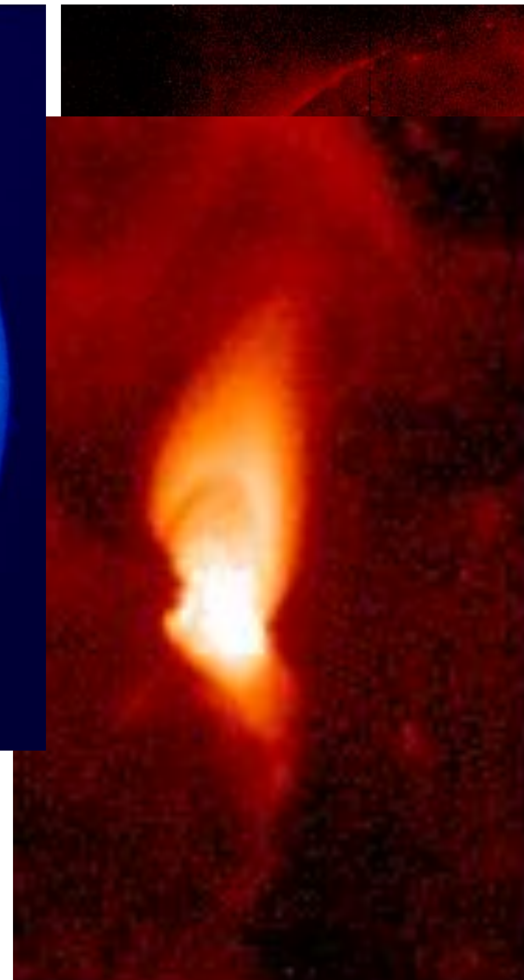
Telegraph systems all over Europe and North America failed, in some cases even shocking telegraph operators. Telegraph pylons threw sparks and telegraph paper spontaneously caught Fire (Loomis 1861)

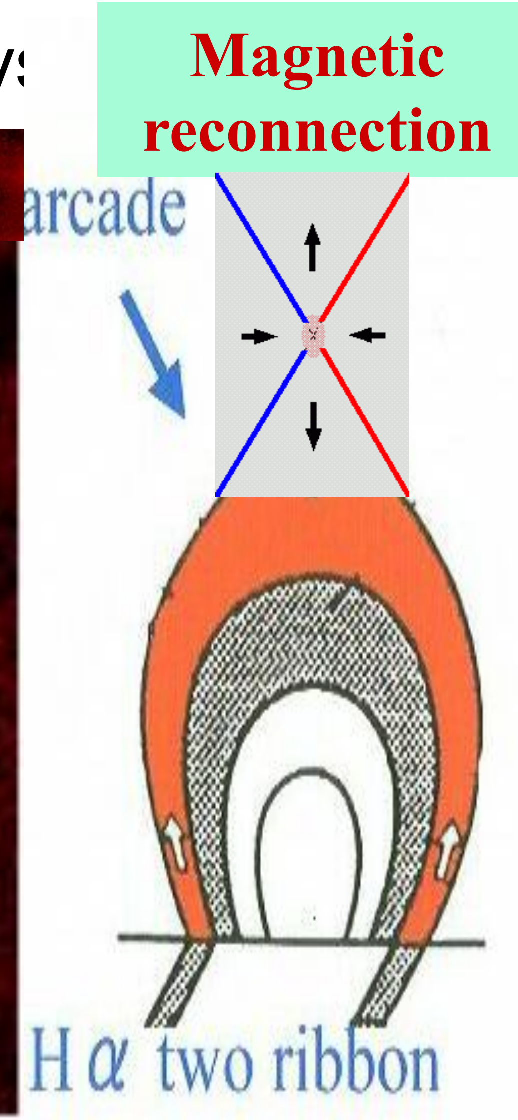
http://en.wikipedia.org/wiki/Solar_storm_of_1859

Solar Flares

Hα

X-rays

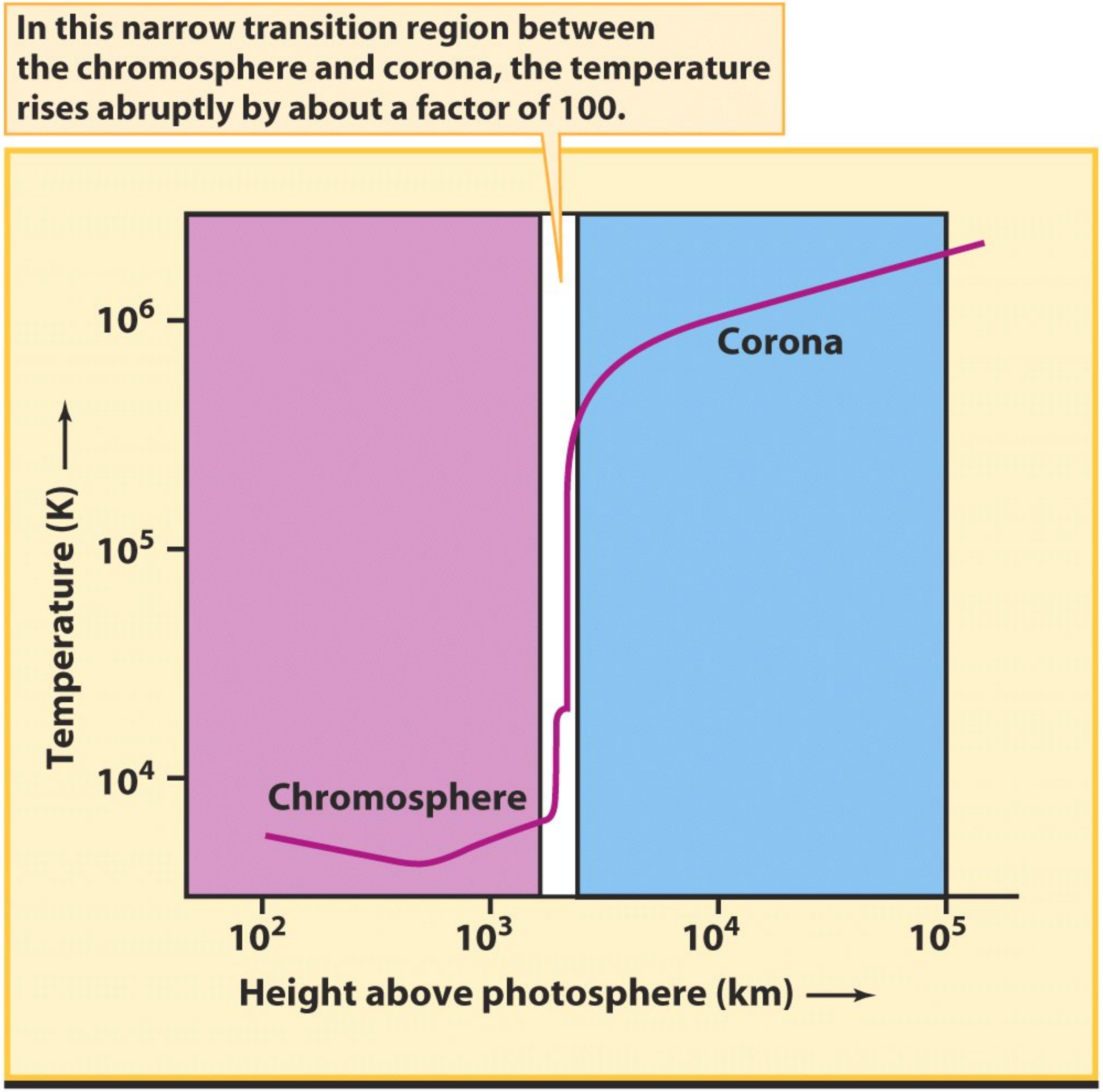




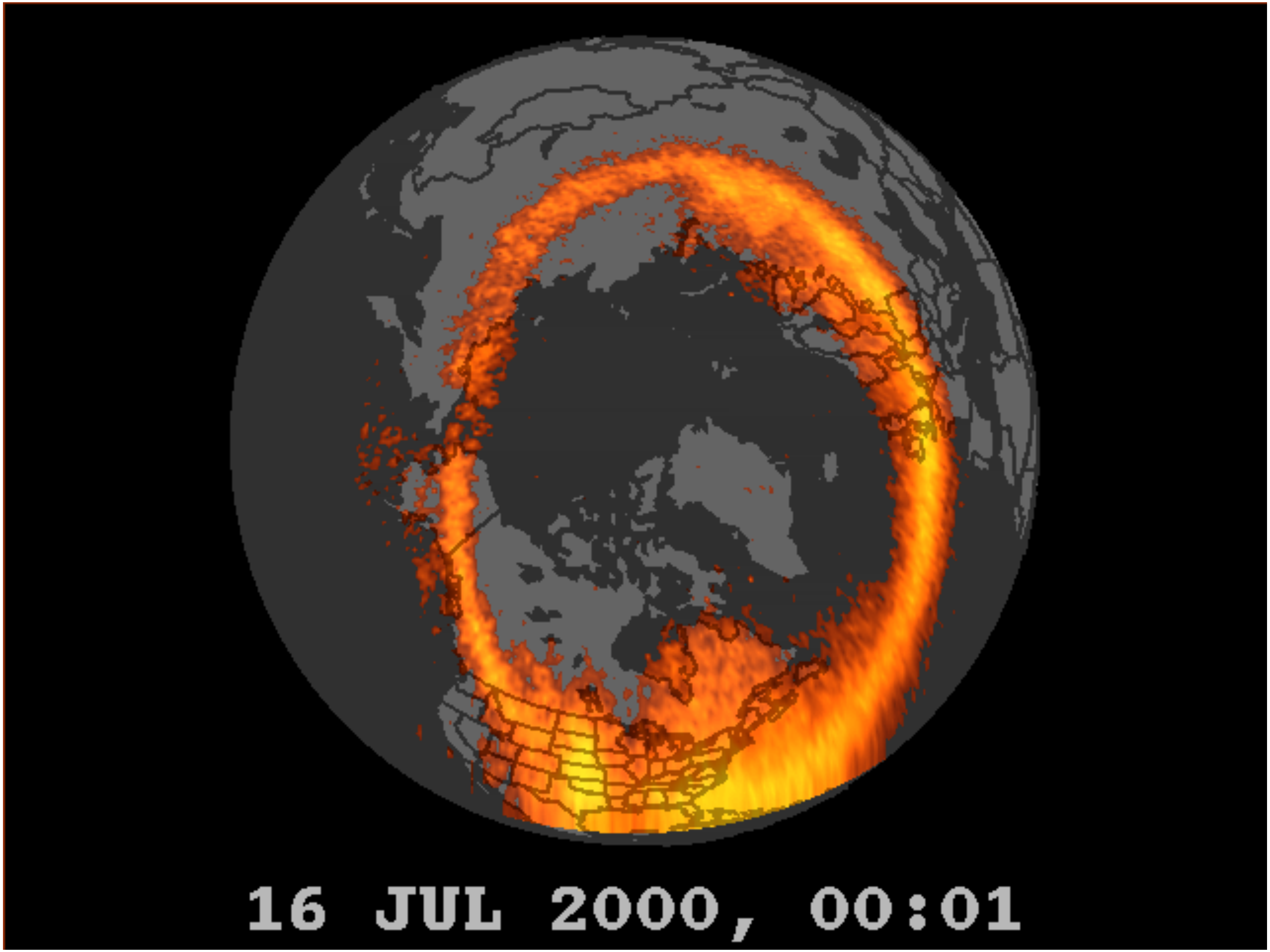
Based on K. Shibata (2007)

SOHO
EIT

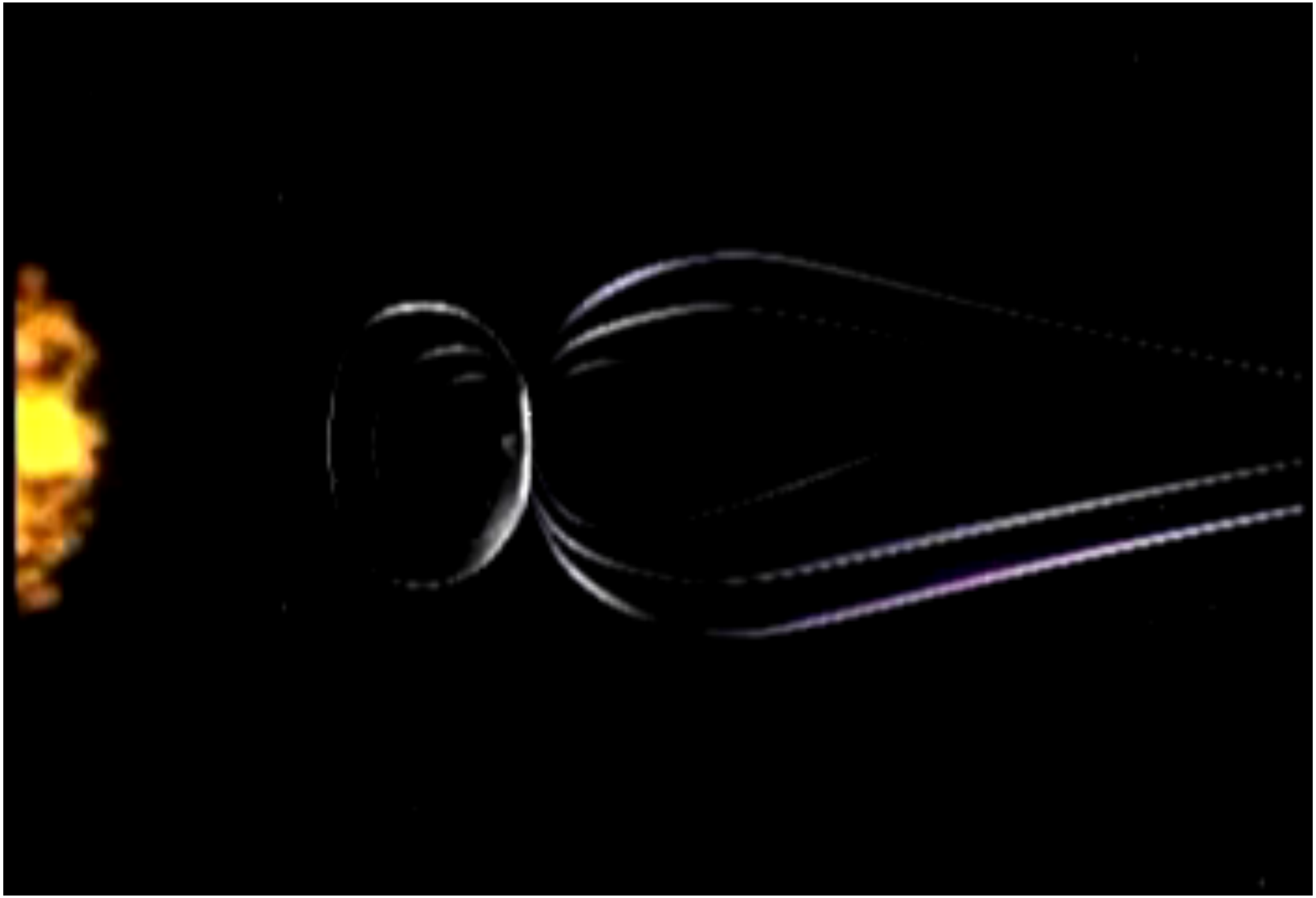
Million Degrees Coronal Plasmas



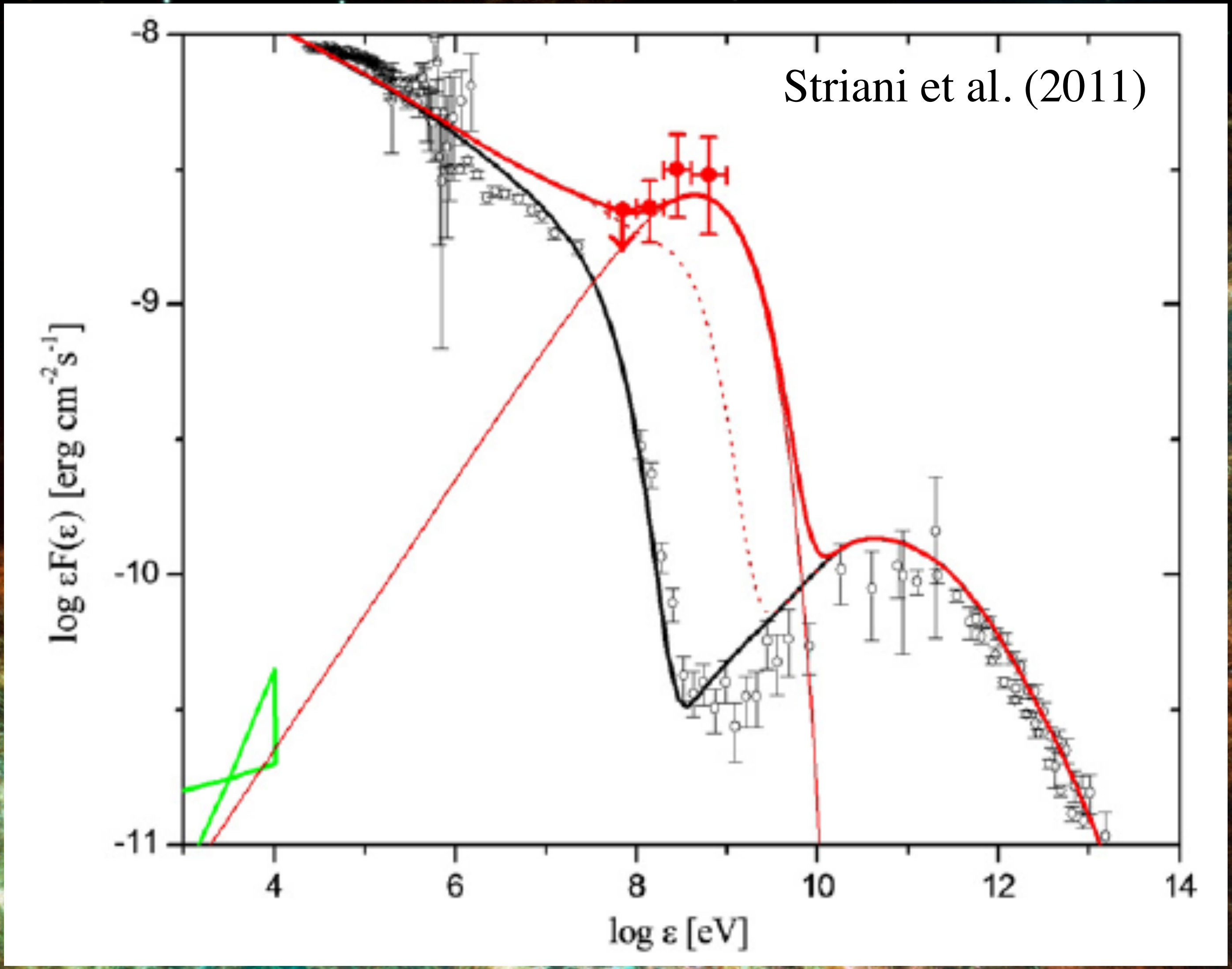
Aurora From Space (POLAR)



Solar Wind Interacts With Earth's Magnetosphere

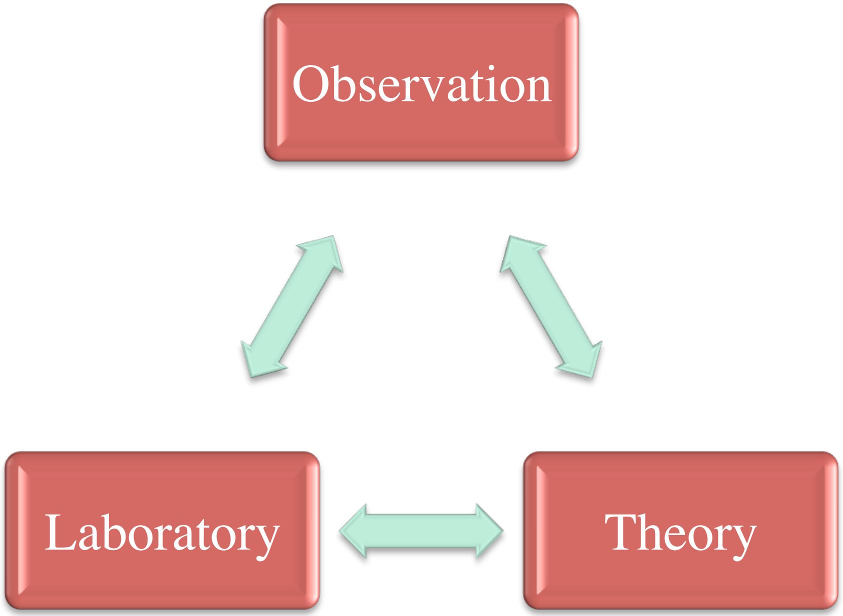


ϒ-Ray Flares from Crab Nebula (Fermi)



Roles of Laboratory Experiments in Understanding Astrophysical Plasmas

- **Motivated by space and astrophysical observations**
- **Verify/confront existing theory; discover new physics ➔ essential for application to astrophysics**
- **Benchmark/challenge simulation ➔ unique opportunity to validate codes**
- **Compare with observations ➔ support space missions**



Collaboration Research for Plasma Astrophysics

Two Types of Experiments

- All-in-one: many competing processes coexist; difficult to differentiate
  - *e.g.* tokamaks

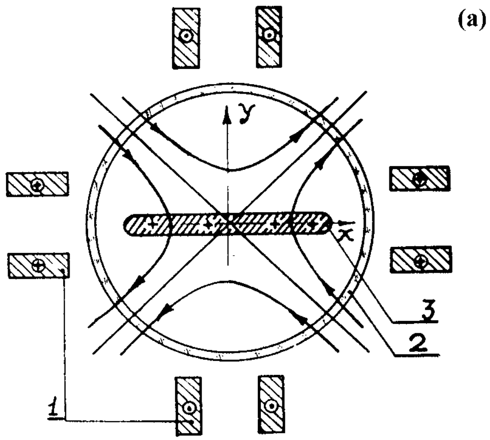
- Problem-specific: one process dominates
  - *e.g.* MRX for magnetic reconnection

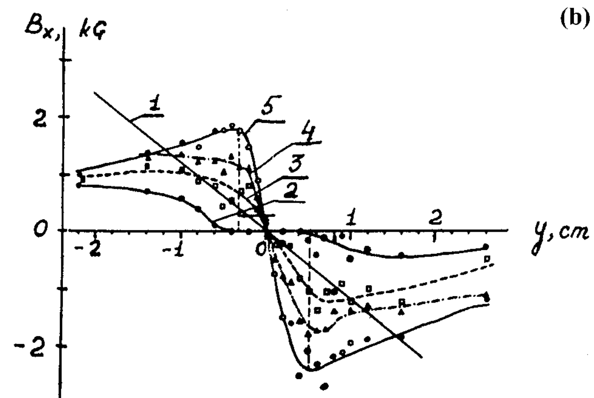
Controllability is the key:

specify conditions, when, and where
to observe how; diagnostics is the other key

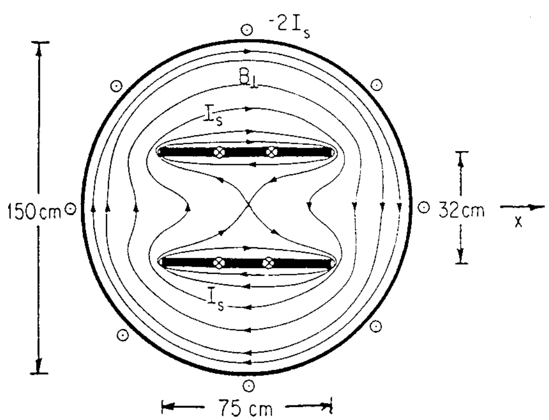
Early Linear Experiments

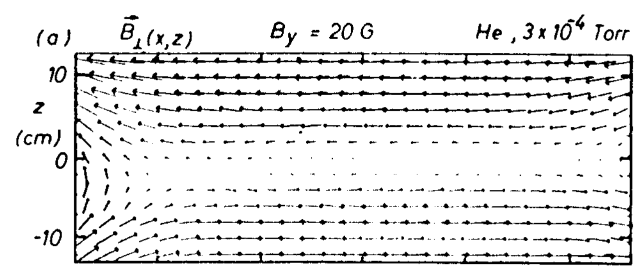
70’ Syrovatskii & Frank: ρ_i << L but S=1-10: diffusive MHD



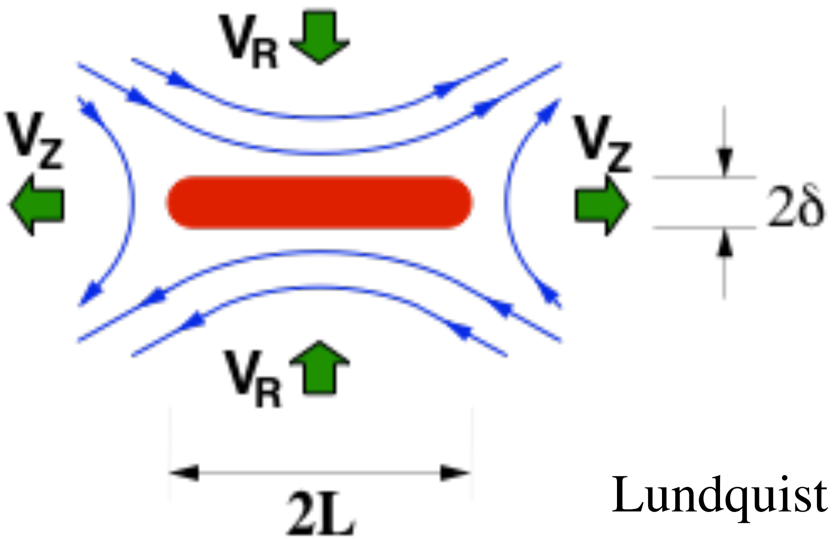


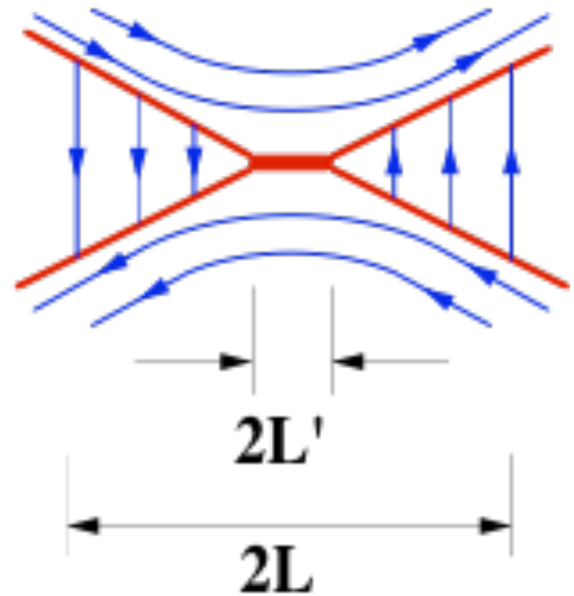
80’ Stenzel & Gekelman: S=1-10 but ρ_i >> L: EMHD





Classical 2D Reconnection Model: Sweet-Parker Model vs Petschek Model





Lundquist #:

$$S = \frac{\mu_0 L V_A}{\eta}$$

$$\frac{V_\mathrm{R}}{V_\mathrm{A}} = \frac{1}{\sqrt{S}} \Rightarrow t_\mathrm{R} \approx months$$

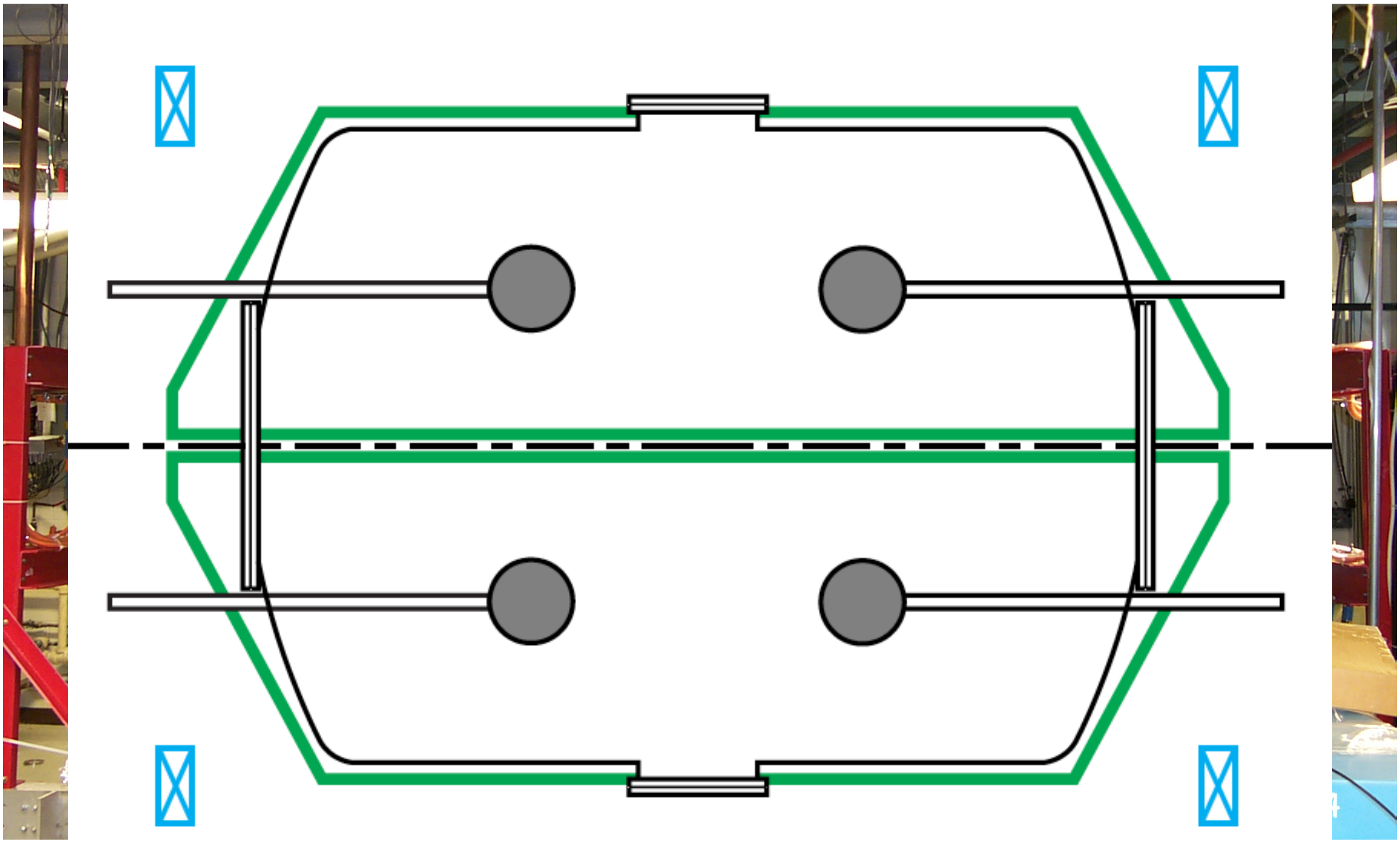
…but still much longer than the observations of a few minutes

$$\frac{V_\mathrm{R}}{V_\mathrm{A}} \approx \frac{1}{8\ln(S)} \Rightarrow t_\mathrm{R} \approx 1\,\mathrm{min}$$

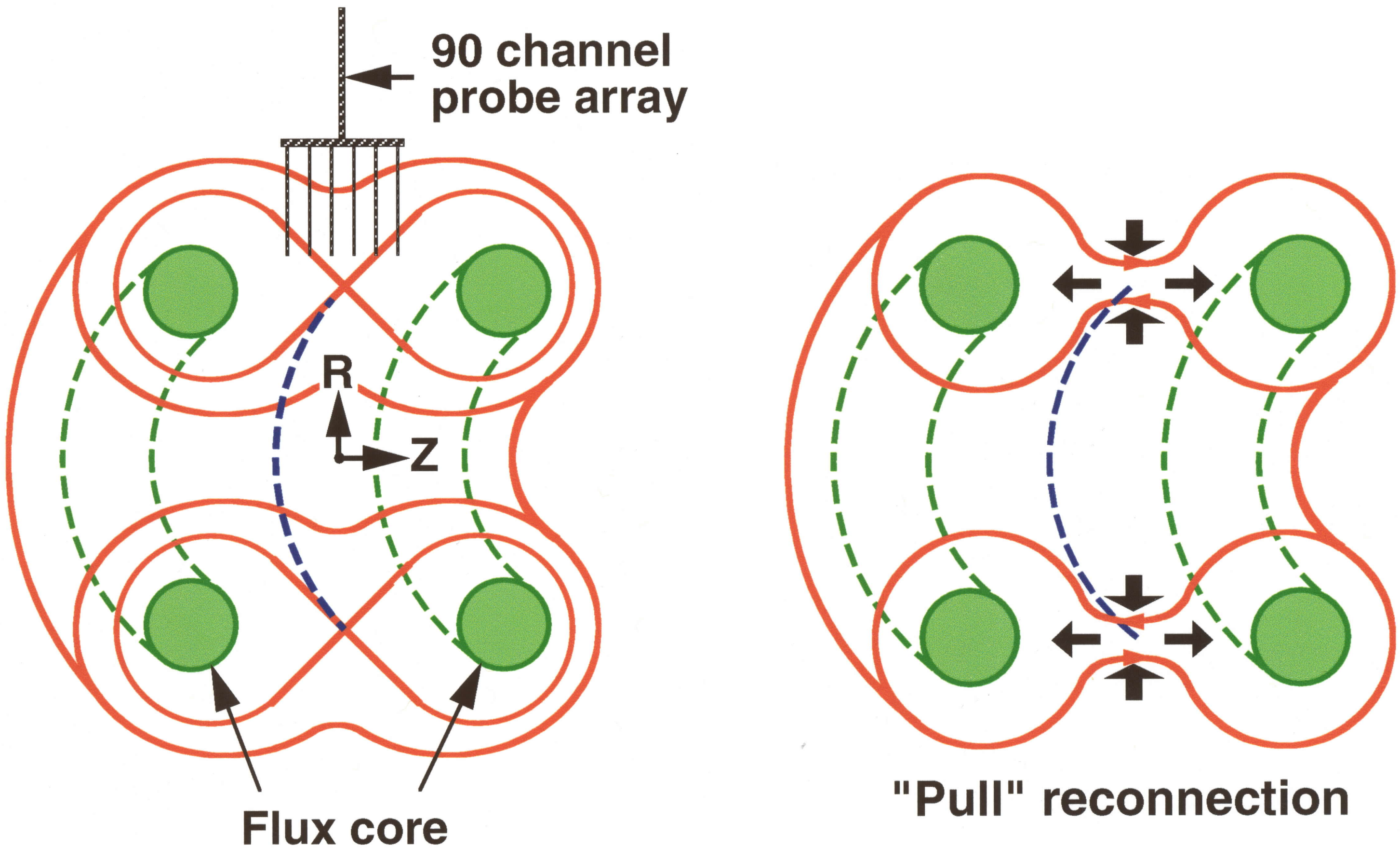
…but not a steady state solution with uniform resistivity

What do we see in the lab?

Magnetic Reconnection Experiment (MRX)
(since 1995, mrx.pppl.gov)

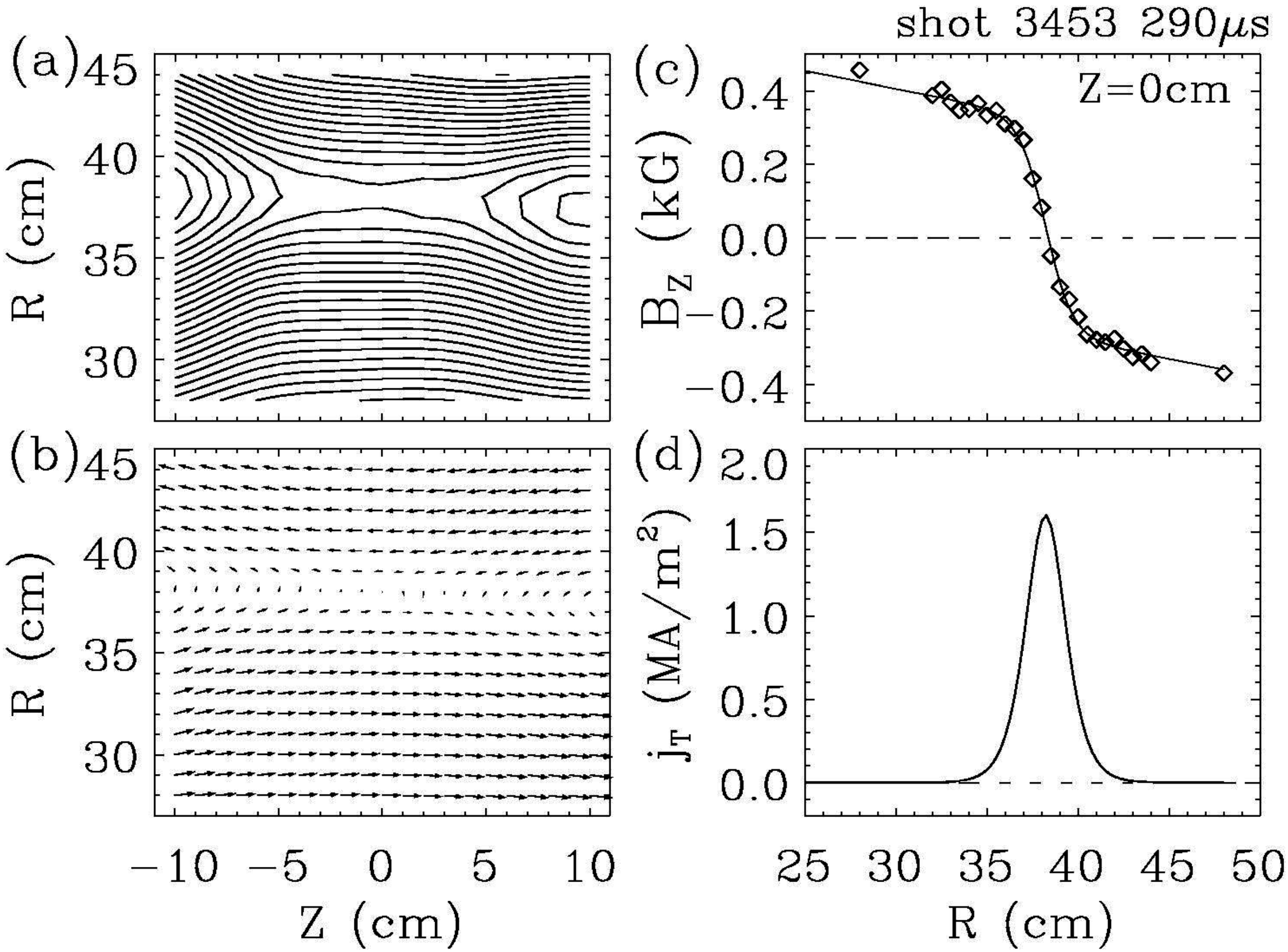


The Basic Experimental Idea



Control + Diagnostics

Realization of Stable Current Sheet and Quasi-steady Reconnection

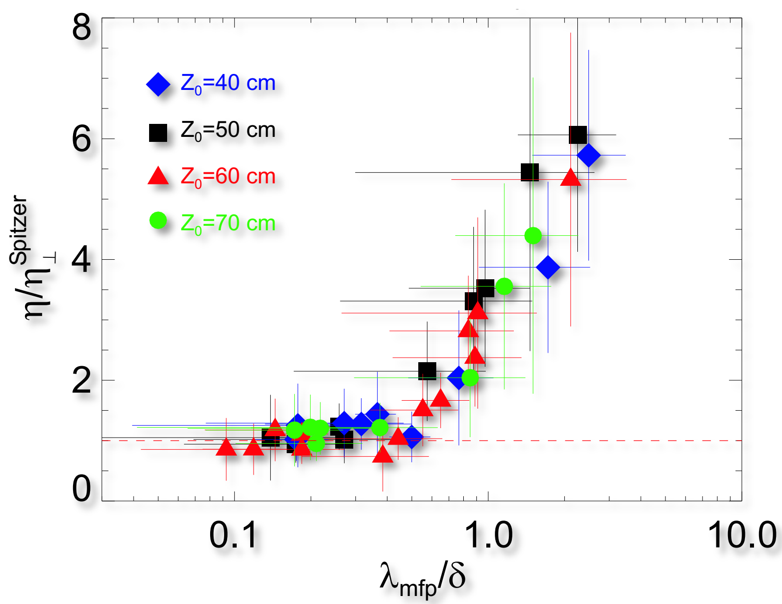


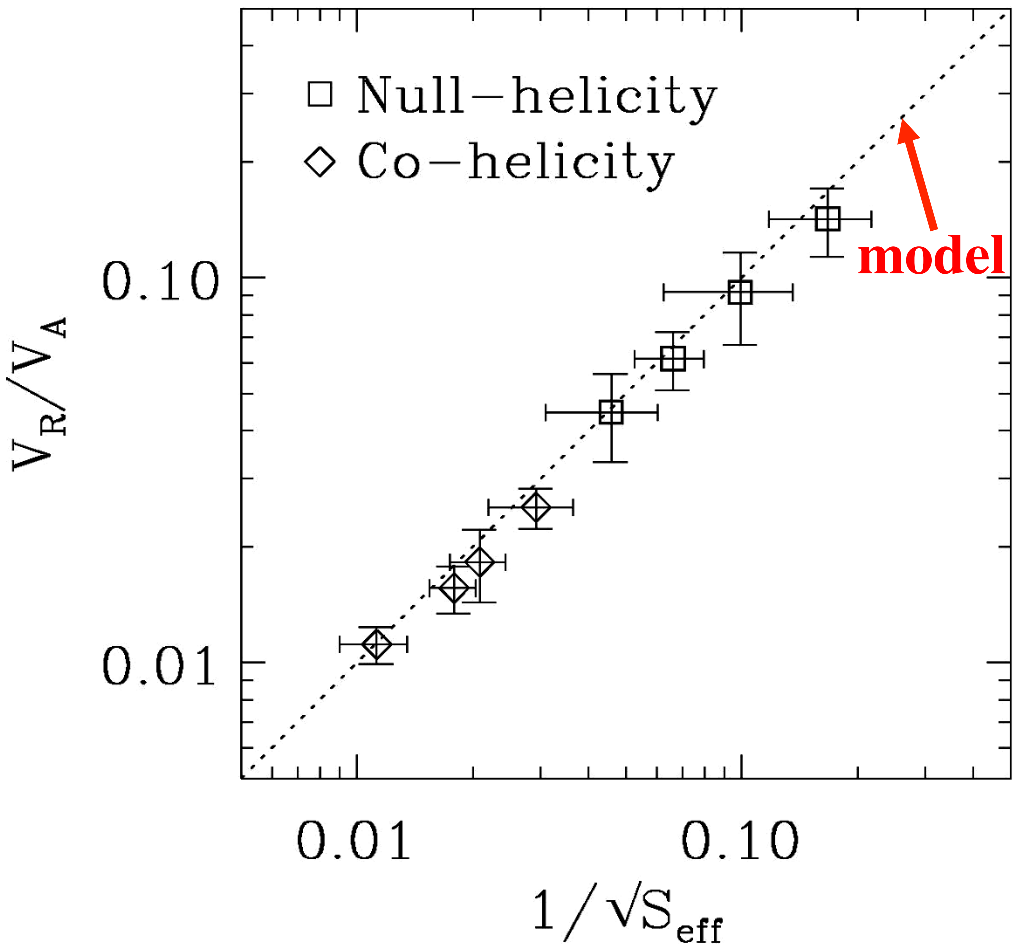
Detailed diagnostics: quantitative studies possible

Sweet-Parker Model Works in *Collisional MHD*!

Ji et al., PRL (1998)
Ji et al., PoP (1999)

- **Adjustments by compressibility and boundary conditions**
- **When collisionless, the apparent resistivity (*E*/*j*) increases beyond Spitzer values** (Kuritsyn et al. 2006)





Central Q: how is the apparent resistivity enhanced?

Collisionless: Apparent Resistivity Explained by Two-fluid Effects (separate ion and electron motions)

Generalized Ohm's law:

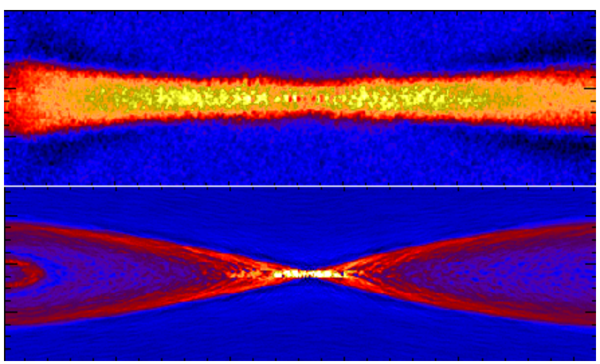
$$\mathbf{E}+\mathbf{V}\times\mathbf{B}=\underbrace{\eta_{Spitzer}\mathbf{j}}_{\text{Resistive term}}+\underbrace{\frac{\mathbf{j}\times\mathbf{B}}{en}-\frac{\nabla\cdot\mathbf{P}_e}{en}}_{\text{Hall terms}}+\underbrace{\frac{m_e}{e}\left(\frac{\partial\mathbf{V}_e}{\partial t}+\left(\mathbf{V}_e\cdot\nabla\right)\mathbf{V}_e\right)}_{\text{Electron inertial terms}}$$

ions

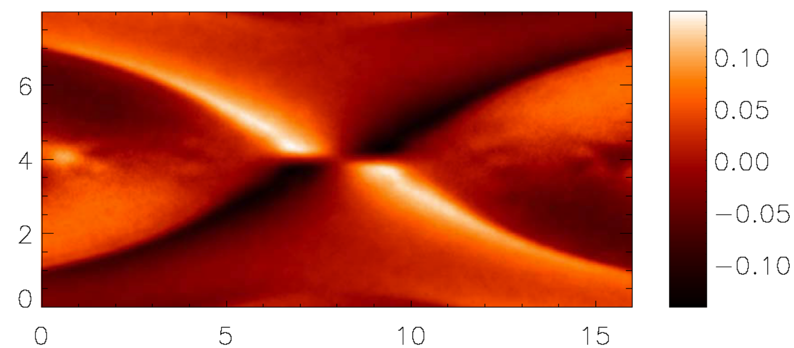
$$d_i \equiv \frac{c}{\omega_{pi}}$$

electrons

$$d_e = \frac{c}{\omega_{pe}}$$

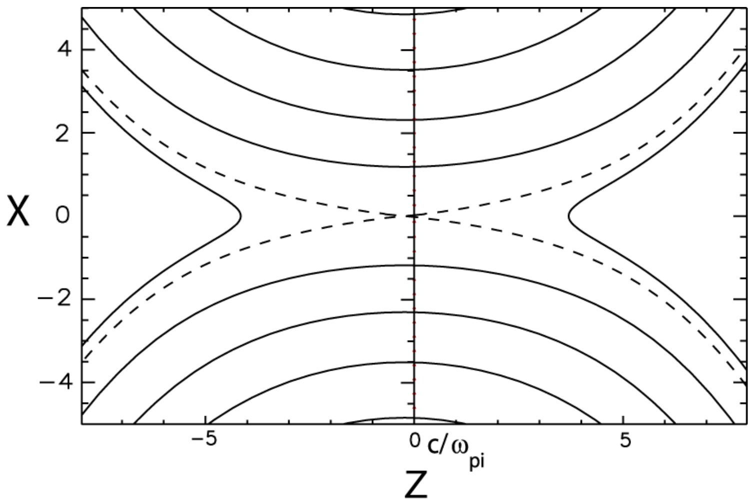


(e.g. Drake et al. '98)



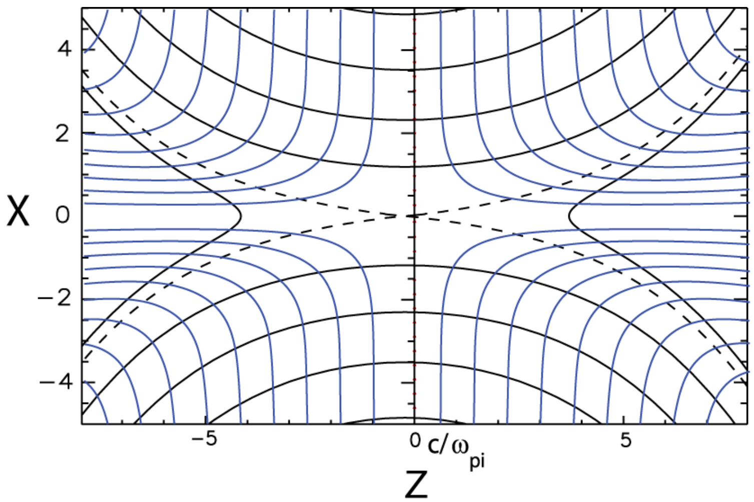
out-of-plane component in a quadrupole structure

Hall Effects in 2D Simulation



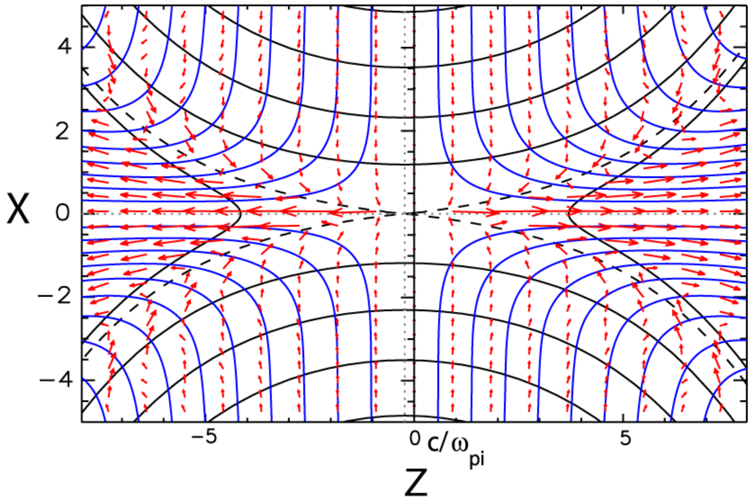
- Black lines $\longrightarrow$magnetic flux.

Hall Effects in 2D Simulation



- Black lines → magnetic flux.
- Blue lines → ion flow streamlines.

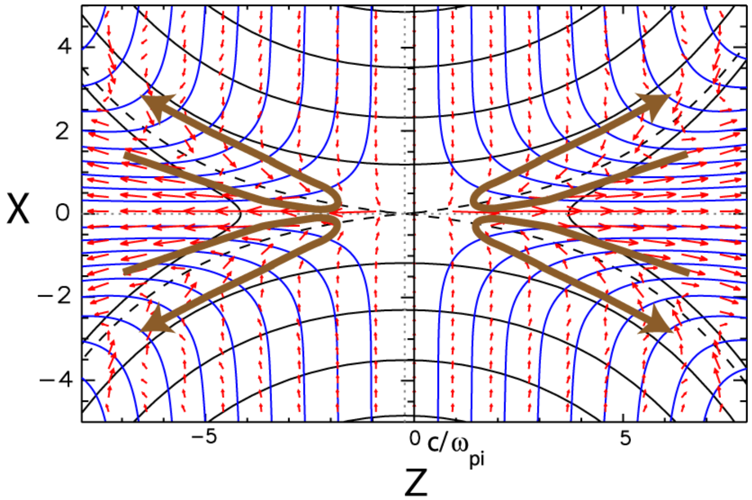
Hall Effects in 2D Simulation



- **Black lines → magnetic flux.**
- **Blue lines → ion flow streamlines.**
- **Red arrows → electron flow velocity.**

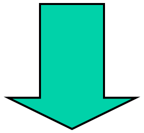
Different motions of ions and electrons

Hall Effects in 2D Simulation

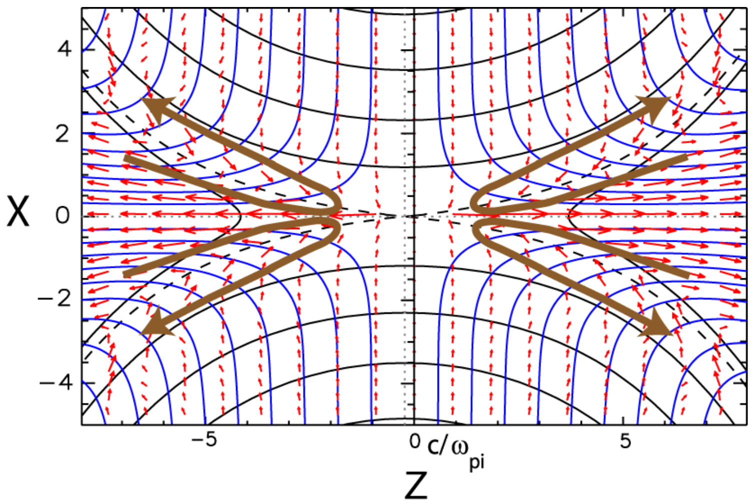


- **Black lines** ⟶ **magnetic flux.**
- **Blue lines** ⟶ **ion flow streamlines.**
- **Red arrows** ⟶ **electron flow velocity.**
- **Brown arrows** ⟶ **In-plane current.**

Different motions of ions and electrons



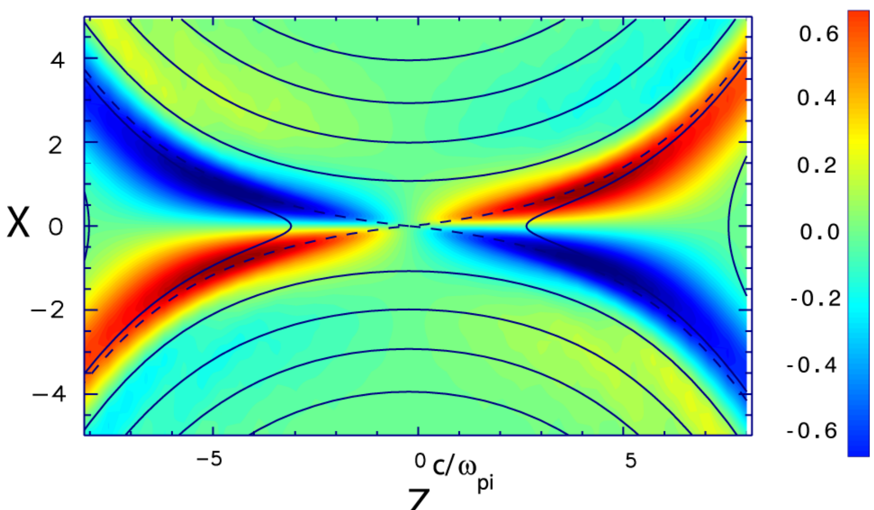
Hall Effects in 2D Simulation



- Black lines → magnetic flux.
- Blue lines → ion flow streamlines.
- Red arrows → electron flow velocity.
- Brown arrows → In-plane current.

Different motions of ions and electrons

In-plane current



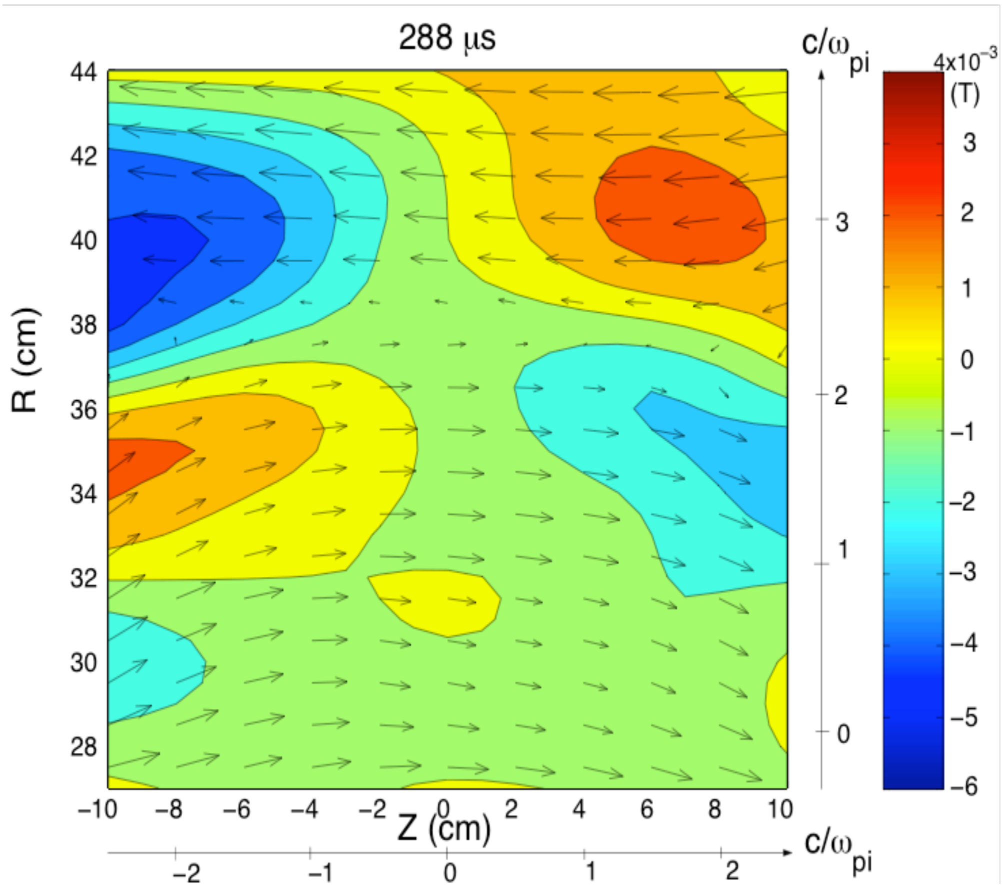
An out-of-plane quadrupole magnetic field

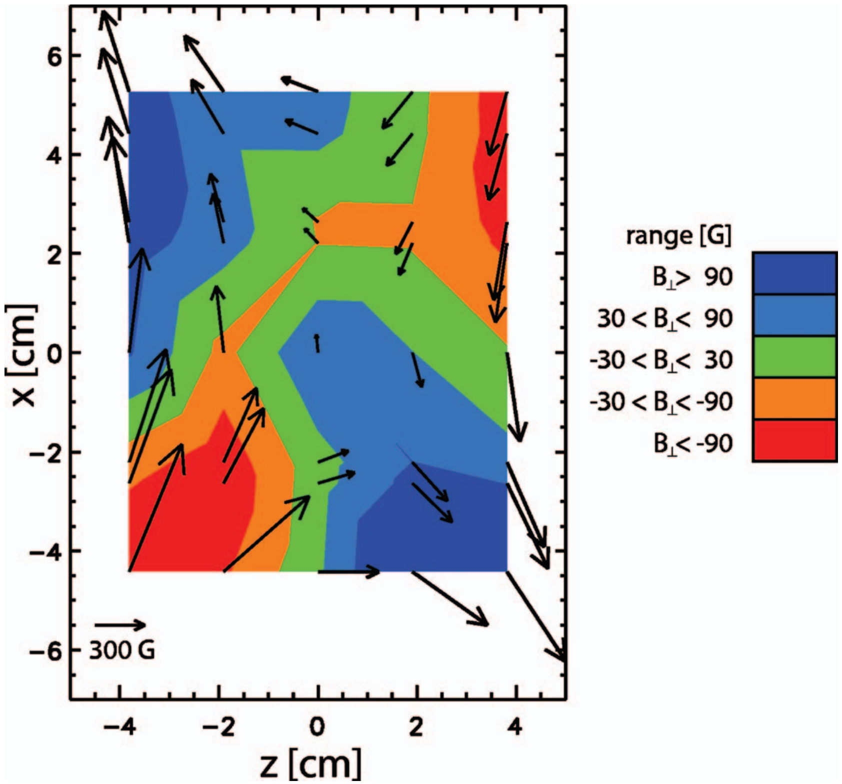
In color code

2-fluid simulation by J. Breslau

What do we see in the lab?

Quadrupole Out-of-Plane Field Detected: Ion Scale Physics Confirmed!

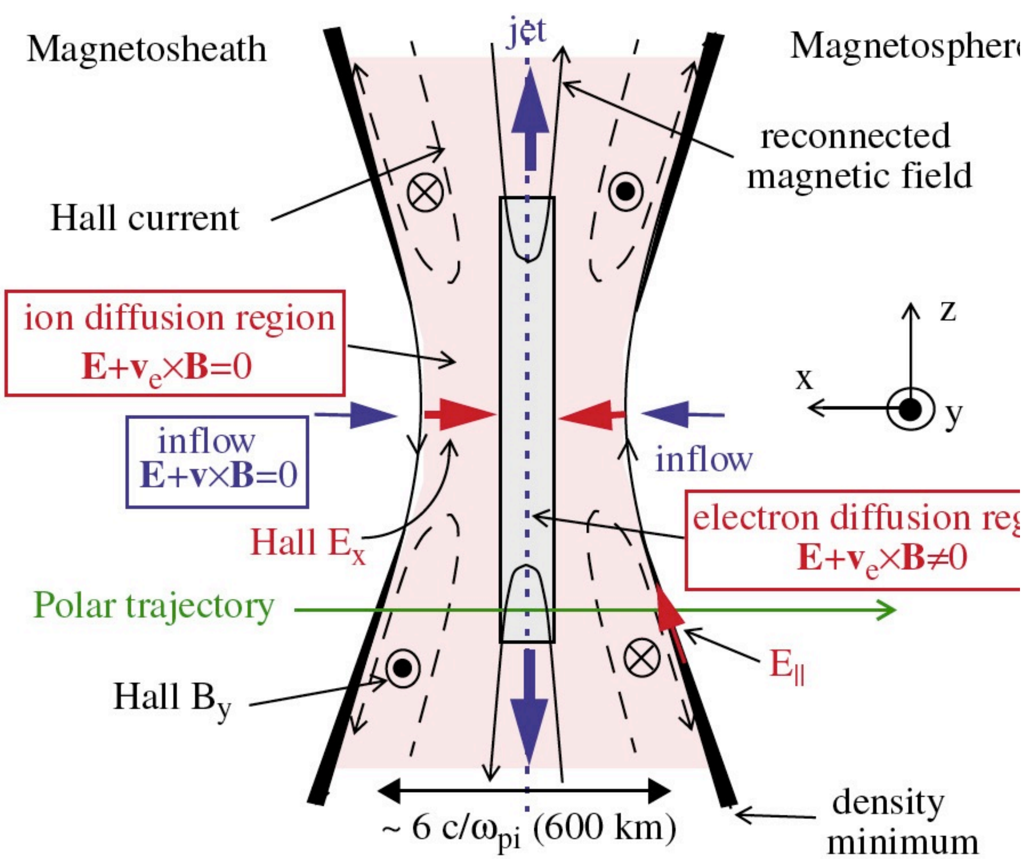


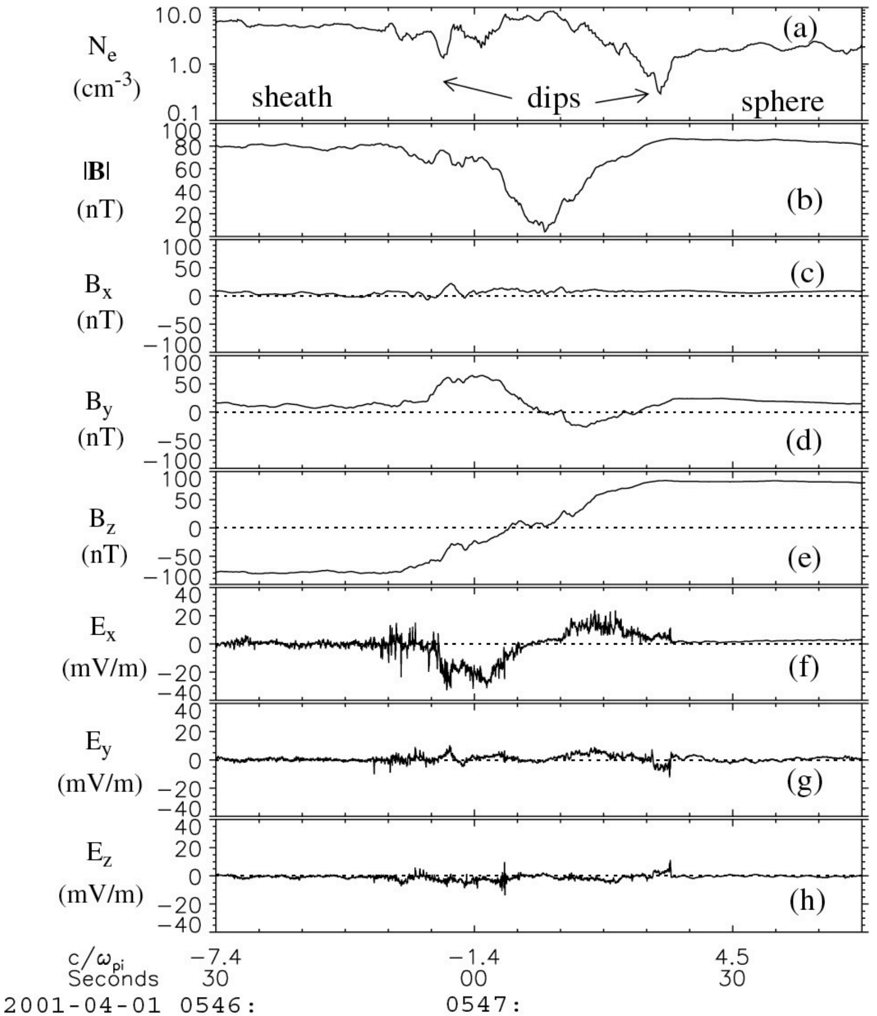


Ren et al, PRL (2005)
Yamada et al. PoP (2006)

Brown et al. PoP (2006)

Consistent with Space Data

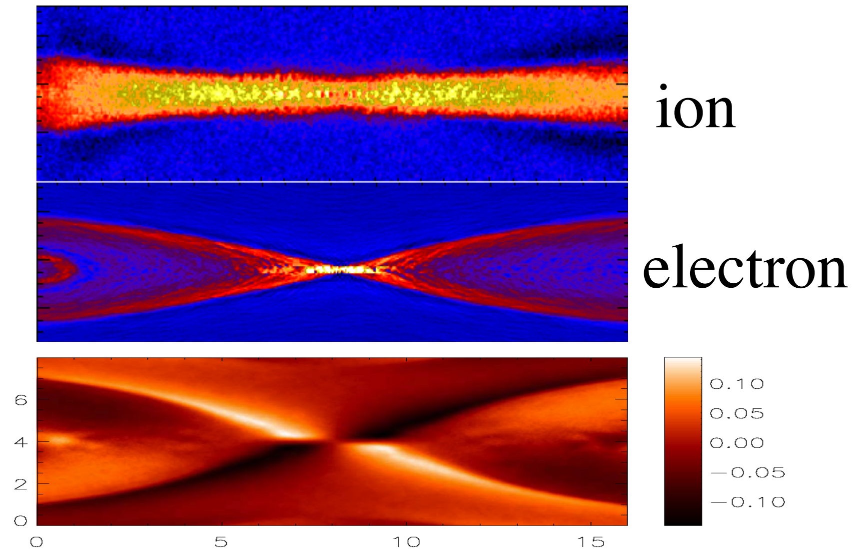




Mozer et al. (2002)

Next Frontier: Electron Diffusion Regions

- Magnetic field *reconnects* in electron layer to change its topology while electrons are energized.



(e.g. Drake et al. '98)

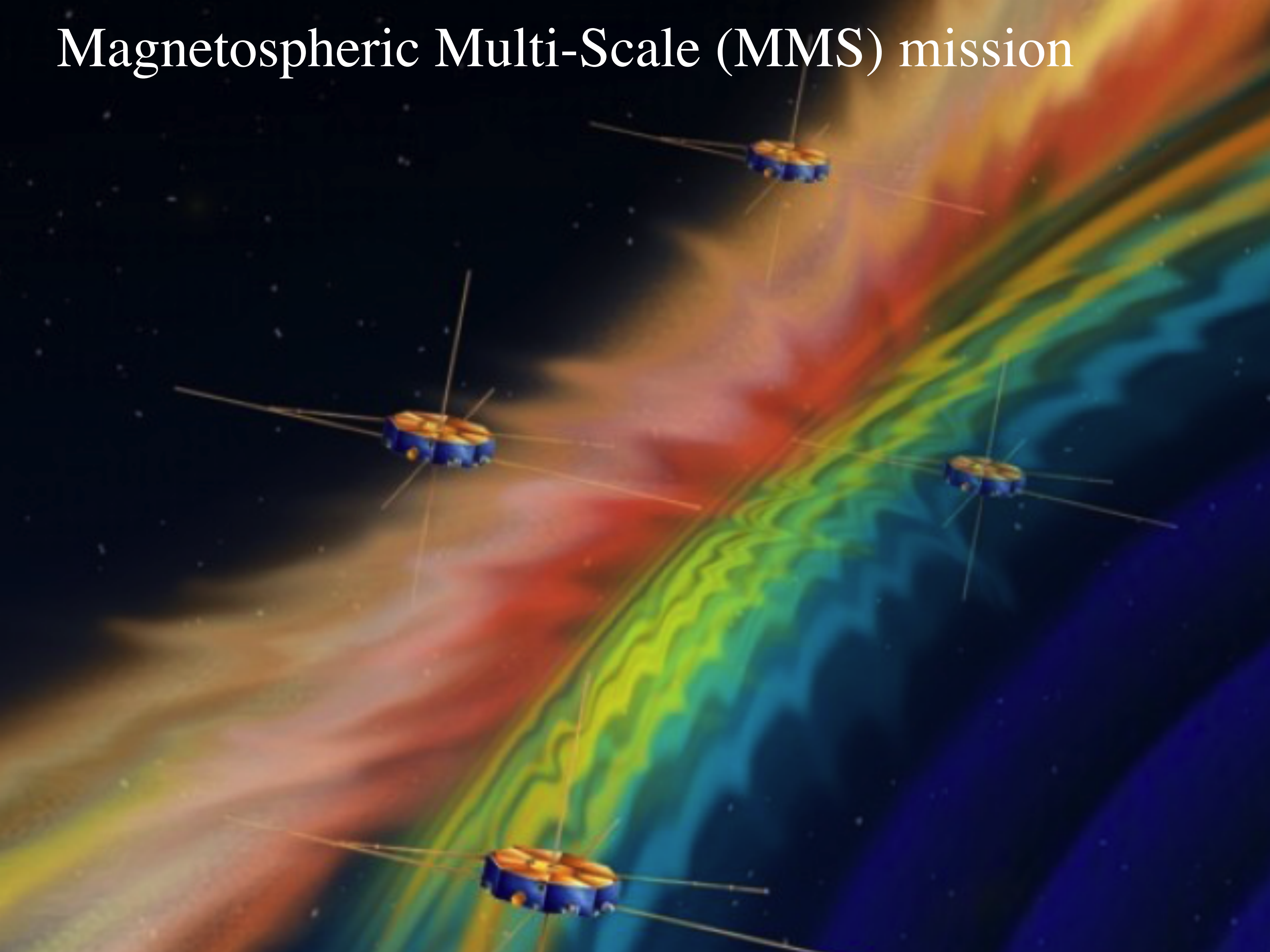
- In 2D collisionless reconnection, electron non-gyrotropic pressure dominates the dissipation.

Vasyliuna ('75), Sonnerup ('88), Dungey ('88), Lyons & Pridmore-Brown ('90)
Cai & Lee ('97), Hesse et al. ('99), Pritchett ('01), Kuznetsova et al. ('01)

- Limited observations in space

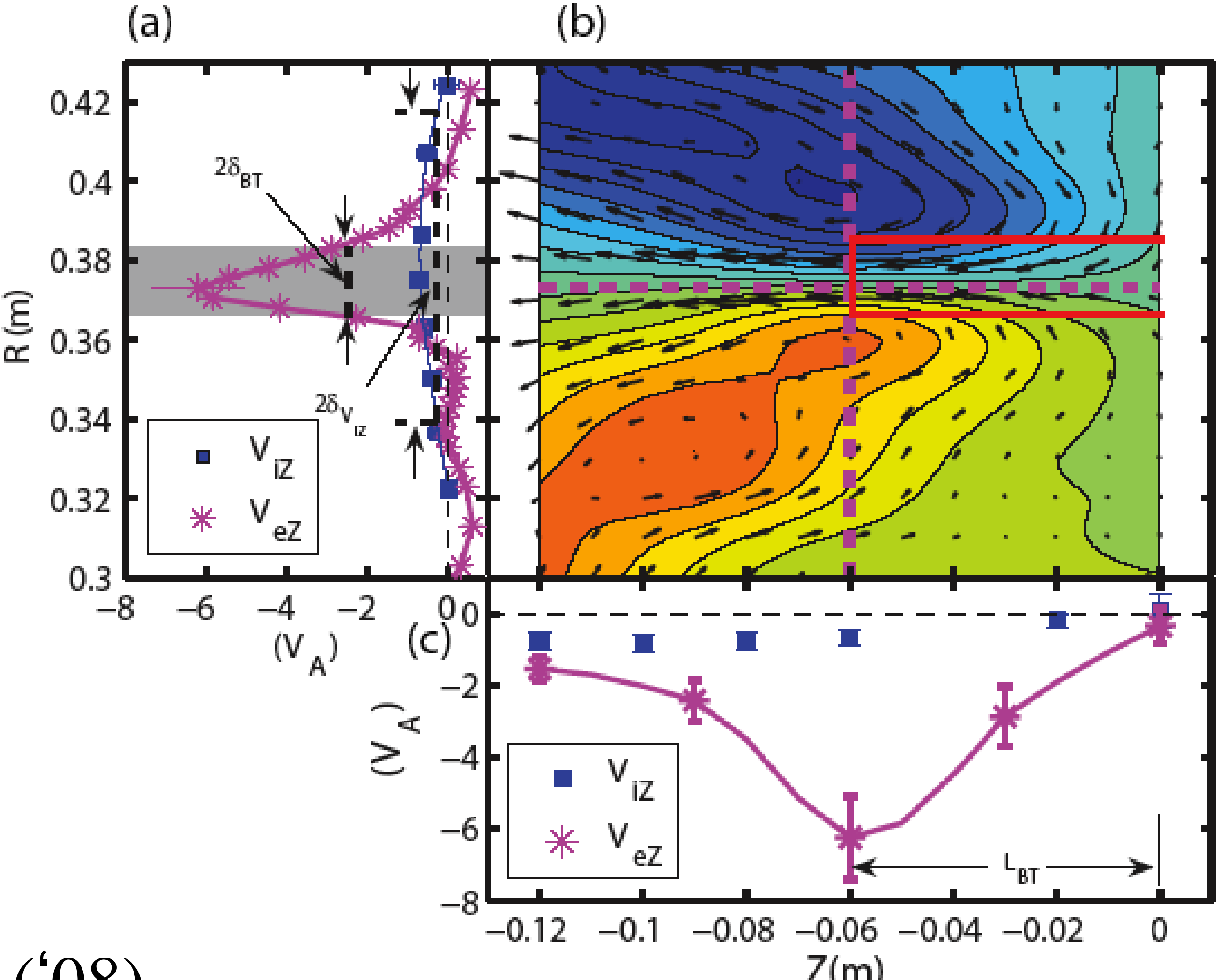
Scudder et al. ('02), Mozer ('05), Wygant et al. ('05), Phan et al. ('07), Chen et al. ('08)
Scudder et al. ('12)

Magnetospheric Multi-Scale (MMS) mission



First Detection of Electron Diffusion Region in Laboratory

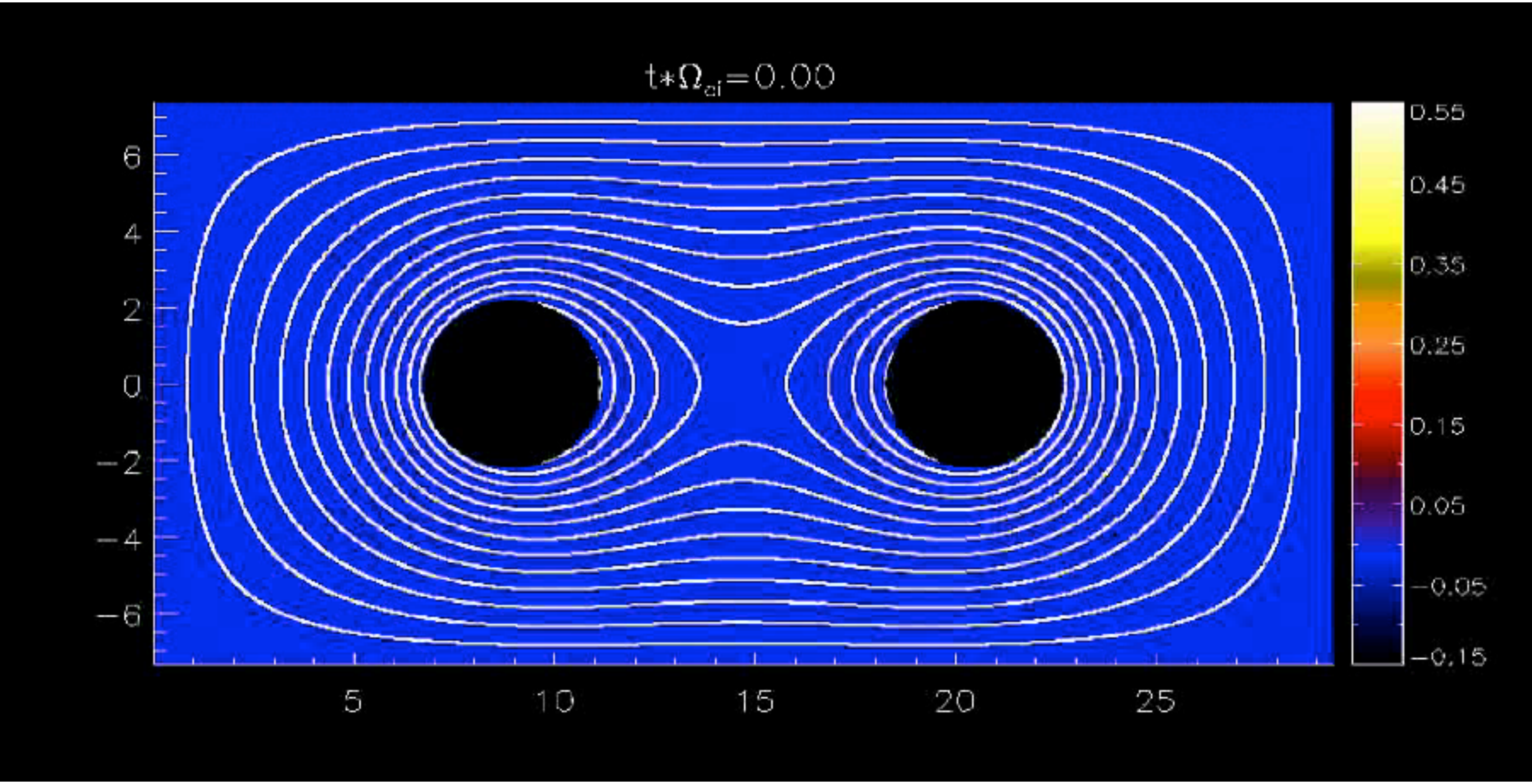
Electron layer



Ren et al. PRL ('08)

2D PIC Simulation in MRX Setup

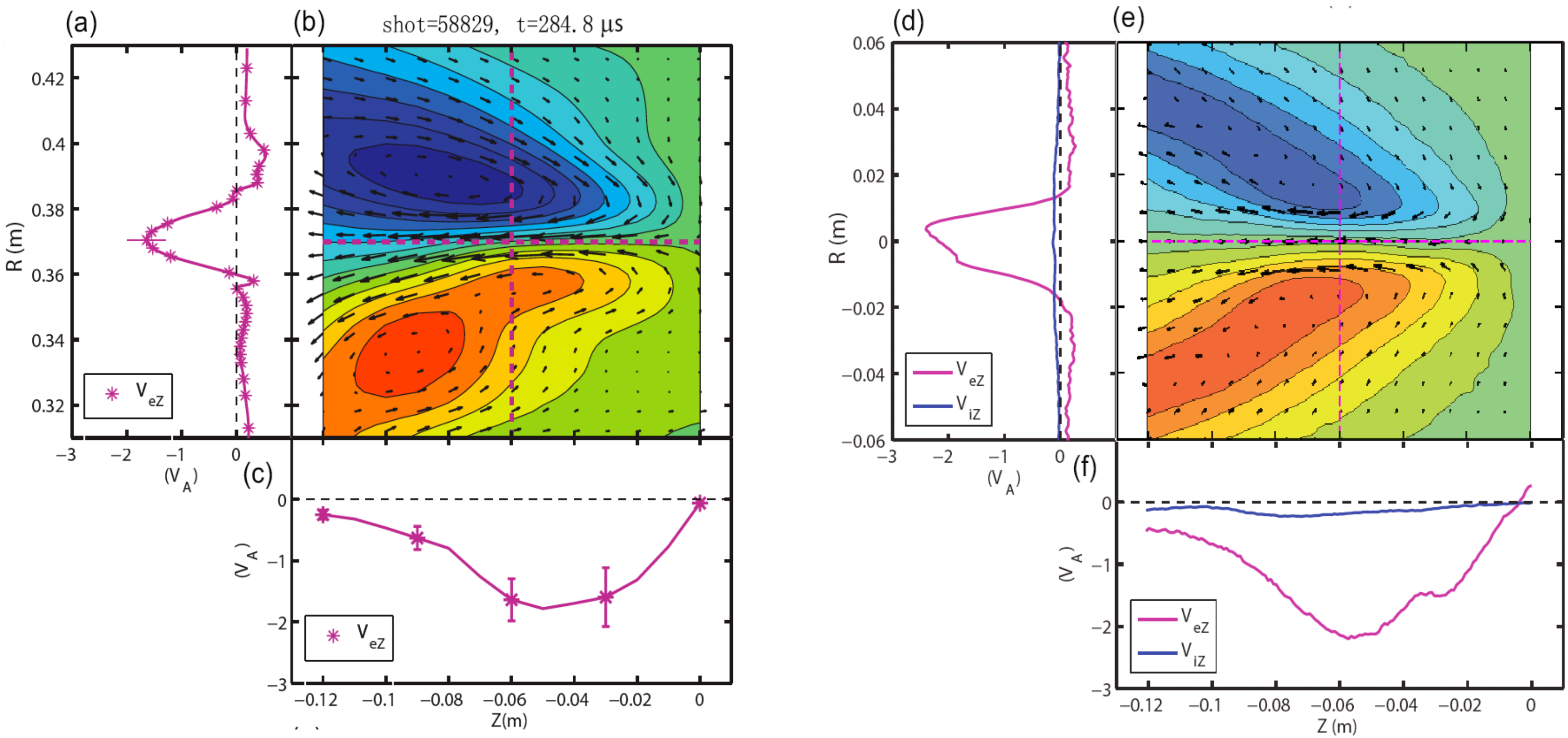
Dorfman, et al. PoP (‘08)



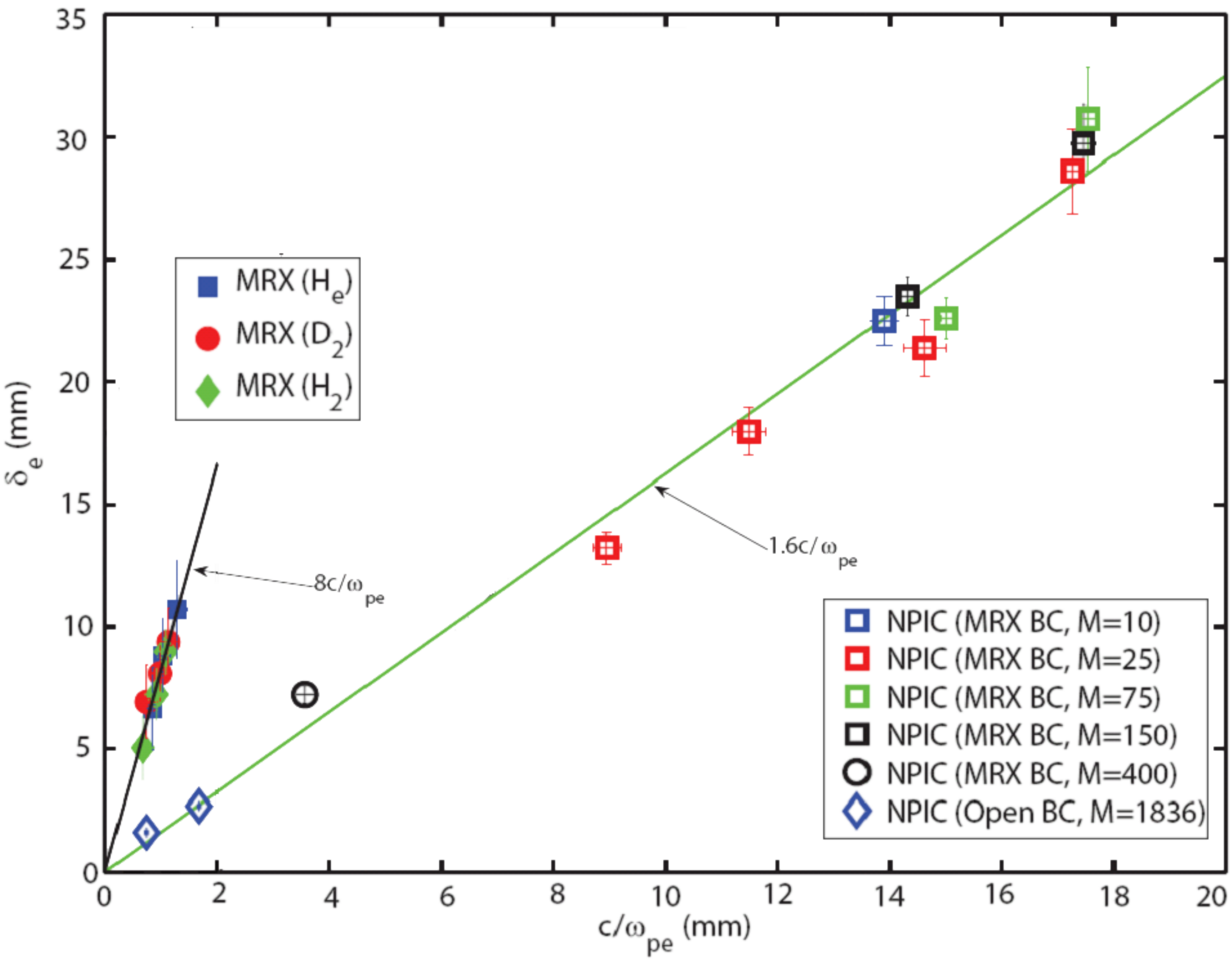
All Ion-Scale Features Are Reproduced By 2D PIC Simulations…

Ji et al. GRL (2008)

Dorfman et al. PoP (2008)



… But NOT on Electron Scales: $\delta_{exp} = 8\ c/\omega_{pe}$ versus δ_{sim}=1.5-2 c/ω_{pe}



All known 2D mechanisms cannot explain the measured width

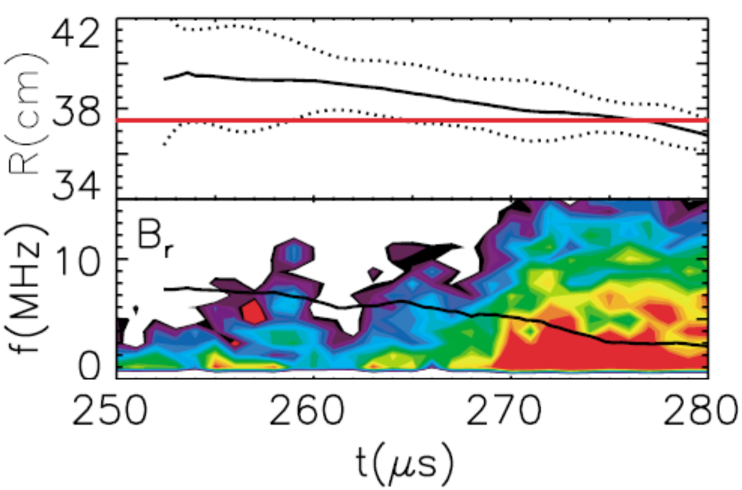
importance of 3D effects

V. Roytershteyn et al. (2010)

How can 3-D dynamics affect the reconnection process?

Waves and Turbulence

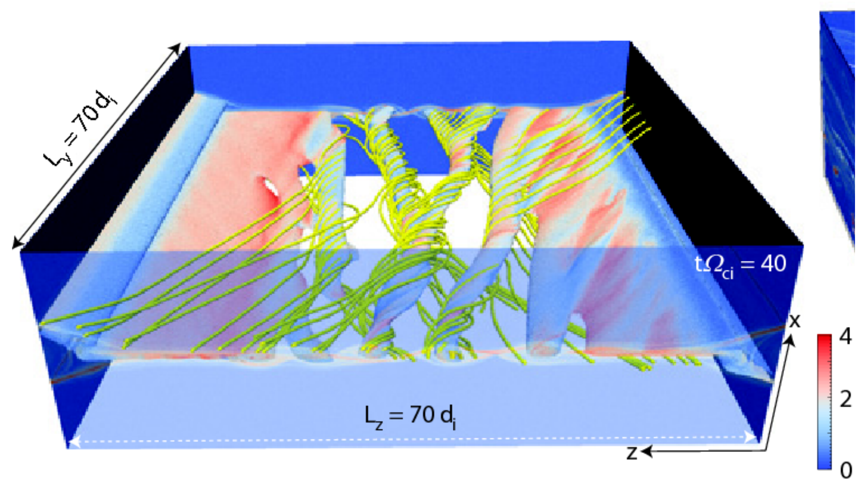
- 3-D variation allows for a large class of waves: Can these waves generate anomalous resistivity that speeds up reconnection?



(Ji, et. al., PRL, 2004)

Flux Rope Structures

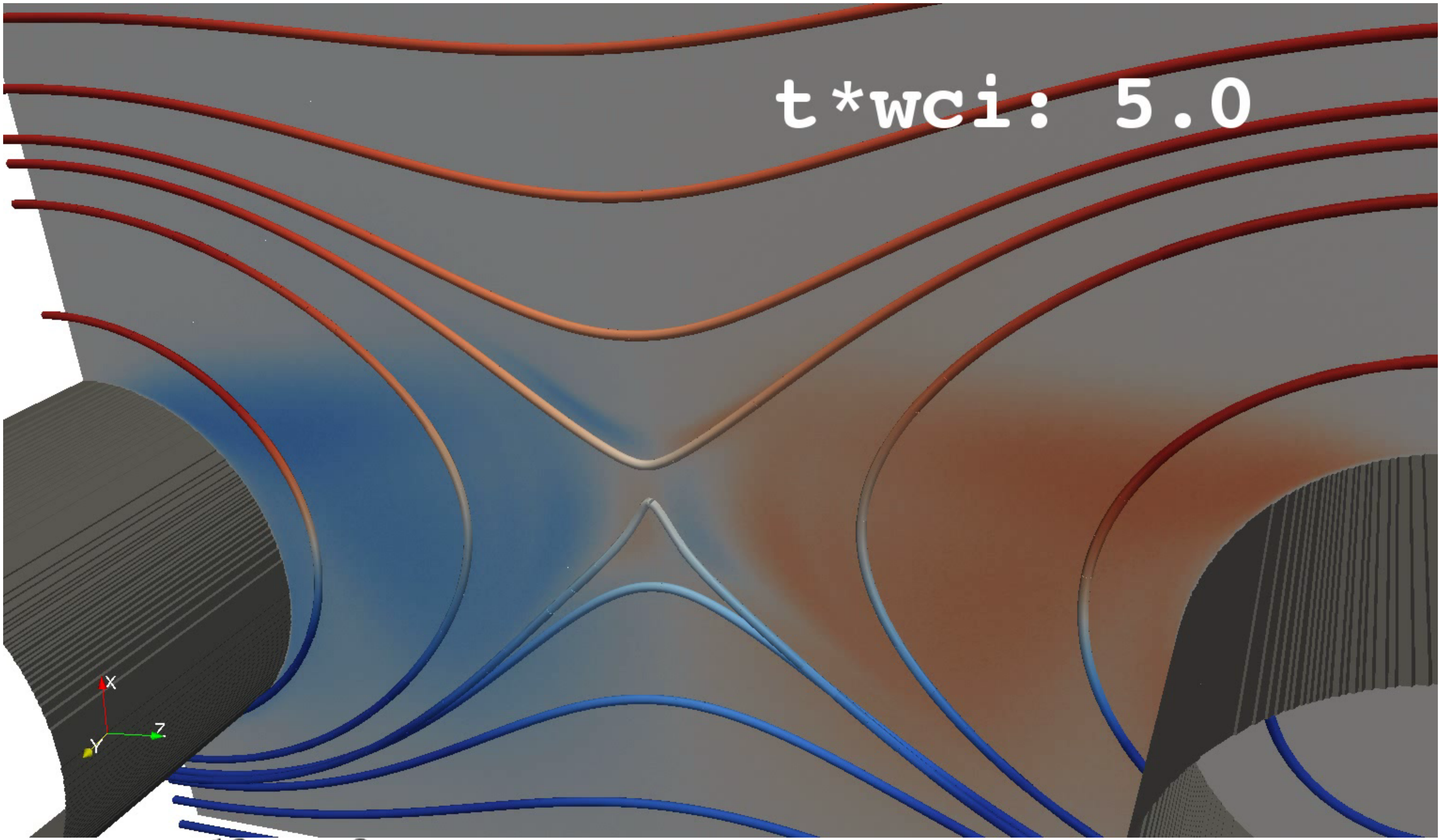
- Islands in 2.5-D are analogous to flux ropes in 3-D



(Daughton, et. al., Nature Physics, 2011)

3D Simulations Show Existence of EM Waves Under Similar Conditions

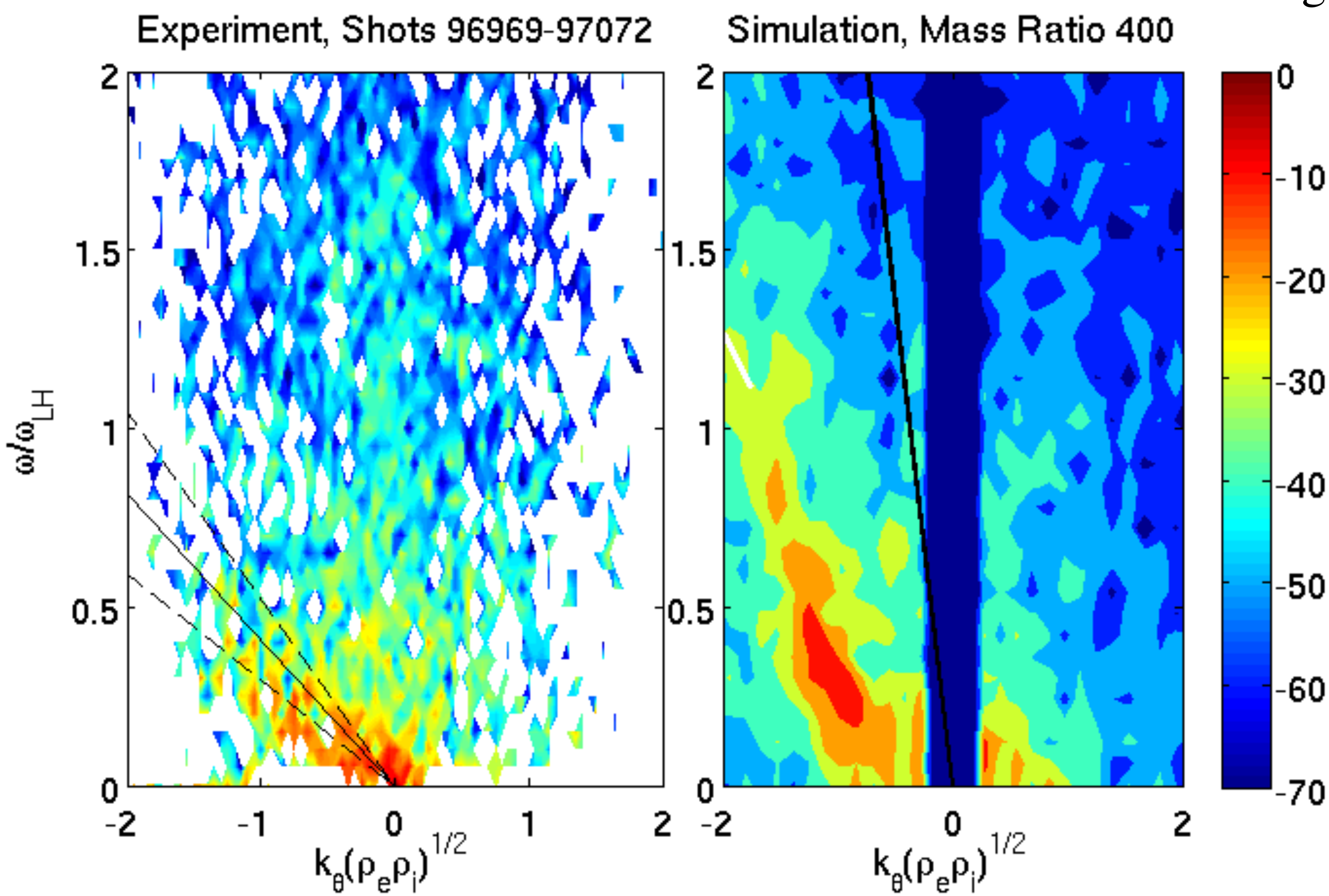
V. Roytershteyn et al. PoP (2013)



$$n_0 = 2 \cdot 10^{13}\mathrm{cm}^{-3}, m_i/m_e = 300, (\nu_{ei}/\Omega_{ce}) \approx 0.01, (9 \times 3 \times 11.5)d_i^0$$

Wave Dispersion Agrees with MRX, Consistent with Intermediate Wavelength EM LHDW

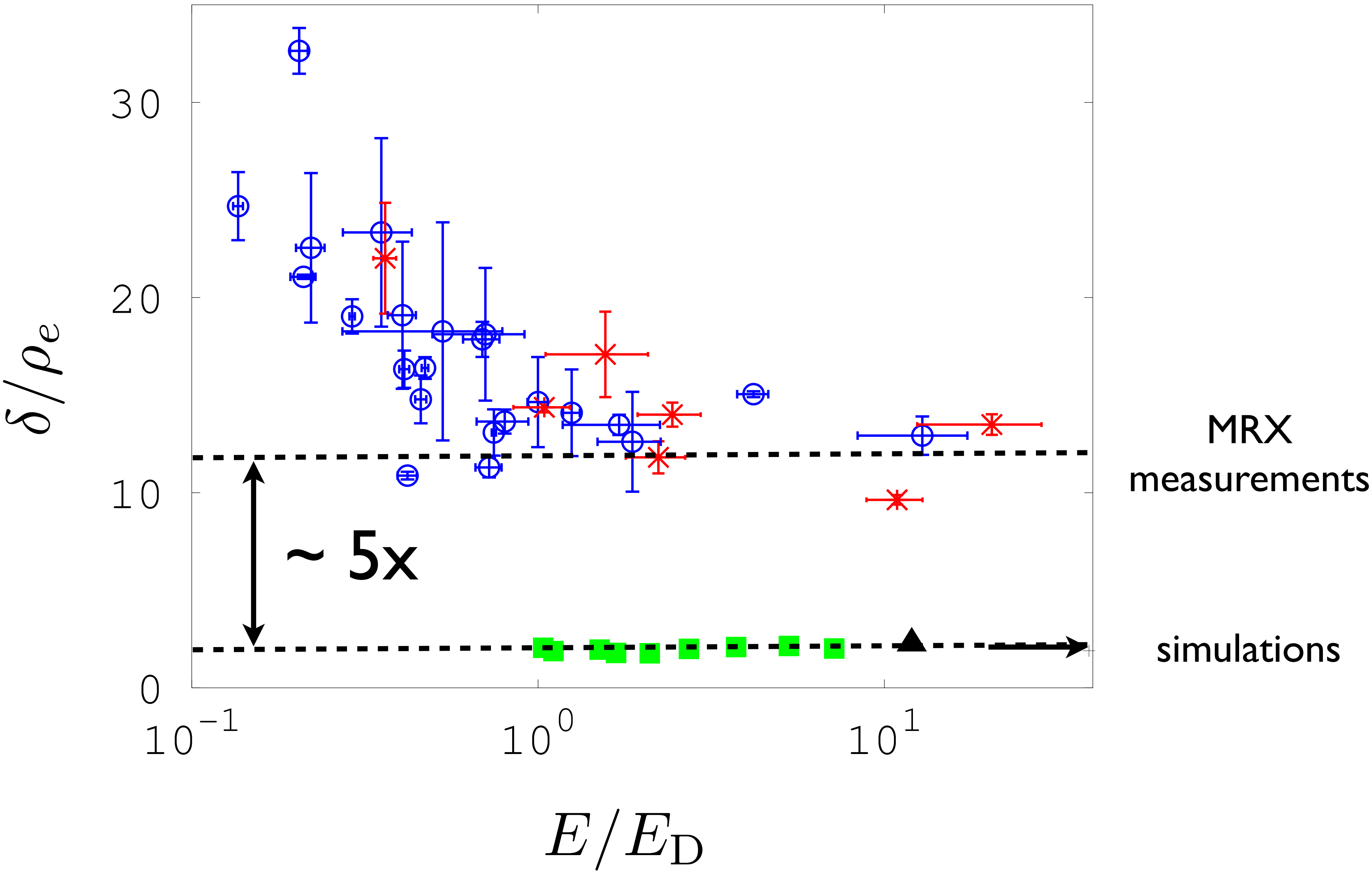
Daughton PoP (2003)



- Also consistent with space observations
- Layer width discrepancy still persists!

V. Roytershteyn et al. PoP (2013)

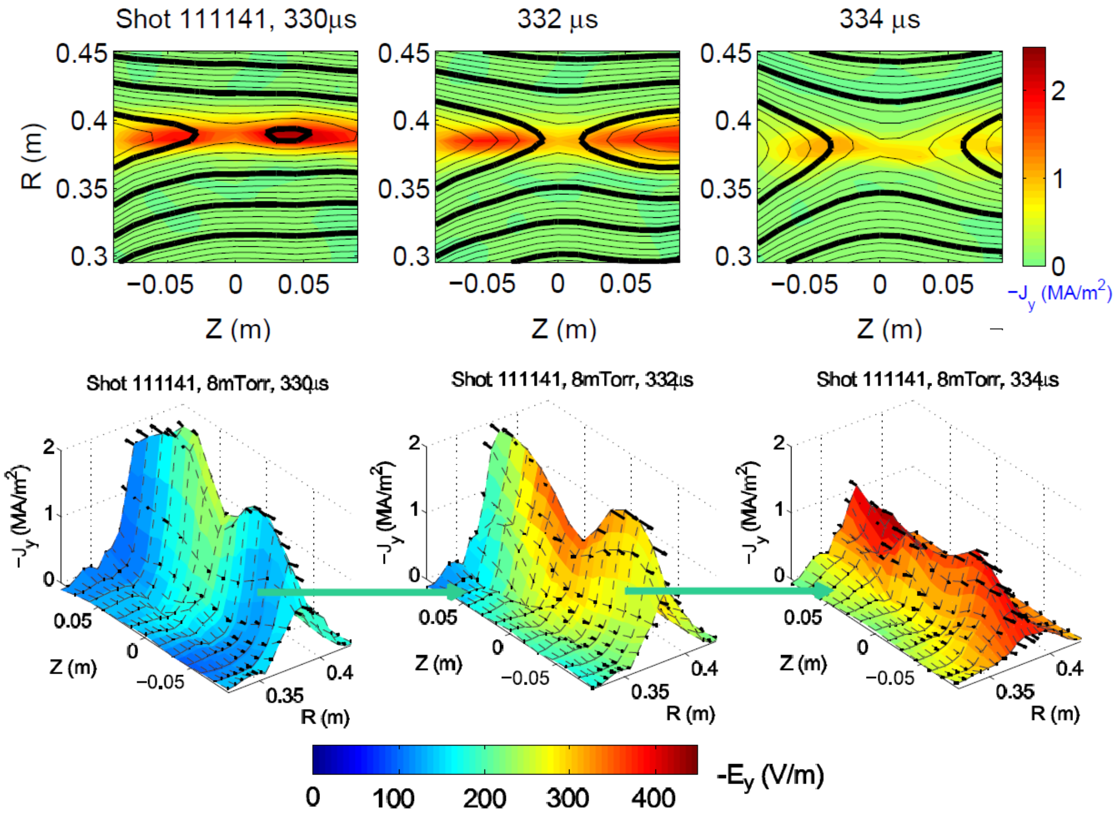
Why???

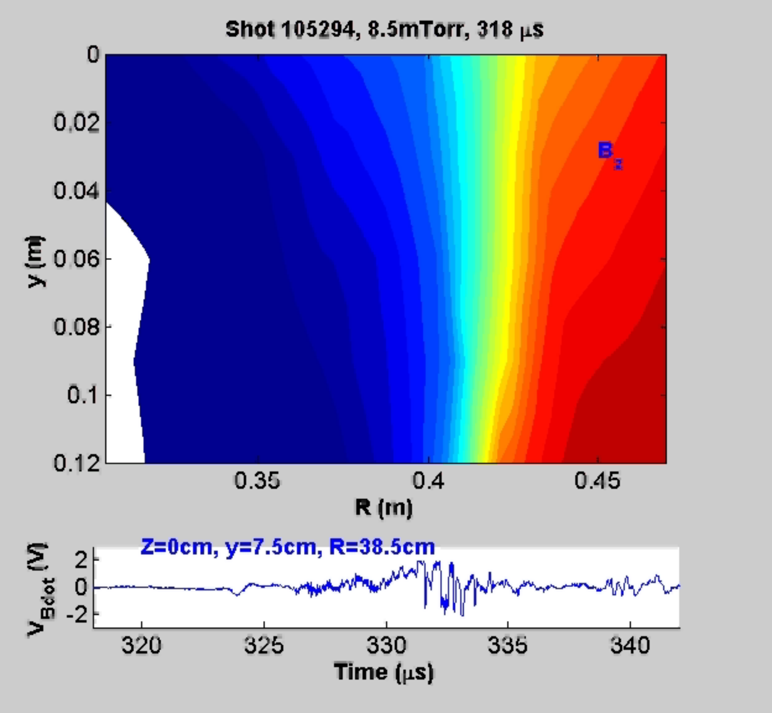


δ/ρ_e
30
20
10
0
10^{-1}
10^{0}
10^{1}
E/E_{D}
~ 5x
MRX measurements
simulations

Impulsive Reconnection due to 3D Flux Rope Ejection Out of Current Sheet

S. Dorfman et al. GRL (2013)



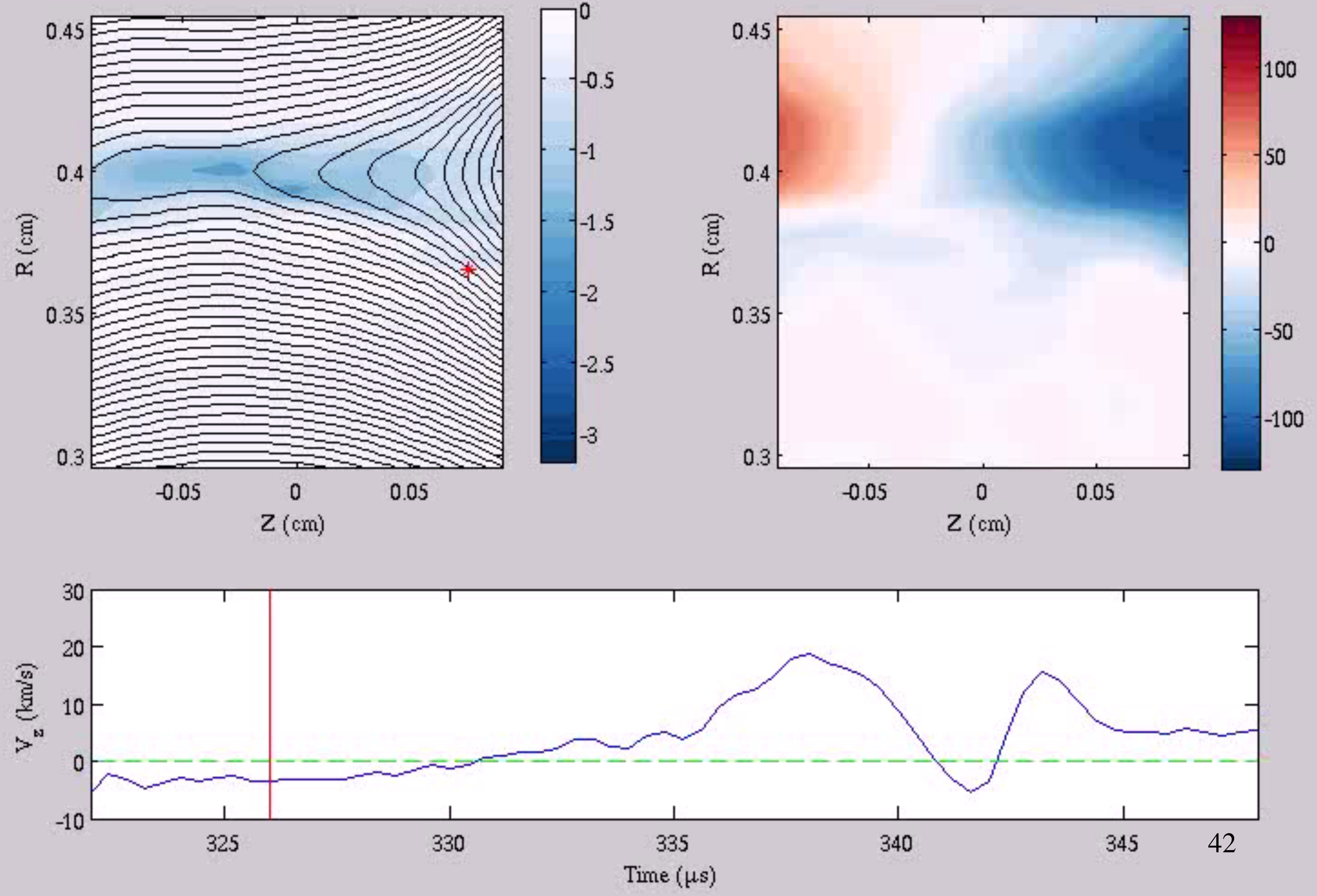


In-plane

Out-of-the-plane

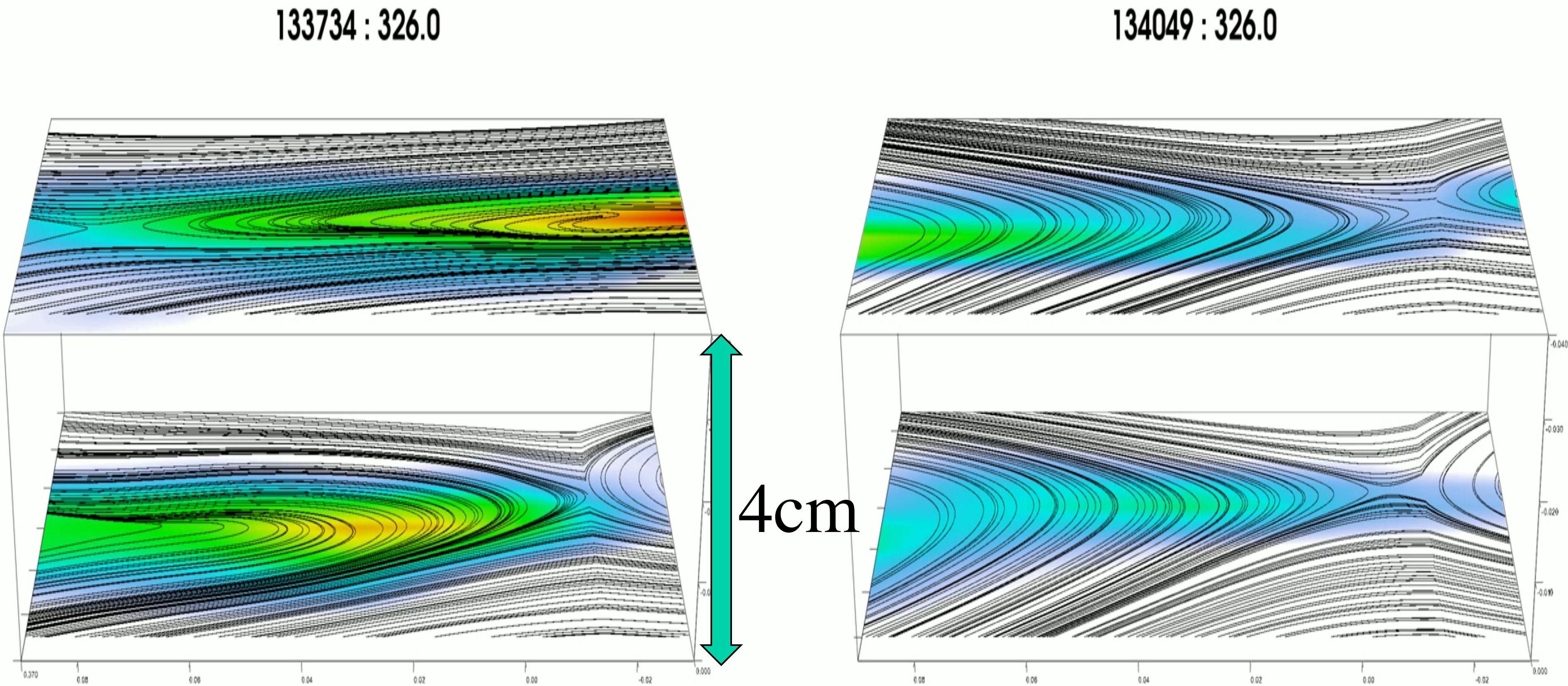
Flux Rope Dynamics

J. Yoo (2012)



3D Flux Ropes Confirmed!

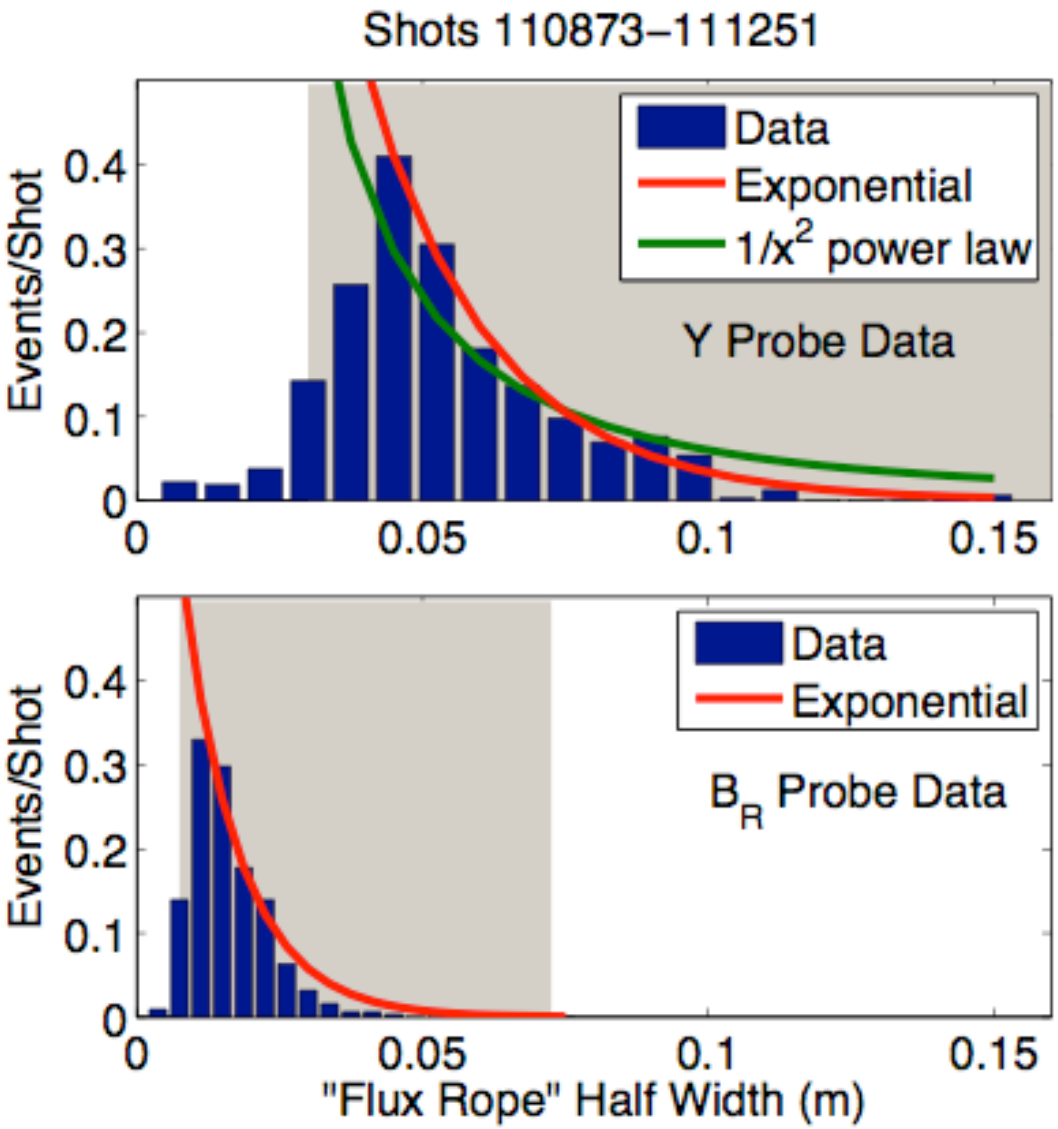
J. Jara-Almonte (2012)



Very 3D

~ 2D

Flux Rope Dynamics May Explain the Observed Thicker Layers



Uzdensky et al. (2010):
1/x^2

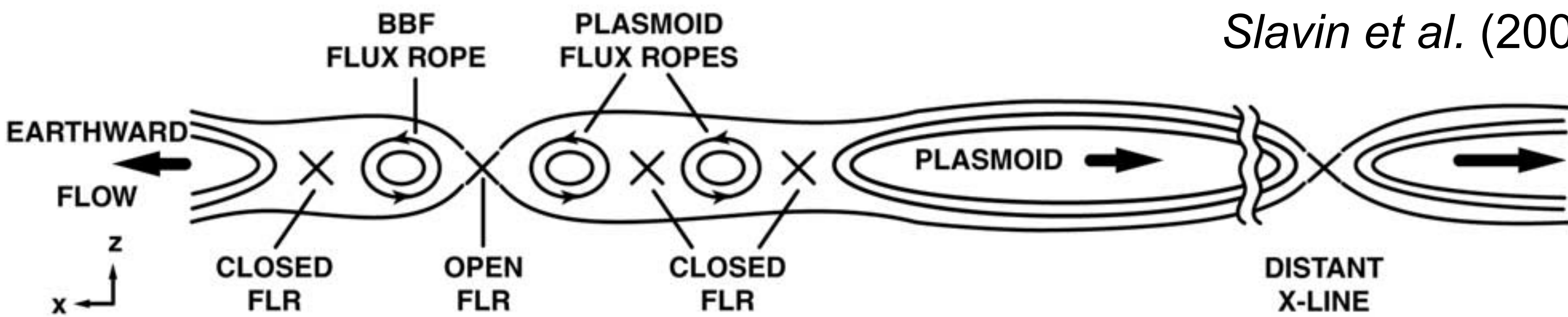
Fermo et al. (2010):
exp(-x)

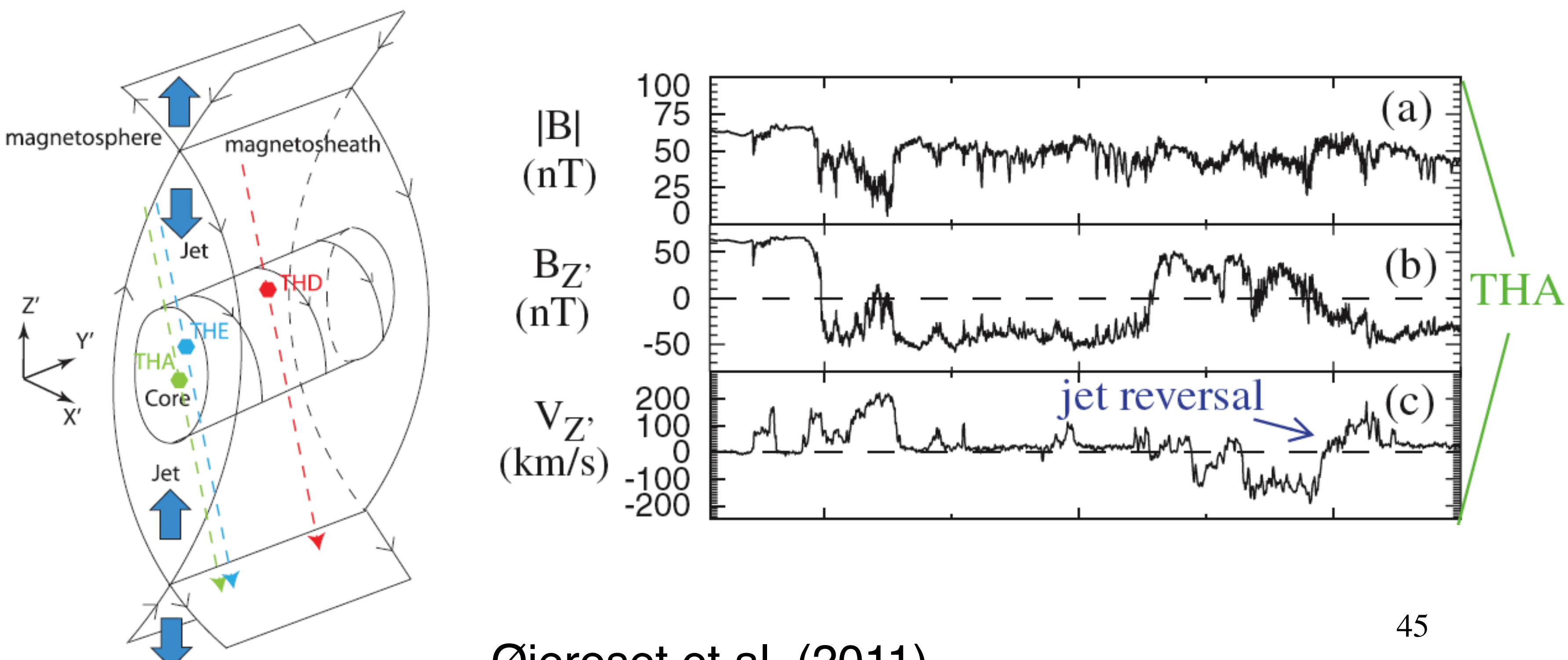
Huang & Bhattacharjee (2012):
1/x

S. Dorfman (2011)

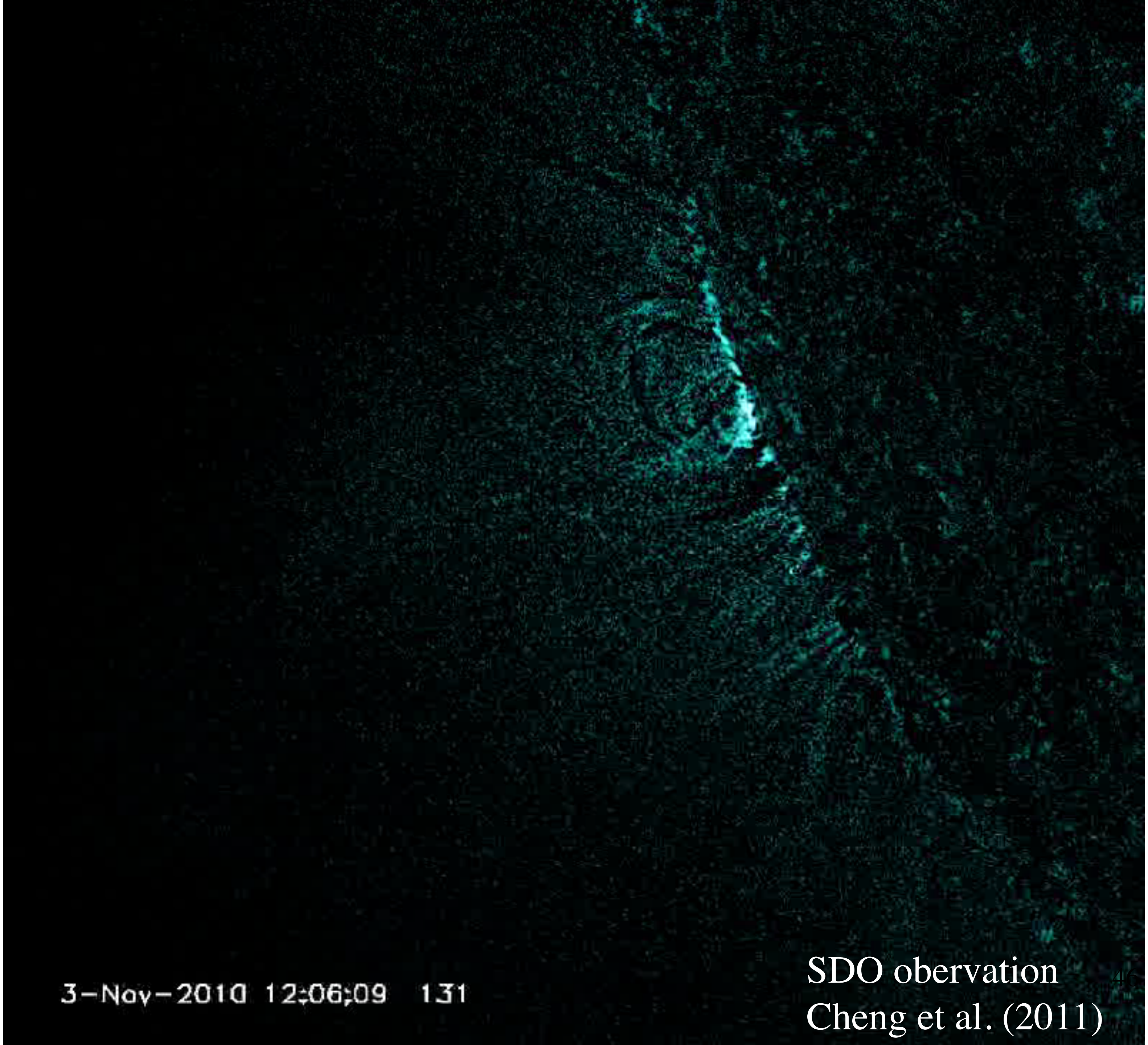
Flux Ropes in Space Plasmas

Slavin et al. (2003)





Øieroset et al. (2011)



SDO obervation
Cheng et al. (2011)

Is the reconnection rate the only question?

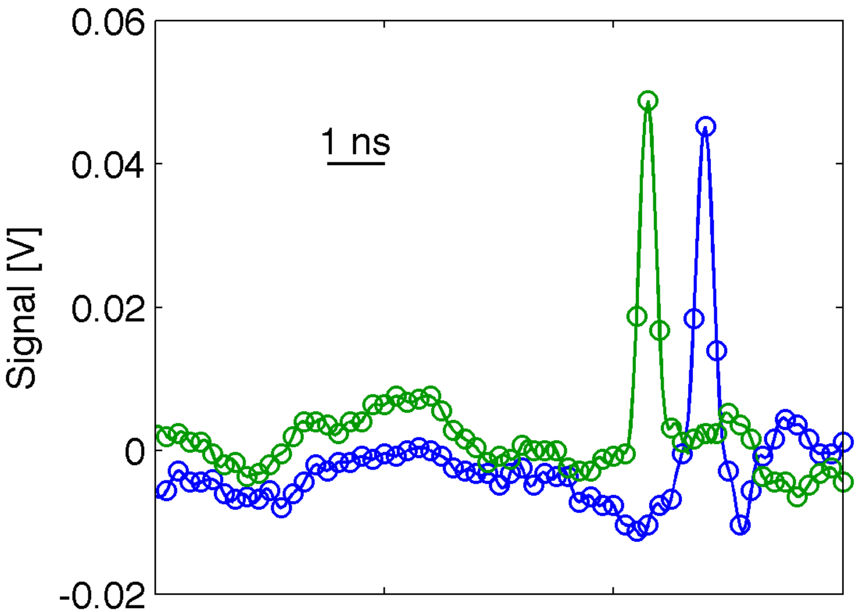
Fundamental Reconnection Questions

- **How is reconnection rate determined?** ***(The rate problem)***

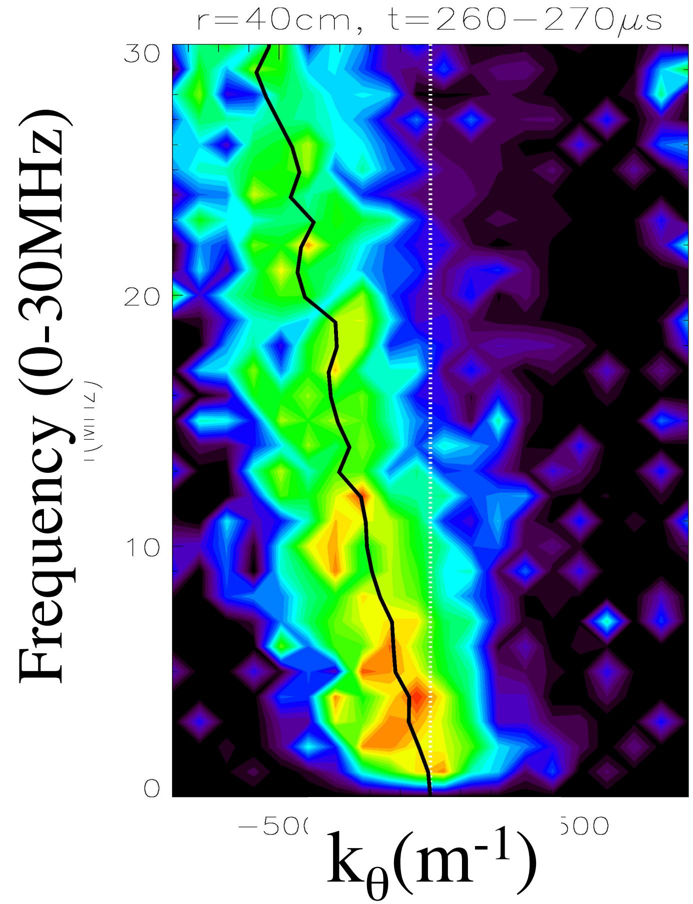
- **How does reconnection take place in 3D?** ***(The 3D problem)***

Local 3D: Micro-Turbulence in Current Sheet Characterized

Carter et al. PRL (2002) Ji et al. PRL (2004) Fox et al. PRL (2008) Dorfman et al. (2011) Inomoto et al. (2012) Roytershteyn et al. (2012)



VTF: electron space holes



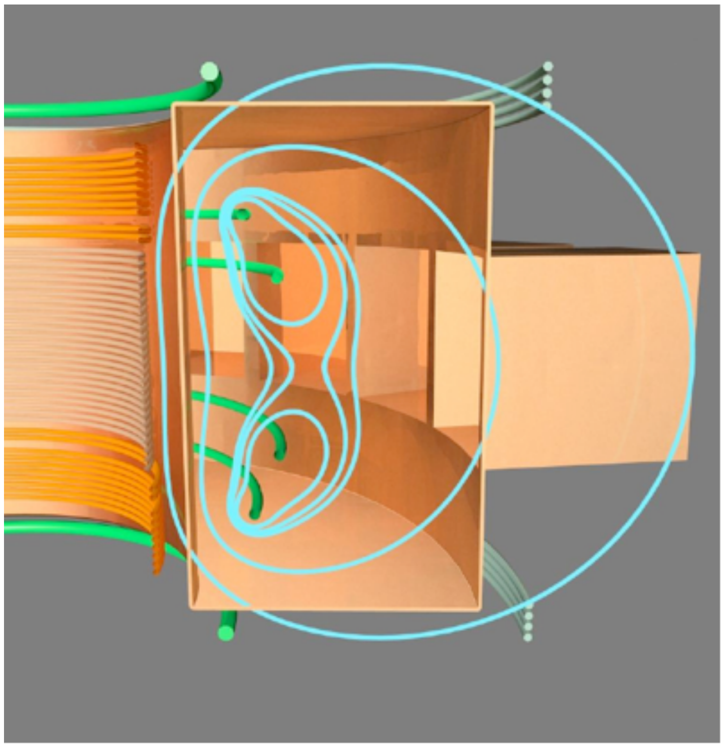
MRX: EM LH waves

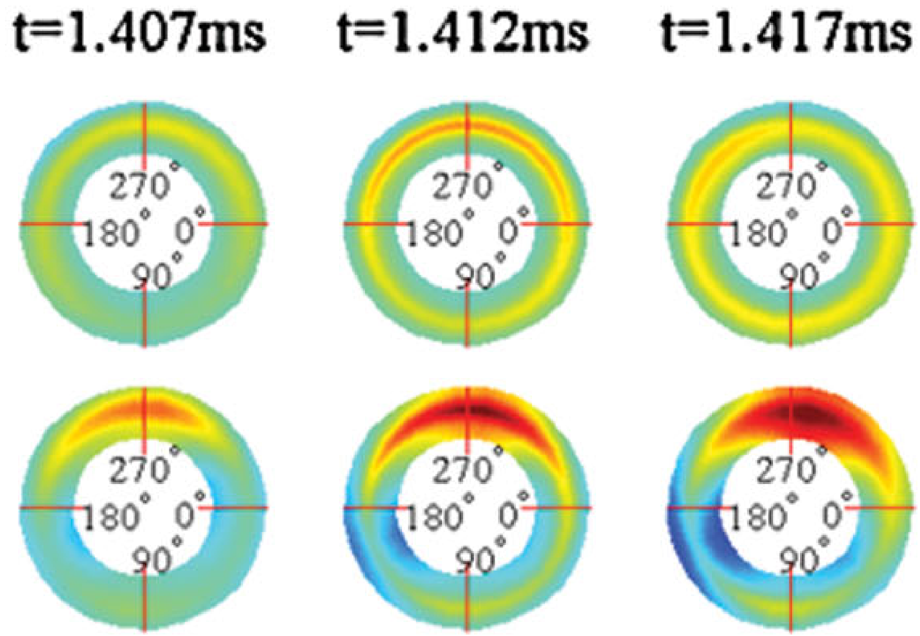
- How about flux ropes?

Fundamental Reconnection Questions

- **How is reconnection rate determined?** ***(The rate problem)***
- **How does reconnection take place in 3D?** ***(The 3D problem)***
- **How does reconnection start?** ***(The onset problem)***

Global 3D: Cause of the Reconnection Onset in Periodic Systems

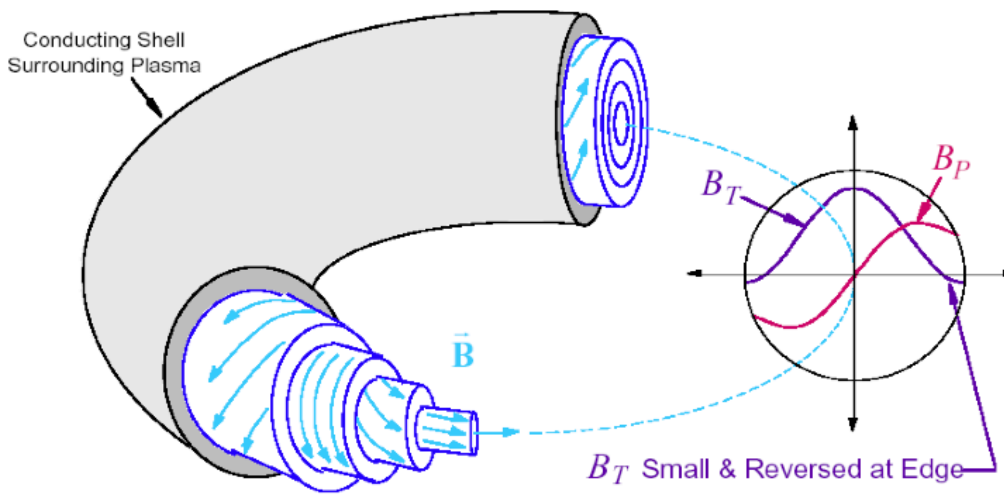




Katz et al. (2010)

Versatile Toroidal Facility (MIT)

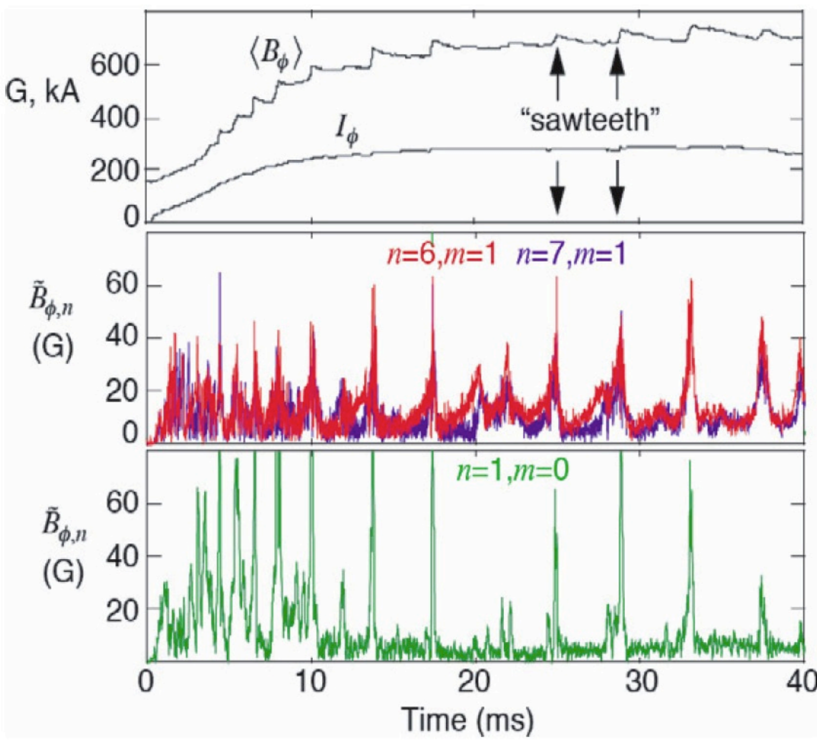
Global 3D: Cause of the Reconnection Onset in Periodic Systems



(a)

b)

c)



Madison Symmetric Torus (Wisconsin)

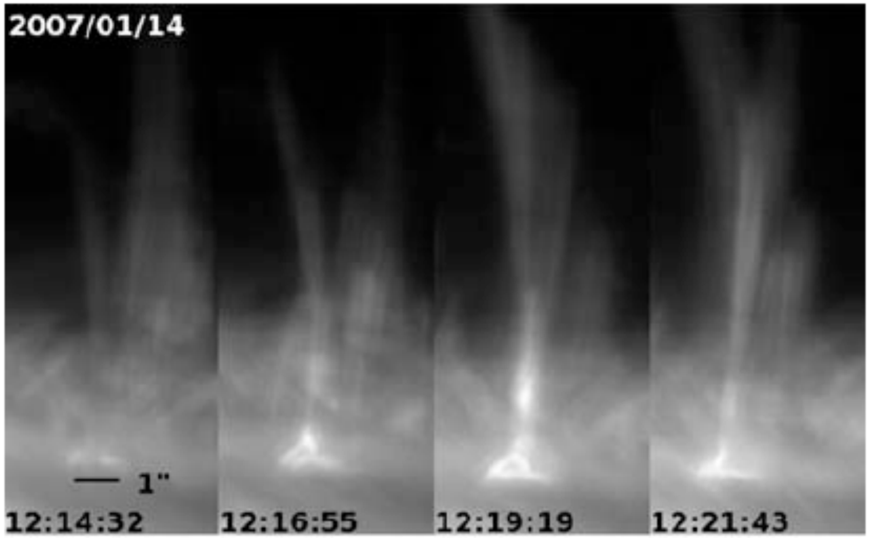
Prager et al. (2005)

Fundamental Reconnection Questions

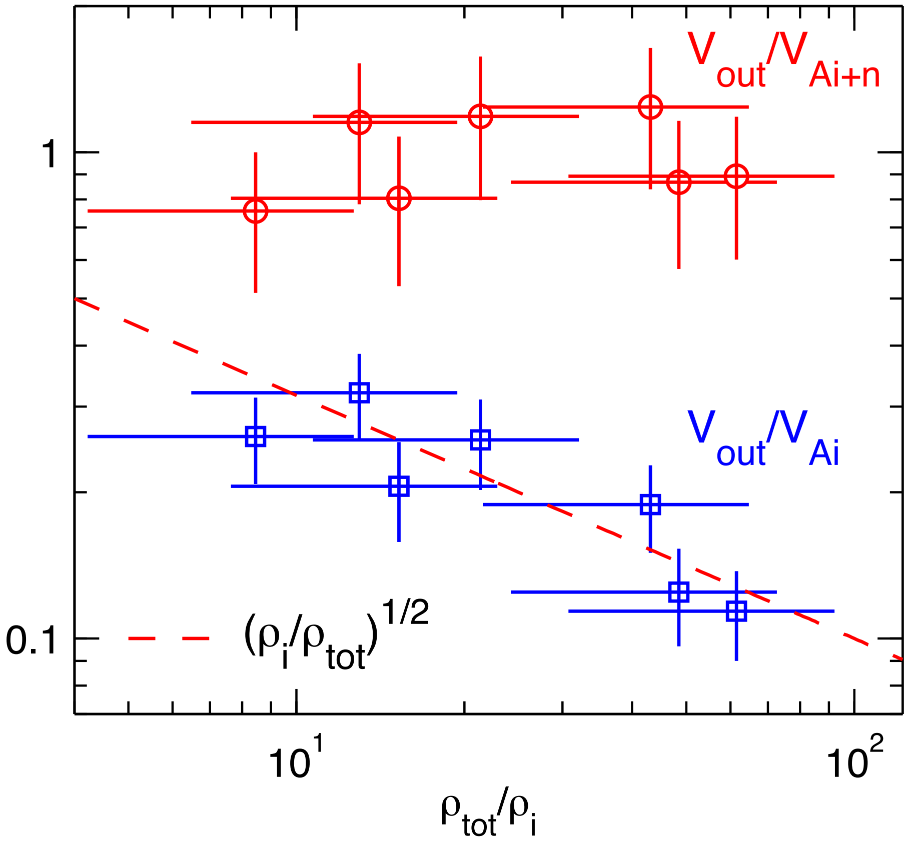
- **How is reconnection rate determined? (*The rate problem*)**
- **How does reconnection take place in 3D? (*The 3D problem*)**
- **How does reconnection start? (*The onset problem*)**
- **How does partial ionization affect reconnection? (*The partial ionization problem*)**

The Partial Ionization Problem: Reconnection is faster or slower?

Solar chromosphere is a dynamic place for magnetic reconnection



Shibata et al., Science (2007)



MRX

Lawrence et al. PRL (2013)

Fundamental Reconnection Questions

- **How is reconnection rate determined? *(The rate problem)***
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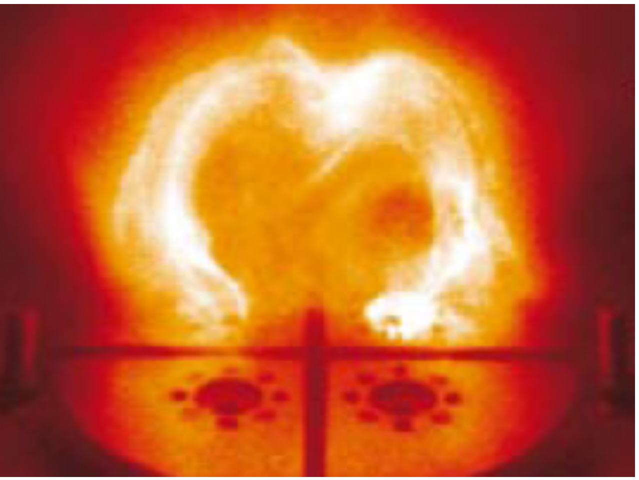
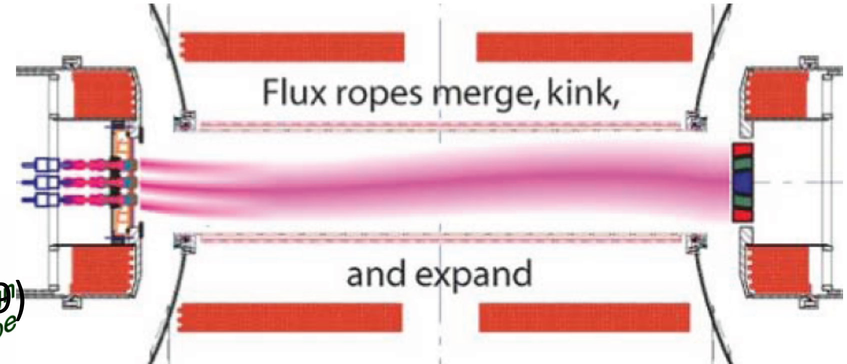
- **How does reconnection start? *(The onset problem)***
- **How does partial ionization affect reconnection? (*The partial ionization problem*)**
- **How do boundary conditions affect reconnection process? *(The boundary condition problem)***

The Boundary Problem: Line-tied or Free-end for Flux Rope Dynamics

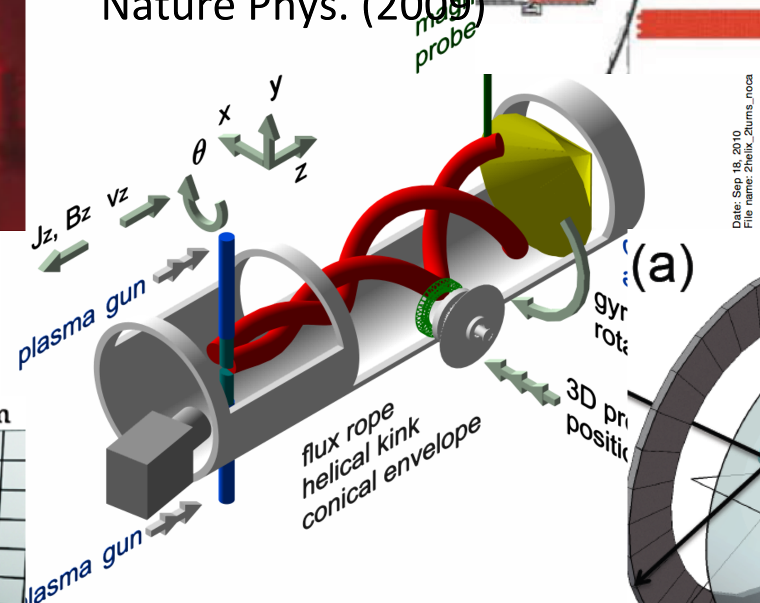
Hansen & Bellan ApJ (2004)

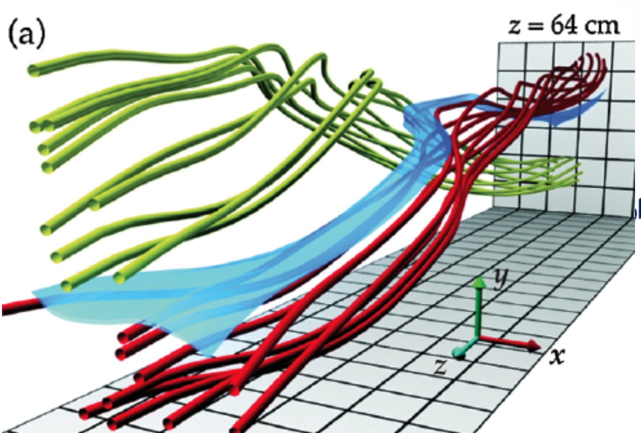


Bergerson et al. PRL (2006)



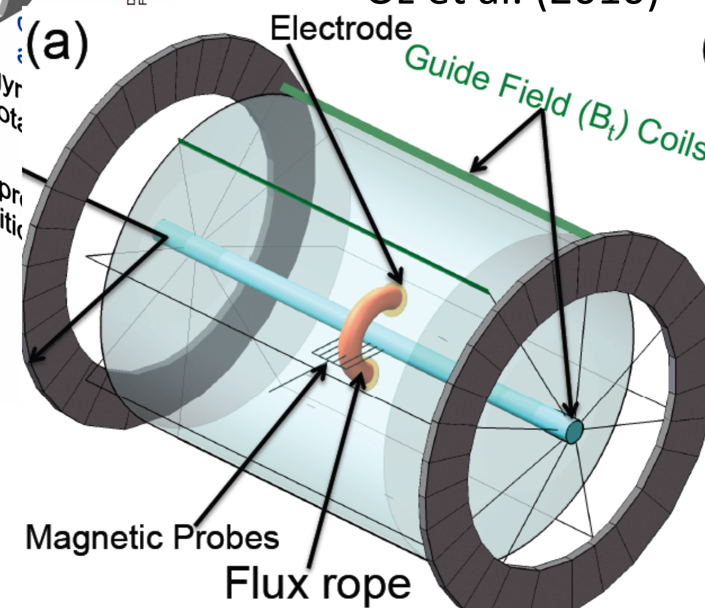
Intrator et al.
Nature Phys. (2009)





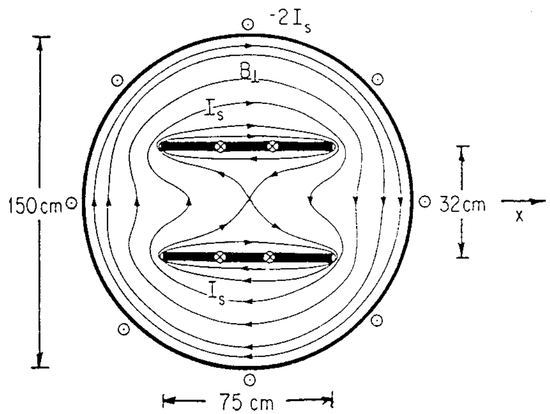
Lawrence & Gekelman
PRL (2009)

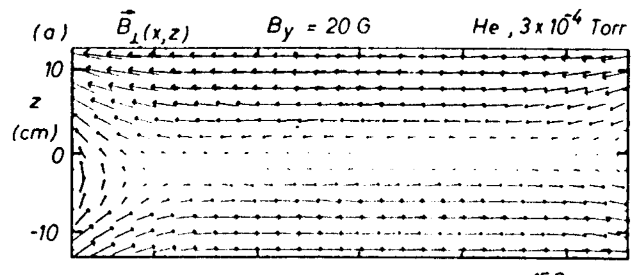
Oz et al. (2010)



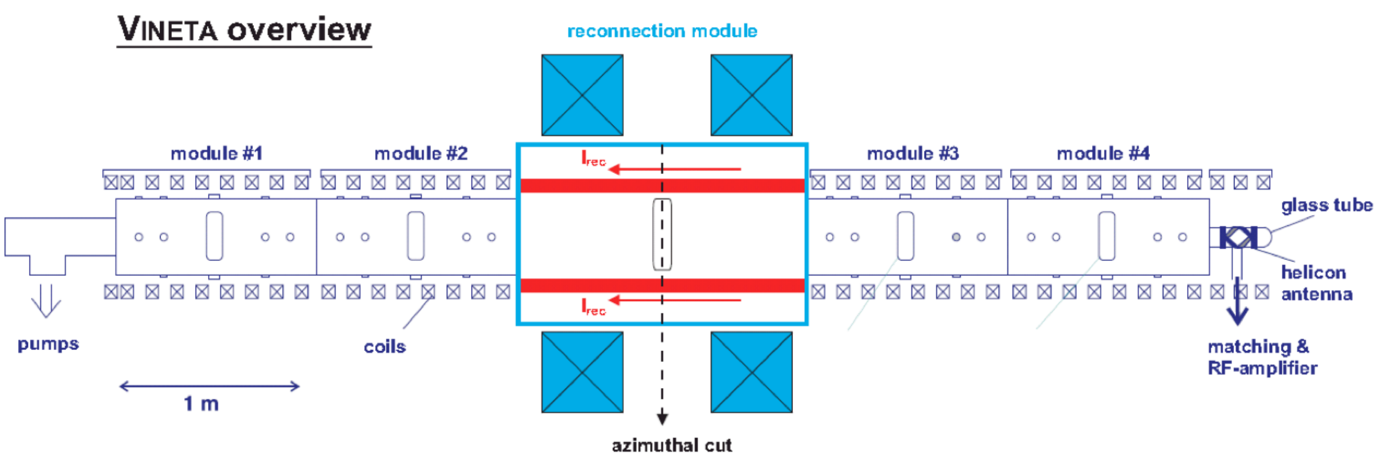
Revisiting EMHD Physics in Current Sheet

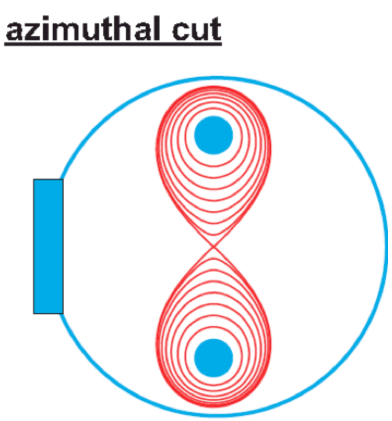
80’ Stenzel & Gekelman: S=1-10 but ρ_i >> L: EMHD





2013 O. Grulke et al. at VINETA





Fundamental Reconnection Questions

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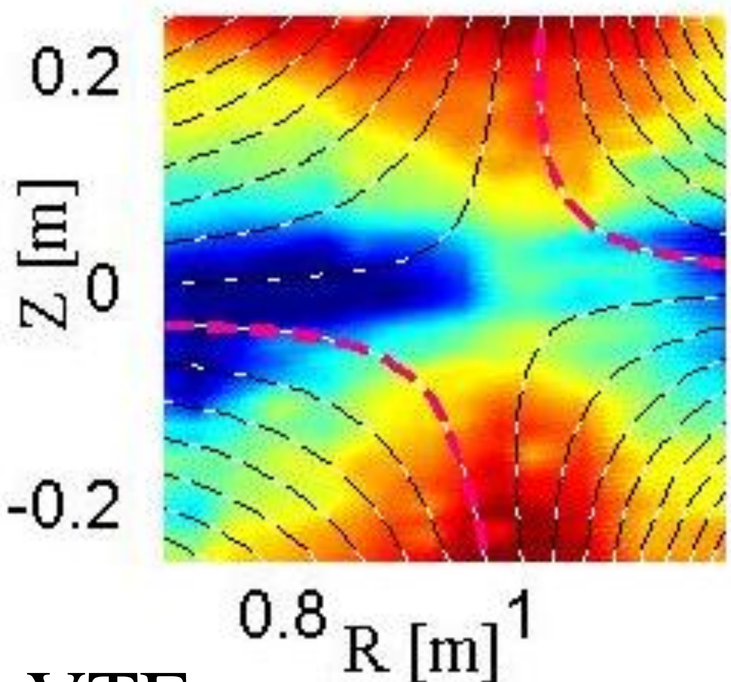
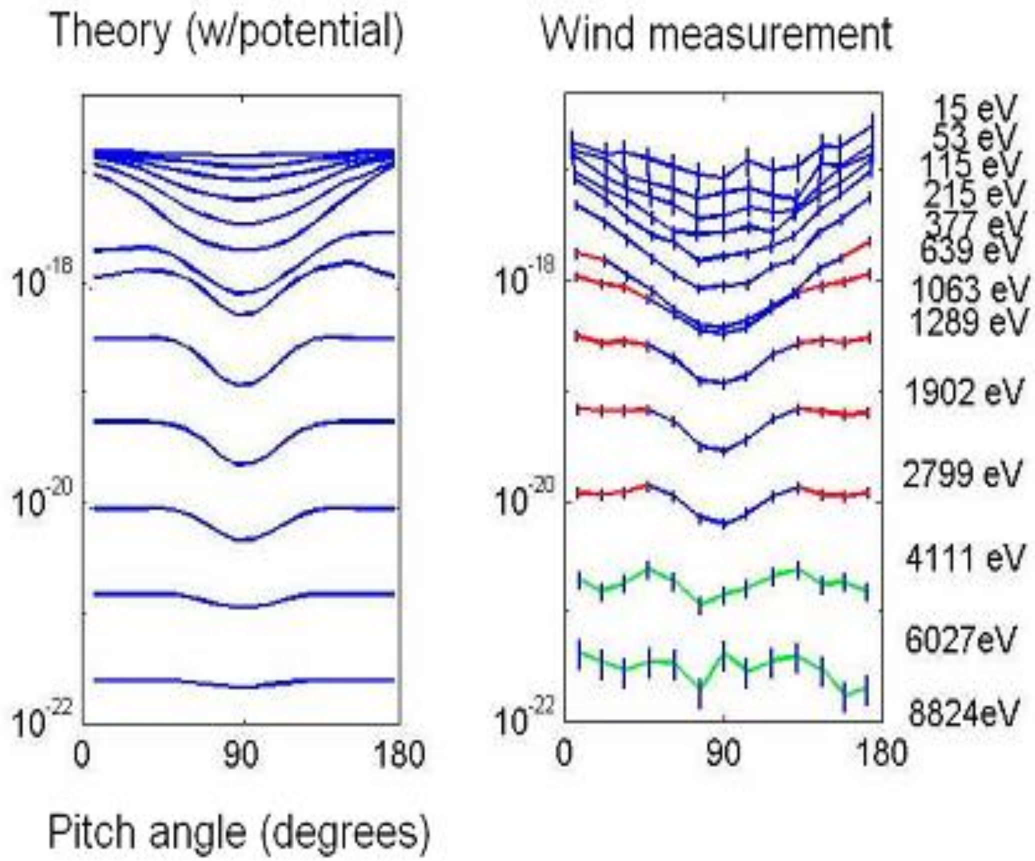
- **How does partial ionization affect reconnection? (*The partial ionization problem*)**
- **How do boundary conditions affect reconnection process? *(The boundary condition problem)***
- **How are particles energized? *(The energy problem)***

The Energy Problem: Electron Energization

Egedal et al. (2005)

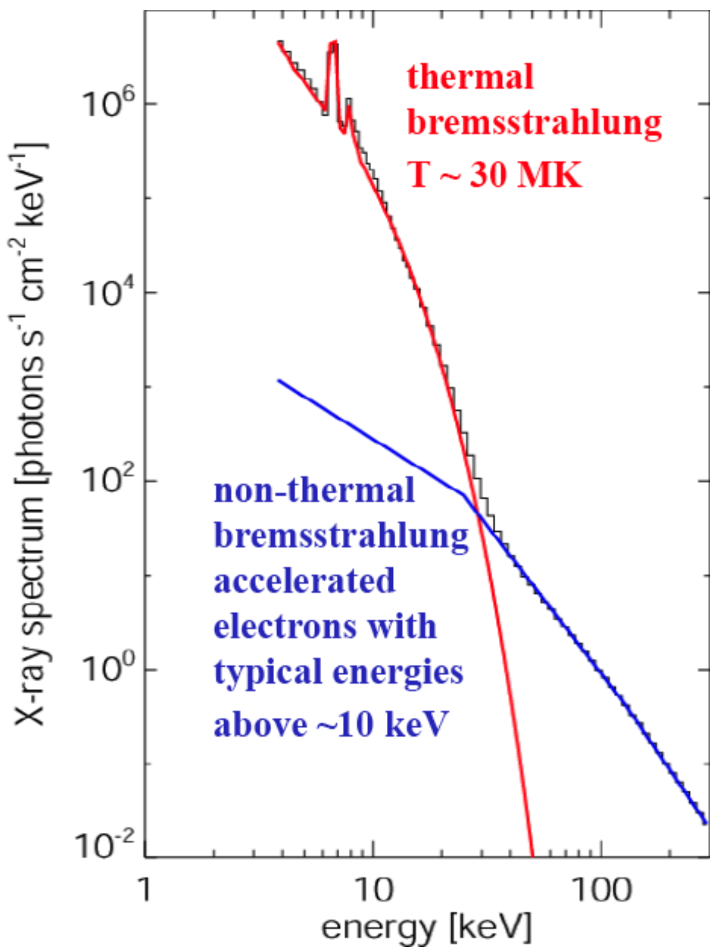


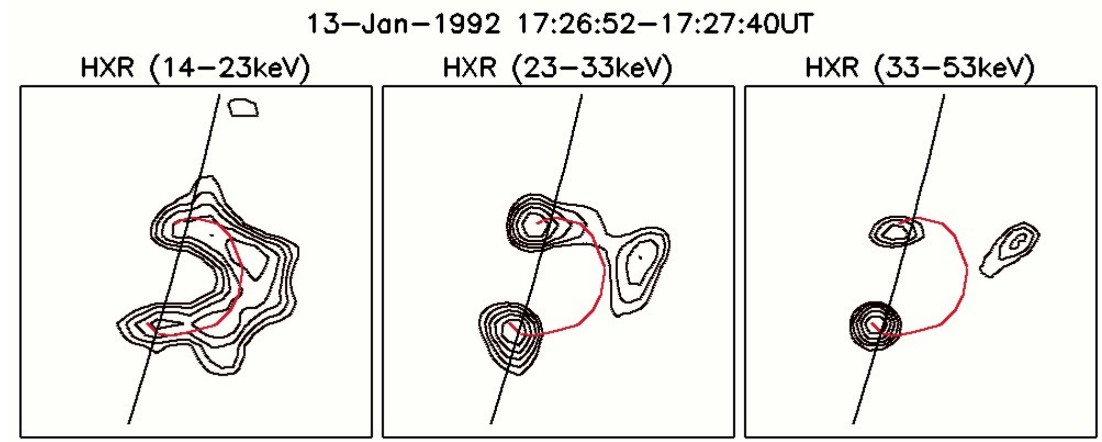
VTF

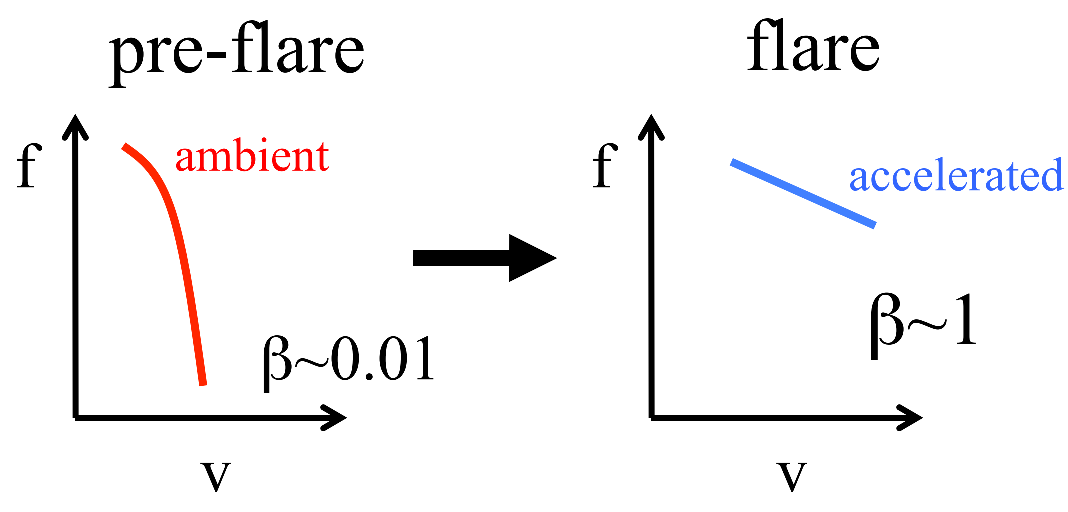


- Potential well around X-line, based on results from VTF experiment, can explain measured electron distribution function in space

“The Number Problem” From Solar Flare







A significant fraction of energetic electrons (even ions) accelerated at reconnection side [e.g. *Krucker et al. (2010), Shih et al. (2009)*].

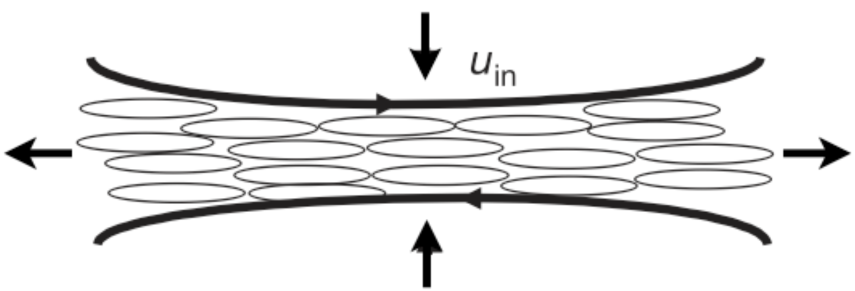
Two Competing Ideas for Electron Energization

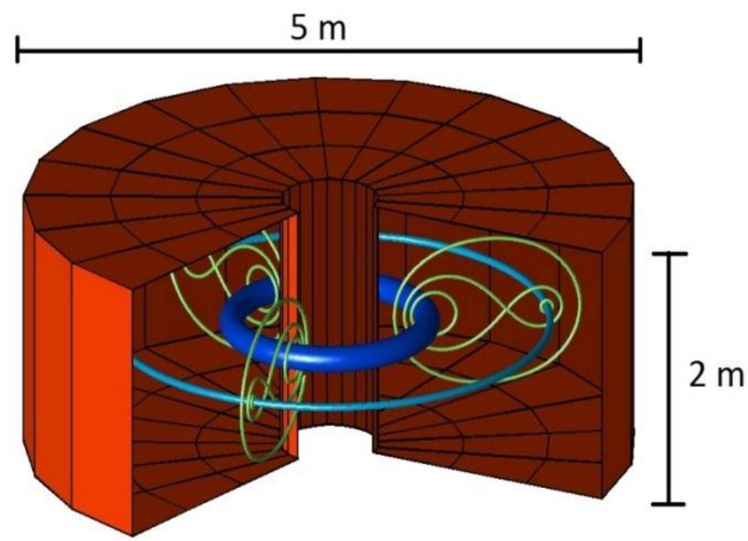
- Electron energization by a single X-line reconnection through a modified CGL model [Egedal et al. (2012)]

$$\Phi_{\|} \gg T_e \;\Rightarrow\; p_{\|} \propto \frac{n^3}{B^2}$$

$$p_{\perp} \propto nB$$

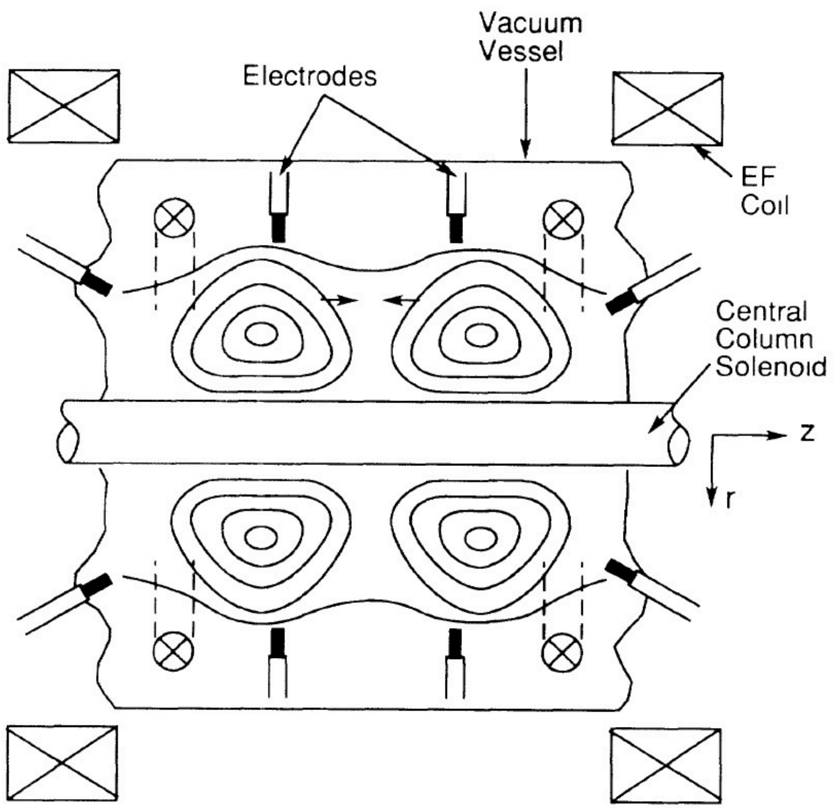
- Electron energization by multiple island interactions [e.g. Drake et al. (2006), Oka et al. (2010)].

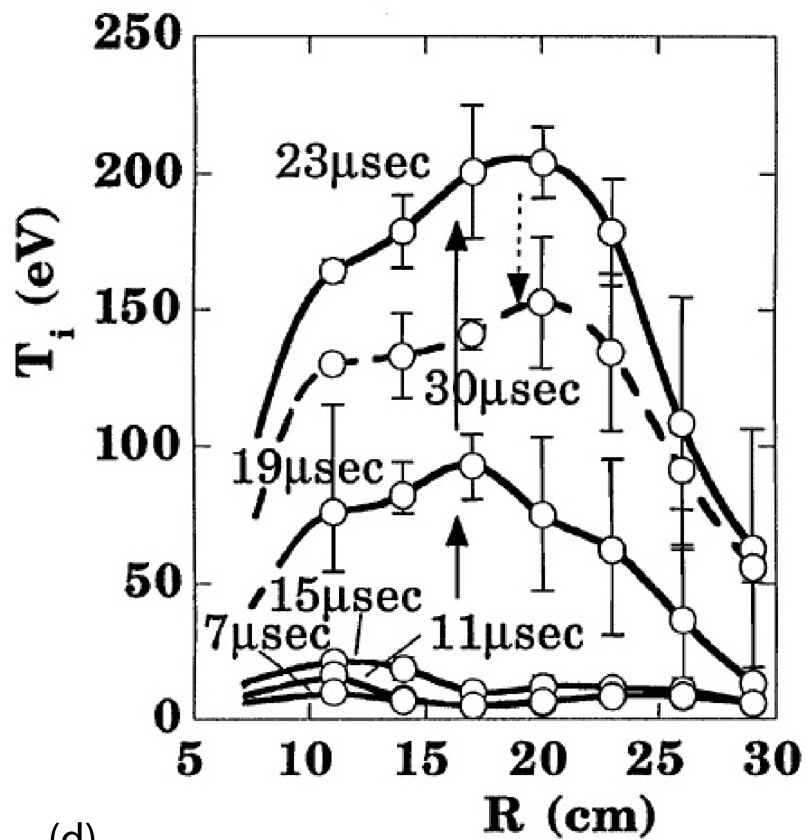




Proposed Large Reconnection Experiment

The Energy Problem: Ion Energization





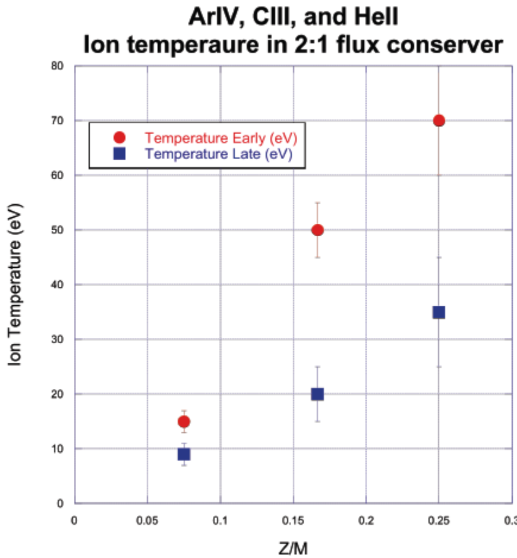
(d)

1990's Y. Ono, M. Yamada +

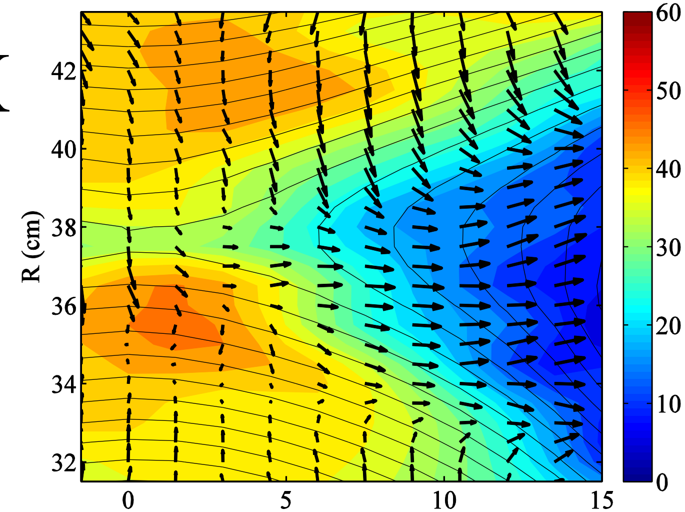
The Energy Problem: Ion Energization

Fiksel et al. PRL (2009) Brown et al. (2009) Magee et al. (2011) Yoo et al. (2013)

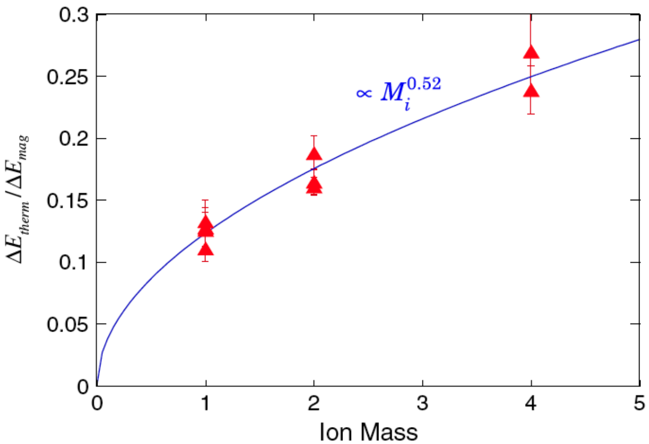
SSX

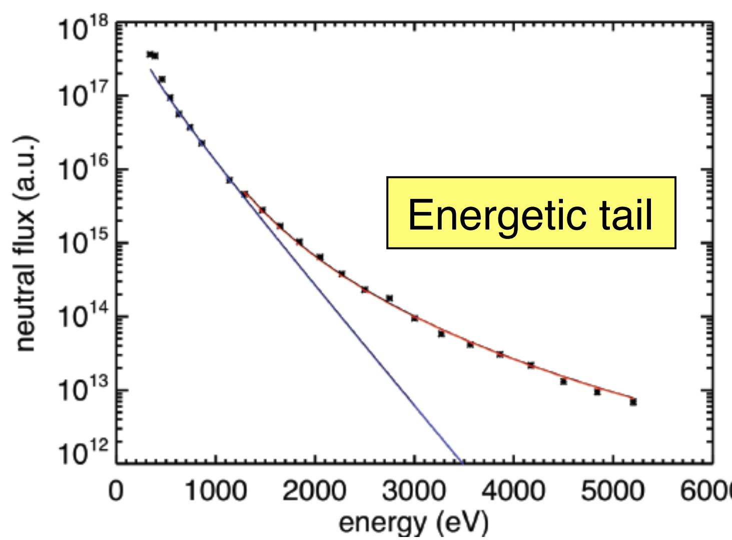


MRX



MST





- Many competing ideas: waves, pick-up process, stochastic process…

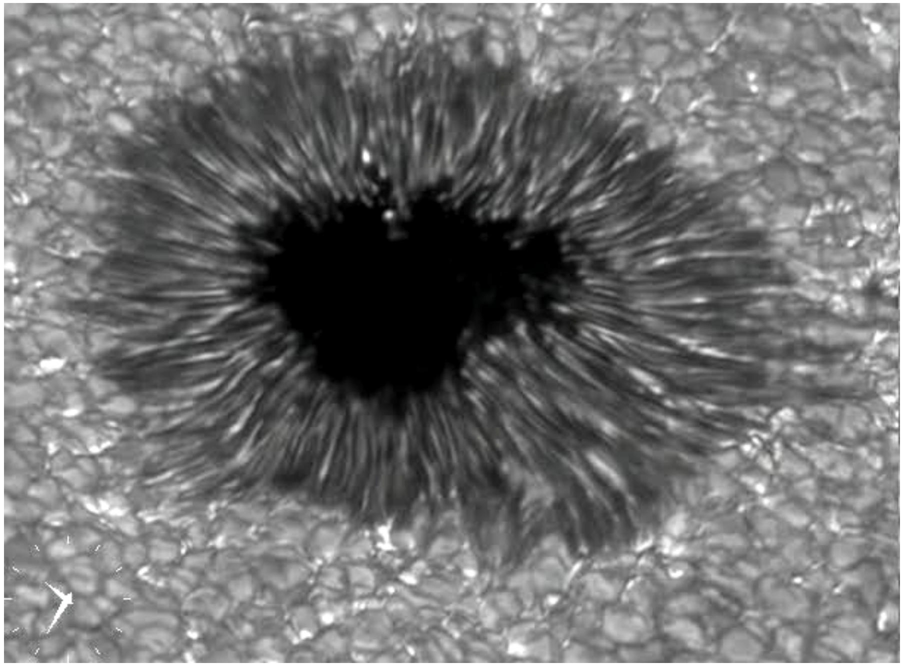
Fundamental Reconnection Questions

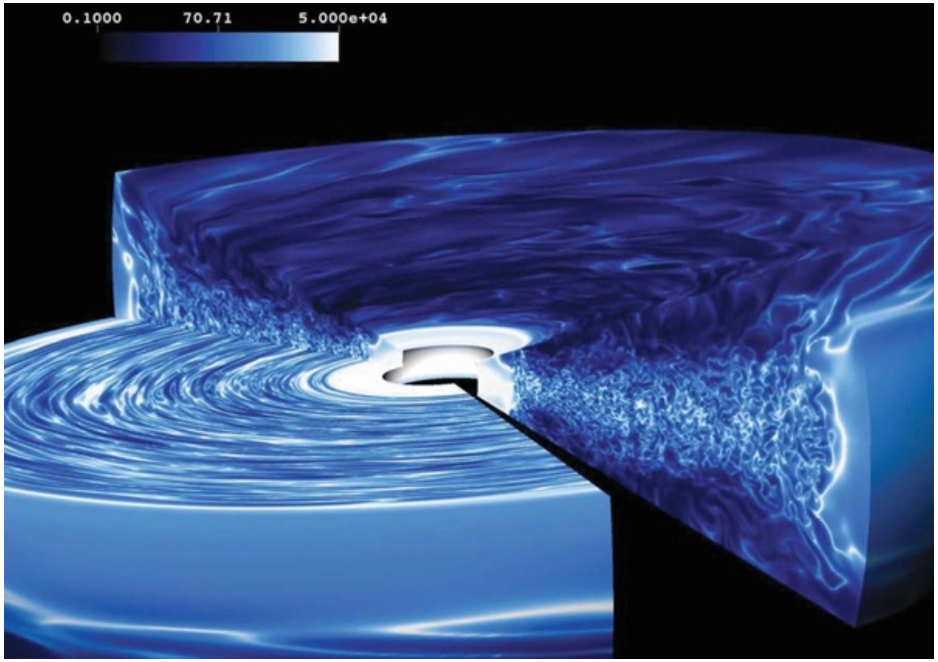
- **How is reconnection rate determined?** ***(The rate problem)***
- **How does reconnection take place in 3D?** ***(The 3D problem)***
- **How does reconnection start?** ***(The onset problem)***
- **How does partial ionization affect reconnection? (*The partial ionization problem*)**
- **How do boundary conditions affect reconnection process?** ***(The boundary condition problem)***
- **How are particles energized?** ***(The energy problem)***
- **How does reconnection take place in flow-driven, radiative, relativistic or strongly magnetized plasmas?** ***(The flow-driven problem)***

Magnetic Reconnection is Considered to be also Important in Flow-Dominated Regimes

- Sunspots are magnetic, drifting towards equator, and then disappear. What happens to these sunspots?
- Reconnection dominates dissipation in low-beta regions of accretion disks

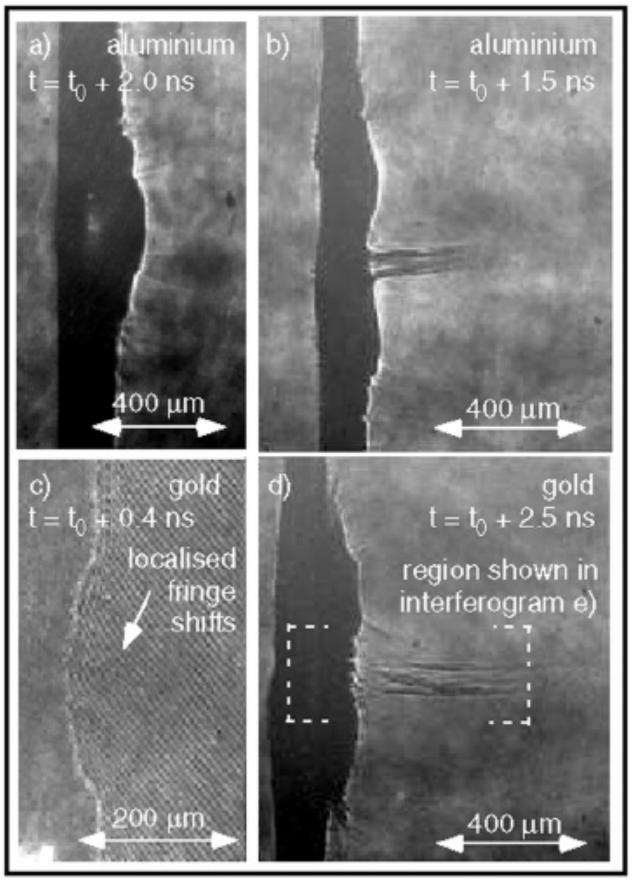
Flock et al. (2011)



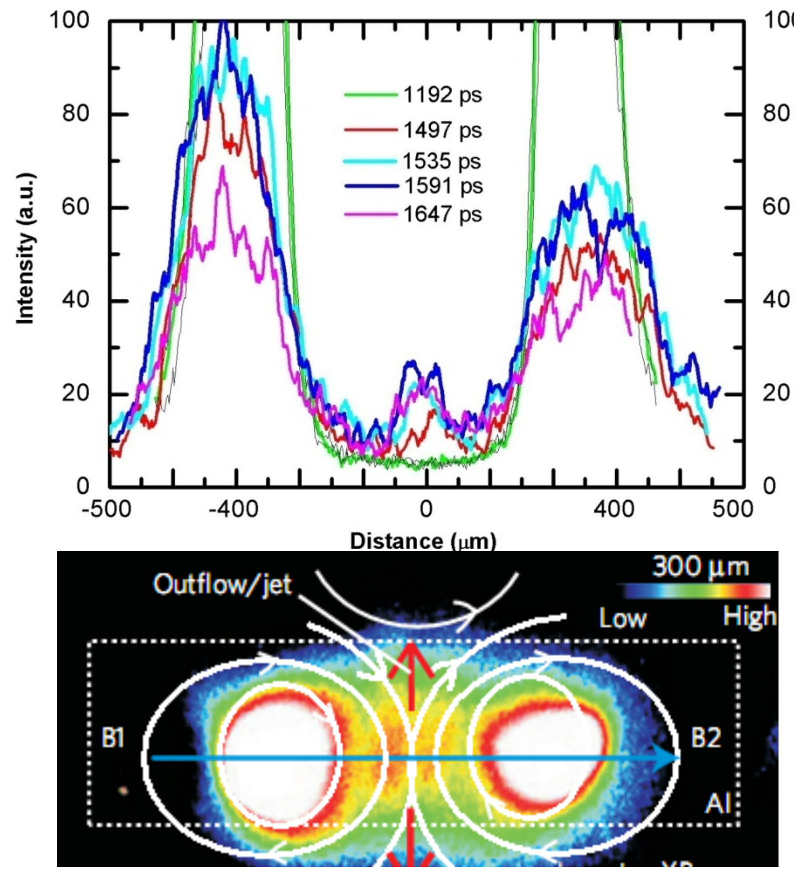


A New Venue Is Emerging to Study Reconnection under Flow-Driven Conditions

Nilson et al. (2006)



Zhong et al. (2010)



- Bi-directional plasma jets observed

- Ion diffusion region with the width of ~d
- Electron diffusion region with the width of ~10d_e

Fundamental Reconnection Questions

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- **How does partial ionization affect reconnection? (*****The partial ionization problem*****)**
- **How do boundary conditions affect reconnection process?** ***(The boundary condition problem)***
- **How are particles energized?** ***(The energy problem)***
- **How does reconnection take place in flow-driven, radiative, relativistic or strongly magnetized plasmas?** ***(The flow-driven problem)***
- **How to apply local reconnection physics to a large system?** ***(The multi-scale problem)***

Characteristics of Space/Astrophysical Plasmas Where Reconnection May Occur

- **Lundquist # (S) is large**
- **Large scale separation between global MHD and ion kinetic scales**

$$\lambda \equiv \frac{L}{\rho_s} \quad \textbf{large}$$

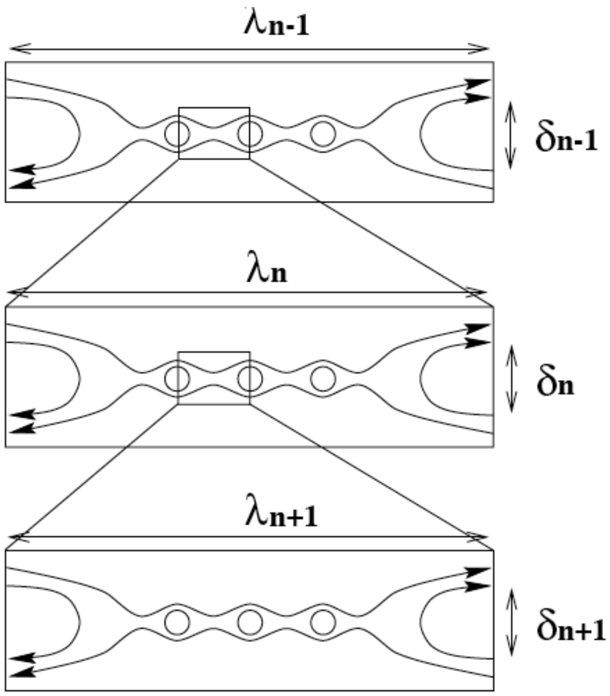
- **How to couple the global MHD scales to kinetic scales?**

location	plasma	S	λ	multiple X-line regime
Space	Magnetopause	6×10^{13}	9×10^{2}	Collisionless
	Magnetotail	4×10^{15}	1.3×10^{3}	Collisionless
	Solar Wind	3×10^{12}	2×10^{5}	Collisionless
Solar	Corona	1×10^{13}	4×10^{7}	Hybrid
	Chromosphere	1×10^{8}	3×10^{8}	Collisional
	Tachocline	1×10^{9}	5×10^{10}	Collisional
Galaxy	Protostellar Disks	8×10^{3}	1×10^{9}	Collisional
	X-ray Binary Disks	3×10^{7}	9×10^{8}	Collisional
	X-B Disk Coronae	1×10^{16}	9×10^{7}	Collisionless
	Crab Nebula Flares	5×10^{20}	2×10^{11}	Hybrid
	Gamma Ray Bursts	6×10^{17}	2×10^{16}	Collisional
	Magnetar Flares	6×10^{16}	5×10^{17}	Collisional
	Sgr A* Flares	2×10^{24}	5×10^{8}	Collisionless
	Molecular Clouds	1×10^{11}	7×10^{12}	Collisional
	Interstellar Media	2×10^{20}	1×10^{14}	Hybrid
Extra-galactic	AGN Disks	2×10^{13}	1×10^{14}	Collisional
	AGN Disk Coronae	10^{23}	3×10^{11}	Collisionless
	Radio Lobes	2×10^{25}	8×10^{12}	Hybrid
	Extragalactic Jets	6×10^{29}	1×10^{14}	Collisionless
	Galaxy Clusters	2×10^{25}	6×10^{11}	Collisionless
Fusion	MST	3×10^{6}	6.2×10^{1}	Collisionless
	TFTR	1×10^{8}	2.3×10^{2}	Collisionless
	ITER	6×10^{8}	5×10^{2}	Collisionless

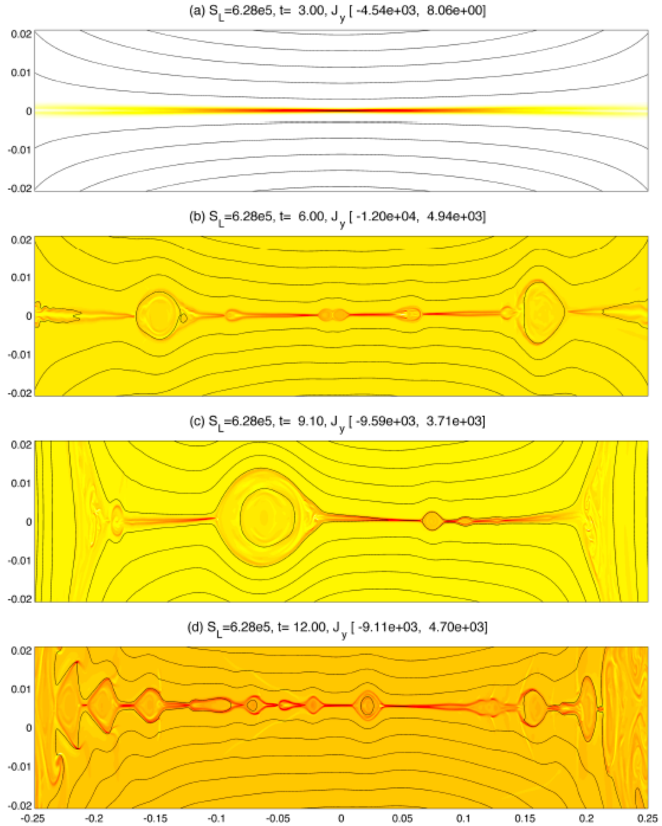
Ji & Daughton (2011)

Plasmoid Dynamics May Solve Scale Separation Problem

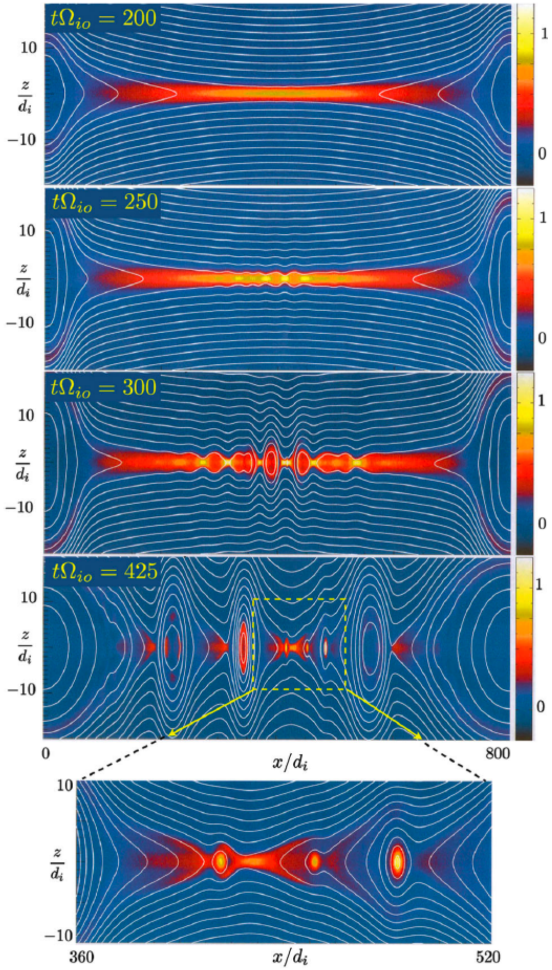
Loureiro et al. (2007); Cassak et al. (2009); Uzdensky et al. (2010) ….



Shibata & Tanuma (2001)



Bhattacharjee et al. (2009)



Daughton et al. (2009)

Can we study this in the lab? We need large plasmas!

Larger is better, but how large is large enough?

A Hierarchy Model of Islands

- Hierarchy of islands:

$$N_1, N_2, N_3, \ldots, N_j$$

$$S_1, S_2, S_3, \ldots, S_j$$

$$\delta_1, \delta_2, \delta_3, \ldots, \delta_j$$

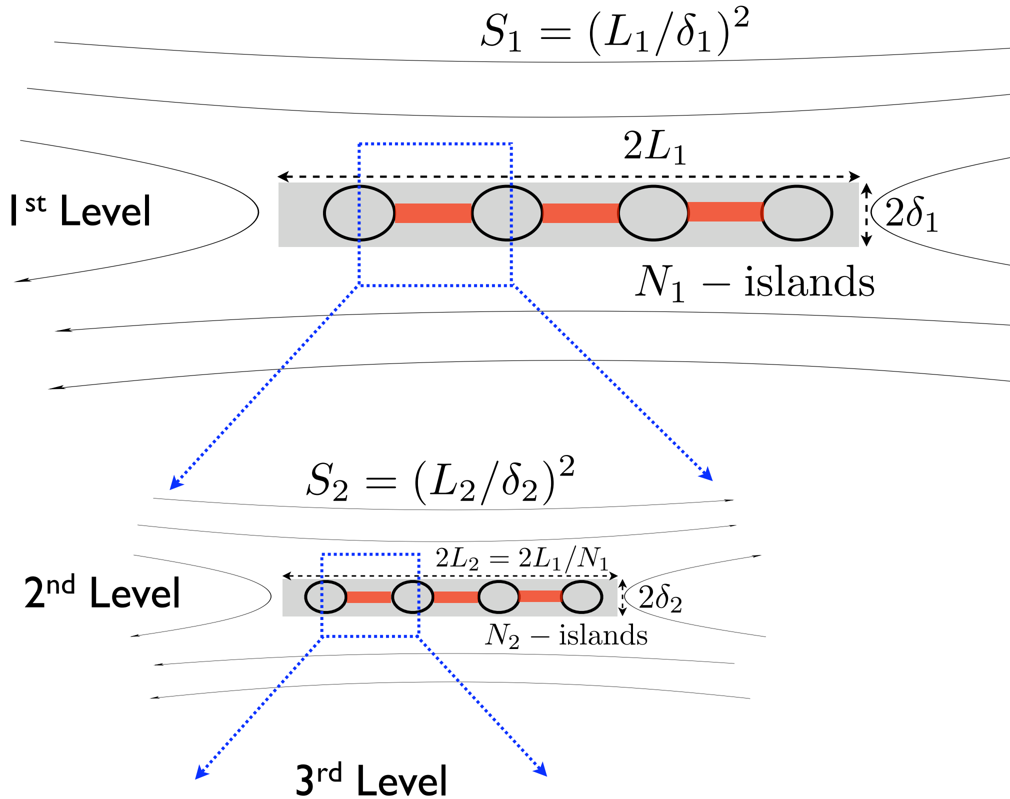
- Assume

$$N_j = \left(\frac{S_j}{S_c}\right)^{\alpha}$$

then

$$\delta_j = \frac{\delta_{j-1}}{\sqrt{N_{j-1}}} = \ldots = \frac{\delta_1}{\sqrt{N_{j-1} N_{j-2} \ldots N_1}} = \rho_s$$

$$\Rightarrow S = \frac{\sqrt{S_c}}{2}\lambda$$

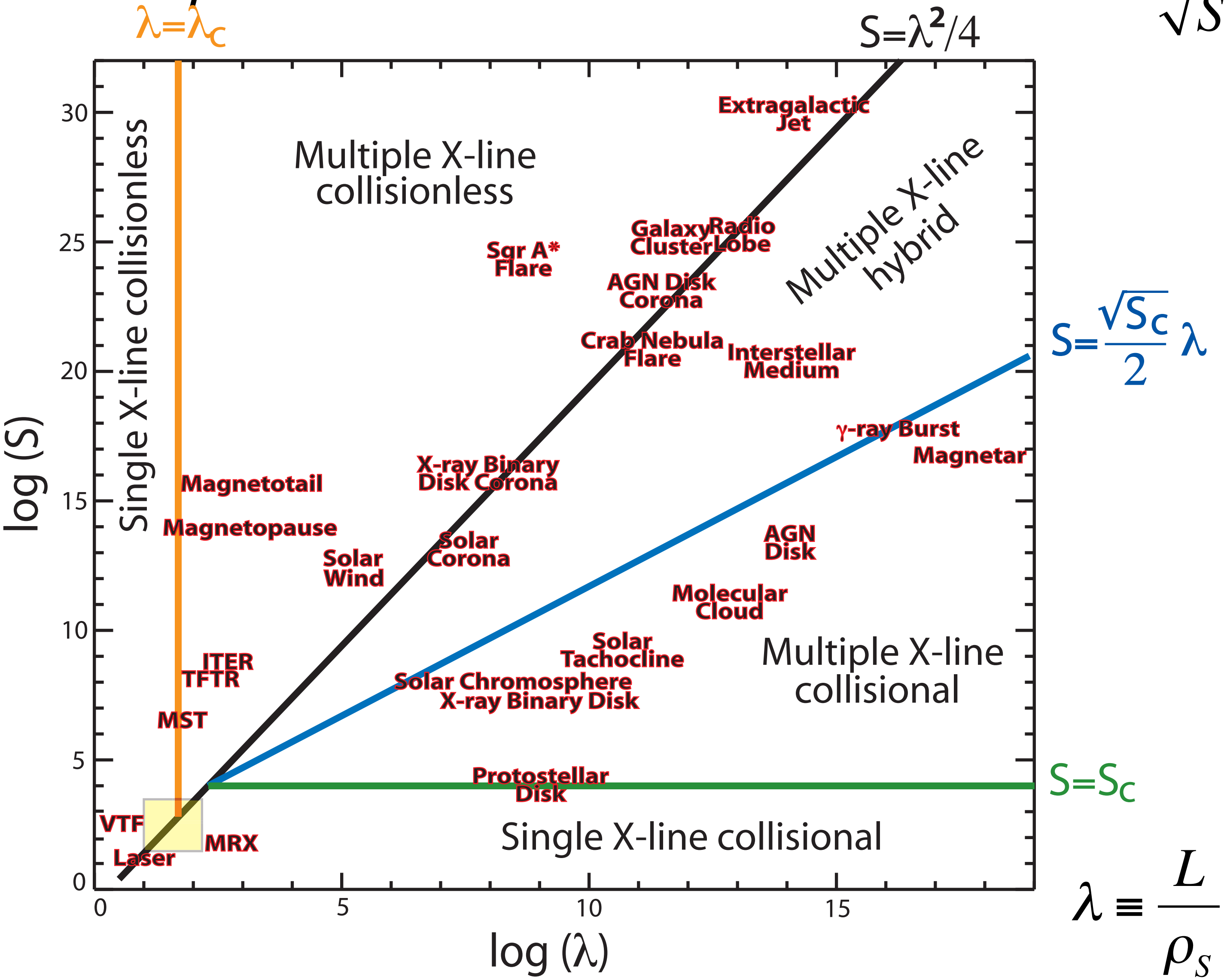


A Reconnection "Phase Diagram"

Ji & Daughton (2011)

$$S = \frac{\mu_0 L_{CS} V_A}{\eta}; \; L_{CS} = \frac{L}{4}$$

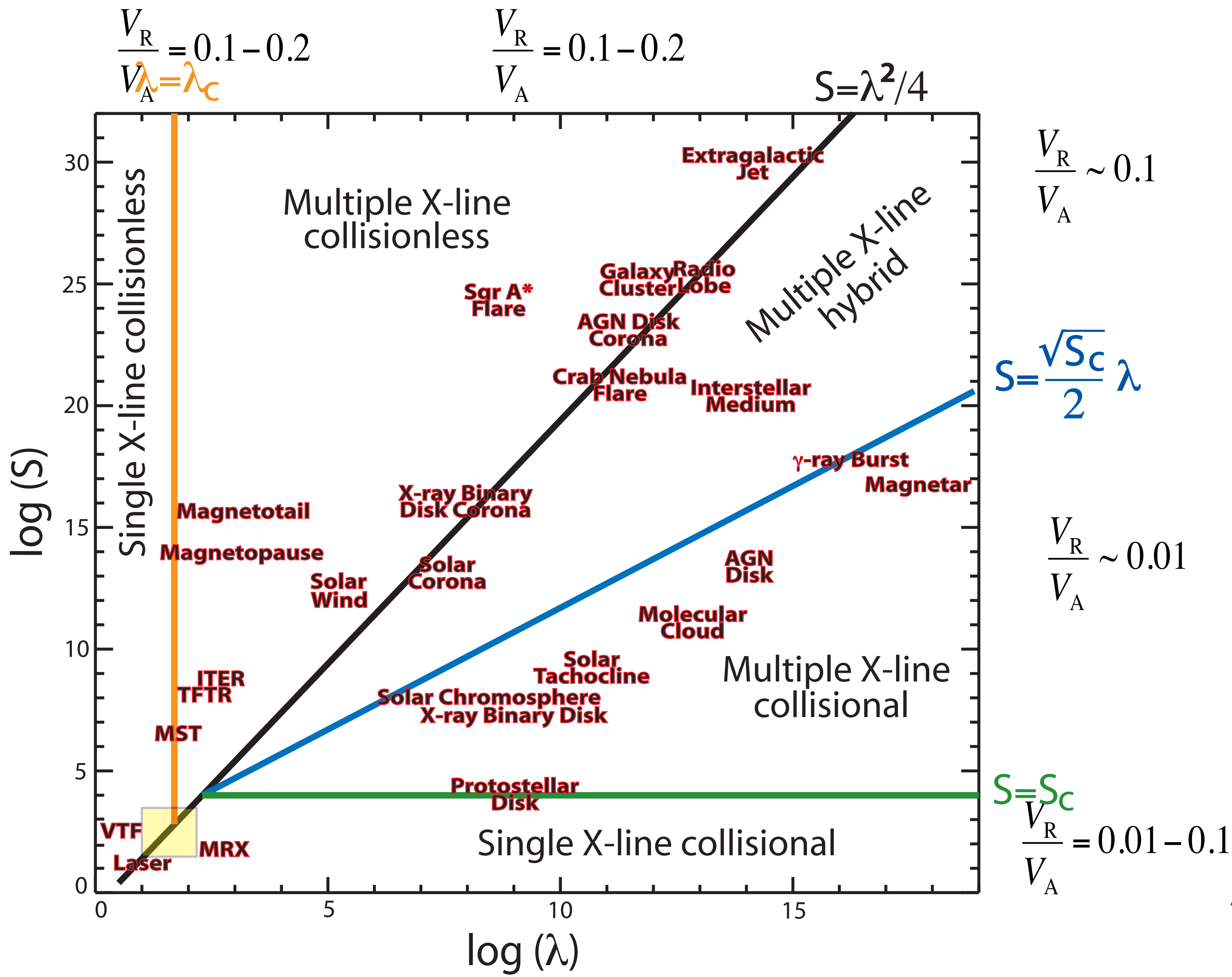
$$\delta_{SP} = \frac{L_{CS}}{\sqrt{S}} = \rho_s \quad \Rightarrow \quad S = \frac{\lambda^2}{4}$$



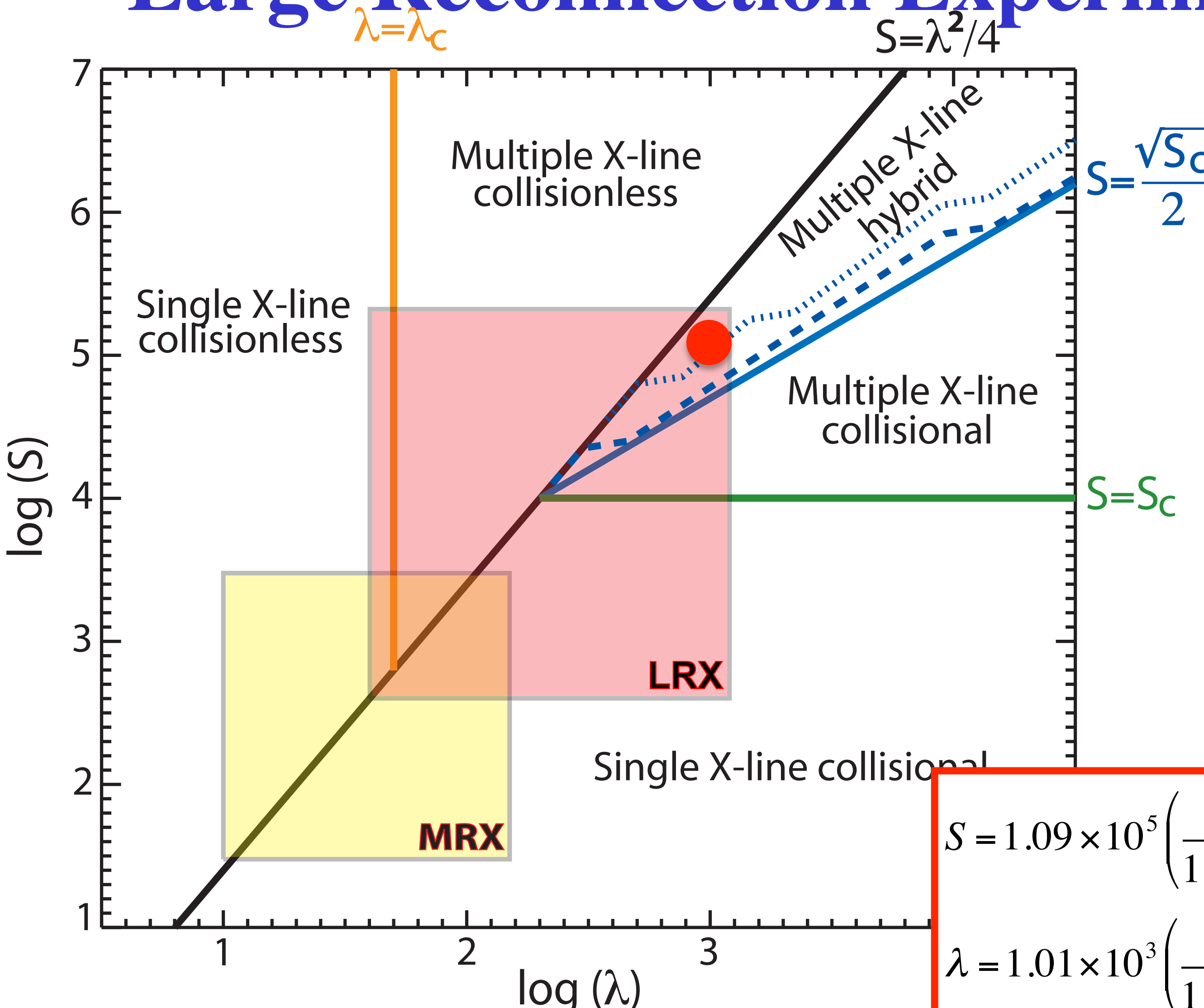
$$\lambda \equiv \frac{L}{\rho_S}$$

A hierarchy of MHD islands terminated kinetically

All Phases Are Fast – But Different Physics Which Should Lead to Different Heating/Acceleration?



Design Goals for A Next Generation Reconnection Experiment: Large Reconnection Experiment (LRX)



$$S = \frac{\mu_0 L_{CS} V_A}{\eta_S} = 10^5$$

$$L_{CS} = \frac{1}{4} L$$

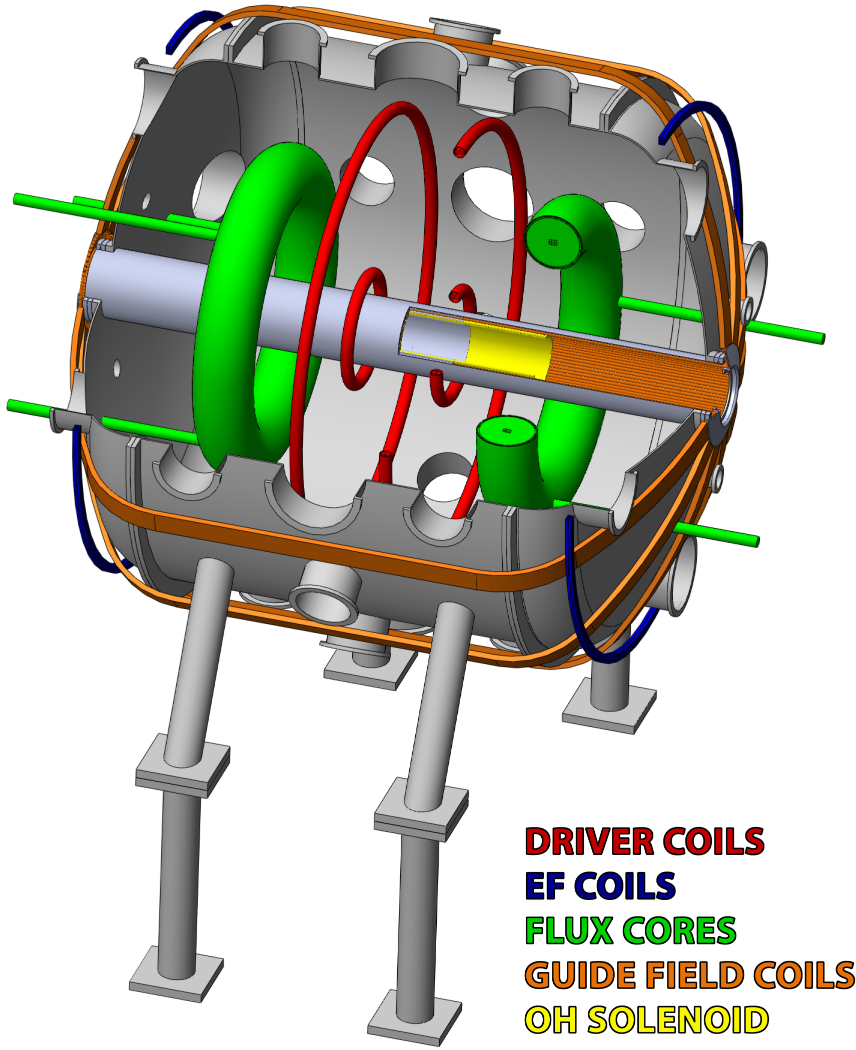
$$\lambda = \frac{L}{\rho_S} = 10^3$$

$$S = 1.09 \times 10^5 \left(\frac{L}{1.6m}\right)\left(\frac{B_{rec}}{0.1T}\right)\left(\frac{n}{10^{19}}\right)^{-1/2}\left(\frac{T_e}{30eV}\right)^{3/2}$$

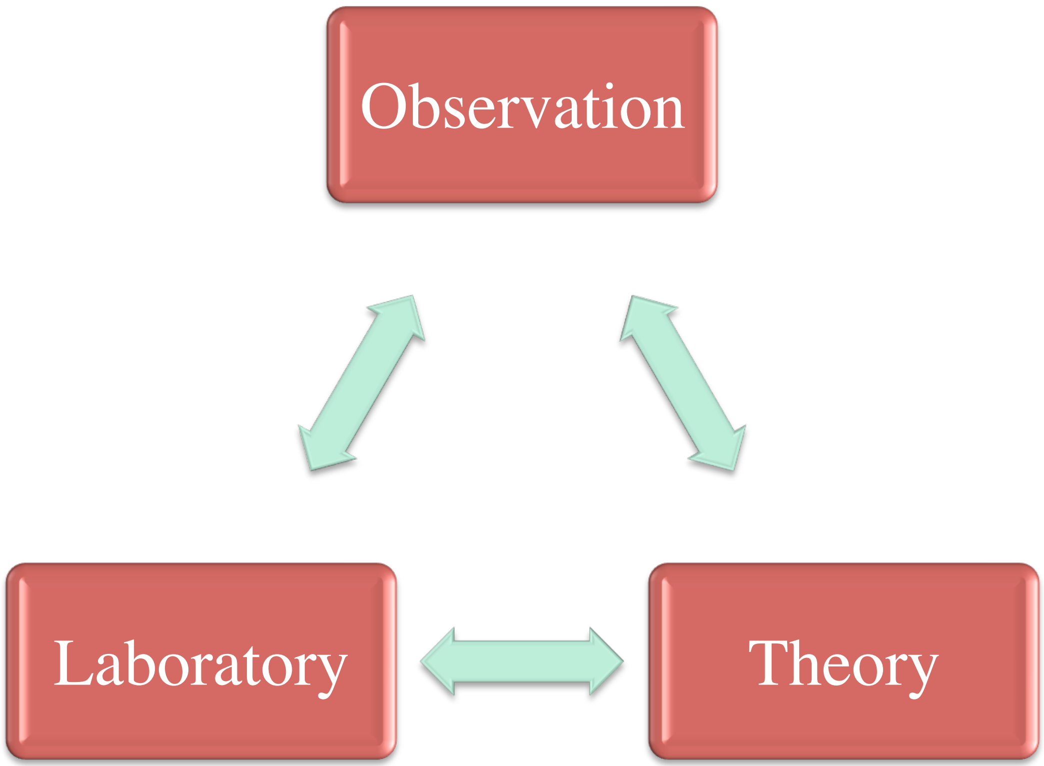
$$\lambda = 1.01 \times 10^3 \left(\frac{L}{1.6m}\right)\left(\frac{B_{guide}}{0.5T}\right)\left(\frac{T_e + T_i}{60eV}\right)^{-1/2}$$

LRX Is to Access New Regimes

Parameters	MRX	LRX
Device diameter	1.5 m	3 m
Device length	2 m	3.2 m
Flux core diameter	0.75 m	1.5 m
Stored energy	25 kJ	4 MJ
Ohmic drive	No	0.3 V-s
S (anti-parallel)	600-1,400	5,000-16,000
$\lambda=(Z/\delta_i)$	35-10	100-30
S (guide field)	2900	100,000
$\lambda=(Z/\varrho_S)$	180	1,000



SDO, FERMI, MMS, SPP…



Many existing LRX, …,VENITA, laser, ITER,

MHD, Hall MHD, PIC, …