Electron-scale Dissipation near the X-line During Magnetic Reconnection
&
The Upcoming FLARE (Facility for Laboratory Reconnection Experiments) Device

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Magnetic Reconnection in Plasmas
August 10, 2015
Nordita, Stockholm, Sweden

Magnetic Reconnection Occurs Throughout Heliophysical Plasmas

- Solar interior
  - Part of solar dynamo which requires changes in magnetic topology
- Solar chromosphere & corona
  - During solar flares, part of Coronal Mass Ejection, likely important for coronal heating
- Solar wind
  - Part of solar wind turbulence and current sheet dissipation
- Planetary magnetospheres
  - Part of plasma transport and magnetic storms, likely important for aurora activity
- Interface with local galactic plasma
  - Part of dissipation in heliospheric sheath and pause

Magnetic Reconnection Occurs Throughout Astrophysical Plasmas

- Star systems
  - As in heliophysics, when they form from *molecular clouds*, when they explode through *supernova*, *flares* from compact objects, e.g. Crab Nebula
- Accretion disks
  - Protostellar disks and jets, X-ray binary disks (interiors and coronae)
- Interstellar medium
  - Part of ISM turbulence and current sheet dissipation, galactic magnetic field topology, galactic wind
- Galactic center
  - Maybe during Sagittarius A* flares
- Extra-galactic objects
  - Active Galactic Nuclei (AGN) disks (interiors and coronae)
  - Dynamics of radio jets and lobes
  - Heating or cooling of galaxy clusters

Magnetic Reconnection Occurs Also in Laboratory Fusion Plasmas

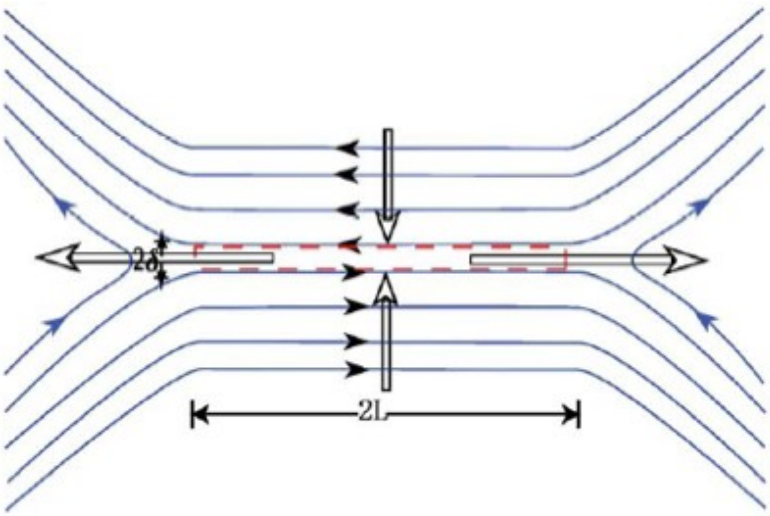
- Magnetic fusion plasmas
  - Sawtooth oscillations in tokamaks
  - (Neoclassic) tearing mode growth
  - Disruptive activity such as major disruptions, possibly edge-localized modes
  - Magnetic self-organization (relaxation) events in low-field systems as in reversed field pinches and spheromaks
  - Formation of field reversed configurations based on plasma merging
- Inertial fusion plasmas
  - Possibly in Z-pinch plasmas, in which magnetic drive dominates
  - Possible even in laser-driven plasmas, in which magnetic field is applied to improve the energy confinement, or magnetic fields could spontaneously arise and then saturate by reconnection

Magnetic reconnection is a fundamental plasma process throughout the Universe and important for laboratory fusion.

Ji & Daughton (2011)

Two Broad Categories of Reconnection Models: Collisional MHD versus Collisionless Kinetic

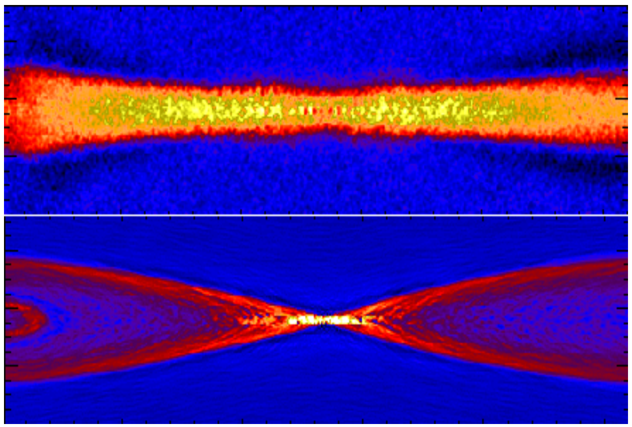
e.g. Sweet-Parker Model



Valid for large plasmas but predicts slow reconnection

$$\frac{V_R}{V_A} = \frac{1}{\sqrt{S}} \qquad S = \frac{\mu_0 L V_A}{\eta}$$

e.g. Kinetic Model



ions

electrons

Predicts fast reconnection but practical only for small plasmas

$$\frac{V_R}{V_A} \sim 0.1$$

How to combine these to explain fast reconnection in large plasmas?

➔A multiple scale problem!

Major Questions for Magnetic Reconnection

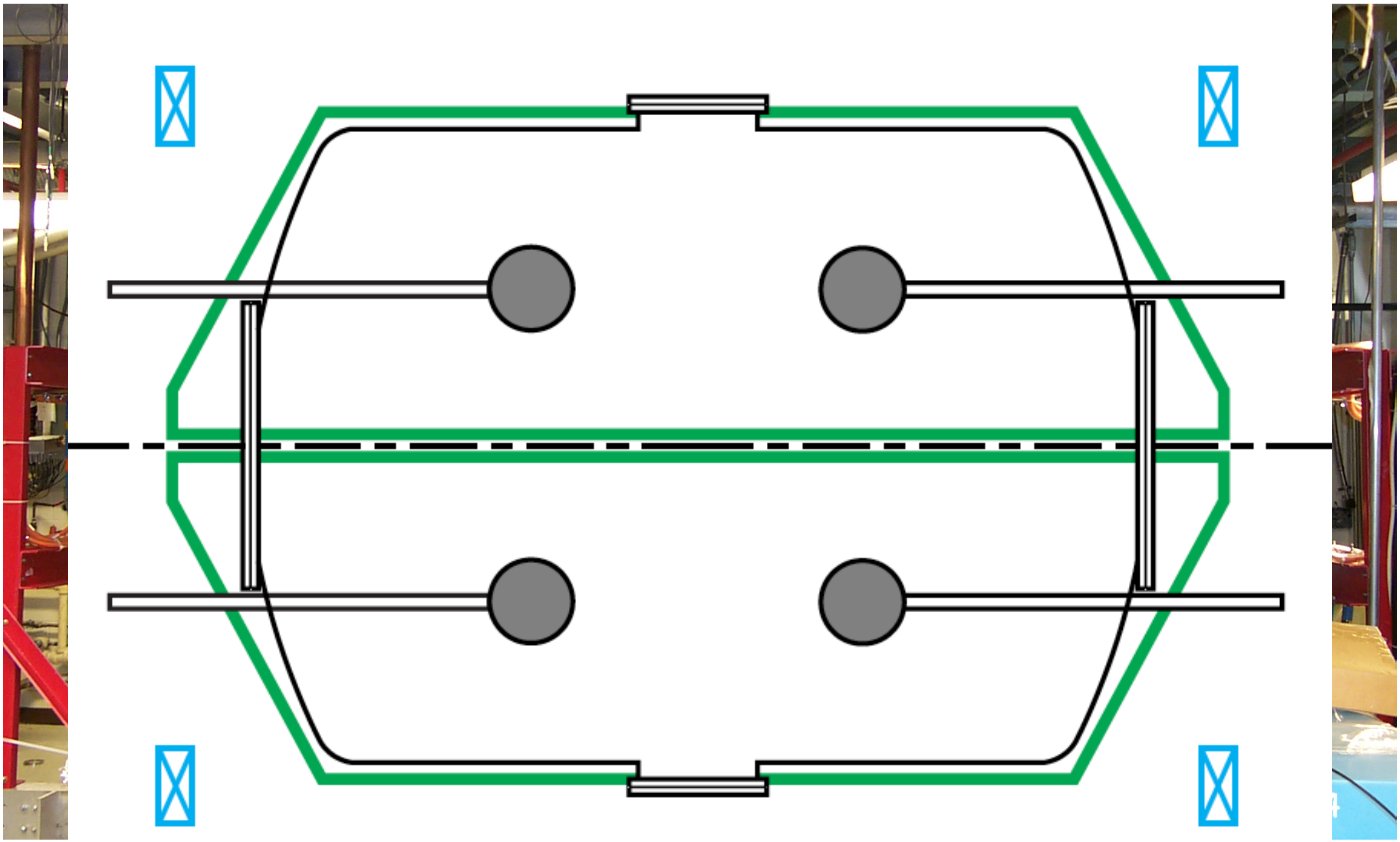
1. **How is reconnection rate determined? *(The rate problem)***
2. **How does reconnection take place in 3D? *(The 3D problem)***
3. **How does reconnection start? *(The onset problem)***
4. **How does partial ionization affect reconnection? (*The partial ionization problem*)**
5. **How do boundary conditions affect reconnection process? *(The boundary problem)***
6. **How are particles energized? *(The energy problem)***
7. **What roles reconnection plays in flow-driven systems (The *flow-driven* problem)**
8. **How does reconnection take place under extreme conditions? (*The extreme problem*)**
9. **How to apply local reconnection physics to a large system? *(The multi-scale problem)***

Can we study these problems in the lab?

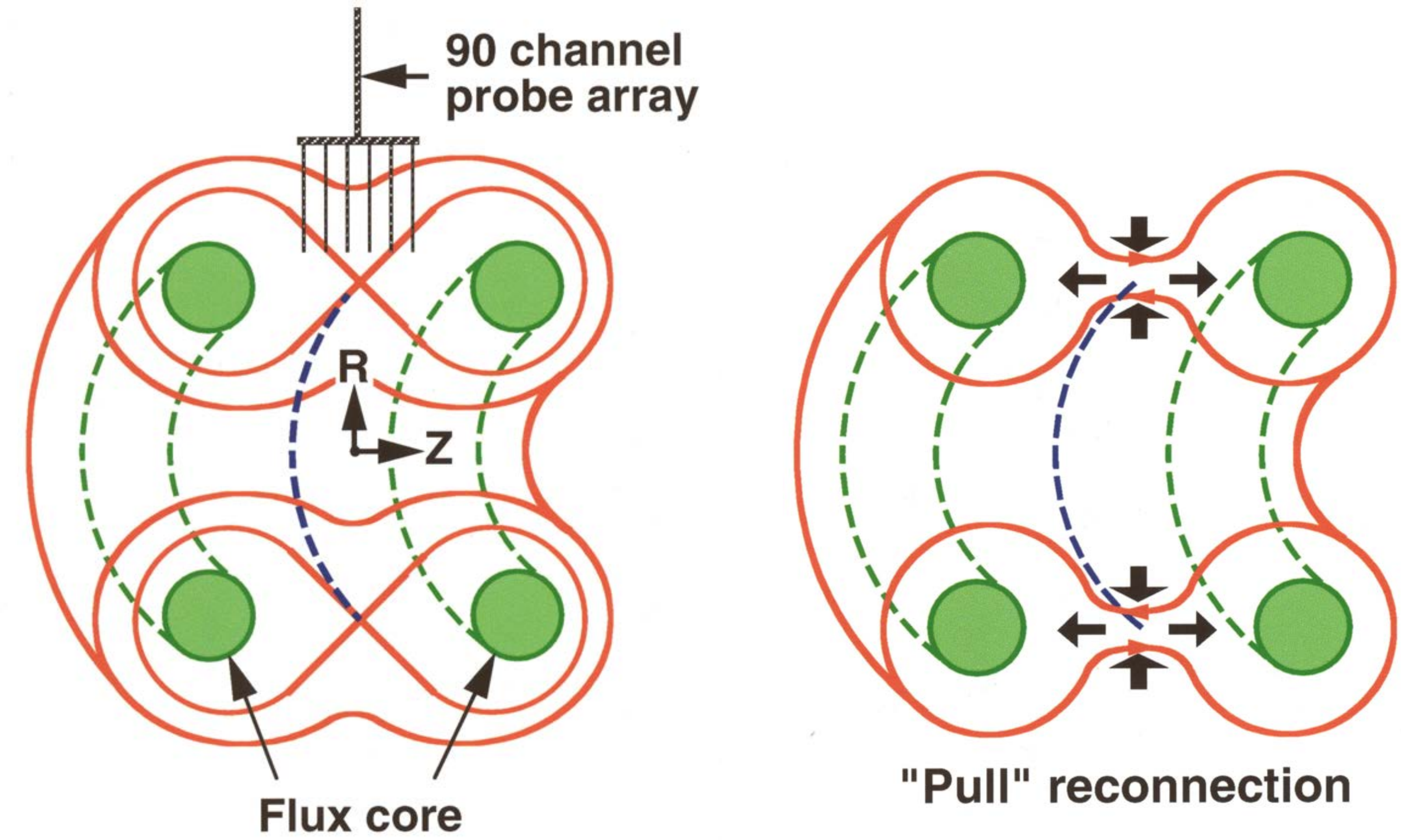
Dedicated Laboratory Experiments on Reconnection

Device	*Where*	*Since*	*Who*	*Geometry*	*Focus*
3D-CS	Russia	1970	Syrovatskii, Frank	Linear	3D, energy
LPD, LAPD	UCLA	1980	Stenzel, Gekelman	Linear	Energy, 3D
TS-3/4	Tokyo	1990	Katsurai, Ono	Merging	Rate, energy
MRX	Princeton	1995	Yamada, Ji	Toroidal, merging	Rate, 3D, energy, partial ionization, boundary, onset
SSX	Swarthmore	1996	Brown	Merging	Energy, 3D
VTF	MIT	1998	Fasoli, Egedal	Toroidal	Onset, 3D
Caltech exp	Caltech	1998	Bellan	Planar	Onset, 3D
RSX	Los Alamos	2002	Intrator	Linear	Boundary, 3D
RWX	Wisconsin	2002	Forest	Linear	Boundary
Laser plasmas	UK, Shanghai, Rochester	2006	Nilson, Li, Zhong, Dong, Fox, Fiksel	Planar	Flow-driven, extreme
VINETA II	Max-Planck	2012	Grulke, Klinger	Linear	3D
TREX	Wisconsin	2013	Egedal, Forest	Toroidal	Energy
FLARE	Princeton	2013	Ji +	Toroidal	All
HRX	Harbin, China	2015	Ren +	3D	3D, energy

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



The Basic Experimental Setup in MRX

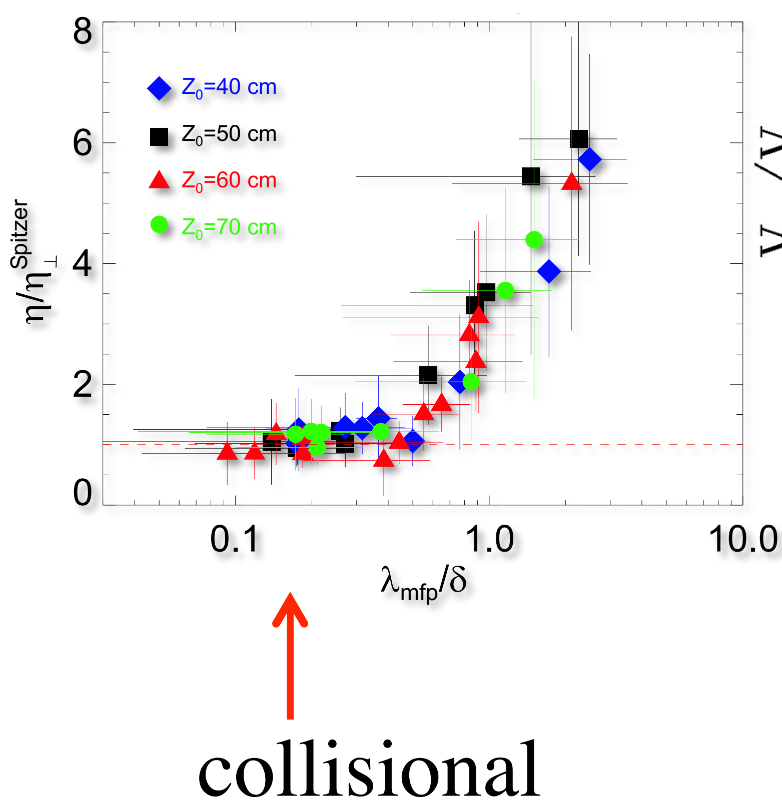


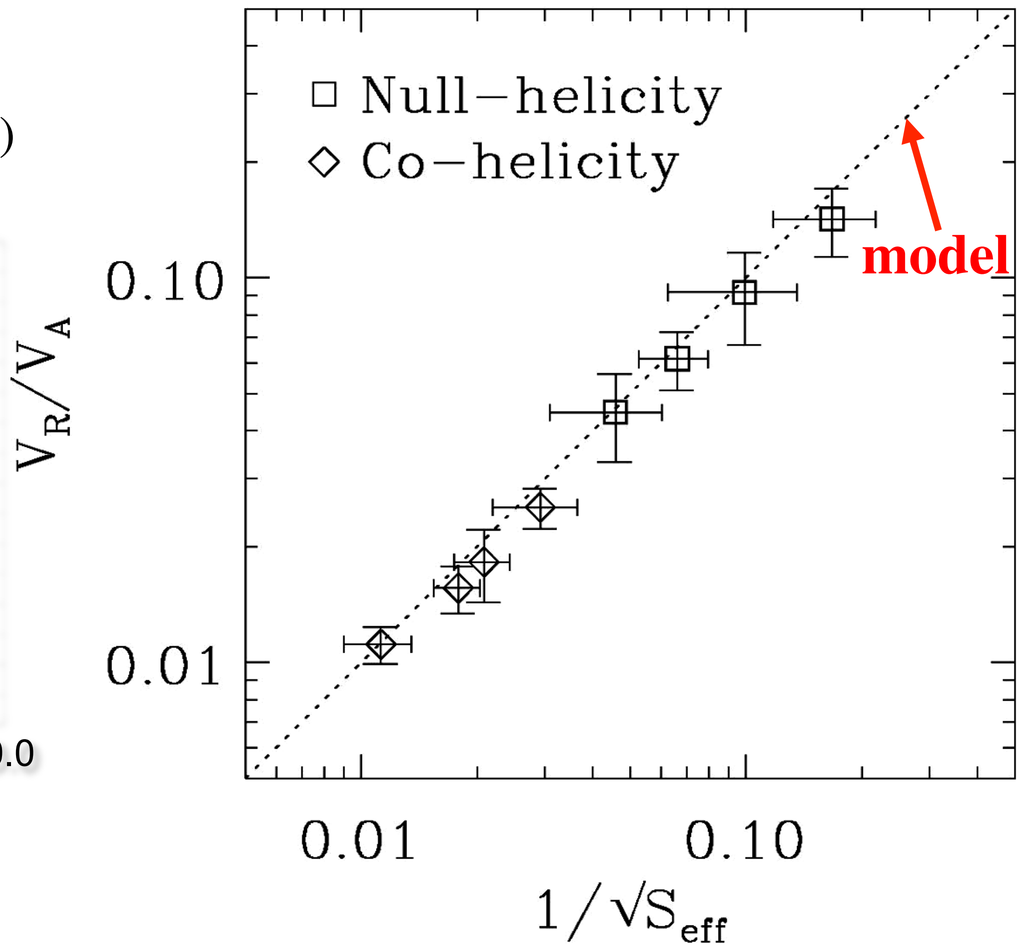
Key: Control + Diagnostics

Sweet-Parker Model Works in *Collisional Plasmas*

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

- **When collisional, the apparent resistivity (*E*/*j*) agrees with Spitzer values** (slow reconnection)

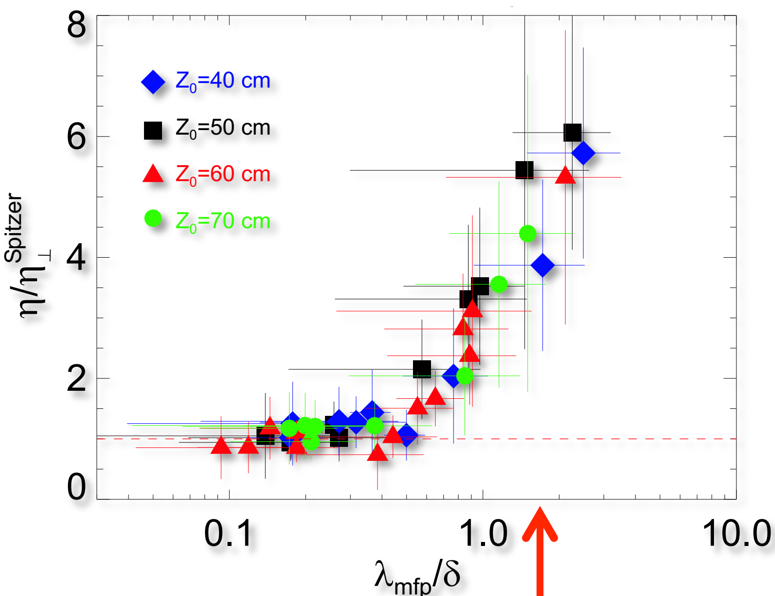




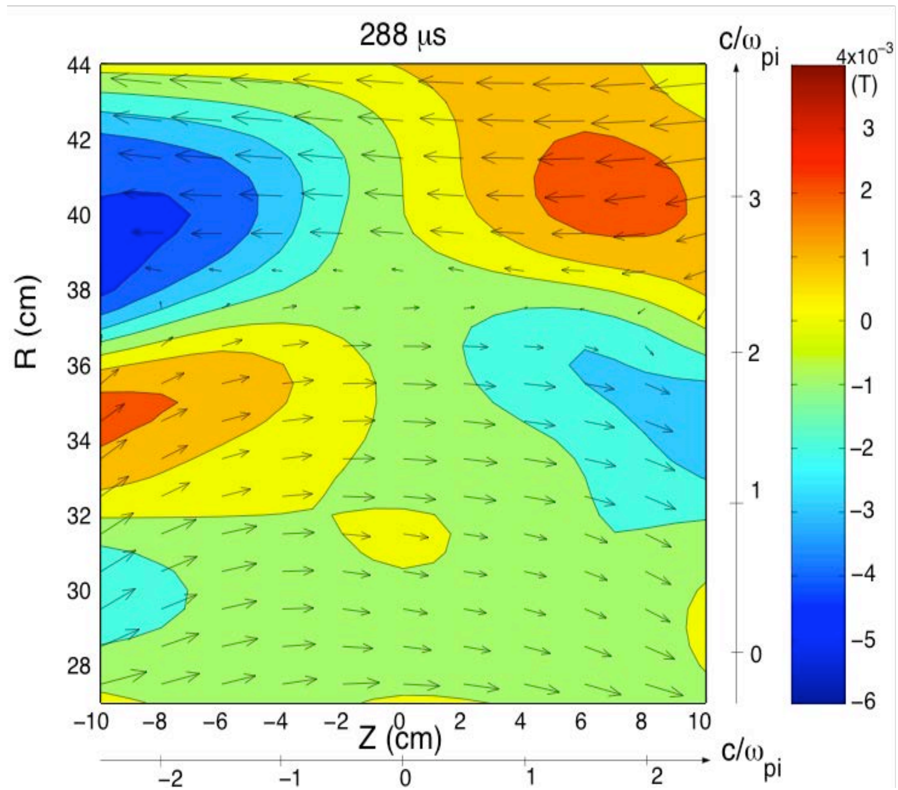
Two-fluid Model Works in *Collisionless Plasmas*

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

- **When collisionless, the apparent resistivity (*E*/*j*) increases beyond Spitzer values** (fast reconnection)



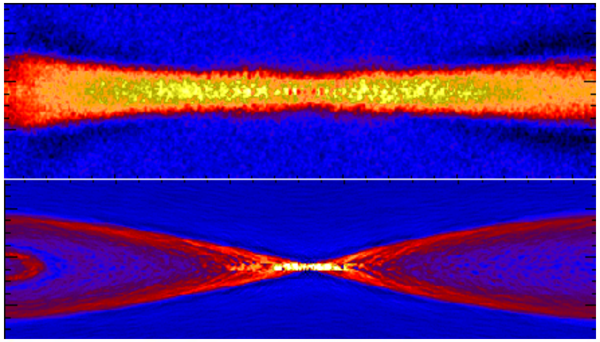
collisionless

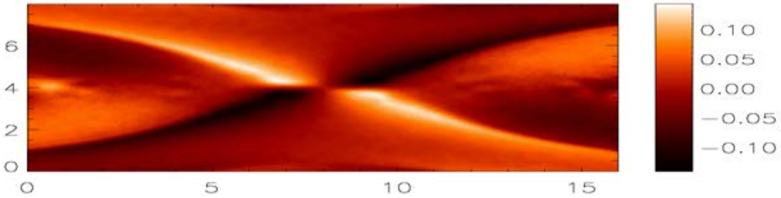


- Predicted quadrupole out-of-plane field detected on the ion scale

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.

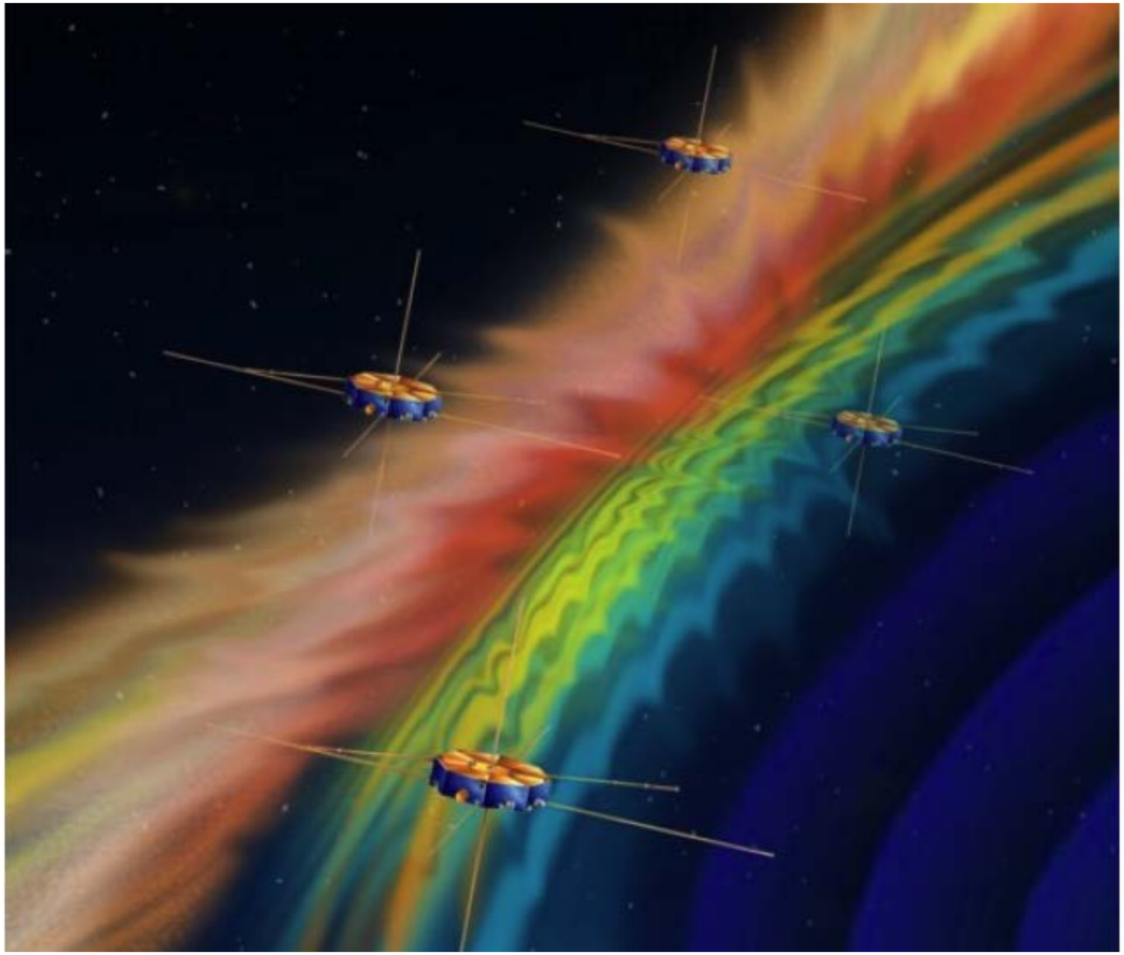
Vasyliuna ('75), Sonnerup ('88), Dungey ('88), Lyons & Pridmore-Brown ('90)
Cai & Lee ('97), Hesse et al. ('99), Pritchett ('01), Kuznetsova et al. ('01)

- Limited observations in space

Scudder et al. ('02), Mozer ('03), Wygant et al. ('05), Phan et al. ('07), Chen et al. ('08)
Scudder et al. ('12), Nagai et al. ('11,'13)

Next frontier: Electron diffusion regions

- **Goals of Magnetospheric Multi-Scale (MMS) mission successfully launched on March 12, 2015**

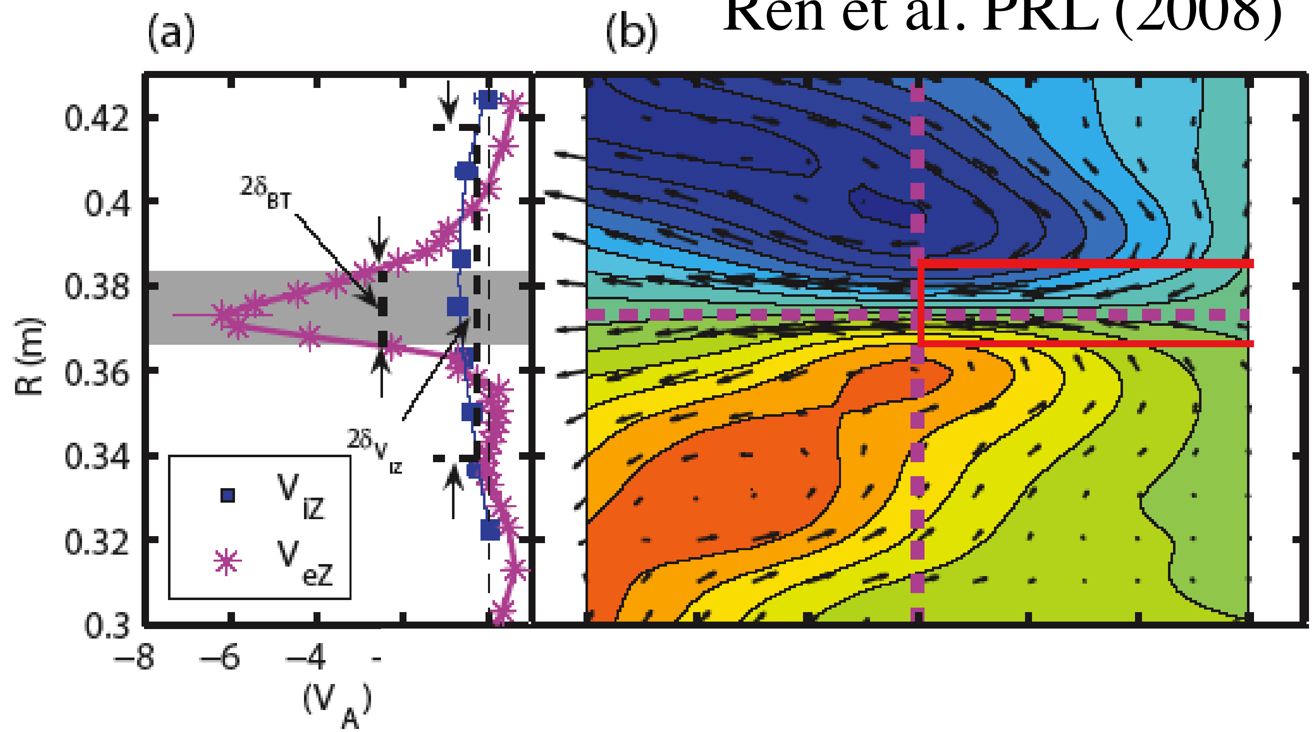


Next frontier: Electron diffusion regions

- **Goals of Magnetospheric Multi-Scale (MMS) mission successfully launched on March 12, 2015**

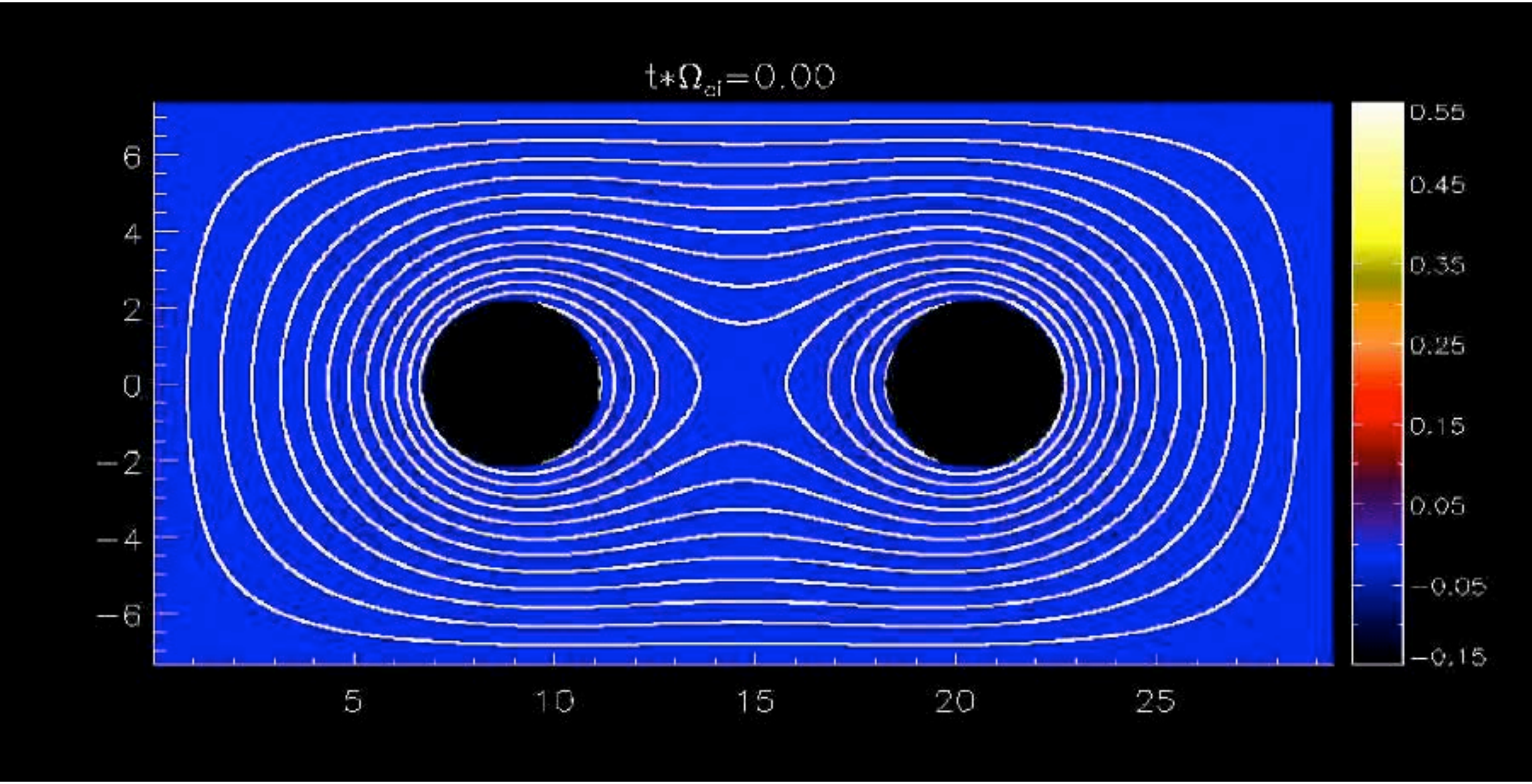
First detection of electron layer in lab!

Ren et al. PRL (2008)



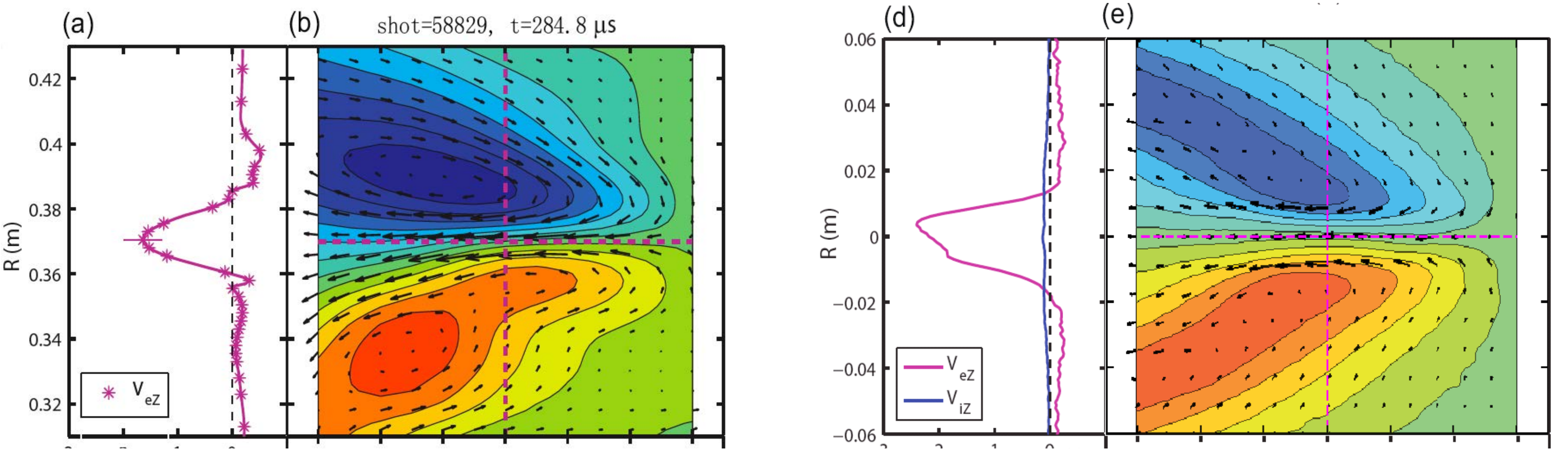
2D PIC Simulation in MRX Setup

Dorfman, Daughton et al. ('08)



All ion-scale features are reproduced by 2D PIC simulations…

Ji et al. GRL (2008); Dorfman et al. PoP (2008)



MRX:

$\delta_e = 8\ c/\omega_{pe}$

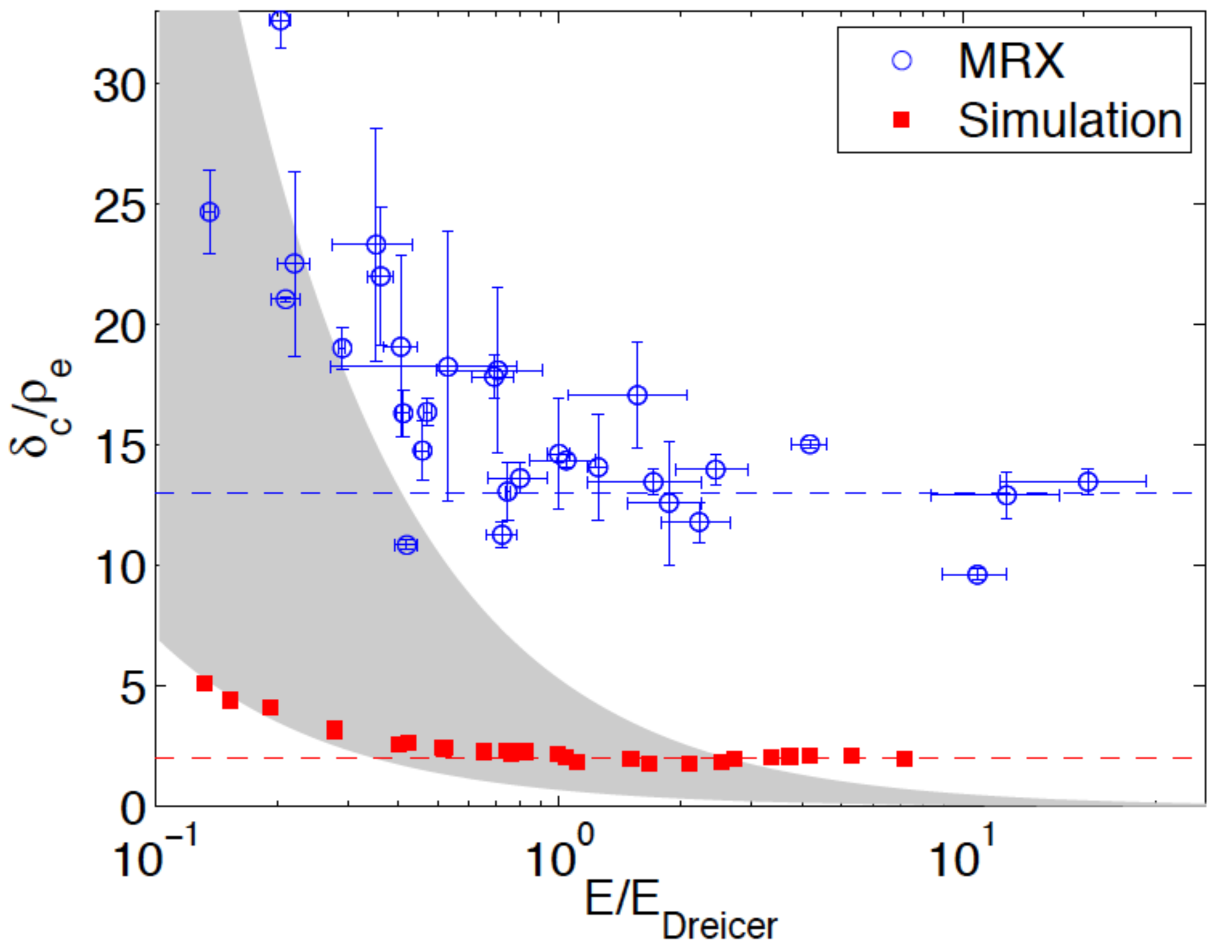
2D PIC Sim:

$\delta_e = 1.6\ c/\omega_{pe}$

… but not on electron scales!

How about collisions?

V. Roytershteyn et al. (2010); S. Dorfman thesis (2012)



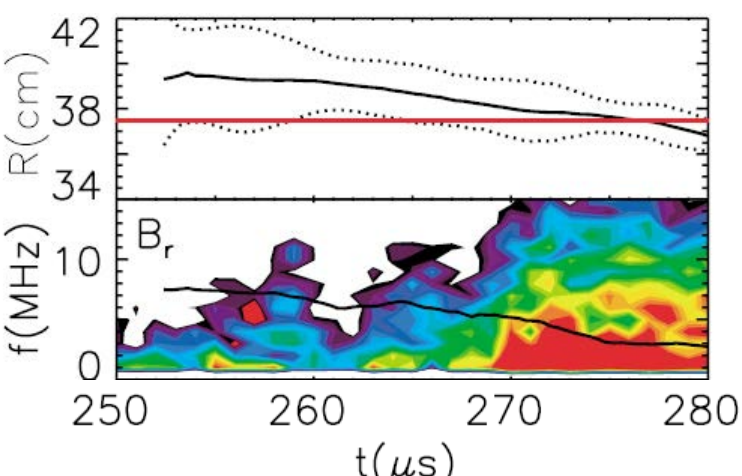
All known 2D mechanisms cannot explain the measured width

importance of 3D effects

How can 3-D dynamics affect the reconnection process?

Waves and Turbulence

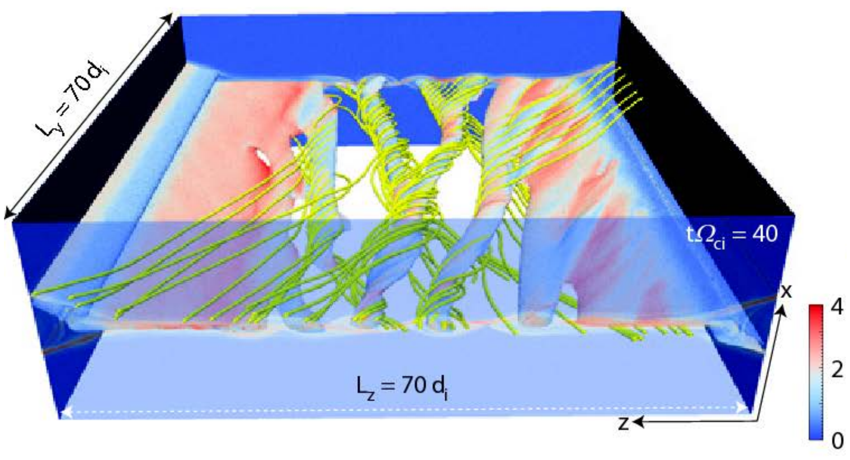
- 3-D variation allows for a large class of waves: Can these waves generate anomalous resistivity that speeds up reconnection?



(Ji et. al., PRL, 2004)

Flux Rope Structures

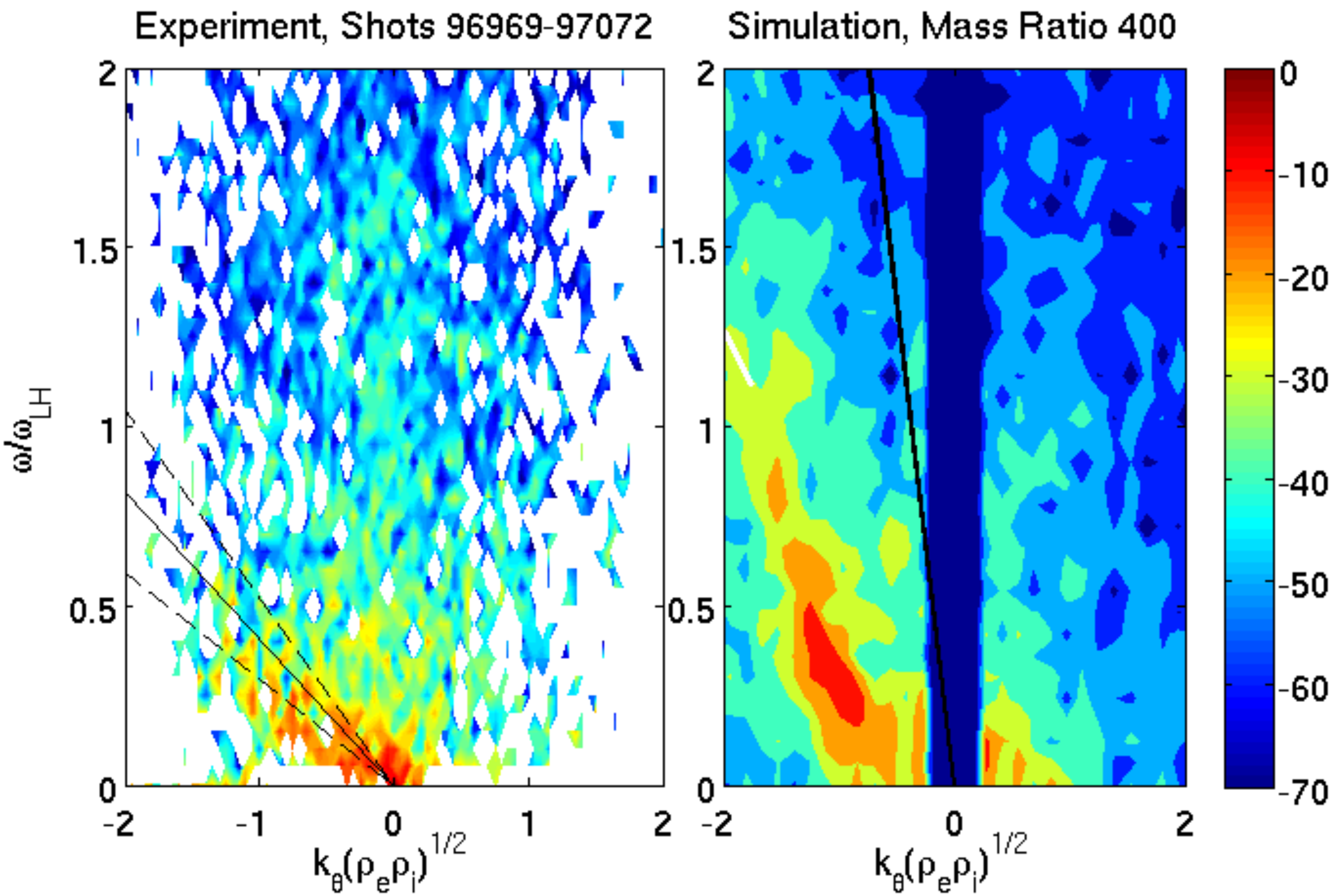
- Islands in 2.5-D are analogous to flux ropes in 3-D



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

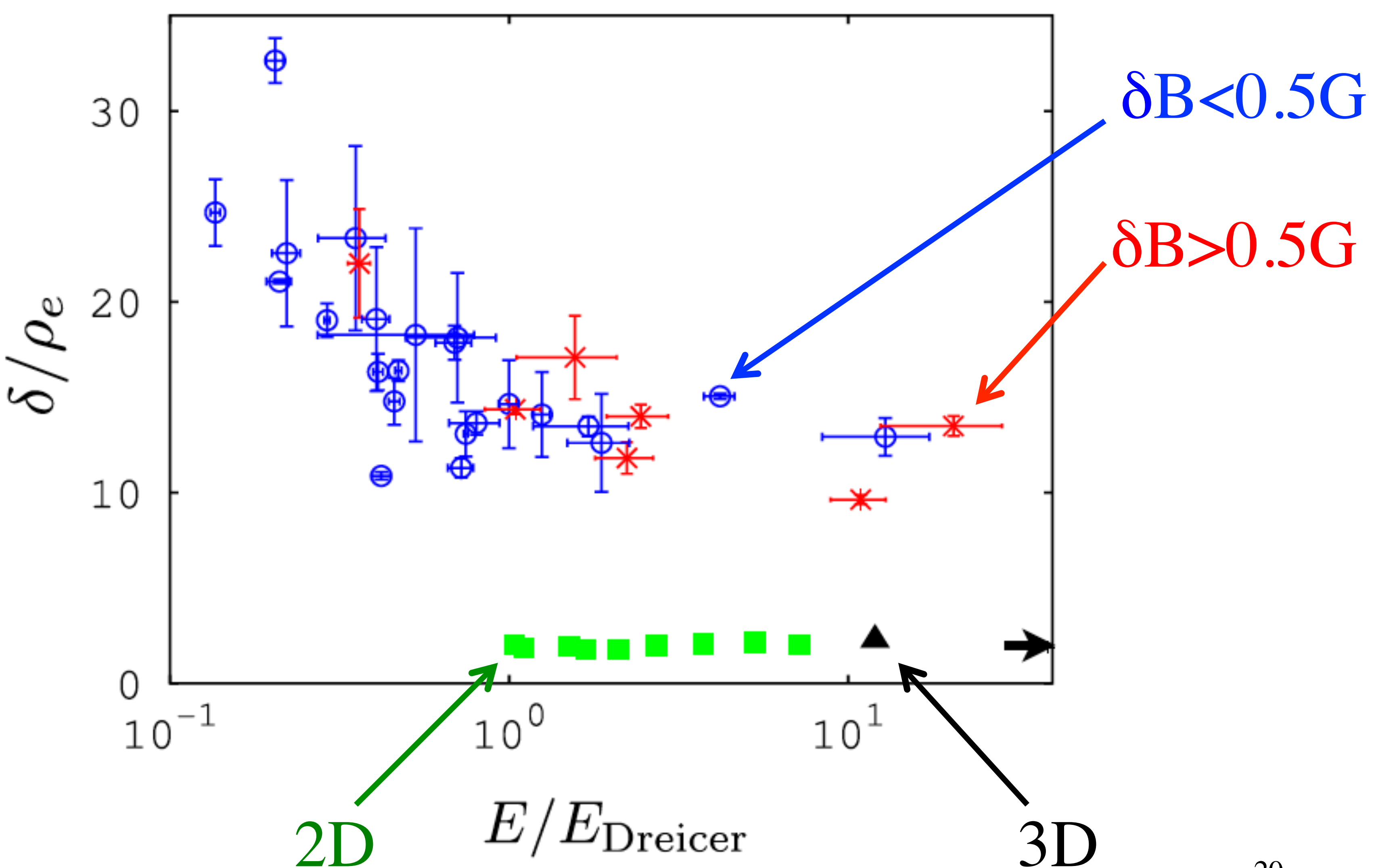
Waves reproduced in 3D PIC: Wave dispersion agrees with MRX

V. Roytershteyn et al. (2013)

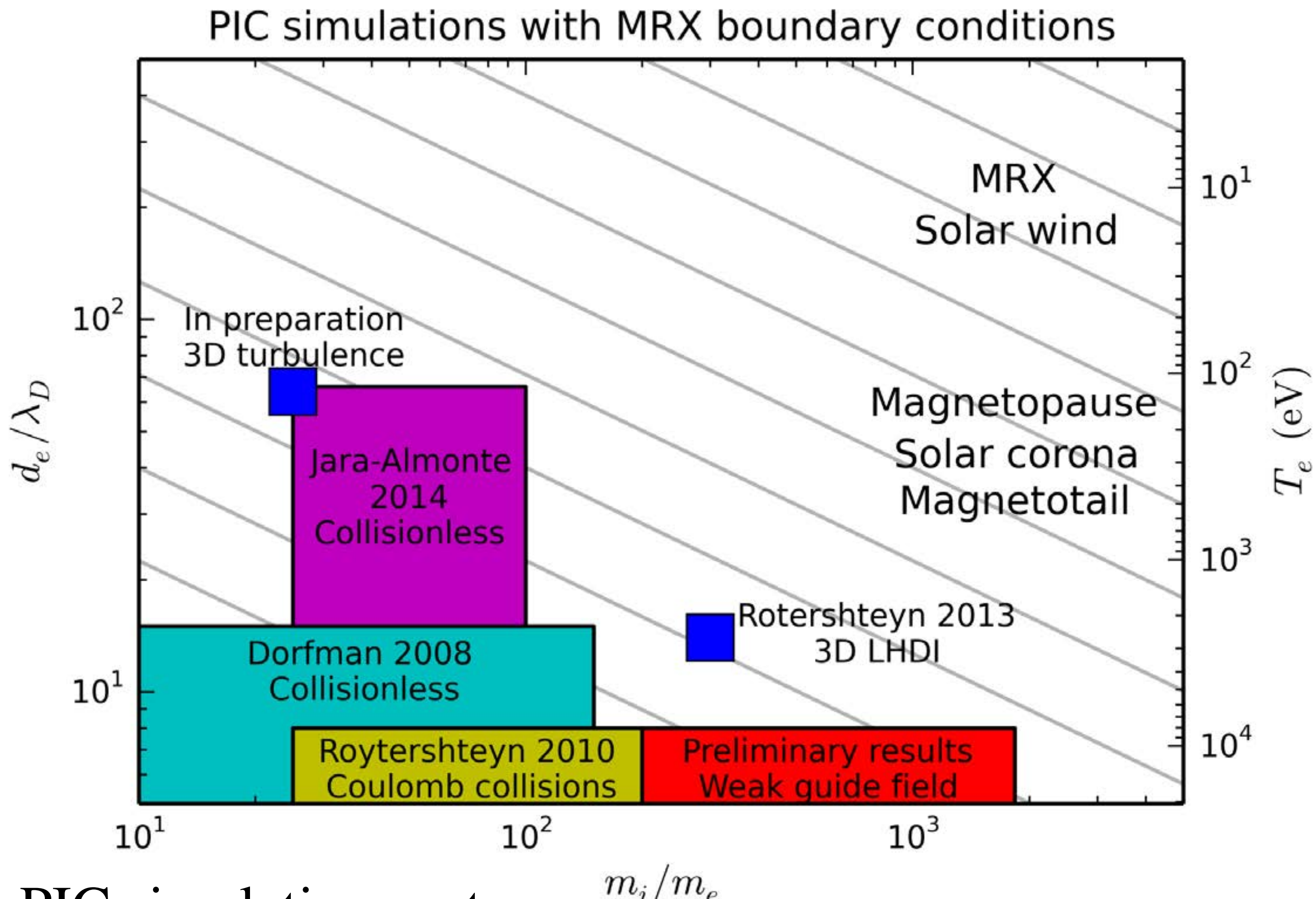


But the electron layer width still stays thin!

V. Roytershteyn et al. (2013)



But parameter space for kinetic simulations is still far from MRX!



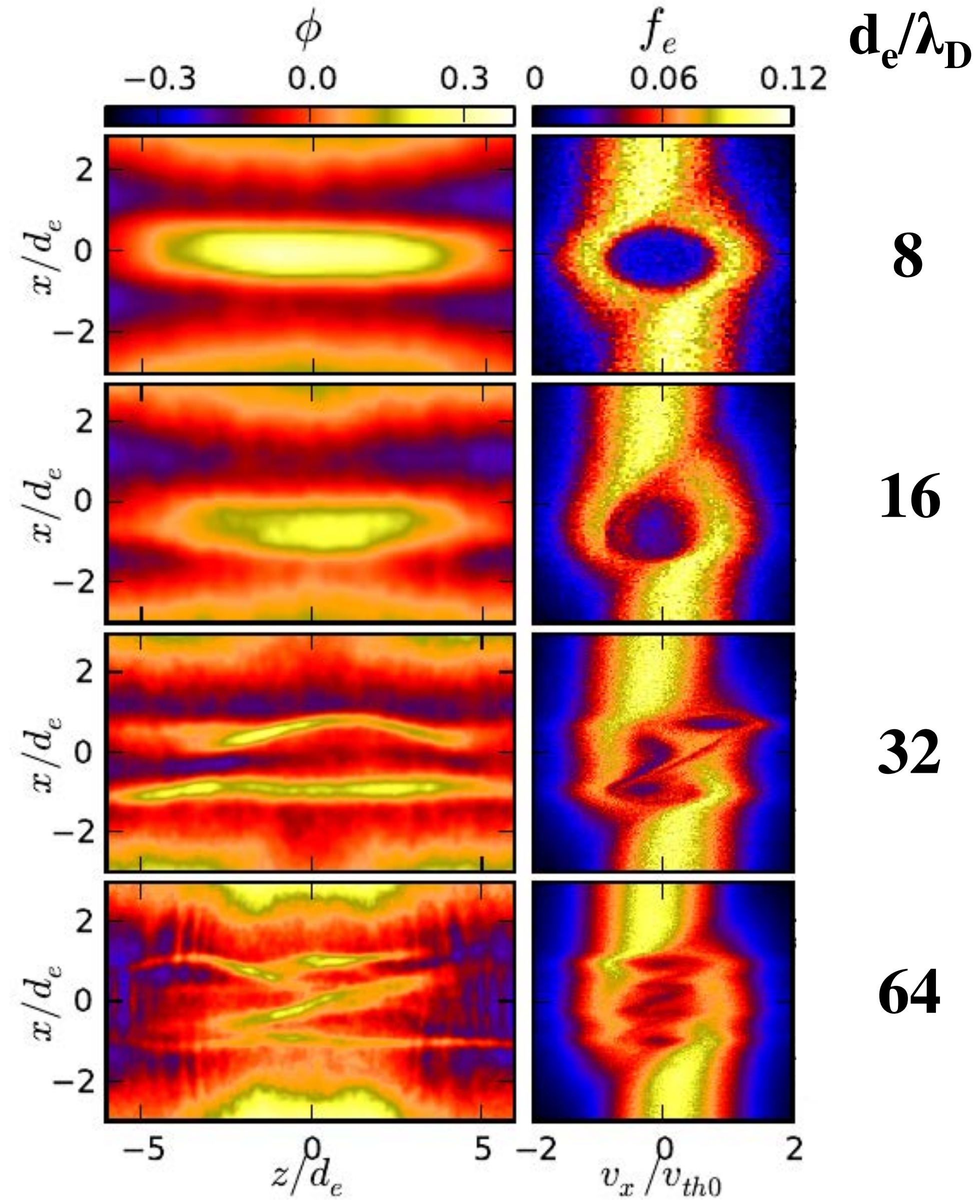
2D Explicit PIC simulation cost

$$N_{ppc}\,\beta_e^{1/2}\left(\tau_{sim}\Omega_i\right)\left(\frac{L}{d_i}\right)^2\left(\frac{m_i}{m_e}\right)^2\left(\frac{d_e}{\lambda_D}\right)^4$$

2D simulations show the onset of instability at large d_e/λ_D

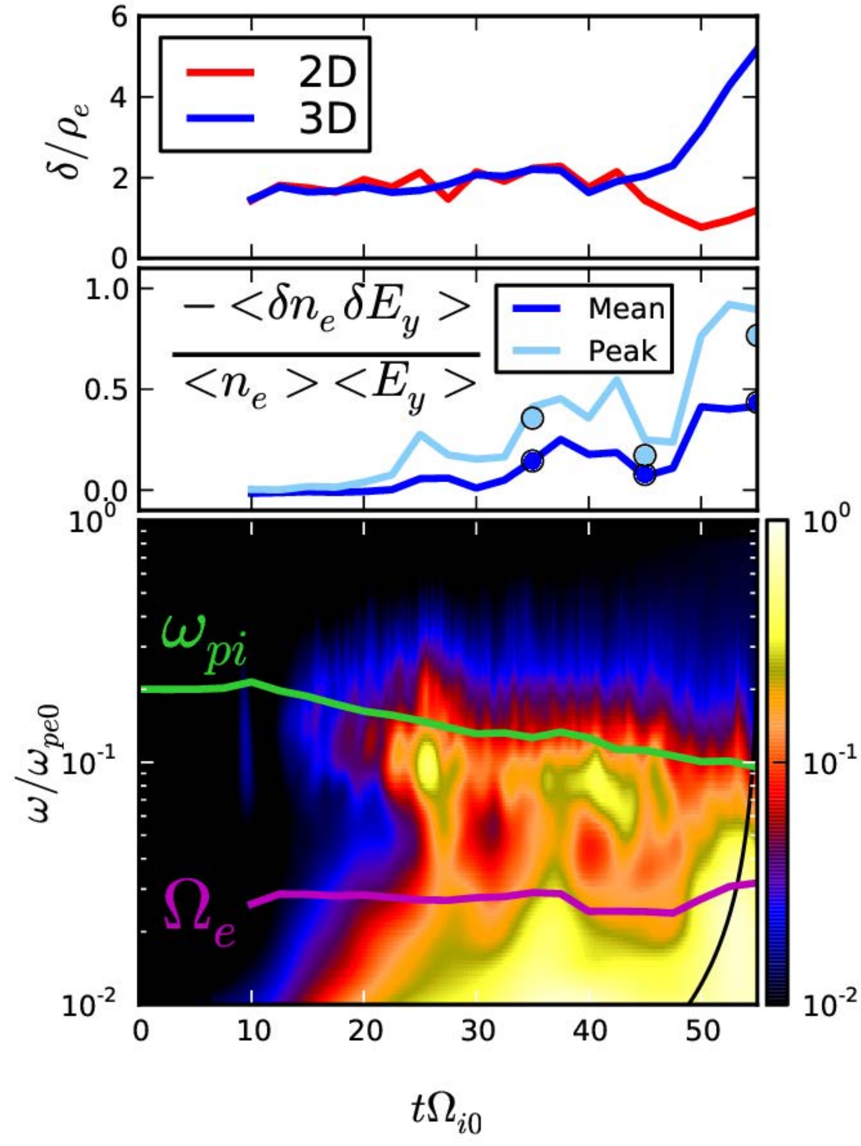
Jara-Almonte et al. (2014)

- **Growth rate and dispersion agree well with linear theory of cross-stream electrostatic instabilities**
- **Particle trapping in small-scale electron holes leads to intense, localized current filaments**



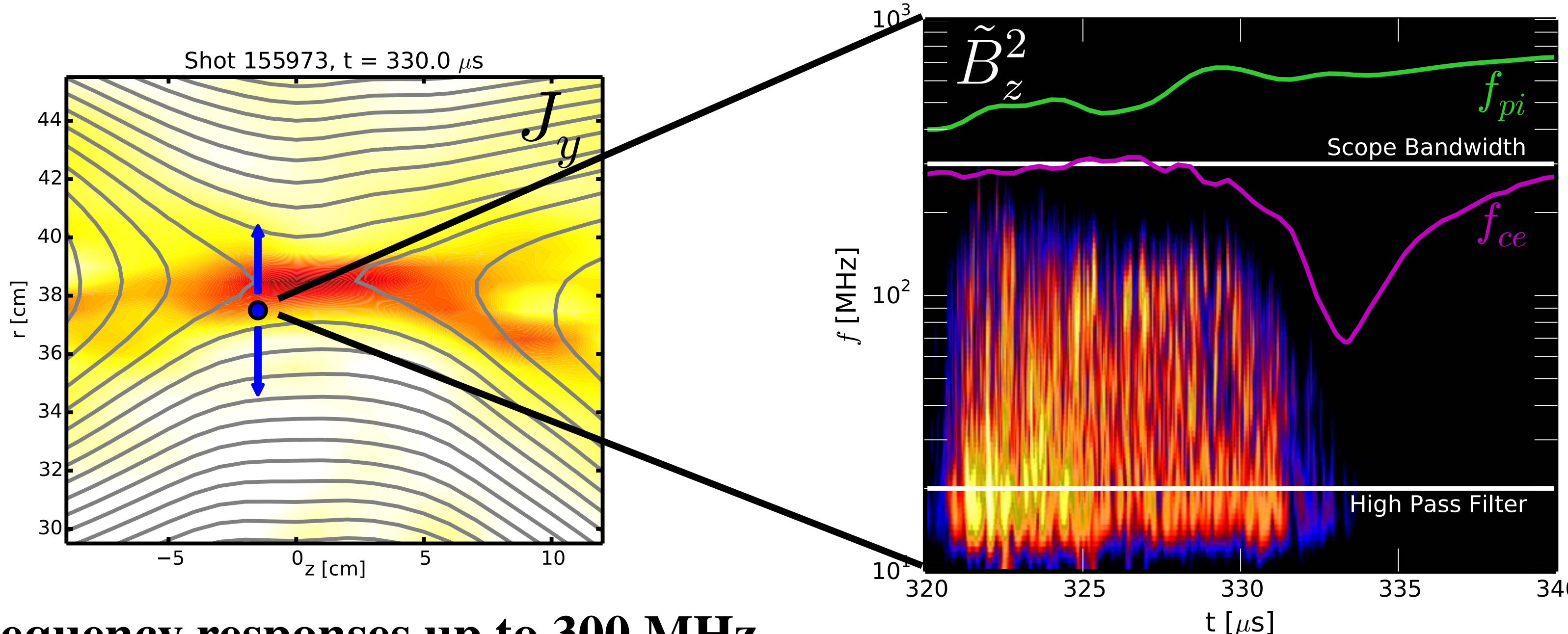
$$\left(\frac{d_e}{\lambda_D} = 8 - 64, \quad \frac{m_i}{m_e} = 25 \right)$$

Instability persists in 3D, leading to anomalous resistivity and a broadened layer

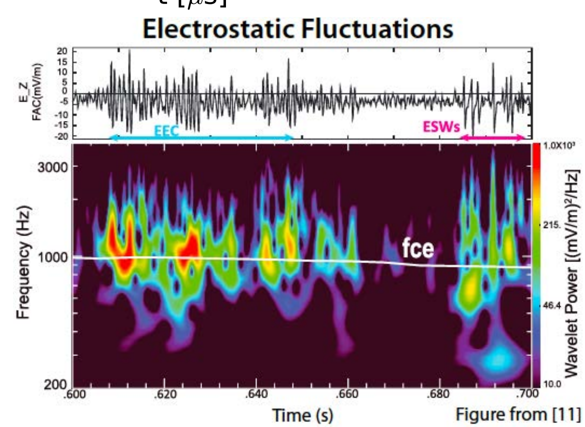


$$\left(\frac{d_e}{\lambda_D} = 64, \quad \frac{m_i}{m_e} = 25 \right)$$

Evidence of high-freq magnetic fluctuations at the low density side of asymmetric reconnection



- **Frequency responses up to 300 MHz, comparable to electron cyclotron frequency**
- **Also capable of detecting Whistler waves predicted with a weak guide field** (Goldman et al. 2014, Chen et al. 2015)
- **Spatial resolution comparable to Debye length**



Tang et al. GRL (2013)

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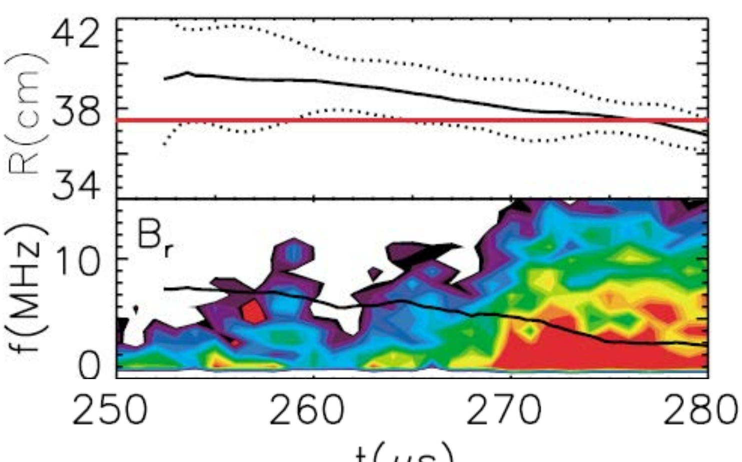

(Ji et. al., PRL, 2004)

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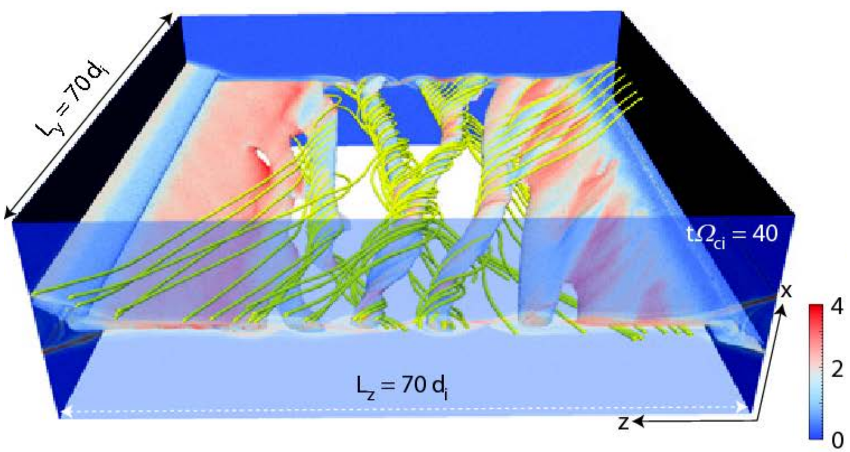
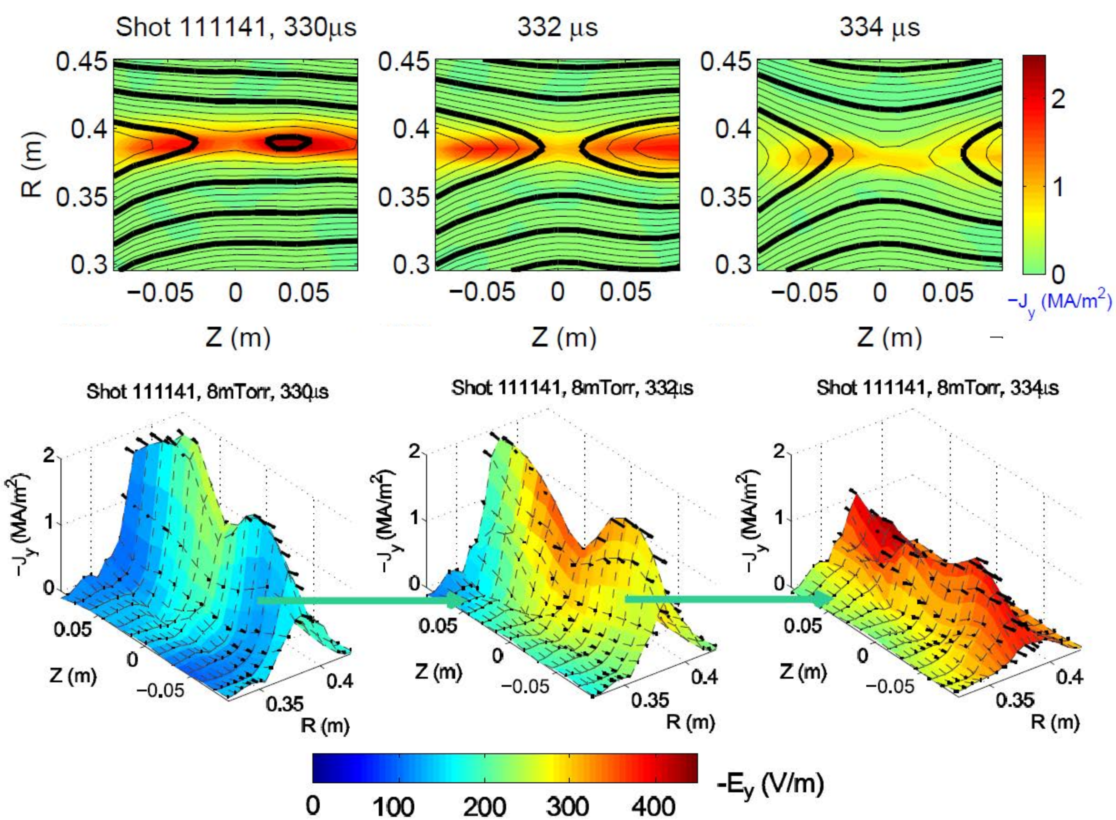
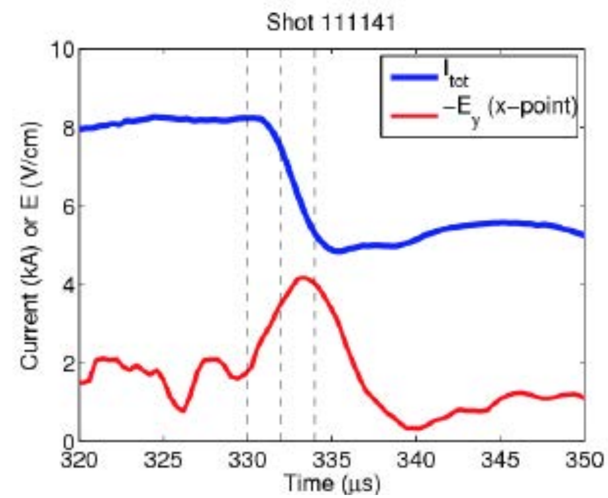


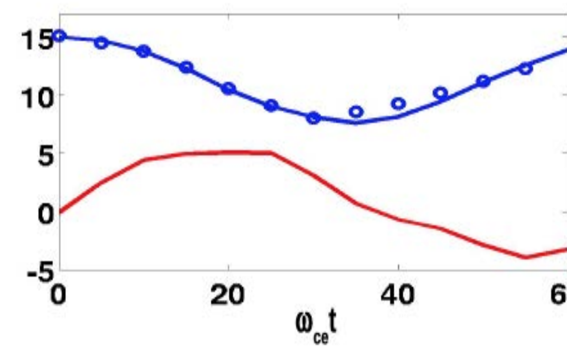
(Daughton et. al., Nature Physics, 2011)

Flux ropes have been also detected and their ejections lead to impulsive reconnection

Dorfman et al. GRL (2013)





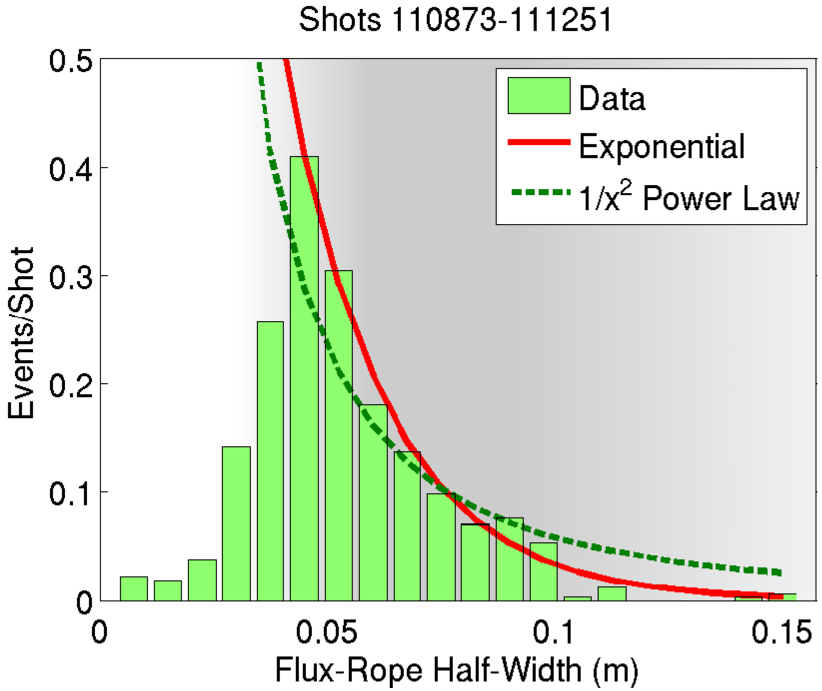


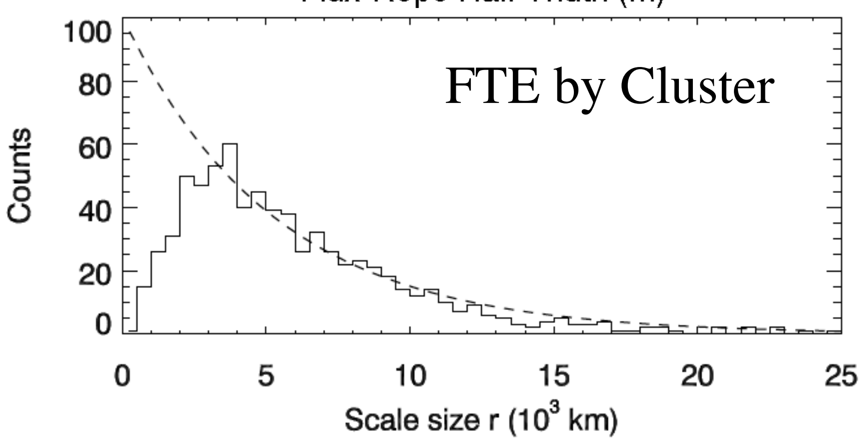
Jain et al. (2013)

- Impulsiveness reproduced by 2D E-MHD simulations
- Spreading in the 3rd direction also consistent with 3D E-MHD

Statistics of flux rope sizes

Dorfman et al. (2014)

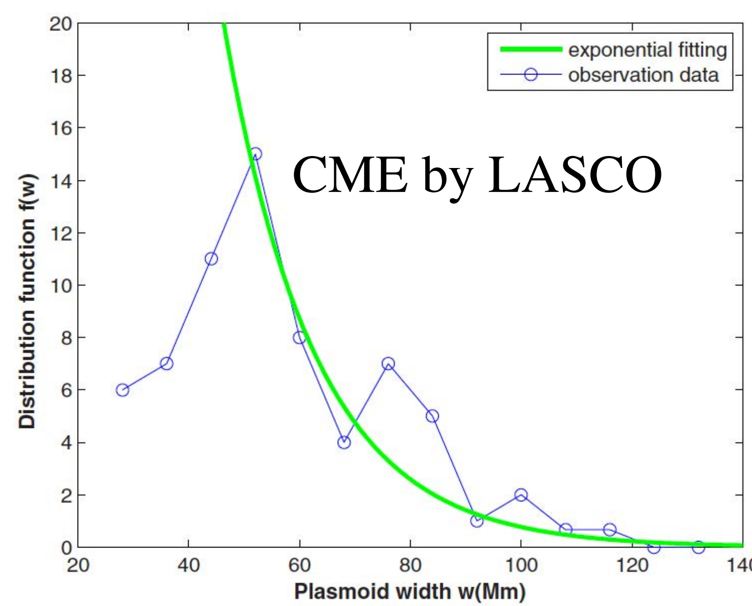




Fermo et al. (2011)

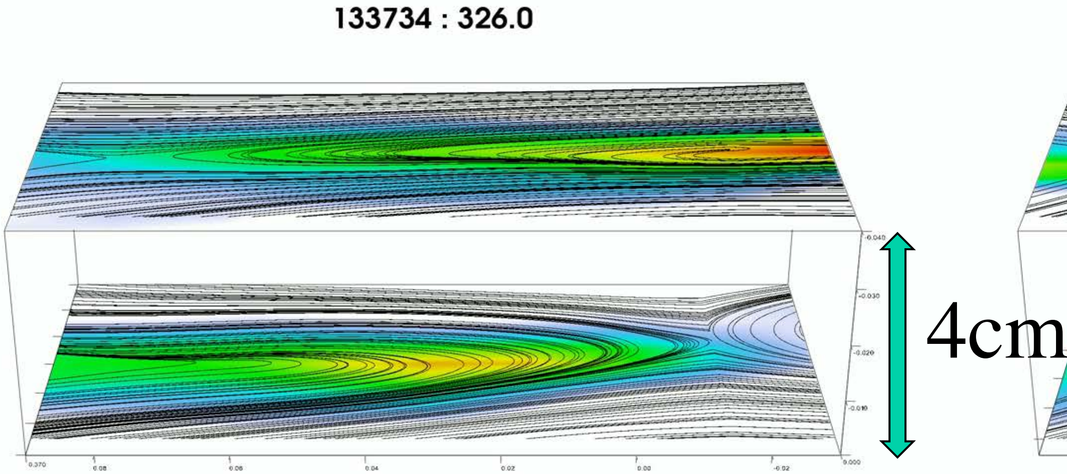
Theory/simulation:

- 1/x^2 in MHD [Uzdensky et al. (2010); Loureiro et al. (2012)]
- exp(-x) in Hall-MHD [Fermo et al. (2010); Fermo et al. (2011)]
- 1/x followed by an exp(-x) tail in MHD [Huang & Bhattacharjee (2012); Guo et al. (2013)]



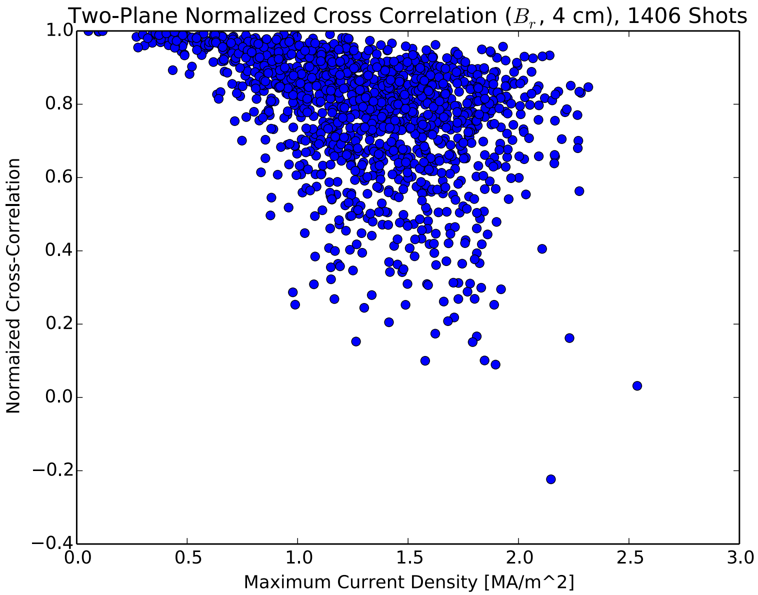
Guo et al. (2013)

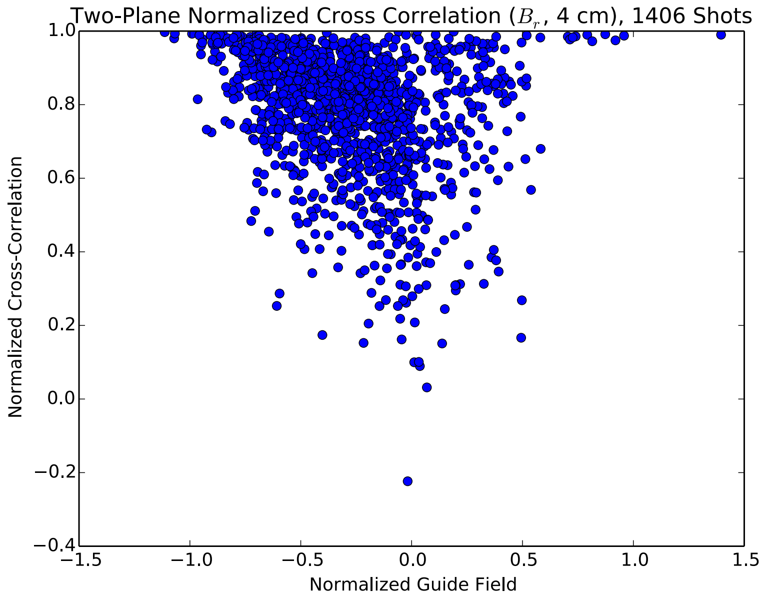
The 3D-ness is being investigated



Very 3D

~ 2D





De-correlates at high current and low guide field

J. Jara-Almonte

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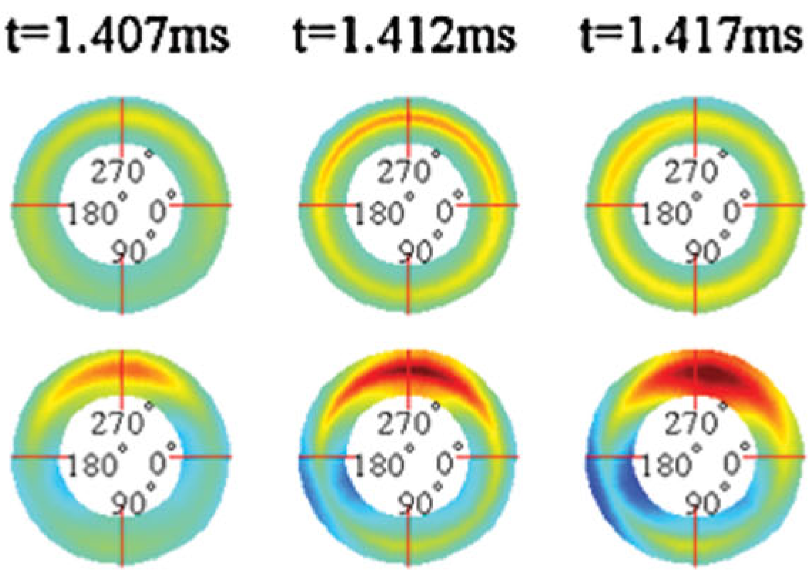
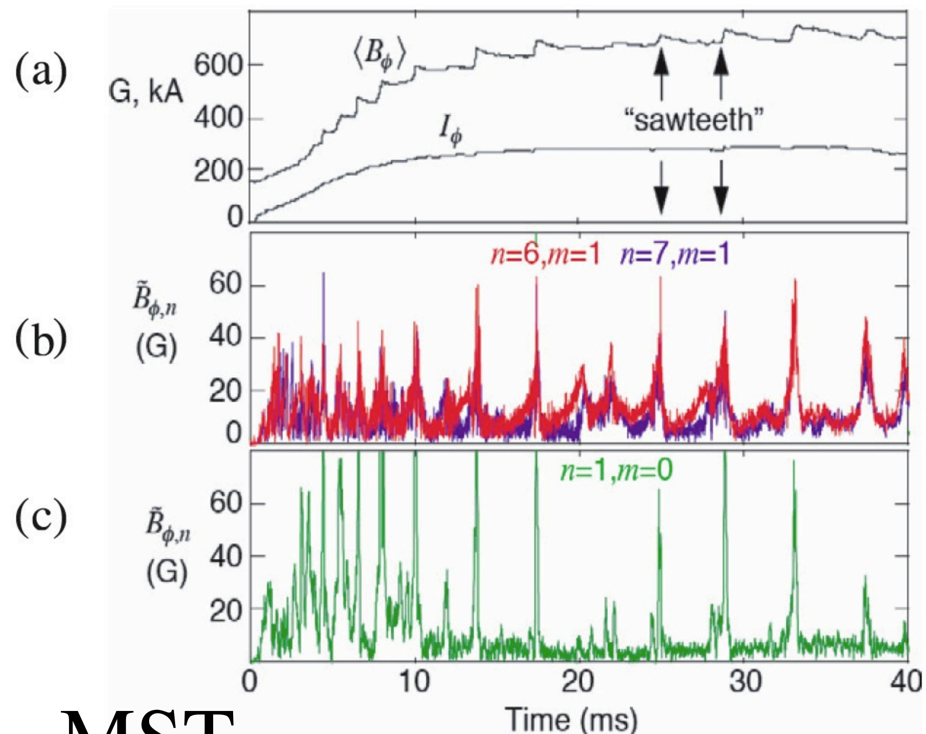
Global 3D: Cause of the Reconnection Onset in Periodic Systems



VTF



MST

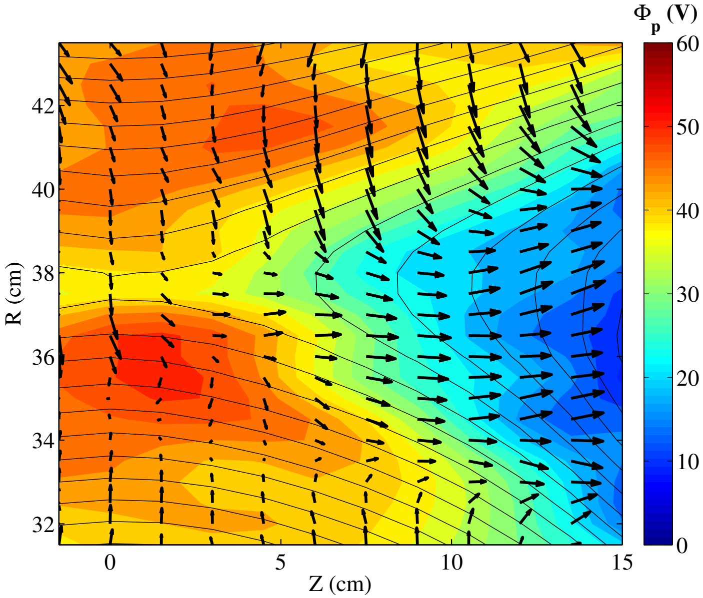
Katz et al. (2010)

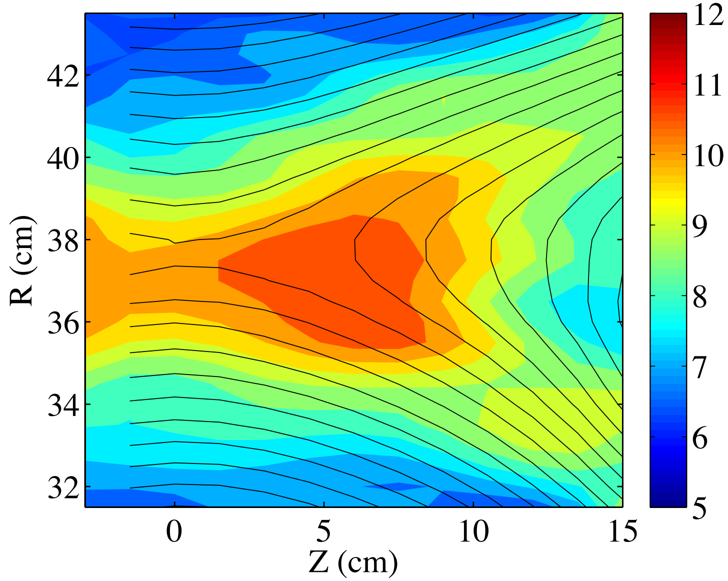
Prager et al. (2005)

Energy converted from magnetic field to plasma: ion flow acceleration, ion and electron heating

Yoo et al. PRL (2013)

Yamada et al. Nature Communications (2014)

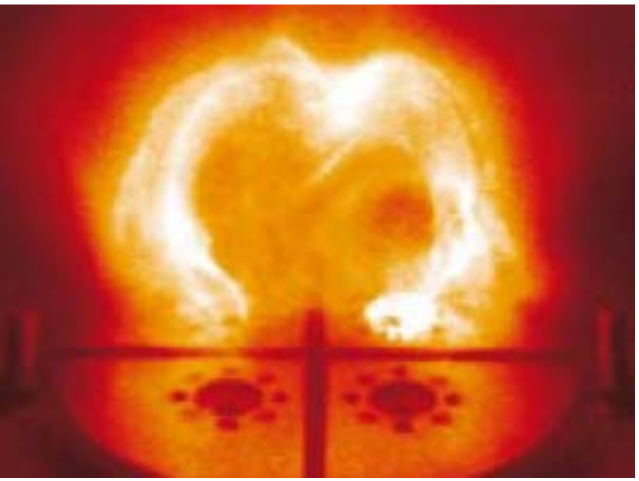




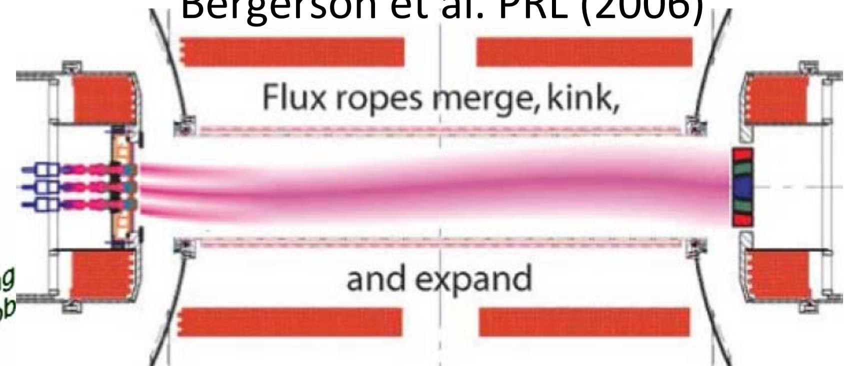
- 1/2 of magnetic energy goes to plasma
  - 2/3 to ion flow energy and heating
  - 1/3 to electron heating
- Effects of asymmetry are being investigated [Yoo et al. PRL (2014)]

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

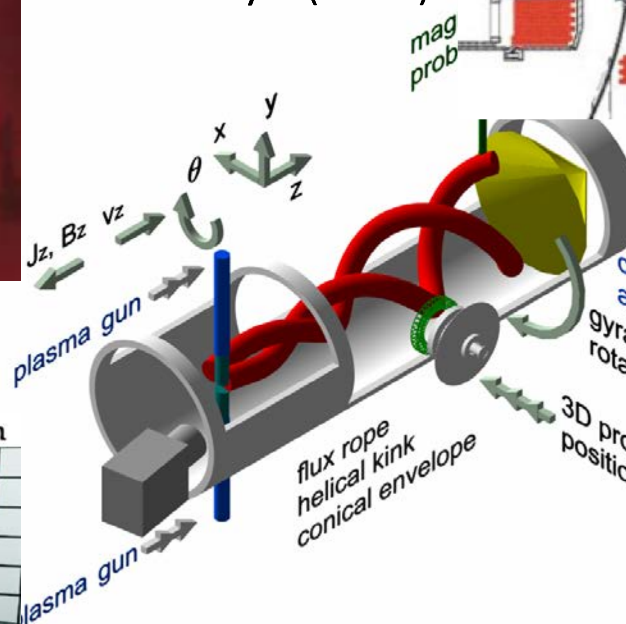
Hansen & Bellan ApJ (2004)



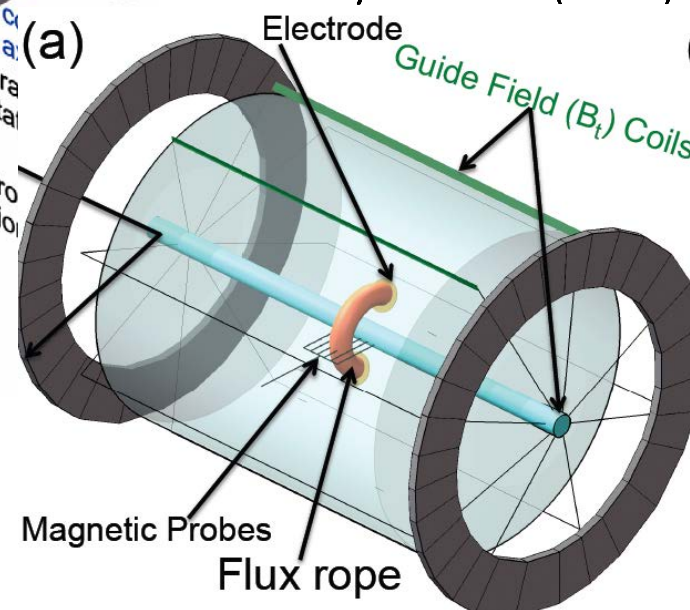
Bergerson et al. PRL (2006)

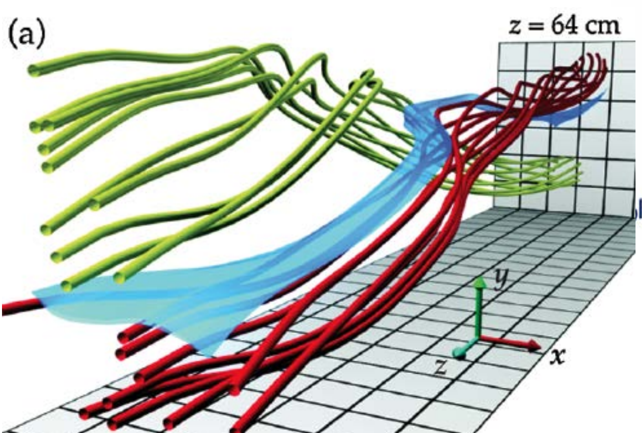


Intrator et al.
Nature Phys. (2009)



Oz et al. (2010)
Myers et al. (2015)





Lawrence & Gekelman
PRL (2009)

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Advanced Ongoing Beginning

The Multi-Scale Problem:

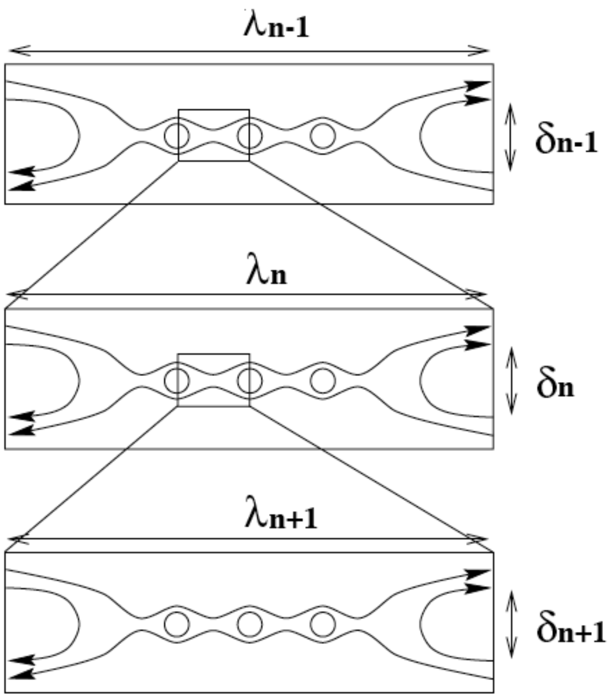
How to apply local reconnection physics to heliophysical and astrophysical plasmas with large sizes and high S?

➔ A reconnection phase diagram

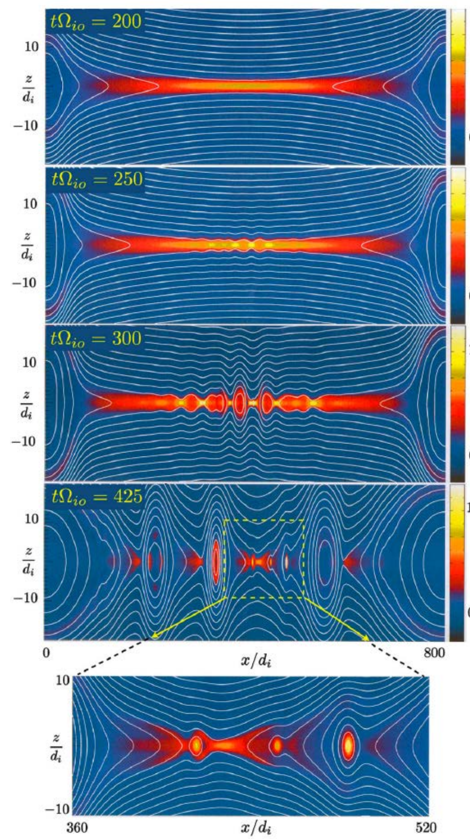
➔ A next generation reconnection experiment: FLARE

Plasmoid Dynamics May Solve Scale Separation Problem

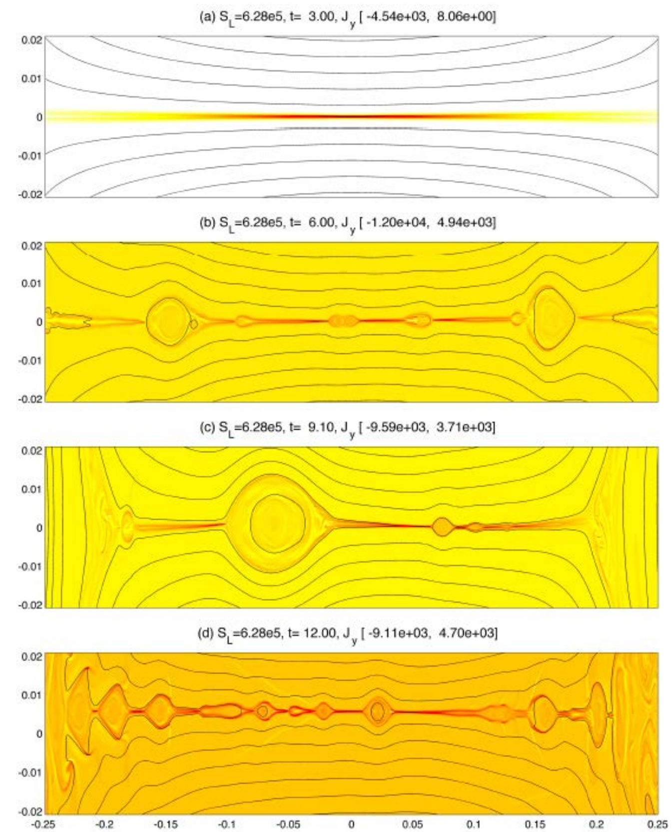
Shibata & Tanuma (2001)



Daughton et al. (2009)



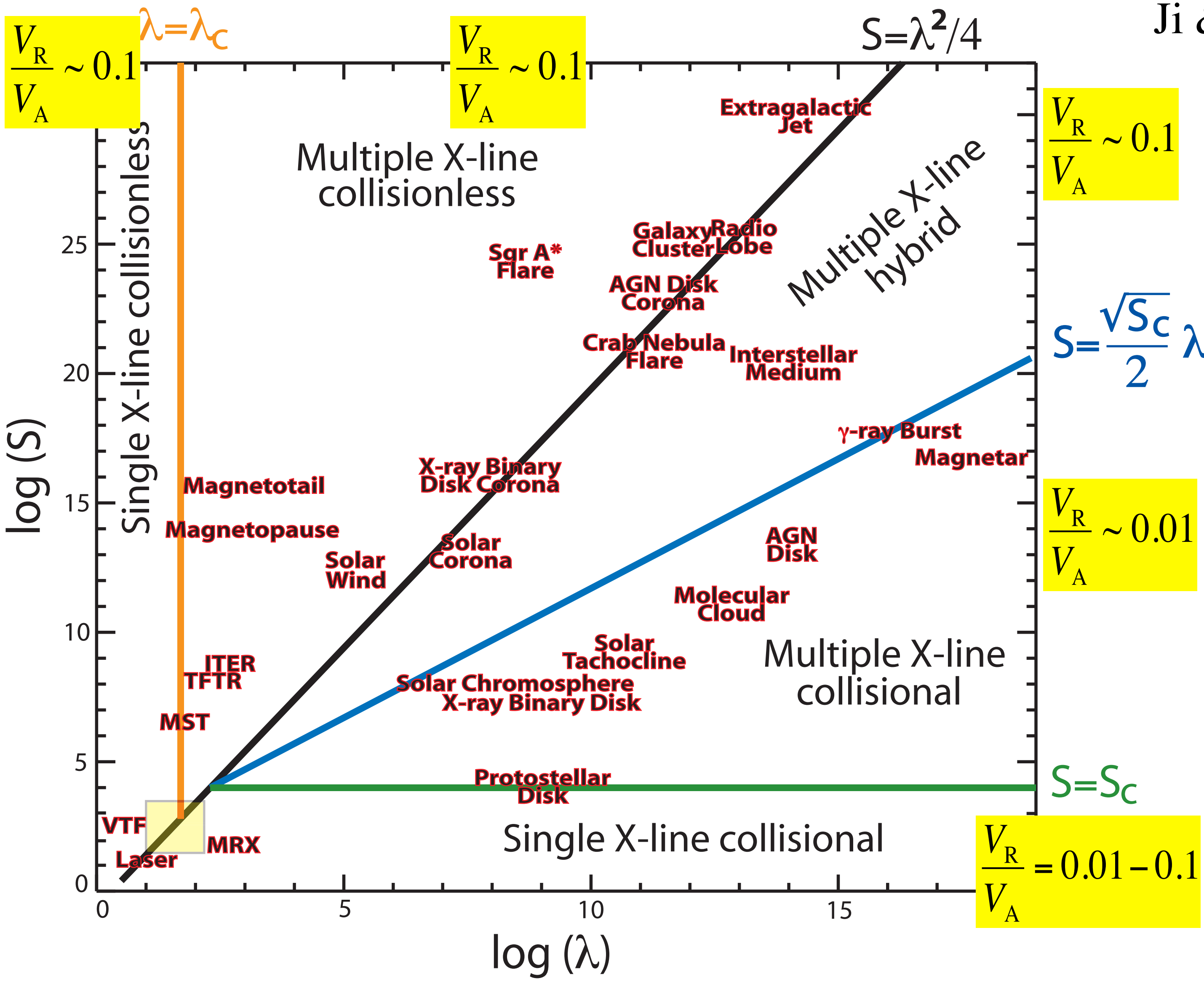
Bhattacharjee et al. (2009)



Many theoretical works: Loureiro et al. (2007); Cassak et al. (2009); Uzdensky et al. (2010) ….

"Phases Diagram" for Different Coupling Mechanisms during Reconnection in Large Plasmas

Ji & Daughton (2011)



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

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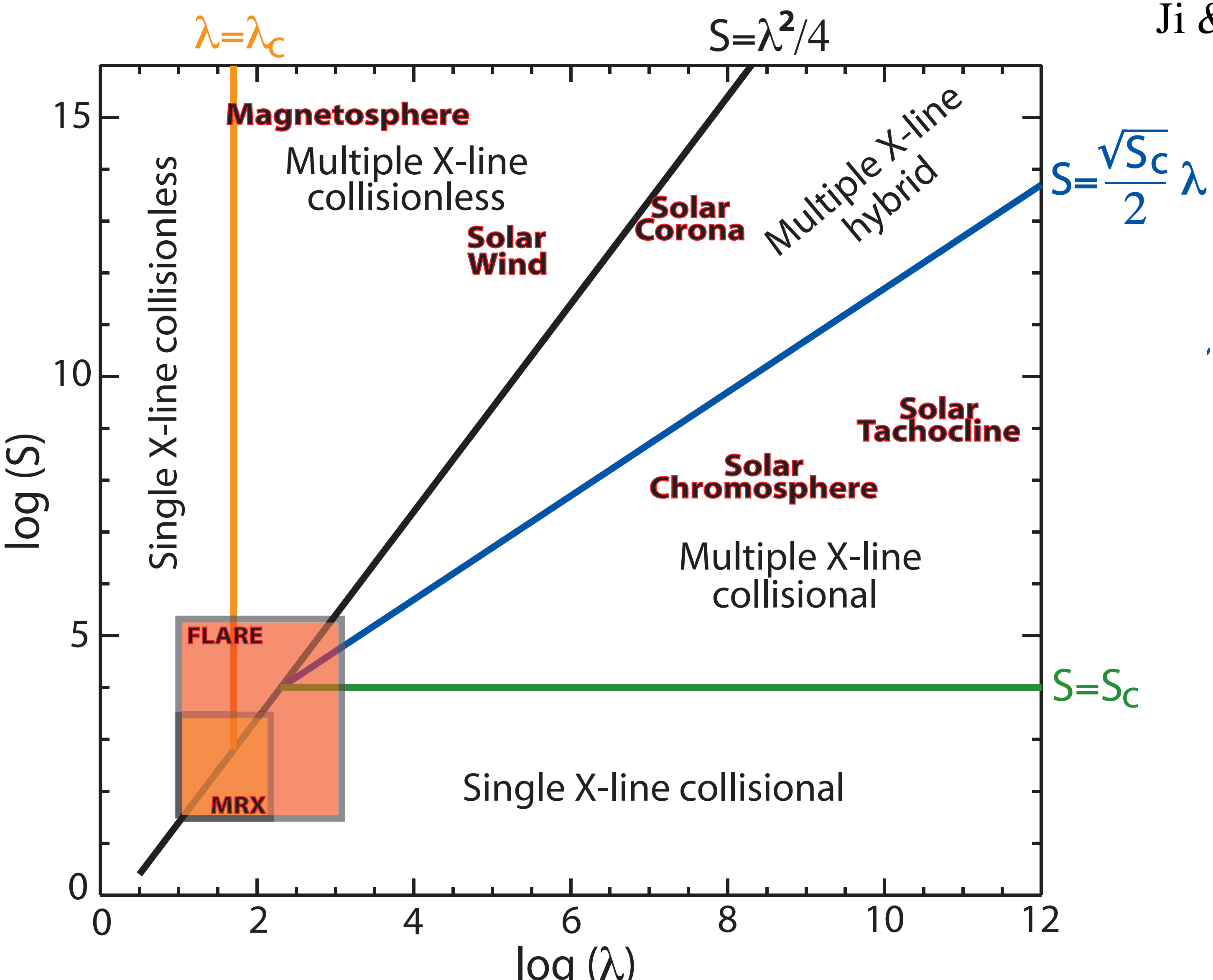

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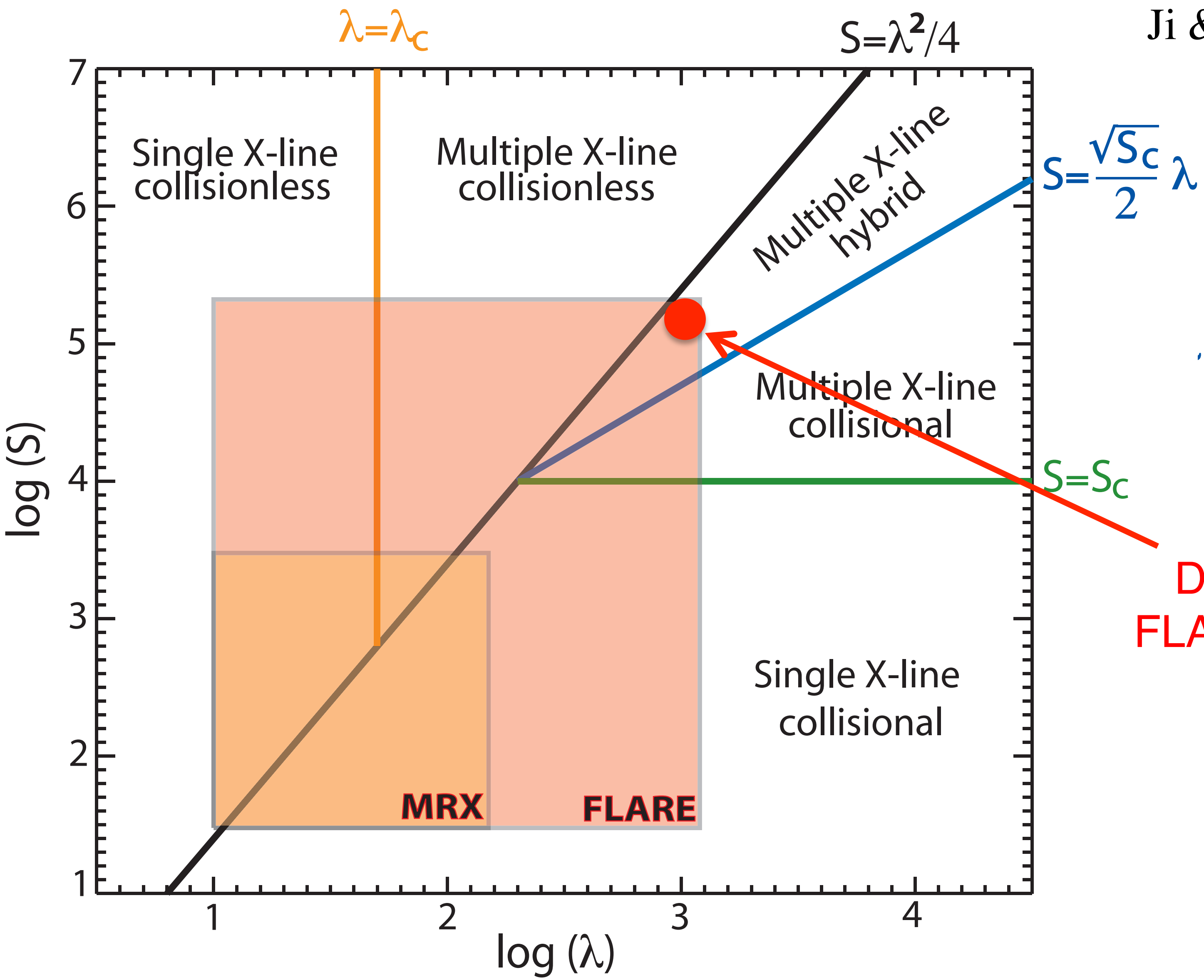
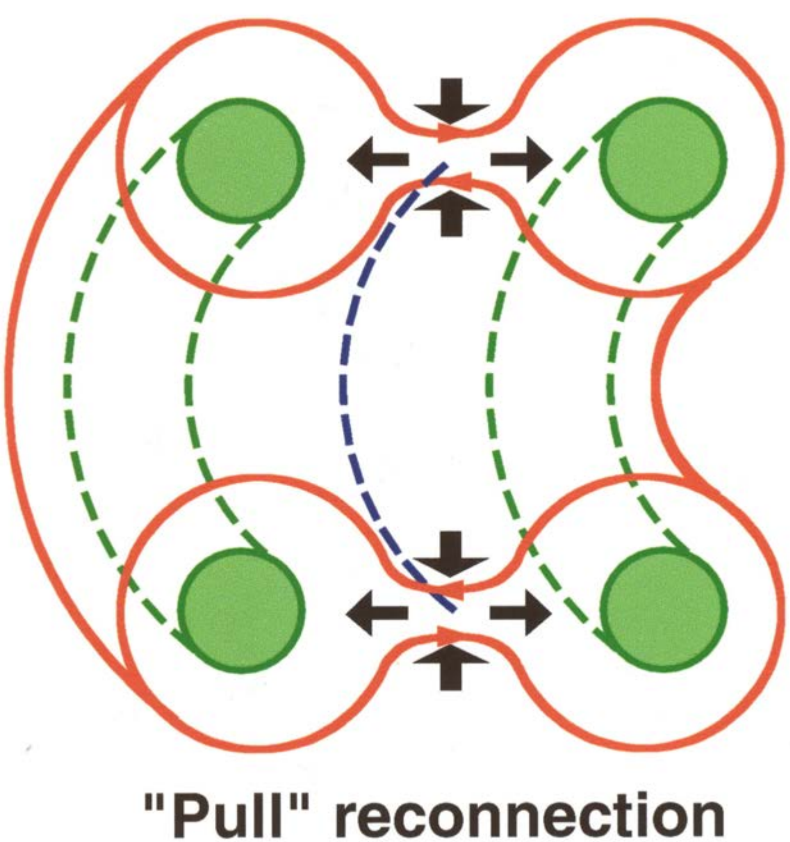
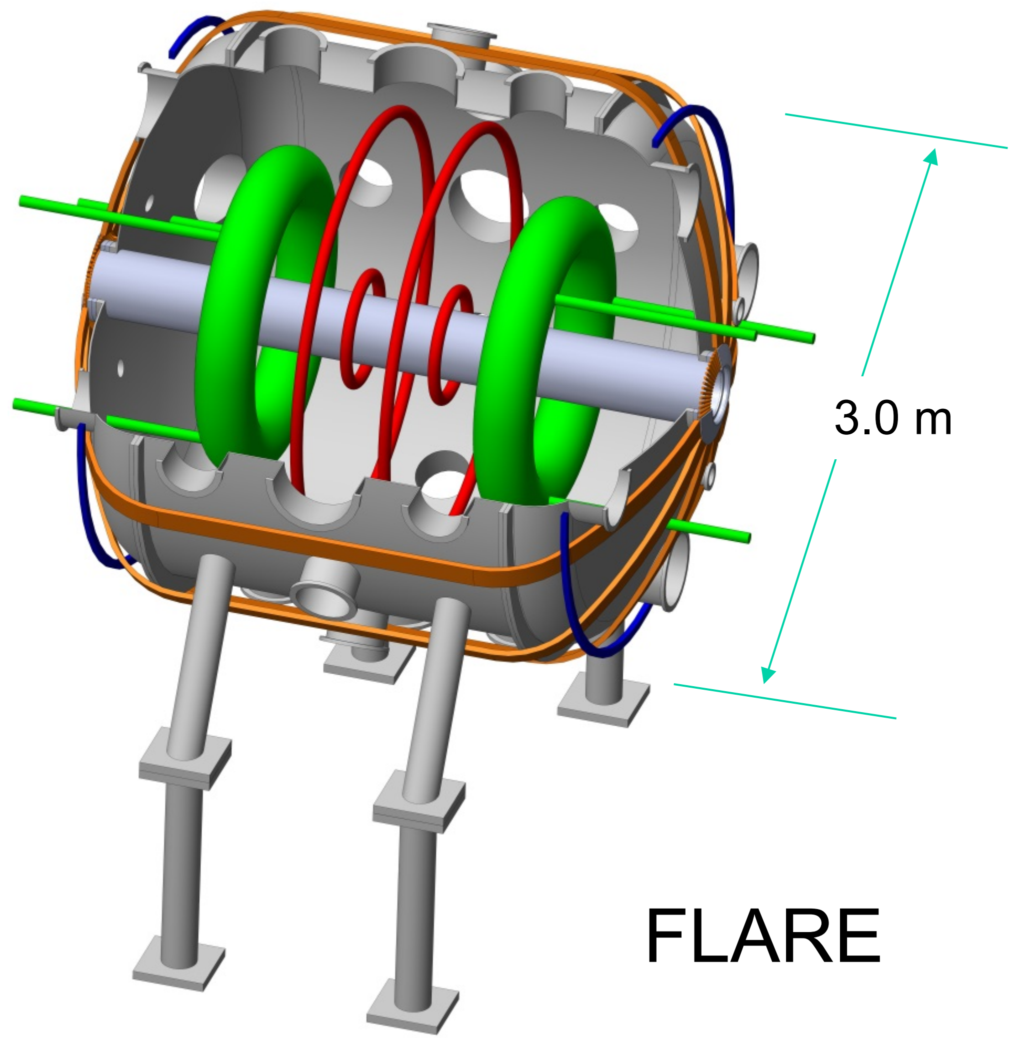


$$\lambda \equiv \frac{L}{\rho_S}$$

FLARE (Facility for Laboratory Reconnection Experiments) project (since 2013; flare.pppl.gov)

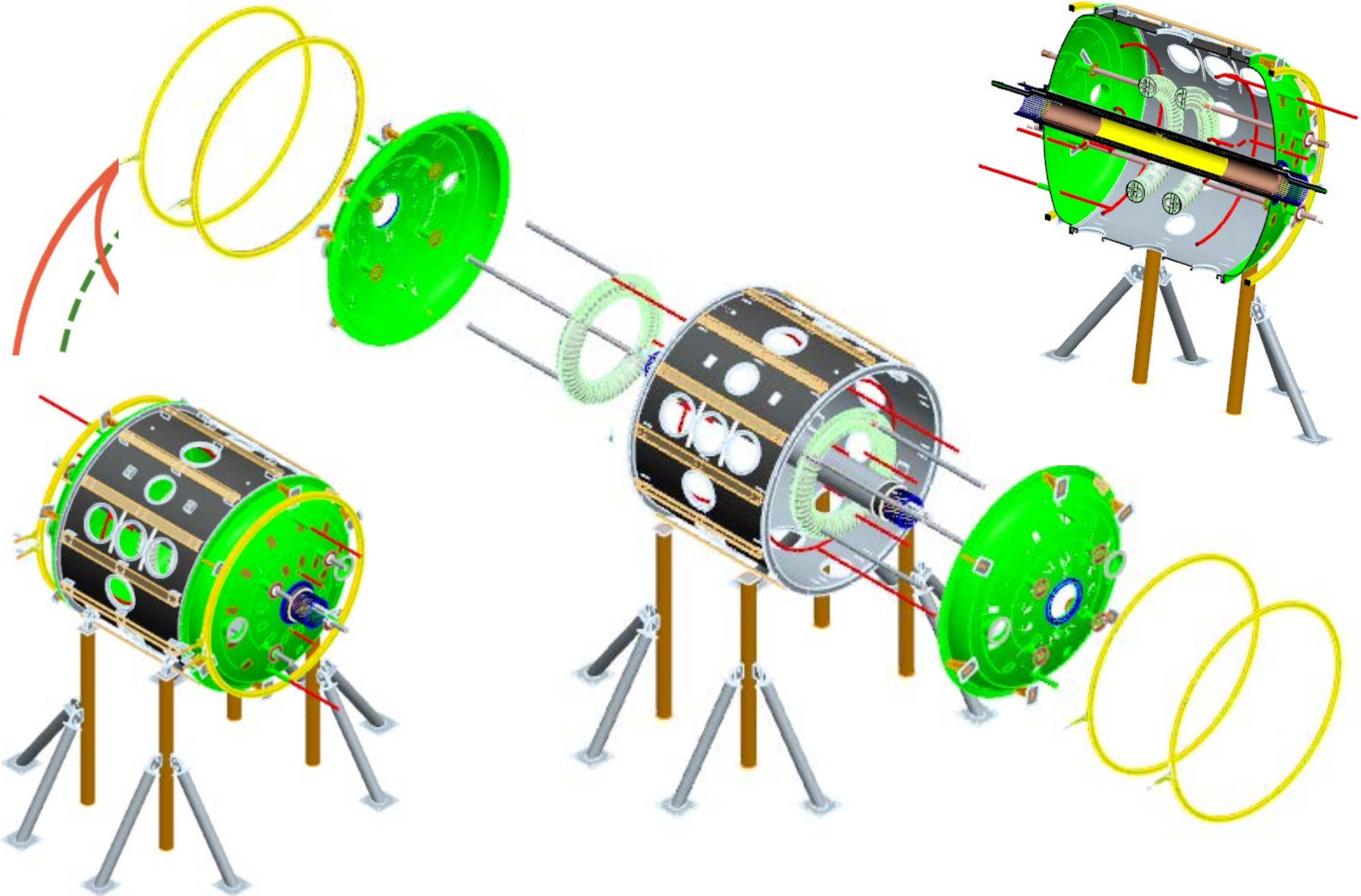


MRX



FLARE

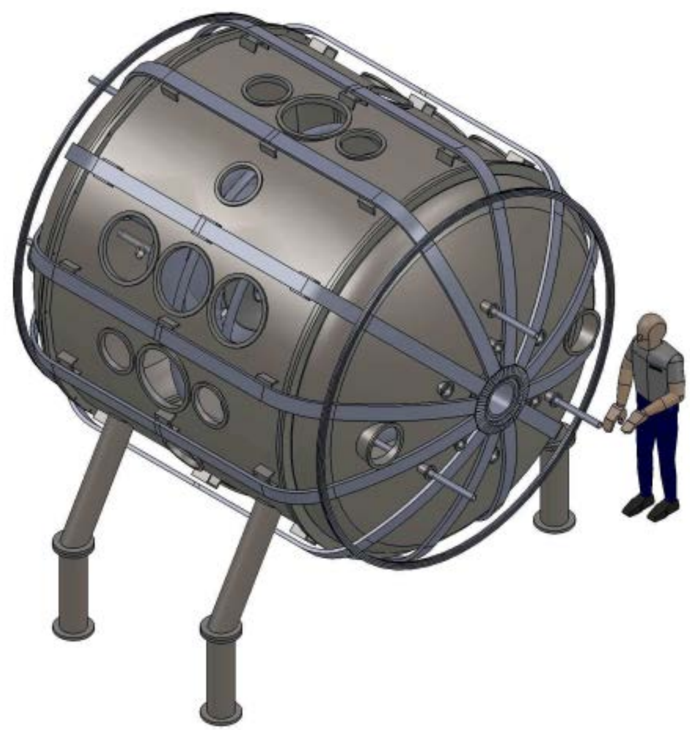
FLARE (Facility for Laboratory Reconnection Experiments) project (since 2013; flare.pppl.gov)



FLARE Parameters & Project Status

Parameters	MRX	FLARE
Device diameter	1.5 m	3 m
Device length	2 m	3.6 m
Flux core major diameters	0.75 m	1.5 m
Flux core minor diameter	0.2 m	0.3 m
Stored energy	25 kJ	4 MJ
Ohmic heating/ drive	No	0.3 V-s
Outer driving coil	Yes	Yes
Inner driving coil	No	Yes
S (anti-parallel)	600-1,400	5,000-16,000
$\lambda=(Z/\delta_i)$	35-10	100-30
S (guide field)	2900	100,000
$\lambda=(Z/\rho_S)$	180	1,000

Phase 1 (Optimization): complete
Phase 1 (Design): complete
Phase 2 (Procurement): ongoing
Phase 2 (Manufacturing): ongoing
Phase 2 (Assembly): FY2016
Phase 2 (Installation): FY2016
Operation and Research: FY2017



FLARE will be a user facility, open to everyone from space, solar, astro and fusion. Sample Topics:

- Multiple-scale
  - Plasmoid instability in MHD
  - Scaling multiple MHD X-lines
  - Transition from MHD to kinetic
  - Scaling of kinetic X-lines
  - Guide field dependence of multiple-scale reconnection
- Reconnection rate
  - Reconnection rate for multiple MHD X-lines
  - Reconnection rate for multiple MHD and kinetic X-lines
  - Upstream asymmetry + guide field effects on reconnection
- Reconnection onset
  - Is reconnection onset local or global?
  - Is reconnection onset 2D or 3D?
- 3D effects
  - Plasmoid inst. in 3D: flux ropes?
  - Third dimension scaling: towards turbulent reconnection?
  - Externally drive tearing recon.
  - Interaction of multiple tearing modes: magnetic stochasity?
  - Line-tied effects in 3rd direction
- Particle heating and acceleration
  - Ion energization in large system
  - Electron energization in large system
  - Scaling of ion energization
  - Scaling of electron energization
- Partial ionization
  - Modification of multiple-scale reconnection by neutral particles
  - Neutral particle energization

Any Ideas and Collaborations are Welcome!

Summary: Frontiers for Laboratory Reconnection Research

- Resolve electron-scale physics (comparisons w/ MMS, THOR)
- Particle energization, especially for non-thermal tails & anisotropy (in competition with shocks and turbulence)
- Realistic 3D geometries (Earth's magnetosphere etc.)
- Onset (key to predict space weather & disruptions)
- Partial ionization (application to solar chromosphere, molecular clouds, & protostellar disks)
- Boundary condition (line-tied flux ropes)
- Shear-driven systems (part of turbulence, dynamo saturation)
- Extreme conditions (radiation, strong B)
- Multi-scale (application to helio/astrophysical reconnection)