Magnetic Reconnection: Past, Present, and Future

Hantao Ji

Princeton University

- Review: "*Magnetic Reconnection in the Era of Exascale Computing and Multiscale Experiments*", Nature Rev. Phys. (2022)
- Review: "*Laboratory Study of Collisionless Magnetic Reconnection*", Space Sci. Rev. (2023)
- Review: "*Study of magnetic reconnection at low-beta using laser-powered capacitor coils*," Phys. Plasmas (2024).
- Whitepapers: "*Major Scientific Challenges and Opportunities in Understanding Magnetic Reconnection and Explosive Phenomena through the Universe*", arXiv:2004.00079; arXiv:2009.08779

Synergies Between Astrophysical, Space, Laboratory, and Fusion Plasma Physics

May 19, 2026

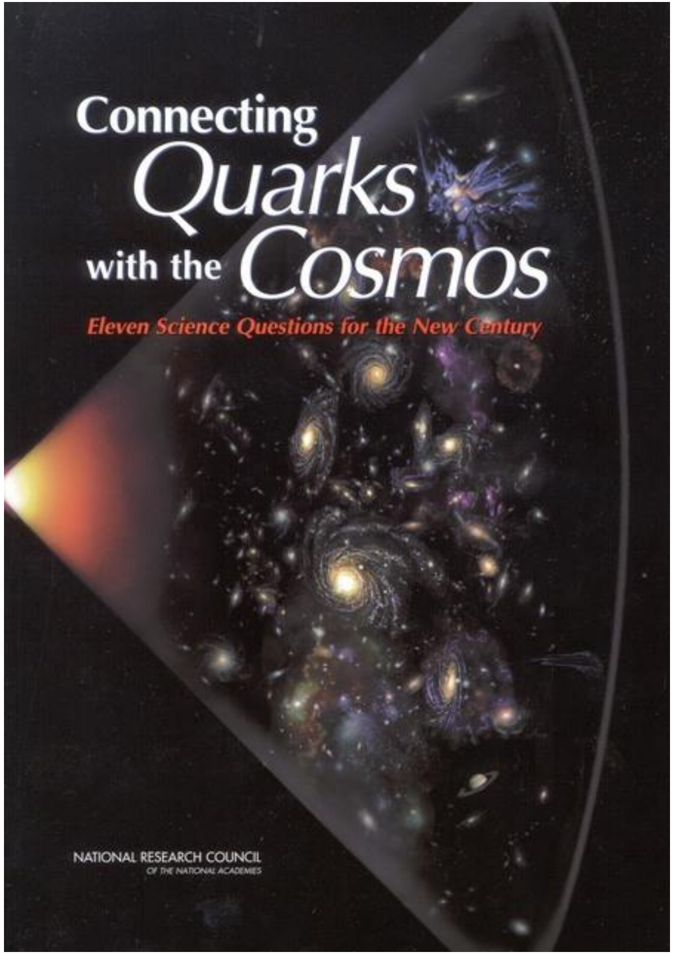
NORDITA, Sweden

August 2015


MAGNETIC RECONNECTION IN PLASMAS
RECONNECTION WORKSHOP


MAGNETIC RECONNECTION IN PLASMAS
RECONNECTION WORKSHOP
10–14 August 2015
Registration and talks are in the AlbaNova main building

11 Physics Questions for the 21th Century



1. What is dark matter?
2. What is dark energy?

?? High Energy Astrophysics/Cosmology

3. How were the heavy elements from iron to uranium made?

"kilonova". Nuclear Astrophysics

4. Do neutrinos have mass?

Yes. High Energy Astrophysics

5. Where do ultra-energy particles come from?
6. Is a new theory of light and matter nee energies and temperat ?
7. Are there new states o and densities (q-g plasma)?
8. Are protons unstable?
9. What is gravity?
10. Are there additional dimensions?
11. How did the Universe begin?

?? Plasma Astrophysics

Shock, Turbulence, Magnetic Reconnection

Special Thanks to Reconnection Community

White Paper for 2024 Heliophysics Decadal Survey

Major Scientific Challenges and Opportunities in Understanding Magnetic Reconnection and Related Explosive Phenomena in Heliophysics and Beyond

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August 30, 2022

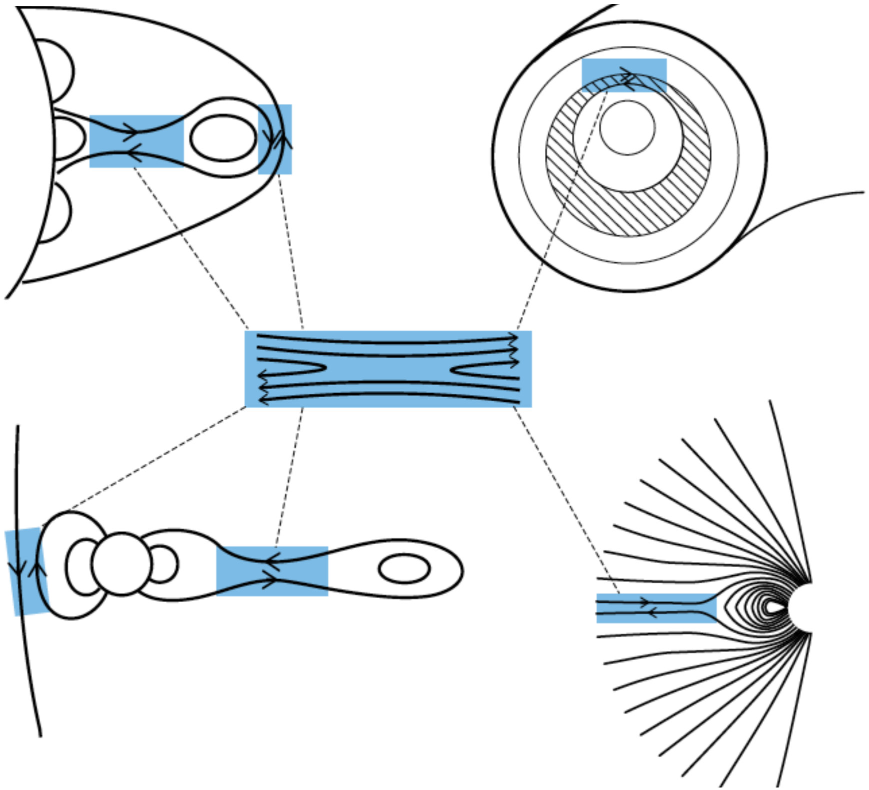
also to 2020 plasma/astro decadal surveys

Outline

- Magnetic reconnection – a long history with three phases
  - Phase I on MHD physics
  - Phase II on physics beyond MHD
- Phase III is to understand multiscale physics across the huge gap between kinetic and system (fluid) scales
  - FLARE (Facility for Laboratory Reconnection Experiments) has been constructed to provide access to new regimes of multiscale reconnection, directly relevant to space and astrophysics, with promising initial results
  - Reconnection onset, relevant to space weather event understanding and prediction
  - Reconnection under extreme conditions using pulsed powers and high-power lasers (HED plasmas)
  - Turbulent magnetotail reconnection
- Collaborations are key to solve magnetic reconnection problem.

Magnetic Reconnection Occurs throughout the Universe

H. Ji, W. Daughton, J. Jara-Almonte, A. Le, A. Stanier, and J. Yoo, Nat. Rev. Phys. (2022)



- Nearly collisionless

  $$\text{Lundquist number } S \equiv \frac{\mu_0 L V_A}{\eta} \sim 10^6 - 10^{30}$$

- Plasma is large

  $$\text{effective size } \lambda \equiv \frac{L}{\rho_{\text{sound}}} \sim 10^2 - 10^{14}$$

- Occurs impulsively and energetically, often at low-β or extreme conditions with abundant magnetic free energy

  $$\text{average energy increase } \frac{\Delta E}{E_0} = \frac{1}{\beta} \gg 1$$

Progress in Magnetic Reconnection Research

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  - Focus on MHD/fluid physics – reconnection rate
  - Sweet-Parker model vs Petschek model
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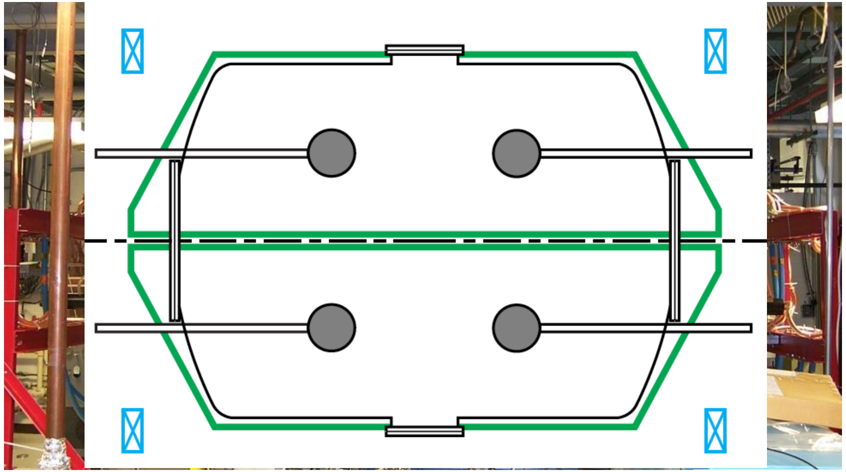
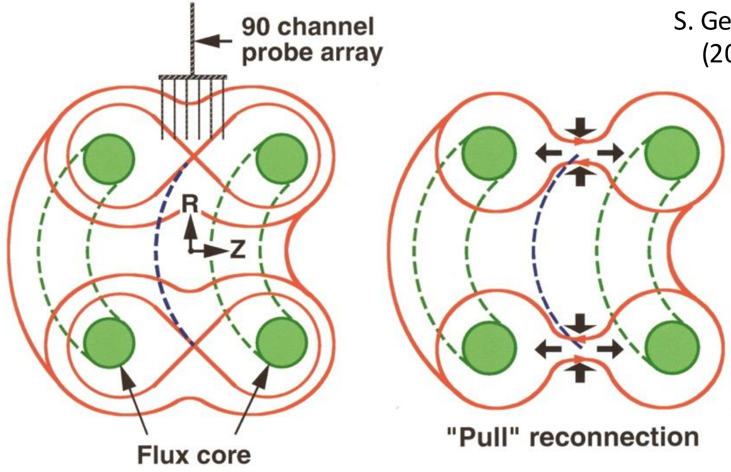
 Ji+ Space Sci Rev (2023)

Magnetic Reconnection Experiment (MRX)

Table 1 A non-exhaustive list of relevant experiments on collisionless reconnection

Facility / location	Main features / topics	Main or relevant references
Linear device / UCLA	electron-only / waves, non-thermal electrons, plasmoids	Stenzel and Gekelman (1979), Gekelman and Stenzel (1984, 1985), Stenzel et al. (1986)
TS-3/4 / U. Tokyo	toroidal plasma merging / heating, plasmoids	Yamada et al. (1990), Ono et al. (1993, 2011)
MRX / Princeton	axisymmetric current sheet, toroidal plasma merging / reconnection rate, structure, heating, waves, 3D, plasmoids	Yamada et al. (1997, 2006, 2014, 2018), Ji et al. (1998, 2004, 2005, 2008), Hsu et al. (2000), Carter et al. (2001), Ren et al. (2005, 2008), Kulsrud et al. (2005), Tharp et al. (2012), Lawrence et al. (2013), Dorfman et al. (2013, 2014), Yoo et al. (2013, 2014b, 2018, 2023), Jara-Almonte et al. (2016), Fox et al. (2017, 2018), Bose et al. (2023)
SSX / Swarthmore	toroidal plasma merging / heating	Brown (1999), Brown et al. (2002, 2006)
VTF / MIT	axisymmetric current sheet, strong guide field / structure, heating, waves, onset	Egedal et al. (2000, 2003), Egedal and Fasoli (2001), Stark et al. (2005), Katz et al. (2010), Fox et al. (2008, 2010, 2012)
RSX / Los Alamos National Lab	linear plasma merging / onset, 3D	Intrator et al. (2009)
RWX / U. Wisconsin	liner geometry / onset	Bergerson et al. (2006)
TREX / U. Wisconsin	axisymmetric current sheet / structure, plasmoids	Olson et al. (2016, 2021), Greess et al. (2021)
MAGPIE / Imperial	Z-pinch / heating, plasmoids	Hare et al. (2017)
PHASMA / West Virginia U.	linear plasma merging, electron-only / heating	Shi et al. (2022)
Capacitor coil powered by laser / U. Rochester	current sheet / electron acceleration, waves	Chien et al. (2023), Zhang et al. (2023)
FLARE / Princeton	axisymmetric current sheet / multiscale	Ji et al. (2018, 2022)

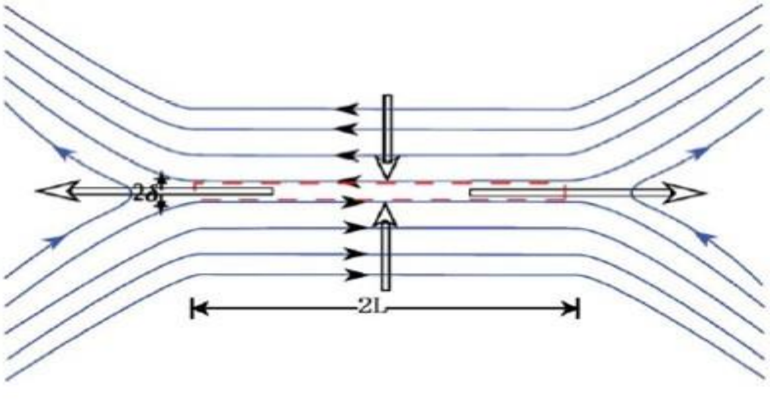


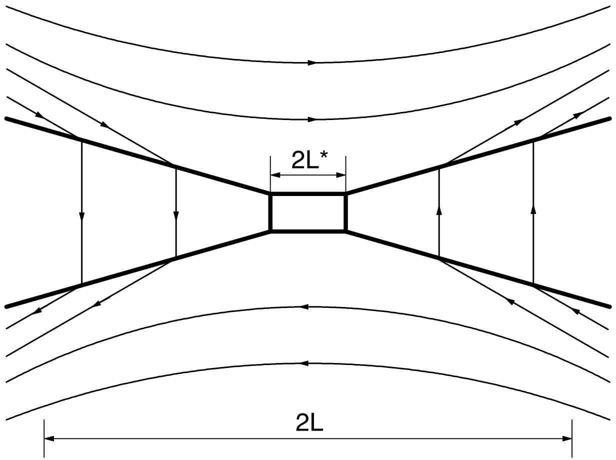


S. Gerhardt (2005)

Key: Control + Diagnostics

Phase I: MHD Reconnection Models





Sweet-Parker model (1957) has been verified numerically (Biskamp 1986) but predicts slow reconnection.

Petschek model (1964) predicts fast reconnection but needs localized anomalous resistivity and slow-mode shocks (Ugai & Tsuda 1977, Sato & Hayashi 1979).

How about laboratory experiments?

Sweet-Parker MHD Model Works in *Collisional Plasmas*

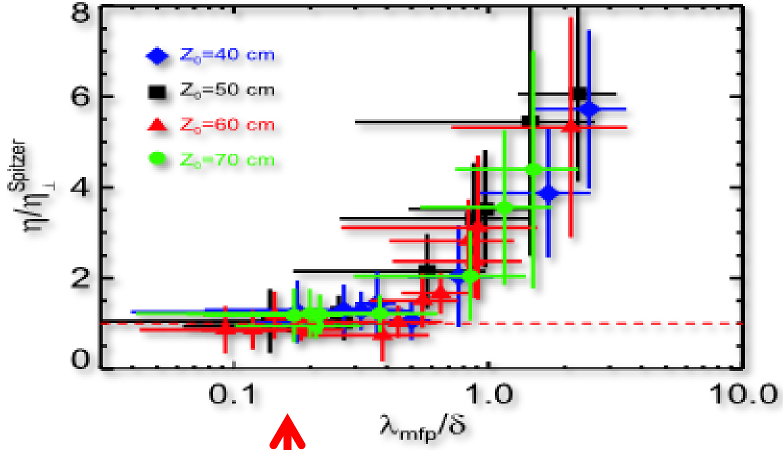
(Magnetic Reconnection Experiment, **MRX**)

Ji+ PRL 1998

Ji+ PoP 1999

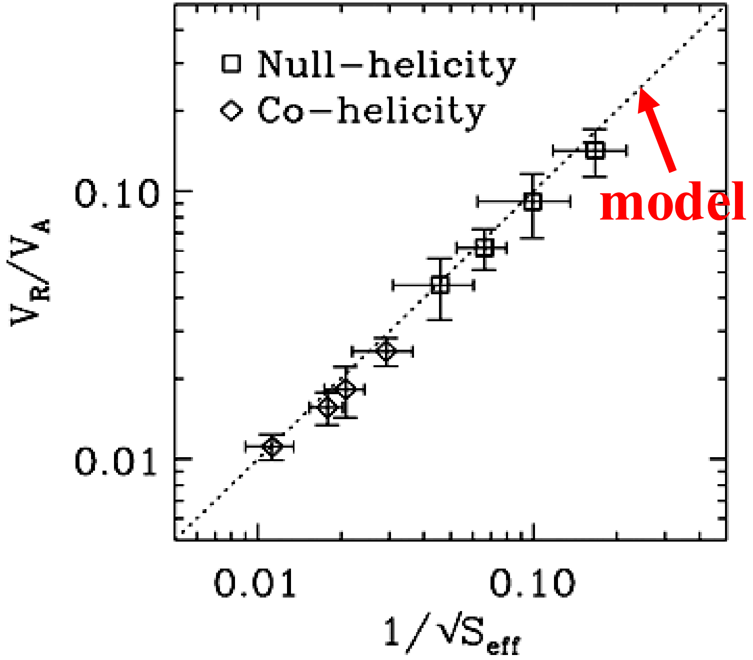
MHD Ohm's law: $\mathbf{E}+\mathbf{V}\square\mathbf{B}=\eta_{Spitzer}\mathbf{j}$

- **When collisional, resistivity (*E*/*j*) dominated by Spitzer values**



Kuritsyn+ PoP 2006

collisional



No slow-mode shocks observed for Petschek model

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Phase II: Models based on Physics beyond MHD

Two-fluid, Collisionless Kinetic Physics (Ion and Electron Scales)

Generalized Ohm's law: $\mathbf{E}+\mathbf{V}\times\mathbf{B}=\eta_{Spitzer}\mathbf{j}+\frac{\mathbf{j}\times\mathbf{B}}{en}-\frac{\nabla\cdot\mathbf{P}_e}{en}+\frac{m_e}{e}\left(\frac{\partial\mathbf{V}_e}{\partial t}+(\mathbf{V}_e\cdot\nabla)\mathbf{V}_e\right)$

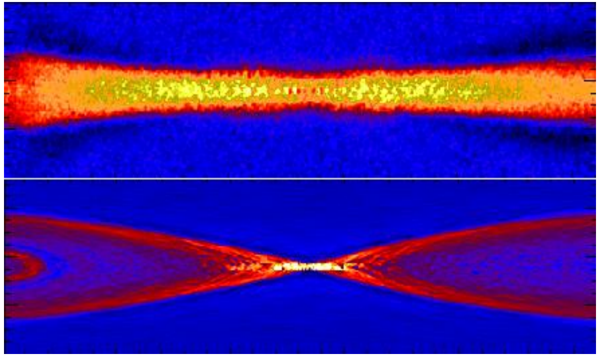
J. Drake

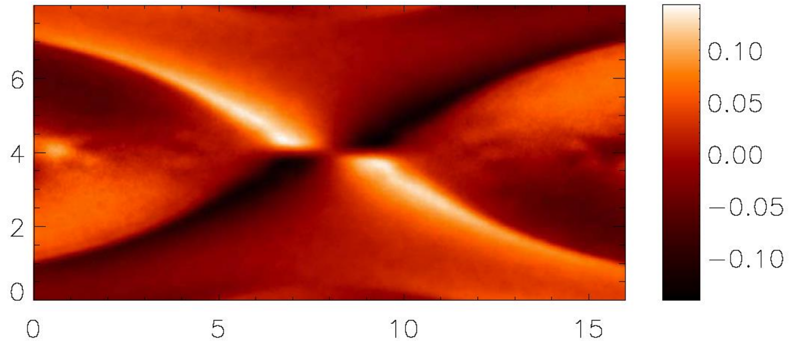
ions

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

electrons

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





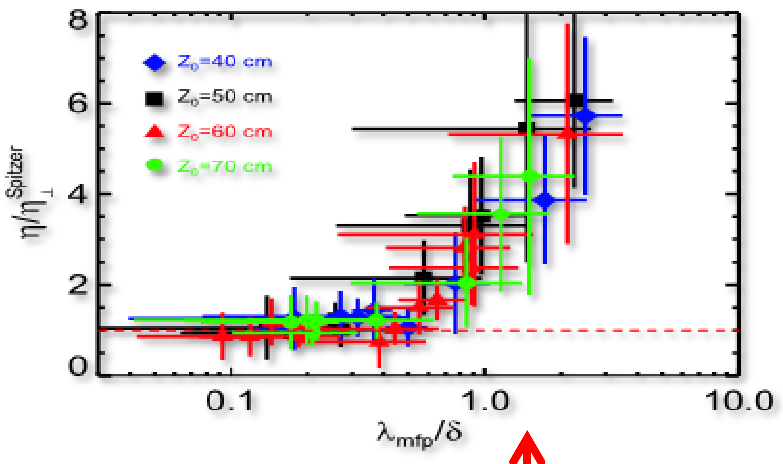
decoupled ion & electron motions
to avoid bottleneck effects

fast reconnection with a quadrupole structure for out-of-plane field

Does this really work? Yes!

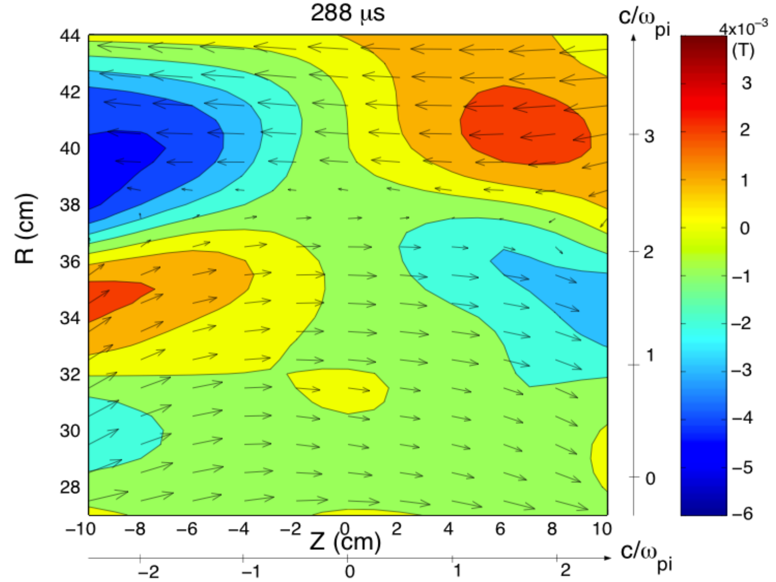
Fast Kinetic Reconnection Model Confirmed

Kuritsyn+ PoP 2006



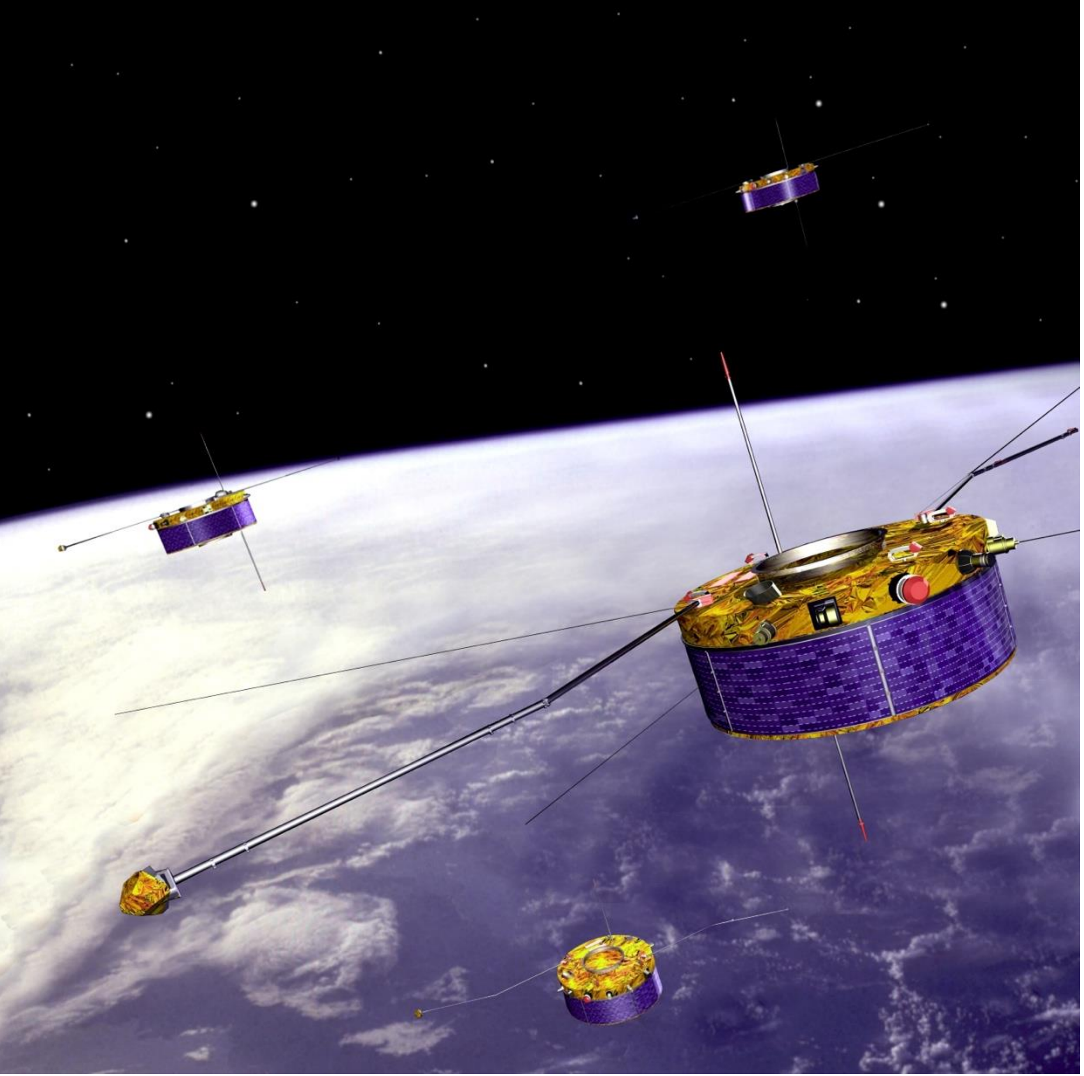
collisionless

Ren+ PRL (2005)



- **When collisionless, Spitzer resistivity unimportant**

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

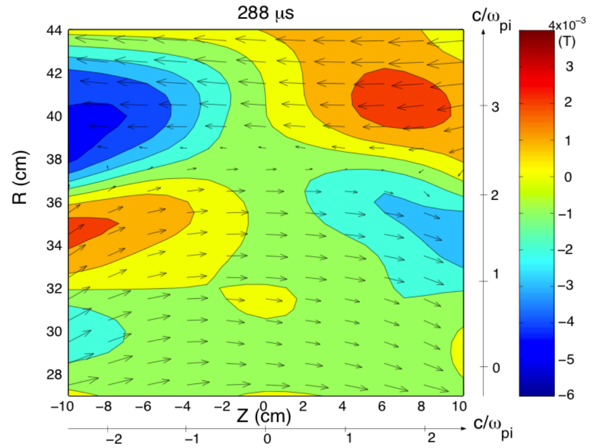


CLUSTER mission 2000-2024

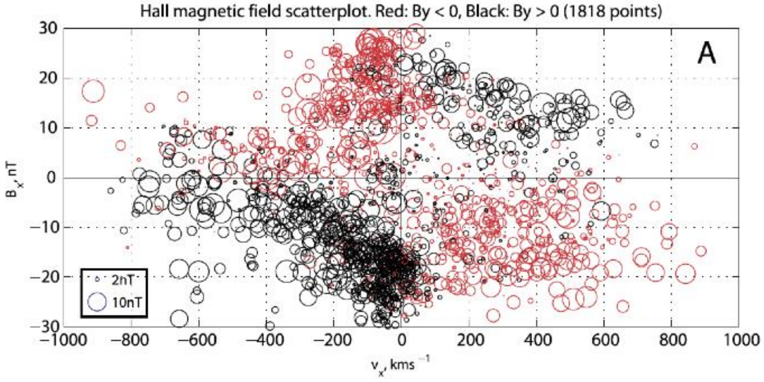
(4 satellites separated by ion scale)

MRX-Cluster Comparisons

Out-of-plane magnetic field:

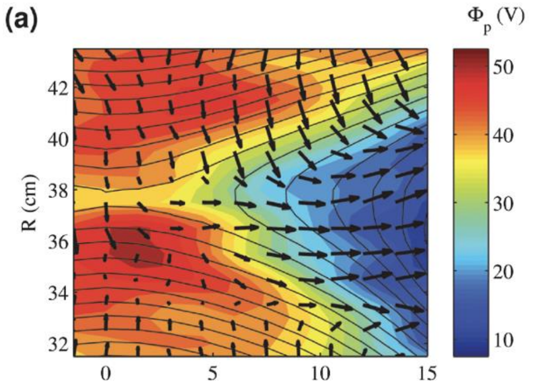


Ren+ PRL 2005

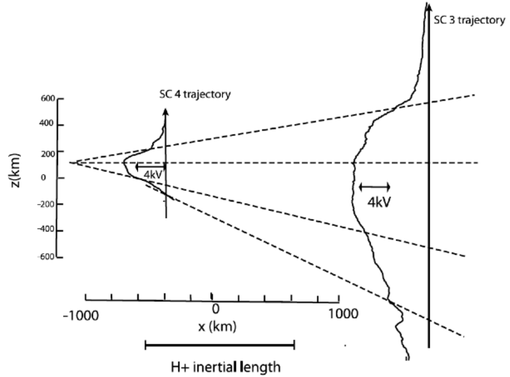


Eastwood+ GRL 2010

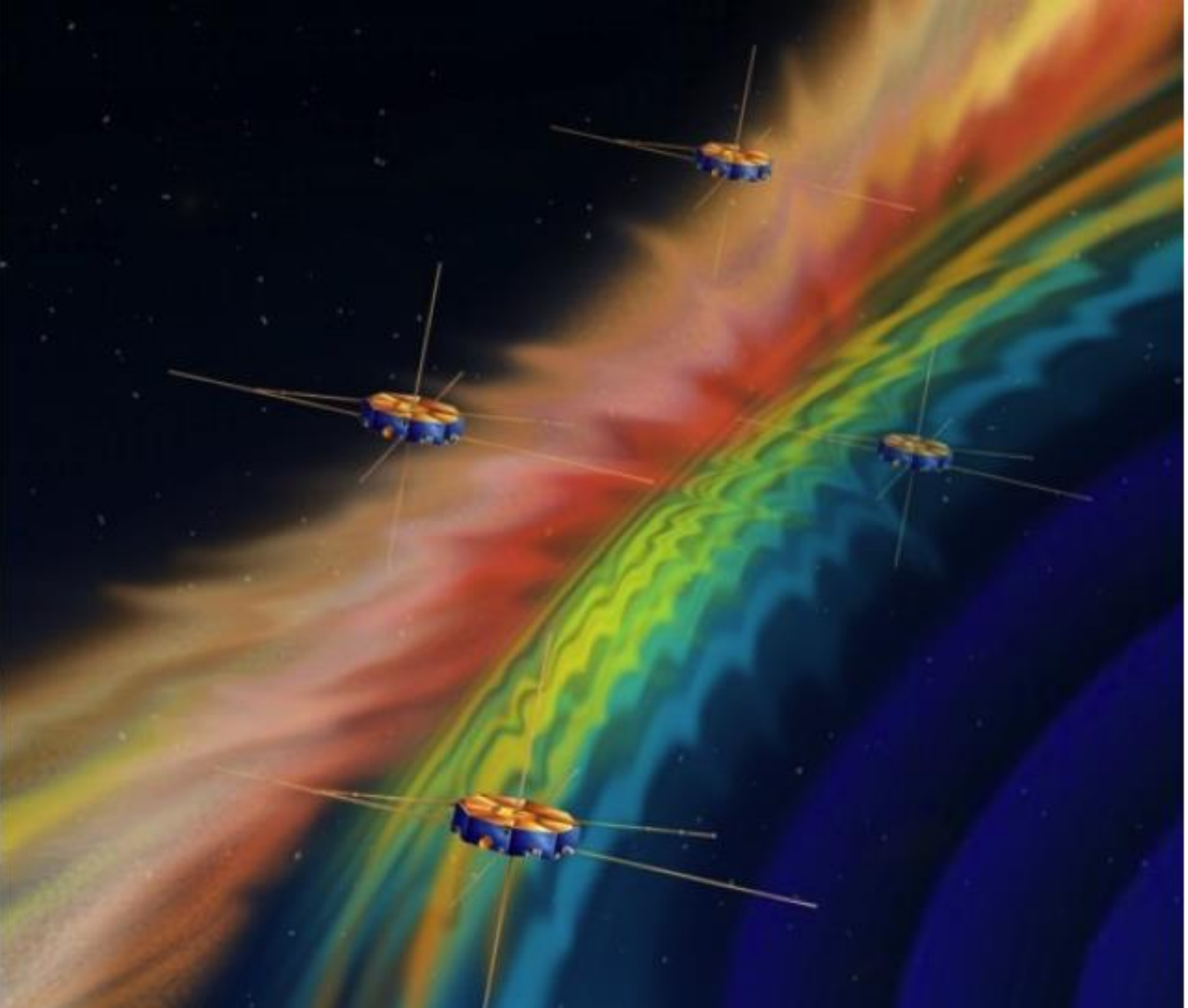
In-plane electric field:



Yamada+ PoP 2015



Wygant+ JGR 2005

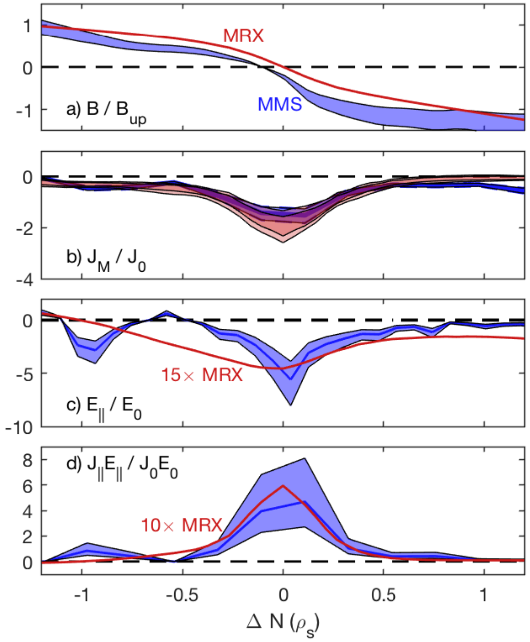


Magnetospheric MultiScale (MMS) mission 2015-

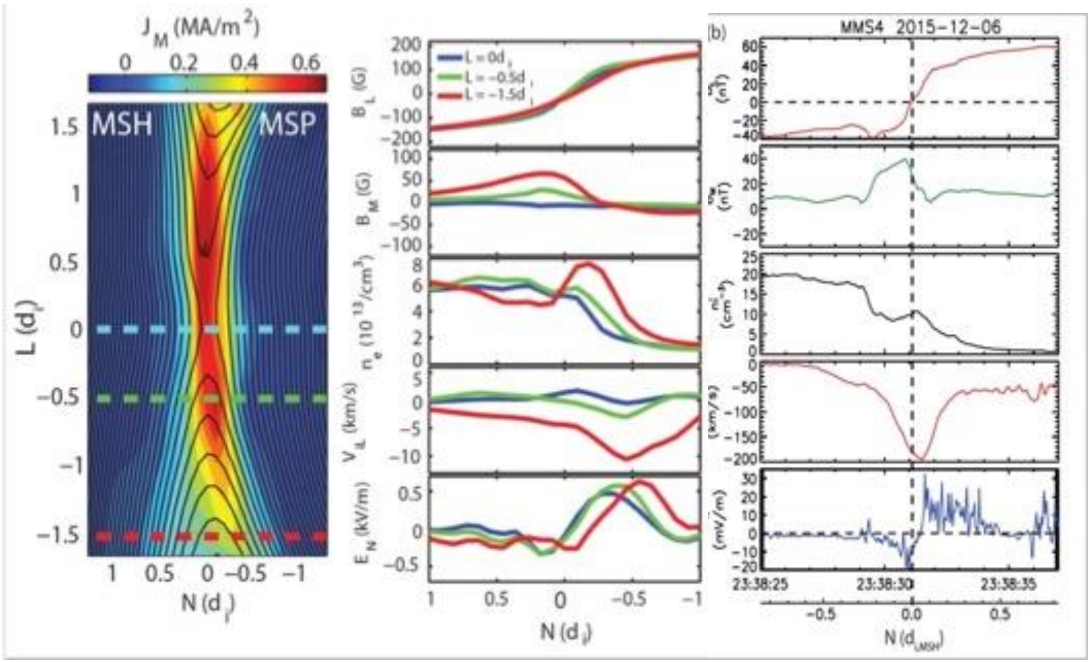
(4 satellites separated by electron scale)

MRX-MMS Comparisons

Profiles of B, J, E:



Profiles of asymmetric reconnection:

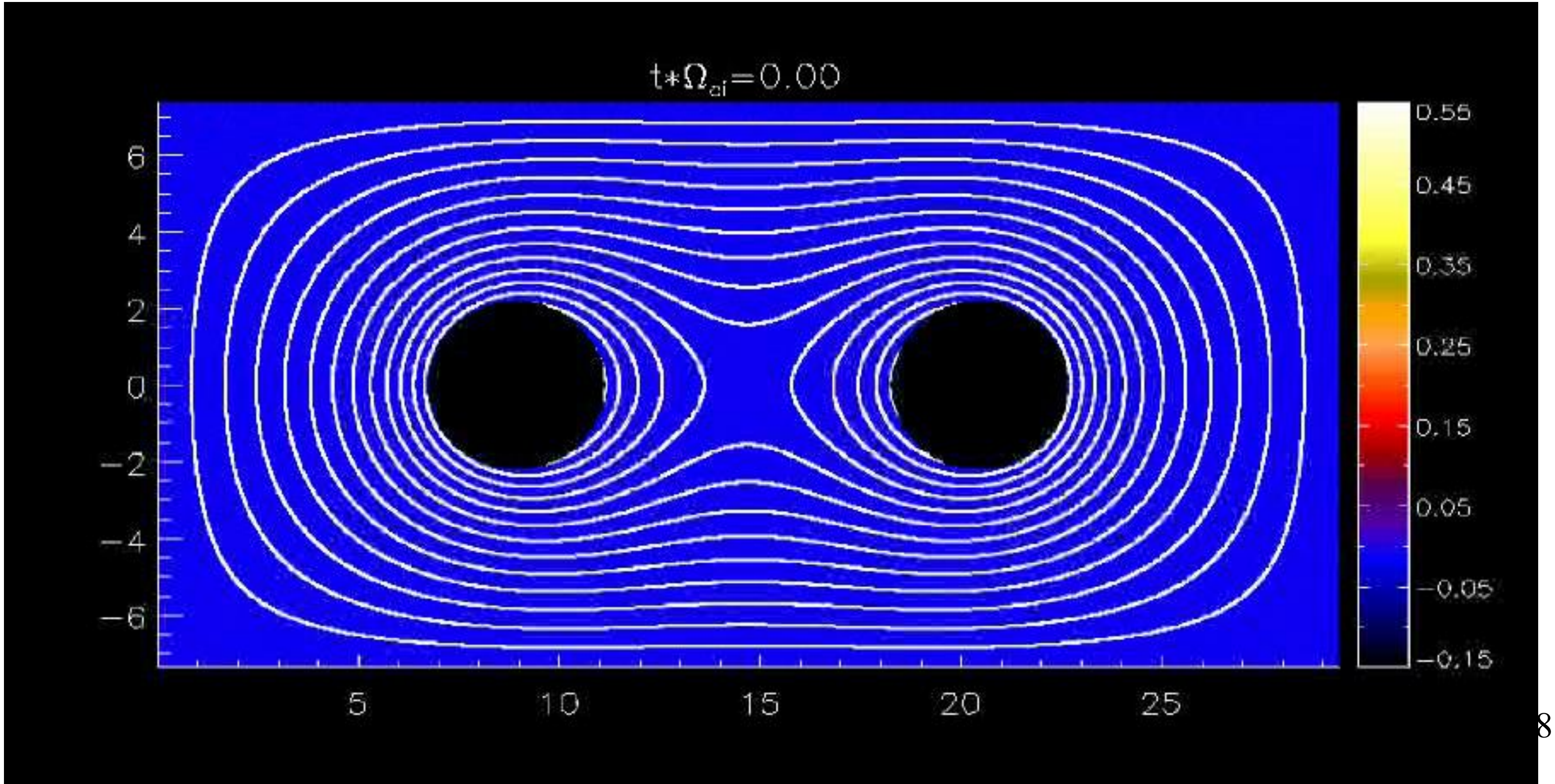


Fox+ GRL 2018

Argall (2023)

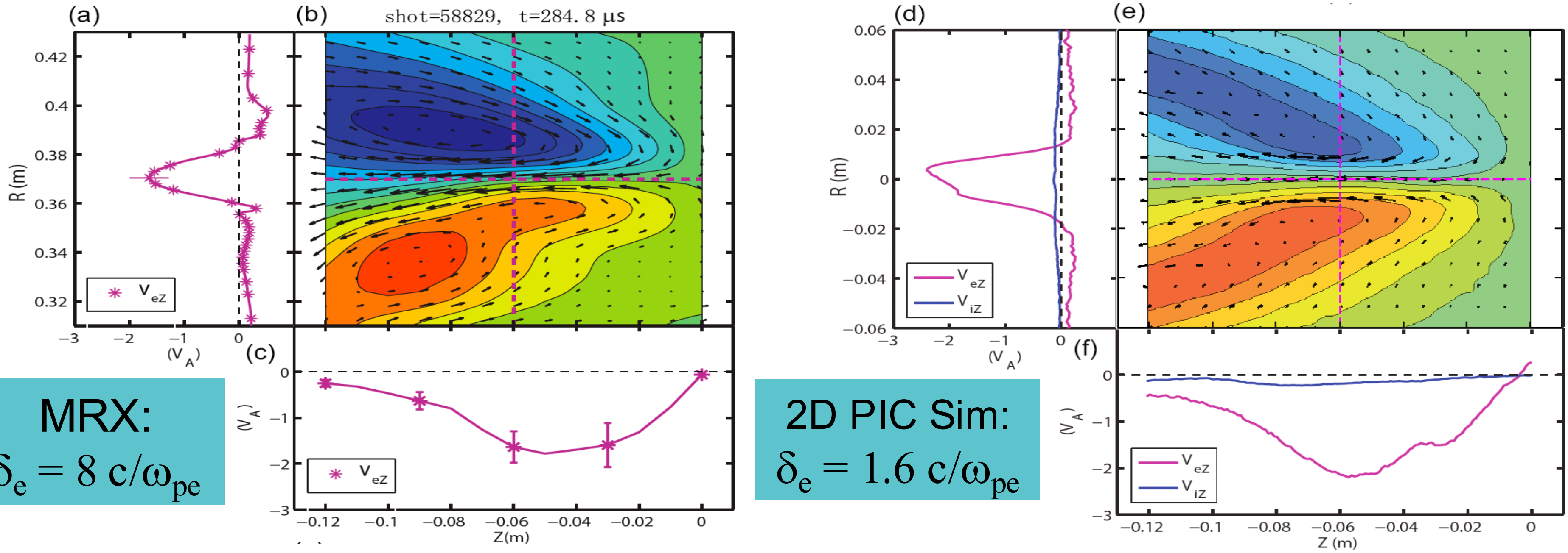
2D PIC Simulation of Single X-line Reconnection on MRX

Dorfman+ PoP 2008



MRX-PIC Comparisons

Ji+ GRL (2008)



MRX:

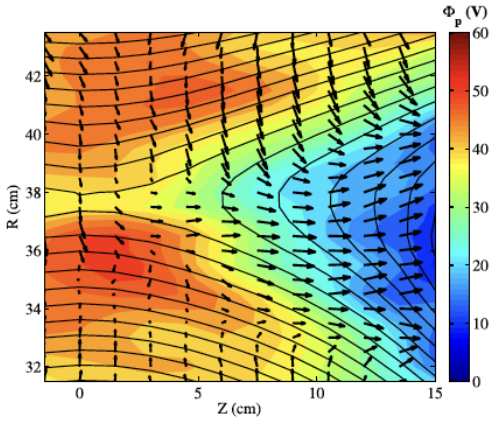
$\delta_e = 8\ c/\omega_{pe}$

2D PIC Sim:

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

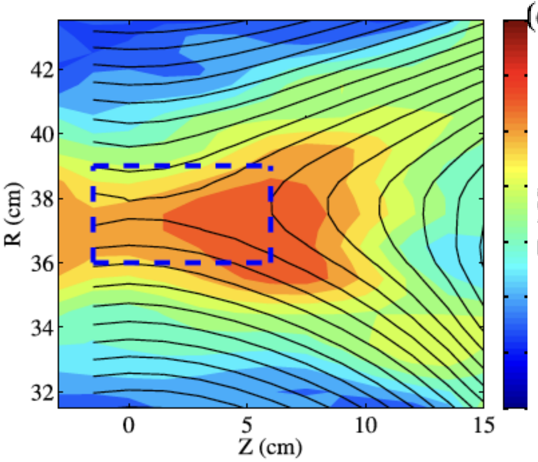
- Disagreements on electron scale on MRX (Roytershteyn+ PoP 2013)
  - Being resolved by real mass-ratios and finite collisions in 2D PIC (S.H. Son+ 2026)
- Agreements on electron scale on TREX (Greess+ JGR 2021)

Energy Budget of Magnetic Reconnection



Ion flow

Te



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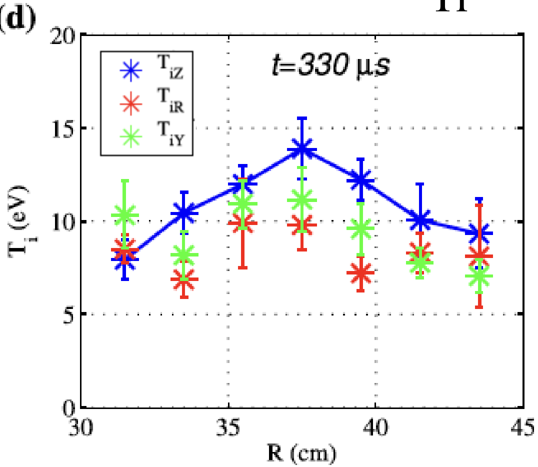
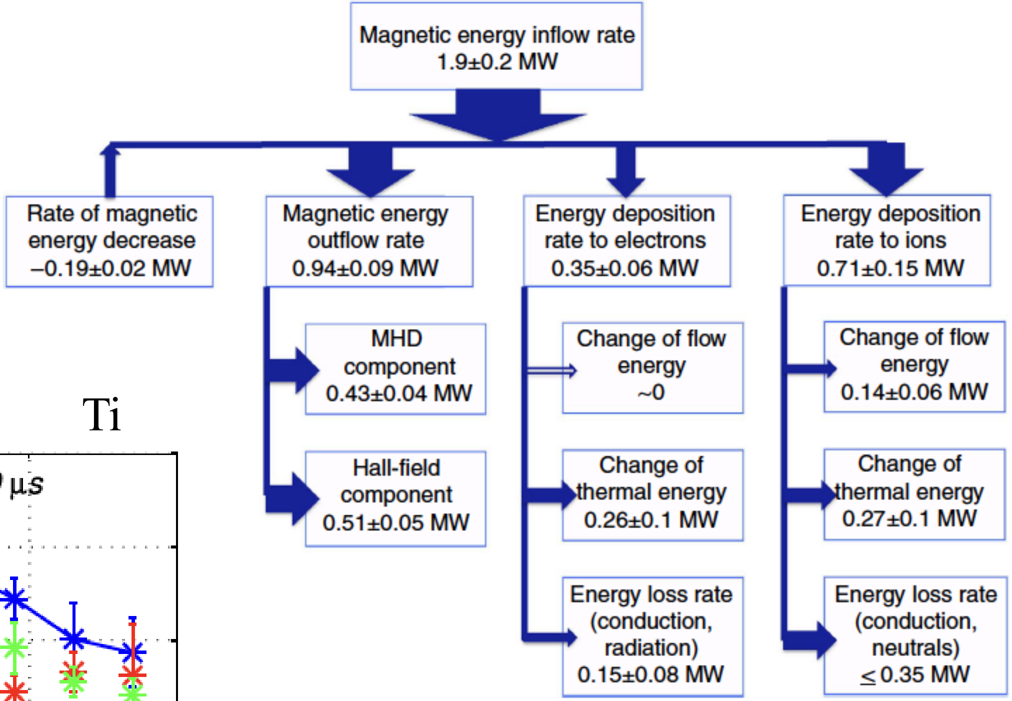
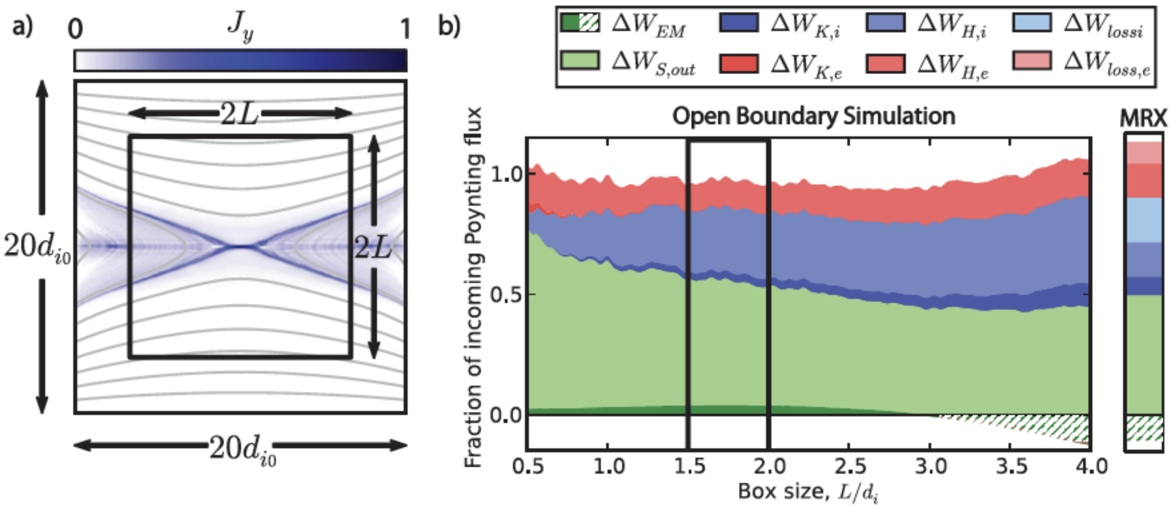




Yoo+ PoP 2014

Yamada+ PoP 2015

Comparisons with PIC Simulations



Yamada+ PoP 2015

Case	Incoming (MW)	Outgoing	Electron	Ion
Symmetric, antiparallel, lab	1 (1.9 ± 0.2)	0.45	0.20	0.35
Symmetric, antiparallel, PIC	1	0.42	0.22	0.34
Symmetric, antiparallel, space	1	0.1-0.3	0.18	0.39
Asymmetric, antiparallel, lab	1 (1.4 ± 0.2)	0.44	0.25	0.31
Asymmetric, antiparallel, PIC	1	0.43	0.25	0.32
Symmetric, guide field, lab	1 (1.5 ± 0.2)	0.65	0.15	0.29

Yamada+ NatCom 2014
Yoo+ JGR 2017
Yamada+ NatCom 2018
Bose+ PRL 2023

Table by Ji+ SSR 2023

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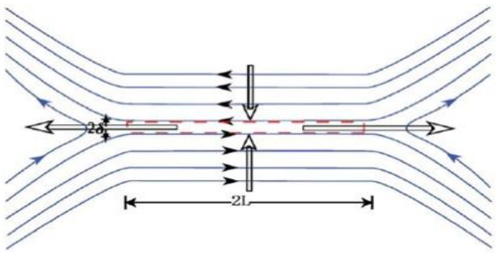
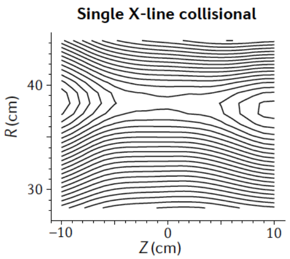
Phase III in Magnetic Reconnection Research:

Collisional MHD Models (Phase I) versus Collisionless Kinetic Models (Phase II)

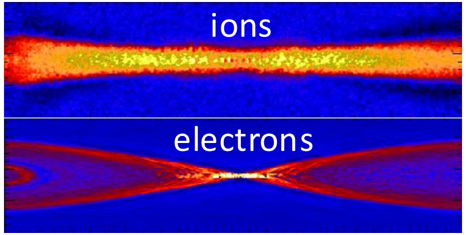
e.g. Sweet-Parker Model

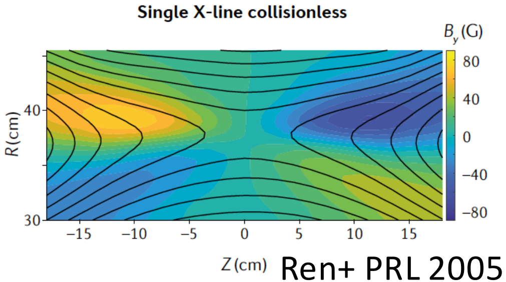




Ji+ PRL 1998

e.g. Kinetic Model





Ren+ PRL 2005

Yoo+ PRL 2013

Valid for *large* plasmas but predicts slow reconnection

$$\frac{V_R}{V_A} = \frac{1}{\sqrt{S}}$$

Predicts fast reconnection but validated only in *small* plasmas

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

Q: How to combine these models self-consistently in a single model to explain fast reconnection in large & high-S plasmas? ➔ a multi-scale challenge

Ji+ Nat. Rev. Phys. 2022

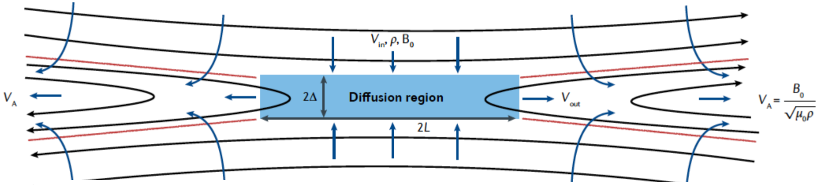
Major Scientific Challenges on Reconnection*

1. ***Multiple scale problem***: How does reconnection couple global fluid (MHD) scales to local dissipation (kinetic) scales?
2. ***3D problem***: How does reconnection take place in 3D?
3. ***Energy problem***: How are particles heated and accelerated?
4. ***Boundary problem***: How do boundary conditions affect reconnection process?
5. ***Onset problem***: How does reconnection start?
6. ***Partial ionization problem***: How does partial ionization affect reconnection?
7. ***Flow-driven problem***: What role reconnection plays in flow-driven systems which sometime generate magnetic field itself?
8. ***Extreme problem***: How does reconnection take place under extreme conditions such as intense radiation, relativity, and even QED?
9. ***Turbulence and shock problem***: What role does reconnection play in related processes such as turbulence, shocks and transport?
10. ***Related explosive phenomena***: Understanding how, and under what conditions, magnetic reconnection either as a driver or as a consequence of explosive phenomena such as solar flares and Coronal Mass Ejections, remain major scientific challenges.

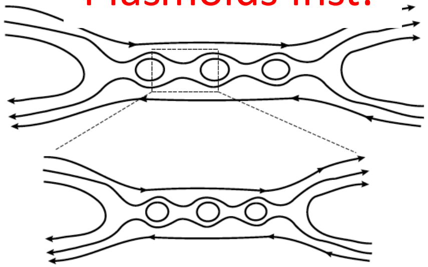
*Ji+ white papers to Plasma 2020, Astro 2020, and Helio 2024 Dacadal Surveys

Two Main Multiscale Mechanisms and Magnetic Reconnection Phase Diagram

Ji & Daughton PoP 2011, 2022

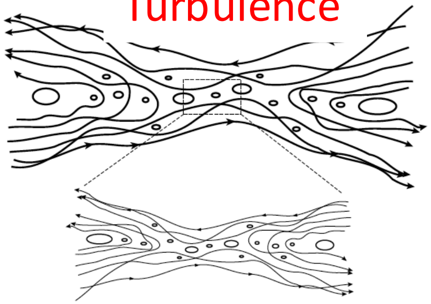


Plasmoids inst.

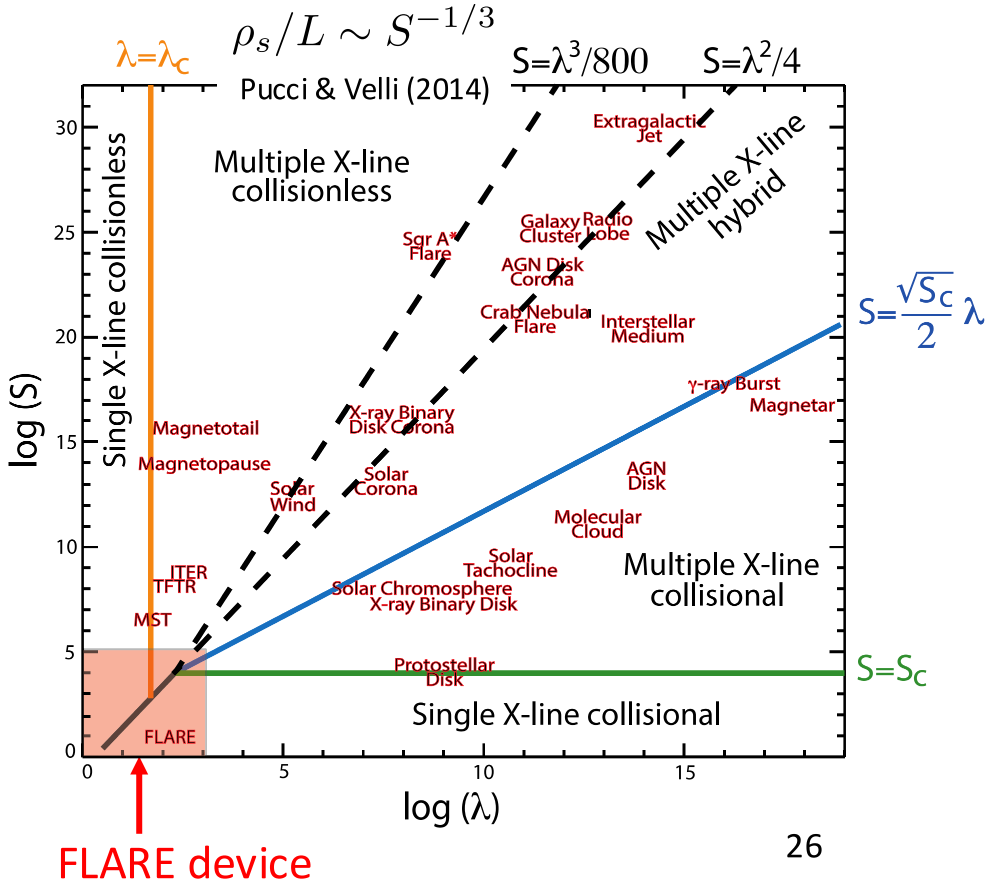


Shibata & Tanuma (2001)
Loureiro+ (2007);
Bhattacharjee & Huang (2009);
Daughton+ (2009);
Cassak+ (2009); Uzdensky+ (2010)
……

Turbulence

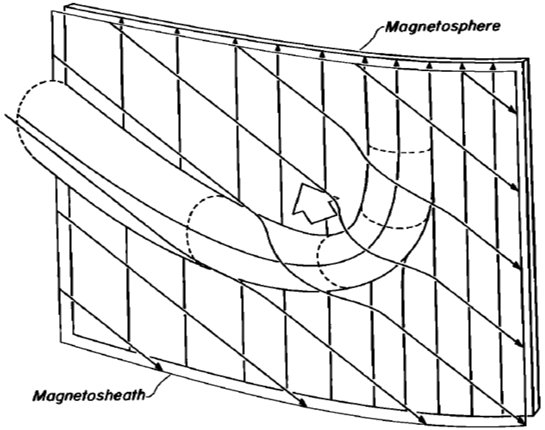


2D: Matthaeus & Lamkin (1985)
……
3D: Lazarian & Vishniac (1999)
……

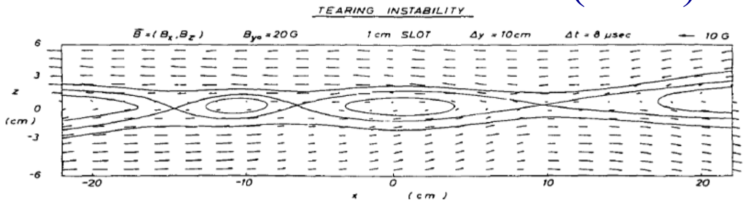


Direct Evidence Exists by *in-situ* Measurements in the Lab and Space for Kinetic Plasmoids

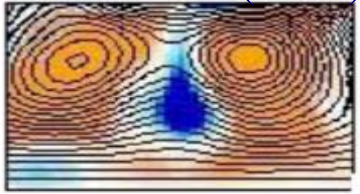
Magnetopause: Russell & Elphic (1979)…



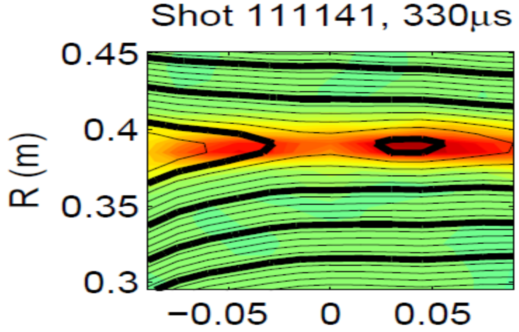
LPD: Stenzel+ (1986)



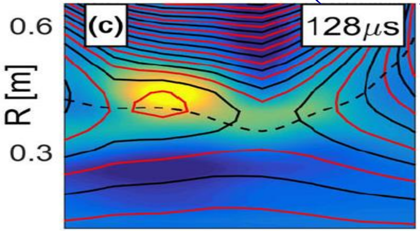
TS-3: Ono+ (2011)



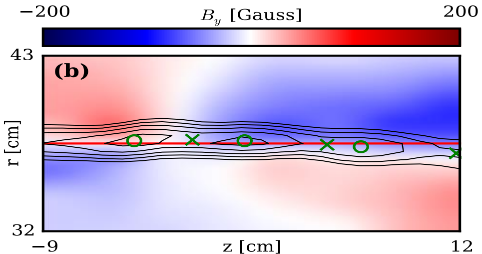
MRX: Dorfman+ (2013)



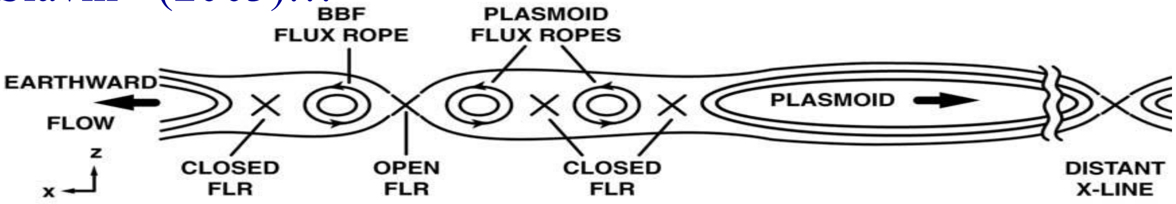
TREX: Olson+ (2016)



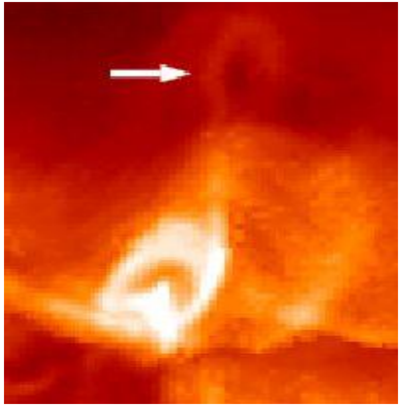
MRX: Jara-Almonte+ (2016) in resistive electron regime



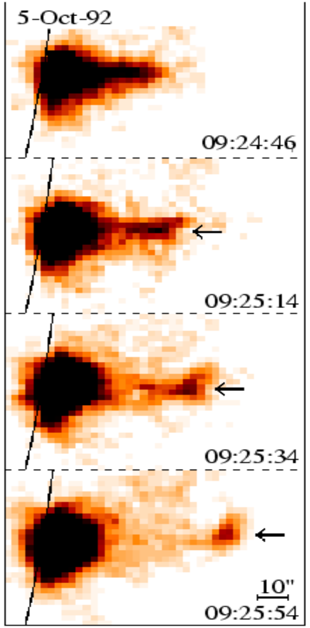
Magnetotail: Baker+ (1984); Slavin+ (2003)…



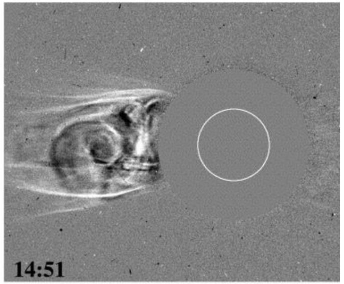
Indirect Evidence Exists for Fluid Plasmoids by Remote-Sensing of the Sun and in the Lab



Hudson (1994); Magara+ (1997)



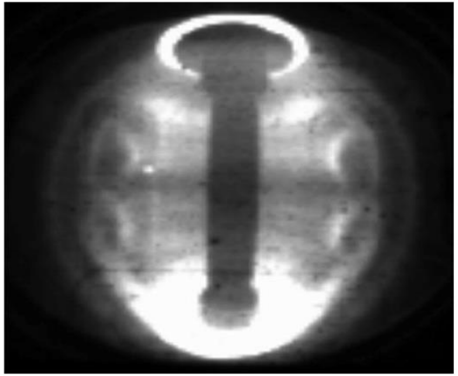
Ohyama & Shibata (1998)

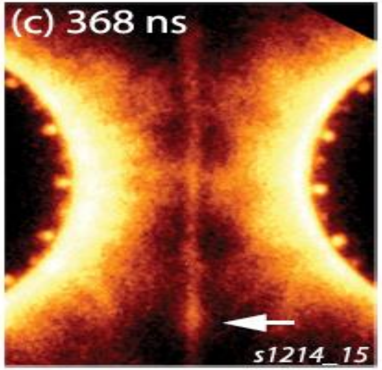


Dere+ (1999)

Laser plasma (Dong+, 2012)

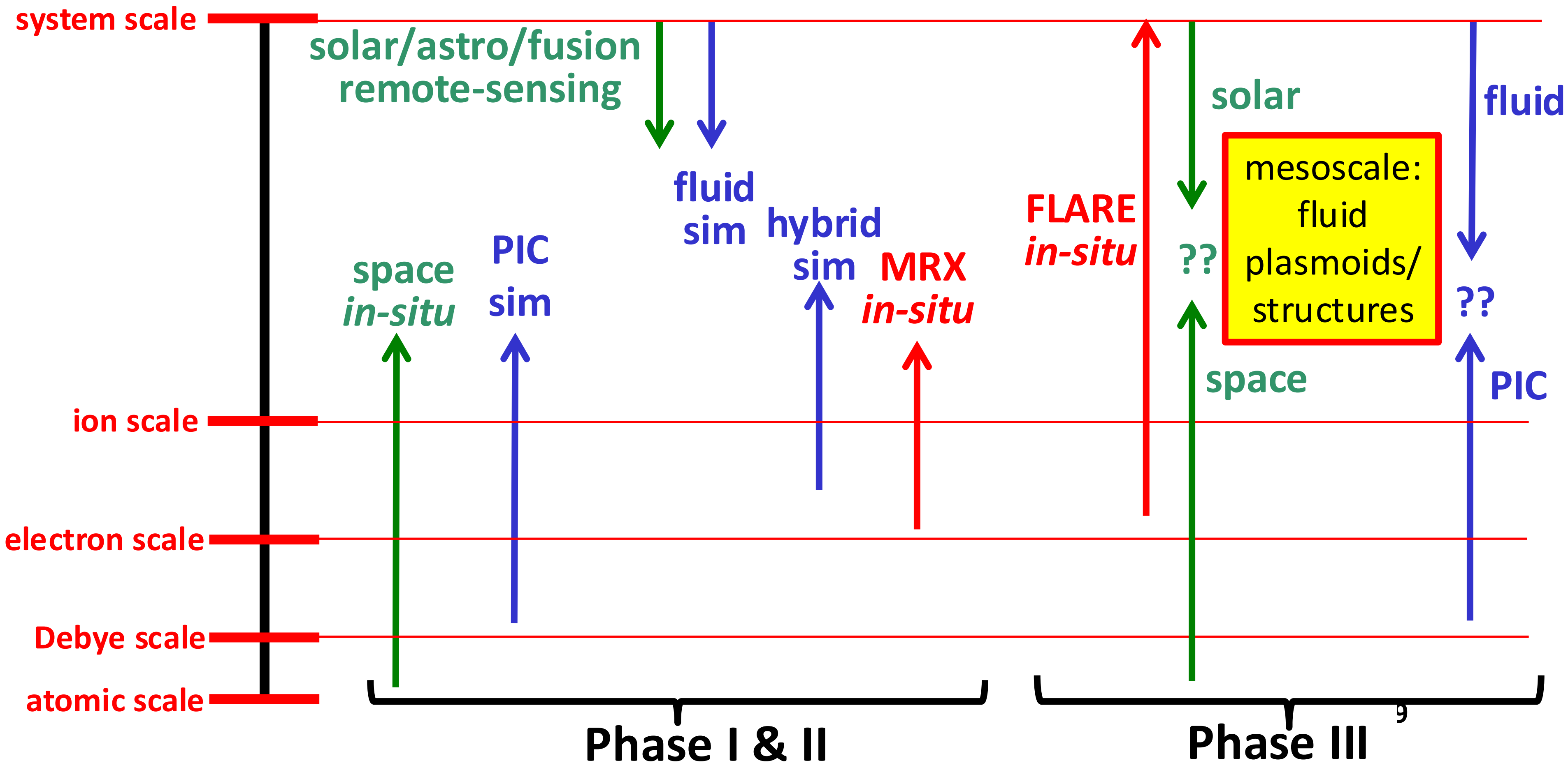
Tokamak plasma (Ebrahimi & Raman, 2015)



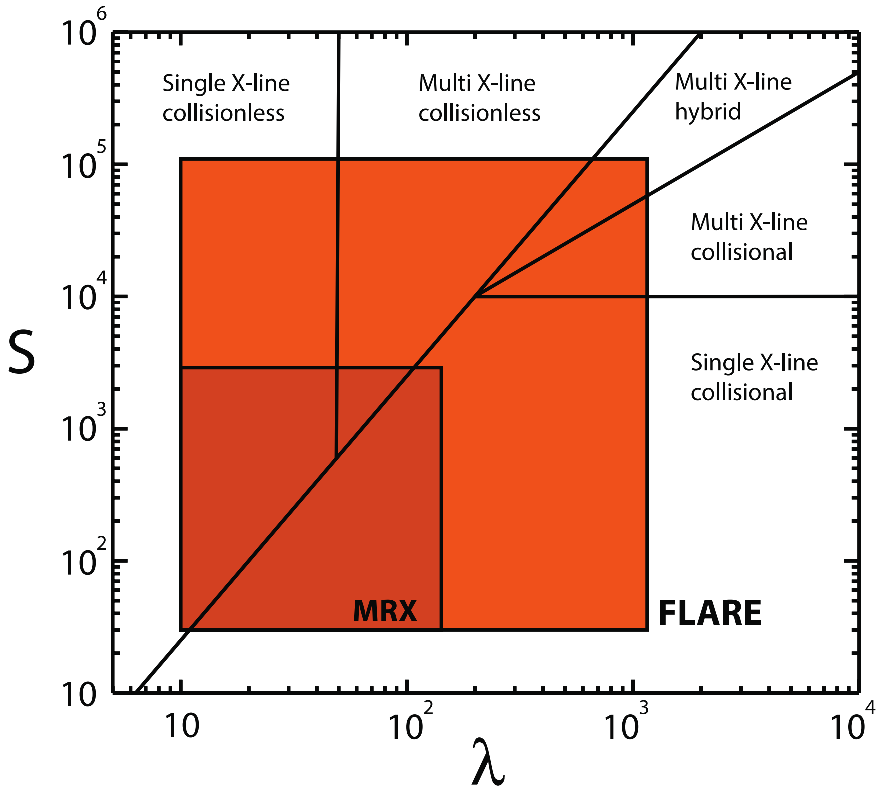


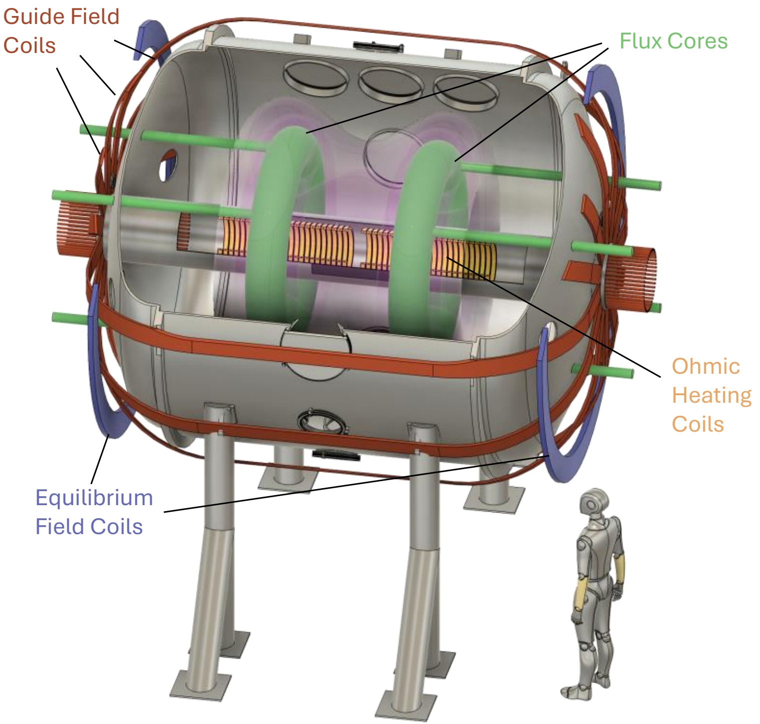
Z-pinch plasma (Hare+, 2017)

Access of Multi-Scale Physics (MHD/fluid, Ion & Electron): Key to Succeed in Reconnection Research in Phase III

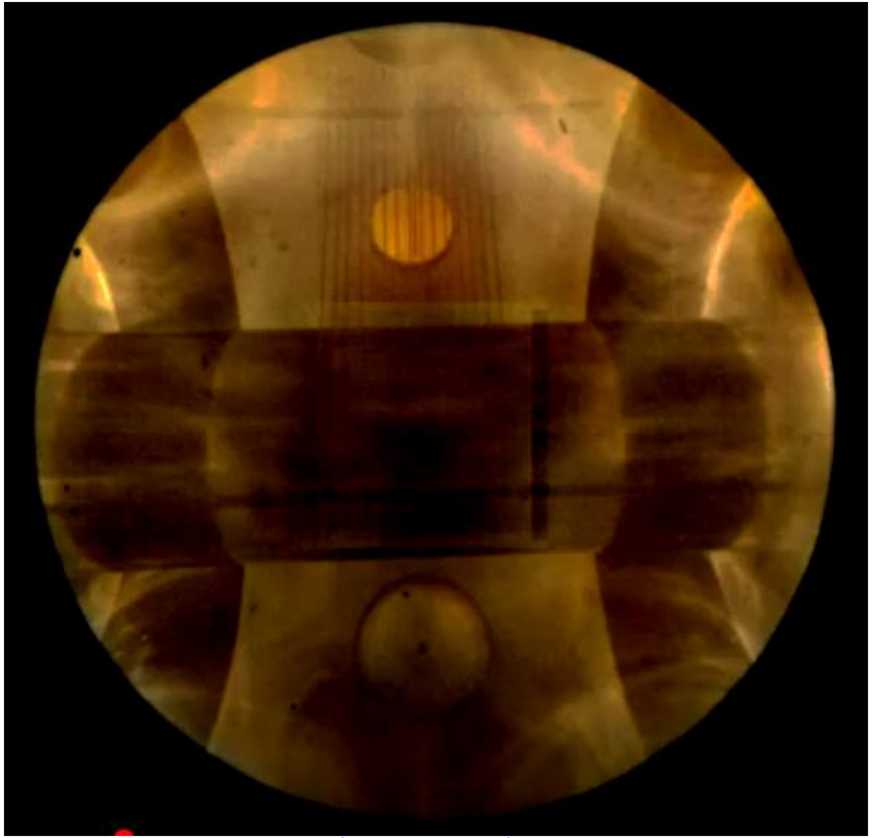


FLARE (Facility for Laboratory Reconnection Experiments) Proposed in 2013 to Provide in-situ Access to New Regimes





"First Plasmas" Achieved in April 2025 and Operating since June

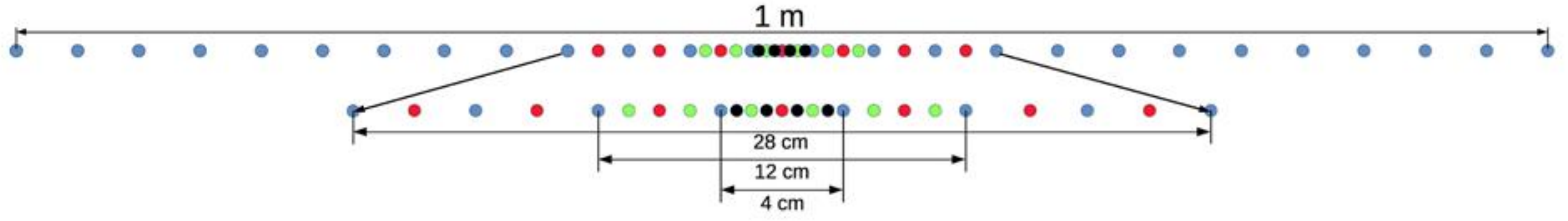


- FLARE (Stage 2.5): ~3.67MJ
- FLARE (Stage 3): ~6.5MJ

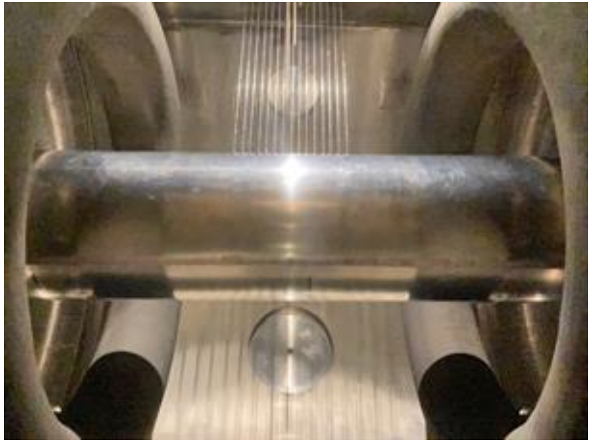
- Capabilities at Stage 2.5 w/o drive coils and guide field coil bracing
- Extensive set of diagnostics

FLARE Diagnostics Provide Unprecedented *in-situ* Coverage of Fluid and Kinetic Scales

The main diagnostics: magnetic probe arrays

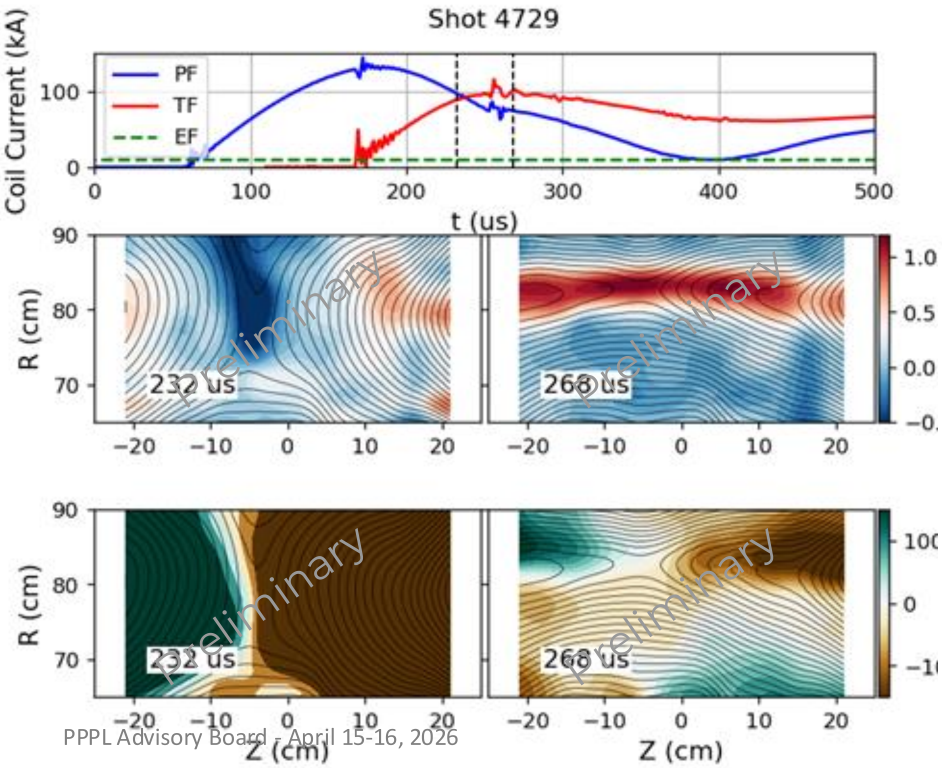


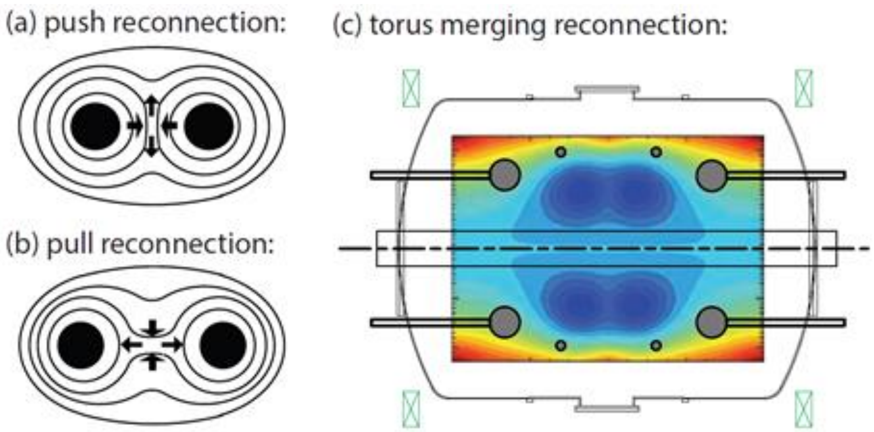
- Coverage of 1 m and maximum radial resolution of 5 mm.
- 128 coils in one probe.
- 15 axial locations: 128 × 15 ~ 2000 total coils, of which ~ 1000 are recorded.
- Covers 42 cm in axial direction with 3 cm resolution.

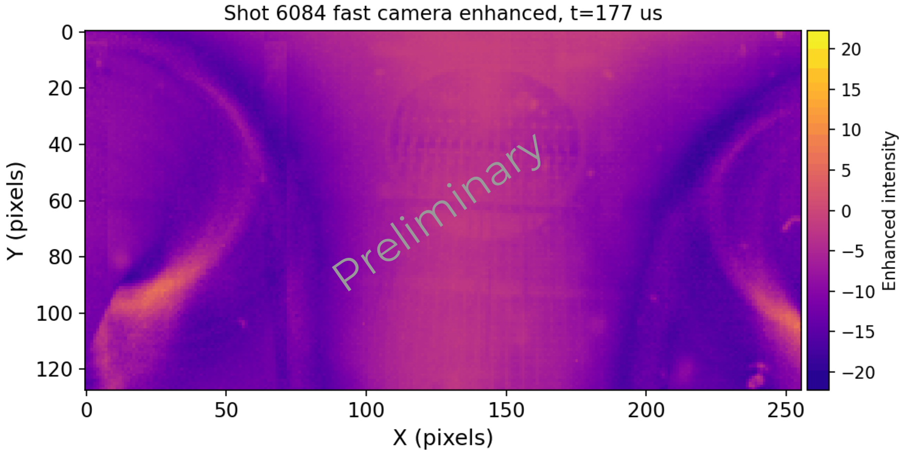


- Fast camera
- Langmuir and Mach probes
  - n, Te, Vi
- Fiber-based interferometer
  - line-integrated n
- Ion Doppler tomography
  - Ti, Vi

Push - Pull Reconnection Visualized by Fast Camera

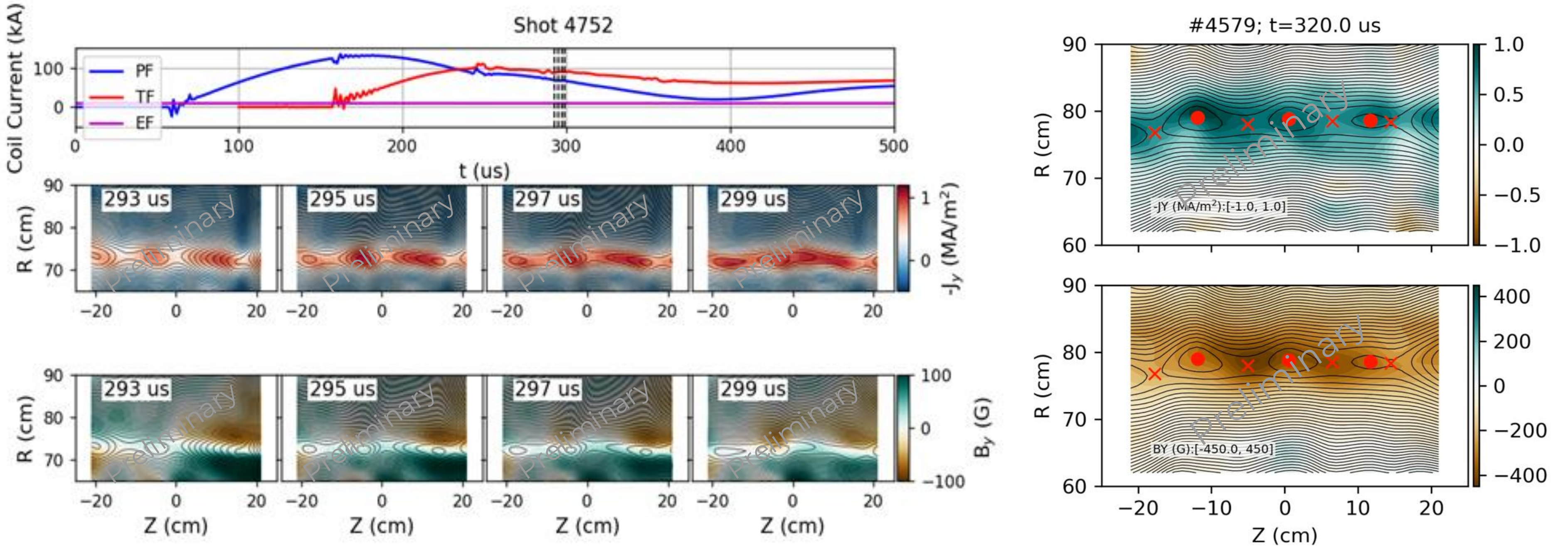






Observation of Chain of Ion-scale, Kinetic Plasmoids at S~3000

P. Shi+ (2026)



- Dynamic plasmoids (generation, merging, and ejection), have been observed in approximately 50% of similar discharges.

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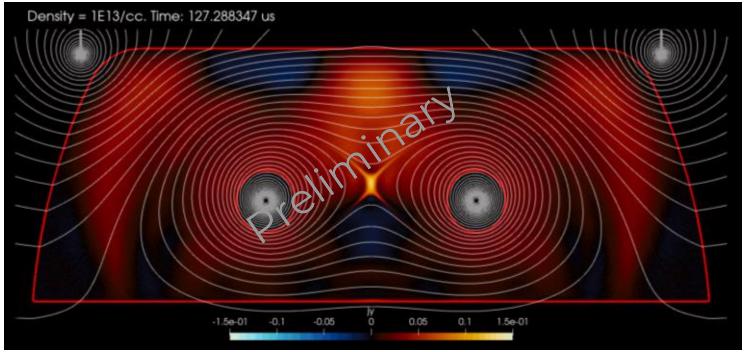
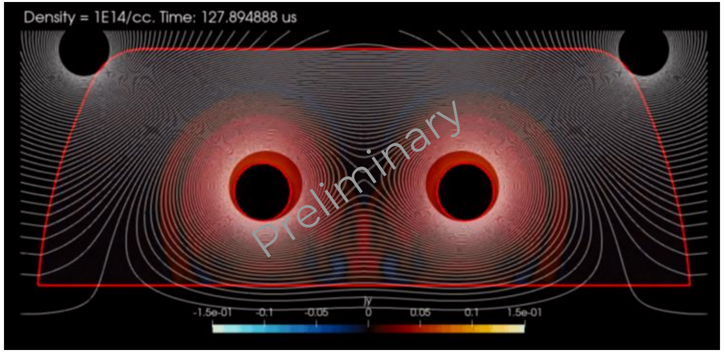
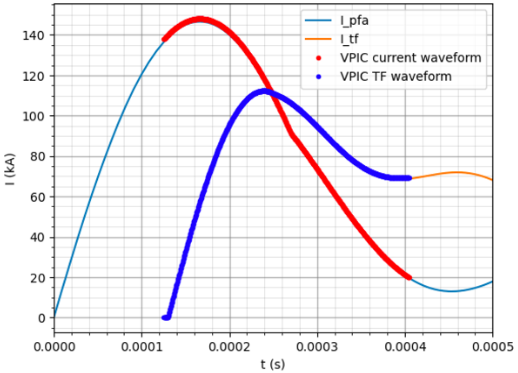
Reproduction by VPIC Simulations in FLARE Geometry and Conditions

Low density (10^13/cc): Single X-line



High density (10^14/cc): Multiple X-lines





TF and PF coil current waveforms

- Increasing density leads to stronger drive (t_{drive}/t_A decrease) and larger effective plasma size normalized by ion skin depth.
- … to current sheet elongation for larger Lundquist numbers, associated with plasmoid formation and multiple X-lines.
- Theoretical estimates and simulations suggest tearing (plasmoid) instability in semi-collisional (or weakly collisional) regime as in most magnetically confined fusion plasmas.

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Initial Research Topics on FLARE

- Multiple-scale
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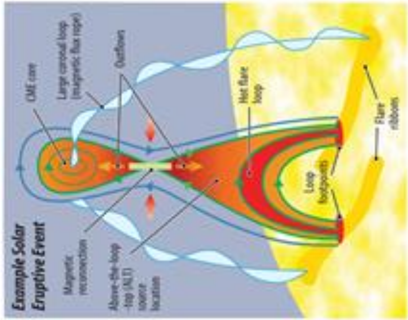
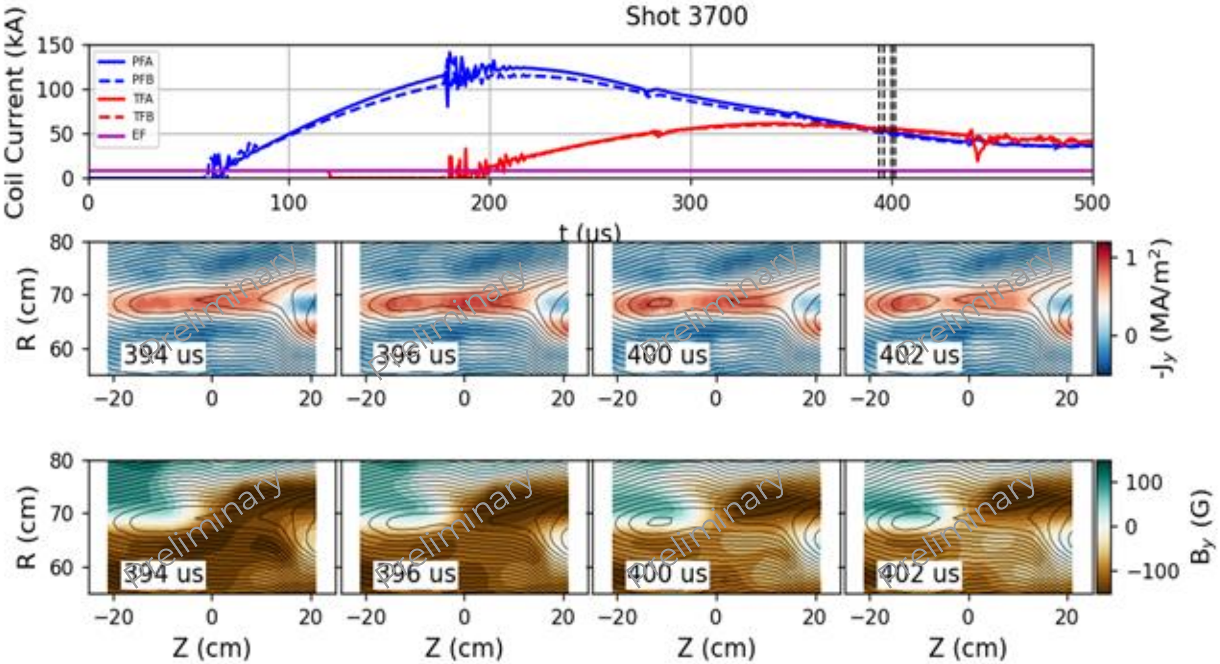
Initial Results from Reconnection with Asymmetric Downstream Conditions





- A 10% difference in coil current generates an asymmetric downstream condition.
    - The resulting higher magnetic pressure on the right side simulates solar flare and magnetotail geometry.

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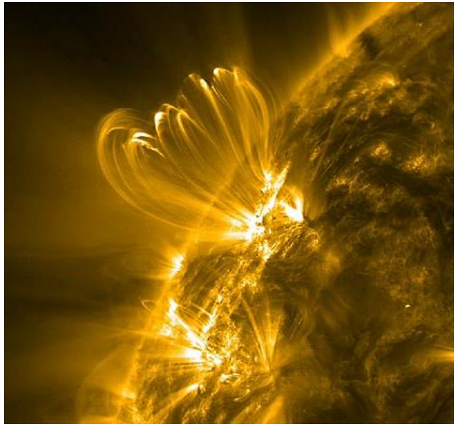
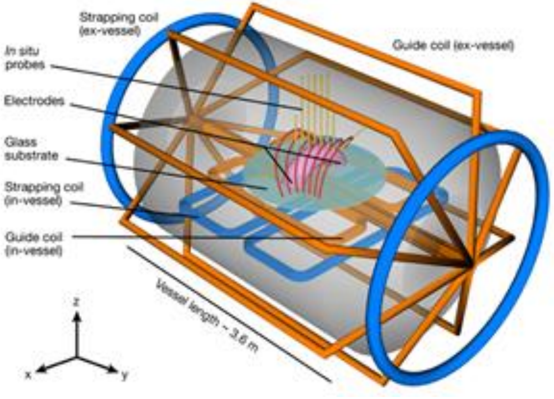
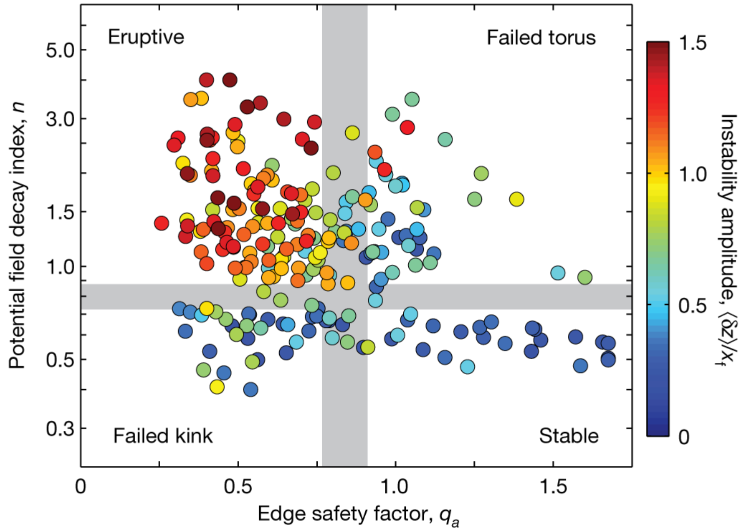
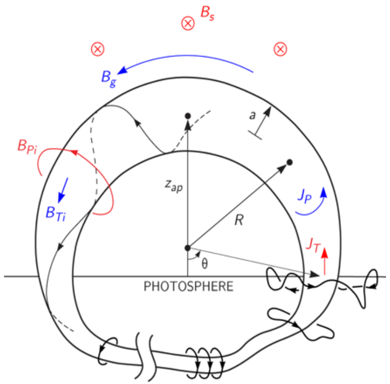
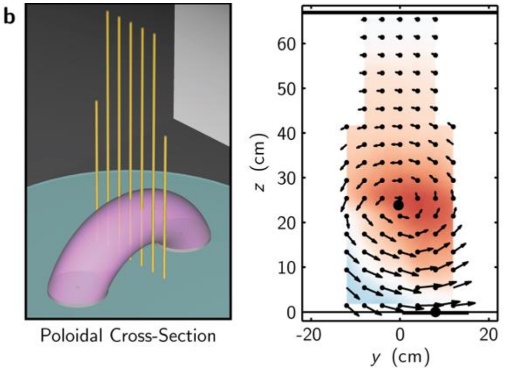
Coronal Mass Ejection due to Kink or Torus Inst?











Failed CMEs explained by Failed torus inst.

Adapted from J. Chen, *ApJ*, 1989, 2010

Myers+ Nature (2015)

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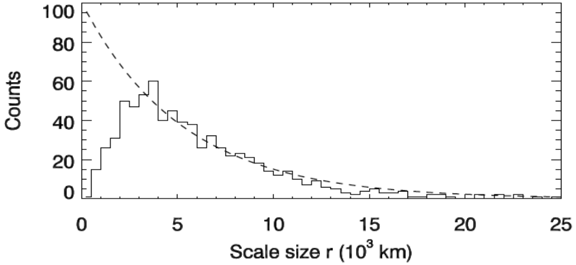
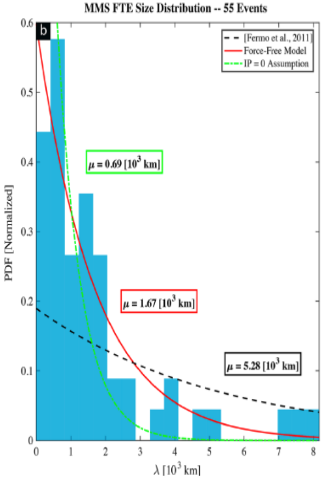
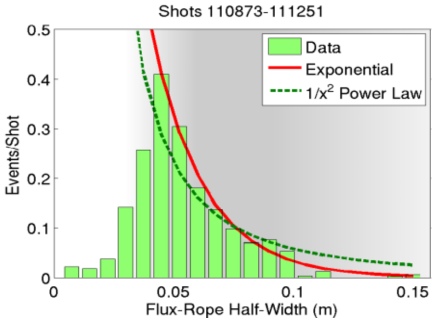
Plasmoid Size Distributions in Space and in the Lab

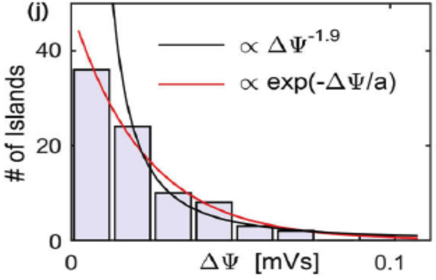
Flux Transfer Events (FTEs) by CLUSTER in Earth's magnetopause (Fermo+ 2011)



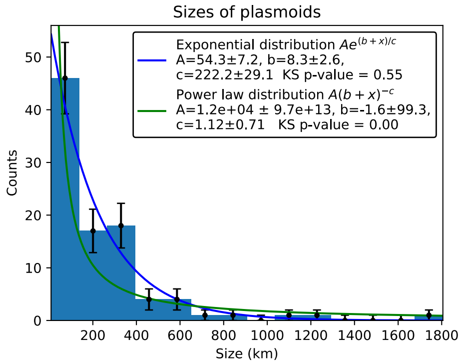
FTEs by MMS in Earth's magnetopause (Akhavan-Tafti+ 2017)







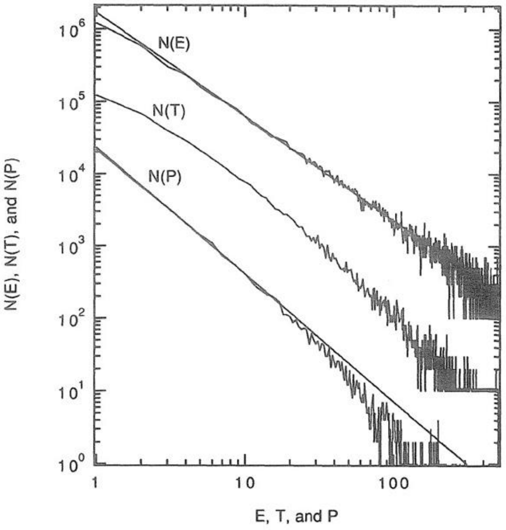
MRX (Dorfman+ 2014); TREX (Olson+ 2016)



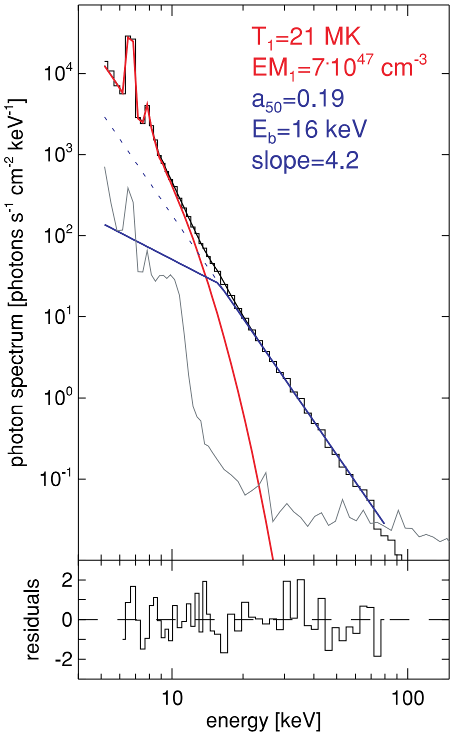
Plasmoids by MMS in Earth's magnetotail (Bergstedt+ 2020)

All exponential – no power-laws observed: haven't reached fluid plasmoids statistics yet

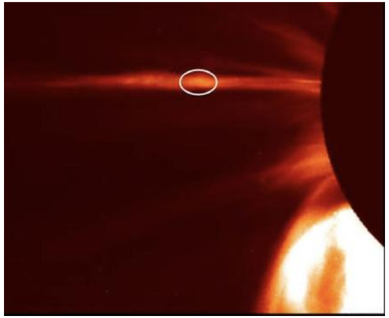
Statistical Studies in Solar Plasmas

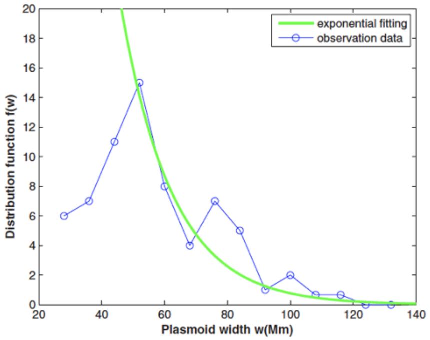


Flares follow power laws (Lu & Hamilton, 1991)



X-ray photons follow power laws (Krucker+ 2010)

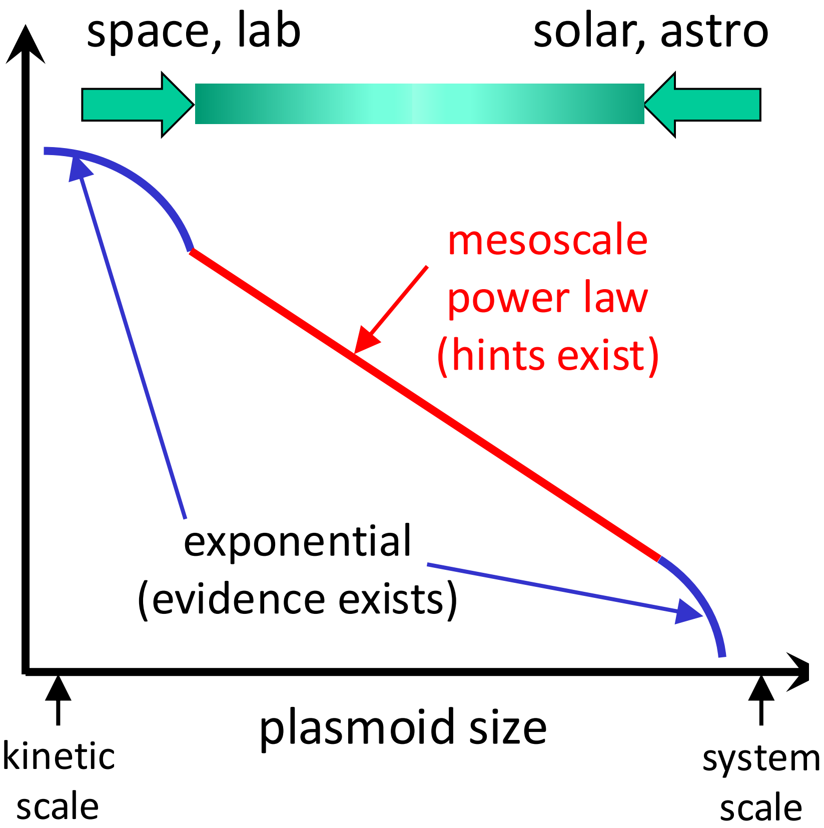


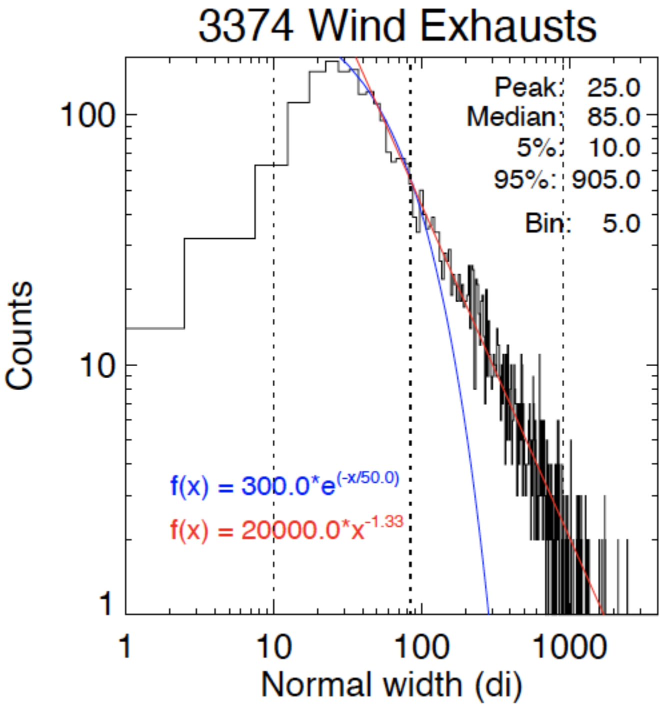


Exponential in plasmoid size in a current sheet structure post-CME (Guo + 2013)

No power-laws observed for plasmoids yet

Scaling of X-line/plasmoid/current sheet





S. Eriksson (2023)

H. Ji+, White paper to 2024 Helio Decadal Survey.

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  - 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
  - Partition between ions and electrons

Intend to operate as a Collaborative Research Facility: collaborations are welcome

Major Scientific Challenges on Reconnection*

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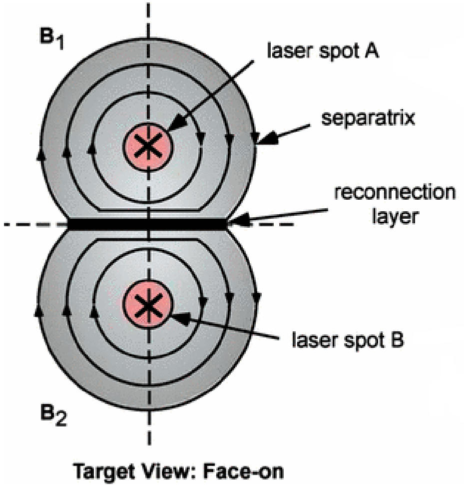
*Ji+ white papers to Plasma 2020, Astro 2020, and Helio 2024 Dacadal Surveys

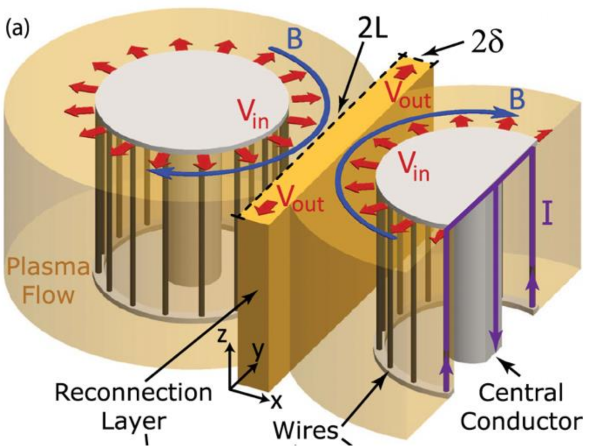
Magnetic Reconnection Experiments in HED Plasmas



Nilson+ 2006; Li+ 2007; Willingale+ 2010; Zhong+ 2010; Fiksel+ 2014; Rosenberg+ 2015; Raymond+ 2018; Fox+ 2020, 2021; Ping+ 2023; Pearcy+ 2024….

Lasers

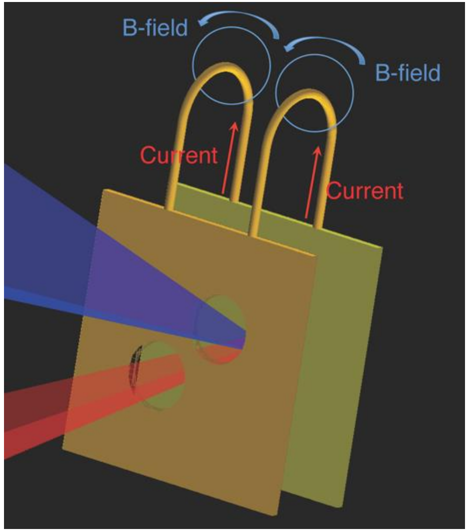
Flow-driven: $\beta \gg 1$



Hare+ 2017; Datta+ 2024

Pulsed Powers

Magnetically driven: $\beta > 1$



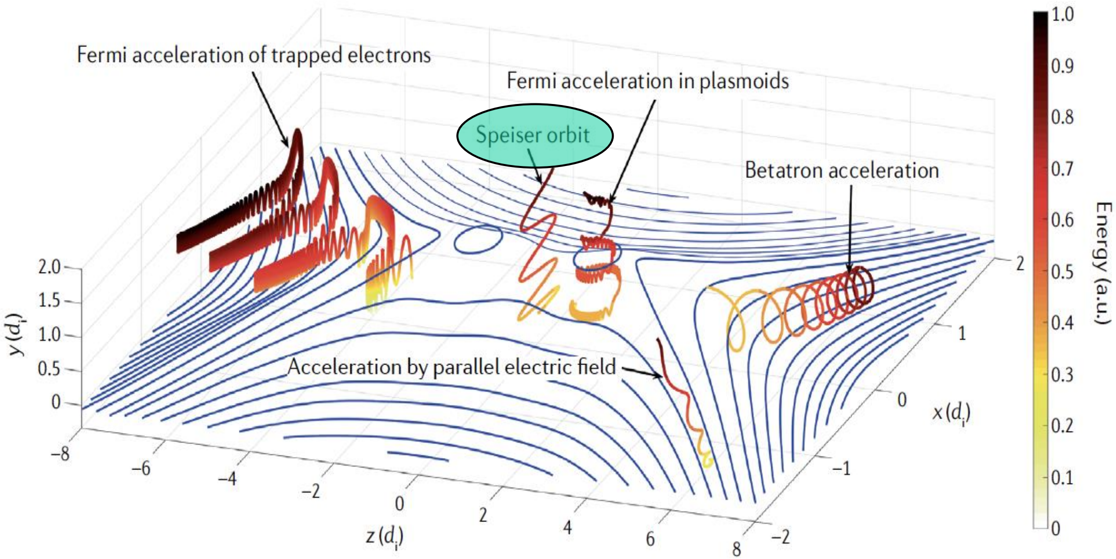
Pei+ 2016; Yuan+ 2018; Chien+ 2019, 2023; Yuan+ 2023; Zhang+ 2023; Zhang+ 2026; Pomraning+ 2026

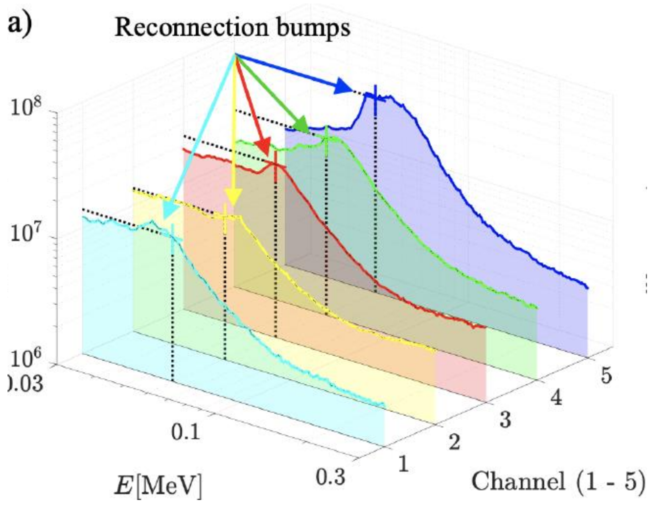
Laser-driven Capacitor Coils

Magnetically driven: $\beta \ll 1$

Importance of low-β: available magnetic free energy per particle is $\frac{\Delta E}{E_0} = \frac{1}{\beta}$

μ-MRX: Reconnection Experiments using Capacitor Coils Driven by High-power Lasers at Low-β





Similar to MRX (Ji+ 2024):

- Magnetically-driven
- Low upstream β

But at much larger B:

- 50T by ns, kJ lasers
- 200T by ps, kJ lasers

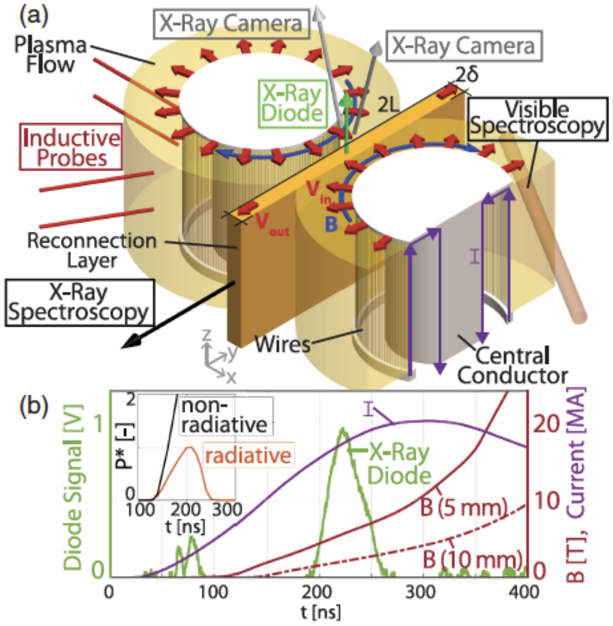
proton-radiography

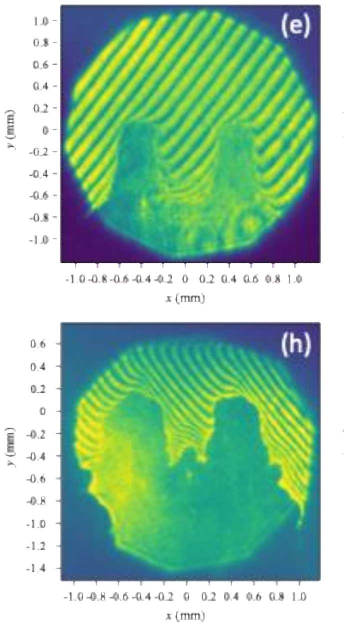
Gao+ PoP (2016)
Gao+ APL (2025)

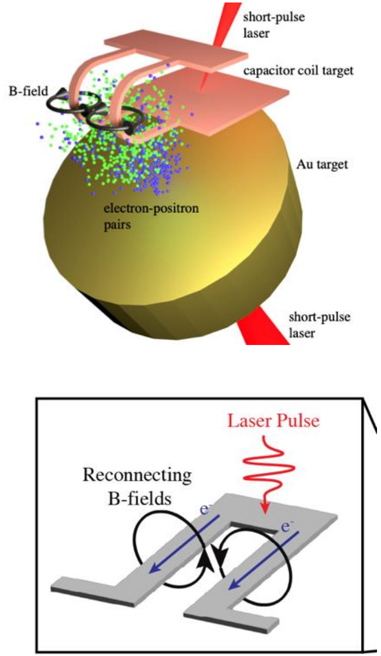
Energetic electrons detected by reconnection

Chien+ Nature Phys. (2023)

Magnetic Reconnection in HED Plasmas under Extreme Conditions







Radiatively cooled reconnection at Z machine

Datta+ PRL (2024)

Relativistic conditions (σ_e from ~0.01 to ~1) by short-pulse lasers at ILE

Zhang+ APL (2026); Pomraning+ 2026

Pair-injected experiment, Strong Field QED experiments proposed

Russell+ arXiv:2603.17127 2026

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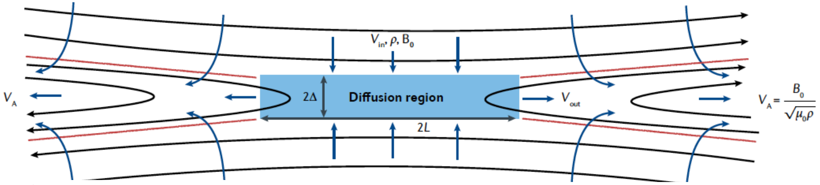
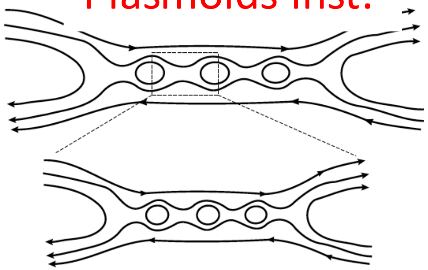
*Ji+ white papers to Plasma 2020, Astro 2020, and Helio 2024 Dacadal Surveys

Two Main Multiscale Mechanisms and Magnetic Reconnection Phase Diagram



Plasmoids inst.



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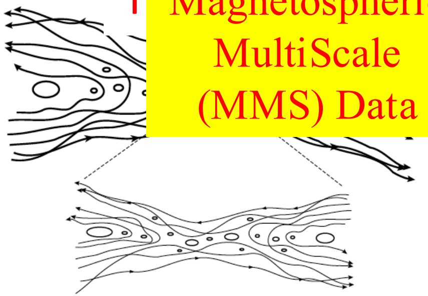
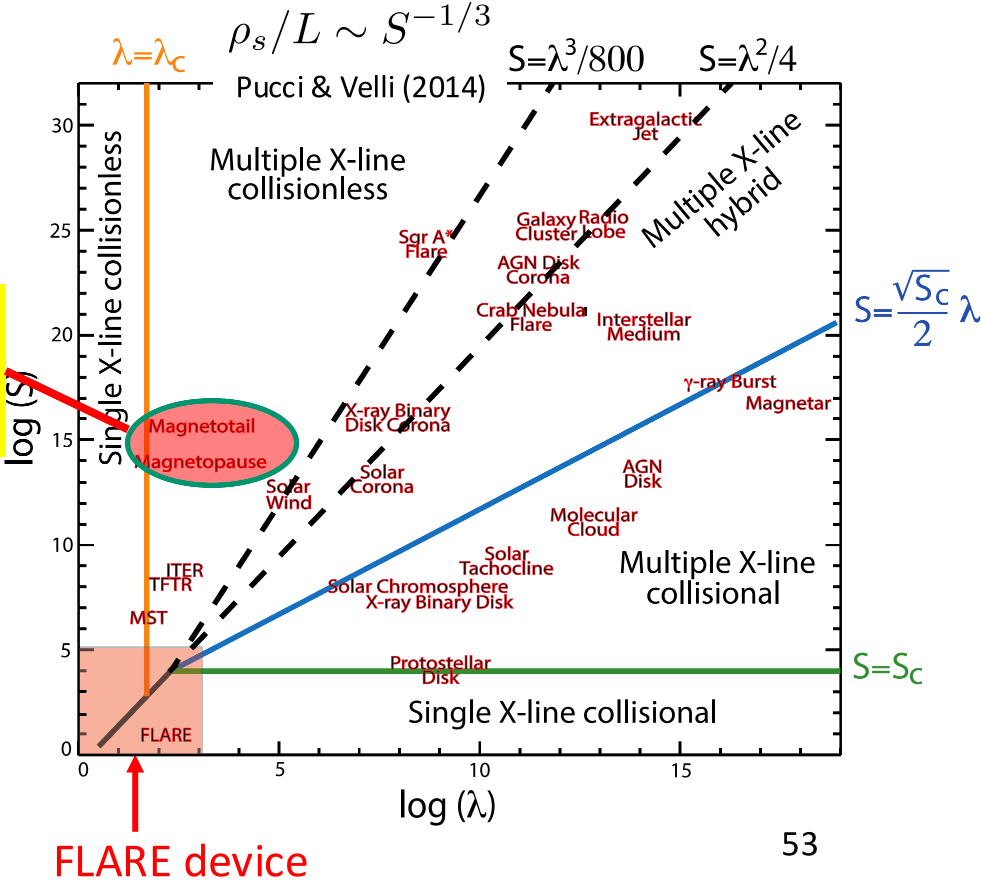


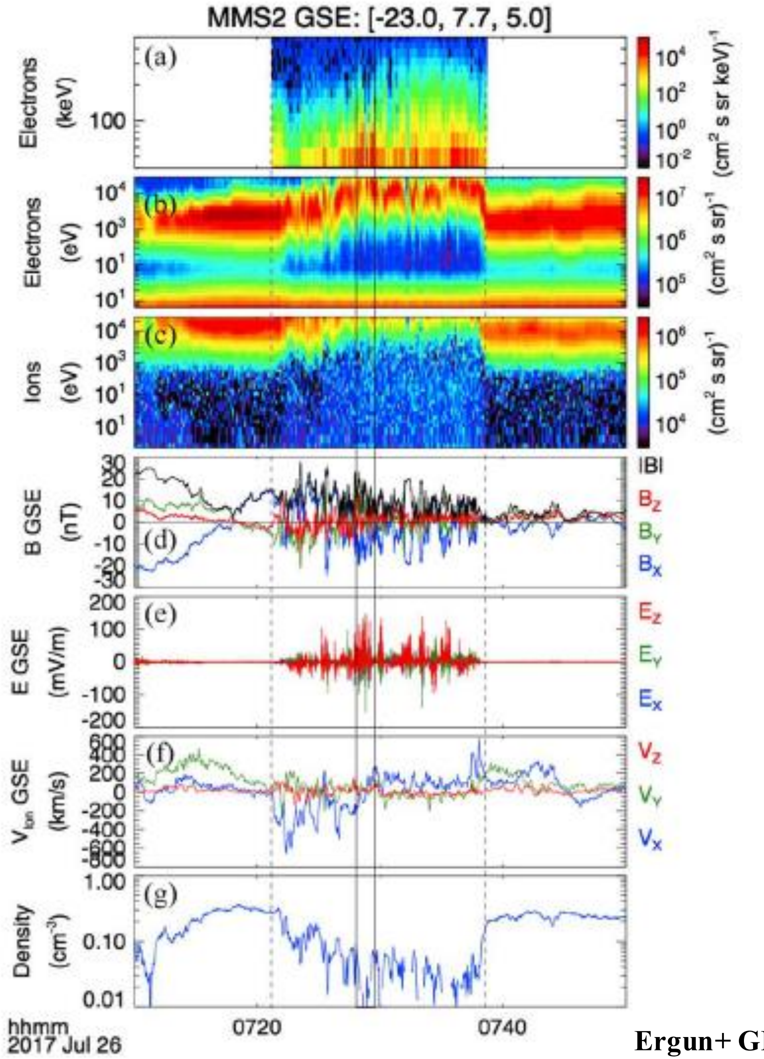
Magnetospheric MultiScale (MMS) Data

Shibata & Tanuma (2001)
Loureiro+ (2007);
Bhattacharjee & Huang (2009);
Daughton+ (2009);
Cassak+ (2009); Uzdensky+ (2010)
……

2D: Matthaeus & Lamkin (1985)
……
3D: Lazarian & Vishniac (1999)
……

Ji & Daughton PoP 2011, 2022

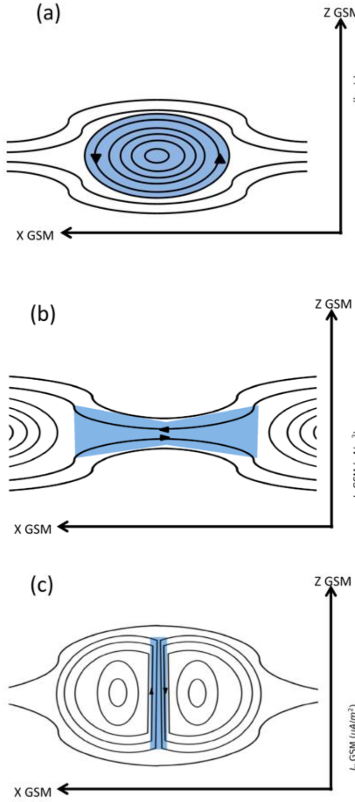




Ergun+ GRL 2018

Detecting Magnetic Structures during **Turbulent Magnetotail Reconnection**

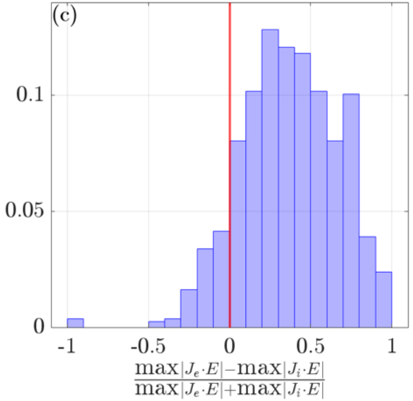
- Plasmoids (O points)
  - Tearing instability, or between two X points
- Current sheets (X points)
  - May be reconnecting or not
  - Between plasmoids ("pull" reconnection)
  - Plasmoids merge ("push" reconnection)
- 10 days in summer 2017
- ~80 intervals
- 796 magnetic structures with B_z crossing 0



Bergstedt+ GRL 2020

Energy Exchange is Bi-directional, Dominated by Perpendicular Electron Flows via Fermi Acceleration Mechanism

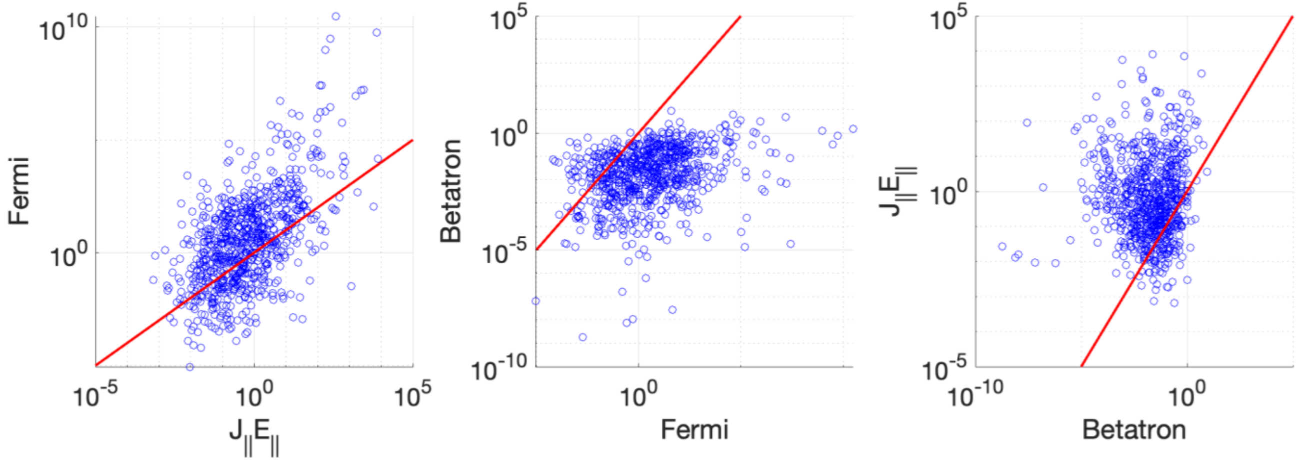
Wang+ submitted to JGR

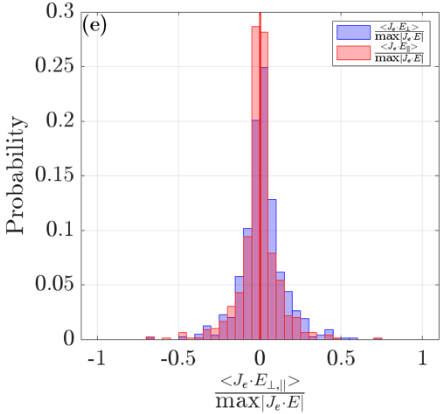


electron>ion

$$\frac{d\varepsilon}{dt} = qE_{||}v_{||} + \mu\frac{dB}{dt} + q\mathbf{E}\cdot\mathbf{u}_c + \frac{1}{2}m\frac{d}{dt}|\mathbf{u}_E|^2.$$

$|\mathrm{Fermi}| > |J_{||}E_{||}| > |\mathrm{Betatron}|$





Bi-directional;
perpendicular>parallel

Qualitatively reproduced by VPIC in 3D and even in 2D?

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Co-locate a laser facility with FLARE?

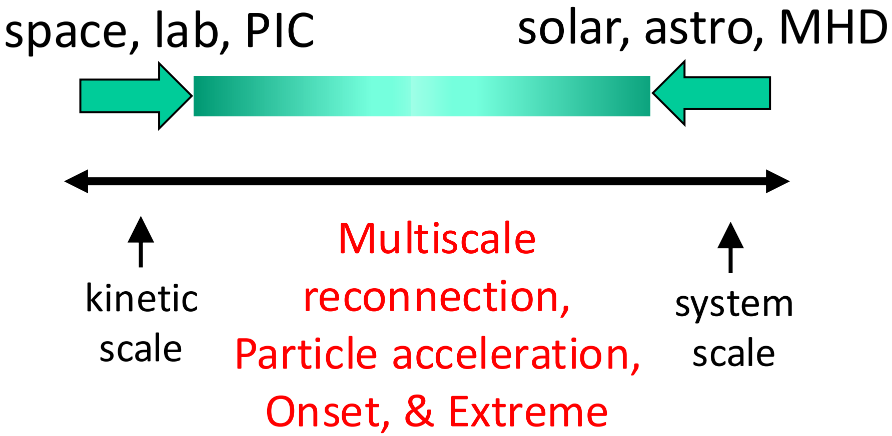
*Ji+ white papers to Plasma 2020, Astro 2020, and Helio 2024 Dacadal Surveys

Summary: A Roadmap Forward

- Phase III on multiscale physics between fluid and kinetic scales is the final step to understand reconnection in large plasmas
  - Plasmoid chains vs turbulence. FLARE is operational
- Particle acceleration by multiscale reconnection is still largely unknown
  - Acceleration by reconnection/parallel electric field, Fermi, and betatron mechanisms?
- Onset problem is challenging – related to forecast of space weather events and disruptive phenomena in tokamaks
- Extreme problem is also challenging but new petawatt lasers provides the hope

References:

1. *H. Ji+, Space Science Reviews* **219**, 76 (2023)
2. *H. Ji+, Nature Reviews Physics* ***4****, 263-282 (2022)*
3. *H. Ji+, whitepapers to Plasma/Astro2020 and Helio2024 Decadal Survey*



Solving reconnection problem requires close collaboration of basic, fusion, space, solar, astro communities!