FLARE: a collaborative research facility to study magnetic reconnection and related phenomena

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Princeton Plasma Physics Laboratory

W. Daughton and A. Stanier

Los Alamos National Laboratory

2020 AGU Fall Meeting

December 1-17, 2020

Outline

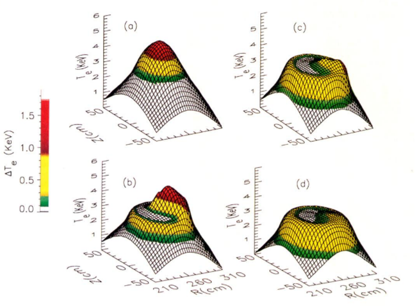
- Collisional MHD fluid reconnection versus collisionless kinetic reconnection
- Frontier: Multiple-Scale Magnetic Reconnection and Its Statistical Characterizations, such as plasmoid size distributions
- FLARE as a collaborative research facility for studies of multi-scale reconnection relevant to space and solar physics

Fast Magnetic Reconnection Observed throughout the Universe and in Fusion Plasmas

Laboratory fusion plasmas:
Confinement degradation

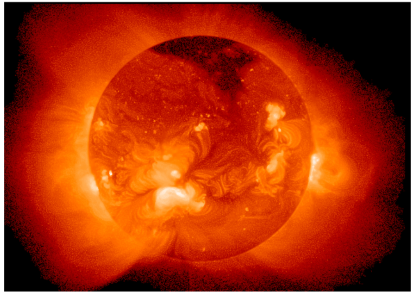
Solar plasma:
Flares and coronal heating

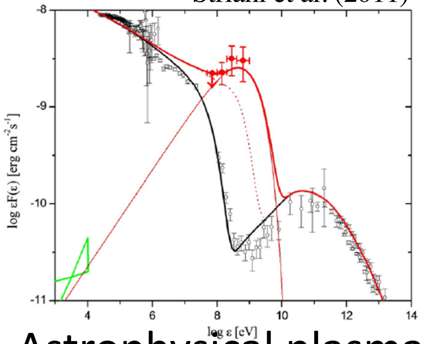
Crab Nebula
gamma-ray flares
Striani et al. (2011)



Yamada et al. (1994)
TFTR sawtooth

Magnetospheric plasma:
Cause of aurora & substorms



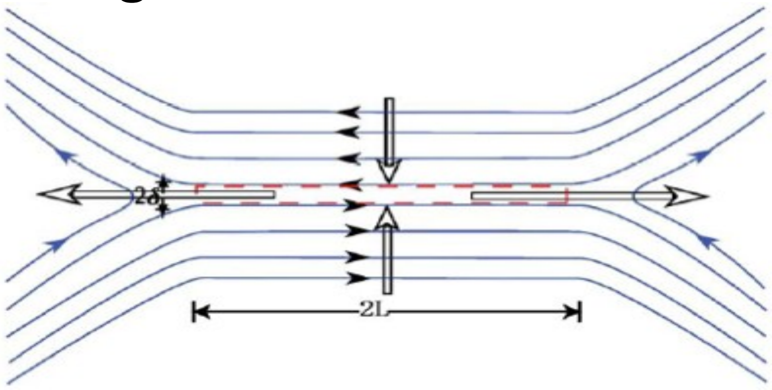


Astrophysical plasmas:
Particle acceleration

- Understanding and predicting reconnection events has practical importance for nuclear fusion research, space weather forecast, and understanding explosive astrophysical phenomena.
- A common feature of these plasmas is that their Lundquist numbers ($S \equiv \mu_0 L V_A/\eta$) are high and their normalized sizes ($\lambda \equiv L/\rho_S$) are large.

Collisional MHD fluid Models versus Collisionless Kinetic Models in Single X-line Regimes

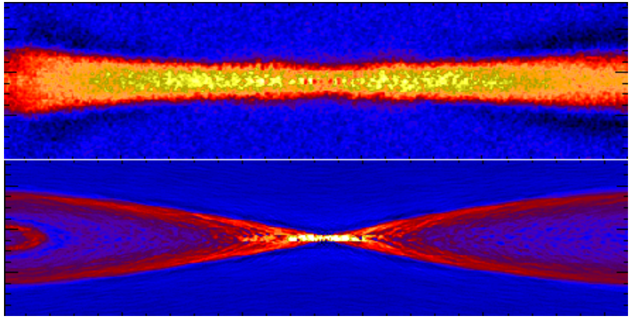
e.g. Sweet-Parker Model



Valid for *large (collisional)* plasmas but predicts *slow* reconnection due to outflow bottleneck in a narrow current sheet

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

e.g. Kinetic Model



ions

electrons

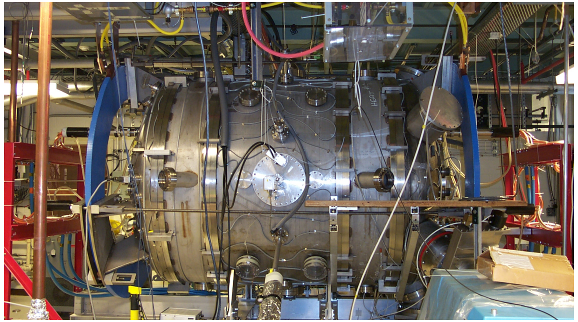
Drake +

Predicts *fast* reconnection from decoupled ions/electrons but applicable only to *small* (collisionless) plasmas

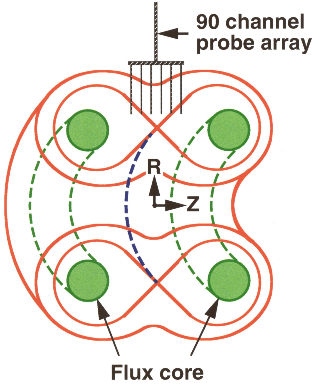
$$\frac{V_R}{V_A} \sim 0.1$$

Both Models Qualitatively and Quantitatively Verified in Magnetic Reconnection Experiment (MRX)

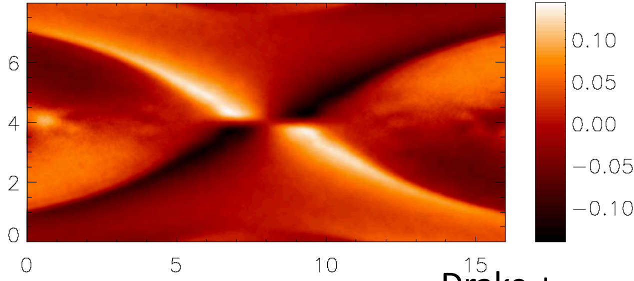
MRX device



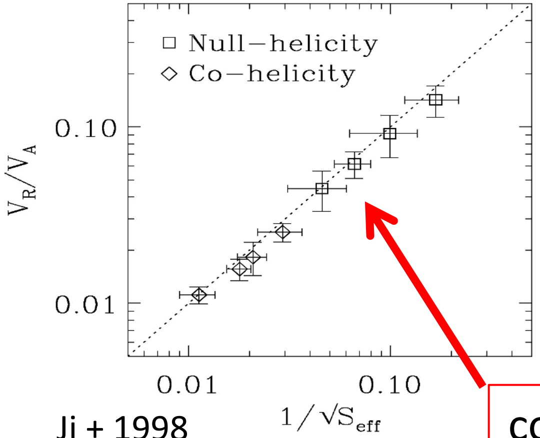
Yamada, Ji + since 1995



Numerical prediction

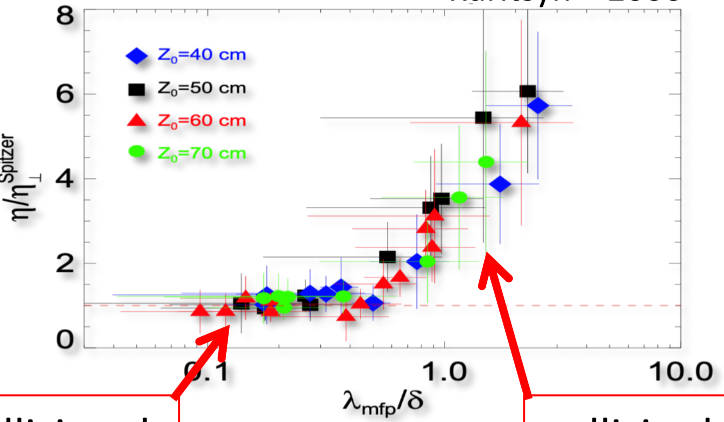


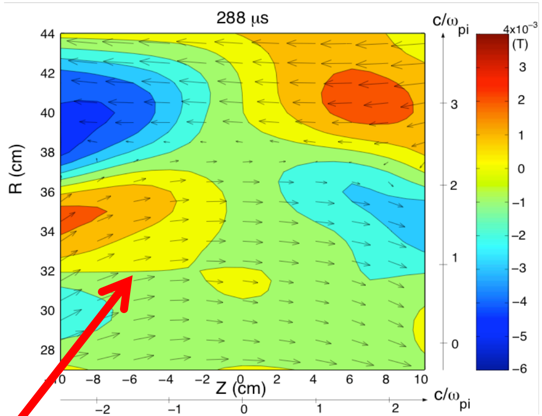
Drake +



Ji + 1998

Kuritsyn + 2006





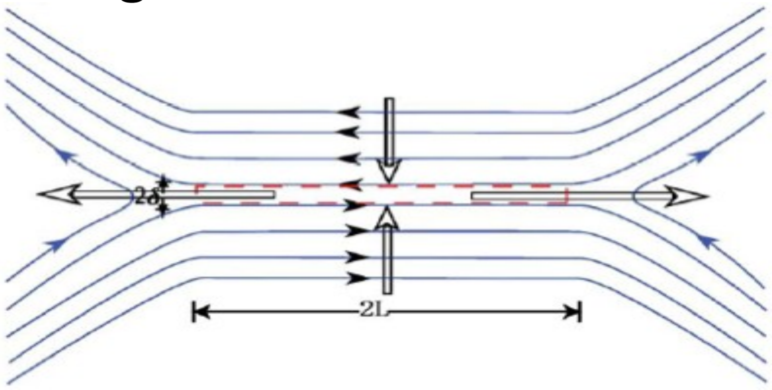
collisional

collisionless

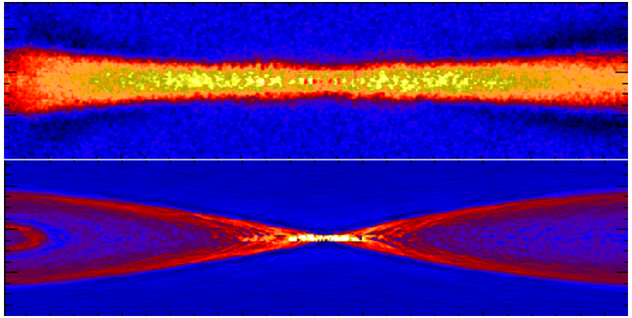
Ren + 2005

Collisional MHD fluid Models versus Collisionless Kinetic Models in Single X-line Regimes

e.g. Sweet-Parker Model



e.g. Kinetic Model



Drake +

Valid for *large (collisional)* plasmas but predicts *slow* reconnection due to outflow bottleneck in a narrow current sheet

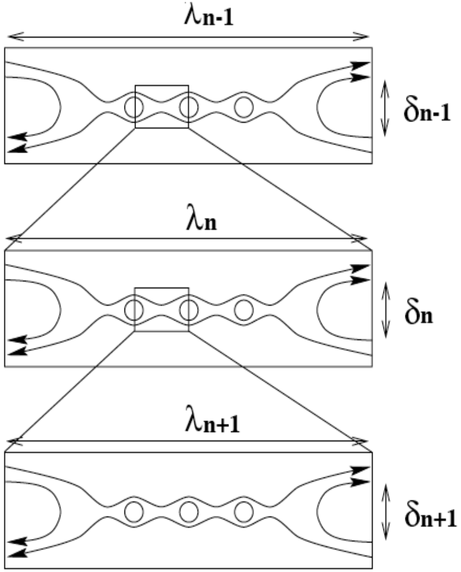
Predicts *fast* reconnection from decoupled ions/electrons but applicable only to *small* (collisionless) plasmas

The frontier question: How to combine these models self-consistently to explain and predict fast reconnection in large & high-S plasmas? ➔ a multi-scale challenge!

A Promising Multi-scale Idea to Combine Fluid and Kinetic Models: Plasmoid Instability of Large-scale Current Sheets

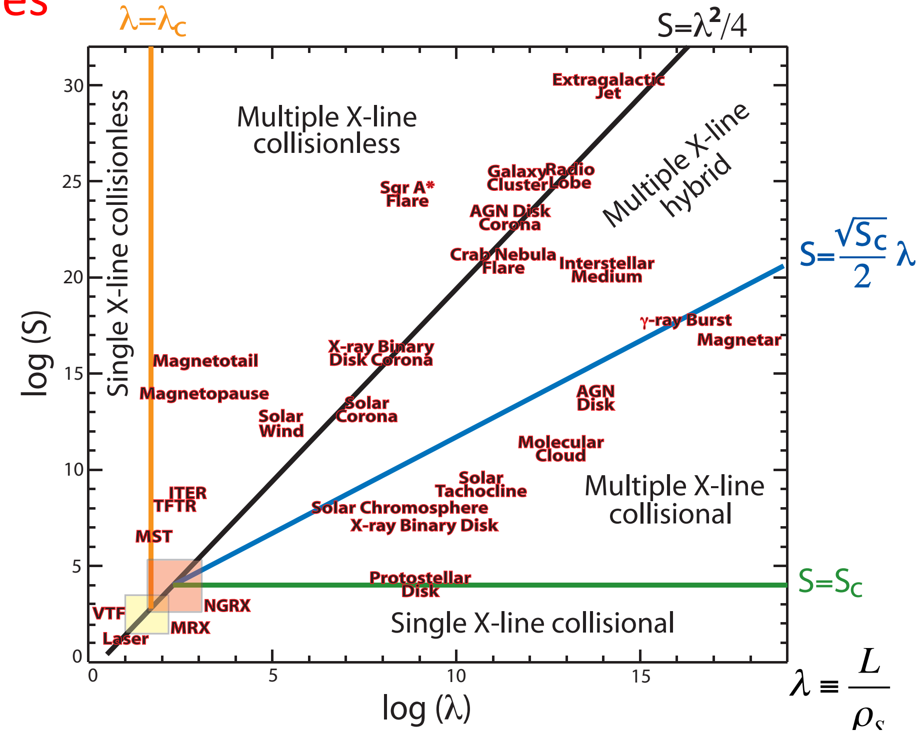
Idea: a hierarchy of plasmoids to couple fluid to kinetic models with multiple X-lines

Shibata & Tanuma (2001)



Reconnection Phase Diagram

Ji & Daughton (2011)

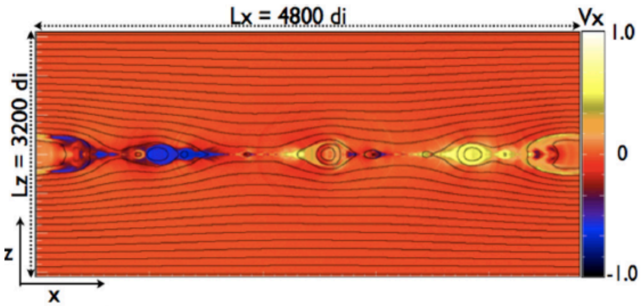


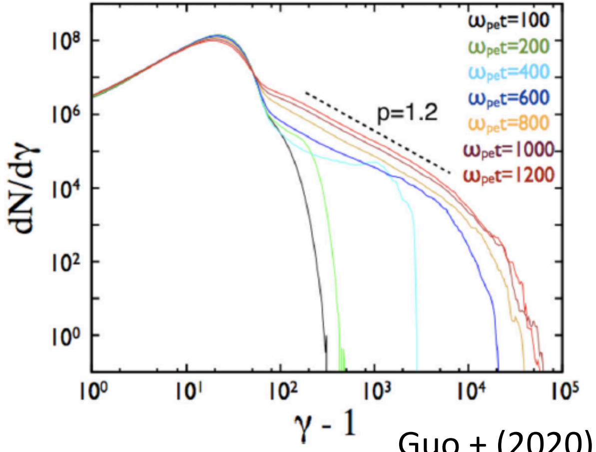
Loureiro+ 2007, Bhattacharjee+ 2009, Daughton+ 2009, Cassak+ 2009, Uzdensky+ 2010 ….

Statistical Properties of Multiple X-line Reconnection

- Important for overall reconnection rate but also for detailed energy conversion
  - Generation of large-scale plasma flow
  - Heating of ions and electrons
  - Acceleration of nonthermal ions and electrons
  - Scaling dependence on Lundquist number and plasma size

- Comparisons with other multiple-scale phenomena, such as:
  - Turbulent flow (e.g. solar wind)
  - Turbulent convection (e.g. solar convection)

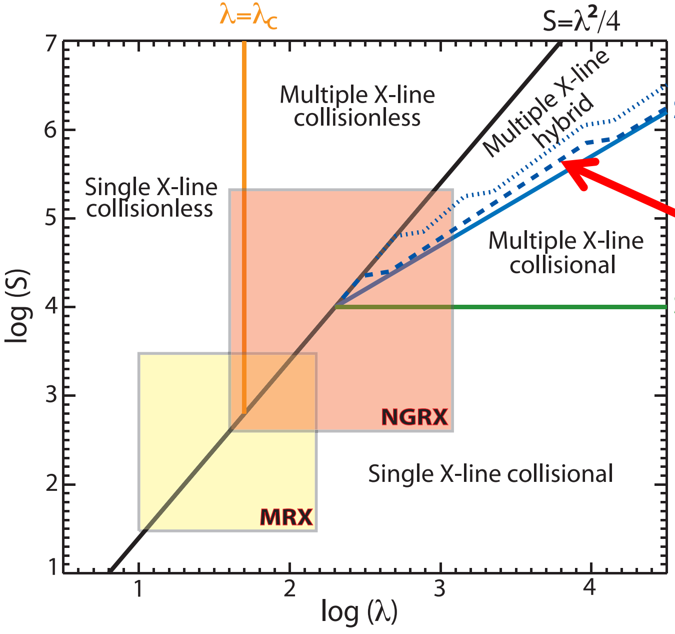




Guo + (2020)

plasmoid size distribution ⟷ nonthermal particle energy distribution

Statistical Properties: Scaling Law for Number of Plasmoids

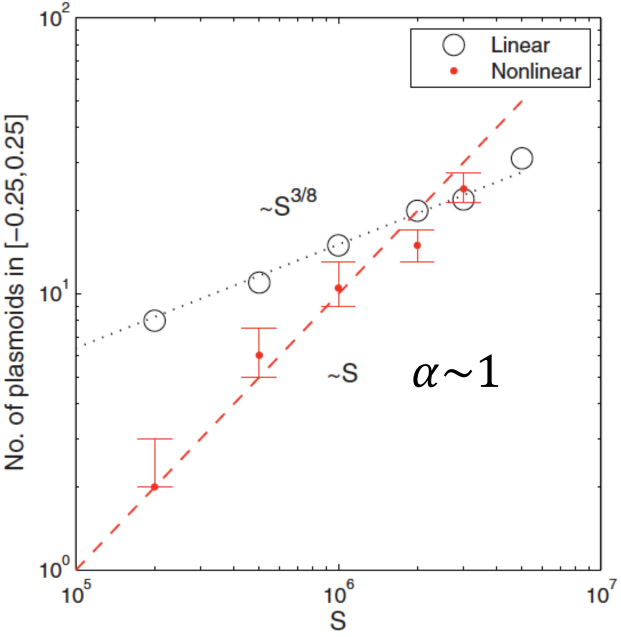


$S=\frac{\sqrt{S_c}}{2}\lambda$

α=3/8, 0.8, or 1

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

Huang & Bhattacharjee (2010)



$\alpha \sim 1$

- Important for determining the boundary between “hybrid” and “collisional”

Cassak, Shay & Drake (2009)

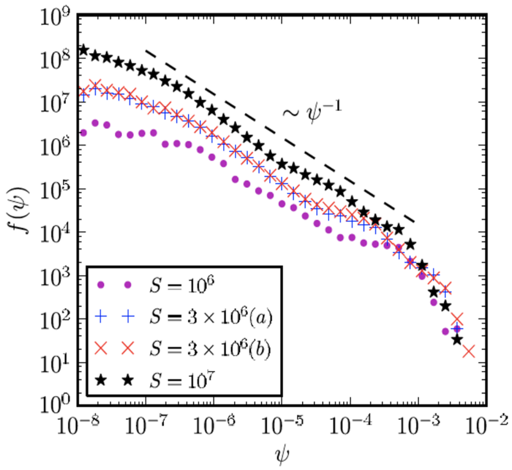
$\alpha \sim 0.6 - 1$

Plasmoid Size Distributions at Sufficiently Large S and λ

Plasmoid kinetic equation: $$\frac{\partial f(\psi)}{\partial t} + \gamma \frac{\partial f(\psi)}{\partial \psi} = \xi\delta(\psi) - \frac{Hf(\psi)}{\tau_A} - \frac{f(\psi)}{\tau_A}$$

Reconnection Creation Absorption Advection

- ψ^{-2} in 2D MHD simulation [Uzdensky et al. (2010); Loureiro et al. (2012); Takamoto (2013), Shen+ (2013)]
- ψ^{-3} in 3D MHD maximum entropy variational principle [Lingam & Comisso (2017)]
- $\psi^{-(1-2)}$ by Monte-Carlo [Petropoulou et al. (2018)]
- $e^{-\psi}$ in Hall-MHD [Fermo et al. (2010); Fermo et al. (2011)]
- ψ^{-1} followed by an $e^{-\psi}$ tail in MHD theory and simulation [Huang & Bhattacharjee (2012); Guo et al. (2013)]

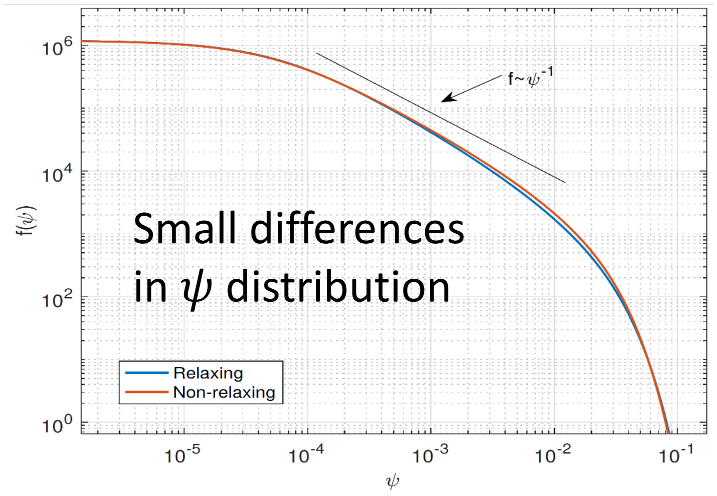


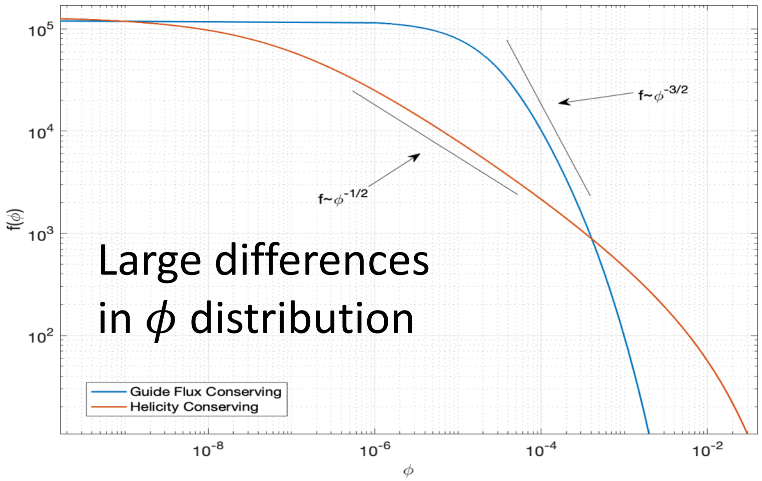
Huang & Bhattacharjee (2012)

No guide field effects have been explicitly studied

Guide Field Effects on Plasmoid Size Distributions

1. Conservation of guide field flux during plasmoid mergers: $f(\psi)$ is unchanged from zero-guide field case but $f(\phi)$ needs an integral term over all mergers to sum to ϕ.
2. Taylor relaxation minimizing energy while conserving magnetic helicity to convert flux from guide field to reconnecting field: both $f(\psi)$ and $f(\phi)$ change.
   - Assuming enough time (~10 τ_A) to relax as in Reversed Field Pinches (RFP).

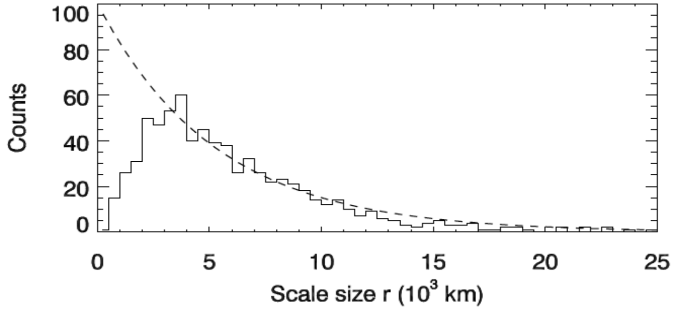




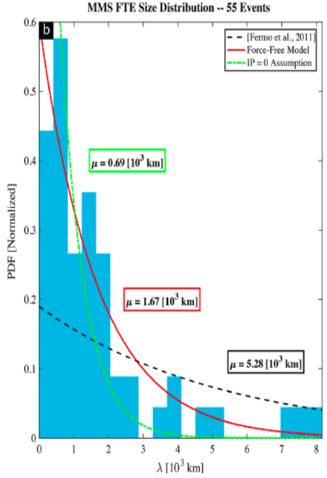
S. Majeski + to be submitted

Plasmoid Size Distributions in Space and Solar Plasmas

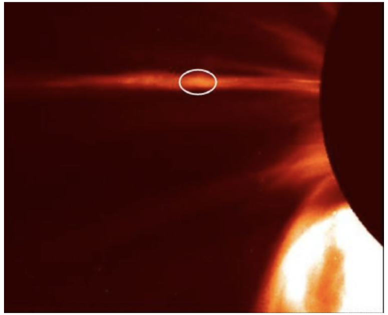
Statistics of Flux Transfer Events (FTEs) by CLUSTER satellites in Earth's magnetopause [Fermo et al. (2011)]

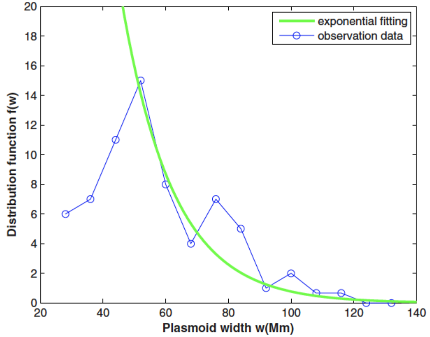


Statistics of FTEs by Magnetospheric Multi-Scale (MMS) satellites in Earth's magnetopause [Akhavan-Tafti + (2017)]



Plasmoids in a current sheet structure post-CME (Coronal Mass Ejections) by LASCO on SOHO satellite [Guo + (2013)]

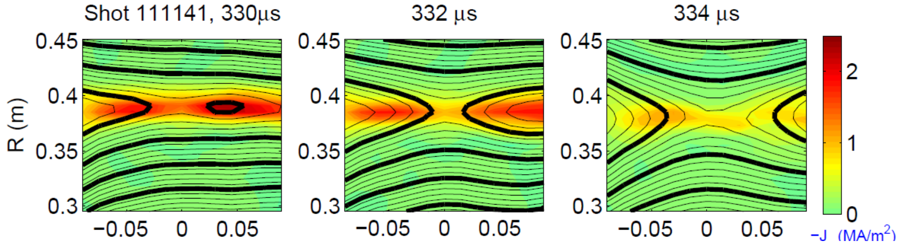


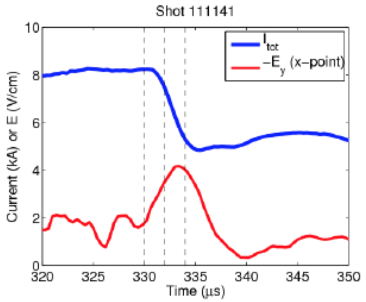


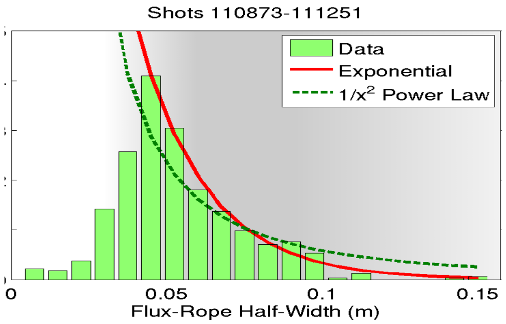
- All exponential – no power-laws observed

Plasmoid Size Distributions in the Lab

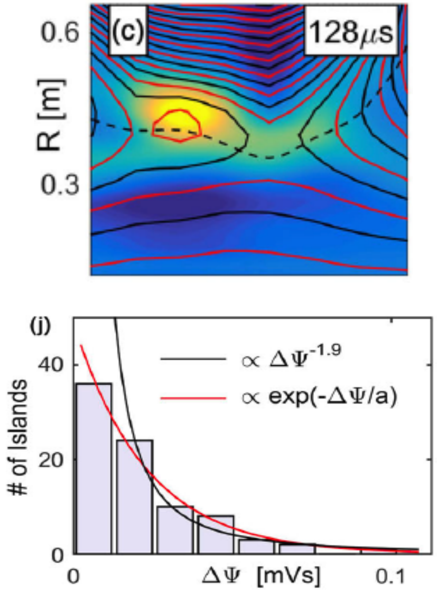
Impulsive reconnection in MRX [Dorfman + (2013, 2014)]







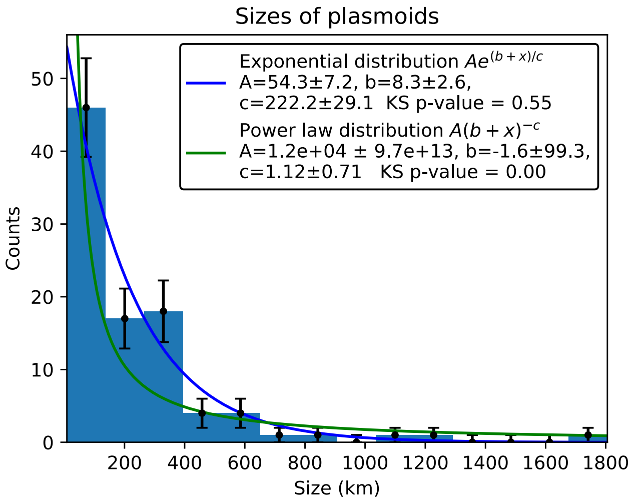
Strongly (one-side) driven reconnection in TREX [Olson + (2016)]



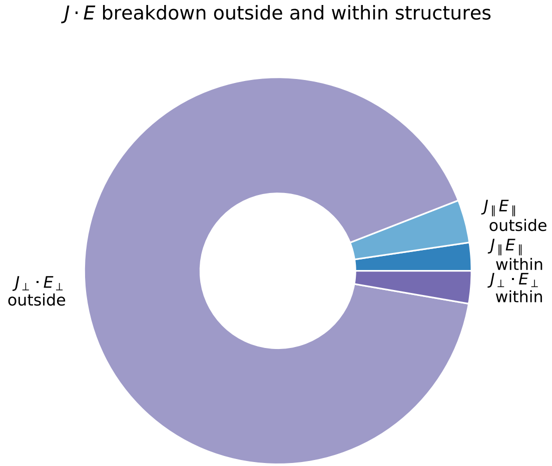
- Also exponential – no power-laws observed

Plasmoid Size Distributions in Space (again)

Statistics of magnetic structures (including plasmoids) by an automated algorithm in a single turbulent reconnection period by MMS in Earth's magnetotail



Surprise: 85% of energy dissipation outside of structures and dominated by $\boldsymbol{E}_\perp \cdot \boldsymbol{j}_\perp$, compared to 15% within the structures where $\boldsymbol{E}_\parallel \cdot \boldsymbol{j}_\parallel$ accounts for 40% of $\boldsymbol{E} \cdot \boldsymbol{j}$.

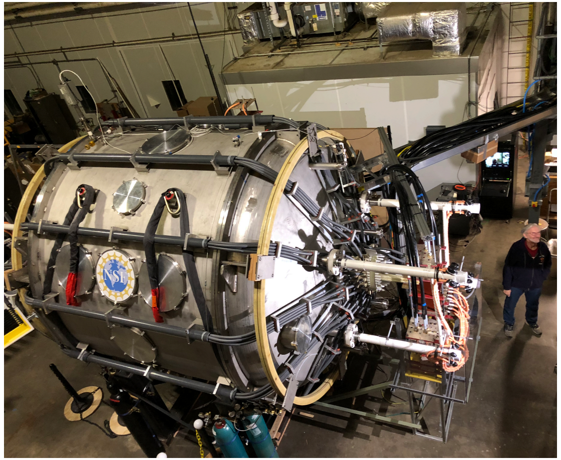


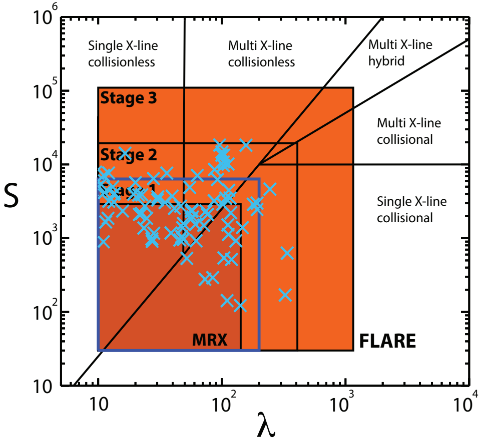
Bergstedt + GRL (2020)

- Still exponential – no power-laws observed

FLARE (Facility for Laboratory Reconnection Experiments) Built to Study Multi-scale Reconnection Physics in New Regimes

November 25, 2020





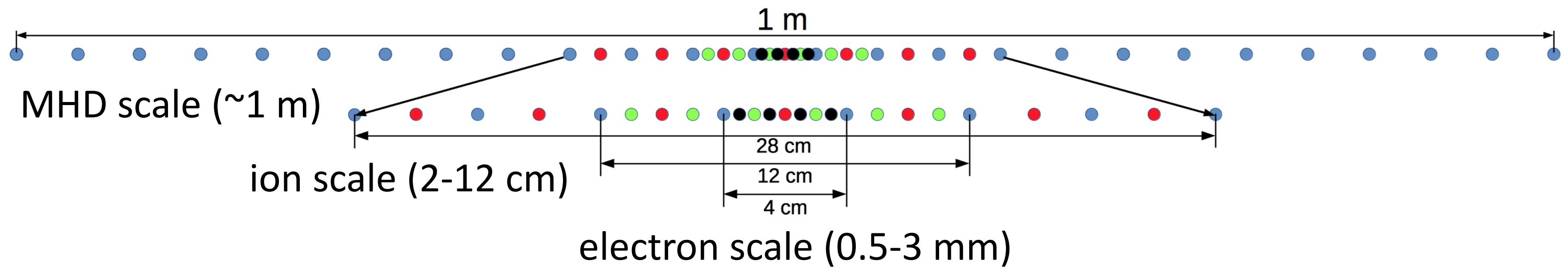
The FLARE device has been successfully built and the data (crosses) from first plasma operation with Stage-1 capabilities exceeded expectations (blue box in phase diagram).

FLARE is currently being installed with upgrade to stage-3 capabilities at PPPL as a DoE collaborative research facility and will be online in 2021

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

J. Yoo+

The main diagnostics: magnetic probe arrays



- Coverage of 1 m and maximum radial resolution of 5 mm, with 128 coils in one probe
- 15 axial locations: 128 × 15 ~ 2000 total coils.
- Covers 42 cm (84 cm) in axial direction with 3 cm (6 cm) resolution.
- Users will be able to select the 1024 coils to digitize at 50MHz (>2 f_{LH}).
- Other diagnostics: electrostatic probes, interferometer, ion Doppler spectroscopy…

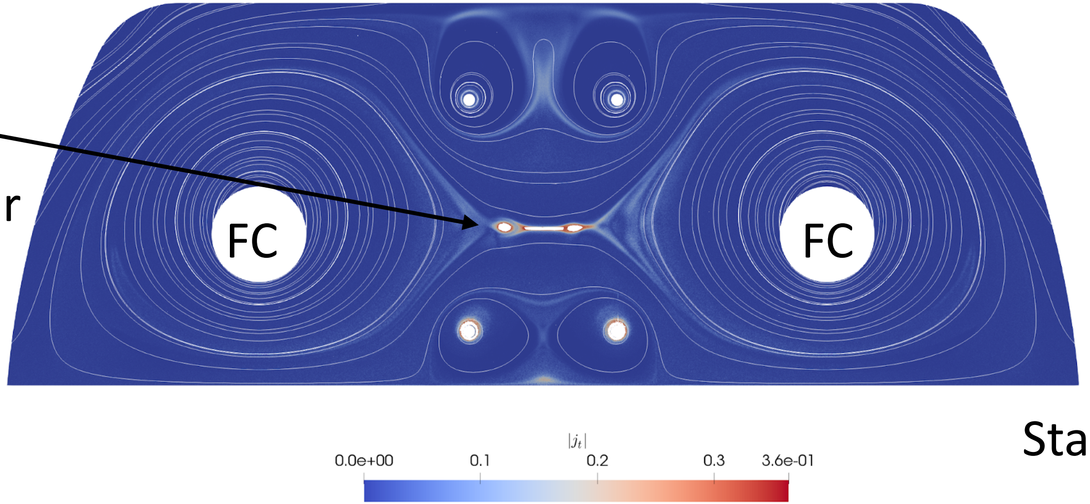
Sample Research Topics on FLARE

- **Multiple-scale**
  - Plasmoid instability in MHD
  - Scaling of multiple MHD X-lines
  - Transition from MHD to kinetic
  - Scaling of kinetic X-lines
  - Guide field dependence
- **Reconnection rate**
  - Reconnection rate for multiple MHD X-lines
  - Reconnection rate for multiple MHD and kinetic X-lines
  - Upstream asymmetry and guide field effects
- **Partial ionization**
  - Modification of multiple-scale reconnection by neutral particles
  - Neutral particle energization
- **Reconnection onset**
  - Is reconnection onset local or global?
  - Is reconnection onset 2D or 3D?
- **3D effects**
  - Plasmoid instability in 3D: flux ropes?
  - 3rd dimension scaling: towards turbulent reconnection?
  - Externally drive tearing reconnection
  - Interaction of multiple islands: magnetic stochasticity?
  - 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

"*Major Scientific Challenges and Opportunities in Understanding Magnetic Reconnection and Related Explosive Phenomena in Solar and Heliospheric Plasmas*", H. Ji, J. Karpen, et al., Whitepaper submitted to Heli2050 Workshop in May 2021 (https://arxiv.org/abs/2009.08779)

Initial Scoping Simulations by VPIC

Plasmoid unstable current layer



Stanier + PoP (2019)

- Collisional current layer forms in response to Poloidal Field Coil current ramp-down in Flux Cores (pull reconnection) & Drive Coil ramp-up.
- Plasmoids cause transition from collisional to collisionless diffusion region physics (multiple X-line "hybrid" regime).
- Guide field allows thinner collisional layers before break-up, but reduces drive and current sheet length due to guide field enhancement via plasma paramagnetic effects.

Summary

- Multiple-scale couplings between global system scales and local kinetic dissipation scales are most challenging to understand magnetic reconnection and to predict the relevant explosive events in space, solar and astrophysical plasmas.
- Statistical properties, such as plasmoid size distribution, are important to quantify multiple-scale reconnection, especially for particle acceleration. However, no evidence of self-similar power laws has been found yet, possibly due to limited resolutions and/or dominance by loss.
  - 85% of energy conversion outside of magnetic structures by MMS (Bergstedt+, GRL 2020)
  - Guide field effects on plasmoid size distribution studied (Majeski+, to be submitted)
- FLARE is an upcoming new facility for multiple communities (basic, space, solar, astro, fusion) to solve these major reconnection problems, facilitated by three user support & research teams:
    - Space Physics Team (J. Yoo lead)
    - Solar & Astrophysics Team (J. Jara-Almonte lead)
    - Basic & Fusion Plasma Physics Team (Y. Ren/W. Fox lead)
- FLARE Science Advisory Committee (SAC):
  - E. Zweibel (Chair, UW-Madison), T. Carter (Vice Chair, UCLA), S. Antiochos (NASA), S. Bale (Berkeley), W. Daughton (LANL), J. Drake (Maryland), J. Egedal (UW-Madison)