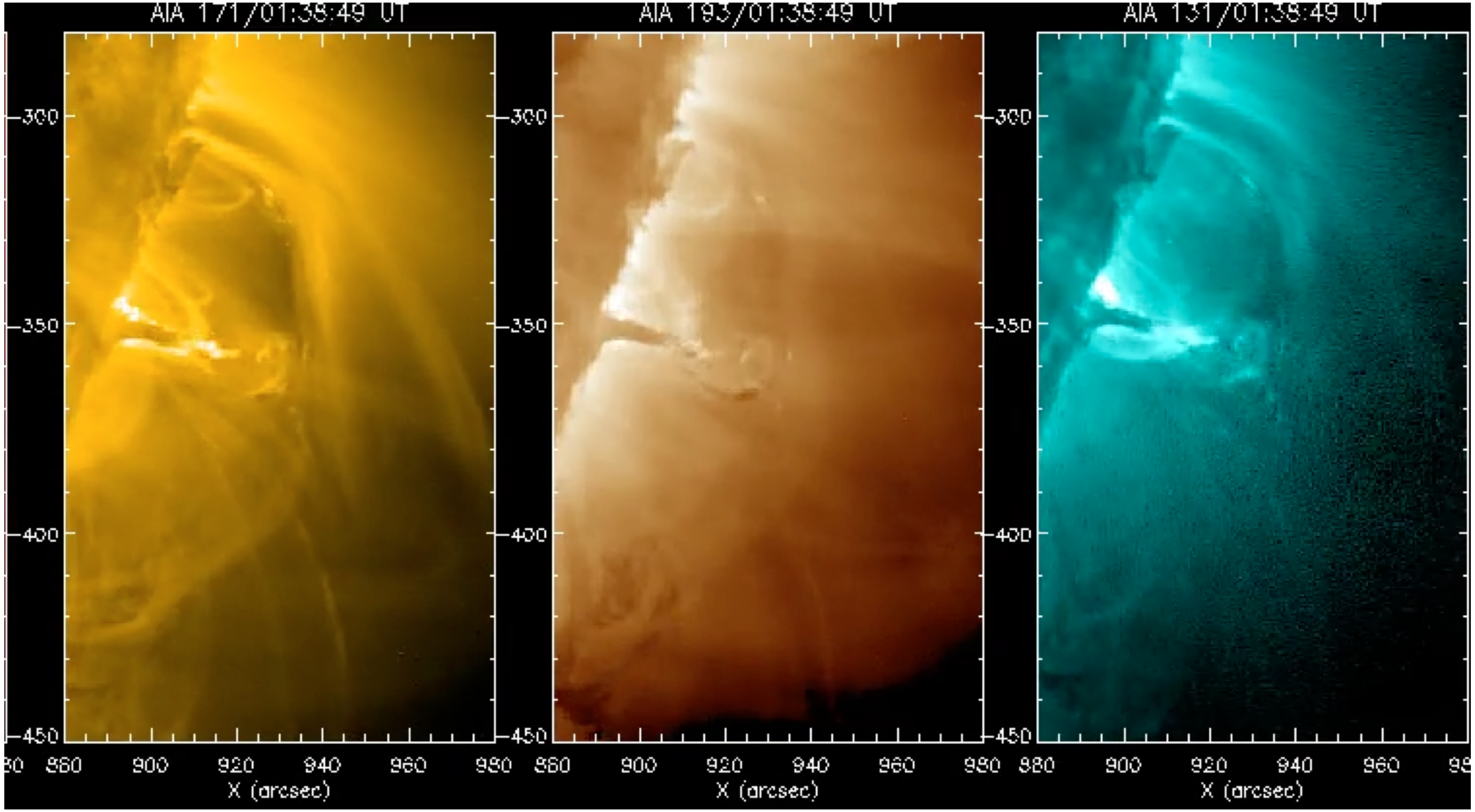
Three-Dimensional Numerical Studies of Plasmoid Formation in Eruptive Flares

J. T. Dahlin

S. K. Antiochos, C. R. DeVore

EGU 2020 Session ST1.7 - Zoom Meeting 16:50 CEST 6 May 2020

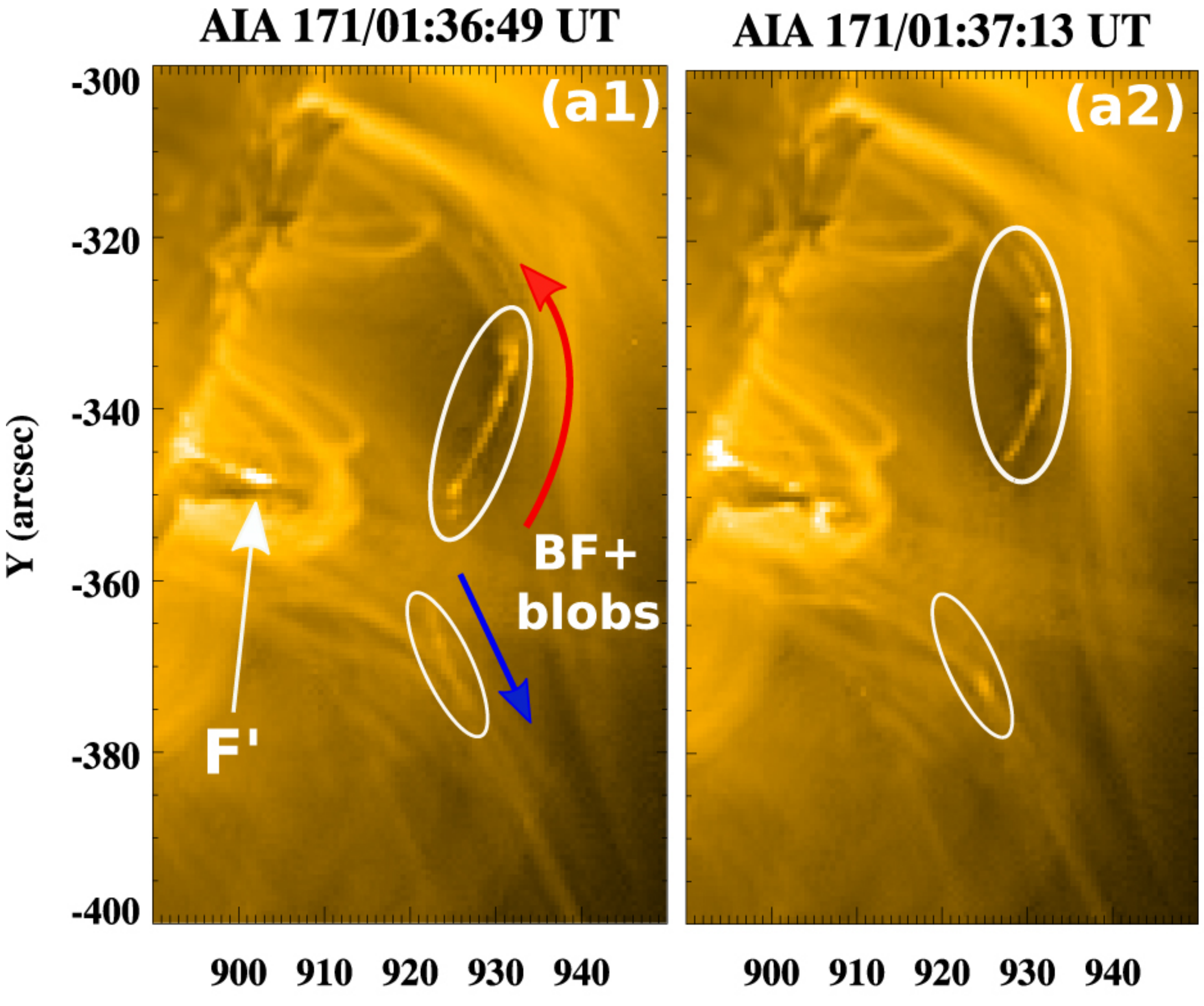
Observations: Plasmoids in the Corona



Kumar+ 2019

Observations: Plasmoids in the Corona

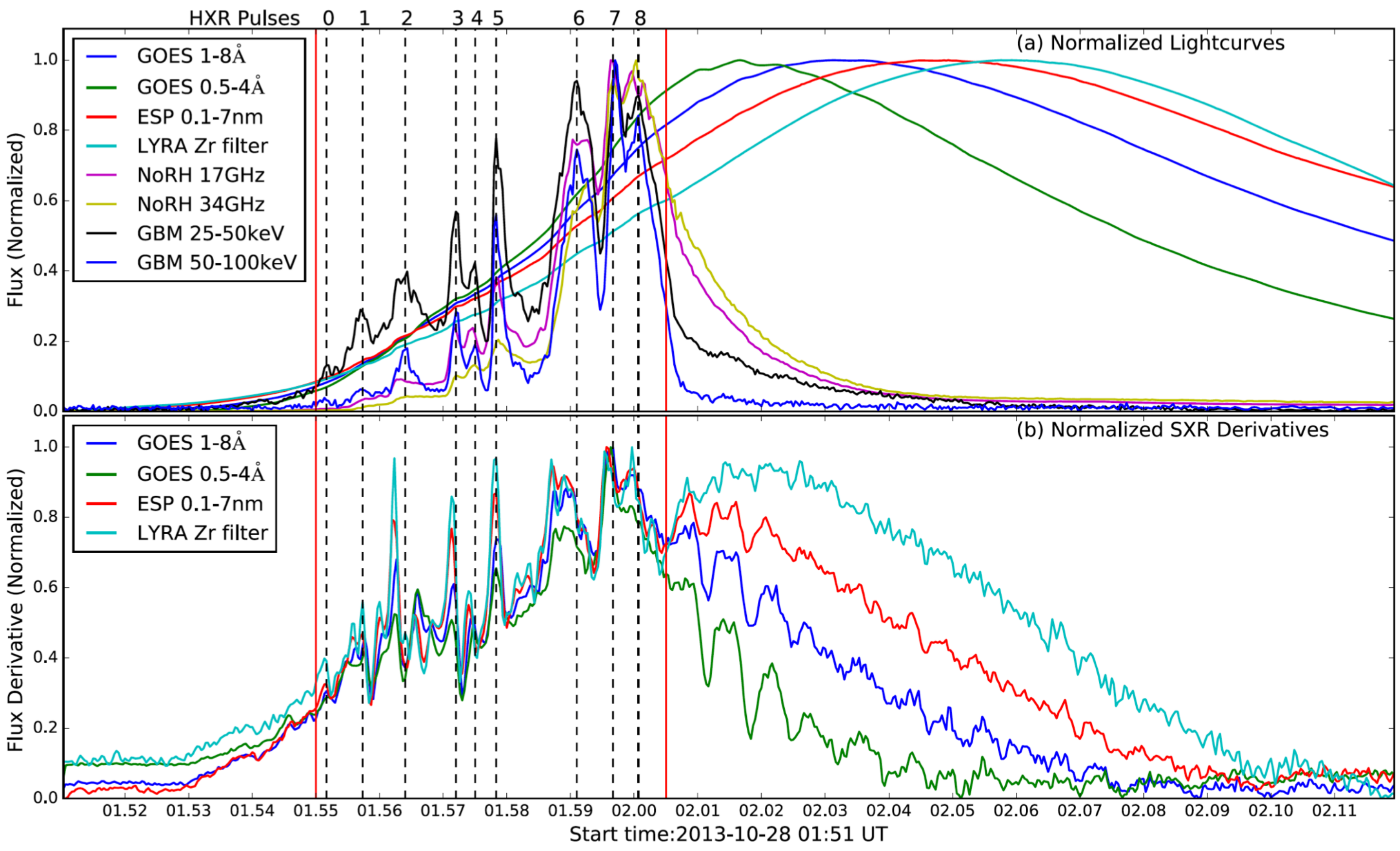
- First observation of plasmoid-like blobs in breakout reconnection (Kumar+ 2019)
    - Also seen in flares (e.g., Liu+ 2013), jets (Kumar+ 2018), PSP/WISPR observations of post-CME current sheet



Kumar+ 2019

Observations: Bursty Energy Release in Flares

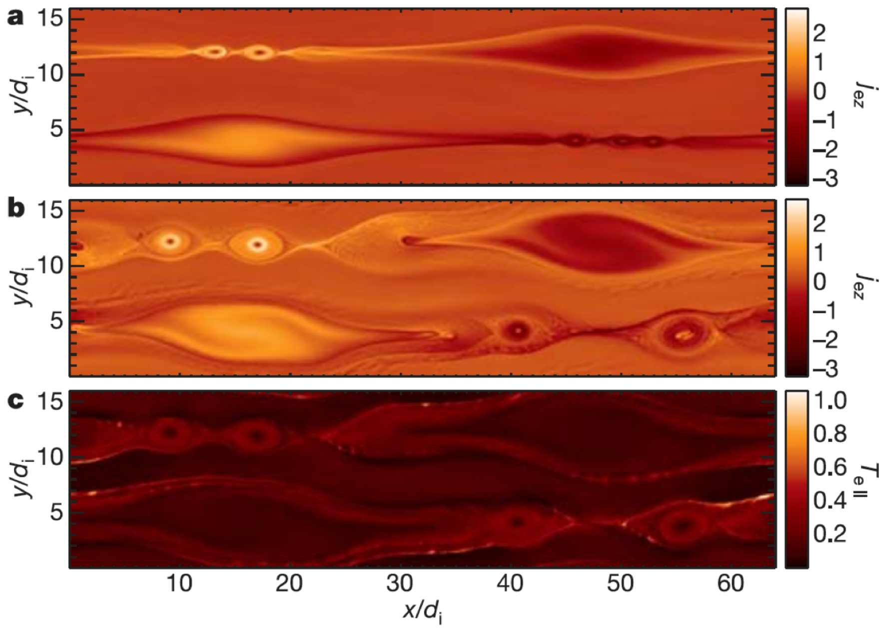
- Quasi Periodic Pulsations (QPPs)
  - Fluctuating emission across electromagnetic spectrum
- Signature of bursty energy release (plasmoids/ turbulence)?



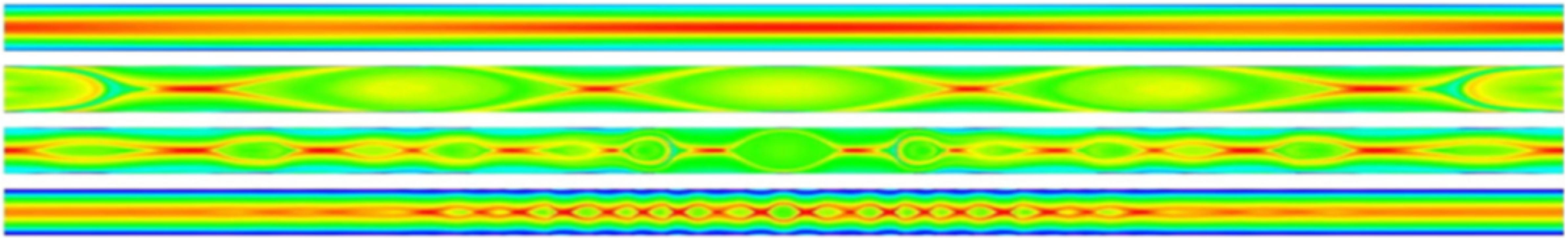
Hayes+ 2016

Theory: Plasmoids in Reconnection

- Critical for fast reconnection in MHD
  - E.g., plasmoid instability (Loureiro+ 2007)
- Efficient particle acceleration sites
  - Drake+ 2006; Dahlin+ 2014; Guo+ 2014



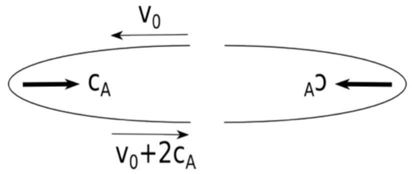
Drake+ 2006

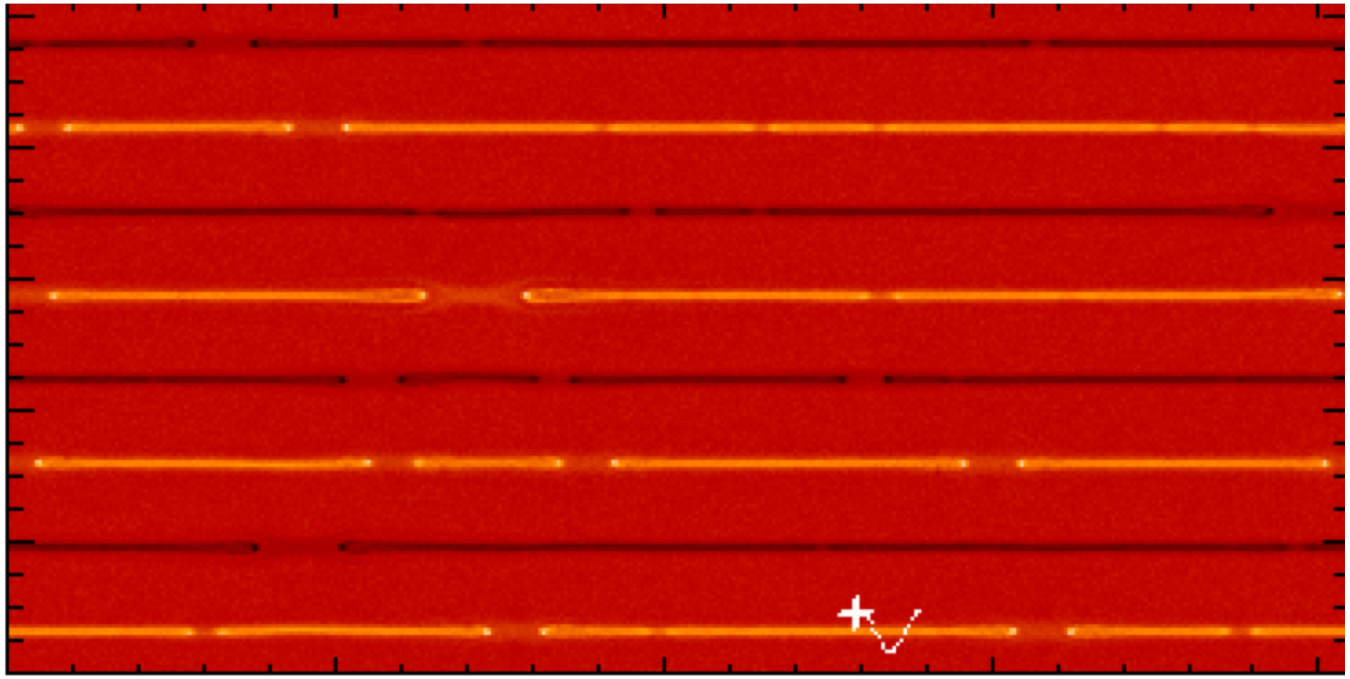


MHD (Samtaney et al., 2009)

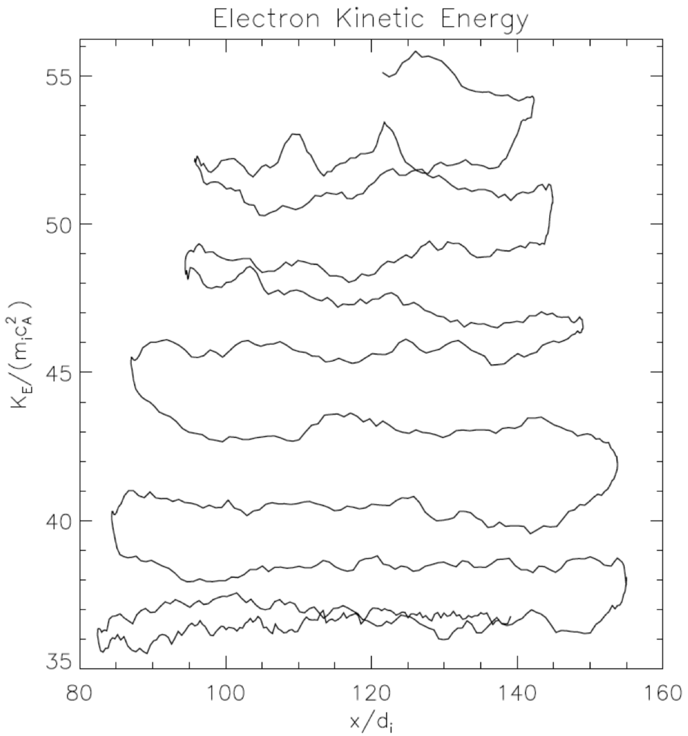
Theory: Particle Acceleration in Plasmoids

- Fermi mechanism of Drake et al., 2006
- Particles trapped in plasmoids reflect from contracting field lines



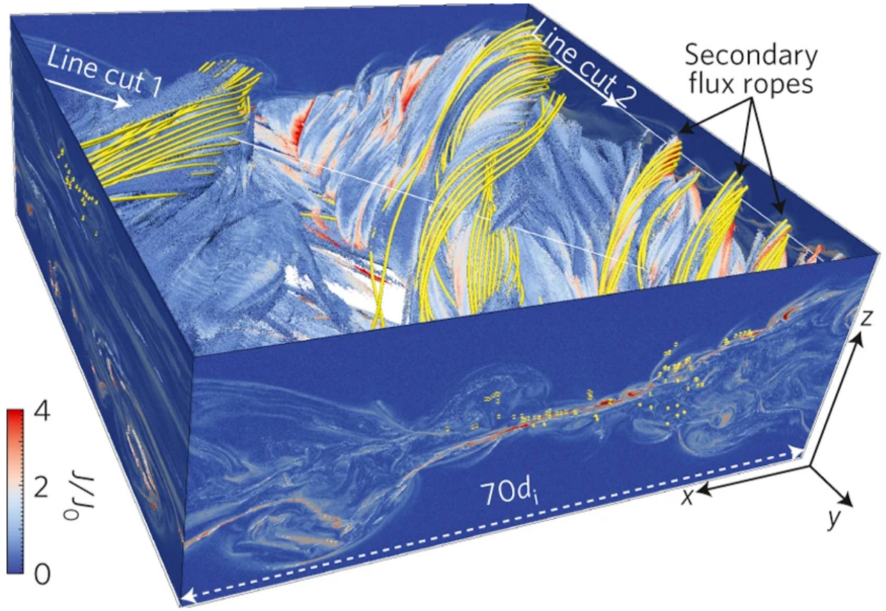


Courtesy of K. Schoeffler

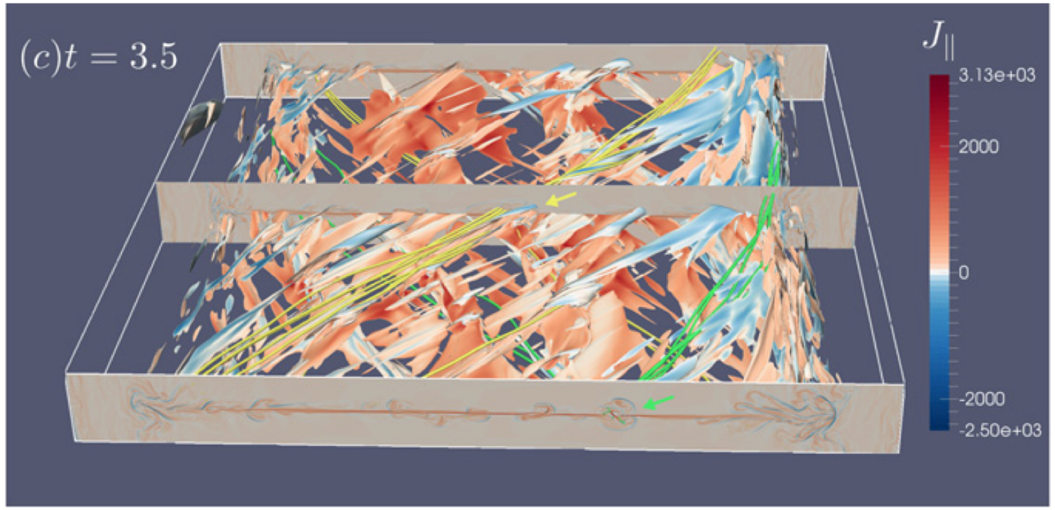


Turbulent 3D Reconnection

- Plasmoid/flux rope structure is highly complex in 3D reconnection (no longer ‘closed particle traps’)
- **What happens to the Fermi acceleration picture?**

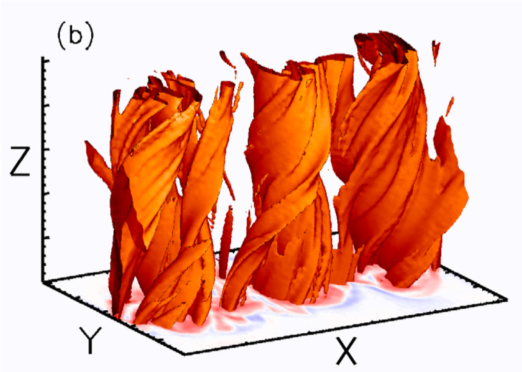


Daughton+ 2011

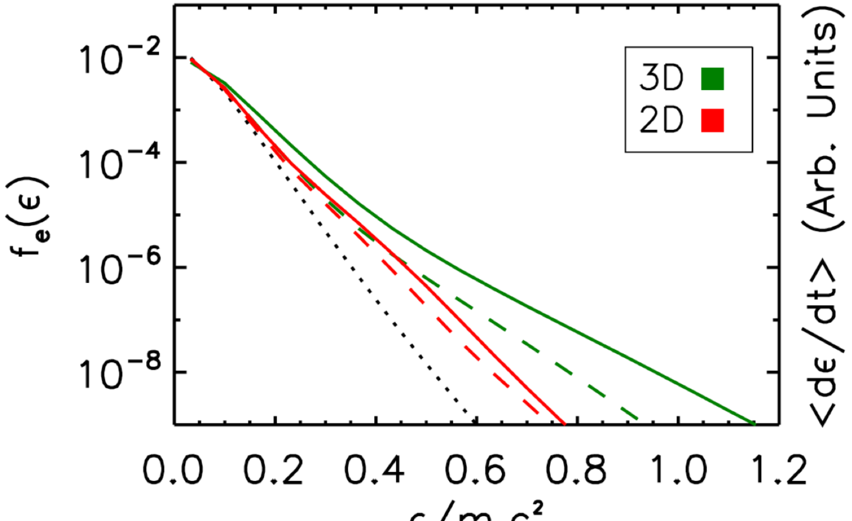


Huang+ 2016

Turbulent 3D Reconnection *Enhances* Acceleration



Current density



Energy spectra

Energetic electron density

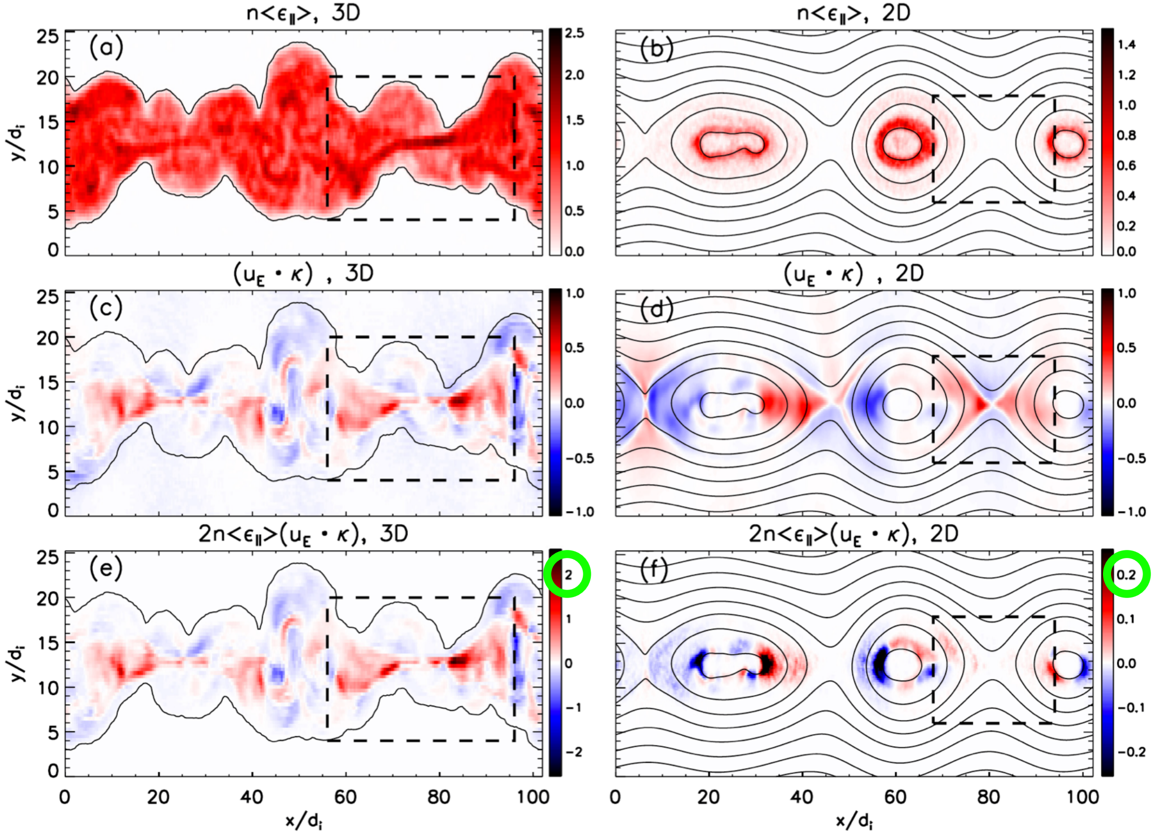
×

Acceleration / cooling rate

=

Energy gain

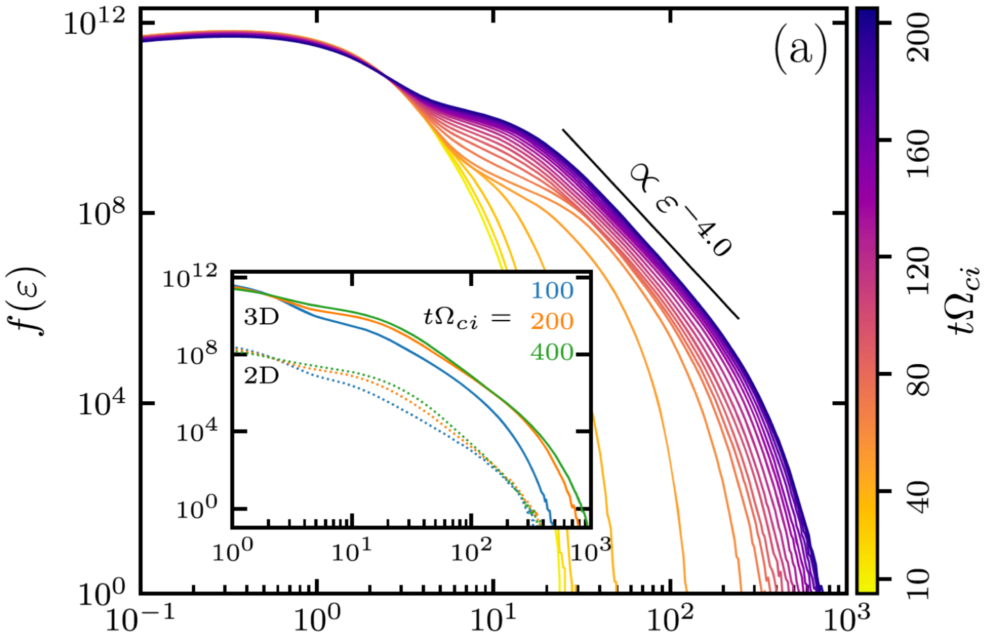
3D **2D**



Dahlin+ 2015, 2017

Power-law Spectra in 3D Kinetic Simulations

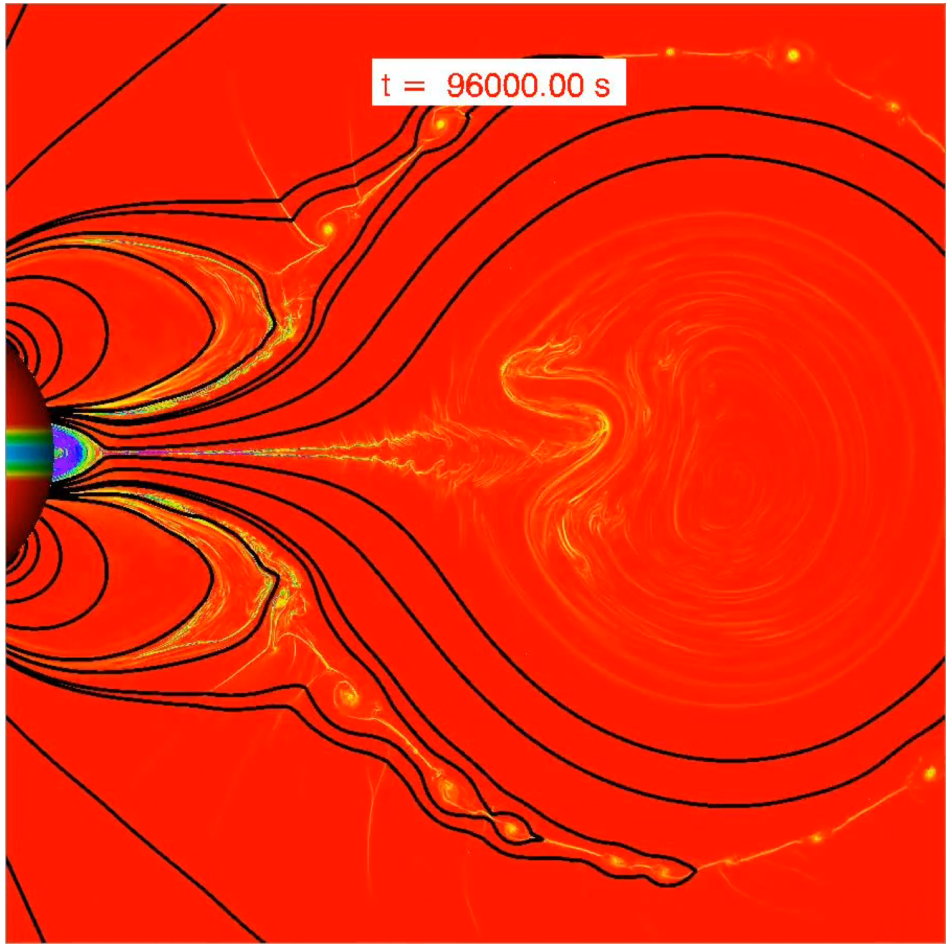
- Li+ 2019 compared 2D, 3D kinetic PIC simulations
  - Low beta (free magnetic energy/particle >> T_0)
  - Power law forms only in 3D (turbulent transport)
- Conclusion: kinetic simulations demonstrate plasmoids are efficient particle accelerators
- However, kinetic simulations are limited to small scales (~m)
  - Cannot capture global dynamics of flares
- Self-consistent MHD simulations are necessary to understand large-scale energy buildup, current sheet formation/destabilization



Li+ 2019

Plasmoid Formation in MHD Simulations of Eruptive Flares

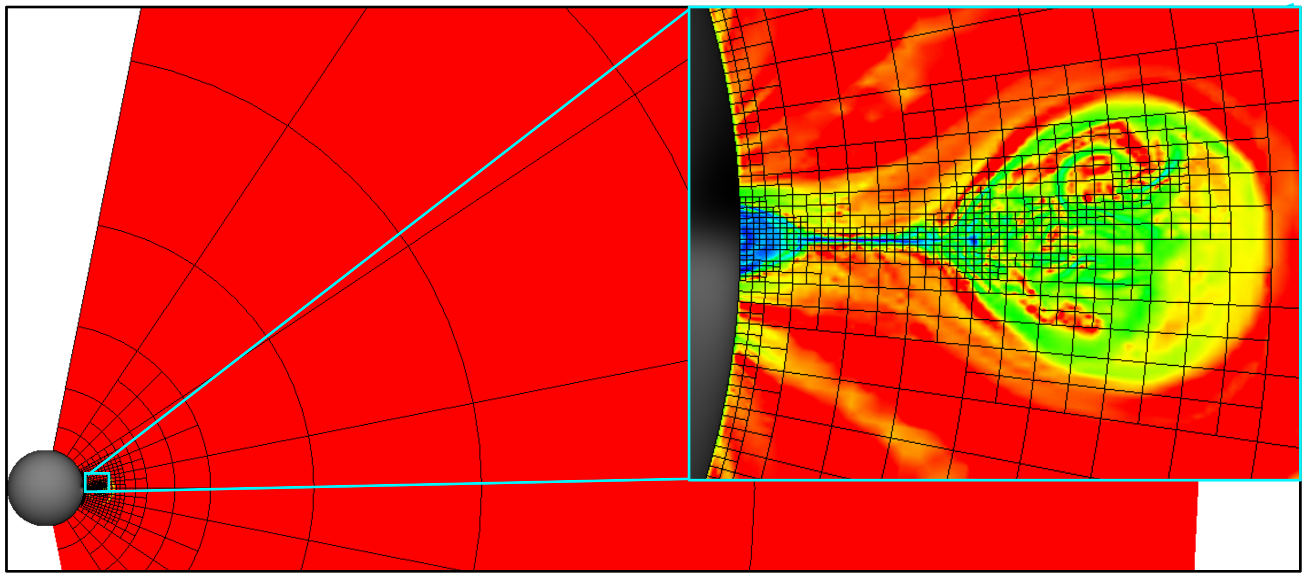
- High resolution 2.5D MHD simulations (Karpen+ 2012, Guidoni+ 2016)
  - Energized by large-scale shear flows
- Two reconnection sites generate many plasmoids
  - *Breakout reconnection* initiates eruption
  - *Flare reconnection* drives bulk energy release
- **What happens in a 3D system?**

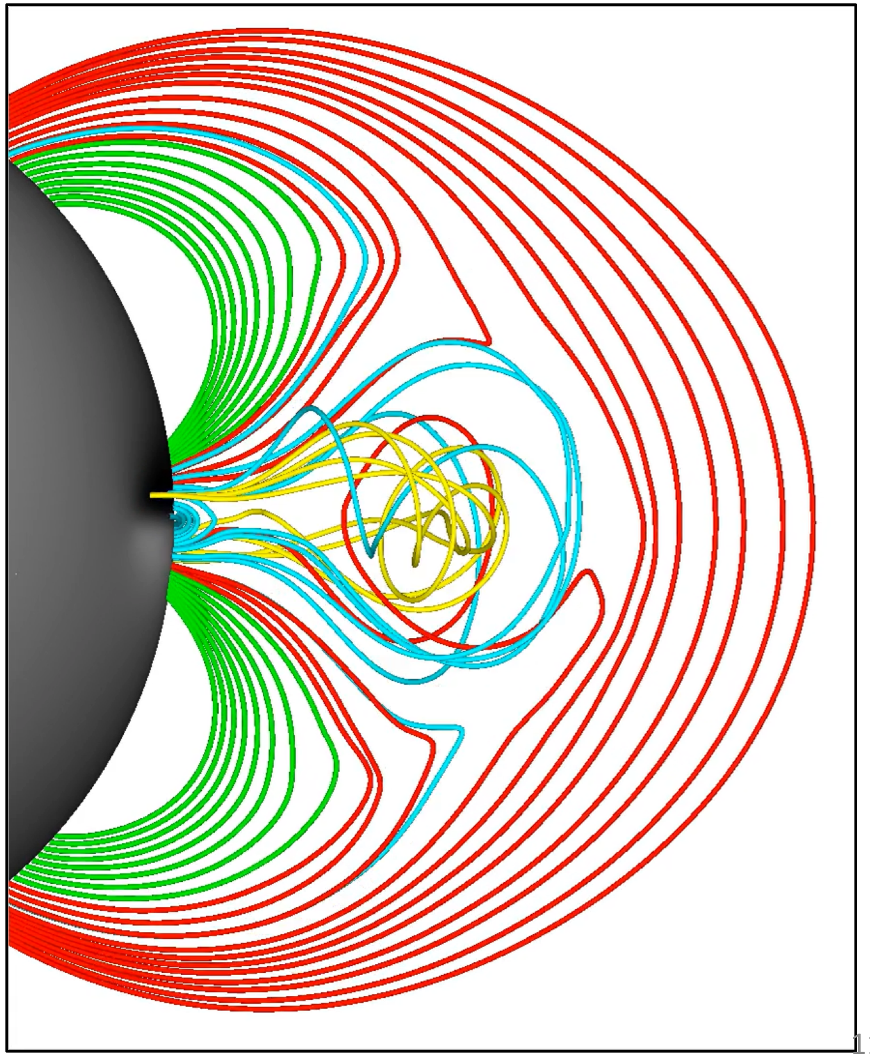


Guidoni et al., 2016

High-Resolution 3D MHD Simulations with ARMS

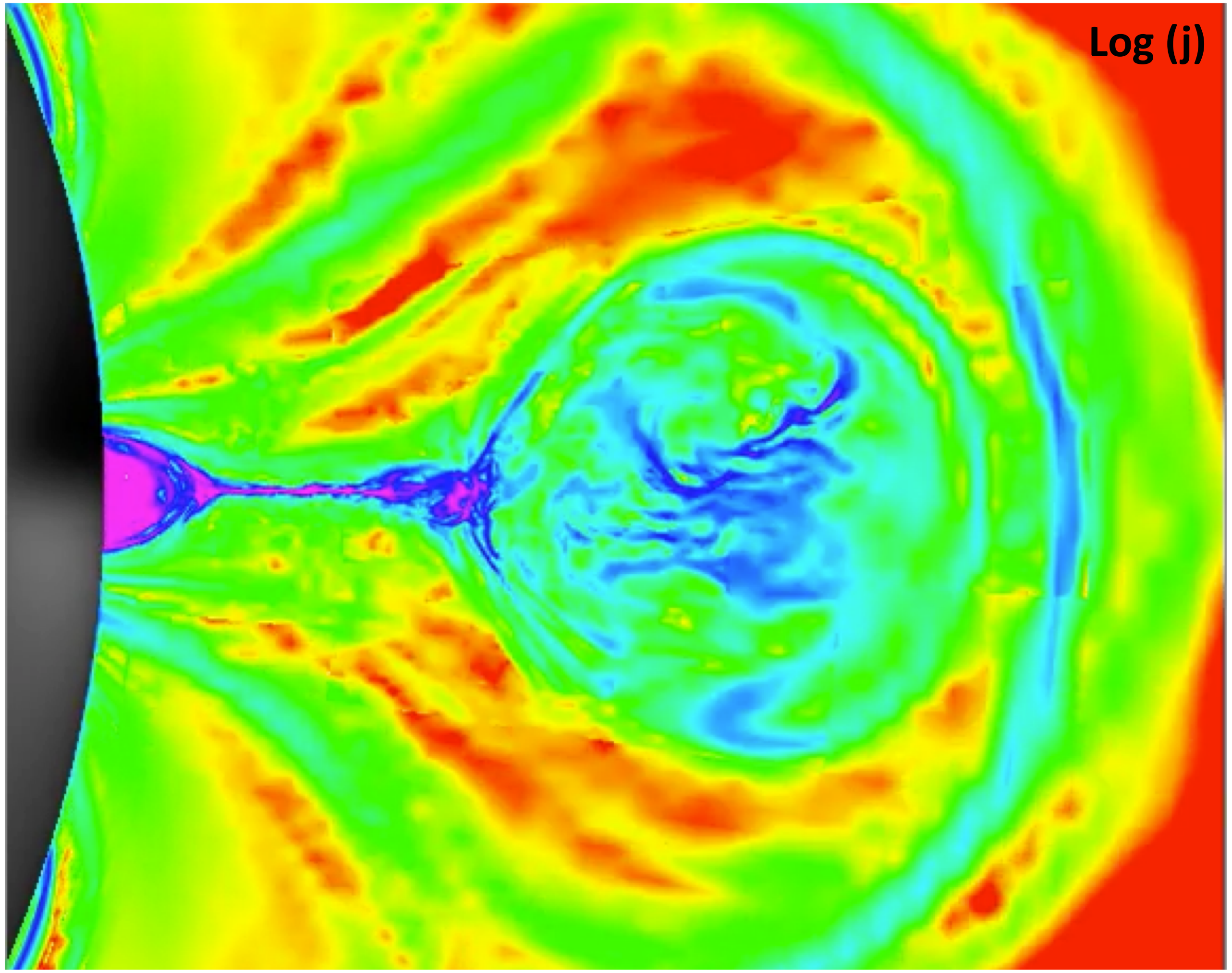
- *Adaptively Refined MHD Solver (DeVore+ 2008)*
  - Achieves high resolution via adaptive mesh refinement (AMR)
  - $R_s < r < 30R_s$, $\delta r \sim 0.6\text{Mm}$ at highest refinement
- Driven using efficient new *STITCH* method
  - Statistical InjecTion of Condensed Helicity (Dahlin+ in prep.)
  - Approximation to *Helicity Condensation* (Knizhnik+ 2017; Dahlin+ 2019)



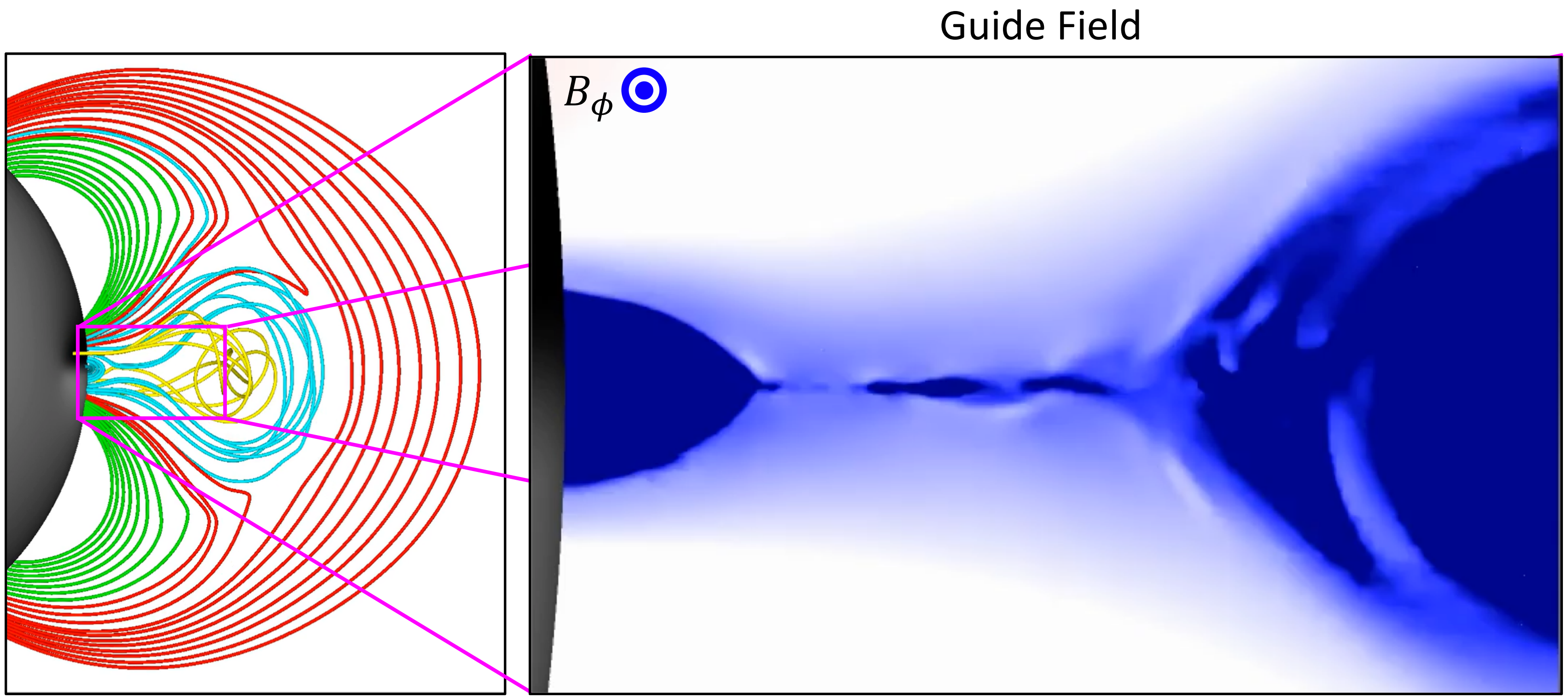


Self-Consistent Energy Build Up, CS Formation, and Energy Release

- Initial magnetic field is potential (current-free)
- STITCH injects free energy/helicity
- Current sheets form & reconnect self-consistently



Fine-scale Current Sheet Structure

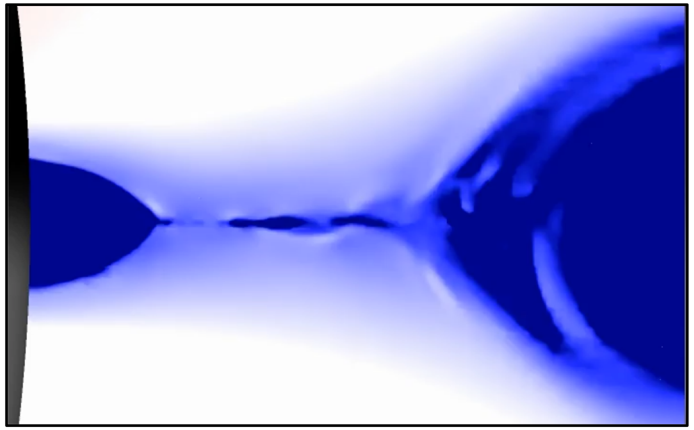


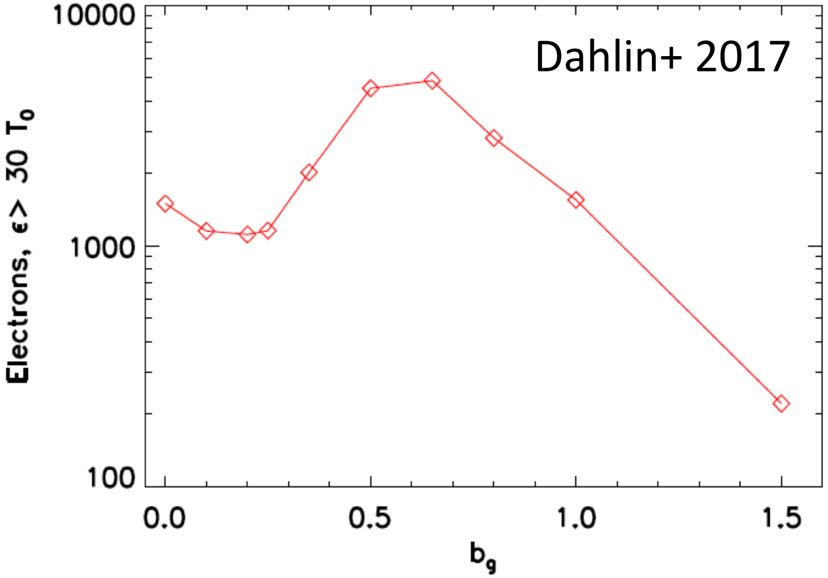
- Two important features: *guide field* and *plasmoids*

Shear/Guide Field

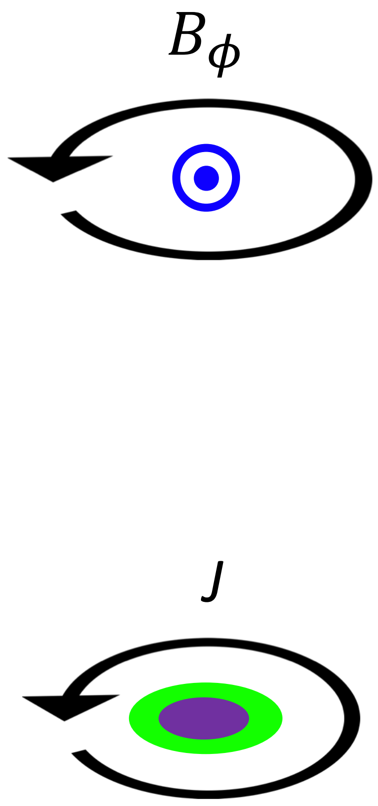
- Guide field weakens over the course of the flare
  - Associated with release of free energy, evolution toward potential field
  - Corresponding observational signature: reduction of shear in post flare loops (e.g., Aschwanden+ 2001)
- Kinetic simulations show electron acceleration is most efficient when b_g ~ 1 (Dahlin+ 2017)
  - J. Qiu+ 2017 study of two-ribbon flares found b_g often ~1

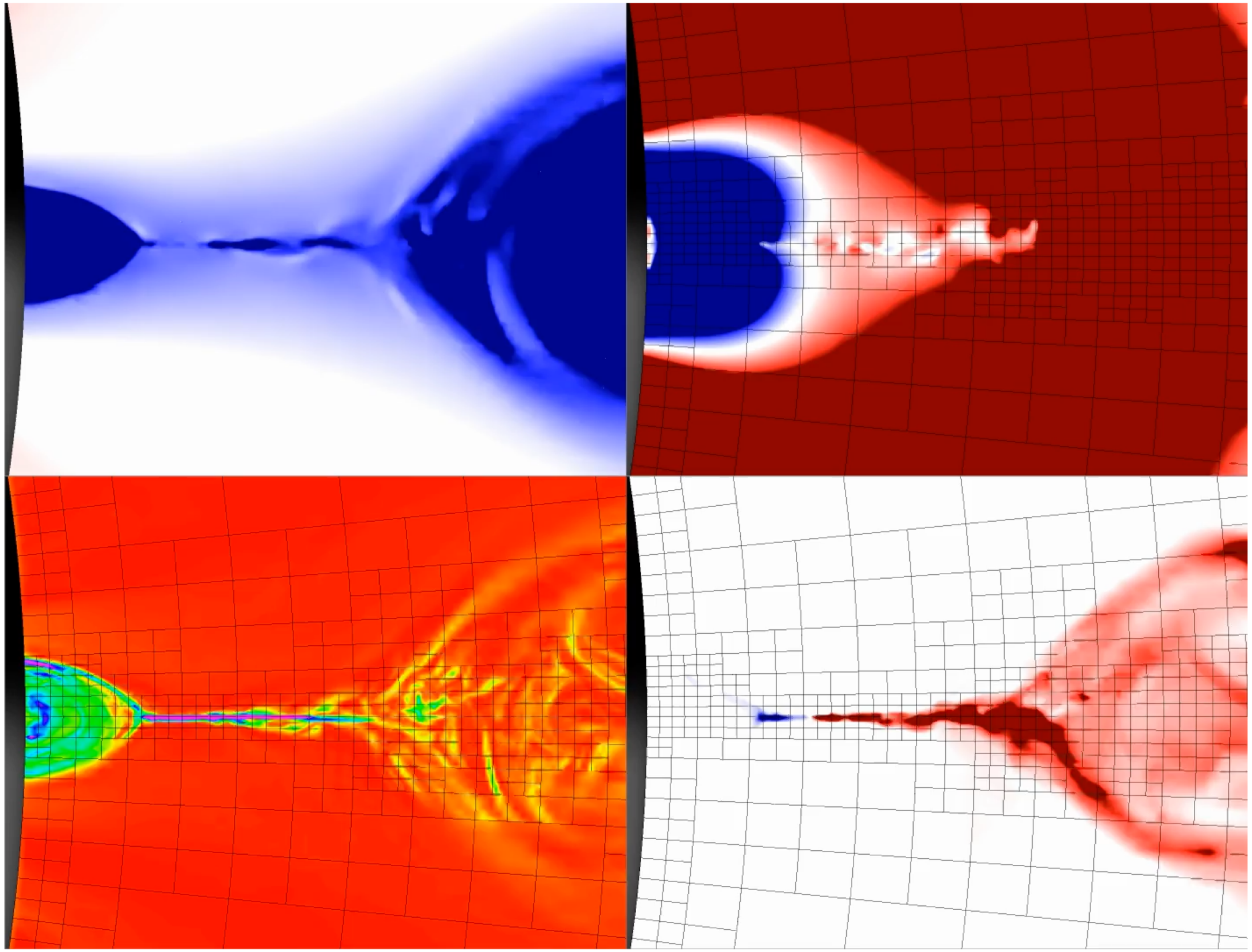
Dahlin+ in prep.

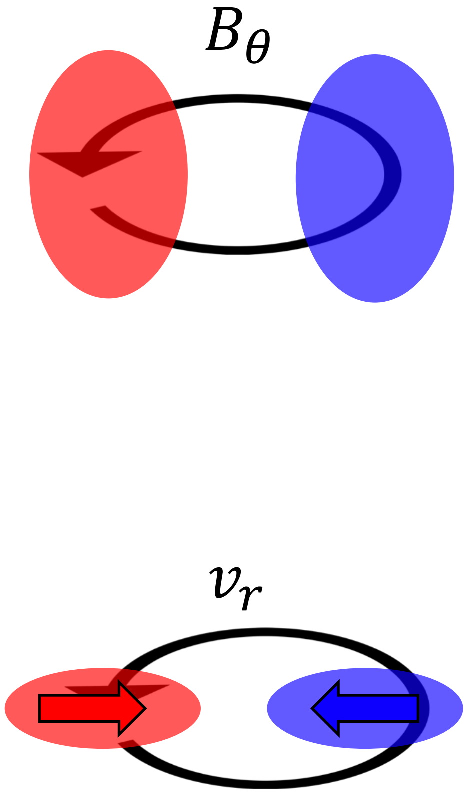




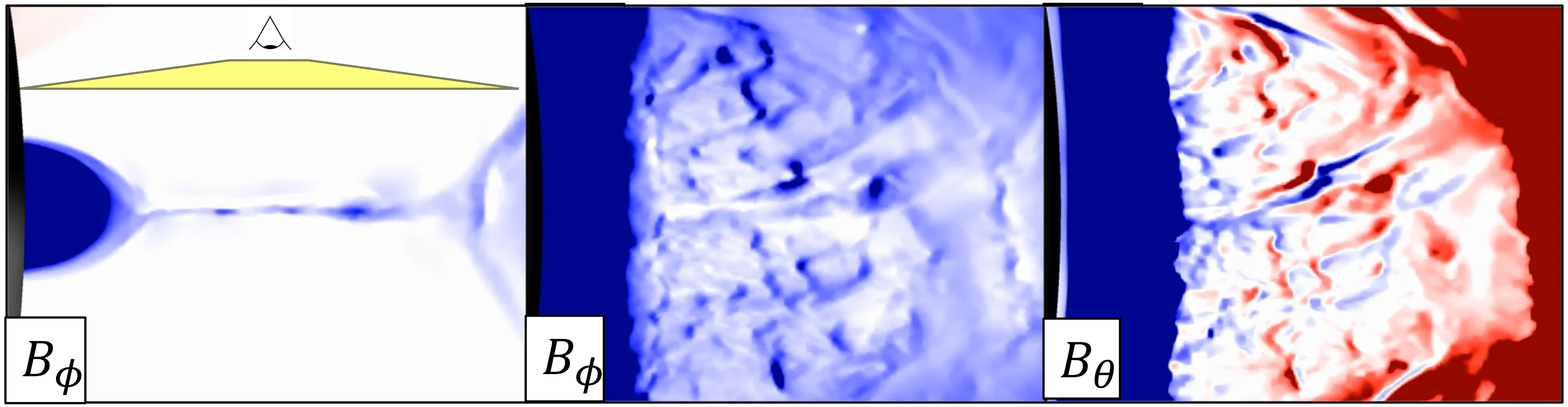
Plasmoid Formation

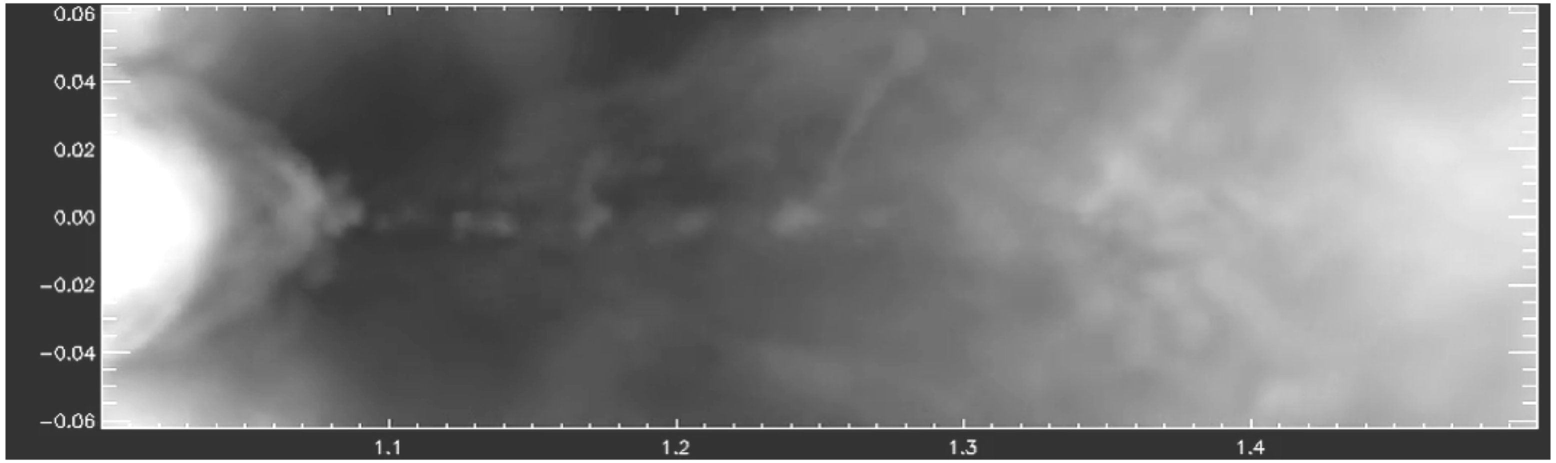






3D Plasmoid Structure

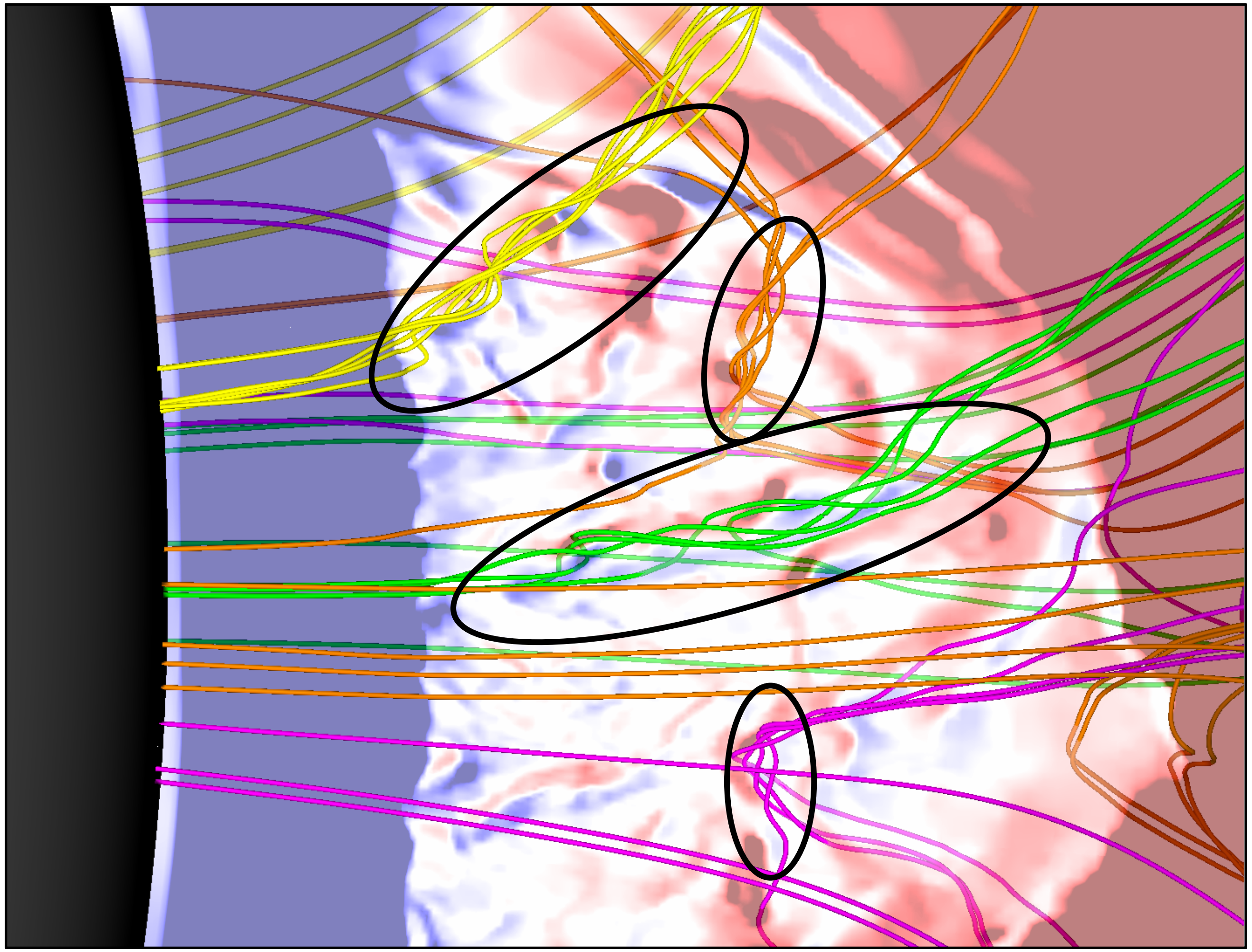




Synthetic White-Light Coronagraph

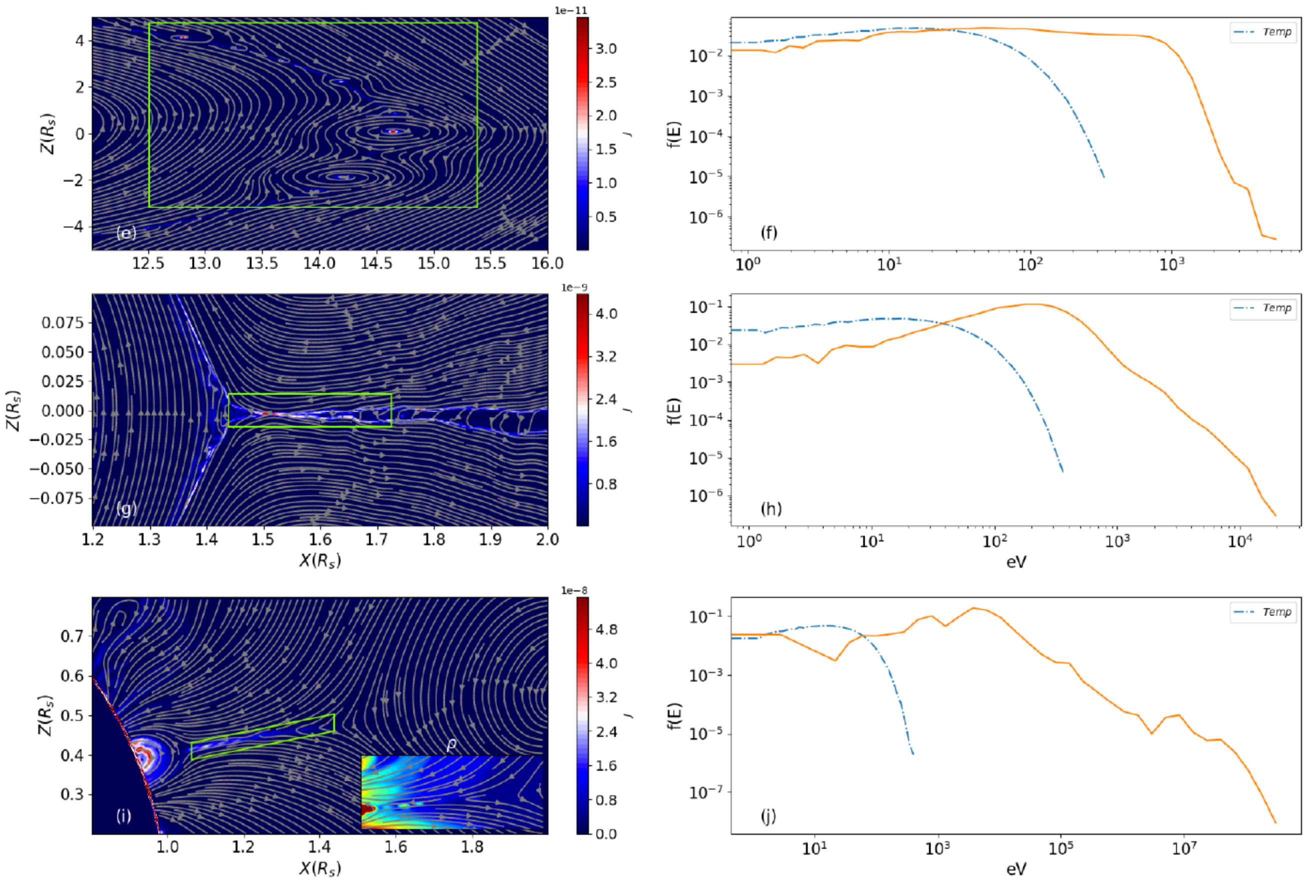
3D Plasmoid Structure

- Field-line chaos
  - Neighboring, tightly wrapped field lines map both upward & downward
- Field line chaos in 3D enhances transport (and acceleration, Dahlin+ 2015,2017; Li+ 2019)



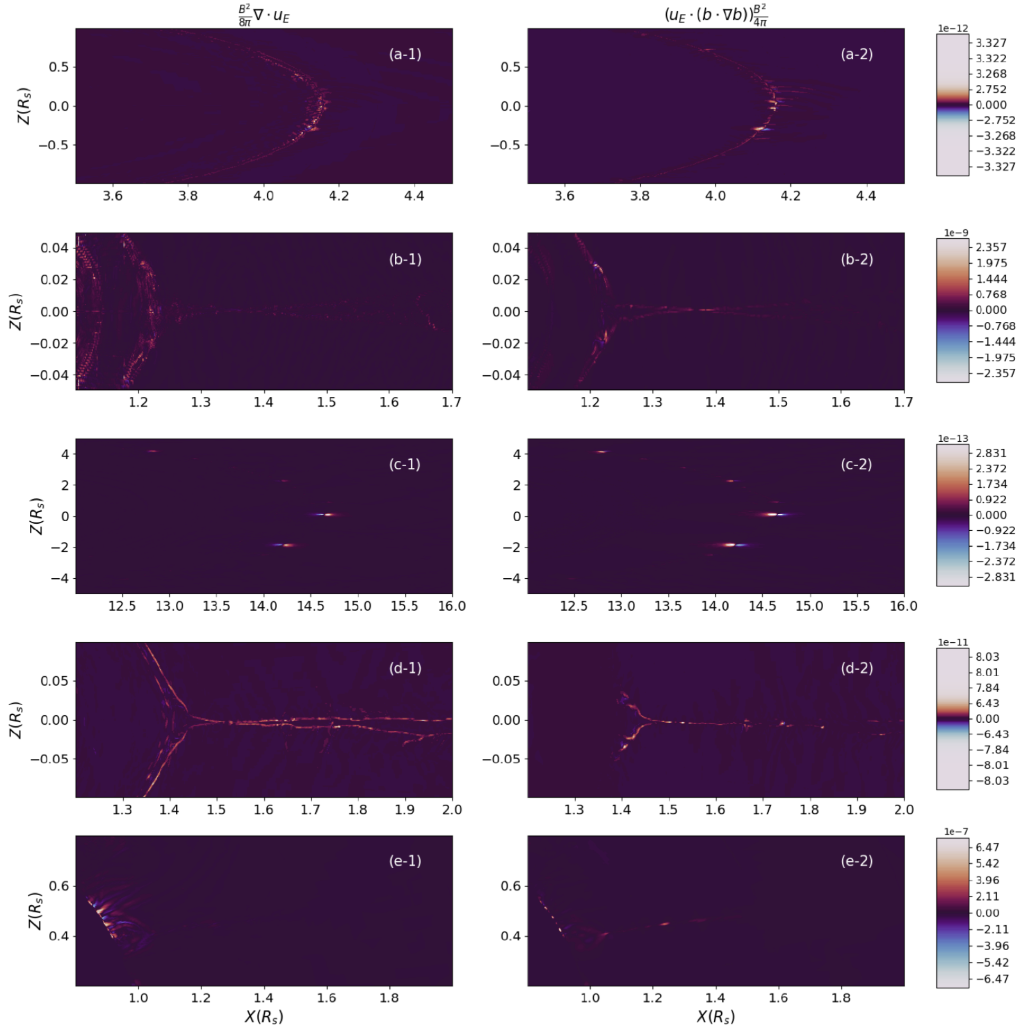
Test Particle Simulations: Acceleration

- Q. Xia+ 2020
  - Uses output from high-resolution 2D (Karpen+ 2012) and 3D simulations (Dahlin+ 2019)
- Acceleration is stronger at flare current sheet than at breakout
  - Strongest acceleration occurs during impulsive phase w/guide field



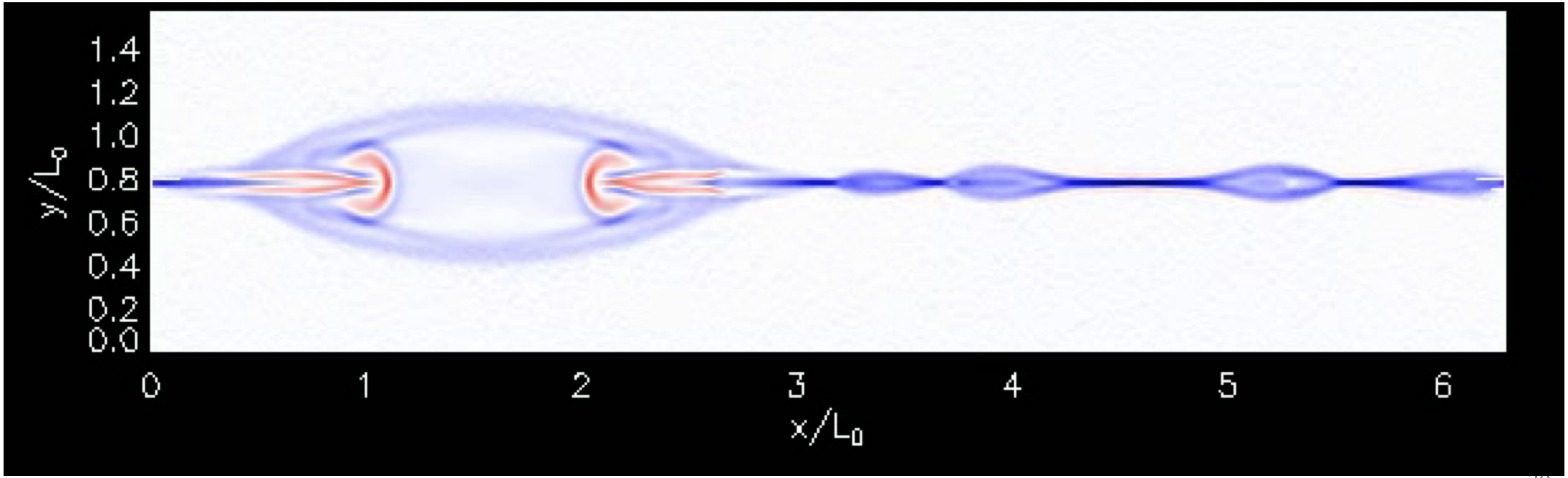
Test Particle Simulations: Mechanisms

- Two primary acceleration mechanisms
  - Fermi acceleration (field-line contraction) primarily plasmoids
  - Compression in post-flare loops
- Up next: test particle simulations in new high-resolution 3D MHD simulation



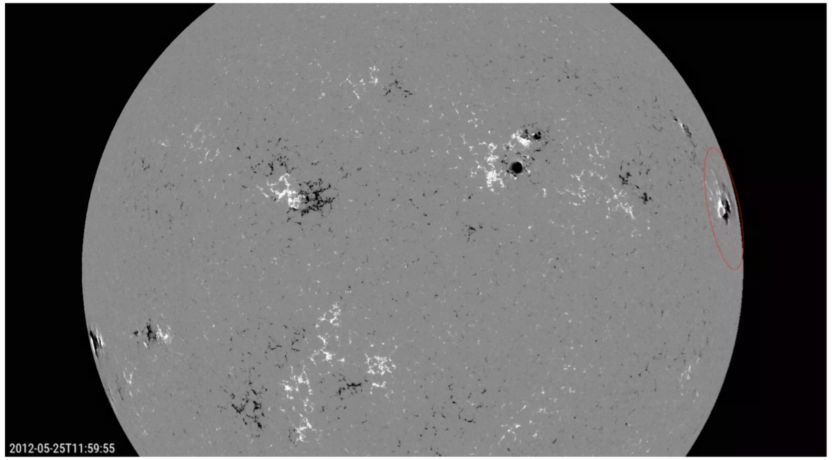
Hybrid Kinetic/MHD Model *kglobal*

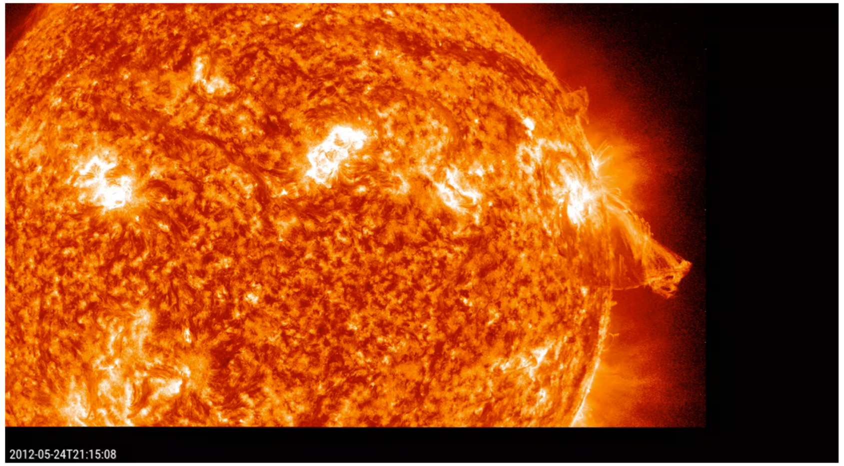
- **Aim: bridge macro/micro-scales of flare particle acceleration in one simulation**
- Hybrid fluid/particle code *kglobal* under development (Drake+ 2019; Arnold+ 2019)
- Captures MHD macro-scale *and* self-consistent particle acceleration & feedback on dynamics
- Micro-scale kinetic structure does not play significant role in particle acceleration and may be neglected (Dahlin+ 2016)



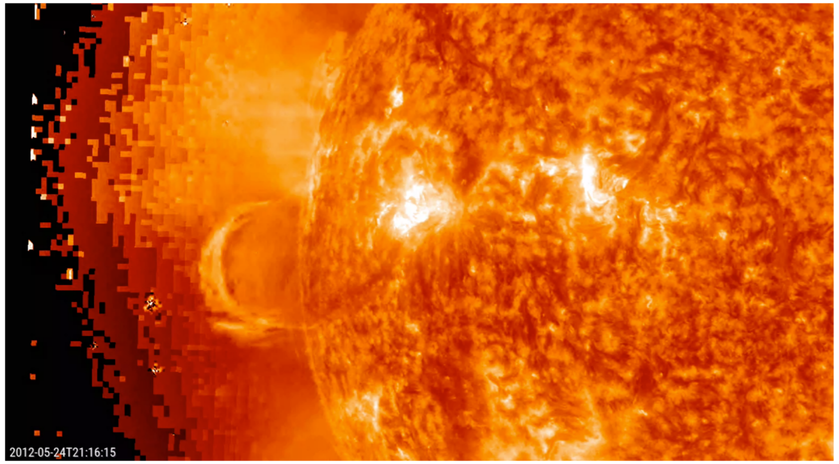
Event Modeling with ARMS

- Goal: model reconnection onset, plasmoid formation, and particle acceleration in real events using ARMS
- Case study: eruption from simple bipolar AR 11484





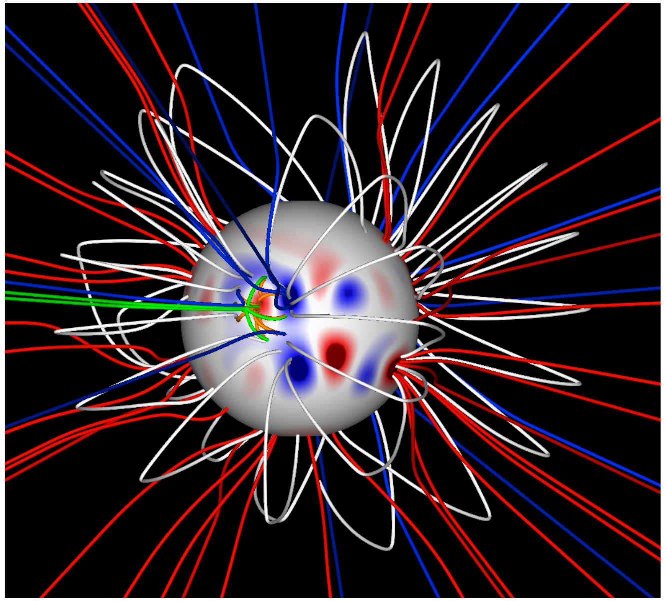
SDO/AIA 304

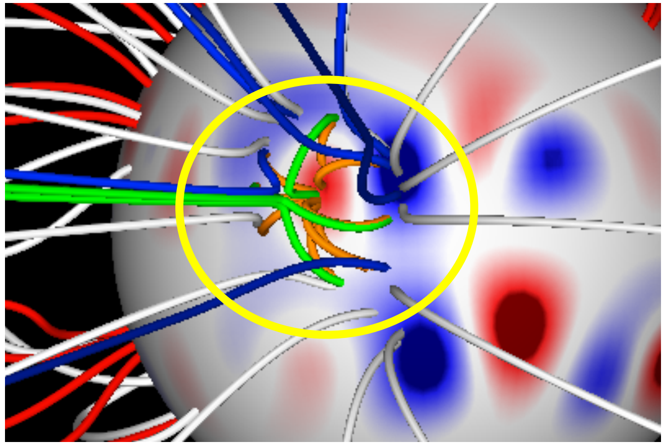


STEREO/EUVI 304

Event Modeling with ARMS

- Global PFSS magnetic field in ARMS
  - AR 11484 is an embedded bipole (jet-like topology) in a coronal hole
- Driving using STITCH
  - *Statistical InjecTion of Condensed Helicity*
  - Statistical approximation to full helicity condensation model (Antiochos+ 2013, Knizhnik+ 2015, Dahlin+ 2019)
  - Simple/portable, flexible, efficient





Conclusions

- New 3D, high resolution (AMR) MHD simulations of an eruptive flare
- Calculation includes self-consistent formation & destabilization of current sheet
- Reconnection guide field (magnetic shear) weakens as flare progresses
    - Implications for flare particle acceleration (optimal guide field, Dahlin+ 2017)
- Many plasmoids are generated
    - Complex, open structure & field line chaos

Stay tuned for…

- Tracking plasmoids (statistical properties, etc.)
- Implications for particle acceleration (test particles, impact of shear/guide field)
- Hybrid model under development
- Event modeling & comparisons to observations

THIS SLIDE INTENTIONALLY LEFT BLANK