Magnetic Reconnection: An Ultimate Problem in Nonlinear Plasma Physics

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Modern Challenges in Nonlinear Plasma Physics A Conference honoring the career of Dennis Papadopoulos June 15-19, 2009, Halkidiki, Greece

How I Chose my Thesis Advisor

- I worked with different advisors in radio astronomy, cosmology, QED, pulsars, but

- I chose **Dennis** because of the **4 P’s**:

  - **Phenomenal physicist**: was always late but still gave people hard time at seminars/colloquia

  - **Parade of generals**: constant parade of military higher ups through the department

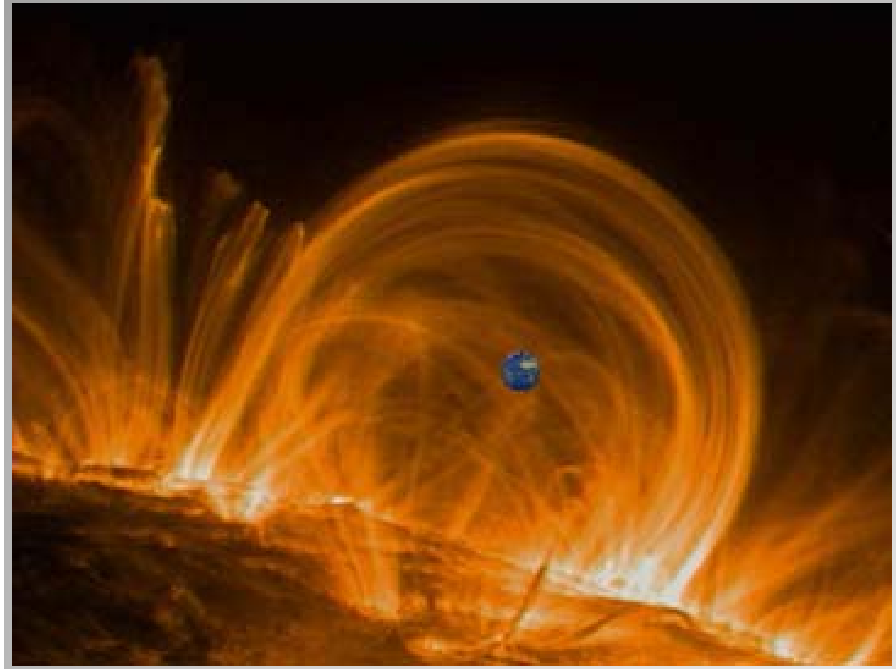
  - **Posh**: Mercedes convertible

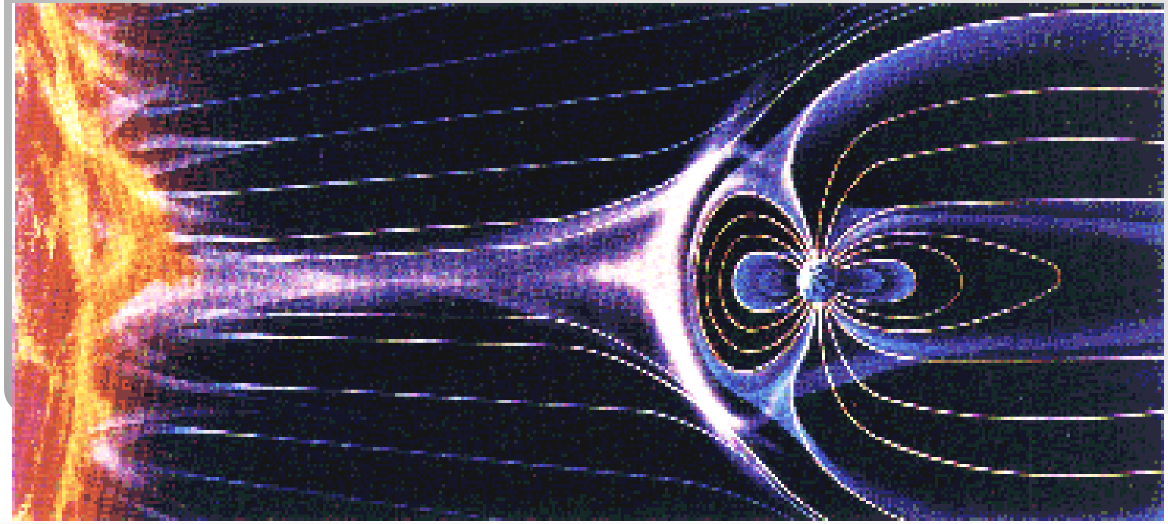
  - **People**: Cargill, Goodrich, Hizanidis, Menyuk, Rowland, Sprangle, Vlahos, Akimoto,Ghosh,Fung, Taaheri, …

Magnetic Reconnection has Many Applications:

- Planetary magnetospheres ⟶ magnetopause, magnetotail
- Solar corona ⟶ flares, prominences, coronal mass ejections
- Laboratory fusion machines
- Astrophysical problems
  - stellar flares, galactic magnetotails, accretion disks } Hydrogen
  - pulsar winds, gamma-ray bursts, jets from AGN } Electron-Positron

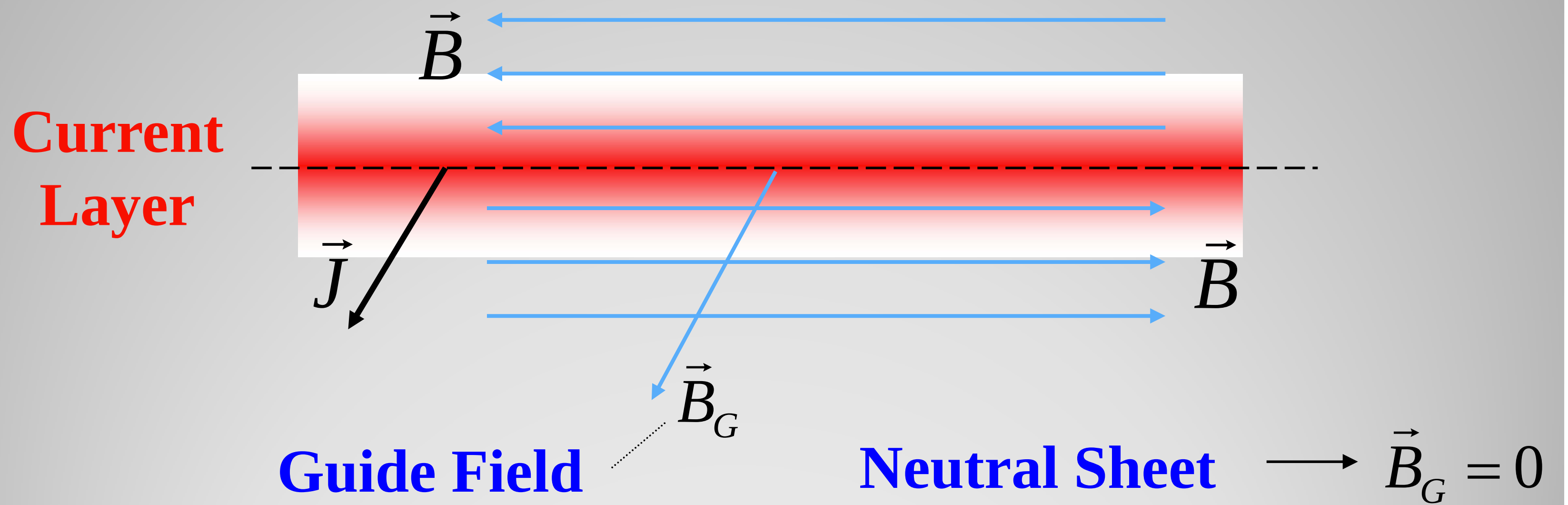
Reconnection in Space Plasmas



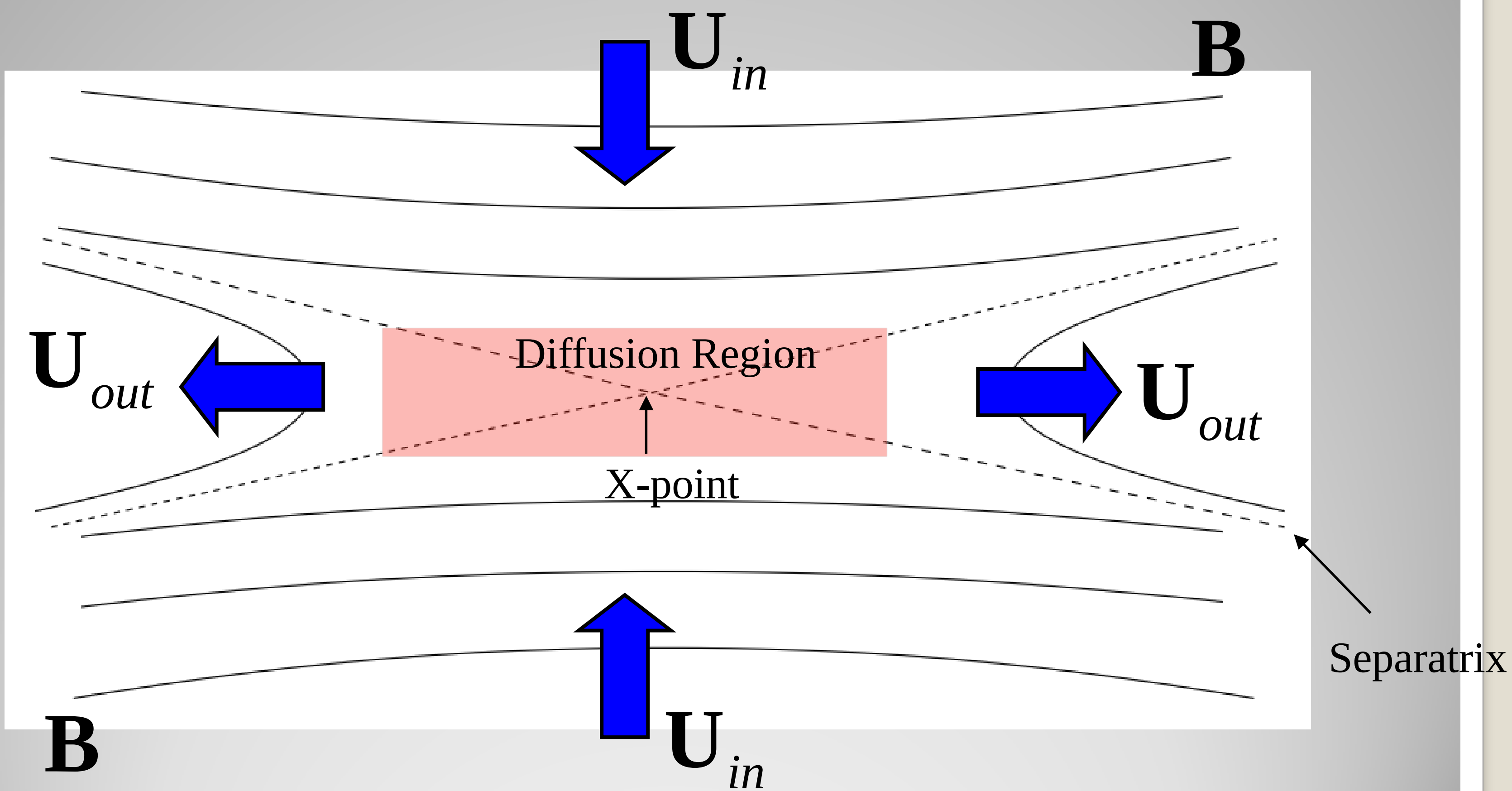


Current Sheet

Current layer + corresponding field reversal



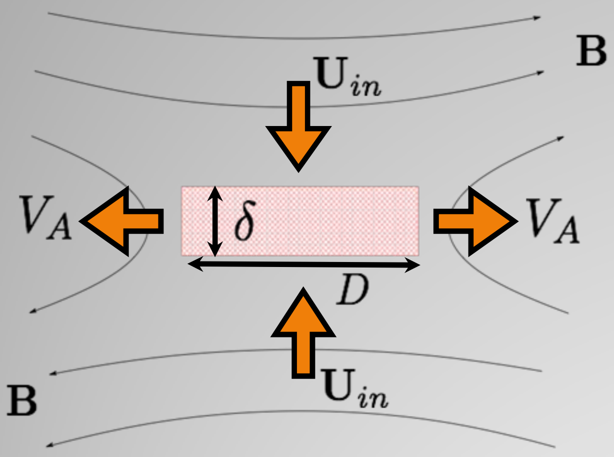
Magnetic Reconnection



Simple Models

Early Models - Resistive MHD

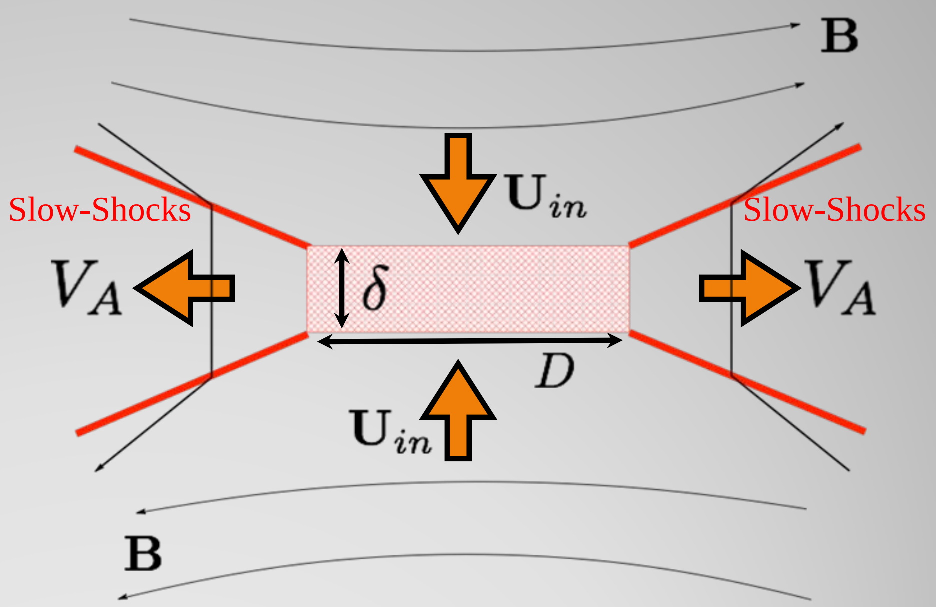
Sweet-Parker - 1957



$$\frac{\mathbf{U}_{in}}{V_A} = \frac{\delta}{D} = \frac{1}{\sqrt{S}}$$

$$S \equiv \frac{4\pi V_A D}{\eta c^2} = \frac{\tau_R}{\tau_A} \sim 10^{10} \rightarrow 10^{14}$$

Petschek - 1964



$$\frac{\mathbf{U}_{in}}{V_A} \sim \frac{1}{\log(S)}$$

Baffling Trends

- Both Sweet-Parker and Petschek models have major flaws but have formed the basis of much research in reconnection physics
- Many researchers continue to use them in modeling solar corona, magnetosphere, ...
- There is a fixation on the reconnection rate which masks a lot of important physics.

During this Talk:

- Show results from recent state-of-the-art simulations to illustrate the complexity of the reconnection process
- Compare 2D vs. 3D results to see whether 2D studies have any relevance

Making Breakthrough Simulations – 100-1000x larger

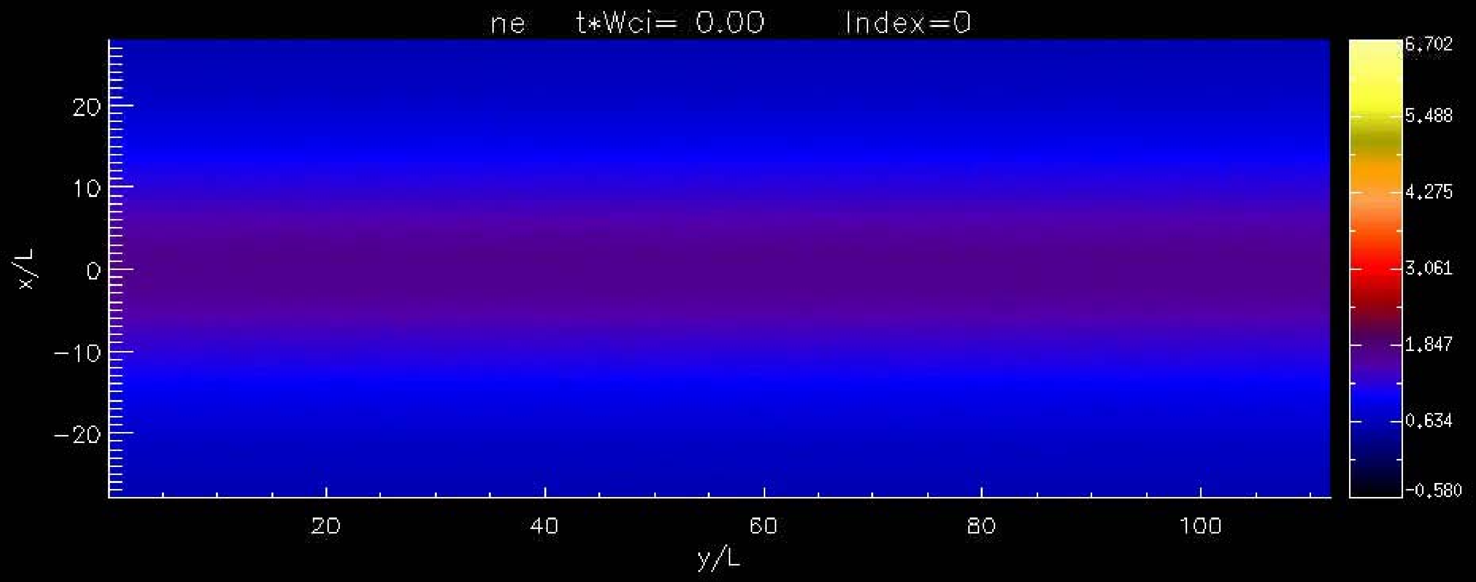
- Use open boundary conditions: Daughton, Scudder, Karimabadi, 2006
- Roadrunner super computer at LANL is enabling Trillion-particle simulations
- Implement collisions in Full PIC using Fokker-Planck treatment of collision operator
- Our largest simulation to date on reconnection:
  - Physical domain $(200\ d_i)^3$
  - 1024^3 cells, 0.32 trillion particles

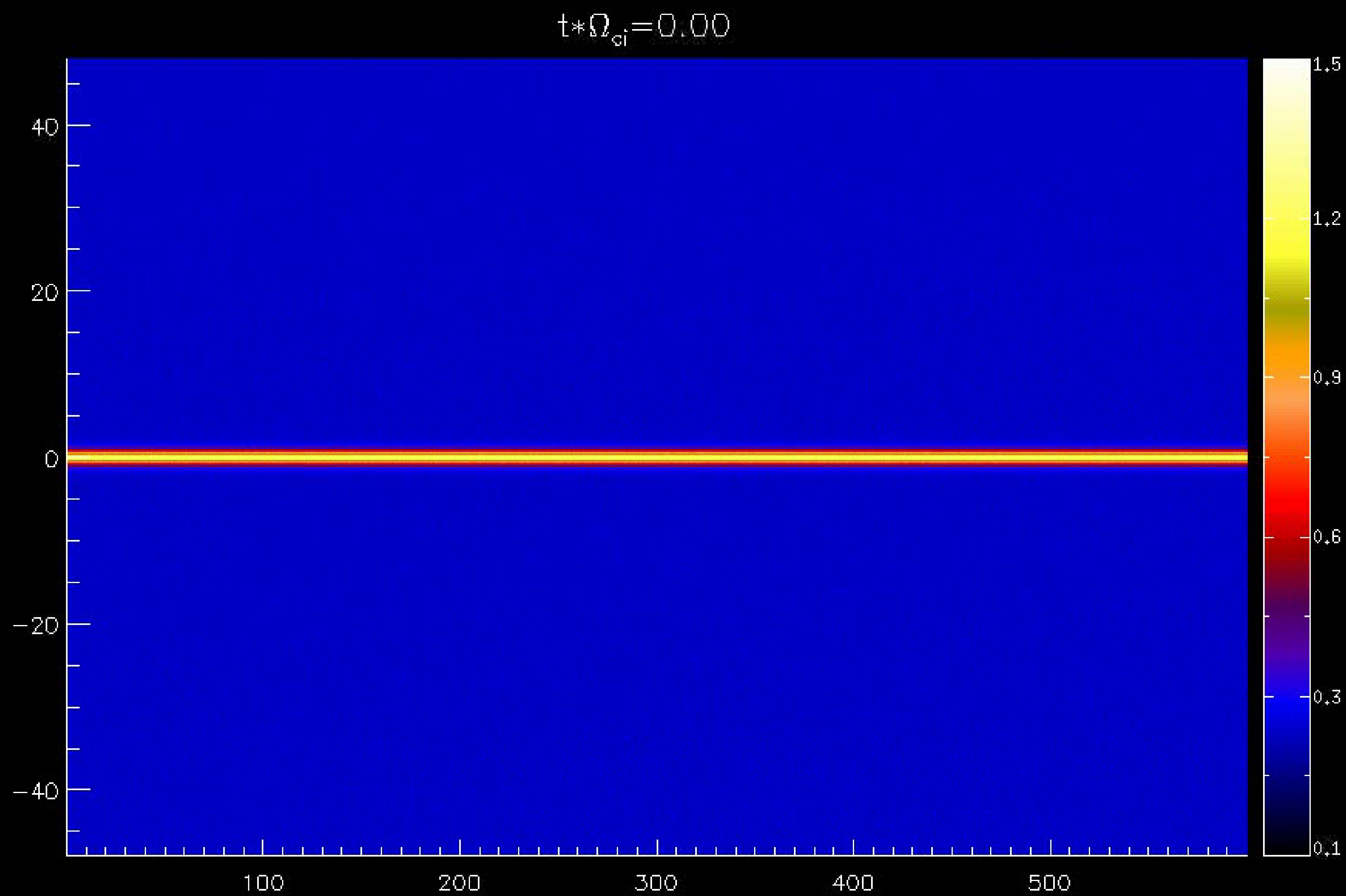
Physics Questions

- **Can long stable current sheets exist in nature?**
- **Are there other means of annihilating the magnetic field besides reconnection?**
- **Can fast reconnection occur in large scale systems in <u>collisionless, and collisionless regimes</u>?** **Magnetosphere is ~1000 d_i, and solar flares are > 10^6 d_i**
- **Can reconnection occur in high beta plasmas?**
- **Does reconnection turn off or is it quasi-steady?**

Collisionless Limit

2D simulation: cyclical formation of plasmoids

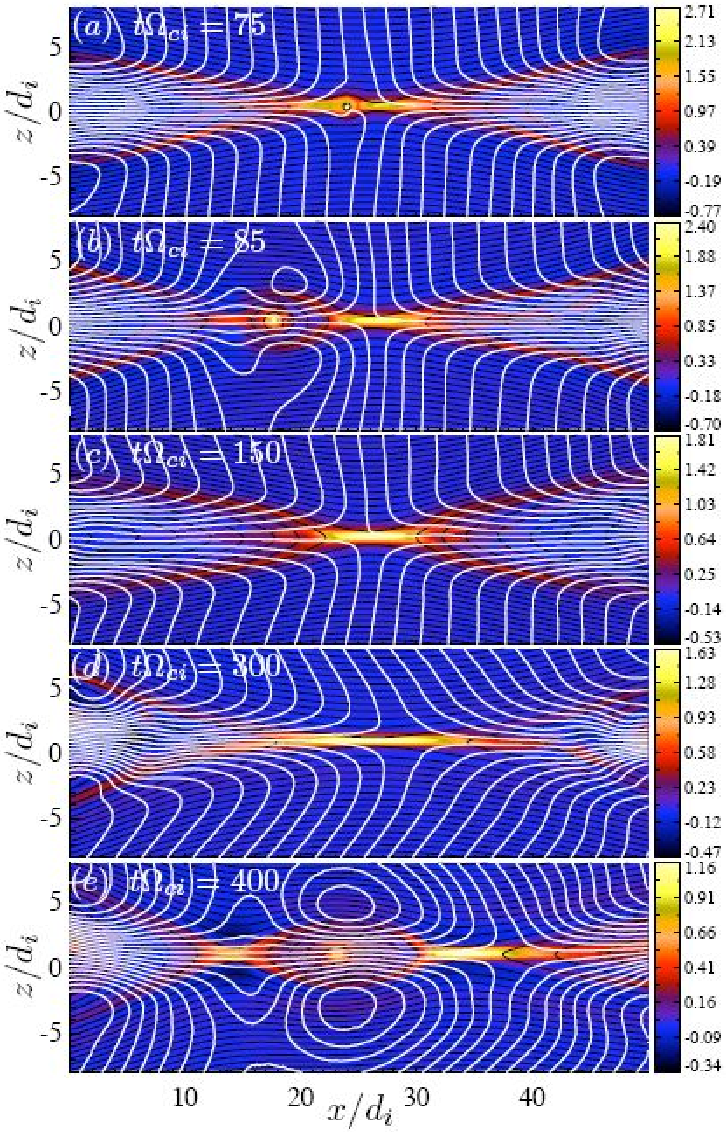




$t*\Omega_{ci}=0.00$
40
20
0
−20
−40
100
200
300
400
500
1.5
1.2
0.9
0.6
0.3
0.1

Surprising New Results → Daughton et al, PoP, 2006

1. Highly elongated electron layer
2. Rate controlled by this layer
3. Unstable to plasmoid formation
4. Inherently time dependent



$D_e \sim 25 d_i$ → Two orders of magnitude larger than previous estimates!

Similar conclusions in K. Fujimoto, PoP, 2006

Essential Physics of Electron Expansion

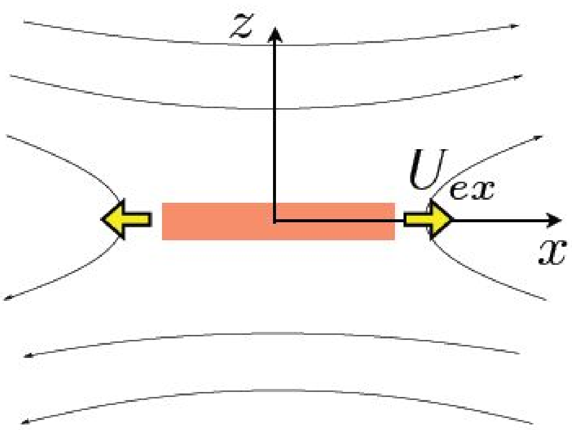
Generalized Ohm's law

$$\mathbf{E} + \frac{\mathbf{U}_e \times \mathbf{B}}{c} = \eta \mathbf{J} - \left[\frac{1}{e n_e} \nabla \cdot \mathbf{P}_e + \frac{m_e}{e} \frac{\mathbf{d}\mathbf{U}_e}{dt} \right] \equiv \mathbf{S}$$

Combine with Faraday's Law

$$\frac{\partial B_z}{\partial t} = -\frac{\partial \left(U_{ex} B_z \right)}{\partial x} - \frac{\left(\partial c S_y \right)}{\partial x}$$

Need contribution to get steady state



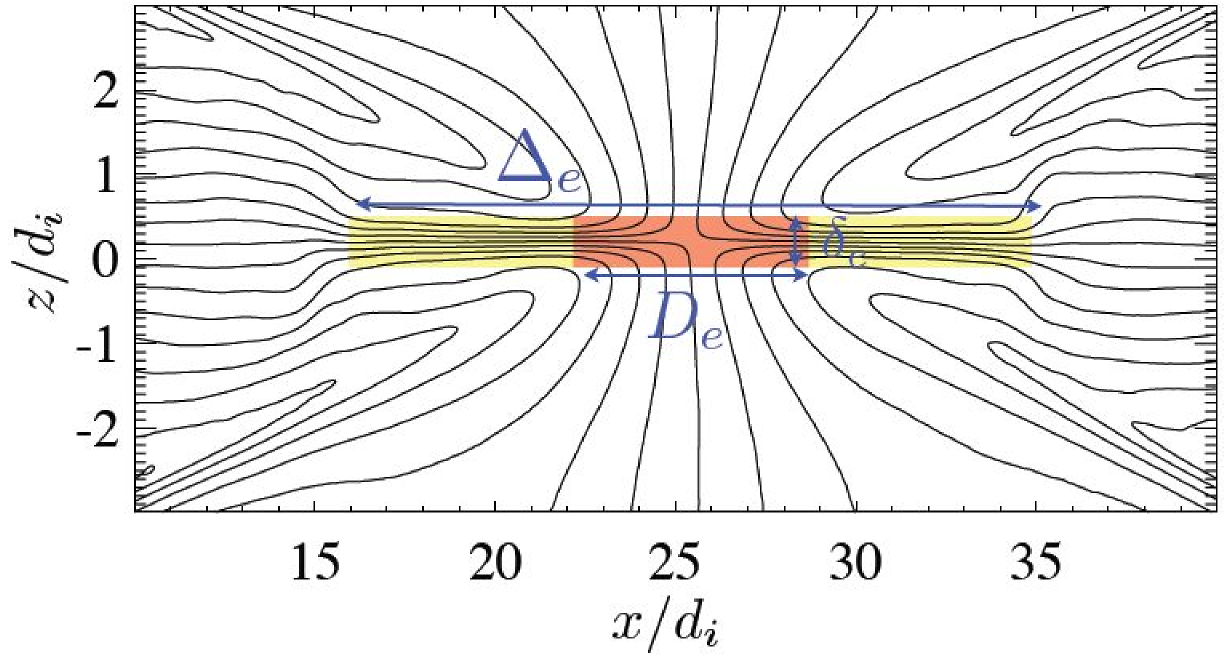
Near x-point:

$$U_{ex} B_z \propto x^2 \longrightarrow \frac{\partial B_z}{\partial t} < 0$$

Layer will expand without non-ideal term to balance

Multi-Scale Structure of the Electron Layer

Karimabadi, Daughton & Scudder, 2007 GRL

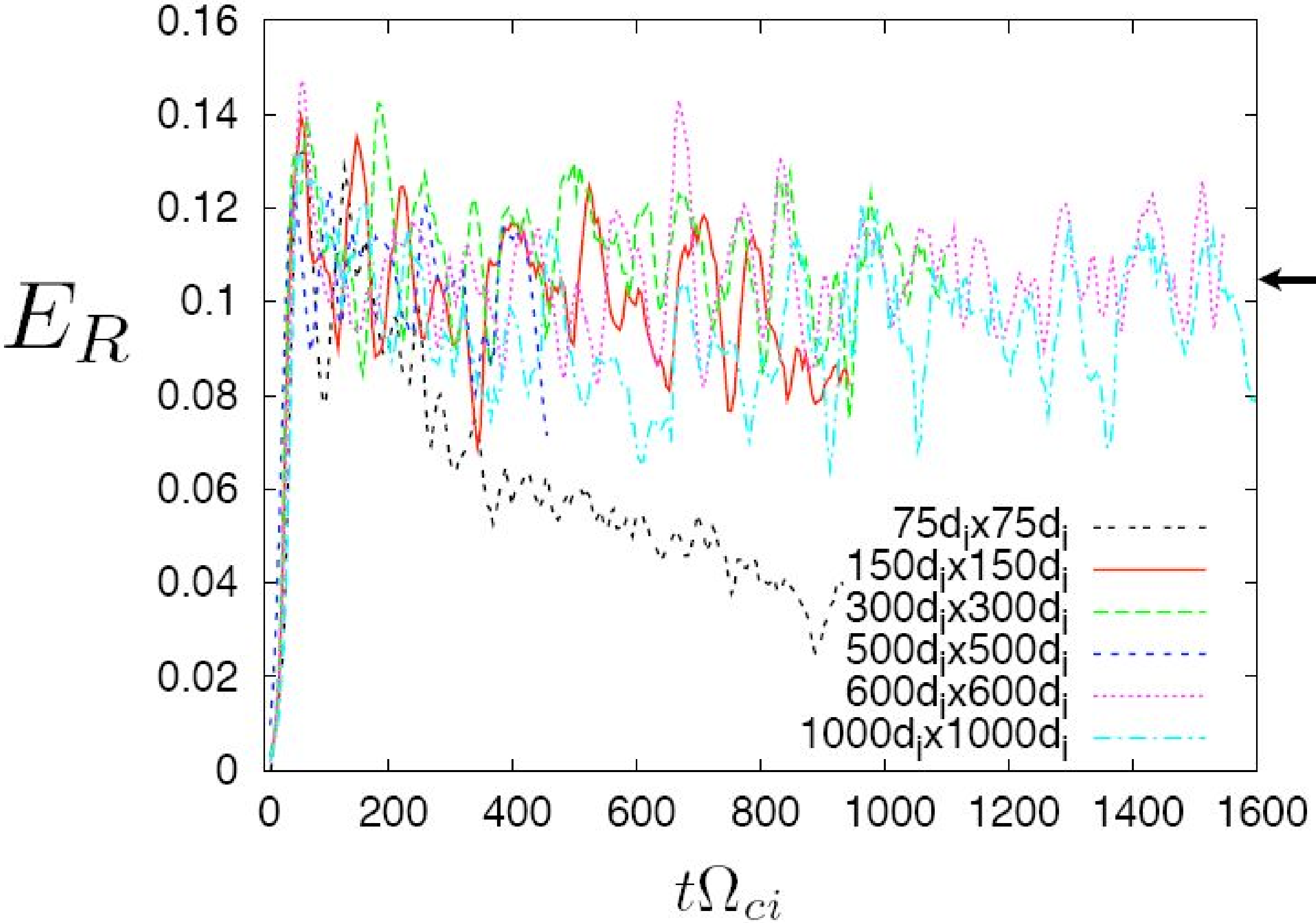


$\Delta_e \longrightarrow$ Total length of non-ideal region

$D_e \longrightarrow$

1. Region of uniform electron inflow
2. Maximum electron outflow
3. Size of out-plane current layer

Reconnection Rate Remains Fast



Remarkably insensitive to system size!

See Daughton & Karimabadi, 2007

Testable New Predictions

1. Much longer electron diffusion region $D_e \sim 3-5d_i$

2. Elongated non-gyotropic electron jets $\Delta_e > 10d_i$

3. Filled-in quadrupole structure out to Δ_e

4. Electrostatic potential structure

5. Continuous reconnection - rate modulated in time

6. Plasmoid production - range of sizes for both anti-parallel and guide field geometry

Observational evidence from Cluster - Eastwood et al, JGR, 2007

Collisional Limit

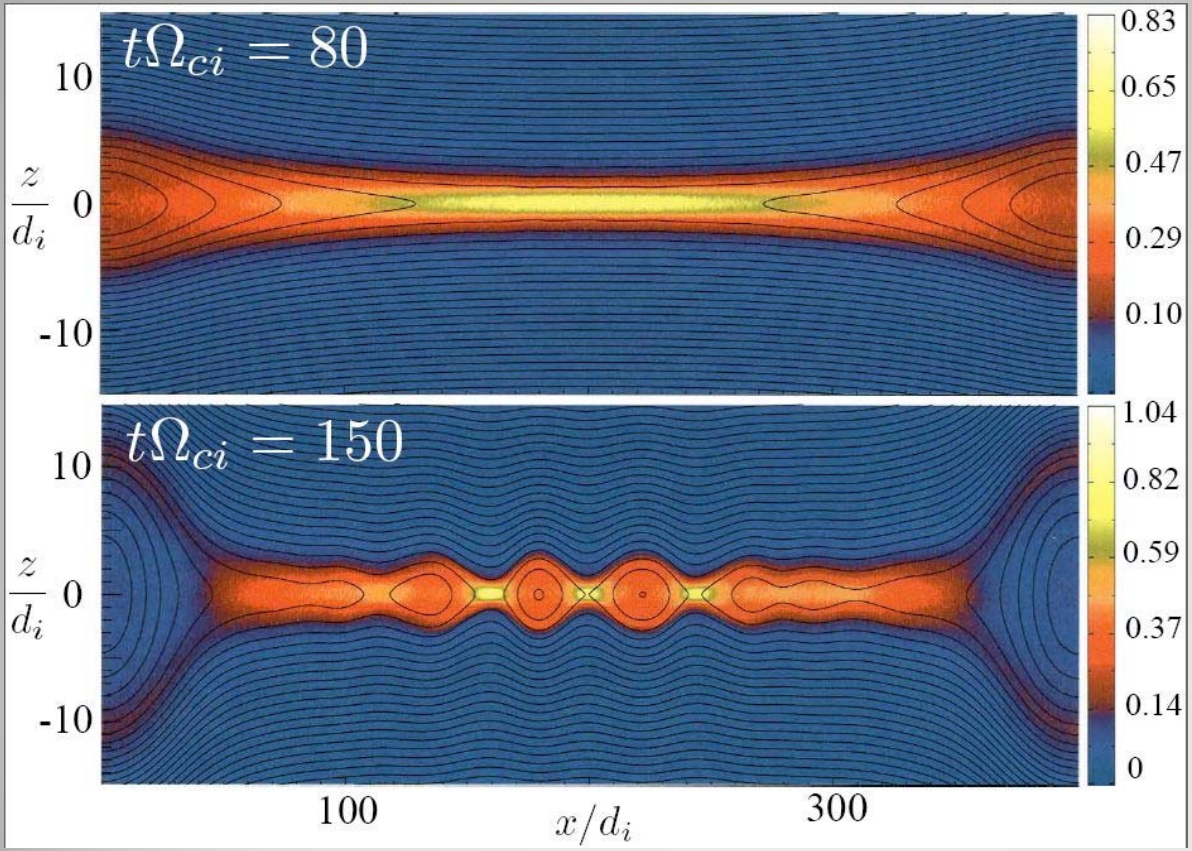
Collisional Reconnection

- Two different behavior based on system size

 - Stable Sweet-Parker and low rate for small system

 - Unstable Sweet-Parker and high rate for large system

Unstable Sweet-Parker Layer



Daughton et al. 2009 a,b

What About 3D?

Linear Vlasov Theory + Simulation Parameters

$m_i = m_e \qquad T_i = T_e \qquad \rho_i = L$

guide field = 0:	drift-kink	k_y*L = 0.44	γ/ω_{ci}=0.258
	tearing	k_x*L = 0.5	γ/ω_{ci}=0.143
intermediate guide field = - 0.5 B_0	drift-kink	k_y*L = 0.44	γ/ω_{ci}=0.203
	tearing	k_x*L = 0.5	γ/ω_{ci}=0.141
strong guide field = - 1.0 B_0	drift-kink	k_y*L = 0.44	γ/ω_{ci}= stable
	tearing	k_x*L = 0.5	γ/ω_{ci}=0.130

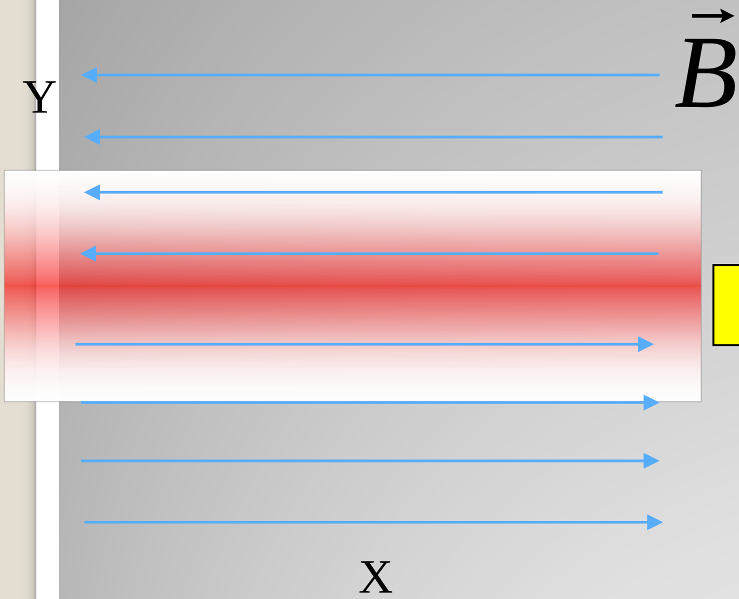
3D VPIC Simulations →

$200d_i \times 20d_i \times 200d_i$

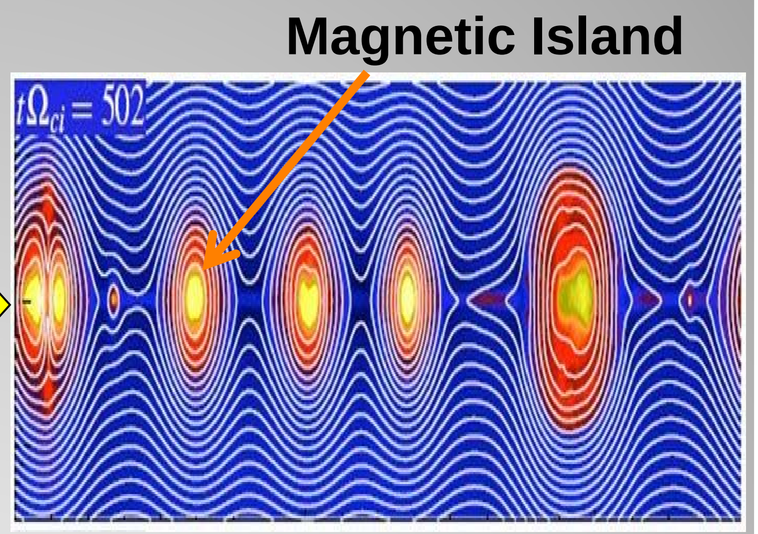
$1000 \times 100 \times 1000 \quad cells$

16×10^9 particles

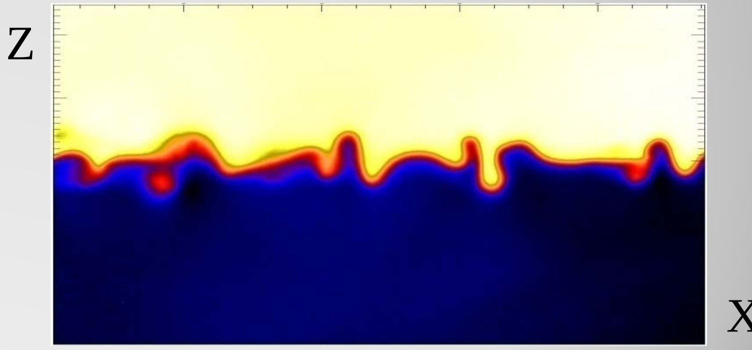
Current Sheet Instabilities



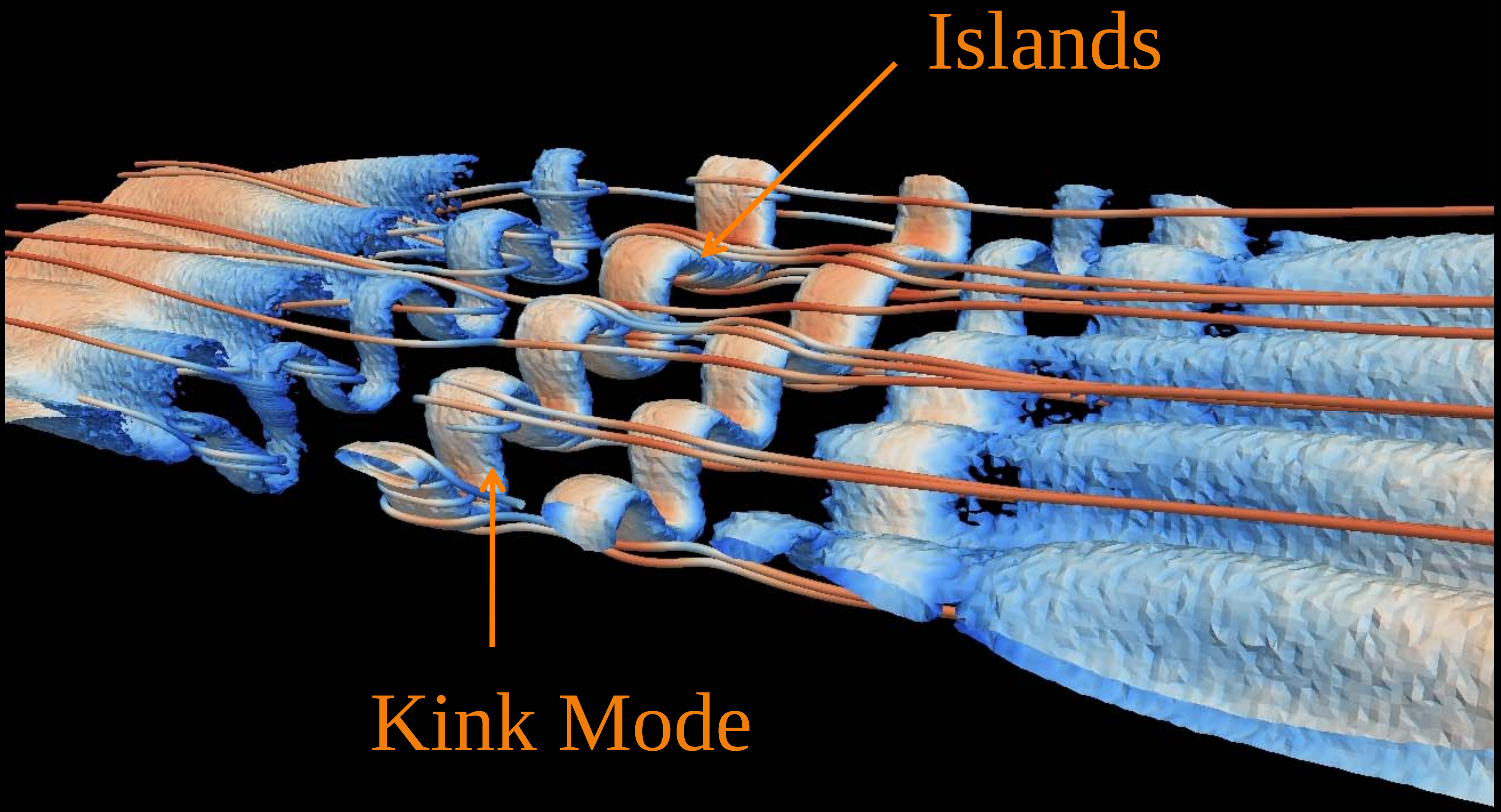
Reconnection



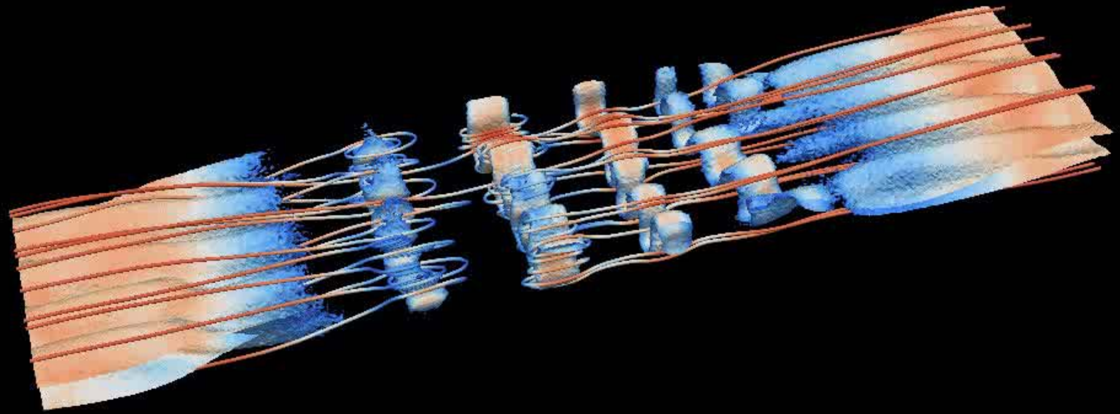
Instabilities in the current direction

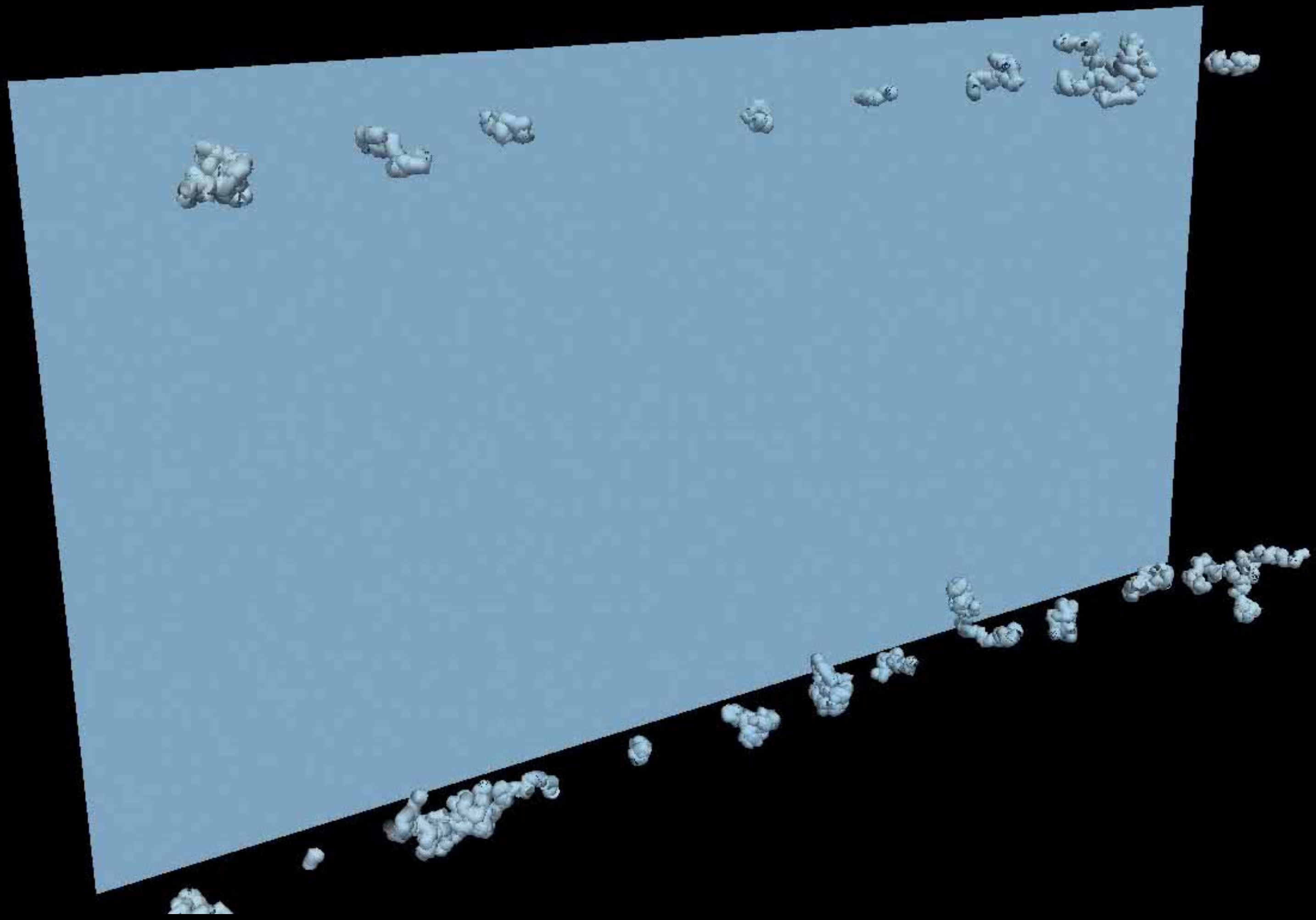


3D simulation of anti-parallel case

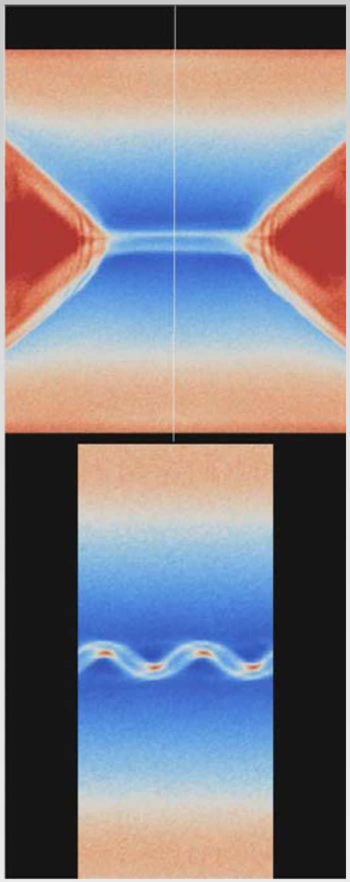


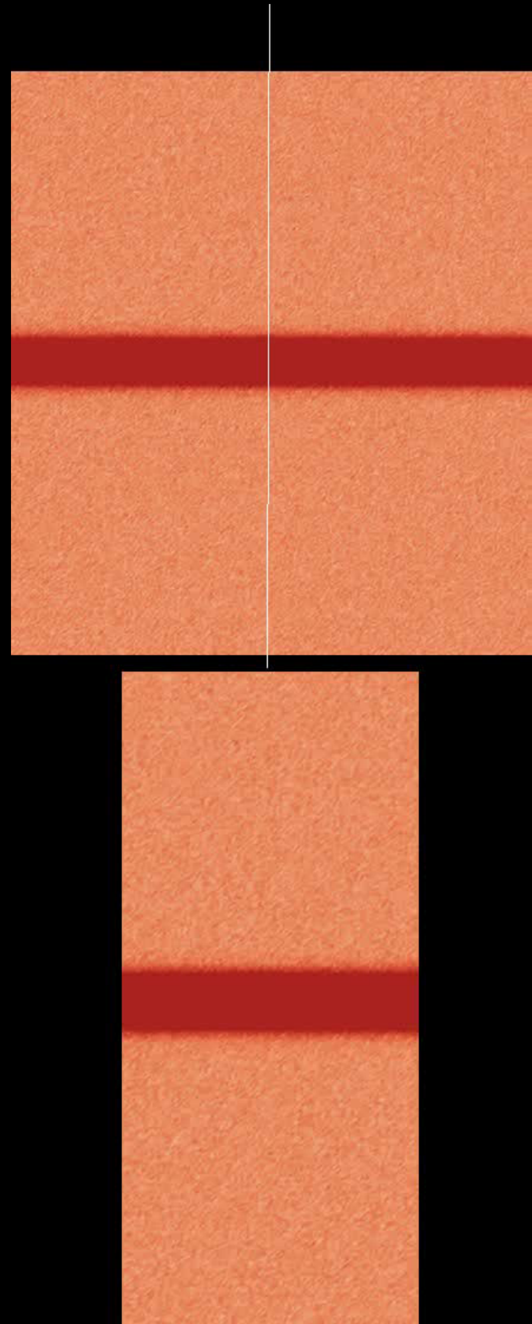
3D simulation of anti-parallel case



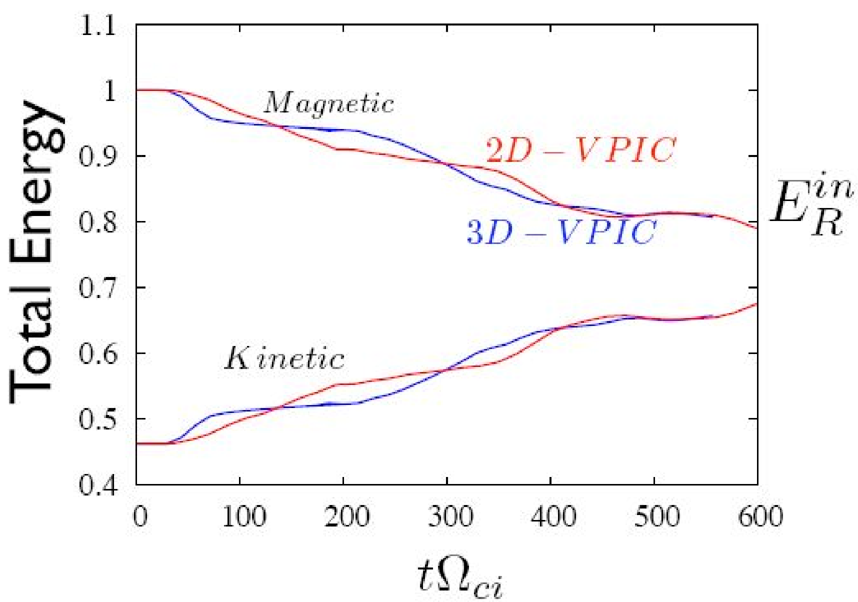


Formation of Standing Structure

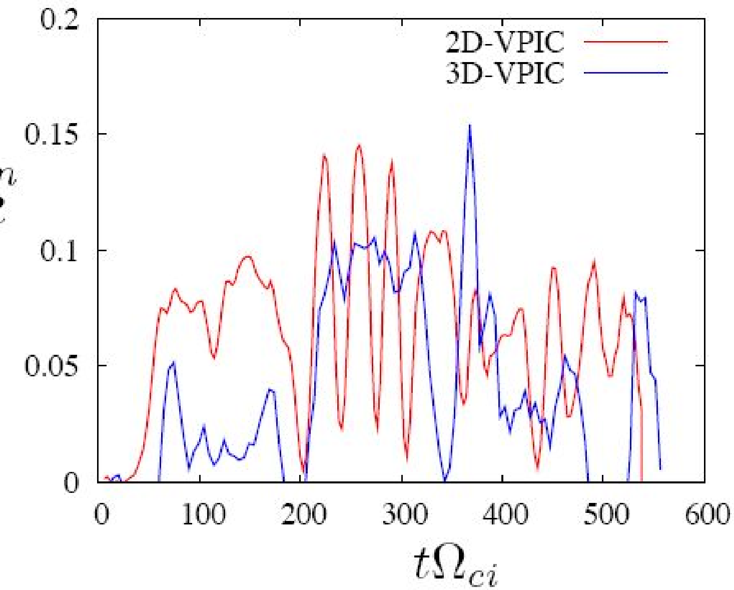




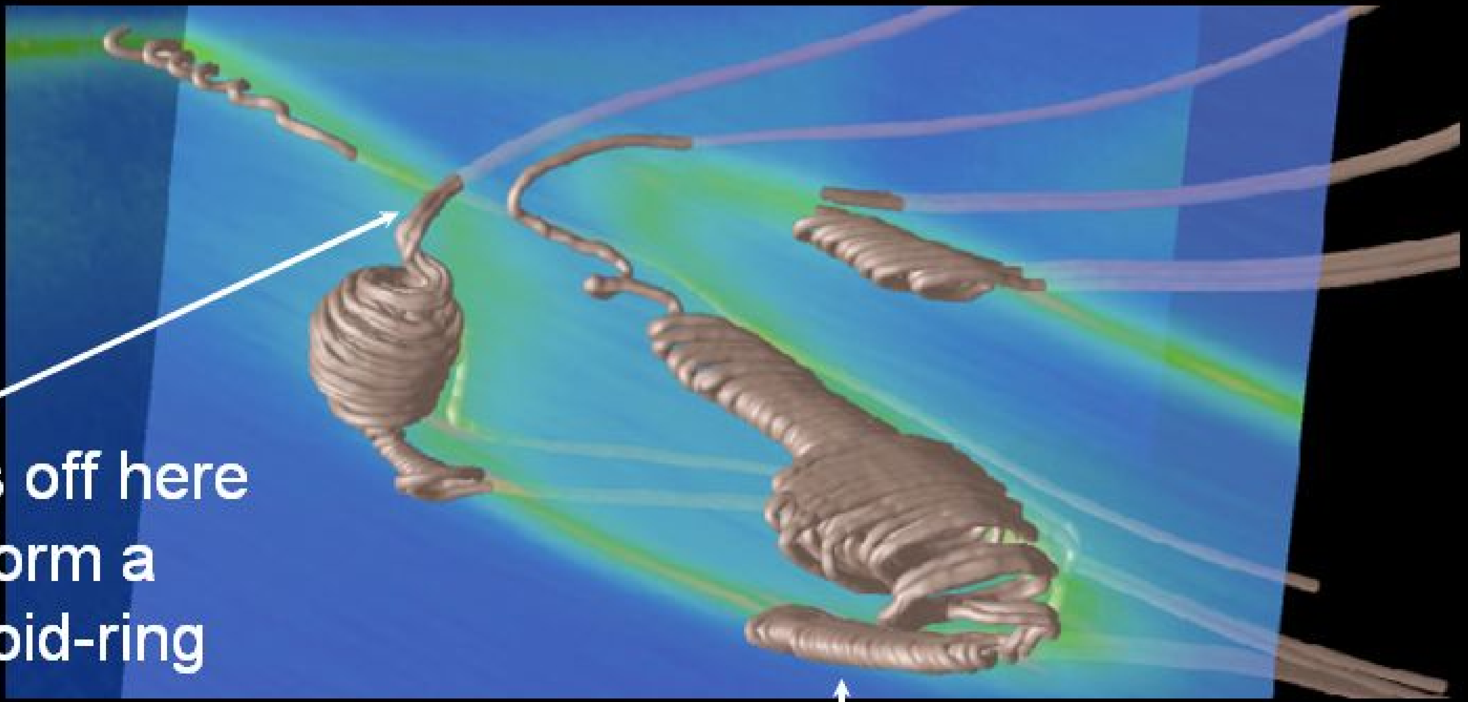
2D vs 3D Comparison



Reconnection Inflow Rate



Kinking Produces Folded Flux Ropes

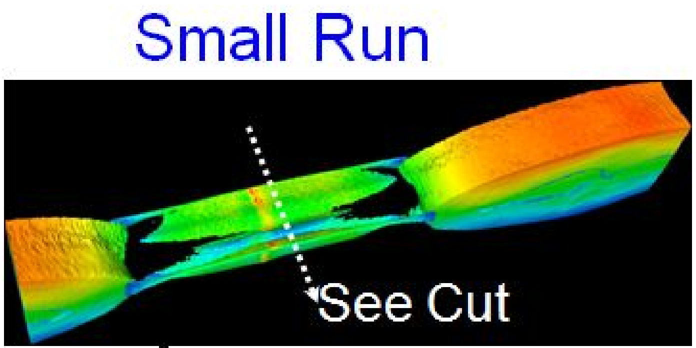


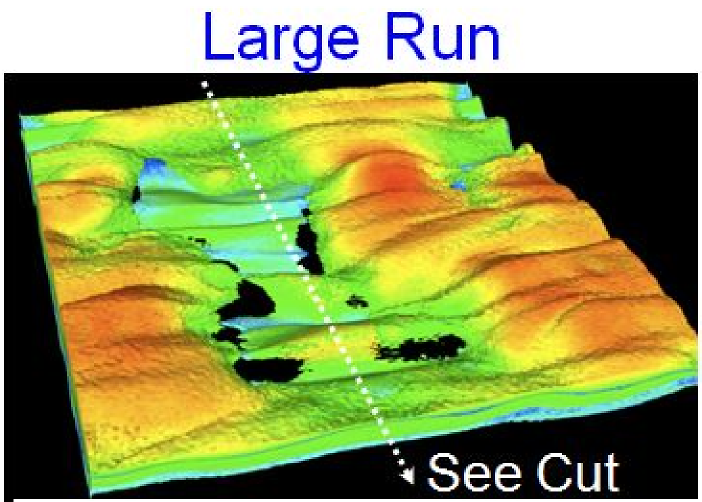
Pinches off here to a form a plasmoid-ring

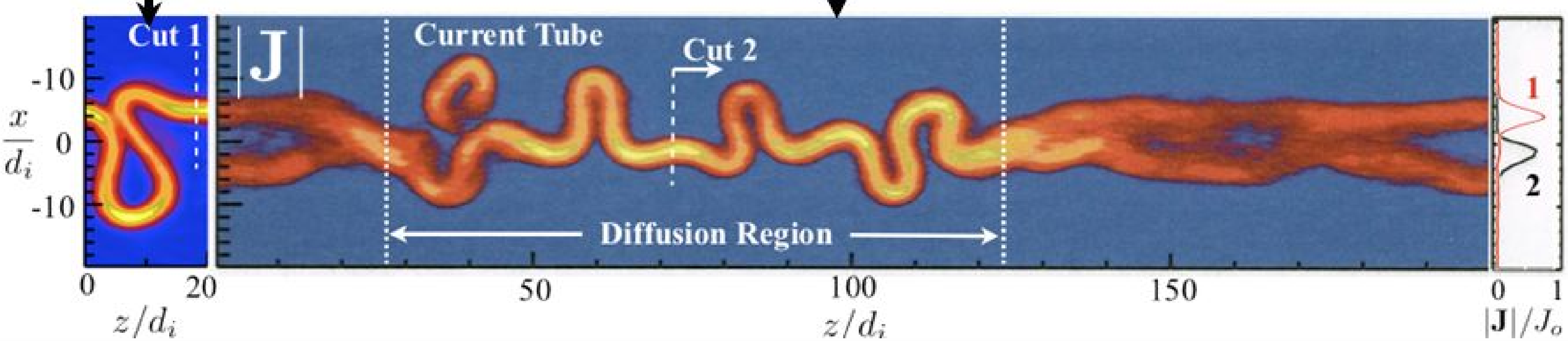
Plasmoid-rope

Compare Large vs Small Case

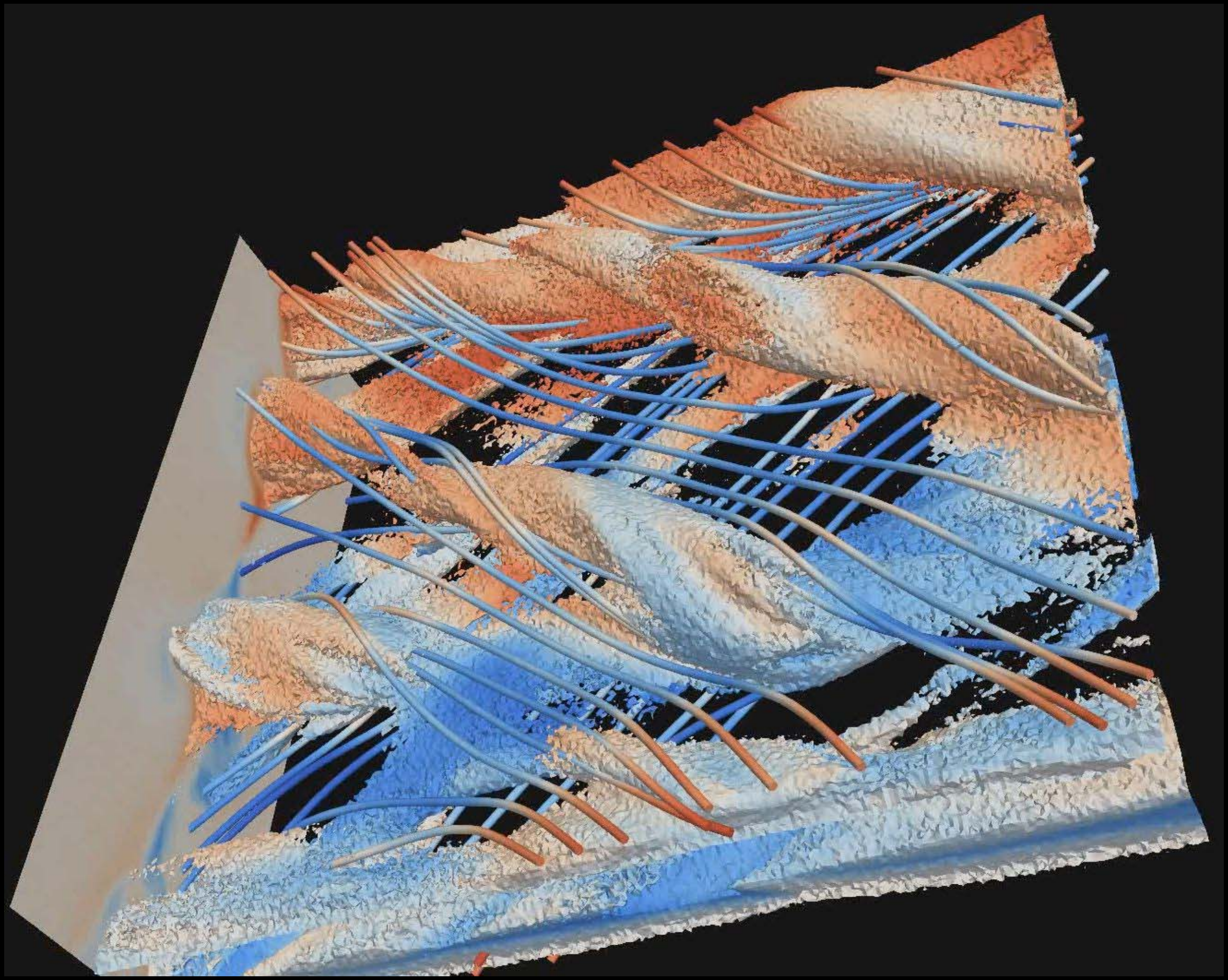
- Wavelength & layer thickness are near the same
- Kinking leads to folding and detached current tubes



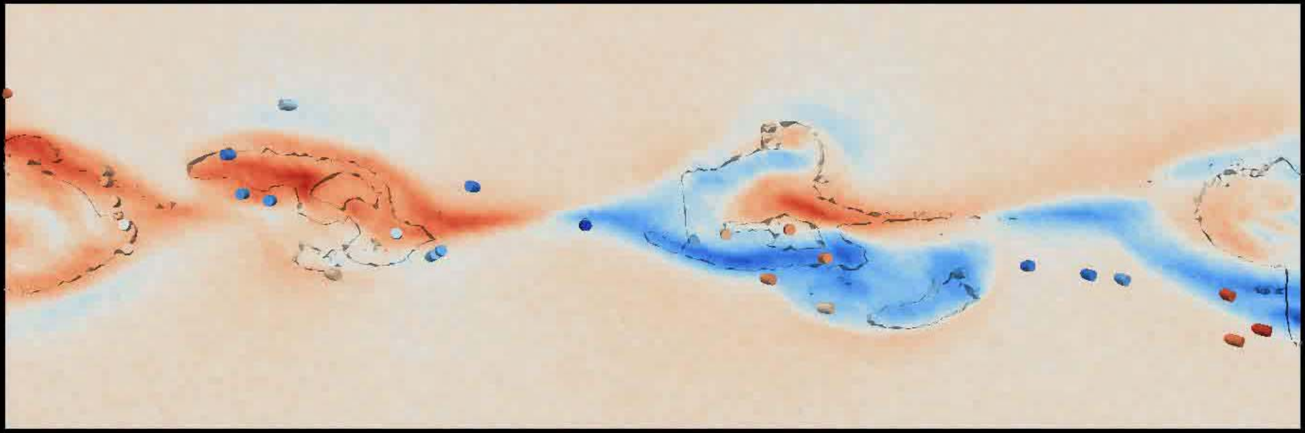




3D simulation of guide field case



3D simulation of guide field case



Summary

- Need to move away from simple models even in the collisional case
- Fully kinetic results at odds with reduced models
- 2D studies useful but 3D adds significant modification to the details
- Depending on the specific question, 2D results may be invalid (e.g., particle acceleration in the presence of a strong guide field)