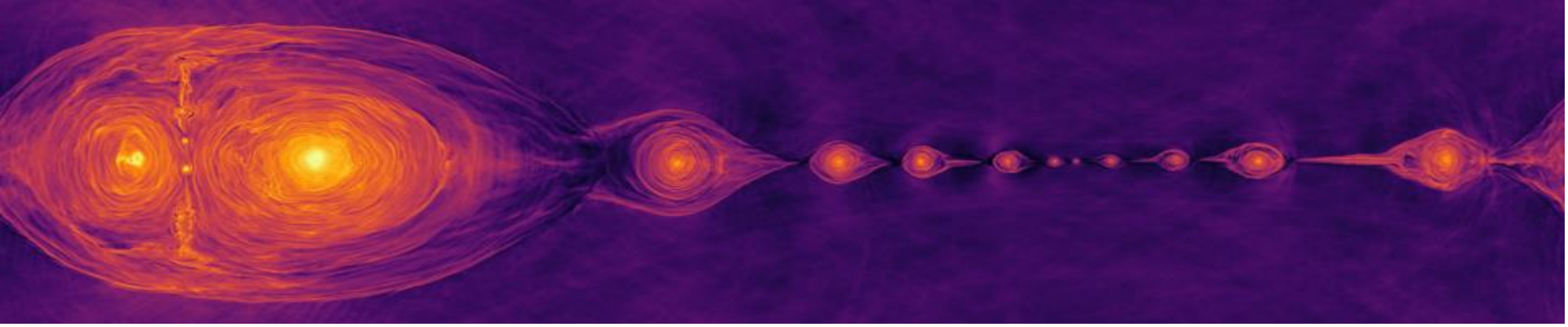

Relativistic Magnetic Reconnection: Theoretical and Computational Perspective

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Thanks:
G. Werner, B. Cerutti, J. Mehlhaff, M. Begelman, K. Nalewajko, O. French, and N. Loureiro

L. Sironi, D. Uzdensky, D. Giannios, Annual Rev. Astron. & Astrophys., in press (2025)
"Relativistic Magnetic Reconnection in Astrophysical Plasmas: A Powerful Mechanism of Nonthermal Emission"

Les Houches, France, April 8, 2025

Outline

- Introduction
- Main Themes:
  1. Multiscale Complexity: 3D reconnection as nonlinear interplay of 4 (at least!) instabilities
  2. Job Security: magnetic reconnection in global context
  3. Getting Things Going: onset of magnetic reconnection in gradually forming current sheet
  4. Obsession: Nonthermal Particle Acceleration (NTPA)
  5. Extremism: radiative and QED reconnection in extreme astrophysical environments
- Summary

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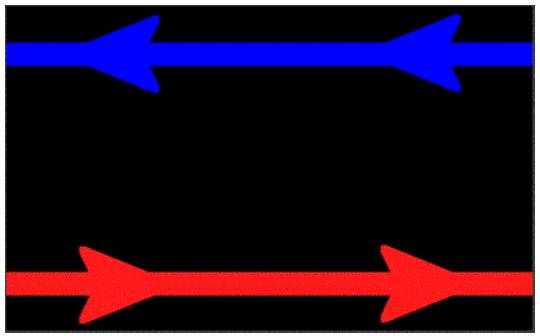
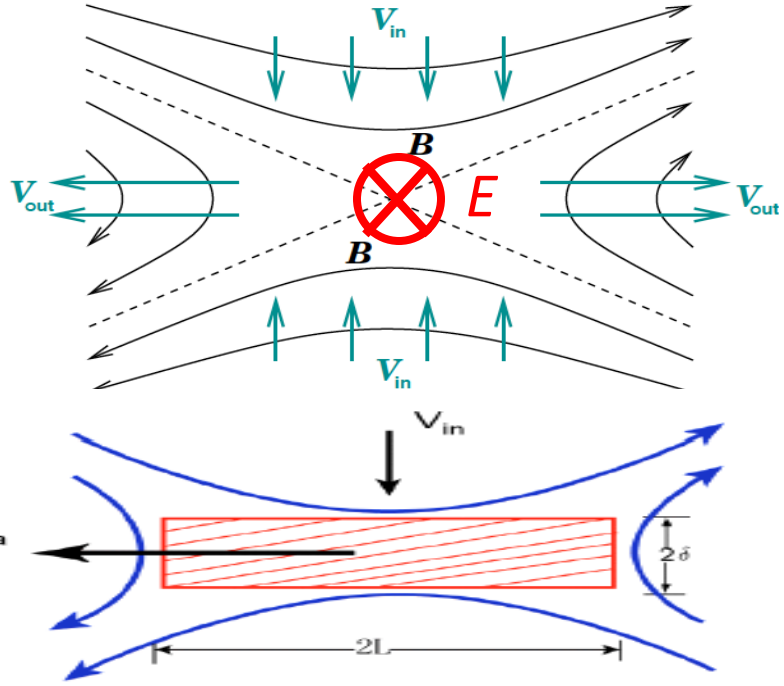
Introduction: Magnetic Reconnection

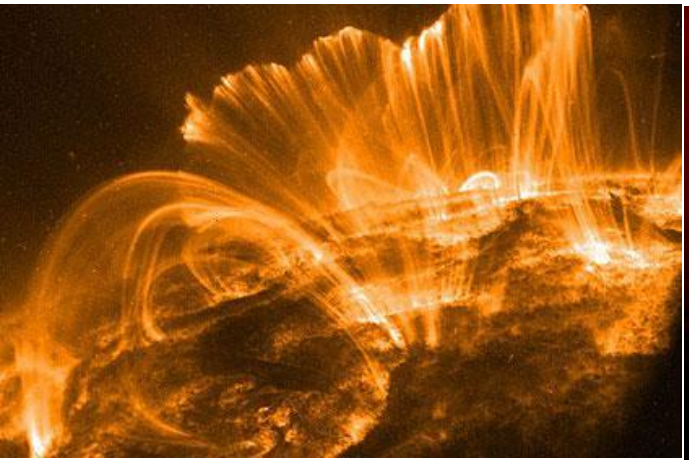
- **Magnetic reconnection:** rapid rearrangement of magnetic topology, breaking ideal-MHD.
- Reconnection requires magnetic **X-points** inside thin intense electric **current sheets**, where ideal-MHD can be violated locally.

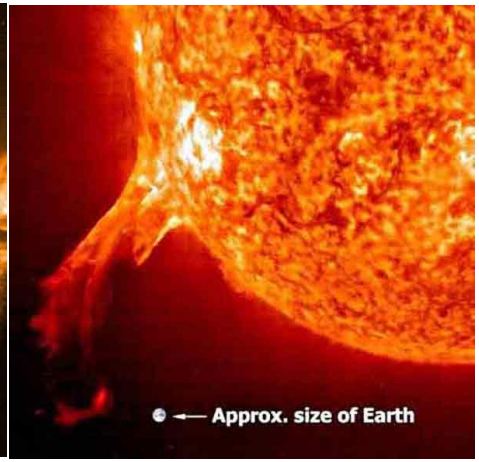


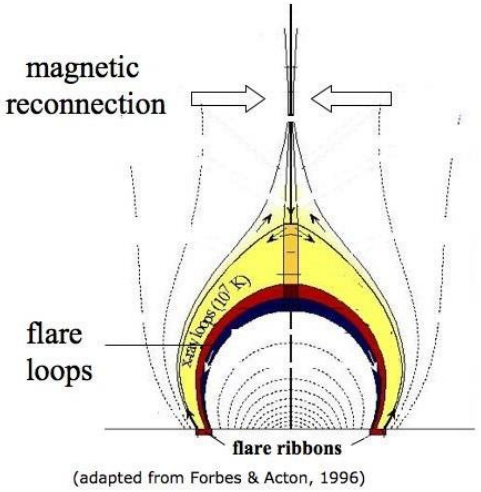
- Reconnection violently releases magnetic energy, converts it to:
  - electron and ion heating
  - bulk flow kinetic energy
  - nonthermal particle acceleration (NTPA)
  - **radiation**



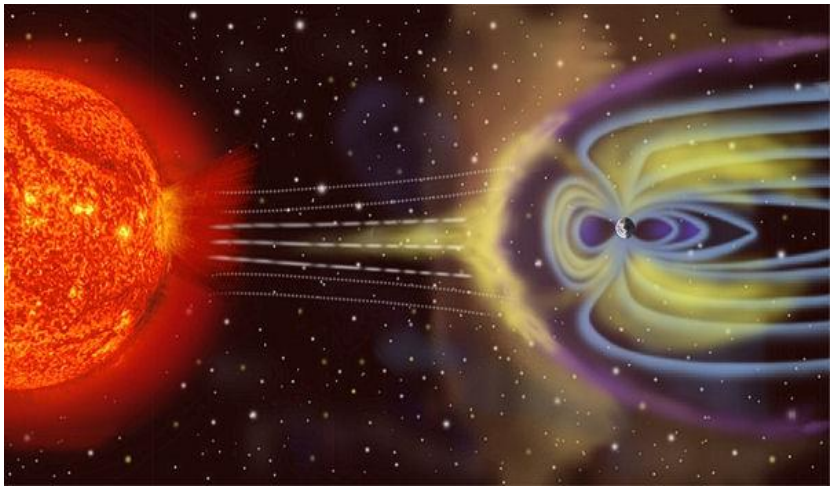
Traditional Magnetic Reconnection in the Solar System

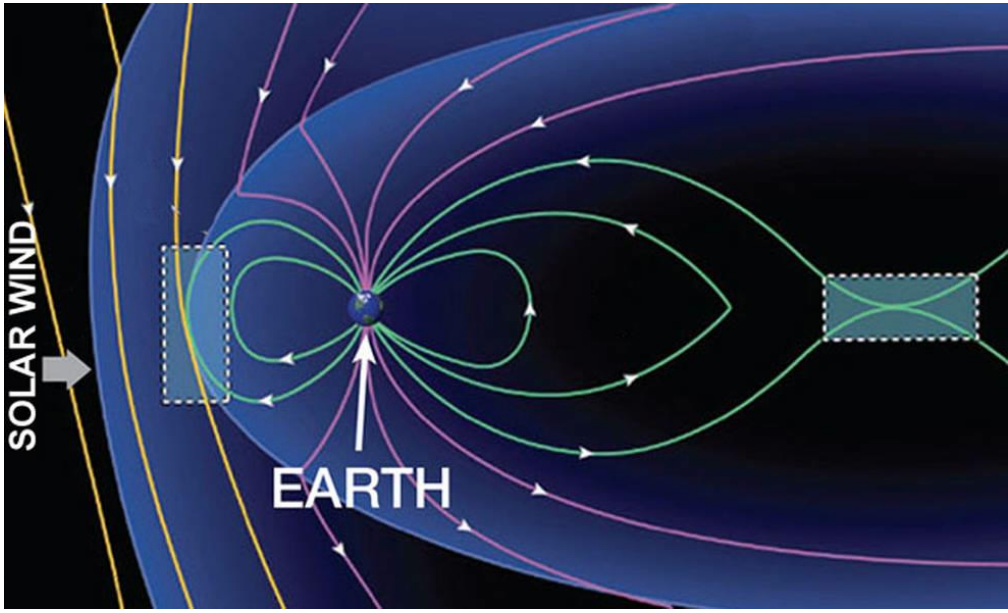






(adapted from Forbes & Acton, 1996)





Relativistic Reconnection in Astrophysics

- Pulsar magnetospheres, winds, nebulae
- Black hole accretion disks & coronae
- Active galactic nuclei (AGN/ blazar) jets* powered by supermassive BHs

(producing CRs, PeV neutrinos, TeV γ-ray flares)

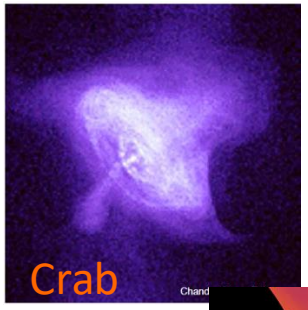
- Gamma-Ray Bursts (GRBs)

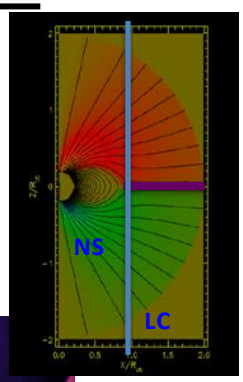
exploding massive stars

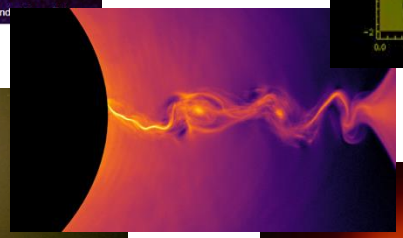
or NS-NS mergers* - gravitational wave sources)

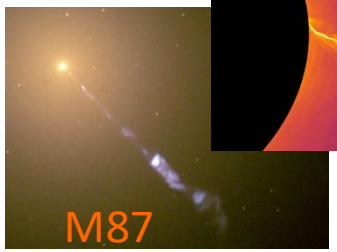
- Magnetar magnetospheres

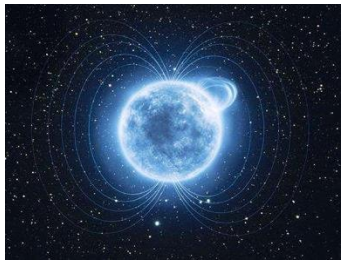
(ultra-magnetized neutron stars: γ-ray flares, FRBs)

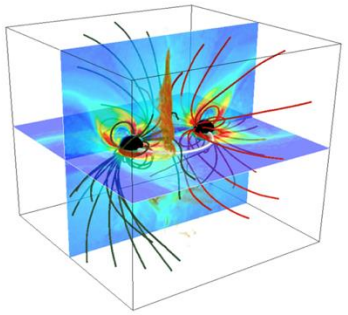






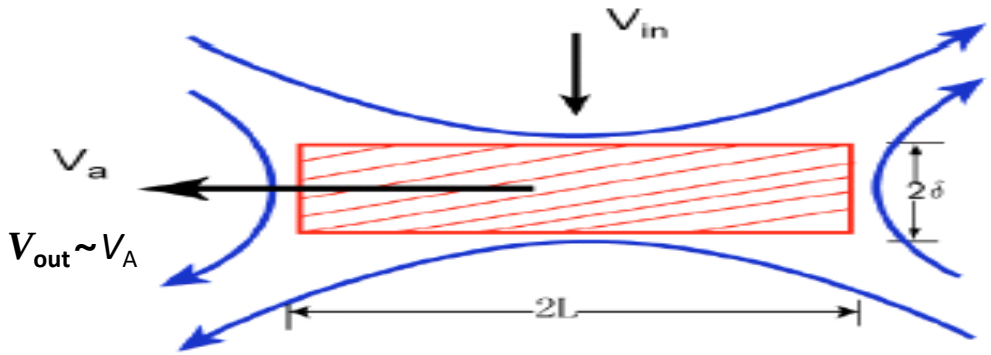






* **Multi-messenger Astrophysics!**

What's inside the black box?



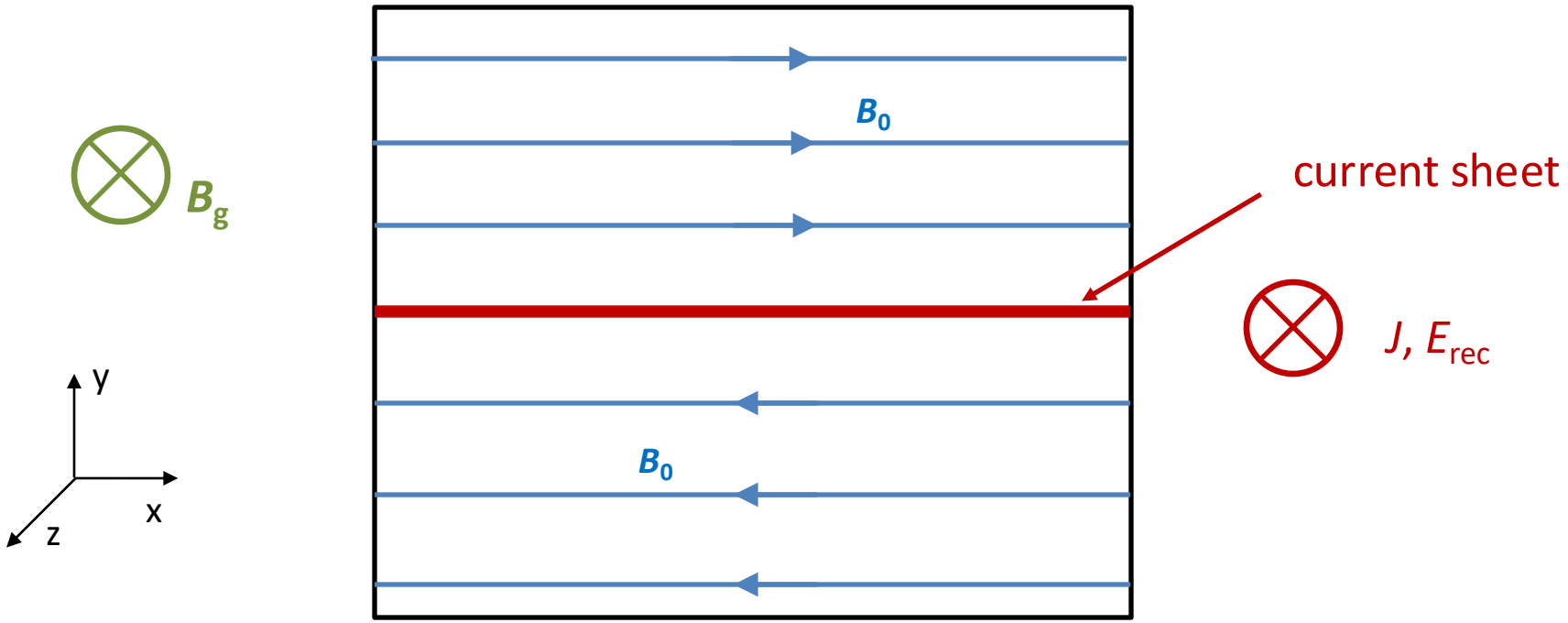
- Observations: $\tau_{rec} \sim 10\, L/V_A \Rightarrow v_{in} \sim 0.1\, v_{out} \sim 0.1\, V_A$
- Astronomical systems are astronomically large: L >>> plasma kinetic scales
- Mass conservation: $L\, v_{in} \approx \delta\, v_{out} \Rightarrow \delta \sim 0.1\, L$ -- macroscopic!
- Reconnection requires breakdown of ideal MHD, which occurs on kinetic scales
- How does one bridge macroscopic reconnection region with microscopic kinetic plasma scales?
- Hierarchical, perhaps self-similar, substructure involving broad range of scales (a kind of turbulence)

[All this applies equally well to relativistic and nonrelativistic reconnection]

Extremely Simple Setup!

Extremely Simple Canonical (Symmetric) Reconnection Setup:

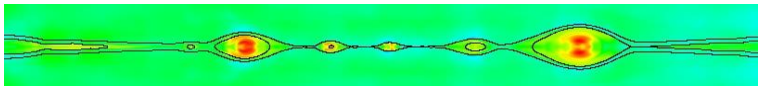
- 2D or 3D slab geometry
- Two identical upstream regions separated by thin current sheet
- Reversing reconnecting magnetic field B_0
- Possibly a finite uniform "guide" out-of-plane magnetic field B_g



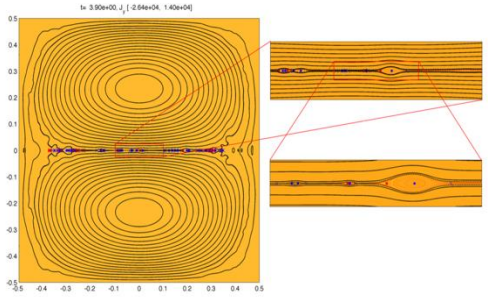
Reconnection as nonlinear evolution & interplay of plasma instabilities in a thin current sheets

2D: Tearing (plasmoid) instability
(*Loureiro et al. 2007*)

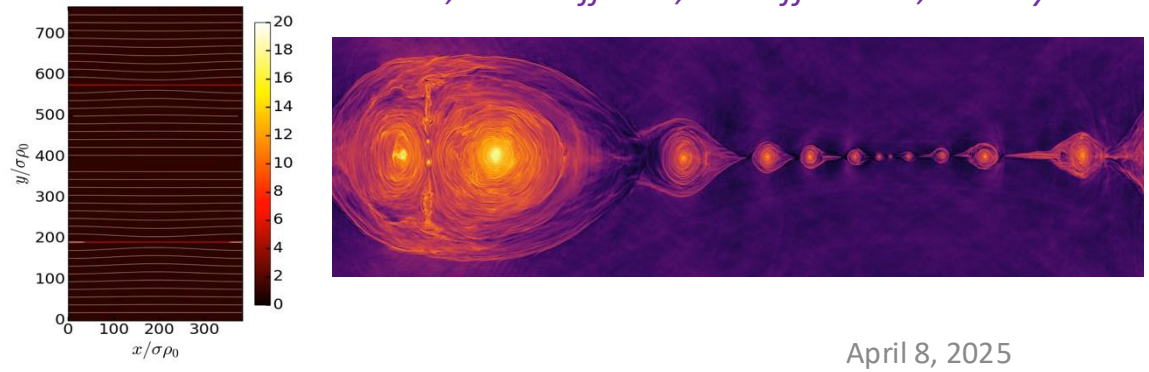
Universal picture in all plasma regimes!



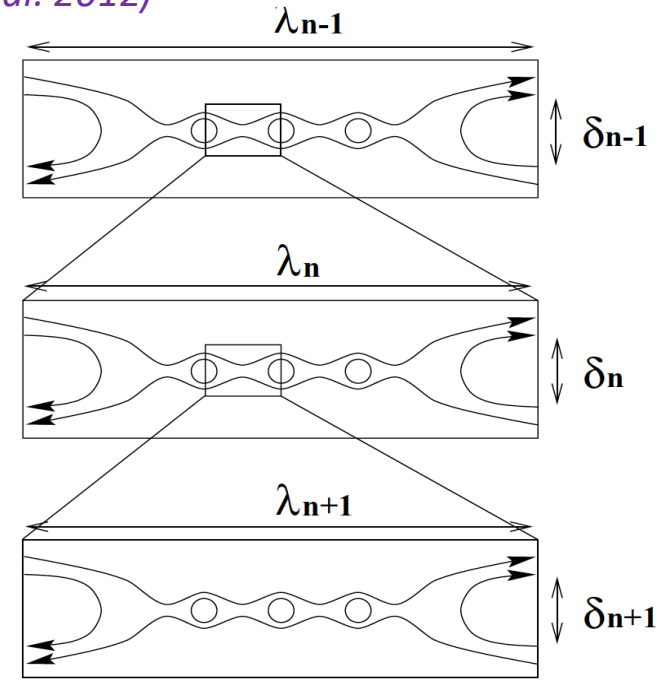
Resistive MHD:
Bhattacharjee et al. '09
Loureiro et al. '12, etc.



Relativistic collisionless plasma (PIC):
e.g., Cerutti+ '12-14, Sironi & Spitkovsky'14, Guo+ '14-16, Werner+ '16-23, Nalewaiko+ '15.18. Sironi+ '16, Mehlhaff+ '20, Schoeffler+ '19, Hakobyan+



Large-system reconnection regime:
self-similar hierarchical plasmoid chain
(Shibata & Tanuma '01, Loureiro et al. 2007, Bhattacharjee et al. 2009, Uzdensky et al. 2010, Loureiro et al. 2012)



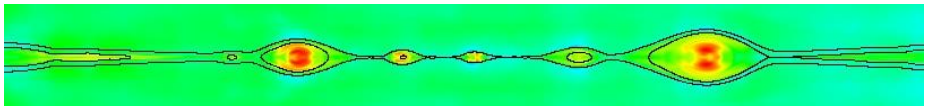
Shibata & Tanuma 2001

Reconnection as nonlinear evolution & interplay of plasma instabilities in a thin current sheets

2D: (parallel currents attract)

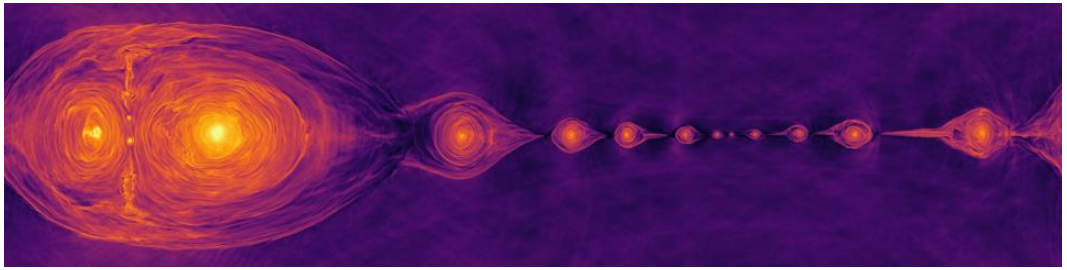
- Tearing (plasmoid) instability:

formation of plasmoids (magnetic islands)

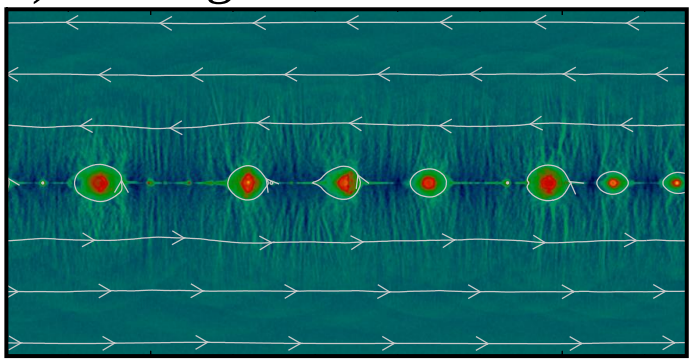


- Coalescence instability:

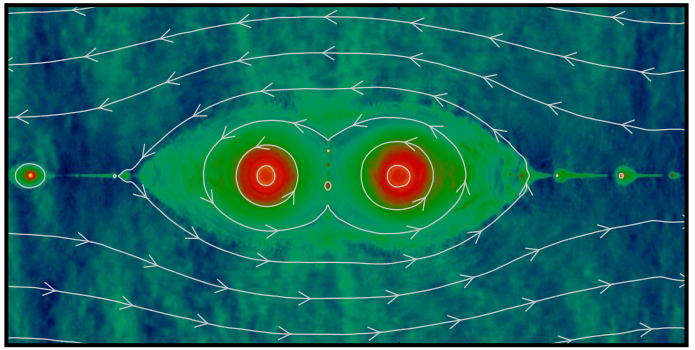
chaotic 1D motions of plasmoids along layer and plasmoid mergers
(parasitic: secondary to tearing)



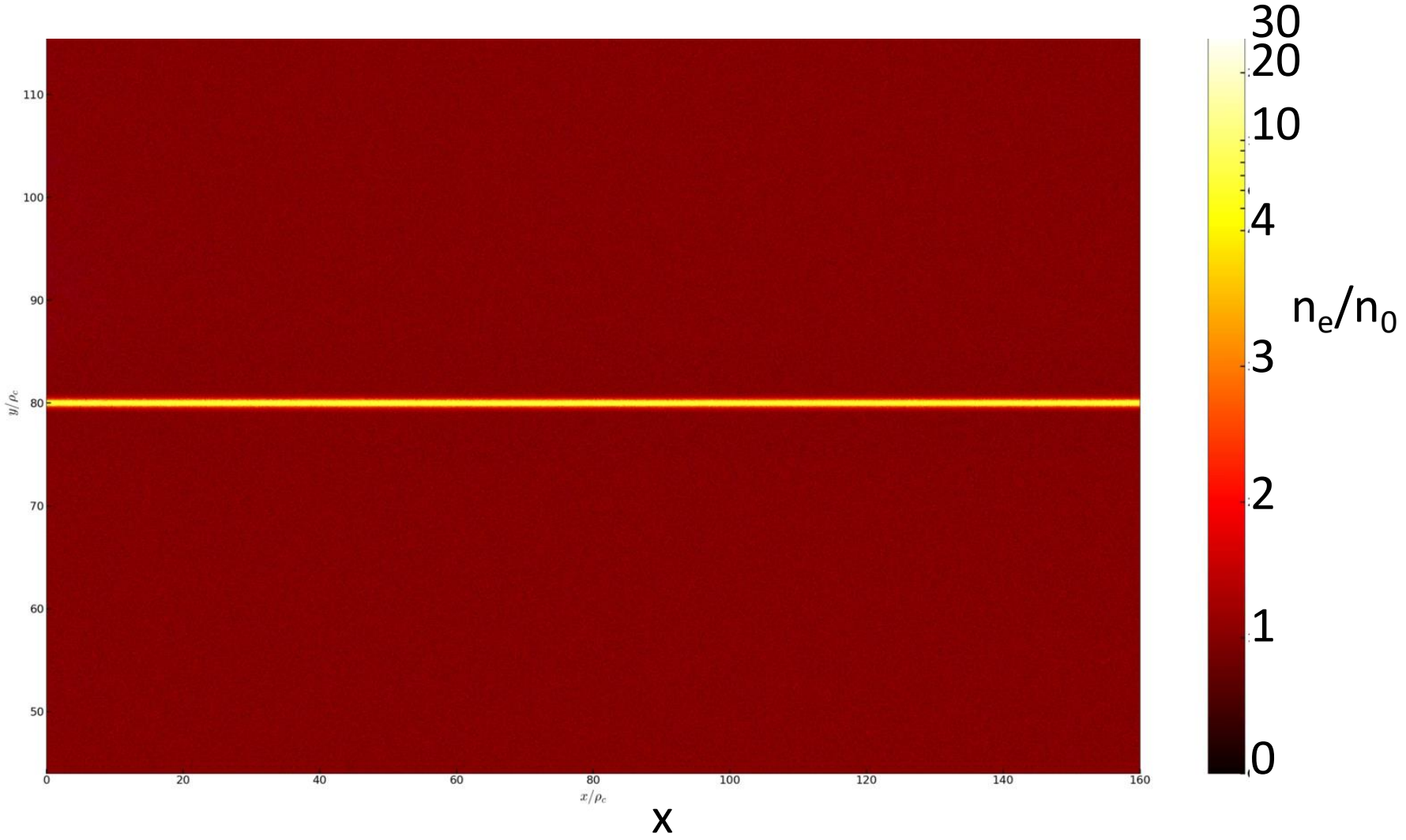
a) Tearing



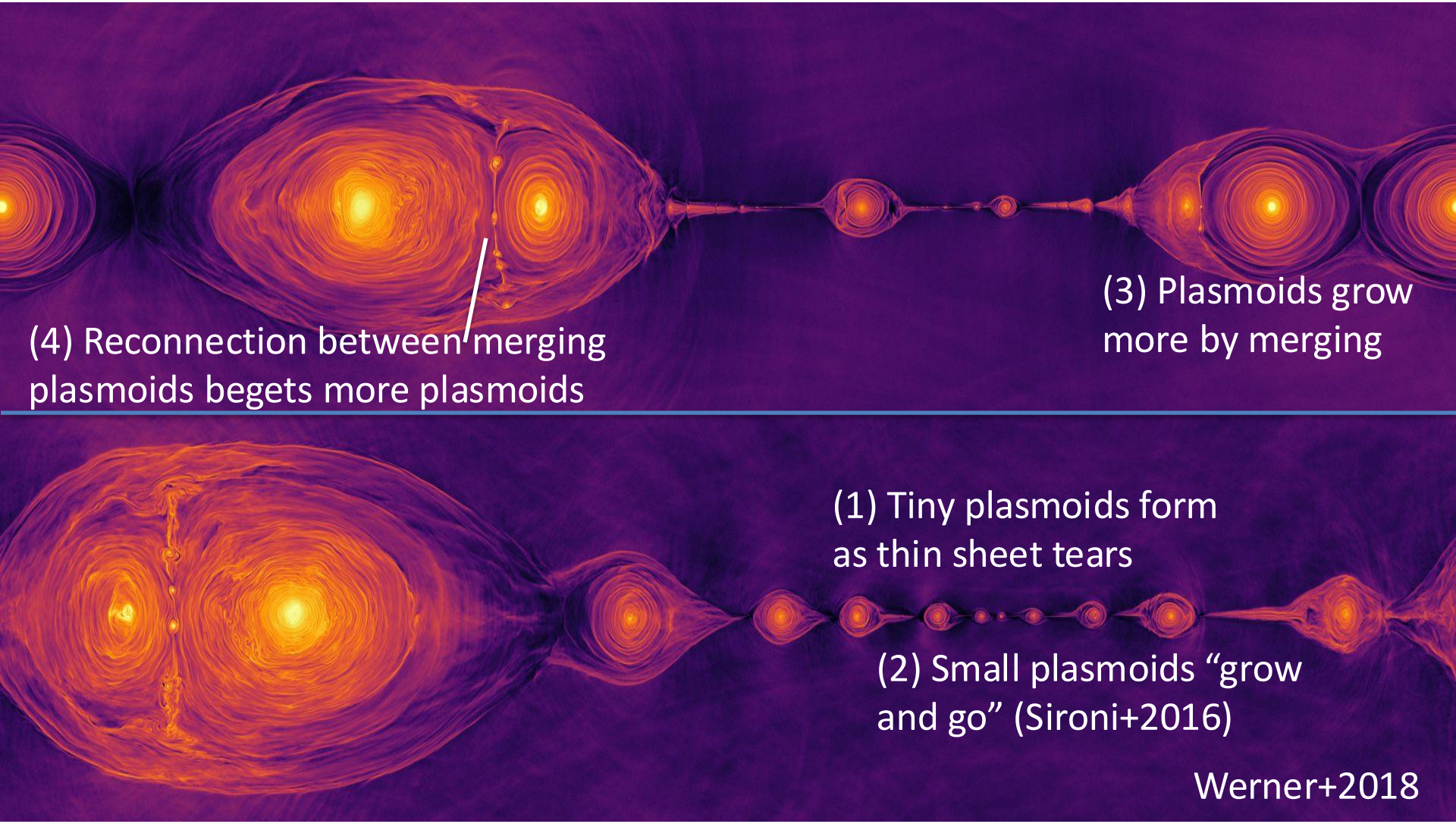
b) Coalescence



Dynamic Hierarchical Multiscale Plasmoid Chain in 2D



Dynamic Hierarchical Multiscale Plasmoid Chain in 2D



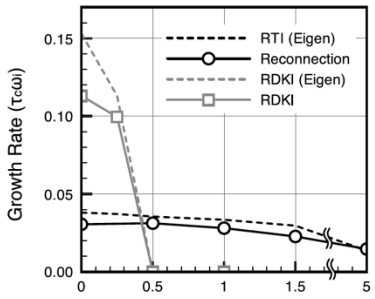
Reconnection as nonlinear evolution & interplay of plasma instabilities in a thin current sheets

Does our 2D reconnection picture reflect what happens in nature?

3D:

- Drift-kink (DKI) instability:

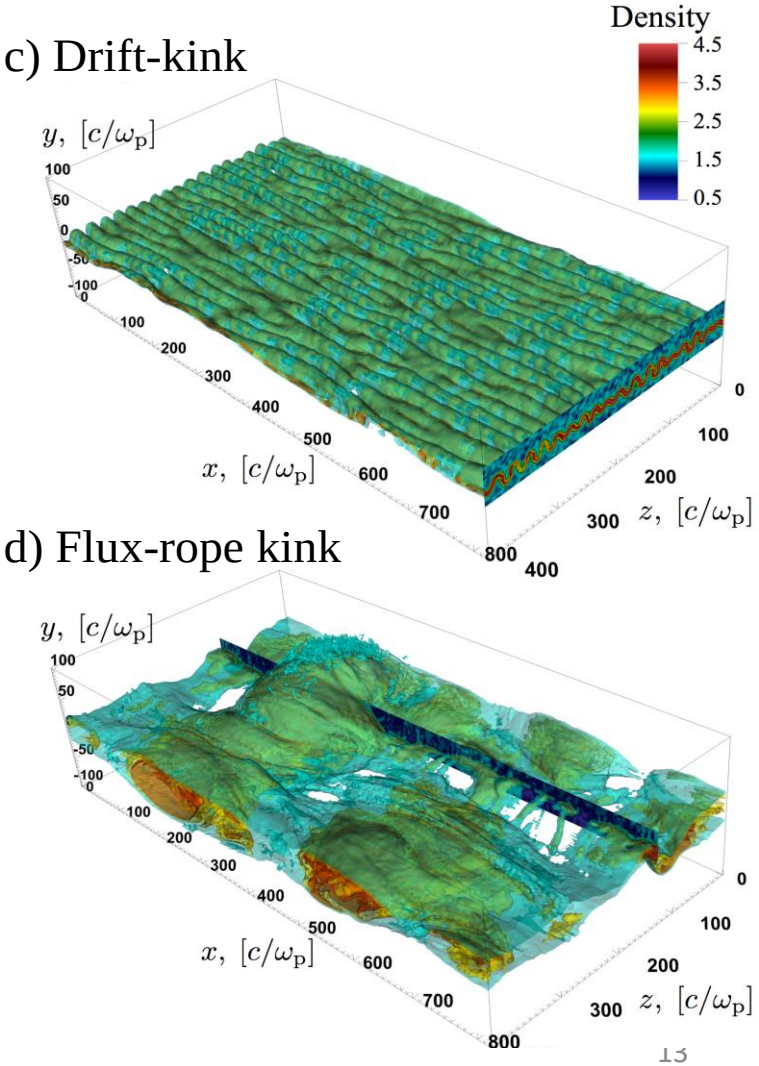
- thin current-sheet kinks in the 3rd direction
- primary instability
- two-fluid
- more important in relativistic pair plasmas
- suppressed by strong guide magnetic field B_g



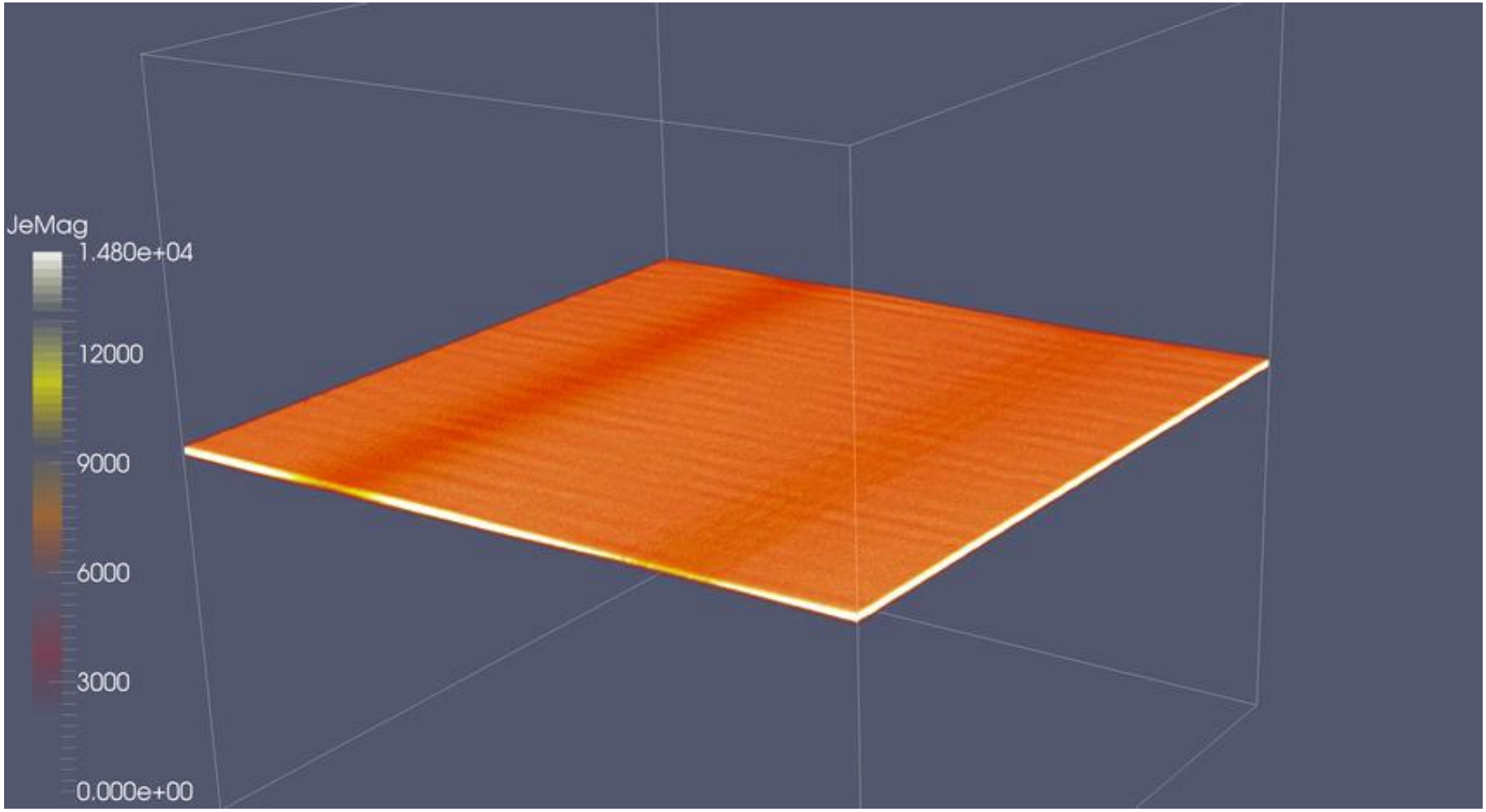
(*Zenitani & Hoshino 2008*)

- Flux-rope kink instability:

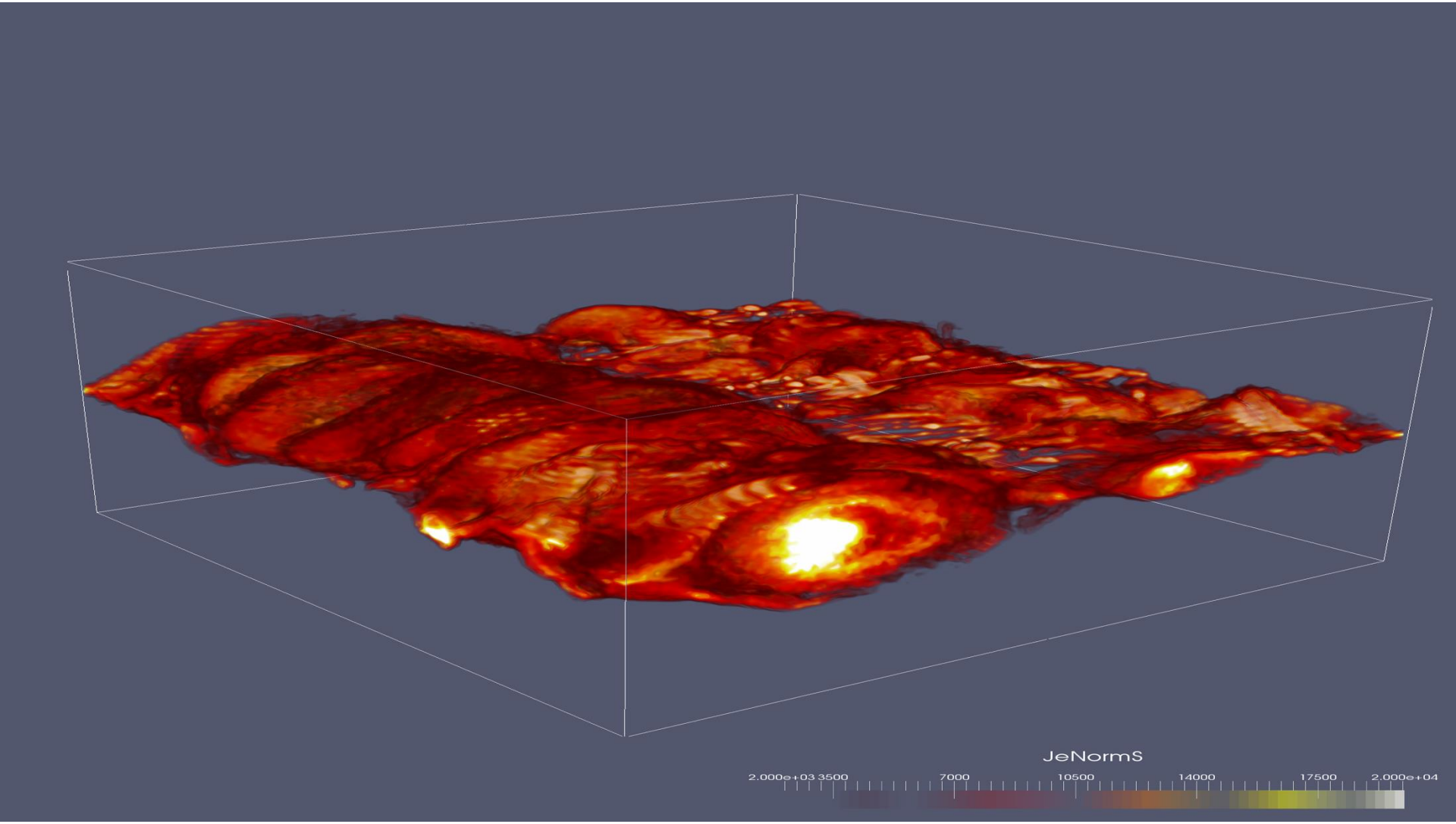
- ideal-MHD kink instability of flux ropes (3D counterparts of plasmoids)
- parasitic: secondary to tearing
- also suppressed by strong guide field



3D Relativistic (σ_h>>1) Collisionless Reconnection



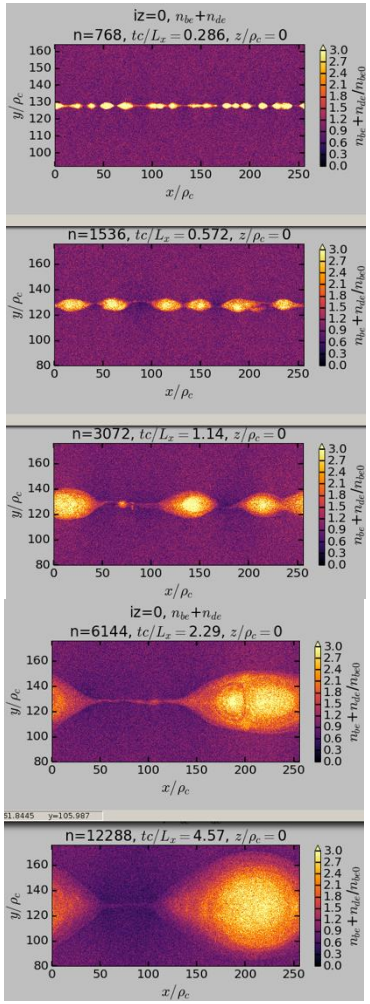
Turbulent 3D Reconnection Layer



3D effects are more disruptive for moderately relativistic reconnection (σ_h=1)

2D:

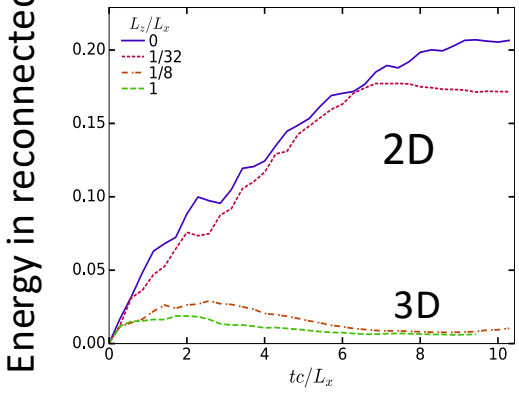
plasmoid hierarchy

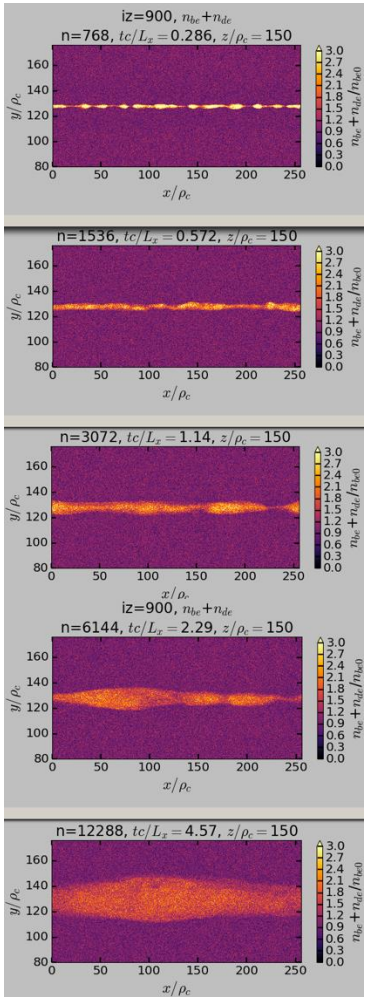


time

3D:

much less structure. Instead of plasmoid chain, we get a turbulent pressure-dominated layer that thickens over time. In 3D, flux ropes just dissipate, magnetic flux is annihilated





3D: Reconnection --> "nonlinear evolution of a thin current sheet"

SUMMARY

- Magnetic Reconnection is a fundamental nonlinear collective plasma process governing energy conversion and powering high-energy flares in numerous space/solar/astrophysical systems.
- In astronomically large systems ($L >> d_{i,e}$, $\rho_{i,e}$) reconnection becomes extremely complex, even in simplest idealized configurations, developing dynamic multi-scale hierarchical sub-structure.
- Dynamics is governed by nonlinear development and interplay by (at least) 4 instabilities:
  - Two are 2D:
    - Tearing: primary, nonideal – creates magnetic islands/plasmoids
    - Coalescence: secondary (to tearing), ideal-MHD – drives plasmoid dynamics along the layer
  - Two are 3D (both suppressed by strong guide field):
    - (Relativistic) Drift-Kink: primary, non-ideal – ripples the current sheet
    - Flux-rope kink: secondary (to tearing), ideal-MHD – kinks flux ropes
- End result: highly structured, dynamic, turbulent mess!

THANK YOU!