Magnetic Reconnection: theory and simulation

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Plasma Science and Fusion Center,

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2016 SULI Introductory Course in Plasma Physics

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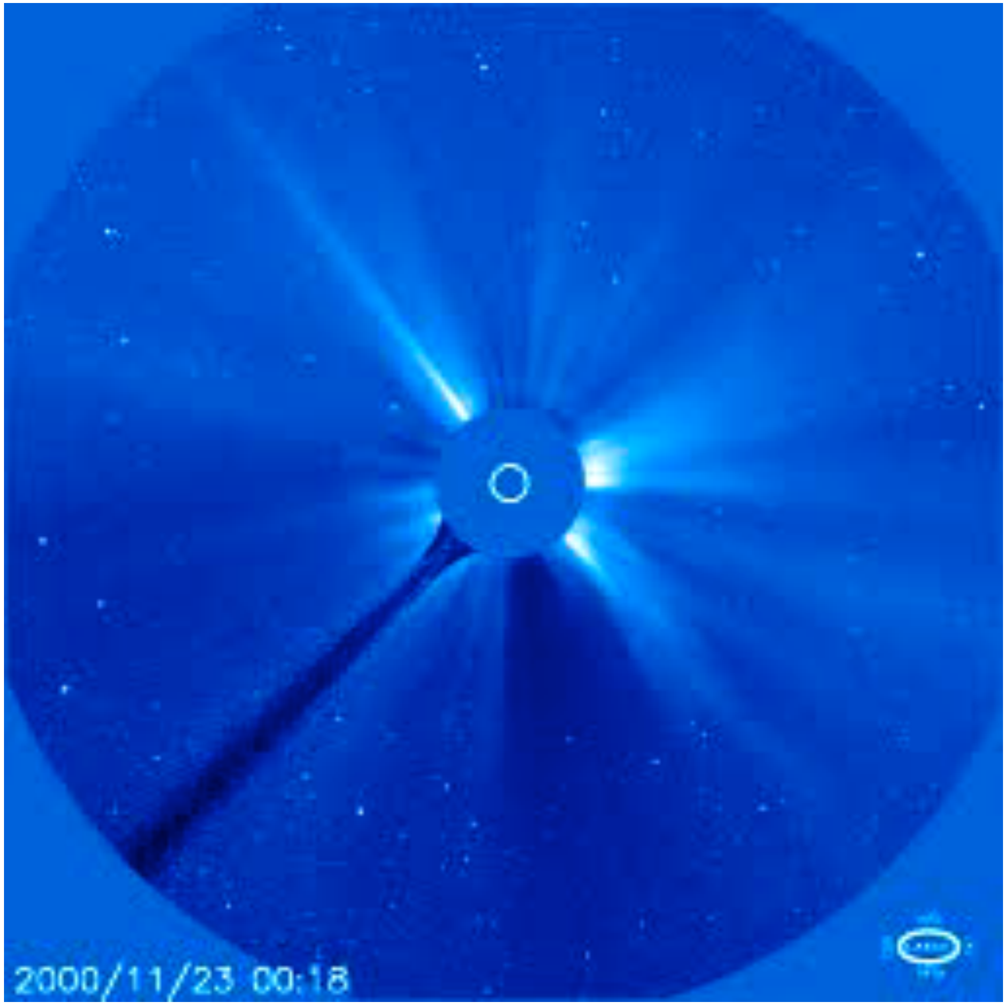
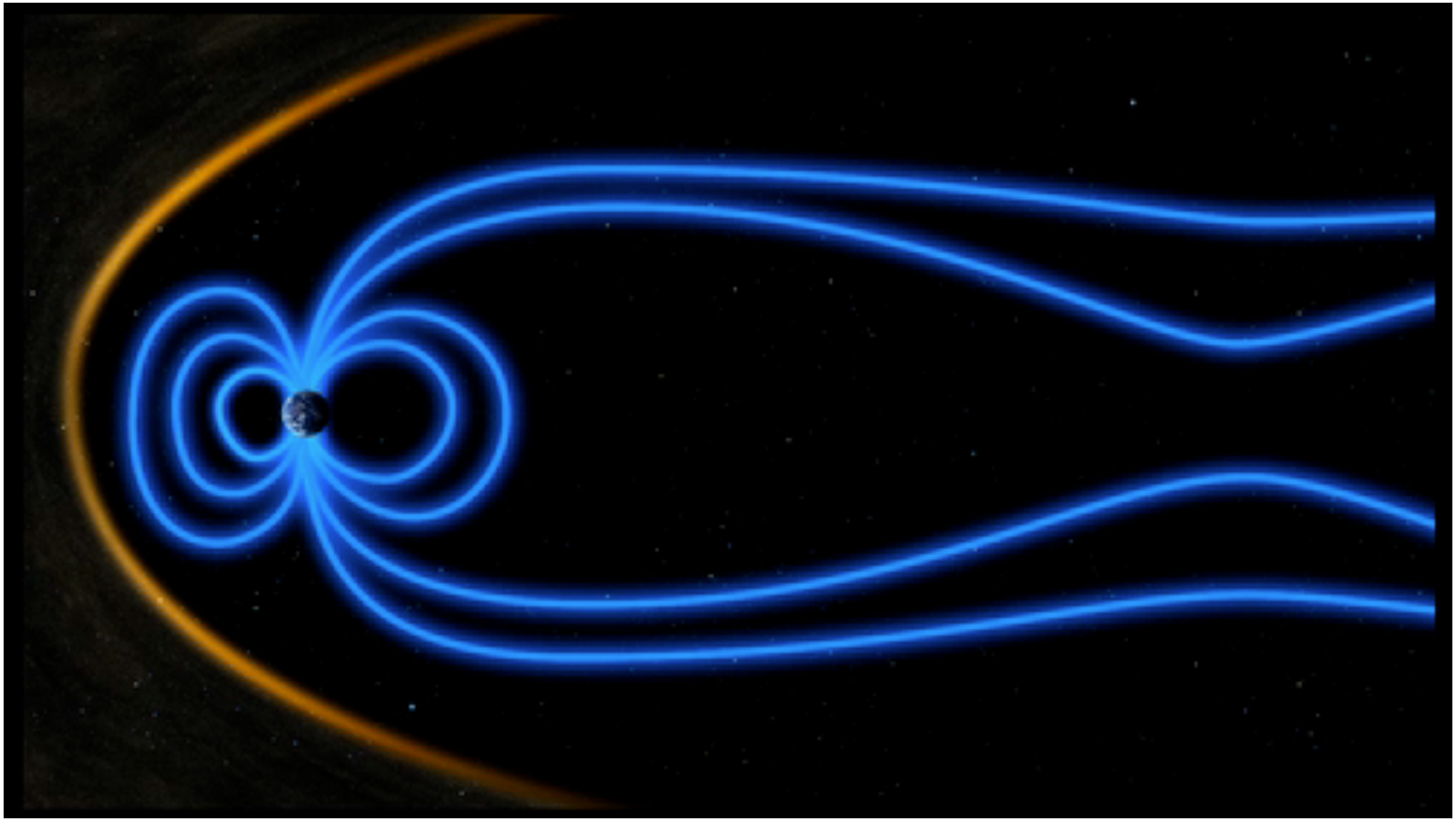
Solar Flares



Earth's Magnetosphere and Geomagnetic Storms



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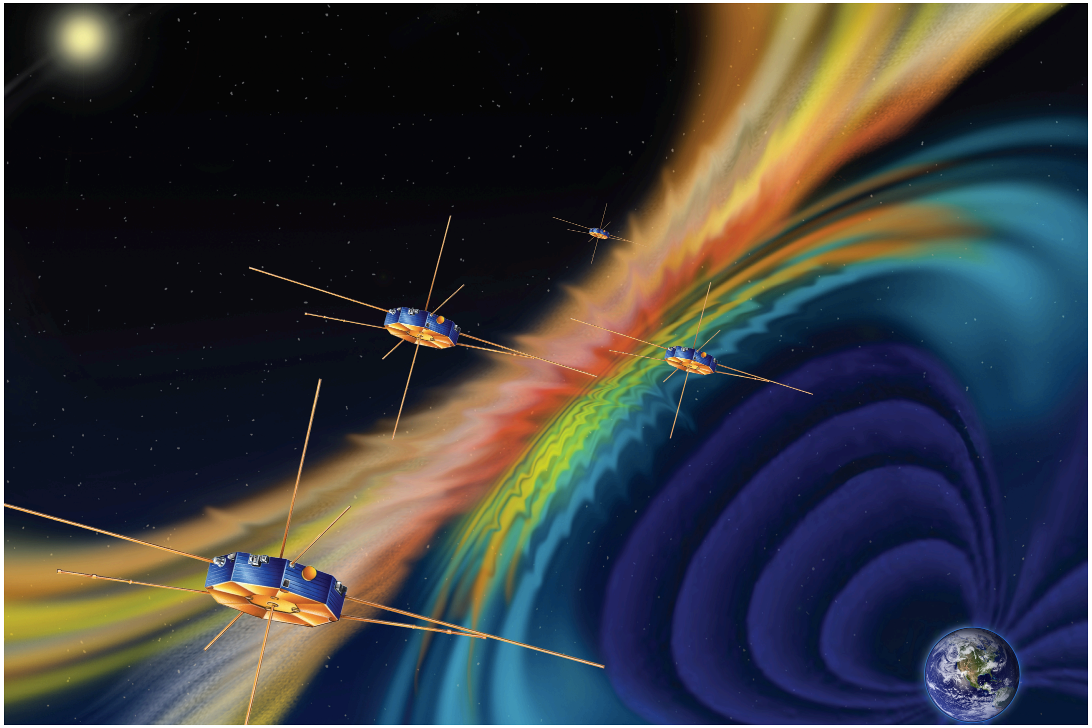
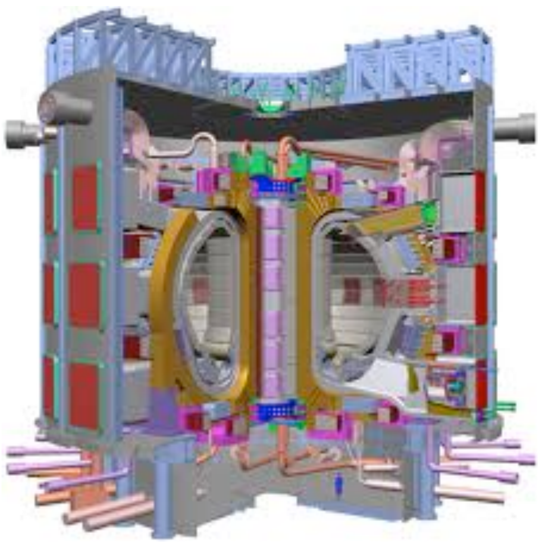


NASA's MMS mission. (Burch *et al.*, Science 2016)

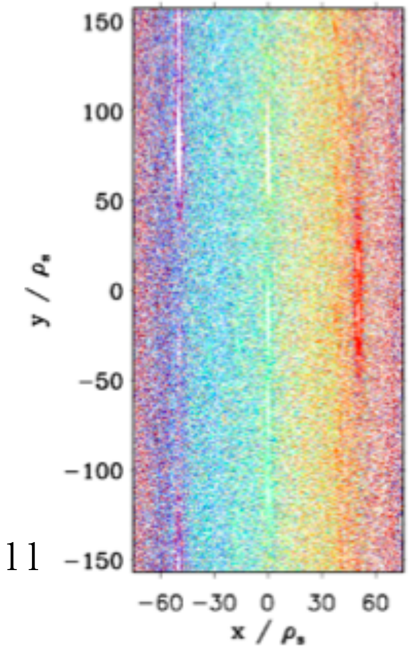
Magnetic Confinement Fusion

ITER

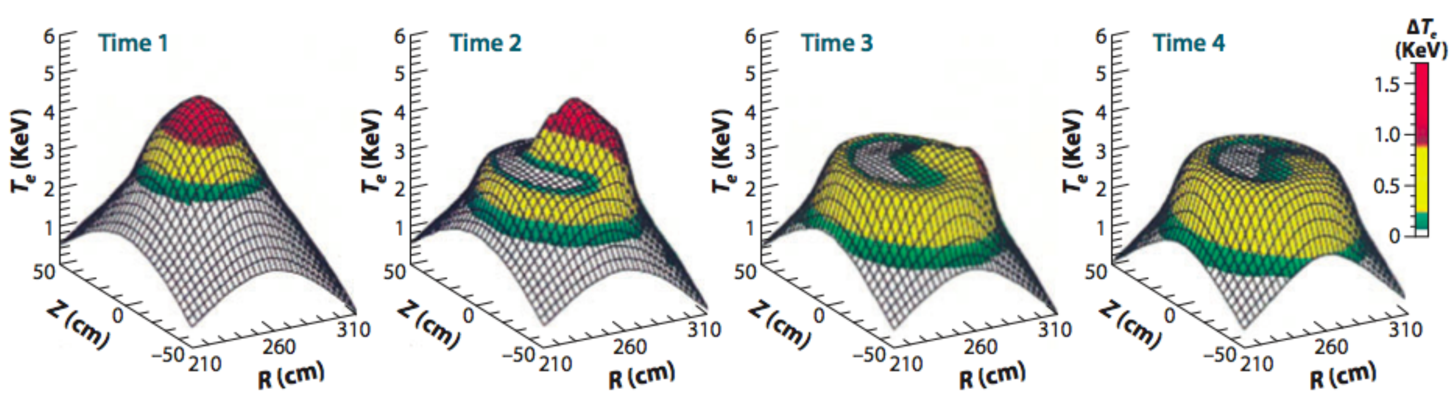


Stochastic field due to multiple microscopic reconnection events (*micro-tearing*)

Doerk '11



Collapse of core temperature due to macroscopic reconnection event (*sawtooth instability*)



Yamada '94

Motivation: plenty of others!

- Fusion reactors (tokamaks): tearing modes, disruptions, edge-localized modes, resonant magnetic perturbations
- Laser-solid interactions (inertial confinement fusion)
- Magnetic dynamo & turbulence in magnetized media
- Flares (accretion disks, magnetars, blazars)
- Space weather
- Etc.

<u>Recent review papers</u>: Zweibel & Yamada '09; Yamada *et al.*, '10
<u>Books</u>: Biskamp and Priest & Forbes.
Reconnection in <u>exotic HED environments</u>: Uzdensky '11

even more motivation…

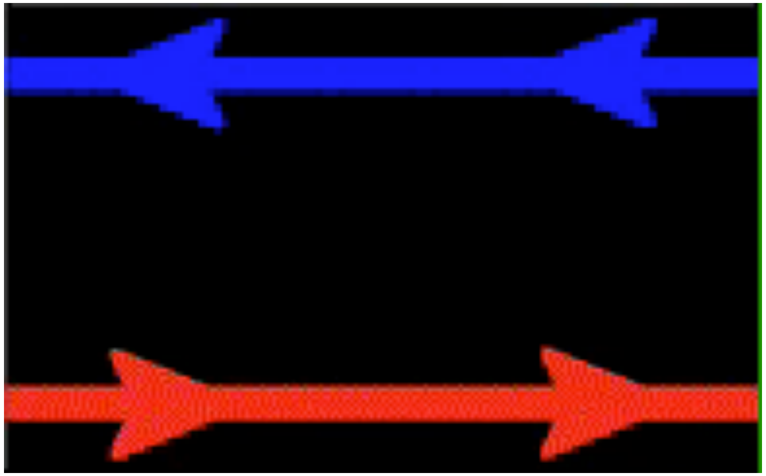
"The prevalence of this research topic is a symptom not of repetition or redundancy in plasma science but of the underlying unity of the intellectual endeavor. As a physical process, magnetic reconnection plays a role in magnetic fusion, space and astrophysical plasmas, and in laboratory experiments. That is, investigations in these different contexts have converged on this common scientific question. If this multipronged attack continues, progress in this area will have a dramatic and broad impact on plasma science."

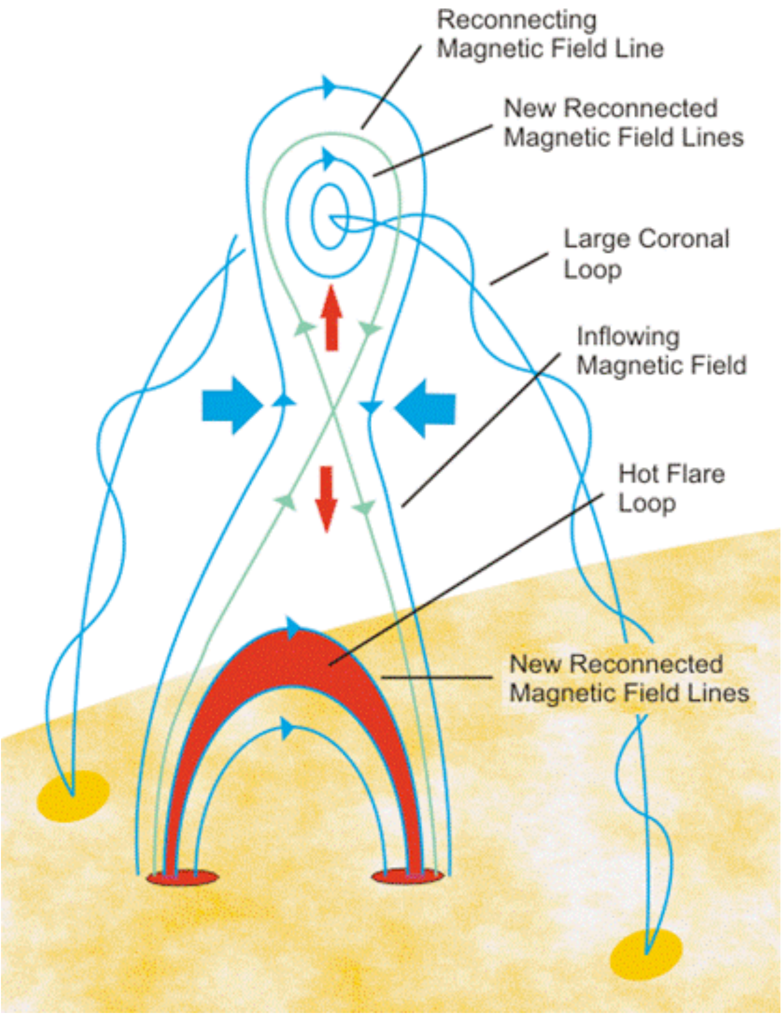
(S. C. Cowley & J. Peoples, Jr., *"Plasma Science: advancing knowledge in the national interest"*, National Academy of Sciences decadal survey on plasma physics, 2010)

RECONNECTION: ESSENTIAL INGREDIENTS

Magnetic Reconnection

Topological change of the **macroscopic** magnetic field configuration due to **microscopic** plasma effects.
Explosive energy release.





Magnetic Reconnection

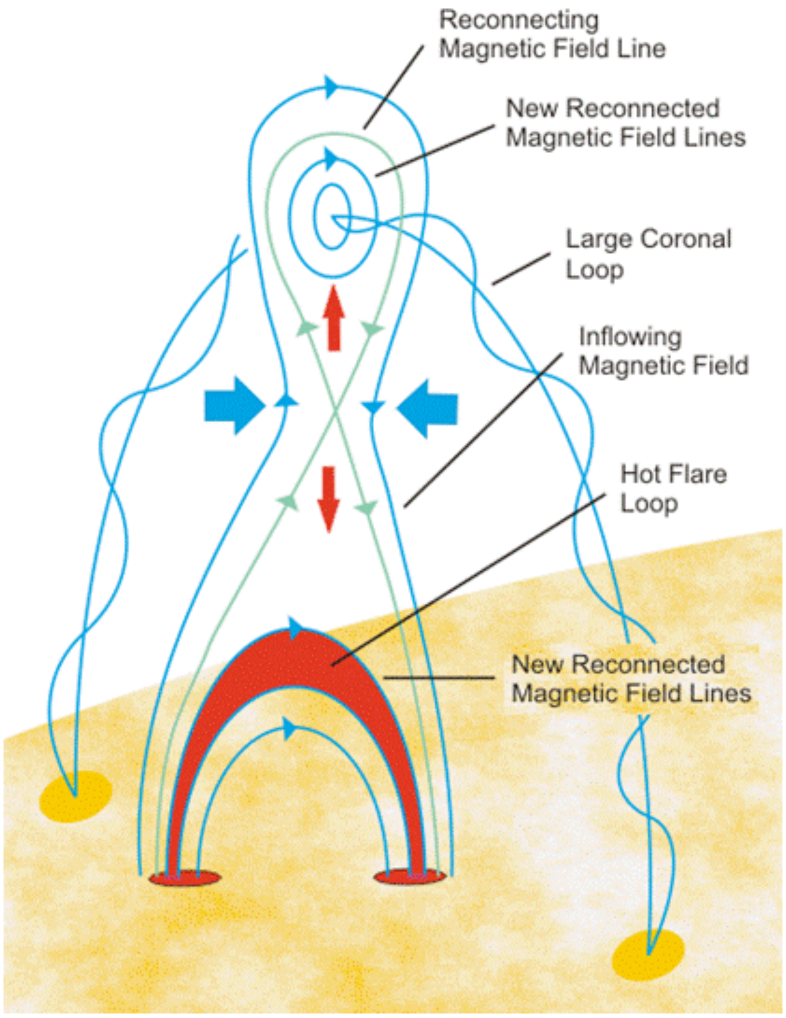
Main features:

- coupling between large and small scales (*multiscale* problem)

- Magnetic energy is converted / dissipated (*energy partition*: what goes where?)

- Reconnection rate ~ 0.01 – 0.1 V_A/L (*fast*)

- often reconnection events are preceded by long, quiescent periods [*two-timescales*, the *trigger* (or *onset*) *problem*]



Reconnection: the key questions

1. **Reconnection rate**

   - Fast, independent of microphysics (?): *why?*

2. **Reconnection trigger**

   - The reconnection stage proper (explosive) is often preceded by long, quiescent periods: *two timescales.*

3. **Energy partition** and **particle acceleration**

   - Magnetic energy is converted / dissipated: *how much energy goes into the different channels?*

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Despite ~60 years of active research, we still don't have a model that accounts for these different aspects in even the simplest plasma description (MHD).

Challenge

- Intrinsic **multiscale** / **multiphysics** character renders analytical understanding and numerical modeling of magnetic reconnection extremely challenging.

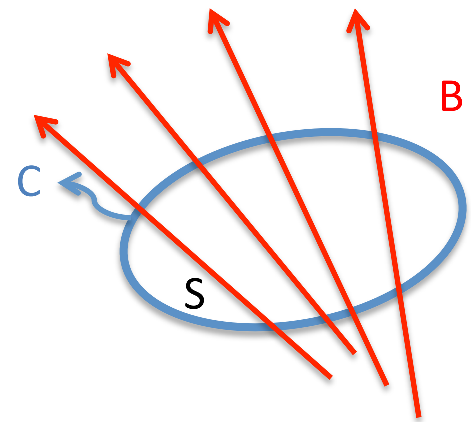
- Inherently **non-steady-state**, so statistical description probably required.

- **Wide variety** and **complexity** of physical environments where reconnection occurs: collisional (MHD) *vs.* collisionless (kinetic) plasmas, turbulent *vs.* laminar backgrounds, weakly *vs.* strongly magnetised, etc.

Frozen flux constraint

Magnetic flux through a surface S, defined by a closed contour C:

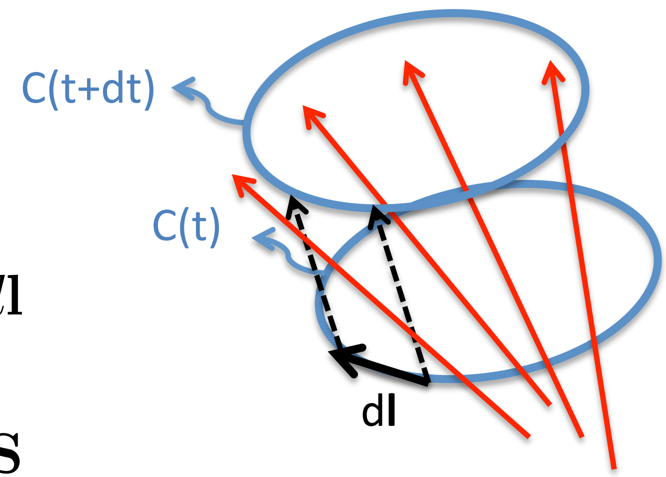
$$\Psi = \int_S \mathbf{B} \cdot d\mathbf{S}$$



How does $\mathbf{\Psi}$ change in time?

1. the magnetic field itself can change:

$$\left(\frac{\partial \Psi}{\partial t}\right)_1 = \int_S \frac{\partial \mathbf{B}}{\partial t} \cdot d\mathbf{S} = -c \int_S \nabla \times \mathbf{E} \cdot d\mathbf{S}$$



2. the surface moves with velocity $\mathbf{u}$:

$$\left(\frac{\partial \Psi}{\partial t}\right)_2 = \int_C \mathbf{B} \cdot \mathbf{u} \times d\mathbf{l} = \int_C \mathbf{B} \times \mathbf{u} \cdot d\mathbf{l}$$

$$= \int_S \nabla \times (\mathbf{B} \times \mathbf{u}) \cdot d\mathbf{S}$$

Frozen flux constraint (cont'd)

Combine the two contributions to get:

$$\frac{d\Psi}{dt} = -\int_S \nabla \times (c\mathbf{E} + \mathbf{u} \times \mathbf{B}) \cdot d\mathbf{S}$$

Up to here, no plasma physics involved – this is a completely general result

Frozen flux constraint (cont'd)

Combine the two contributions to get:

$$\frac{d\Psi}{dt} = -\int_S \nabla \times (c\mathbf{E} + \mathbf{u} \times \mathbf{B}) \cdot d\mathbf{S}$$

Recognize that $\mathbf{u}$ is an arbitrary velocity. Let me chose it to be the plasma velocity: $\mathbf{u} = \mathbf{v}$, and recall Ohm's law:

$$\mathbf{E} + \frac{1}{c}\mathbf{v} \times \mathbf{B} = \eta\mathbf{J}$$

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Neglect collisions (RHS) → ***ideal Ohm's law***

$$\boxed{\frac{d\Psi}{dt} = 0}$$

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Hannes Alfvén

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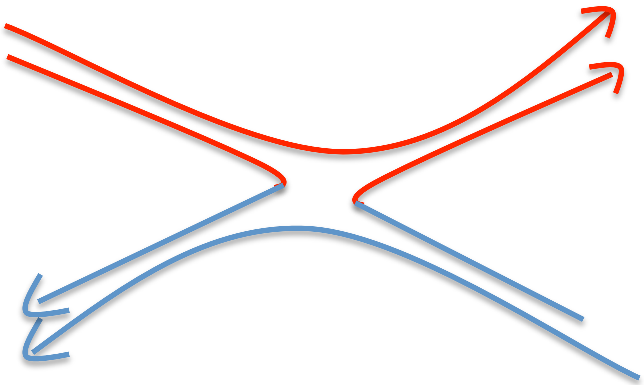
Magnetic flux through the arbitrary contour C is constant: **magnetic field lines must move with** (are ***frozen*** to) **the plasma**

Frozen flux *vs.* reconnection

Reconnection implies breaking the frozen flux constraint, i.e., going beyond the ideal Ohm's law.



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But the plasma is a very good conductor, right?

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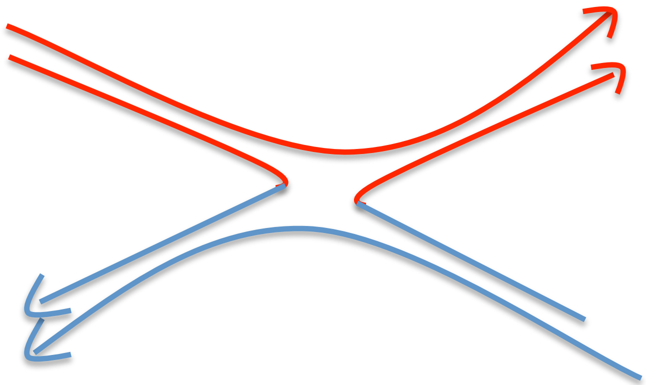


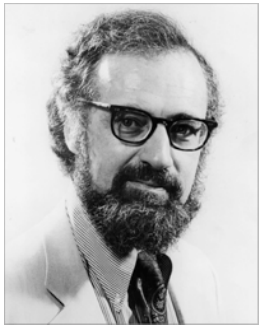
But the plasma is a very good conductor, right?

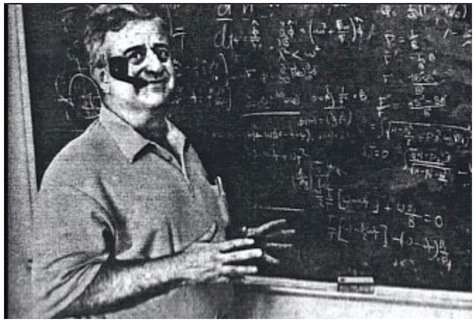
Right. **The RHS becomes important *not* because collisions are large, but because sharp gradients of the magnetic field give rise to a large current (hence the term *current layer*).**

One Way to Get Reconnection Going: the Tearing Mode

The tearing instability

[Furth, Killeen & Rosenbluth (FKR) ‘63; Coppi *et al.* ‘76]





The tearing instability

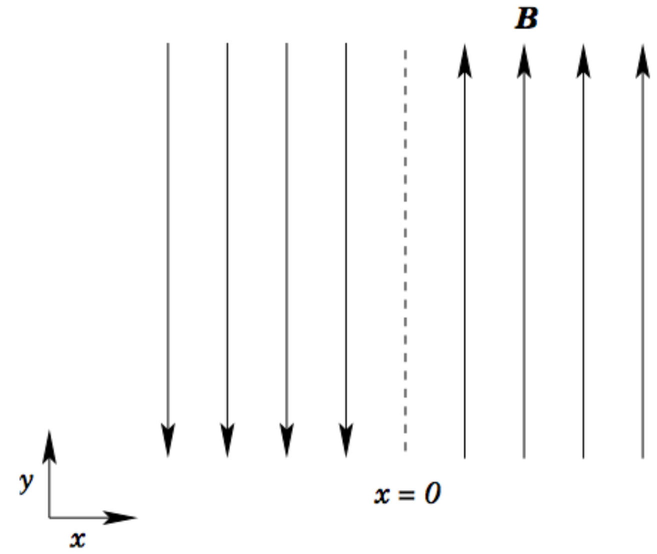
[Furth, Killeen & Rosenbluth (FKR) '63; Coppi *et al.* '76]

$$\mathbf{B}_0 = B_{0y} f(x)\hat{\mathbf{y}}; \quad \mathbf{v}_0 = 0$$

Take MHD eqs:

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}) + \eta \nabla^2 \mathbf{B}$$

$$\rho \frac{d\mathbf{v}}{dt} = -\nabla p + \frac{1}{c}\mathbf{J} \times \mathbf{B}$$



(Fitzpatrick's book)

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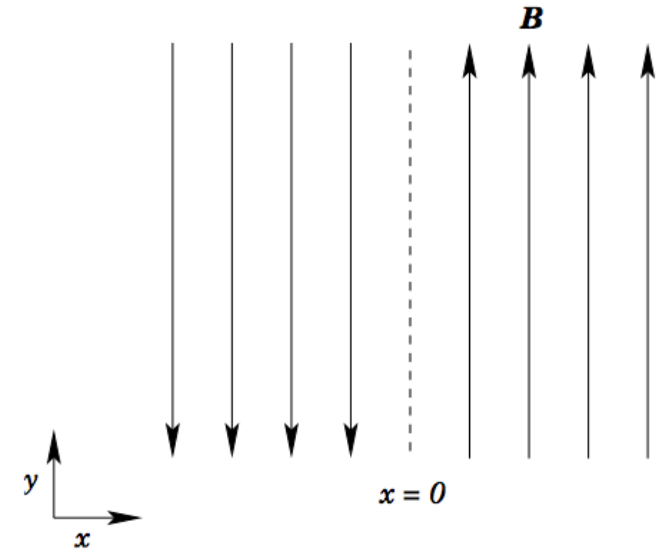

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Linearise (assume $\nabla \cdot \mathbf{v} = 0$):

$$\gamma B_x = ikB_{0y} f(x) v_x + \eta \left(\frac{d^2}{dx^2} - k^2 \right) B_x$$

$$\gamma \left(\frac{d^2}{dx^2} - k^2 \right) v_x = ikB_{0y} f(x) \left[\frac{d^2}{dx^2} - k^2 - \frac{f''(x)}{f(x)} \right] B_x$$

Tearing cont'd

Definitions:

$$\tau_H = 1/kB_{0y}; \quad \tau_\eta = a^2/\eta$$

$$\mathbf{v} = \hat{\mathbf{z}} \times \nabla\phi; \quad \mathbf{B} = \hat{\mathbf{z}} \times \nabla\psi$$

'a' is the equilibrium length scale, e.g., f(x) = tanh(x/a)

Normalize lengths: $x/a \to x; \quad ka \to k$

Rescale (for convenience): $i\phi/\gamma\tau_H \to \phi$

$$\psi - f(x)\phi = \frac{1}{\gamma\tau_\eta}\left[\frac{d^2}{dx^2} - k^2\right]\psi$$

$$\gamma^2\tau_H^2\phi = -f(x)\left[\frac{d^2}{dx^2} - k^2 - \frac{f''(x)}{f(x)}\right]$$

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Ordering: $1/\tau_\eta \ll \gamma \ll 1/\tau_H$

Expect growth rate to be intermediate between resistive diffusion (very slow) and ideal MHD (very fast)

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It's a reconnecting mode: expect *ideal MHD* to be valid *away* from the reconnection layer (**outer region**), and *resistive* effects to be important *in* the reconnection layer (**inner region** = boundary layer)

Tearing cont'd

Outer region: $\phi = \dfrac{\psi}{f(x)}; \quad f(x)\left[\dfrac{d^2}{dx^2} - k^2\right]\psi = f''(x)\psi$

Overlap region: $x \ll 1 \rightarrow f(x) \approx x \Rightarrow \psi'' = 0$

For a reconnecting mode, ψ(0) must be finite. Need even solution.

$$\psi \approx \psi_0 + |x|\psi_0'$$

This solution is discontinuous at x=0. A measure of that discontinuity is the *tearing instability parameter:*

$$\Delta' = \left[\frac{d}{dx}\ln\psi\right]_{0_-}^{0^+} = \frac{2\psi_0'}{\psi_0}$$

(assuming left-right symmetry for simplicity)

Tearing cont'd

Tearing mode Dispersion Relation:

$$\Delta' = -\frac{\pi}{8}\gamma^{5/4}\tau_H^{1/2}\tau_\eta^{3/4}\frac{\Gamma\left[\left(\hat{\lambda}^{3/2}-1\right)/4\right]}{\Gamma\left[\left(\hat{\lambda}^{3/2}+5\right)/4\right]}$$

where $\hat{\lambda} \equiv \gamma\tau_H^{2/3}\tau_\eta^{1/3}$ Two important limits:

$$\hat{\lambda} \ll 1 \Rightarrow \gamma = 0.55\tau_\eta^{-3/5}\tau_H^{-2/5}\Delta'^{4/5}$$ ⟶ small Δ': "FKR"

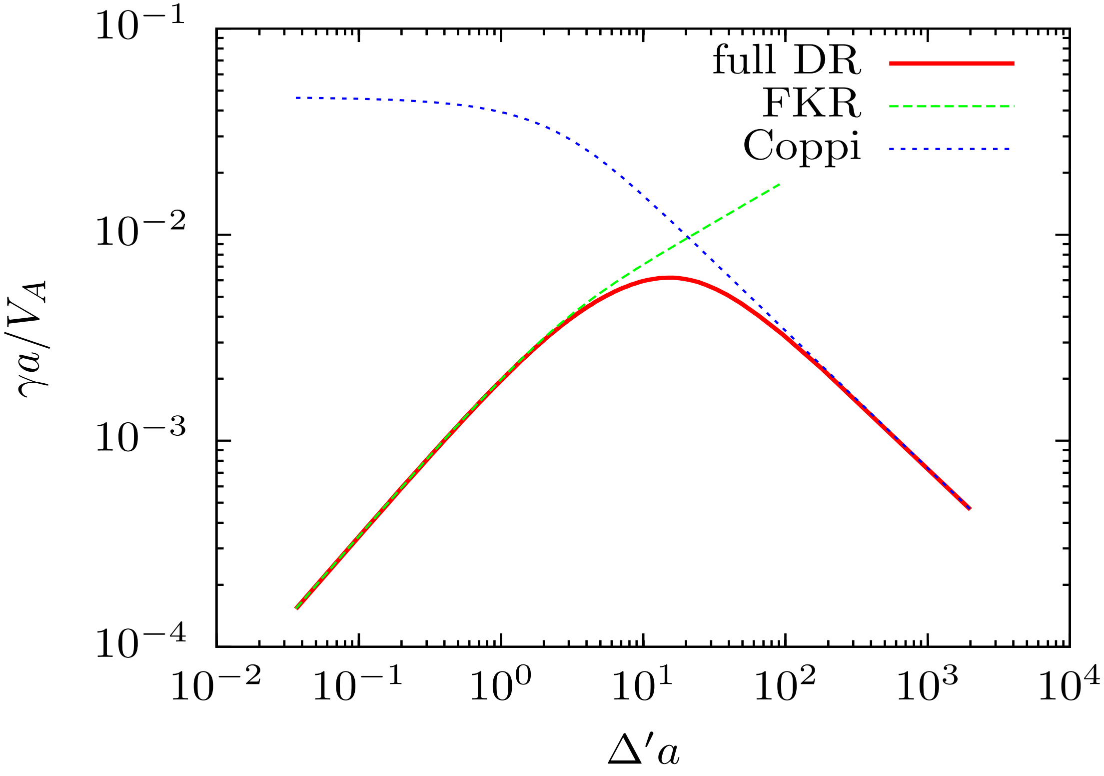
$$\hat{\lambda} \to 1^- \Rightarrow \gamma = \tau_H^{-2/3}\tau_\eta^{-1/3}$$ ⟶ large Δ': "Coppi"

Analytical expressions for Δ' are obtained from solving the outer region eq. for specific equilibrium profiles, *f(x)*. For the Harris sheet:

$$f(x) = \tanh(x) \Rightarrow \Delta' = 2\left(\frac{1}{k} - k\right)$$

Negative Δ' means tearing-stable.

Tearing Dispersion Relation

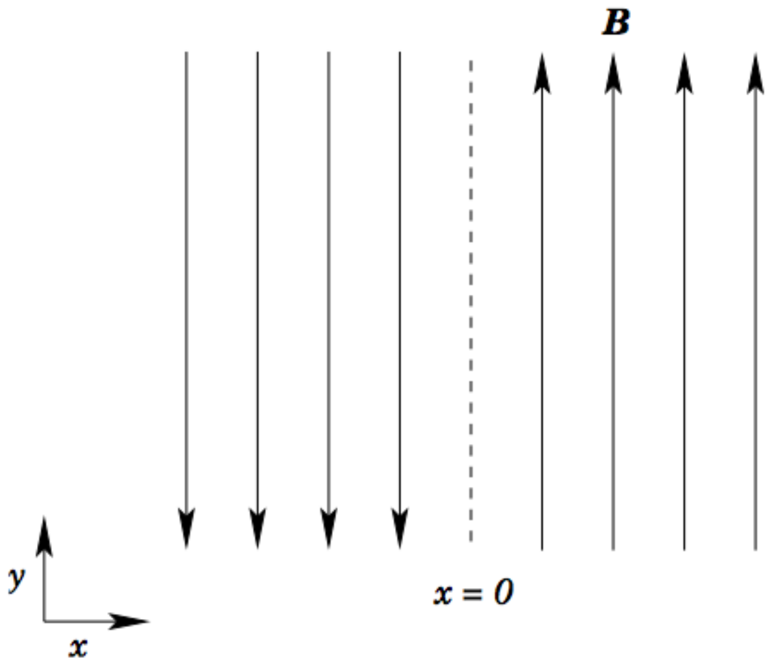


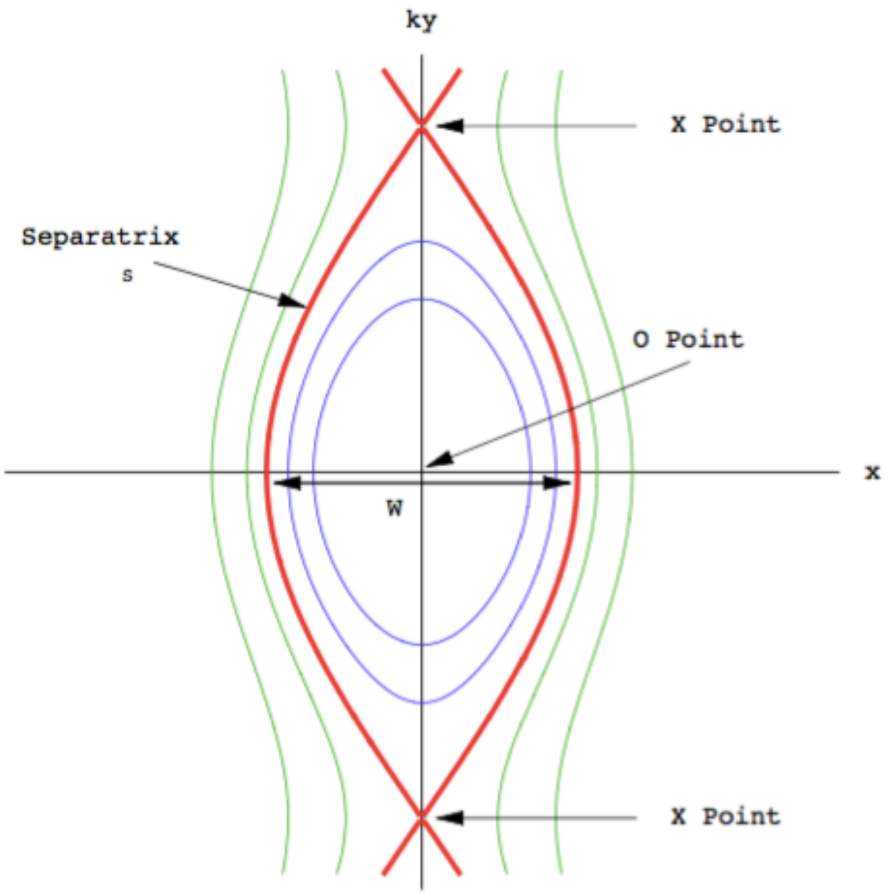
Fastest growing mode can be easily obtained by balancing the FKR and Coppi expressions:

$$\gamma_{\mathrm{FKR}} \sim \gamma_{\mathrm{Coppi}} \Rightarrow k_{\mathrm{max}} a \sim (a/V_A)^{1/4} \tau_\eta^{-1/4}$$

$$\gamma_{\mathrm{max}} \sim (a/V_A)^{-1/2} \tau_\eta^{-1/2}$$

Magnetic Islands





Tearing instability – concluding remarks

- *Nonlinear stage of the tearing instability*
  - Very important as tearing becomes nonlinear at tiny amplitudes, i.e., when $W \sim \delta$. Not covered in this lecture. Key references (Rutherford, Waelbroeck, POEM) provided at the end.

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- *Generalisation to weakly collisional plasmas*
  - Take parameters relevant for modern-day fusion devices:

$$B = 5 \text{ T}; n_e = 10^{20} \text{ m}^{-3}, T_e = 5 \text{ KeV}, a = 1 \text{ m}$$

  - Find from FKR: $\delta \approx 0.15$ mm. Worried?

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  - The ion Larmor radius is about **10 times bigger**. Need **kinetic theory** of tearing modes. Not covered. Refs. at the end.

Nonlinear Reconnection: the Sweet-Parker Model

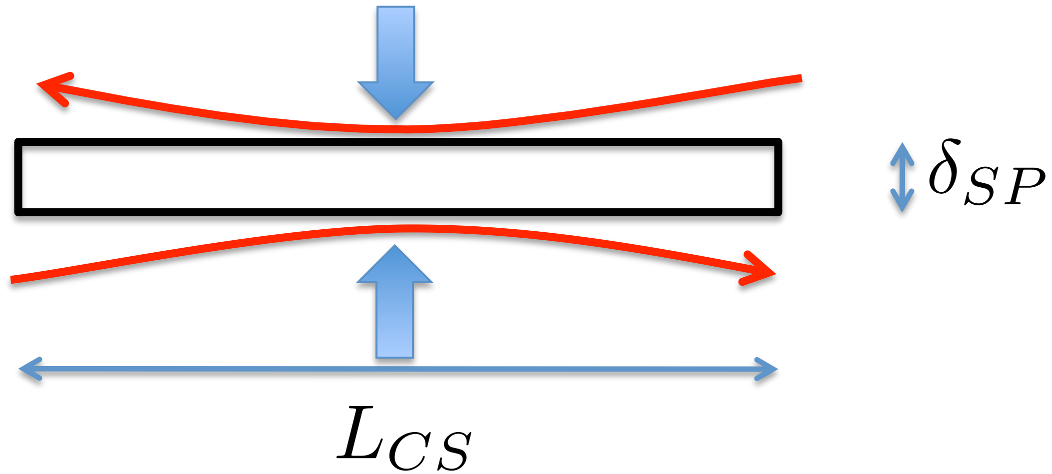
The simplest description of reconnection: the Sweet-Parker model

P. Sweet

E. Parker

Peter Sweet ('58) and Eugene Parker ('57) attempted to describe reconnection within the framework of resistive magnetohydrodynamics (MHD).

The simplest description of reconnection: the Sweet-Parker model



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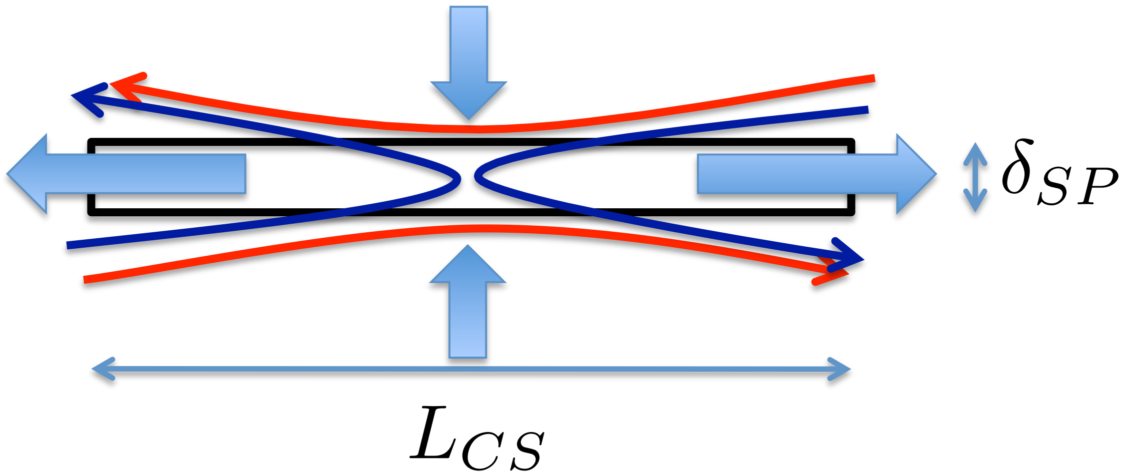


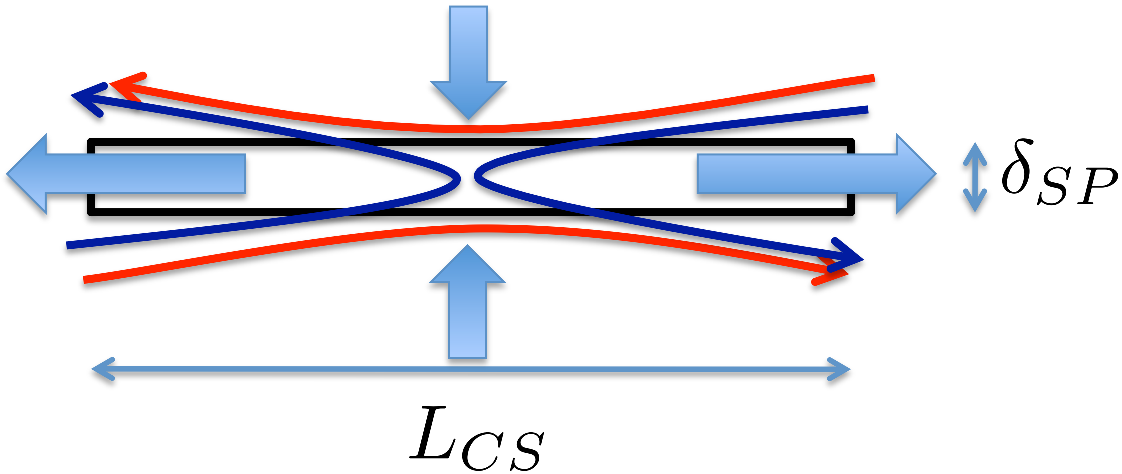
The simplest description of reconnection: the Sweet-Parker model

$$S = L_{CS} V_A / \eta$$

$$\delta_{SP} / L_{CS} \sim S^{-1/2}$$

$$u_{in} / V_A \sim S^{-1/2}$$

$$E \sim c B_0 V_A S^{-1/2}$$



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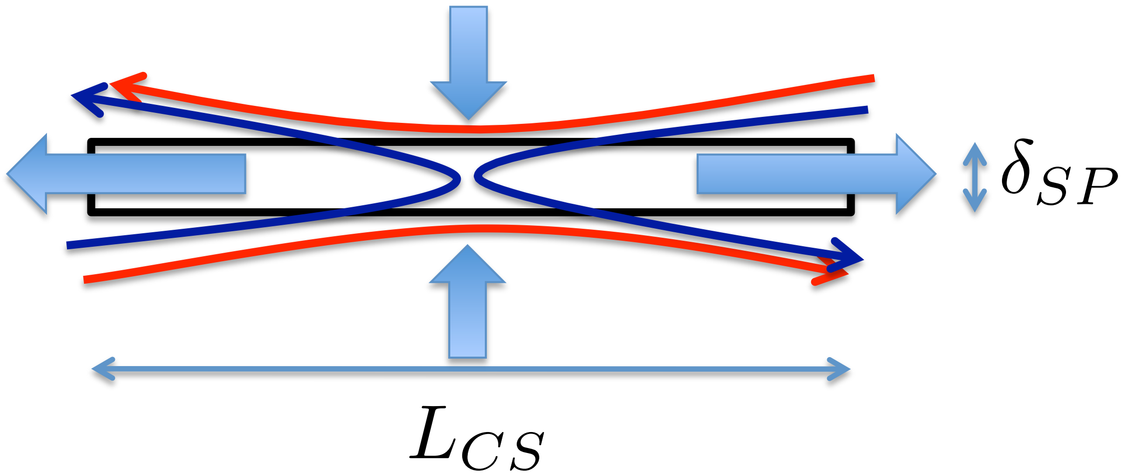


Typical solar corona parameters yield S~10^{14}; this theory then predicts that flares should **last ~2 months**; in fact, flares last **15min – 1h**.

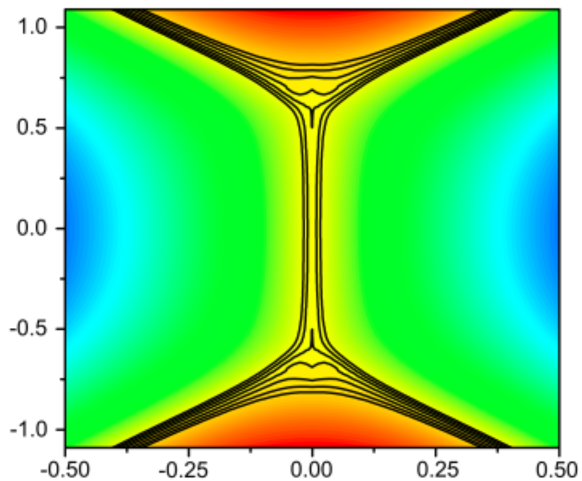
(still, Sweet-Parker (SP) theory was a great improvement on simple resistive diffusion of magnetic fields, which would yield ~3.10^6 years…)

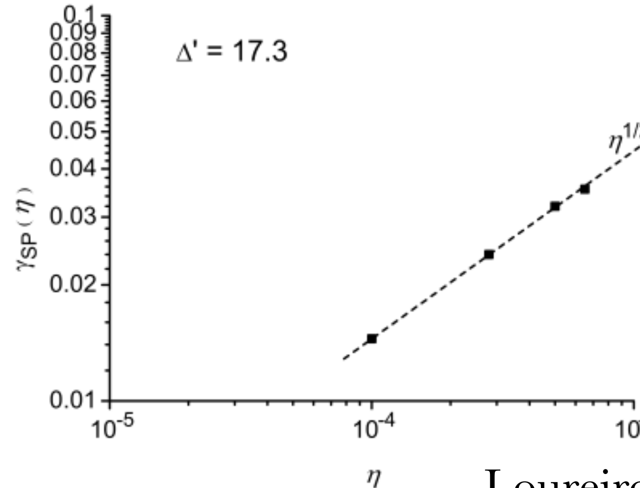
The problem

- Most applications of interest have $S>>1$. SP reconnection rates orders of magnitude too slow to explain observations. This was immediately appreciated – but how to fix it?
- Most notorious attempt to solve the problem within MHD theory was proposed by Petschek ('63) – no convincing evidence for it was ever found.
- Perhaps a more sophisticated description of the plasma is required: kinetic effects?
- *It is now widely believed that kinetic reconnection is fast.*
- However, many astrophysical environments (e.g. *solar chromosphere, interstellar medium, inside stars and accretion disks)* **are sufficiently collisional for MHD to apply, and fast reconnection is expected there.**

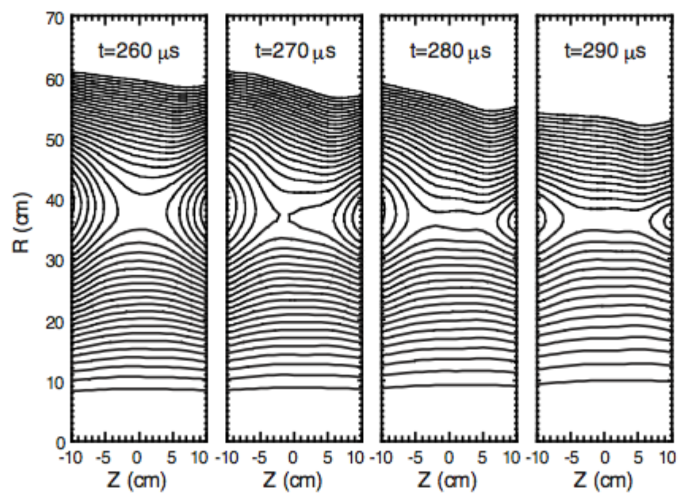
Is the Sweet-Parker model right?

Sure!
For a long time, numerical simulations systematically confirmed the SP model, as did dedicated experiments.

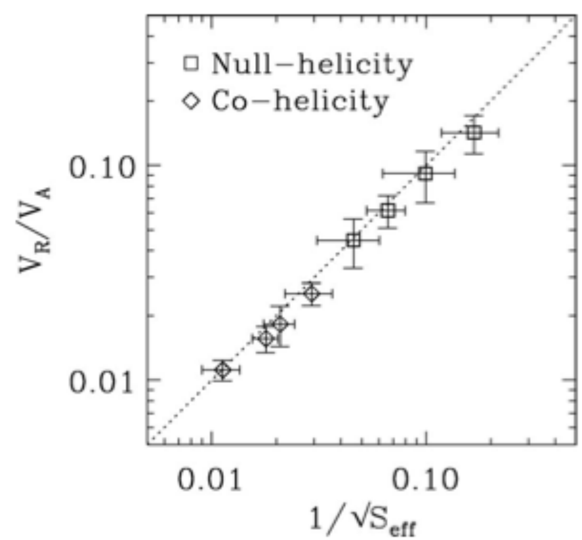




Loureiro '05



Ji '99, Yamada '00



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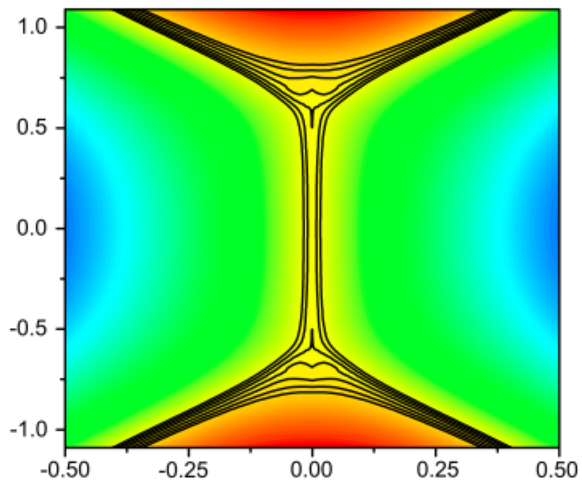
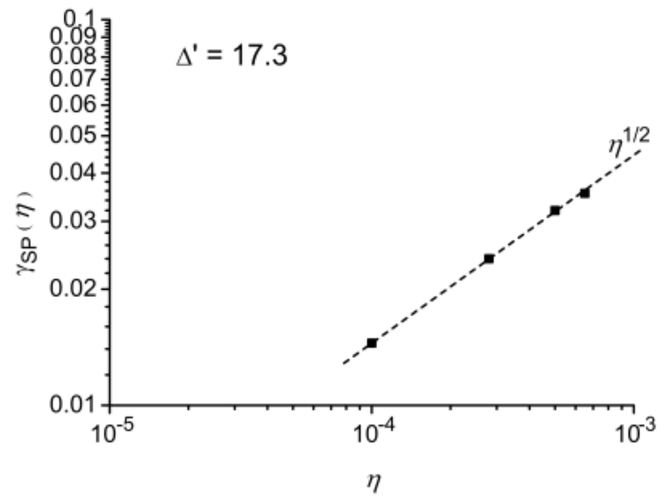
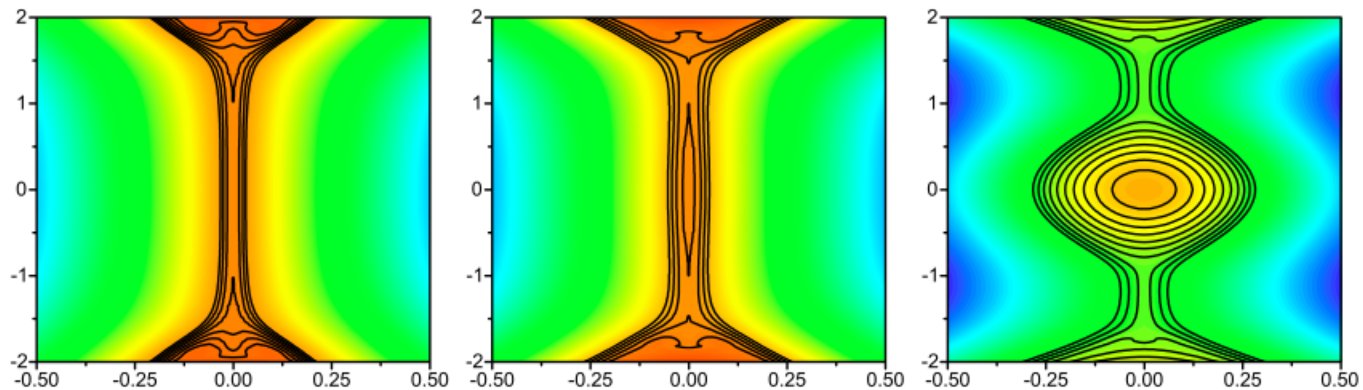




Except…



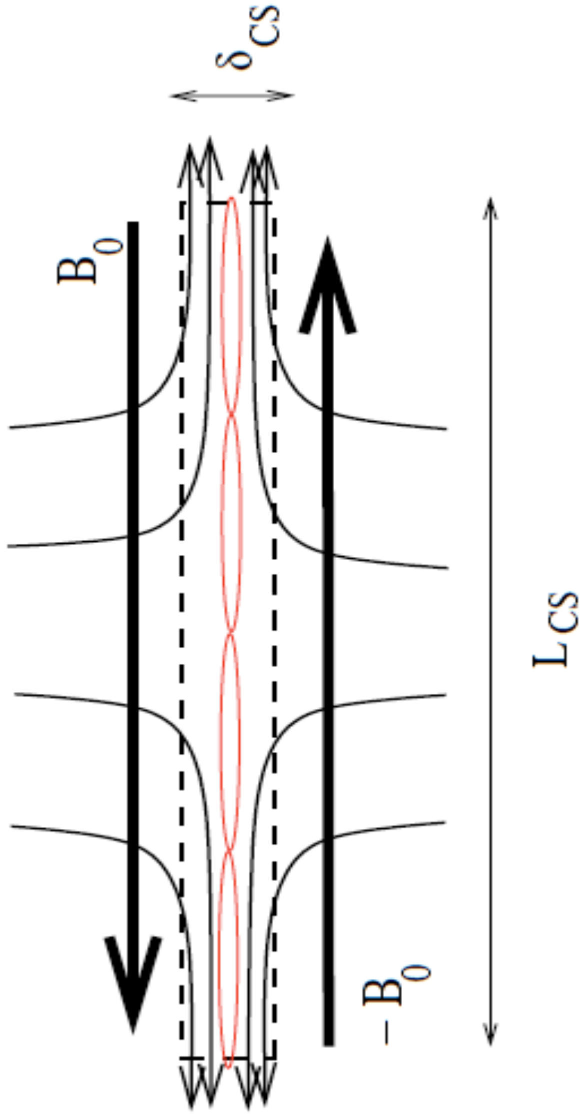
Loureiro *et al.* PRL '05 (see also: Steinolfson 84, Park 84, Biskamp 86)

Beyond Sweet-Parker: Tearing (Plasmoid) Instability of the Current Sheet

Loureiro ‘07, ‘12, ‘13; Samtaney ‘09; Uzdensky ‘10
Lapenta ‘08
Bhattacharjee ‘09; Huang ‘10, ‘12; Baalrud ‘12
Shibata ‘01
Cassak ’09
Etc.

Loureiro and Uzdensky, PPCF **58**, 014021 (2016) (**Review**)

Sweet-Parker current sheet instability

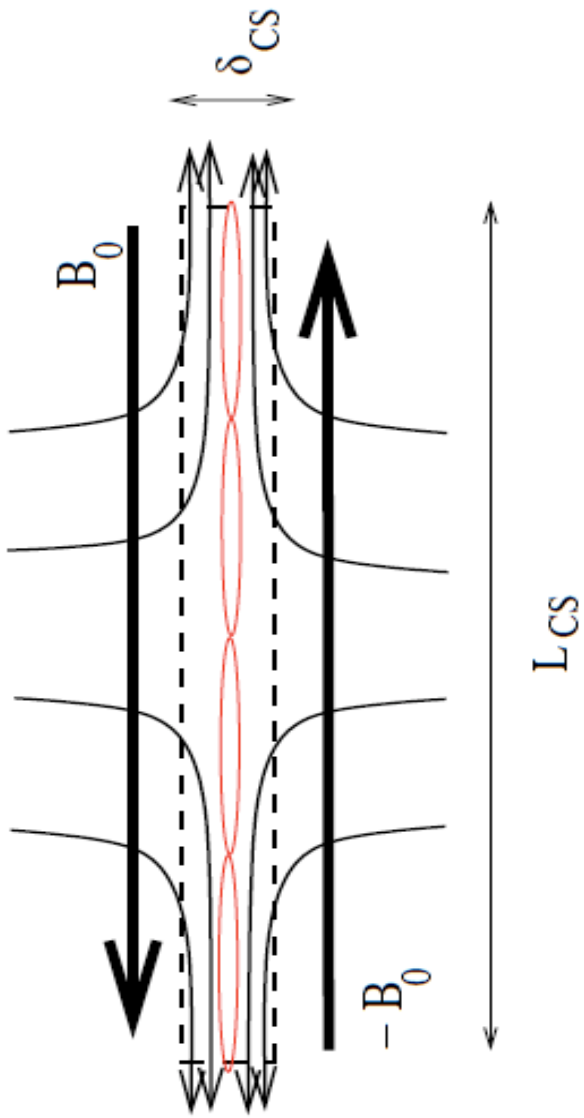


(Loureiro *et al.* '07, '13)

Consider incompressible MHD for simplicity.

1- Obtain analytical form for a SP-like current sheet (nonlinear steady state solution); this describes the background equilibrium

Sweet-Parker current sheet instability



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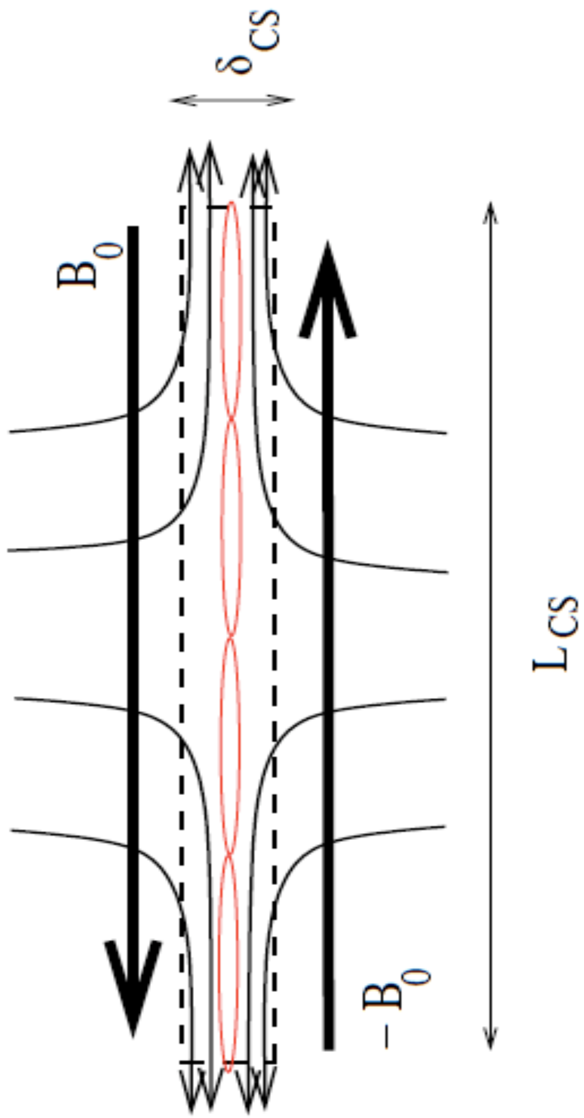
2- Analyse its linear stability using standard tearing-mode instability techniques. Obtain:

$$\gamma_{\max}\tau_A \sim S^{1/4}$$

$$k_{\max}L_{CS} \sim S^{3/8}$$

Sweet-Parker current sheet instability



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Super Alfvénic growth!!

Plasmoids galore!!

Current sheet instability: threshold

Three conditions required for instability:

$$\gamma_{\max}\tau_A \gg 1; k_{\max}L_{CS} \gg 1; \delta_{in}/\delta_{SP} \ll 1$$

Most stringent condition is that on δ_{in} since it bears the weakest dependence on S:

$$\delta_{in}/\delta_{SP} \sim S^{-1/8}$$

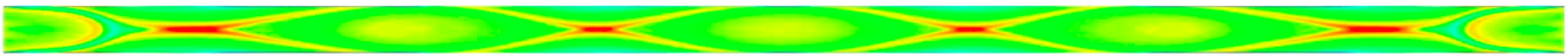
Requiring (non-rigorously!) that this be at most 1/3 yields

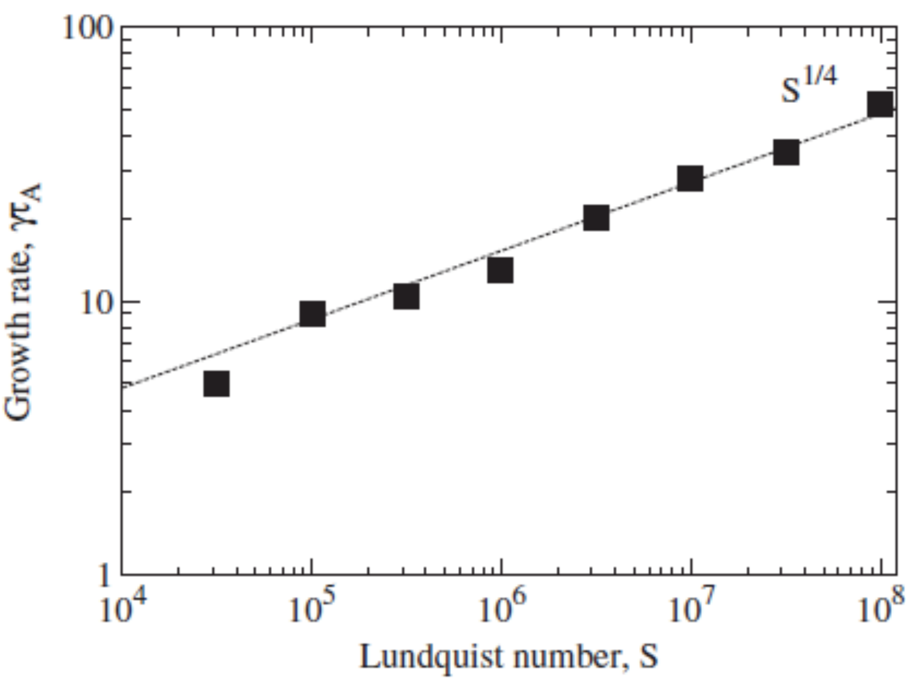
→ *Critical threshold for instability:* $S_c \sim 10^4$

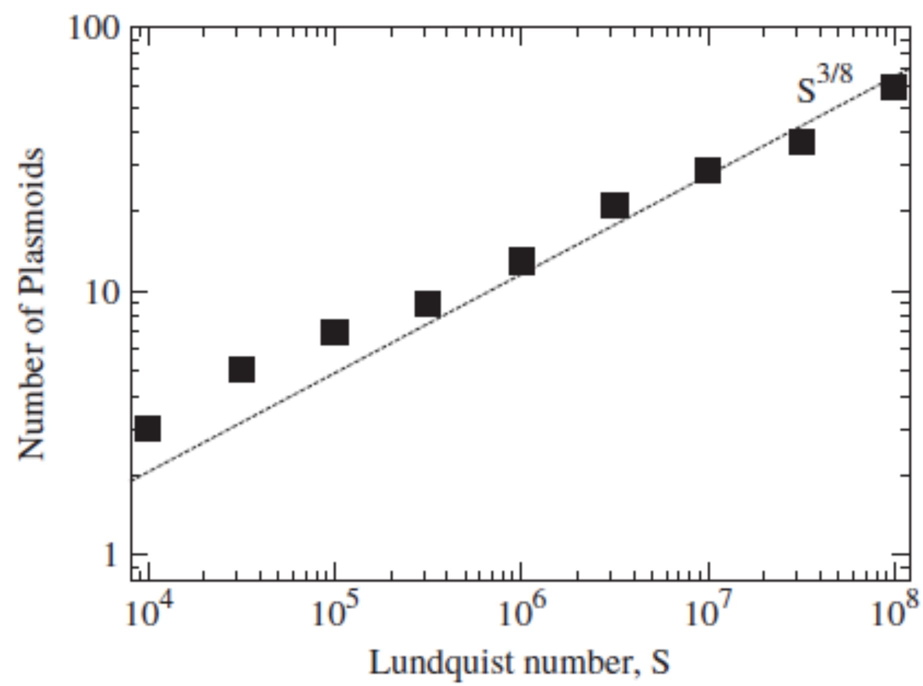
(somewhat similar to the transition to turbulence as the Reynolds number increases in hydrodynamics)

Numerical confirmation of linear theory

Numerical simulations confirm scalings predicted by linear theory (Samtaney *et al.*, PRL '09).





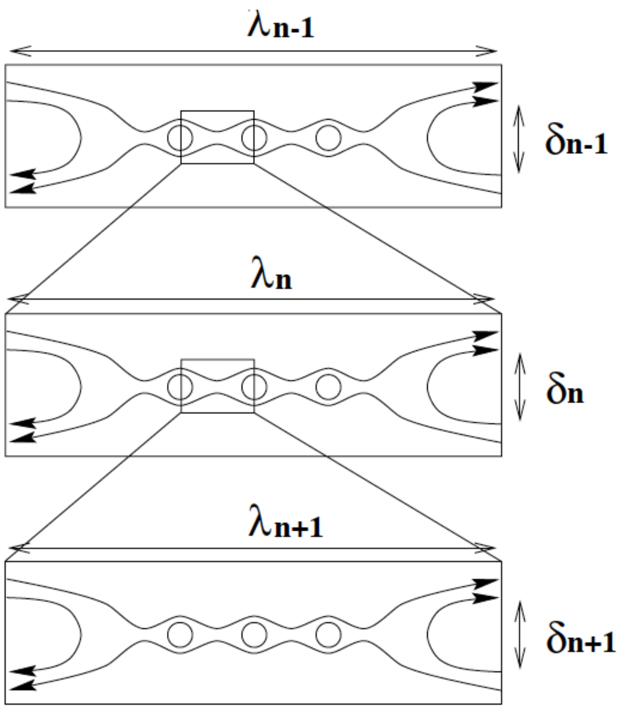


Since been independently confirmed by several different groups.

Nonlinear Theory of Stochastic Plasmoid Chains

Nonlinear stage: hierarchical plasmoid chains

Long current sheets ($S > S_c \sim 10^4$) are violently unstable to multiple plasmoid formation.



(Shibata & Tanuma '01)

- Current layers between any two plasmoids are themselves unstable to the same instability if

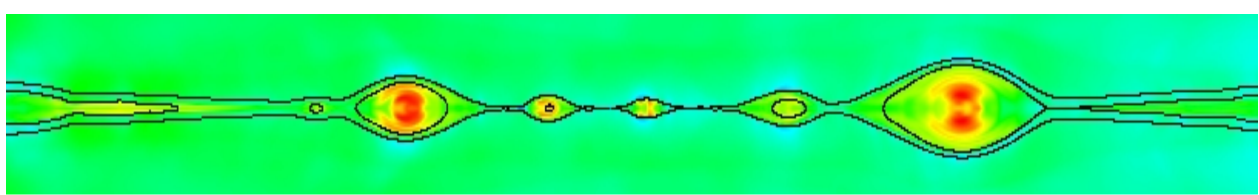
$$S_n = L_n V_A / \eta > S_c$$

- Plasmoid hierarchy ends at *the critical layer*:

$$L_c = S_c \eta / V_A \ ; \ \delta_c = L_c S_c^{-1/2}$$

$$c E_c = B_0 V_A S_c^{-1/2}$$

- $N \sim L / L_c$ plasmoids separated by near-critical current sheets.



Reconnection in stochastic plasmoid chains

Statistical model to describe reconnection in stochastic plasmoid chains (Uzdensky *et al.*, PRL '10).

Key results:

- Nonlinear statistical steady state exists; ***effective reconnection rate*** is:

  $E_{\rm eff} \sim S_c^{-1/2} \sim 0.01$ → fast, independent of S !

- ***Plasmoid flux and size distribution functions*** are:

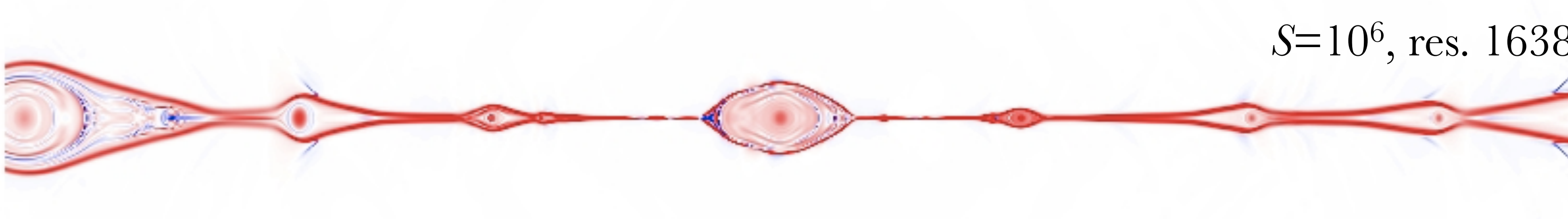
  $f(\psi) \sim \psi^{-2} \quad ; \quad f(w_x) \sim w_x^{-2}$

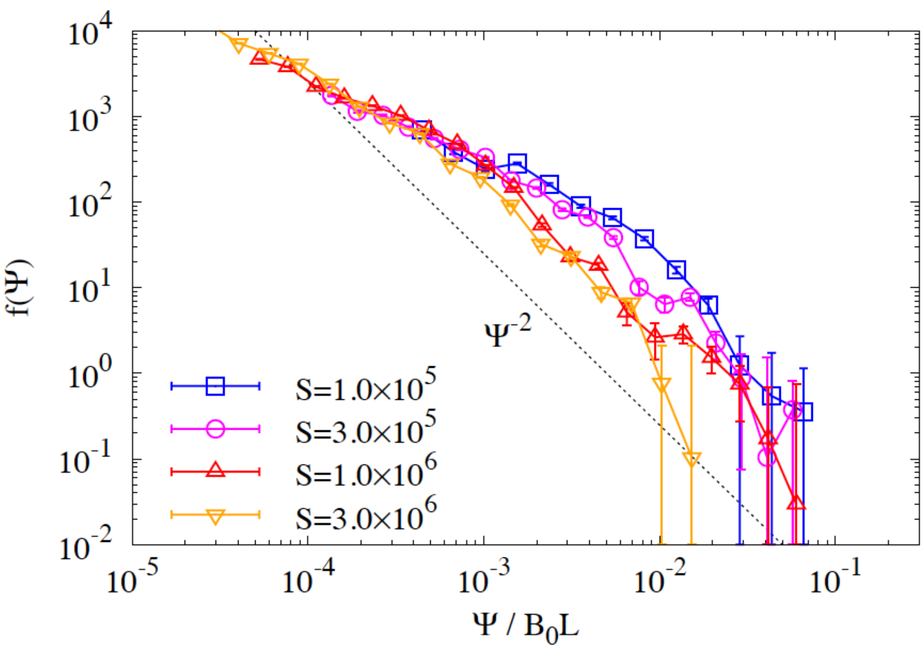
- ***Monster*** plasmoids form occasionally:

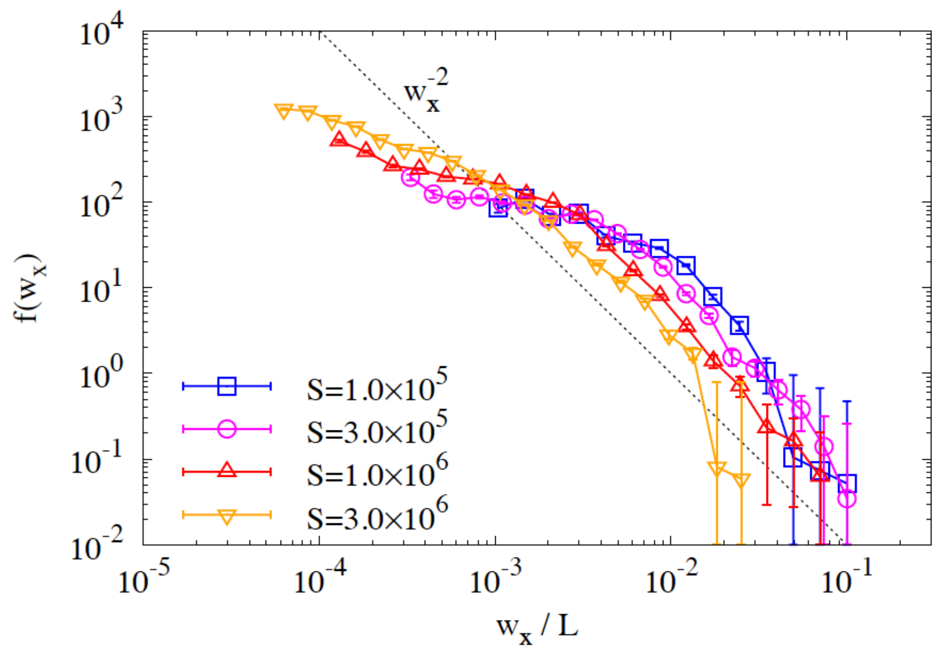
  $w_{\rm max} \sim 0.1L$ → can disrupt the chain, observable

High-Lundquist-number reconnection

Direct numerical simulations to investigate magnetic reconnection at $S>S_c$



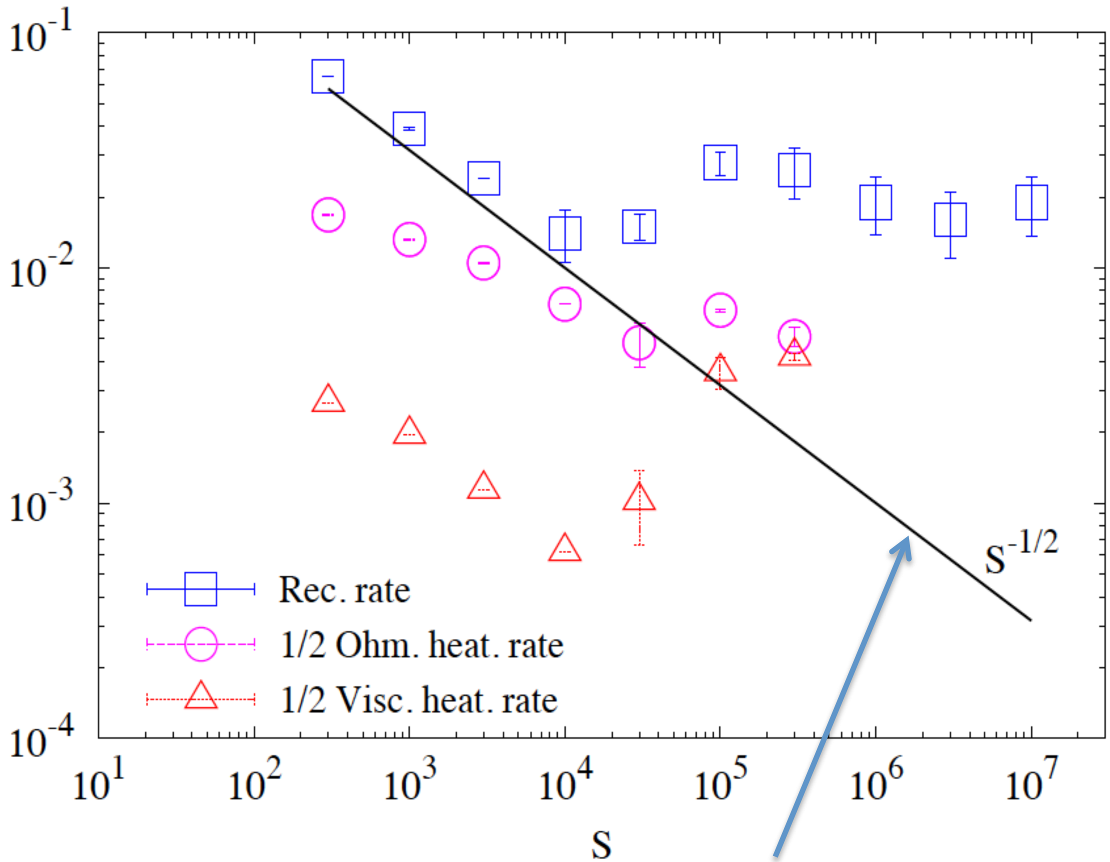




Loureiro *et al.*, Phys. Plasmas '12; see also Huang and Bhattacharjee '12,'13

Reconnection and dissipation rates

Sweet-Parker model breaks down for $S>10^4$



(Loureiro *et al.*, '12)

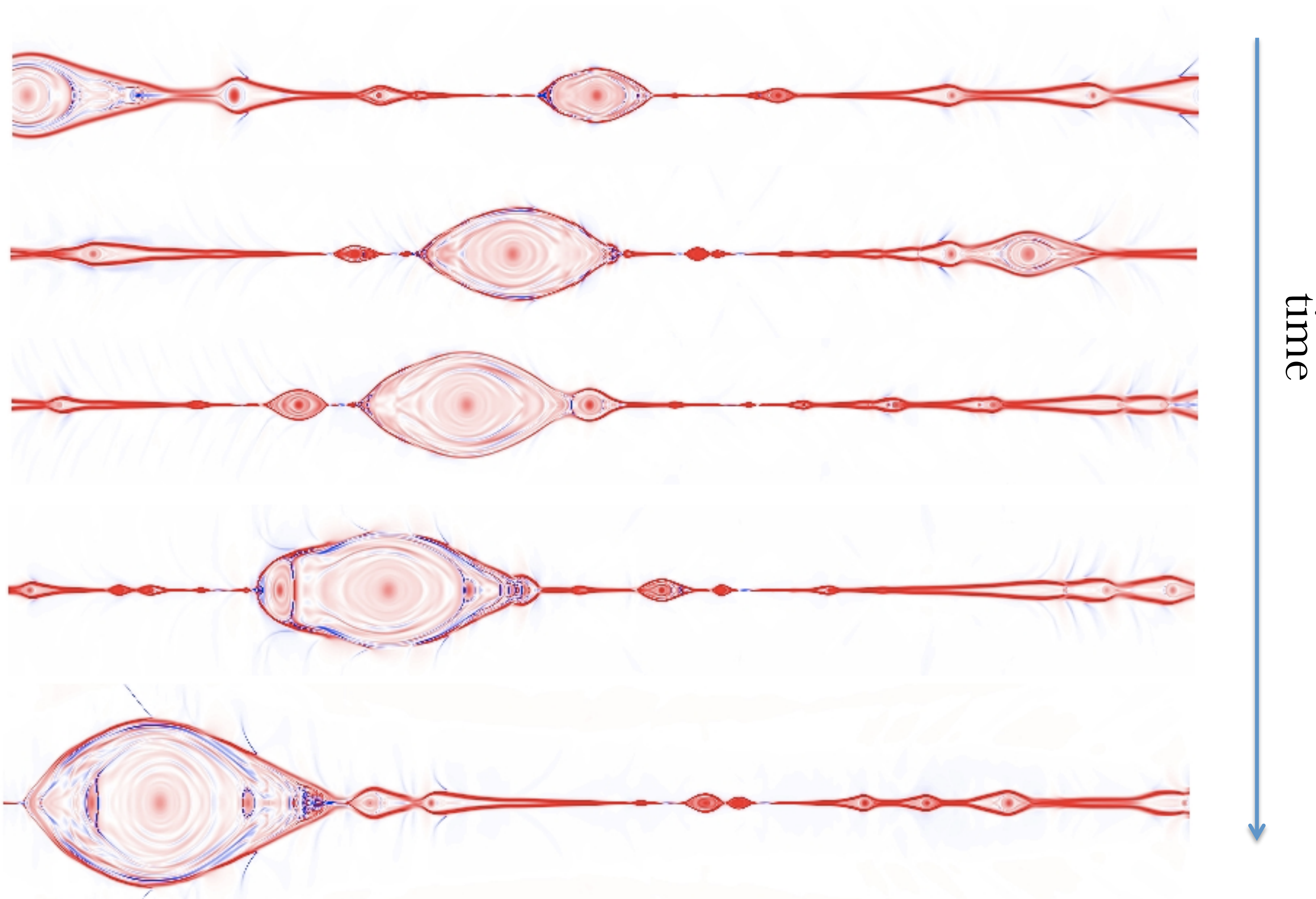
Sweet-Parker rate

$$\tilde{E}_{\rm eff} \approx 0.02$$

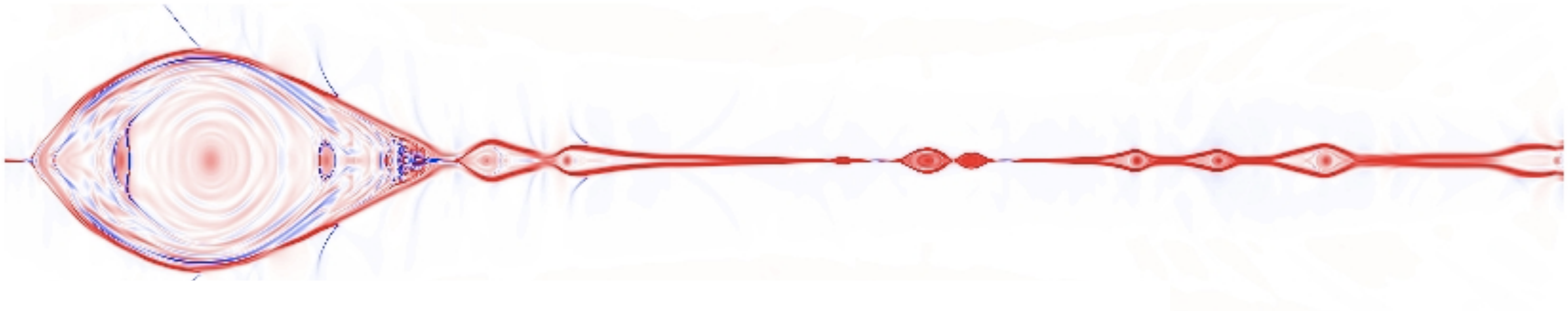
~ 40% *of incoming magnetic energy dissipated into heat*

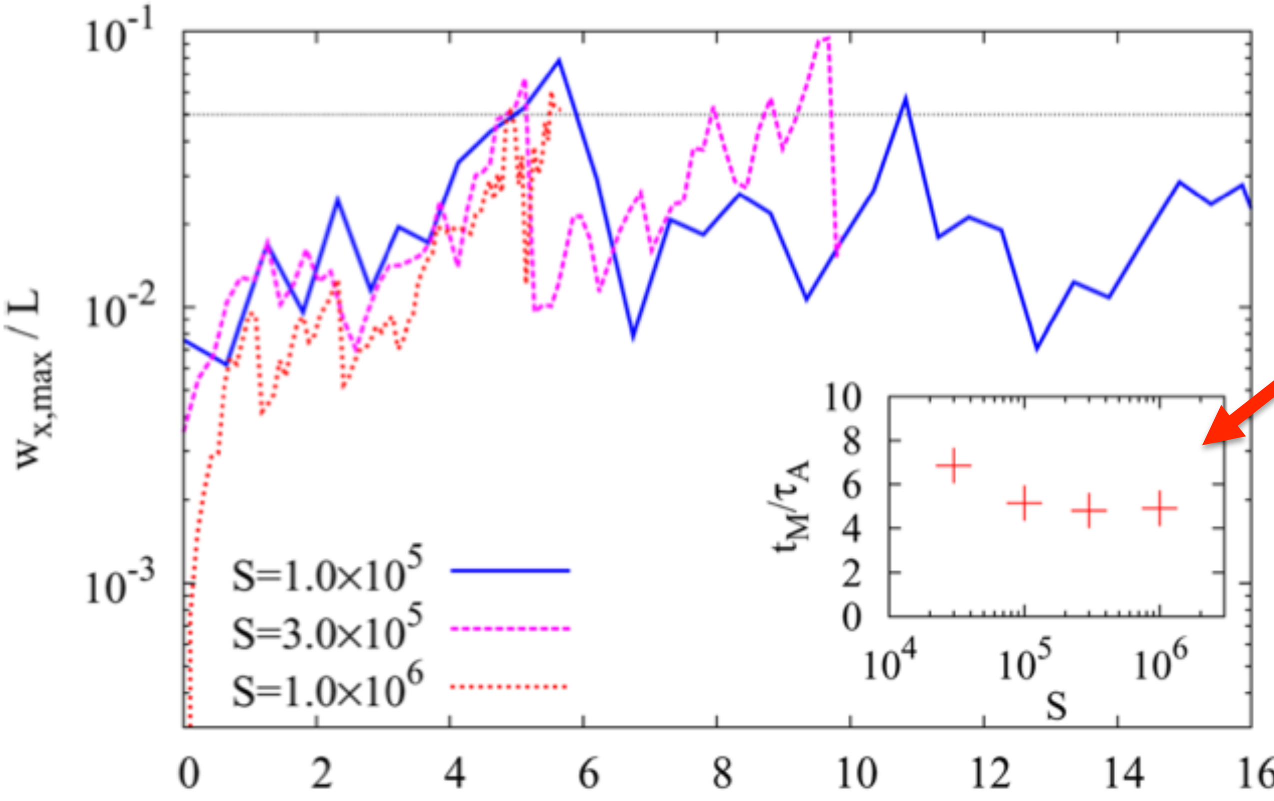
(see also: Lapenta '08, Loureiro '09; Bhattacharjee '09, Huang '10, '12)

Monster plasmoid formation



Monster plasmoid formation



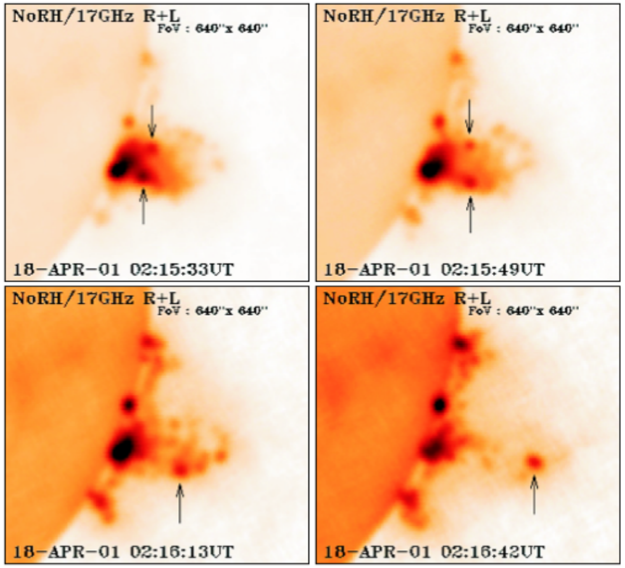


(Loureiro *et al.*, ‘12)

Time-to-monster is a few Alfvén times, independent of *S*

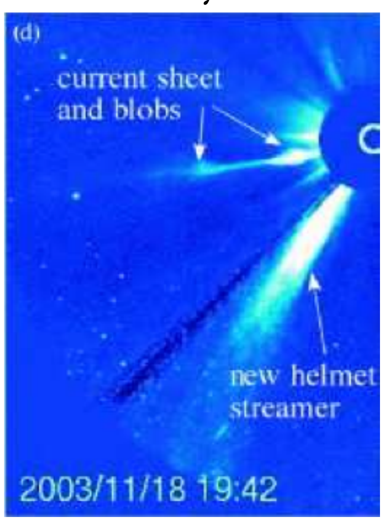
[See Giannios MNRAS ‘13 for an application of monster plasmoids to blazar flares.]

Reality check: plasmoids in flares

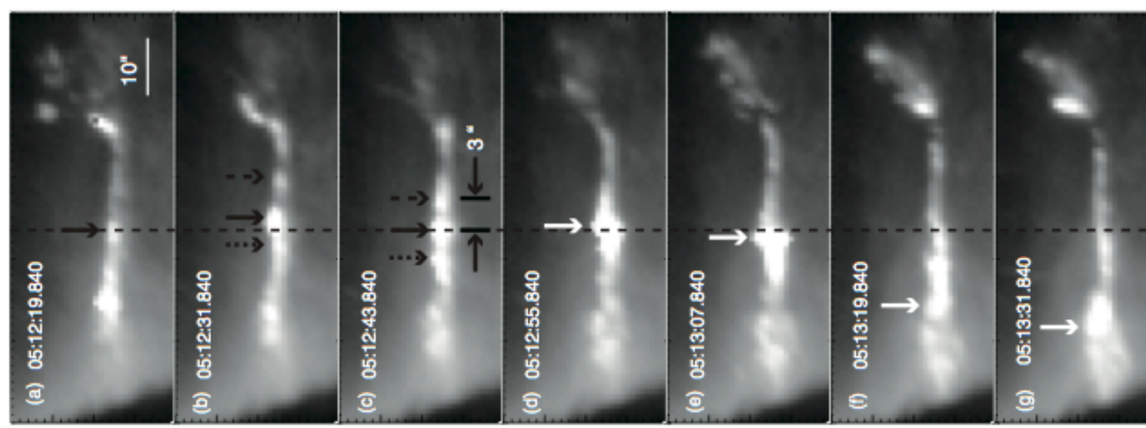


Karlicky & Kliem ‘10

There seems to be abundant evidence for plasmoids in solar flares and in the Earth’s magnetotail (see Lin ‘05, Loureiro ‘13 and refs. therein).



Lin ‘05

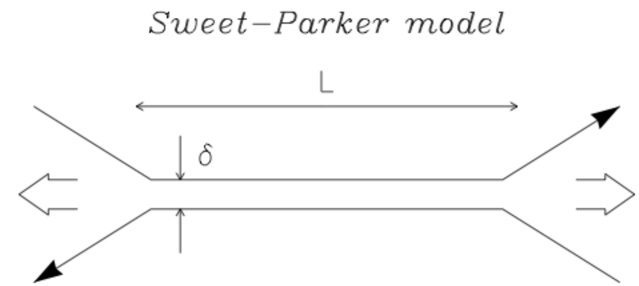


Takasao *et al.* ‘12

Reconnection in a Turbulent Plasma

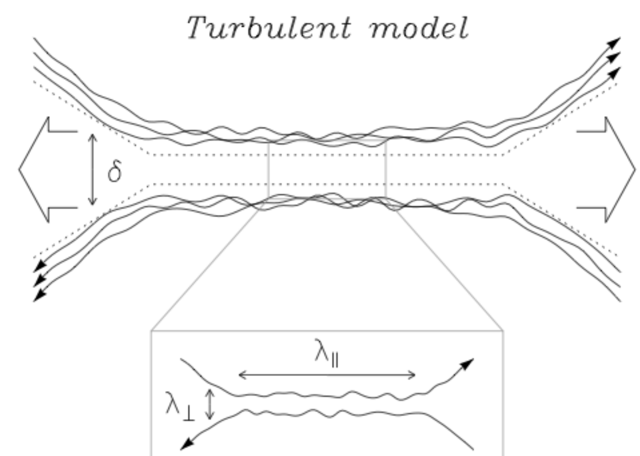
Reconnection in a turbulent background

Many (if not all) environments where reconnection occurs are turbulent – how does that affect reconnection?



Very roughly: it's SP but now the width δ is determined by the typical field line wandering:

$$u_{in} L = V_A \Delta x$$



More precisely:

$$u_{in} = \frac{\lambda_\perp}{\lambda_{||}} \frac{L}{\lambda_{||}} V_A$$

Aspect ratio of each reconnection site.

How many independent reconnection sites there are.

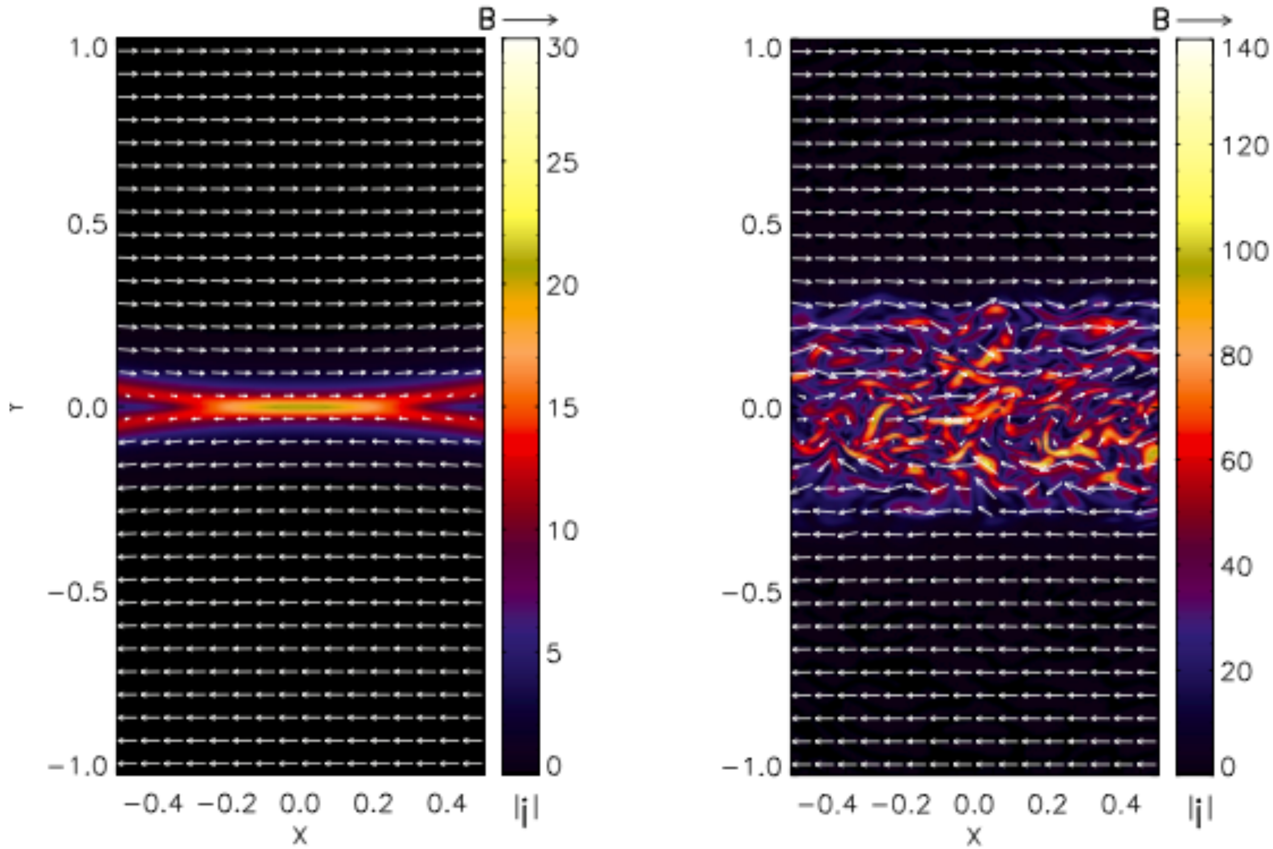
Plug in your favourite turbulence model (e.g., GS95: $\lambda_{||} \sim \lambda_\perp^{2/3}$)

Independent of η.

Lazarian & Vishniac '99

Reconnection in a turbulent background

No background turbulence

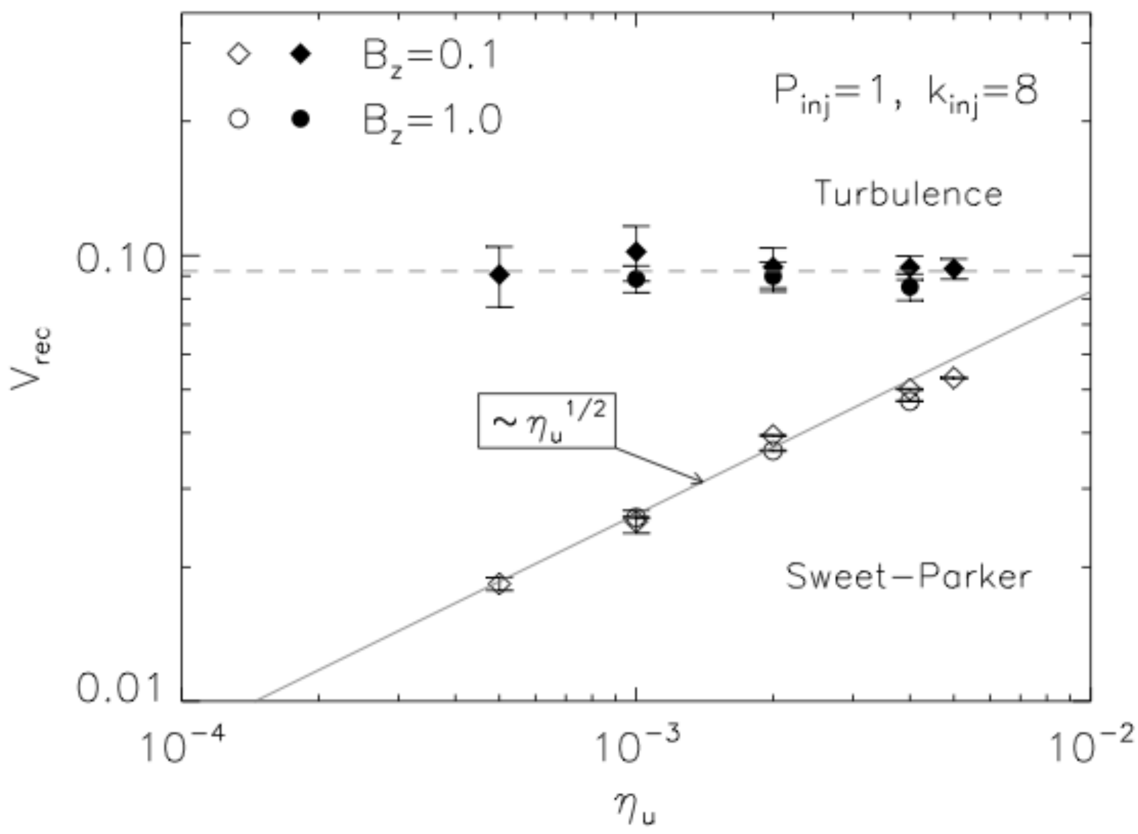


With background turbulence

$S = 10^3$

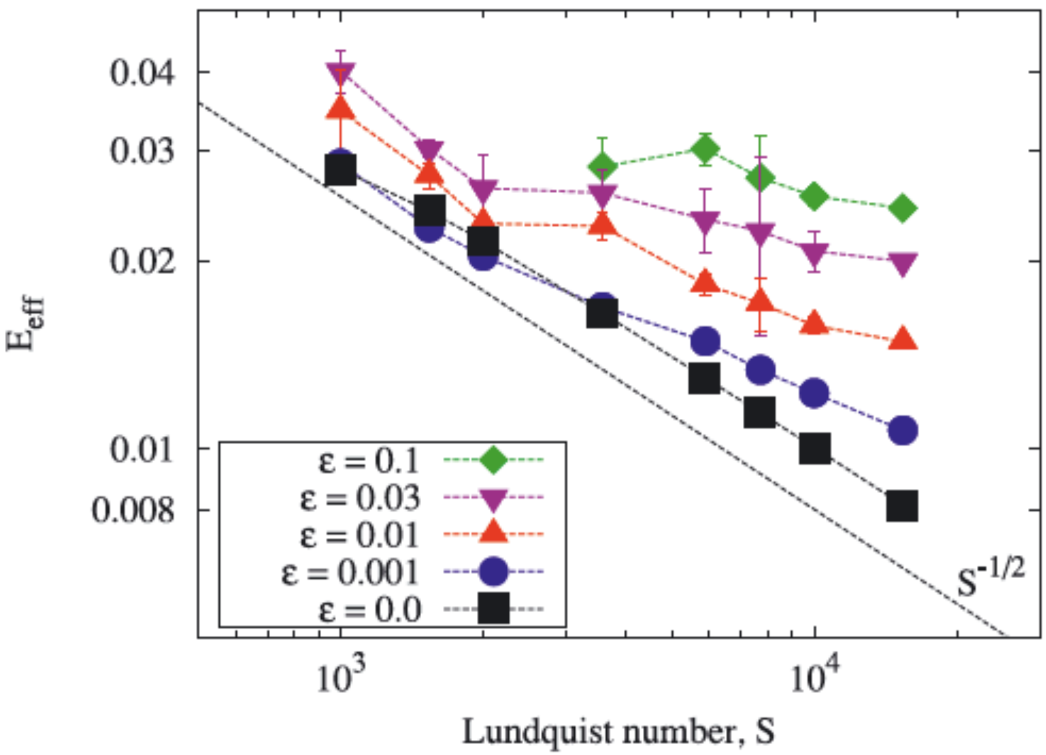
Kowal *et al.* ‘09

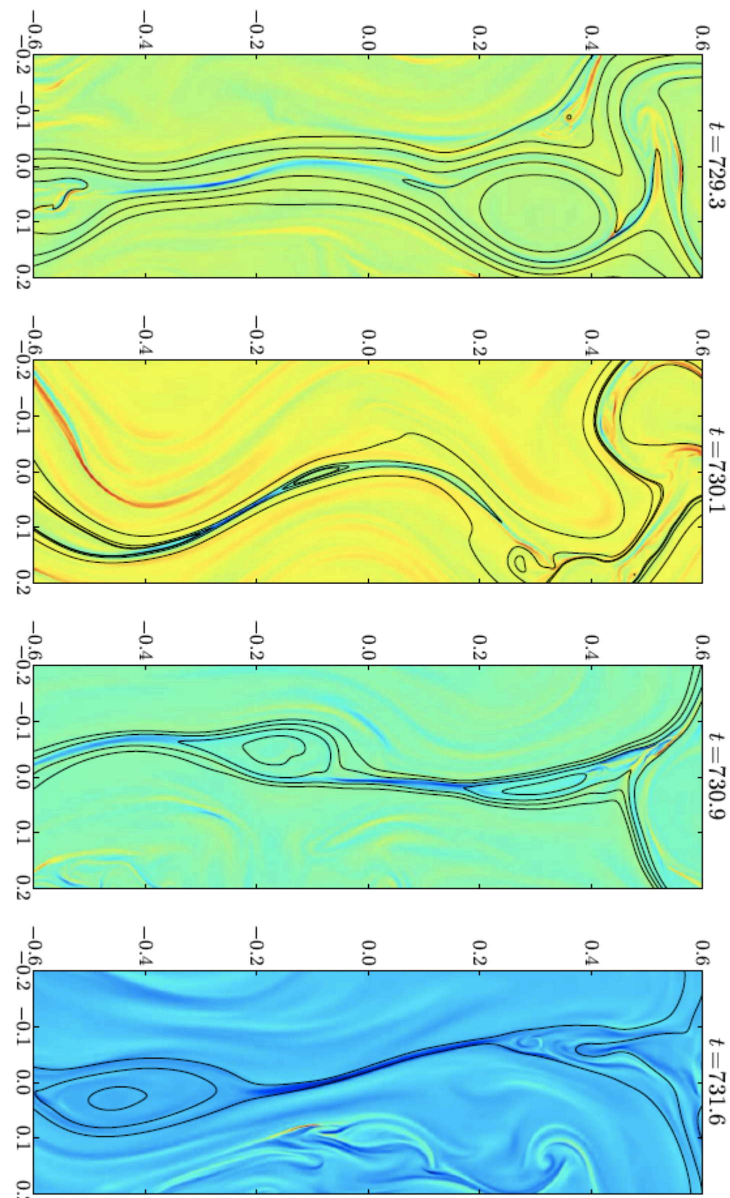
Reconnection in a turbulent background



Kowal *et al.*, '09

Turbulent 2D MHD reconnection is also fast!





Reconnection rate acceleration mechanism here **cannot** be that proposed by LV99 – plasmoids are the likely culprits. <u>How to reconcile these two pictures</u>?

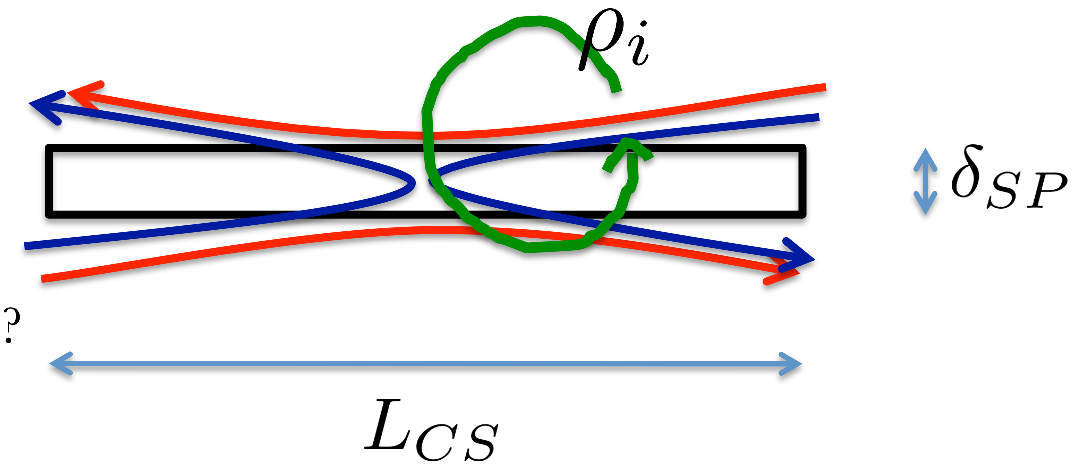
(Loureiro *et al.*, MNRAS '09)

Kinetic Reconnection

Enter kinetics

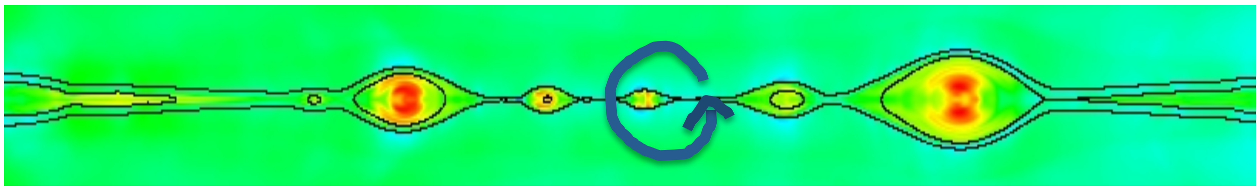
What happens if

$$\delta_{SP} < \rho_i, c/\omega_{pi}$$??



Alternatively, even if $\delta_{SP} > \rho_i, c/\omega_{pi}$, one is almost certain to get:

$$\delta_c < \rho_i, c/\omega_{pi}$$



Generalized Ohm's law

$$\mathbf{E} + \frac{\mathbf{v}_i \times \mathbf{B}}{c} = \eta \mathbf{j}$$

Generalized Ohm's law

$$\mathbf{E} + \frac{\mathbf{v}_i \times \mathbf{B}}{c} = \eta \mathbf{j} + \frac{\mathbf{j} \times \mathbf{B}}{nec}$$

Hall term;
Whistler waves;
c/ω_{pi}

Generalized Ohm's law

$$\mathbf{E} + \frac{\mathbf{v}_i \times \mathbf{B}}{c} = \eta \mathbf{j} + \frac{\mathbf{j} \times \mathbf{B}}{nec} - \frac{1}{ne} \nabla \cdot \mathbf{P}_e$$

Hall term;
Whistler waves;
c/ω_{pi}

Electron pressure tensor;
KAW;
ρ_s

Generalized Ohm's law

$$\mathbf{E} + \frac{\mathbf{v}_i \times \mathbf{B}}{c} = \eta \mathbf{j} + \frac{\mathbf{j} \times \mathbf{B}}{nec} - \frac{1}{ne} \nabla \cdot \mathbf{P}_e - \frac{m_e}{e} \frac{d\mathbf{v}_e}{dt}$$

Hall term;
Whistler waves;
c/ω_{pi}

Electron pressure tensor;
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ρ_s

Electron inertia;
c/ω_{pe}

Generalized Ohm's law

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Hall term;
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pressure
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Electron inertia;
c/ω_{pe}

does NOT break
frozen flux

Break frozen-flux

Generalized Ohm's law

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Hall term; Whistler waves; c/ω_{pi} → does NOT break frozen flux

Electron pressure tensor; KAW; ρ_s

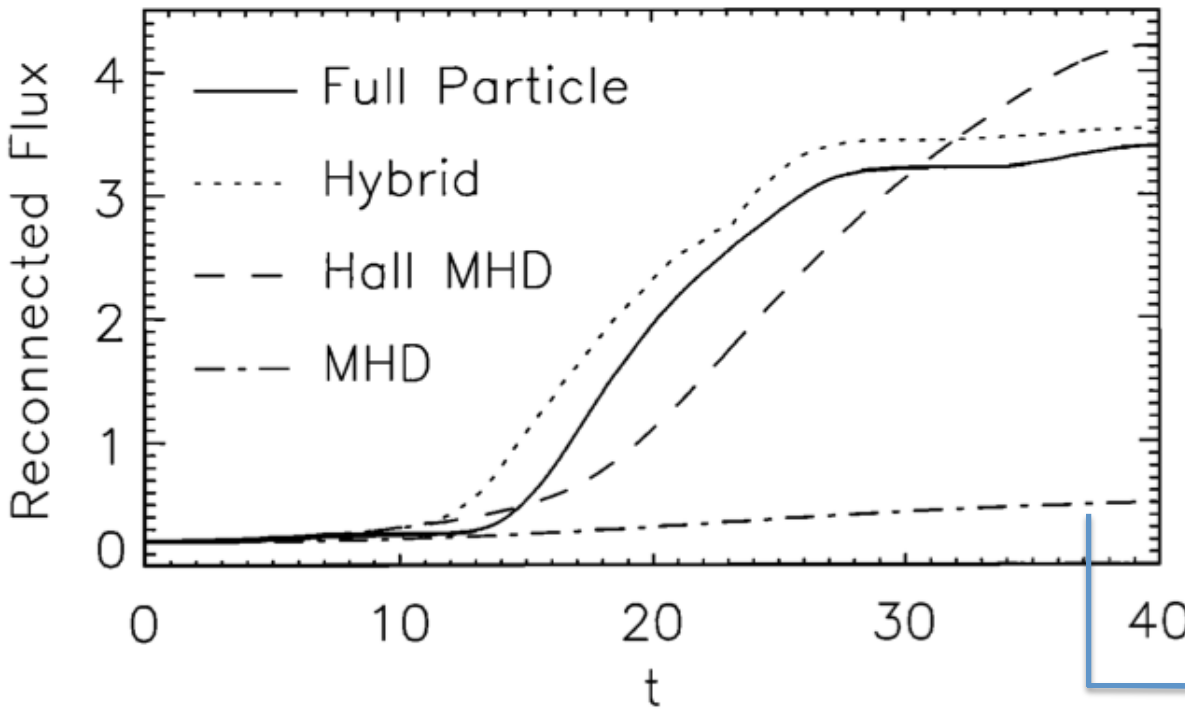
Electron inertia; c/ω_{pe}

→ Break frozen-flux

- MHD is valid at large scales.
- Below c/ω_{pi}, ions and electrons decouple: *plasma is no longer a single fluid*. Electrons remain frozen-in.
- Electrons and field lines decouple below c/ω_{pe} or ρ_e

GEM challenge

What is the minimal plasma description that yields fast reconnection rates?



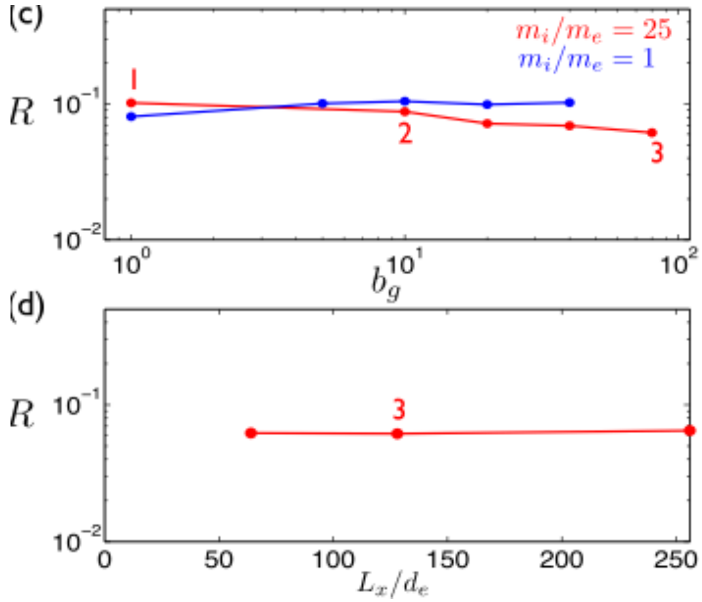
Except for MHD, the reconnection rate found here is **$\sim 0.1 V_A B_0$**

Note that the MHD simulation reported here is at S<S_c, so this line is just the SP rate

GEM challenge, Birn *et al.* '01 (but see Daughton '06)

What is the reconnection rate in collisionless plasmas?

- Is **0.1** a universal constant of nature?



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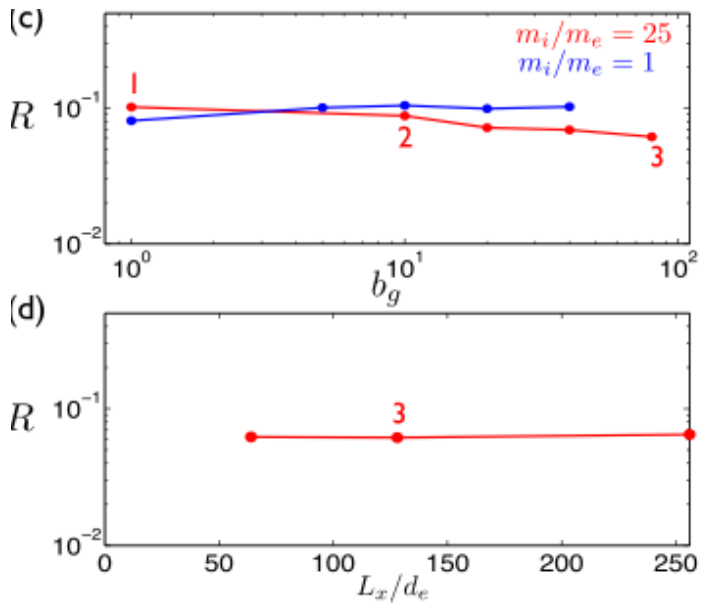

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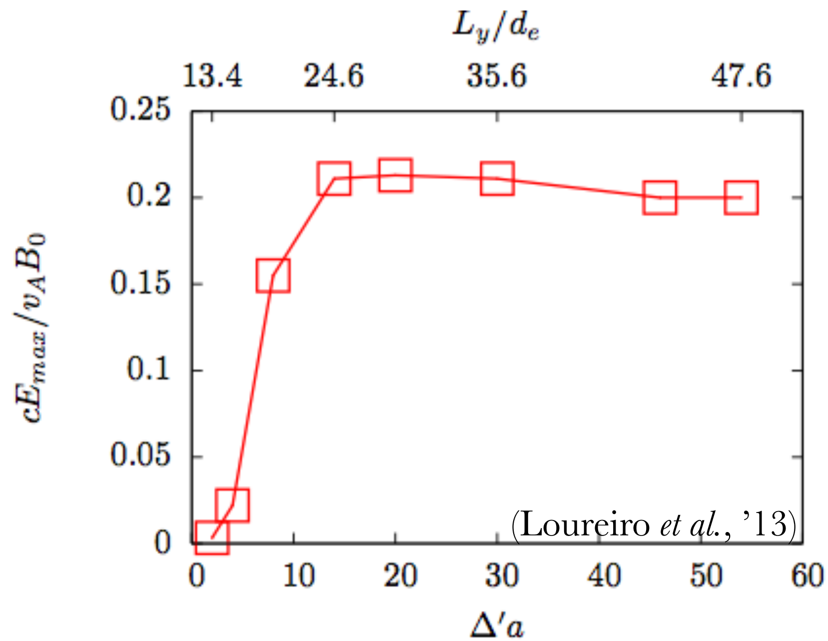
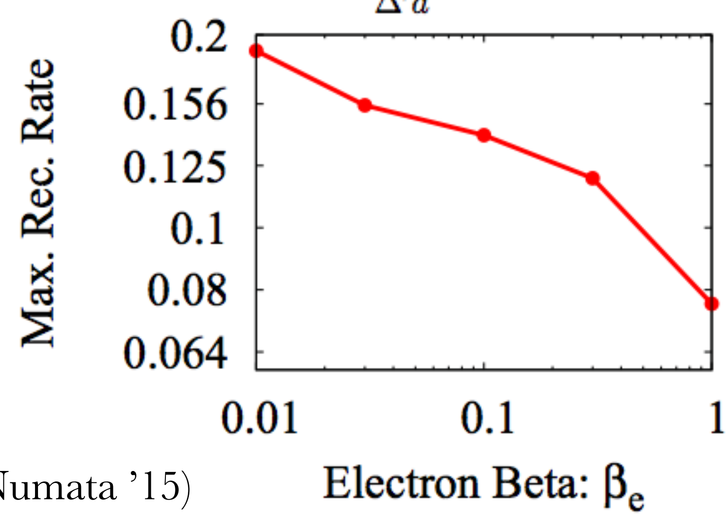


(Loureiro *et al.*, ’13)



(Numata ’15)

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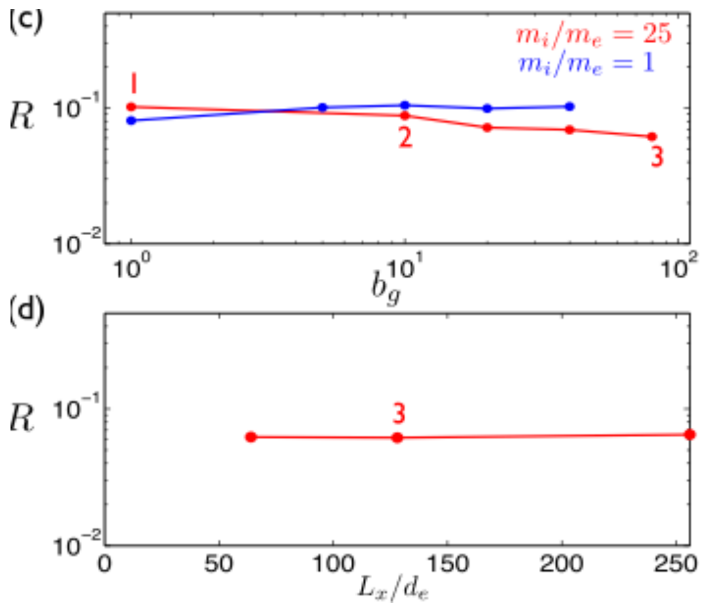

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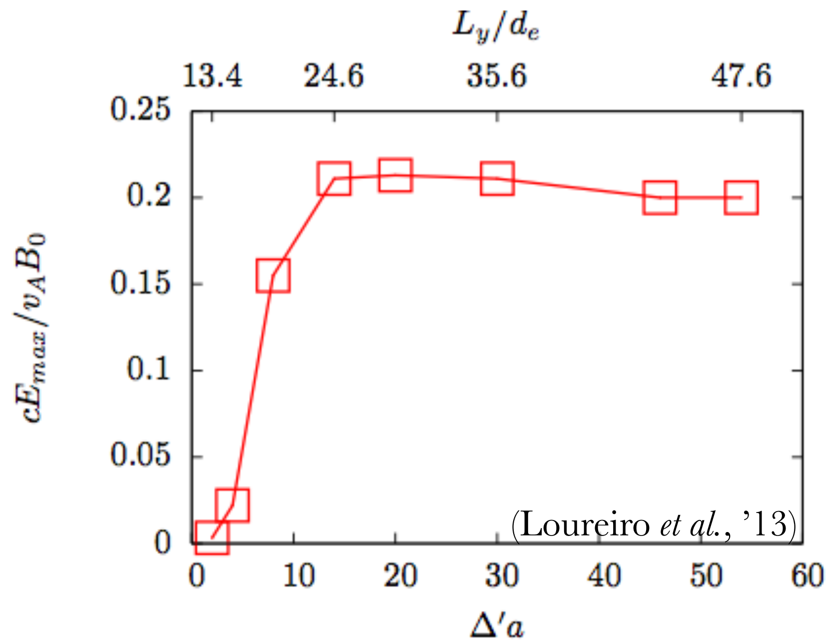

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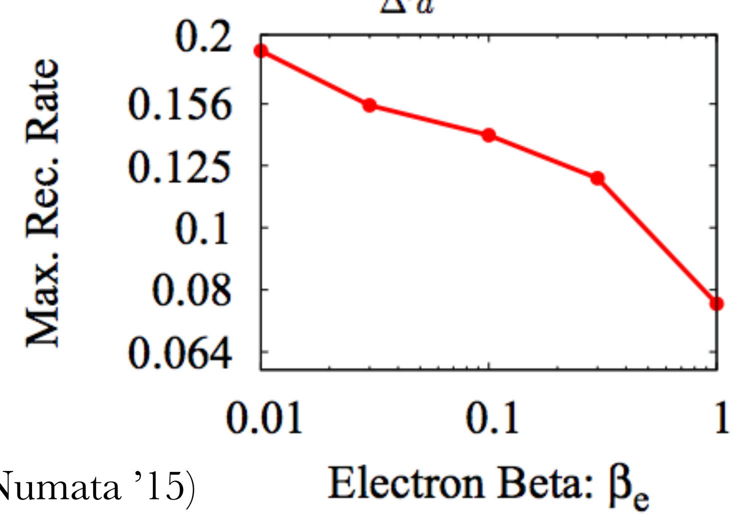


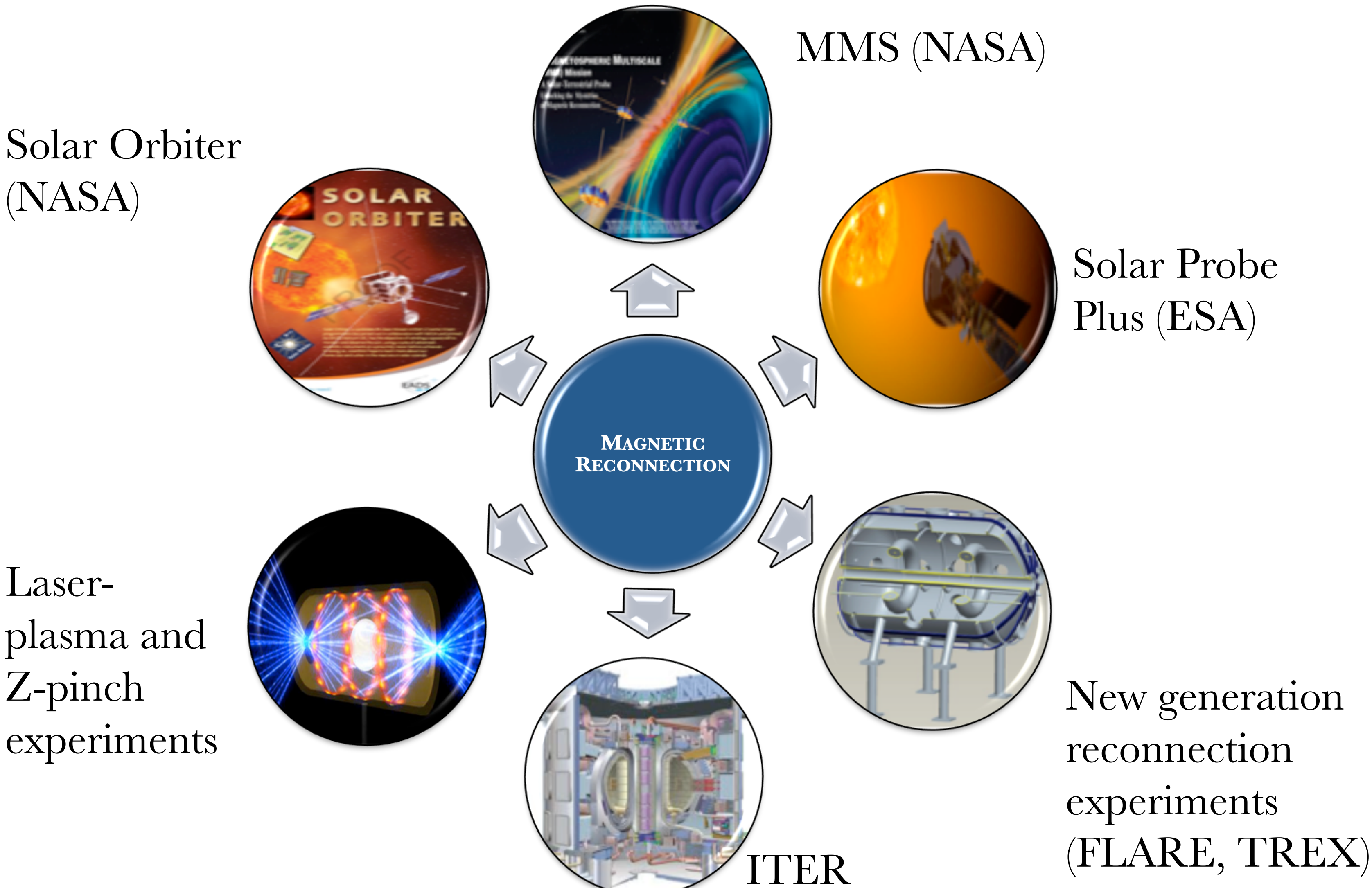
(Numata '15)

To the best of my knowledge, the reconnection rate in collisionless plasmas is an open question.

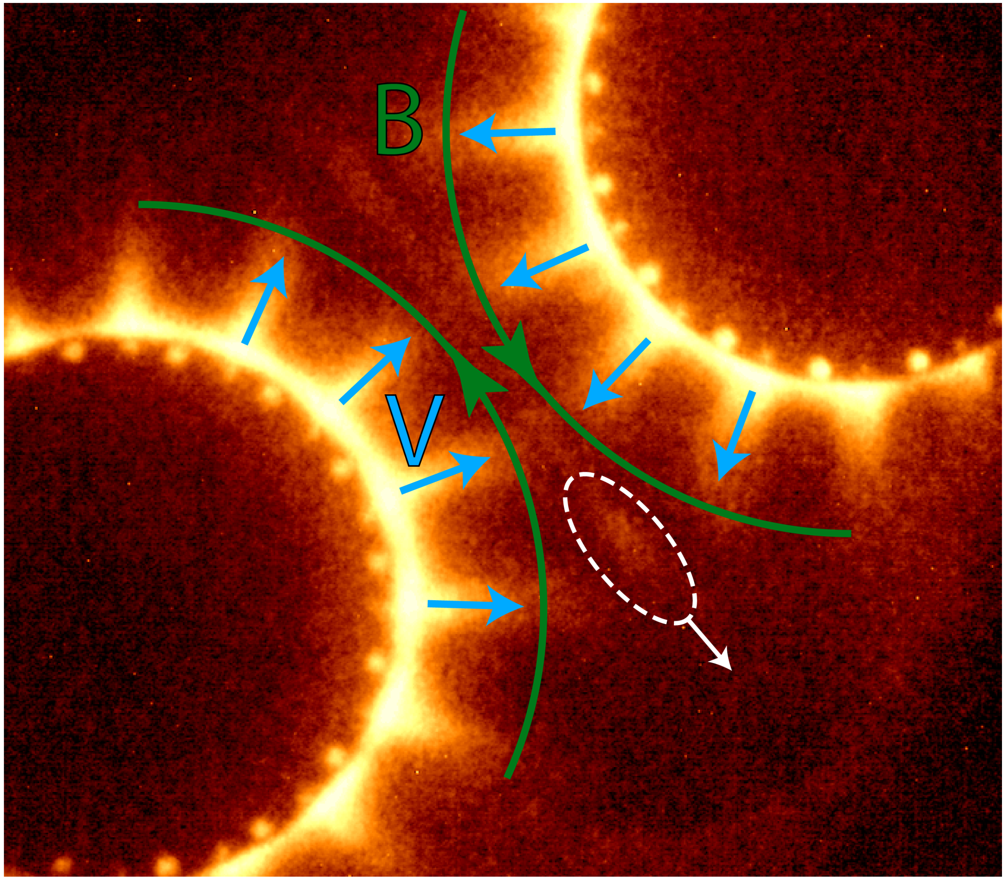
Some open questions

- 3D
- Reconnection onset (the two-timescale problem)
- Energy partition, particle acceleration, dissipation mechanisms
- What is the subgrid model that will reproduce the effect of reconnection on small scales?
- Role of background turbulence?

Exciting times ahead!

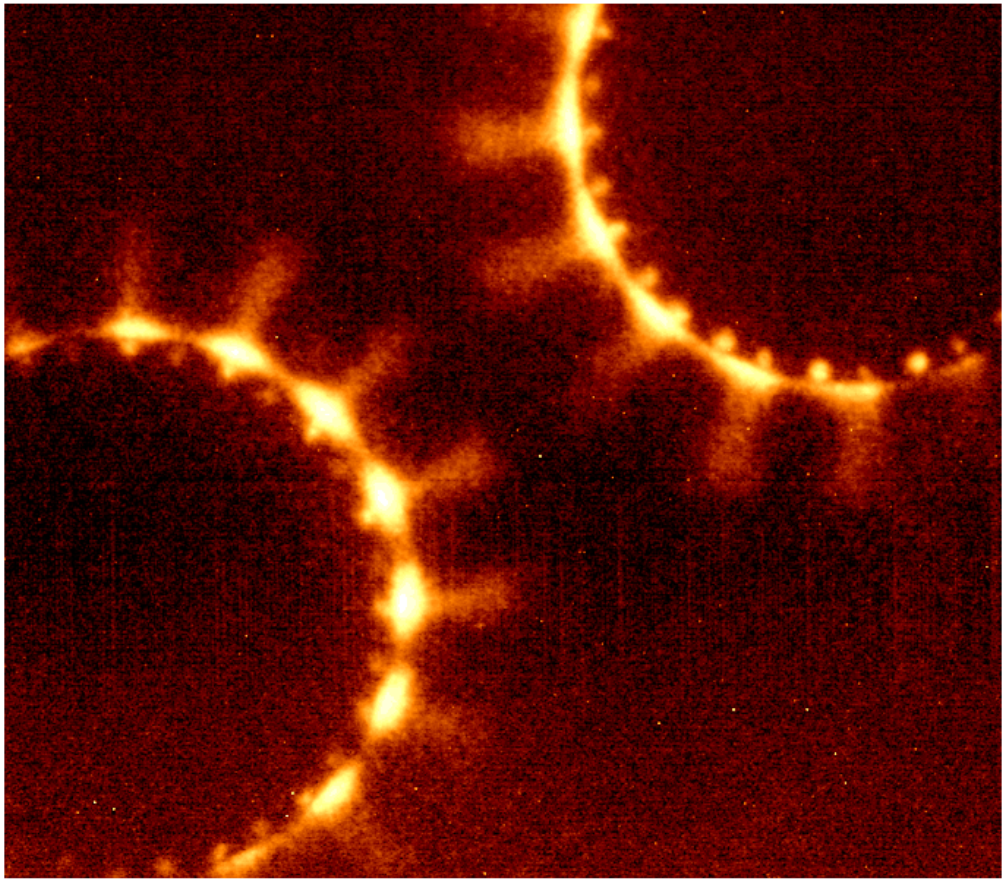


Z-Pinch Reconnection



J. Hare, Lebedev *et al.*
Also Suttle *et al.*, PRL 2016

Z-Pinch Reconnection



J. Hare, Lebedev *et al.*
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Bibliography

Selected references for topics covered or (mentioned) in this talk (this list is NOT exhaustive; many important papers NOT here)

- General:
  - Books by D. Biskamp and Priest & Forbes
  - Recent review papers: Zweibel & Yamada '09, Yamada et al., '10
  - Tutorial: Kulsrud '01

- Tearing mode (fluid):
  - MHD: Furth *et al.* '63, Coppi '75
  - Rutherford '73; Waelbroeck '93 (nonlinear stage)
  - Militello & Porcelli '04, Escande & Ottaviani '04 "POEM", saturation
  - Steinolfson & Van Hoven '84, Loureiro *et al.* '05 (sims.)

- Tearing mode (kinetic):
  - Coppi '65, Drake & Lee '77, Cowley '86, Porcelli '91, Numata '11 (see App. B of Zocco & Schekochihin '11)

- Forced Reconnection:
  - Hahm & Kulsrud '84, Fitzpatrick '03, Cole & Fitzpatrick '04, Comisso '15

Bibliography cont'd

- Sweet-Parker:
  - Parker '57, Sweet '58
  - Biskamp '86, Uzdensky '00

- Petschek '64

- Plasmoids:
  - Shibata & Tanuma '01, Loureiro *et al.* '07,'12,'13, Lapenta '08, Bhattacharjee '09, Daughton '09, Cassak '09, Samtaney '09, Huang '10, '12, '13, Uzdensky '10, Barta '08,'11, etc. **Review:** Loureiro & Uzdensky '15

- Reconnection in a turbulent plasma:
  - Matthaeus & Lamkin '86, Lazarian & Vishniac '99, Kowal '09, Loureiro '09, Karimabadi '13

- Trigger: Bhattacharjee '04, Katz *et al.* '10, Uzdensky & Loureiro, '16

- Reconnection experiments: see Yamada's review