Magnetic Reconnection: an introduction

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2017 SULI Introductory Course in Plasma Physics

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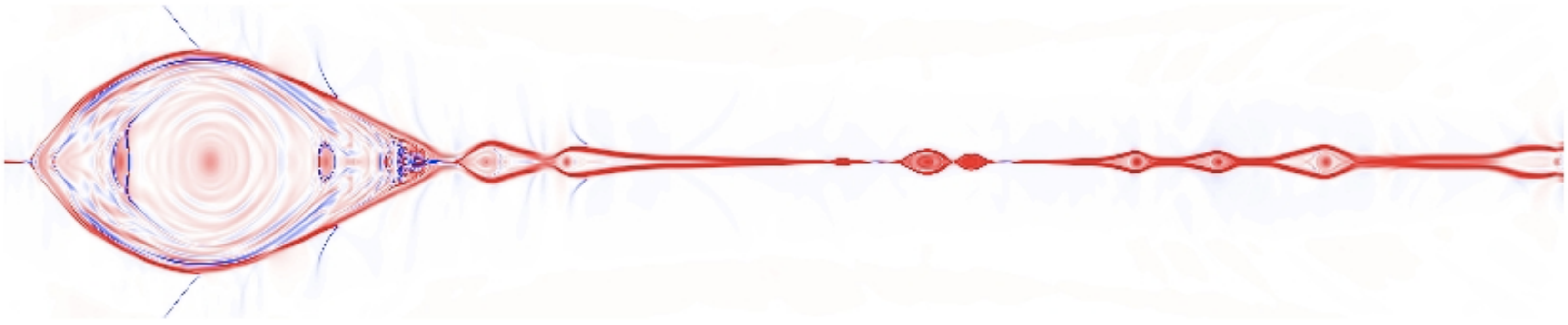
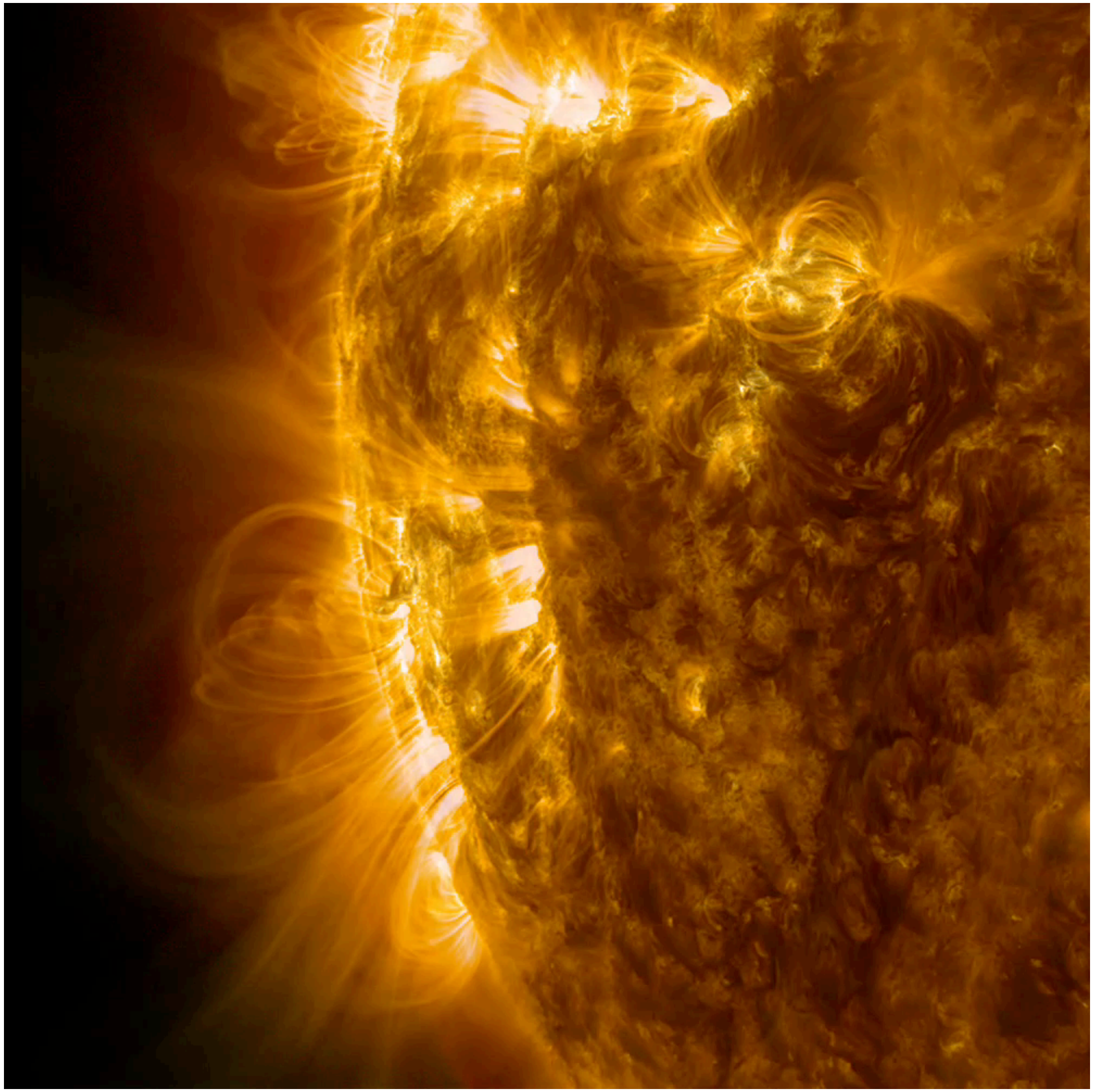
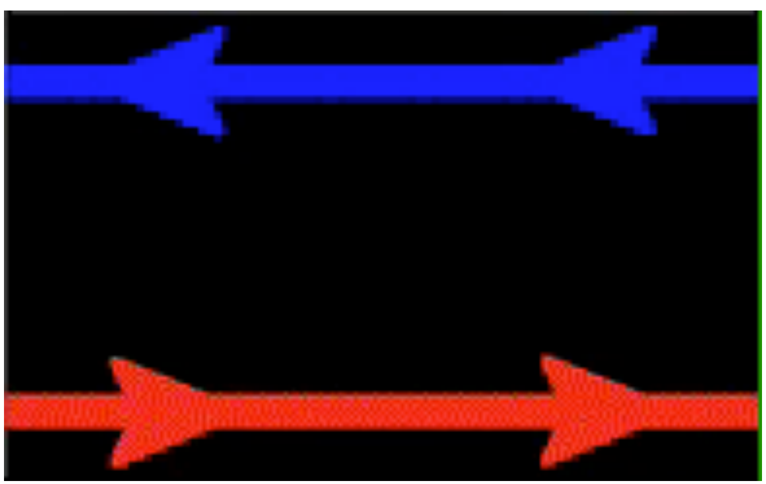


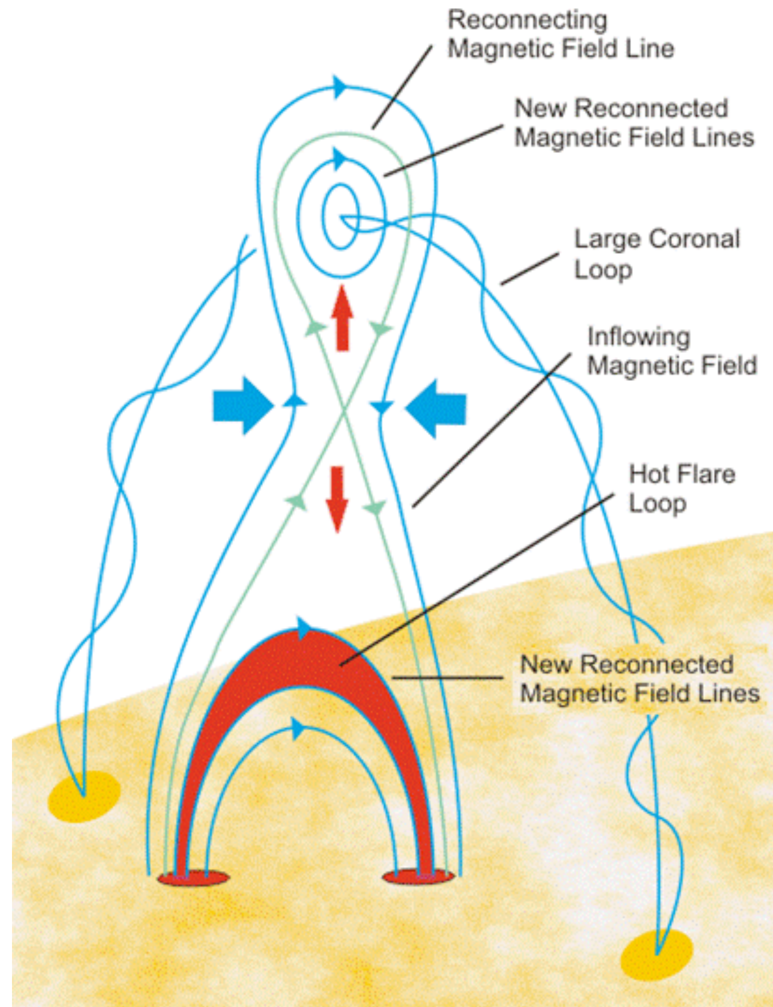
Solar Flares



Magnetic Reconnection

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





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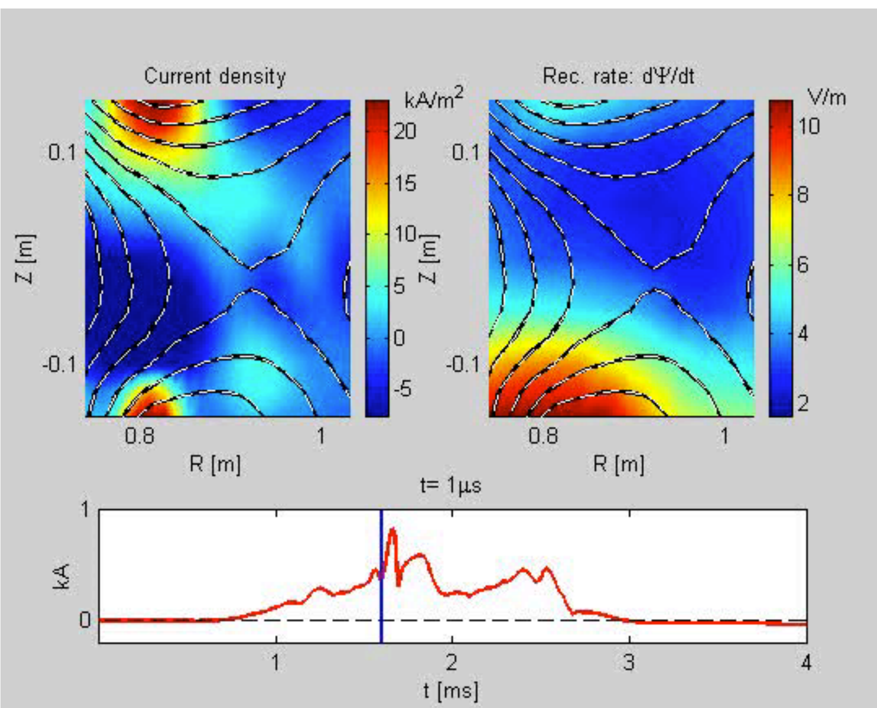
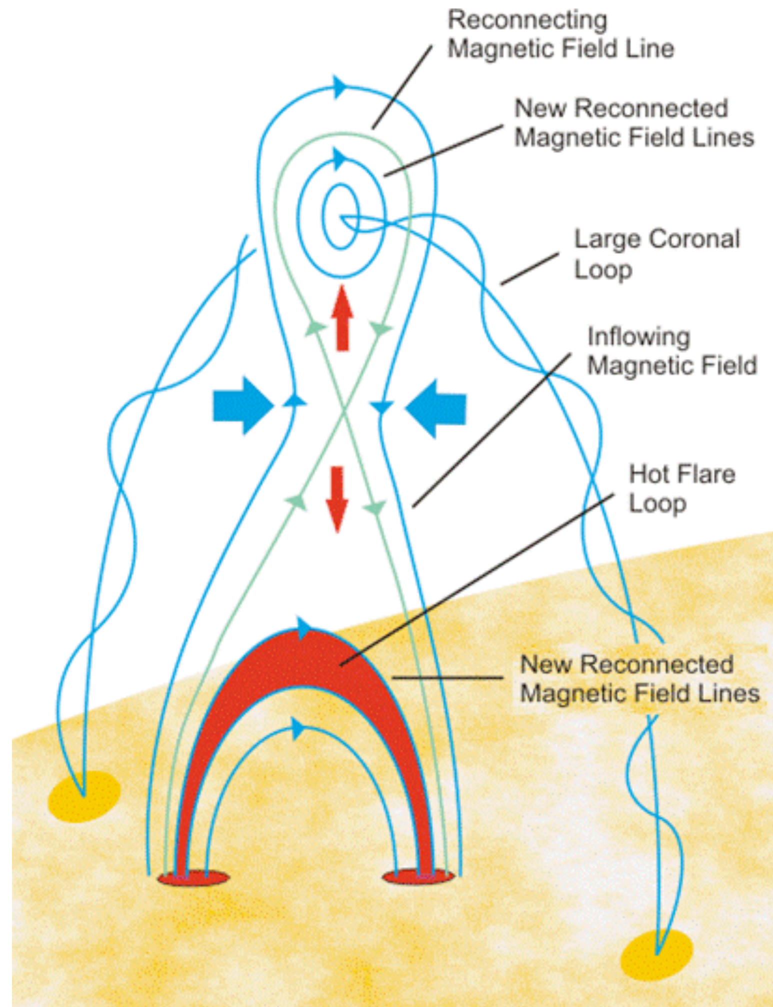
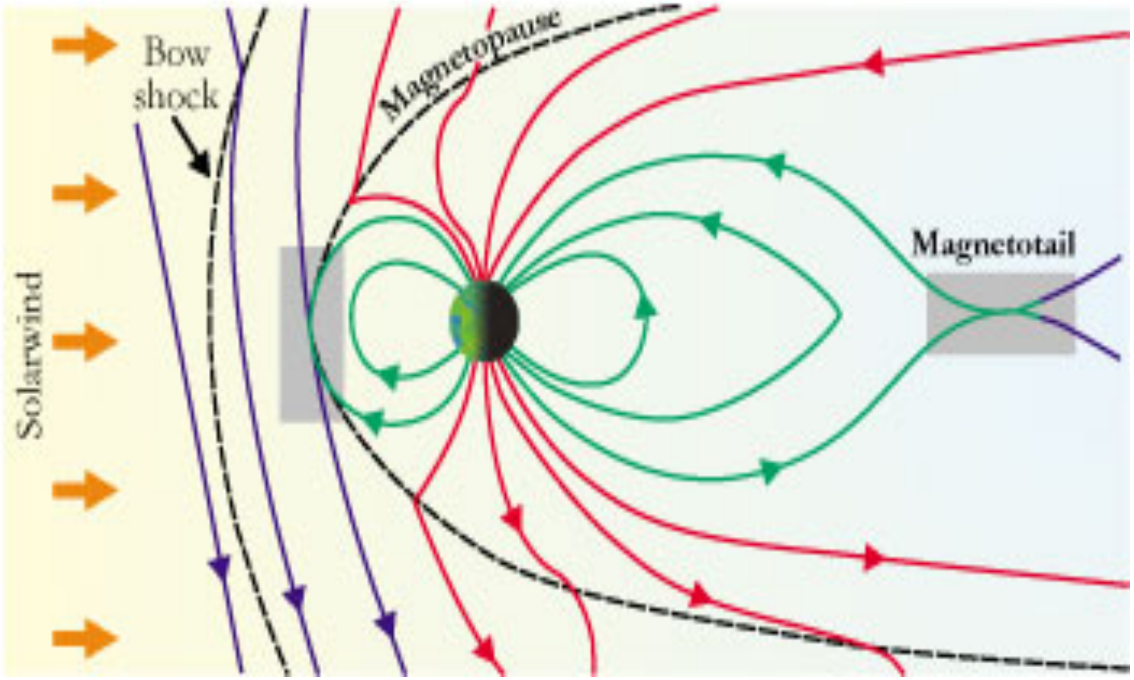




VTF experiment (Jan Egedal)

Earth's Magnetosphere and Geomagnetic Storms



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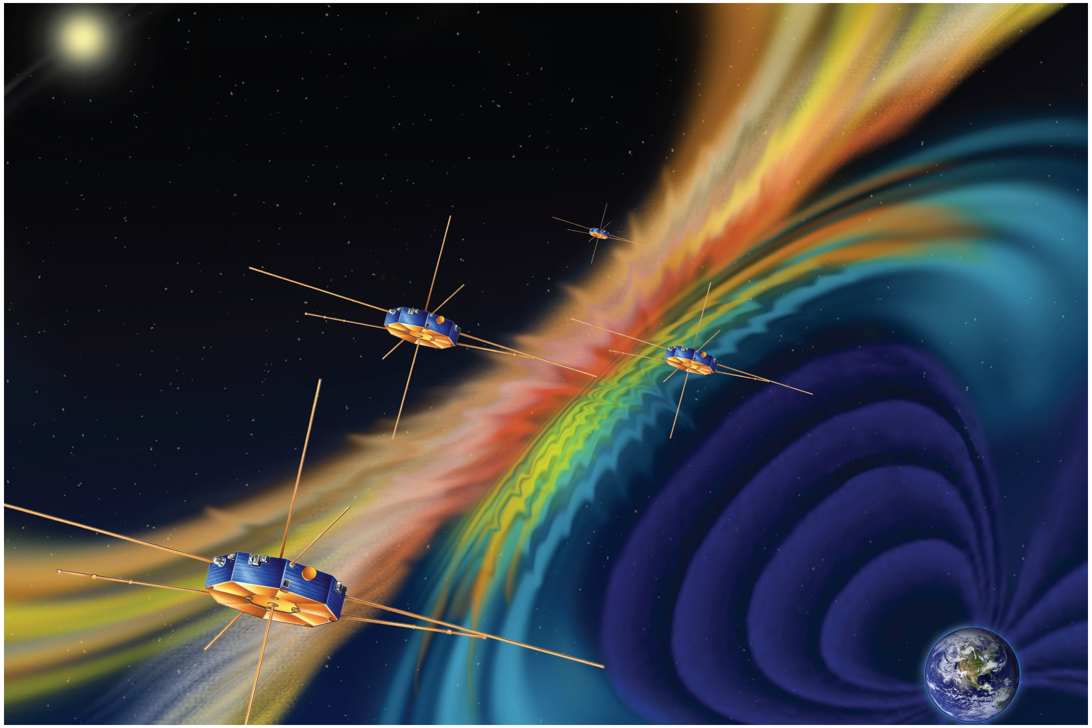
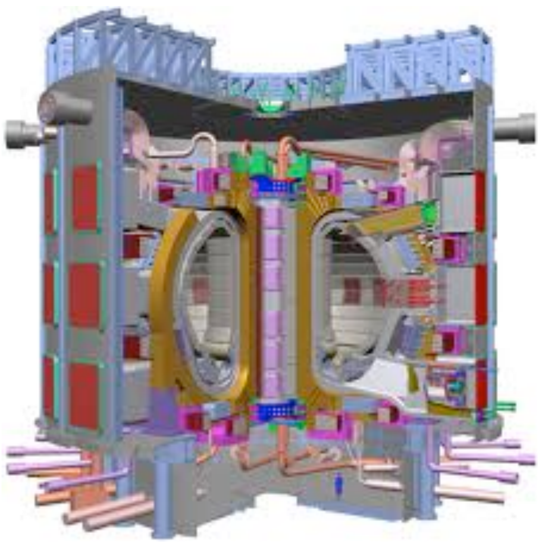


NASA's MMS mission (Burch *et al.*, Science 2016).

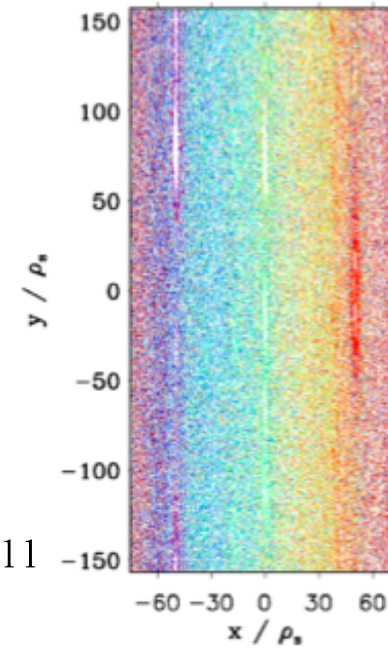
Magnetic Confinement Fusion

ITER

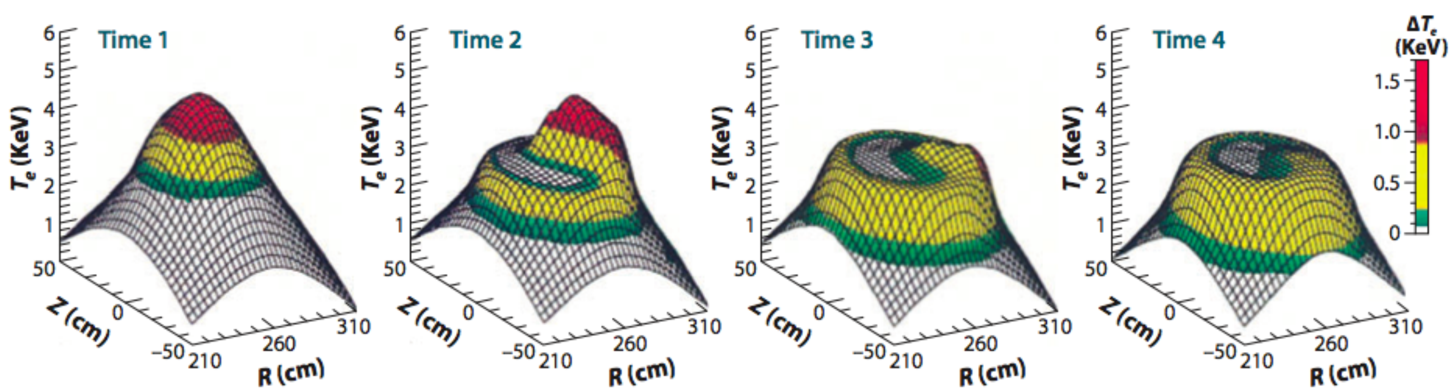


Stochastic field due to multiple microscopic reconnection events (*micro-tearing*)

Doerk '11



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



Yamada '94

Reconnection is as ubiquitous as plasmas themselves

- Magnetically confined laboratory plasmas
- Laser-solid interactions (inertial confinement fusion)
- Flares (stars, accretion disks, magnetars, blazars)
- Dissipation in magnetized turbulence (solar wind, ISM)
- Turbulent dynamo (magnetogenesis)
- Space weather
- Etc.

Recent review papers: Zweibel & Yamada '09; Yamada *et al.*, '10;
also good books by Biskamp and Priest & Forbes.
Reconnection in exotic HED environments: Uzdensky '11

Impact

"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: the key questions

1. **Reconnection rate**

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

2. **Reconnection trigger**

   - The reconnection stage proper (explosive) is often preceded by a long, quiescent period: *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.

MHD equations

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \rho \mathbf{u} = 0$$

$$\rho \left(\frac{\partial}{\partial t} + \mathbf{u} \cdot \nabla \right) \mathbf{u} = \frac{\mathbf{j} \times \mathbf{B}}{c} - \nabla p$$

$$\frac{d}{dt} \left(\frac{p}{\rho^{5/3}} \right) = 0$$

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

$$\nabla \times \mathbf{B} = \frac{4\pi}{c} \mathbf{j}$$

$$\nabla \times \mathbf{E} = -\frac{1}{c} \frac{\partial \mathbf{B}}{\partial t}$$

- No intrinsic spatial or temporal scales: all kinetic physics has disappeared. Valid when collisions dominate.

- Very useful set of equations: very often yield key physical insight, even if not rigorously valid for the particular plasma under consideration.

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Assuming incompressibility, the linear dispersion relation is

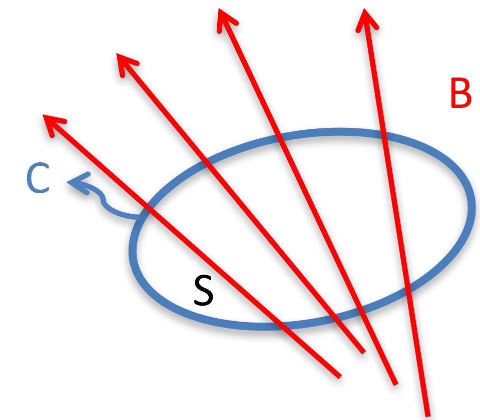
$$\omega = \mathbf{k} \cdot \mathbf{v}_A, \quad \mathbf{v}_A = \frac{\mathbf{B}}{\sqrt{4\pi\rho}}$$

i.e., Alfvén waves.

Frozen flux constraint

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

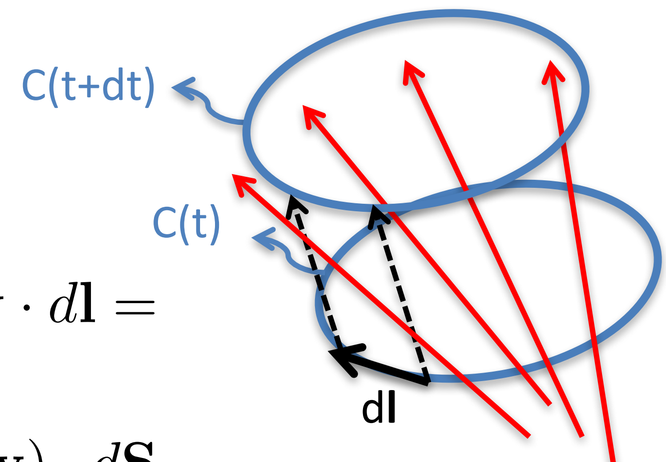
$$\Psi = \int_S \mathbf{B} \cdot d\mathbf{S}$$



How does Ψ 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 **u**:

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

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

Frozen flux constraint (cont'd)

Combine the two contributions to get:

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

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

Frozen flux constraint (cont'd)

Combine the two contributions to get:

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

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

$$\mathbf{E} + \frac{1}{c}\mathbf{u} \times \mathbf{B} = \eta\mathbf{j}$$

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

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Hannes Alfvén

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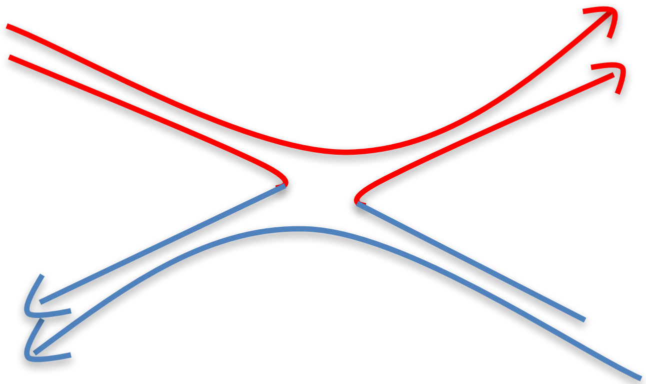
$$\boxed{\frac{d\Psi}{dt} = 0}$$

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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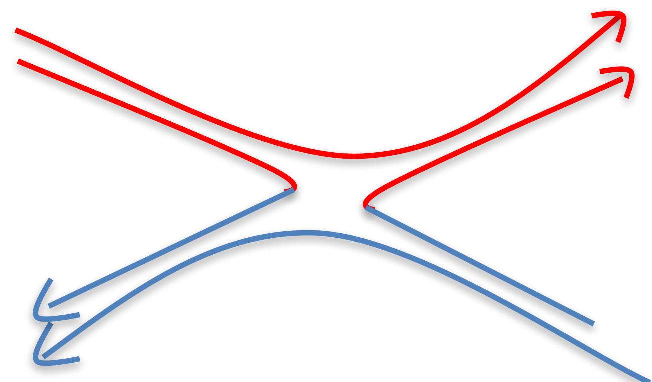

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But the plasma is a very good conductor, right?

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*).**

The simplest description of reconnection: the Sweet-Parker model

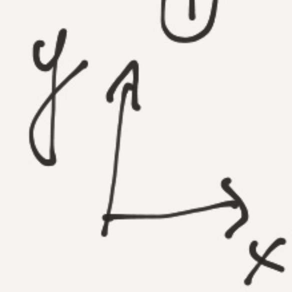
P. Sweet

E. Parker

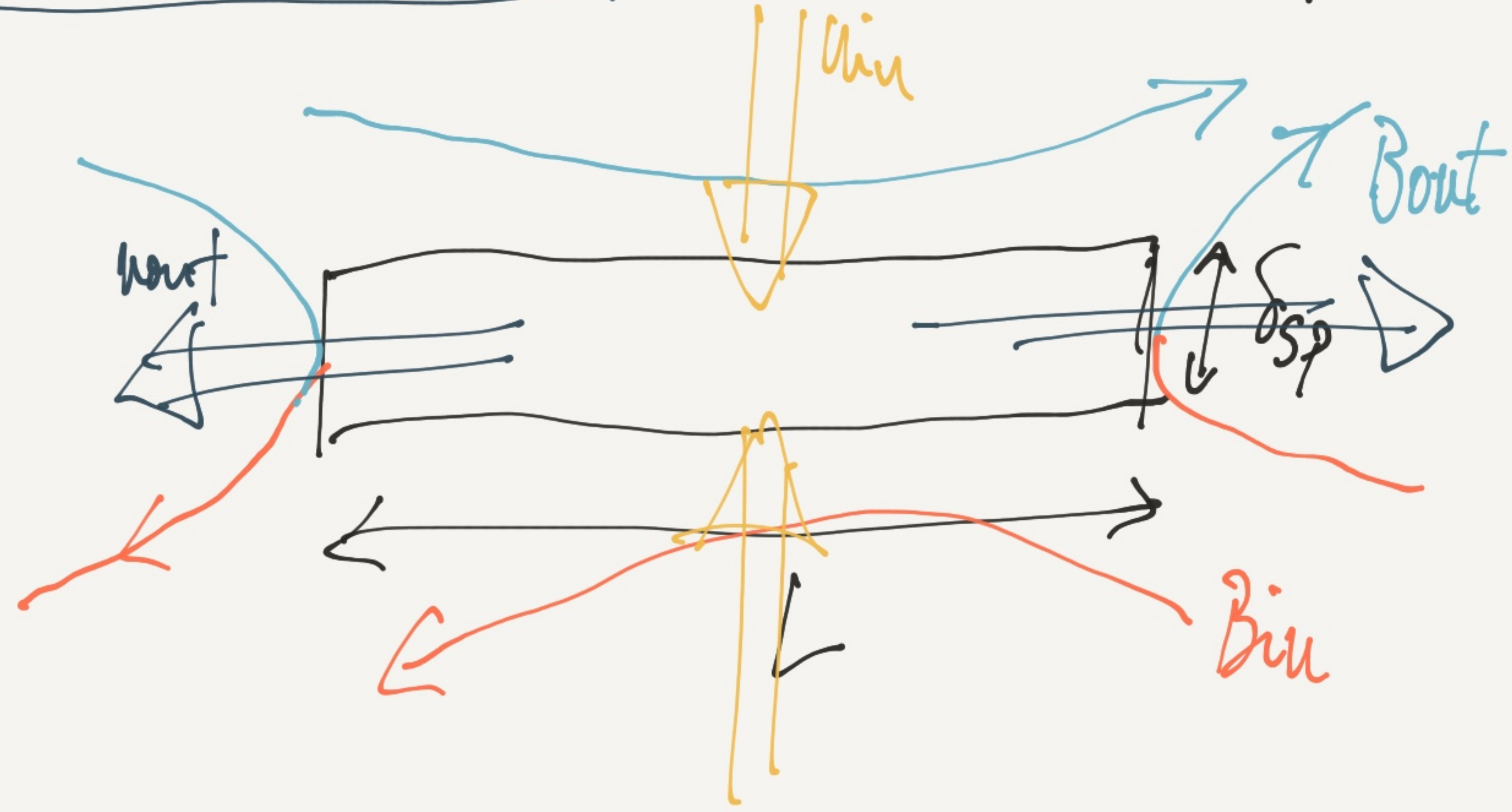
Peter Sweet ('58) and Eugene Parker ('57) attempted to describe reconnection within the framework of resistive magnetohydrodynamics (MHD).

Derivation of the Sweet-Parker model.

Nuno Loureiro, MIT.



Geometry:



Define Lundquist number $S = \frac{L V_A}{\bar{\eta}}$

Where $\bar{\eta} \equiv \eta \frac{c^2}{4\pi}$ is the magnetic diffusivity.

The black box is the "current sheet" (where current is intense). L is its length, δ_{SP} its width.

(2)

Assume steady-state: the geometry is fixed, the current sheet does not change in time. Flows come into the sheet, flows leave the sheet.

Continuity: $\rho_{in} u_{in} L = \rho_{out} u_{out} \delta$.

Assume incompressibility, constant ρ. So

$$\boxed{u_{in} L = u_{out} \delta \quad (1)}$$

Note that this is the same thing you'd get from saying $\nabla \cdot \vec{u} = 0 \Rightarrow \partial_x u_x = -\partial_y u_y \Rightarrow \frac{u_{out}}{L} \sim \frac{u_{in}}{\delta}$.

(3)

Now, let's solve Ohm's law: $\vec{E} + \frac{\vec{v} \times \vec{B}}{c} = \eta \vec{j}$.

Note that away from the sheet, $\eta \vec{j}$ is very small (no intense currents there, the current is only important in the current sheet, by definition).

So

$$E_{away} \sim \frac{u_{in} B_{in}}{c}. \quad (2)$$

At the center of the current sheet $u_{in} \to 0$, $B_{in} \to 0$, so:

$$E_{center} \sim \eta j \sim \frac{\eta c}{4\pi} \frac{B_{in}}{\delta} \quad (3)$$

, using $\vec{j} = \frac{c}{4\pi} \nabla \times \vec{B}$

and assuming $\delta \ll L$, so $\frac{\partial}{\partial y} \simeq \frac{1}{\delta} \gg \frac{\partial}{\partial x} \simeq \frac{1}{L}$

(4)

The assumption of steady-state means $\frac{\partial}{\partial t} = 0$. Thus:

$$\nabla \times \vec{E} = -\frac{1}{c}\frac{\partial \vec{B}}{\partial t} = 0 \Rightarrow \vec{E} = \underline{\underline{\text{constant}}}.$$

So, we must have $E_{\text{away}} = E_{\text{center}}$, i.e.,

$$\frac{u_{\text{in}} B_{\text{in}}}{c} \sim \frac{\eta c}{4\pi}\frac{B_{\text{in}}}{\delta} \Rightarrow \boxed{\delta = \frac{\eta c^2/4\pi}{u_{\text{in}}} = \frac{\bar{\eta}}{u_{\text{in}}}.} \quad (4)$$

We're not done yet, because we don't know δ or u_{in}.

But we have one more equation to work with, momentum.

(5)

Equivalently we can think in terms of energy:

$$W = \frac{B^2}{8\pi} + \frac{1}{2}\rho u^2$$

magnetic

kinetic

Now, magnetic reconnection is about releasing magnetic energy. That means you must have a significant amount of it to release! So, it's reasonable to assume that upstream magnetic energy dominates:

$$W_{in} \simeq B^2/8\pi \, .$$

⑥

If conversion of energy is efficient, then we expect that a significant portion of it has been transferred to the plasma kinetic energy. I.e., downstream we should expect:

$$W_{out} \approx \frac{1}{2} \rho u_{out}^2 .$$

Let's assume energy is conserved in this process. Then

$$W_{in} \approx W_{out}$$

$$\Rightarrow \frac{B_{in}^2}{8\pi} \sim \frac{1}{2} \rho u_{out}^2 \Rightarrow \boxed{u_{out} = \frac{B_{in}}{\sqrt{4\pi\rho}} \equiv V_A}$$

Alfvén velocity.

(7)

Great. Go back to eq. (4):

$u_{in} L \sim u_{out}\, \delta \sim v_A \delta$. So $\boxed{\delta \sim \frac{u_{in} L}{v_A}}$.

But also, from Ohm's law, we had

$$\delta \simeq \eta / u_{in} \Rightarrow \frac{u_{in} L}{v_A} \sim \frac{\eta}{u_{in}} \Rightarrow u_{in} \sim \sqrt{\frac{\eta v_A}{L}}$$

i.e., $\frac{u_{in}}{v_A} \sim \sqrt{\frac{\eta}{L v_A}} \equiv S^{-1/2}$.

Great! Now we know the inflow velocity!

Replace back in δ: $\delta \sim \frac{u_{in} L}{v_A} \sim S^{-1/2} L$. Solved!

Finally the electric field:

$$cE = u_{in} B_{in} \sim V_A S^{-1/2} B_{in}. \quad \text{Done!}$$

Sweet-Parker is easy to remember: all normalized quantities scale as $S^{-1/2}$:

$$\frac{\delta}{L} \sim S^{-1/2}$$

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

$$\frac{cE}{V_A B_{in}} \sim S^{-1/2}.$$

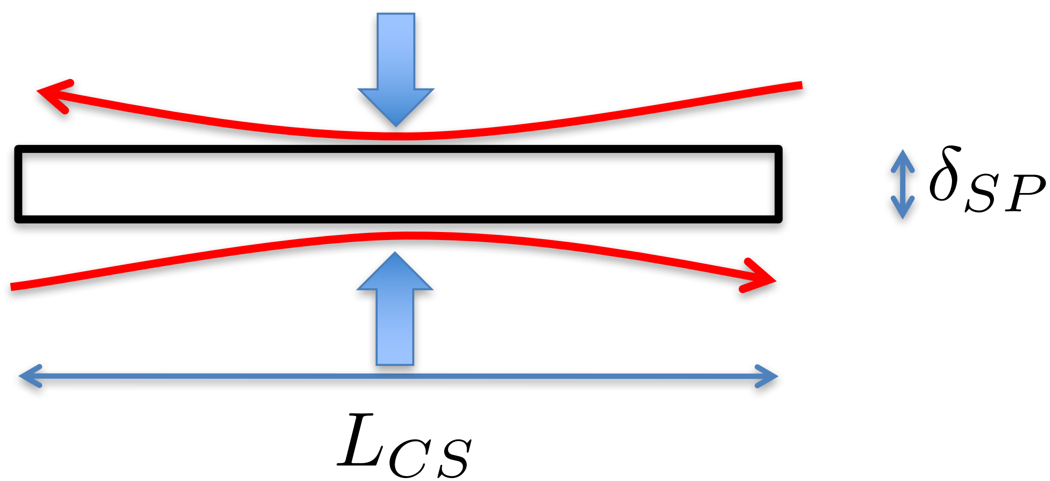
Think $S = 10^{14}$ ($\sim$ solar corona)

$\frac{\delta}{L} \sim 10^{-7}$ (!!!)

Can you imagine a nozzle with aspect ratio 10^{-7} remain stable? (Neither can I...)

The simplest description of reconnection: the Sweet-Parker model

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



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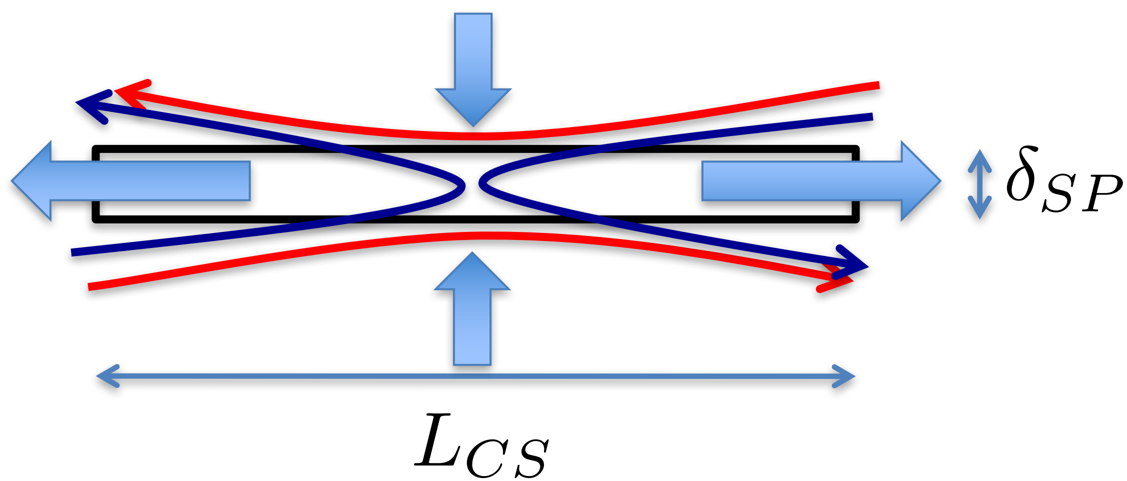

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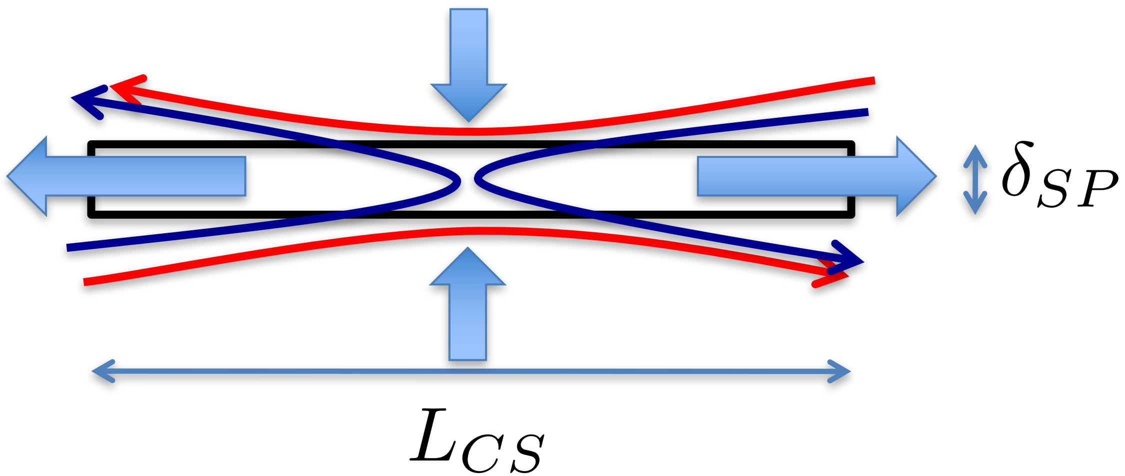

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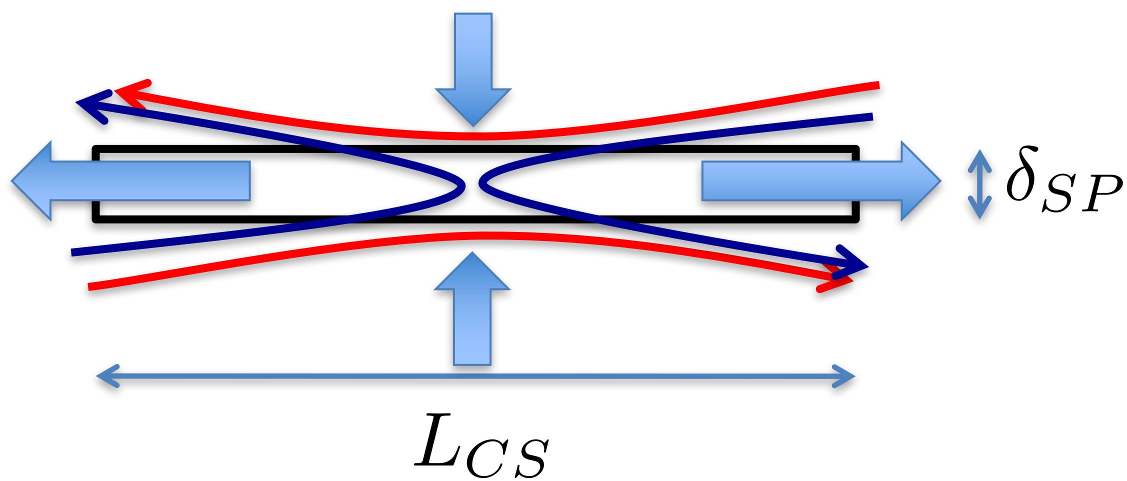

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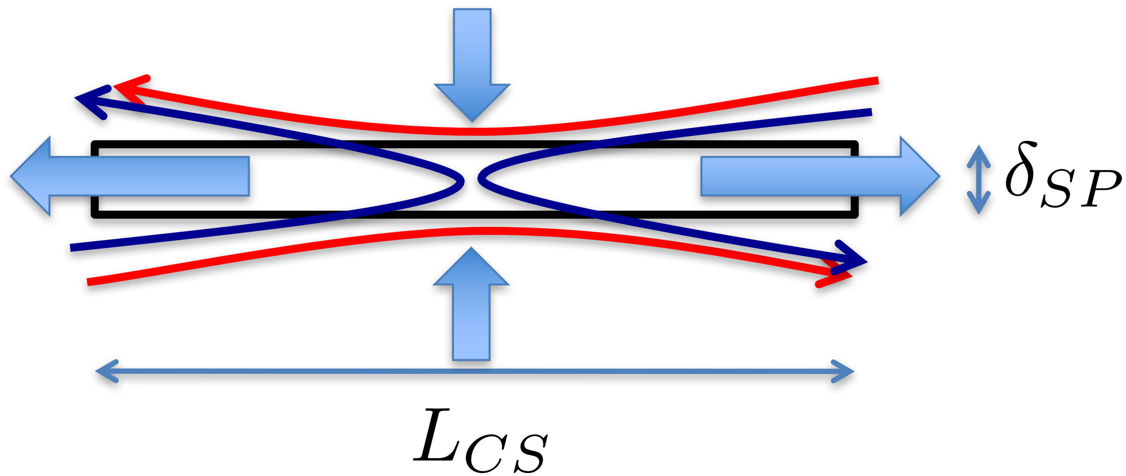


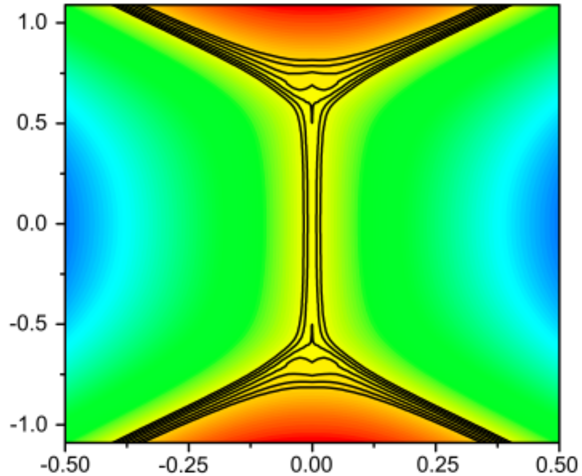
Typical solar corona parameters yield S~10^{14} ; this theory then predicts that flares should **last ~2 months**; in fact, flares last **15min – 1h**.
[still, Sweet-Parker (SP) theory was a great improvement on simple resistive diffusion of magnetic fields, which would yield ~3.10^{6} years…]

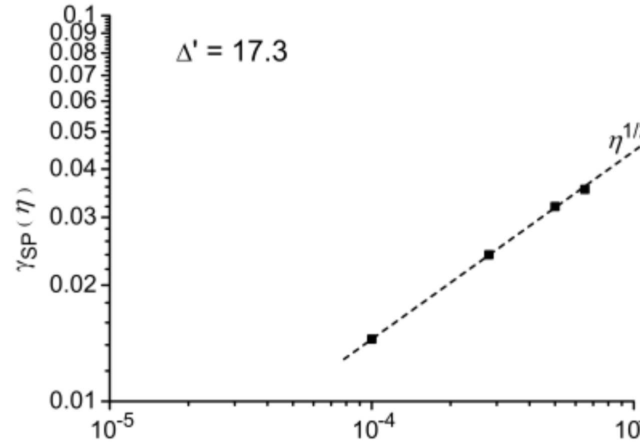
The problem

- 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.**

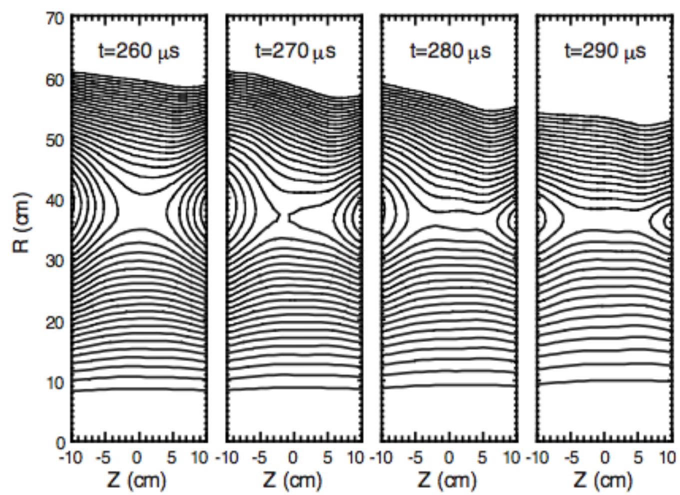
Is the Sweet-Parker model right?

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

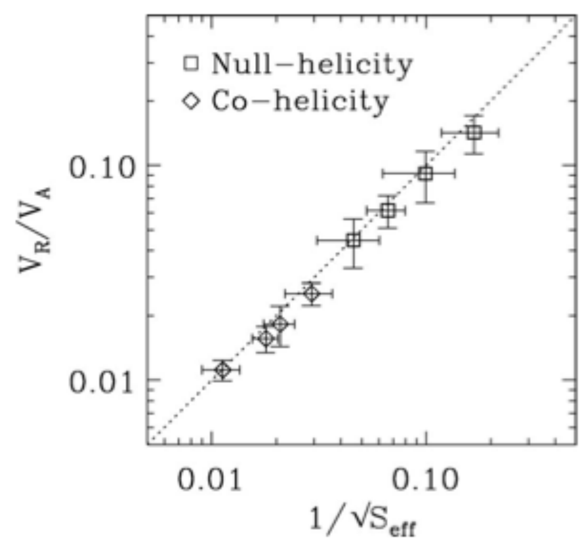




Loureiro '05



Ji '99, Yamada '00



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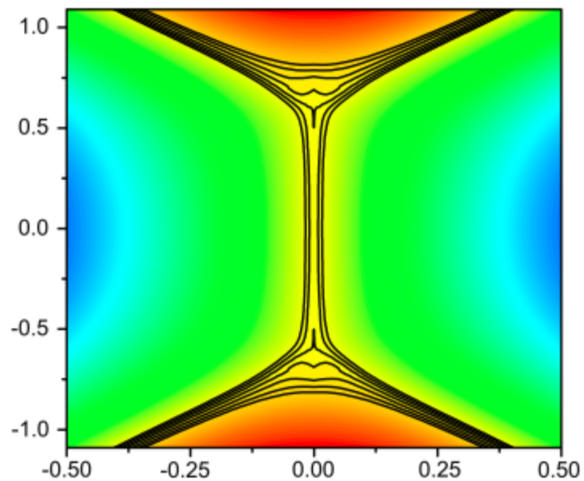
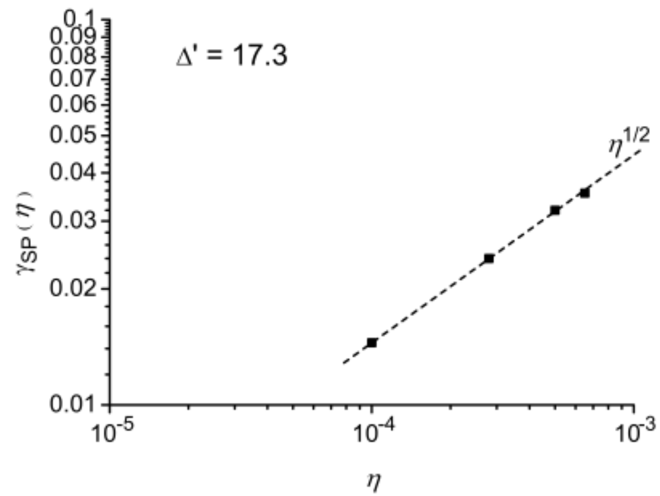
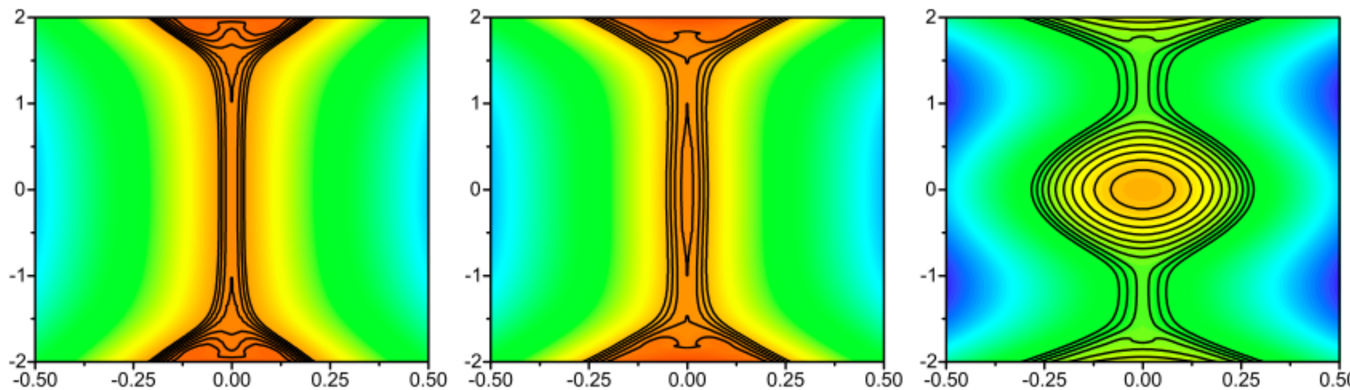




Except…



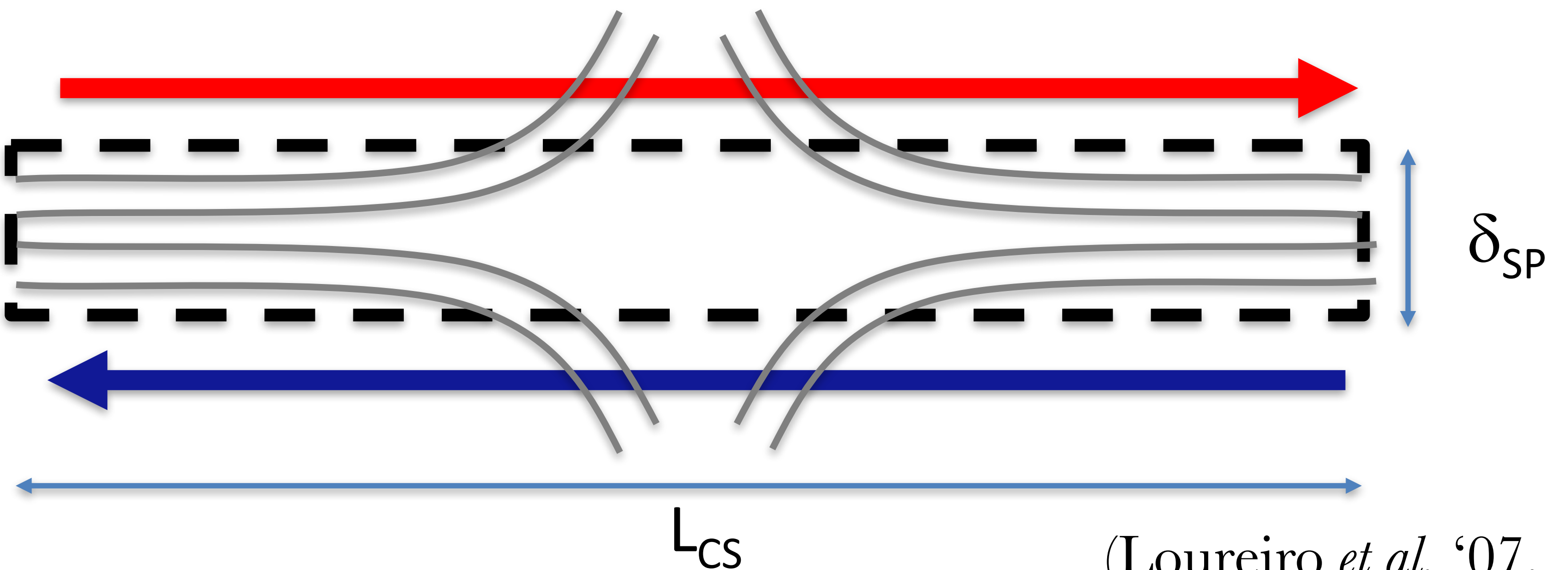
Loureiro *et al.* PRL '05 (see also: Steinolfson 84, Park 84, Biskamp 86)

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**)

Instability of Sweet-Parker current sheets



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

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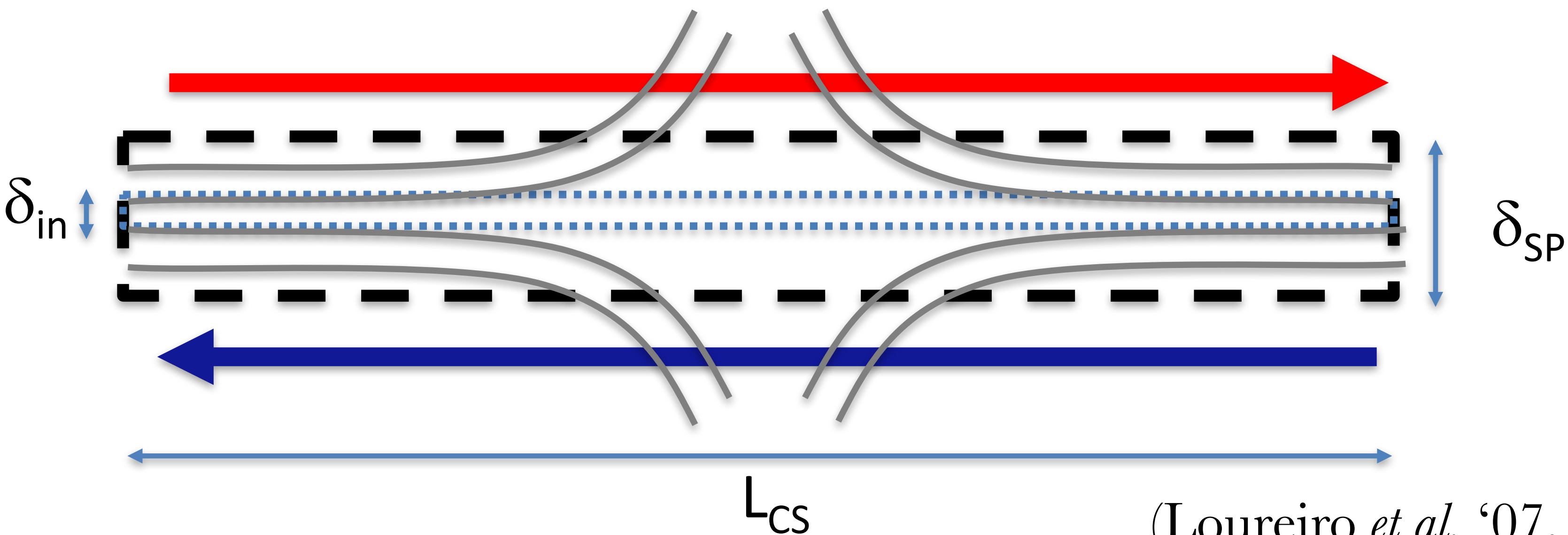
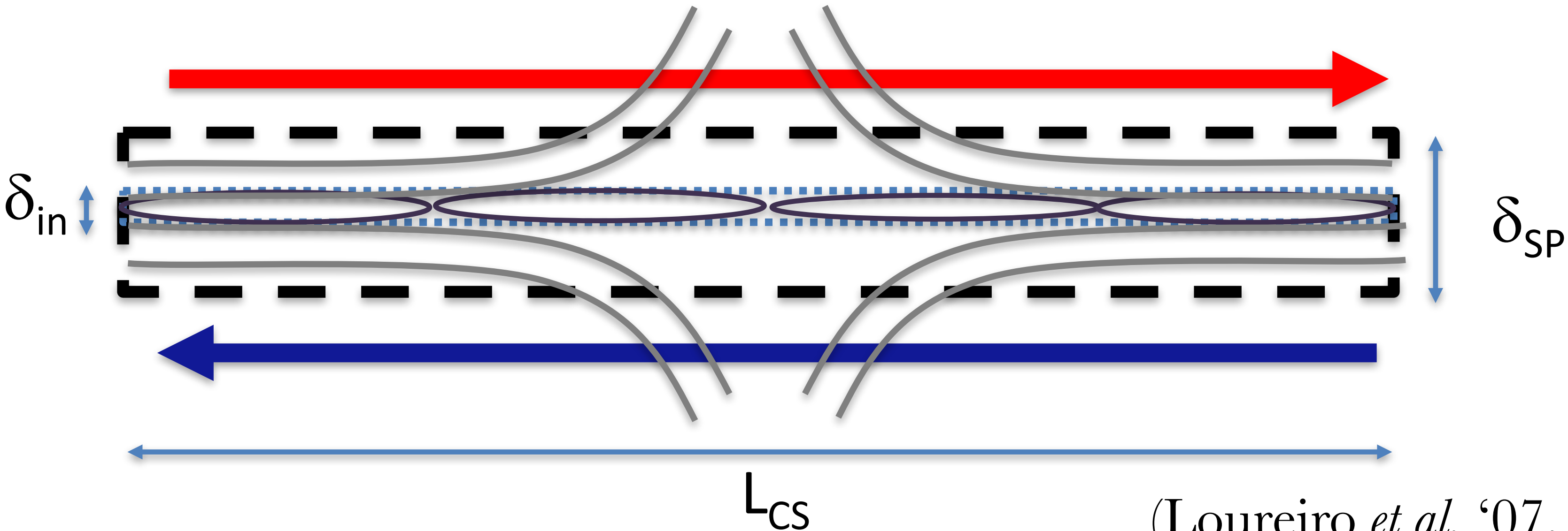


(Loureiro *et al.* '07, '13)

Instability of Sweet-Parker current sheets



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

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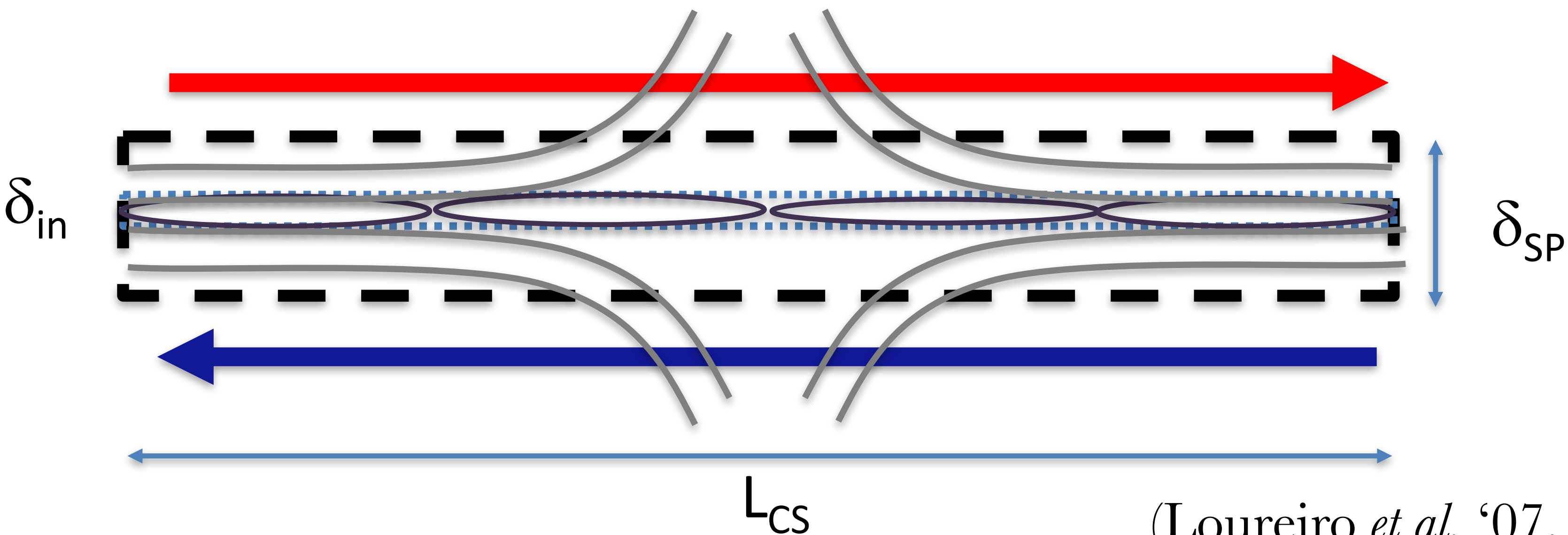

(Loureiro *et al.* '07, '13)

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

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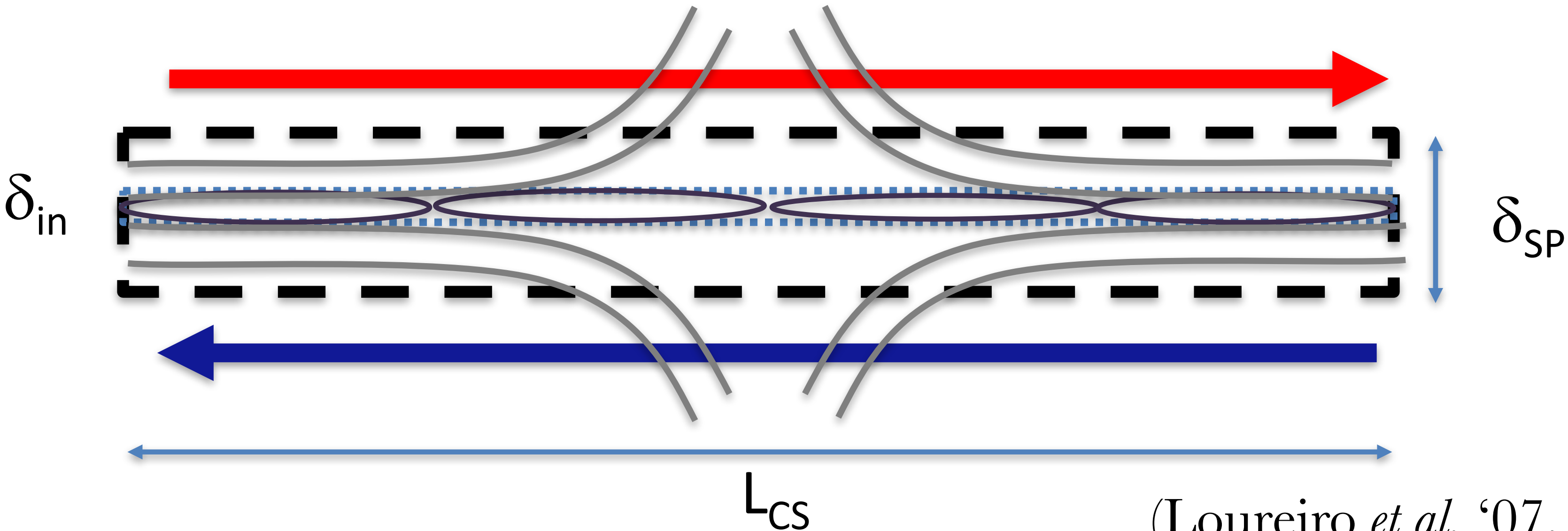


(Loureiro *et al.* '07, '13)

1- Obtain analytical form for a SP-like current sheet (nonlinear steady state solution); this describes the background equilibrium.
2- Analyze its linear stability using standard tearing-mode instability techniques. Obtain:

$$\boxed{\begin{aligned} \gamma_{\max} L_{CS}/V_A &\sim S^{1/4} \\ k_{\max} L_{CS} &\sim S^{3/8} \end{aligned}}$$

Current sheet instability: Threshold

Three conditions required for instability:

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

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

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

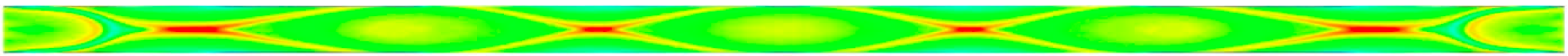
Requiring (*non-rigorously!*) that this be at most 1/3 yields

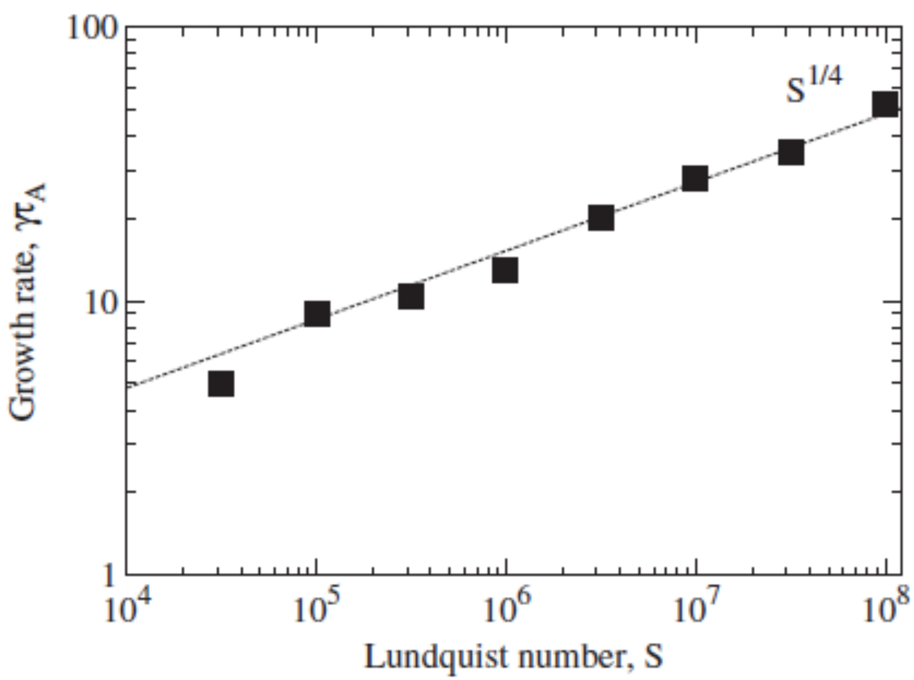
→ *Critical threshold for instability:* $\boxed{S_c \sim 10^4}$

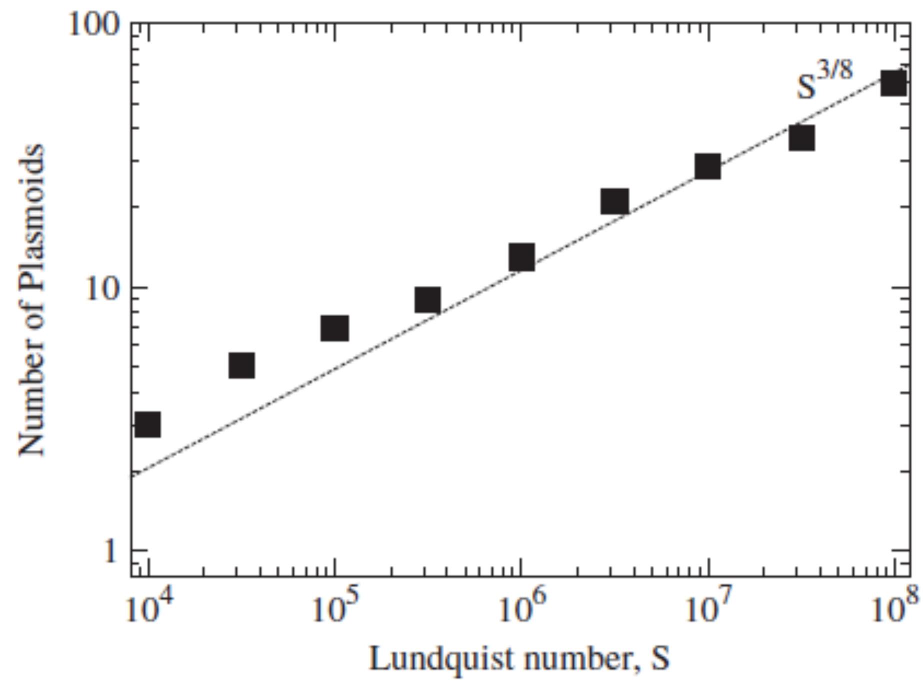
(somewhat similar to the transition to turbulence as the Reynolds number increases in hydrodynamics)

Numerical confirmation of linear theory

Direct numerical simulations confirm scalings predicted by linear theory.





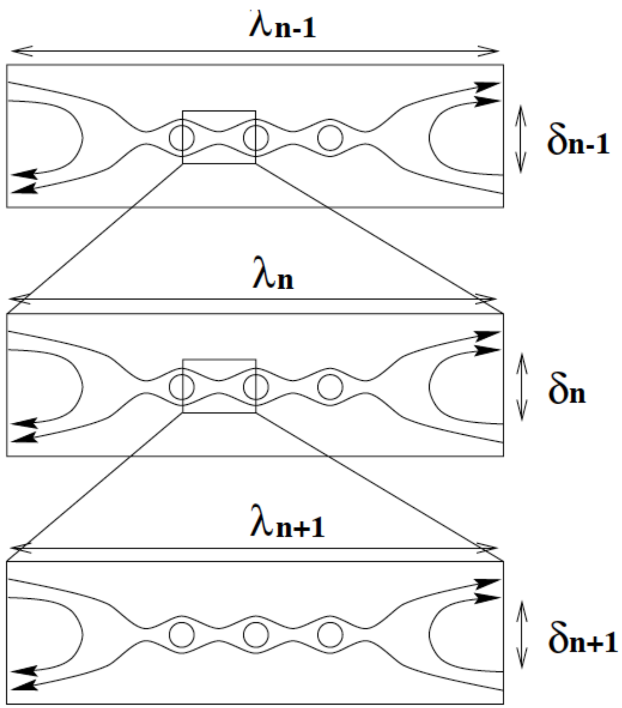


Samtaney, Loureiro *et al.*, PRL '09

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

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

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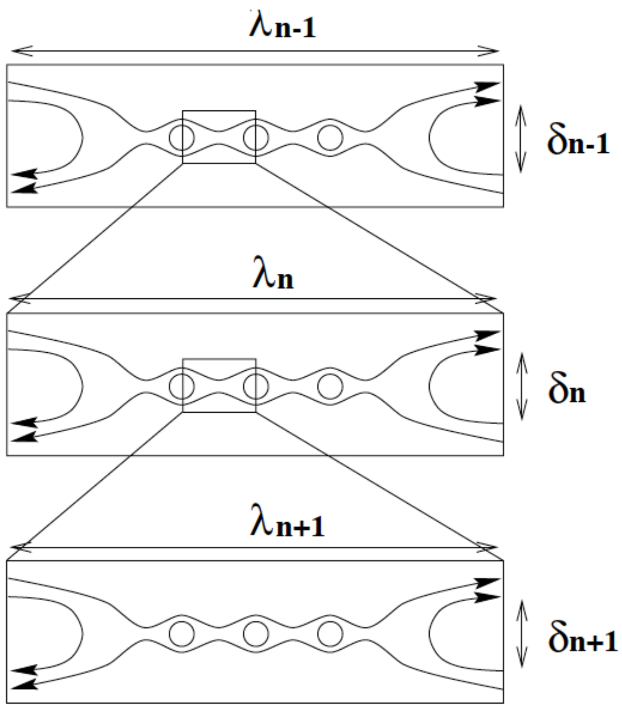

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$$S_n = L_n V_A/\eta > S_c$$

- Plasmoid hierarchy ends at *the critical layer*:

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

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

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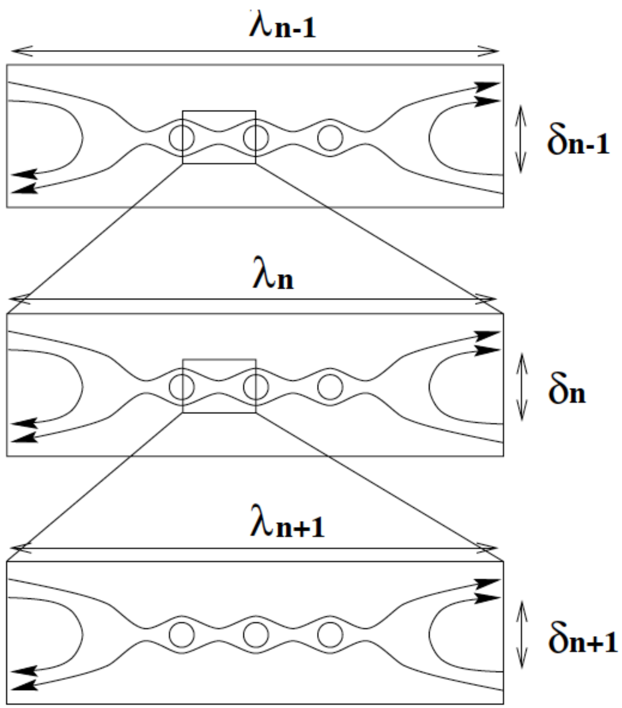

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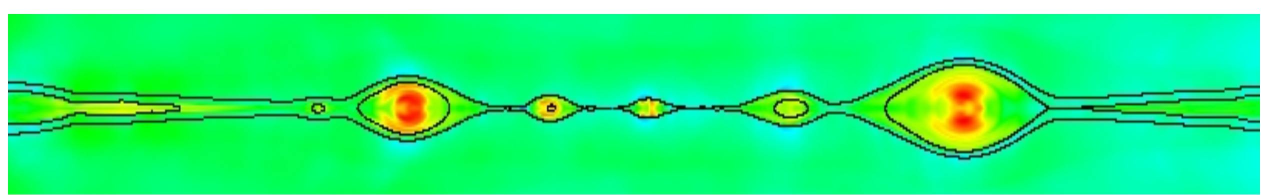
- $N \sim L / L_c$ plasmoids separated by near-critical current sheets.



Reconnection in stochastic plasmoid chains

We proposed a 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:

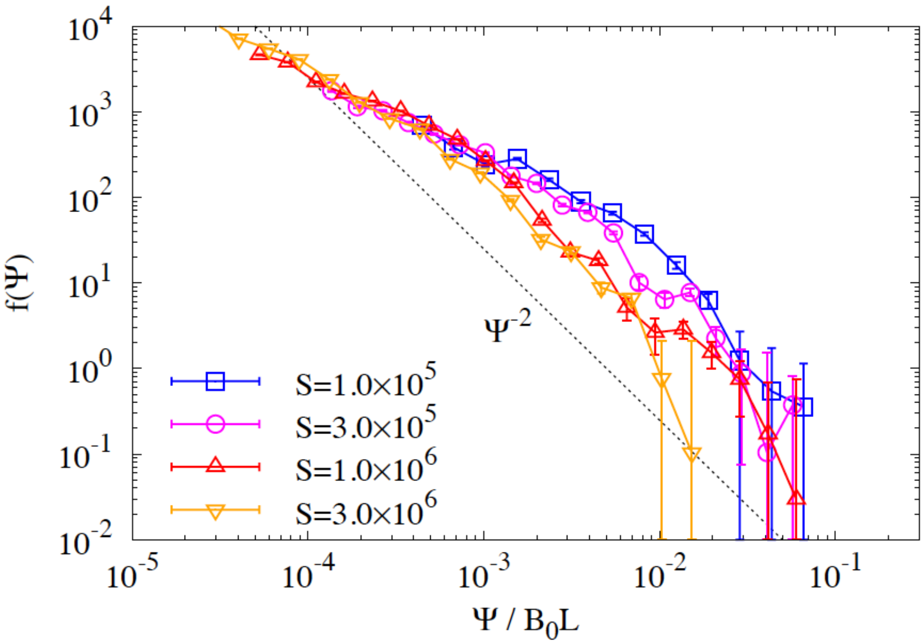
  $w_{\rm max} \sim 0.1L$ → can disrupt the chain, **observable**.

High-Lundquist-number reconnection

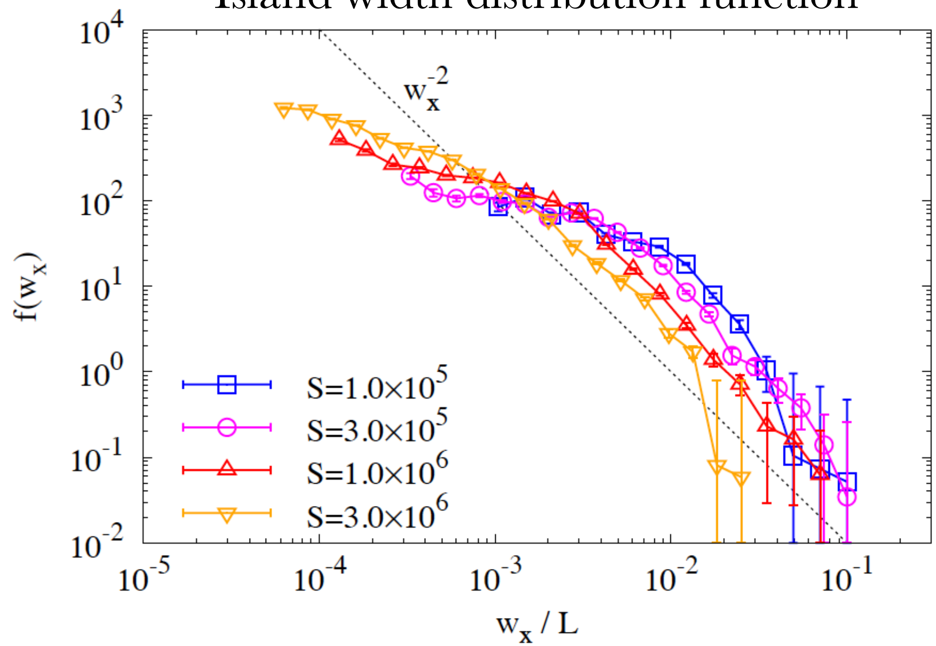
Direct numerical simulations of magnetic reconnection at $S>S_c$

$S=10^6$, res. 16384^2

Flux distribution function



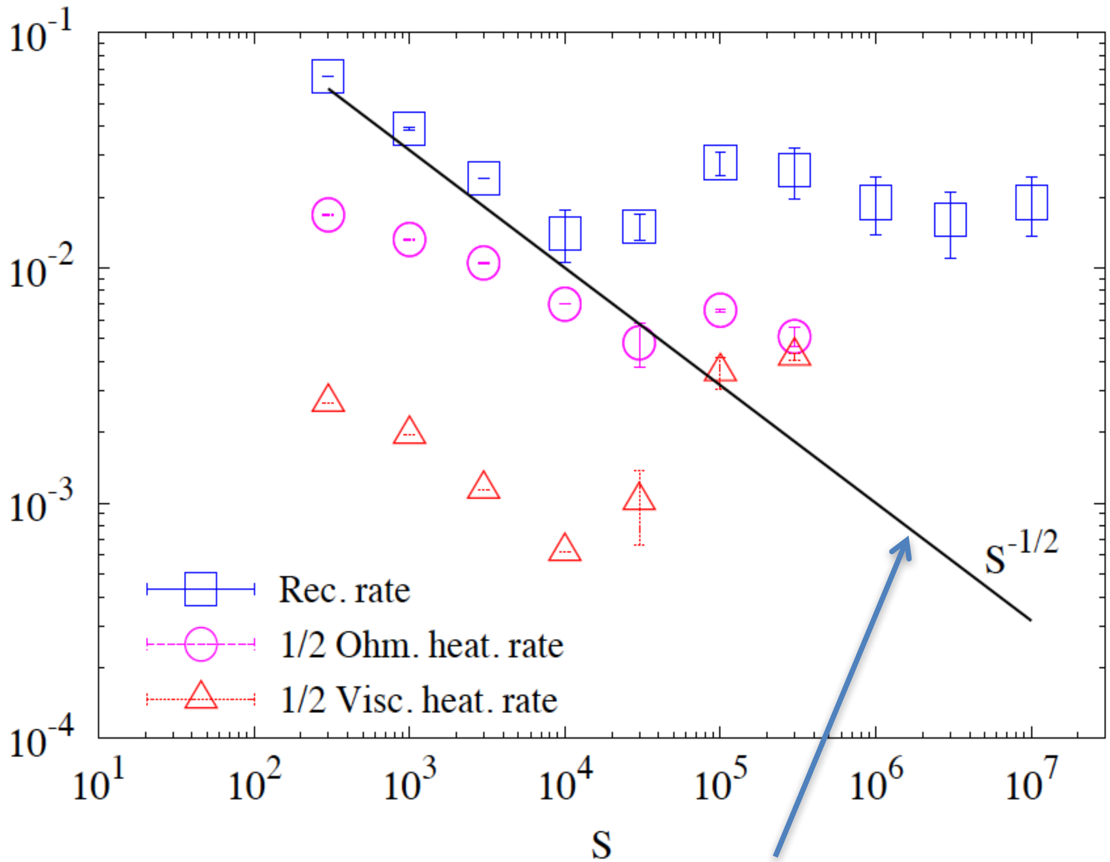
Island width distribution function



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

Reconnection and dissipation rates

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



(Loureiro *et al.*, '12)

Sweet-Parker rate

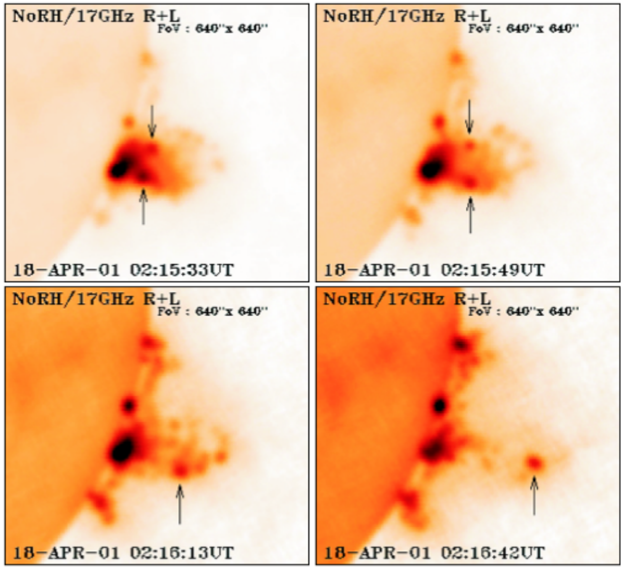
$$\boxed{\tilde{E}_{\text{eff}} \approx 0.02}$$

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

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

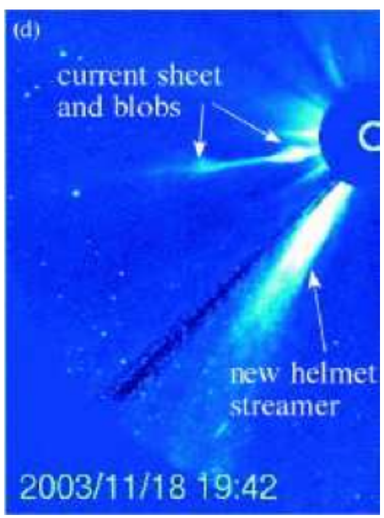
Plasmoids in Context

Plasmoids in solar flares

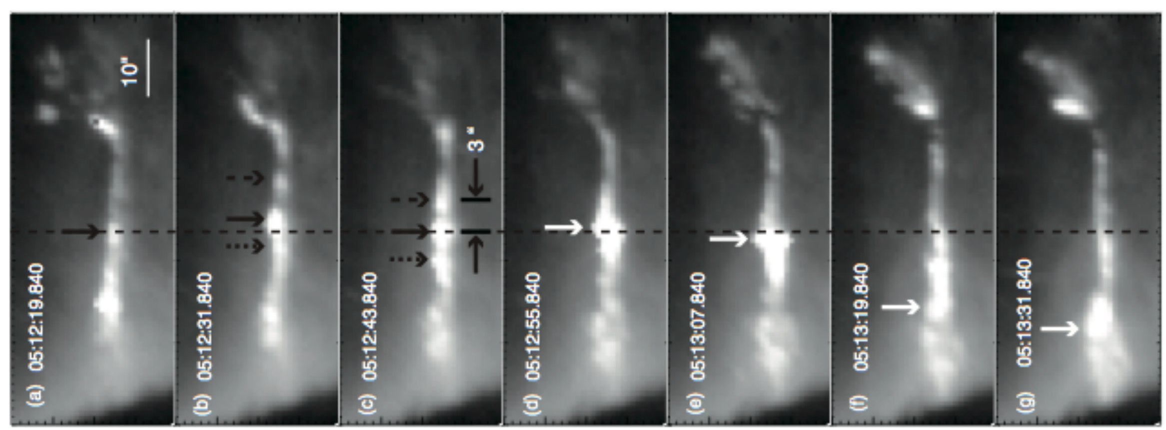


Karlicky & Kliem '10

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).



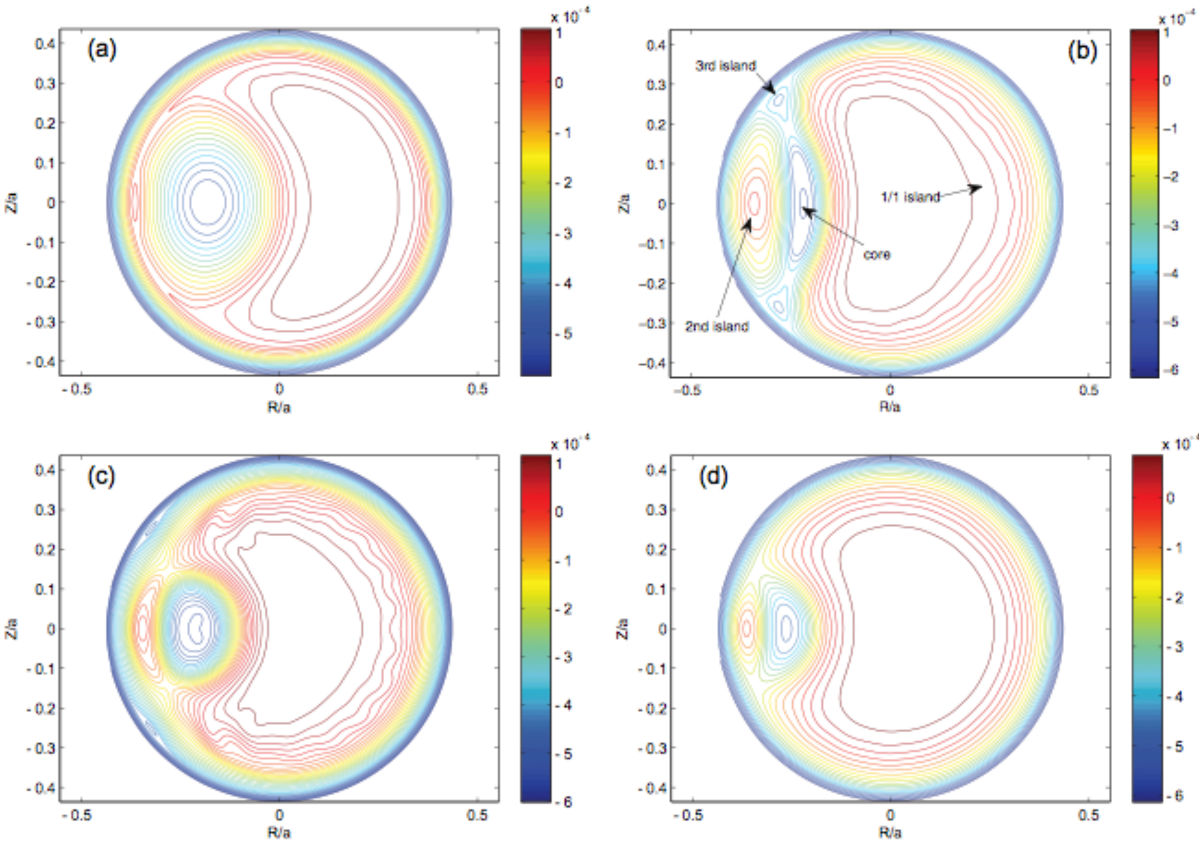
Lin '05



Takasao *et al.* '12

Plasmoids in tokamaks

Sawtooth instability: Kadomtsev revisited

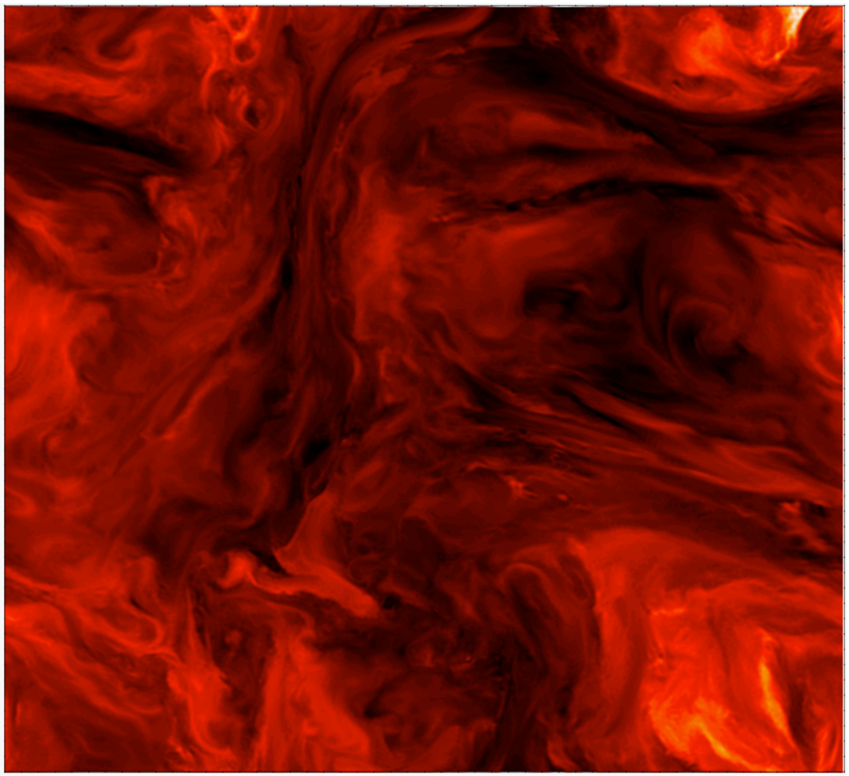


Plasmoid instability leads to a 2/2 perturbation, which is experimentally observed (possible explanation for the triggering of 3/2 NTMs by sawteeth)

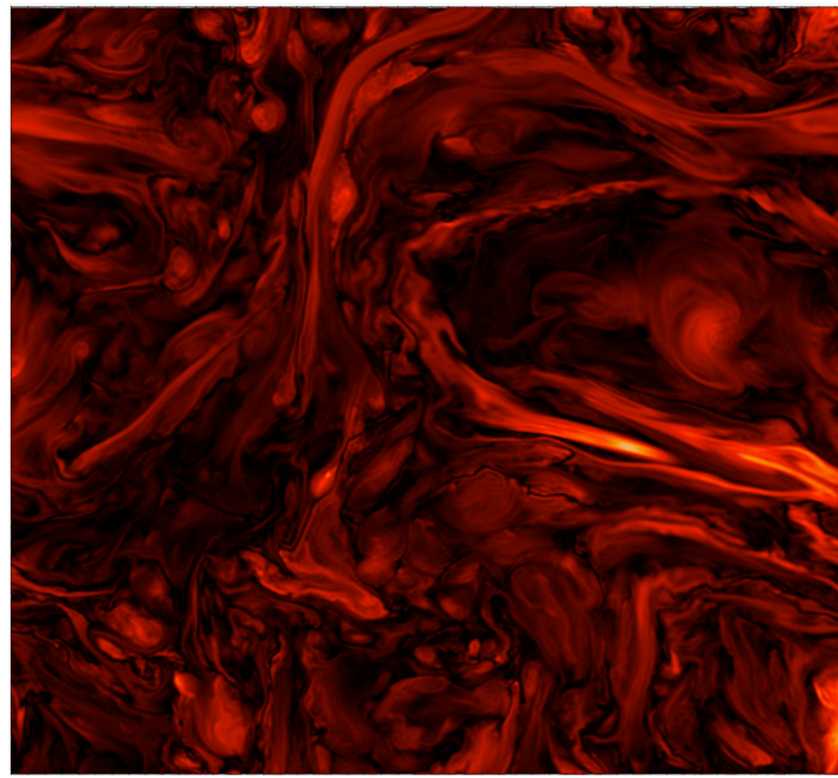
Yu, Günter & Lackner, '14; Gunter *et al.* '15

Plasmoids in turbulent small-scale dynamo

The current sheets that arise in the nonlinear state break into plasmoids when the Reynolds number is large enough (and moderate Pm).



$|\mathbf{u}|$

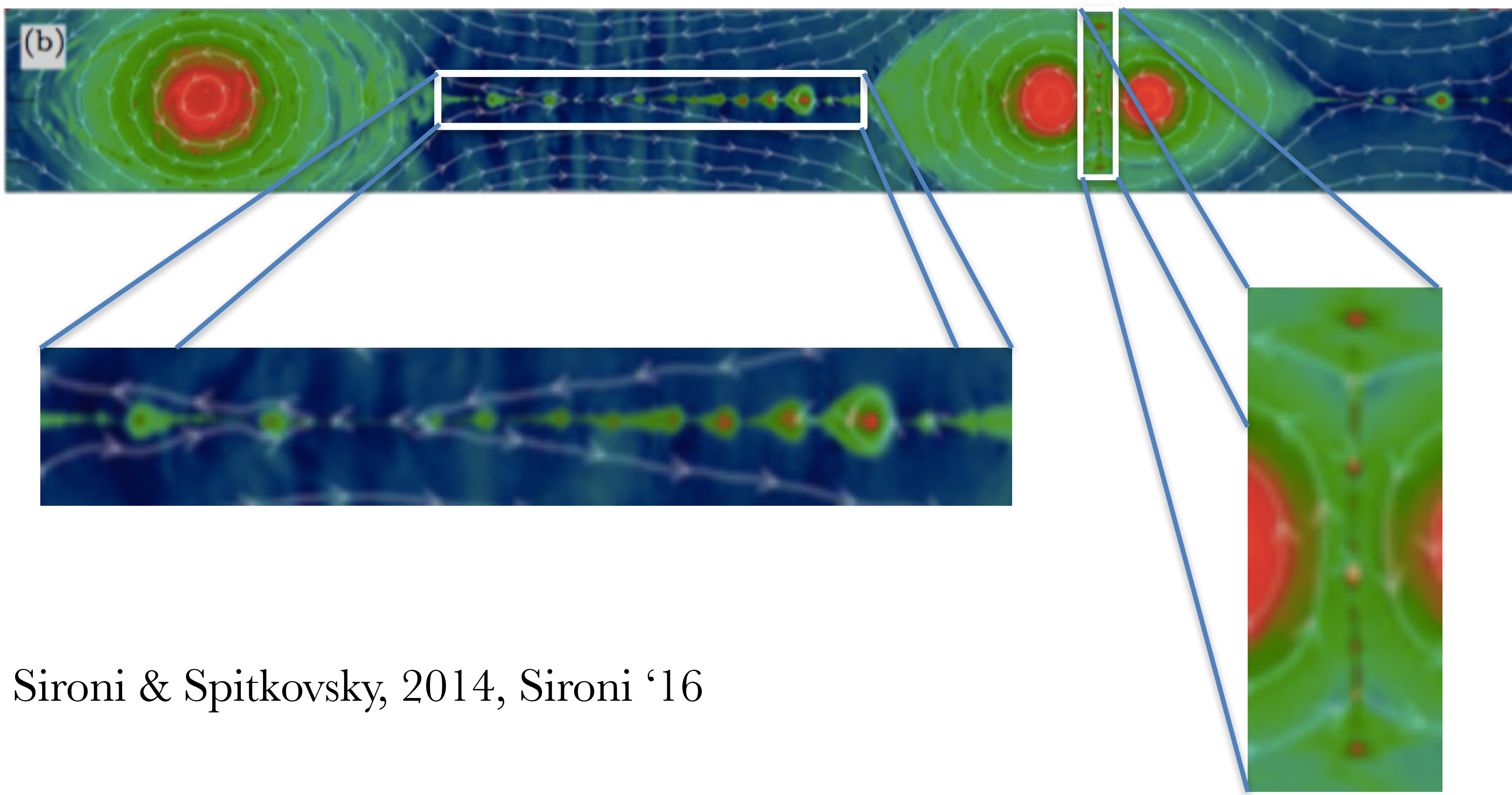


$|\mathbf{B}|$

Schekochihin and Iskakov 2007, *unpublished*

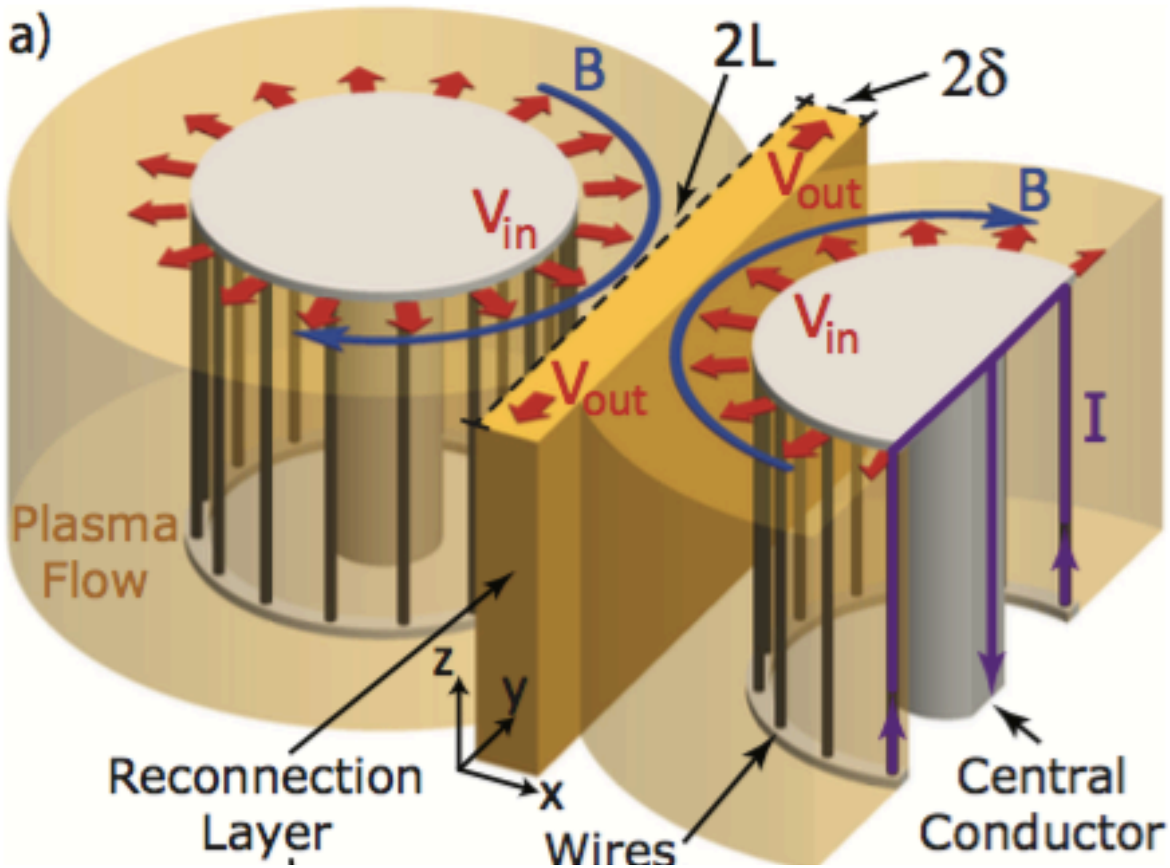
Relativistic pair-plasma reconnection

These ideas remain qualitatively valid in very different plasmas, e.g. relativistic pair-plasma reconnection:



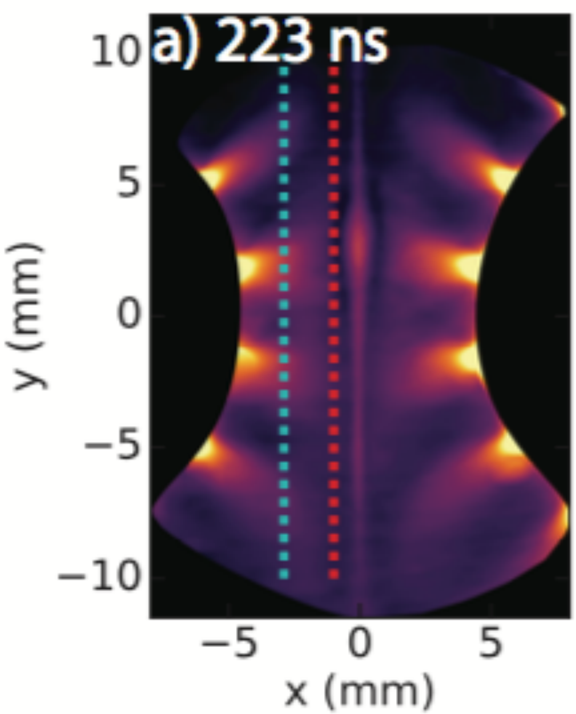
Sironi & Spitkovsky, 2014, Sironi '16

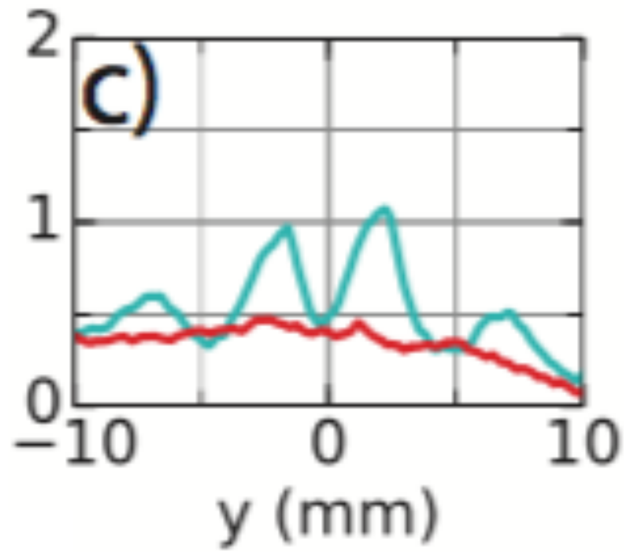
Plasmoids in the laboratory

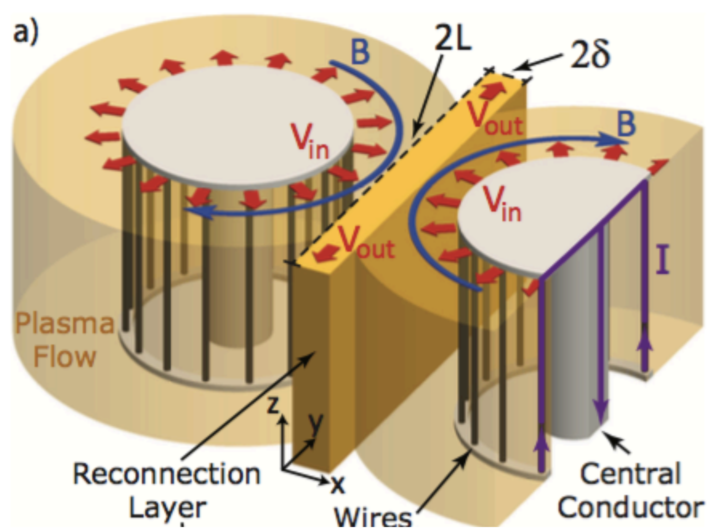


(Hare *et al.*, PRL'17)

Plasmoids in the laboratory







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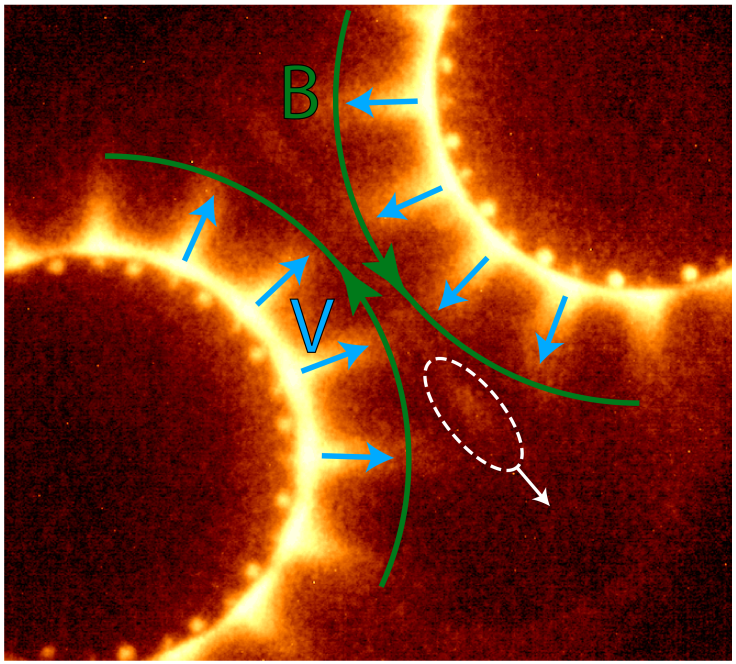
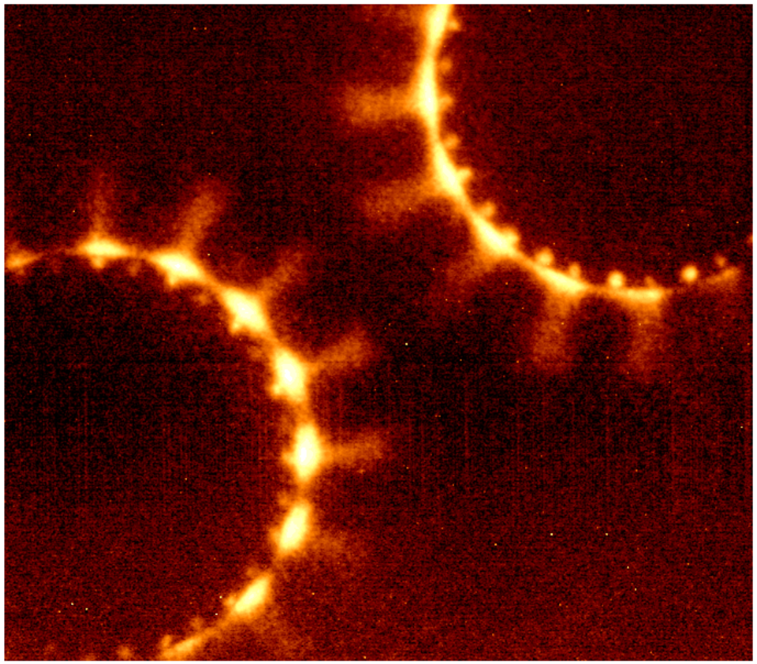




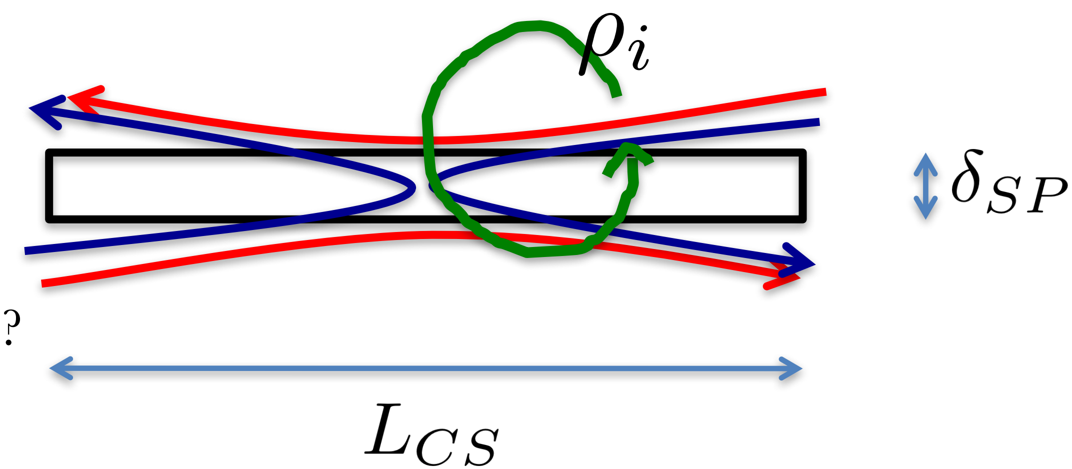
Hare, Lebedev, Suttle, Loureiro et al., PRL '17

Kinetic Reconnection

Enter kinetics

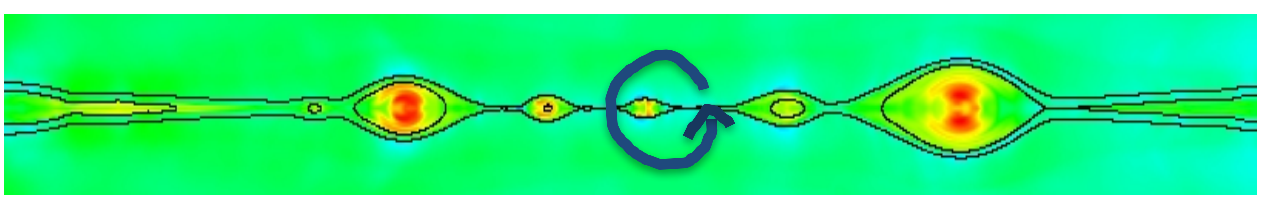
What happens if

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



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

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



Generalized Ohm's law

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

Generalized Ohm's law

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

Hall term;
Whistler waves;
c/ω_{pi}

Generalized Ohm's law

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

Hall term;
Whistler waves;
c/ω_{pi}

Electron
pressure
tensor;
KAW;
ρ_s

Generalized Ohm's law

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

Hall term; Whistler waves; c/ω_{pi}

Electron pressure tensor; KAW; ρ_s

Electron inertia; c/ω_{pe}

Generalized Ohm's law

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

Hall term;
Whistler waves;
c/ω_{pi}

Electron
pressure
tensor;
KAW;
ρ_s

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}

Electron
pressure
tensor;
KAW;
ρ_s

Electron inertia;
c/ω_{pe}

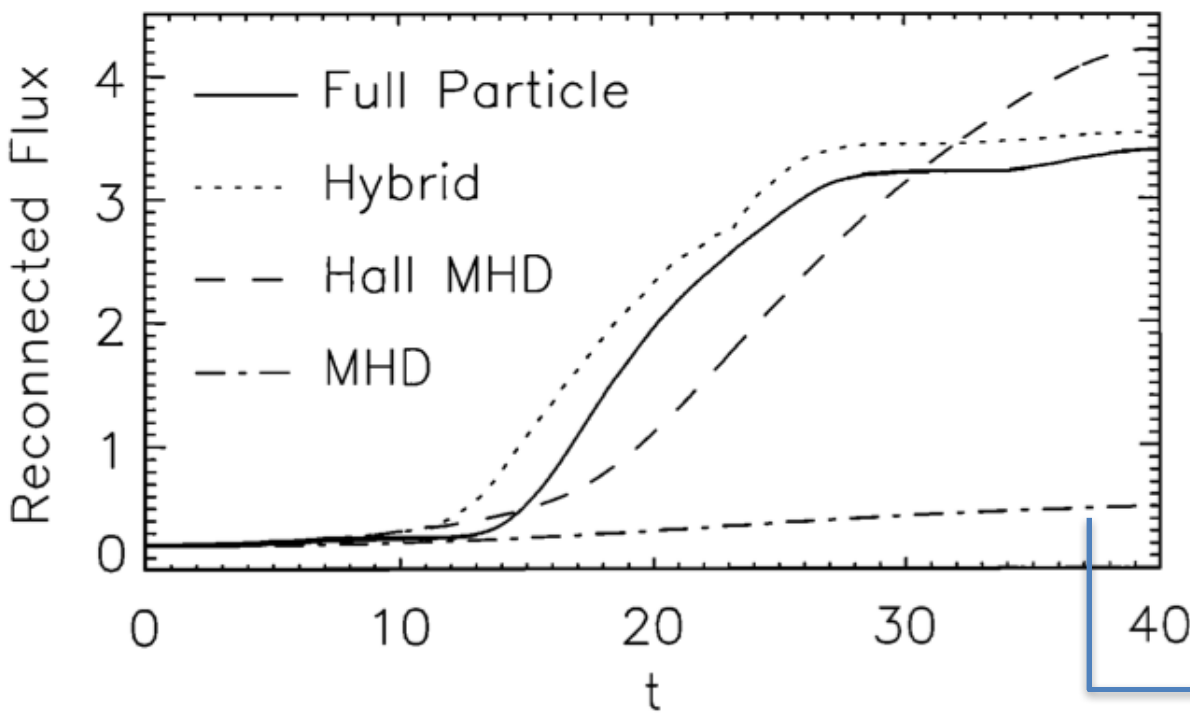
does NOT break
frozen flux

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?



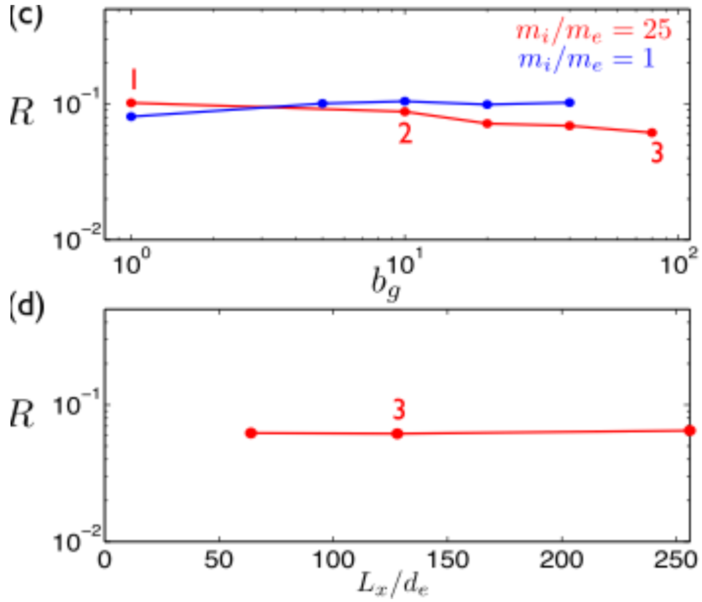
GEM challenge, Birn *et al.* '01 (but see Daughton '06)

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

What is the reconnection rate in collisionless plasmas?

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



(Y.-H. Liu *et al.*, ‘14)

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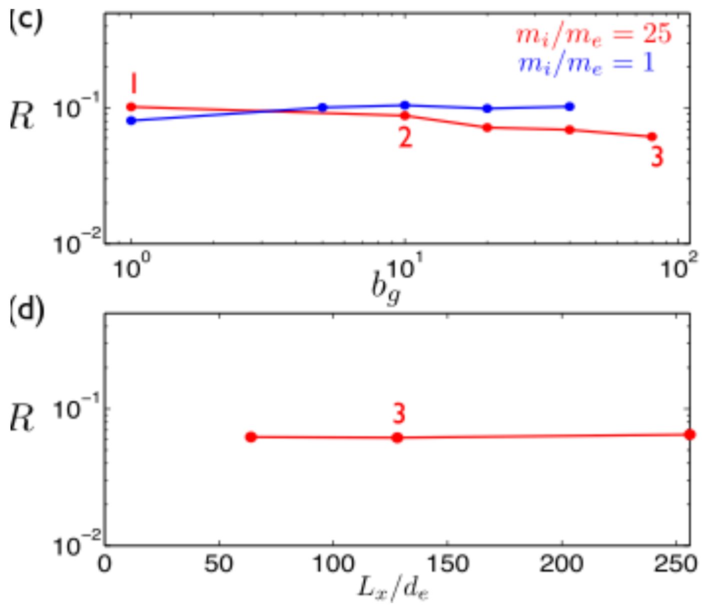

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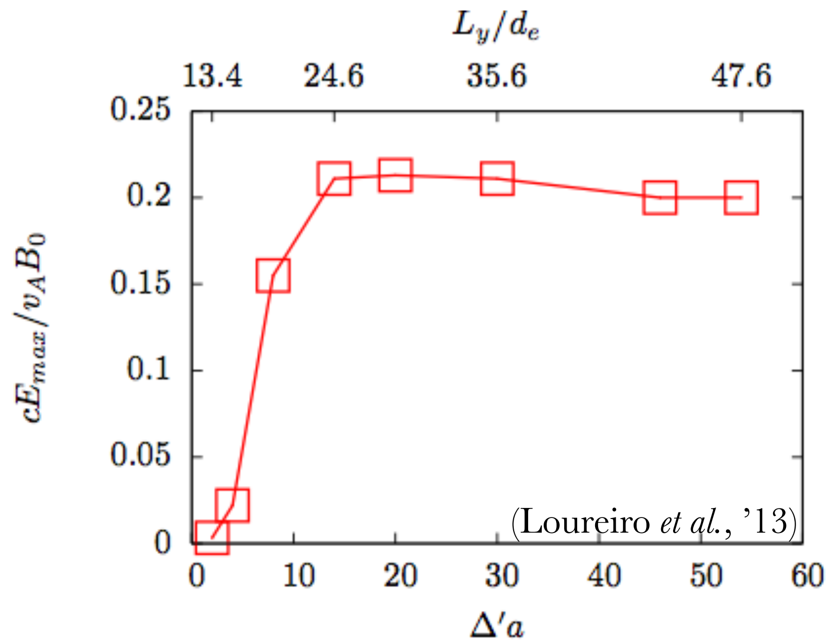

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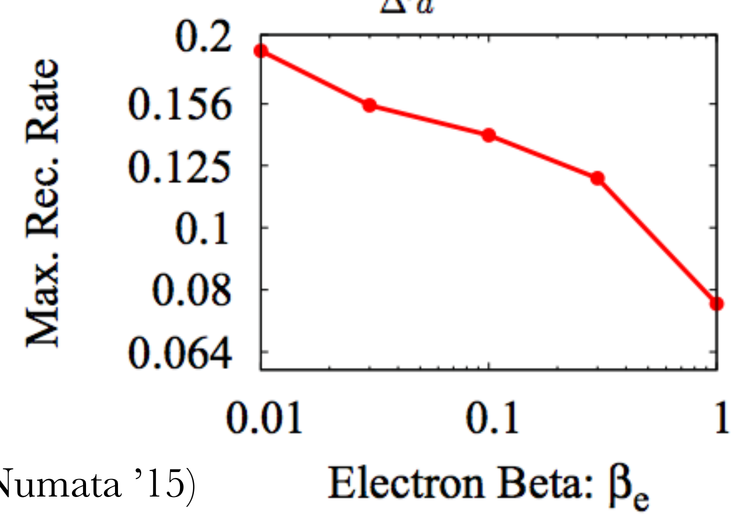

(Numata '15)

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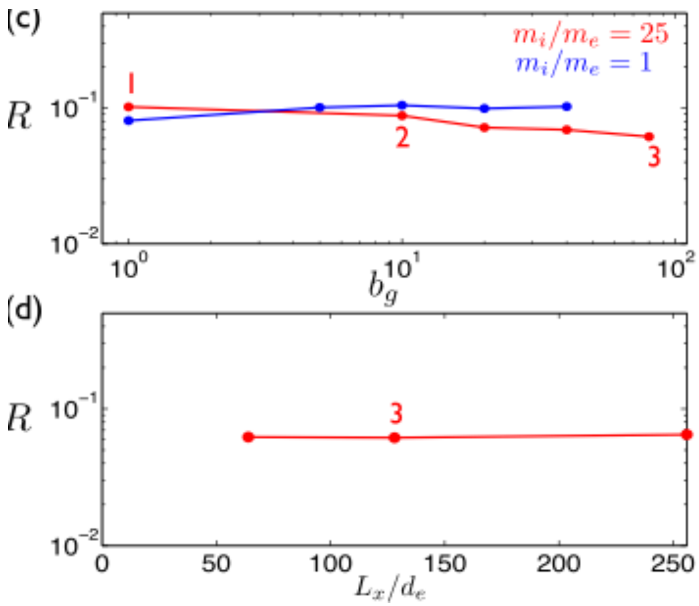

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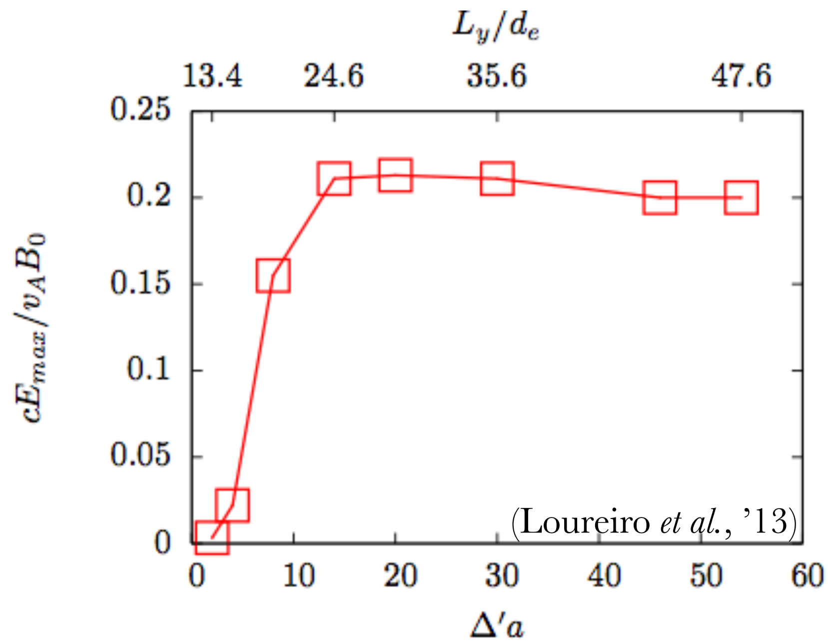

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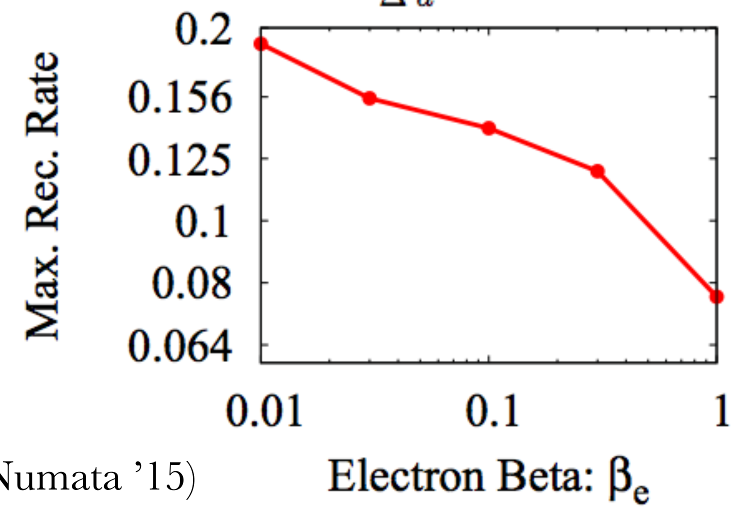


(Numata '15)

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?
- Role of reconnection in turbulence?

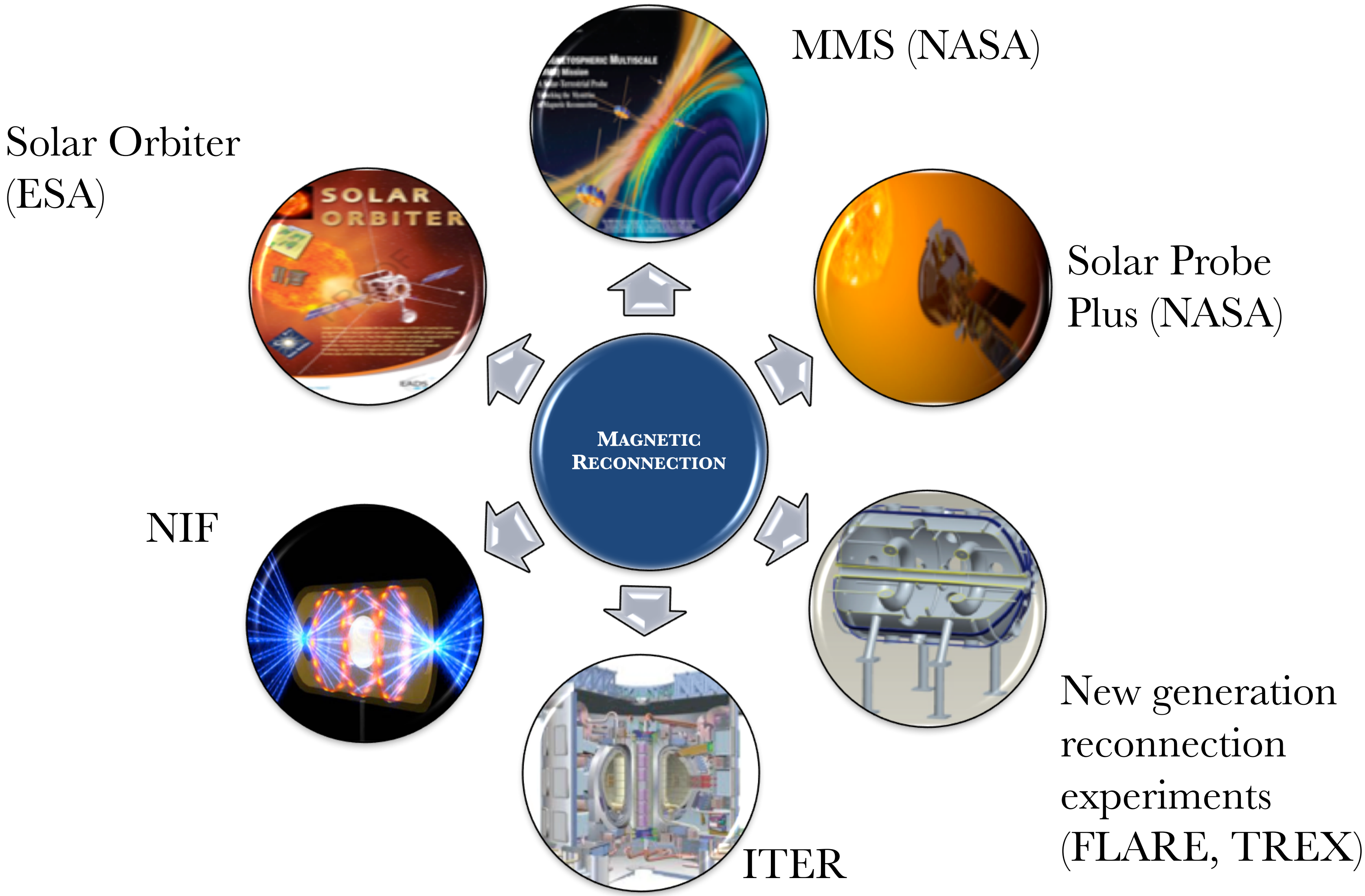
Summary and Conclusions

- Magnetic reconnection is one of the most (the most?) important basic plasma physics phenomenon.
- Basically, it is an explosive reconfiguration of the magnetic field.
- Leads to energy release (e.g., a solar flare)
- It is quite challenging to understand, and has remained at the cutting edge of plasma research for over 50 years (and probably for the next 50 also!)

Summary and Conclusions

- A lot of progress has been made over the last decade or so: very dynamic and symbiotic collaboration between theory, high-performance computing, experiment and observations
- It is credible that in the next 5 years we will have a fairly complete understanding of reconnection in the simplest plasma description – about time!!

Exciting times ahead!



Extra Slides