Magnetic Reconnection

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… reconnecting to my SULI roots…
…and subsequent diffusion through plasma physics …

NUF student — GENERAL ATOMICS

High-school Physics and math in Nepal

PhD student — MIT

UNH Space Science Center

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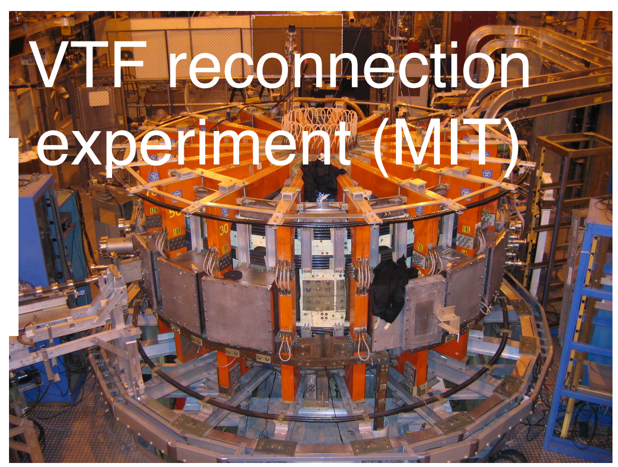
Undergrad thesis at PPPL

2001 | 2002 | 2002-2009 | 2009-2013 | 2013 - now

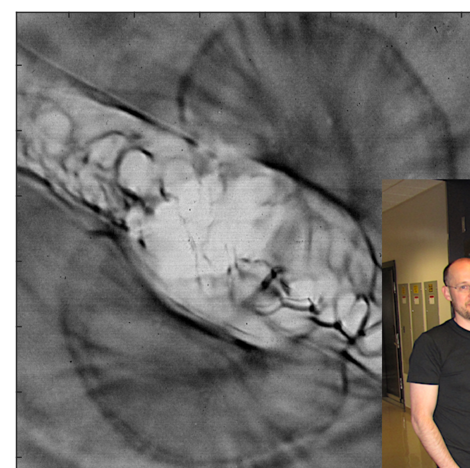
Institute of Physics Publishing and International Atomic Energy Agency — Nuclear Fusion

Nucl. Fusion 42 (2002) 1124–1133 — PII: S0029-5515(02)38137-7

Analysis of current drive using MSE polarimetry without equilibrium reconstruction



Expts at NIF and OMEGA



Key Points to Take Away

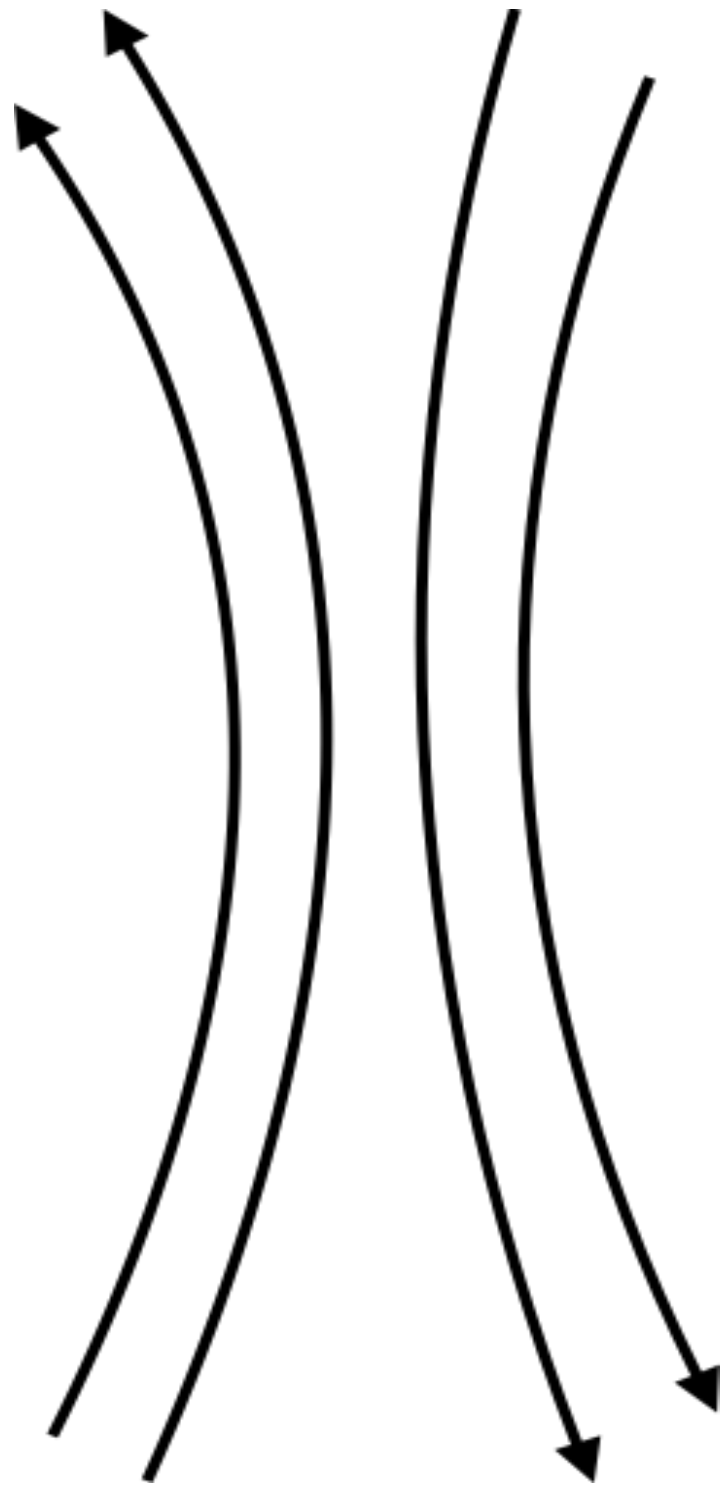
- **Magnetic reconnection** is a ubiquitous plasma process to explain dynamic and explosive plasma events from astrophysics to the laboratory

- All about **energy conversion** in plasma: re-arrangement of magnetic field leads to conversion of magnetic energy to plasma energy (kinetic flows + heat + accelerated particles)

- The problem is nearly as old as plasma physics, but continues to provide challenges:
    - **2-D (and likely 3-D**): complex geometry
    - **Multi-scale:** it connects plasma behavior from global to kinetic (single-particle) scales
    - **Explosive** and non-steady

Fundamental Picture

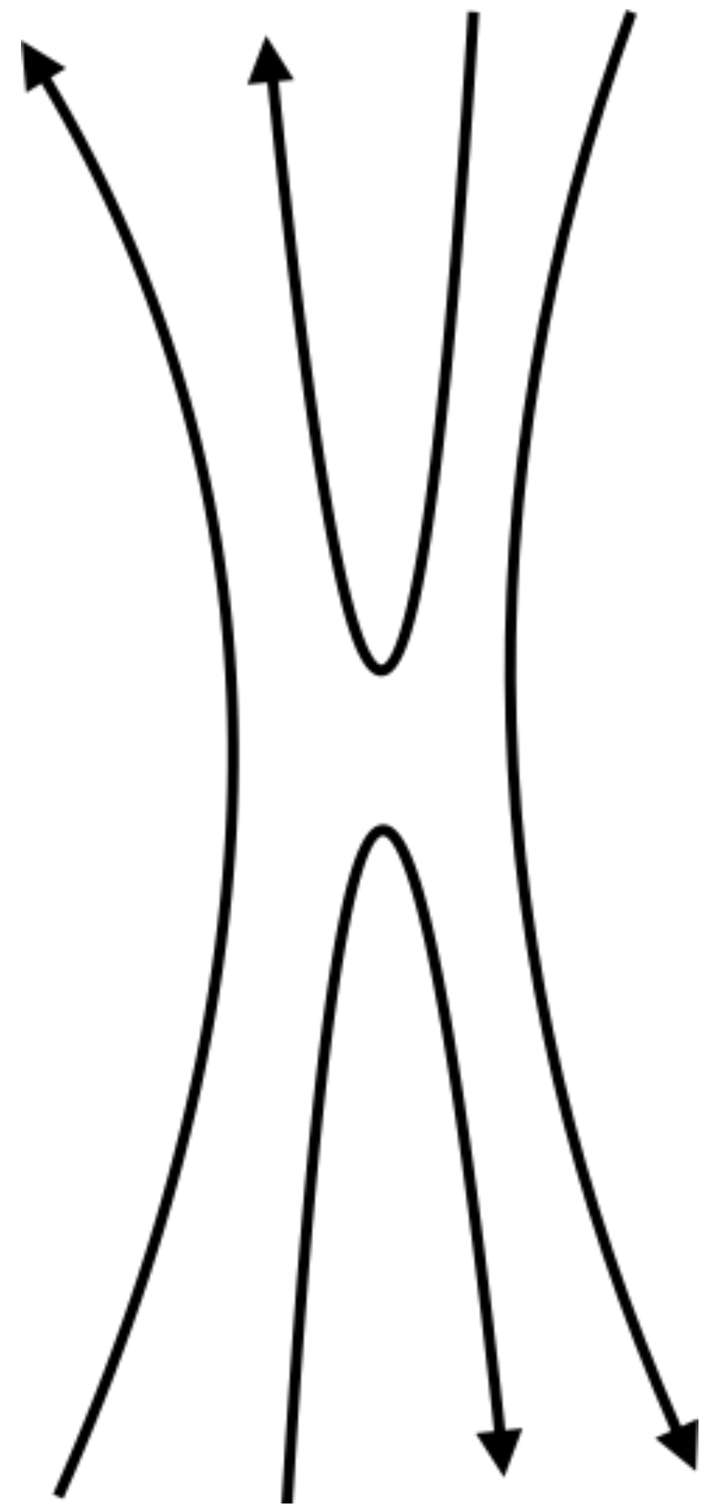
Magnetic fields in plasma store energy and have a tension force



Before reconnection

Fundamental Picture

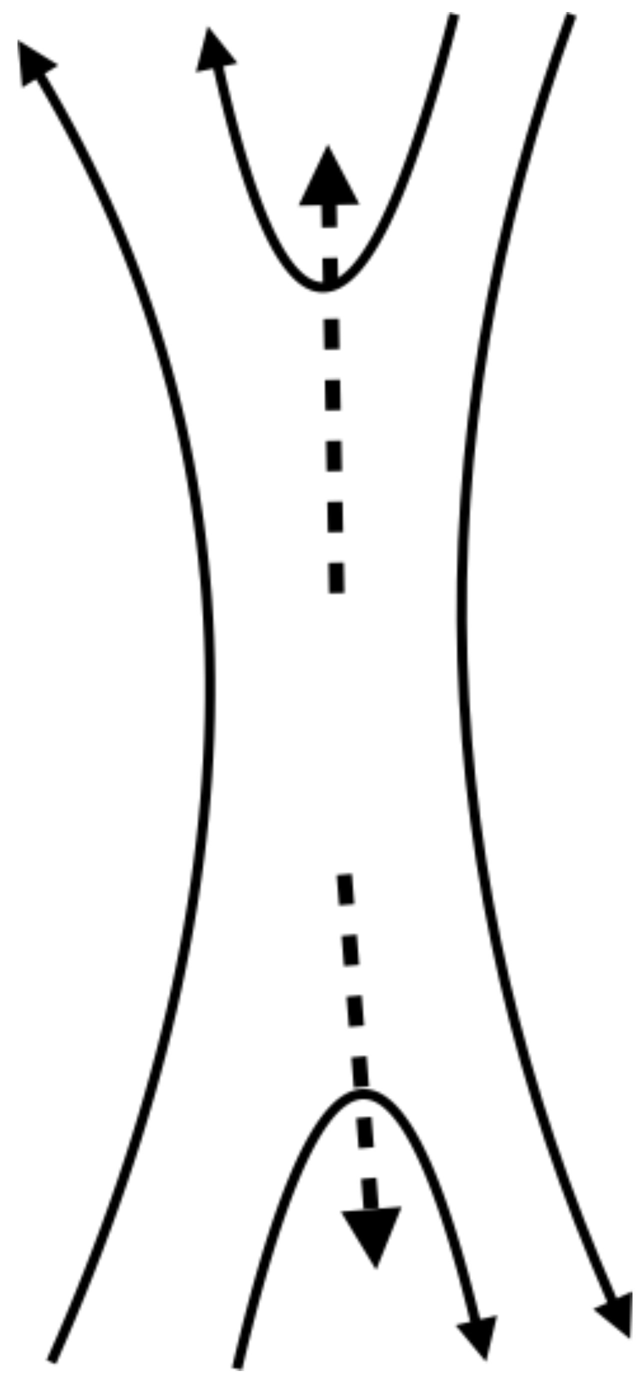
Energy can be released through topology change: magnetic reconnection



Field lines break and reconnect

Fundamental Picture

Energy can be released through topology change: Magnetic Reconnection



Tension force slings plasma out.

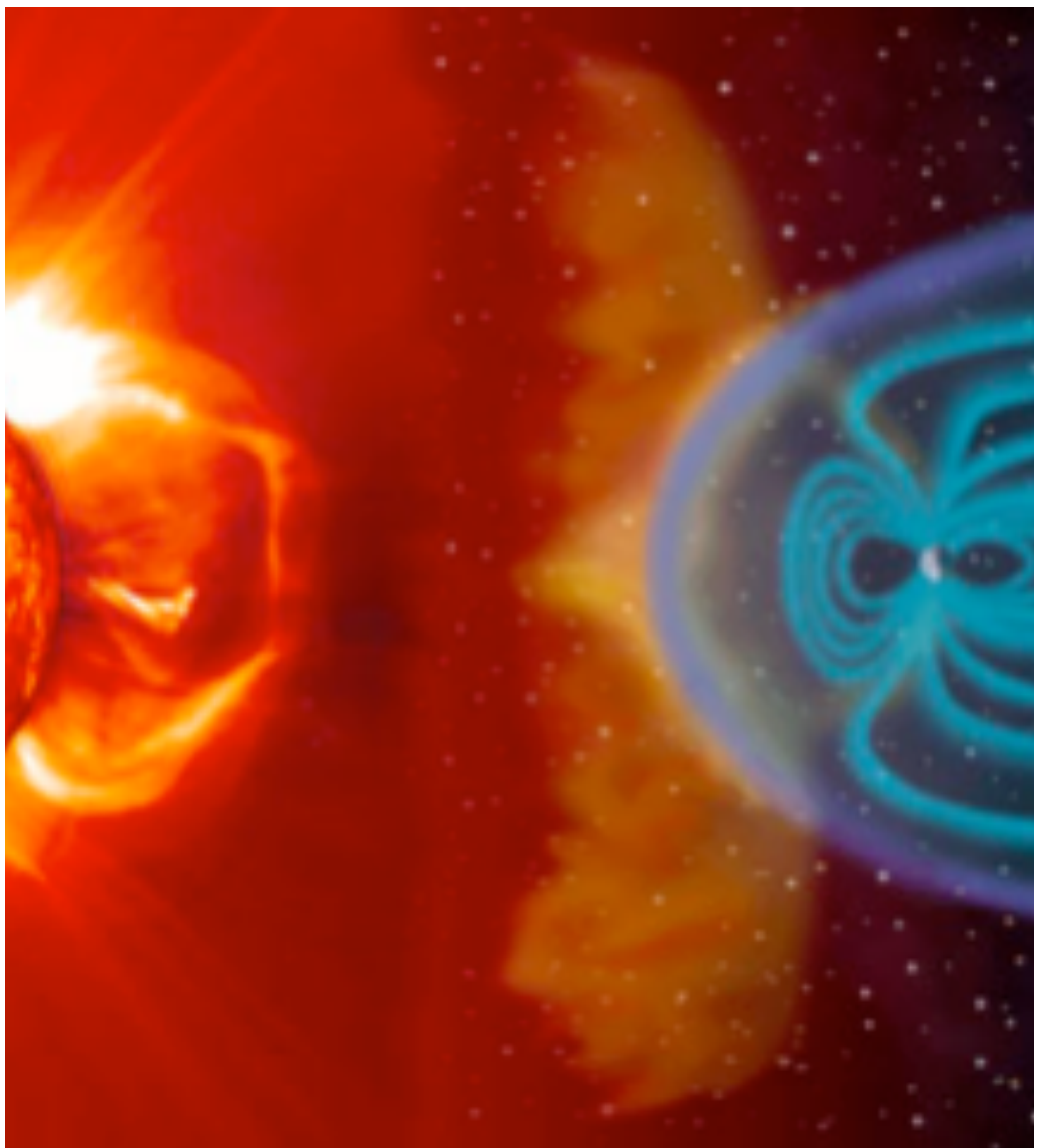
B^2 energy converted to heat and flows

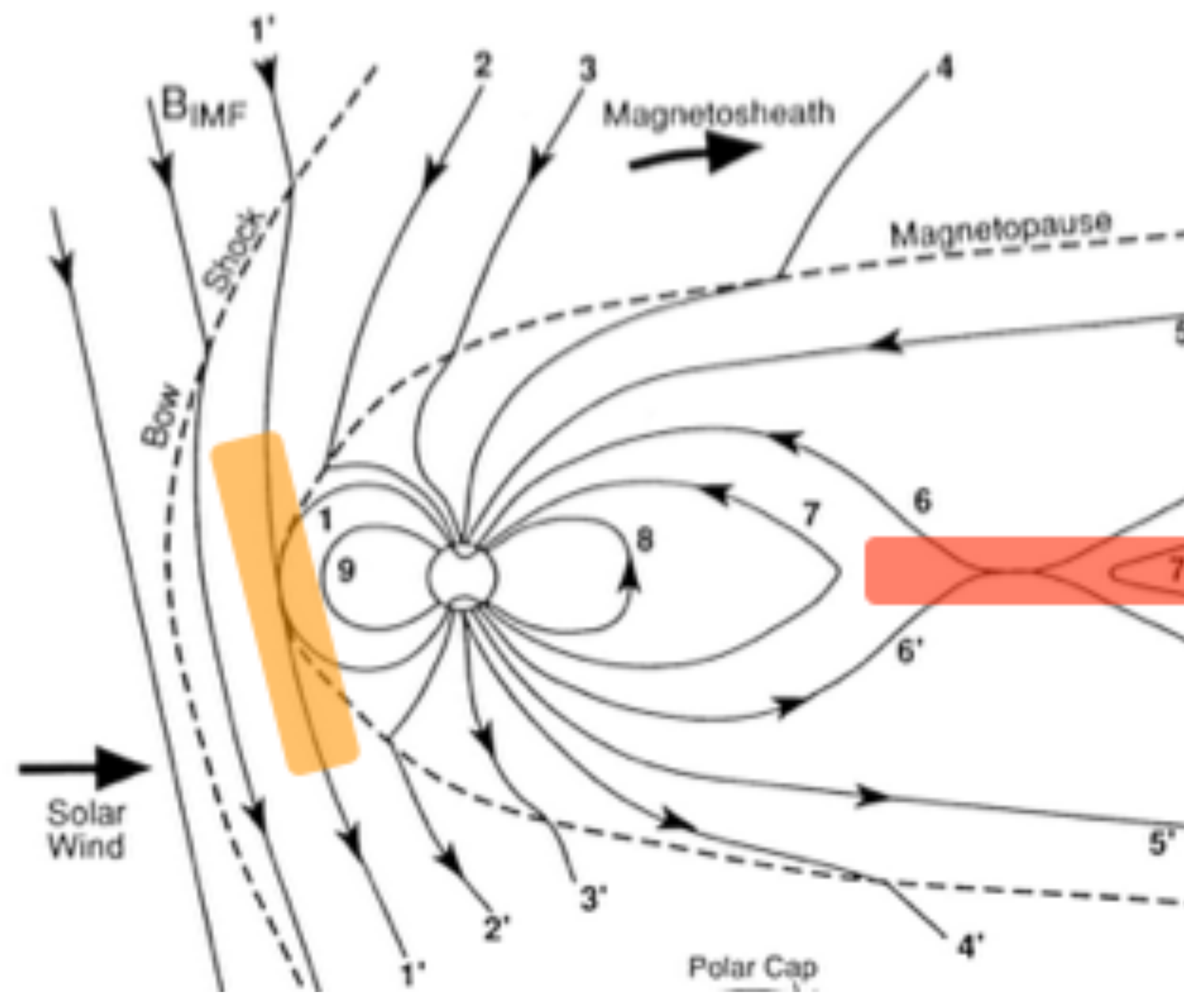
Outline

- Reconnection in space and laboratory plasmas
- Reconnection Fundamentals - Current sheets and Sweet-Parker model
- Extensions
  - Two-fluid speed-up of reconnection
  - Plasmoid instabilities
- Frontier of reconnection

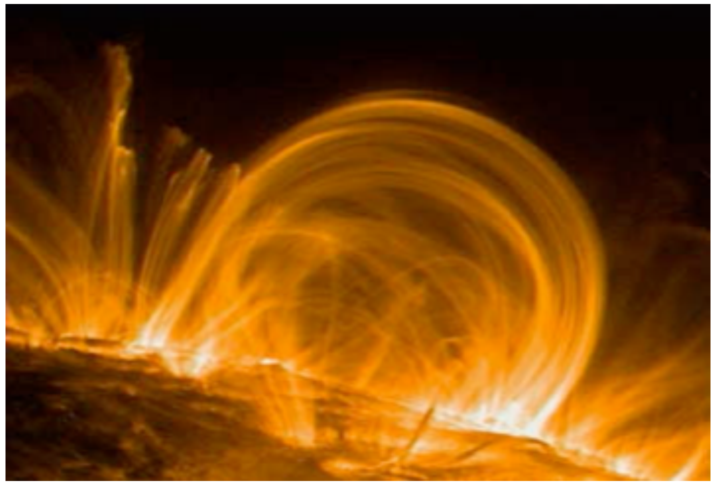
A tour through explosive reconnection in plasmas

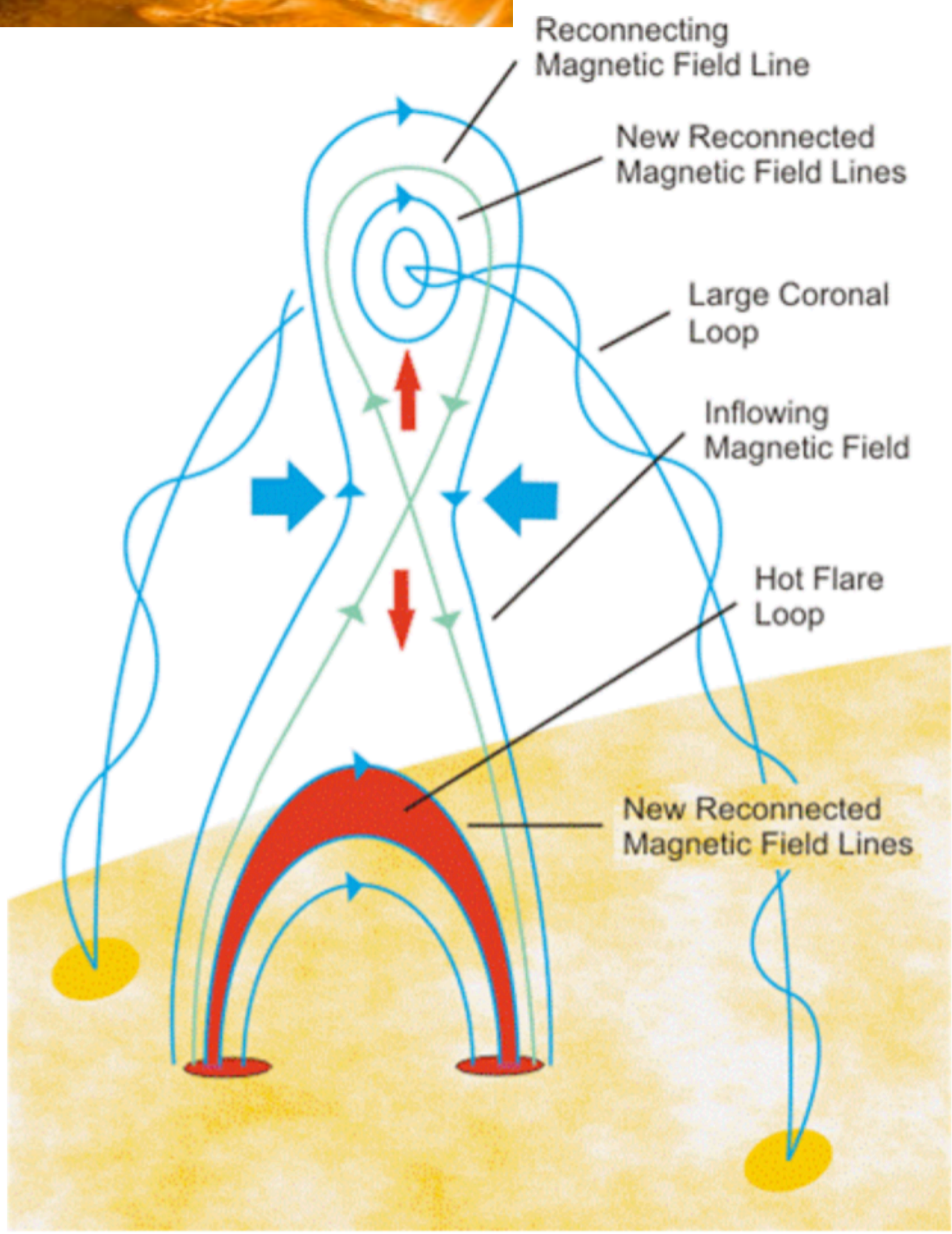
Magnetic reconnection in solar-wind-magnetosphere interaction

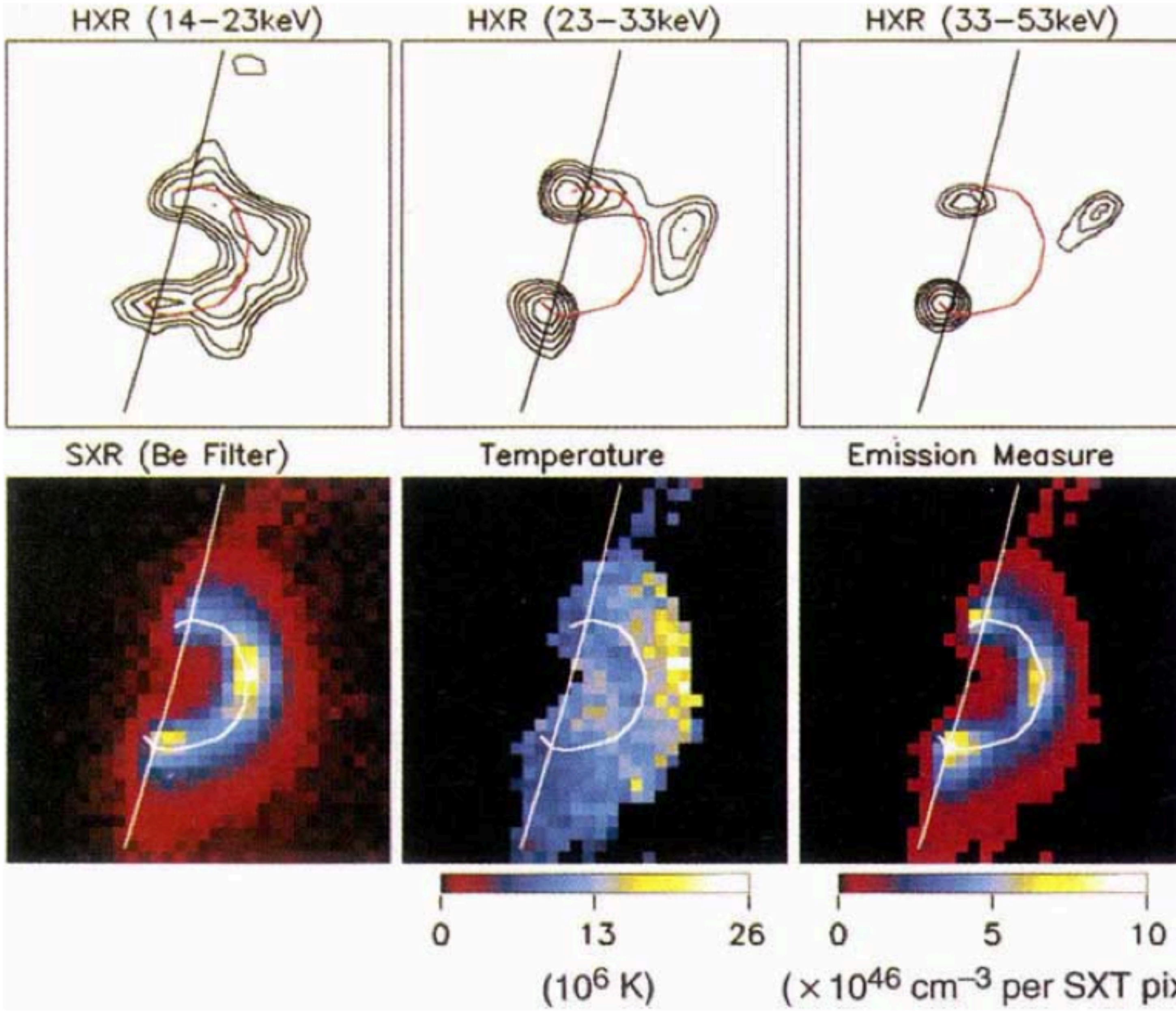




Solar flares: "loop-top" x-ray source supports reconnection picture

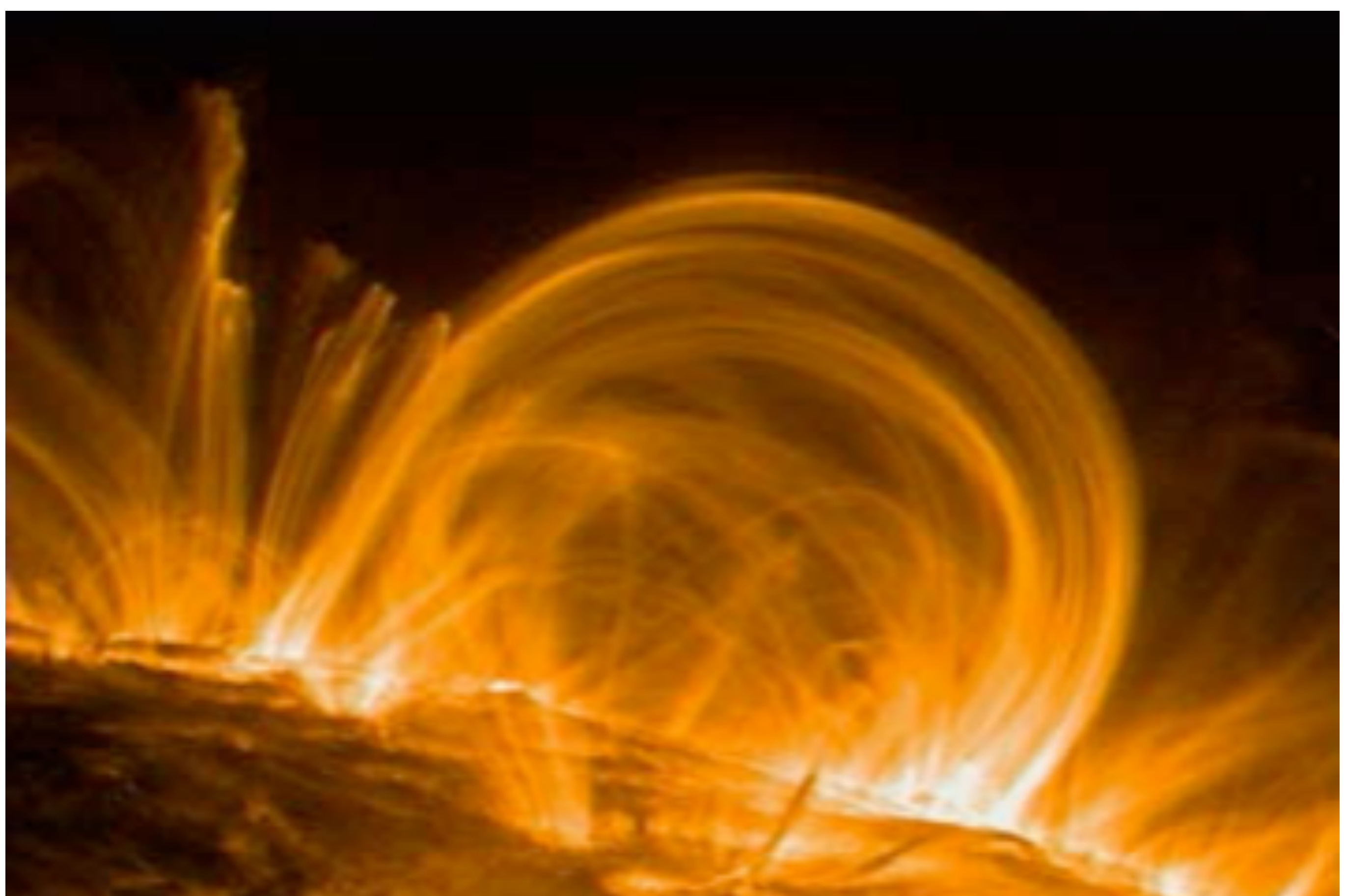




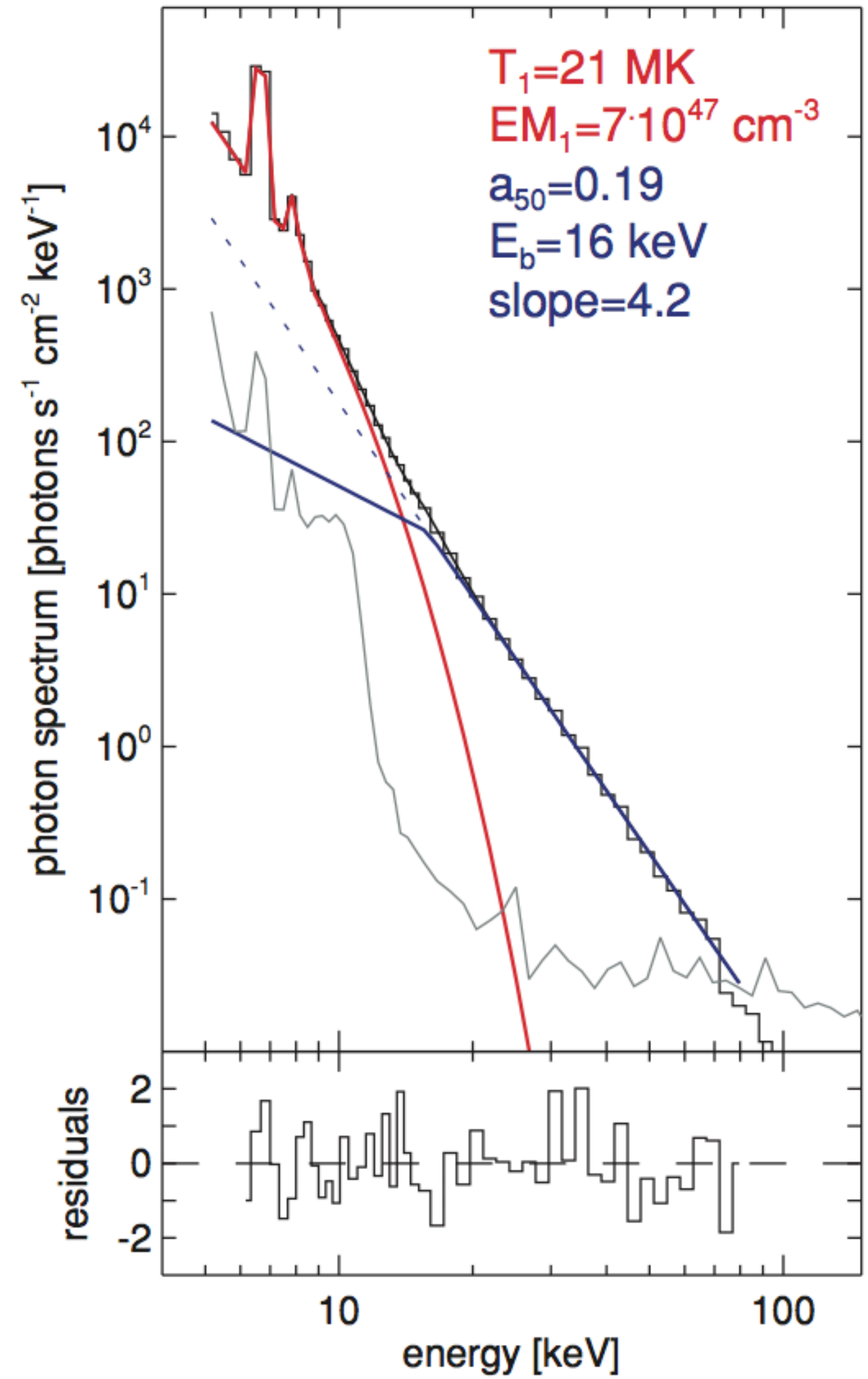


Masuda, Nature 1994

Significant particle acceleration in stellar flares

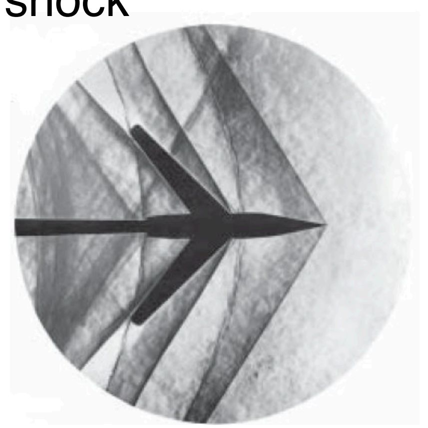


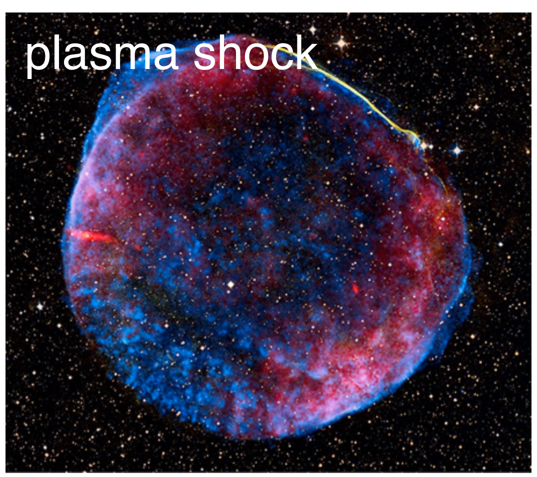
X-ray spectrum
Krucker (2010)



Cosmic particle acceleration by reconnection embedded within collisionless shocks

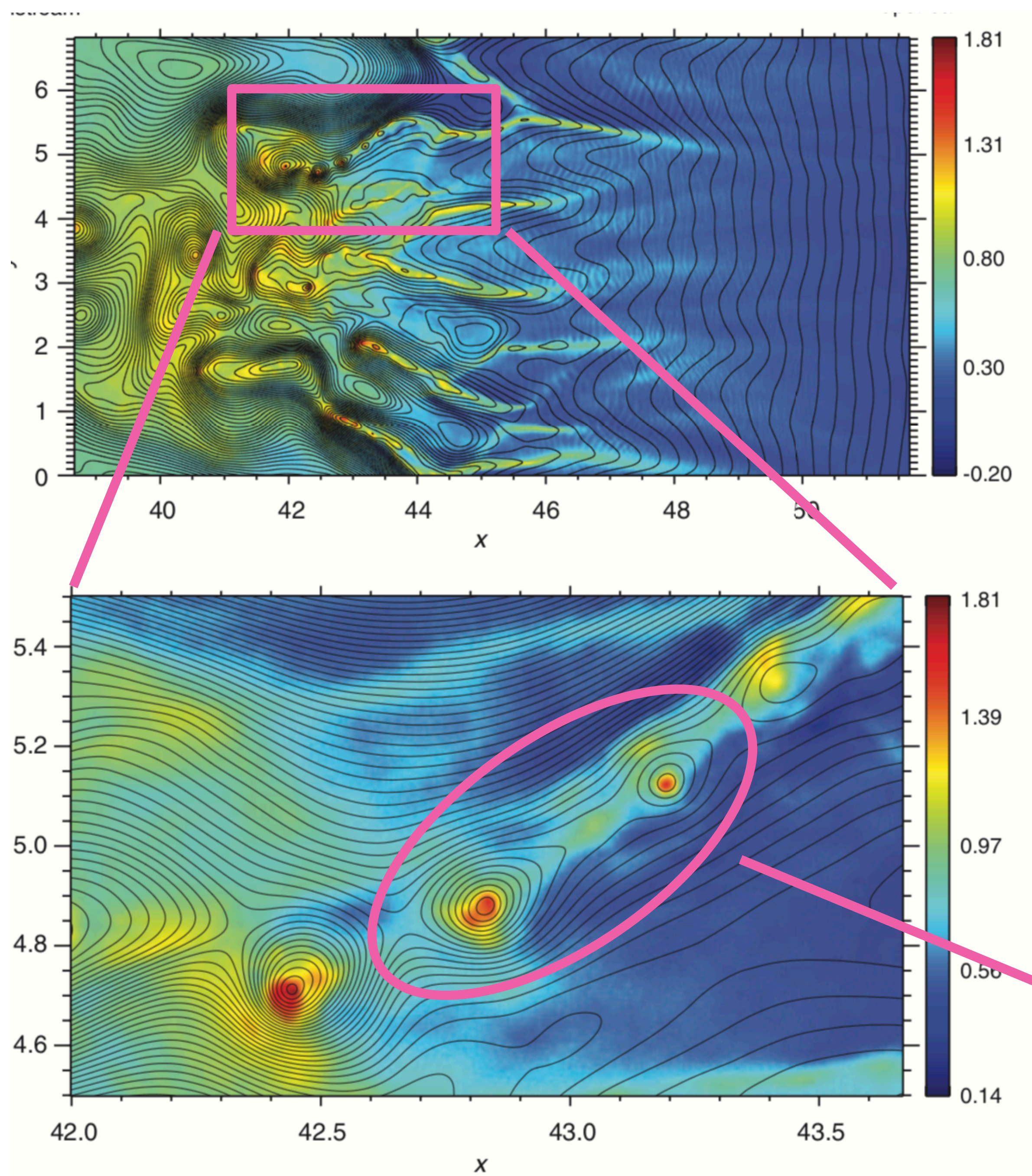
gas shock





SNR1006

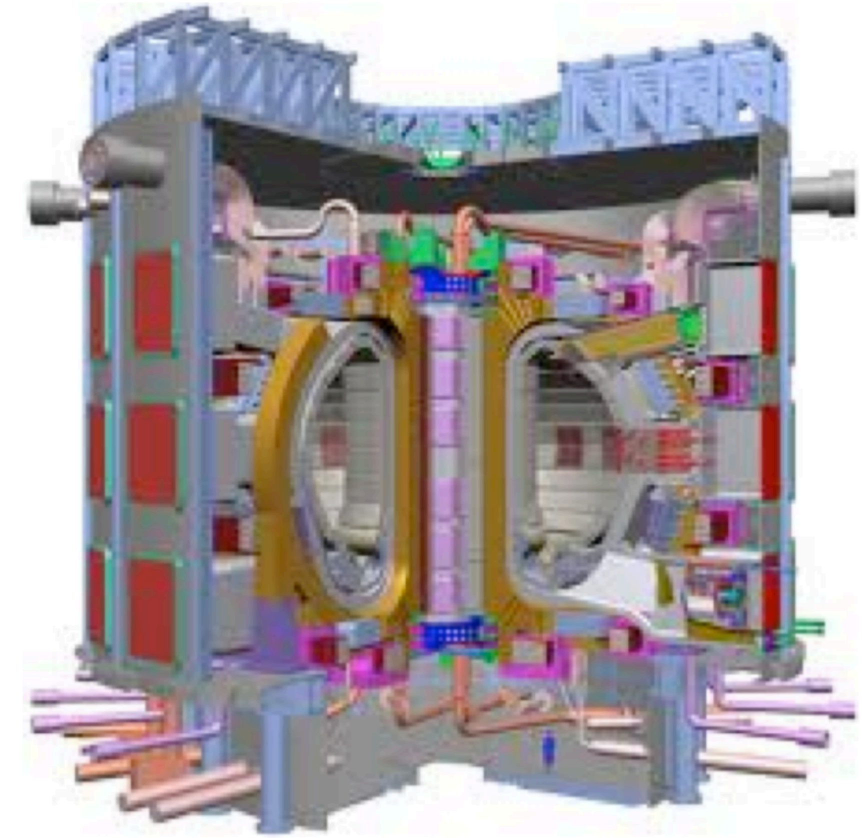
Collisionless SNR shocks shown to be the sites of cosmic ray acceleration. [Ackerman Science 2013]



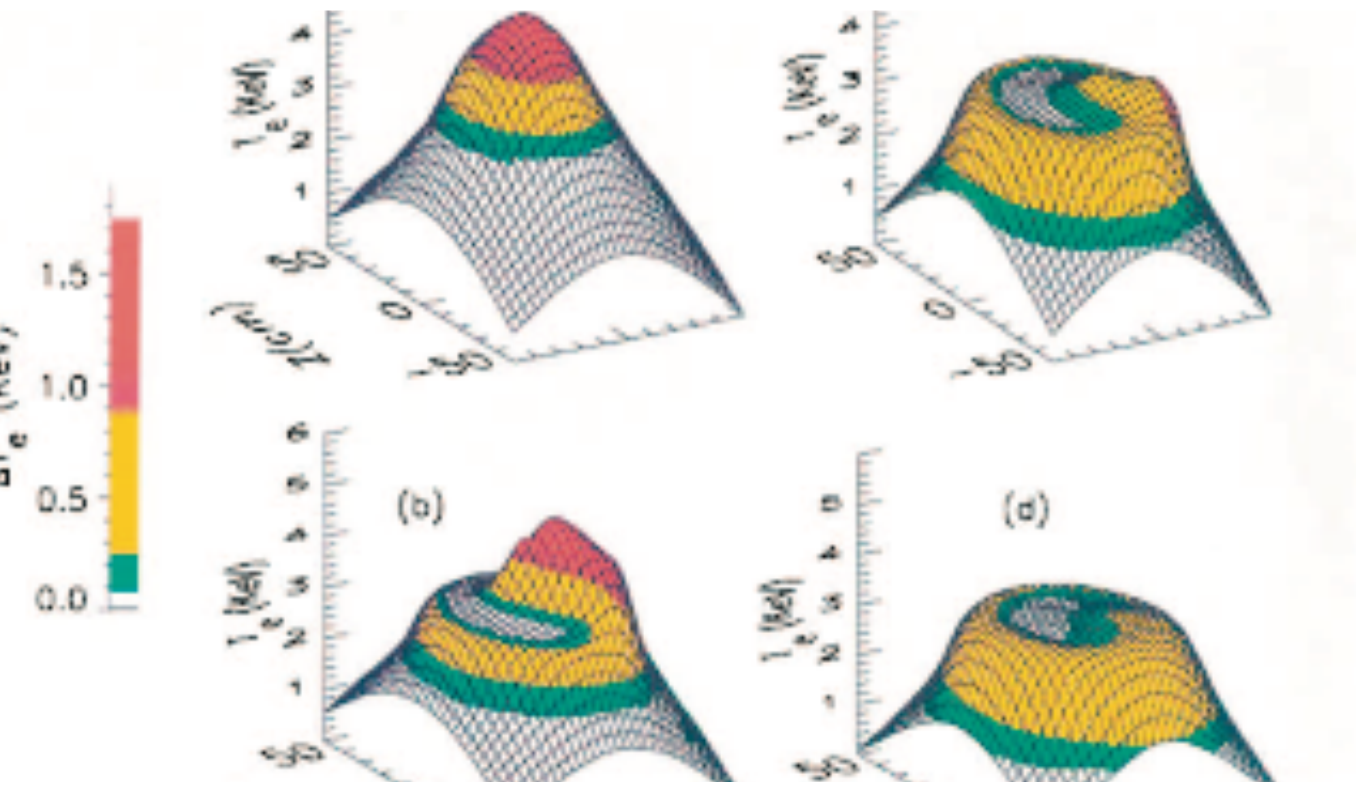
Reconnection current sheet

Matsumoto, Science (2015)

“Sawtooth events” reconfigure central fields in fusion devices and lead to fast energy loss

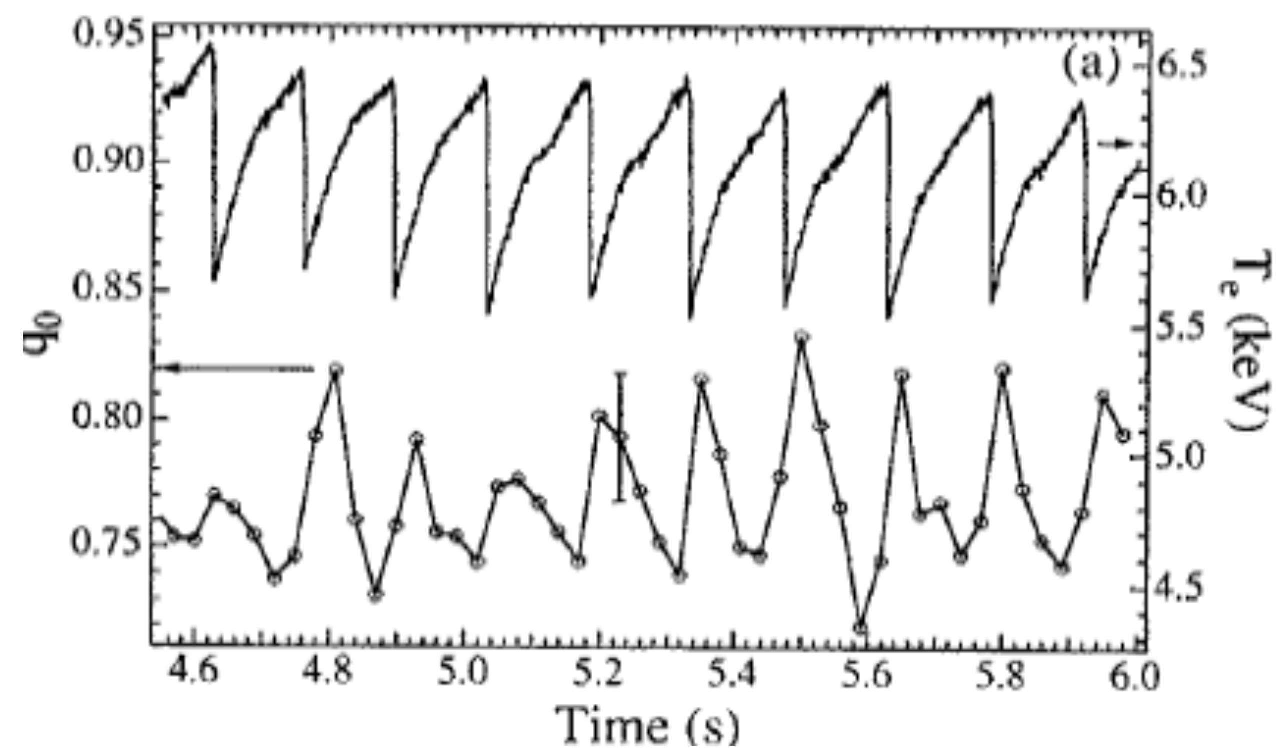


Tomography of temperature profile



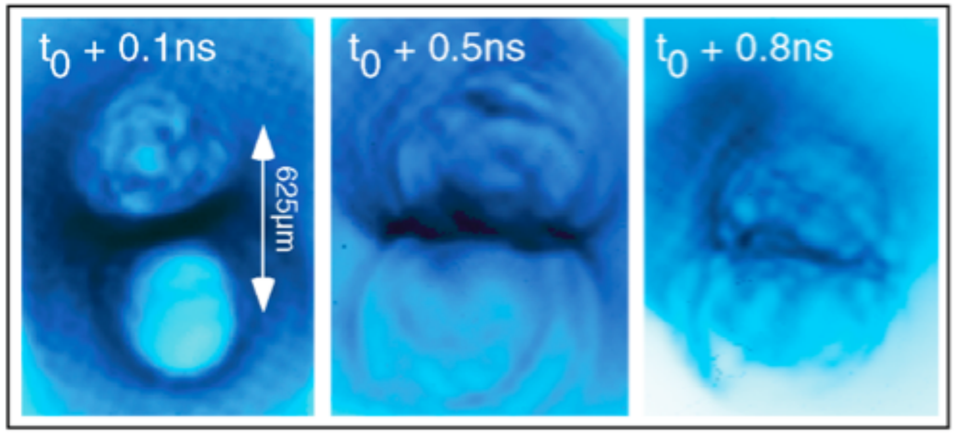
Yamada PoP (1994)

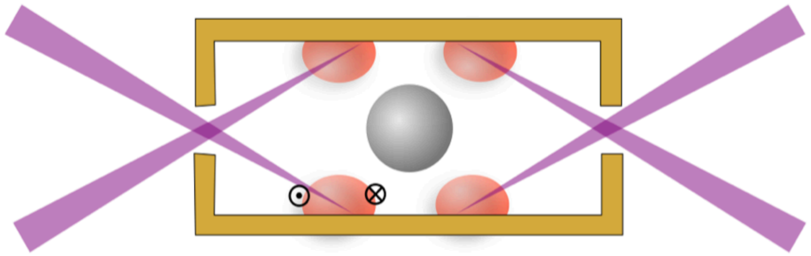
Central temperature crashes



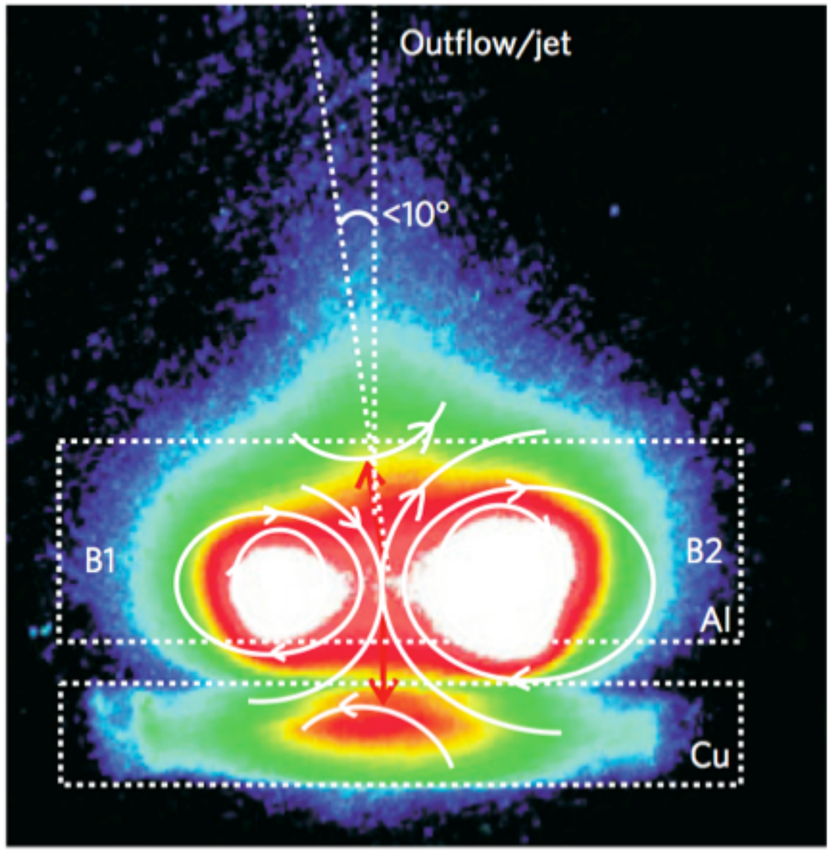
Reconnection observed in laser-driven plasma experiments

Rutherford [Nilson, *et al* PRL 2006, PoP 2008, Willingale *et al* PoP 2010]

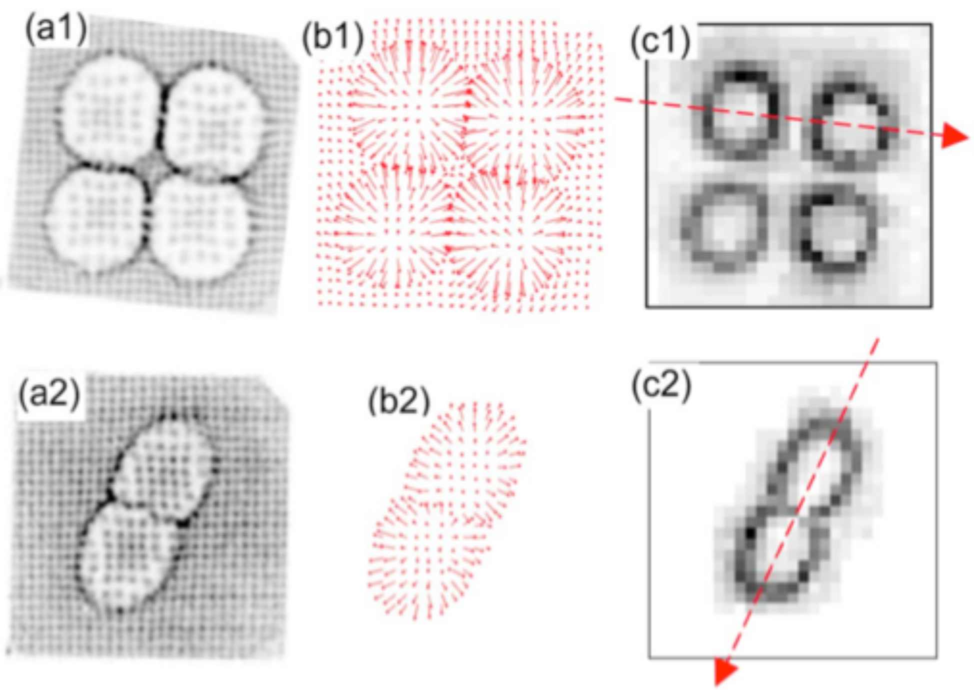




Shenguang [Zhong *et al* Nature Phys 2010]



Omega: [C.K. Li, et al PRL 2007]



WFox Caltech 2013

Reconnection fundamentals

- flux-freezing
- Sweet-Parker reconnection

MHD equations

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

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

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

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

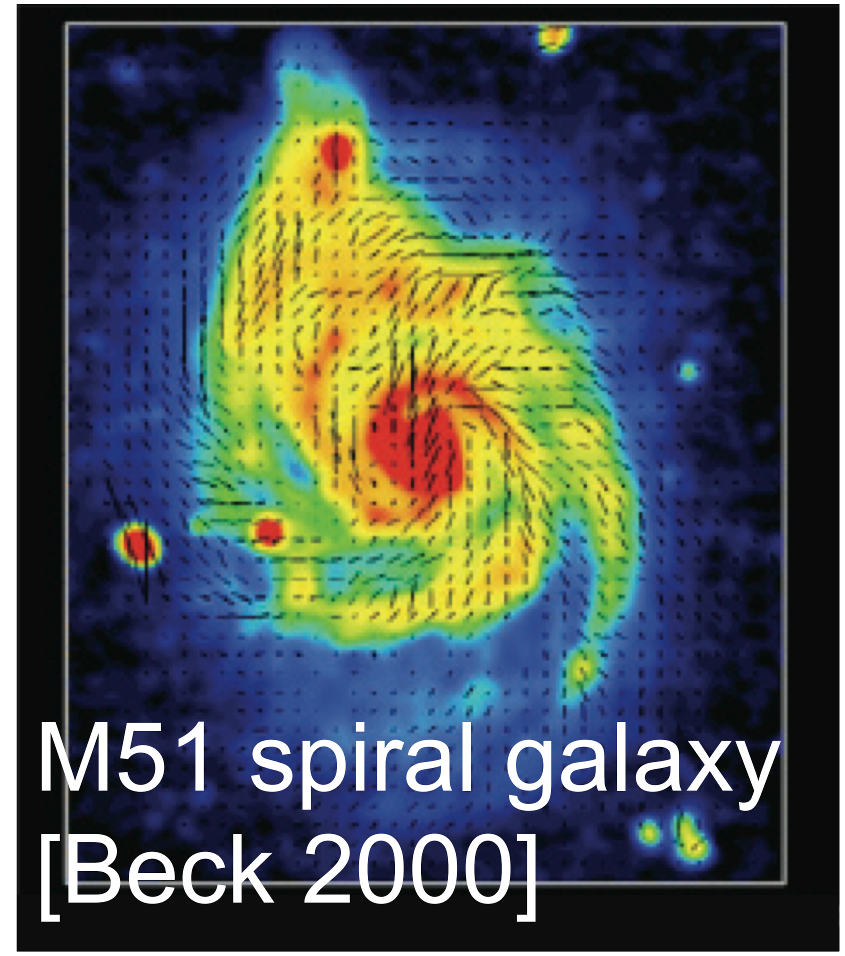
$$\nabla \times \mathbf{B} = \frac{4\pi}{c} \mathbf{j}$$

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

• 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.

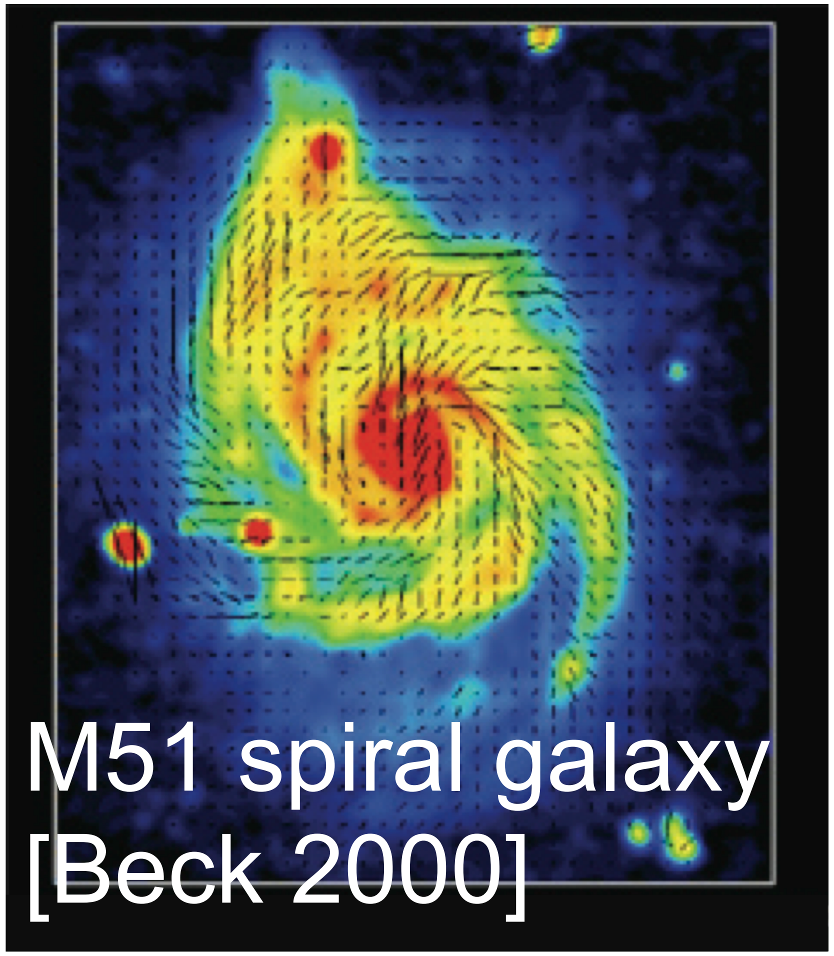
…To see the universe in a cup of coffee…



M51 spiral galaxy [Beck 2000]

- We can rephrase it like a plasma physicist: "the fundamental MHD equations are *scale invariant*"

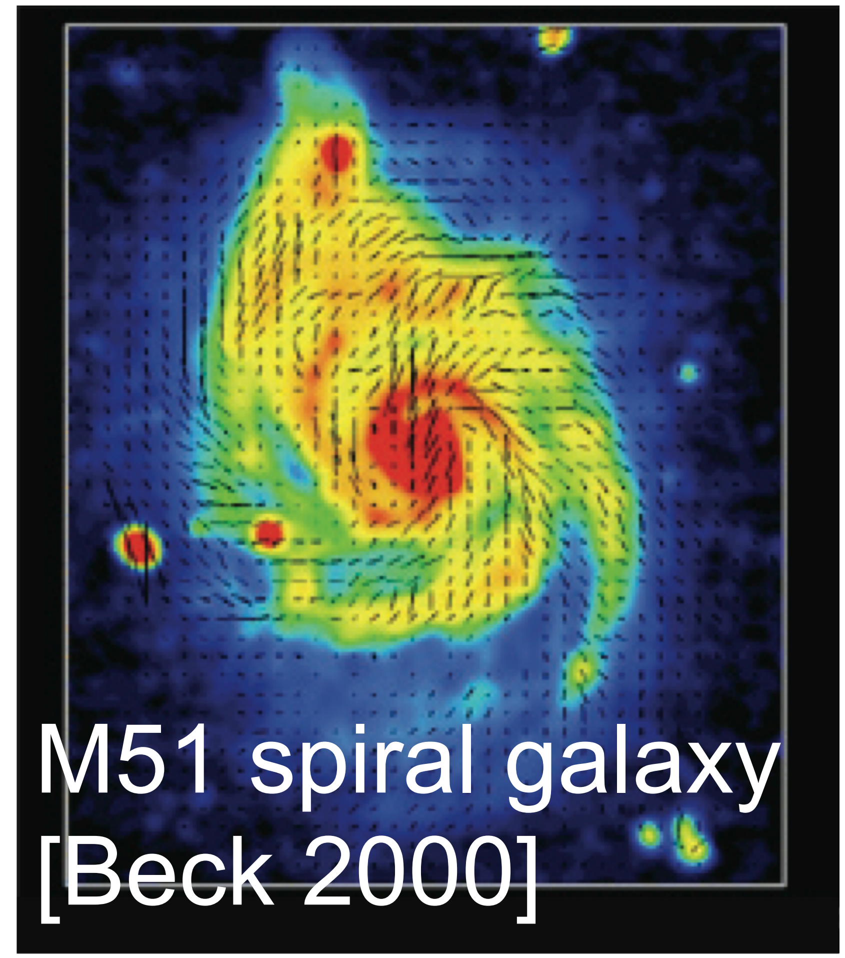
…To see the universe in a cup of coffee…



M51 spiral galaxy [Beck 2000]

- We can rephrase it like a plasma physicist: “the fundamental MHD equations are *scale invariant*”
  - *Similar phenomenon occur in the laboratory and cosmos*
  - *Laboratory experiments can study cosmic behavior!*

…To see the universe in a cup of coffee…



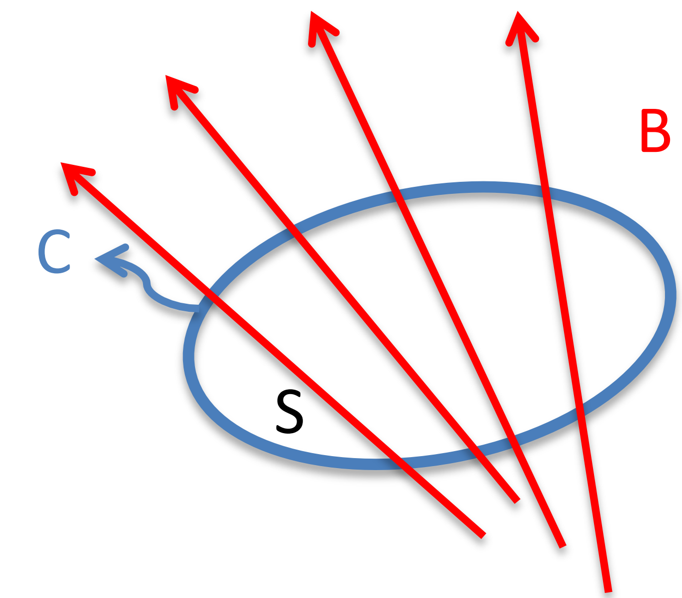
M51 spiral galaxy [Beck 2000]

- We can rephrase it like a plasma physicist: the fundamental MHD equations are *scale invariant*
- (In reality: real plasmas can have viscosity, resistivity, and two-fluid plasma effect, finite Larmor radius, ion skin depth, transport processes, …)
  - More precisely, MHD is a limit of sufficient *scale separation* ($S \sim LV_A/\eta$, $Re \sim LV/\nu$, L/ρ)
  - (This will come back!)

Frozen flux constraint

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

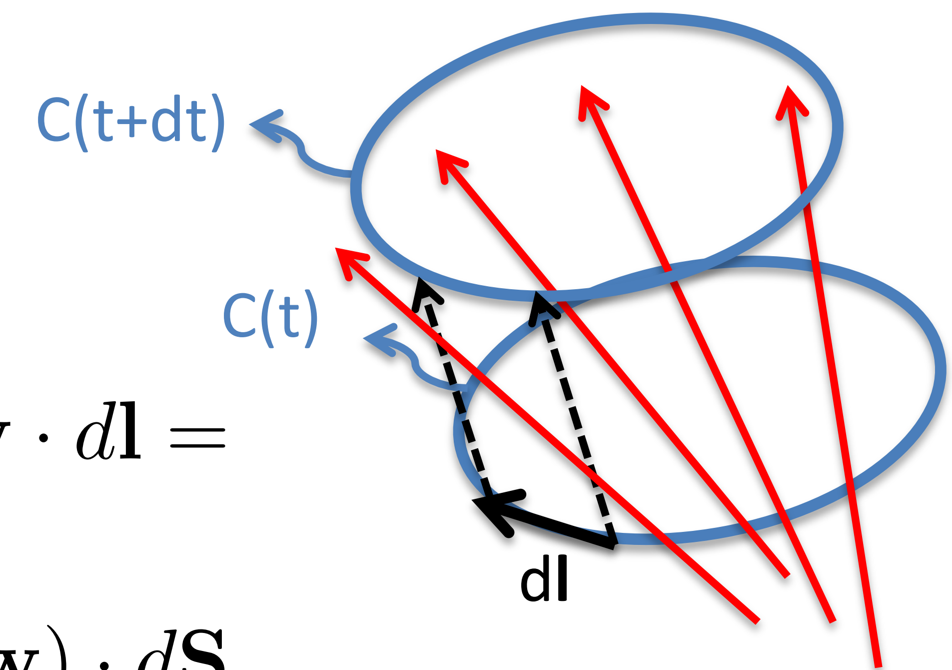
$$\Psi = \int_S \mathbf{B} \cdot d\mathbf{S}$$



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 **w**:

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

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

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:

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

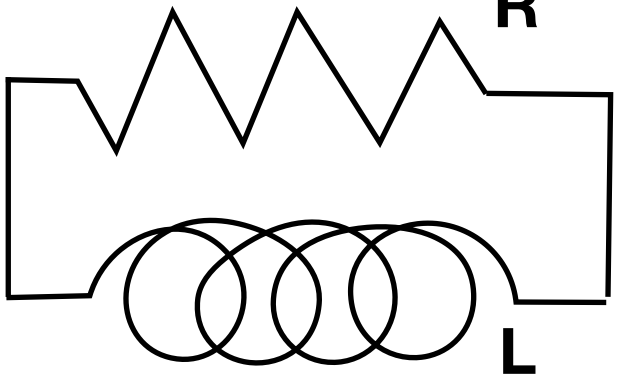
Recognize that $\mathbf{w}$ is an arbitrary velocity. Let me chose it to be the plasma velocity: $\mathbf{w} = \mathbf{u}$, and recall Ohm's law:

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

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

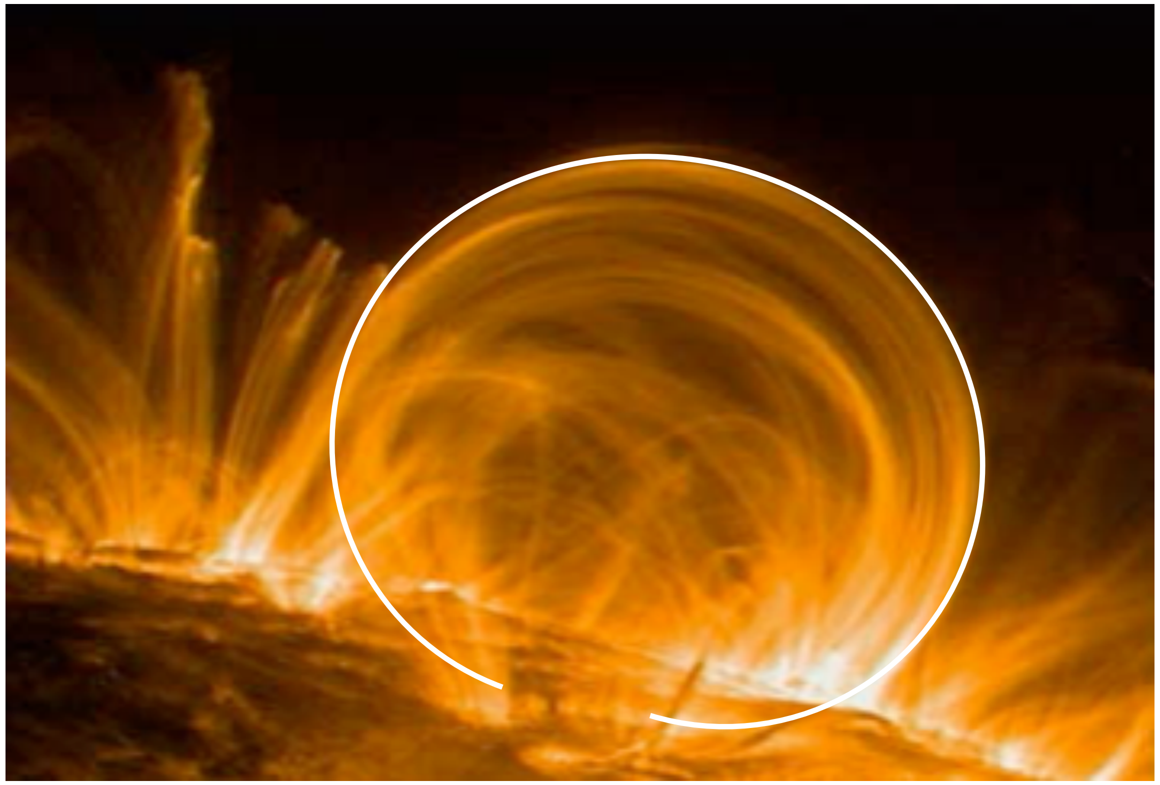
$$\boxed{\frac{d\Psi}{dt} = 0}$$

Simple Resistive Dissipation of Magnetic Field in 1-D Is Extremely Slow



1-D magnetic diffusion is analogous to inductive decay

$$\tau_{diff} = \frac{\mu_0 a^2}{\eta}$$



Resistive diffusion time:

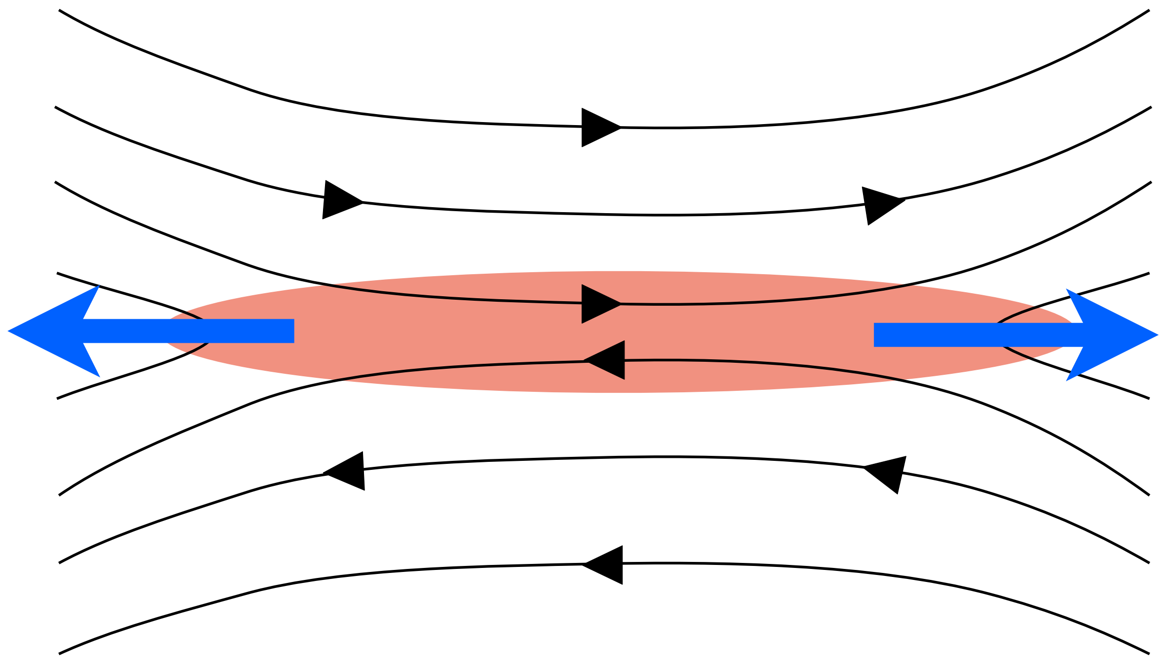
L=10,000km　　τ_{diff}~ 3 Myr!

Te=100eV　　vs flare time: minutes to hours

How to make it faster?

Sweet-Parker model of reconnection

- Key insights
  - Reconnection through a narrow current sheet - much faster than global resistive decay
  - Coupling of reconnection to outflow jets



Sweet-Parker model of reconnection

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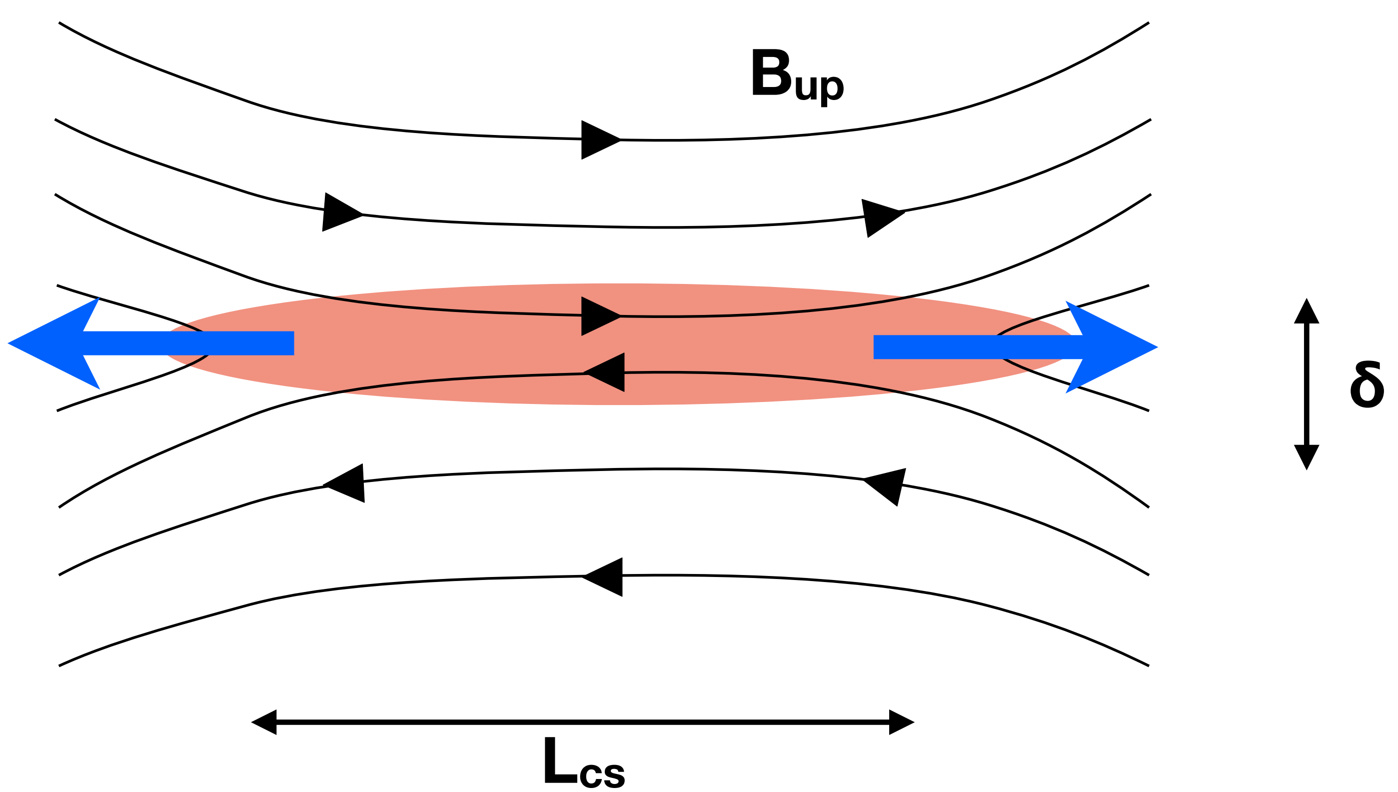
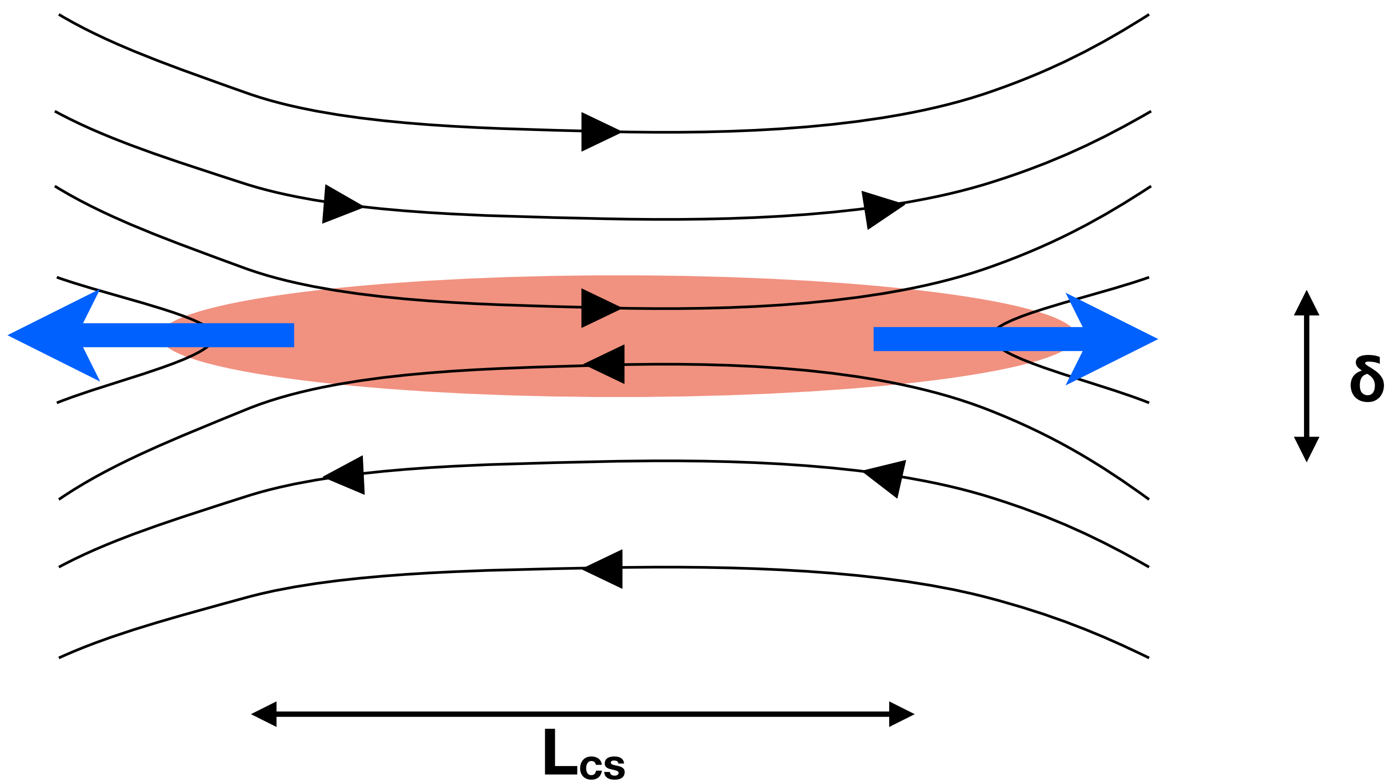


$V_A = B_{up} / (\mu_0 n_0 m_i)^{1/2}$

Typical upstream magnetic field B_{up}, density n0, resistivity η
Lundquist number $S = L V_A / \eta$.

***S* can be very large in cosmic plasmas. Solar flare S ~ 10^{12}!**

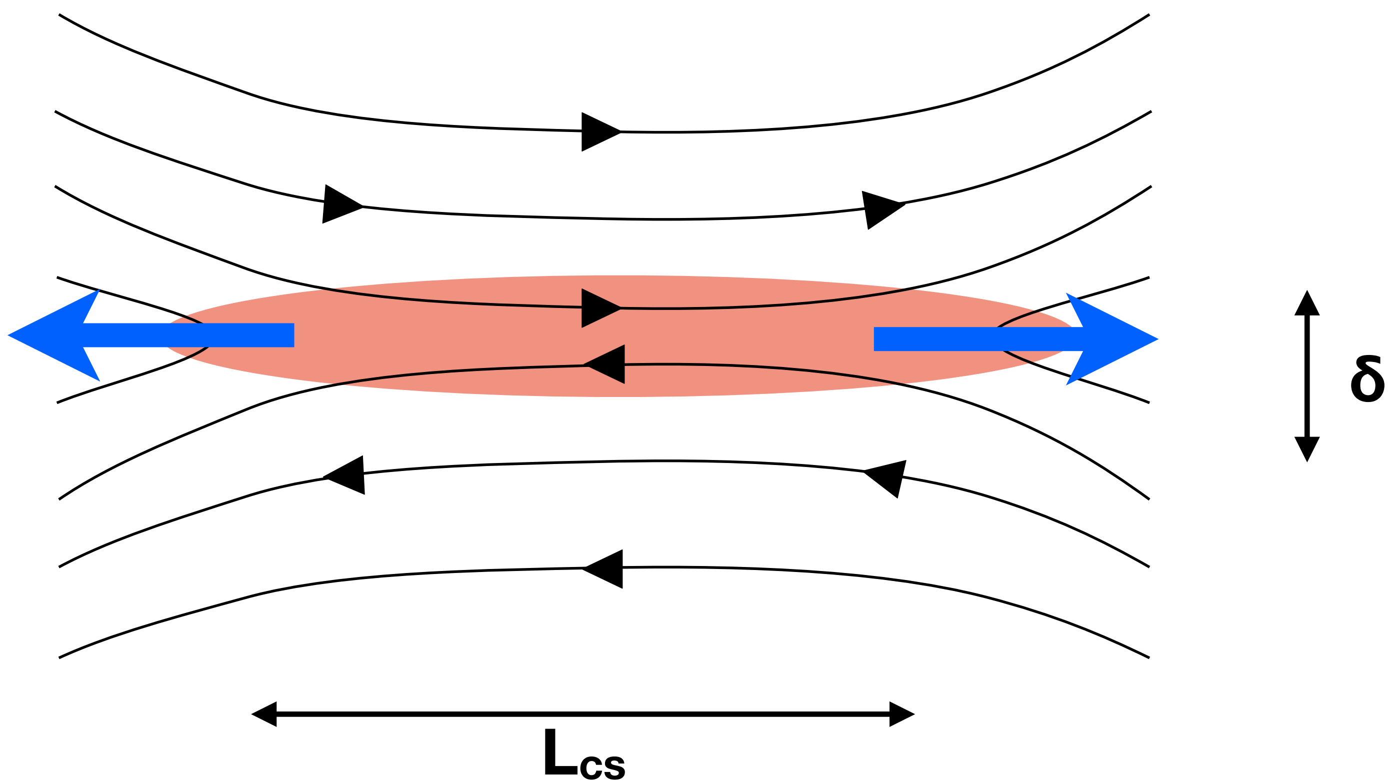
Sweet-Parker model of reconnection



Typical upstream magnetic field B_{up}, density n0, resistivity η.
Lundquist number $S = L\, V_A / \eta$

Ingredients:
1) **Mass balance and steady state: $\delta\, V_{out} \sim L\, V_{in}$**

Sweet-Parker model of reconnection



Typical upstream magnetic field B_{up}, density n0, resistivity η.

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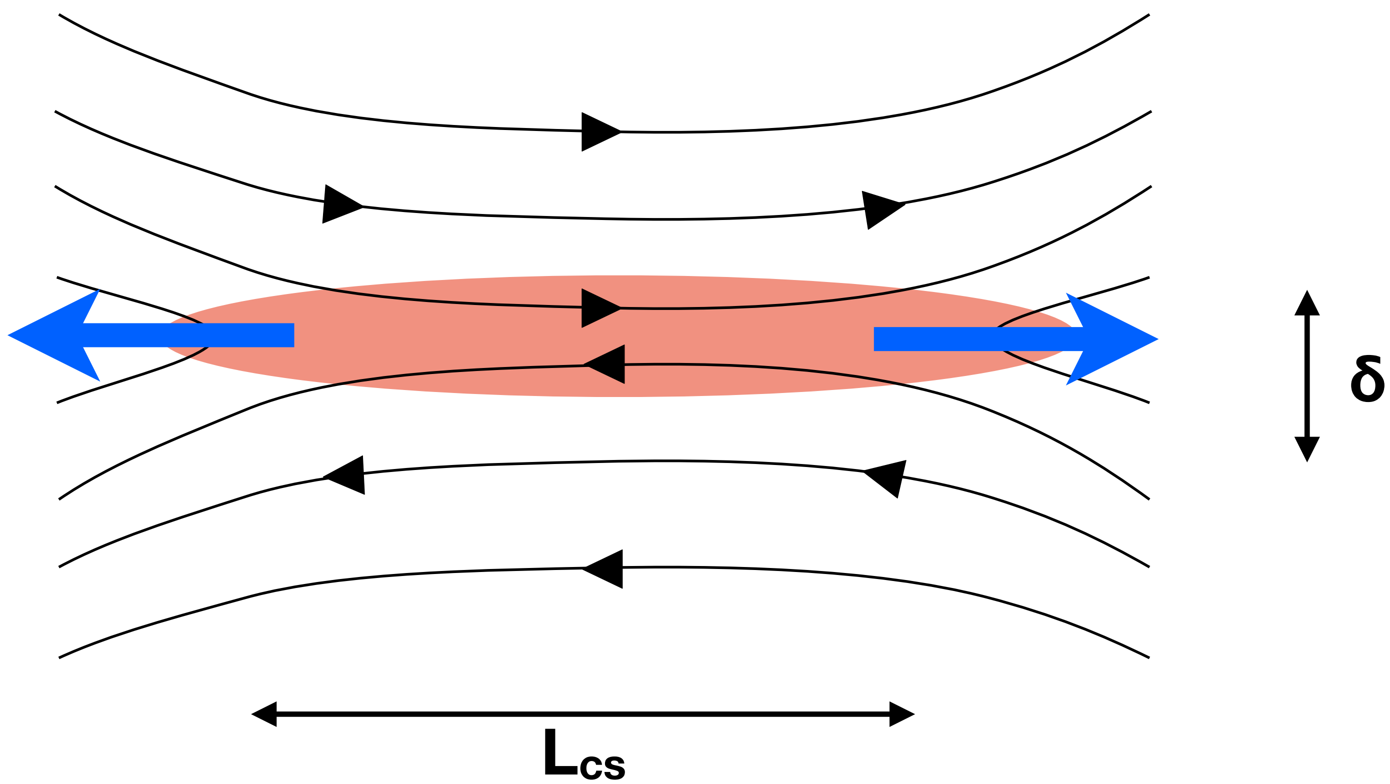
Ingredients:

1) **Mass balance and steady state: $\delta\, V_{out} \sim L\, V_{in}$**
2) **Energy conversion to drive outflow: $nm\, V_{out}^2 \sim B_{up}^2 / \mu_0$. So $V_{out} = V_A$**

Sweet-Parker model of reconnection



Typical upstream magnetic field $B_{up,}$ density n0, resistivity η.
Lundquist number $S = L\, V_A / \eta$

Ingredients:

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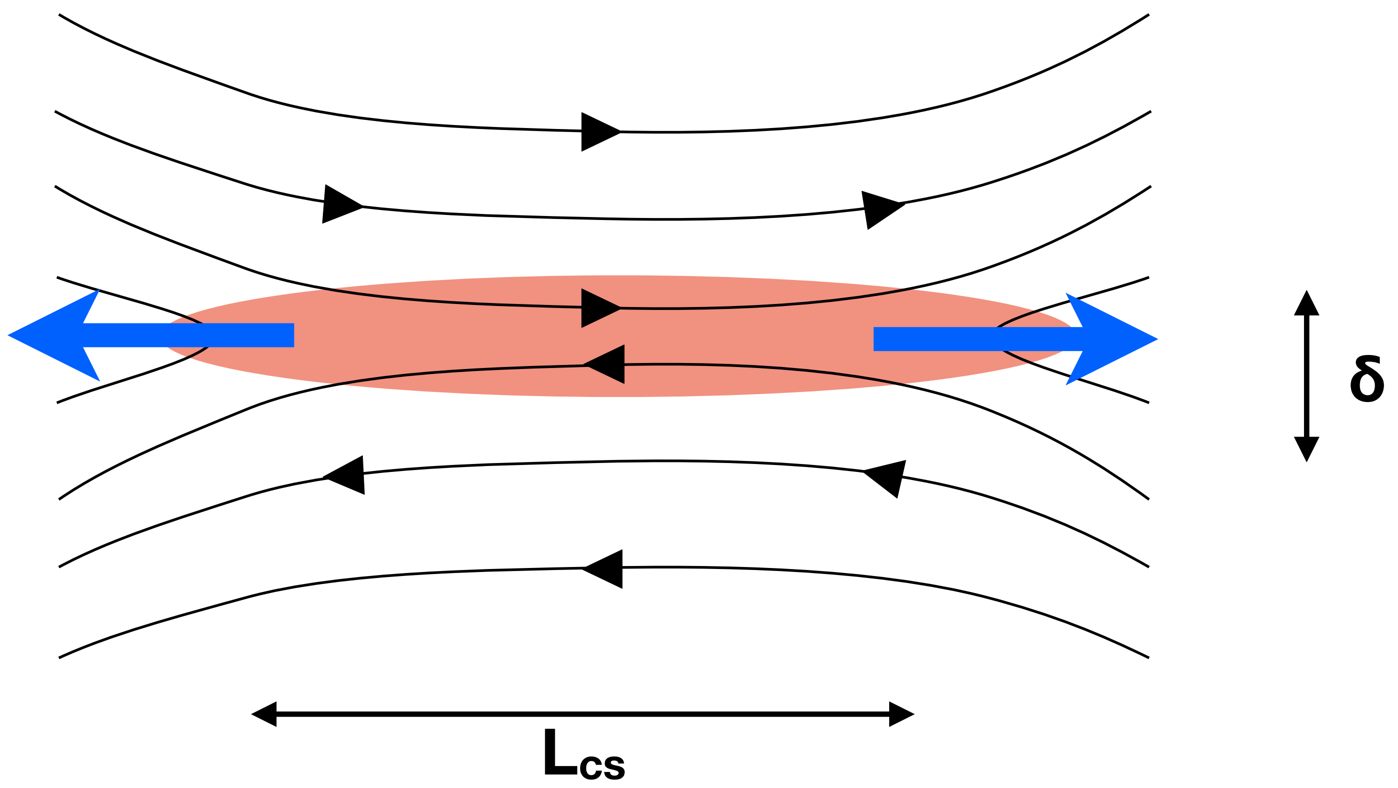
2) **Energy conversion to drive outflow: $nm\, V_{out}^2 \sim B_{up}^2 / \mu_0$. So $V_{out} = V_A$**
3) **Reconnection through thin current sheet (flux balance):**
   - **$E = V_{in} B_{up} = \eta\, J$**

Sweet-Parker model of reconnection



Typical upstream magnetic field B_{up}, density n0, resistivity η.
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Ingredients:
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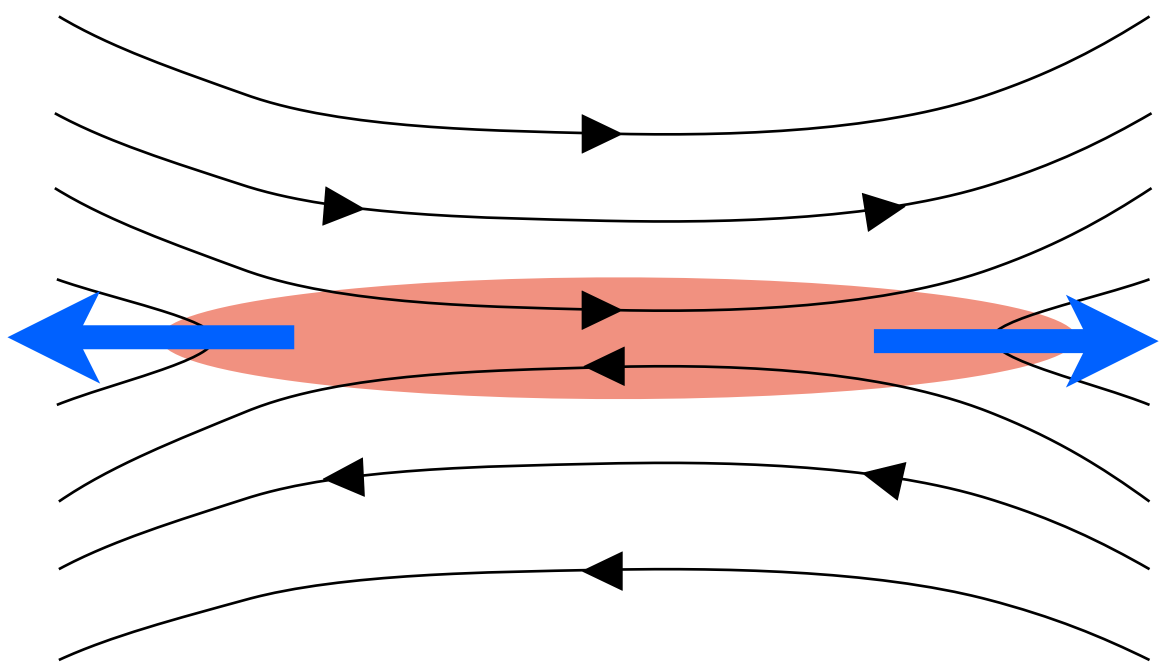
3) **Reconnection through thin current sheet (flux balance):**
   - **$E = V_{in} B_{up} = \eta J$**

Sweet-Parker model of reconnection

- Key insights
  - Good geometry, but very narrow CS due to low resistivity.



$$V_{in}/V_{out} = \delta/L$$

$$V_{in} \sim \eta/\mu_0\delta$$

$$\rho V_{out}^2 \sim B^2/\mu_0$$

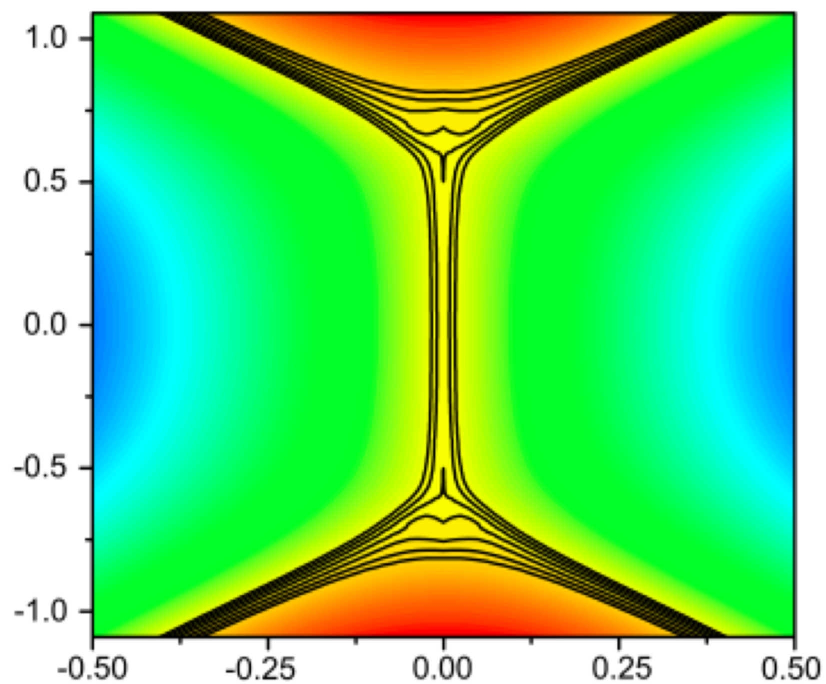
Slow inflow and therefore rate $$V_{in} \sim V_A/S^{1/2}$$

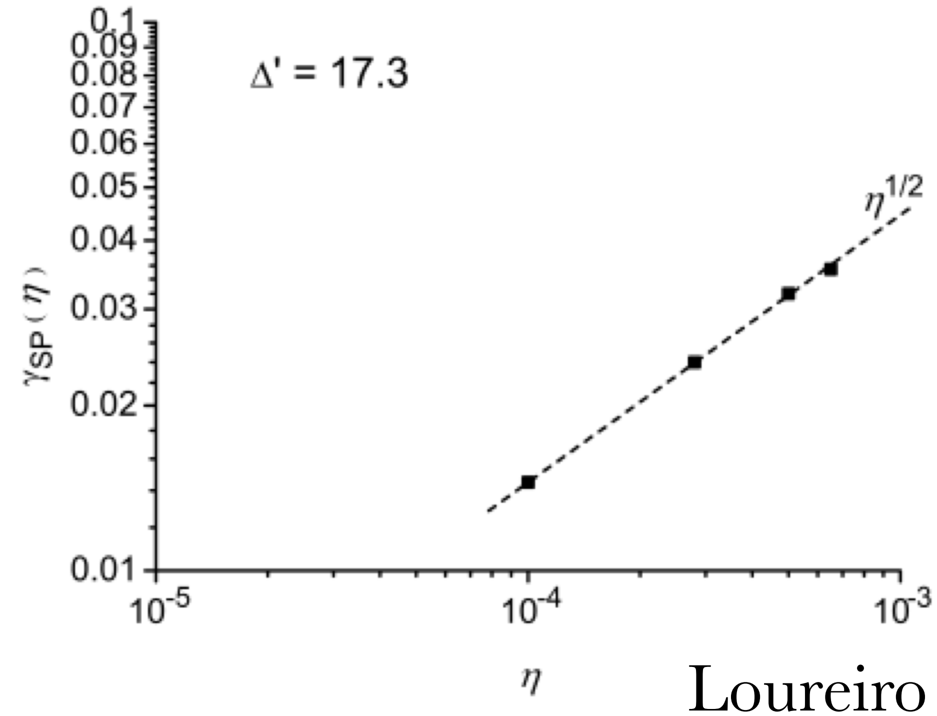
Very extended current sheet $$L/\delta \sim S^{1/2}$$

Solar flare S ~ 10^{12}
SP time ~ weeks…

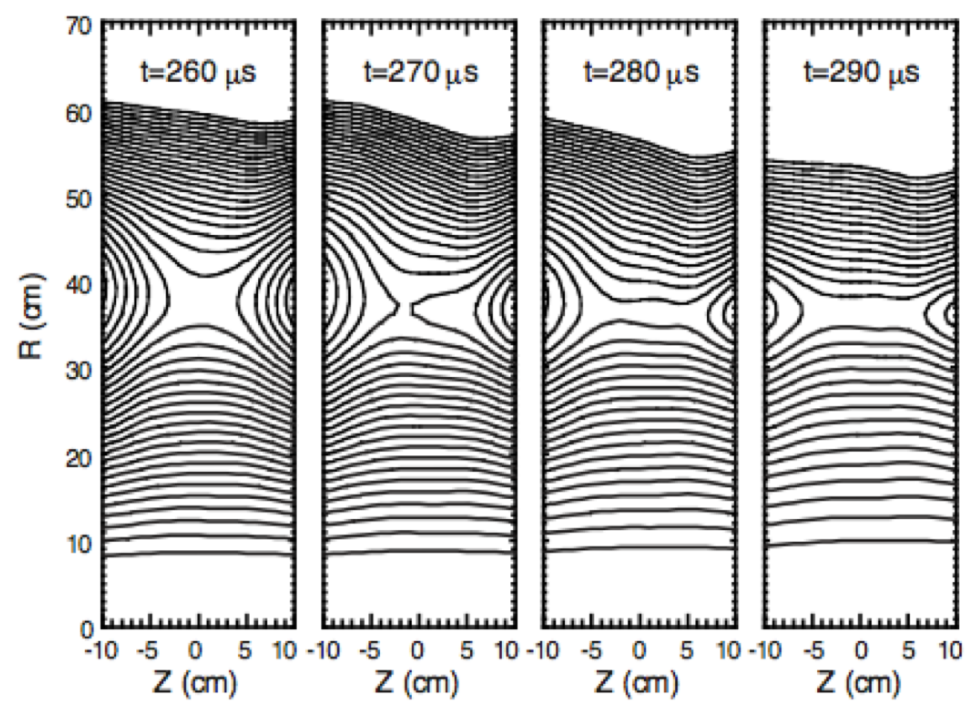
Is the Sweet-Parker model right?

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

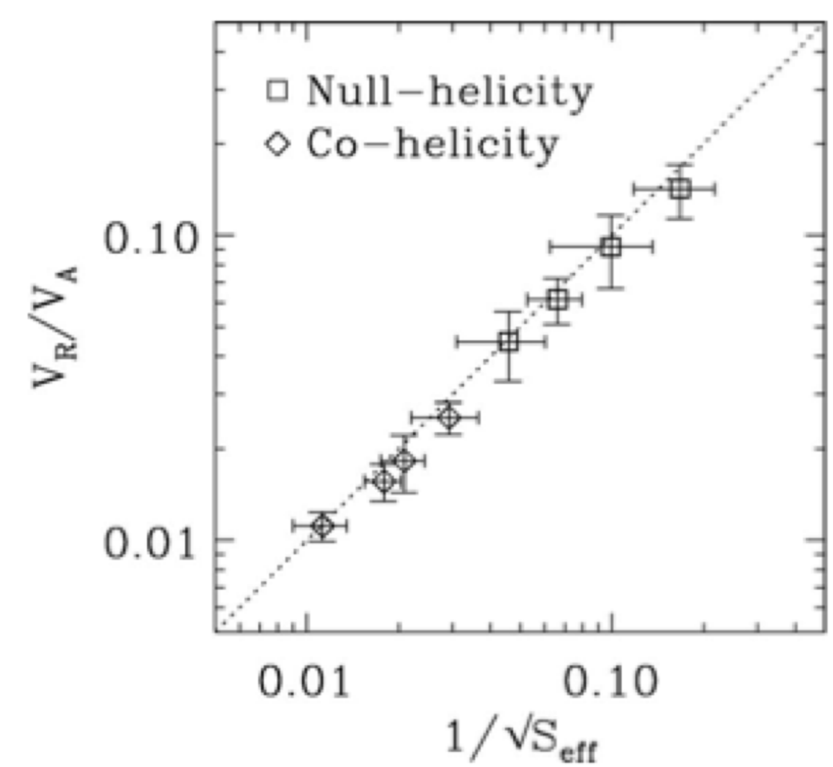




Loureiro '05



Ji '99, Yamada '00



- What does Sweet-Parker get right?
    - Coupling of global geometry to narrow current sheet
    - Drives a reconnection outflow,
    - Satisfies constraints such as mass and energy conservation

- What could it get wrong? **Current sheet** physics
    - Do we need physics beyond resistive MHD? Two-fluid and Kinetic effects?
    - Is the current sheet really laminar?

- The frontier links these questions and particle acceleration

Two-fluid and kinetic effects

Let's expand our horizons - *Generalized* Ohm's law

$$\mathbf{E} + \mathbf{v} \times \mathbf{B} = \eta \mathbf{J} + \frac{1}{ne}\mathbf{j} \times \mathbf{B} - \frac{1}{ne}\nabla p_e - \frac{1}{ne}\nabla \cdot \pi_e - \frac{1}{n}\langle \tilde{n}\tilde{E}\rangle + \ldots.$$

Resistive diffusion

(parameterized by $S = \mu_0 L V_A/\eta$)

Two-fluid effects

$L/(d_i, \rho_i)$

$d_i = c/\omega_{pi}$

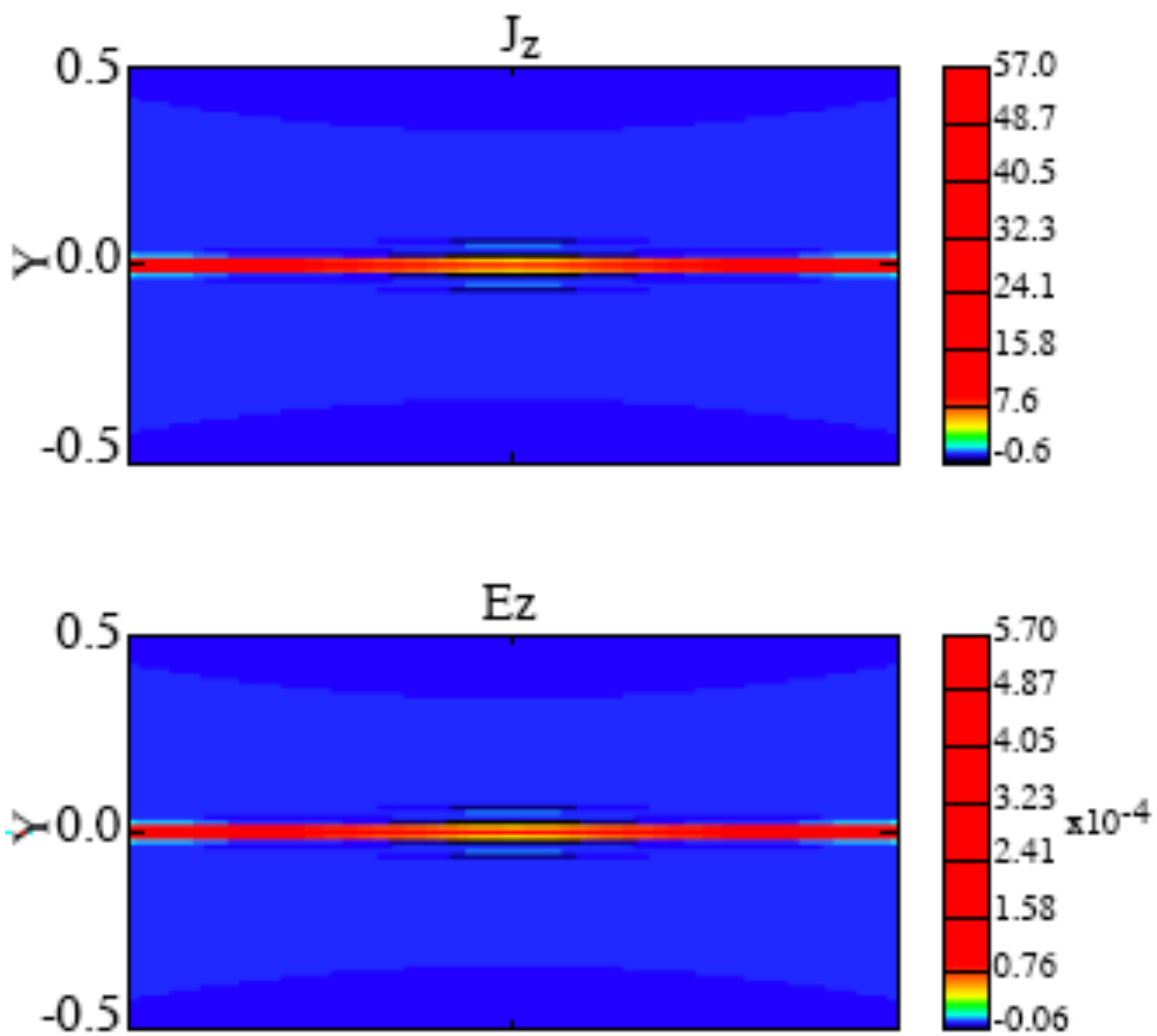
Pressure tensor (observed in particle simulations)

Fluctuations: "anomalous resistivity" and viscosity (3-D effects)

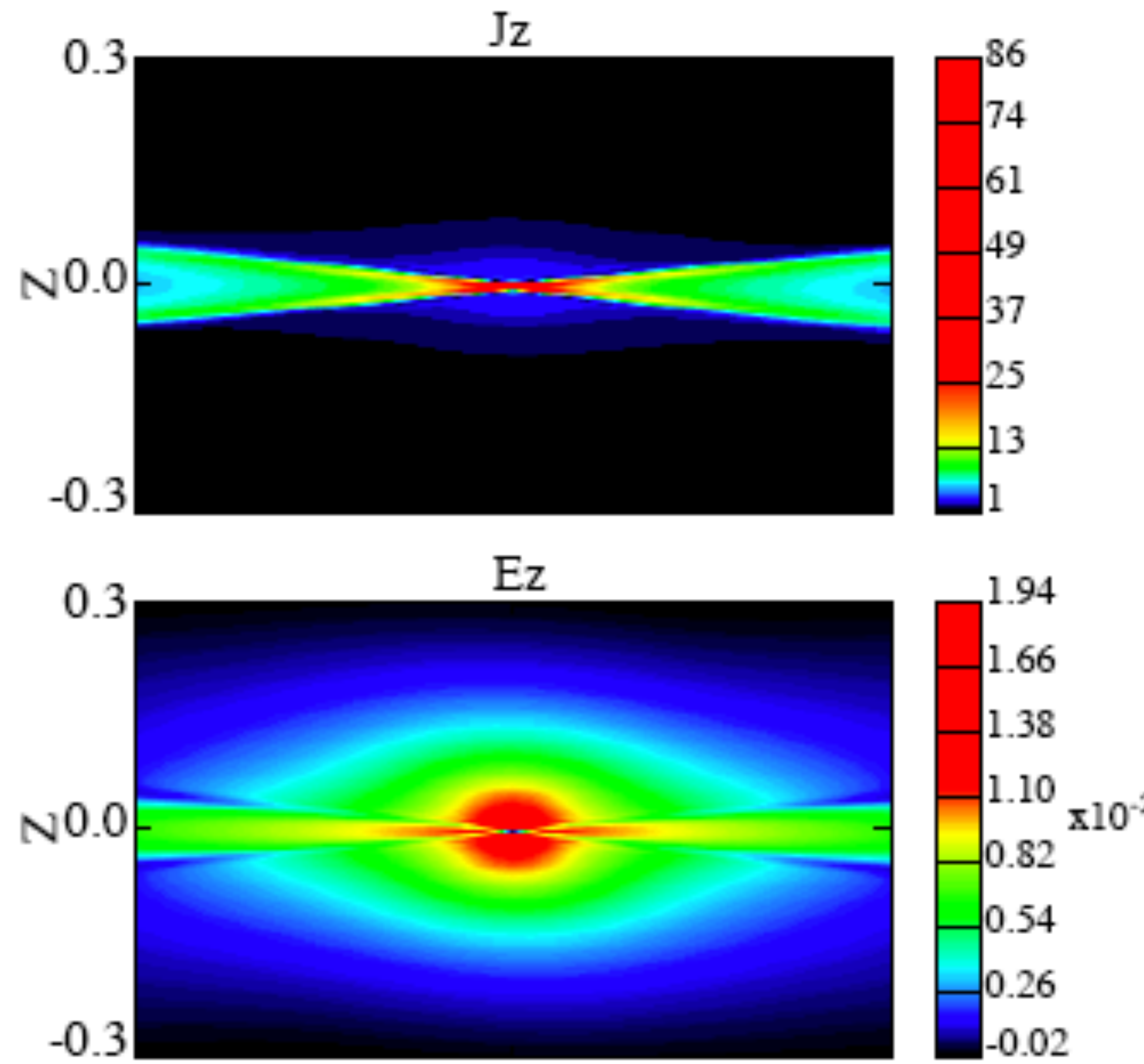
(G.O.L. = momentum equation for electrons)

Including the Hall effect in simulations has been shown to “open” the geometry of the reconnection layer and boost reconnection rate to E ~ 0.1 BV_A

no-Hall (pure resistive)



With Hall

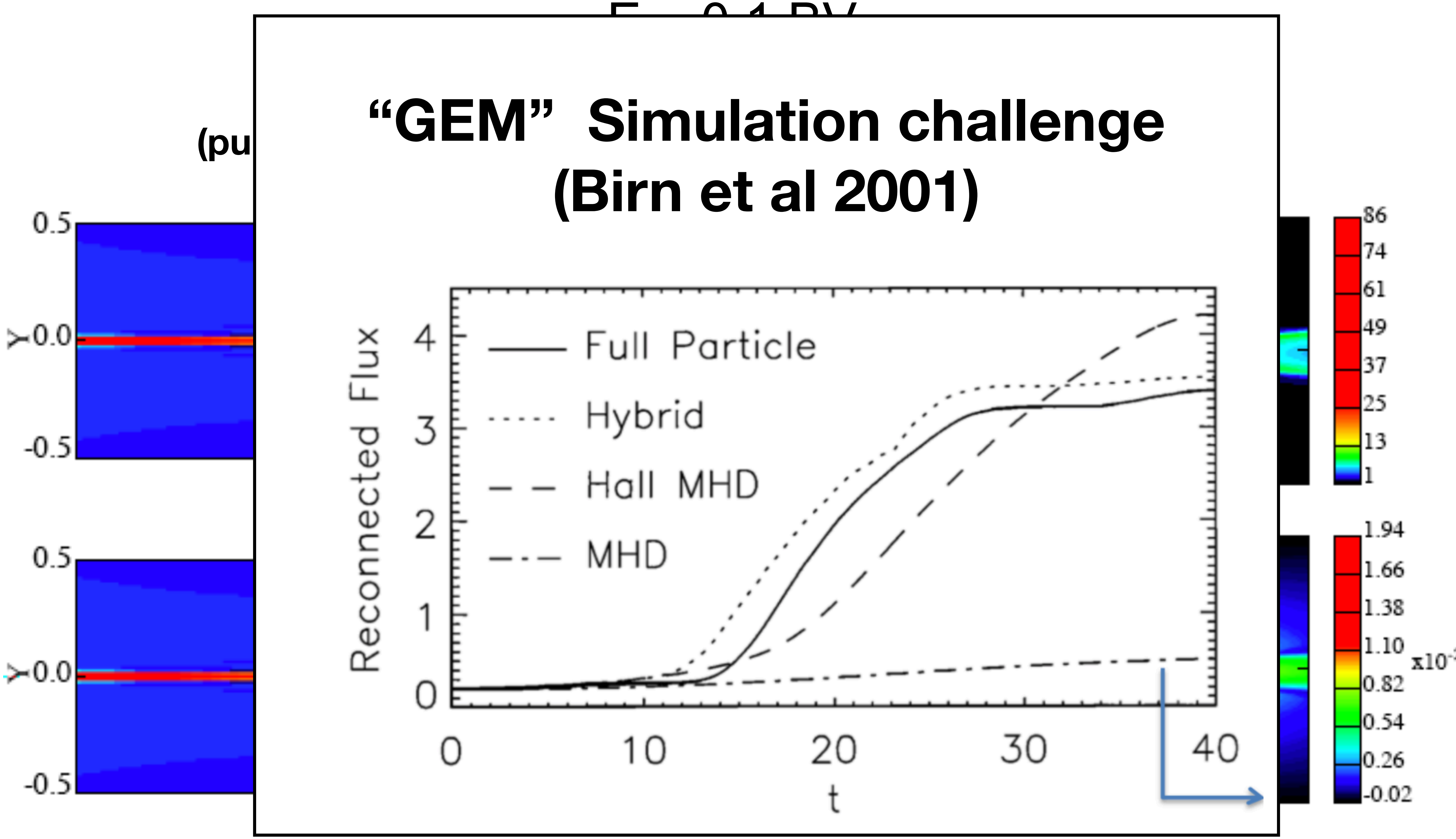


- **Hall effects create X-shaped reconnection layer**

Ma and Bhattacharjee, GRL 1996

Note: analogous analytic “Sweet-Parker” model with two-fluid effects is still an open problem!

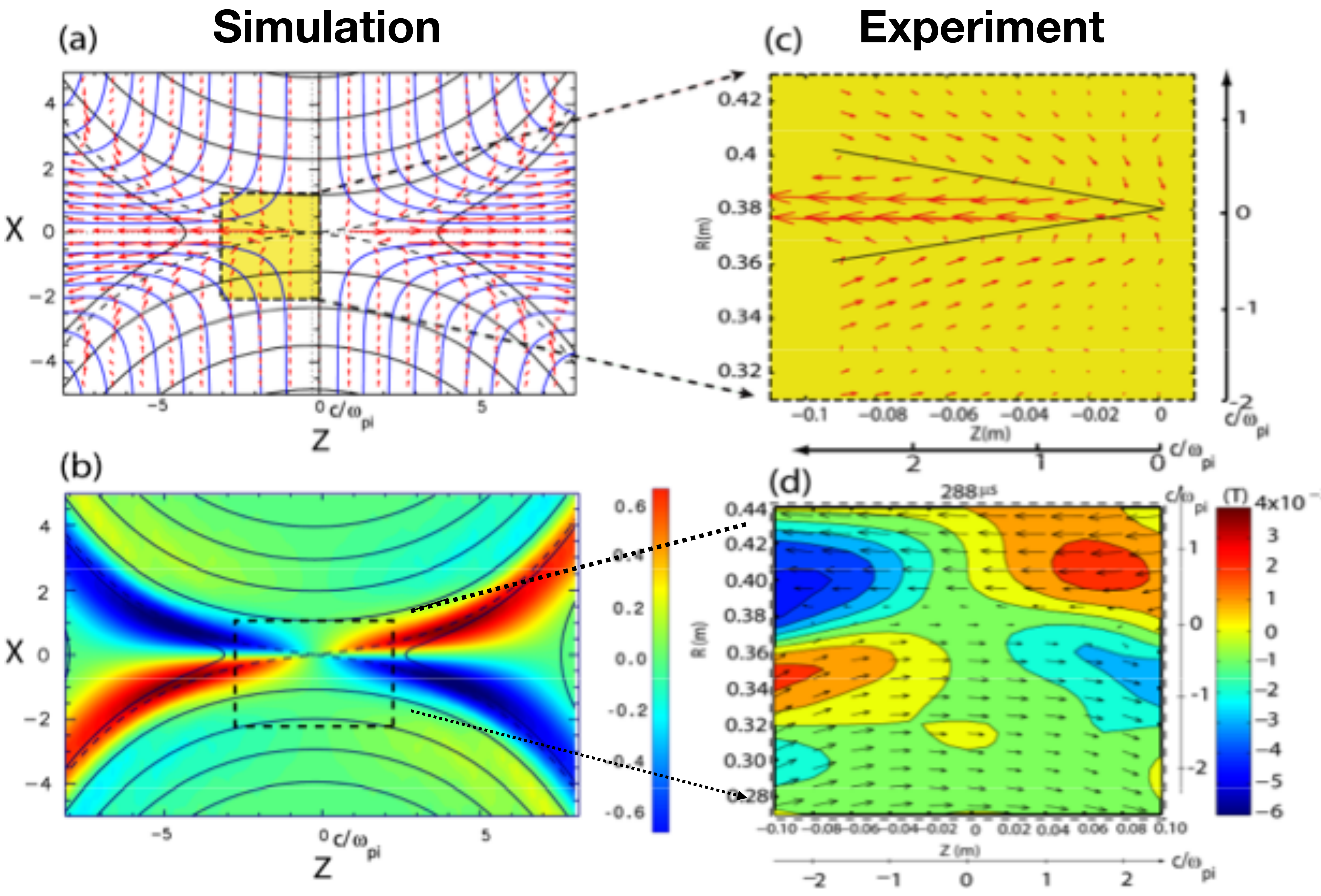
Including the Hall effect has been shown to “open” the geometry of the reconnection layer and boost reconnection rate to



- **Hall effects create X-shaped reconnection layer**

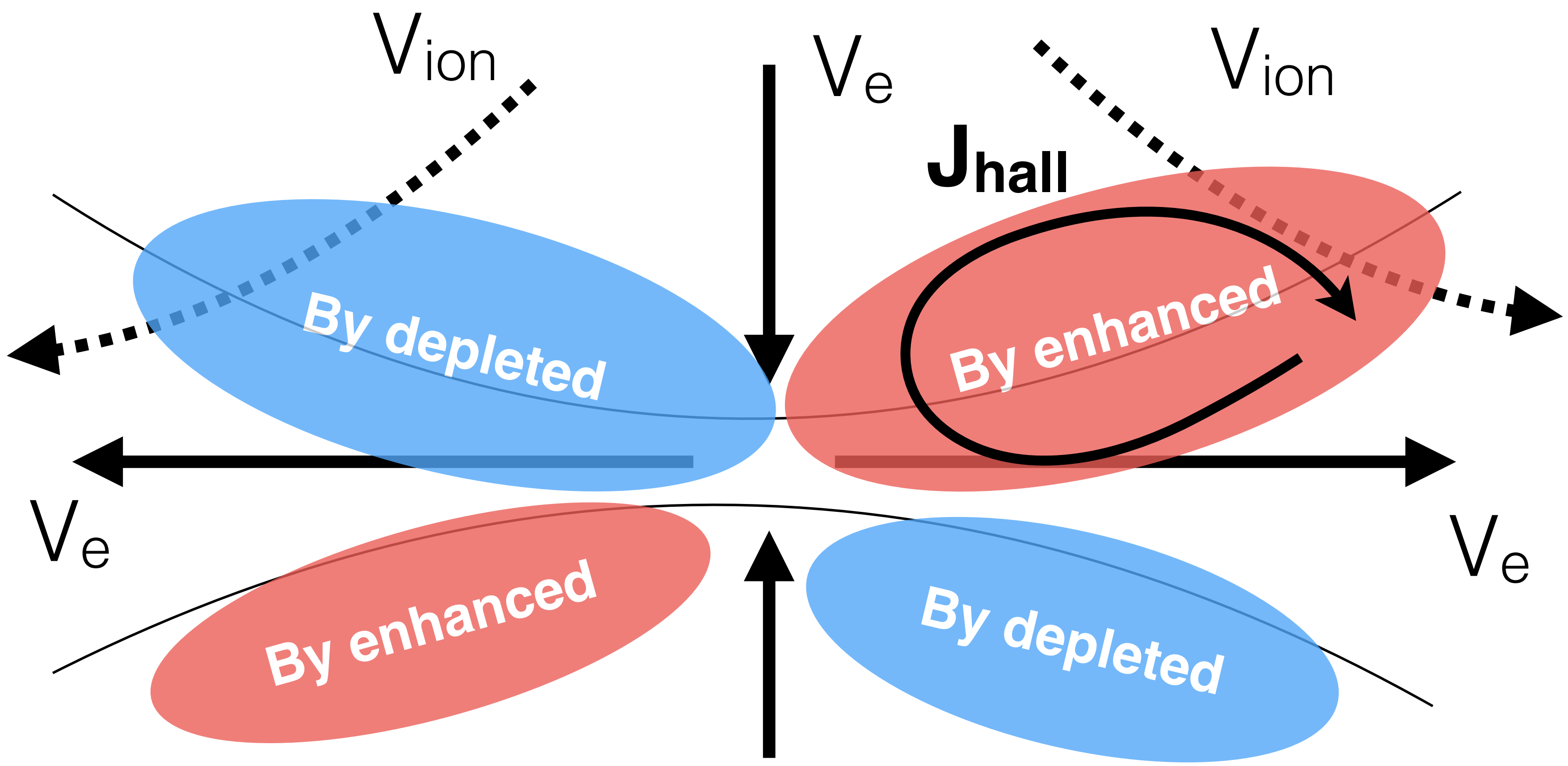
Ma and Bhattacharjee, GRL 1996

Reconnection rate increase by two-fluid effects
“Hall-fields” have been clearly observed on MRX



Y.Ren + MRX group, PRL (2005)

How do the Hall-fields arise?



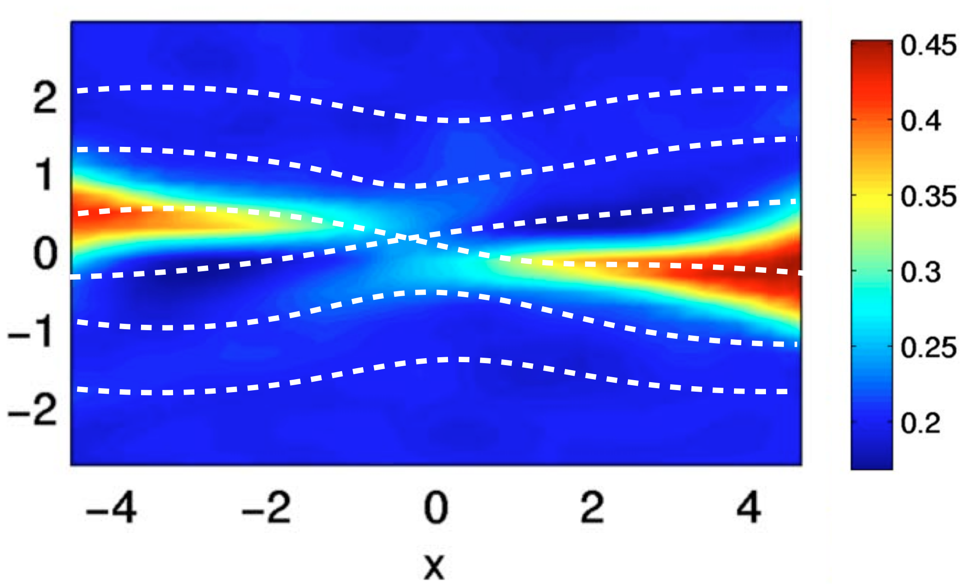
1. Two-fluid reconnection: **e- and ion take different paths through reconnection layer.**
2. They create in-plane current loops: “Hall currents”

Recent: Two-Fluid effect *with guide field*: *Electron pressure* variations also arise in reconnection layer and balance parallel electric fields

<u>Theory prediction</u>:
In-plane p_e gradients arise in recon layer and balance parallel electric field in Generalized Ohm's law:

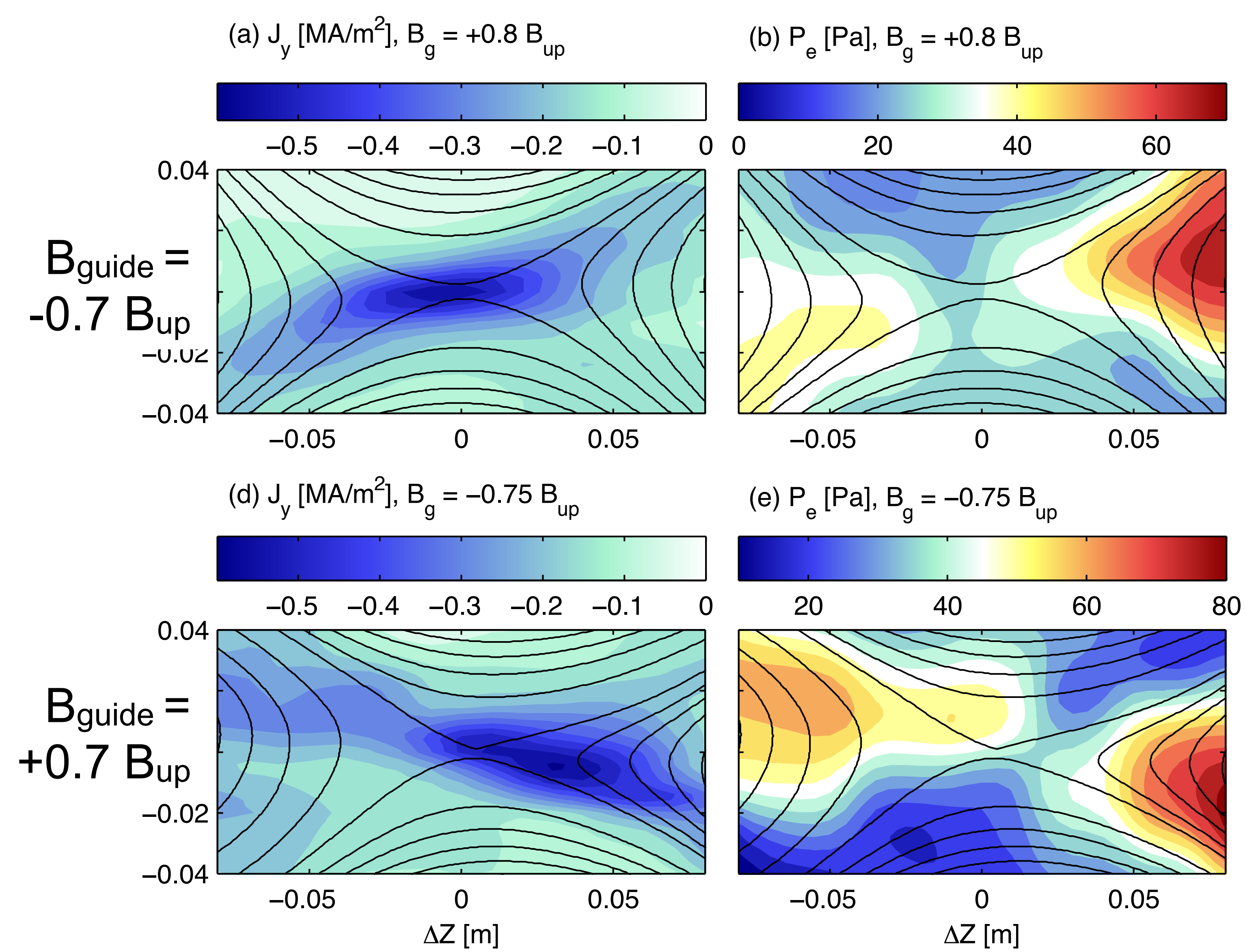
$$E_{||} + (1/ne)\nabla_{||}p_e = \eta \mathbf{J}_{||} +$$

quadrupolar n_e
from particle simulation [Ricci 2004]



<u>Experiment:</u>

J_y [MA/m²]   pe (N/m²)



W.Fox, F. Sciortino, A.v.Stechow + MRX group, PRL (2017)

Let's expand our horizons - *Generalized* Ohm's law

$$\mathbf{E} + \mathbf{v} \times \mathbf{B} = \eta \mathbf{J} + \frac{1}{ne}\mathbf{j} \times \mathbf{B} - \frac{1}{ne}\nabla p_e - \frac{1}{ne}\nabla \cdot \pi_e - \frac{1}{n}\langle \tilde{n}\tilde{E}\rangle + \ldots$$

Resistive diffusion

(parameterized by $S = \mu_0 L V_A / \eta$)

Two-fluid effects

$L/(d_i, \rho_i)$

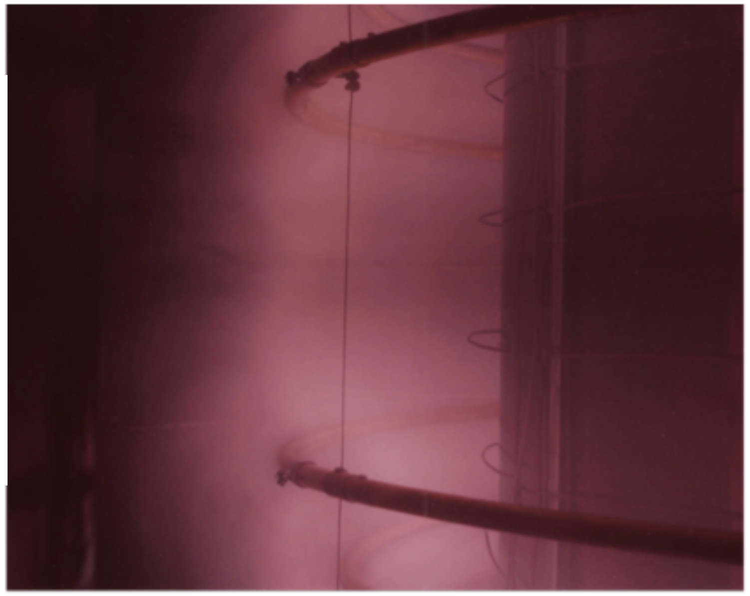
$d_i = c/\omega_{pi}$

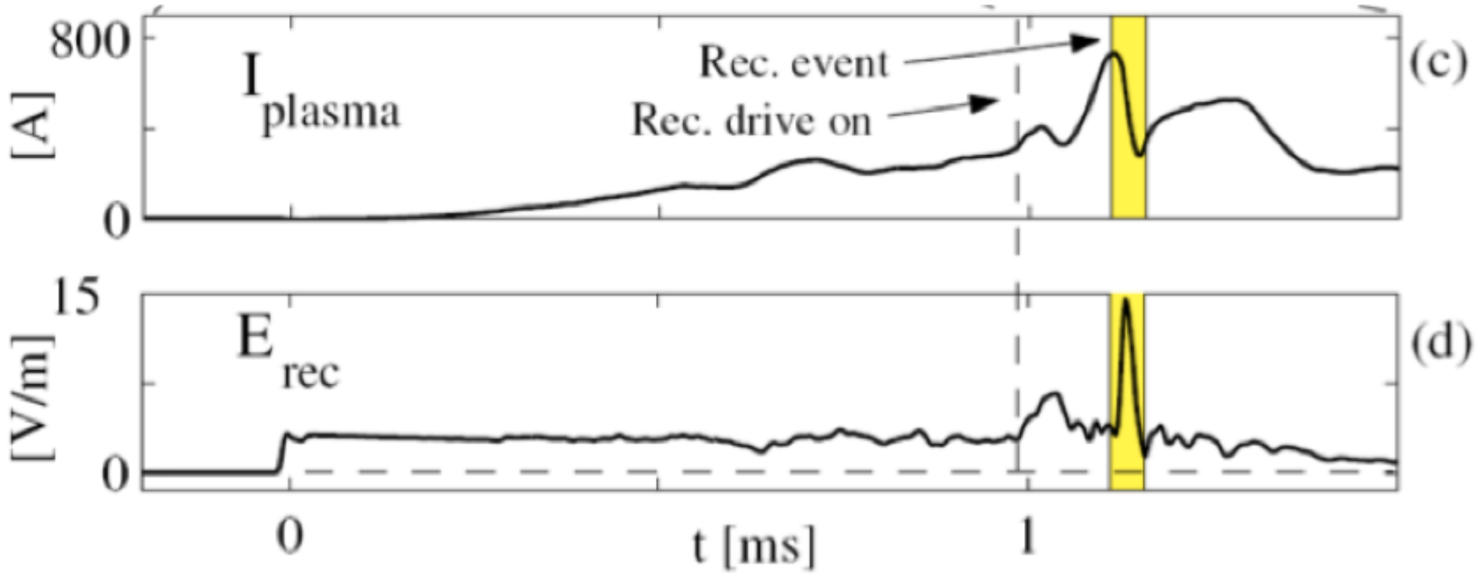
Pressure tensor (observed in particle simulations)

Fluctuations: "anomalous resistivity" and viscosity (3-D effects)

(GOL = momentum equation for electrons)

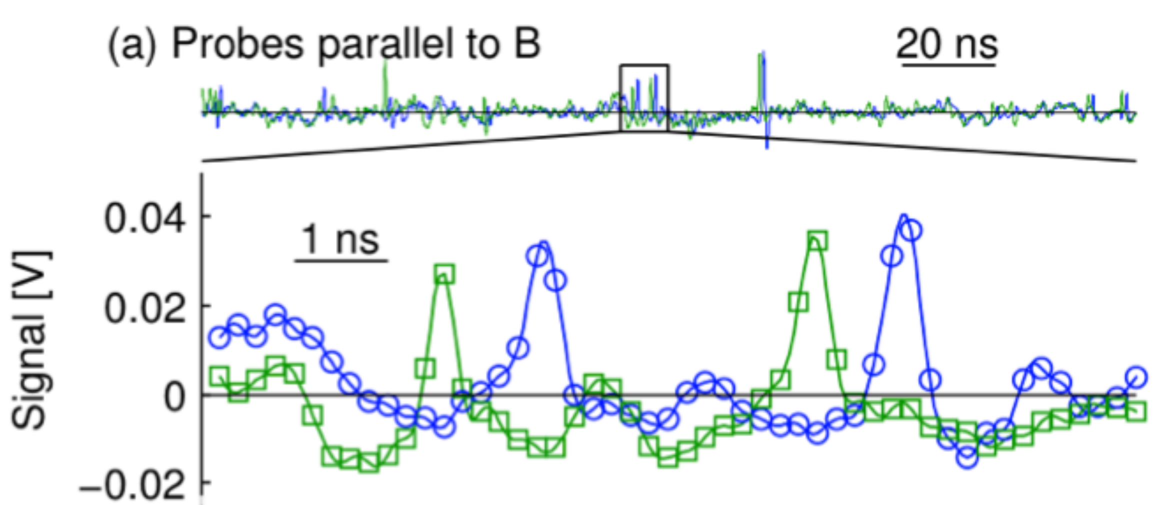
Strong electrostatic waves can be driven during reconnection.





Spontaneous onset of reconnection events [J. Egedal et al PRL 2007, N. Katz et al PRL 2010]

Turbulence in reconnection region discrete positive potential spikes [Fox, *et al* PRL 2008]



WFox Caltech 2013

It remains to be shown that they can control reconnection (large E_{eff})
See also: Carter et al PRL 2001, Ji PRL 2008, many others

Plasmoid instabilities

Plasmoid instabilities

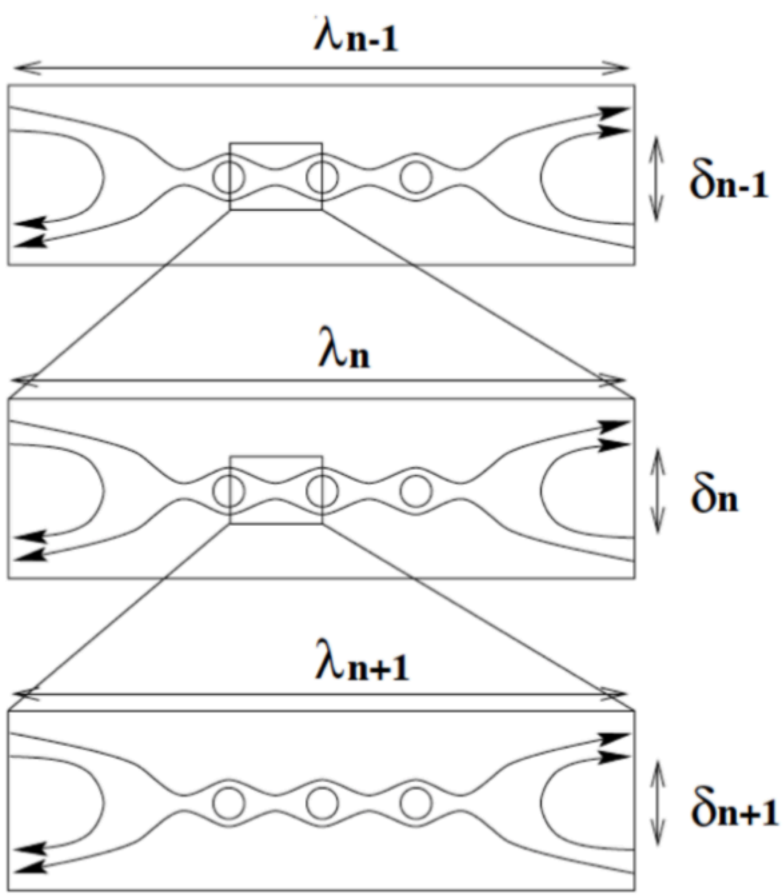
- Two fluid effects seem to account for fast reconnection at small system size (L/d_i, $L/\rho_i < 10$)
- However, many astrophysical systems are much larger than this.
- Possible solution: the plasmoid instability of thin current sheets.

Recent (2D) Simulations with Large S show violent breakup of the current sheet into plasmoid structures

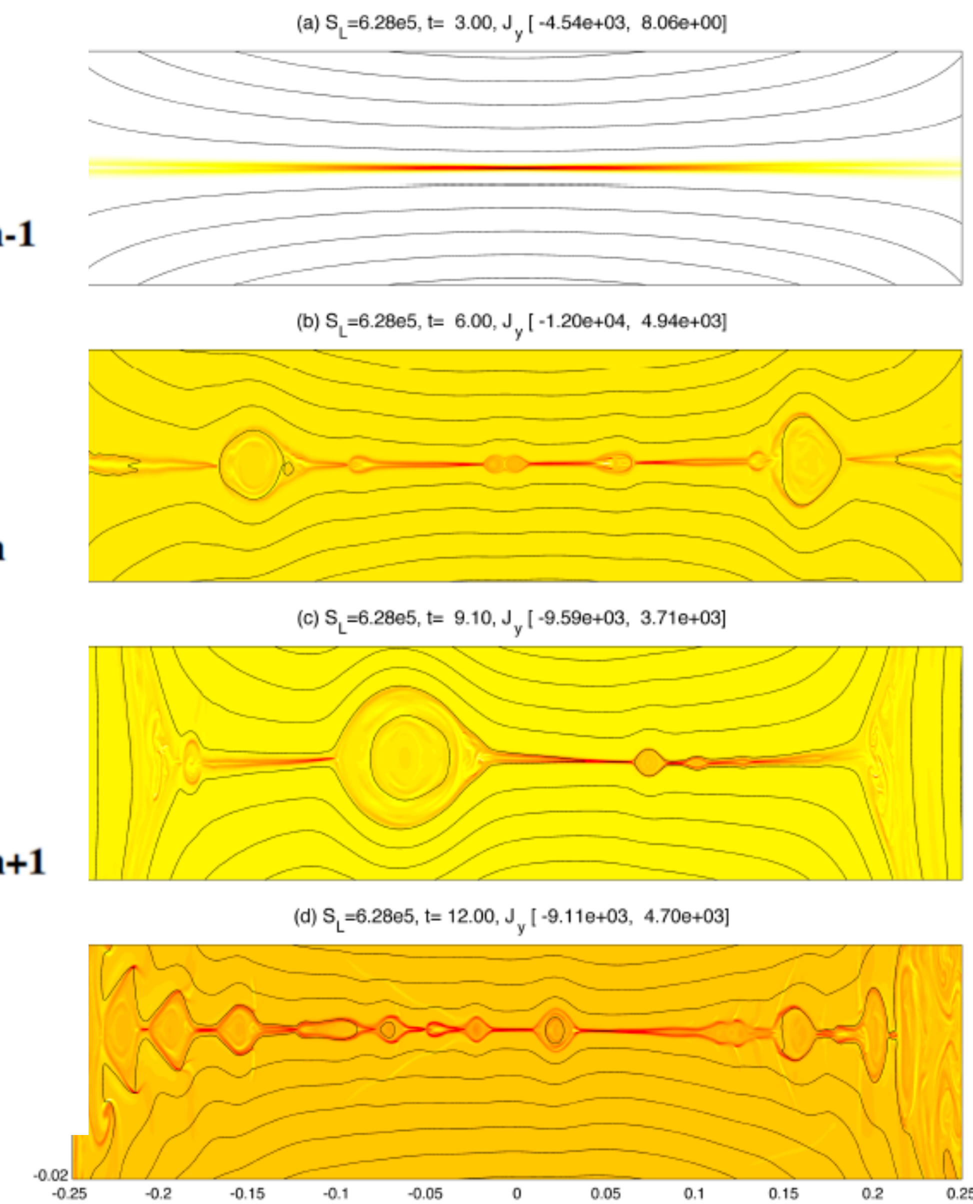
Daughton et al. (2009): PIC

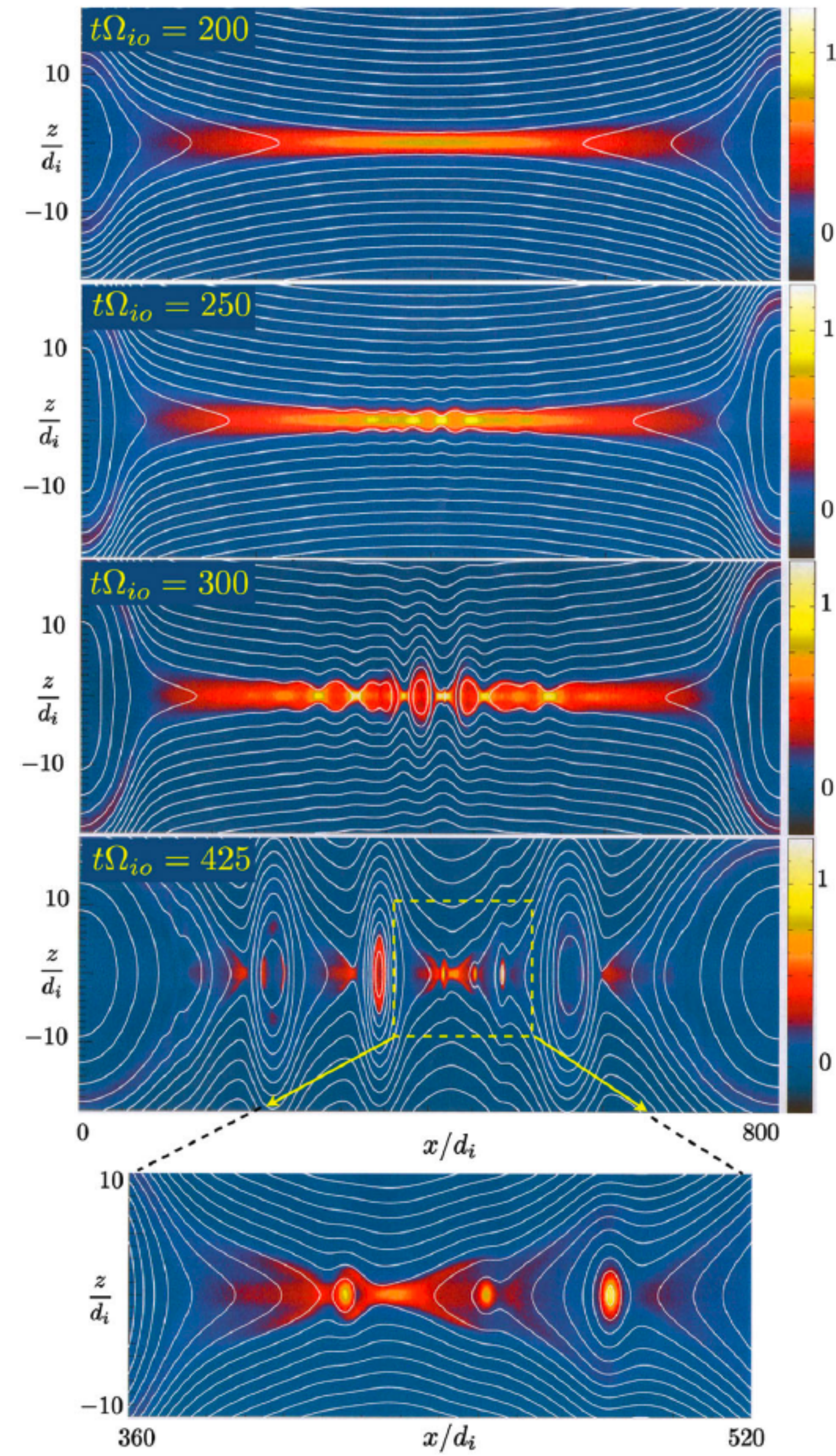
Bhattacharjee et al. (2009):MHD

Shibata and Tanuma (2001)



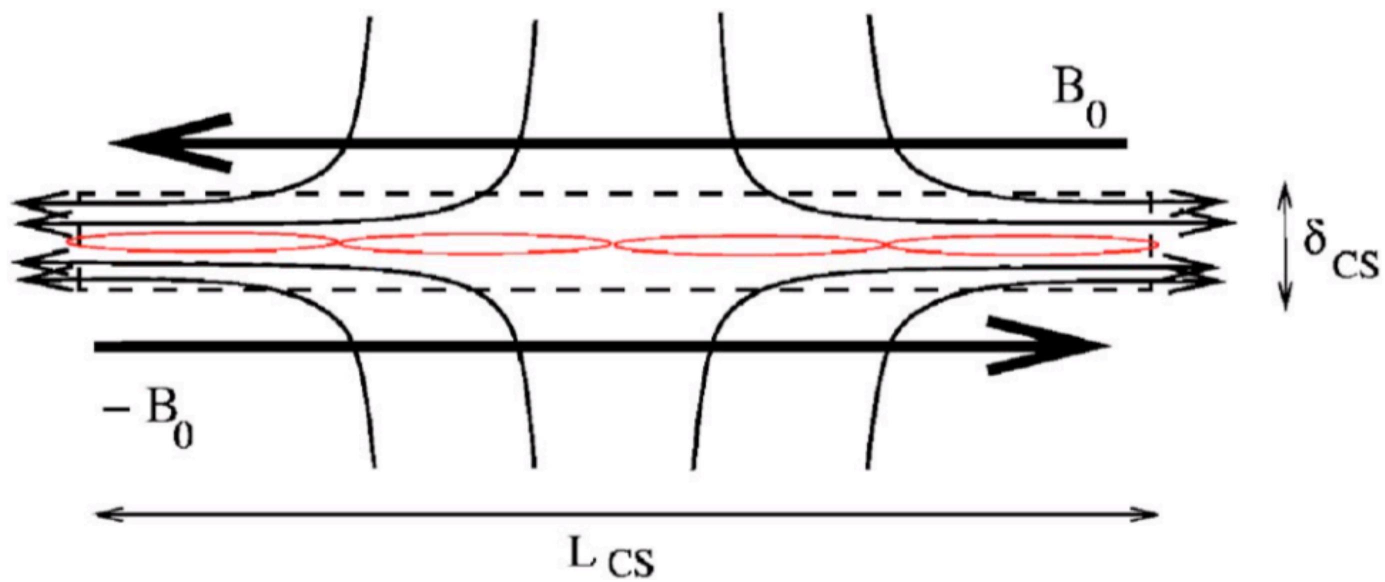
(Shibata & Tanuma '01)





See: Loureiro PRL 2005, Uzdensky PRL 2010

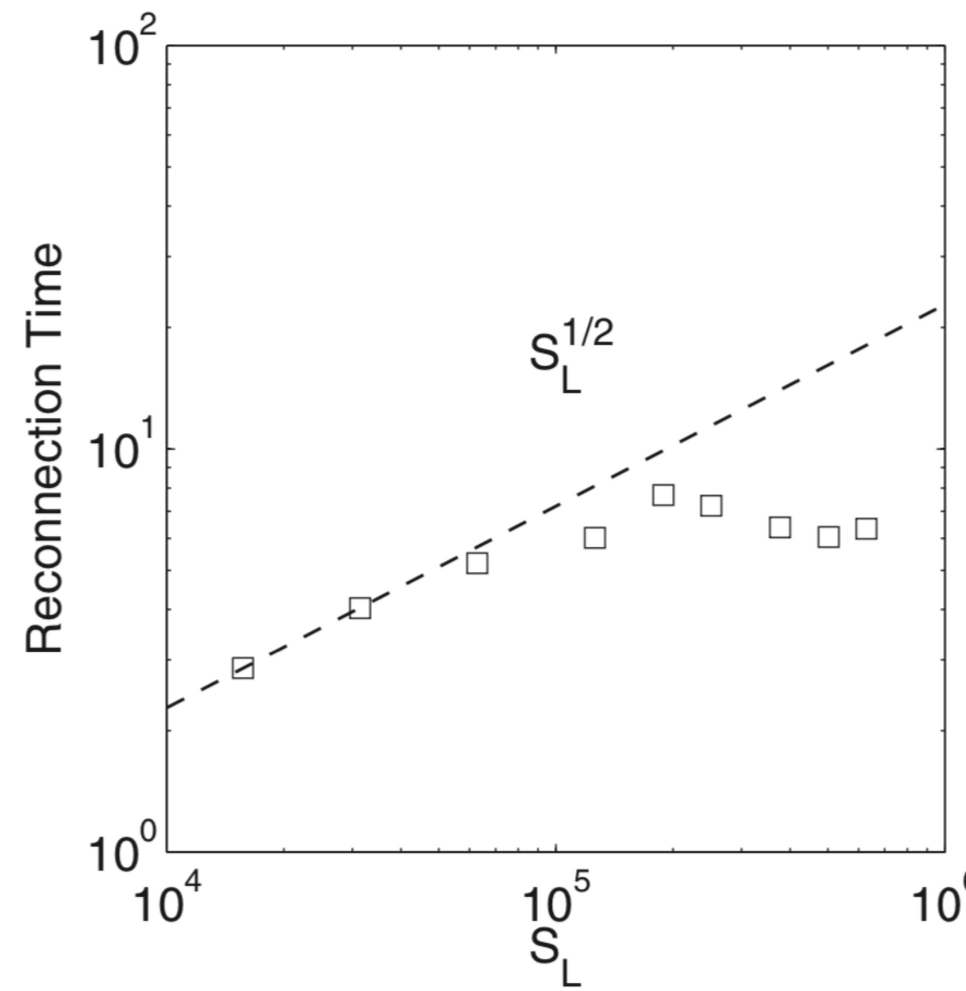
Instability is super-Alfvenic and leads to resistivity-independent reconnection rates



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

Loureiro 2007, Bhattacharjee 2009

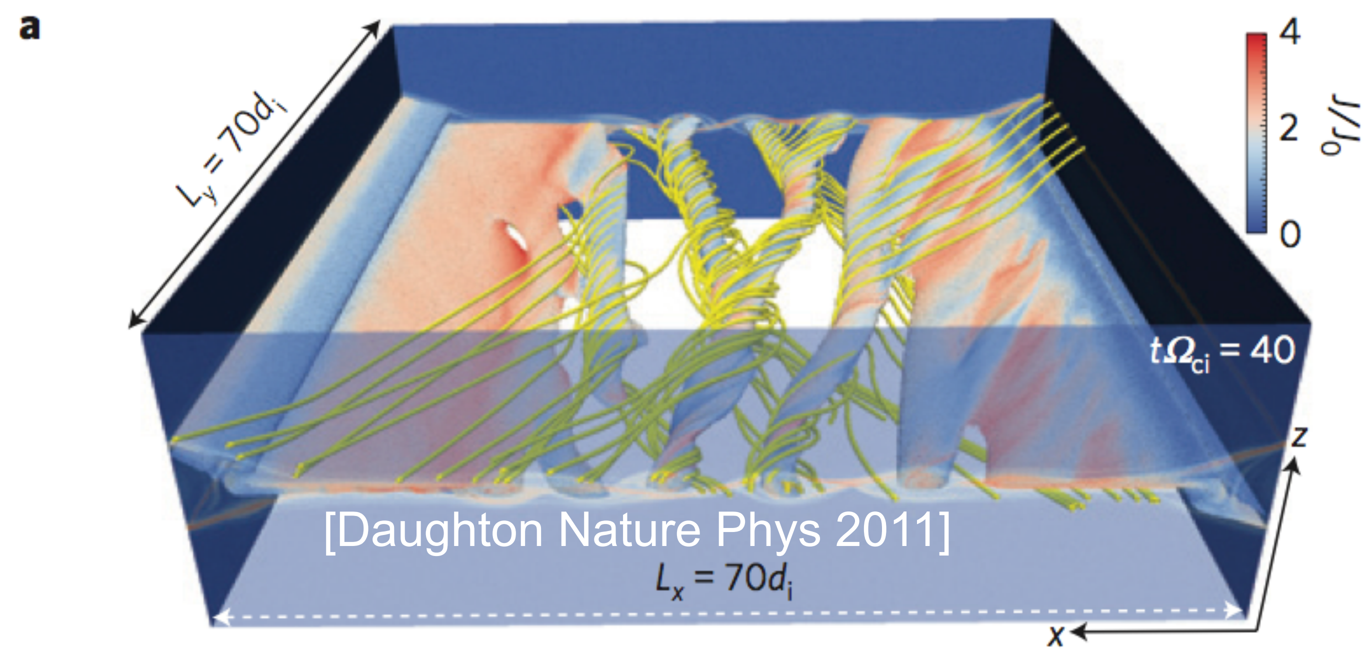
Bhattacharjee PoP (2009)



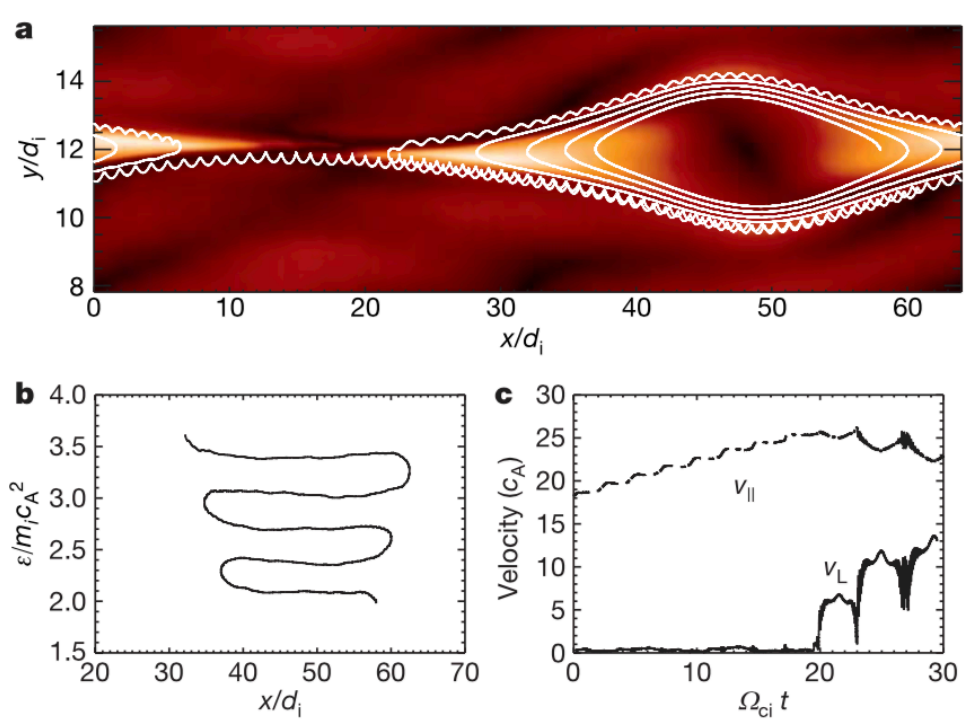
- Compared to Sweet-Parker: plasmoid chains relieves “mass-throttling” of long current sheet.
  - Rate ~ δ_{crit} / L_{crit} instead of δ_{SP} / L_{CS} (see Uzdensky 2010)
  - Can drive current sheets at kinetic scales

Frontier questions for reconnection experiments

- Study "Multiple island" reconnection aka "Plasmoids" and turbulent reconnection [Loureiro 2007, Bhattacharjee 2009]
  - turbulence predicted to enhance reconnection and energy conversion rate

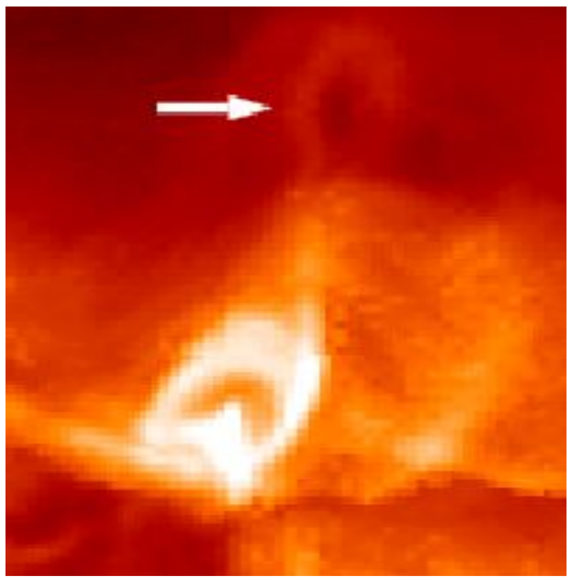


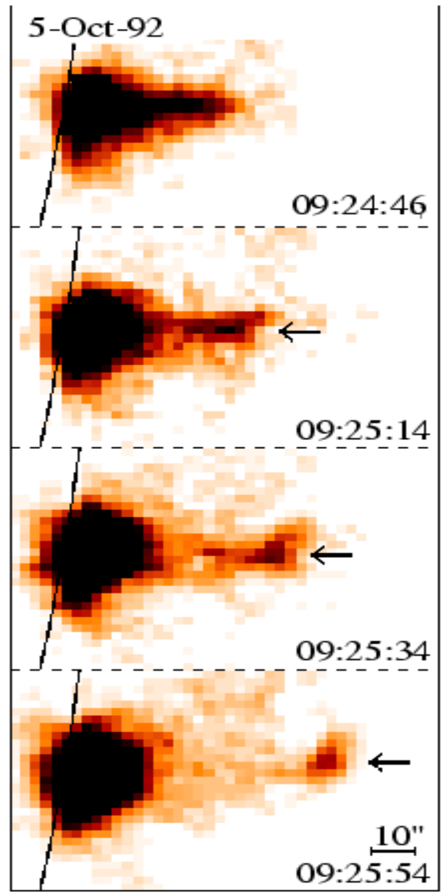
[Daughton Nature Phys 2011]



- Particle acceleration by reconnection, efficient generation of power-law tail populations (e.g. solar flares). Proposed mechanisms:
  - direct acceleration along x-lines [e.g. Hoshino 2001]
  - "Fermi" acceleration by interaction of particles with islands *in multiple island regime.* [Drake et al Nature 2006]

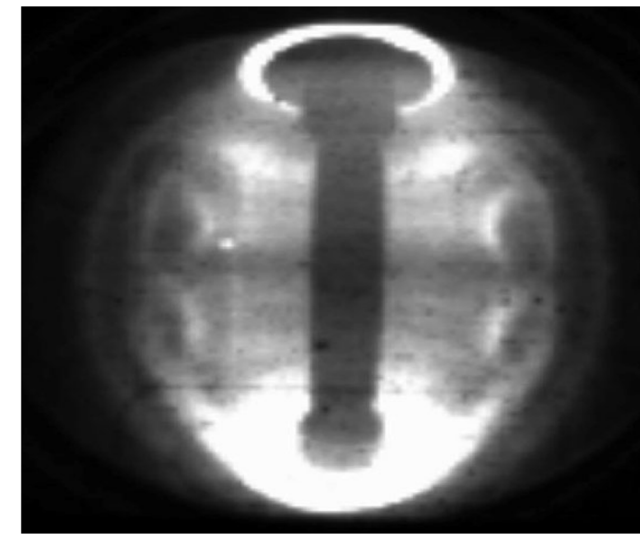
Plasmoid reconnection has begun to be observed and studied in the laboratory and solar observations



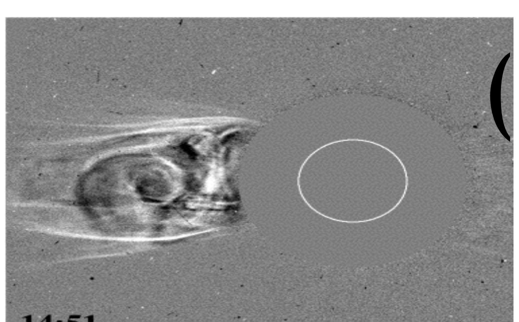


Hudson (1994); Magara+ (1997)

Laser plasma (Dong+, 2012)

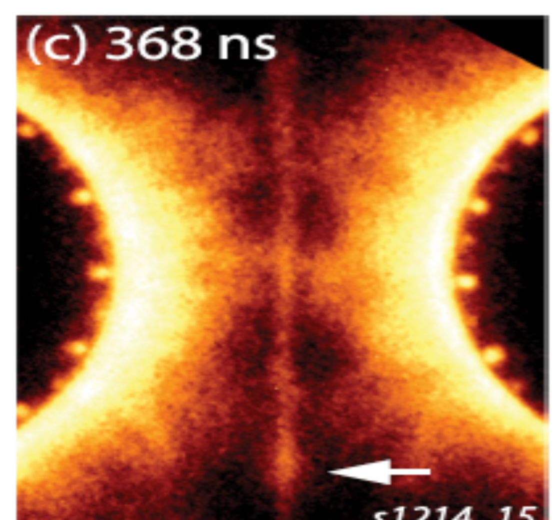


Tokamak plasma (Ebrahimi & Raman, 2015)



Ohyama & Shibata (1998)

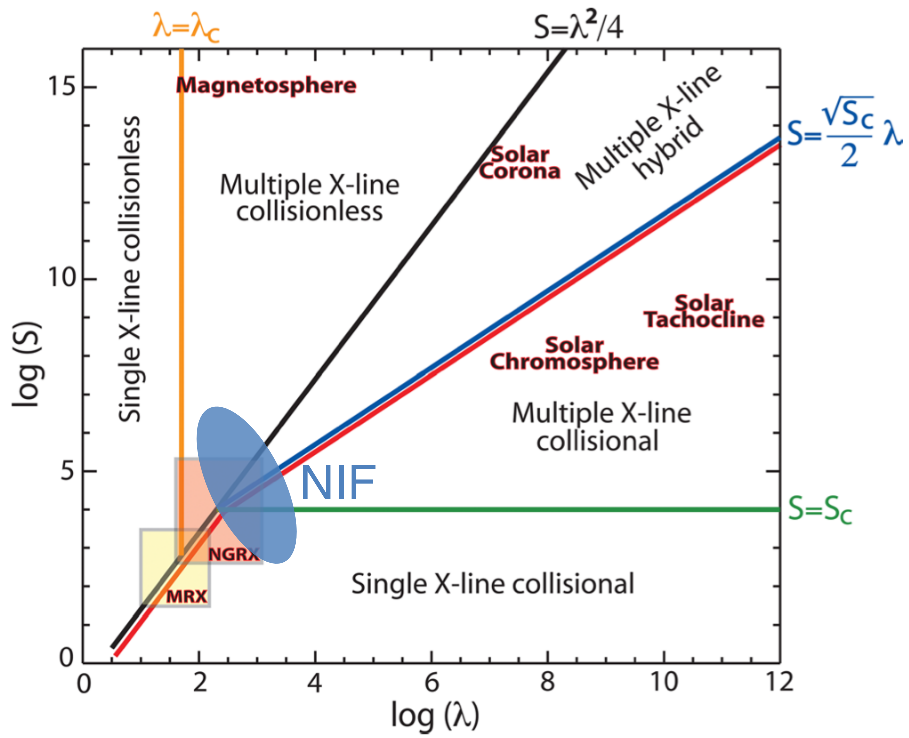
Dere+ (1999)



Z-pinch plasma (Hare+, 2017)

Experimental Frontiers

A frontier is to observe reconnection physics at large system size and low dissipation



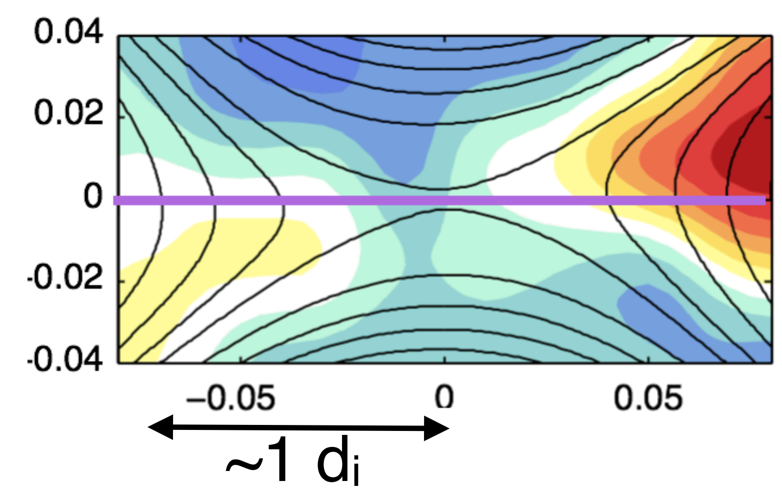
- Reconnection regimes parameterized by:
  - **Dissipation**: "Lundquist number" $S = \mu_0 L V_A / \eta$. *Resistive plasma, collisionless, or in-between?*
  - ***System size:*** $\lambda = L/d_i$
- Plasmoid/turbulent regime at simultaneous large *S* and *L*
  - requires energy! $E \sim nTL^3 \sim S^{0.25} (\lambda_{mfp}/L)^{0.25} (L/d_i)^3$

Proposed "Phase diagram" for reconnection (Ji and Daughton PoP 2010)

<u>How about competing experiments?:</u>

- discharge lab experiments (e.g. MRX, TREX): Very detailed measurements, but limited system size (L/d_i ~ few). Isolated plasmoids observed
- Pulsed power (Hare et al 2017) - plasmoids observed
- solar observation: global evolution observed, but limited by remote-sensing nature
- spacecraft: fully kinetic data, but limited by single-spacecraft nature of data

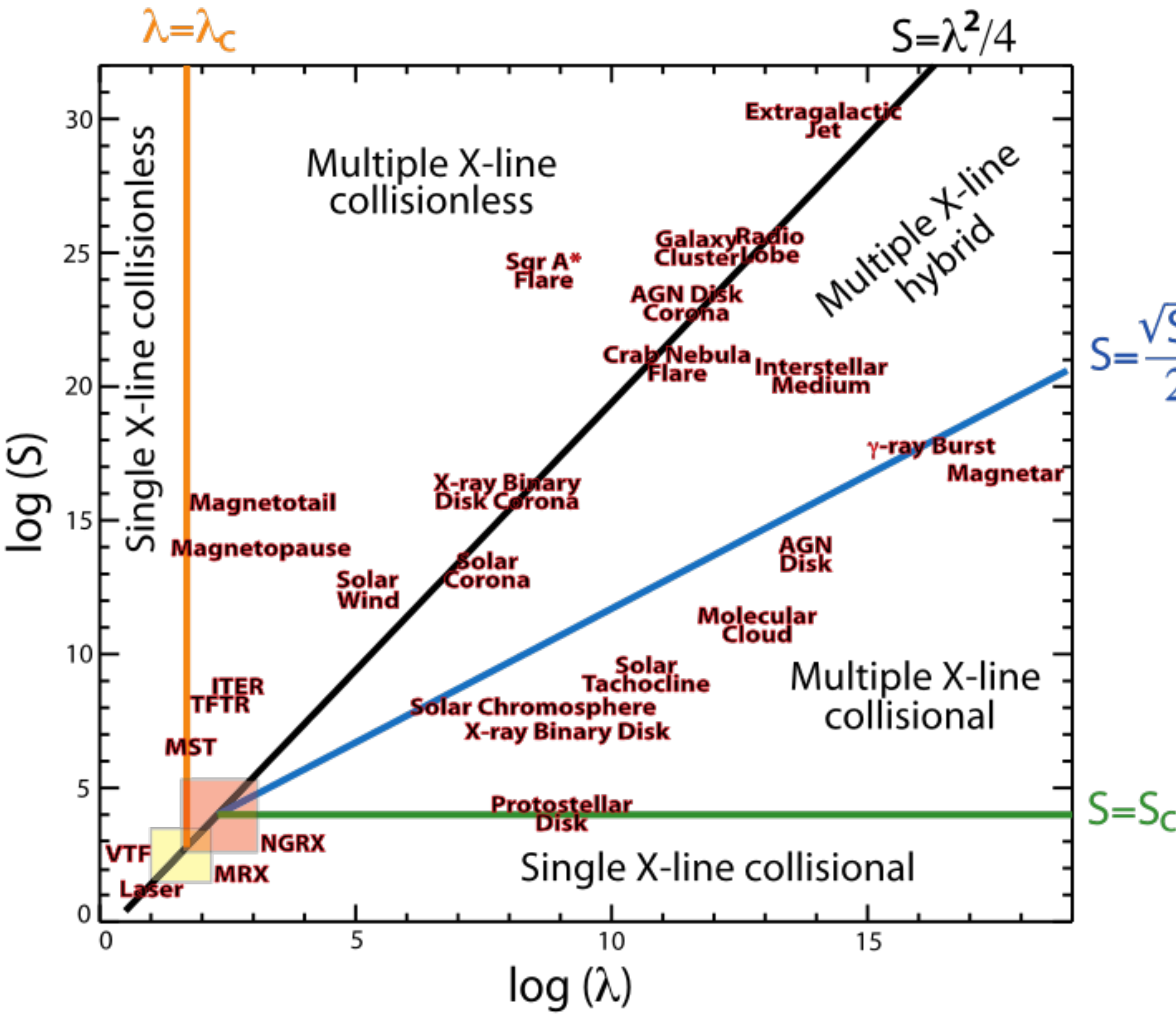
e.g. MRX observations: "zoom-in" to see details of how electron pressure structure enables fast reconnection (W. Fox+ PRL 2017)



Goal for experiments is to study reconnection deep in plasmoid regime

Goal for new FLARE experiment at PPPL (PI: H.Ji) is to study plasmoid physics initiated at MHD scale

Location	Plasma	Size (m)	T_e (eV)	n_e (m^{-3})
Lab	MRX[75]	0.8	10	1×10^{19}
	VTF[14]	0.4	25	1.5×10^{18}
	Laser plasma[76]	2×10^{-4}	10^3	5×10^{25}
	MST[77]	1.0	1.3×10^3	9×10^{18}
	TFTR[78]	0.9	1.3×10^4	1×10^{20}
	ITER[79]	4	2×10^4	1×10^{20}
	NGRX[80]	1.6	25	1×10^{19}
Solar system	Magnetopause[81]	6×10^7	300	1×10^7
	Magnetotail[81]	6×10^8	600	3×10^5
	Solar wind[81]	2×10^{10}	10	7×10^6
	Solar corona[81]	1×10^7	200	1×10^{15}
	Solar chromosphere[82]	1×10^7	0.5	1×10^{17}
	Solar tachocline[83,84]	1×10^7	200	1×10^{29}
Galaxy	Protostellar disks[85]	9×10^9	3×10^{-2}	6×10^8
	X-ray binary disks[86,87]	4×10^4	75	1×10^{27}
	X-ray binary disk coronae[88]	3×10^4	5×10^5	1×10^{24}
	Crab nebula flares[89–91]	1×10^{14}	130	10^6
	Gamma ray bursts[92]	10^4	3×10^5	2×10^{35}
	Magnetar flares[92,93]	10^4	5×10^5	10^{41}
	Sgr A* flares[94,95]	2×10^{11}	7×10^6	10^{13}
	Molecular clouds[96,97]	3×10^{16}	10^{-3}	10^9
	Interstellar media[96,97]	5×10^{19}	1	10^5
Extra-galactic	AGN disks[86,87,98]	2×10^{11}	24	8×10^{23}
	AGN disk coronae[88]	3×10^{11}	5×10^5	1×10^{17}
	Radio lobes[69]	3×10^{19}	100	1
	Extragalactic jets[99]	3×10^{19}	10^4	3×10^1
	Galaxy clusters[100]	6×10^{18}	5×10^3	4×10^4



FLARE was successfully constructed and generated first plasmas

Plan: Move FLARE to PPPL over the summer and get it setup with Stage-3 capabilities within ~1.5 years for research operation as a collaborative user facility.

Laser facilities produce highly useful and interesting plasmas for laboratory astrophysics

TOPICS

- magnetic reconnection
- collisionless shocks
- collisionless plasmas, kinetic instabilities
- magnetized flows, magnetized shocks
- self-generated magnetic fields, dynamos
- ….

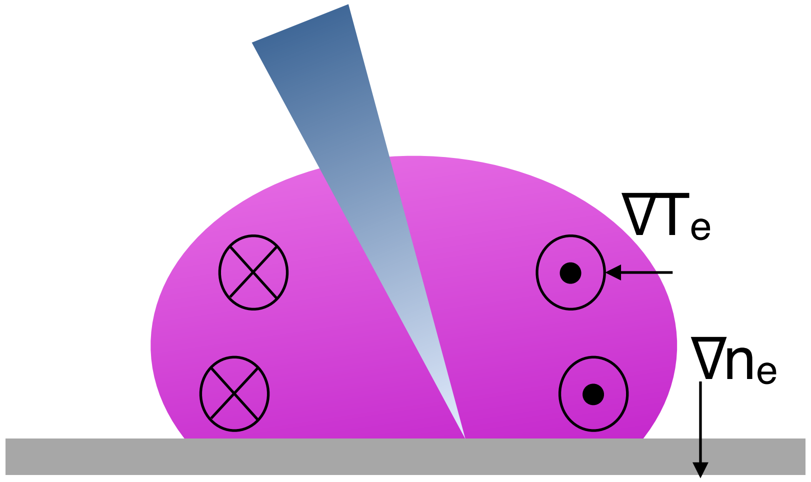
DESIRED PROPERTIES

- large Energy translates to large density n, temperature T, and size L^3
- high magnetic Reynold's number $R_M \sim L\,T^2$ = low dissipation
- scale separation L / d_i large, e.g. fully formed shocks; turbulent "plasmoid" regime for reconnection; kinetic plasma turbulence
- long mean-free path: $L_{mfp} \sim T^2/n$ for collisionless plasma behavior,
- $V \sim C_s$: supersonic flows and shocks

Complementarity to other approaches:

- discharge lab experiments (e.g. MRX, TREX): Very detailed measurements, but limited system size ($L/d_i \sim$ few), so far
- solar observation: global evolution observed, but limited by remote-sensing nature
- spacecraft: fully kinetic data, but limited by single-spacecraft nature of data

Magnetic fields for reconnection are generated in expanding plasmas by Biermann battery effect

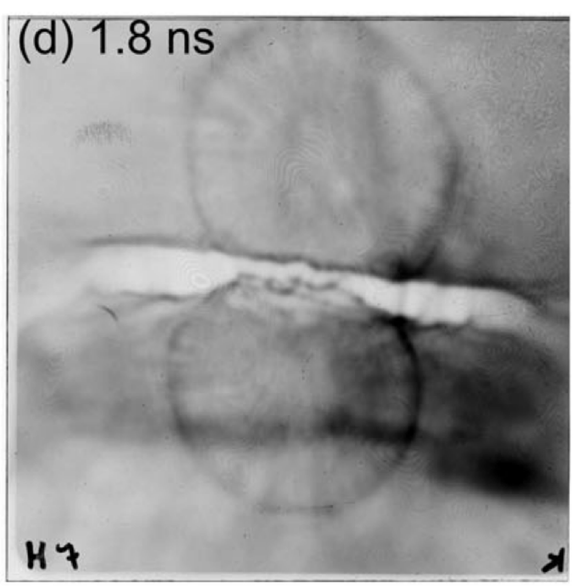


$$\left(\frac{\partial B}{\partial t}\right)_{Biermann} = \frac{1}{ne}\nabla n_e \times \nabla T_e$$

- Laser-plasmas ~50 T w/ long-pulse lasers [Yates PRL 1982]
- In astrophysics, e.g. primordial seed fields at ~ 10^{-20} G [Kulsrud ApJ 1997]

Collision of two plumes drives magnetic reconnection between the opposing magnetic fields

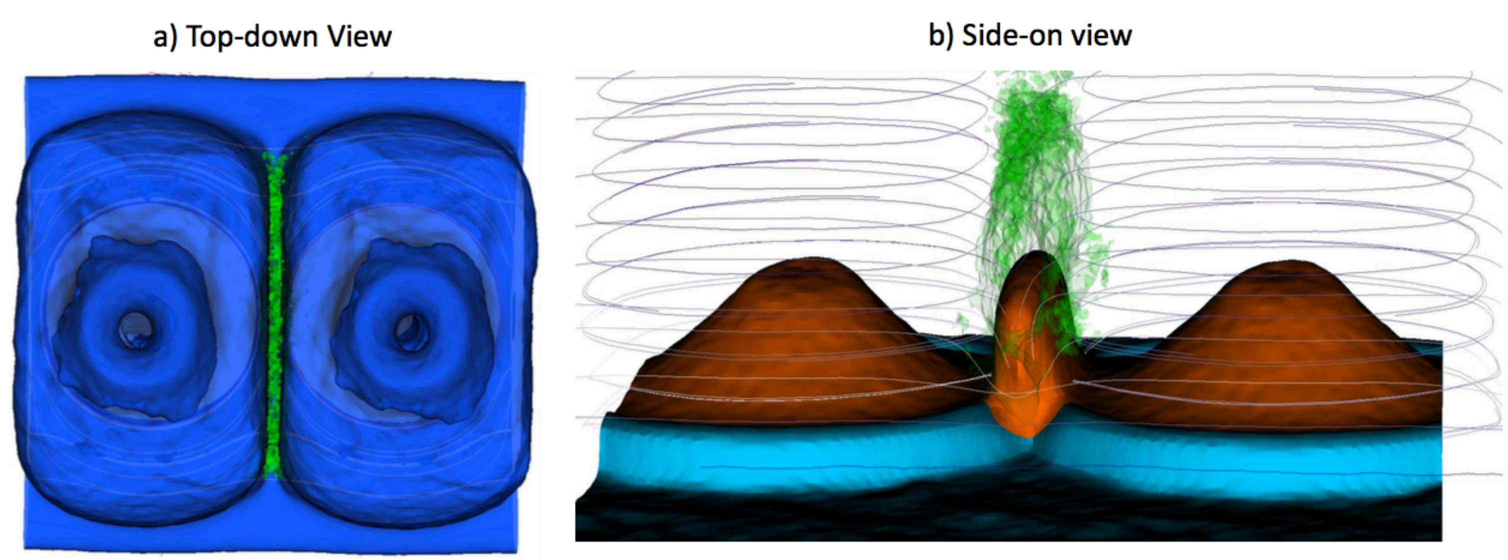
<u>Experiment</u>



Rosenberg PRL 2015

See also: Nilson+ 2006, C.K.Li+ 2007, Jhong+ 2012, Fiksel+ 2014

<u>Simulation</u>

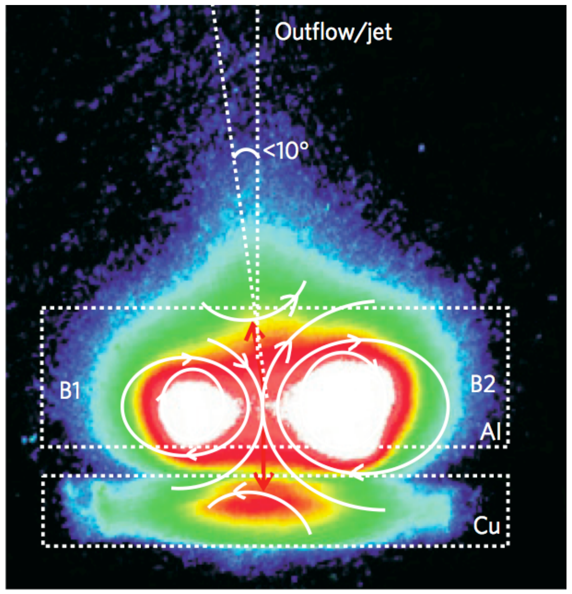


Magnetic energy, j.E **Plasma pressure, j.E, field lines**

[J. Matteucci*, WF, A. Bhattacharjee, et al, PRL (2018)]

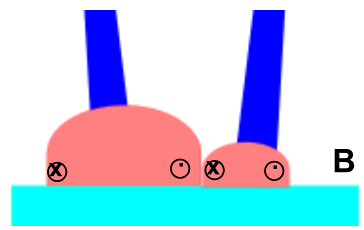
See also: Fox+ PRL 2011, 2012, S. Lu+ NJP 2015, Totorica+ PRL 2016

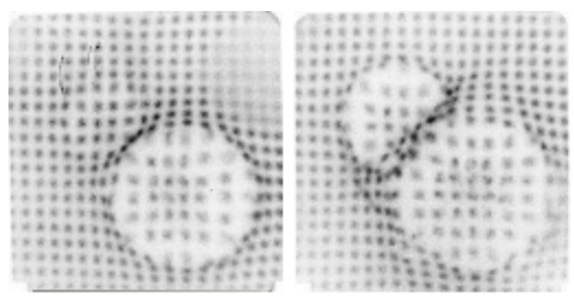
Laboratory reconnection experiments in laser plasmas provides another way to collide magnetized plasmas for reconnection and particle acceleration

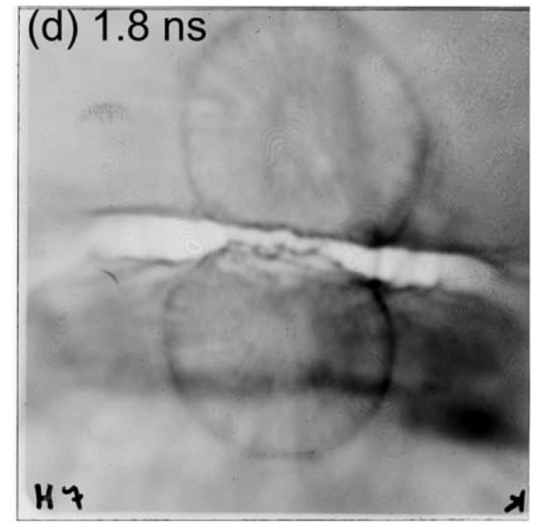


outflow jets and particle energization (Zhong *et al* Nature Phys 2010, Dong et al PRL 2012)

Reconnection between asymmetric plasmas (M. Rosenberg, C.K. Li, W. Fox, et al Nature Comms 2014)

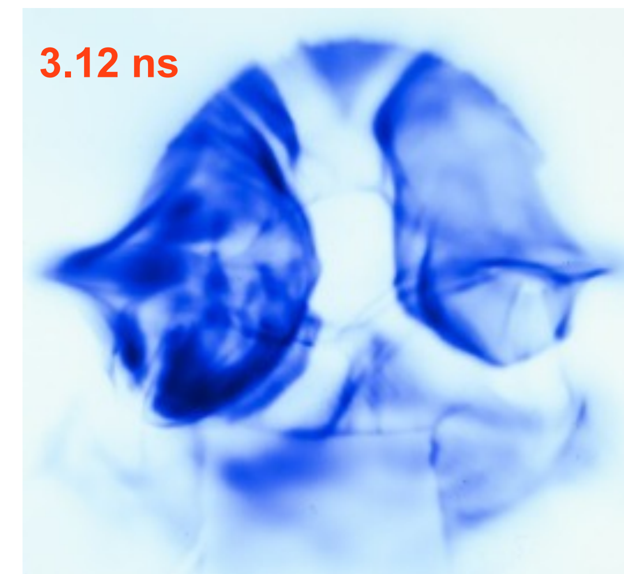






Stagnation of reconnection (M. Rosenberg, CK Li, WF, PRL 2015)

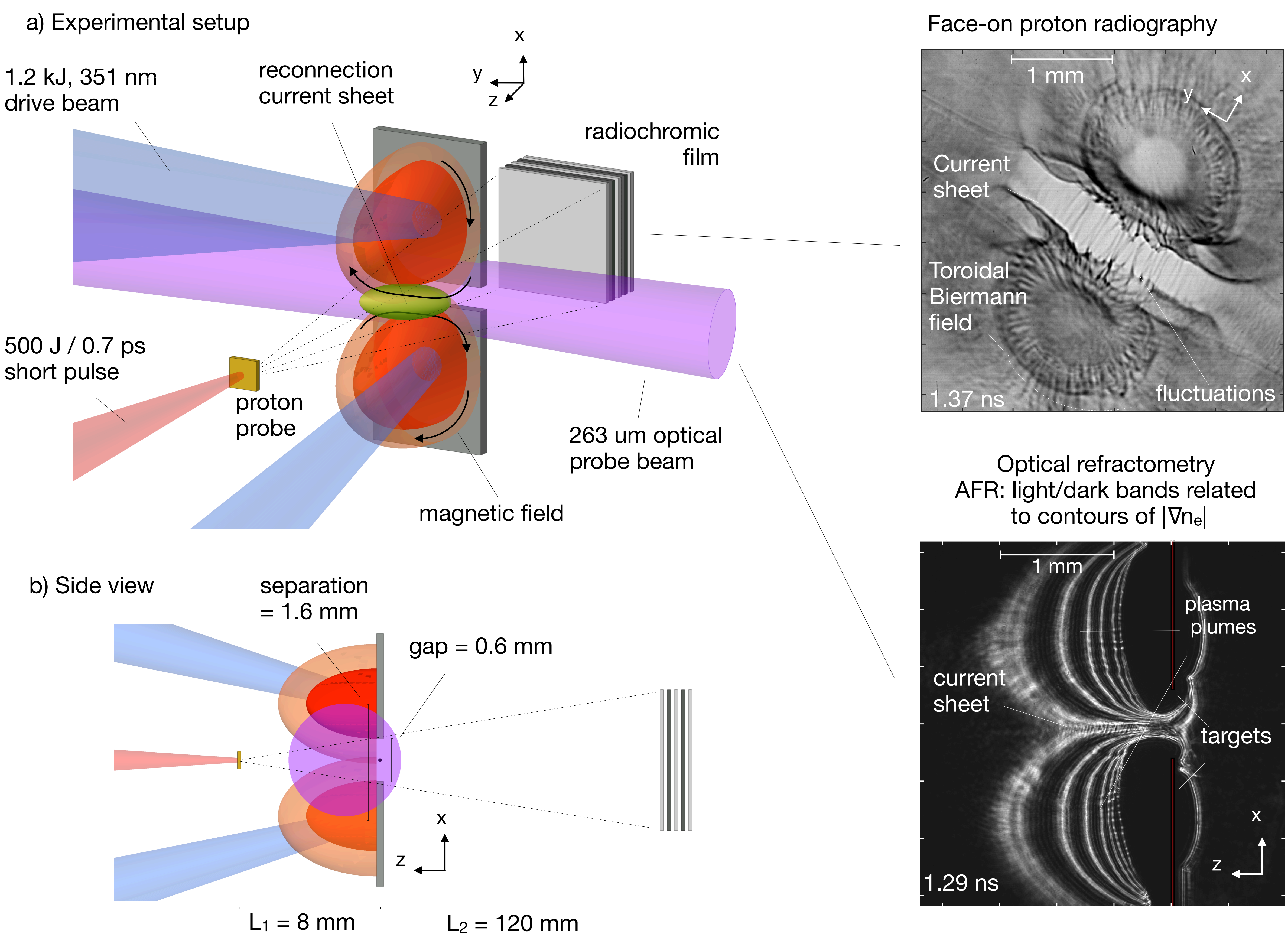
Reconnection between externally-magnetized plasmas (G. Fiksel, WF, AB, et al PRL 2014)



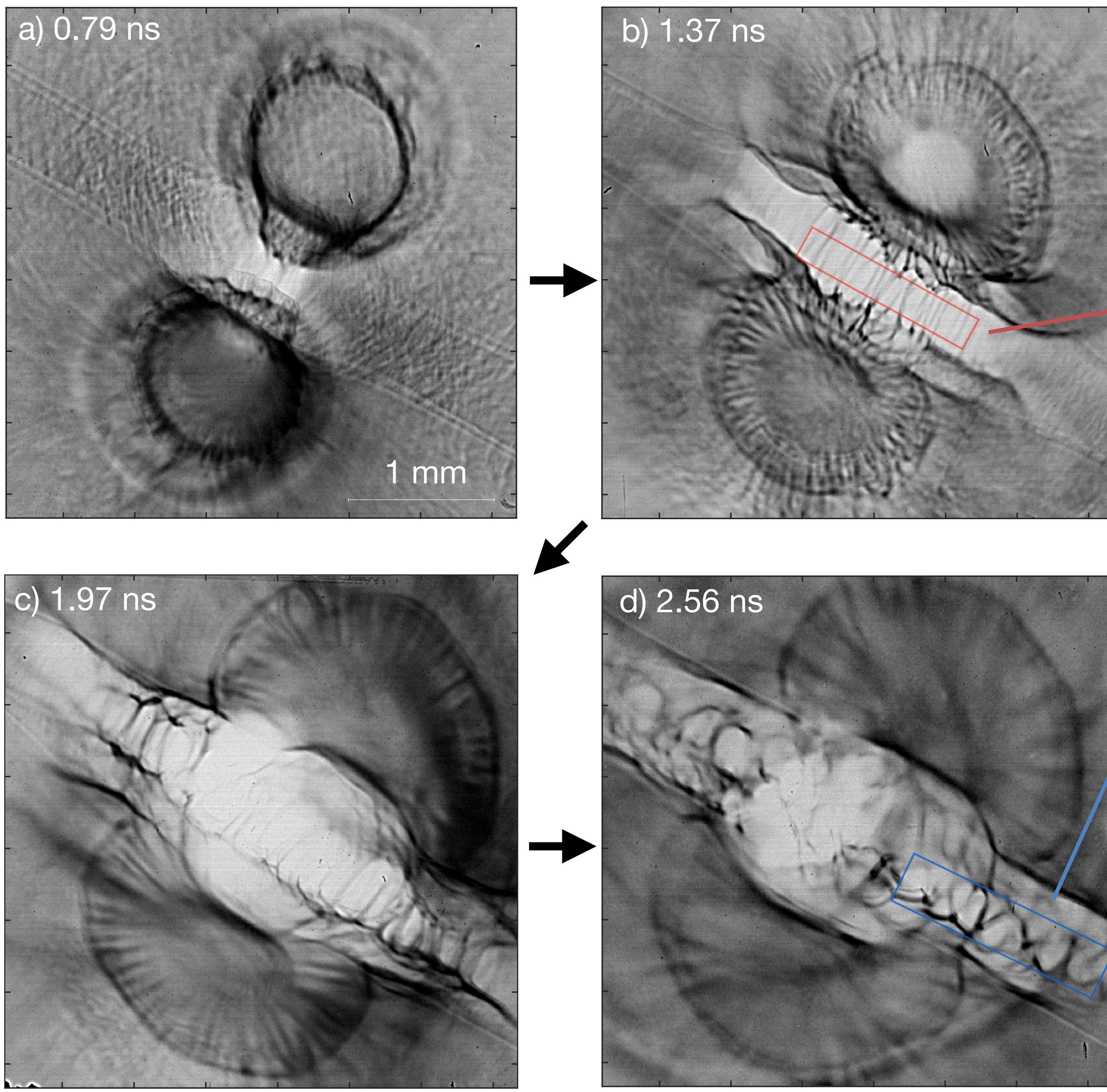
Experiment	Te	Separation	L/di (at ne ~ 10^{20})	Lundquist number S
Vulcan (Nilson 2006)	1 keV	0.4 mm	~ 10 (at 10^{19})	~ 150
SG-II (Zhong 2012)	1 keV	0.4 mm	~ 30	~ 500
OMEGA (Rosenberg)	1 keV	1.5 mm	~ 80	~ 3000
NIF	~3 keV	6 mm (length)	~ 300	~ 60000

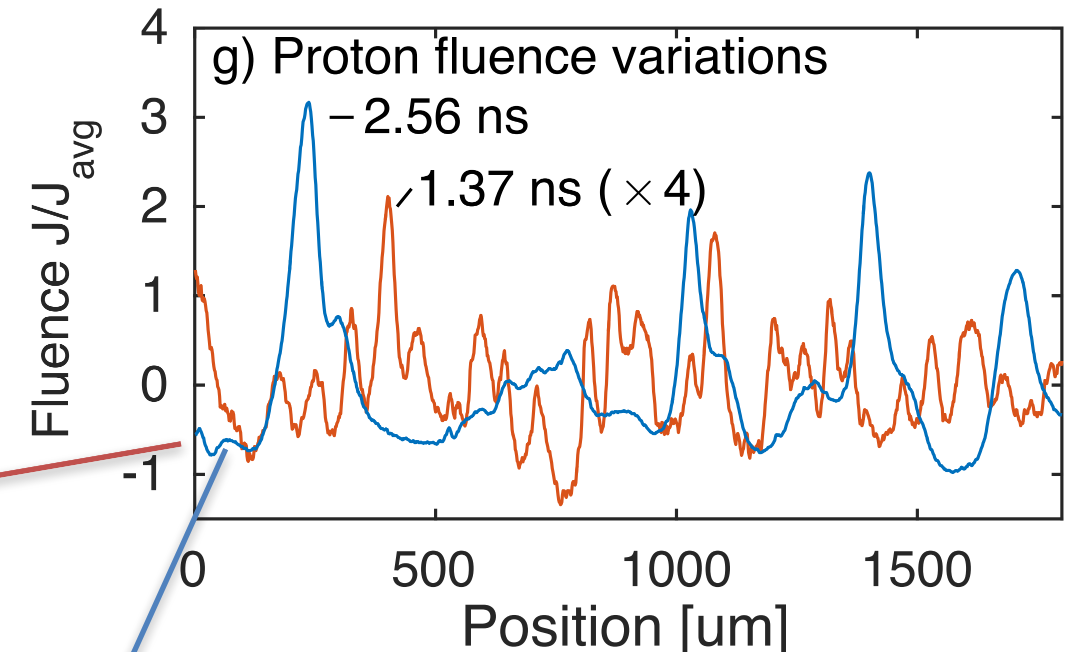
Early 2-D simulations showed that the very fast reconnection in these experiments could be mediated by flux pileup and plasmoid instability (WF, AB, et al PRL 2011, PoP 2012)

Proton and optical probes show development of current sheet

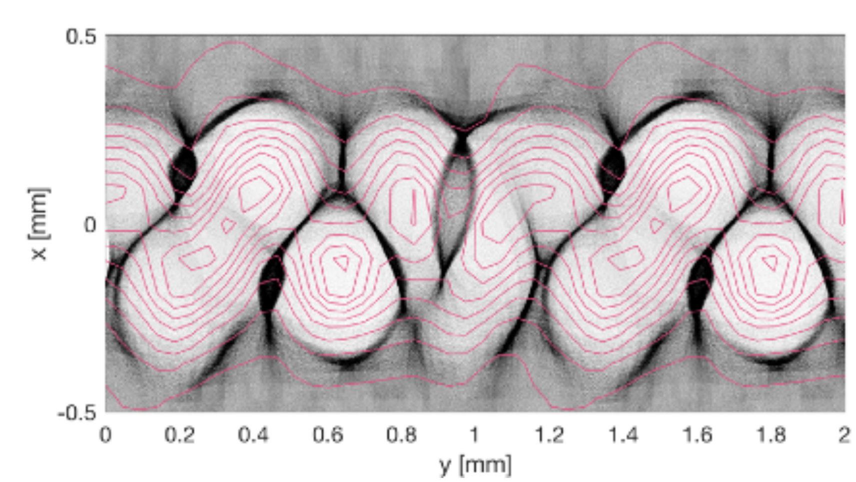


Proton radiography sequence shows the development of structures in current sheet



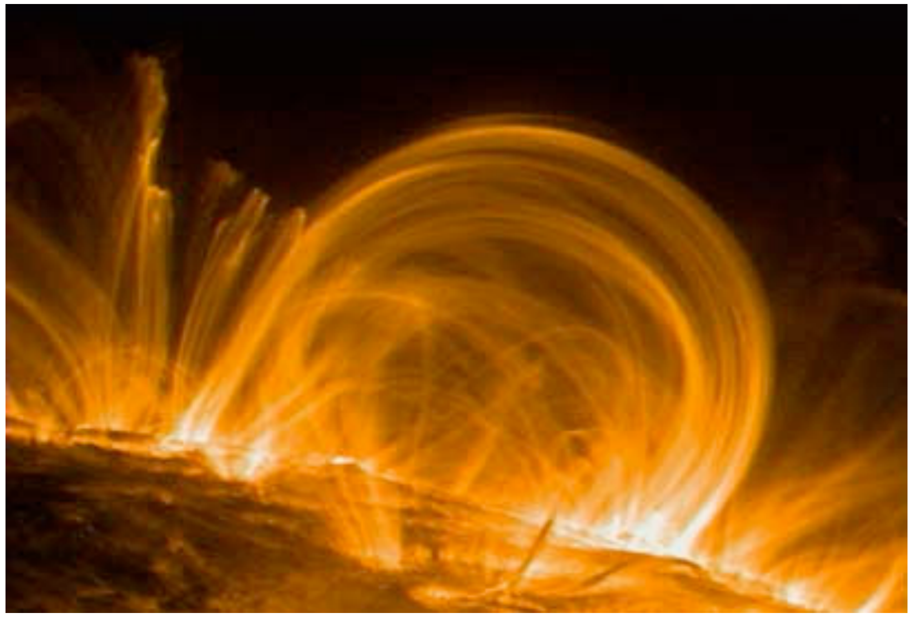


Synthetic radiography from simulations: closed-cellular proton features reflect magnetic islands structure and reconnection into plasmoids

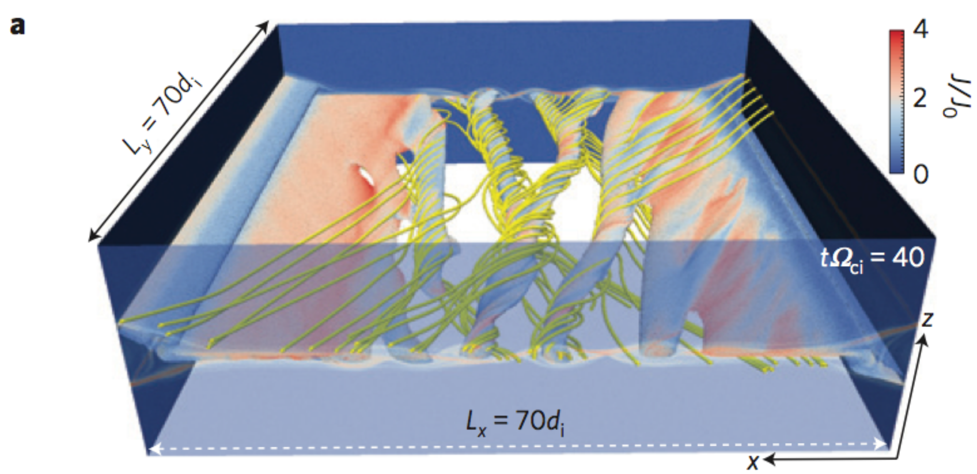


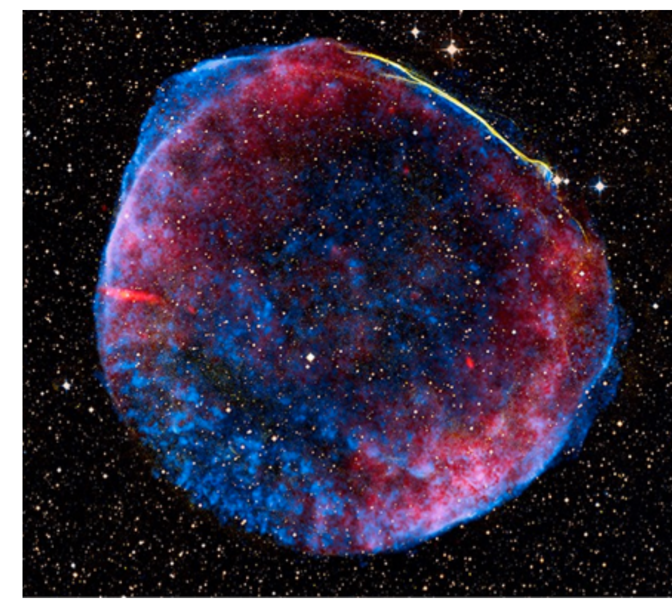
Fox et al, submitted (2018)

Summary



- **Magnetic reconnection forces us to contemplate the full range of plasma physics**
  - **Coupling of global and local (kinetic), turbulence. Instabilities. Energy conversion**





- I hope this has energized you (but not shocked you!)
- Work hard and soak in your SULI experience. Have a good summer!