Magnetic Reconnection

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Outline

A broad view on magnetic reconnection

Fundamental problems & research

- Reconnection rate problem
- Three-dimensional (3D) nature of reconnection

Summary

Background

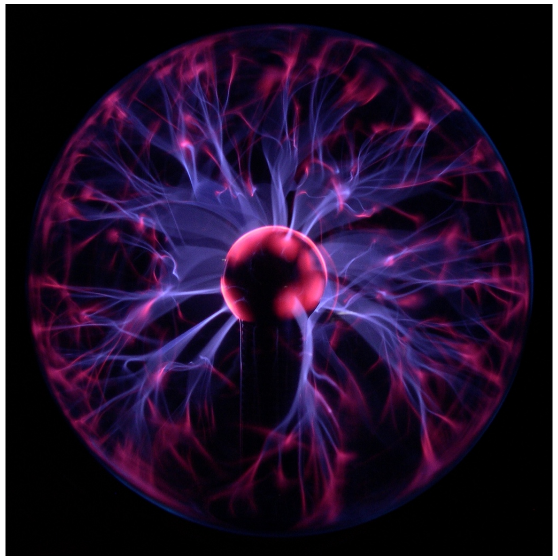
-- All about the geometry & topology of magnetic field lines

Plasmas

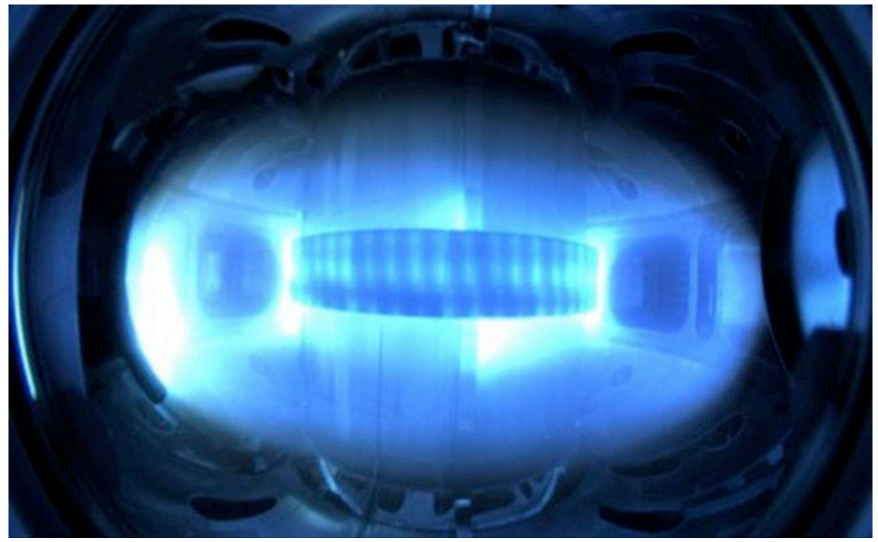
4th state of matter

> 99% of visible universe*

Plasma Lamp



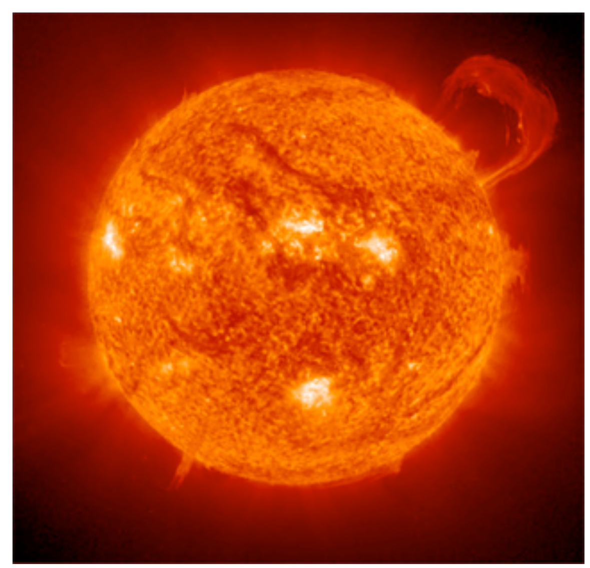
Fusion device



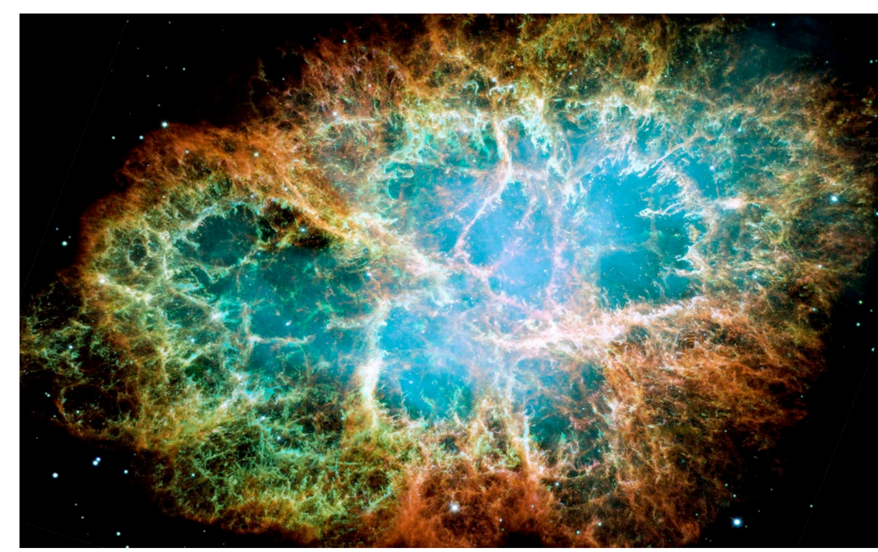
Lighting

Aurora Borealis

Solar Eruption

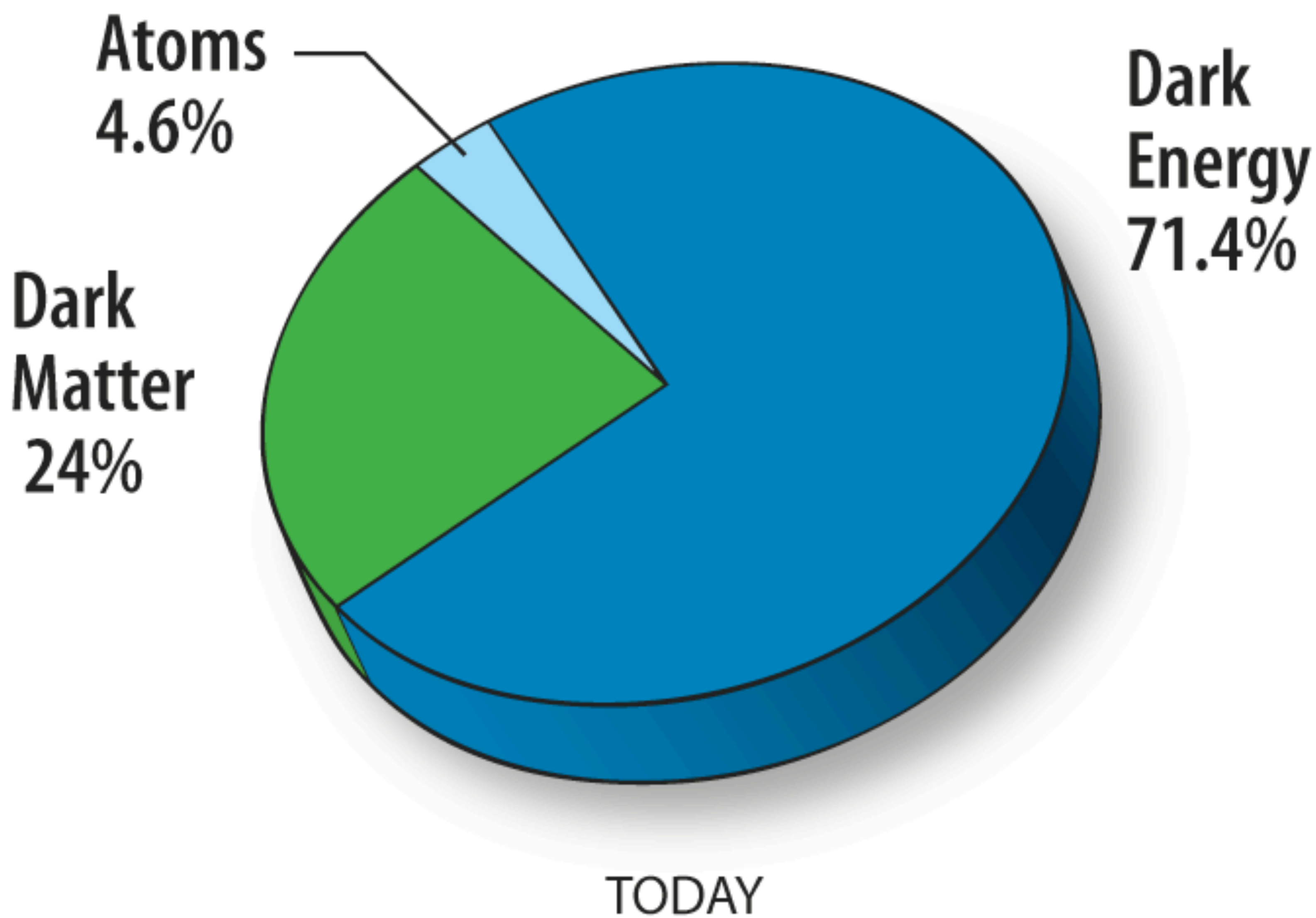


Nebula



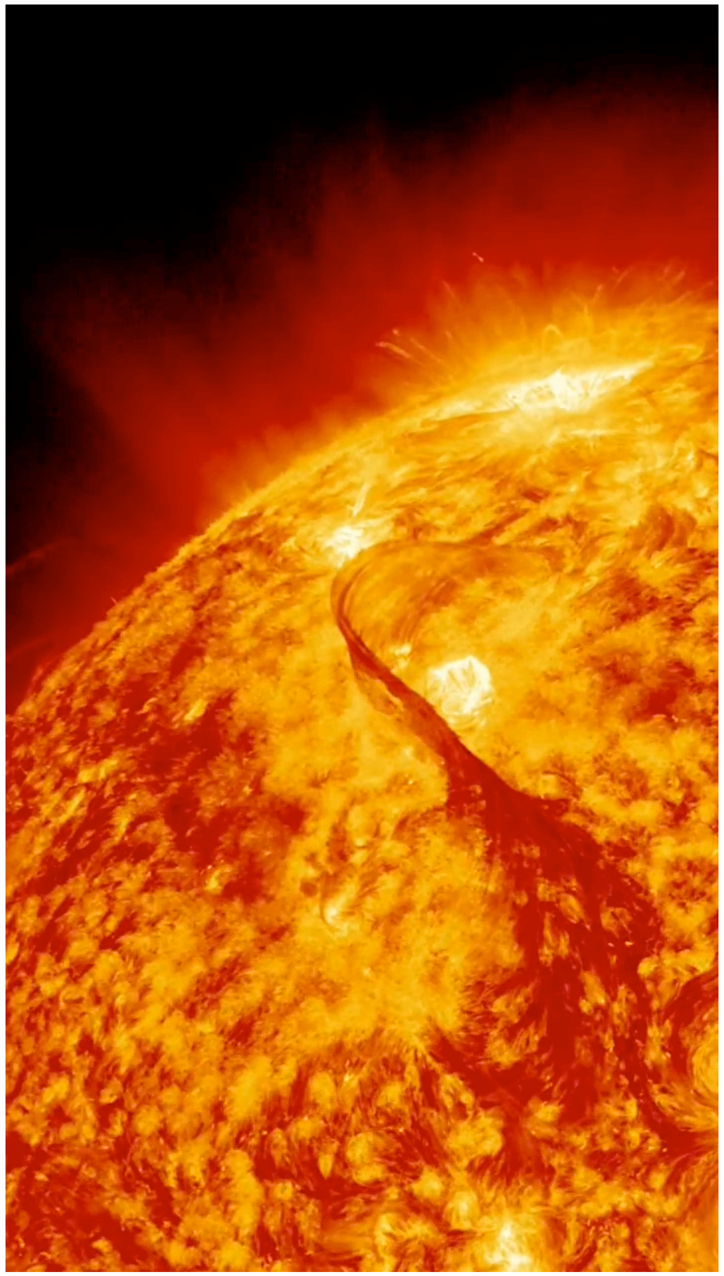
- Interaction between lots^n of charge particles + electromagnetic fields
  -- complicated & nonlinear!!
- Long range electromagnetic interaction!!
  -- the evolution CANNOT be described by thermodynamics.

*Footnote



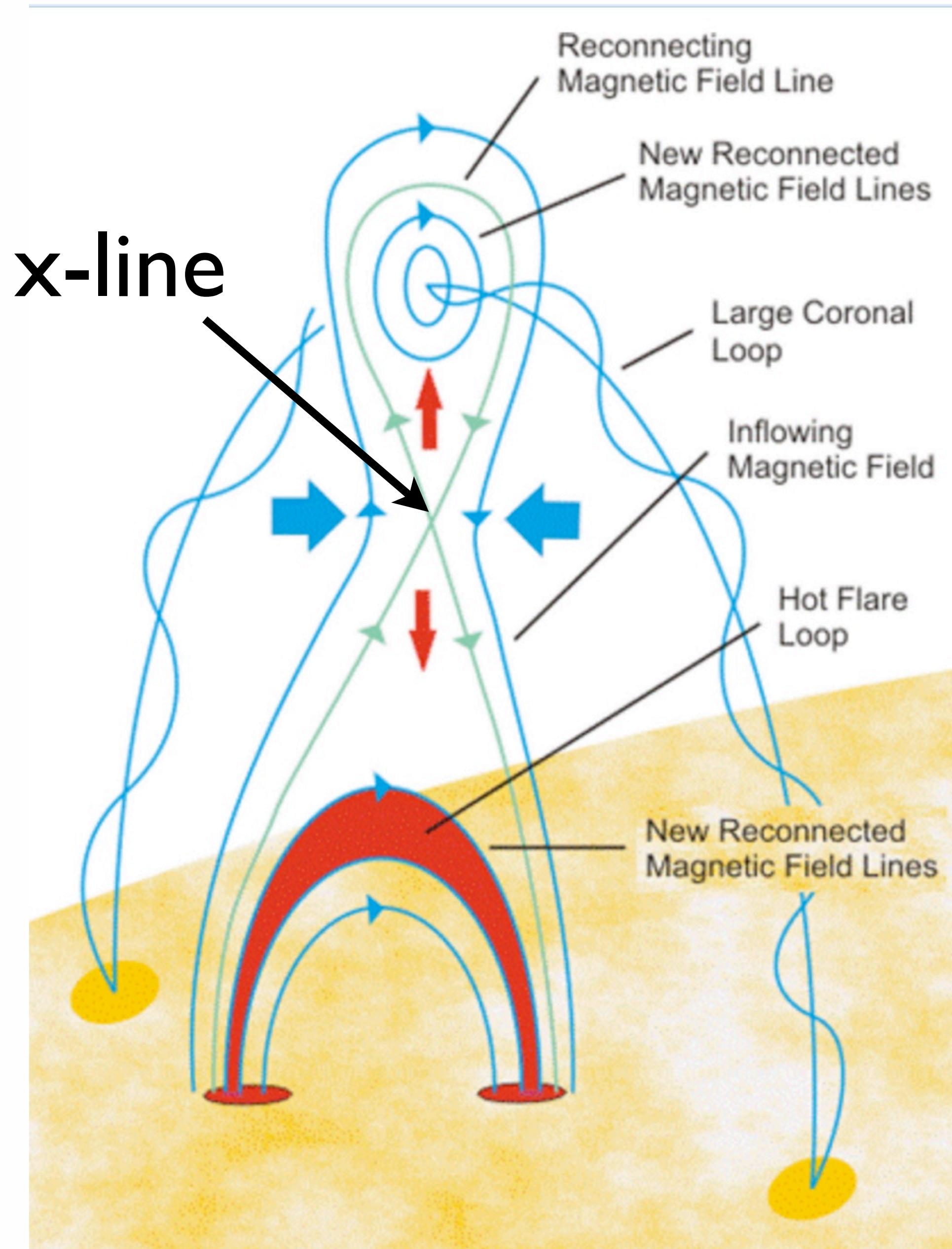
Solar Eruption

Earth



(Courtesy of SDO mission)

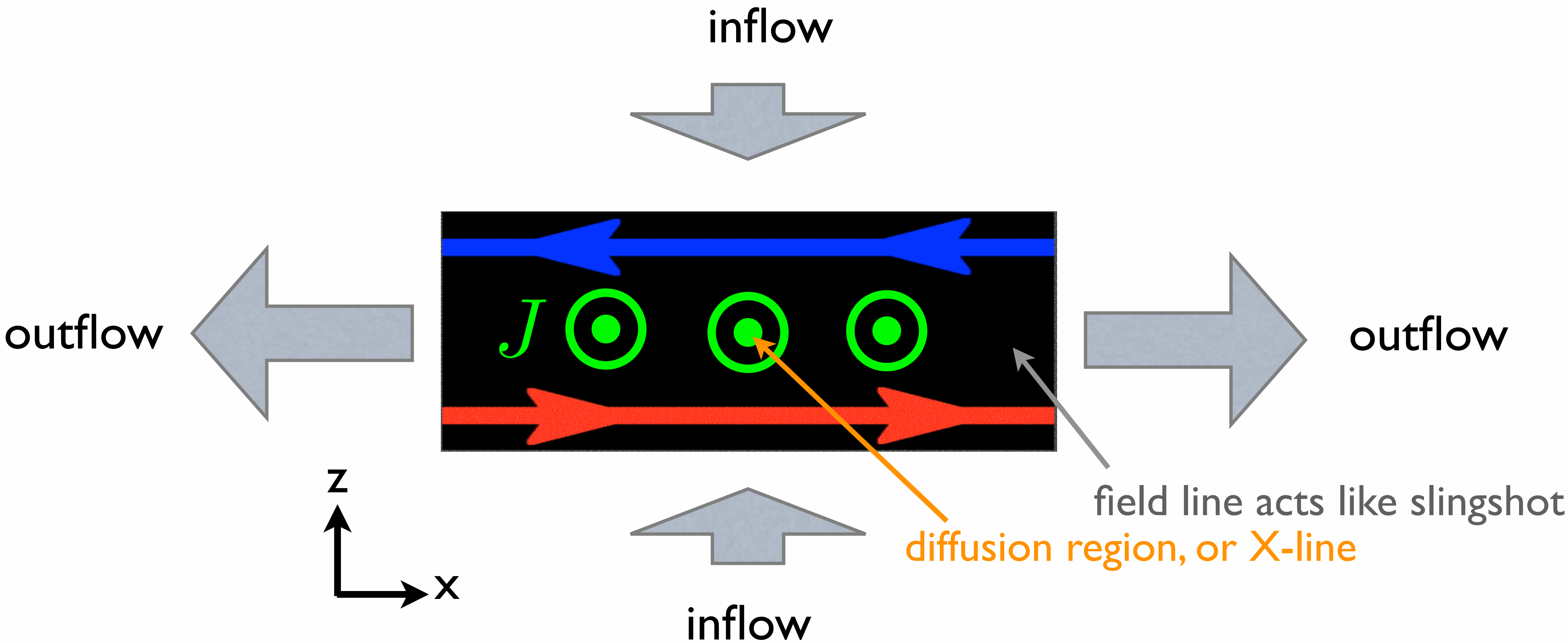
B~200 Gauss
T~3,000,000 K



(Courtesy of NASA)

- Energy up to 10^{32} ergs is released in ~ 20 mins
  -- 40 billion atomic bombs!
- Matter up to 10^{10} tons is erupted.

Magnetic Reconnection?

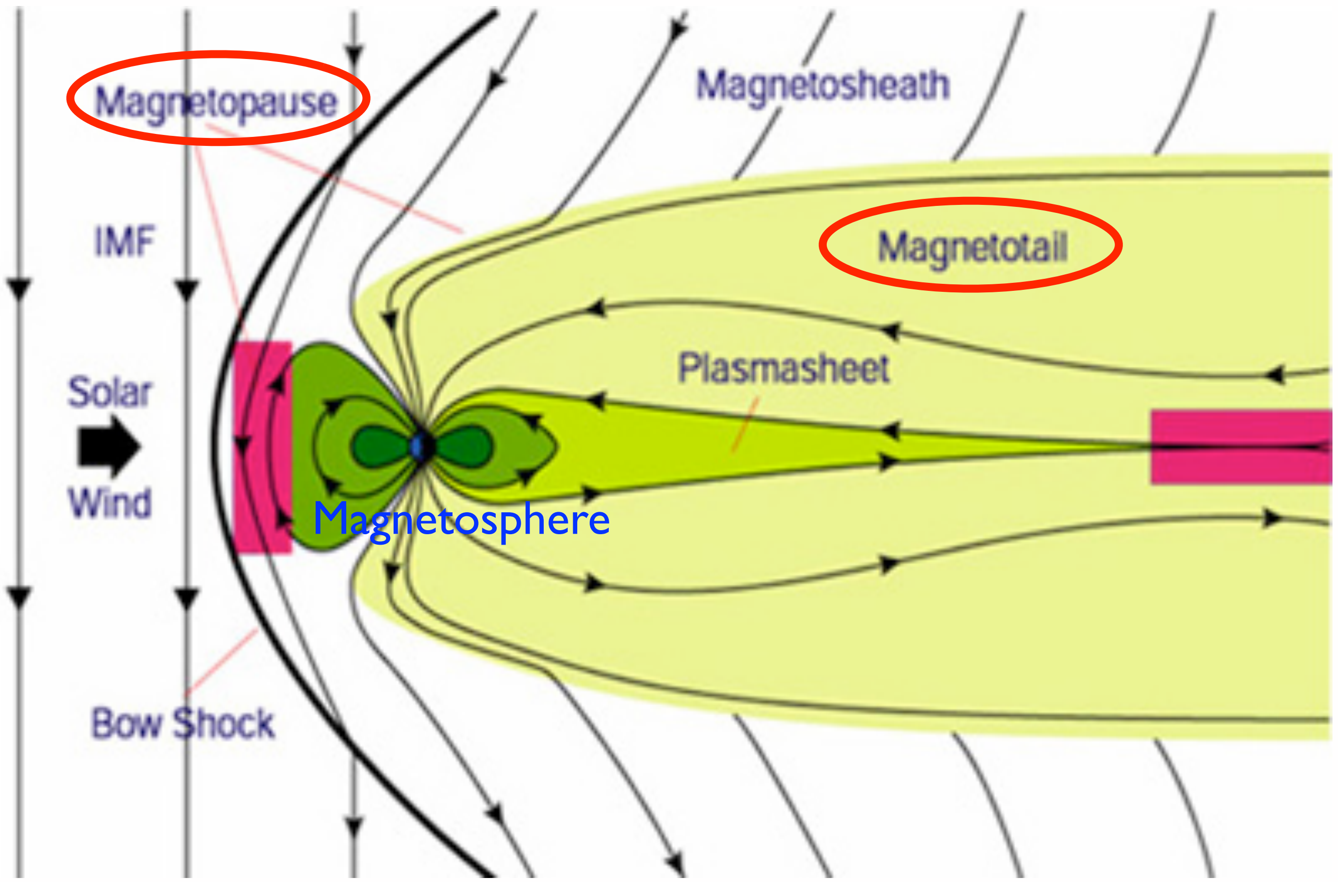


1. Inflow brings in magnetic flux (*frozen-in*)
2. Field lines break & reconnect (*frozen-in* is violated *!!*)
3. Reconnected field line shoots out plasma (*frozen-in*)
4. Pressure drop sucks in plasma inflow
1. Inflow brings in magnetic flux (*frozen-in*)
2. .....
3. ...

A self-driven process!!!

Earth's magnetosphere

IMF
(Interplanetary
Magnetic Field)

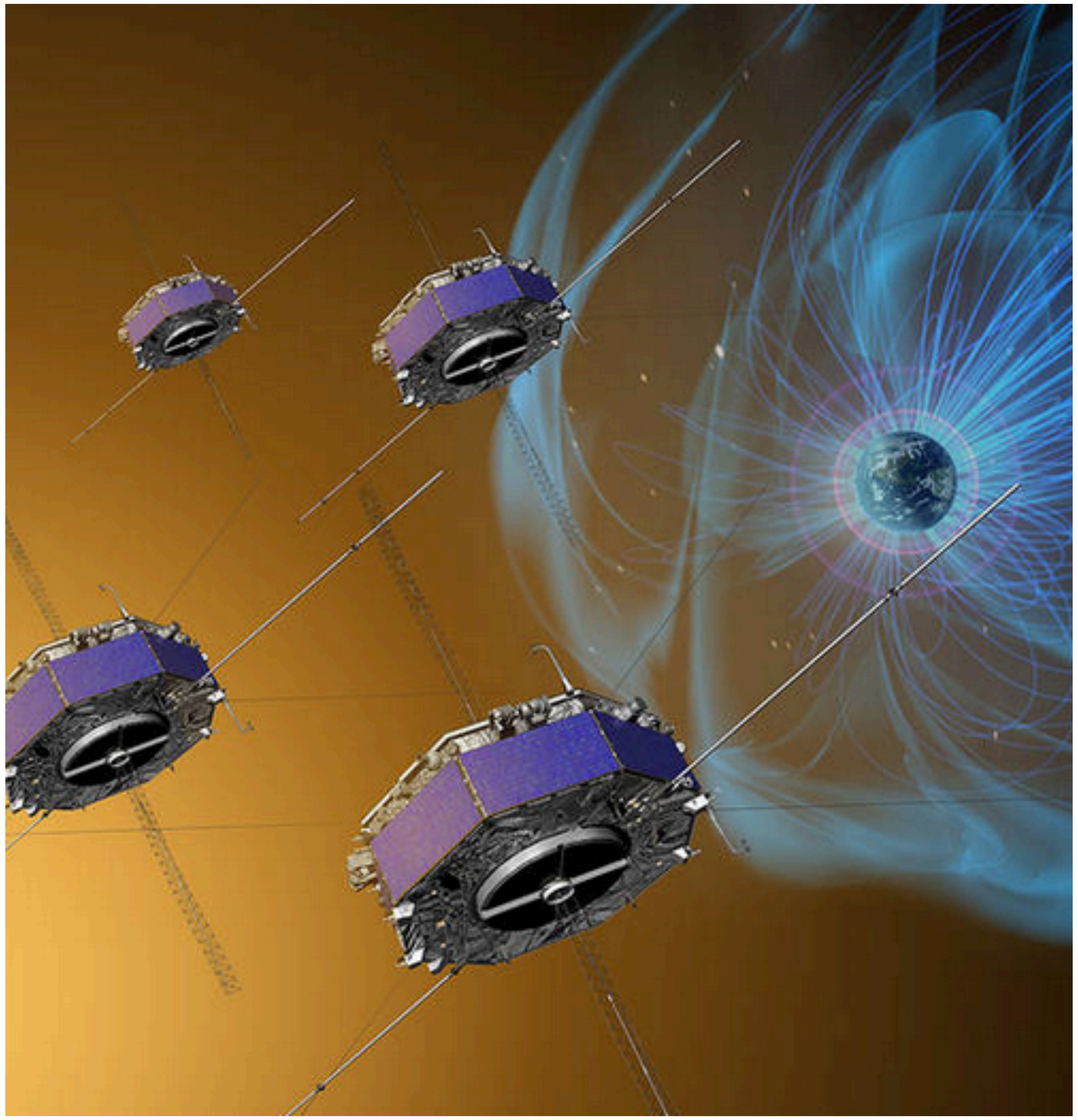


magnetosheath	magnetosphere	magnetotail
$B \sim 20nT$	$B \sim 60nT$	$B \sim 20nT$
$n \sim 15cm^{-3}$	$n \sim 0.5cm^{-3}$	$n \sim 0.01cm^{-3}$

- Reconnection occurs at both the magnetopause & magnetotail.
- Reconnection at the magnetotail drives magnetospheric substorm & enhances aurora.

A billion $ NASA mission designed to study magnetic reconnection

Magnetospheric Multiscale Mission (MMS)

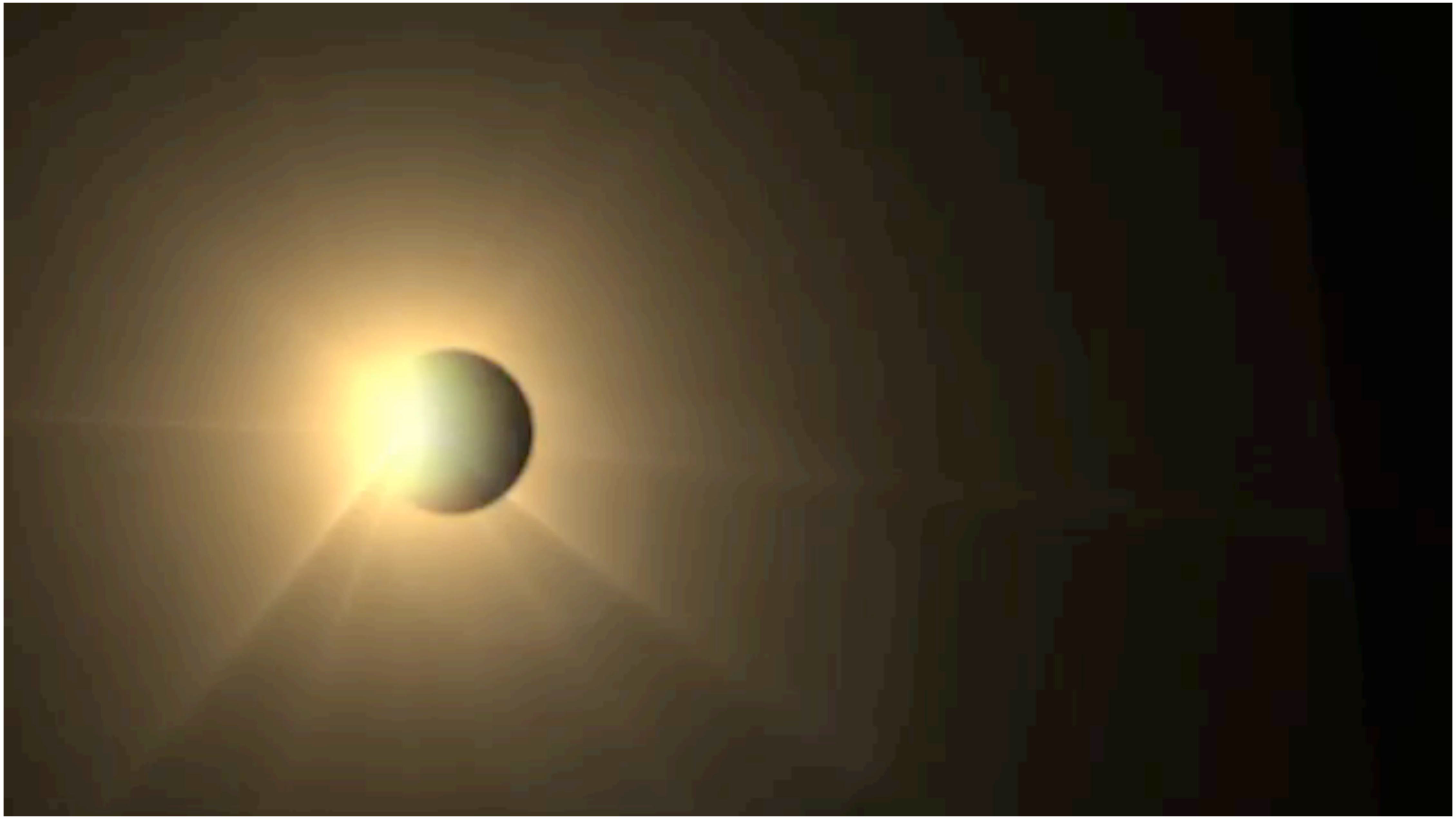


http://mms.gsfc.nasa.gov

tight tetrahedron formation: separation down to 7 km!
100x faster for electrons measurement (30 ms)
30x faster for ions measurement (150 ms)

- MMS leads us into a stage where the electron-scale physics of magnetic reconnection, in nature, can be resolved in an unprecedented manner!!

The trailer of MMS ...



Science

RESEARCH ARTICLES

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Electron-scale measurements of magnetic reconnection in space

J. L. Burch,[1*] R. B. Torbert
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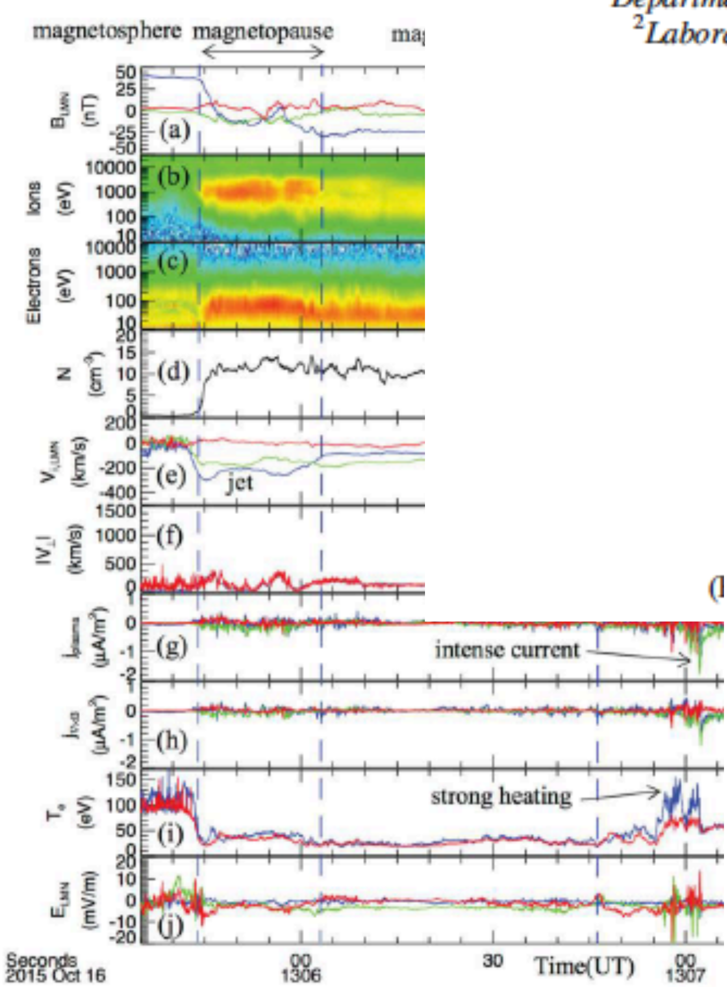

PRL 116, 235102 (2016) PHYSICAL REVIEW LETTERS week ending 10 JUNE 2016

Magnetospheric Multiscale Satellites Observations of Parallel Electric Fields Associated with Magnetic Reconnection

R. E. Ergun,[1,2] K. A. Goodrich,[1,2] F. D. Wilder,[2] J. C. Holmes,[1,2] J. E. Stawarz,[1,2] S. Eriksson,[2] A. P. Sturner,[1,2] D. M. Malaspina,[1] M. E. Usanova,[1] R. B. Torbert,[3,4] P.-A. Lindqvist,[5] Y. Khotyaintsev,[6] J. L. Burch,[4] R. J. Strangeway,[7] C. T. Russell,[7] C. J. Pollock,[8] B. L. Giles,[8] M. Hesse,[8] L. J. Chen,[9] G. Lapenta,[10] M. V. Goldman,[11] D. L. Newman,[11] S. J. Schwartz,[2,12] J. P. Eastwood,[12] T. D. Phan,[13] F. S. Mozer,[13] J. Drake,[9] M. A. Shay,[14] P. A. Cassak,[15] R. Nakamura,[16] and G. Marklund[5]

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AGU PUBLICATIONS

JGR

Journal of Geophysical Research: Space Physics

RESEARCH ARTICLE

10.1002/2017JA024004

Special Section:
Magnetospheric Multiscale (MMS) mission results throughout the first primary mission phase

Electron diffusion region during magnetopause reconnection with an intermediate guide field: Magnetospheric multiscale observations

L.-J. Chen[1,2], M. Hesse[1], S. Wang[1,2], D. Gershman[1,2], R. E. Ergun[3], J. Burch[4], N. Bessho[1,2], R. B. Torbert[4,5], B. Giles[1], J. Webster[6], C. Pollock[7], J. Dorelli[1], T. Moore[1], W. Paterson[1], B. Lavraud[8,9], R. Strangeway[10], C. Russell[10], Y. Khotyaintsev[11], P.-A. Lindqvist[12], and L. Avanov[1,2]

Briefing of MMS mission
02/25/2015 @ NASA headquarter

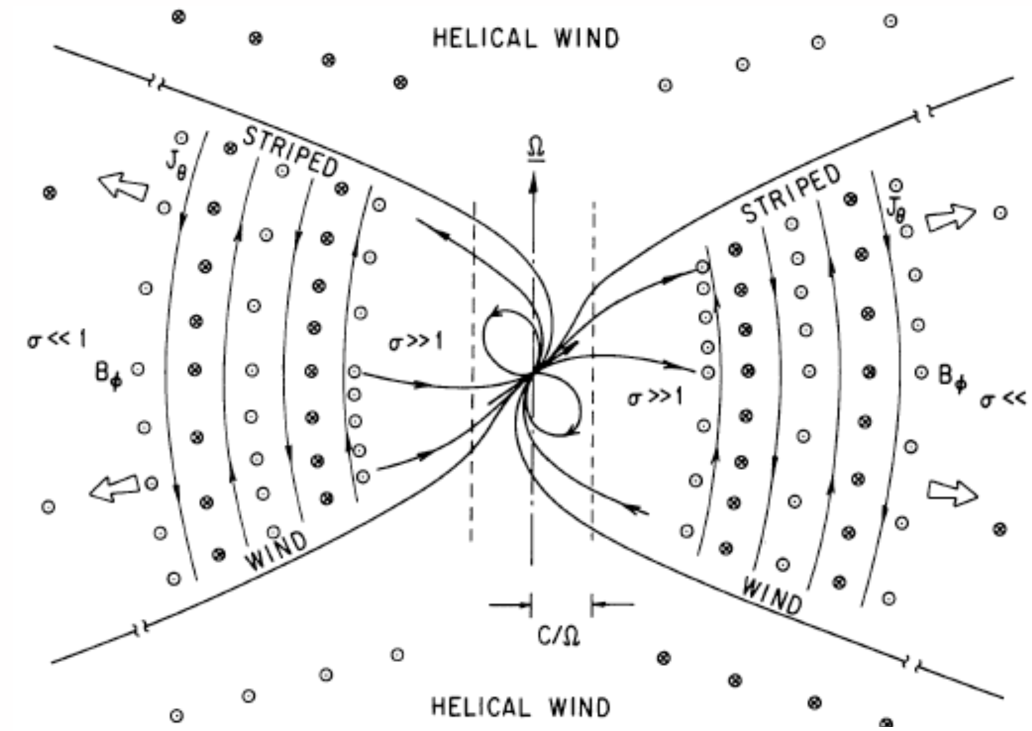
Moderator | NASA Headquarter | Project PI | Project Scientist | Guest Researcher

Astrophysical systems

Superflares @ Crab Nebula

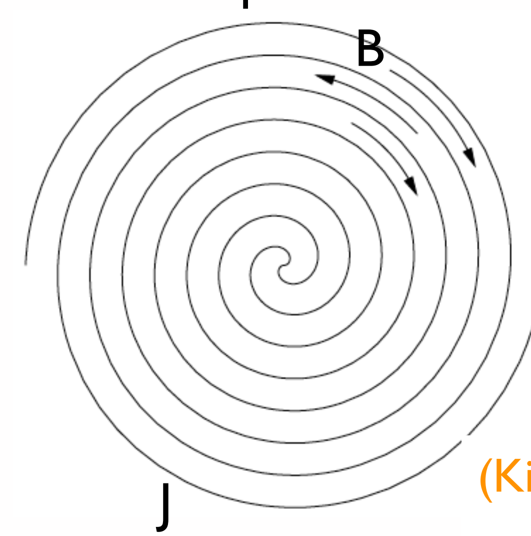
(Striani et al. 2011)

time scale ~days



(Coroniti 1990)

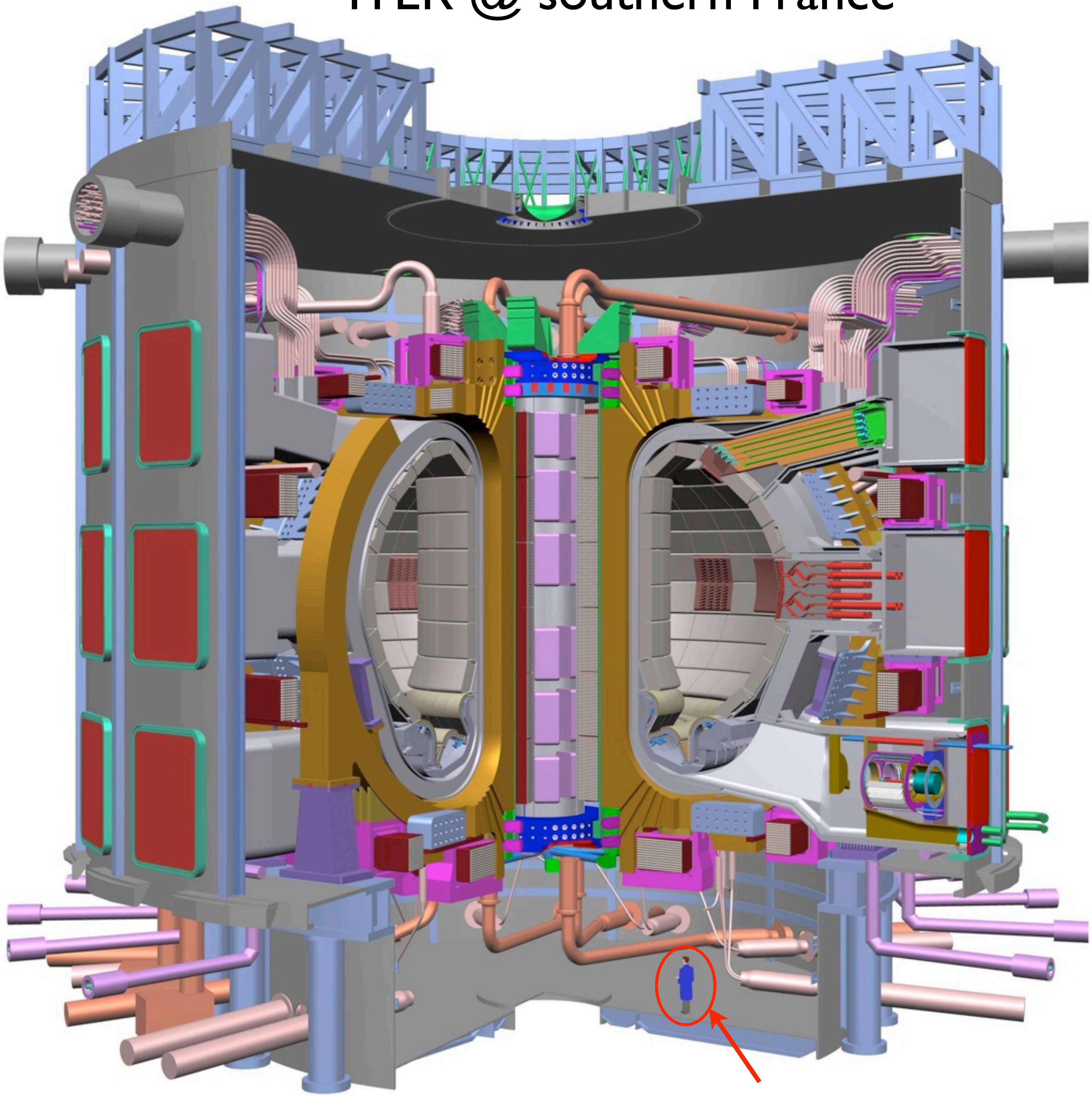
Top view



(Kirk & Skaeraasen 2003)

- Strong magnetic fields are dissipated quickly! (σ-problem)
- Relativistic reconnection could be important, and at other places like:
  Jets from active galactic nuclei (AGN)/ black holes
  Gamma-Ray bursts (GRBs)

ITER @ southern France



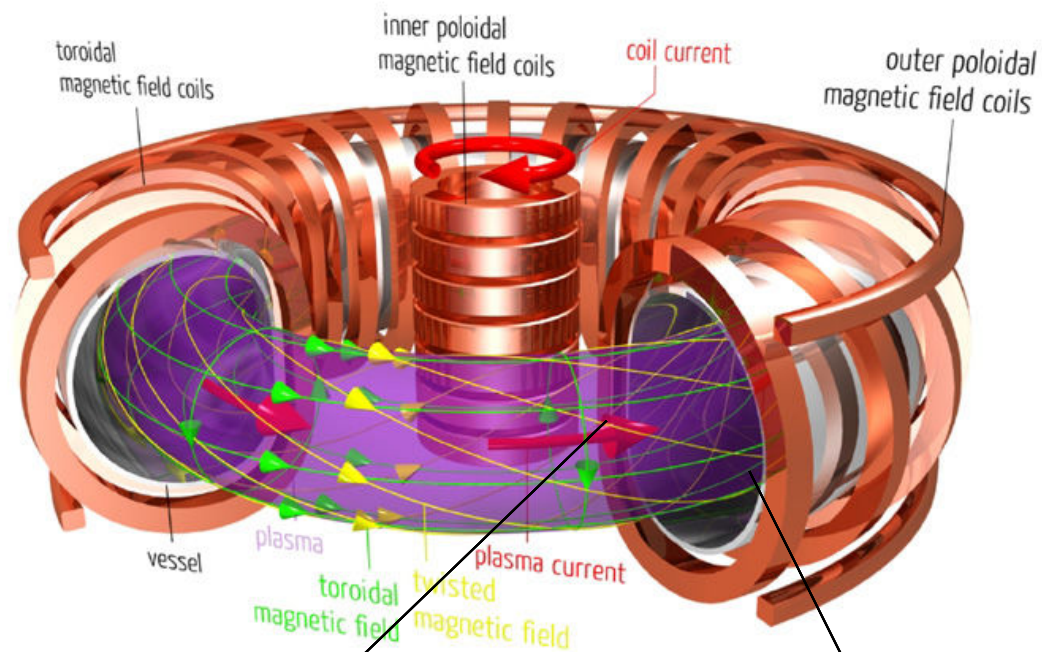
(fake) Fusion reactors in Hollywood

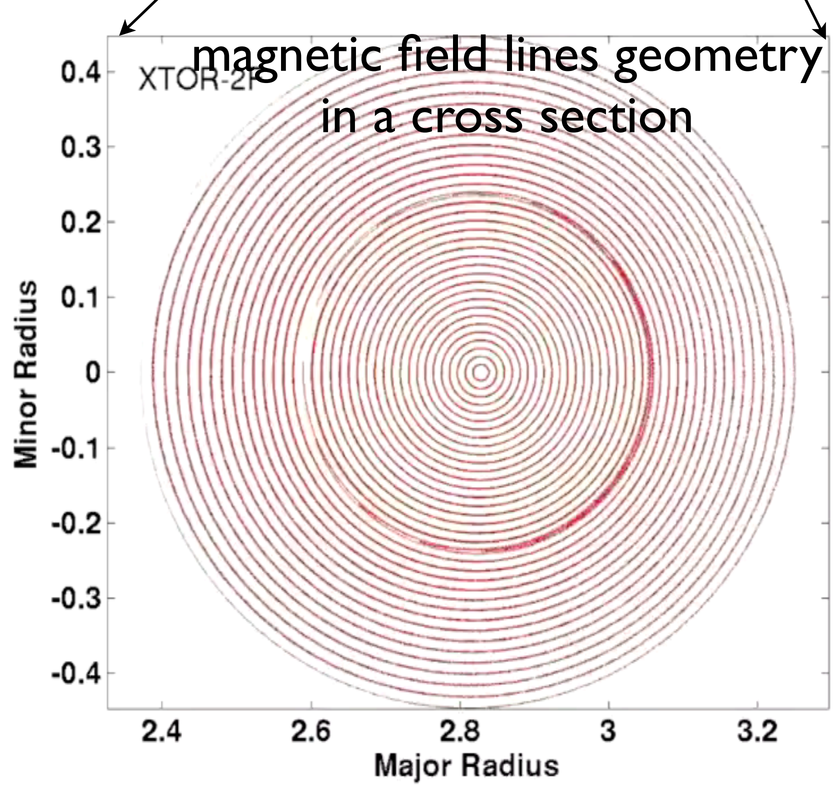
Doctor Octopus in Spider man 1

Laboratory plasmas

Fusion device

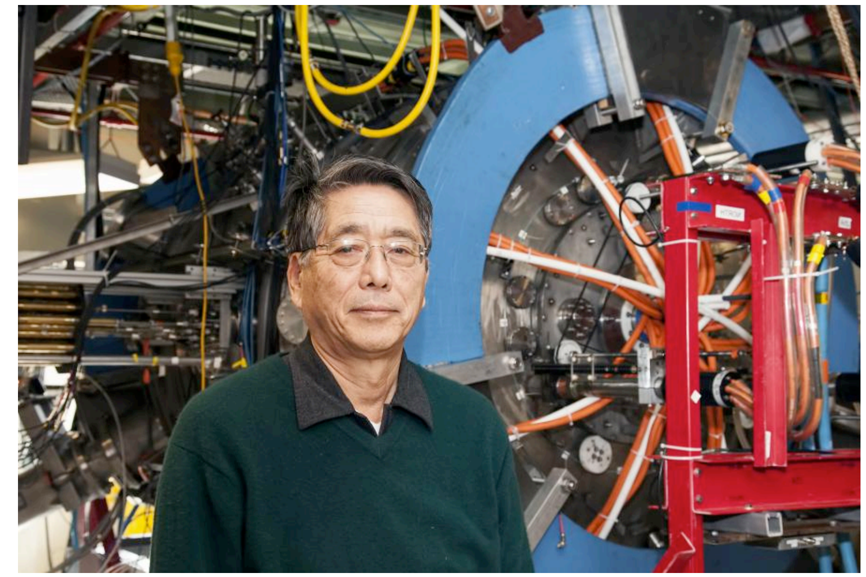
e.g,, ITER Tokamak @ France



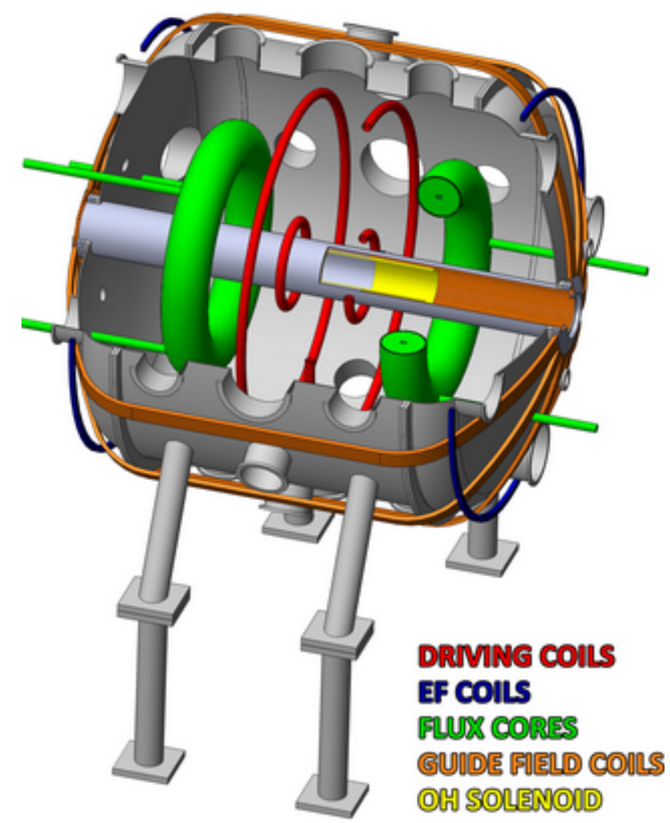


Reconnection Experiment

MRX @ PPPL



FLARE @ PPPL



TREX @ U. Wisconsin

LAPD @ UCLA

- Reconnection causes the Sawtooth crashes in Tokamak!

Honey, I Blew Up the Tokamak

+ Play Audio | + Download Audio | + Join mailing list

August 31, 2009: Magnetic reconnection could be the Universe's favorite way to make things explode. It operates anywhere magnetic fields pervade space--which is to say almost everywhere. On the sun magnetic reconnection causes solar flares as powerful as a billion atomic bombs. In Earth's atmosphere, it fuels magnetic storms and auroras. In laboratories, it can cause big problems in fusion reactors. It's ubiquitous.

!

Top
1
2
3
4

Fundamental problems & research

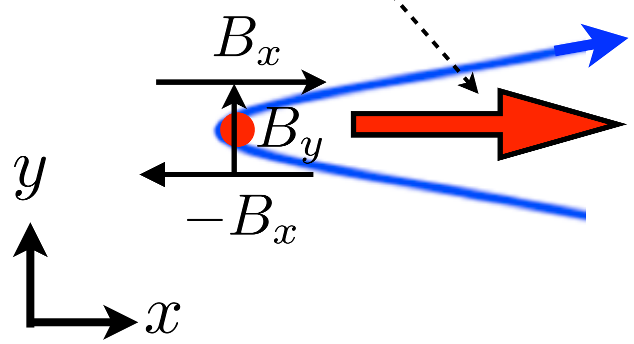
1/2. Reconnection Rate Problem

- How quickly can reconnection process magnetic flux?

Magnetic tension & Alfvén waves

$$\frac{B_y(\partial_y B_x)}{4\pi}\hat{x}$$

magnetic tension: $\dfrac{\mathbf{B}\cdot\nabla\mathbf{B}}{4\pi}$

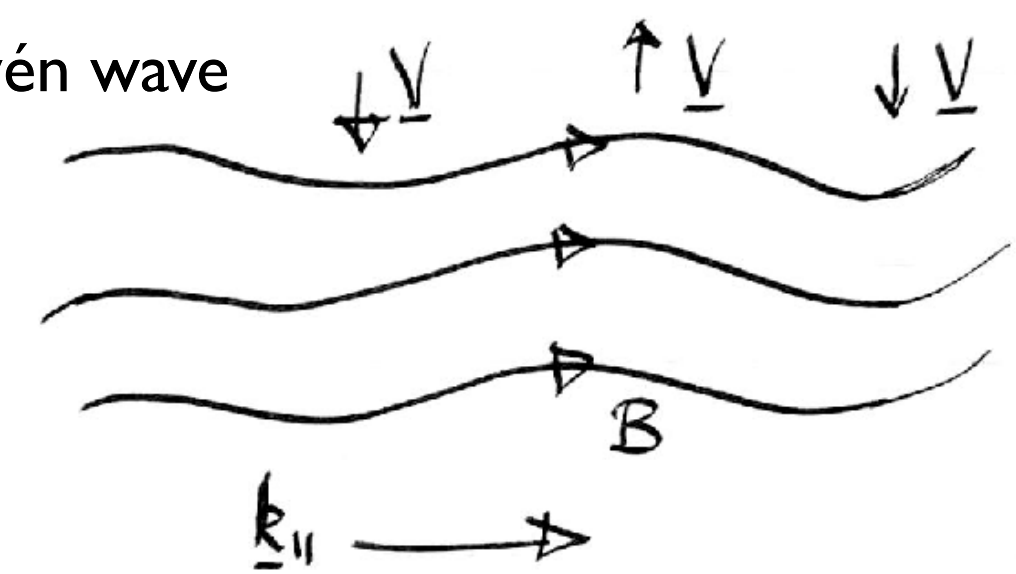


vibration of guitar strings

(Youtube: iphone 4 inside a guitar oscillation! VERY COOL!)

plasma inertia: $nm_i\dfrac{d\mathbf{V}}{dt}$

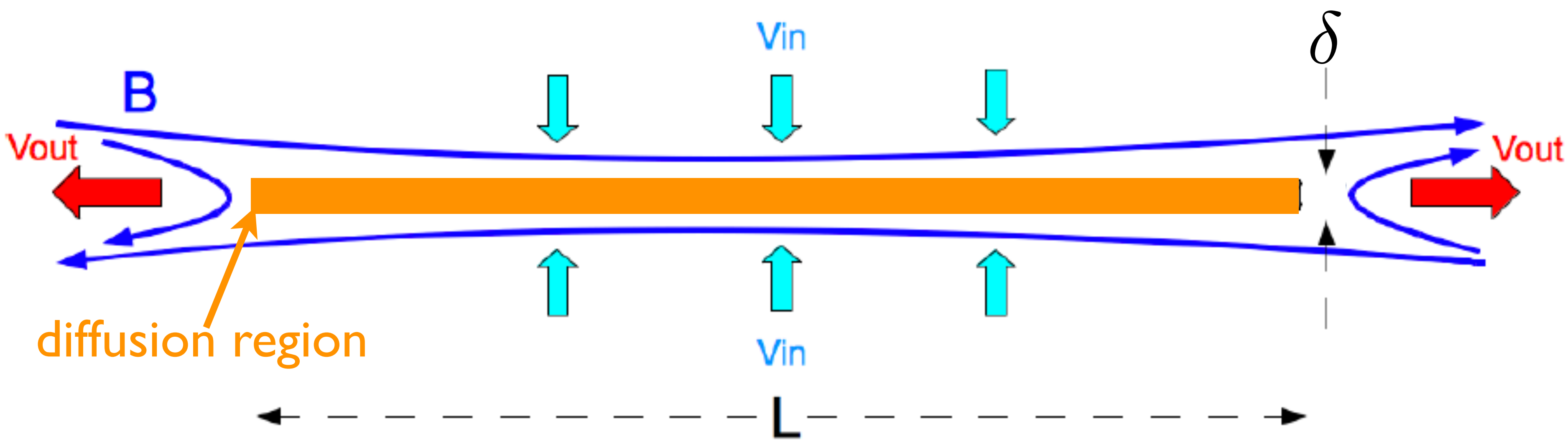
Alfvén wave



Alfvén speed

$$\rightarrow V_A \sim \frac{B}{\sqrt{4\pi n m_i}}$$

Sweet-Parker solution (1957)



mass conservation: $\nabla \cdot (n\mathbf{V}) \simeq 0$ $\rightarrow V_{in} L \simeq V_{out} \delta$

momentum eq.: $\dfrac{\mathbf{B} \cdot \nabla \mathbf{B}}{4\pi} \simeq n m_i \mathbf{V} \cdot \nabla \mathbf{V}$ $\rightarrow V_{out} \simeq \dfrac{B}{\sqrt{4\pi n m_i}} = V_A$!

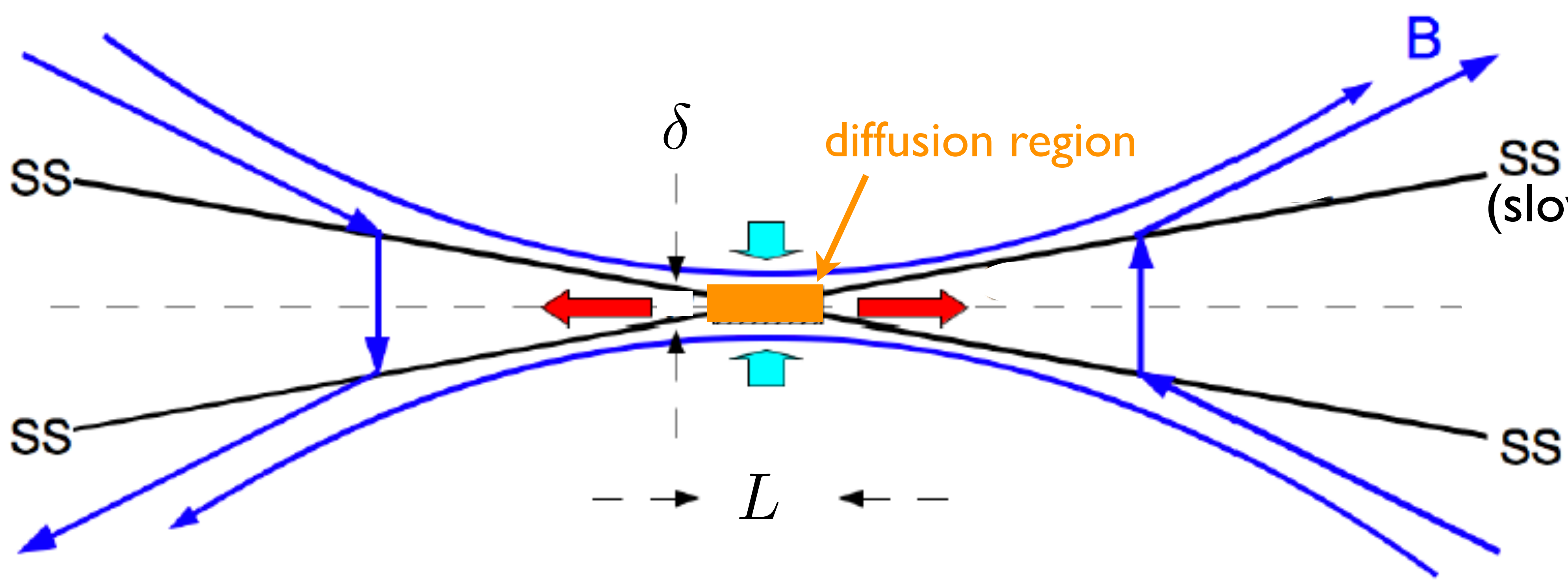
tension inertia

normalized reconnection rate $\rightarrow$ $\boxed{R \equiv \dfrac{V_{in}}{V_A} \sim \dfrac{\delta}{L}}$

- However, this model has a small δ/L , the rate is too small to explain the time-scales in solar flare. (Parker 1963)

- To explain the flares, it requires R~ 0.1. (Parker 1973)

Petschek solution (1964)

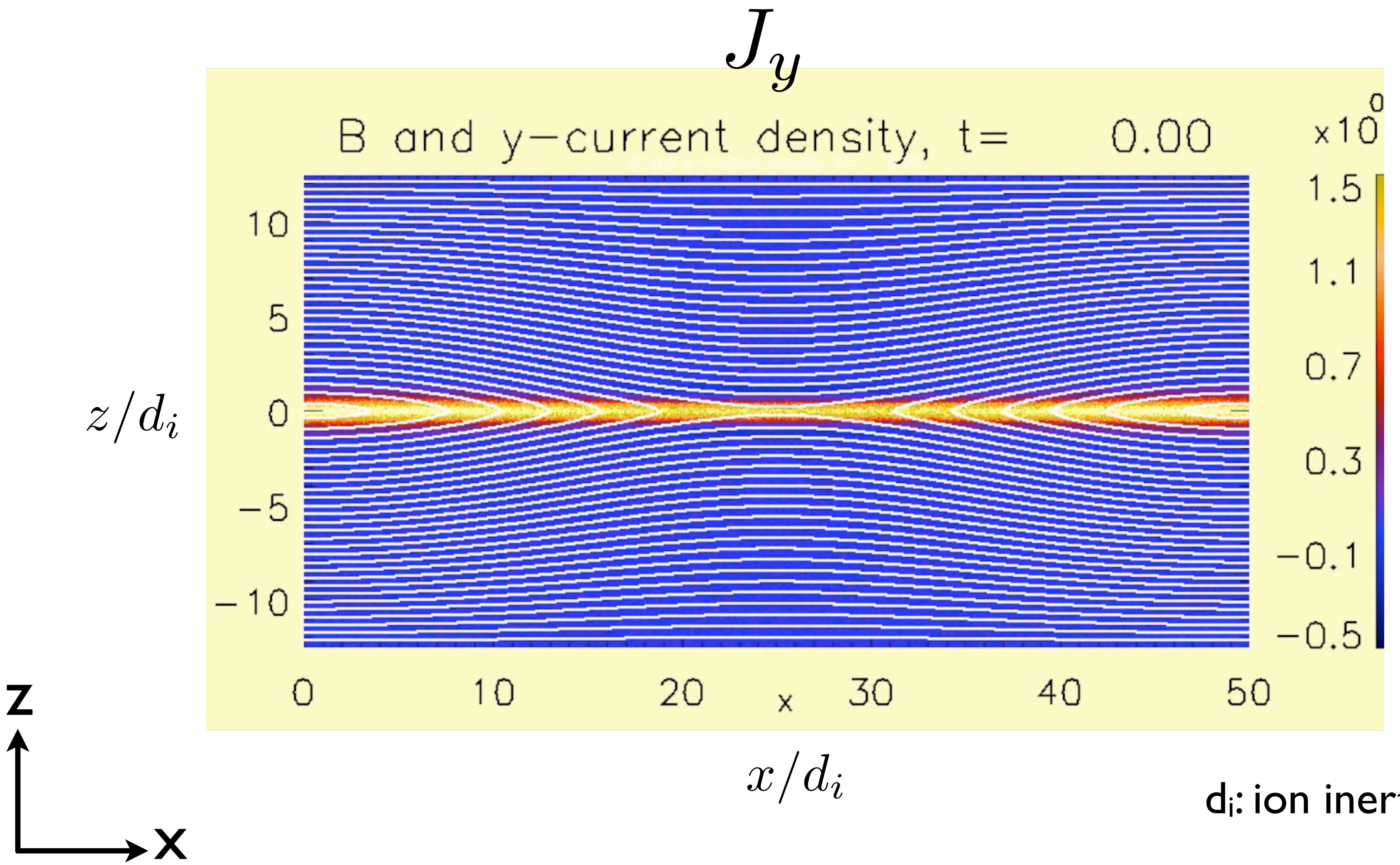


Reconnection rate is much larger because $R \sim \dfrac{\delta}{L} \uparrow$

- However, this is not a self-consistent solution. (Sato & Hayashi, 79; Biskamp, 86)

*aspect ration ≡ aspect ratio of the diffusion region

Reconnection in particle-in-cell (PIC) simulations



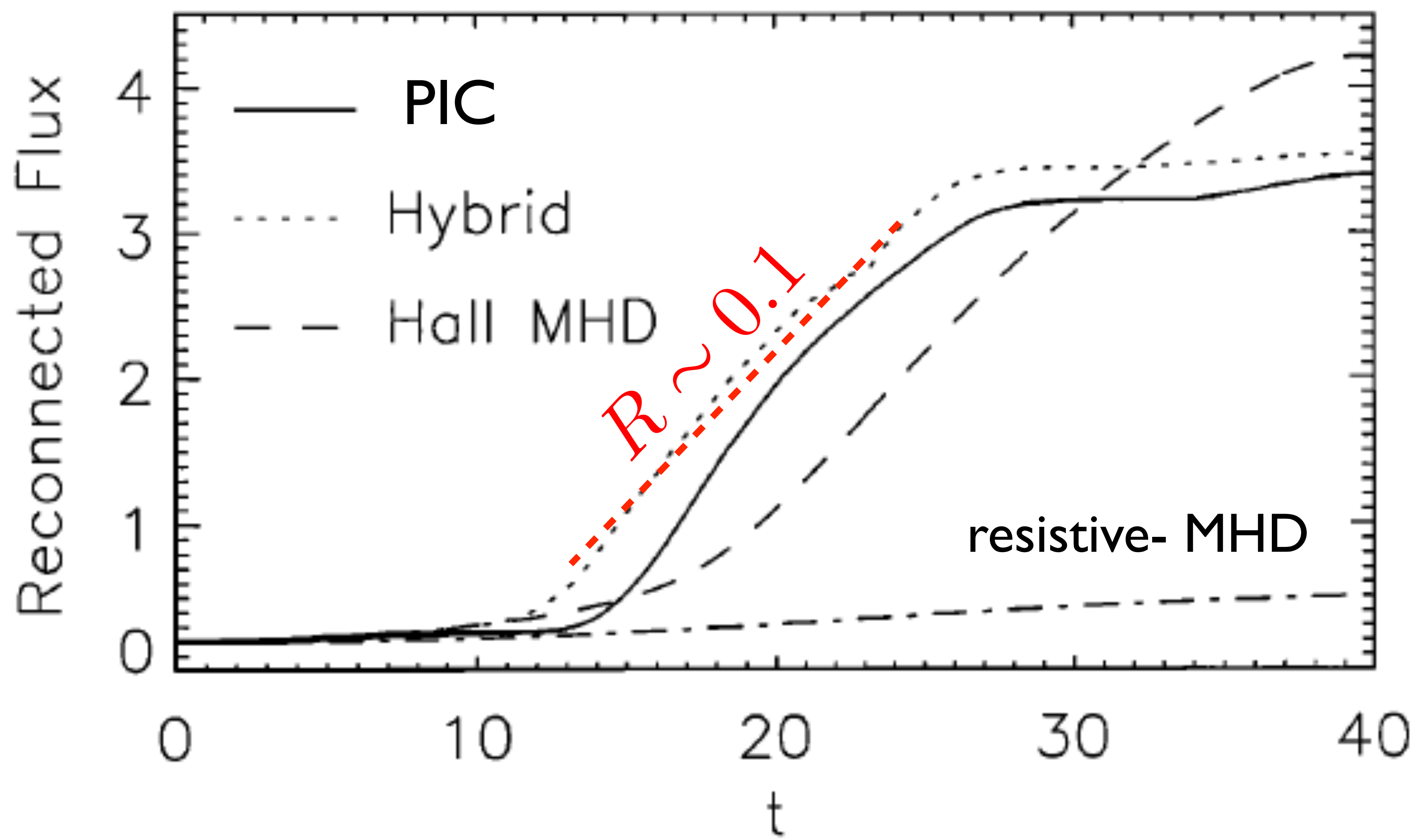
d_i: ion inertial scale.

- The diffusion region is localized like the Petschek solution.
- Why PIC? Why not using magnetohydrodynamics (MHD)?

-- because PIC captures the key physics that breaks the frozen-in condition in nature.

GEM Reconnection Challenge (2001)

(Birn et al. 2001)



* the importance of Hall term in Ohm's Law was debated for the past 16 years.
(Sonnerup 79)

- A similar reconnection rate R~ 0.1 is reported in most models & over a wide parameter range!

To be solved.

Q: Why is the fast reconnection rate order 0.1 in disparate systems?

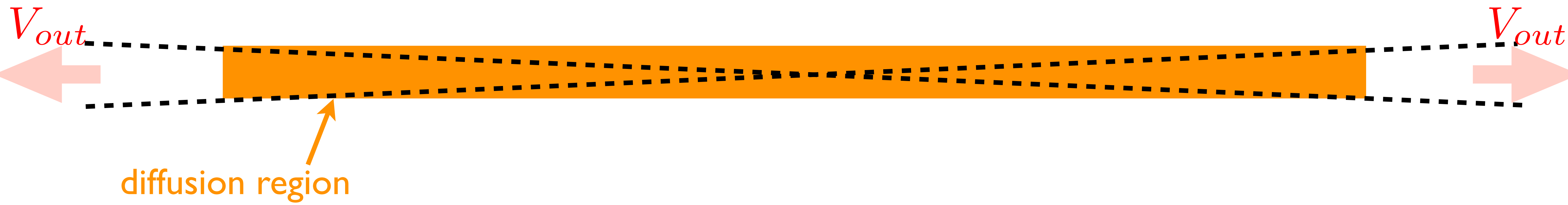
-- including PIC, hybrid, Hall-MHD, MHD with a localized resistivity...etc

*clue: can not be the diffusion-scale physics!

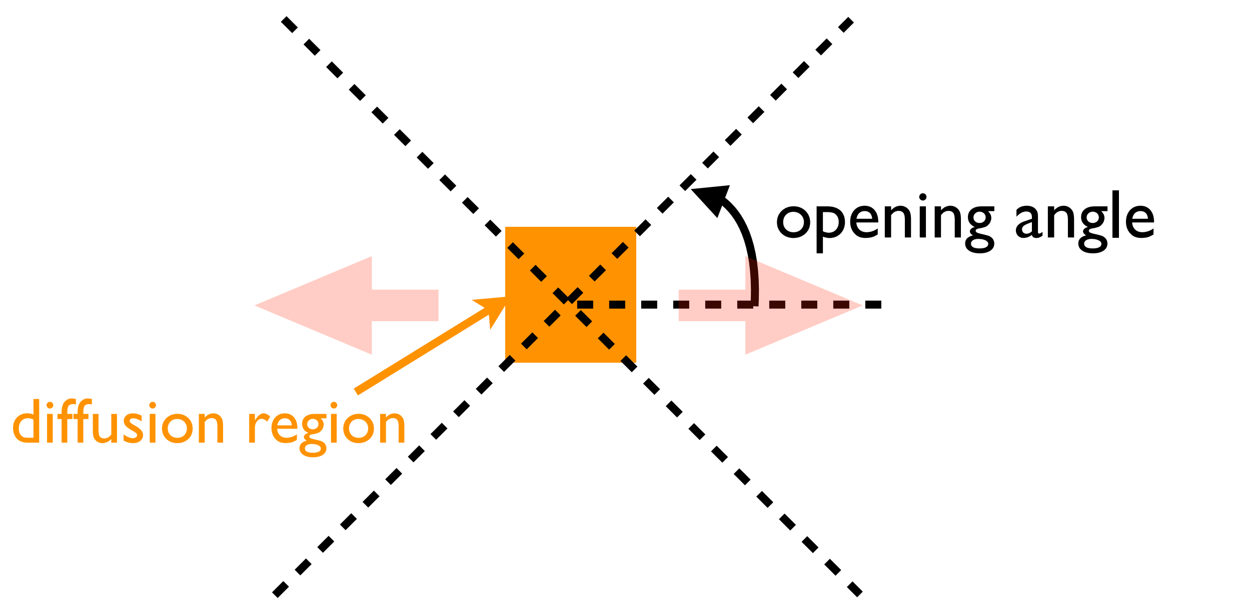
Explanation of rate ~ 0.1

-- Geometrical consideration!

In the small δ/L limit, $R \sim \delta/L \rightarrow 0$



How about the large δ/L limit?



It turns out that when $\delta/L \rightarrow 1$, $R \rightarrow 0$!

-- Hey~ then there should be an optimized R_{max} in between!

-- This R_{max} may explains the value 0.1 !

Explanation of rate ~ 0.1

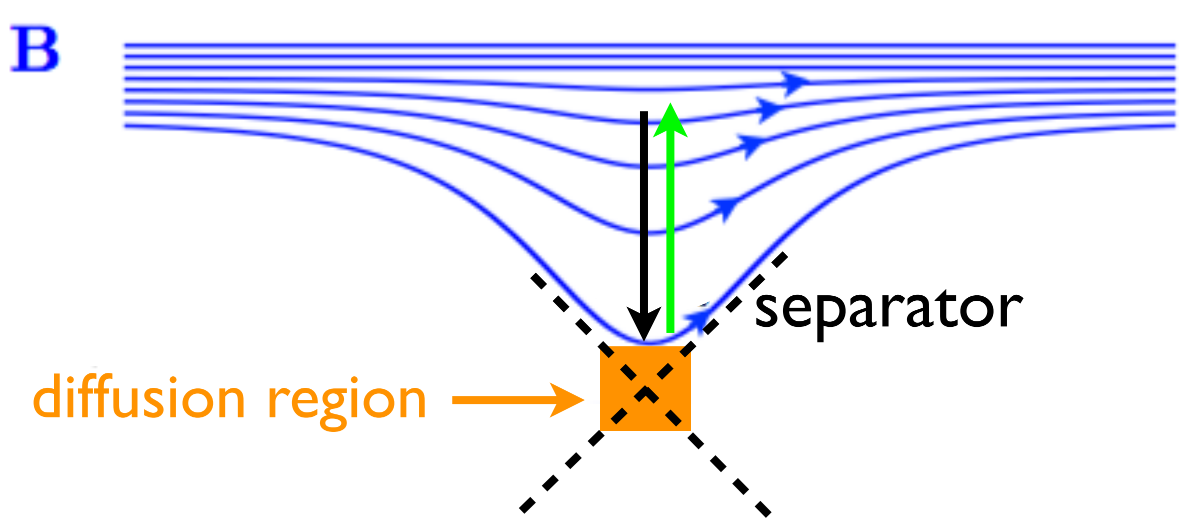
-- Geometrical consideration!

In the large δ/L limit .....

tension — magnetic pressure — inertia

$$\frac{\mathbf{B}\cdot\nabla\mathbf{B}}{4\pi} \simeq \frac{\nabla(B^2)}{8\pi} + nm_i\mathbf{V}\cdot\nabla\mathbf{V}$$

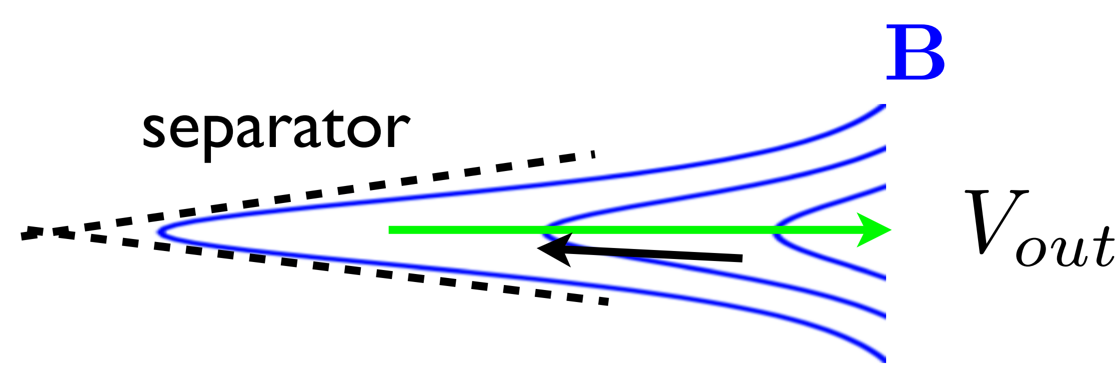
@ inflow region



$\rightarrow$ decease the reconnecting field!!!

$\rightarrow R\downarrow$

@ outflow region



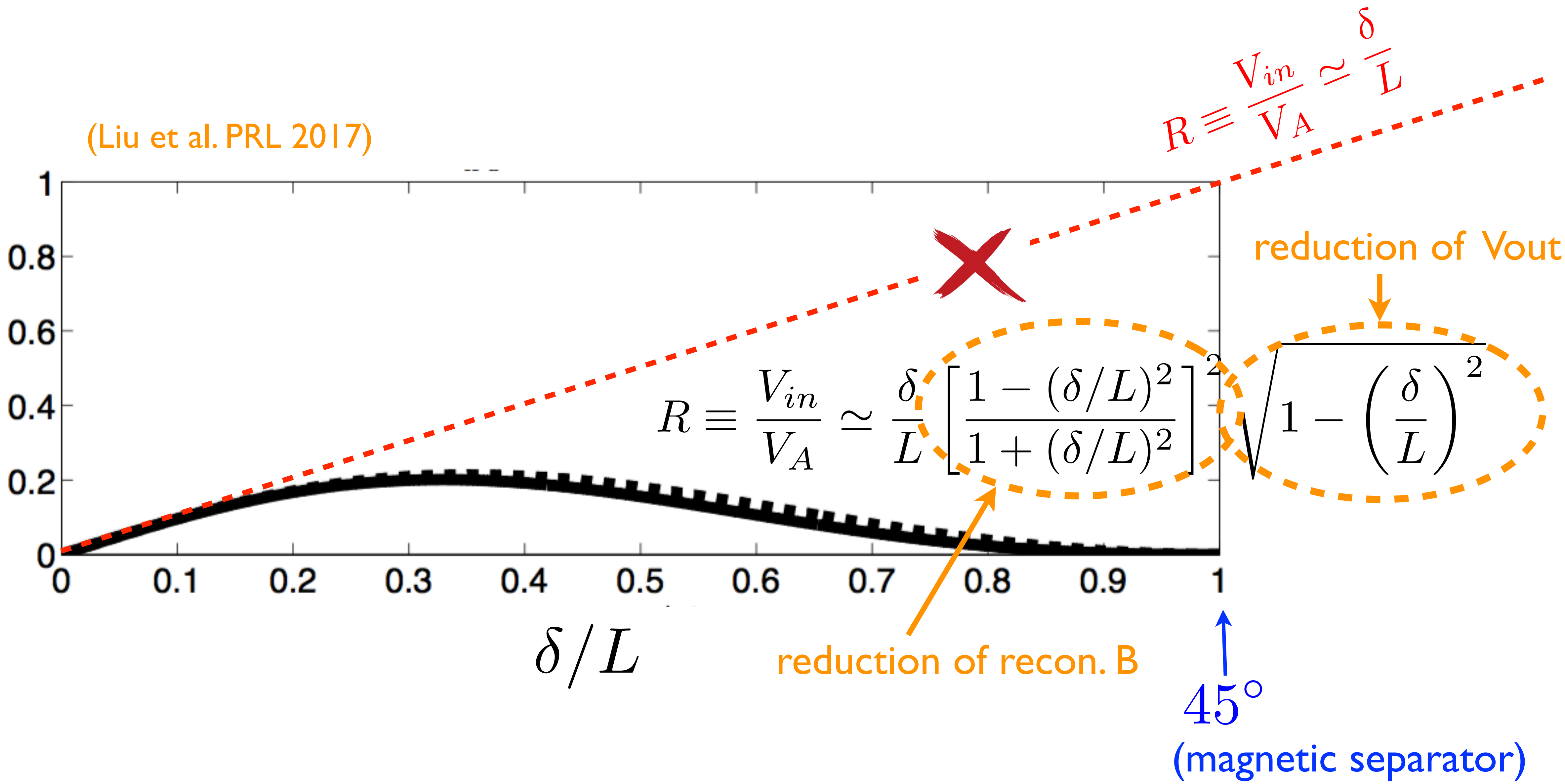
$\rightarrow$ decrease the outflow speed!!!

$\rightarrow R\downarrow$

- Constraints imposed at the inflow & outflow region (upper) bound the rate!

Explanation of rate ~ 0.1

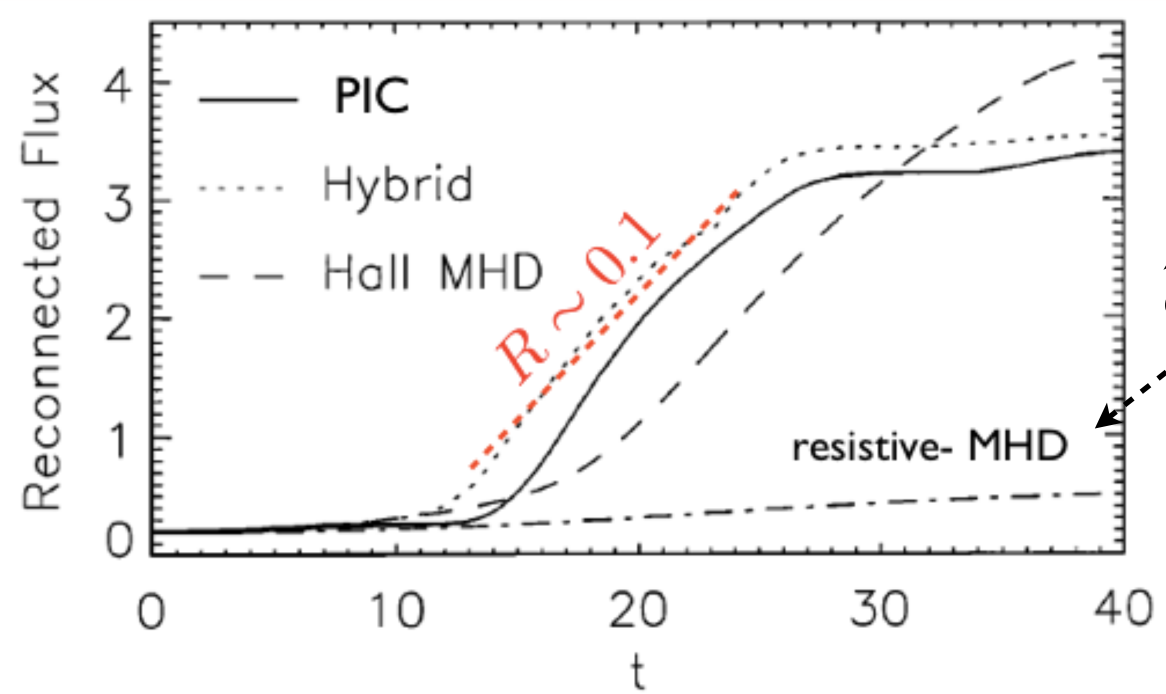
-- Geometrical consideration!

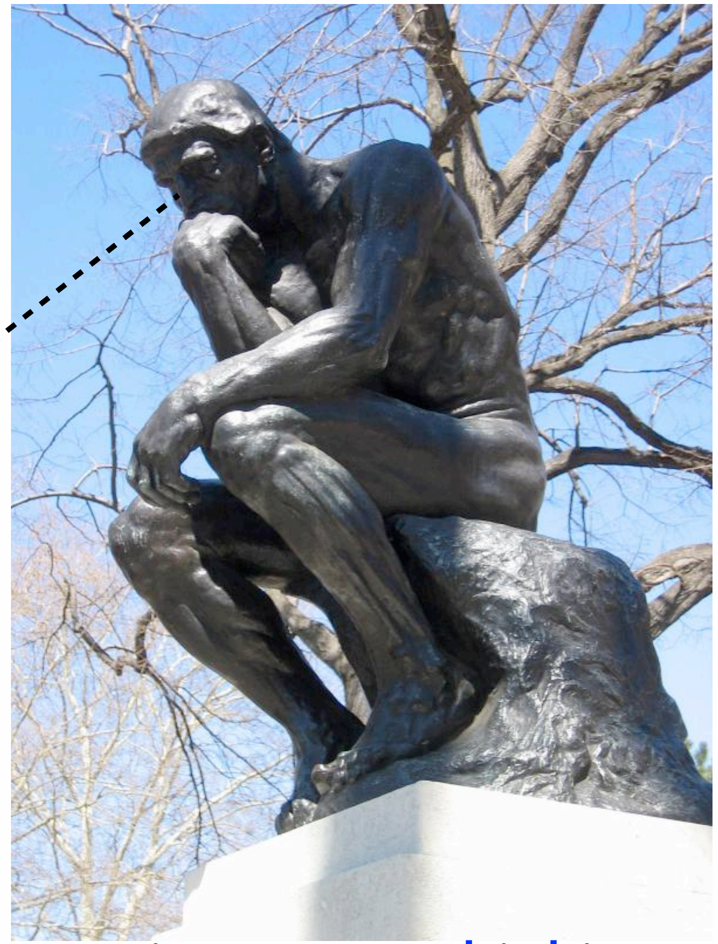


- Reconnection tends to proceed near the most efficient state with R ~ O(0.1).
- Nicely, rate is insensitive to δ/L near this state.

Q1: Why fast rate R~ O(0.1)? ✓

Q2: Why is reconnection slow in the resistive-MHD case?



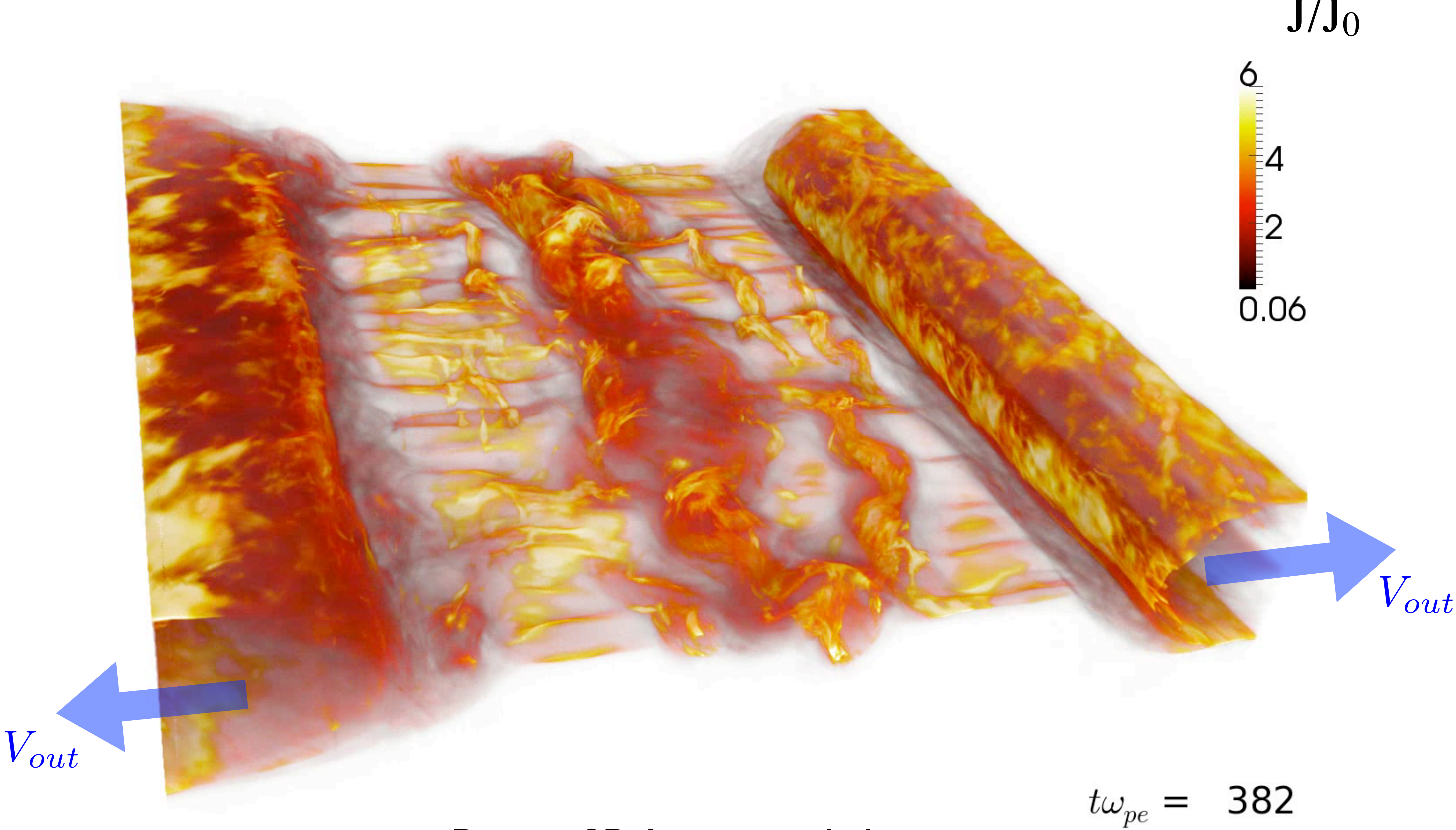


requires more thinking...

2/2. Three- dimensional nature of reconnection

- How about the freedom coming from the extra dimension?

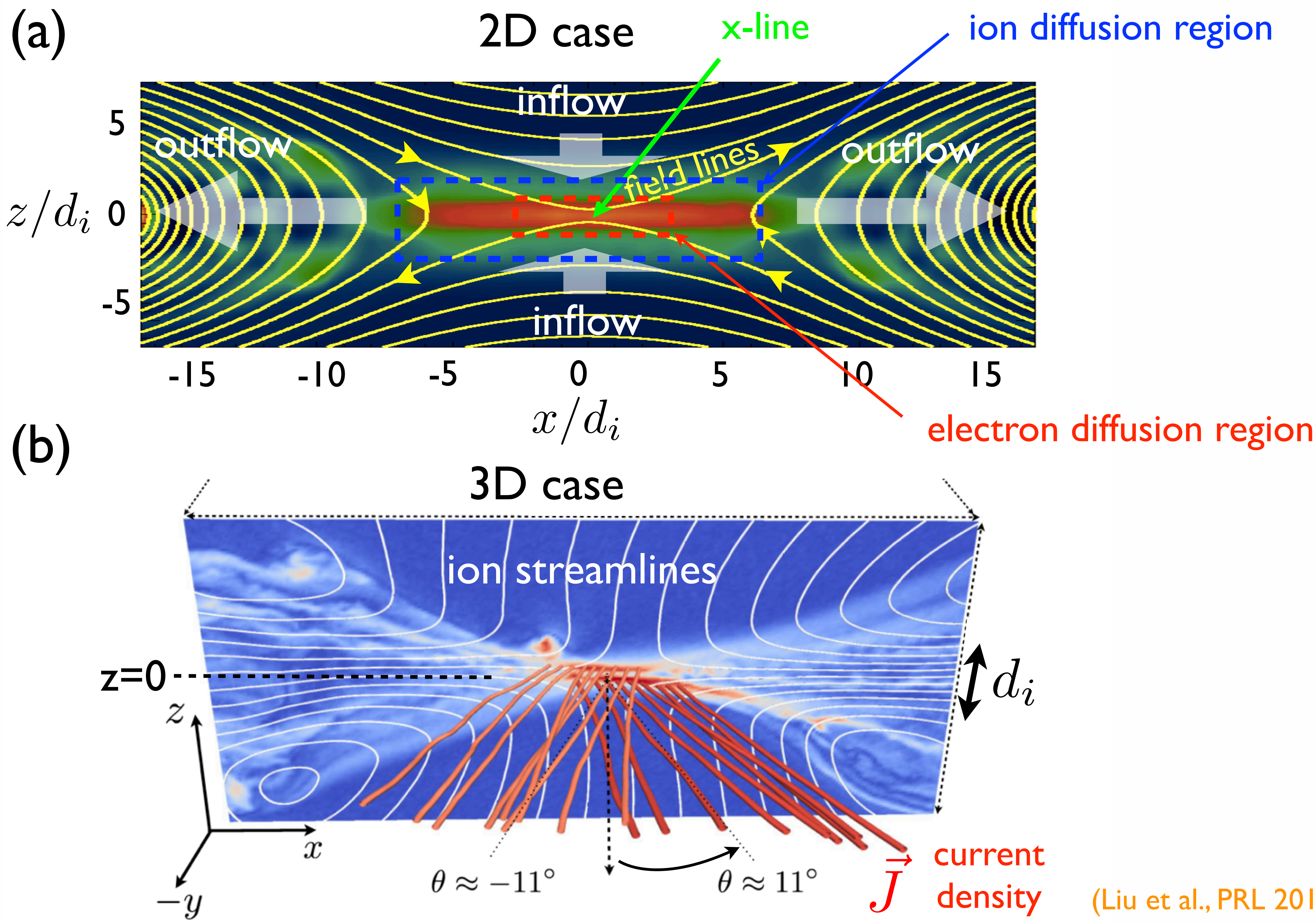
An example 3D simulation



Distinct 3D features, including

- flux ropes.
- kink instability.
- turbulence.

3D diffusion region can be fundamentally different!!



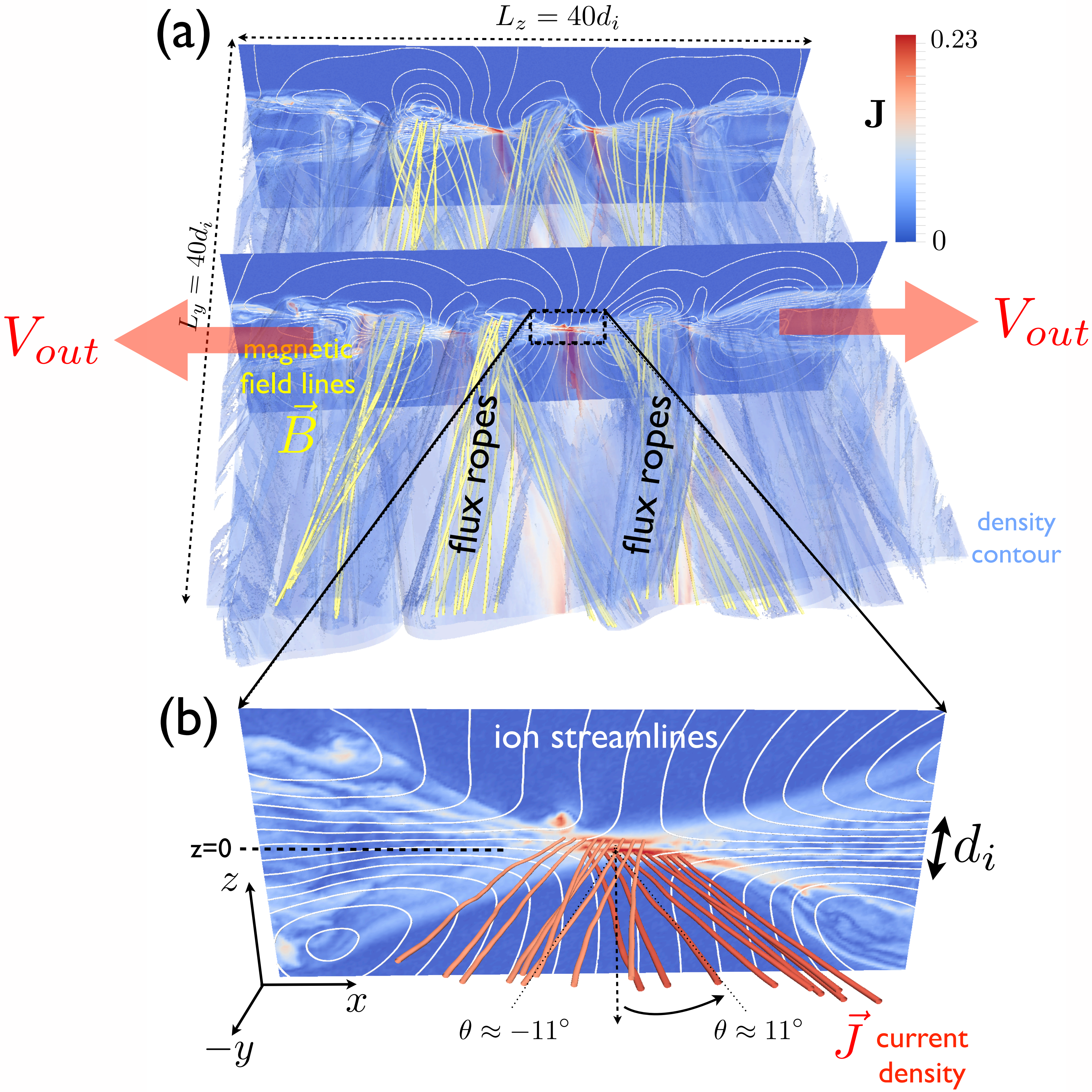
(Liu et al., PRL 2013)

Q:What is causing this? consequence?

To be solved.

Q: What is causing the bifurcation of electron diffusion region?

Global structure



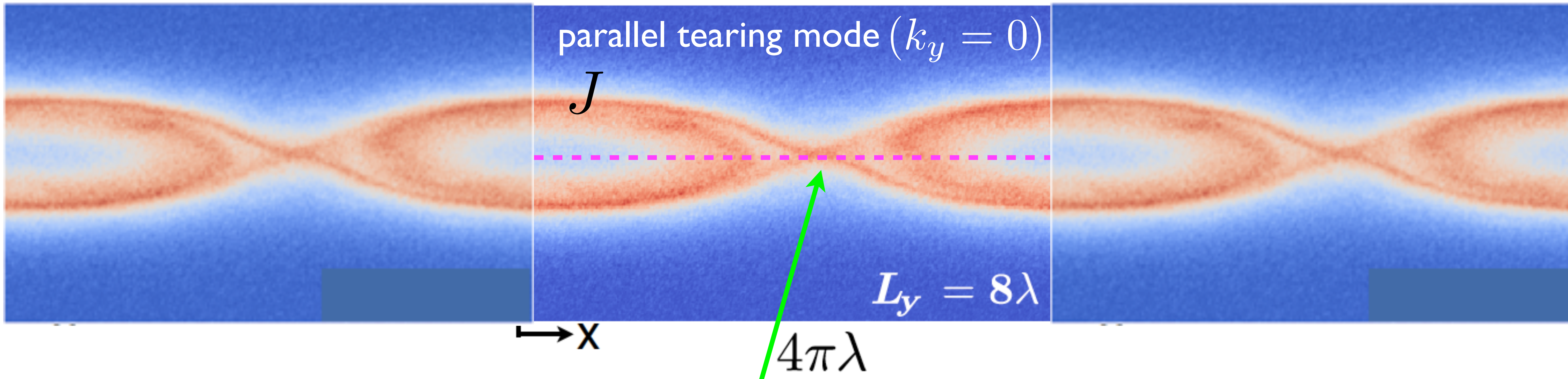
guide field
$B_{y0}/B_{x0} = 2.5$

Computation
10 million CPU-hours
1 trillion particles

*clue: bifurcated layer is located in between these intertwined flux ropes.
& tearing modes give rise to these flux ropes!

Explanation of the bifurcation

-- oblique tearing modes!



Resonant surfaces @ $\mathbf{k} \cdot \mathbf{B} = 0$

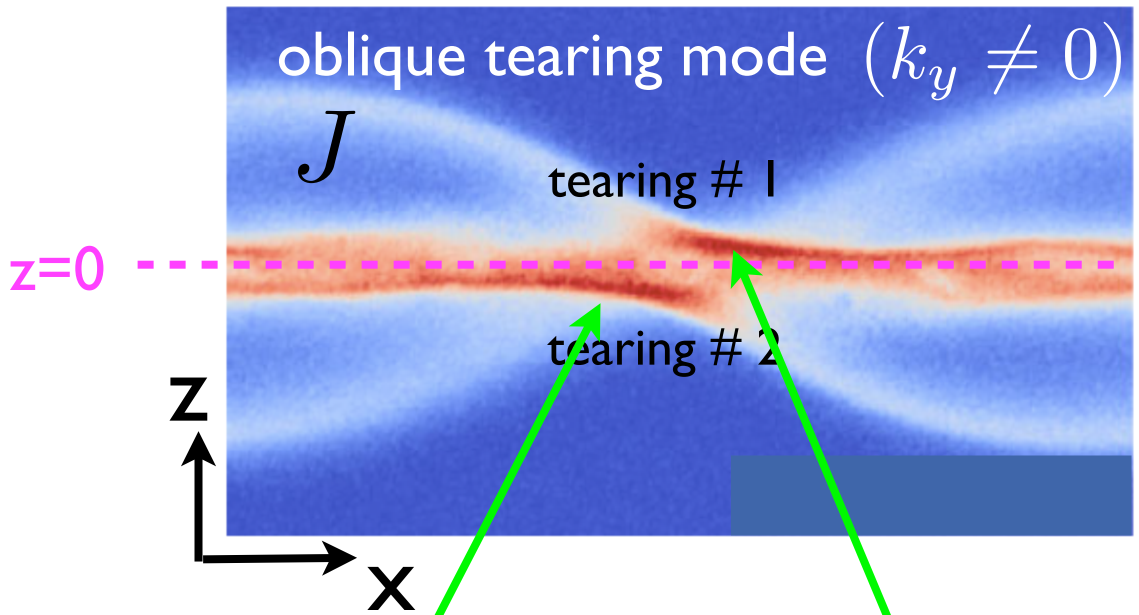
initial thickness → $$\frac{z_s}{\lambda} = -\tanh^{-1}\left(\frac{k_y B_{yo}}{k_x B_{xo}}\right)$$

$$\theta \equiv \tan(k_y/k_x)$$

- 2D only allows the parallel tearing mode. i.e., no bifurcation.

Explanation of the bifurcation

-- oblique tearing modes!



Resonant surfaces @ $\mathbf{k} \cdot \mathbf{B} = 0$

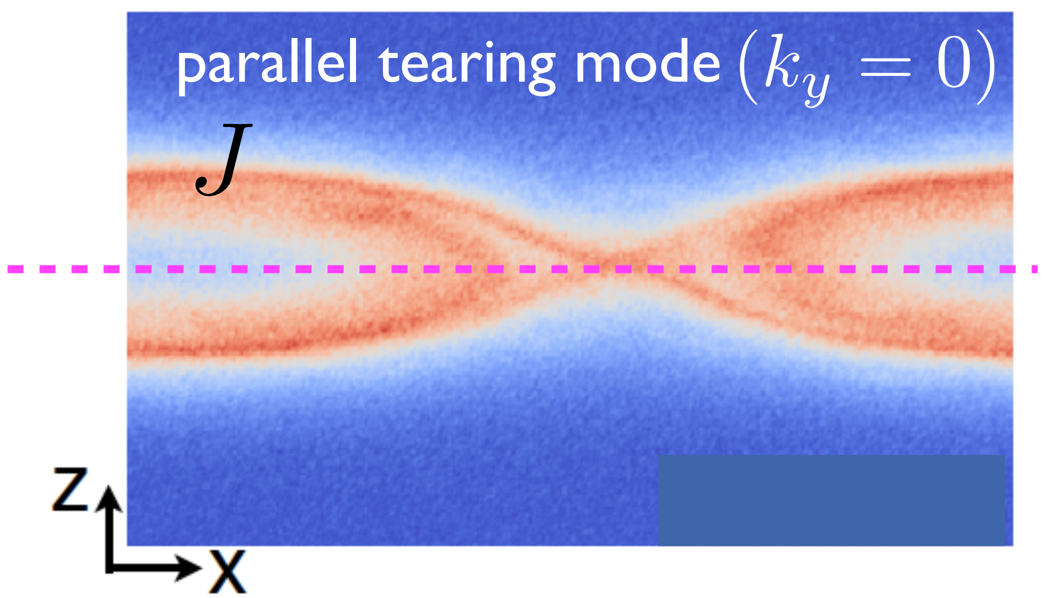
$$\frac{z_s}{\lambda} = -\tanh^{-1}\left(\frac{k_y B_{yo}}{k_x B_{xo}}\right)$$

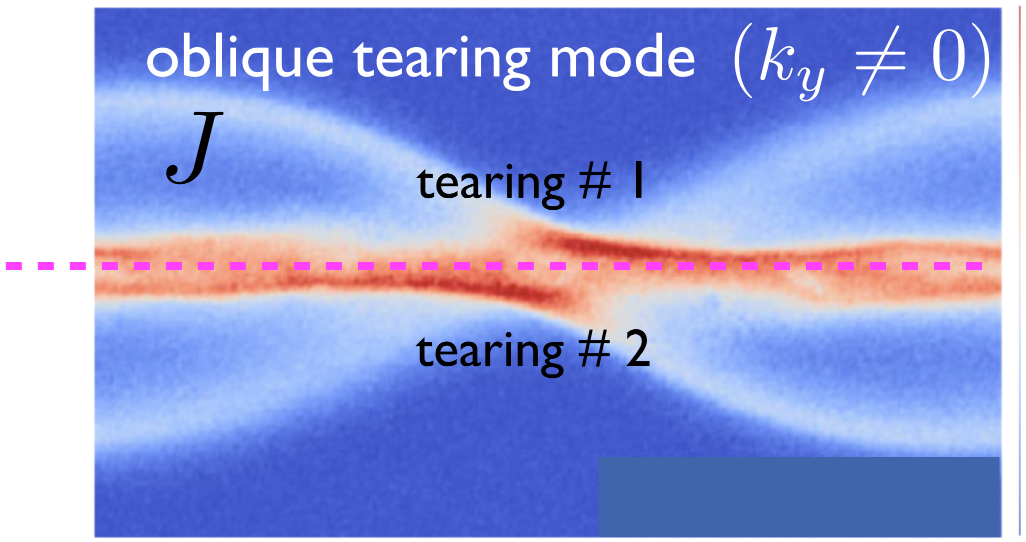
$$\theta \equiv \tan(k_y / k_x)$$

- 3D allows a spectrum of oblique tearing modes, unlike 2D.

Explanation of the bifurcation

-- oblique tearing modes!



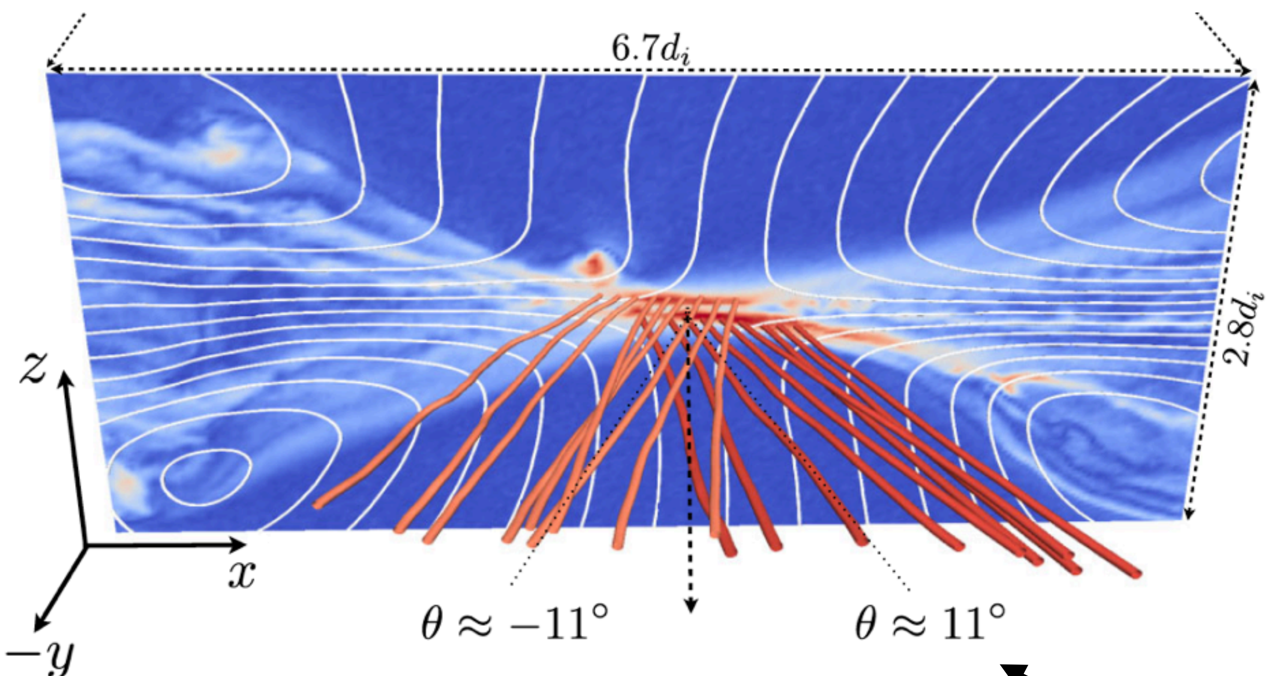


- Bifurcated or Not, depends on the competition between oblique & parallel tearing modes!

Explanation of the bifurcation

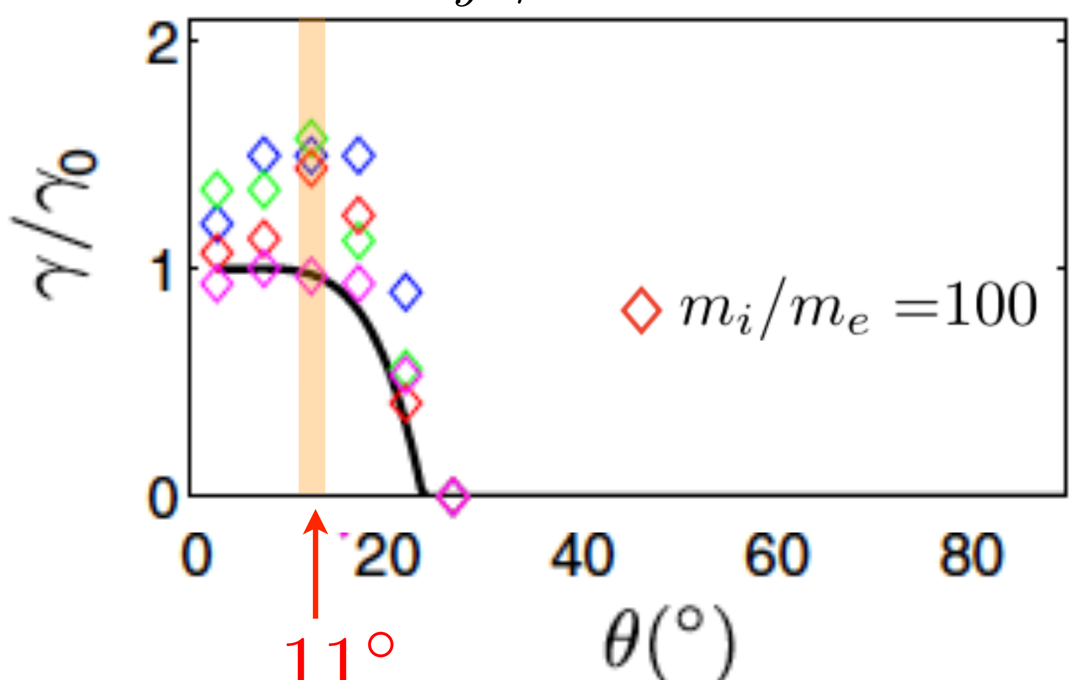
-- oblique tearing modes!

A reminder



growth rate of tearing modes

$B_{y0}/B_{x0} = 2.5$

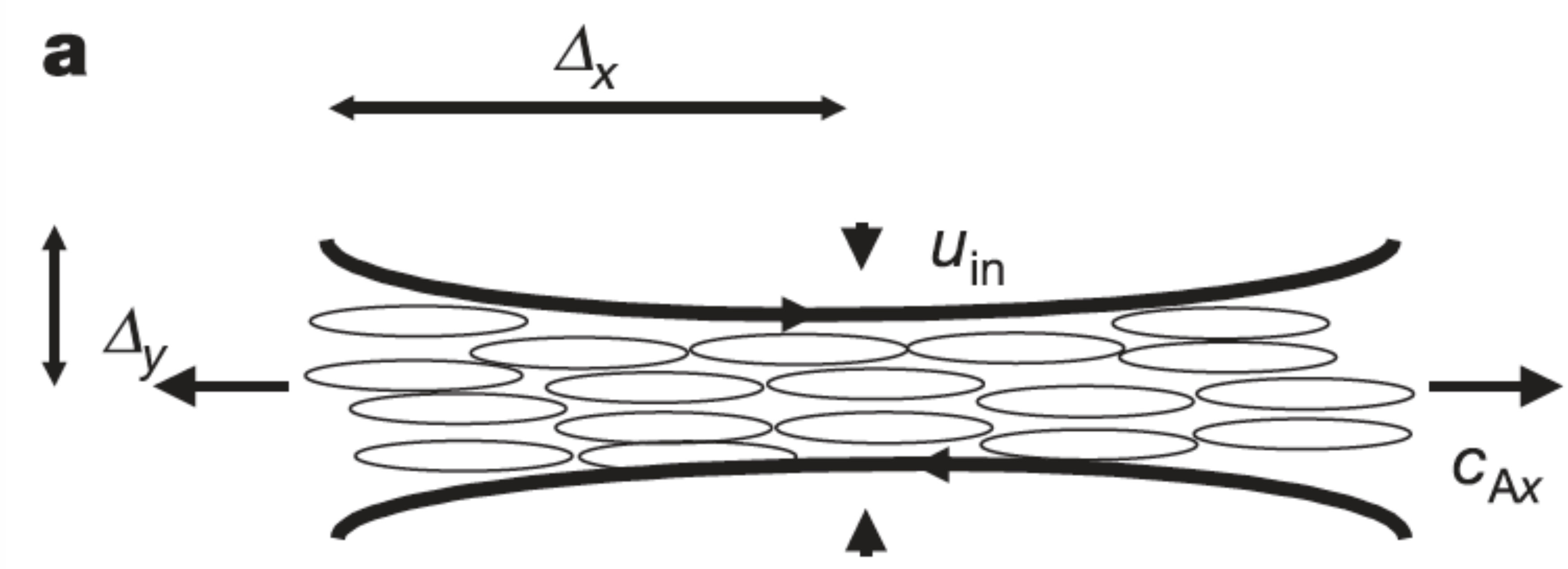


$11°$

- The most unstable tearing mode should dominate!!
- Theory predicts that the oblique mode dominates when $B_{y0}/B_{x0} > 1$. ✓

Open Questions

With a thicker current sheet, like that in the solar flare



(Drake et al., NATURE 2006)

Lots of resonant surfaces are possible!
Q: How do these oblique tearing modes interact & volume-fill the current sheet?
Q: Reconnection rate? Energy dissipation? Particle acceleration??
(Fermi-type acceleration? or direct acceleration?)

Summary

- Magnetic reconnection is an important energy release process in plasmas, and it is relevant in space, solar, astrophysical & laboratory plasmas.

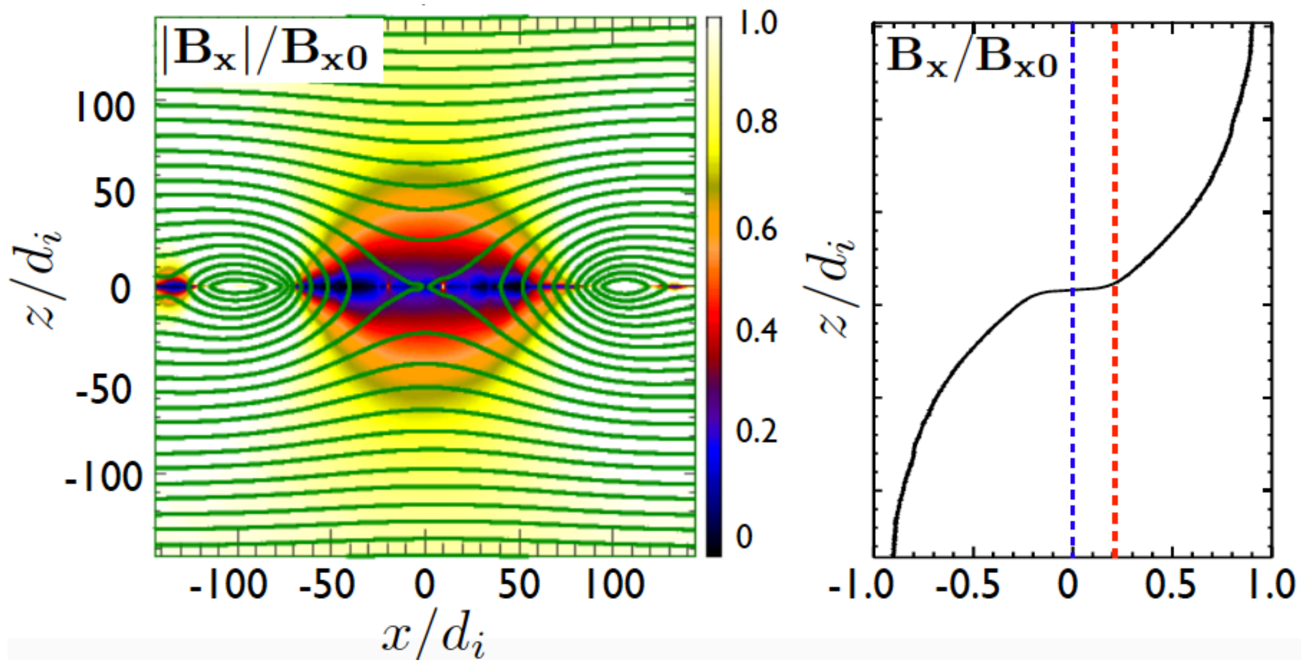
- Reconnection rate problem & 3D nature of reconnection are discussed.

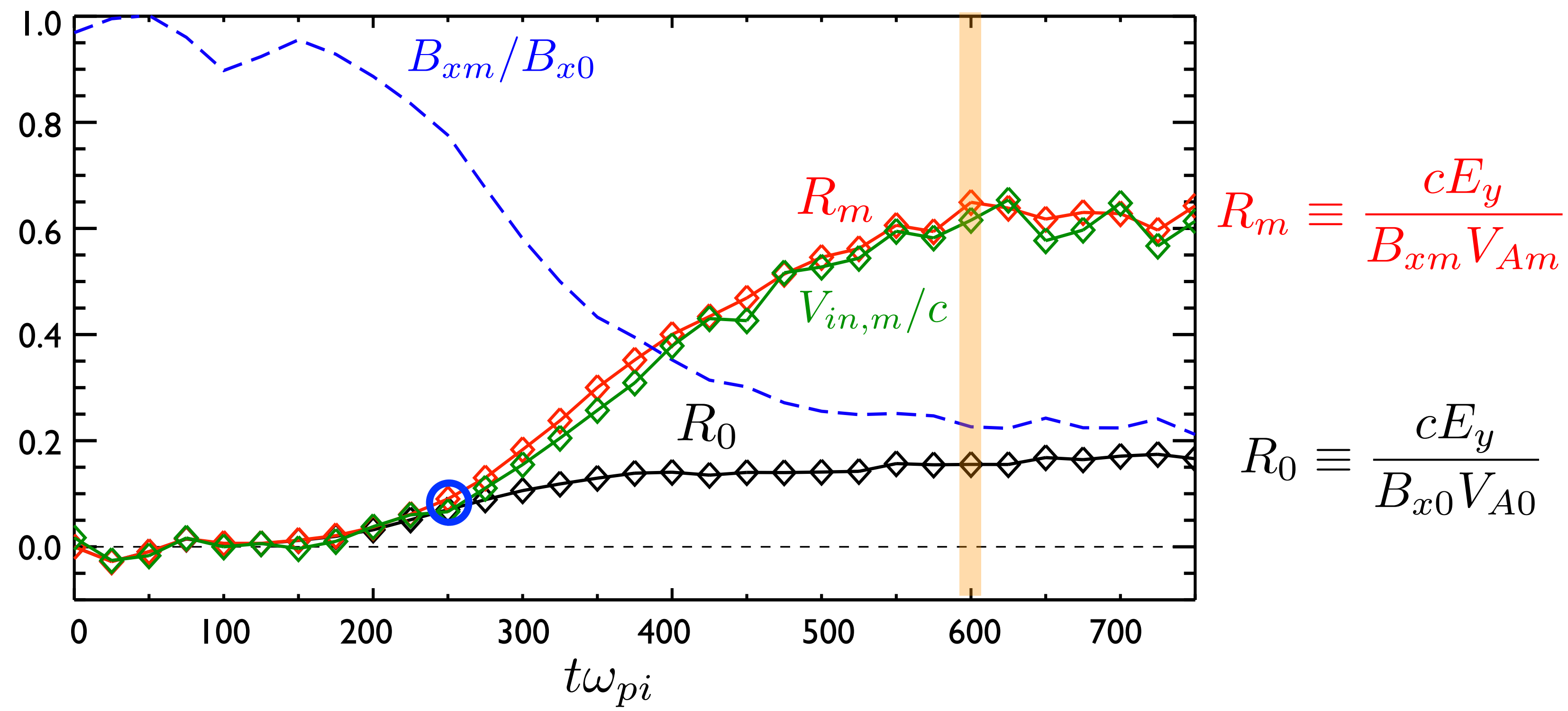
- Reconnection is relevant to many exciting on-going & future projects:
  MMS, Solar Prob +, FLARE, TREX, LAPD, ITER, HAWC,......etc.

- Nowadays, simulations and analytical techniques allow us to study a wide range of problems in plasmas physics.

- Lots of interesting problems; Lots of opportunities for students.

An example run shows the imbedding effect





- Reduction of the reconnecting field immediately upstream of the diffusion region (micro-scale) is observed.
- Local reconnection rate R_0~ O(0.1) does not go up even when the micro-scale rate R_m goes up to ~ O(1).

Let a fluid filament initially following the closed contour S be given and let Φ be the initial flux of $\mathbf{B}$ through it. A short interval dt later, each element $d\boldsymbol{l}$ of the contour will have been displaced by an amount $\mathbf{v}\,dt$, sweeping in the process an area $(\mathbf{v} \times \mathbf{dl})\,dt$ (Figure 1). In this time interval, Φ changes by an amount $d\Phi$, ascribable

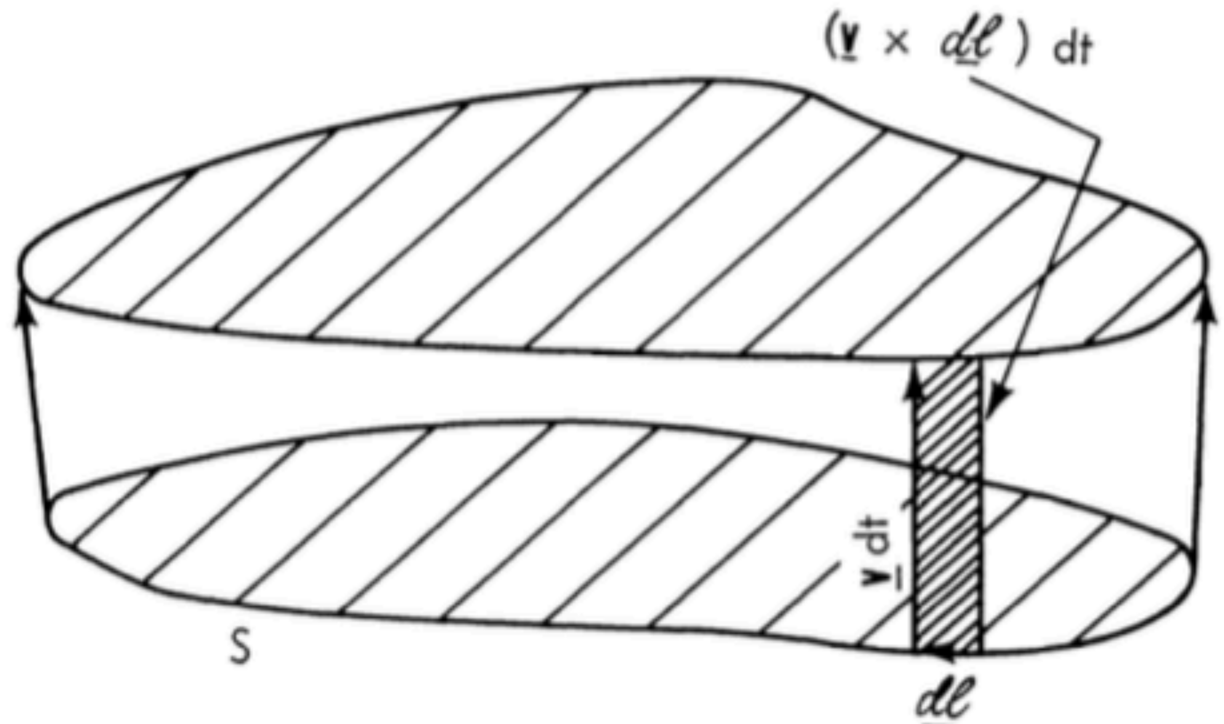


Fig. 1.

to two causes. The time variation of the field contributes the surface integral

$$\int_s \frac{\partial \mathbf{B}}{\partial t} \cdot d\mathbf{A}\,dt \tag{4-4}$$

while the variation of the area bounded by the filament adds the flux through the area swept by it (Figure 1), equaling

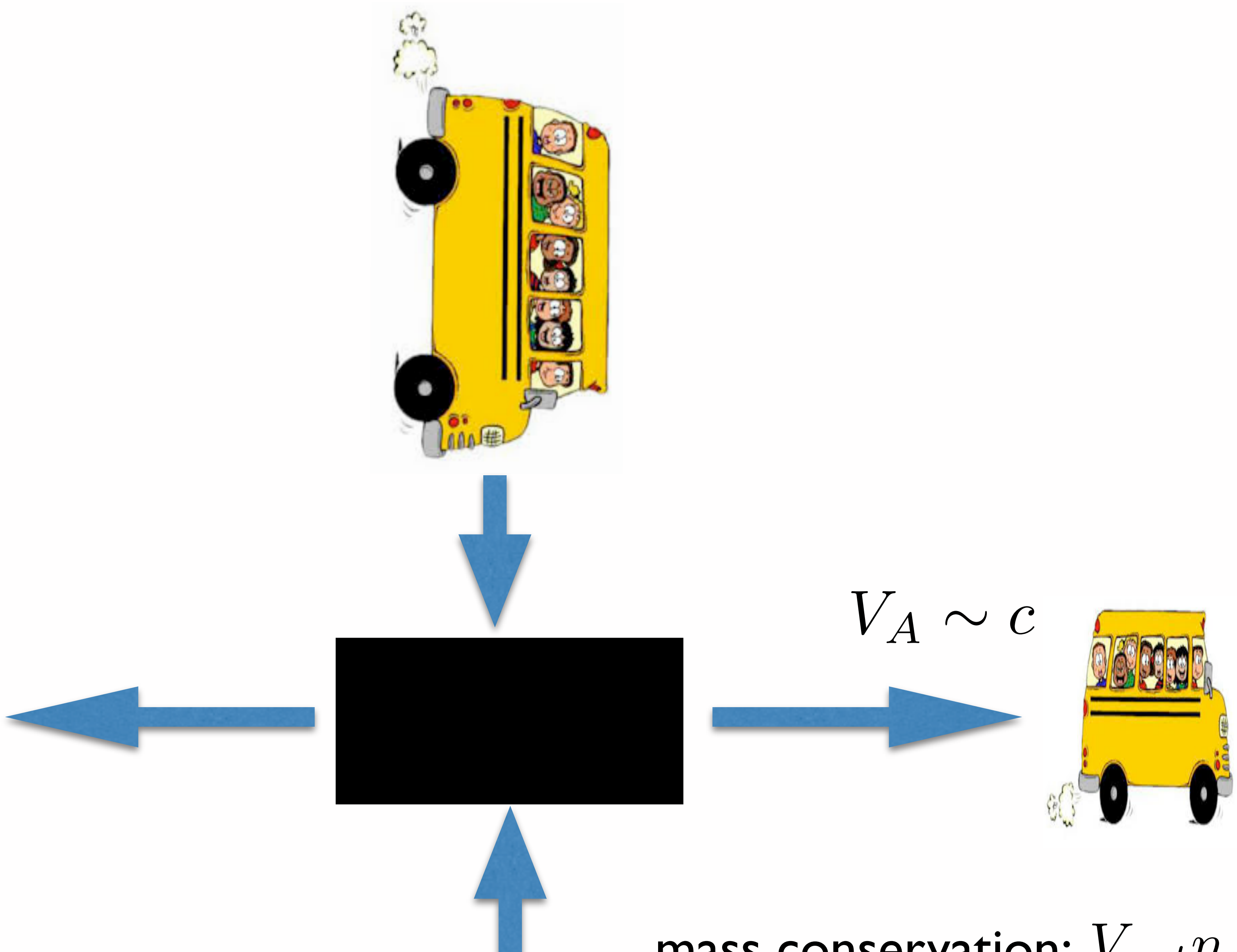
$$\oint \mathbf{B} \cdot (\mathbf{v} \times \mathbf{dl})\,dt = -\int \nabla \times (\mathbf{v} \times \mathbf{B}) \cdot d\mathbf{A}\,dt \tag{4-5}$$

Thus

$$d\Phi = \int \left(\frac{\partial \mathbf{B}}{\partial t} - \nabla \times (\mathbf{v} \times \mathbf{B}) \right) \cdot d\mathbf{A}\,dt \tag{4-6}$$

Combined with Faraday's law $\quad d\Phi = 0 \quad$ (Frozen-in) $\quad$ if $\quad \mathbf{E} + \dfrac{\mathbf{v} \times \mathbf{B}}{c} = \nabla P$

Q: How could special relativity affect reconnection?



$V_A \sim c$

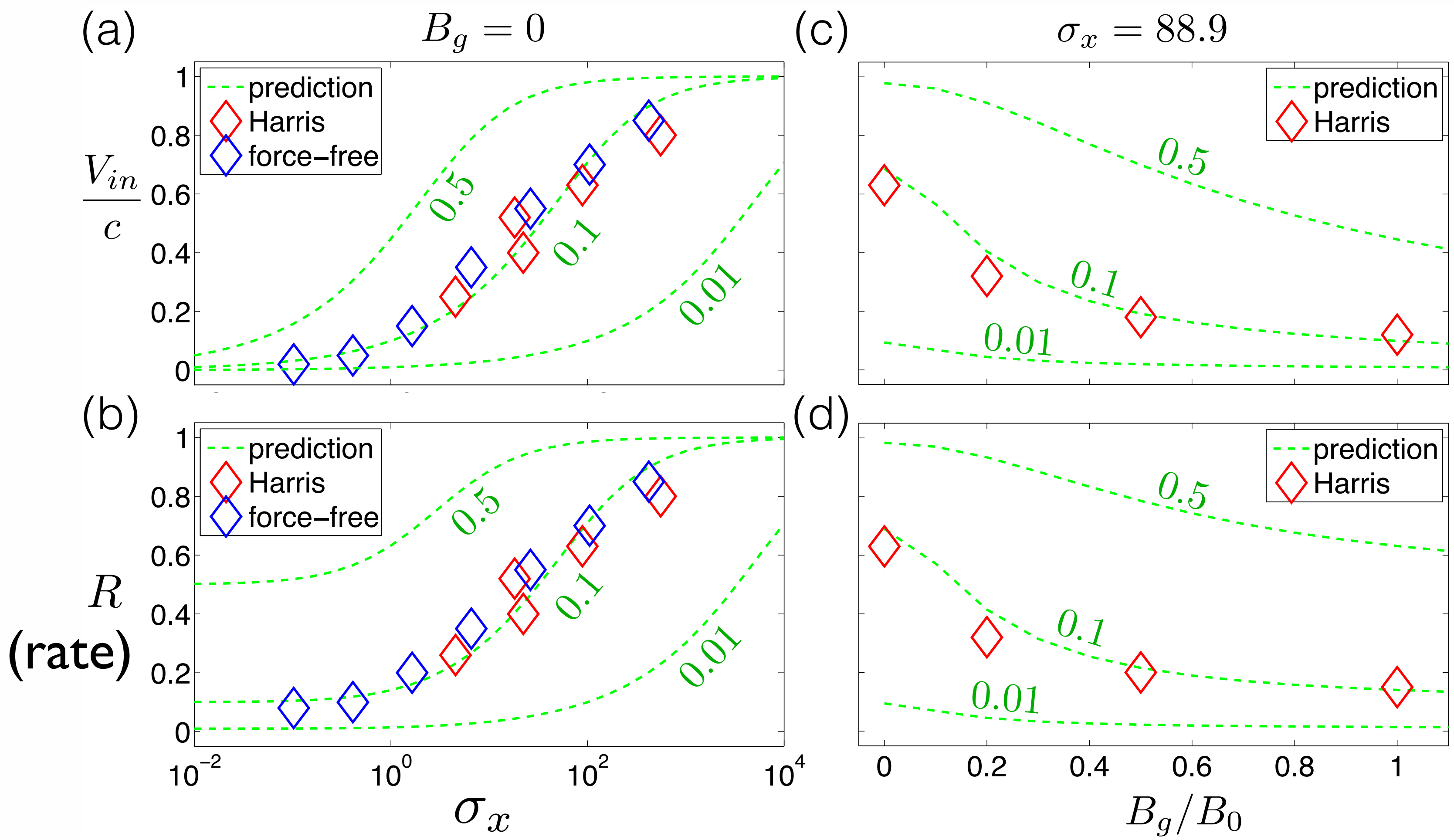
mass conservation: $V_{out} n_{out} \delta = V_{in} n_{in} L$

Alfven Speed: $\dfrac{V_A}{c} = \sqrt{\dfrac{\sigma}{1+\sigma}}$ (e.g., Anile1989)

Magnetization param: $\sigma = \dfrac{B^2}{8\pi w}$ Enthalpy: $w = n_e' m_e c^2 + \dfrac{\Gamma}{\Gamma - 1} P_e'$

- Reconnection rate can be enhanced?

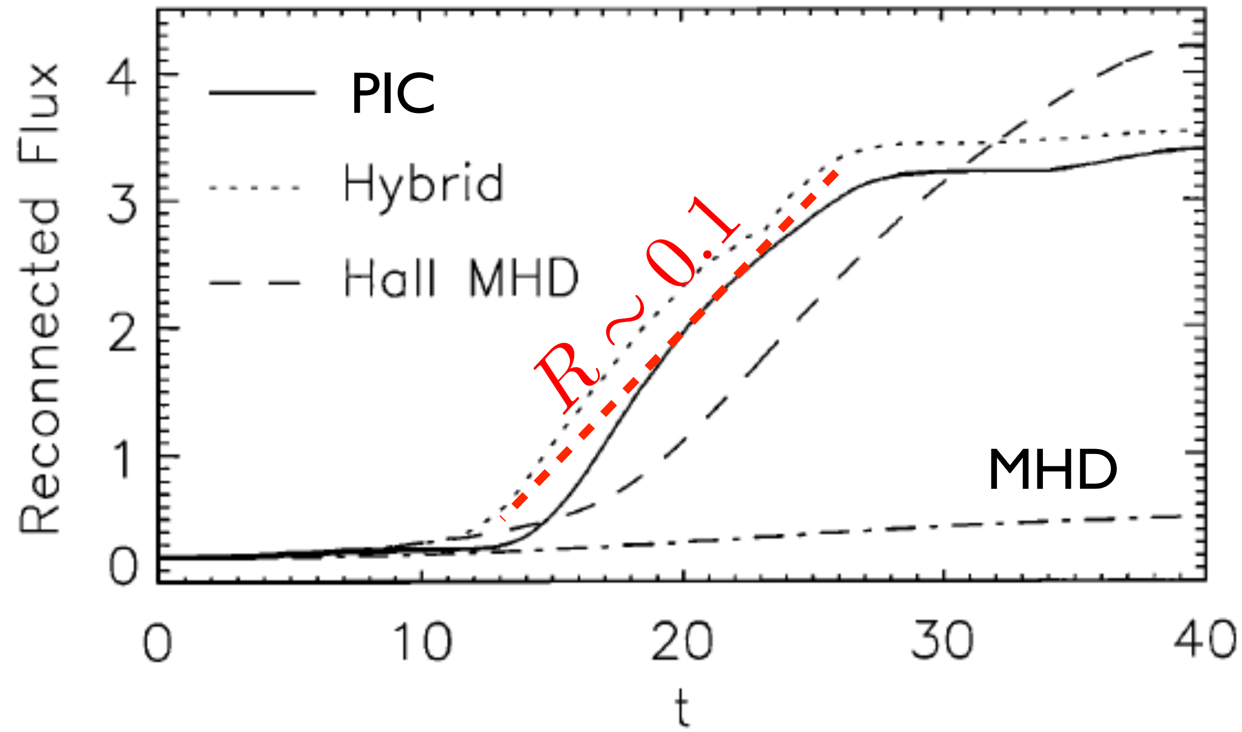
Scaling of micro-scale inflow speed & reconn. rate



- Lorentz contraction + geometry factor ~ 0.1 (Liu et al., PRL 2015)

$$\rightarrow \frac{V_{in}}{c} = 0.1\sqrt{\frac{\sigma_x}{1+\sigma_g+0.01\sigma_x}}$$

GEM Reconnection Challenge (2001)



(Birn et al., 2001)

Ohm's Law: $V = RI$

Ohm's Law in plasmas: $\mathbf{E} + \underbrace{\frac{\mathbf{v}_i \times \mathbf{B}}{c}}_{\text{convection}} = \underbrace{\eta \mathbf{J}}_{\text{resis.}} + \underbrace{\frac{1}{nec}\mathbf{J} \times \mathbf{B}}_{\text{Hall term}} - \underbrace{\frac{1}{ne}\nabla \cdot \mathbf{P}_e}_{\text{pressure}} + \underbrace{\frac{m_e}{e^2}\frac{d\mathbf{J}/n}{dt}}_{\text{inertia}}$

	resis.	Hall term	pressure	inertia	
MHD:	✓				slow
Hall MHD:	✓	✓			↑
Hybrid:	✓	✓		✓	fast
PIC:		✓	✓	✓	↓
However, electron-positron (PIC):			✓	✓	
strong guide field limit (PIC):			✓	✓	

Q: Why is the fast rate R~ 0.1?