A Tutorial

Progress toward resolving Magnetic Reconnection Rate Problem

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Outlines

- ★ Past —Present
- ★ MMS observations
- ★ Summary & Future (Unsolved questions)

Biased by my limited knowledge
& personal preference…

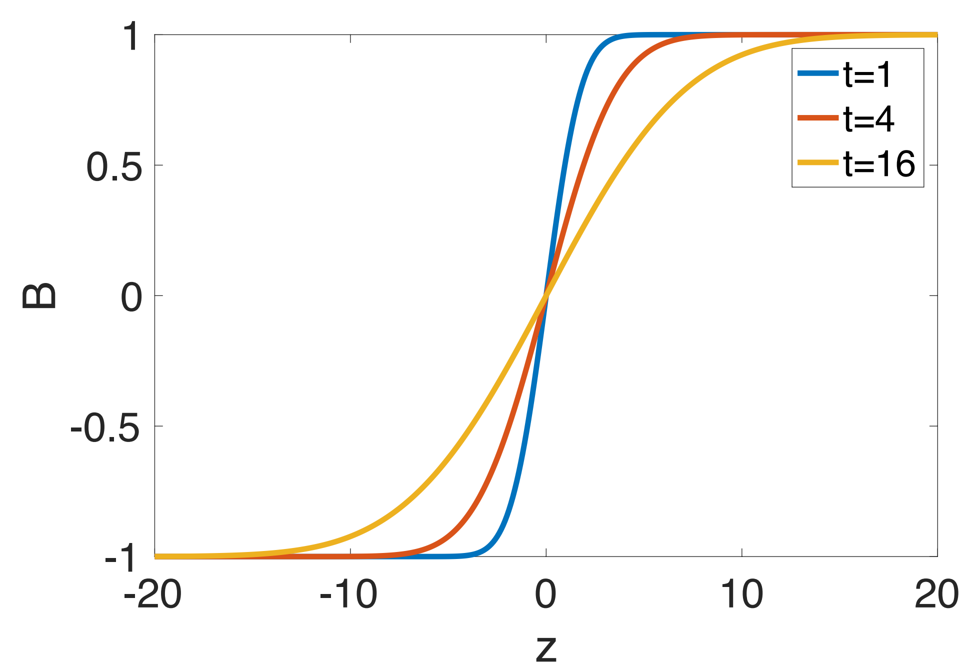
Past — Present

Magnetic Diffusion (<1953) (i.e., Dungey, 1953)

Induction eqn:

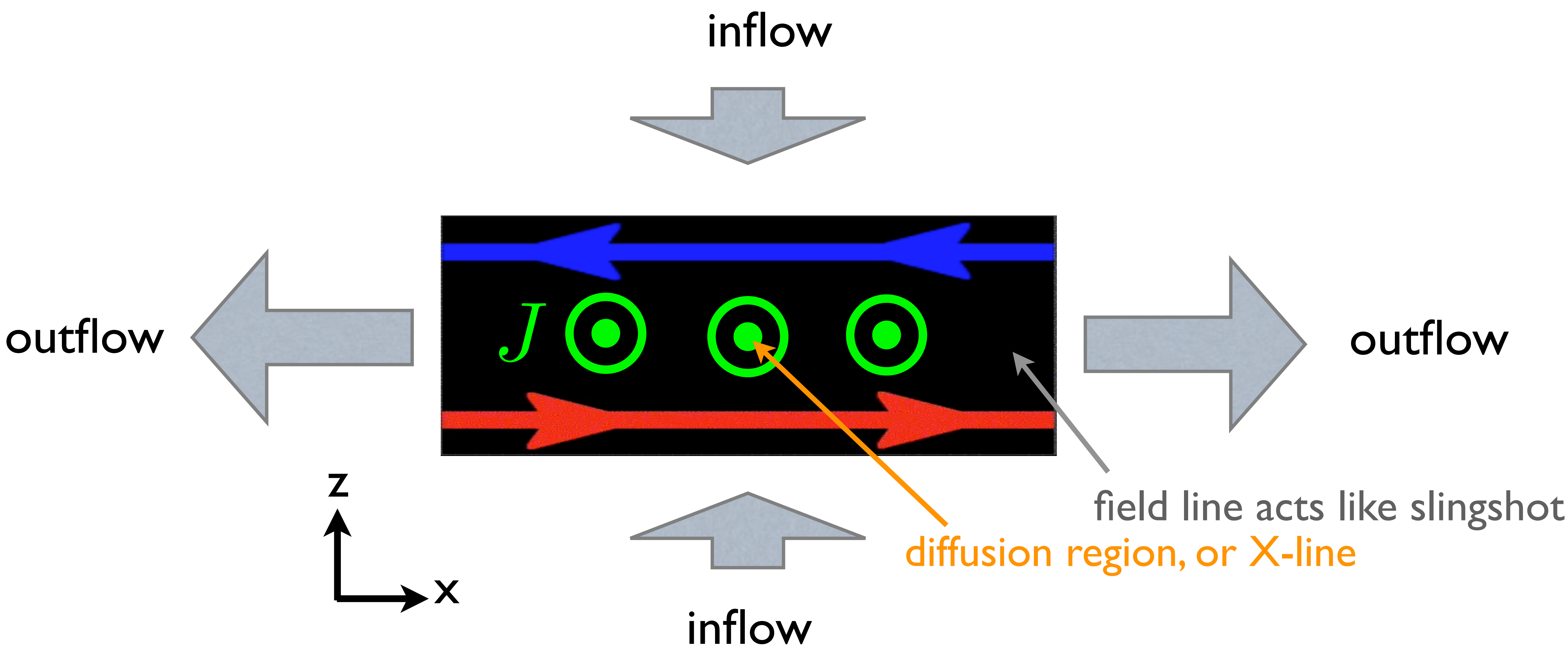
$$\frac{\partial \mathbf{B}}{\partial t} = \cancel{\nabla \times (\mathbf{V} \times \mathbf{B})} + \eta \nabla^2 \mathbf{B}$$

$$\rightarrow B = B_0 \mathrm{erf}\left[z/\sqrt{4\eta t}\right]$$



- Becomes broader & broader over time…. No steady state…
- Too slow to explain the dissipation of magnetic energy

Magnetic Reconnection



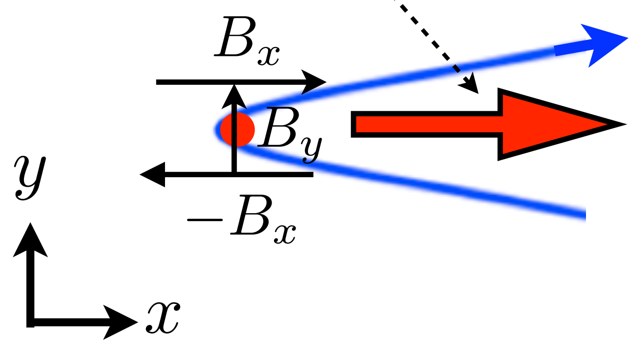
1. Inflow brings in magnetic flux (*frozen-in*)
2. Field lines break & reconnect (*frozen-in* is violated *!!*)
3. Reconnected field line shoots out plasma (*frozen-in*)
4. Pressure drop sucks in plasma inflow
1. Inflow brings in magnetic flux (*frozen-in*)
2. .....
3. ...

A self-driven process!!!

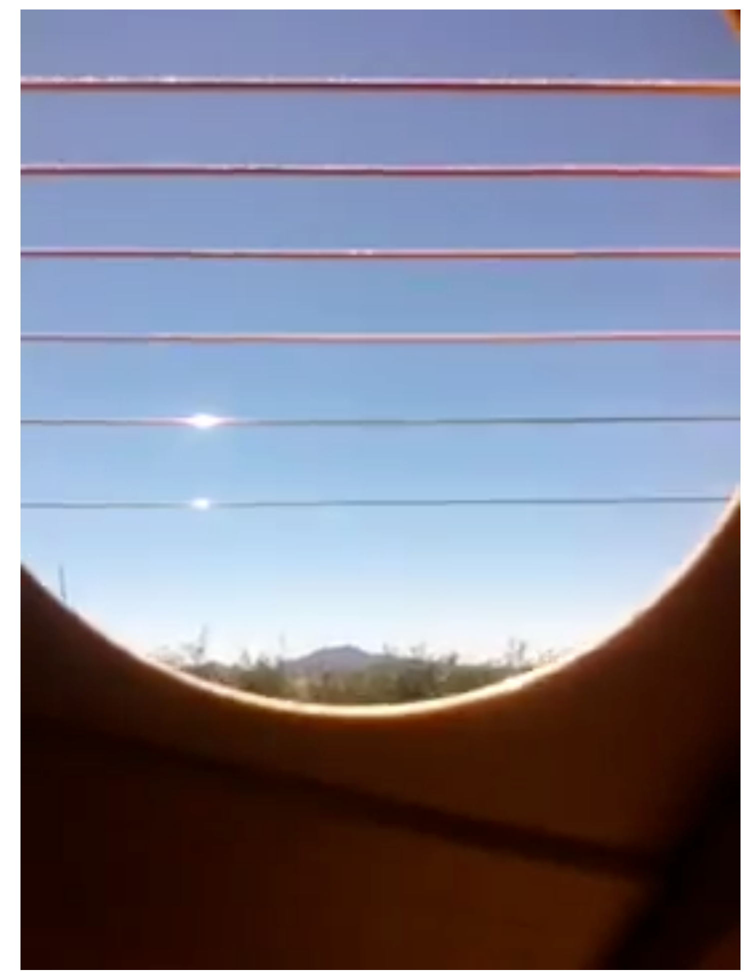
Magnetic tension & Alfvén waves

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

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



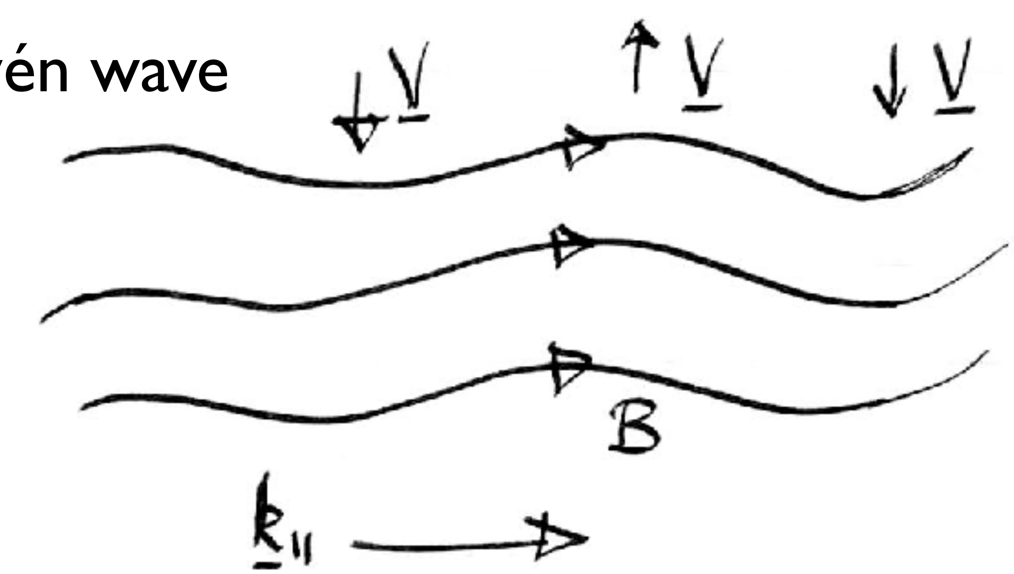
vibration of guitar strings



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

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

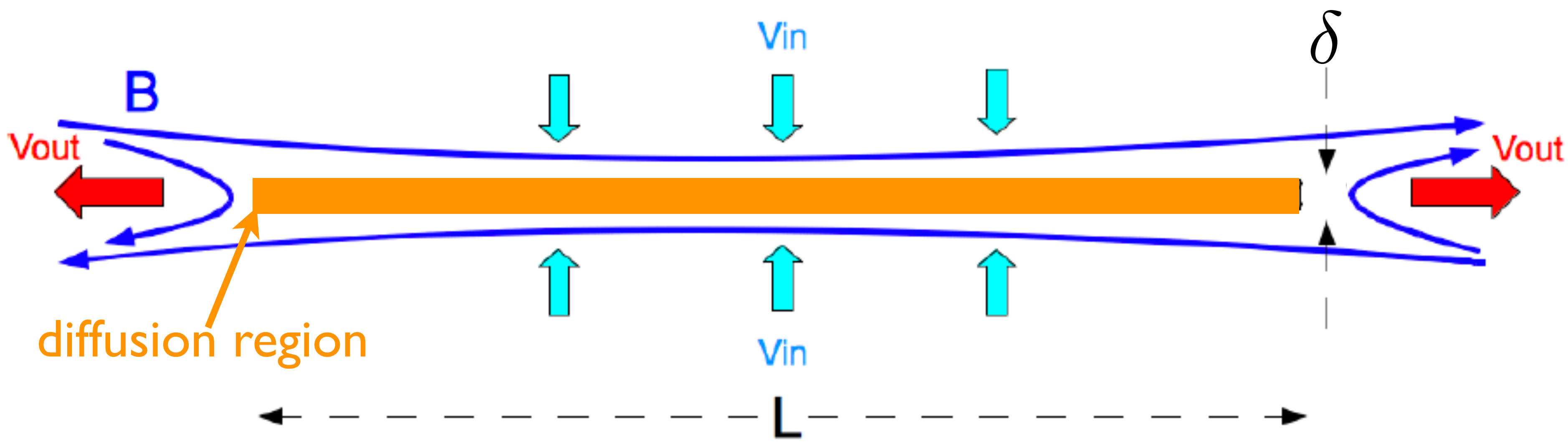
Alfvén wave



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

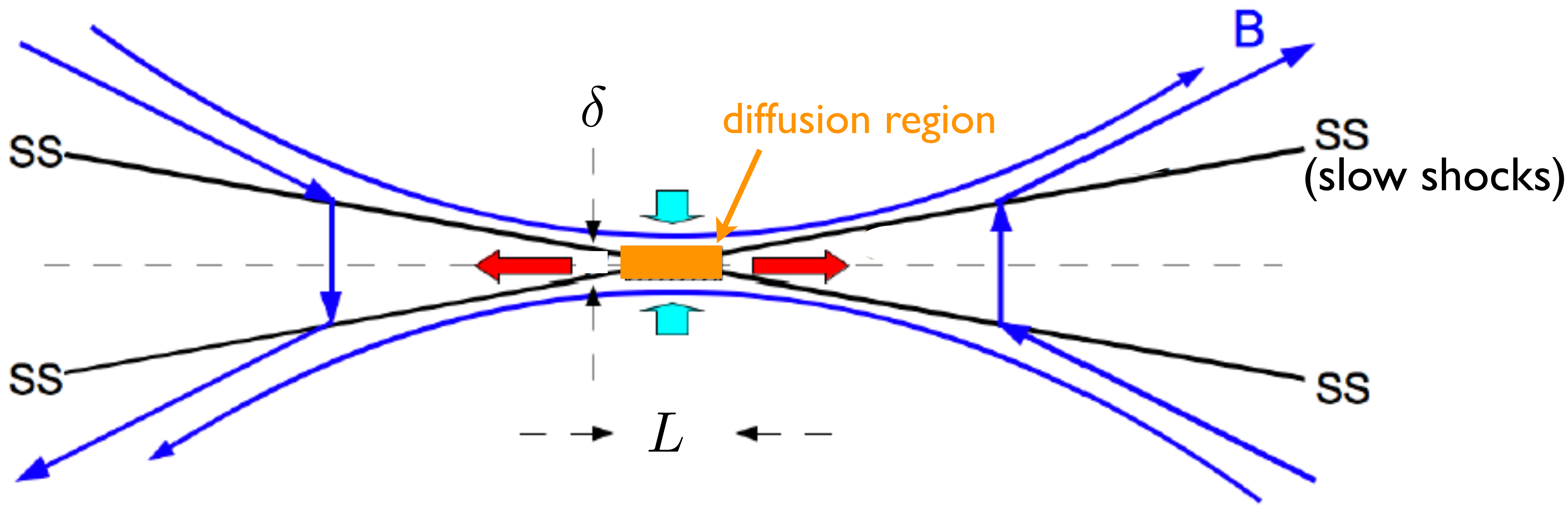
tension inertia

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 also 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)

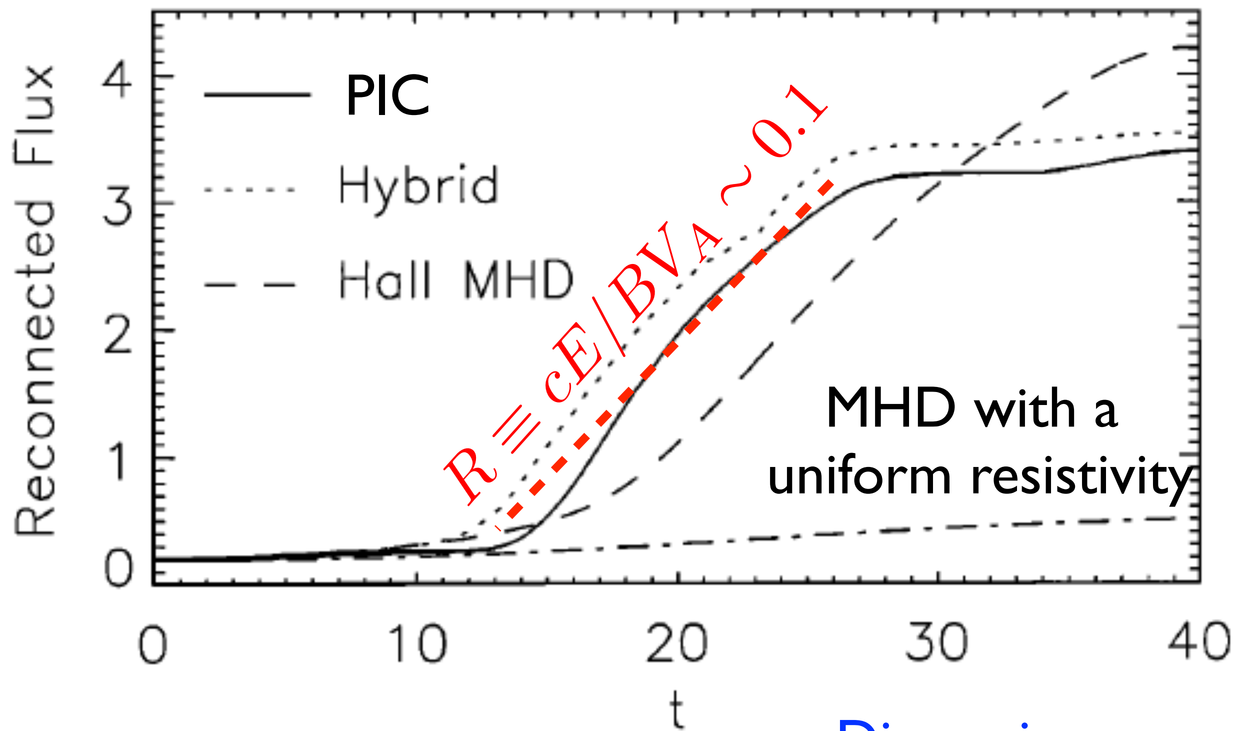


Reconnection rate is much larger if $R \sim \dfrac{\delta}{L} \uparrow$

- However, this is not a self-consistent solution. (Sato & Hayashi, 79; Biskamp, 86)
- In fact, standing switch-off slow shocks can hardly develop in fully kinetic simulations. (Liu+ 2011,2012)

*aspect ration ≡ aspect ratio of the diffusion region

GEM Reconnection Challenge (2001)



(Birn+, 2001)

Dispersive wave picture

(Sonnerup 79; Shay+ 98; Rogers+ 01; Drake+ 08)

Ohm's Law in plasmas:

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

	resis.	Hall term	pressure	inertia	
MHD:	✓				slow
Hall MHD:	✓	✓			fast with R~0.1
Hybrid:	✓	✓		✓	fast with R~0.1
PIC:		✓	✓	✓	fast with R~0.1

Standing Dispersive Wave Picture

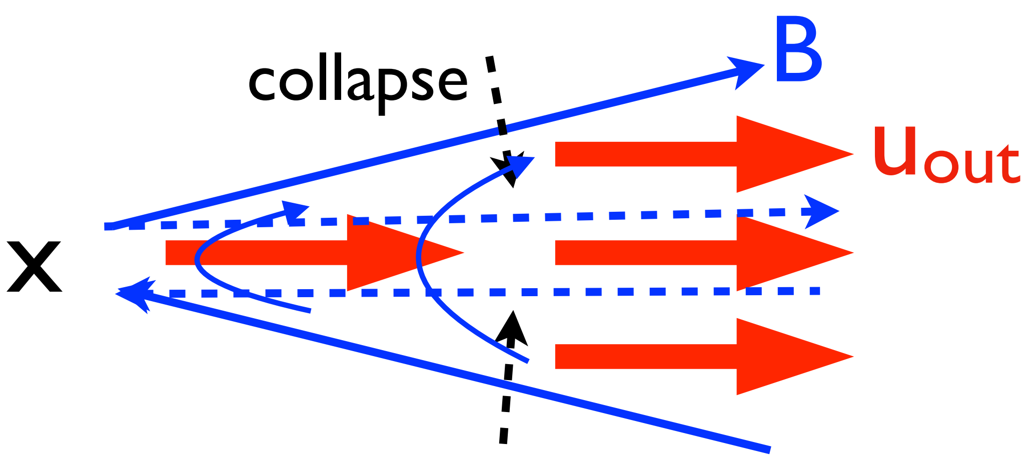
— outflow is driven by magnetic tension force

Without the Hall term…

Alfvén wave

$$\omega \propto k$$

$$\rightarrow u_{out} \sim \omega / k \sim constant$$



— collapses back to a long Sweet-Parker layer

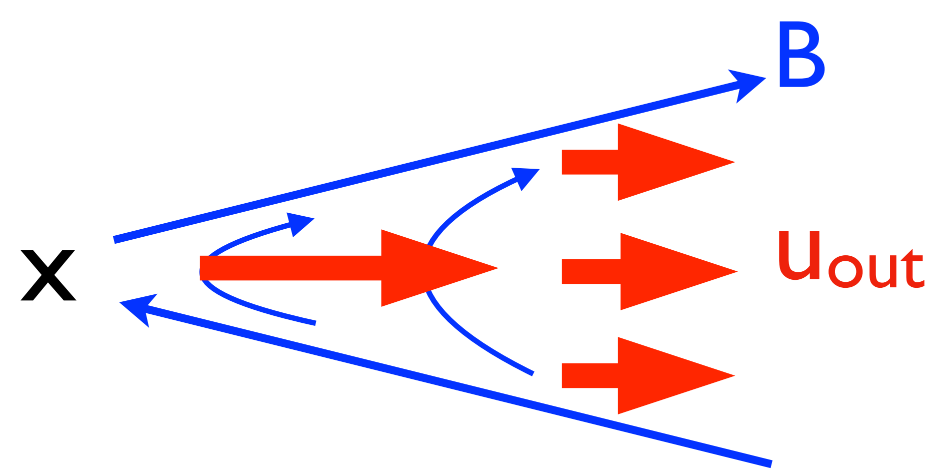
With the Hall term…

Whistler wave $(b_g = 0)$

Kinetic Alfvén wave $(b_g \neq 0)$

$$\omega \propto k^2$$

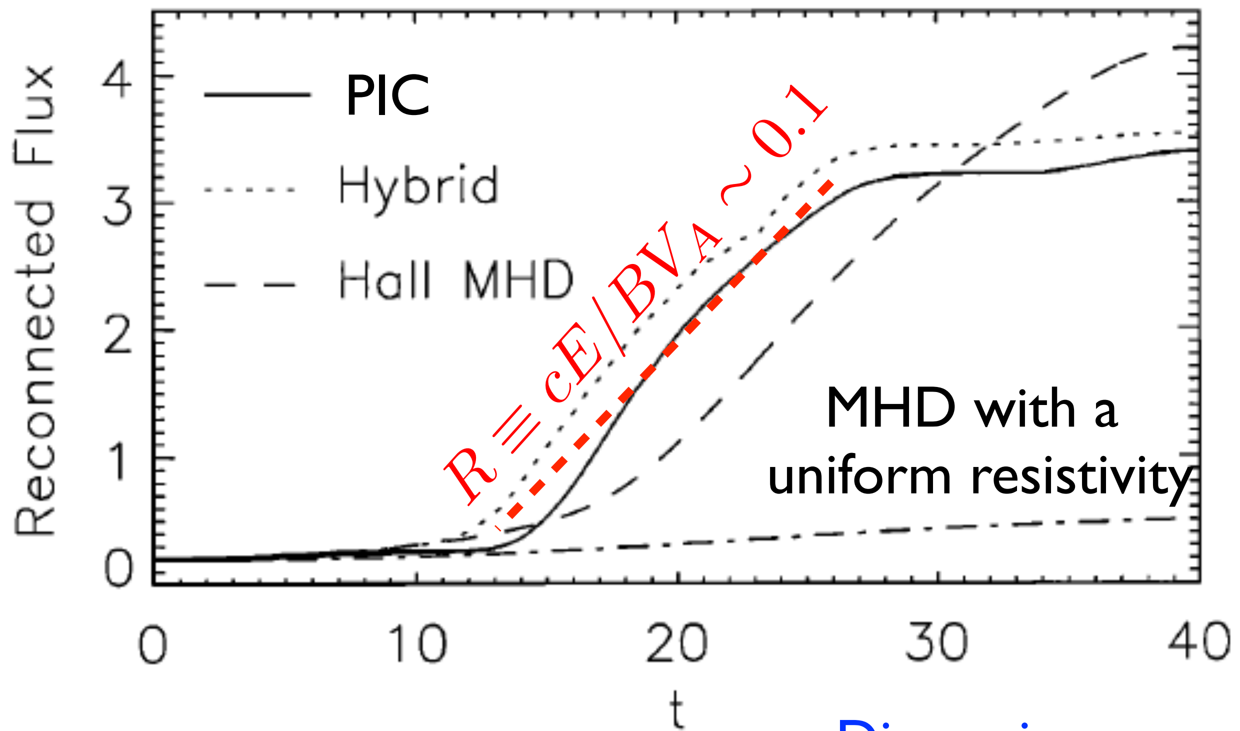
$$\rightarrow u_{out} \sim \omega / k \propto k$$



— stays opened!

- This seems to explain the difference of reconnections in resistive-MHD vs. Two-fluid/Hybrid/PIC models. (Birn+ 2001, Rogers+ 2001, Shay+ 1998, Mandt+ 1994)

GEM Reconnection Challenge (2001)



(Birn+ 2001)

Dispersive wave picture
(Sonnerup 79; Shay+ 98; Rogers+ 01; Drake+ 08)

convection, resis., Hall term, pressure, inertia

Ohm's Law in plasmas: $\mathbf{E} + \frac{\mathbf{v}_i \times \mathbf{B}}{c} = \eta \mathbf{J} + \frac{1}{nec}\mathbf{J} \times \mathbf{B} - \frac{1}{ne}\nabla \cdot \mathbf{P}_e + \frac{m_e}{e^2}\frac{d\mathbf{J}/n}{dt}$

	resis.	Hall term	pressure	inertia	
MHD:	✓				slow
Hall MHD:	✓	✓			↑
Hybrid:	✓	✓		✓	fast with R~0.1
PIC:		✓	✓	✓	↓

However, electron-positron (PIC): ✓ ✓
(Bessho & Bhattacharjee, 05; Daughton+ 07; Swisdak+ 08; Liu+ 09)
strong guide field limit (PIC): ✓ ✓ also fast with R~0.1
(Liu+14; TenBarge+14; Stainer+15; Cassak+15)

Q1: Why is the fast rate R~ 0.1? Q2: What is the localization mech.?

To be solved.

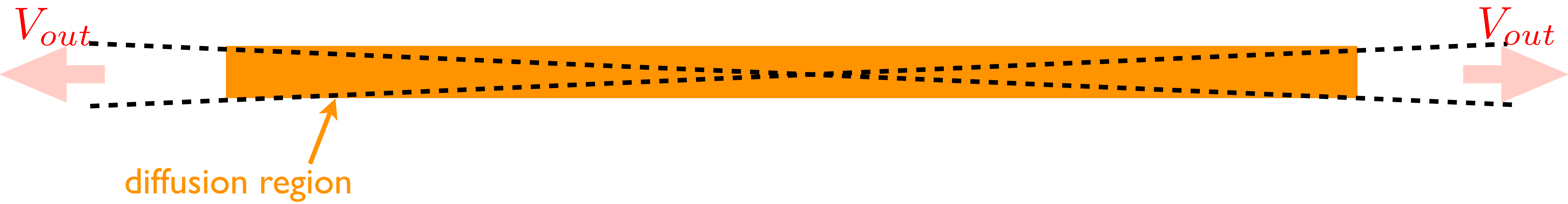
Q1: How to explain the fast reconnection rate value of order 0.1 in different systems?

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

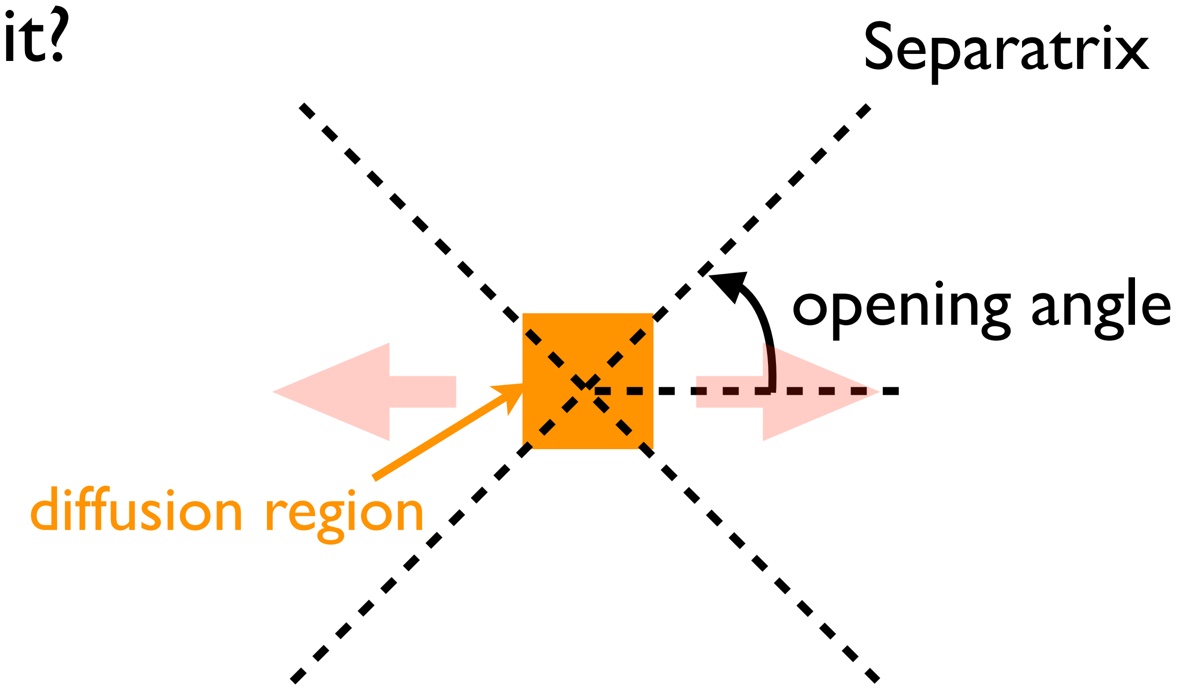
*clue: can not be the diffusion-scale physics!

Two extreme limits…

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



How about the large δ/L limit?



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

✦ There must be a maximum in between these two limits~

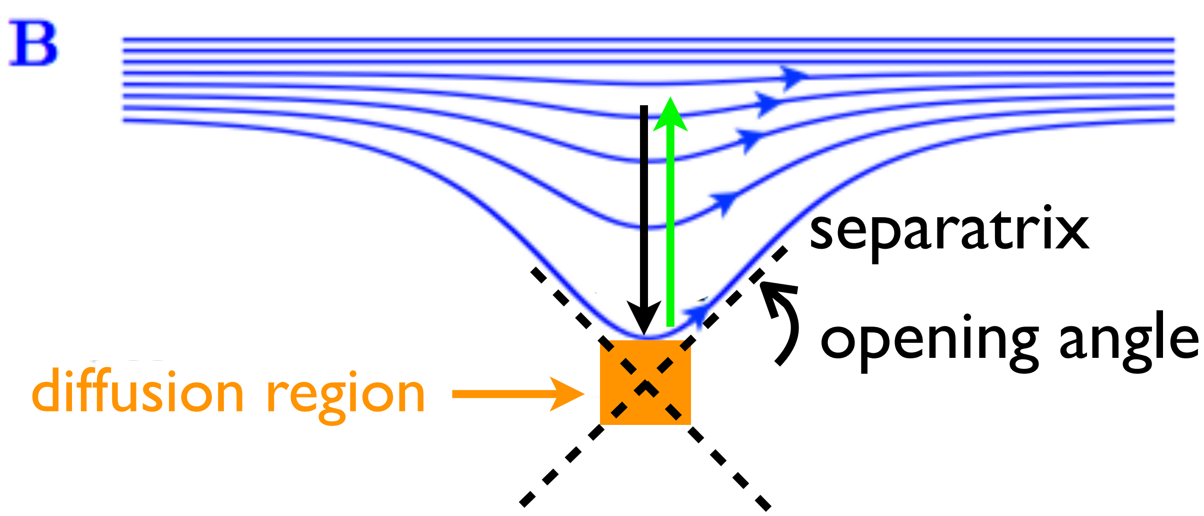
The Key: Geometry & Force balance!

In the large diffusion region aspect ratio, δ/L , limit .....

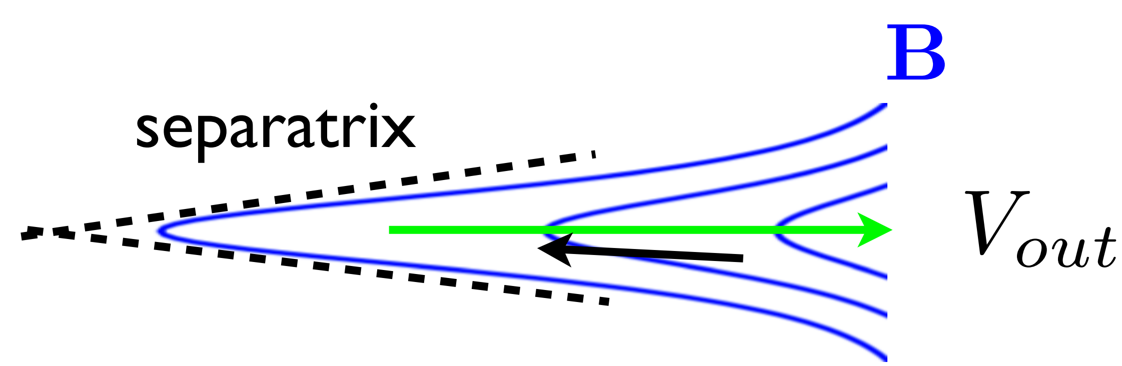
tension magnetic pressure inertia

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

@ inflow region



@ outflow region



$\rightarrow$ reduction of the reconnecting field!!!

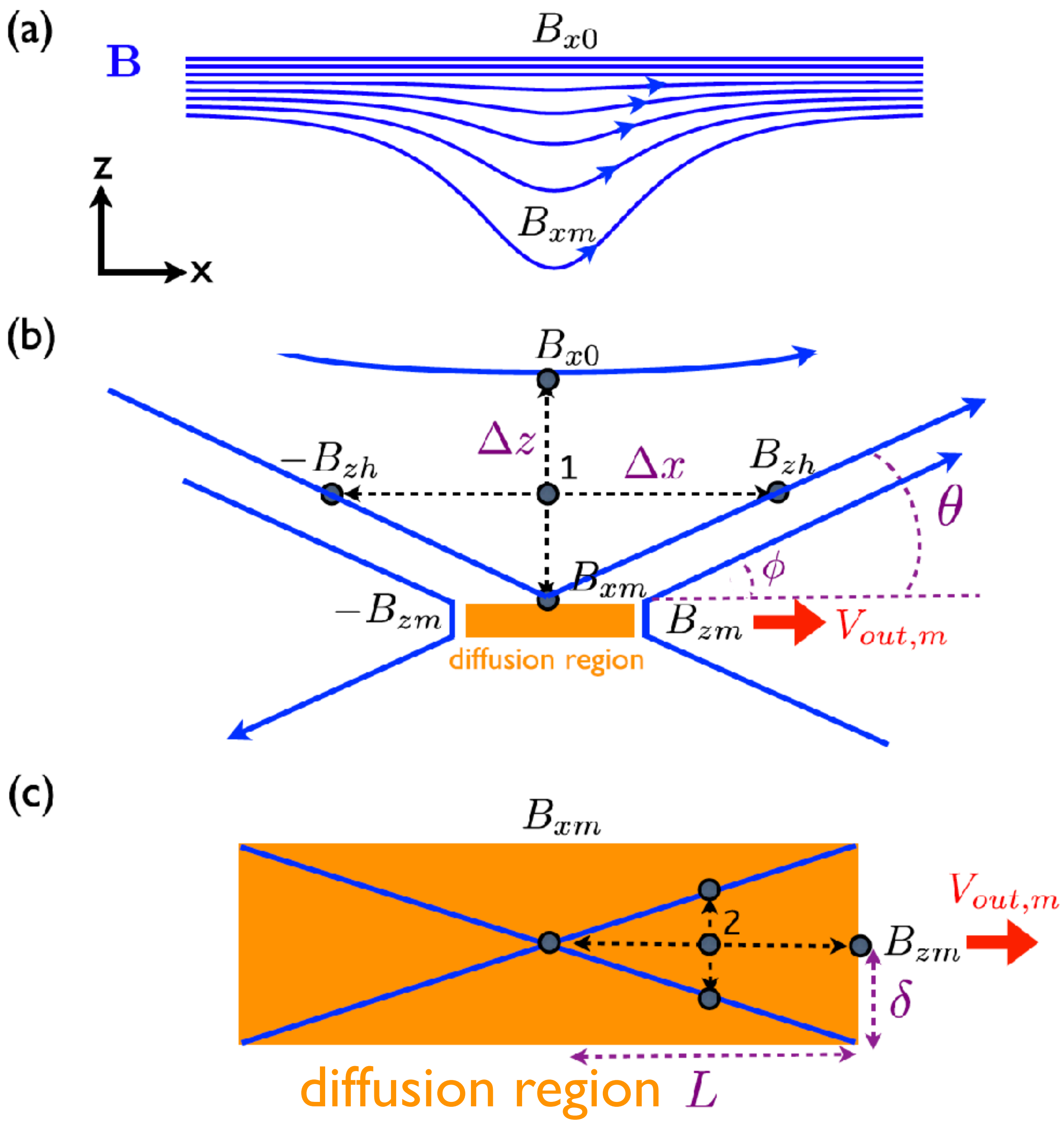
$\rightarrow R\downarrow$

$\rightarrow$ reduction of the outflow speed!!!

$\rightarrow R\downarrow$

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

Back-of-the-envelope calculation…



Introduce the scale-separation~

analyze the force-balance at point 1

$\rightarrow B_{zm}(S)$

analyze the force-balance at point 2

$\rightarrow V_{out,m}(S)$

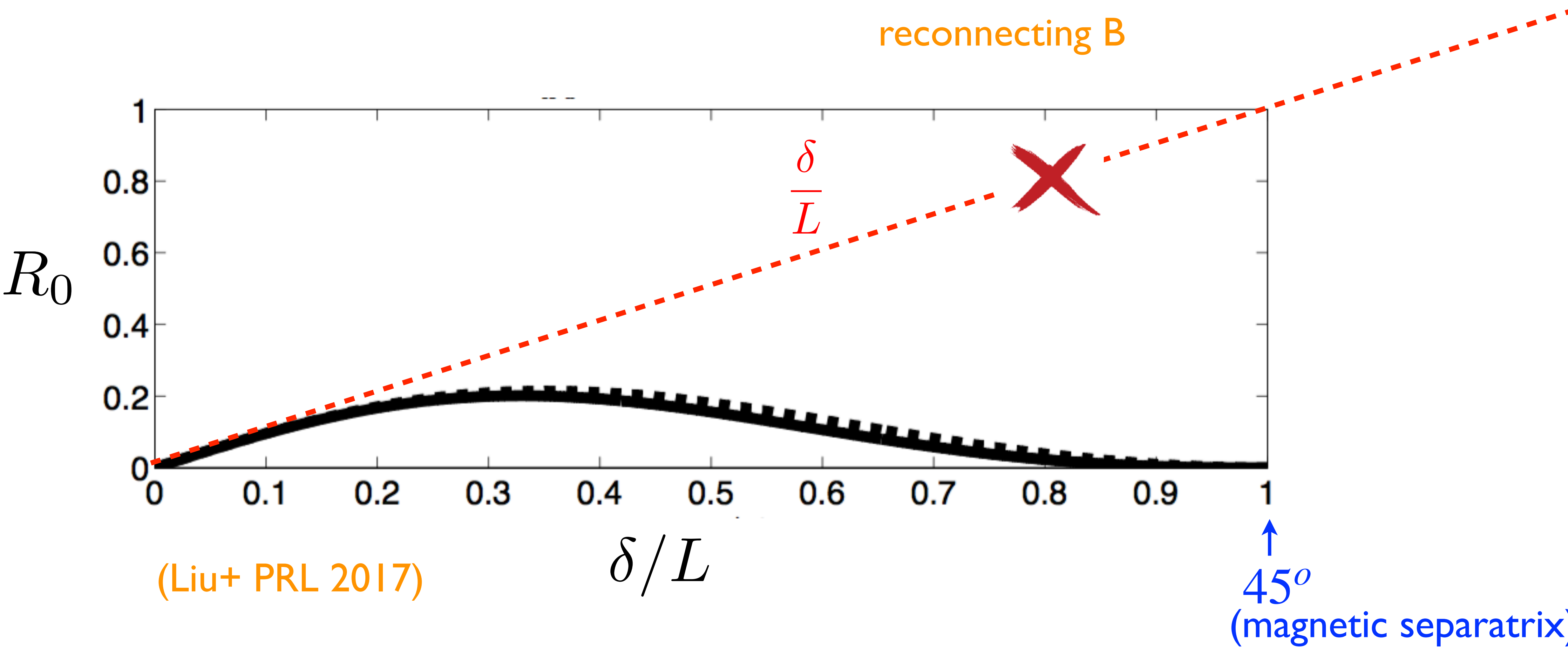
Connecting these two regions to get the rate~

$$E_y = B_{zm}V_{out,m}/c$$

Explanation of the fast rate ~ 0.1

-- Geometrical consideration!

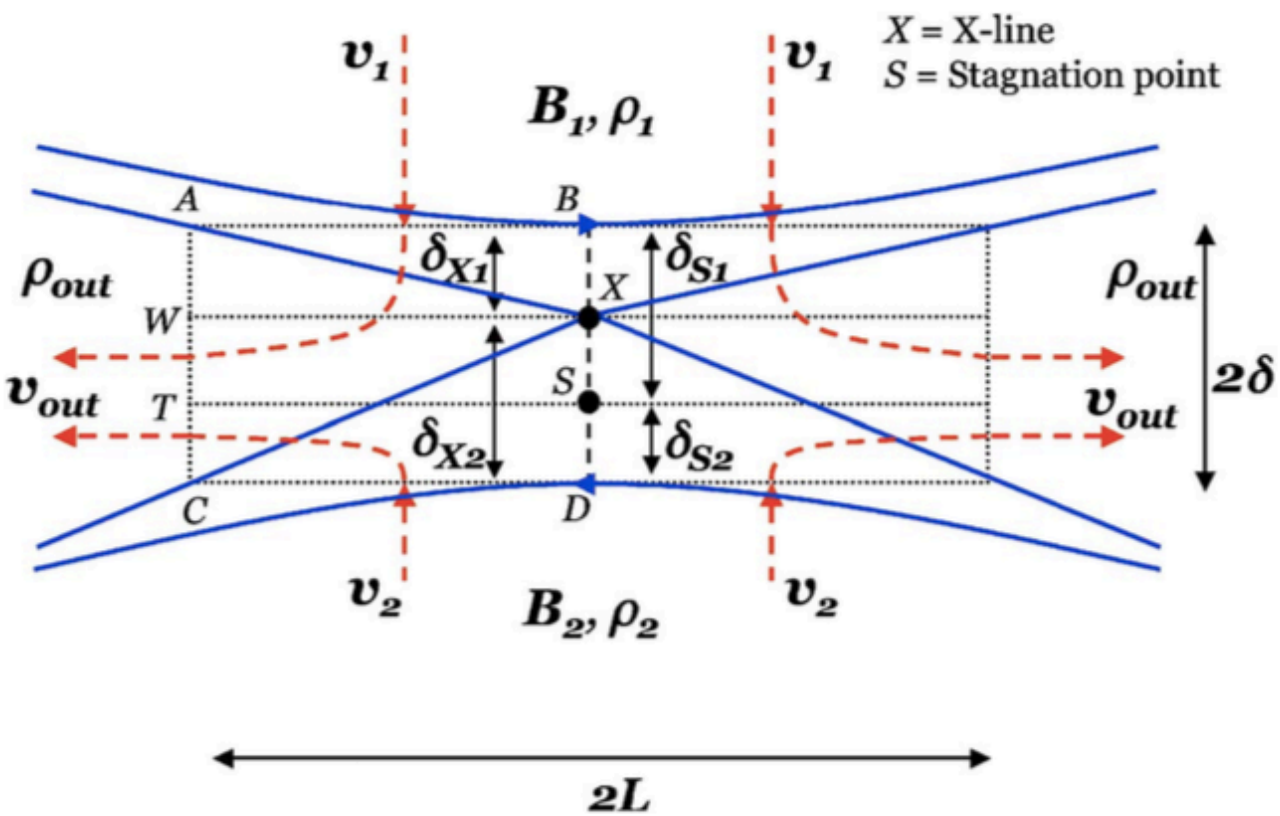
$$R_0 \equiv \frac{cE_y}{B_{x0}V_{A0}} = \left(\frac{B_{zm}}{B_{x0}}\right)\left(\frac{V_{out,m}}{V_{A0}}\right) \simeq \frac{\delta}{L}\underbrace{\left[\frac{1-(\delta/L)^2}{1+(\delta/L)^2}\right]^2}_{\text{reduction of reconnecting B}}\overbrace{\sqrt{1-\left(\frac{\delta}{L}\right)^2}}^{\text{reduction of } V_{out}}$$



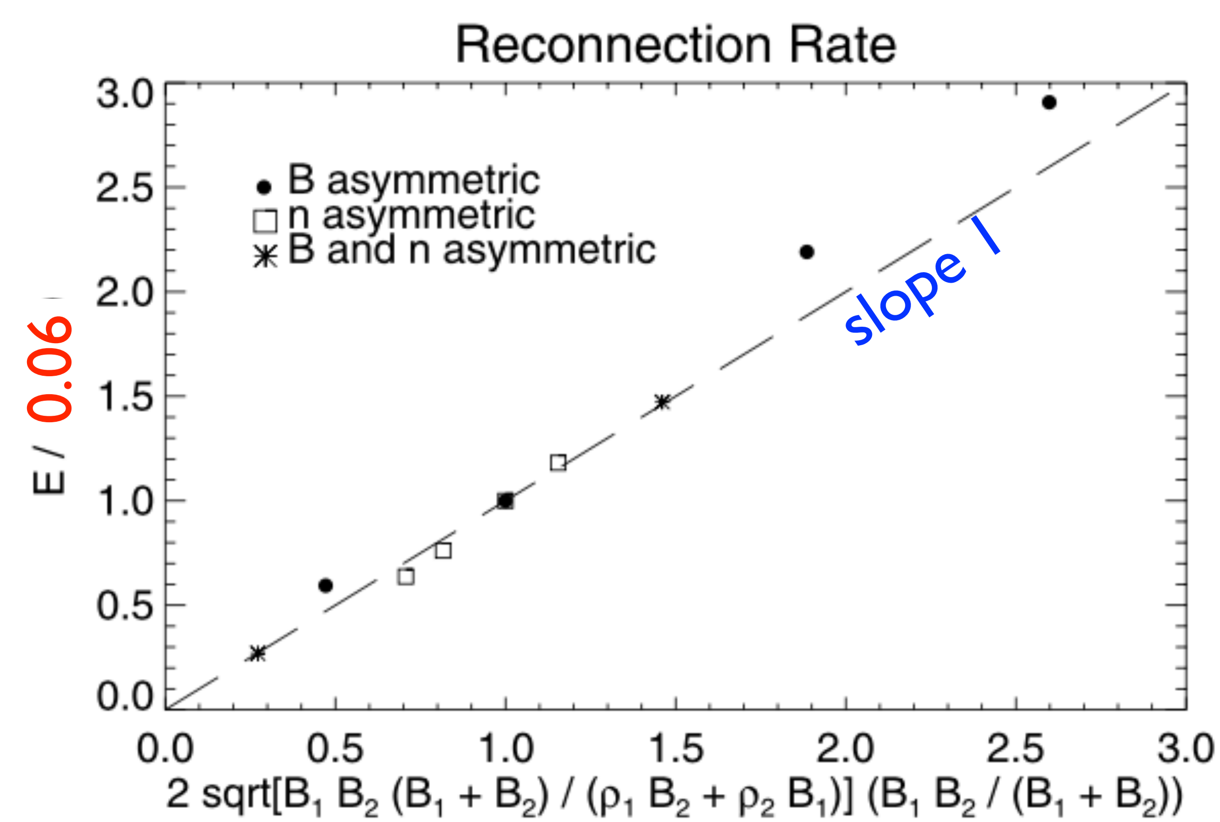
(Liu+ PRL 2017)

- Fast rate R~ O(0.1) is an upper bound value.
- Reconnection tends to proceed near the most efficient state, which has R ~ O(0.1).
- Nicely, rate is insensitive to δ/L near this state.

Asymmetric Reconnection



Two-fluid simulations



Cassak & Shay GRL (2008)

Cassak-Shay formula

$$E_{CS} = 2\left(\frac{B_1 B_2}{B_1 + B_2}\right)\left(\frac{V_{out}}{c}\right)\left(\frac{\delta}{L}\right)_{eff}$$

Cassak & Shay, PoP (2007)

where

$$\frac{V_{out}}{c} = \sqrt{\frac{B_1 B_2}{4\pi}\left(\frac{B_1 + B_2}{B_1 \rho_2 + B_2 \rho_1}\right)}$$

Swisdak & Drake, GRL (2007)

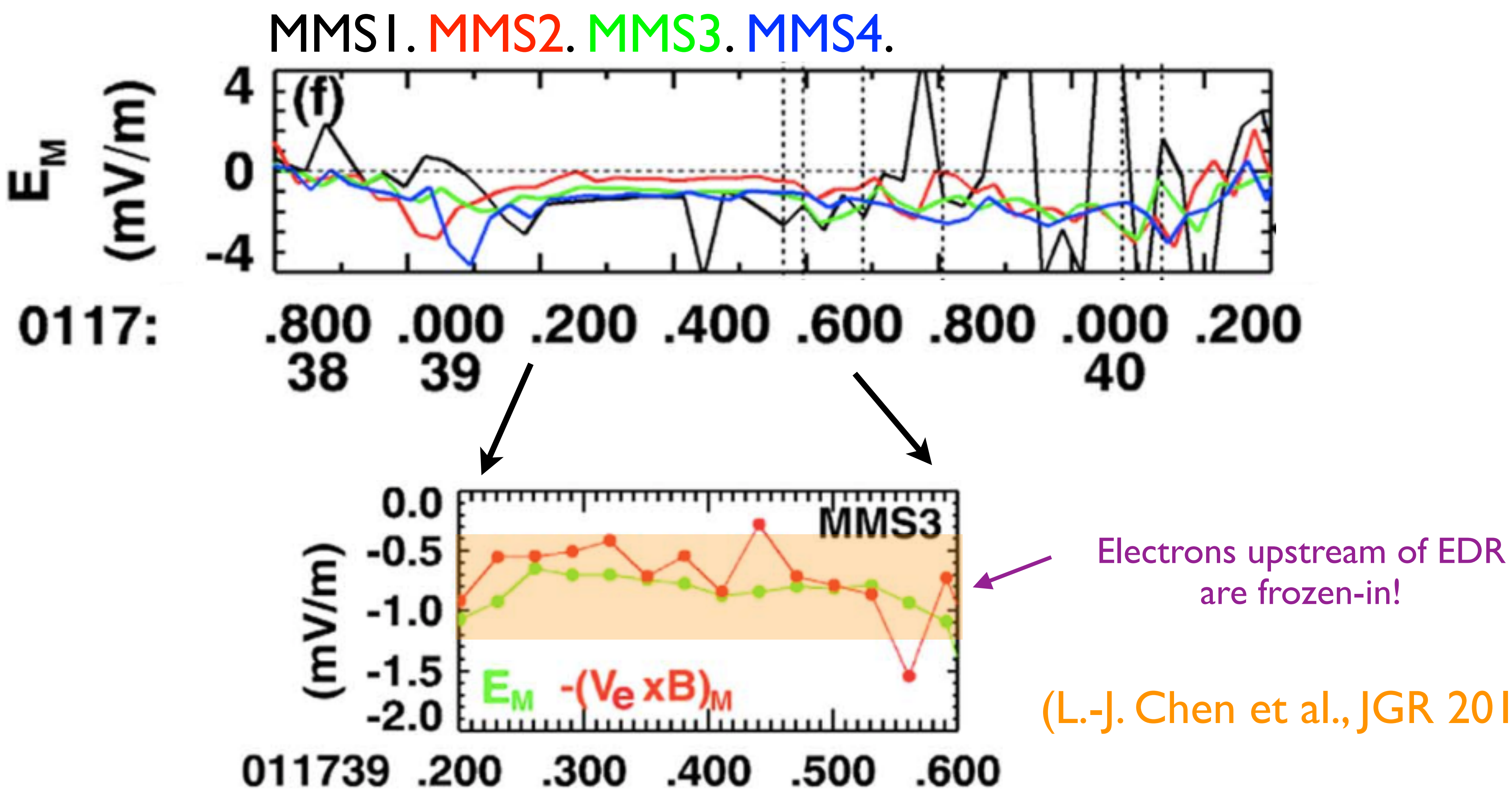
and $(\delta/L)_{eff} \simeq 0.1$

Liu+ GRL (2018)

MMS observations

MMS observations

December 14, 2015 event: $B_g \sim 0.2$, $B_{L2}/B_{L1} \sim 1.3$, $n_2/n_1 \sim 6.8$

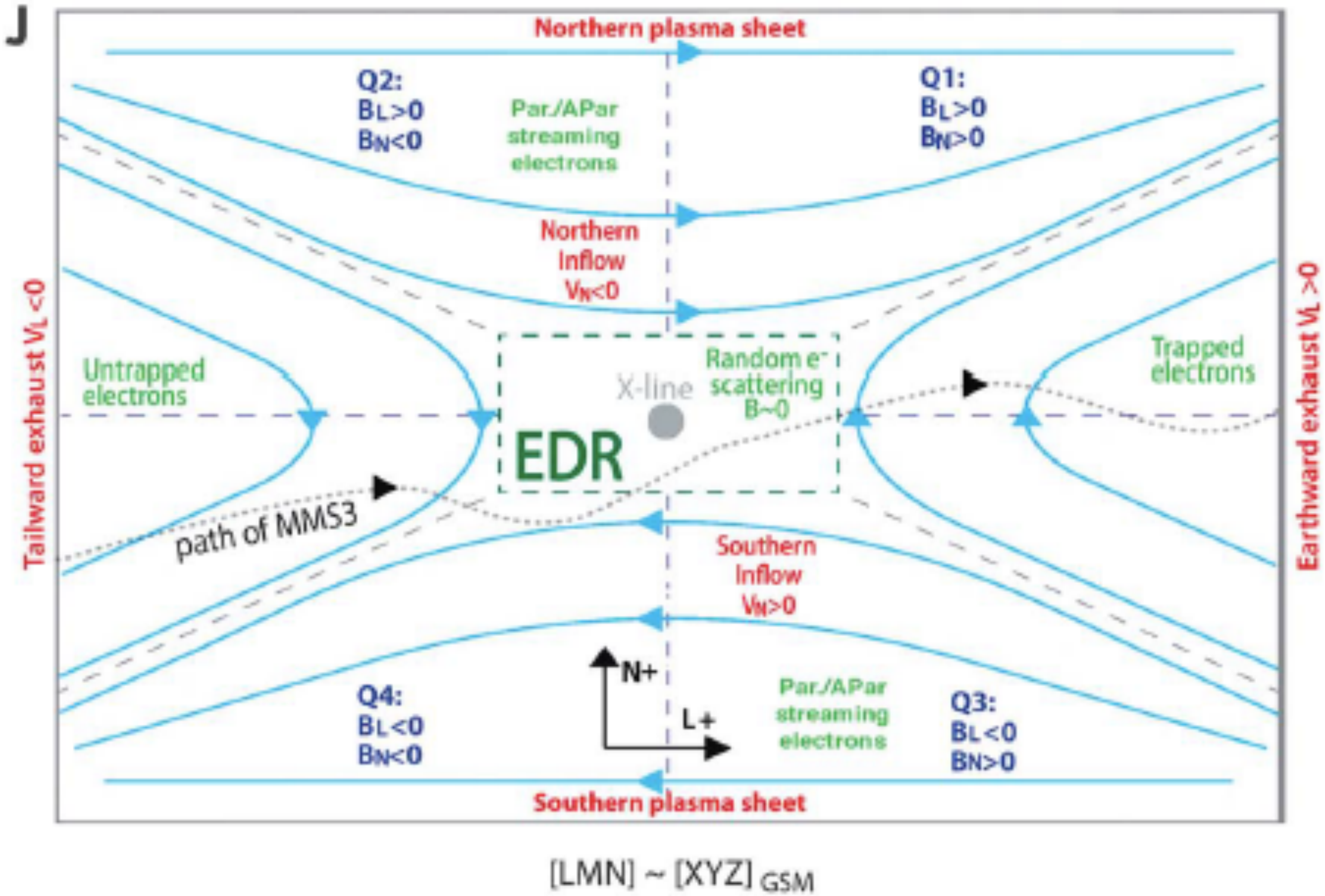


(L.-J. Chen et al., JGR 2017)

- An uniform electric field over at least 8 electron skin depths corresponds to a normalized rate ~ 0.1.
- The rate of the October 16, 2015 event was estimated to be ~ 0.3. (Burch+ Science 2016)

MMS observations

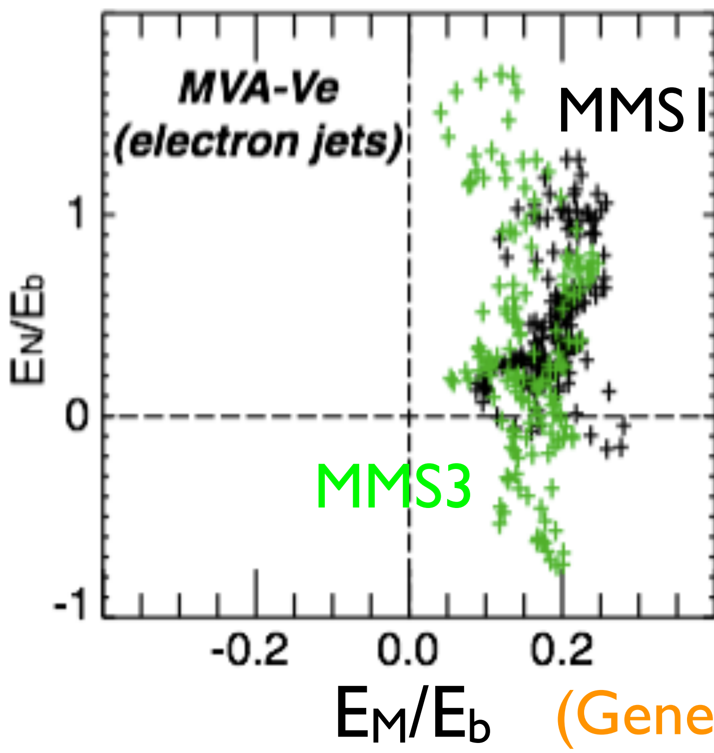
Torbert' 7/11 event



(Torbert+ Science 2018)

• Measuring the aspect ratio of EDR~ 0.1–0.2
— Using timing analysis to get L.
— Using current density to get δ.

MMS observations
7/11 event

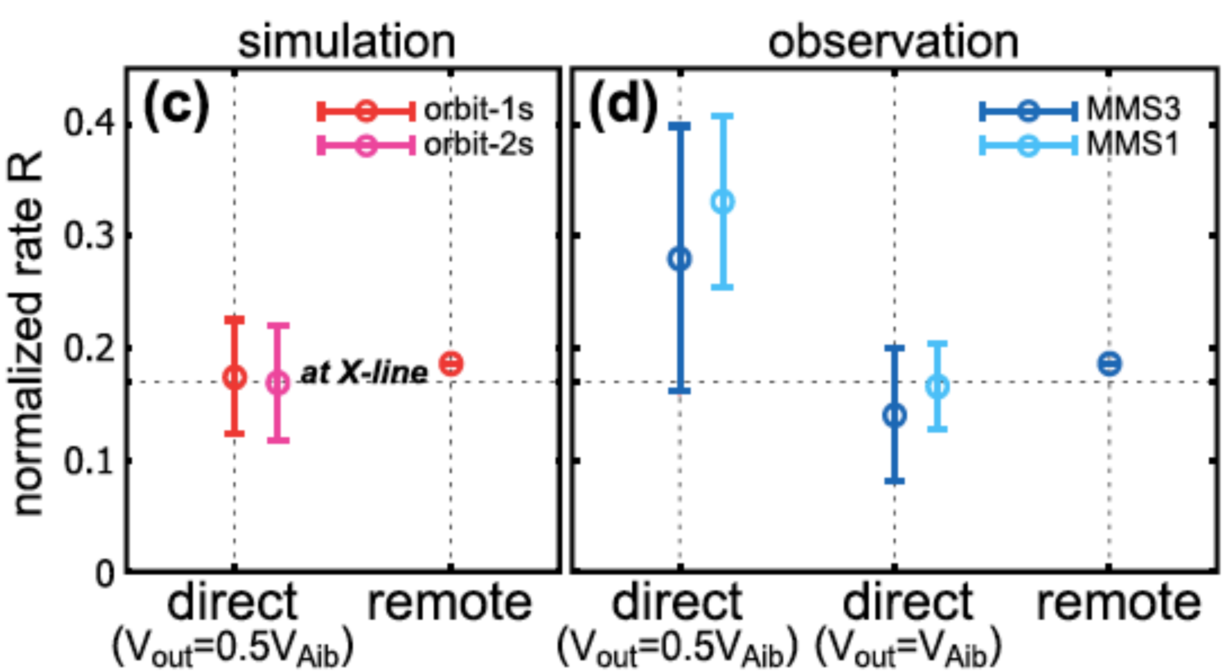


(Genestreti+ JGR 2018)

Measuring E_M

—Tried 14 different LMN coordinate systems

R~0.18 ± 0.035



(Nakamura+ JGR 2018)

Measuring E_M

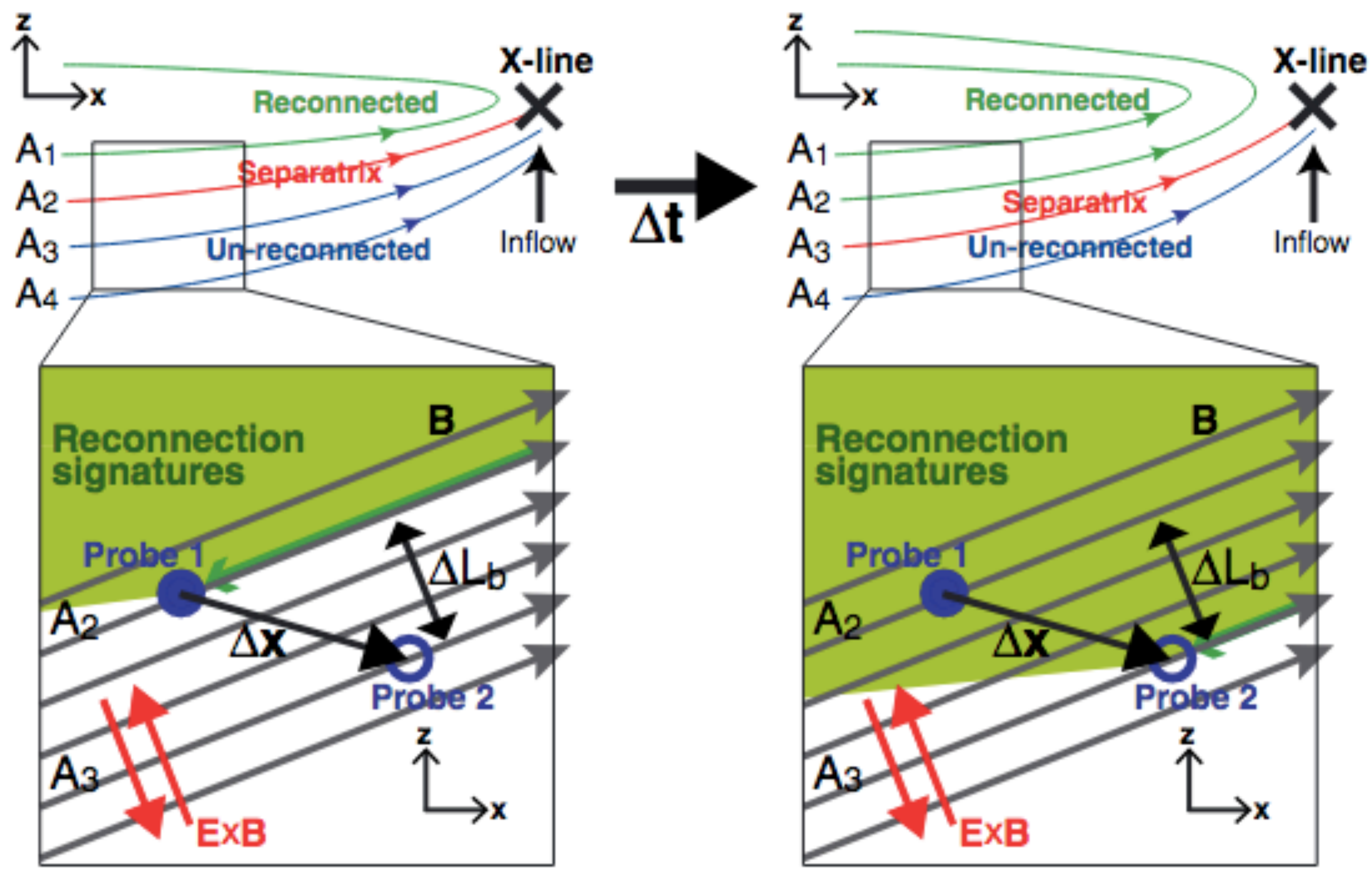
—Took advantage of the close comparison

with 2D PIC simulations~

MMS observations

— new technique in measuring the rate

t_0 $t_0 + \Delta t$



(Nakamura+ JGR 2018)

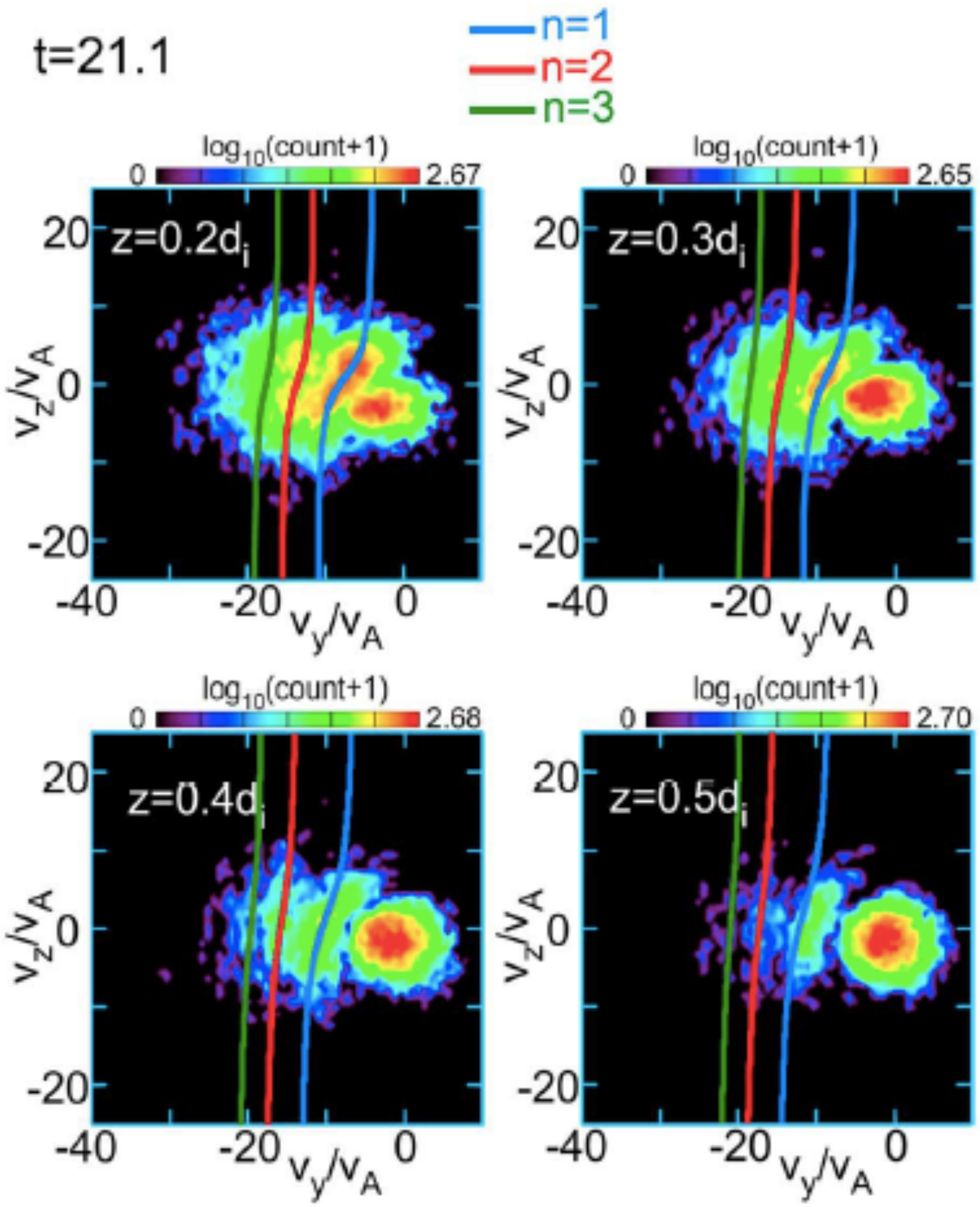
$$E_r \sim -\frac{(\boldsymbol{\Delta X} \times \boldsymbol{B})_y}{\Delta t} \sim [-(\boldsymbol{V}_{\mathrm{tim}} - \boldsymbol{V}_c) \times \boldsymbol{B}]_y$$

convection of the magnetic flux
respect to the probe

- Measuring the flux difference at separatrix to infer the reconnection rate remotely!

MMS observations

— new technique in measuring the rate



(Bessho+ GRL 2018)

$$b = dB_x/dz$$

$$k = dE_z/dz$$

$$\Delta v_y = \left[\left(-v_{y0} - \frac{ck}{b}\right)^{3/2} + \frac{3\pi}{4}(2n+1)\left(\frac{mc}{eb}\right)^{1/2}\frac{eE_r}{m}\right]^{2/3} - \left[\left(-v_{y0} - \frac{ck}{b}\right)^{3/2} + \frac{3\pi}{4}(2n-1)\left(\frac{mc}{eb}\right)^{1/2}\frac{eE_r}{m}\right]^{2/3}.$$

- Inferring reconnection rate from particle distributions at the diffusion region.
  — E_R accelerates electrons in the out-of-plane (-y) direction.
  — R~ 0.22-0.28 for the 7/11 event.

Summary & future (unsolved questions)

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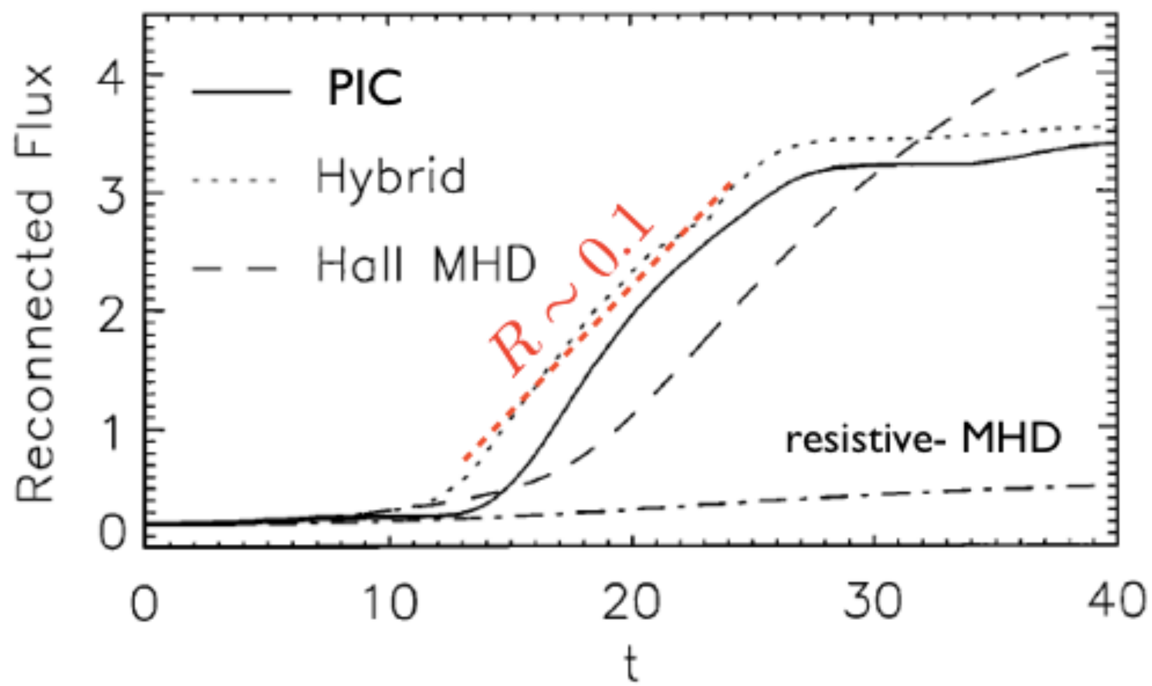
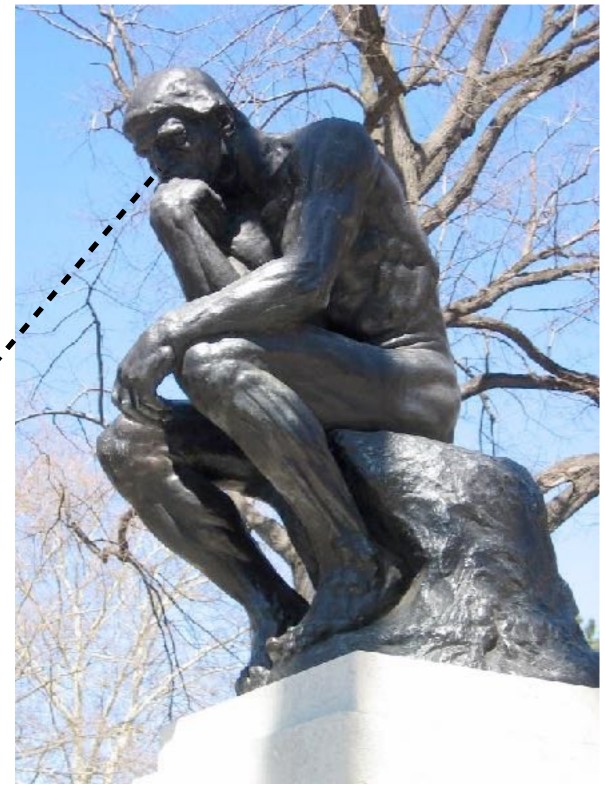
★ 0.1 is an upper bound value.



?

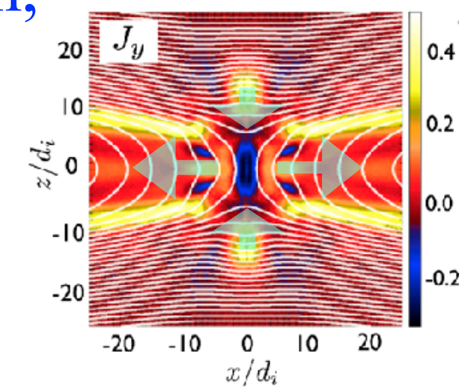


★ What is the localization mechanism in the standard regime?

— Why is MHD with an uniform resistivity so different? (the only exception.?)

— While a localization mechanism is needed for fast reconnection, different systems may have different localization mechanisms.

(Liu+, PoP, 2018)



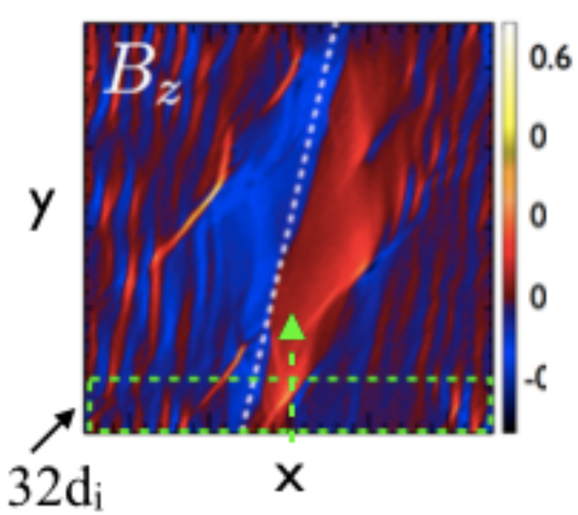
Summary & future (unsolved questions)

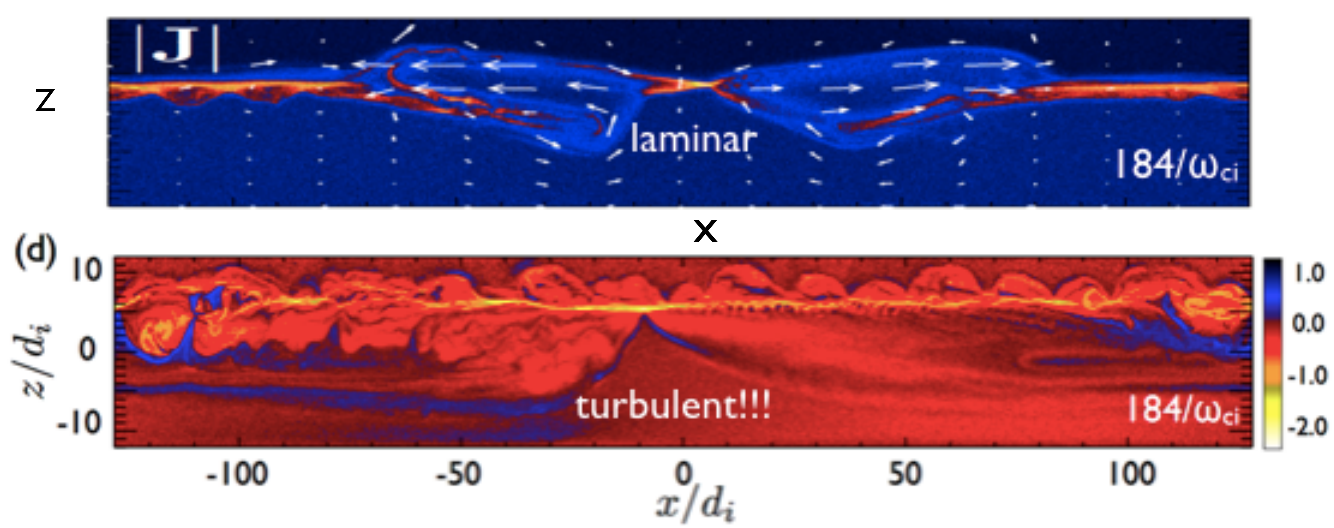
★ Turbulence!? if yes, how does it affect reconnection rate?

— and how to measure the rate in a turbulent sheet using MMS???

p.s. be cautious about the periodic boundary condition in small simulations.

(Liu+ JGR 2018)



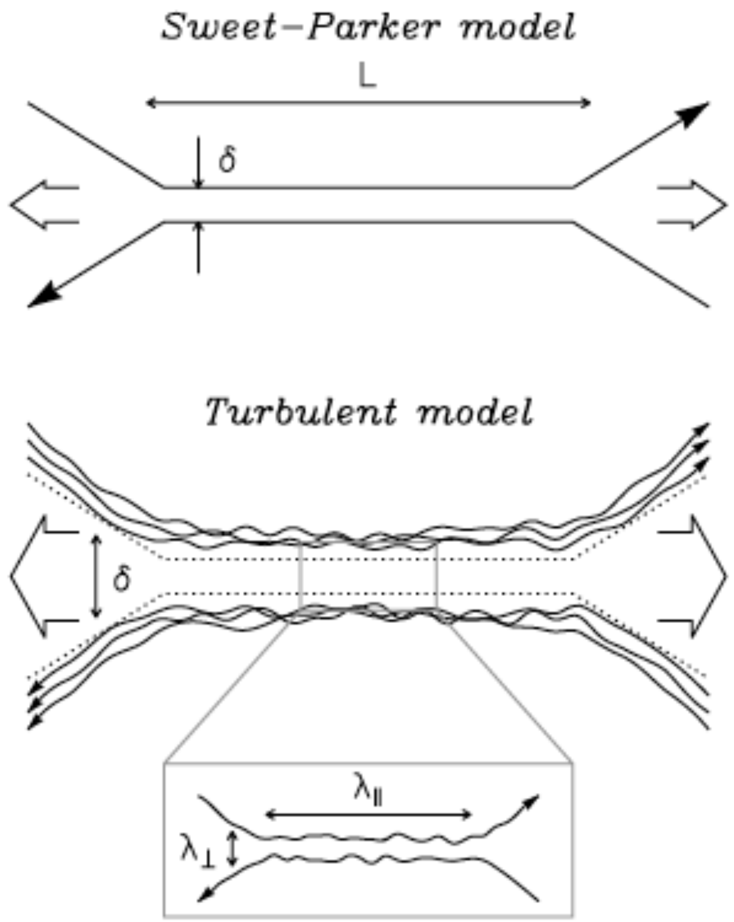


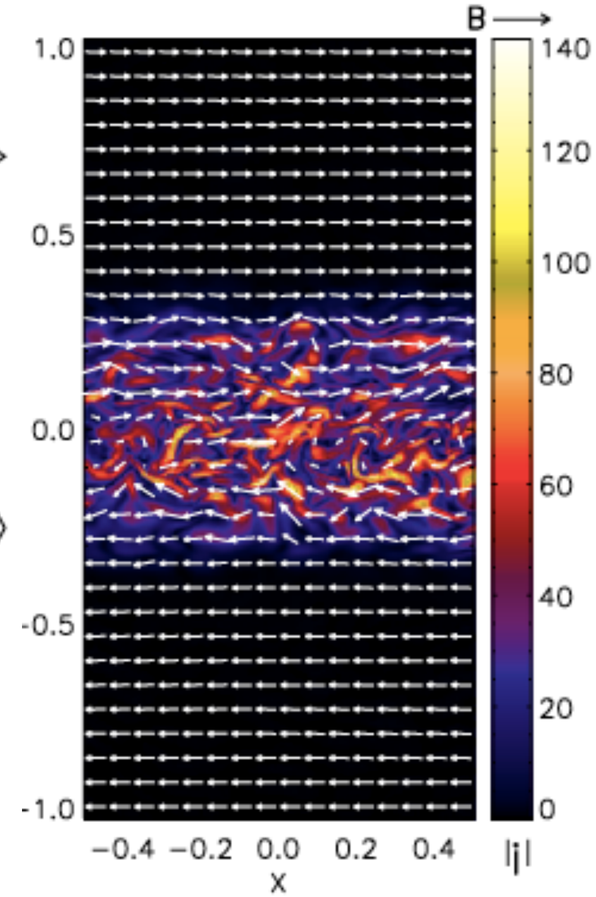
Large box

Small box

Turbulence

resistive-MHD
+ external driving

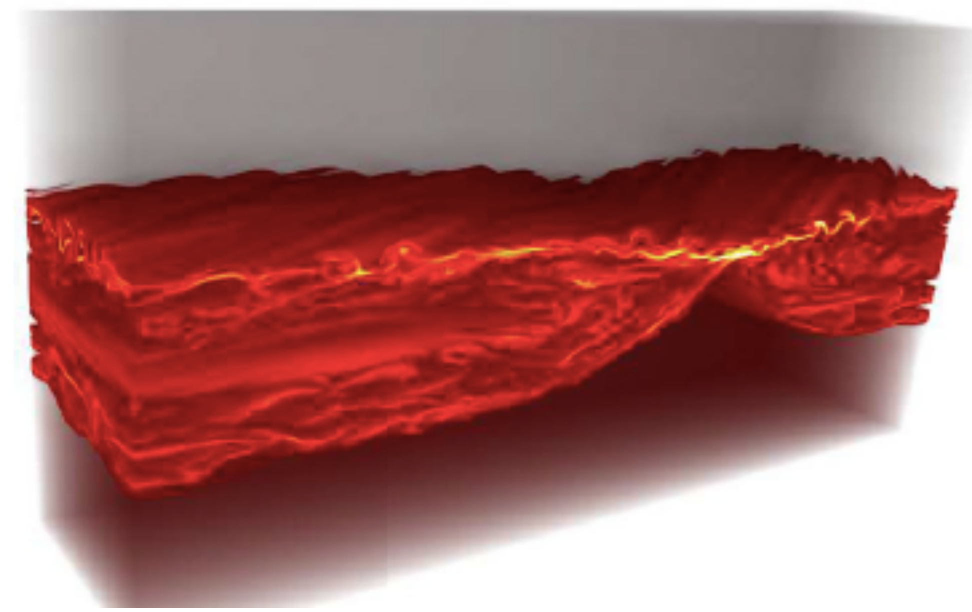


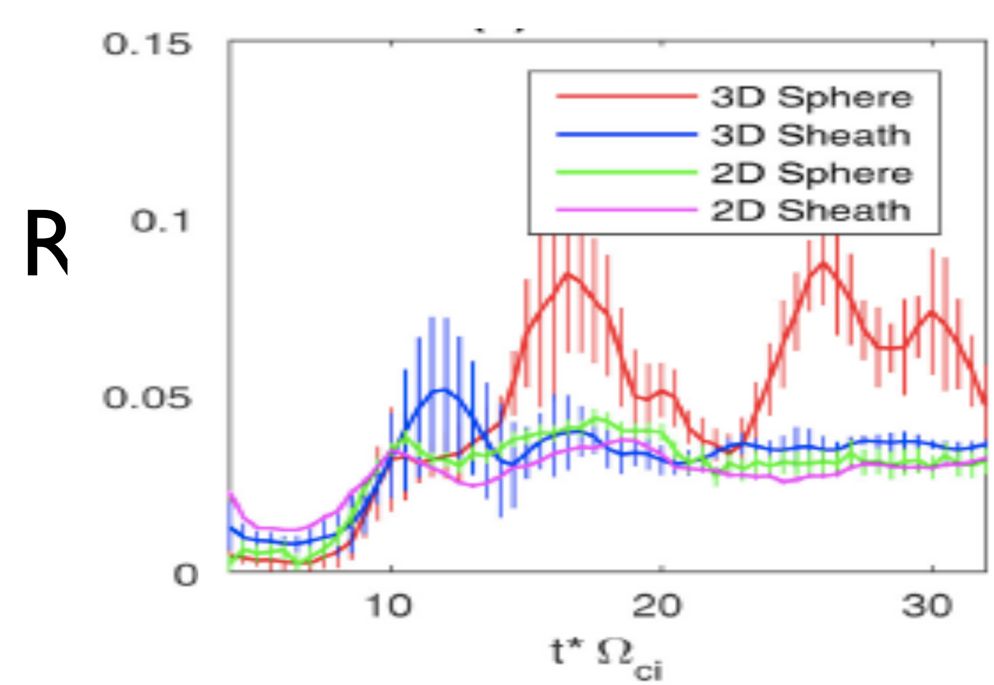


$$V_{\rm rec} = V_A \min\left[\left(\frac{L}{l}\right)^{1/2}, \left(\frac{l}{L}\right)^{1/2}\right]\left(\frac{v_l}{V_A}\right)^2$$

(Kowal+ ApJ 2009,
Lazarian & Vishniac, 1999)

PIC- asymmetric





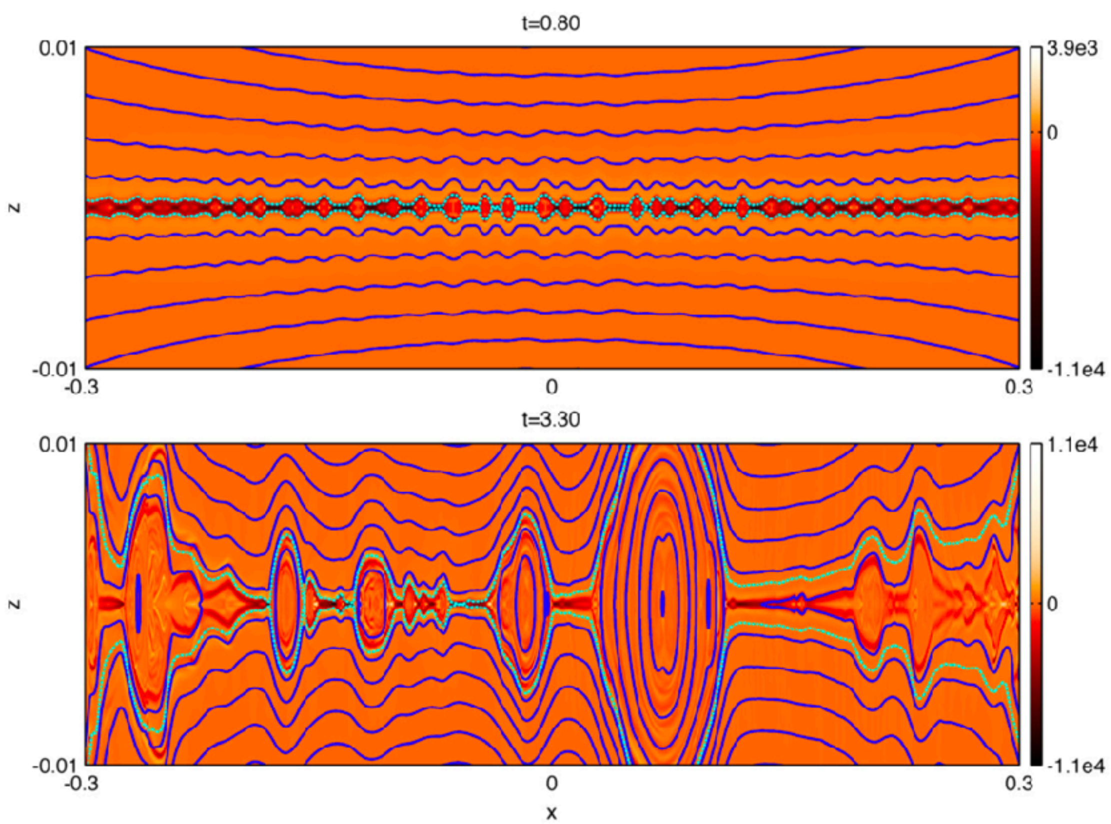
(Le+, PoP 2018)

- Self-generated turbulence in 3D sheet does NOT change the rate much~

Backup slides

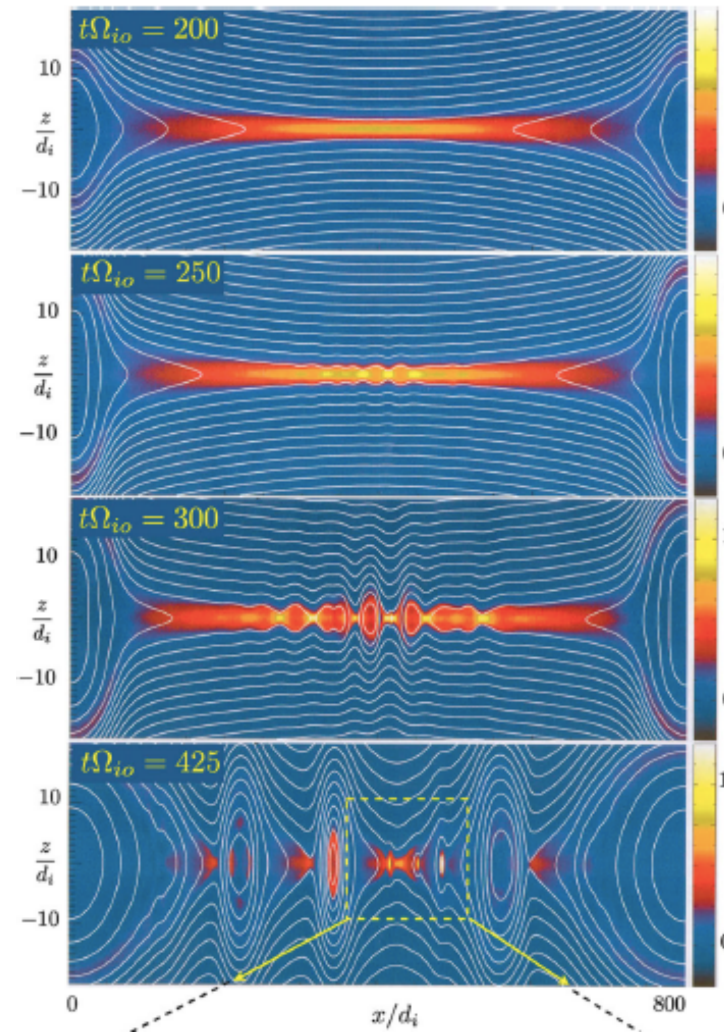
Plasmoids (i.e., secondary tearing modes)

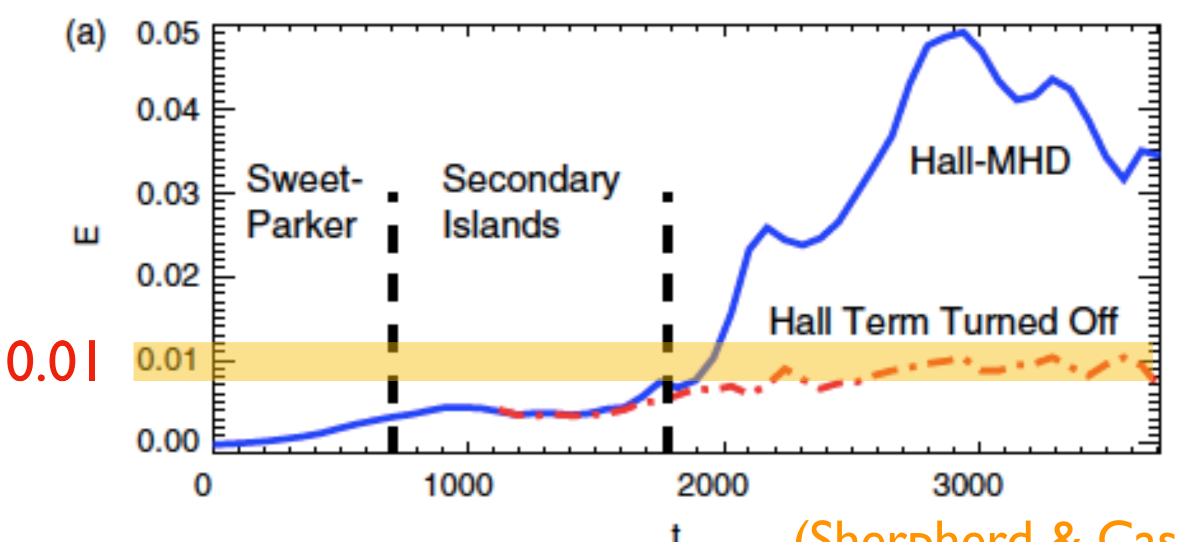
resistive-MHD when η is very small

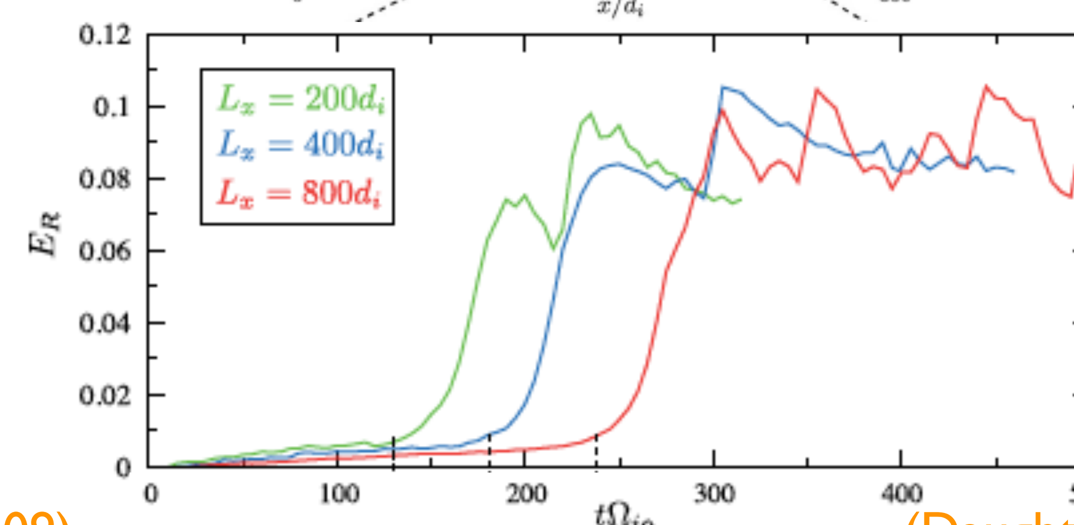


(Y. -M. Huang+ 2010, Loureiro+ 2007…)

PIC with collisions







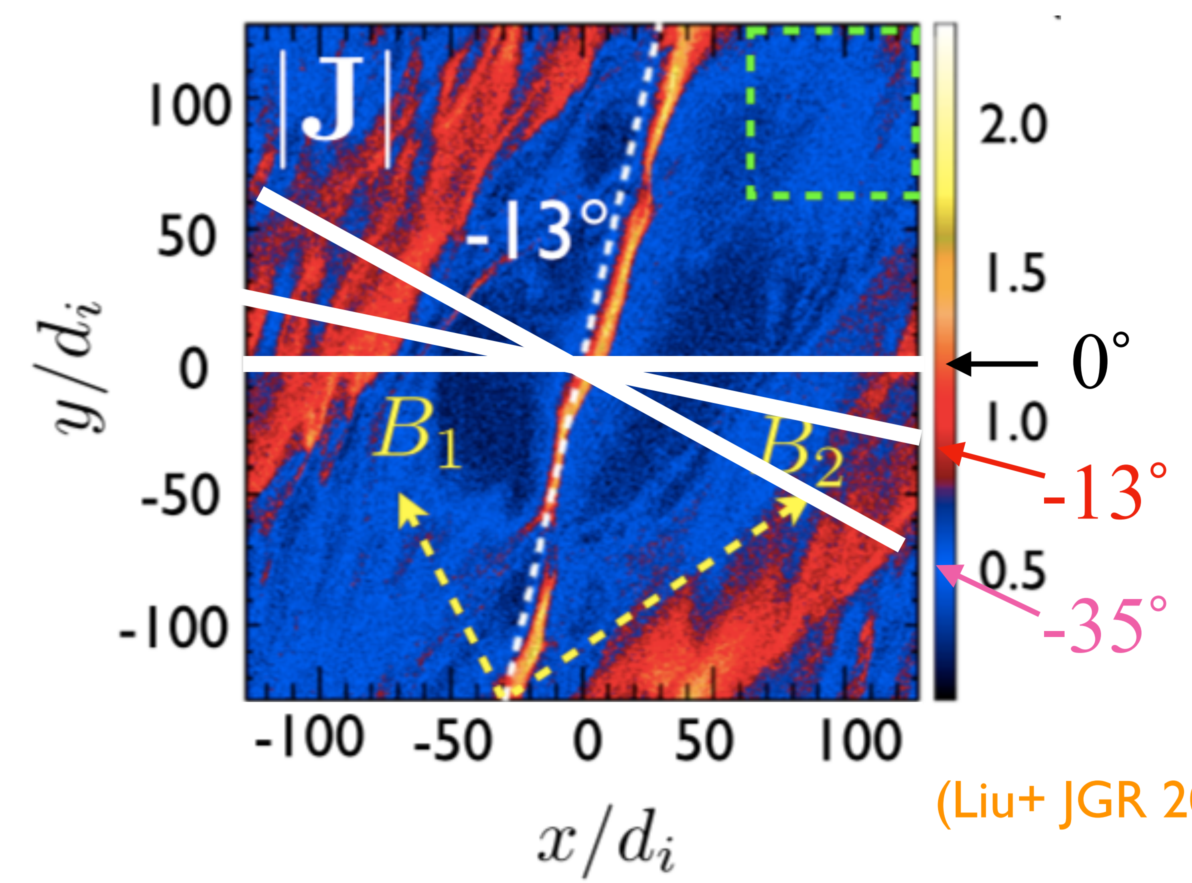
(Sherpherd & Cassak+ 09)

(Daughton+ 09)

- (my opinion) Tearing may provides the localization, enhancing the rate, but cannot explain the fast rate value ~ O(0.1).

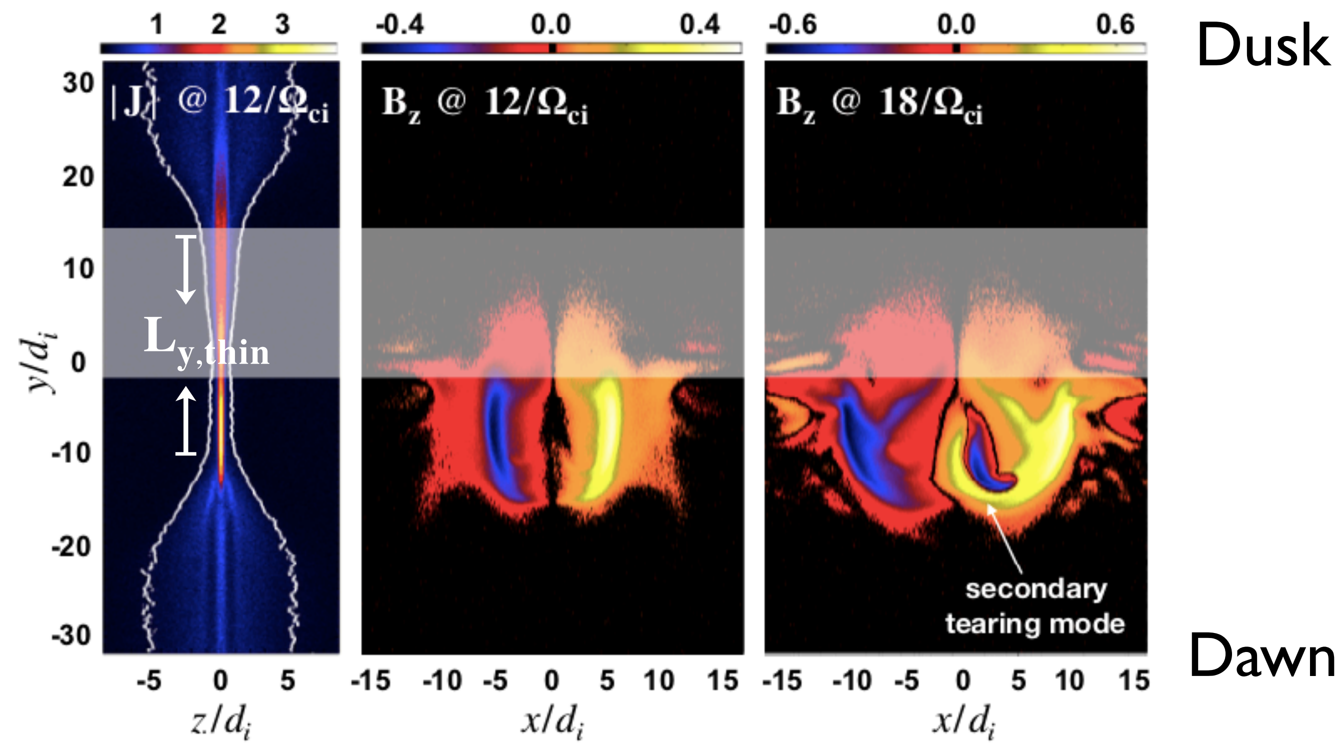
3D nature

X-line orientation



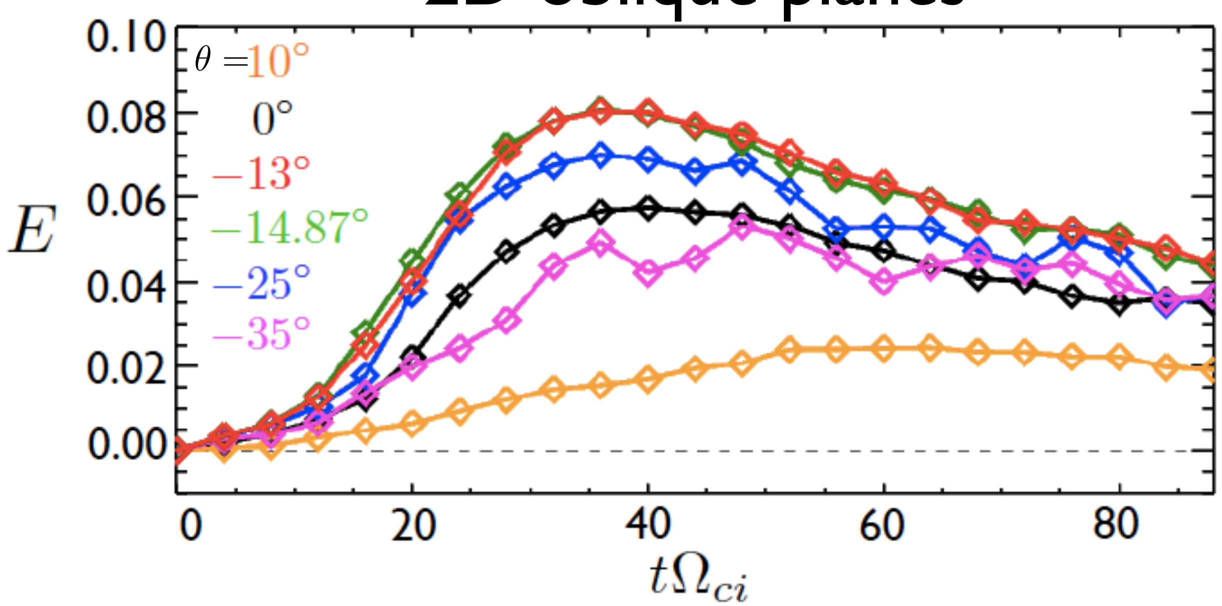
(Liu+ JGR 2018)

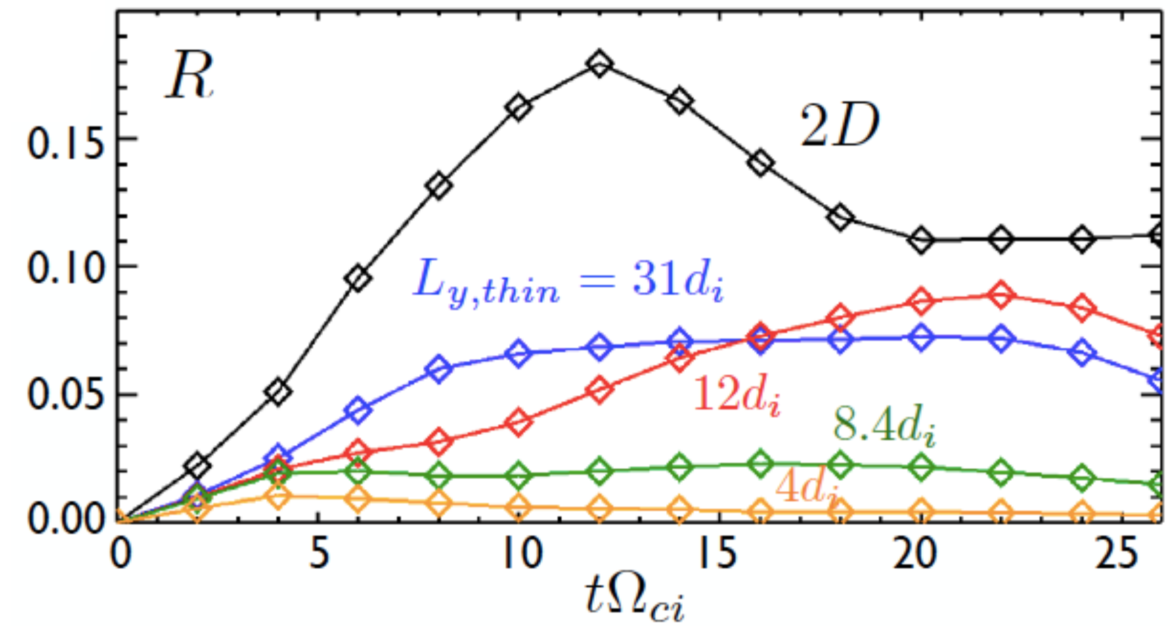
shortest possible x-line extent?



(Liu+ arXiv 2019)

2D oblique planes

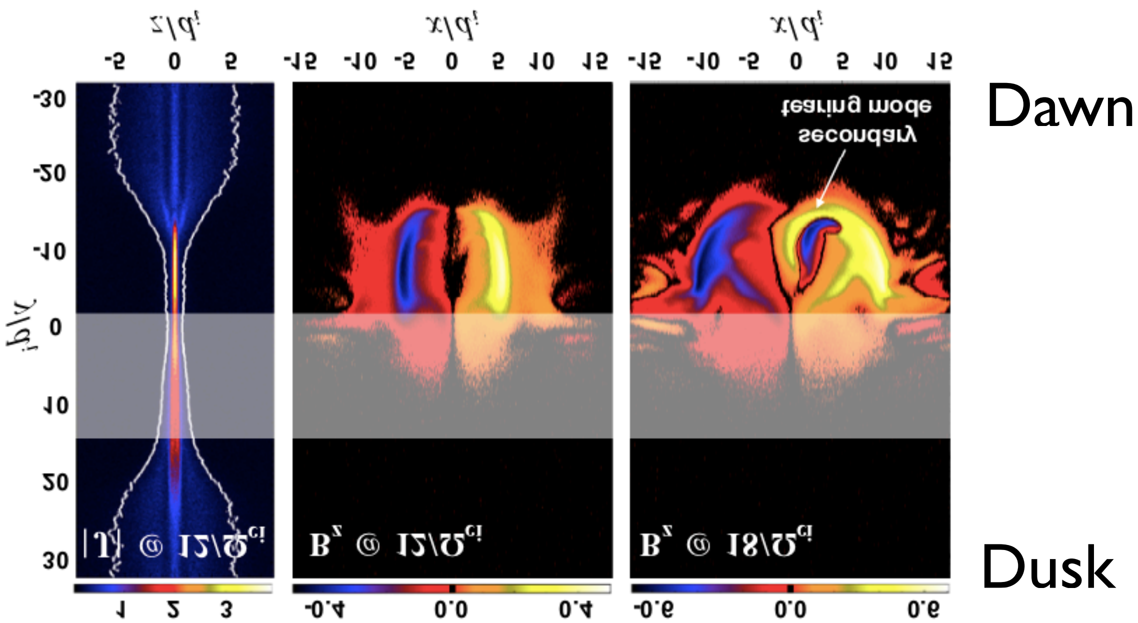


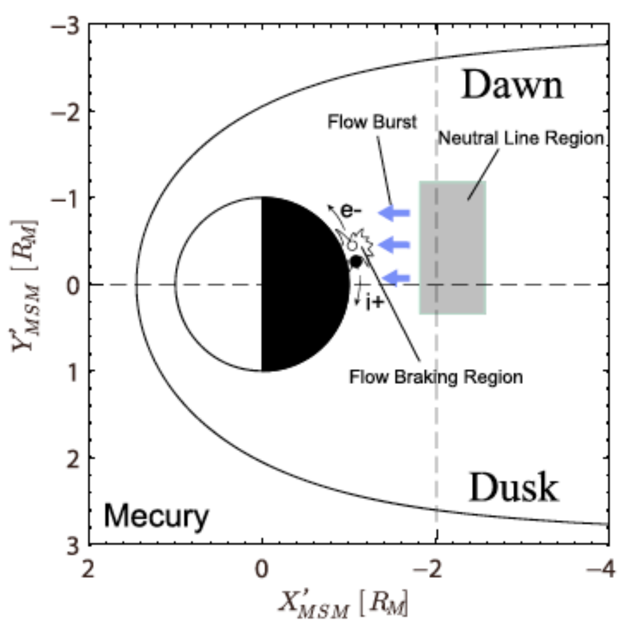


- The system tries to maximize the rate.?

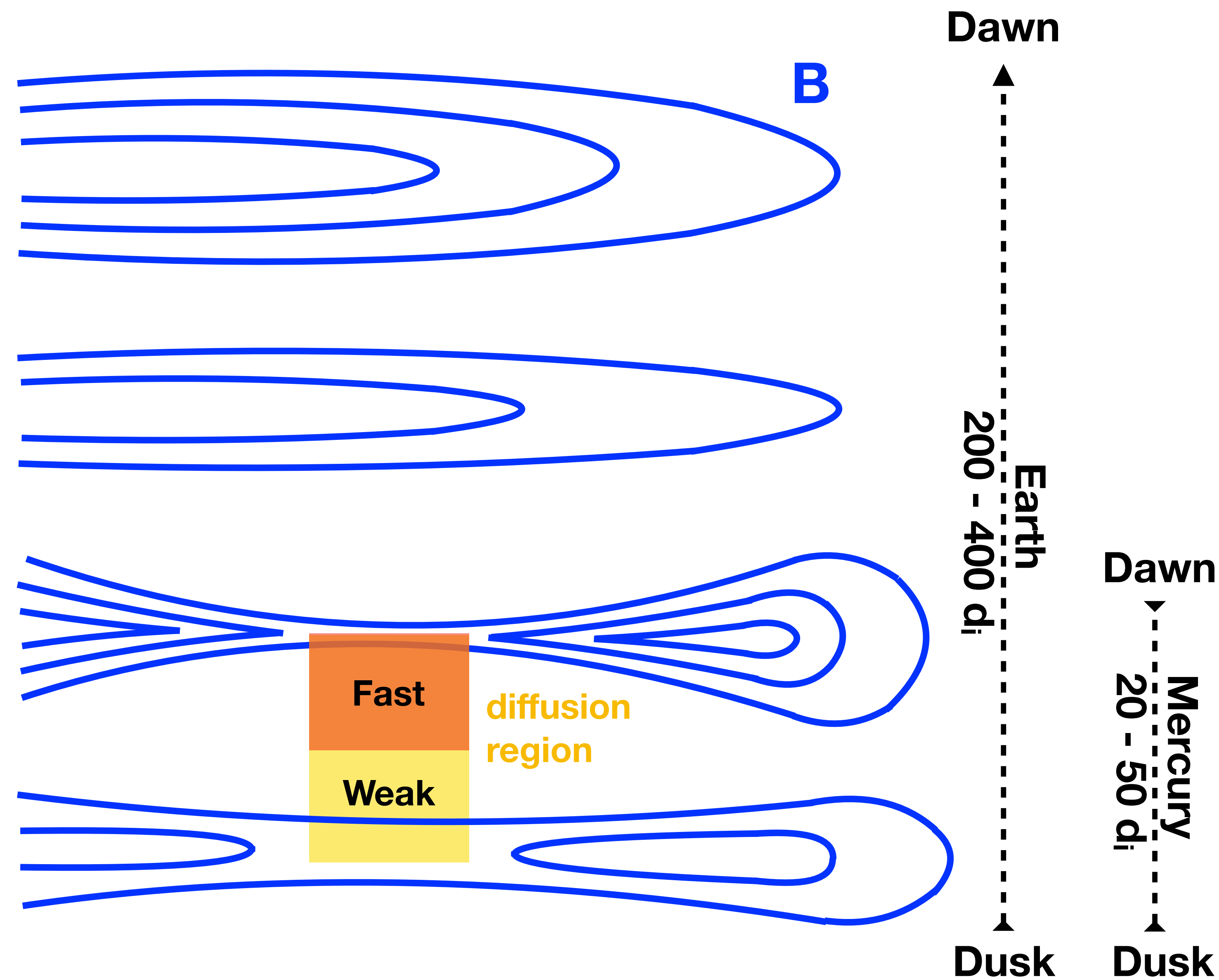
- Rate drops when the x-line extent is too short (<10 d_i) — shortest possible BBF!?
- Can explain the dawn-dusk asymmetry @ Mercury!

Explanation of the opposite dawn-dusk asymmetry at Earth & Mercury's magnetotails





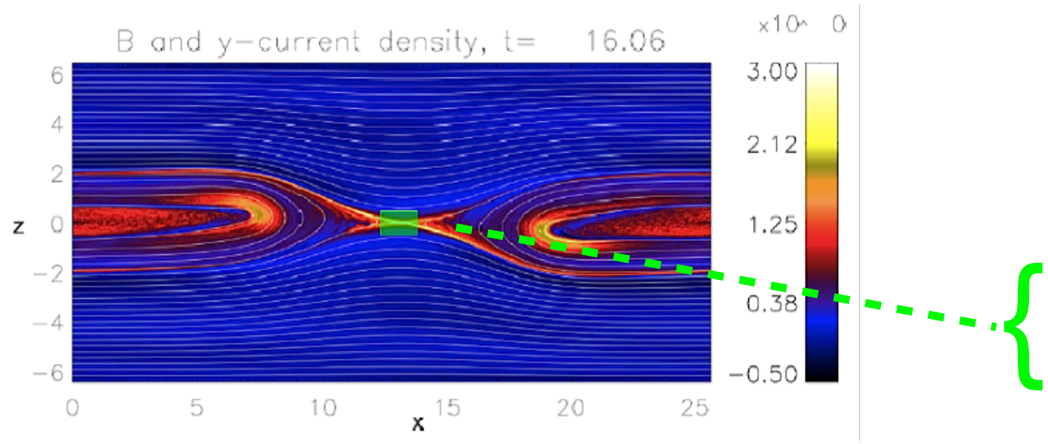
(Sun+ 2016)

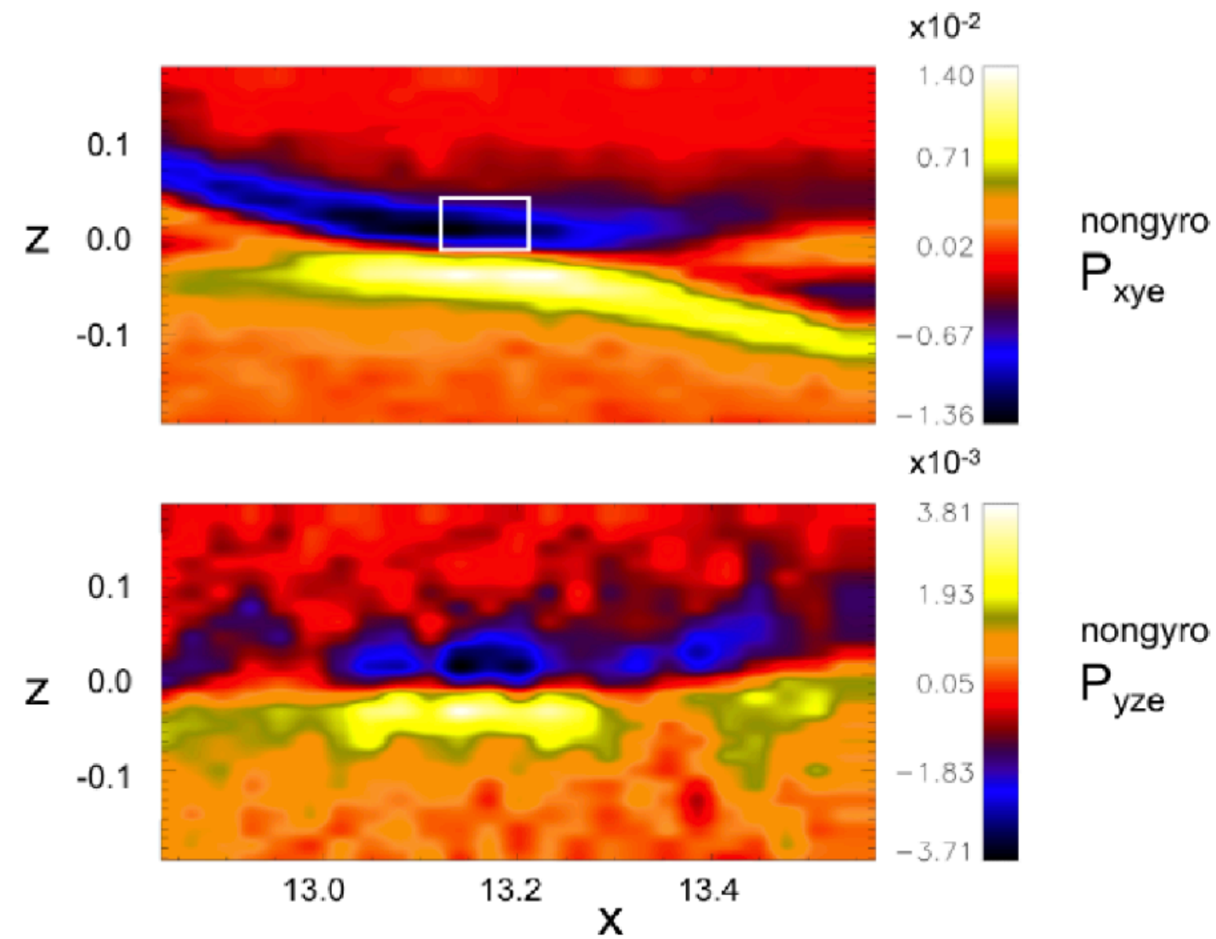


(Liu+ 2019)

- An argument based on the dawn-ward flux transport & reconnection physics.

DivPe and the role of reconnection electric field





$$E_y = -\frac{1}{n_e e}\left(\frac{\partial P_{xye}}{\partial x} + \frac{\partial P_{yze}}{\partial z}\right)$$

$$E \approx \frac{1}{2en} r_L^2 \frac{\partial v_x}{\partial x} \nabla^2 (mnv_y)$$

(Hesse+ Space Sci. Rev. 2011, tested by R. Nakamura 2018)

✦ Accelerates the current carriers

$$-\frac{\partial}{\partial t} e n_e v_{ey} = \frac{e^2 n_e}{m_e} E_y + \frac{e^2 n_e}{m_e} v_{ez} B_x - \frac{e^2 n_e}{m_e} v_{ex} B_z + \frac{e}{m_e}\left(\frac{\partial P_{yze}}{\partial z} + \frac{\partial P_{xye}}{\partial x}\right) + e\nabla \cdot n_e \vec{v}_e v_{ey}.$$

✦ Heats the sheet plasma

$$\frac{\partial p}{\partial t} = -\nabla \cdot (\vec{v} p) - \frac{2}{3}\sum_l P_{ll} \frac{\partial}{\partial x_l} v_l - \frac{1}{3}\sum_{l,i} \frac{\partial}{\partial x_i} Q_{lii} - \frac{2}{3}\sum_{\substack{l,i \\ l \neq i}} P_{li} \frac{\partial}{\partial x_i} v_l.$$

(Hesse+ PoP 2018)

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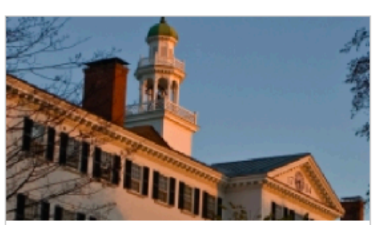

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