# 無衝突磁気リコネクションの内部構造 再考

## The inner structure of collisionless magnetic reconnection


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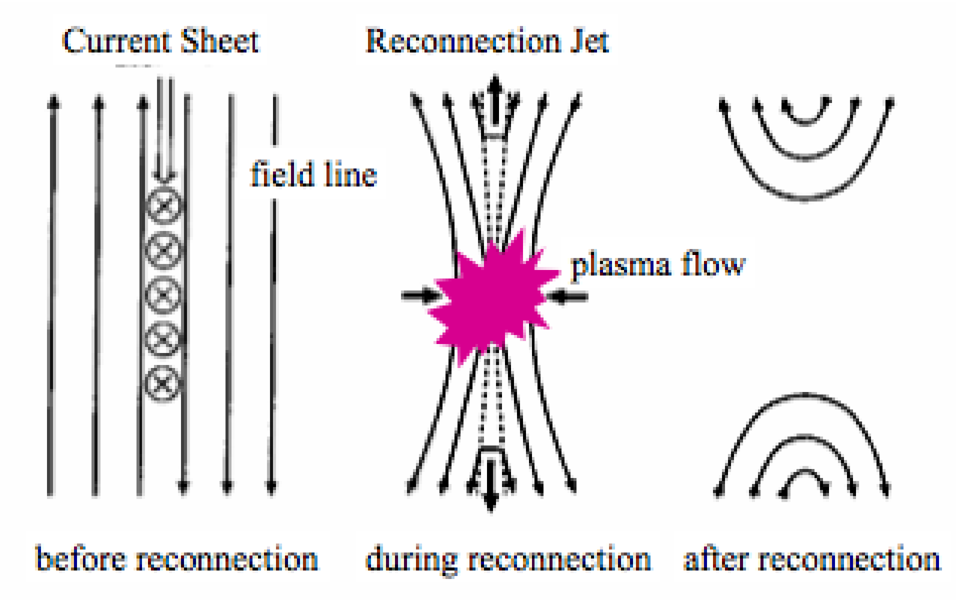
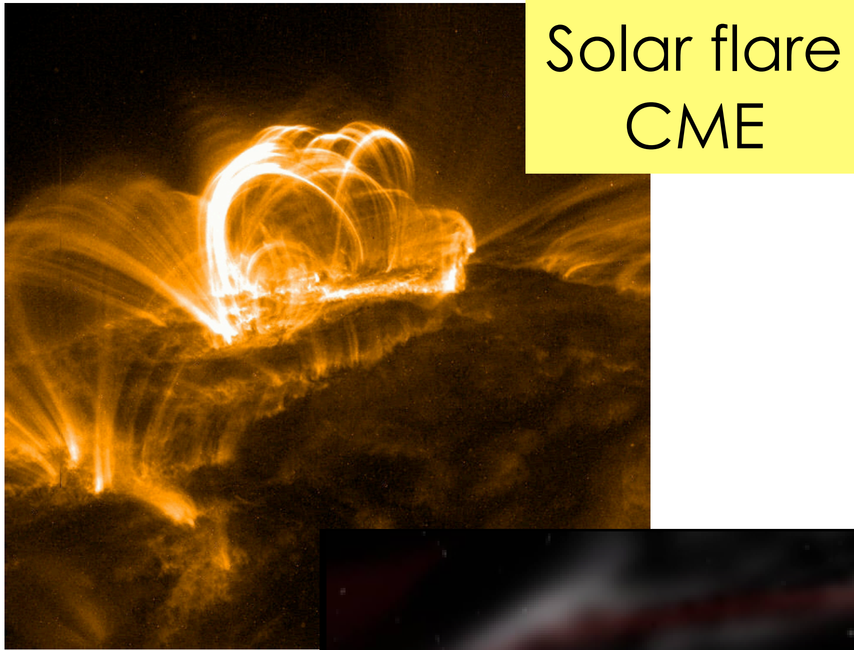
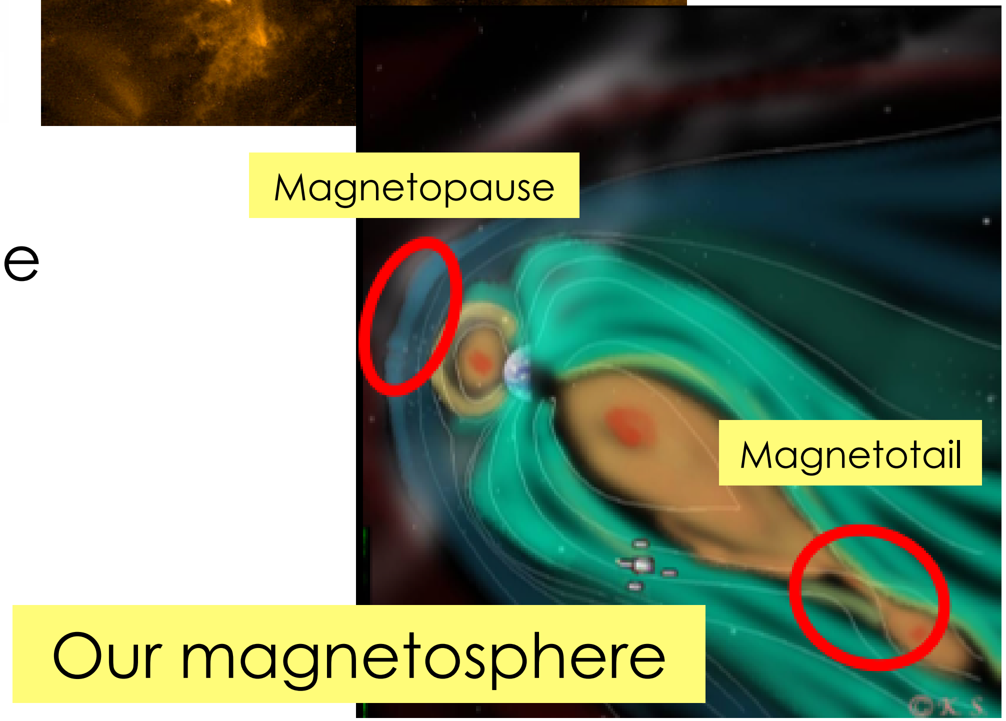
# Magnetic reconnection



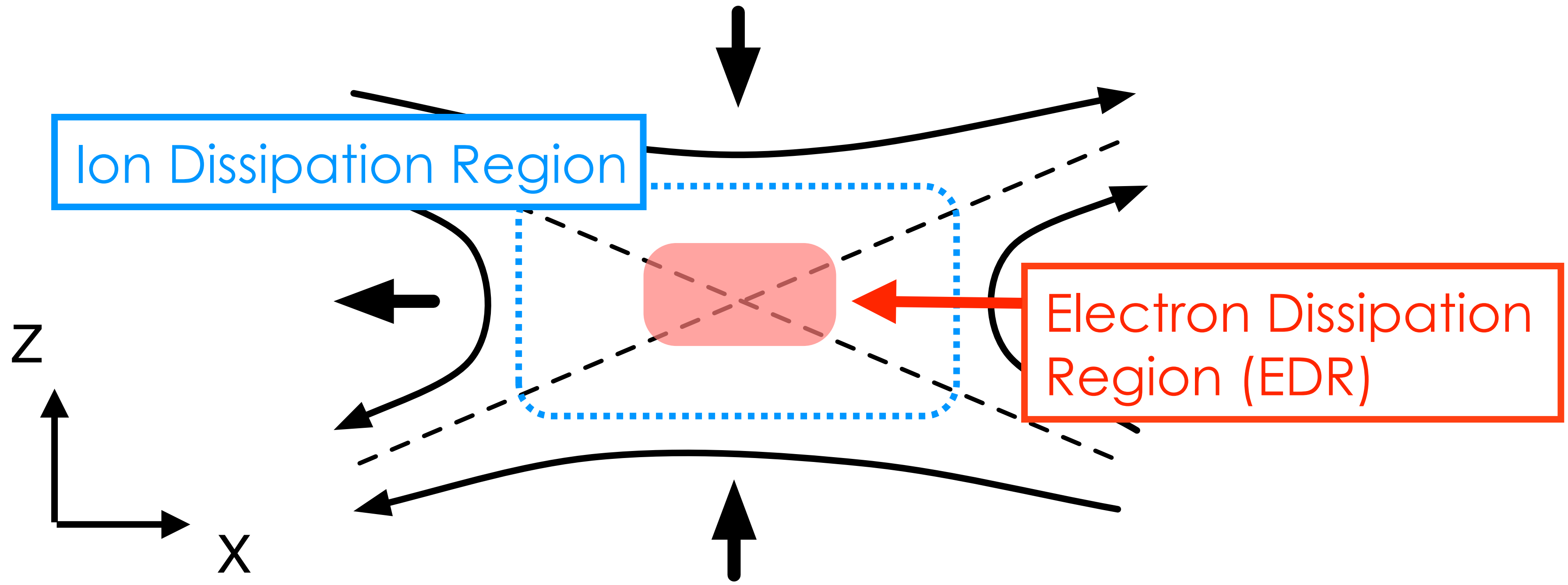

- Explosive topological change of magnetic field lines
- Beyond ideal-MHD

$$\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B} \neq 0$$

# Kinetic dissipation regions

- The ideal condition $\boldsymbol{E} + \boldsymbol{v}_s \times \boldsymbol{B} = 0$

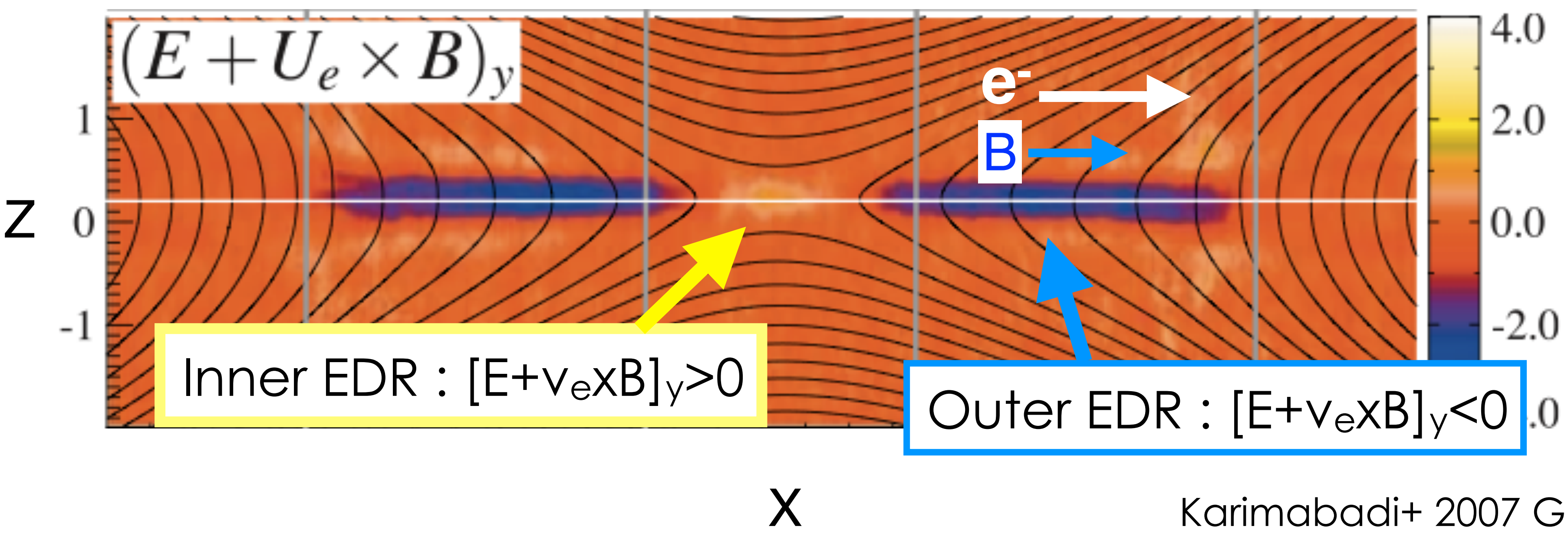
- We expected a multi-scale structure




- We are interested in the innermost EDR

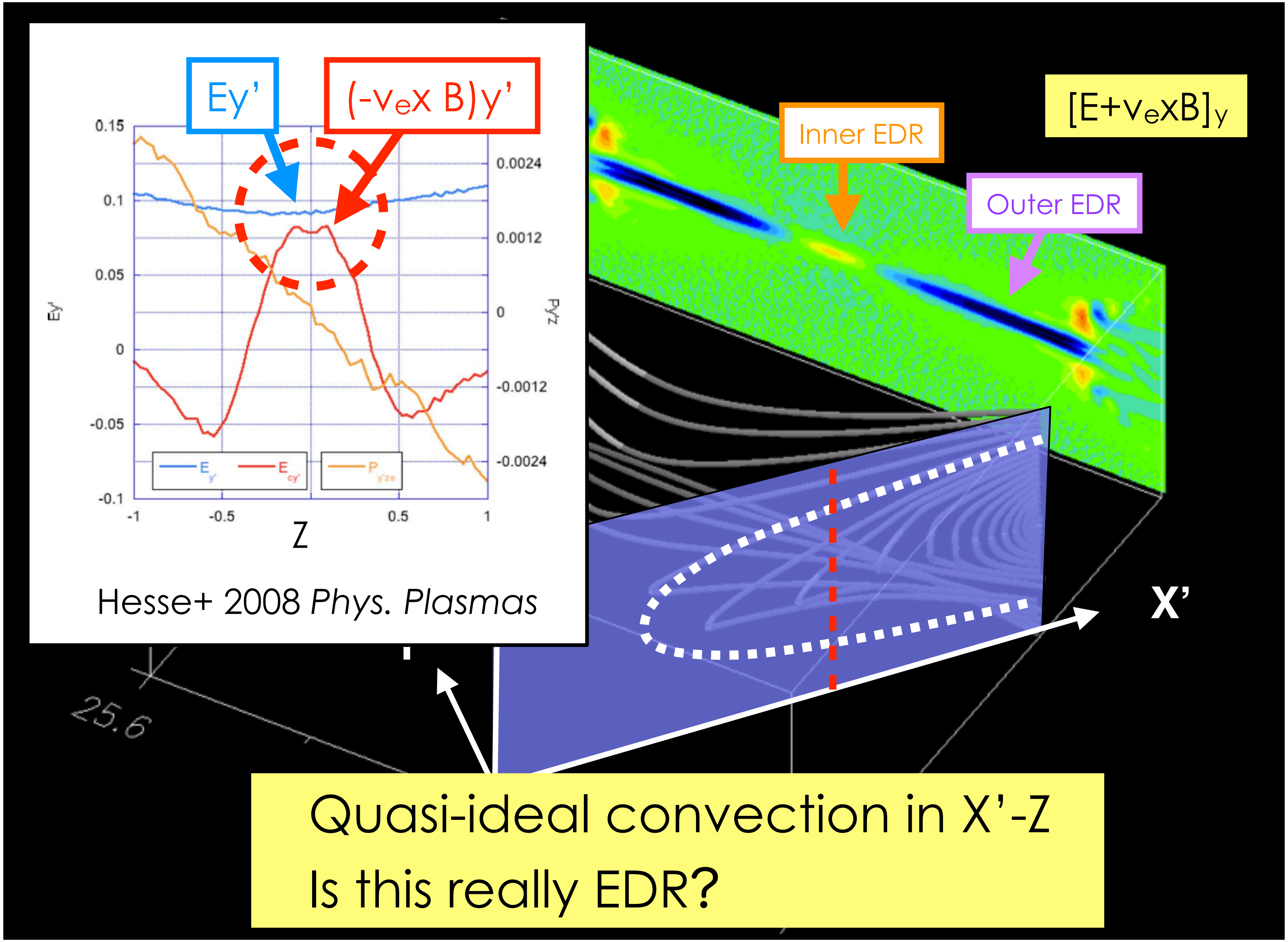
# EDR in 2D kinetic PIC simulations

- Large-scale PIC simulations
  - Daughton+ 2006, Fujimoto 2006, Karimabadi+ 2007, Shay+ 2007
- A two-scale structure
  - Inner region surrounding the X-point
  - Outer region elongated in the outflow (X) direction. A fast electron jet outruns the field lines.

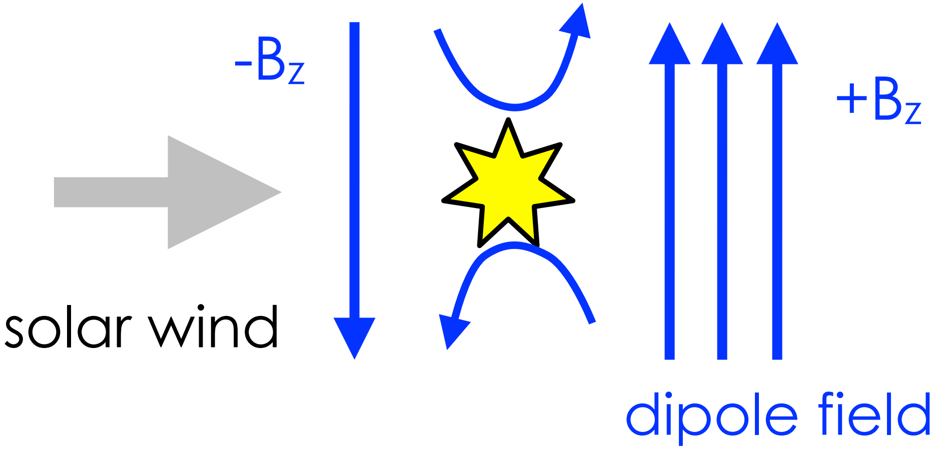



Karimabadi+ 2007 GRL

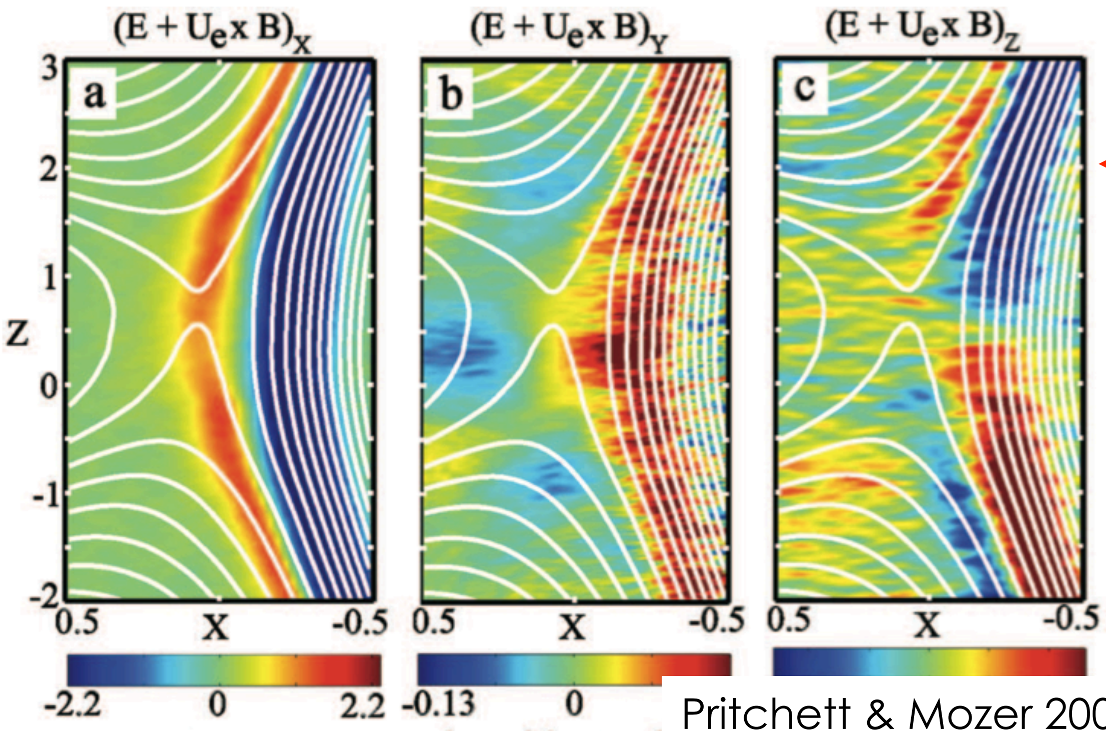
# From a different angle

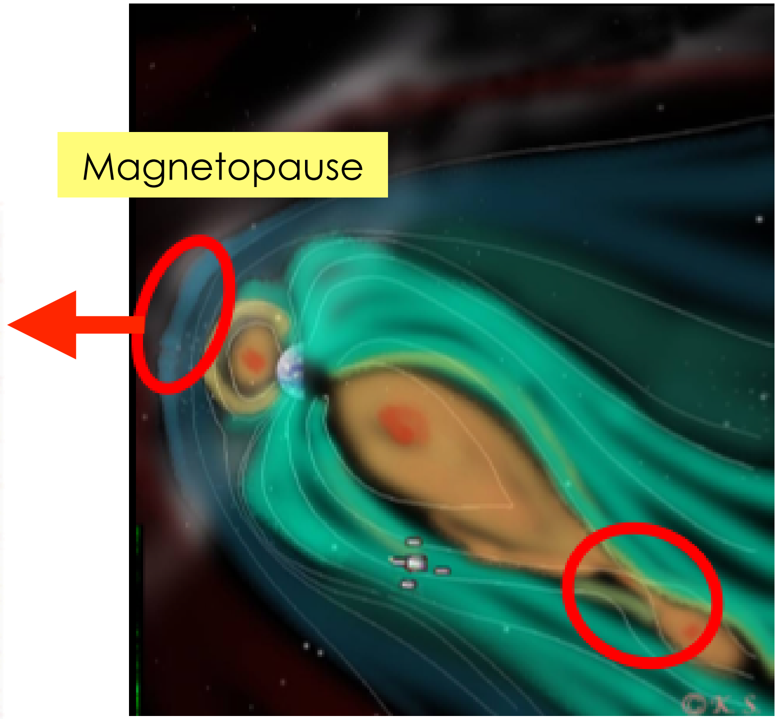


# EDR in asymmetric Rx




- "Asymmetric" reconnection
- All three components of $[E+v_e x B]$ are puzzling

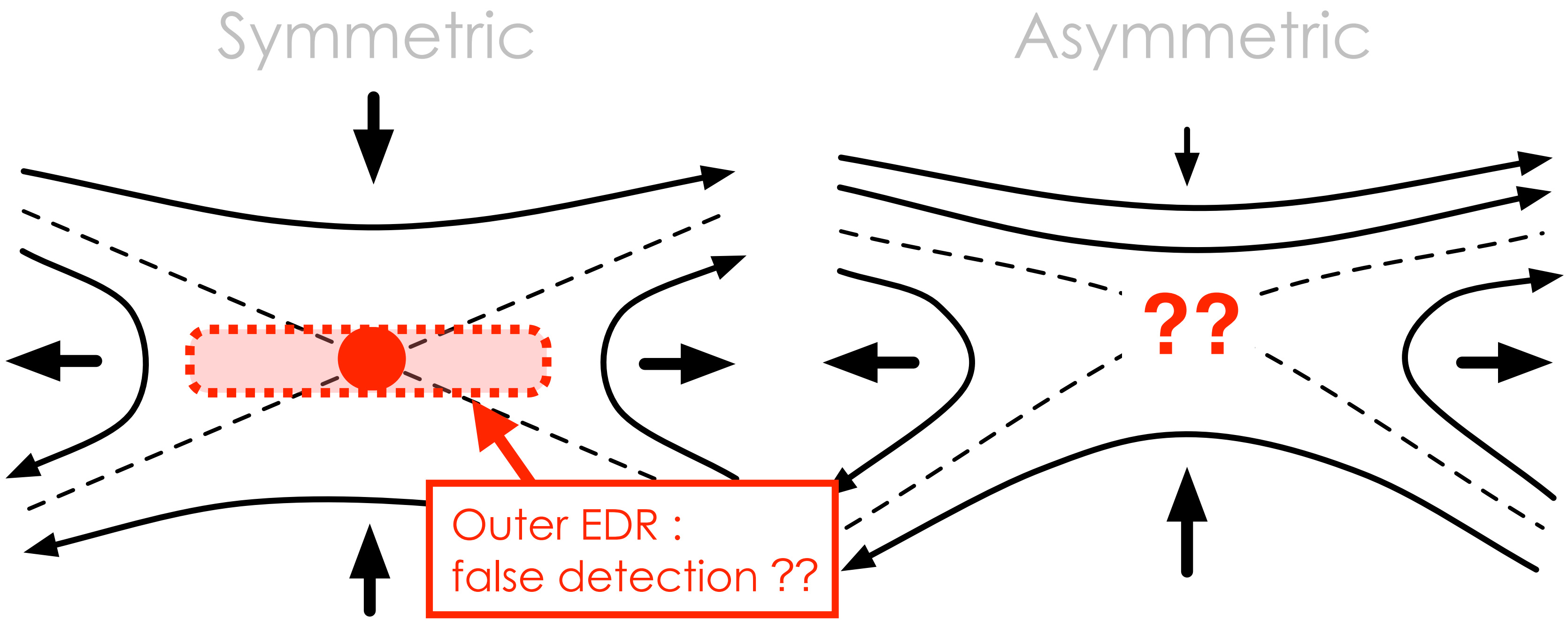



Pritchett & Mozer 2009 *Phys. Plasmas*

# Something is wrong

- The violation of the electron ideal condition ($E + v_e xB \neq 0$) may not identify the critical region.



# A new measure "D"

- Let us construct a new measure "D" to identify the critical region.

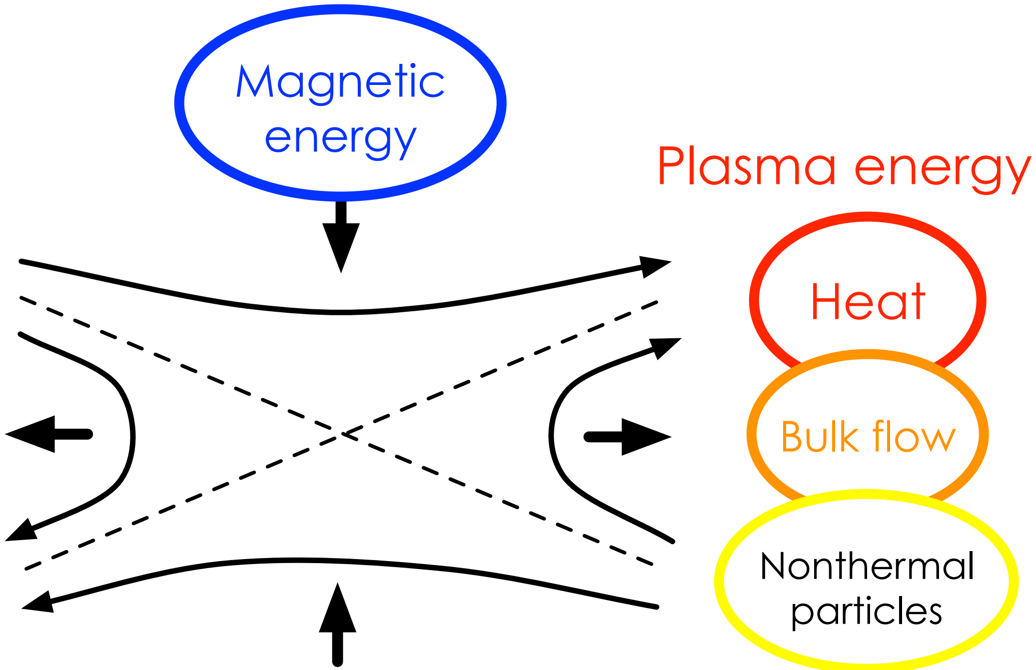
$$D_e = \gamma_e\left[\boldsymbol{j}\cdot(\boldsymbol{E}+\boldsymbol{v}_e\times\boldsymbol{B})-\rho_e(\boldsymbol{v}_e\cdot\boldsymbol{E})\right]$$

? ? ? ? ?

- We derive our formula from 3 requirements.

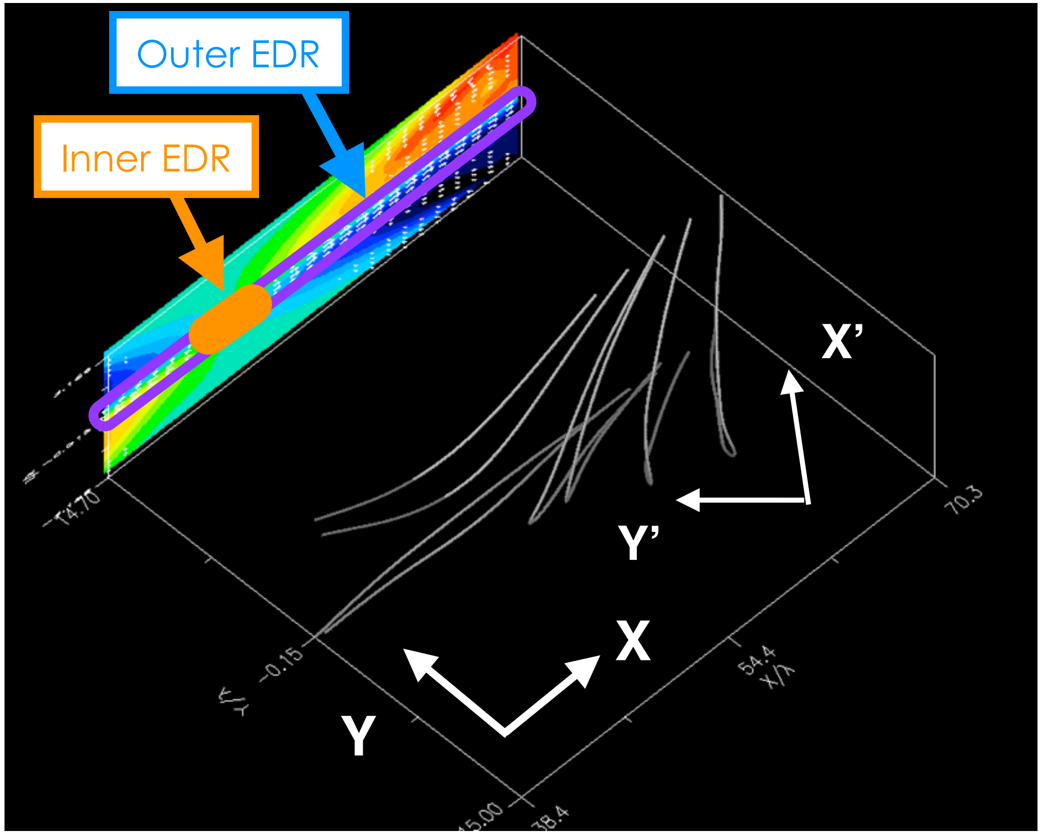
# Desirable conditions for "D" (1/3)

1. Magnetic energy consumption
2. Scalar quantity
3. Insensitive to observer motion



# Desirable conditions for "D" (2/3)

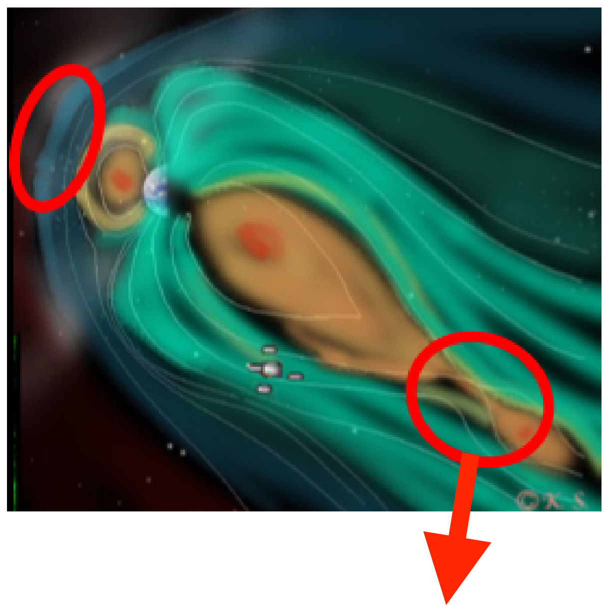
1. Magnetic energy consumption
2. Scalar quantity
3. Insensitive to observer motion

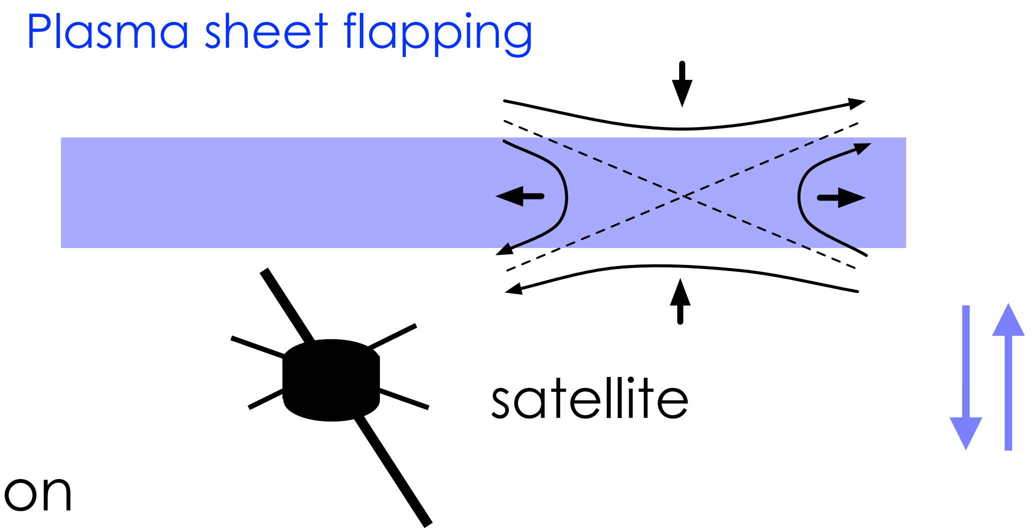



- If we employ a scalar quantity, we don't need to worry about the coordinate. The Y direction or the Y' direction do not matter.

# Desirable conditions for “D” (3/3)

1. Magnetic energy consumption
2. Scalar quantity
3. Insensitive to observer motion






- There is always relative motion between the observer (satellite) and the reconnection site

# Electron-frame dissipation measure

電子系散逸量

$$D_e = J_\mu F^{\mu\nu} u_{e,\nu} = \gamma_e \left[ \boldsymbol{j} \cdot (\boldsymbol{E} + \boldsymbol{v}_e \times \boldsymbol{B}) - \rho_c (\boldsymbol{v}_e \cdot \boldsymbol{E}) \right]$$
$$= \boldsymbol{j}' \cdot \boldsymbol{E}'$$

Charge density

- The prime sign (‘) : quantities in the electron flow’s frame

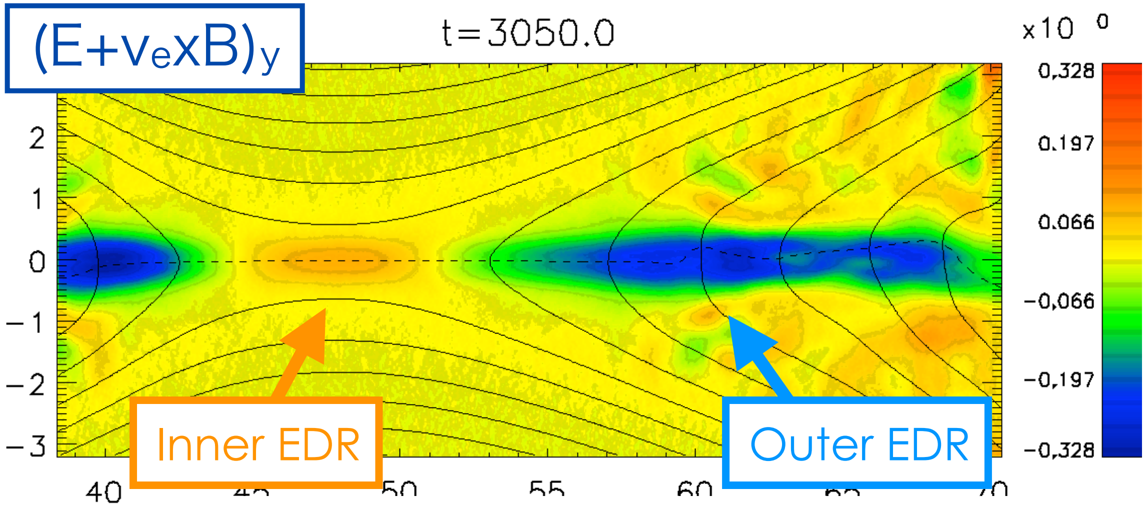
Desirable conditions

✓ 1. Magnetic energy consumption

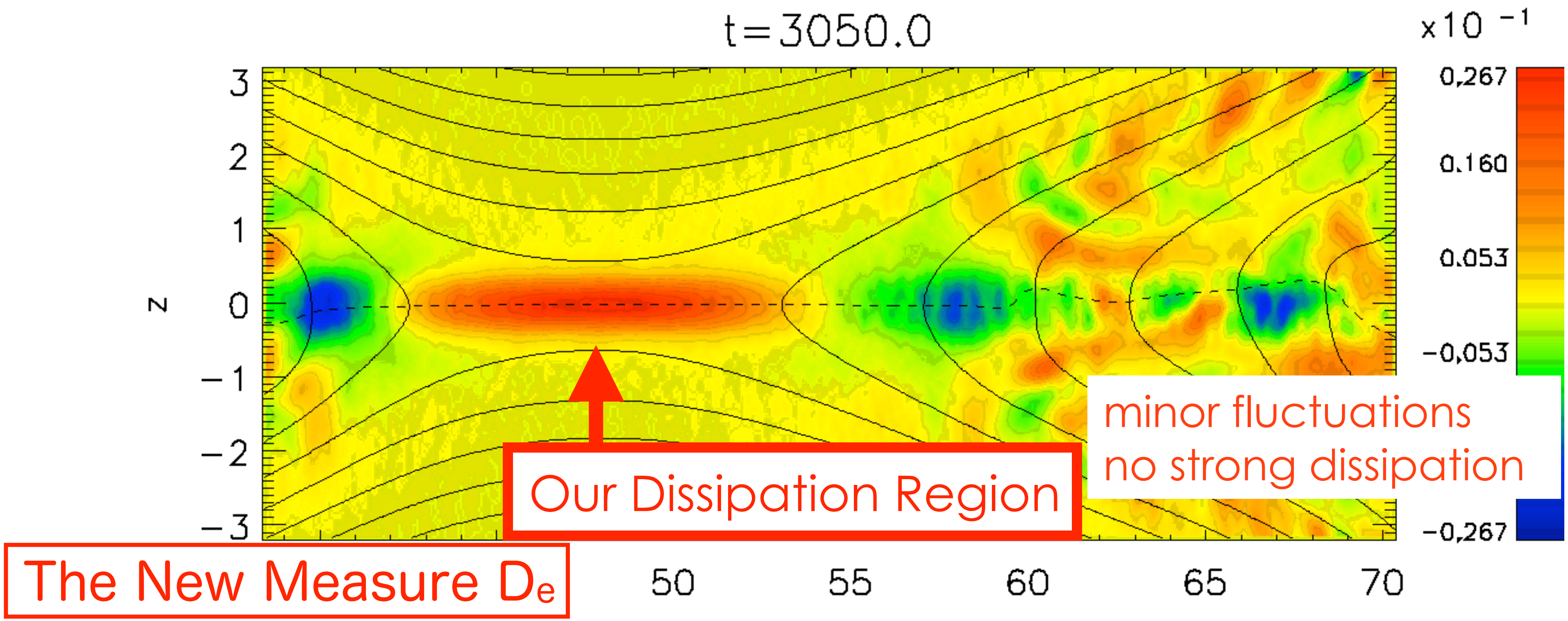
✓ 2. Scalar quantity

✓ 3. Insensitive to observer motion

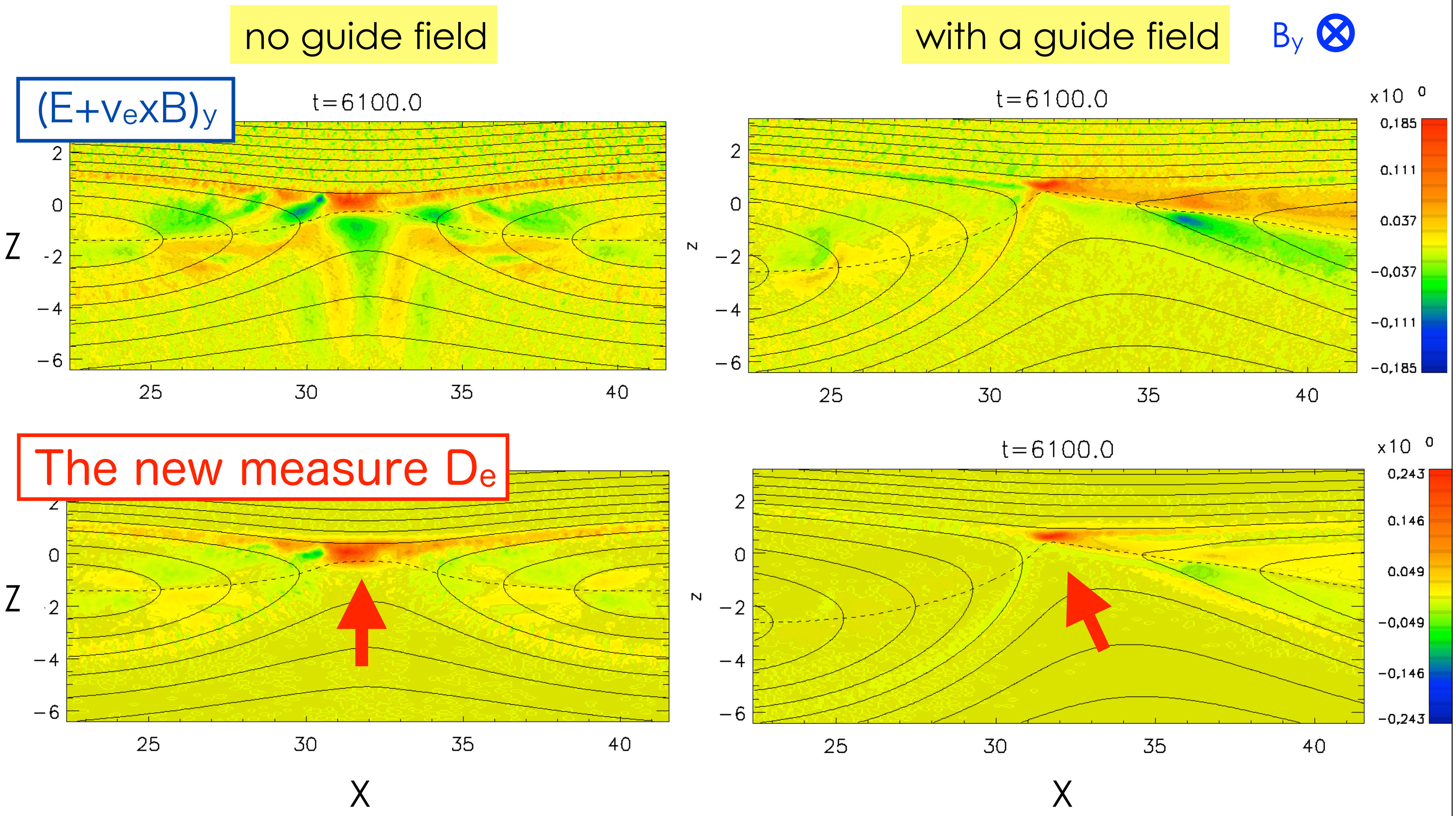
# 2D PIC simulation (1/2) : Symmetric Rx




- Mass ratio $m_i/m_e$=25
- $10^9$ particles



# 2D PIC simulation (2/2) : Asymmetric Rx



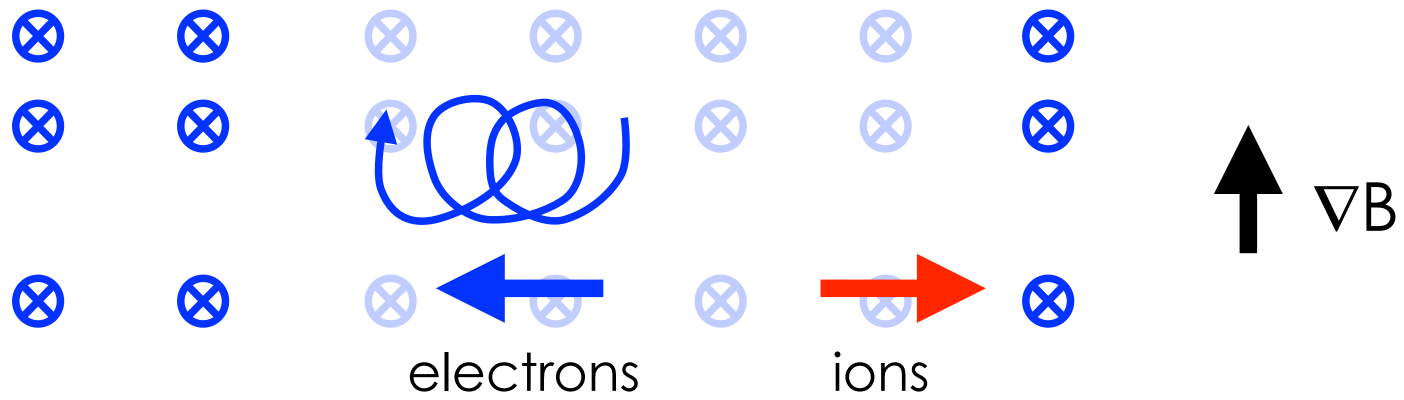

- $D_e$ accurately locates the reconnection site
- The field reversal line is located inside the dissipation region

# Why (E+$v_e$xB) does not work?

- The ideal condition assumes the E x B drift motion.

$$\boldsymbol{E} + \boldsymbol{v}_s \times \boldsymbol{B} = 0$$

- Example: ∇B drift in no background E
  - Particles don't consume the field energy neither in this frame nor in the electron frame: $D_e$=0




- Line conservation

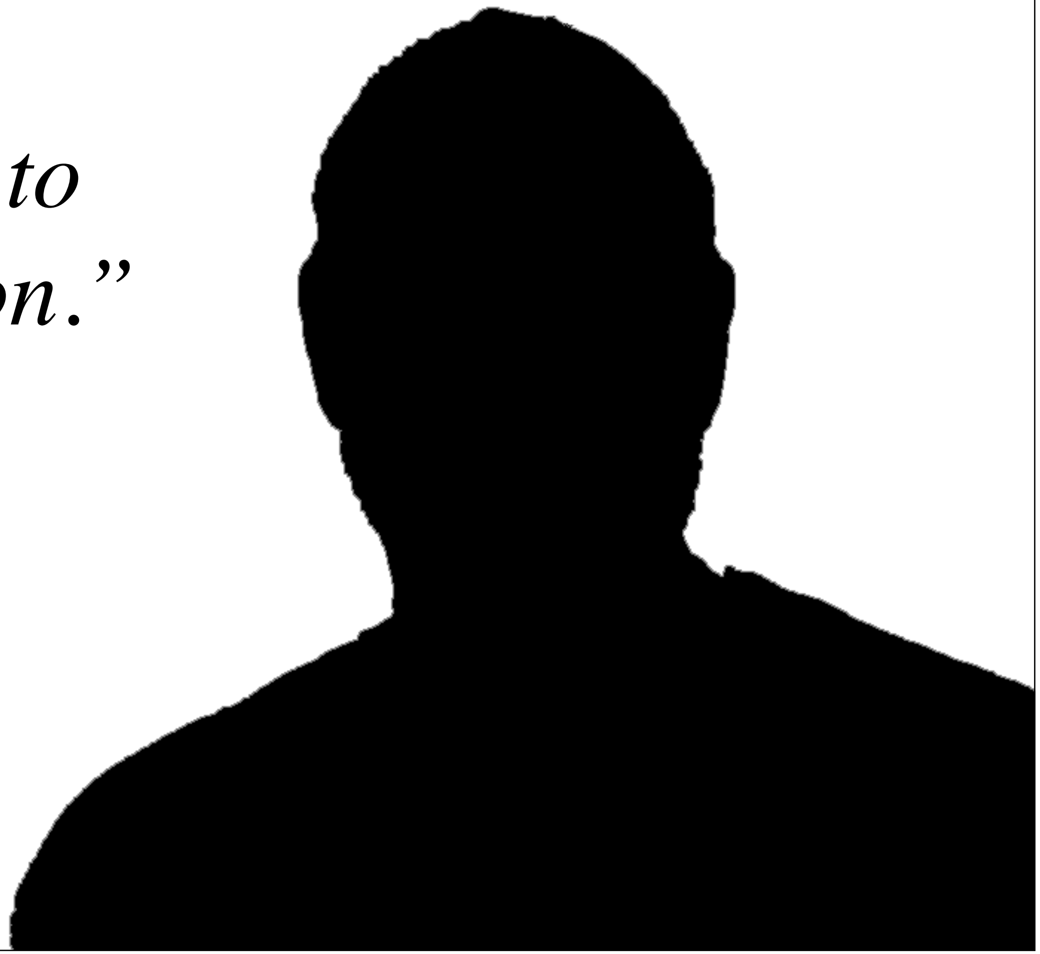
$$\boldsymbol{E} + \boldsymbol{v}_e \times \boldsymbol{B} = \boldsymbol{R}, \quad \boldsymbol{B} \times (\nabla \times \boldsymbol{R}) = 0$$

- The ideal frozen-in condition does not always work, however, we paid too much attention to the frozen-in.

$$\boldsymbol{E} + \boldsymbol{v}_e \times \boldsymbol{B} \neq 0$$

*"We were frozen-in to the frozen-in condition."*

*Steve Jobs*



# Energy budget

- Resistive MHD (e.g. Birn & Hesse 2005)

$$\boldsymbol{E} + \boldsymbol{v}_{\rm mhd} \times \boldsymbol{B} = \eta \boldsymbol{j}$$

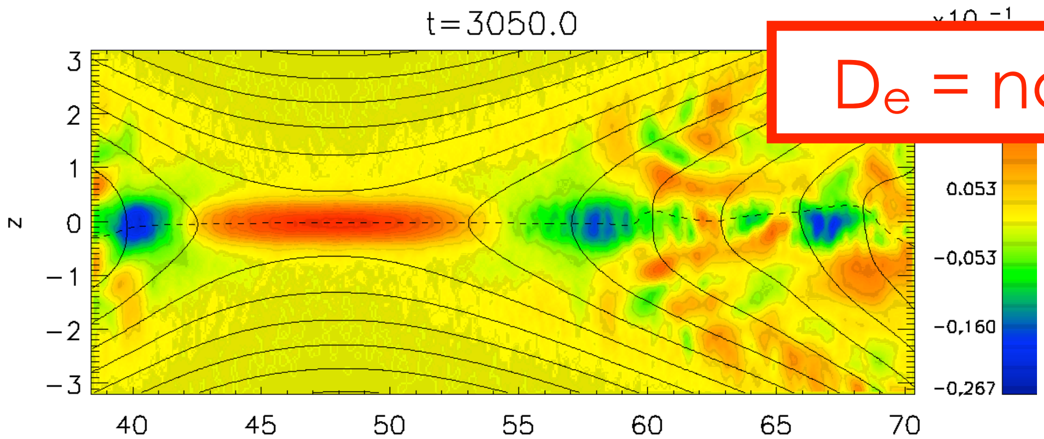
$$\boldsymbol{j} \cdot \boldsymbol{E} = (\boldsymbol{j} \times \boldsymbol{B}) \cdot \boldsymbol{v}_{\rm mhd} + \eta \boldsymbol{j}^2$$

work by Lorentz force — Non-ideal

- Kinetic neutral plasma

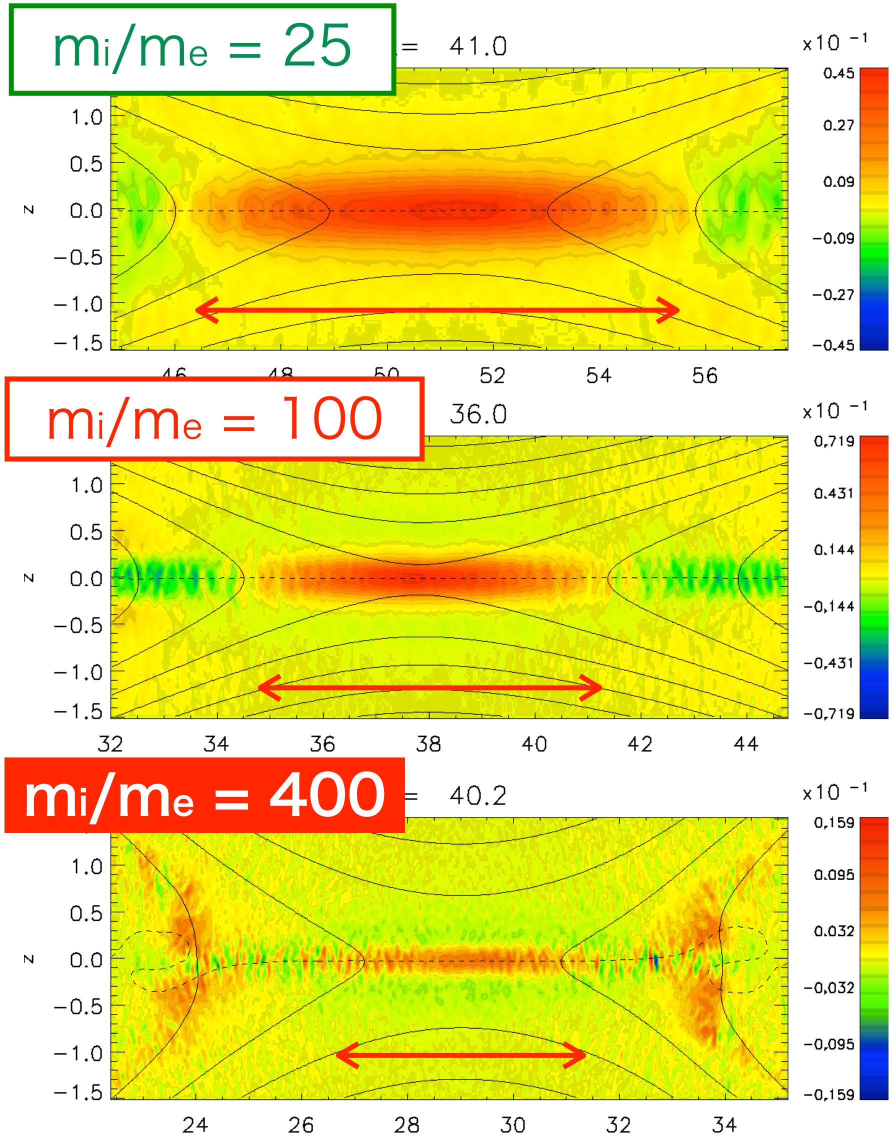
$$\boldsymbol{j} \cdot \boldsymbol{E} \approx (\boldsymbol{j} \times \boldsymbol{B}) \cdot \boldsymbol{v}_{\rm mhd} + D_e$$

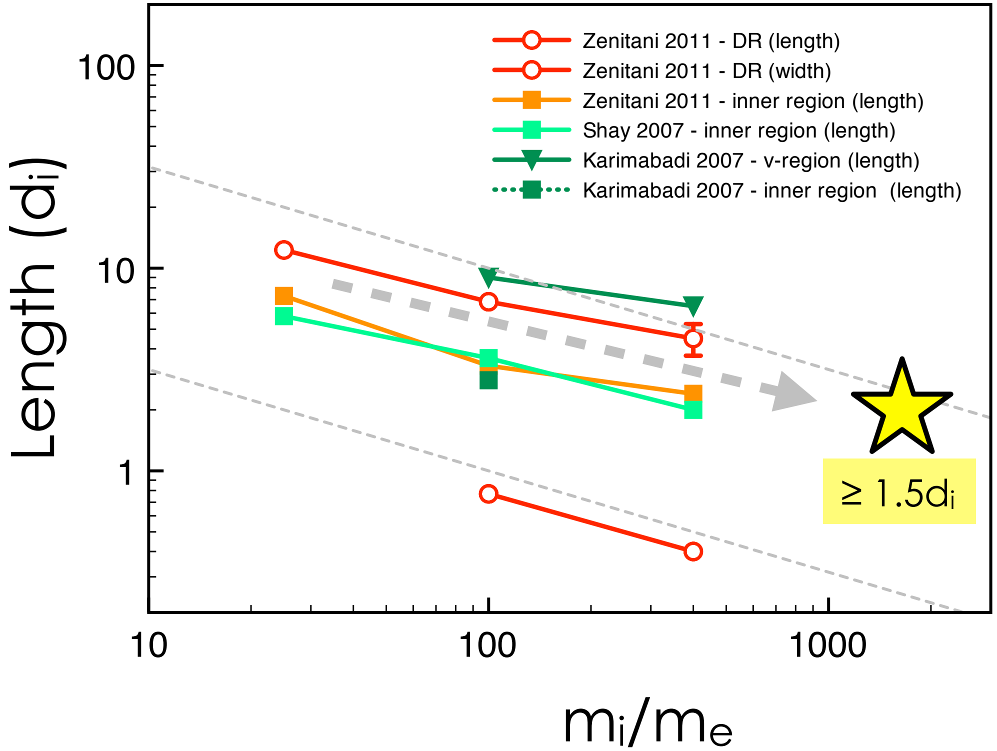
Non-ideal




$D_e$ = nonideal energy transfer

# Mass-ratio scaling

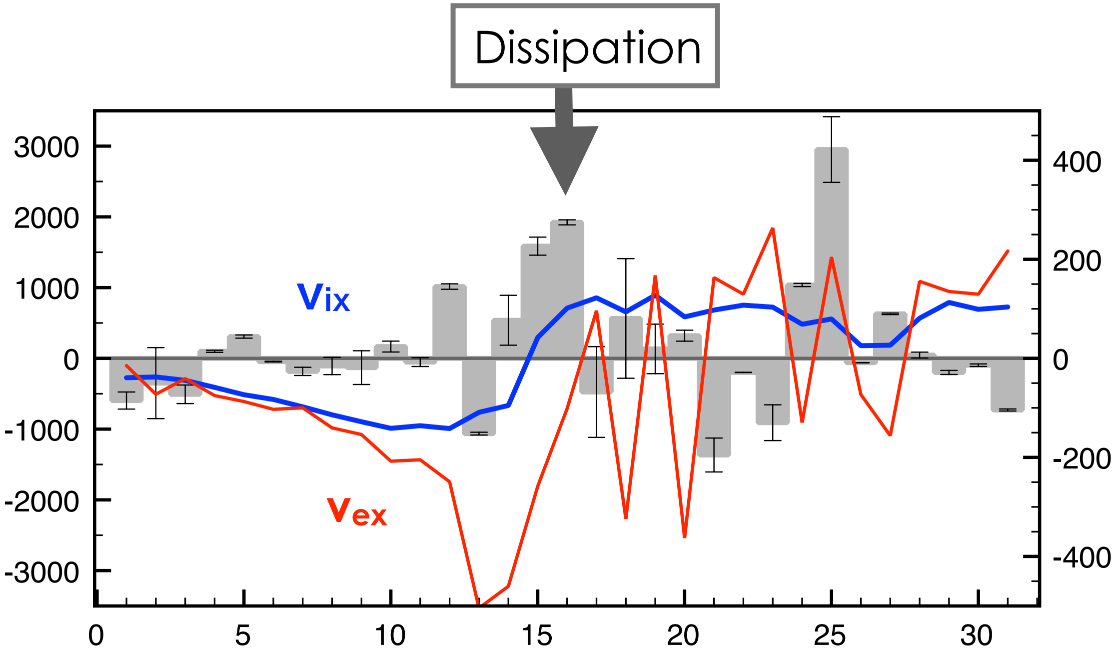


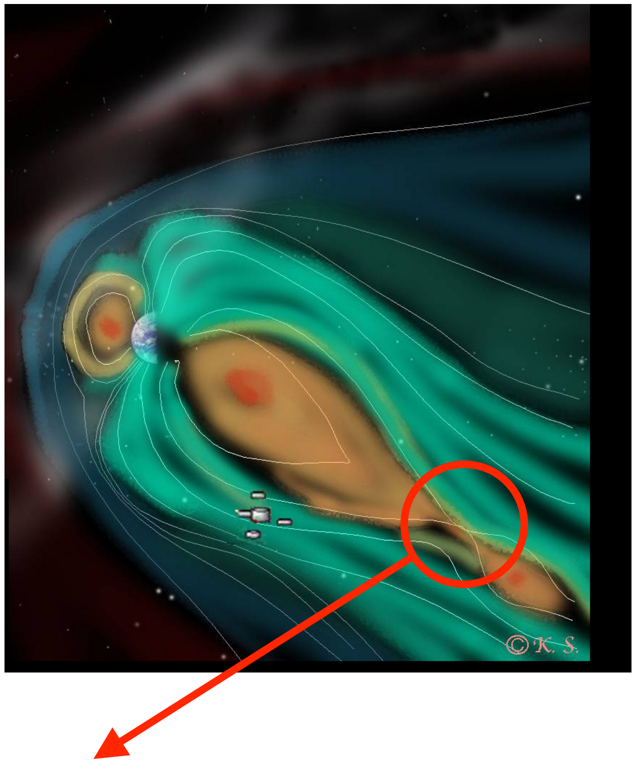



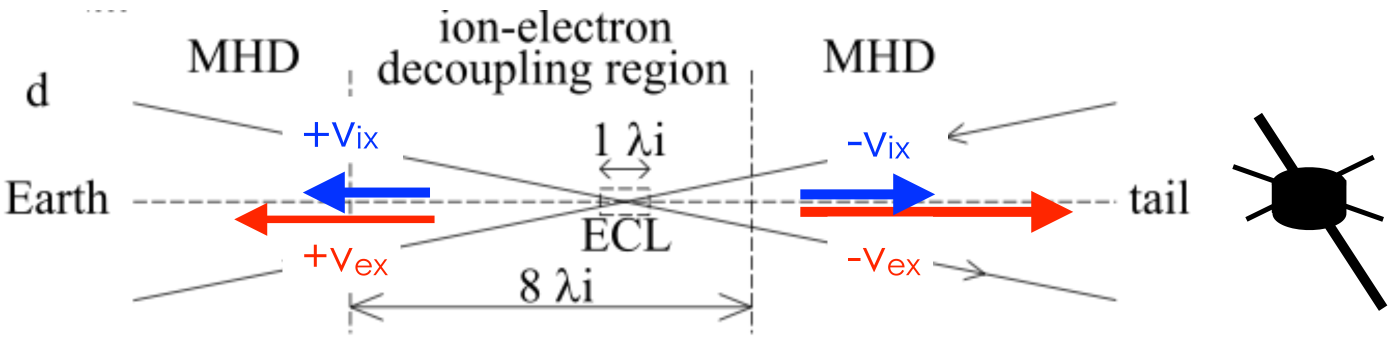

- $L_{DR} \geq 1.5 d_i$ in the real world
- After Aug 2014, MMS satellites will probe sub-$d_i$ scales.

# GEOTAIL observation (May 15 2003)

- A very lucky reconnection event

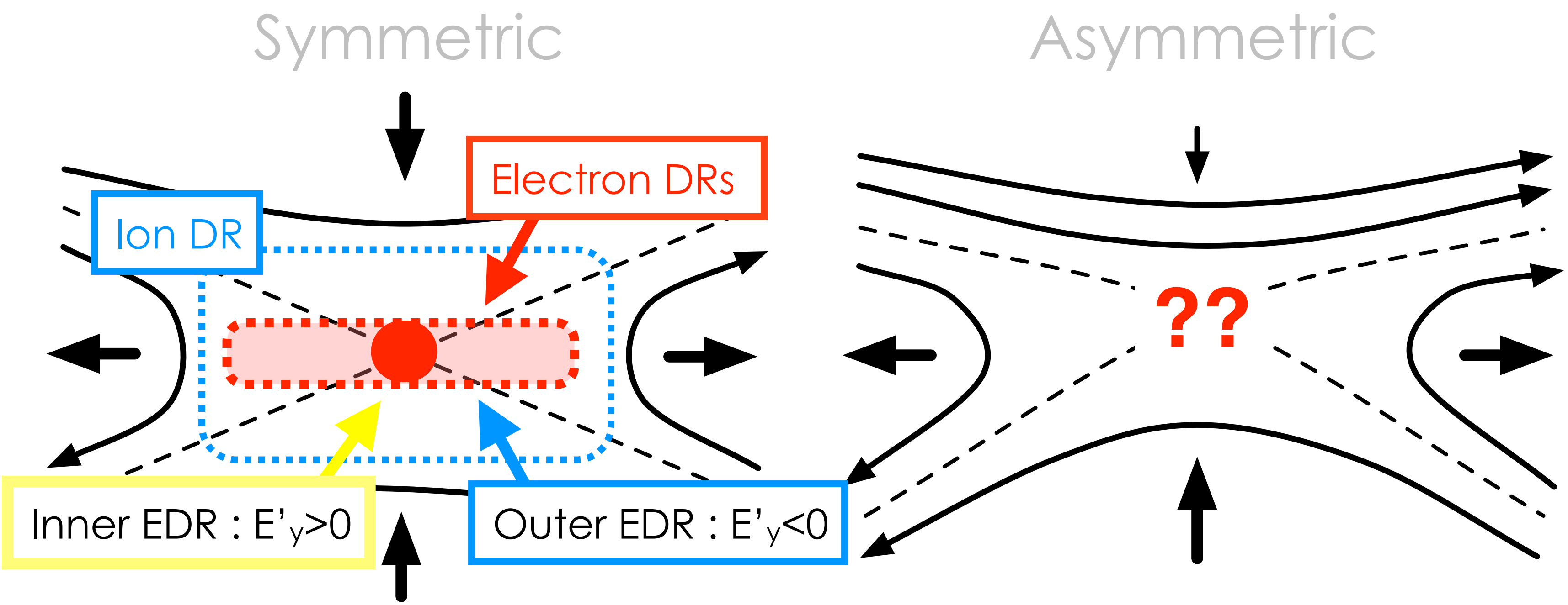


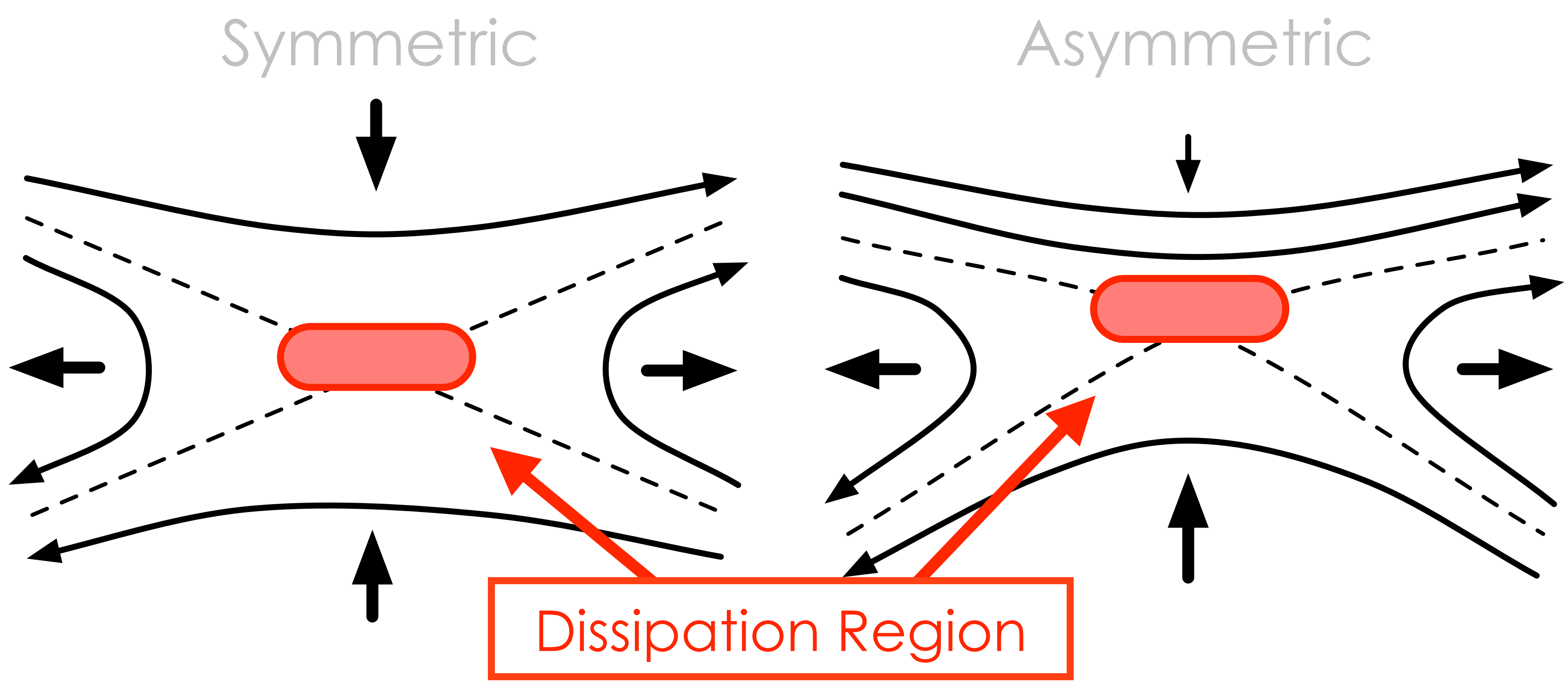

Nagai et al. 2011 JGR, SZ & Shinohara, in prep

# Summary (1/2): previous picture




$$\boldsymbol{E} + \boldsymbol{v}_e \times \boldsymbol{B} \neq 0$$

# Summary (2/2): new picture




- We propose to redefine the dissipation region using the *electron-frame dissipation measure*.

$$D_e = \gamma_e \left[ \boldsymbol{j} \cdot (\boldsymbol{E} + \boldsymbol{v}_e \times \boldsymbol{B}) - \rho_c (\boldsymbol{v}_e \cdot \boldsymbol{E}) \right]$$

- It excellently works both in simulations and observations.

*Thank you for your attention!!*

- Zenitani et al., *Phys. Rev. Lett.*, **106**, 195003 (2011)
- Zenitani et al., *Phys. Plasmas*, **18**, 122108 (2011)