A new measure of the dissipation region in collisionless magnetic reconnection

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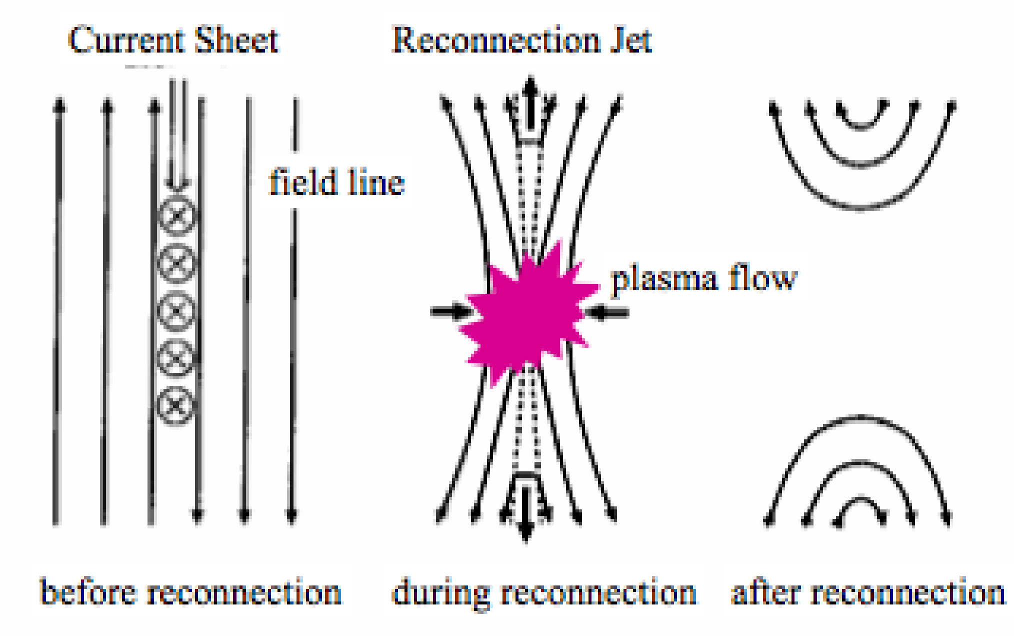
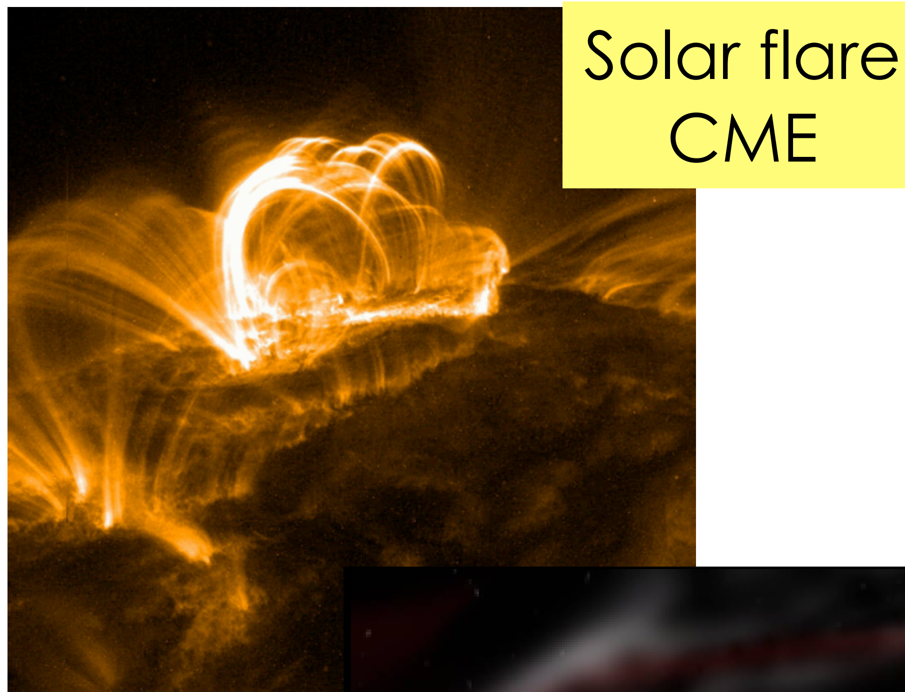
Outline

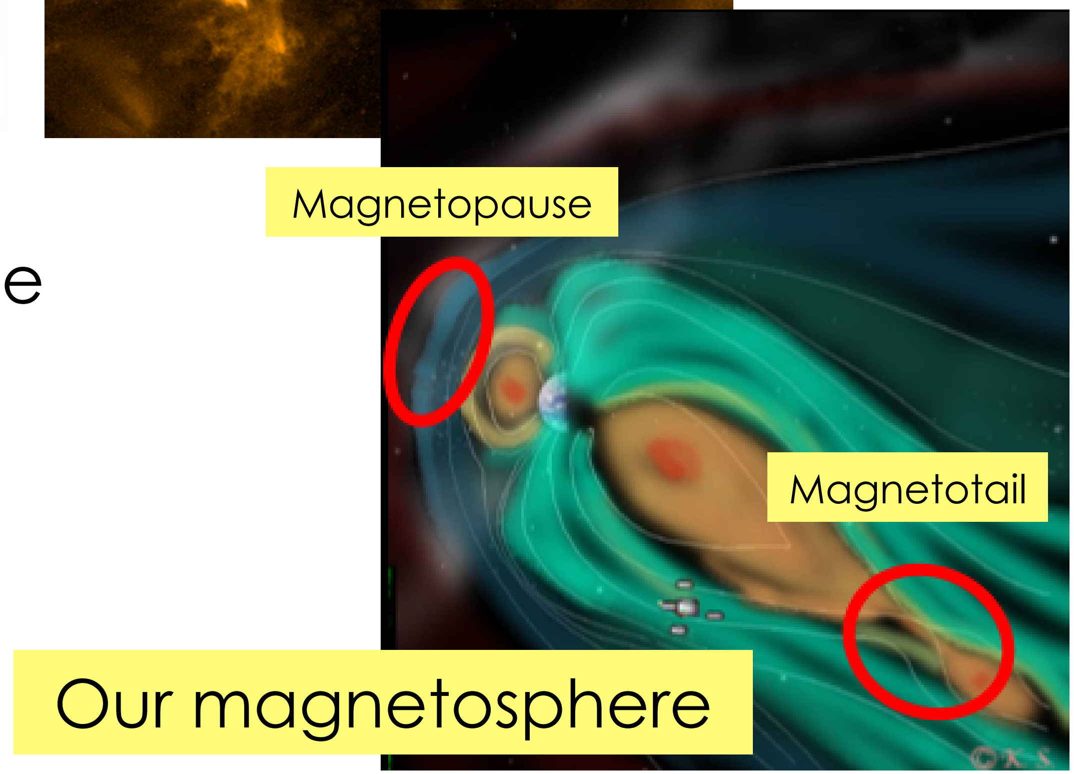
- 1. Introduction
  - Recent debates on the electron diffusion region (EDR)
- 2. Theory
  - Introducing a new measure D_e
- 3. Numerical tests & discussions
  - 2D kinetic PIC simulations
  - What's wrong with the frozen-in and why D_e works?
- 4 & 5. Applications
  - Closer look at the reconnection structure
  - Satellite observation

1. Introduction

Magnetic reconnection







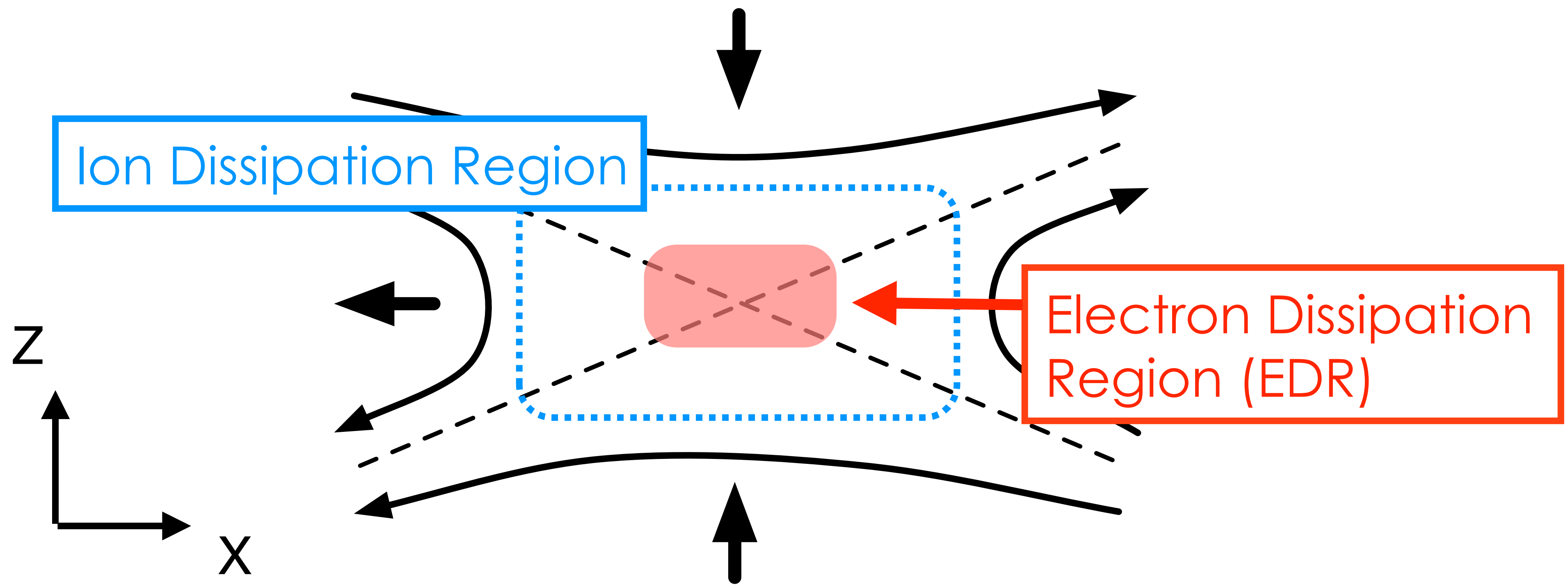
- Explosive topological change of magnetic field lines
- Beyond ideal-MHD

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

The dissipation region

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

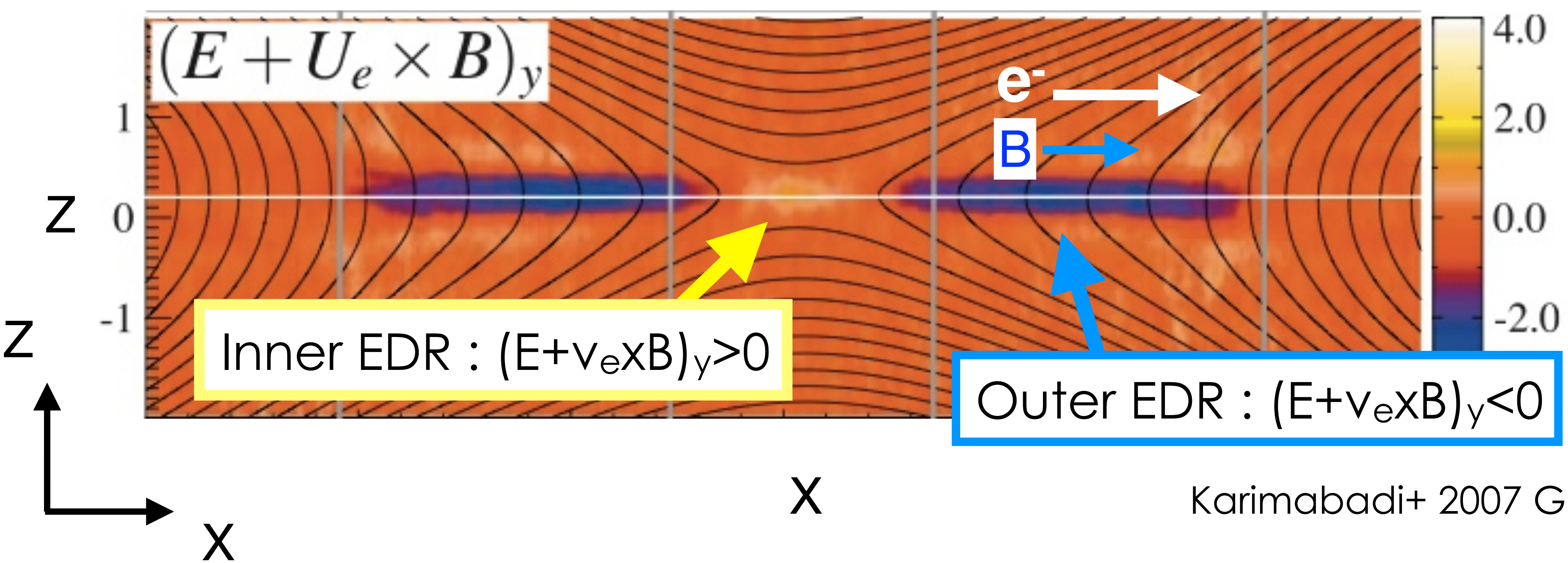
- We expected a multi-scale structure



- We are interested in the innermost EDR
  - It is traditionally identified by $\boldsymbol{E}'_y = (\boldsymbol{E} + \boldsymbol{v}_e \times \boldsymbol{B})_y \neq 0$

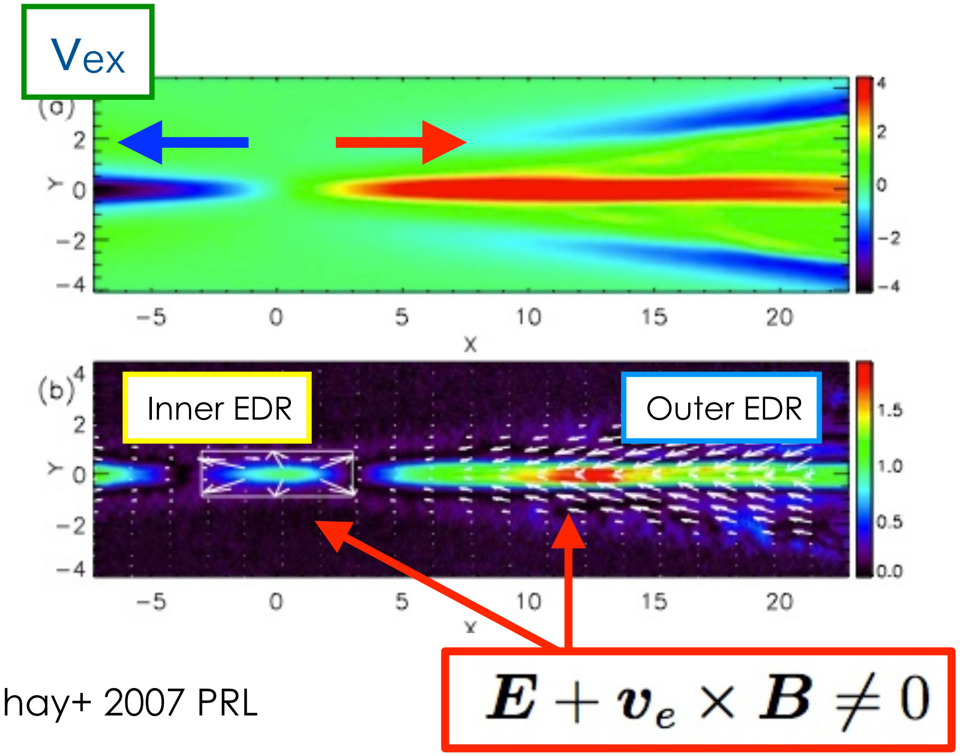
EDR in 2D kinetic PIC simulations (1/2)

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

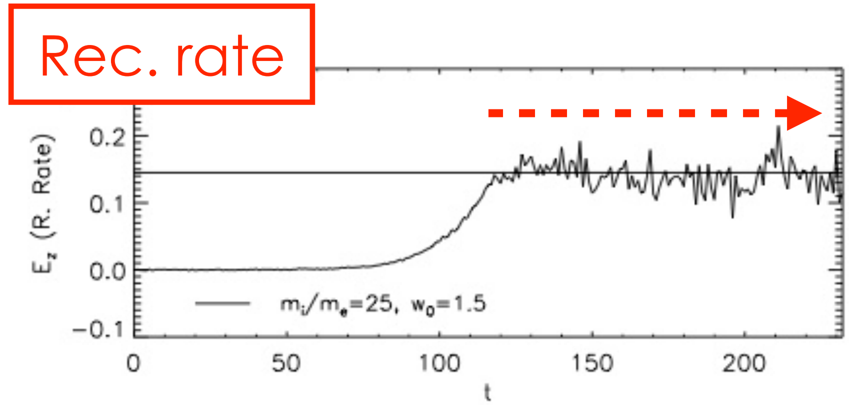


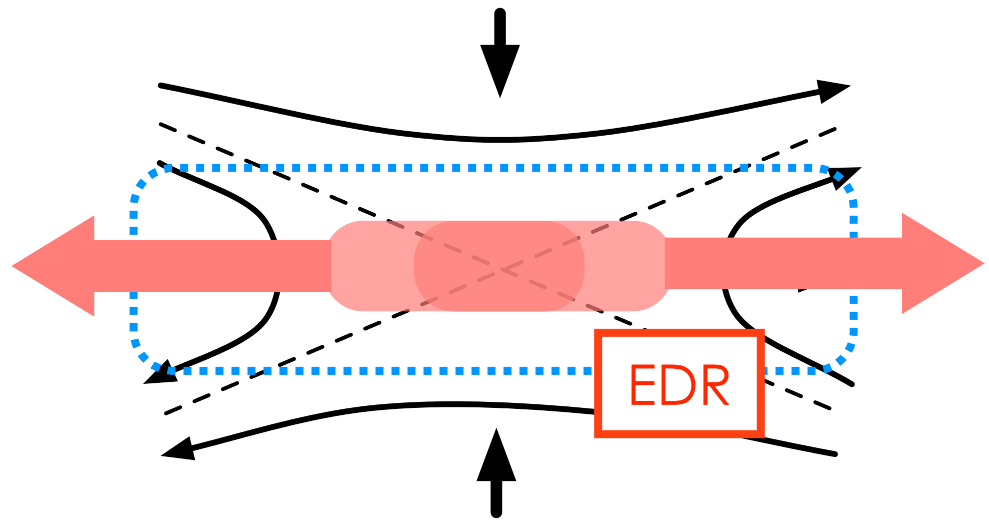
Karimabadi+ 2007 GRL

EDR in 2D kinetic PIC simulations (2/2)



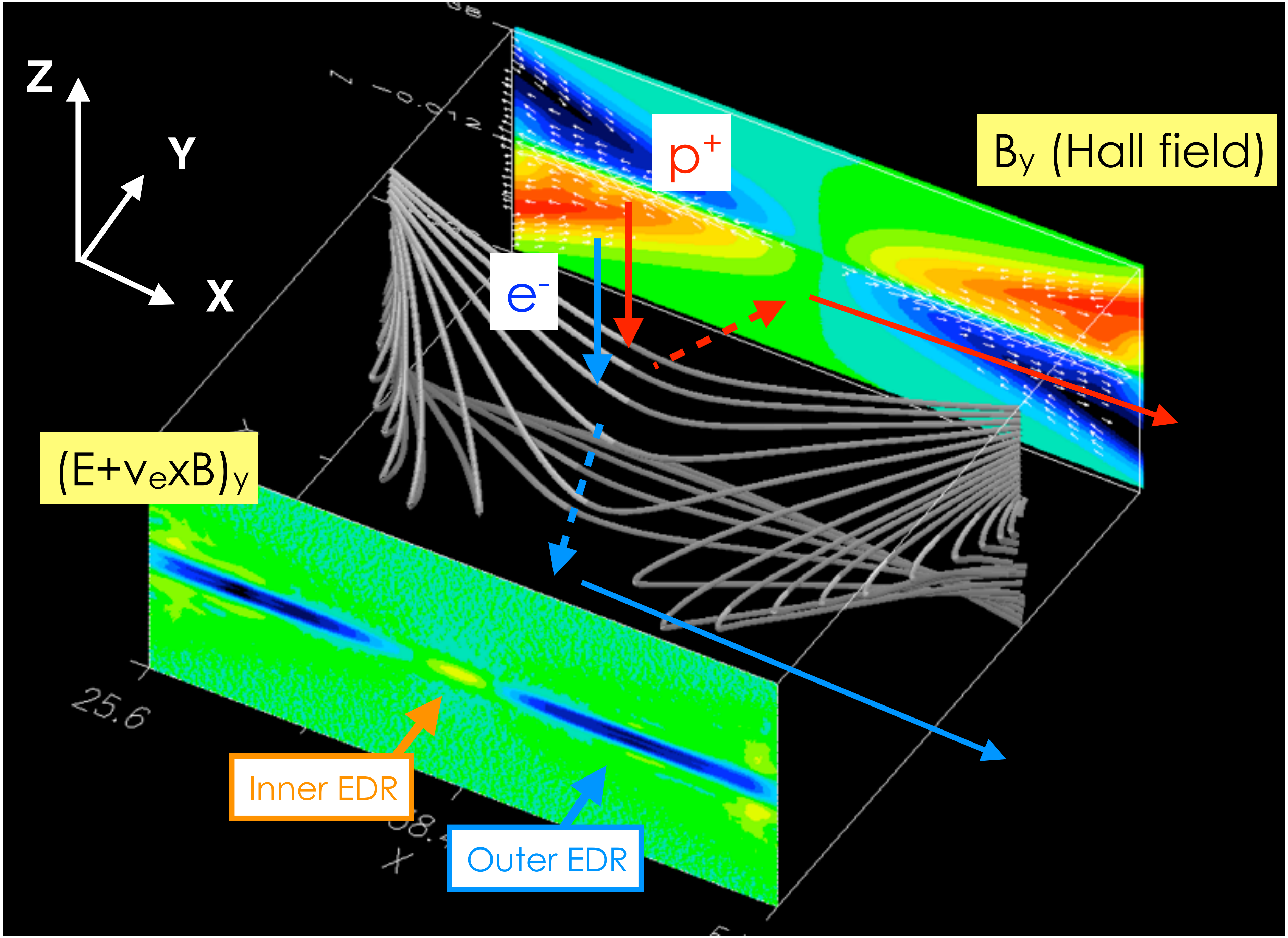
Shay+ 2007 PRL



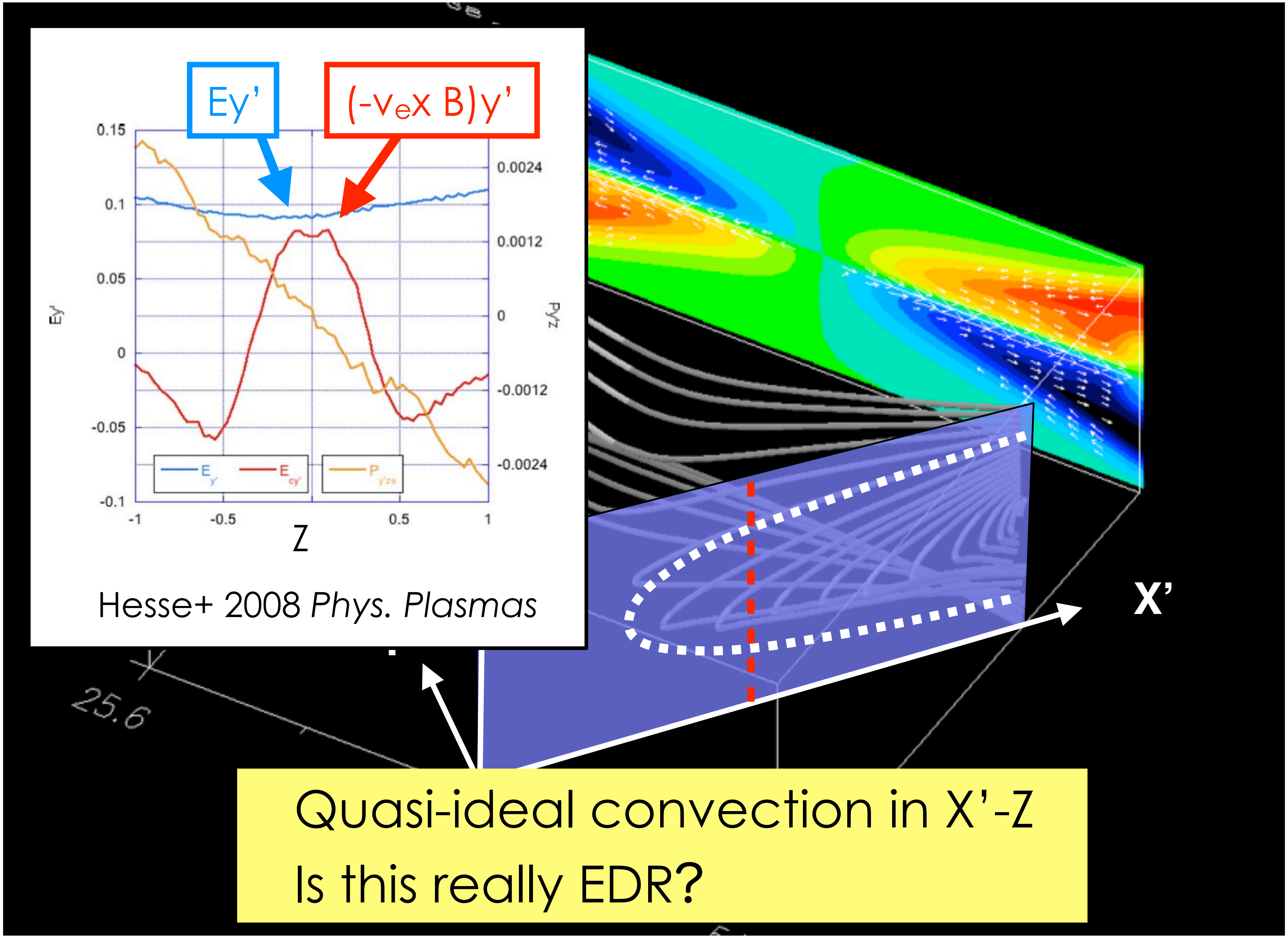


- By analogy with fast reconnection in MHD, we expect a compact localized DR.
- If the "DR" is elongated, the inflow speed (rec. rate) should decrease.

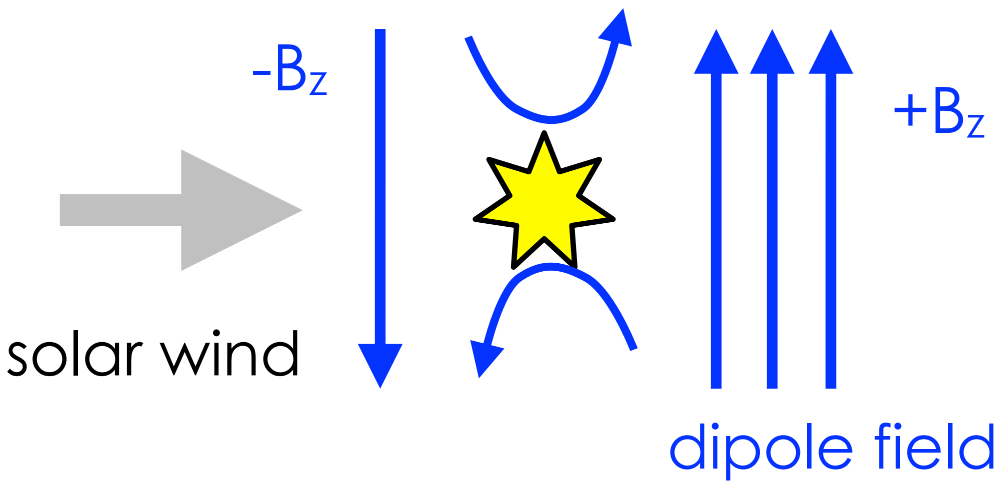
Magnetic field lines are "flipped"



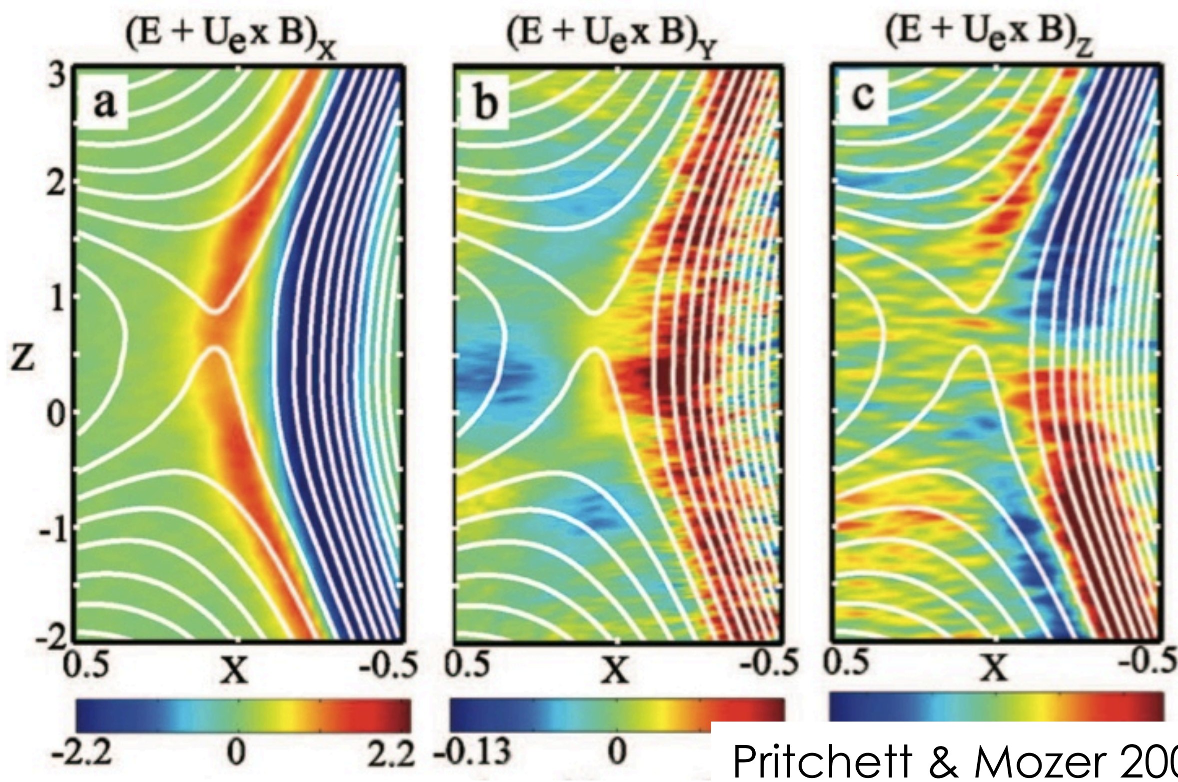
From a different angle



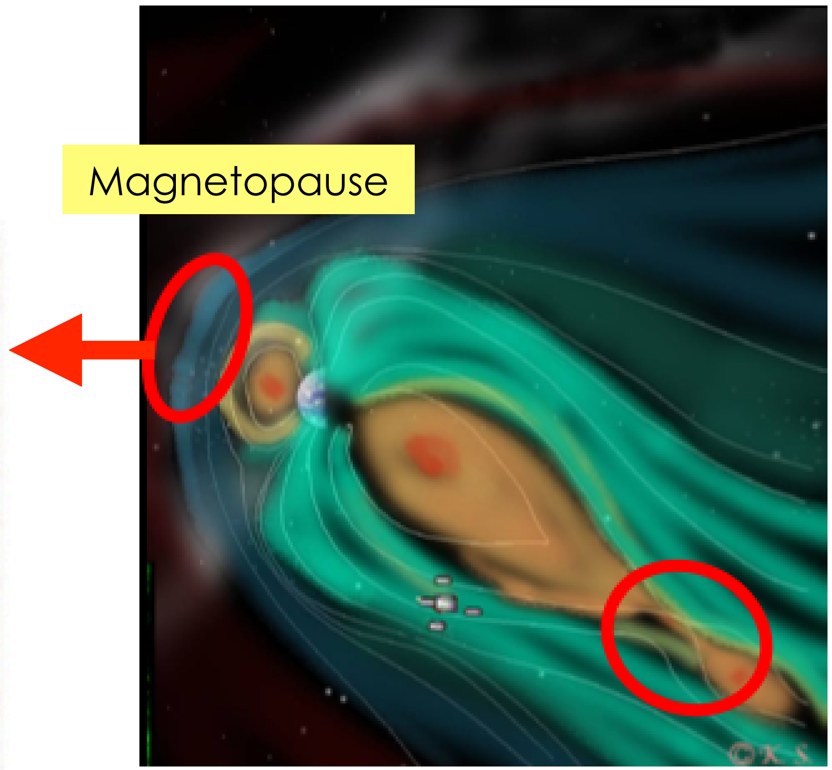
EDR in asymmetric Rx (1/2)



- “Asymmetric” reconnection
- All three components of $[E+v_e xB]$ are puzzling



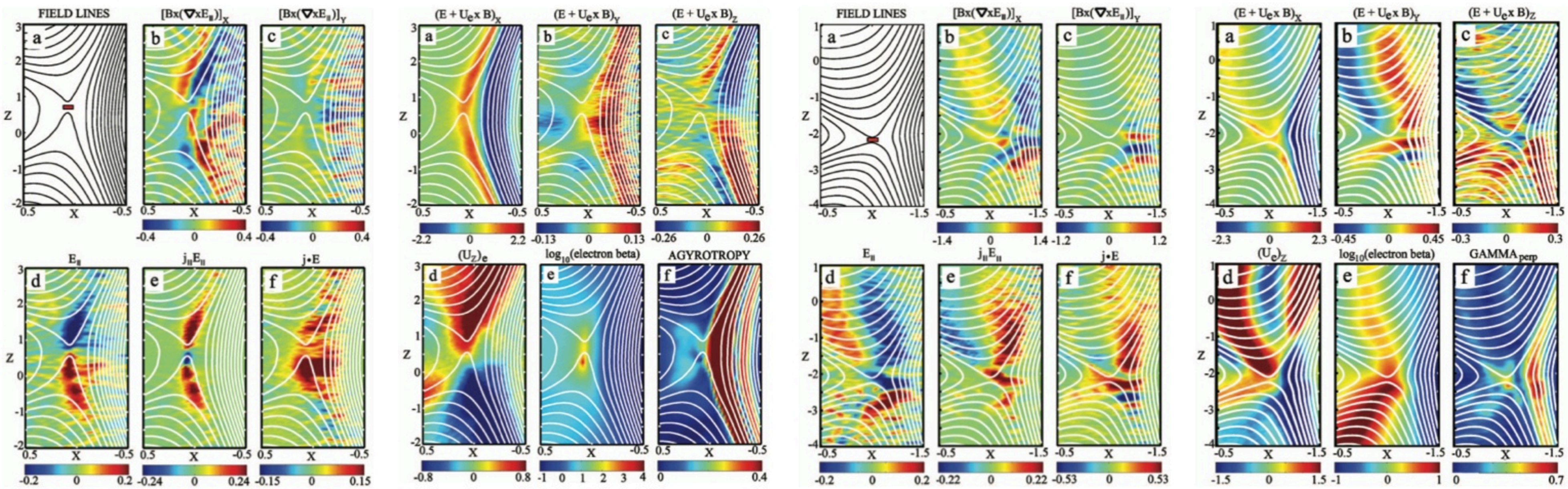
Pritchett & Mozer 2009 *Phys. Plasmas*



EDR in asymmetric Rx (2/2)

Case A: antiparallel

Case B: +guide-field ⊗

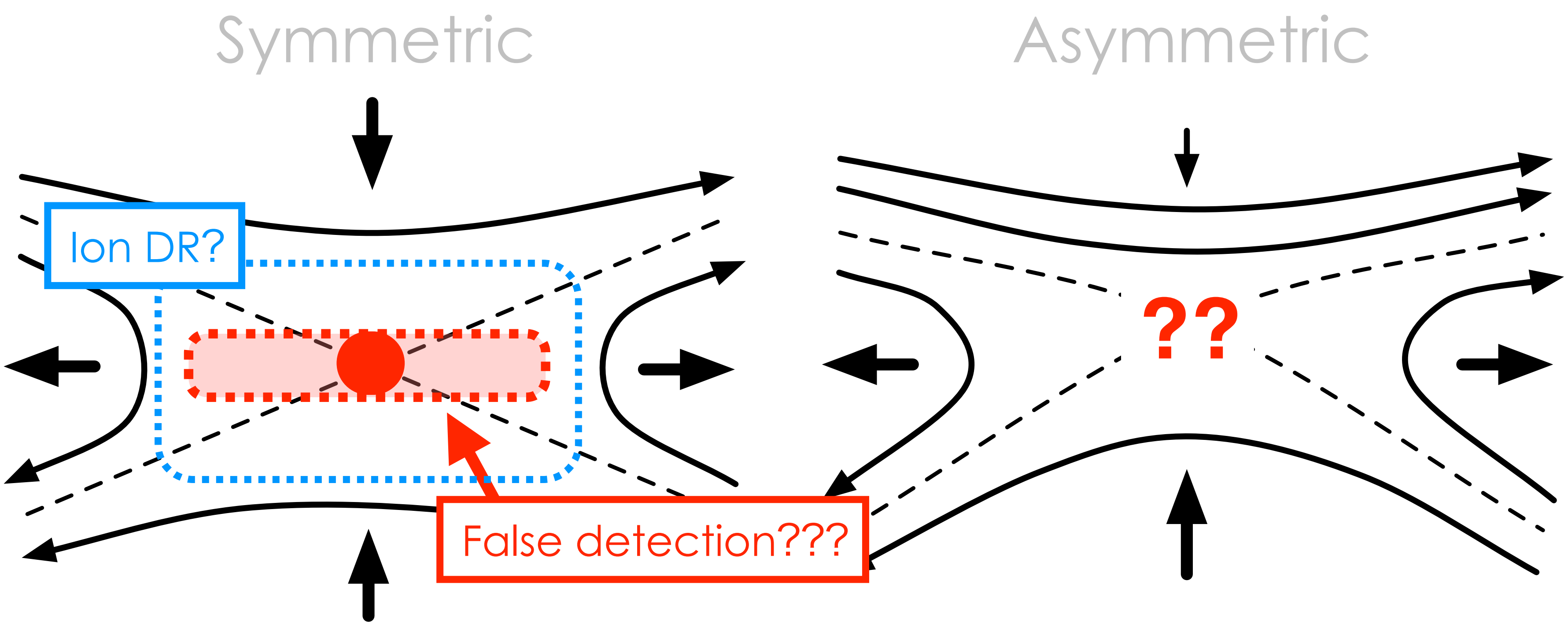


Pritchett & Mozer 2009

- The situation is worse for asymmetric reconnection with a guide field
- Any quantities to characterize the EDR-like region surrounding the reconnection site?

Part 1 summary : something is wrong!

- The violation of the electron ideal condition ($E + v_e xB \neq 0$) may not identify the critical region.
  - The controversial outer EDR
  - No EDR signature in asymmetric reconnection



Part 1 summary : something is wrong!

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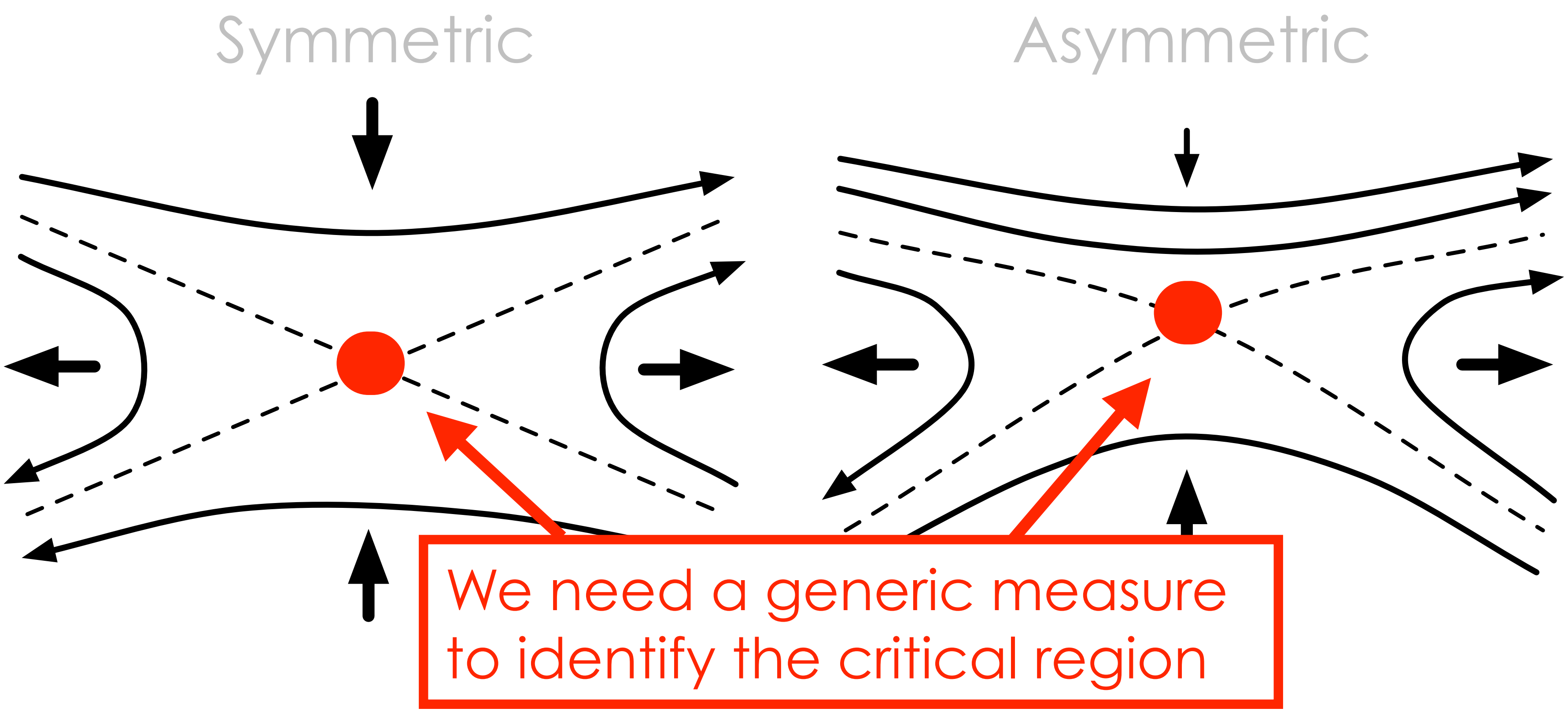


2. Theory

A new measure "D"

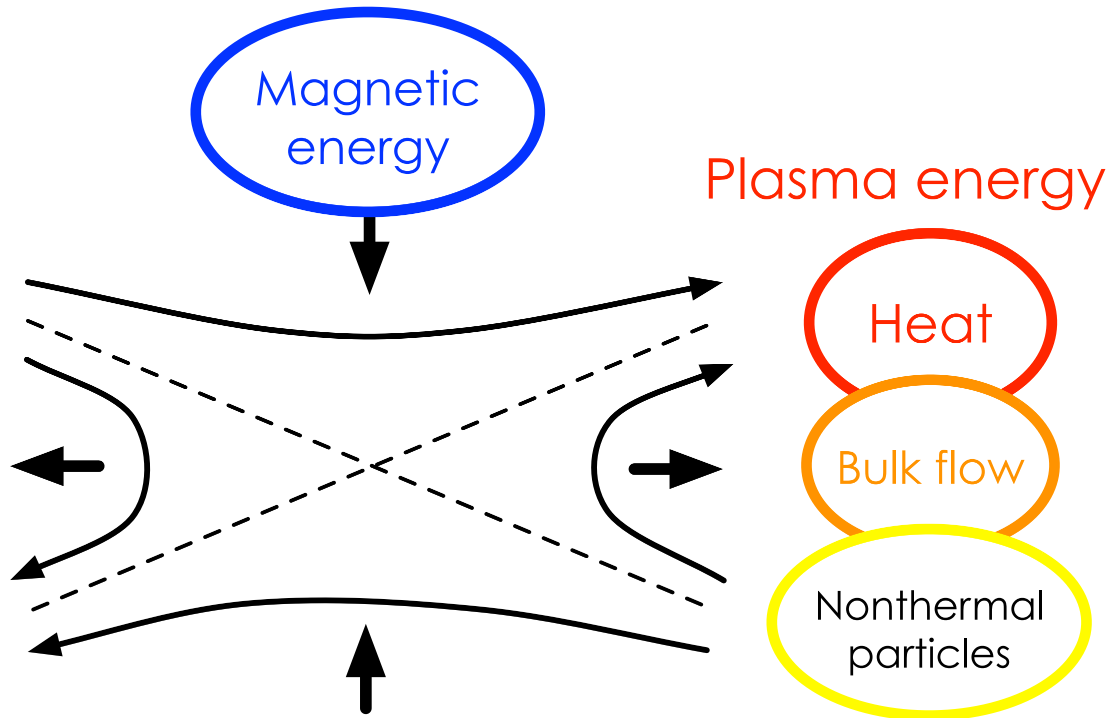
- Let us construct a new measure "D" to identify the critical region.

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

- We derive our formula from scratch, considering three basic requirements.

Desirable conditions for "D" (1/3)

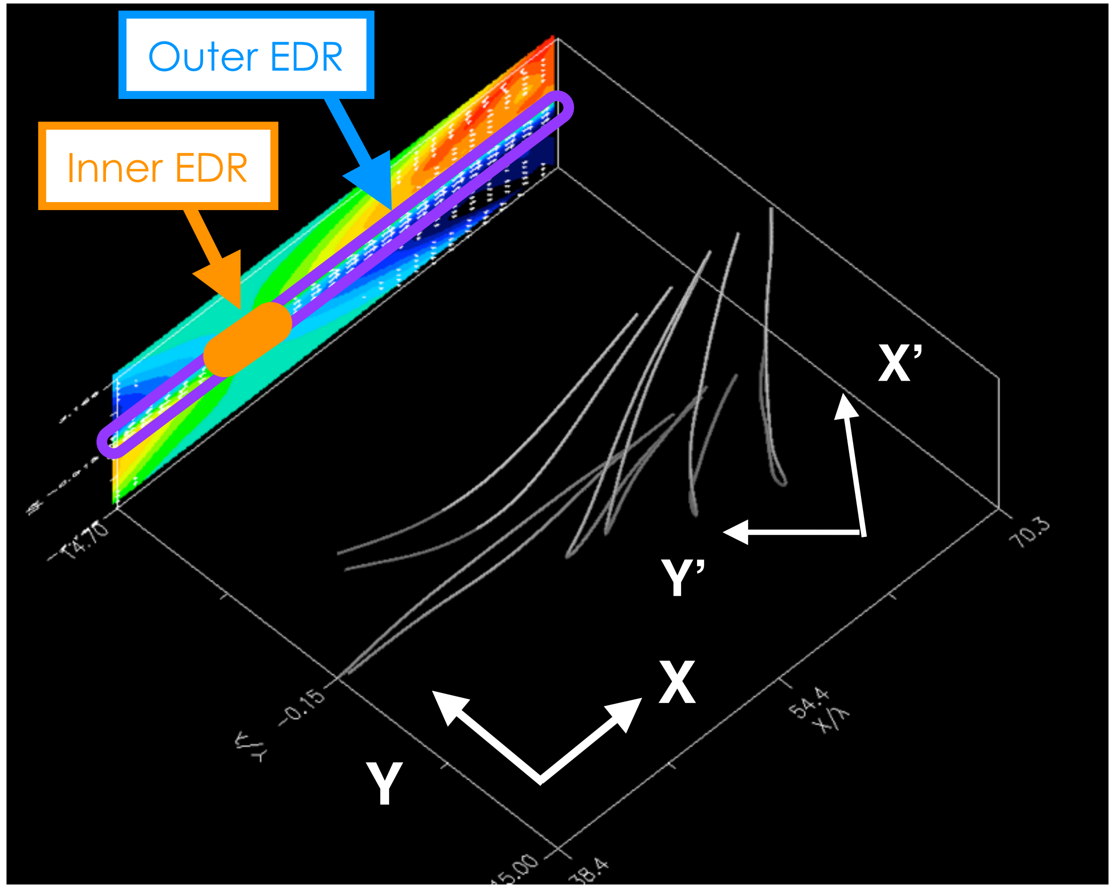
1. Physical meaning
2. Scalar quantity
3. Insensitive to observer motion



- Reconnection consumes the magnetic energy
- Magnetic energy consumption or similar quantities should characterize the reconnection region

Desirable conditions for "D" (2/3)

1. Physical meaning
2. Scalar quantity
3. Insensitive to observer motion



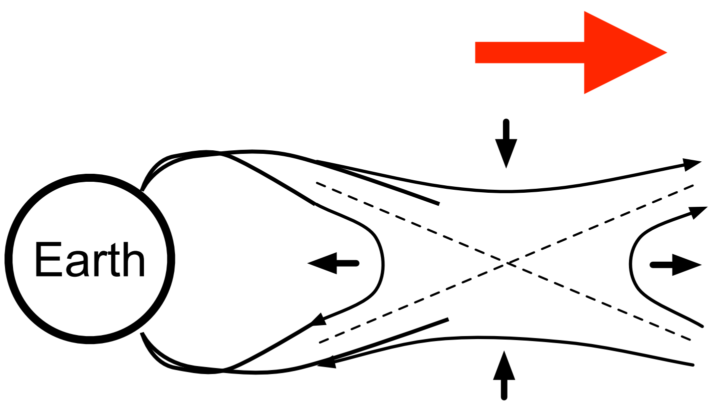
- If we employ a scalar quantity, we don't need to worry about the coordinate. The Y direction or the Y' direction do not matter.

Desirable conditions for “D” (3/3)

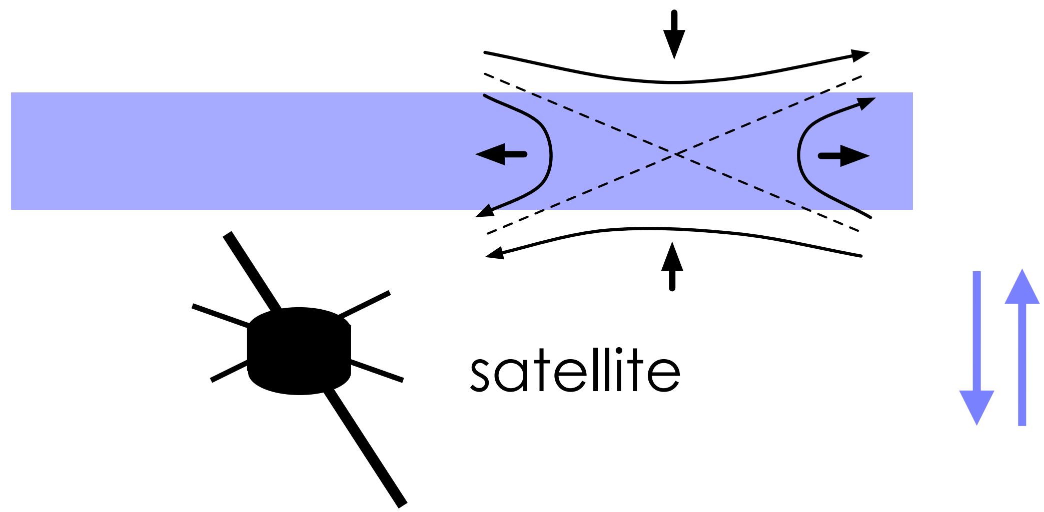
1. Physical meaning
2. Scalar quantity
3. Insensitive to observer motion

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

X-line retreat (NENL)

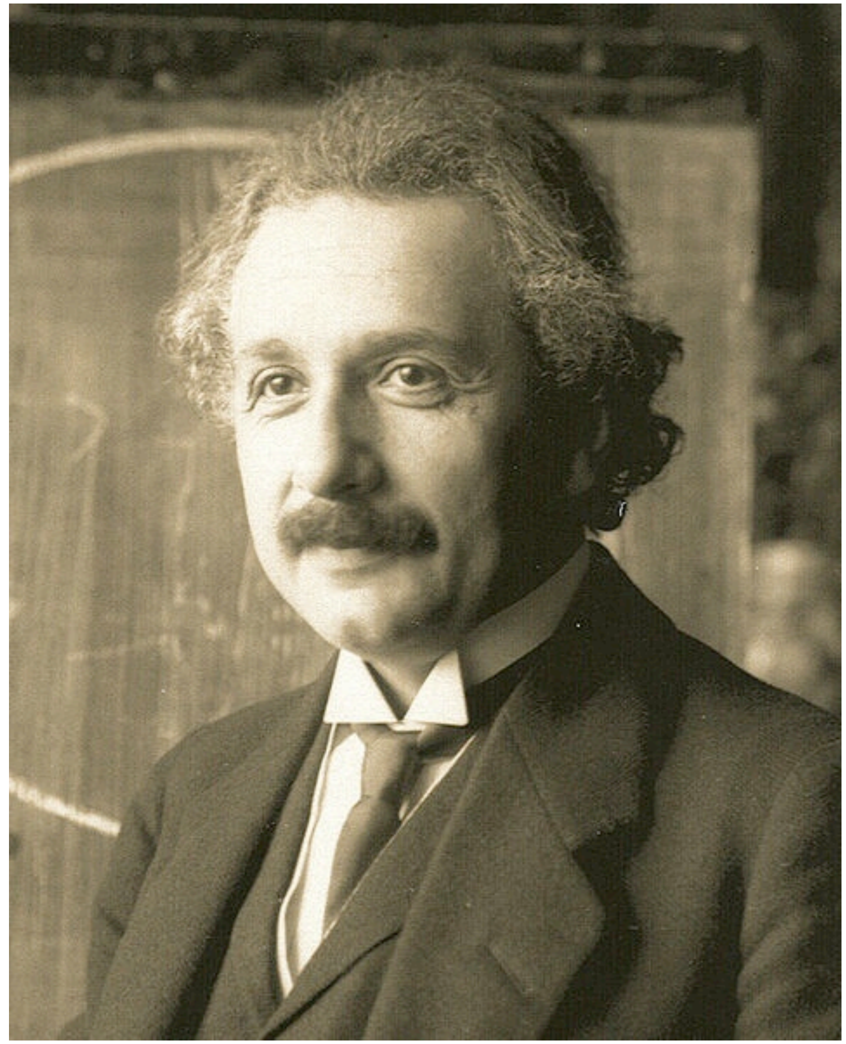


Plasma sheet flapping



Desirable conditions

1. Physical meaning
2. Scalar quantity
3. Insensitive to observer motion



"The reconnection measure D should be a Lorentz-invariant."

A. Einstein

Making a Lorentz invariant

- 4-vector quantities

$$a^\mu = (a_0, \boldsymbol{a}) = (a_0, a_1, a_2, a_3) \qquad a'^\mu = \Lambda^\mu_\nu a^\nu$$

- Contracting two, we obtain an invariant scalar.

$$a_\mu b^\mu = -a_0 b_0 + a_1 b_1 + a_2 b_2 + a_3 b_3$$

$$a'_\mu b'^\mu = a_\mu b^\mu = \text{const.}$$

- We list up all 4-vector quantities in the system.
- We find out a good combination(s) from all possible patterns.

Our choices : j^μ and e^μ

- Spacelike current

$$j^\mu = J^\mu - c^{-2}(-J^\nu u_{e,\nu})u_e^\mu$$

- Covariant electric field

$$e^\mu = F^{\mu\nu}u_{e,\nu} = \left(\frac{\gamma_e \boldsymbol{v}_e \cdot \boldsymbol{E}}{c}, \gamma_e(\boldsymbol{E} + \boldsymbol{v}_e \times \boldsymbol{B})\right)$$

4-current

$$J^\mu = (\rho_c c, \boldsymbol{j})$$

Electron fluid 4-velocity

$$u_e^\mu = \gamma_e(c, \boldsymbol{v}_e)$$

Electromagnetic tensor

$$F^{\mu\nu} = \begin{pmatrix} 0 & E_x/c & E_y/c & E_z/c \\ -E_x/c & 0 & B_z & -B_y \\ -E_y/c & -B_z & 0 & B_x \\ -E_z/c & B_y & -B_x & 0 \end{pmatrix}$$

... in the moving frame of electrons

- Spacelike current

$$j'^{\mu} = \Lambda^{\mu}_{\nu} j^{\nu} = (0, \boldsymbol{j}')$$

Electric current in this frame

- Covariant electric field

$$e'^{\mu} = \Lambda^{\mu}_{\nu} e^{\nu} = (0, \boldsymbol{E}')$$

Electric field in this frame

- Their contraction

$$j'_{\mu} e'^{\mu} \;=\; \boldsymbol{j}' \cdot \boldsymbol{E}'$$

Energy transfer from
the electromagnetic field
to plasmas

The invariant measure

- Spacelike current

$$j^\mu = J^\mu - c$$

- Covariant electric fie

$$e^\mu = F^{\mu\nu} u_{e,\nu}$$

Desirable conditions

1. Physical meaning
2. Scalar quantity
3. Insensitive to observer motion

- We introduce the electron-frame dissipation measure
  - The energy transfer in the electron frame (= <u>unique</u> frame)

$$\boxed{\begin{aligned} D_e = j_\mu e^\mu &= \gamma_e \left[\boldsymbol{j} \cdot (\boldsymbol{E} + \boldsymbol{v}_e \times \boldsymbol{B}) - \rho_c (\boldsymbol{v}_e \cdot \boldsymbol{E}) \right] \\ &\equiv \; j'_\mu e'^\mu = \boldsymbol{j}' \cdot \boldsymbol{E}' \end{aligned}}$$

Nonrelativistic formula

- Electric current in the electron's frame

$$\boldsymbol{j}' = en_i\boldsymbol{v}_i' = e(n_i\boldsymbol{v}_i - n_e\boldsymbol{v}_e) - e(n_i - n_e)\boldsymbol{v}_e$$
$$= \boldsymbol{j} - \rho_c\boldsymbol{v}_e.$$

- Electric field in the electron's frame

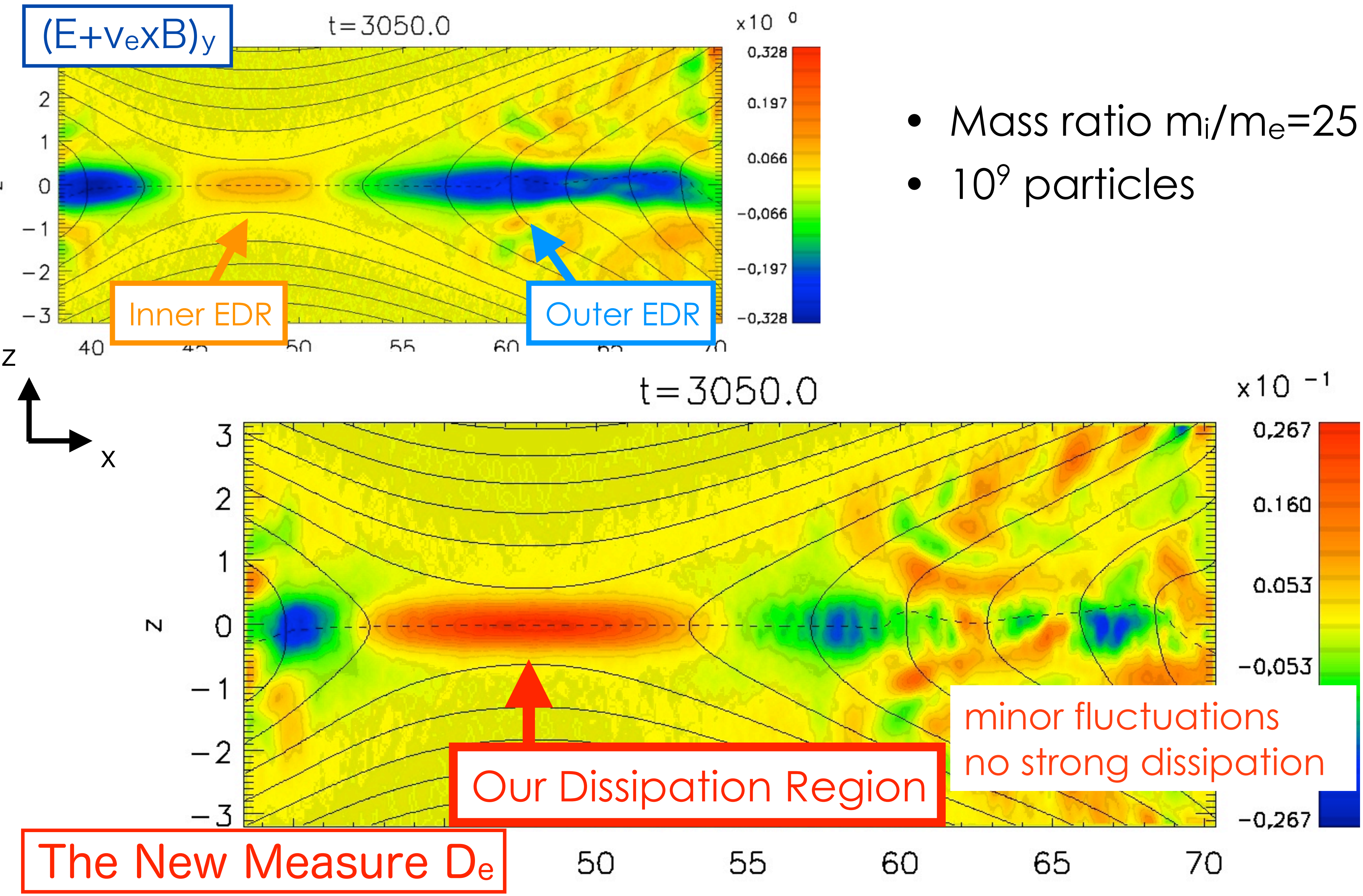
$$\boldsymbol{E}' = \boldsymbol{E} + \boldsymbol{v}_e \times \boldsymbol{B}$$

- The energy transfer in the <u>electron frame</u> (= a unique frame)
  - The relativistic formula in the limit of $\gamma_e \to 1$

$$\boxed{D_e = \boldsymbol{j}' \cdot \boldsymbol{E}' = \boldsymbol{j} \cdot (\boldsymbol{E} + \boldsymbol{v}_e \times \boldsymbol{B}) - \rho_c\boldsymbol{v}_e \cdot \boldsymbol{E}}$$

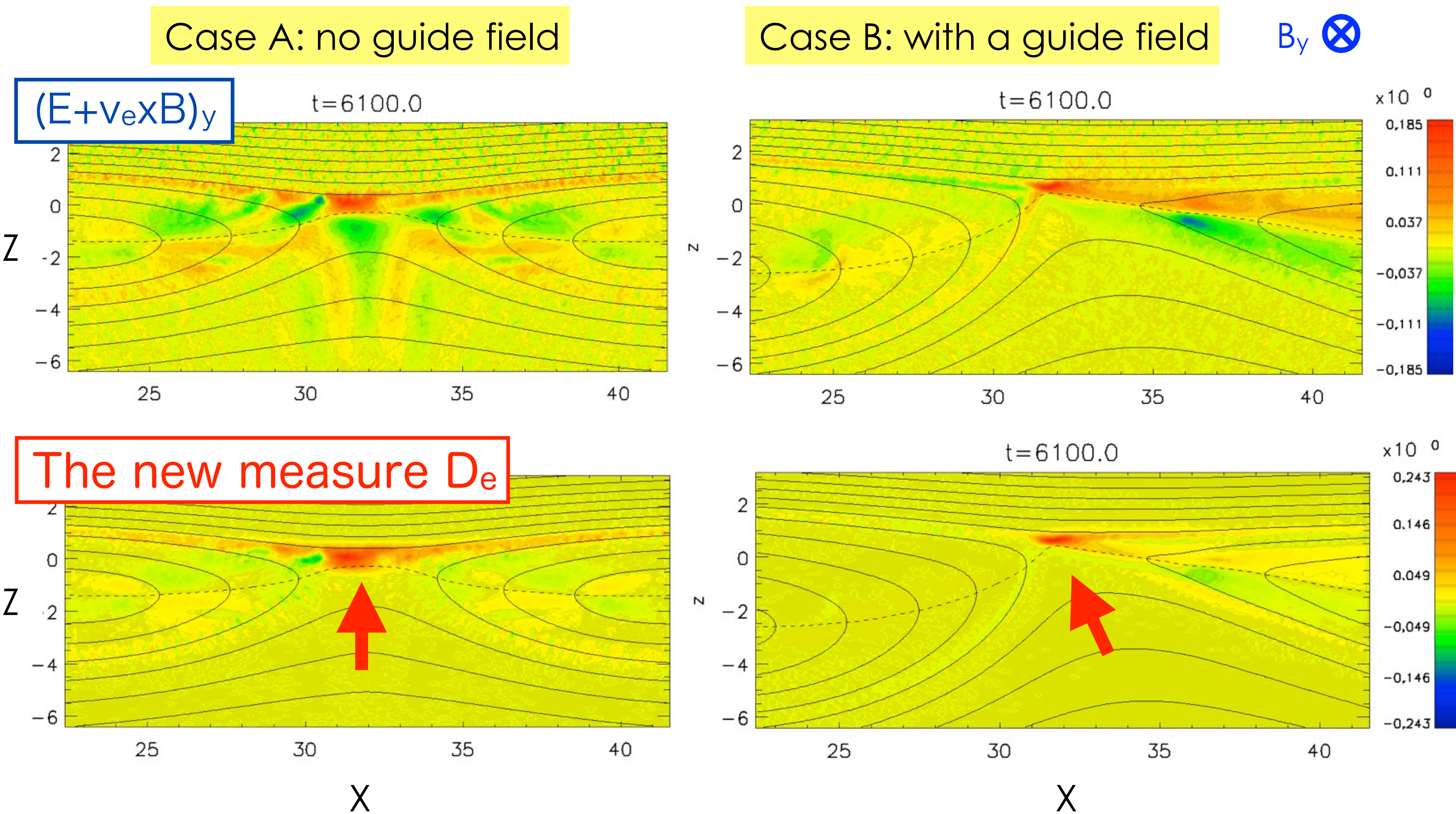
3. Numerical tests & discussions

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



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

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



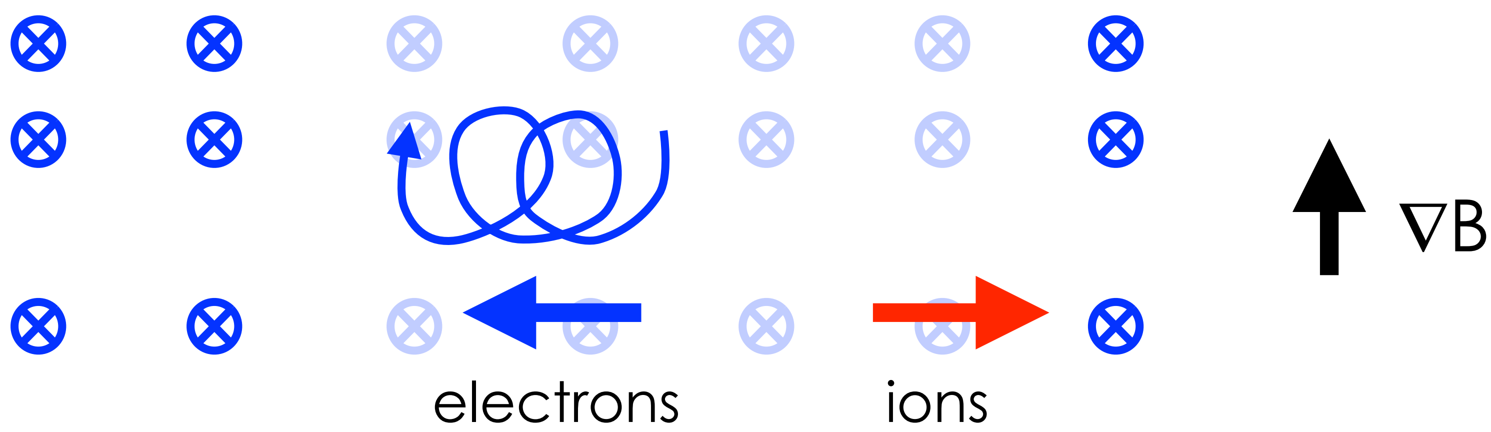
- D_e accurately locates the reconnection site
- The field reversal line is located inside the dissipation region

Why (E+v_exB) 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



- Condition for connection (Schindler+ 1988)

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

- 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 (ideal) frozen-in condition."

- In the kinetic regime, nonidealness ≠ dissipation.

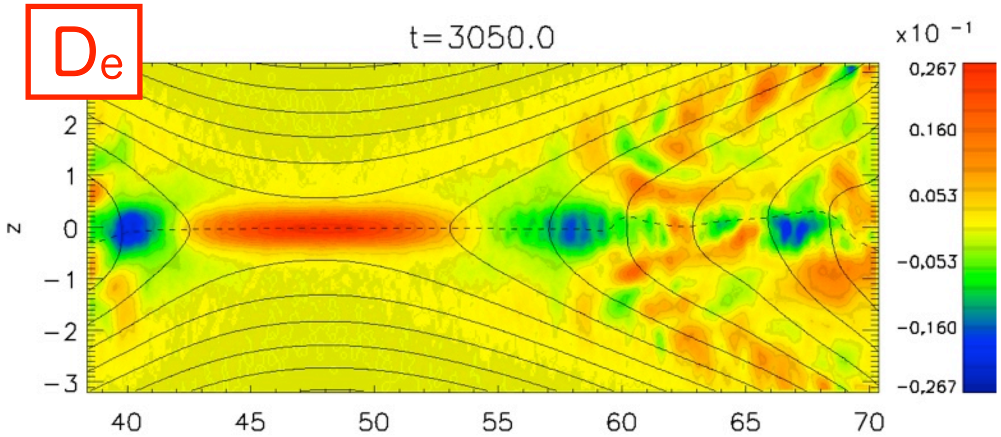
Why does D_e work? (1/2) : Variants of D_e

- D_e : (j . E) in the electron's frame
- D_i : (j . E) in the ion's frame
- D_{mhd} : (j . E) in the MHD frame

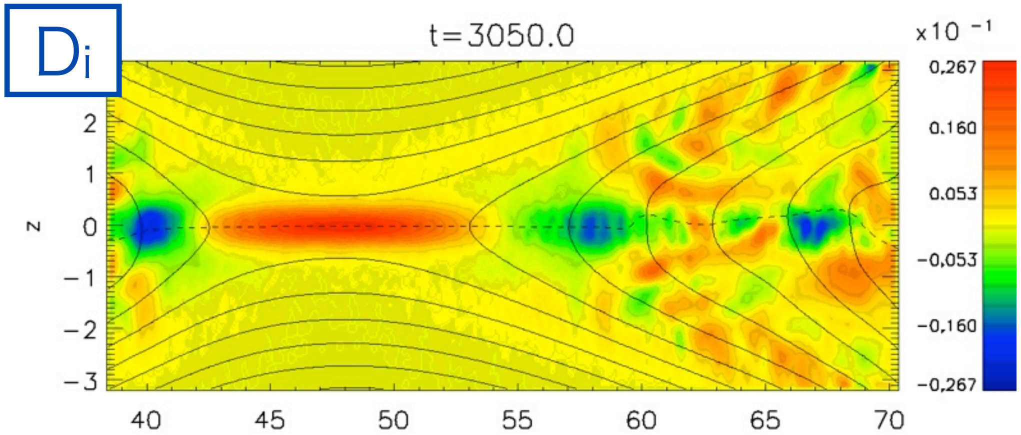
Nonrelativistic relation:

$$n_e D_e = n_i D_i = \frac{m_i n_i + m_e n_e}{m_i + m_e} D_{\rm mhd}$$

D_e



D_i



Why does D_e work? (2/2) : Energy balance

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

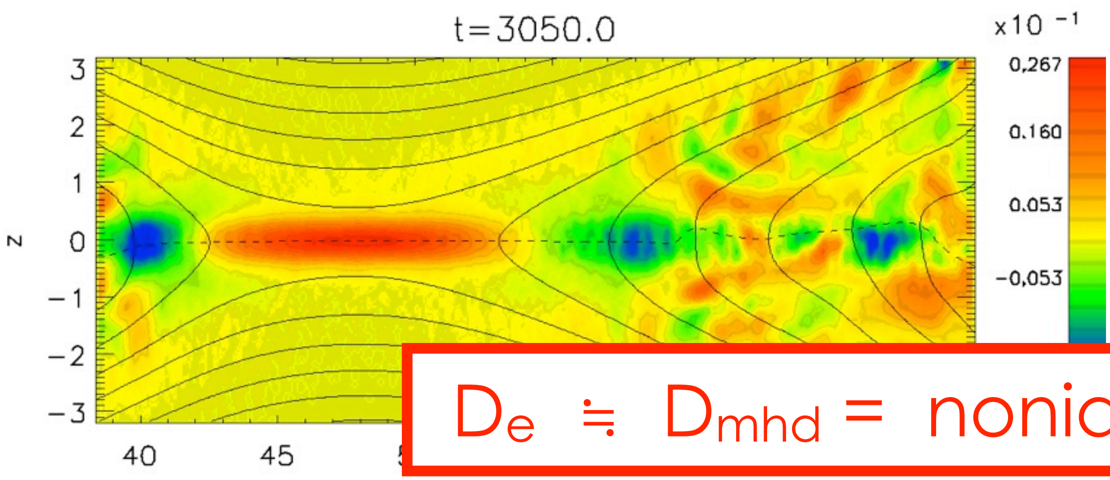
$$\boldsymbol{E} + \boldsymbol{v}_{\mathrm{mhd}} \times \boldsymbol{B} = \eta \boldsymbol{j}$$

$$\boldsymbol{j} \cdot \boldsymbol{E} = \underbrace{(\boldsymbol{j} \times \boldsymbol{B}) \cdot \boldsymbol{v}_{\mathrm{mhd}}}_{\text{work by Lorentz force}} + \underbrace{\eta \boldsymbol{j}^2}_{\text{Non-ideal}}$$

- Kinetic plasma

$$\boldsymbol{j} \cdot \boldsymbol{E} = (\boldsymbol{j} \times \boldsymbol{B}) \cdot \boldsymbol{v}_{\mathrm{mhd}} + \underbrace{\cancel{\rho_c \boldsymbol{E} \cdot \boldsymbol{v}_{\mathrm{mhd}}}}_{\text{by Coulomb force}} + \underbrace{D_{\mathrm{mhd}}}_{\text{Non-ideal}}.$$

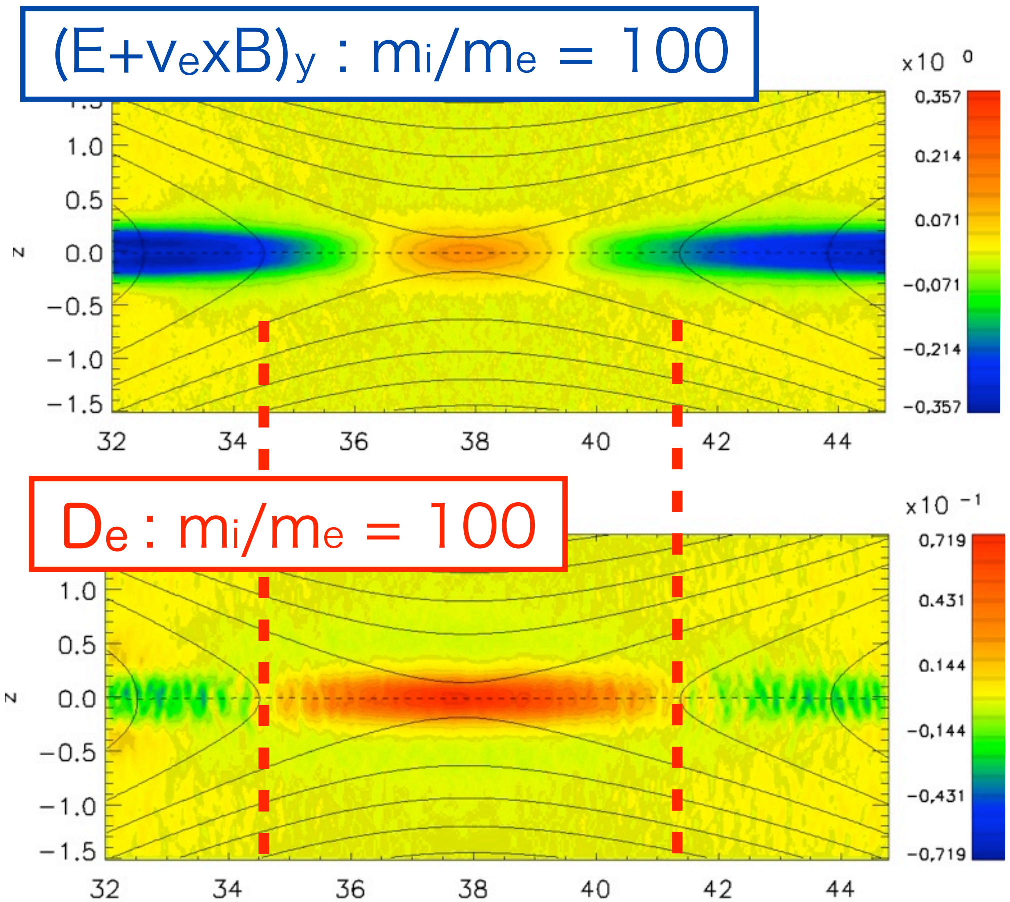
$$\approx (\boldsymbol{j} \times \boldsymbol{B}) \cdot \boldsymbol{v}_{\mathrm{mhd}} + \underbrace{D_e}_{\text{Non-ideal}}$$



$\boxed{D_e \fallingdotseq D_{\mathrm{mhd}} = \text{ nonideal energy conversion}}$

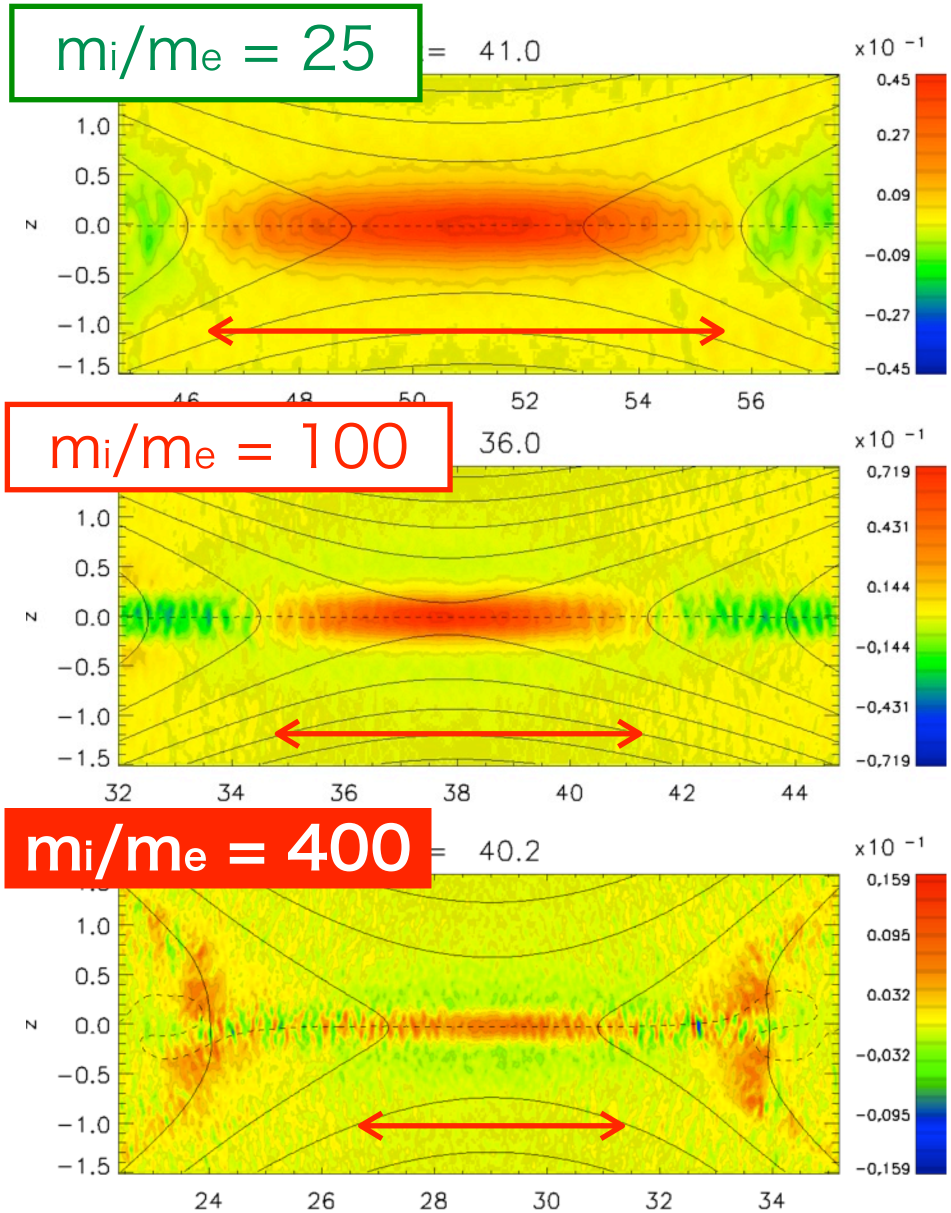
4. Application to antiparallel reconnection

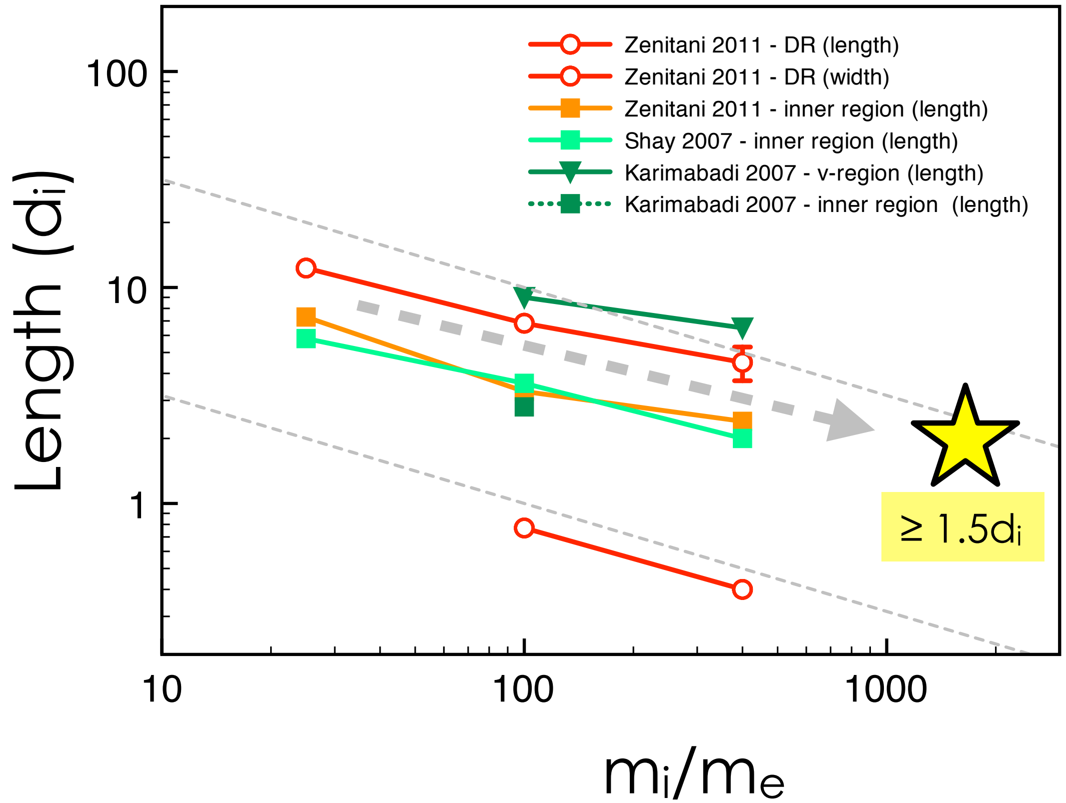
Closer look at the dissipation region (1/2)



- The dissipation region is usually twice longer than the popular inner region of $(E+v_e xB)_y > 0$.
- Many previous works on the $(E+v_e xB)_y > 0$ region may be useful.

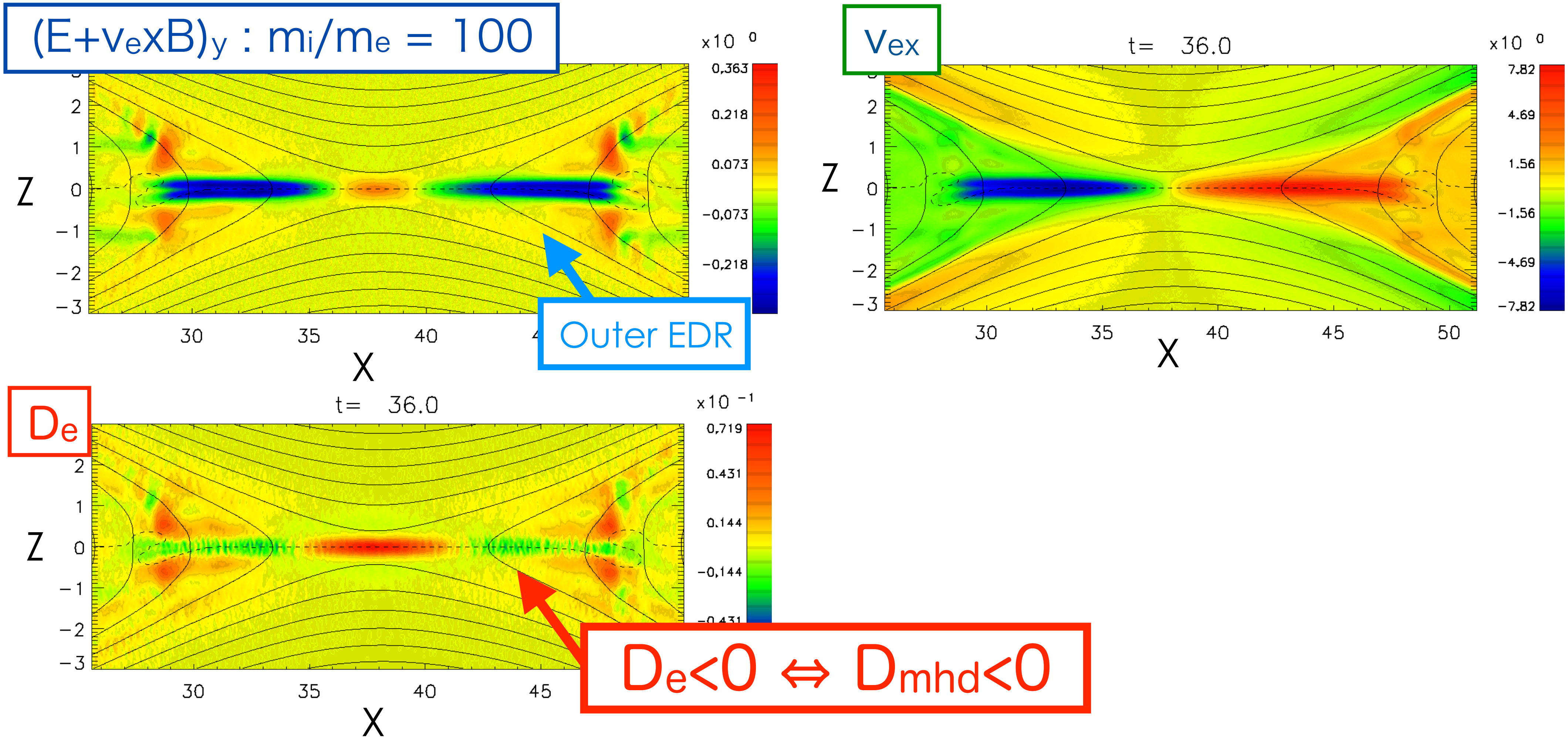
Closer look at the dissipation region (2/2)





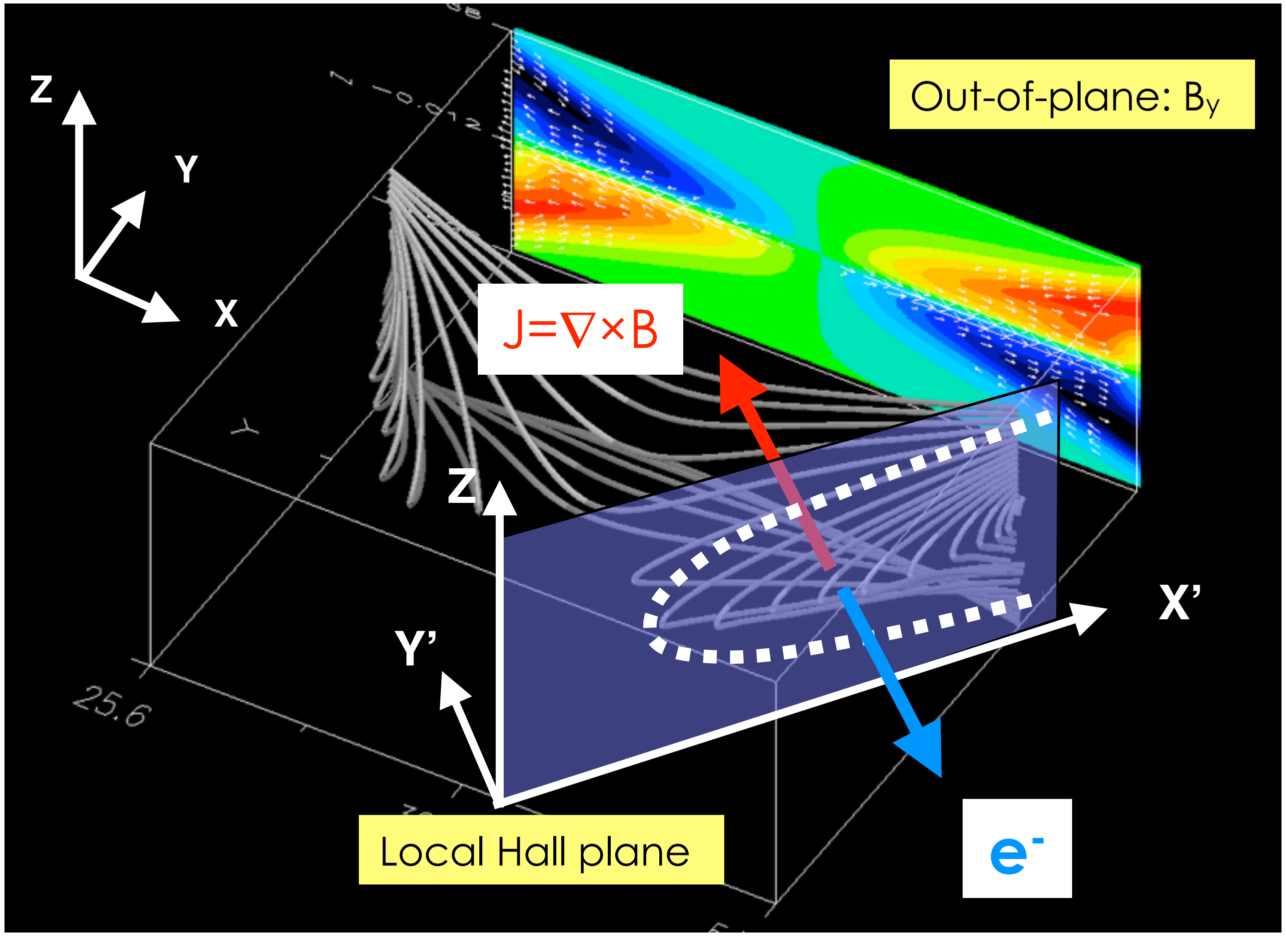
- Electron physics is essential.
- We need more computer resources for better prediction.

Closer look at the “outer EDR” (1/3)



- The “outer EDR” is weakly anti-dissipative
- It is not appropriate to call it “dissipation” nor “diffusion” region

Closer look at the “outer EDR” (2/3)

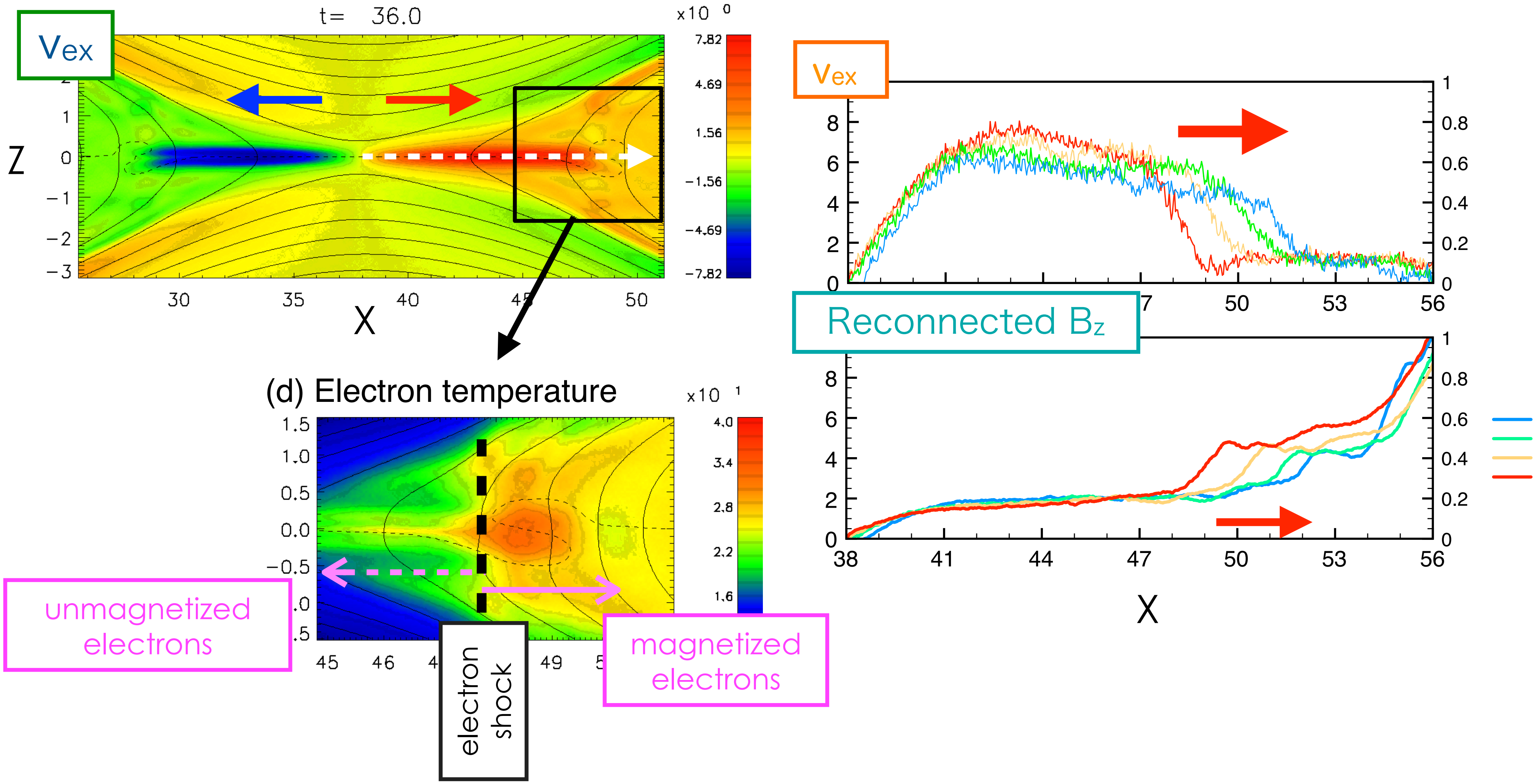


Reduced form of D_e

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

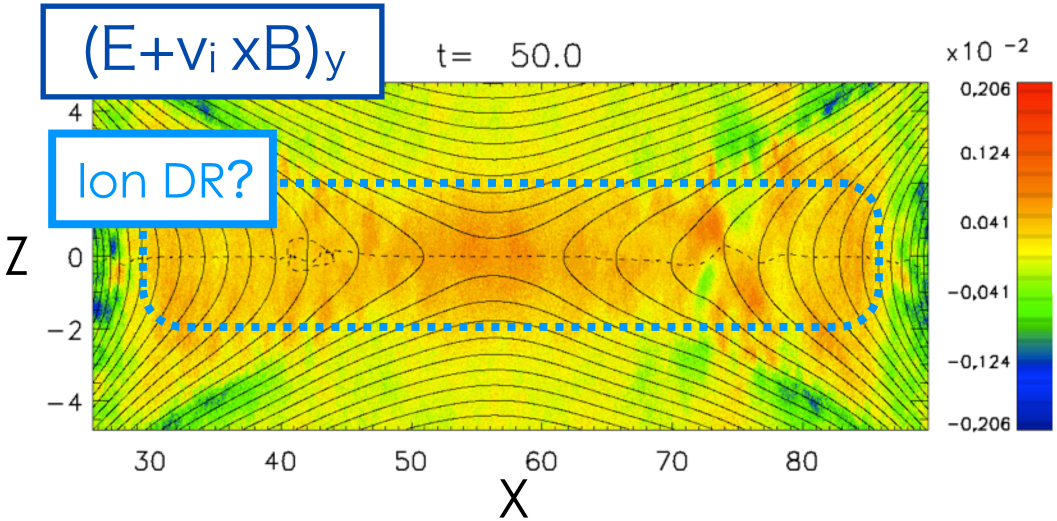
- Consistent with the rotated picture (Hesse+ 2008)
- The J-aligned component $[E+v_e xB]_{//}$ is related to the nonideal energy transfer
- $[E+v_e xB]_{\perp} \neq 0$ by non-dissipative drifts

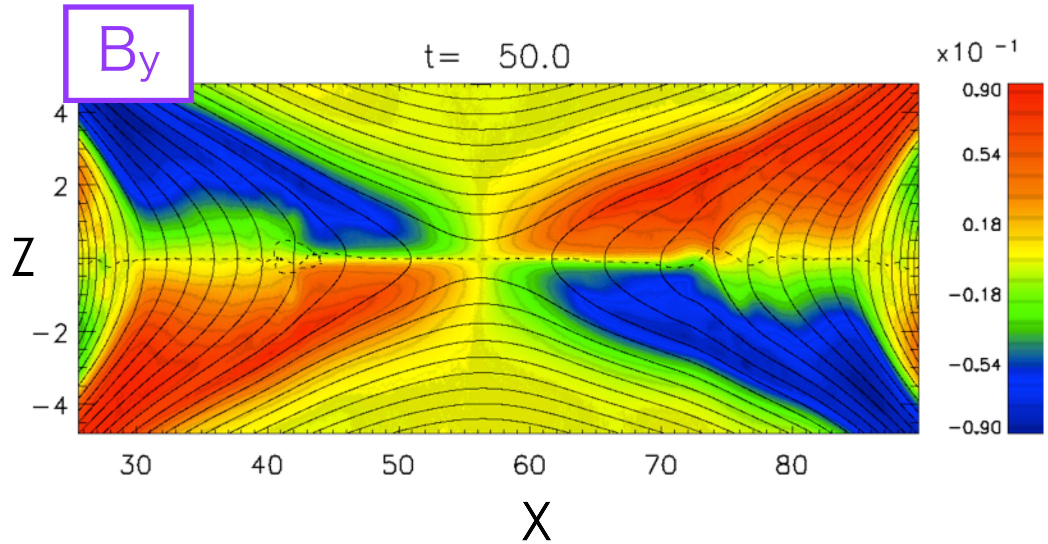
Closer look at the "outer EDR" (3/3)

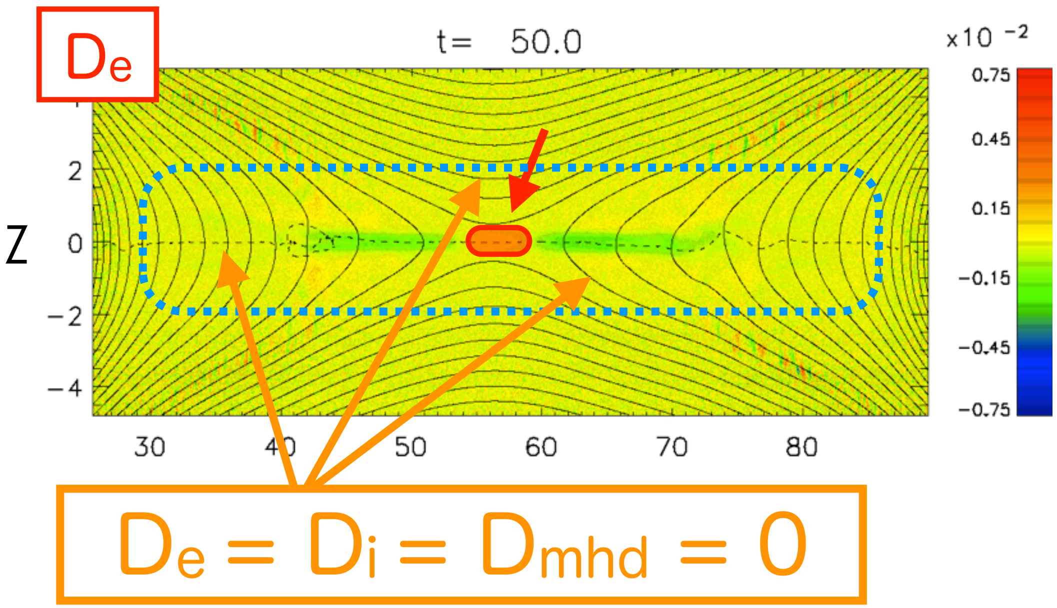


- Terminated by a shock-like transition region
- The unmagnetized electron jet gets magnetized

“Ion dissipation region?”

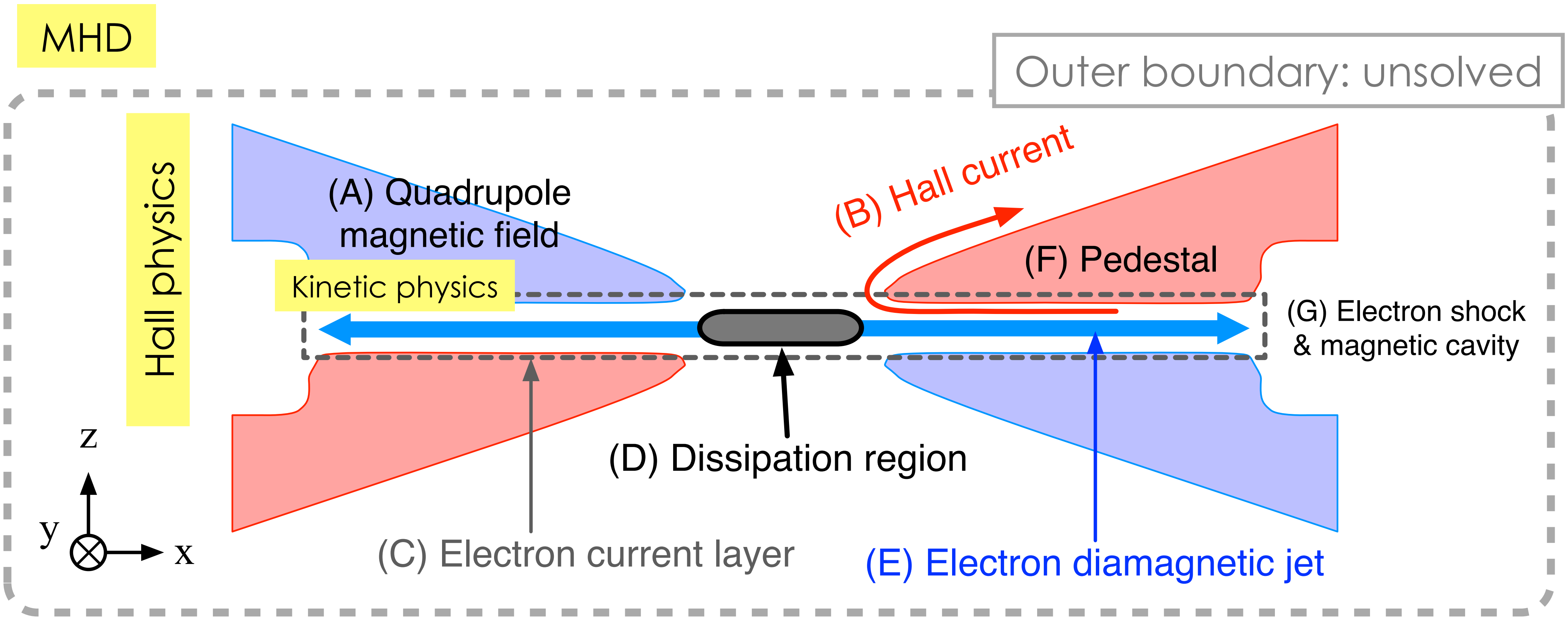






- No clear “dissipation” over the ion nonideal region.
- Signatures of Hall physics certainly appear: B_y.
- We need a good measure for the Hall physics region.

Our understanding of 2D reconnection structure

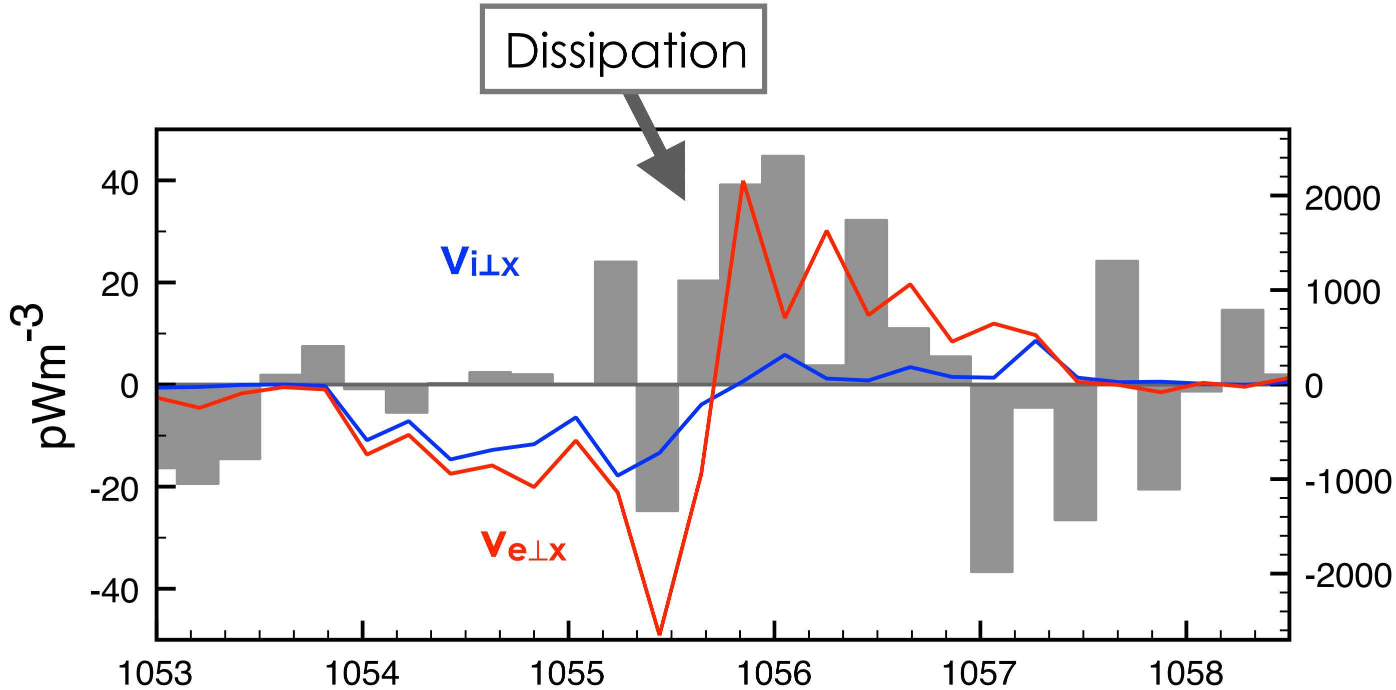


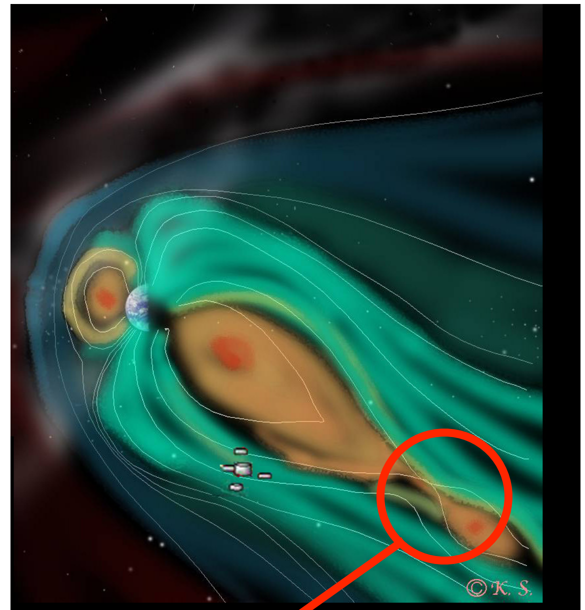
Zenitani+ 2011 PoP

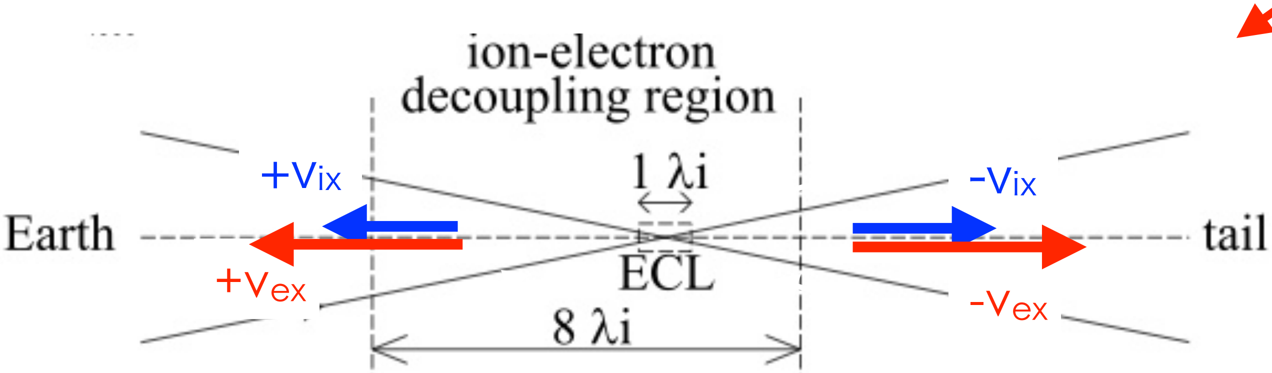
(A) Quadrupole magnetic field B_y (Sonnerup 1979, Terasawa 1983)
(B) Hall current system (Sonnerup 1979)
(C) electron current layer (Daughton+ 2006, Fujimoto 2006)
(D) dissipation region (Zenitani+ 2011a)
(E) electron diamagnetic jet (Karimabadi+ 2007, Shay+ 2007, Hesse+ 2008)
(F) pedestal (Drake+ 2008)
(G) electron shock and magnetic cavity (Zenitani+ 2011b)

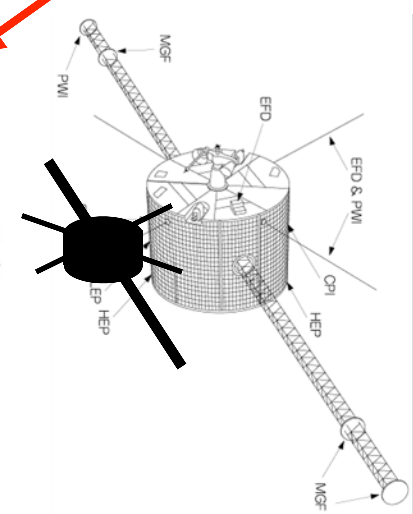
5. Satellite observation

GEOTAIL observation



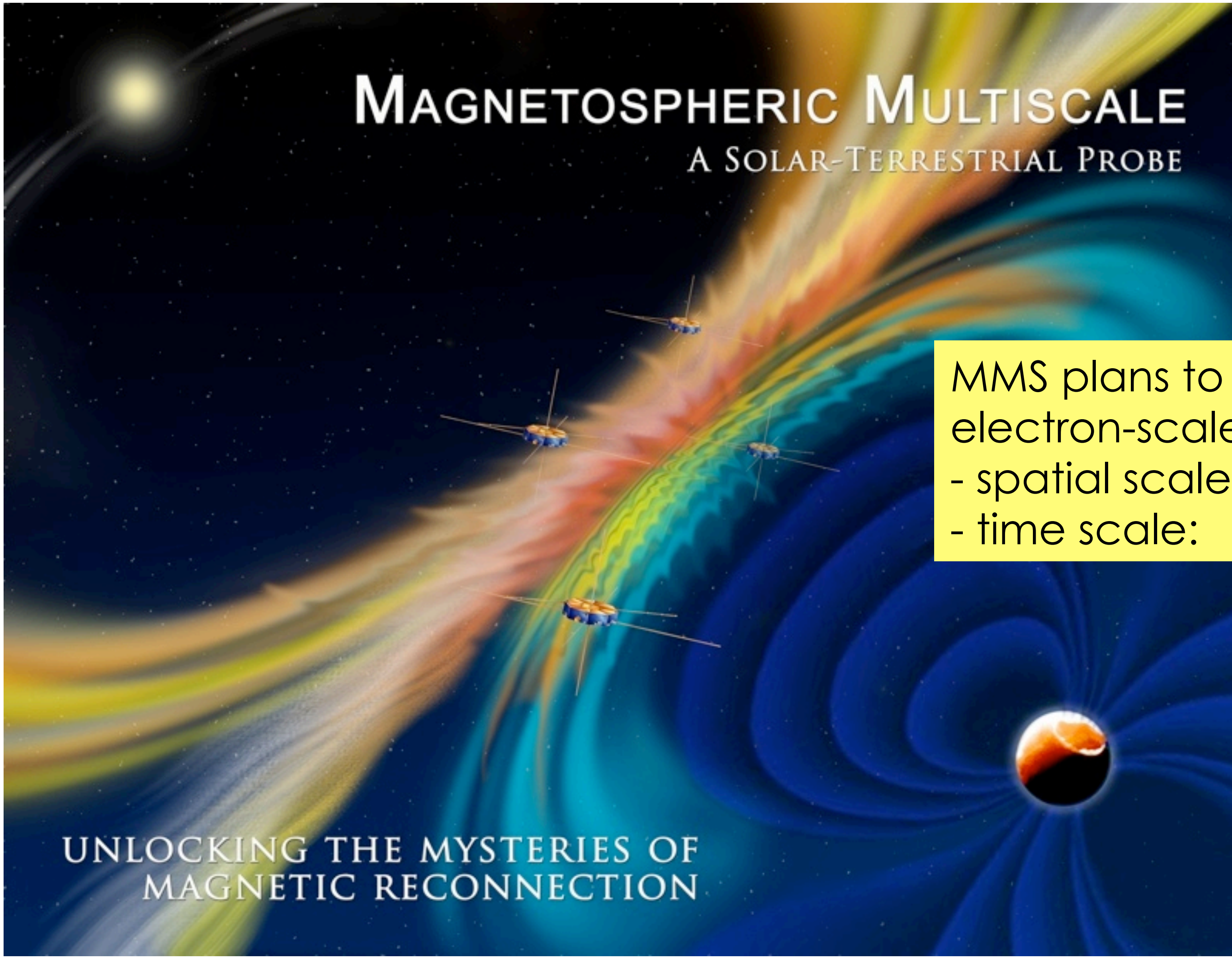






- 20030515 event (Nagai+ 2011)

NASA MMS Mission (2014~)



MMS plans to probe electron-scale structures
- spatial scale: 10km
- time scale: 30 msec.

- We will be able to see better pictures of reconnection sites

Summary

- We have introduced the *electron-frame dissipation measure*.

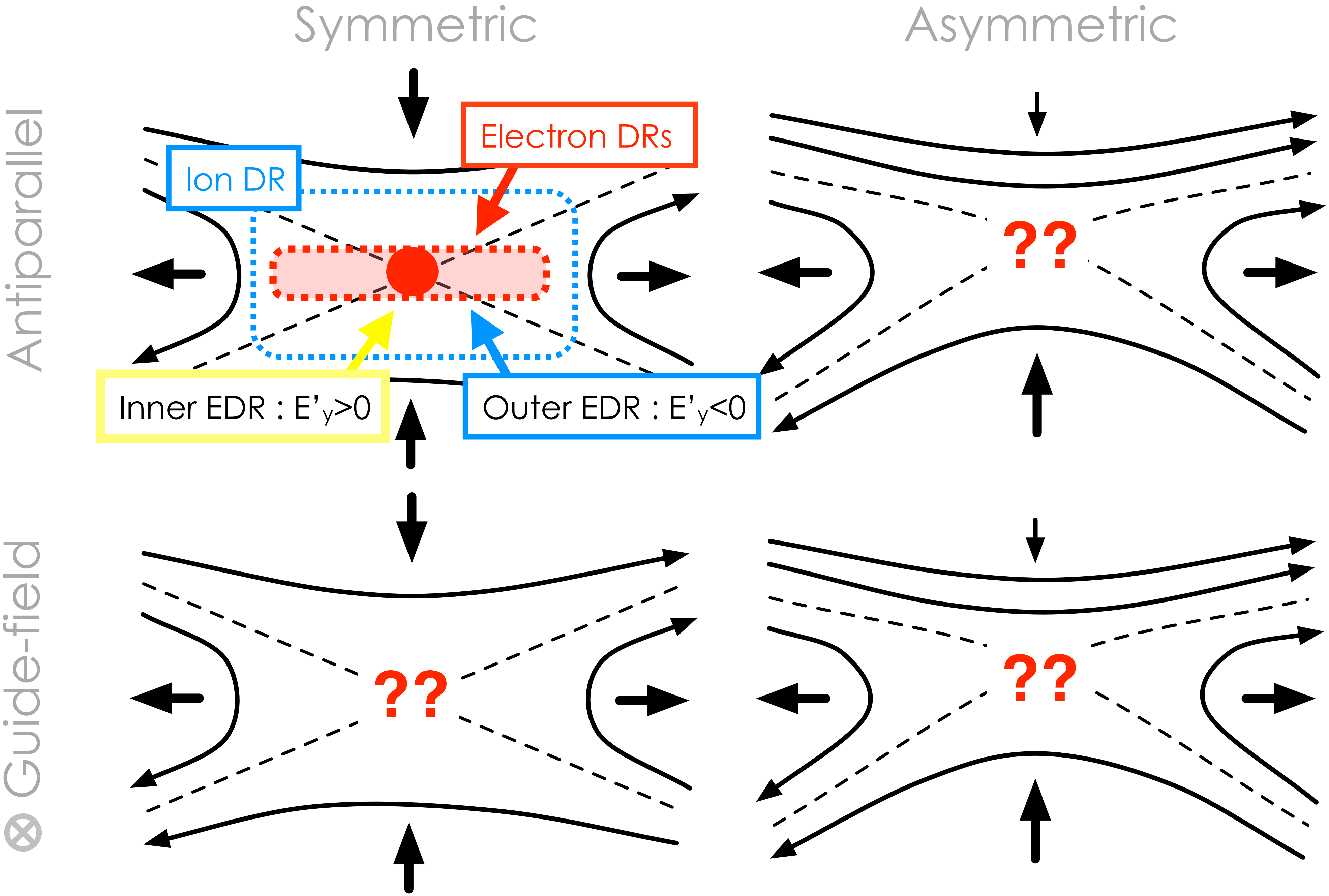
$$D_e = \gamma_e \left[\boldsymbol{j} \cdot (\boldsymbol{E} + \boldsymbol{v}_e \times \boldsymbol{B}) - \rho_c (\boldsymbol{v}_e \cdot \boldsymbol{E}) \right]$$

  - Energy transfer in the electron's frame
  - Lorentz invariant scalar
  - Nonideal energy conversion

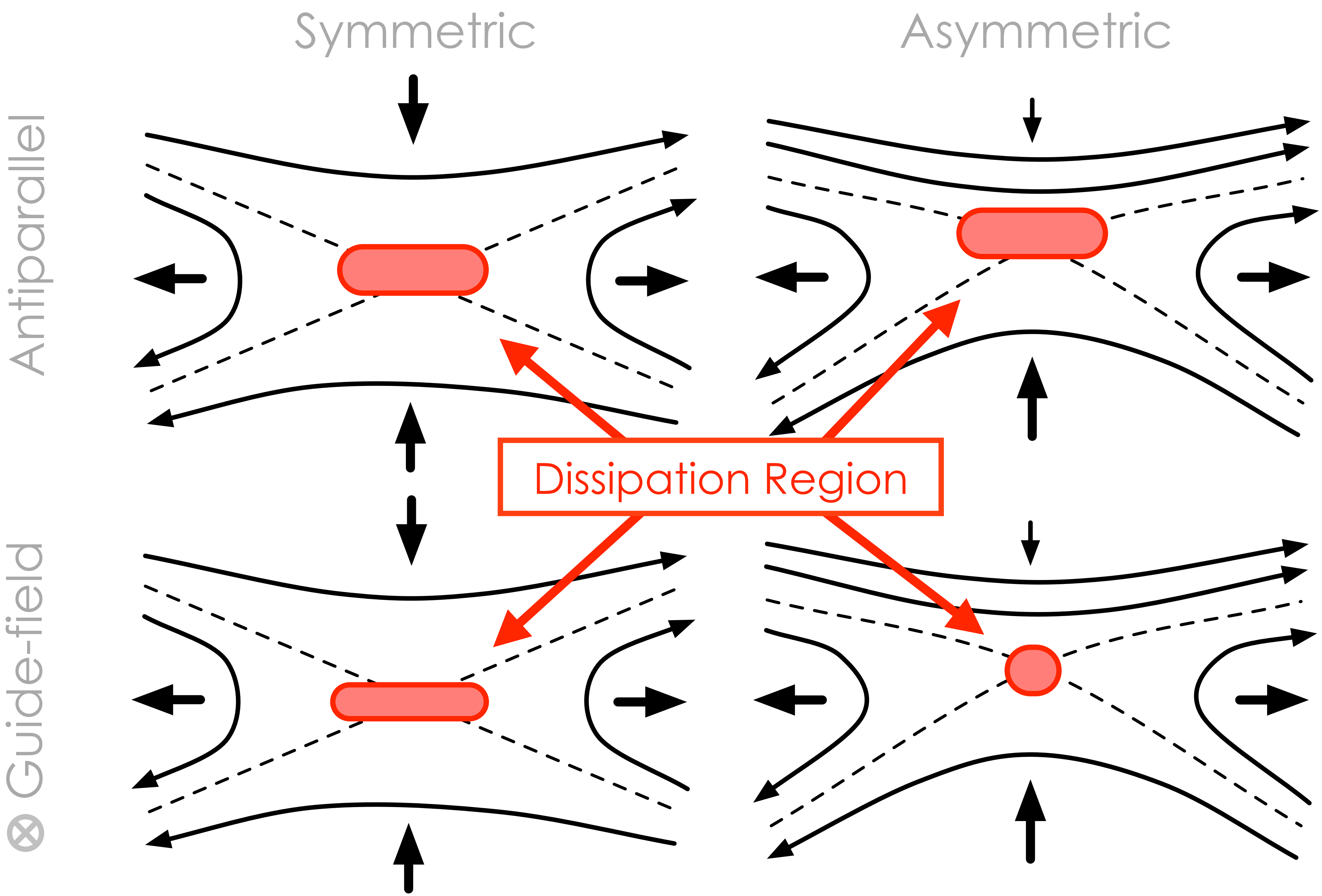
- Generic, electron-scale dissipation region
- Verified by PIC simulations and satellite observations
- Better understanding of 2D reconnection structure
- ... and lot of unsolved issues.

We propose to redefine the dissipation region by D_e

Previous picture



New picture


Symmetric
Asymmetric
Antiparallel
⊗ Guide-field
Dissipation Region

Thank you for your attention!!

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