A new measure of the dissipation region in collisionless magnetic reconnection: Theory, simulation, and observation

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Princeton, 24 May 2012

Collaborators

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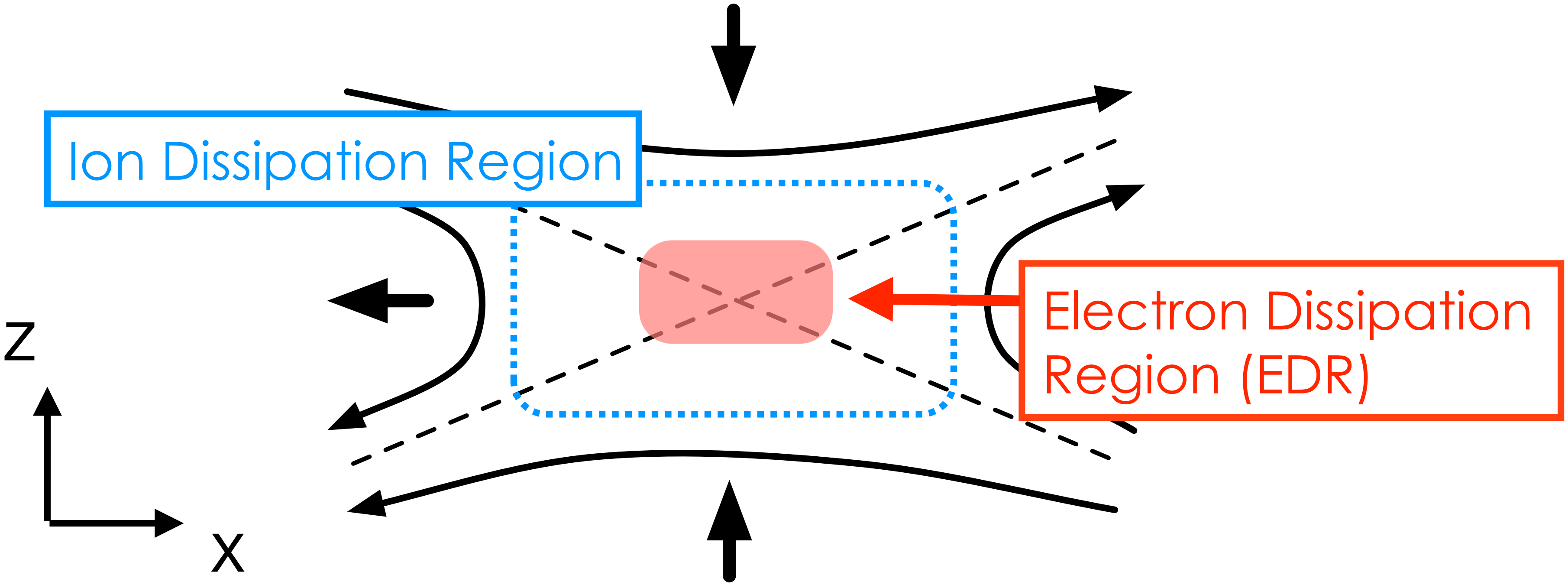
Outline

- 1. Introduction
  - Recent debates on the electron dissipation region
- 2. Theory
  - Introducing a new measure D_e
- 3. Simulations
  - 2D kinetic PIC simulations in various configurations
  - Reconsidering multi-scale dissipation regions
- 4. Observation
  - Geotail observation in the magnetotail

1. Introduction

The dissipation region

- The ideal condition $$\boldsymbol{E} + \boldsymbol{v}_s \times \boldsymbol{B} = 0$$
- We expected a multi-scale structure

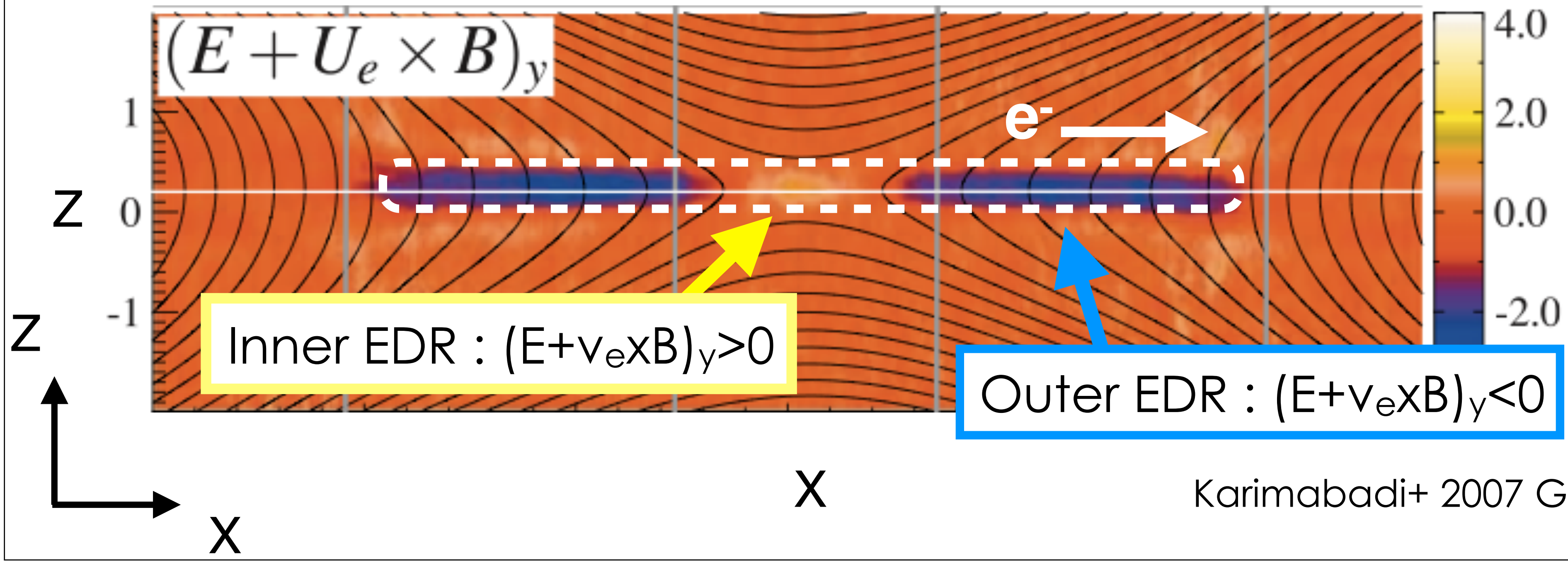


- We are interested in the innermost EDR
  - It is traditionally identified by $\boldsymbol{E}'_y = (\boldsymbol{E} + \boldsymbol{v}_e \times \boldsymbol{B})_y \neq 0$

Elongated "EDRs"

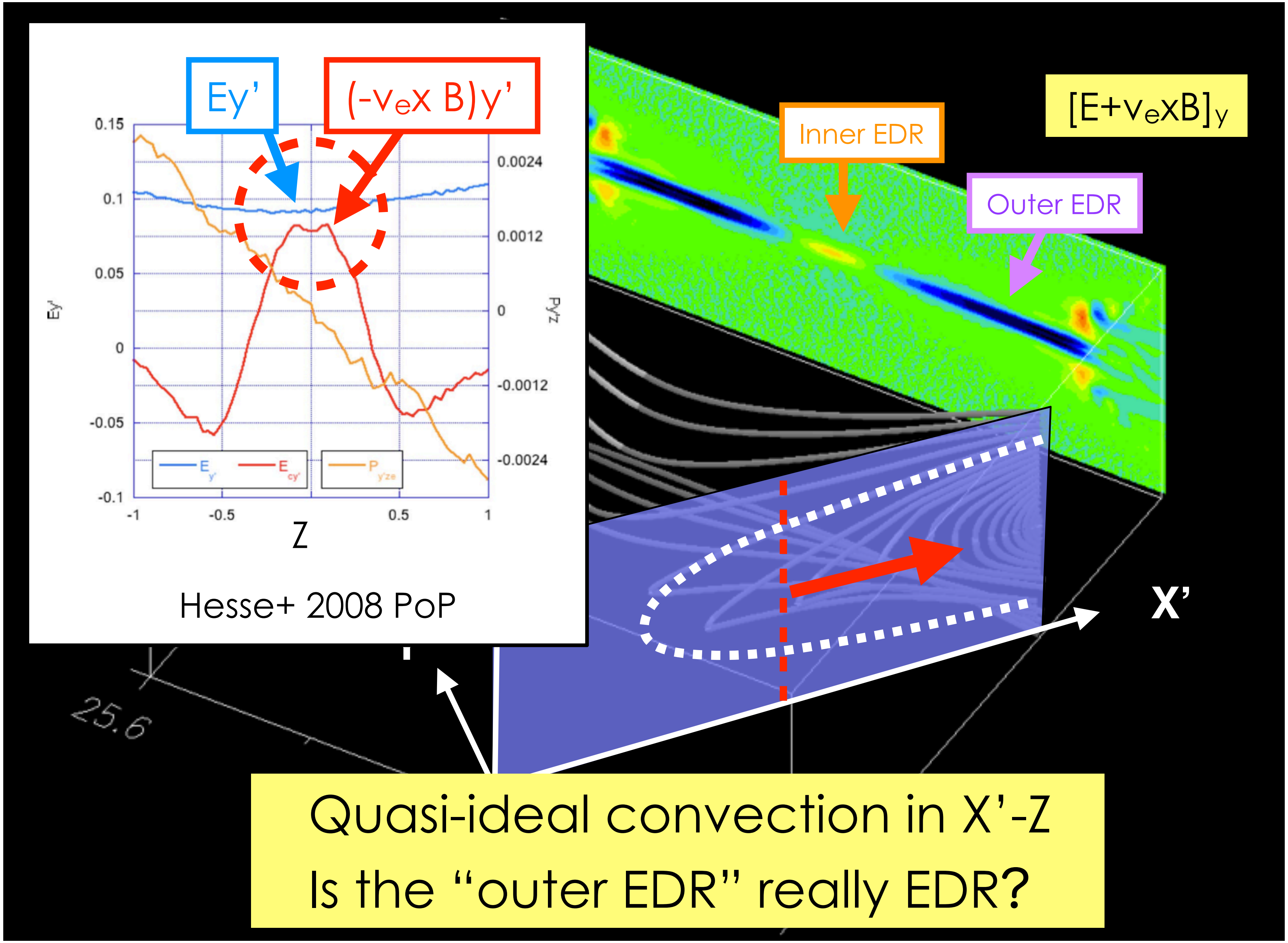
- Large-scale PIC simulations [Since Daughton+ 2006]
- Two-scale substructure
  - Inner region near the X-point
  - Outer region elongated with a fast electron jet

controversial



Karimabadi+ 2007 GRL

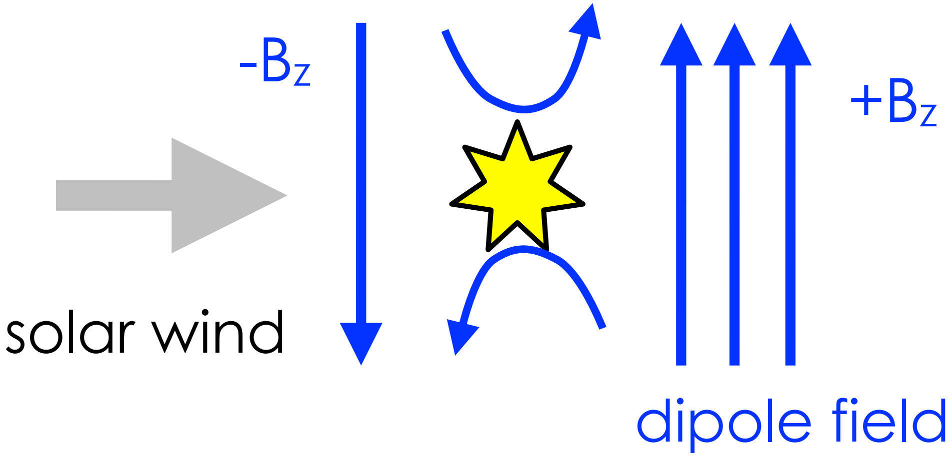
From a different angle [Hesse+ 2008]



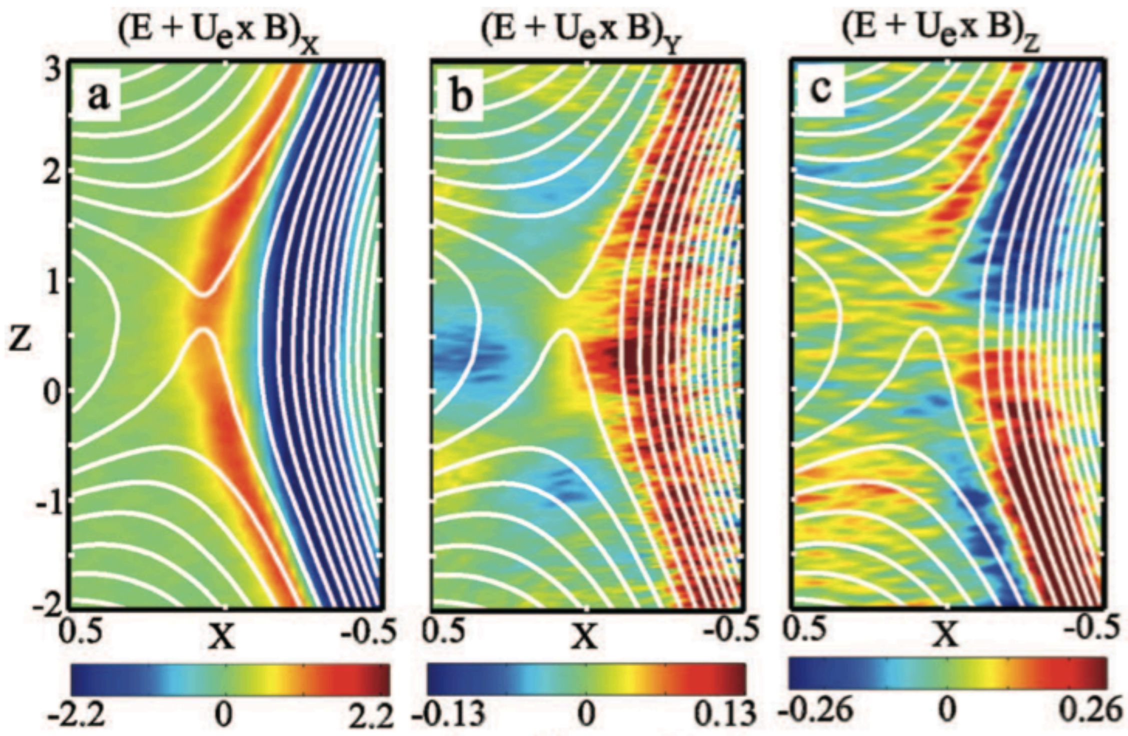
Quasi-ideal convection in X'-Z

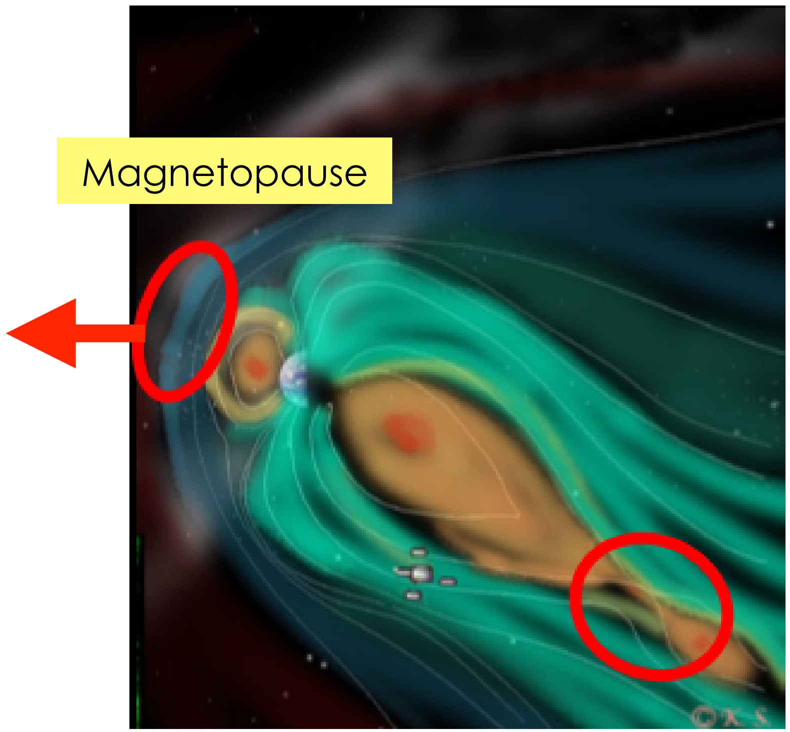
Is the "outer EDR" really EDR?

EDR in asymmetric Rx



- All three components of $[E+v_e xB]$ are puzzling

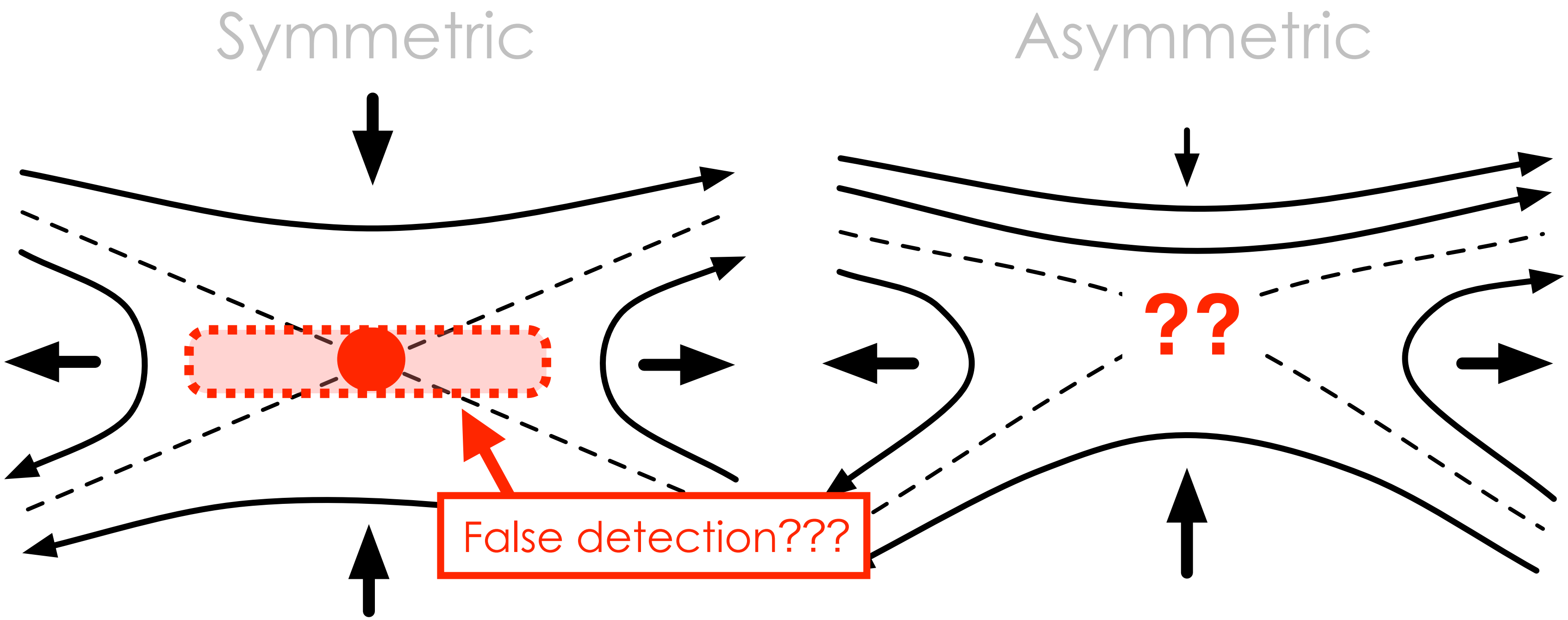




Pritchett & Mozer 2009 PoP

Something is wrong

- $E + v_e x B \neq 0$ may not identify the critical region.
  - The controversial outer EDR
  - No EDR signature in asymmetric reconnection



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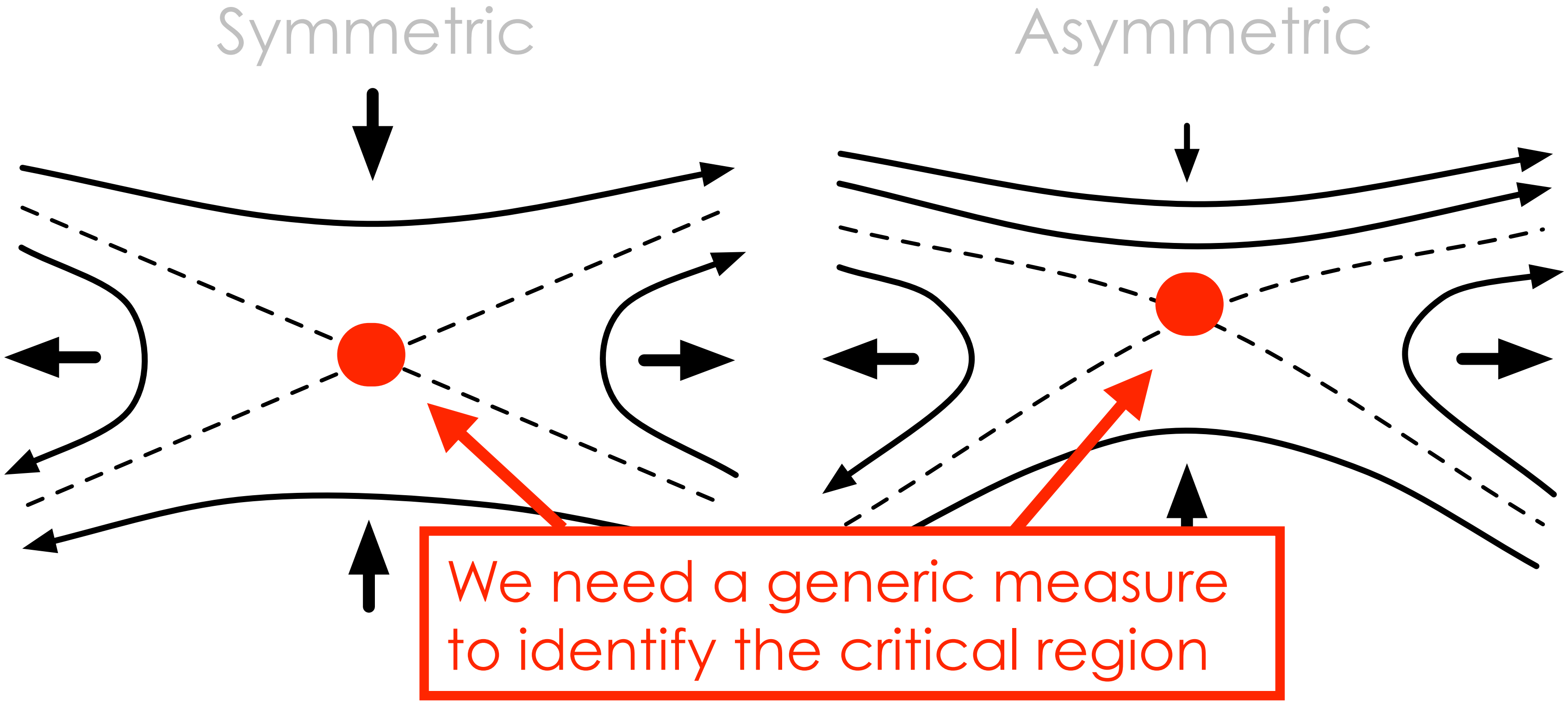


2. Theory

A new measure "D"

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

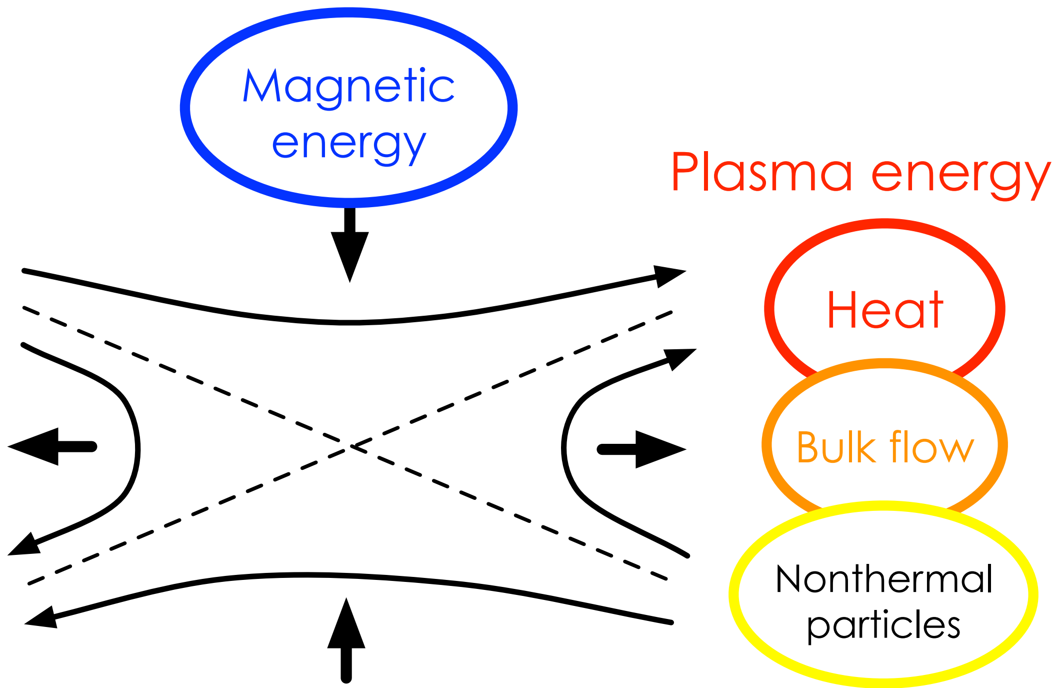
$$D_e = \gamma_e \left[\boldsymbol{j} \cdot (\boldsymbol{E} + \boldsymbol{v}_e \times \boldsymbol{B}) - \rho_c (\boldsymbol{v}_e \cdot \boldsymbol{E}) \right]$$

Charge density

- We derive our formula, considering three basic requirements.

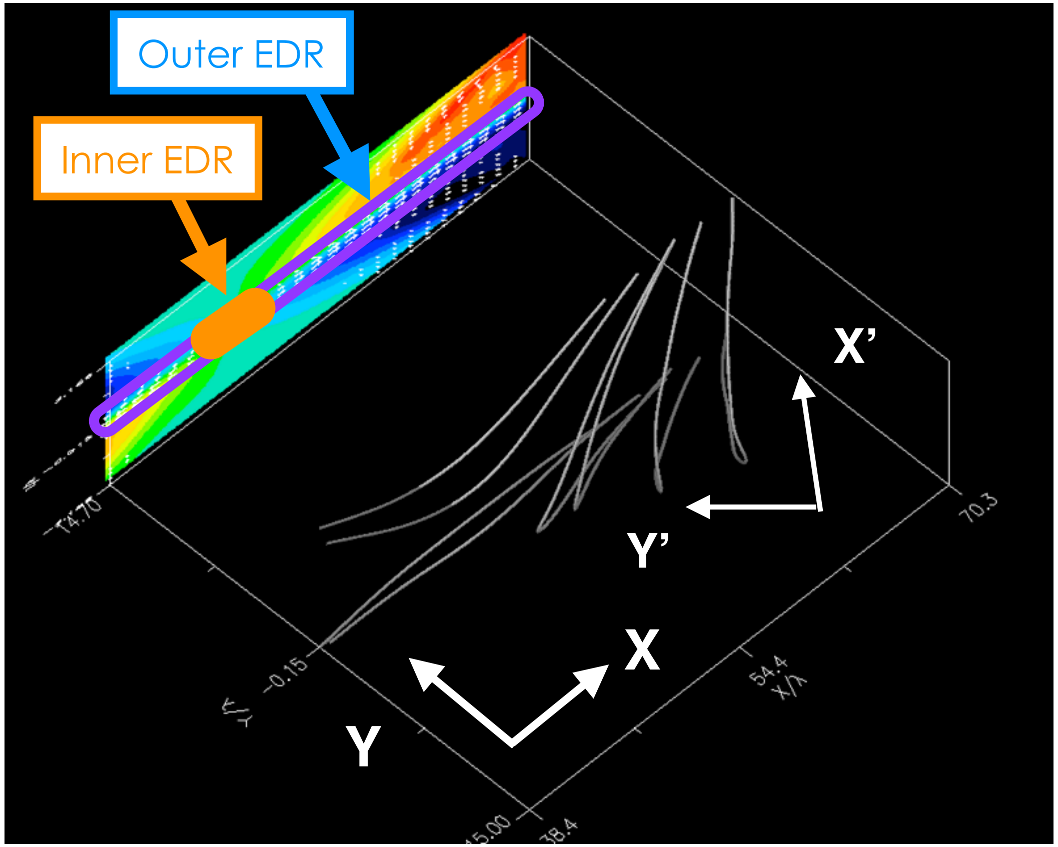
Desirable conditions for "D" (1/3)

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



Desirable conditions for "D" (2/3)

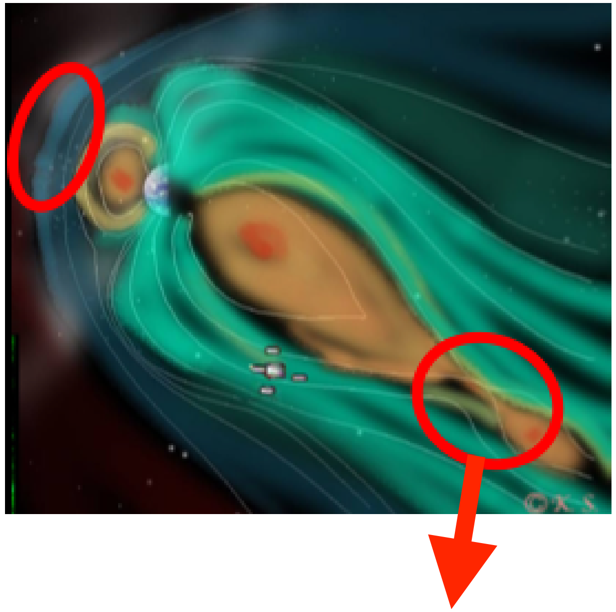
1. Magnetic energy consumption
2. Scalar quantity
3. Insensitive to observer motion



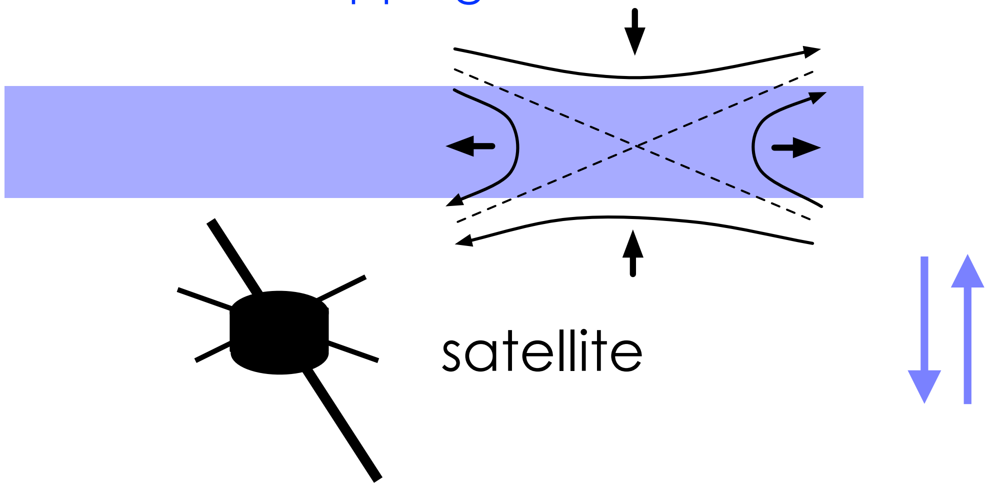
- A scalar quantity is rotation-free: The Y direction or the Y' direction do not matter.

Desirable conditions for “D” (3/3)

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



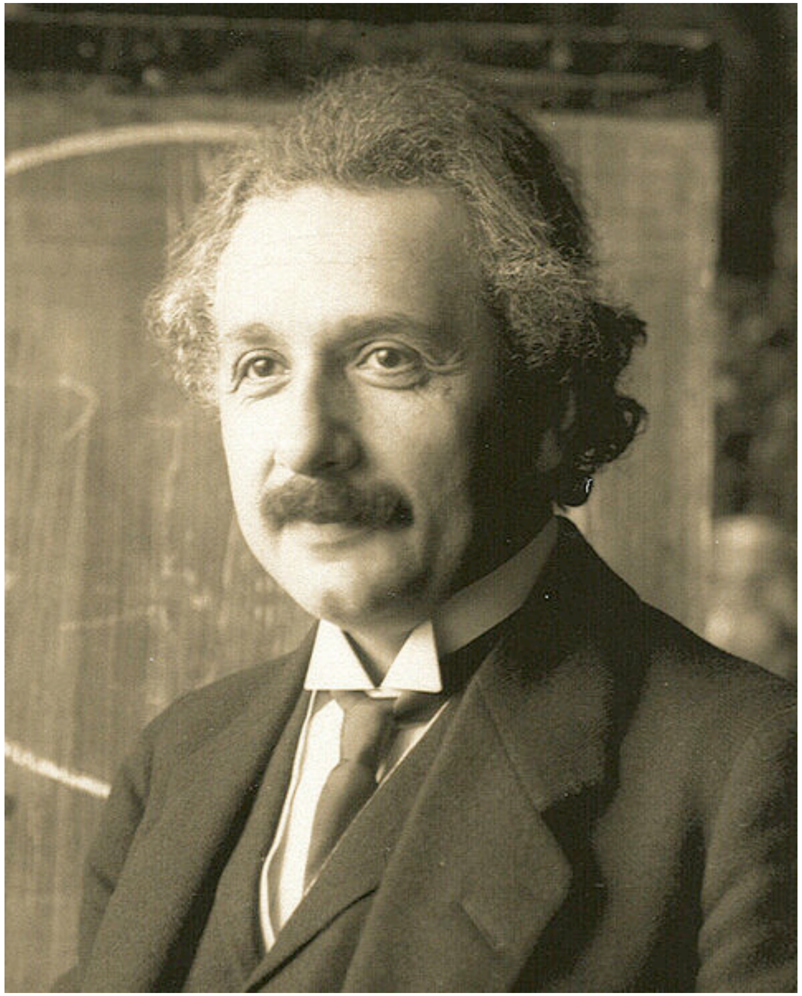
Plasma sheet flapping



- Relative motion between the observer (satellite) and the reconnection site

Desirable conditions

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



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

A. Einstein

A Lorentz-invariant measure

- The electron-frame dissipation measure

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

$$\Longleftrightarrow \quad D_e = \boldsymbol{j}' \cdot \boldsymbol{E}'$$

Charge density

– The prime sign (') : quantiti

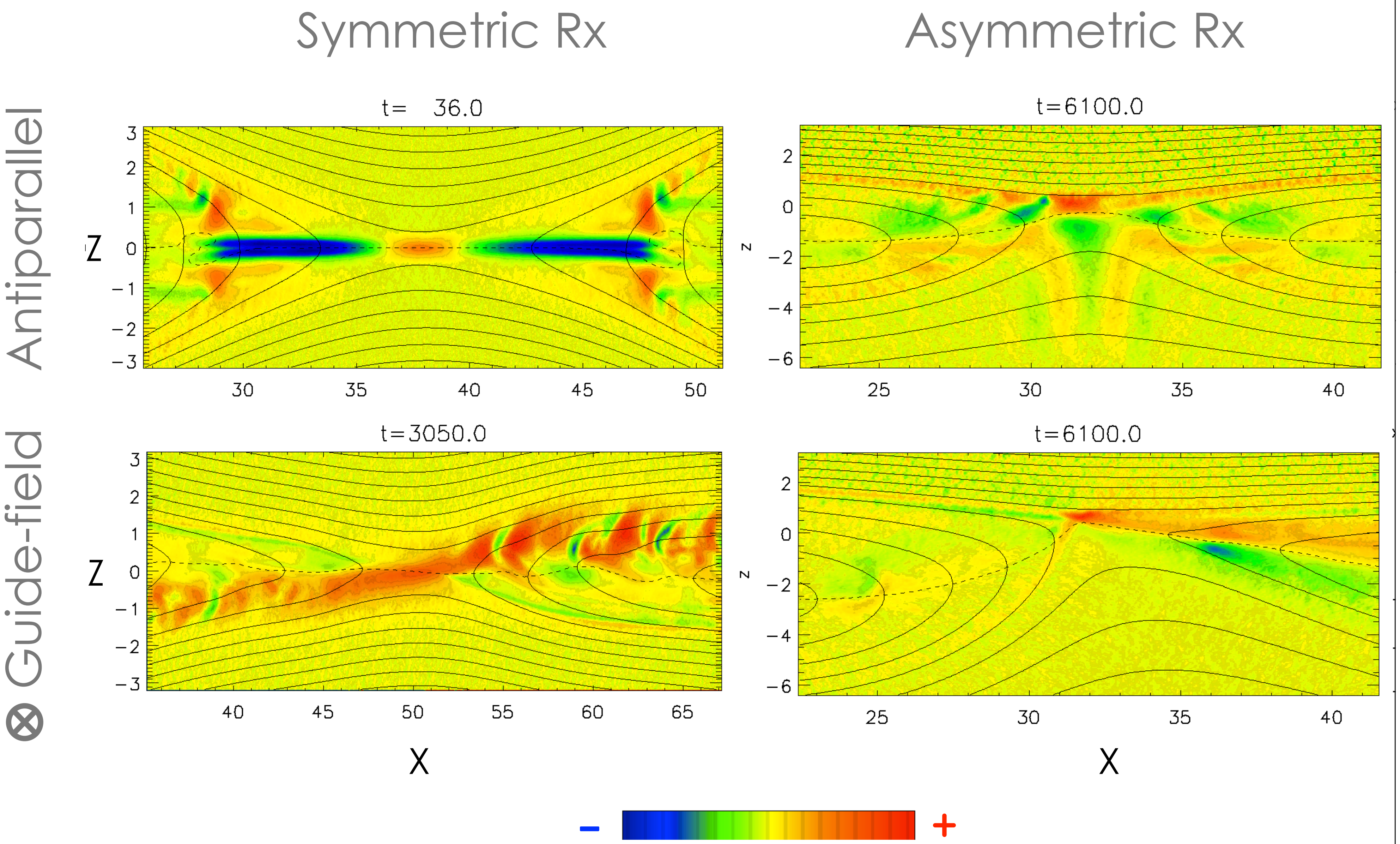
- Ohmic dissipation in the electron's moving frame

Desirable conditions

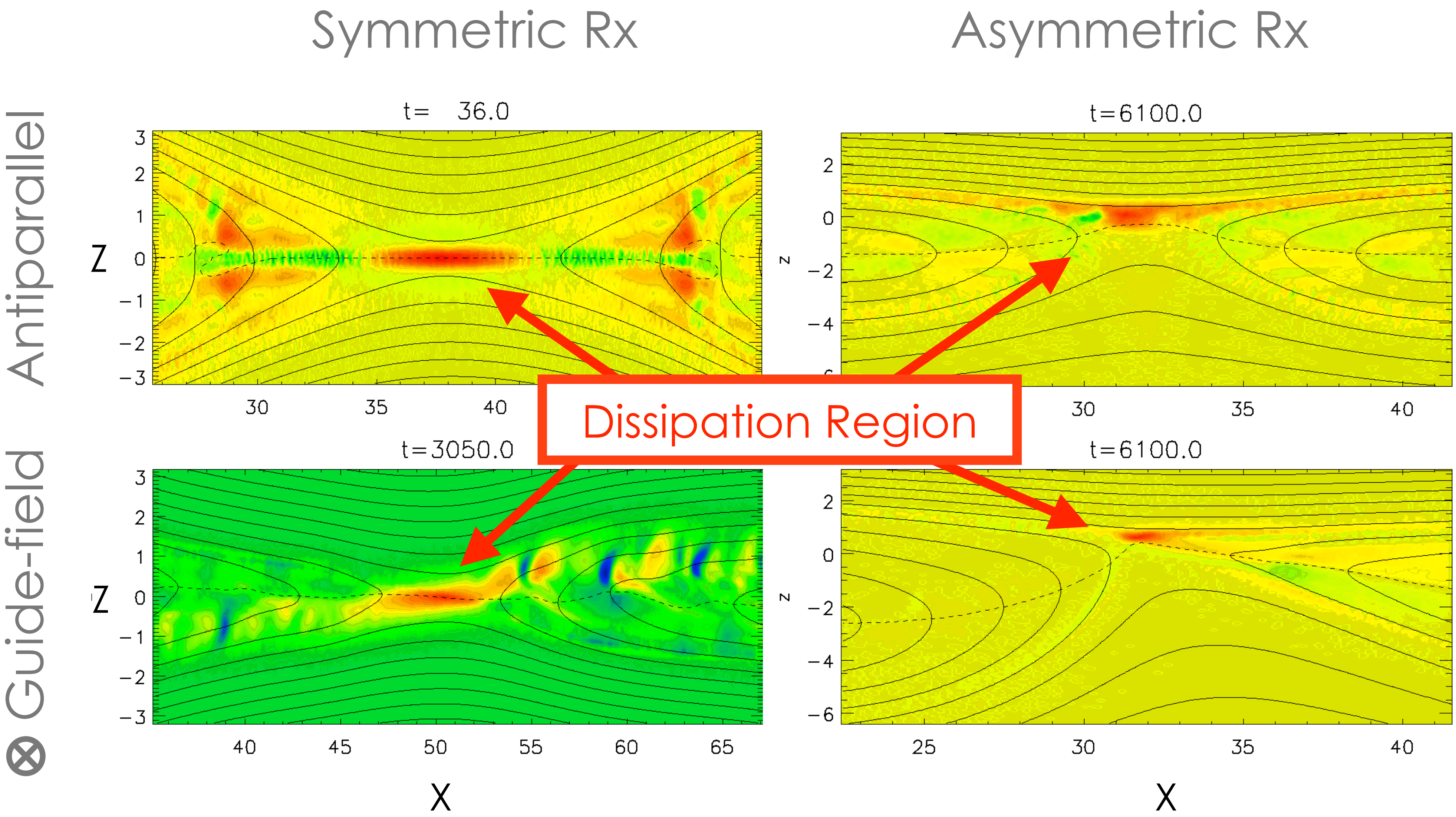
1. Magnetic energy consumption
2. Scalar quantity
3. Insensitive to observer motion

3. Two-dimensional PIC simulations

Previous measure: $(E + v_e x B)_y$

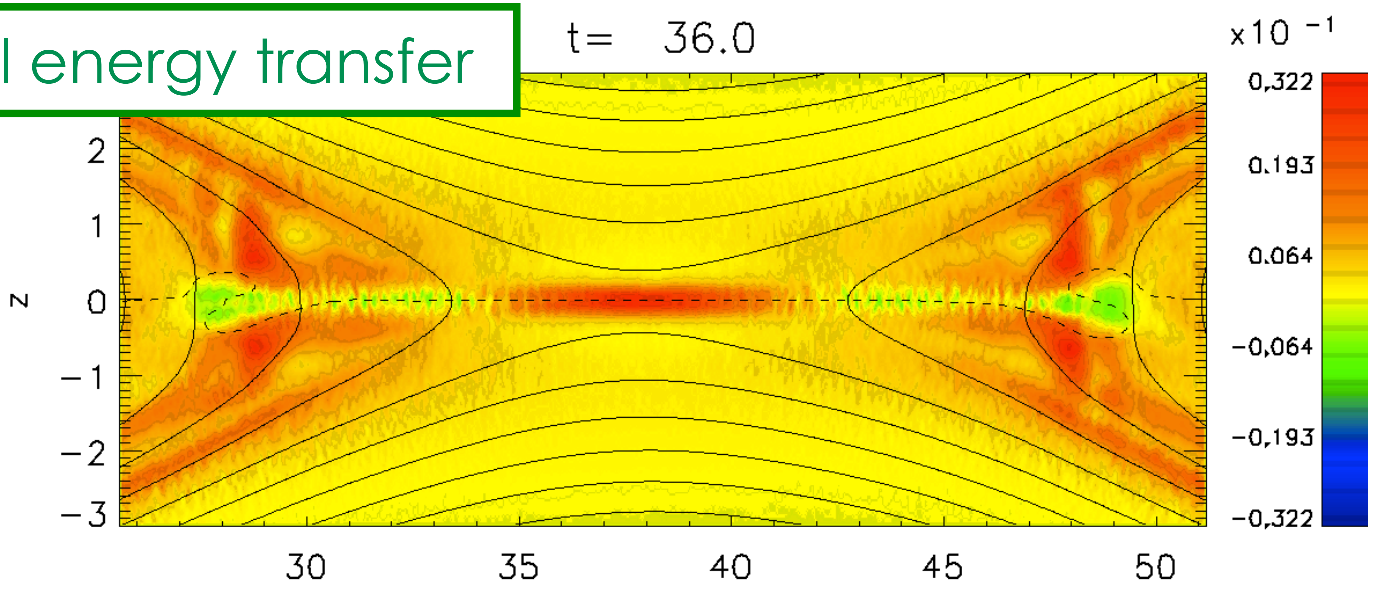


New measure: D_e



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

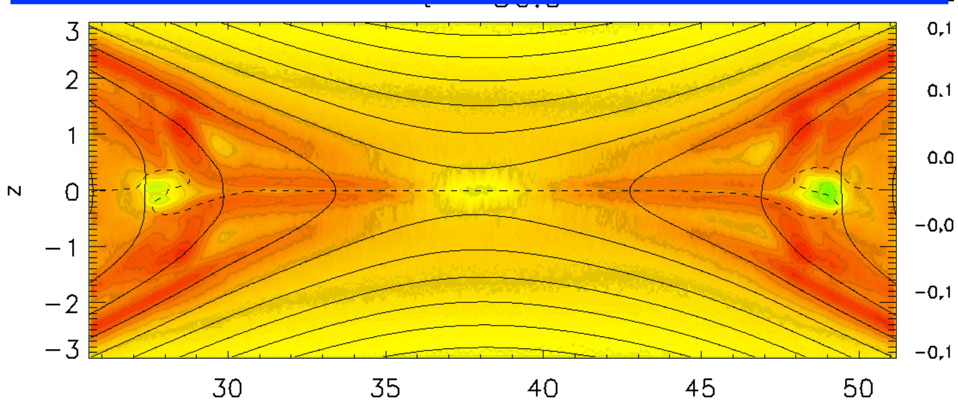
Total energy transfer



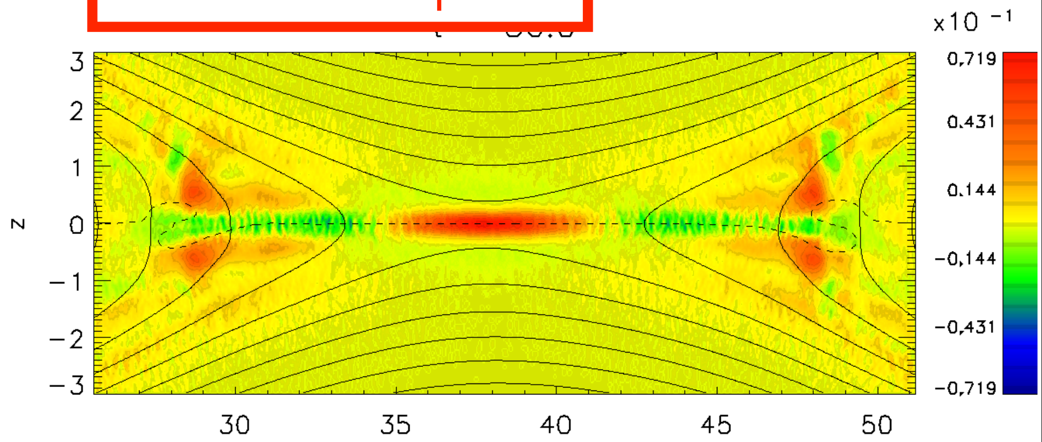
$$\boldsymbol{j} \cdot \boldsymbol{E} = (\boldsymbol{j} \times \boldsymbol{B}) \cdot \boldsymbol{v}_{\mathrm{mhd}} + D_e$$

$\eta \boldsymbol{j}^2$ in Resistive MHD

Ideal part (work by Lorentz force)

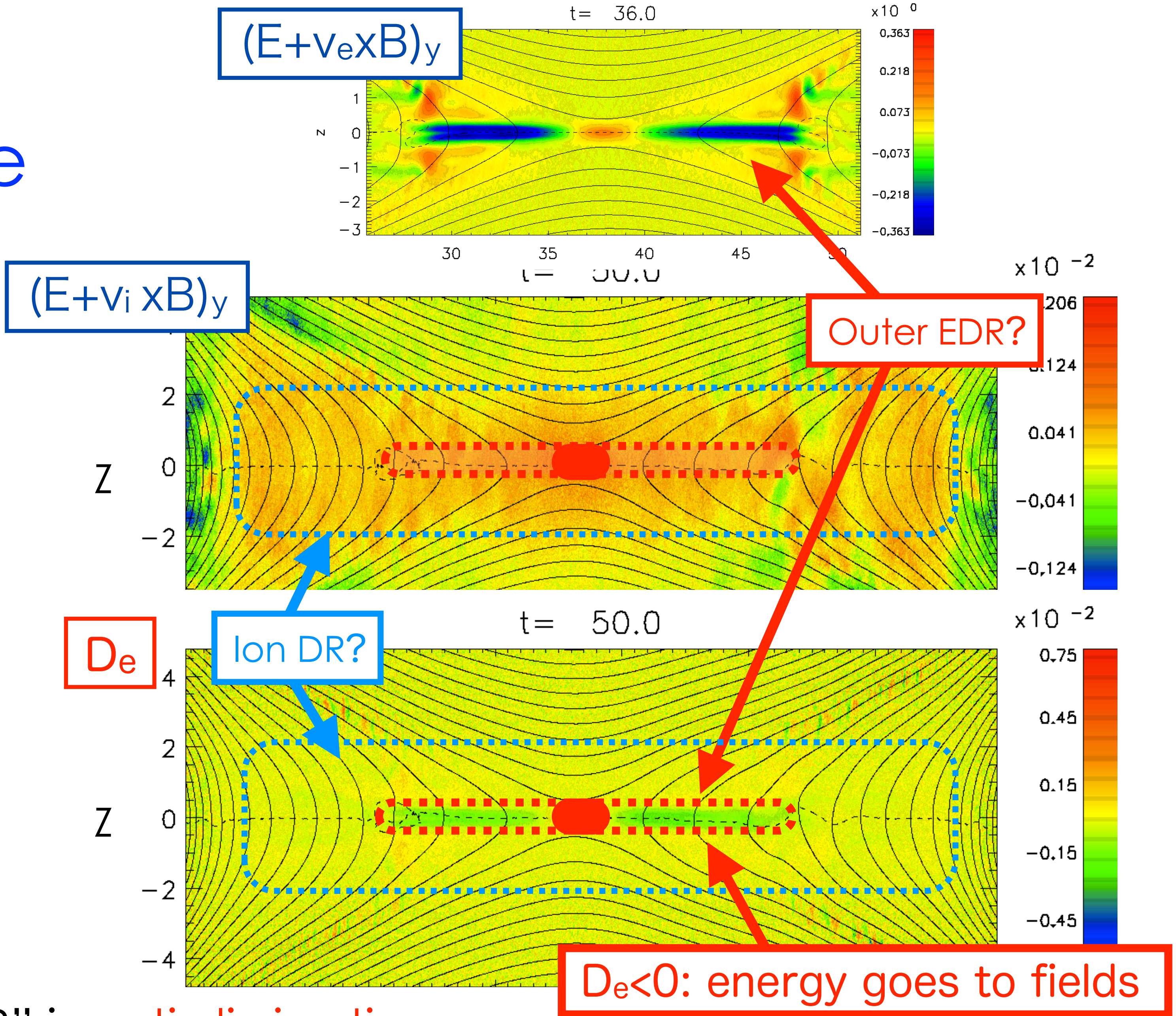


Non-ideal part



Birn & Hesse 2005

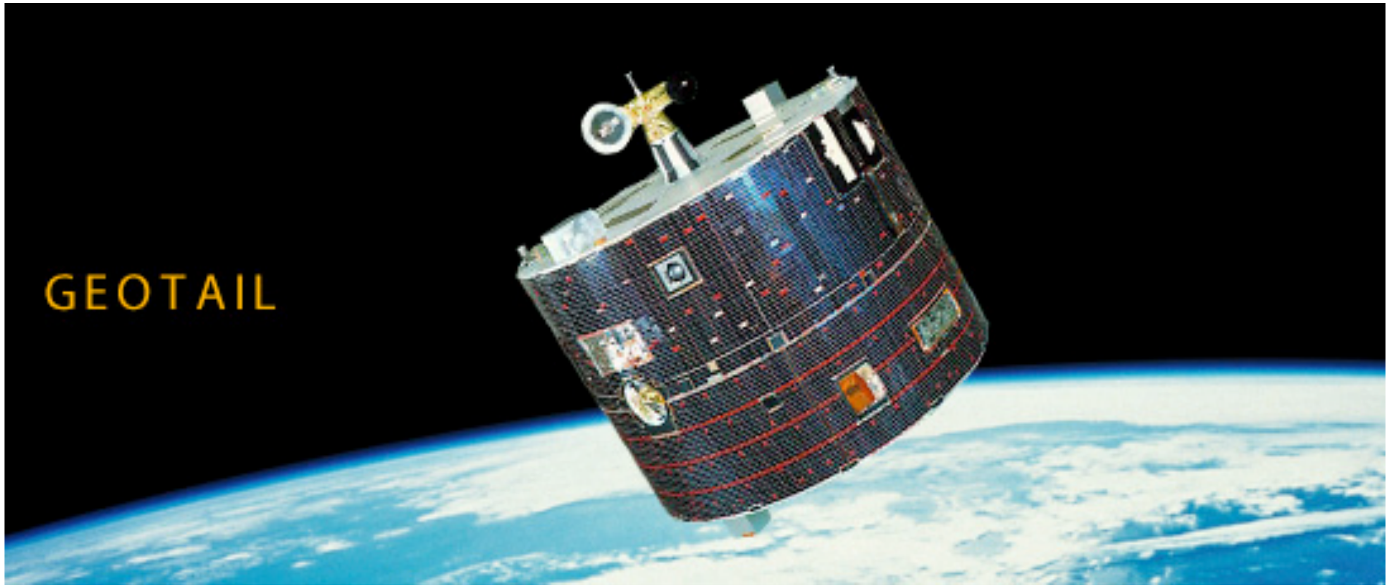
Previous multi-scale picture



- "Outer EDR" is anti-dissipative.
- "Ion DR" is non-dissipative. Oblique projection of an ion current sheet explains $(E+v_i xB)_y \neq 0$ (Hesse+ 2008).

4. Observation

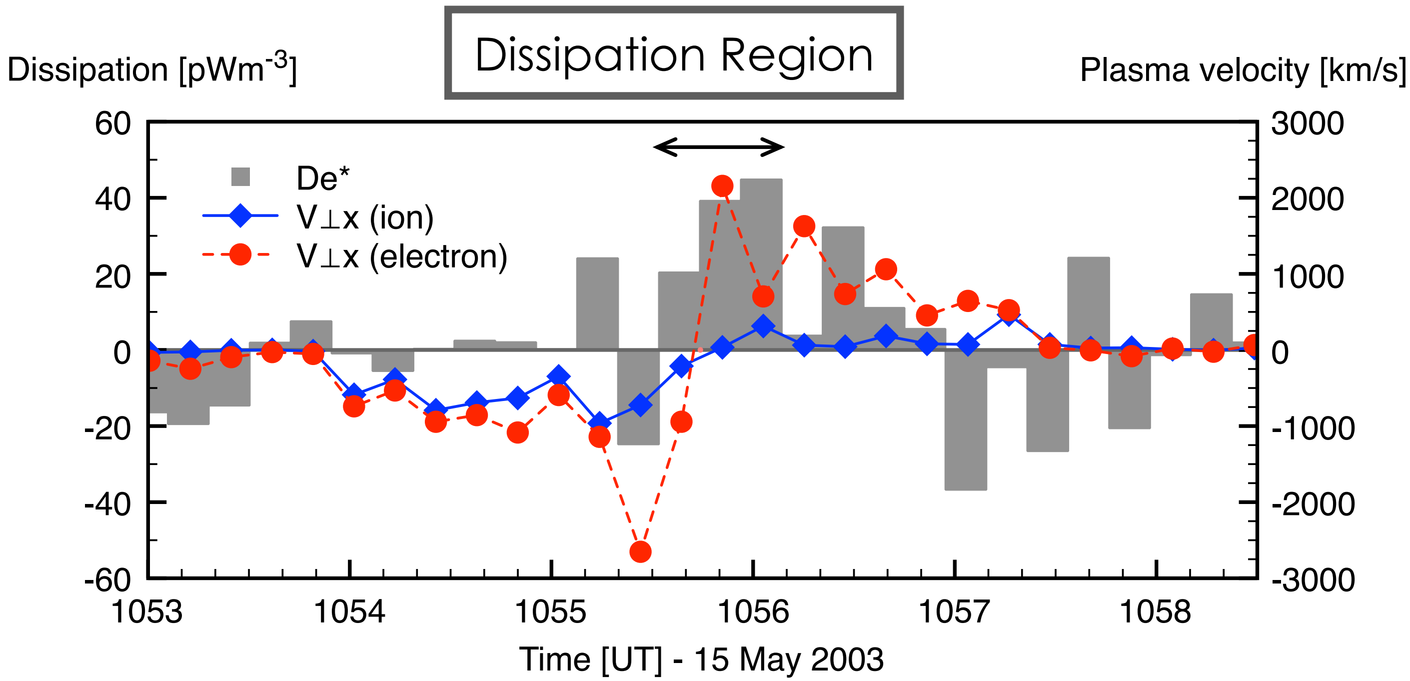
GEOTAIL satellite

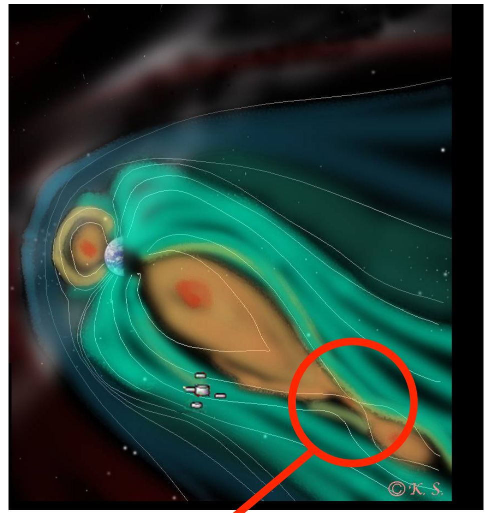


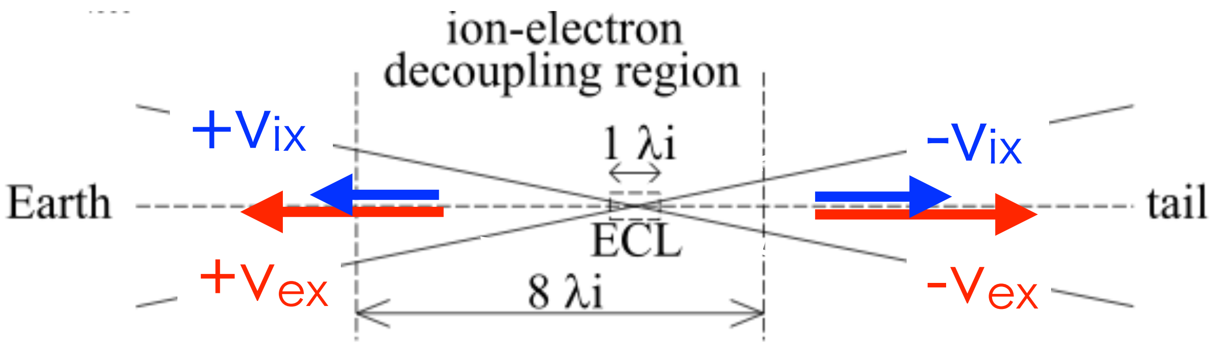
$$
\begin{aligned}
D_e &= \gamma_e \left[\boldsymbol{j} \cdot (\boldsymbol{E} + \boldsymbol{v}_e \times \boldsymbol{B}) - \rho_c (\boldsymbol{v}_e \cdot \boldsymbol{E}) \right] \\
&\approx \boldsymbol{j} \cdot (\boldsymbol{E} + \boldsymbol{v}_e \times \boldsymbol{B})
\end{aligned}
$$

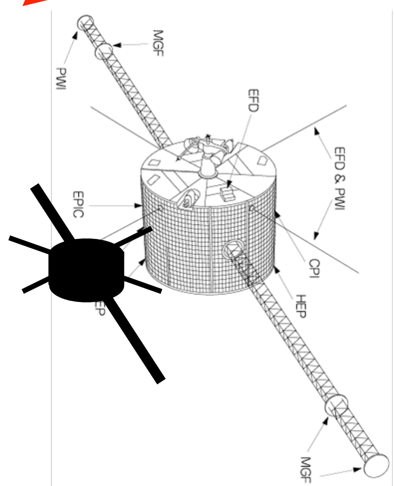
- $\mathbf{J} = e\, n_i\, (\mathbf{v}_i - \mathbf{v}_e)$ ← LEP moment data
- $\mathbf{v}_e$ ← LEP moment data
- E_x, E_y ← EFD raw data (some sub-spin noises dropped)
- E_z ← reconstructed from $E'_z = 0$

2003-05-15 event [Nagai+ 2011]



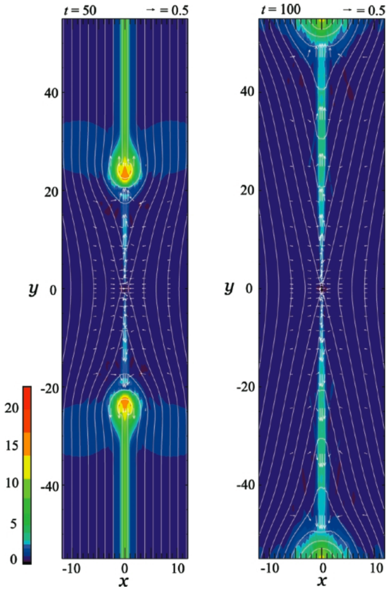


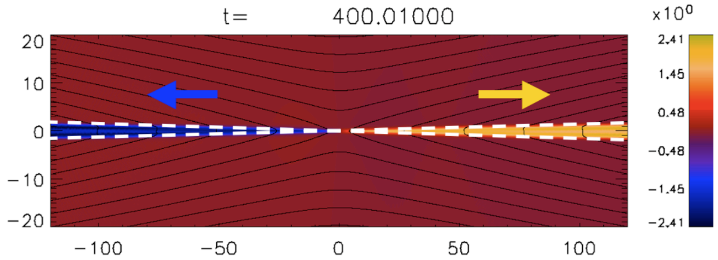


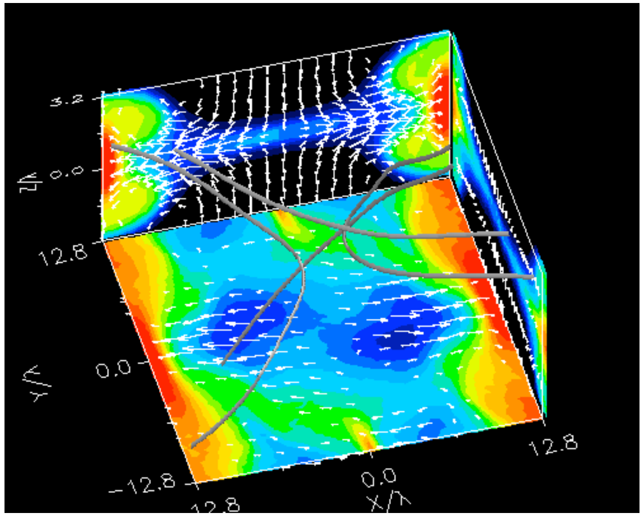


One more thing
5. Astrophysical extension

Reconnection with [special] relativity







Simulations

MHD

Watanabe & Yokoyama 2006
Zenitani+ 2010
Takahashi+ 2011

Multi-fluid

Zenitani+ 2009

Kinetic

Zenitani & Hoshino 2001-2008
Jaroschek+ 2004-2009
Bessho & Bhattacharjee 2007-2012

Blackman & Field 1994
Lyutikov & Uzdensky 2003
Lyubarsky 2005

MHD models

New measure

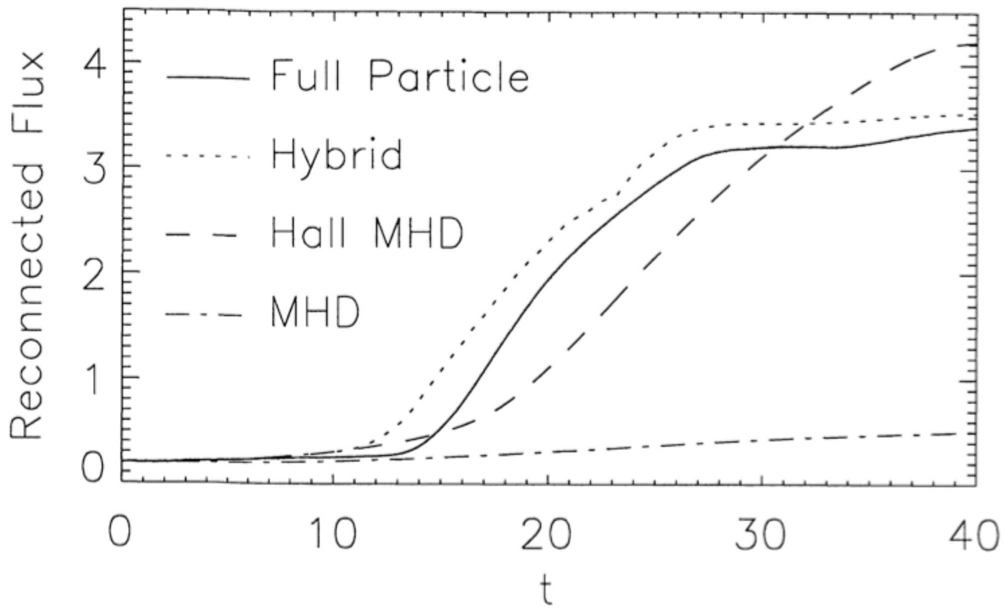
$$D_e = J_\mu F^{\mu\nu} u_{e,\nu}$$

Statistical mechanics
(very complicated)

Theories

Reconnection with [special] relativity

2001



2012

Watanabe & Yokoyama 2006
Zenitani+ 2010
Takahashi+ 2011

Blackman & Field 1994
Lyutikov & Uzdensky 2003
Lyubarsky 2005

Zenitani+ 2009

New measure

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

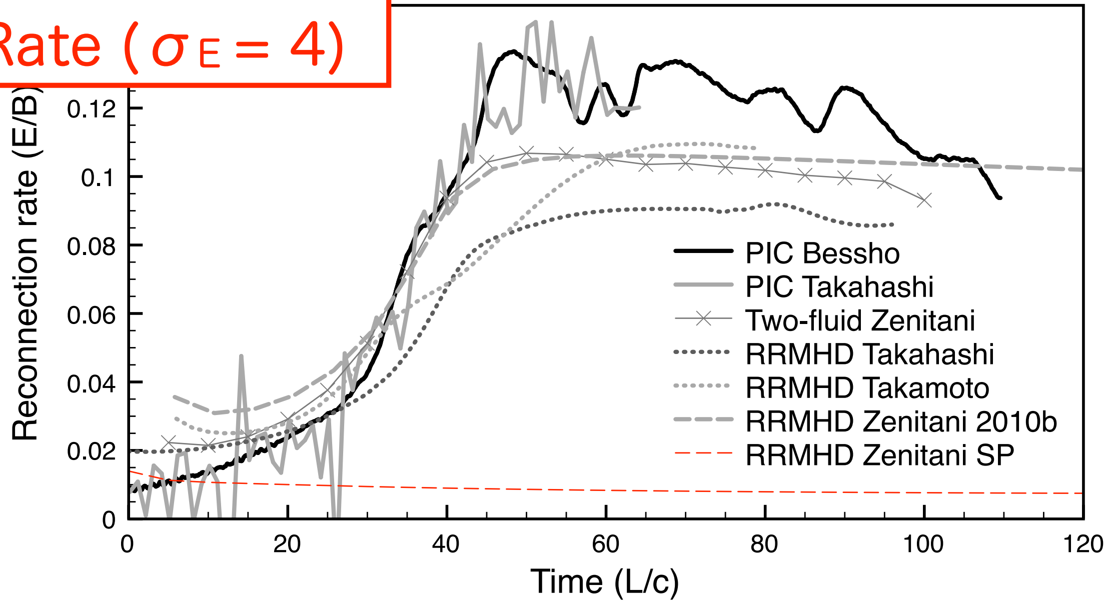
Zenitani & Hoshino 2001-2008
Jaroschek+ 2004-2009
Bessho & Bhattacharjee 2007-2012

Statistical mechanics
(very complicated)

The Relativistic Reconnection Challenge

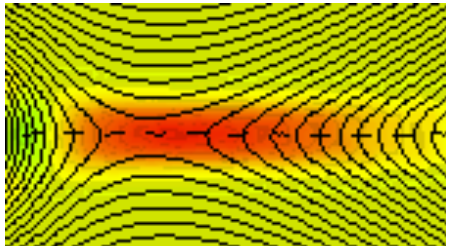
[Zenitani, Takahashi, Takamoto, & Bessho 2012]

Reconnection Rate ($\sigma_E = 4$)



New measure

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



- A milestone in relativistic reconnection research!

Summary

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

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

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

- Traditional DR picture needs to be reconsidered
- First in situ detection of the DR in a planetary magnetotail
- Ready for the relativistic regime

We propose to redefine the dissipation region by D_e

Thank you for your attention!!