リコネクションアウトフローのマルチスケール構造

Multi-scale structure of the outflow exhaust in collisionless magnetic reconnection

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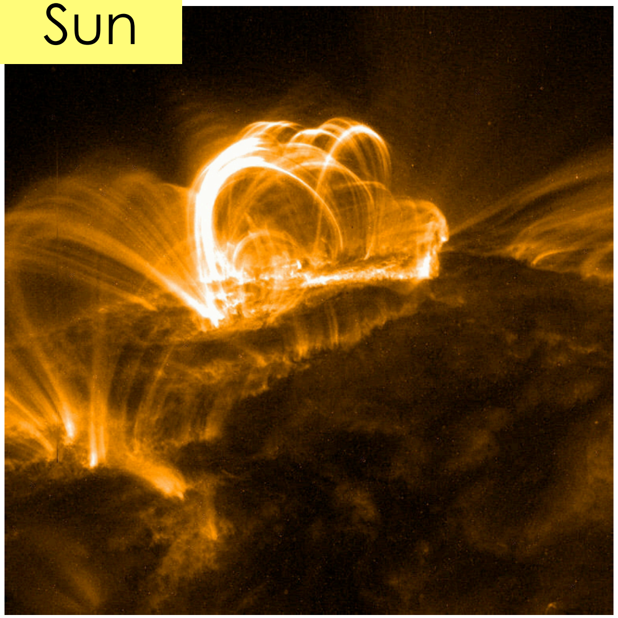
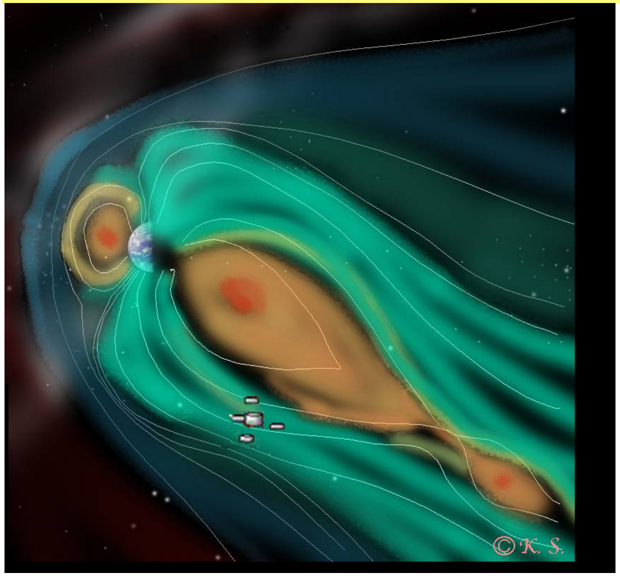
0. Introduction

Magnetic reconnection

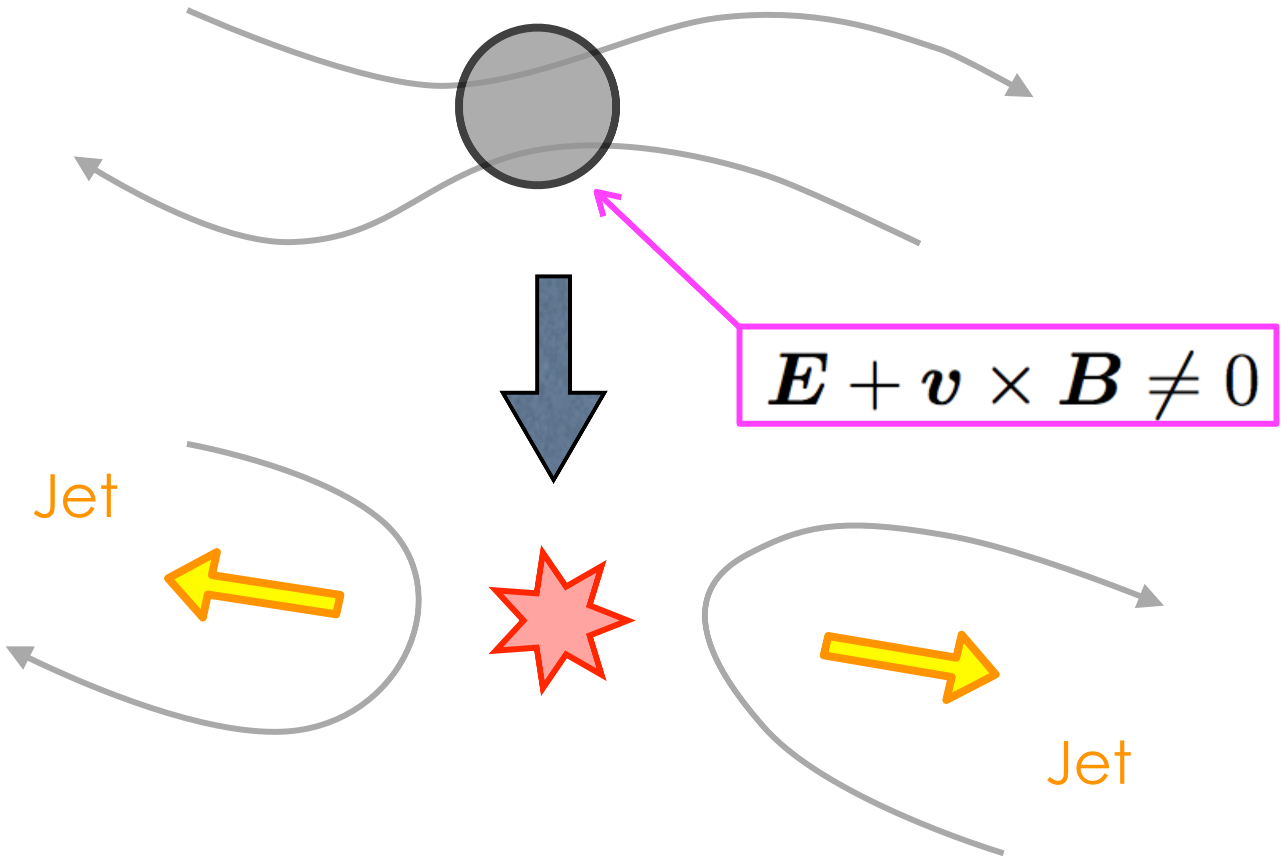
Sun



Earth's Magnetosphere



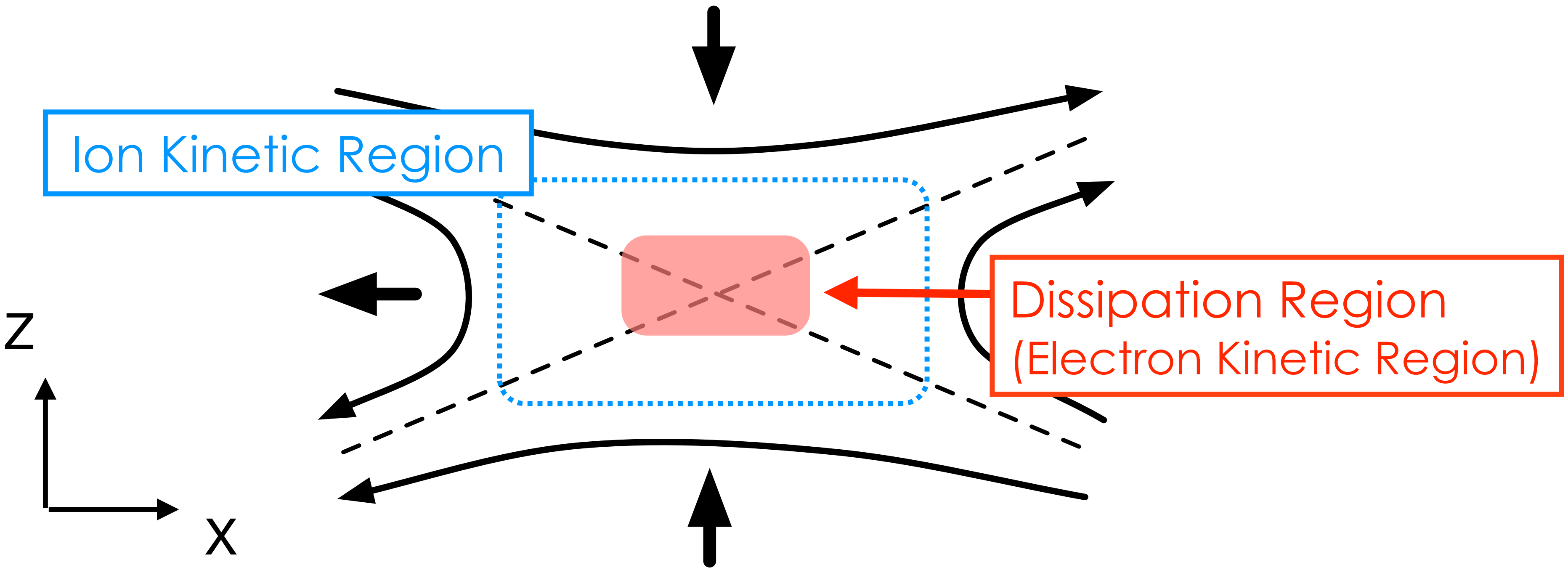
- Dissipation region around the X-point
- Structure and internal physics critically controls the macroscopic evolution



Kinetic dissipation regions

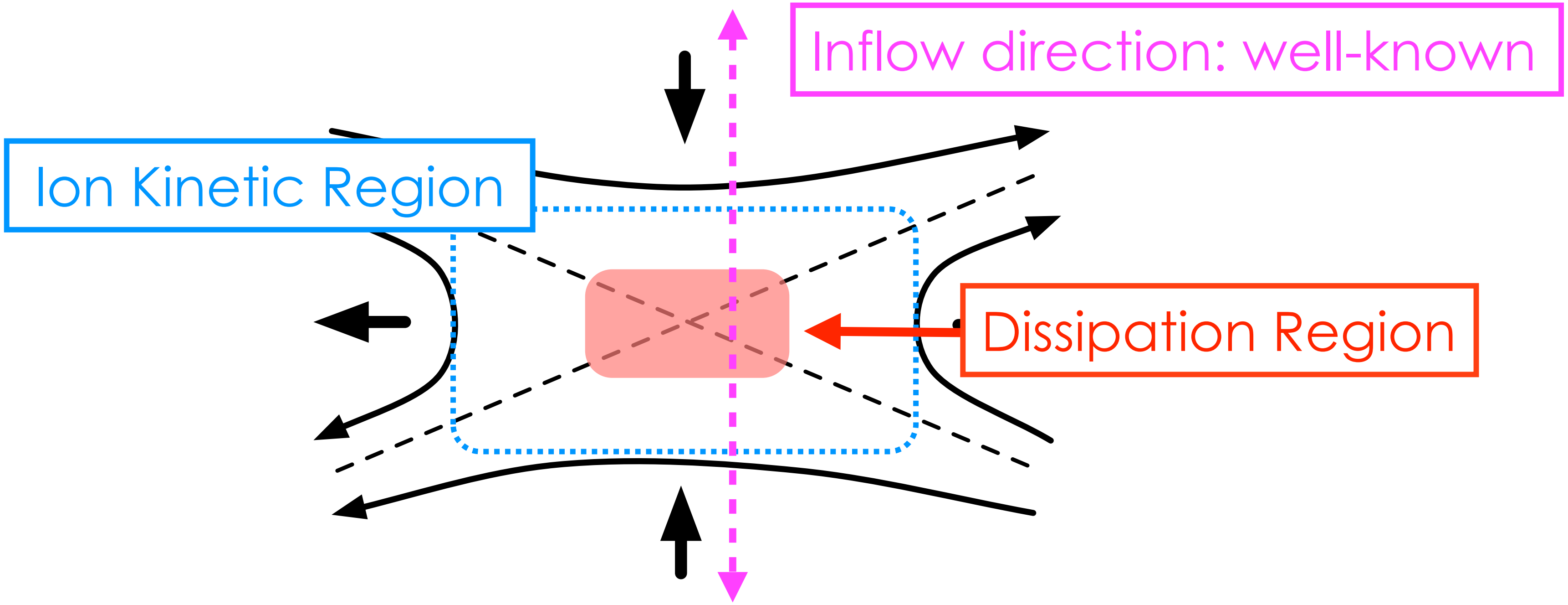
- The ideal condition $$\boldsymbol{E} + \boldsymbol{v}_s \times \boldsymbol{B} = 0$$

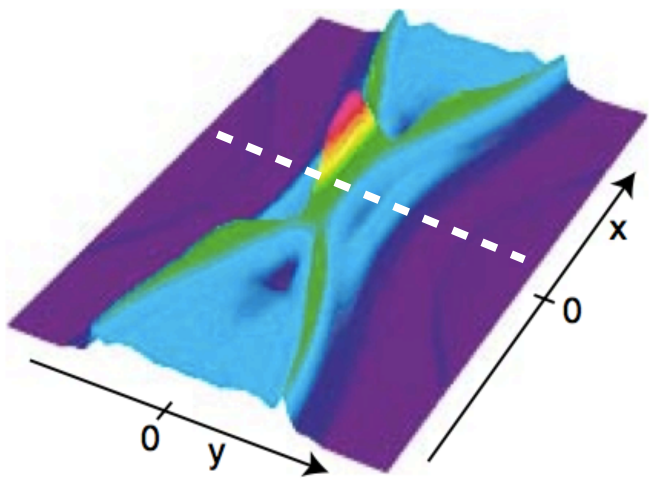
- We expected a multi-scale structure



- Nonideal energy dissipation arises from electron kinetic physics

Multi-scale structure





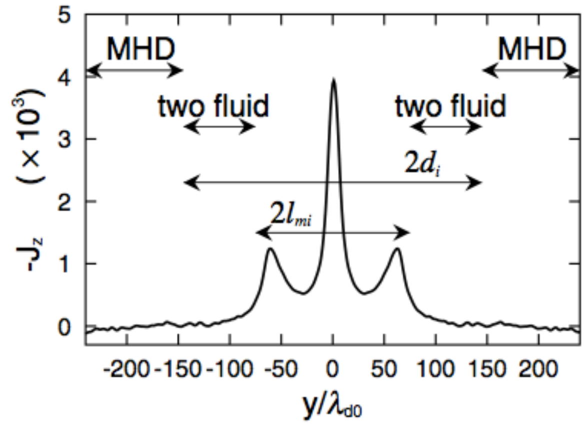
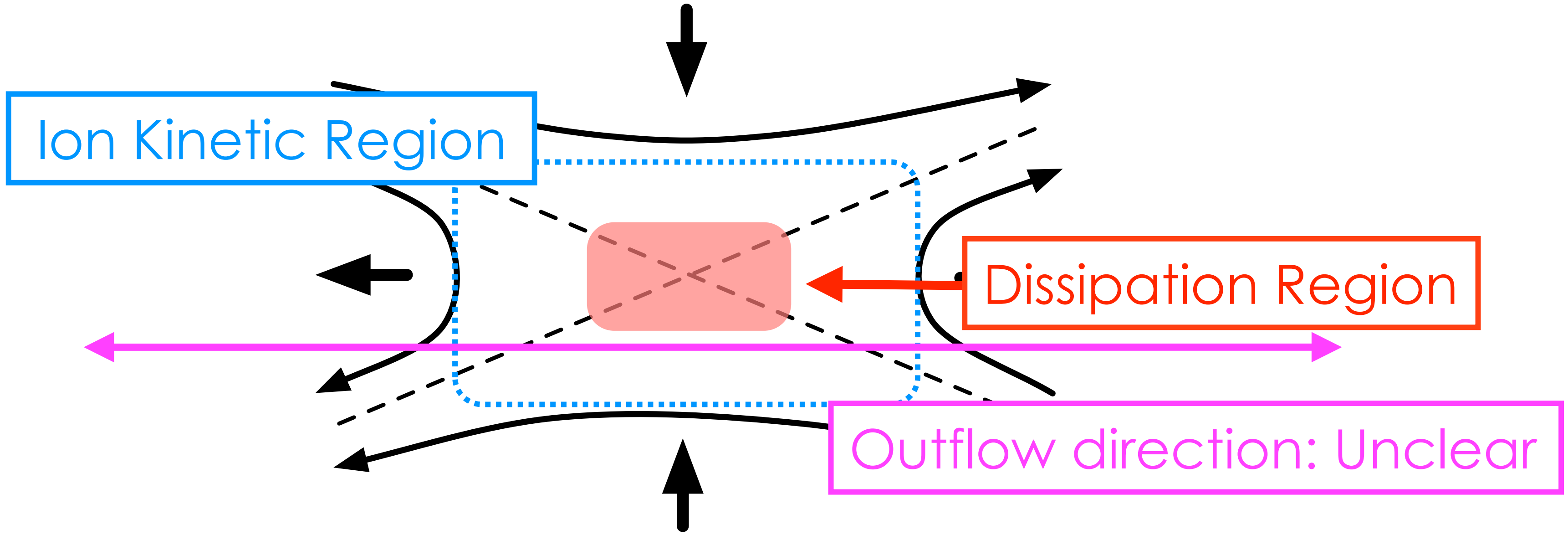
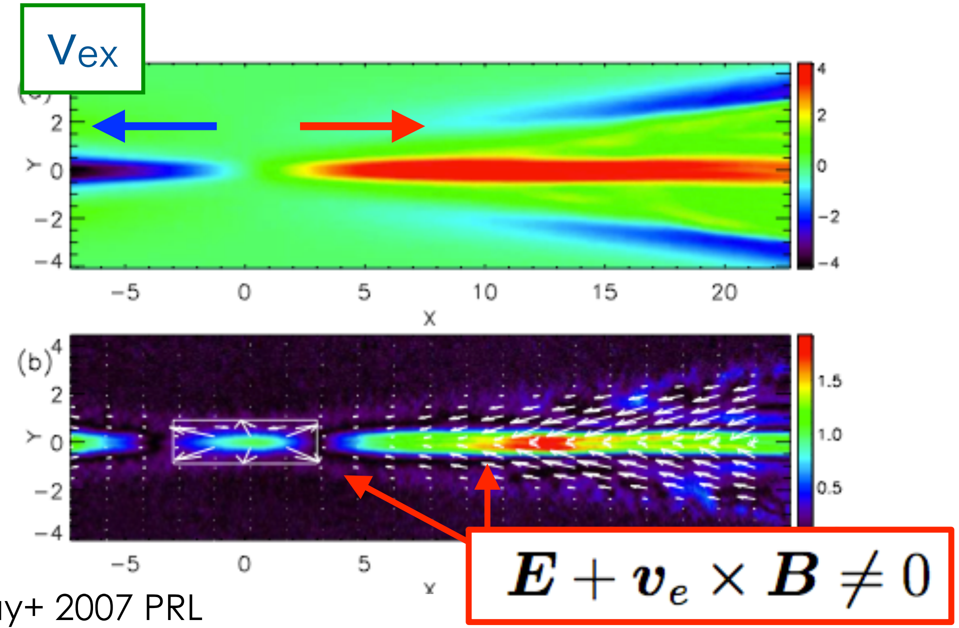


FIG. 2. The spatial profile of the out-of-plane current density along the vertical line passing the X point in the steady state.

Ishizawa & Horiuchi 2005 PRL

Multi-scale structure



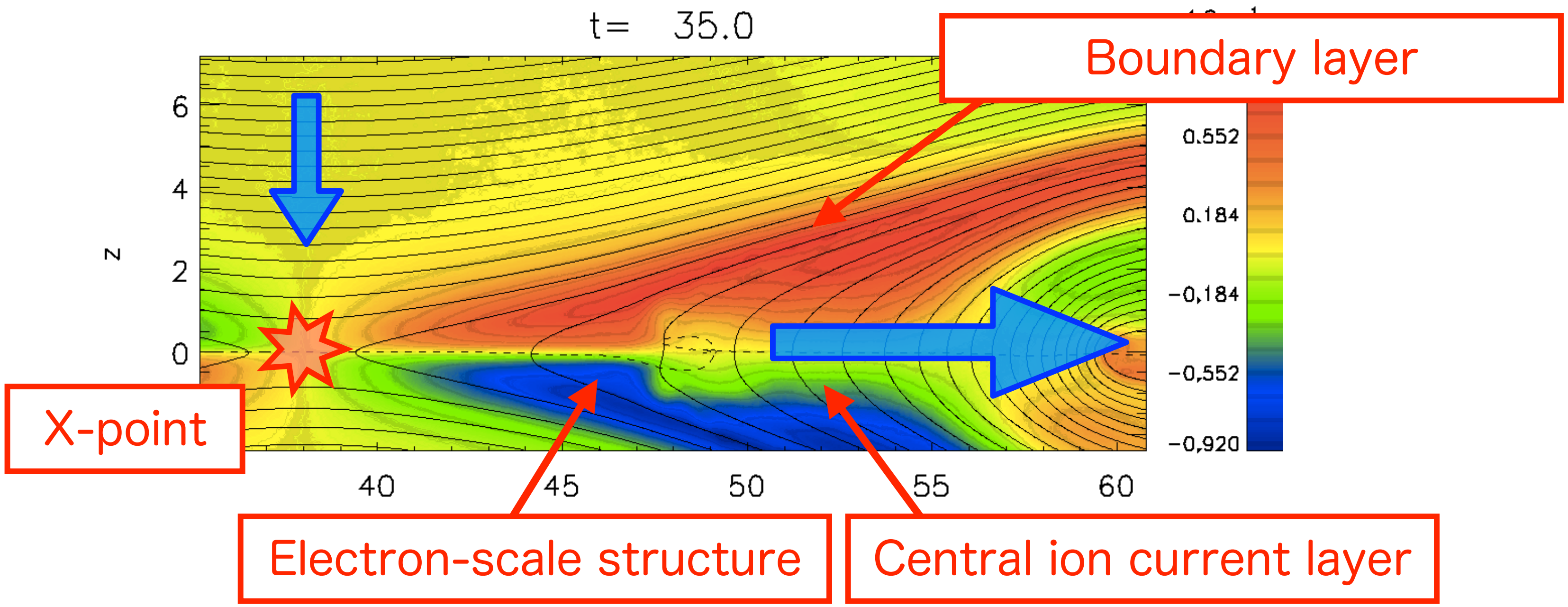


Shay+ 2007 PRL

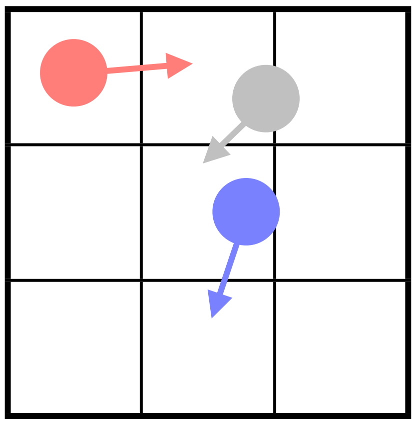
- No unified picture yet
  - Spatial scale
  - Lack of interest

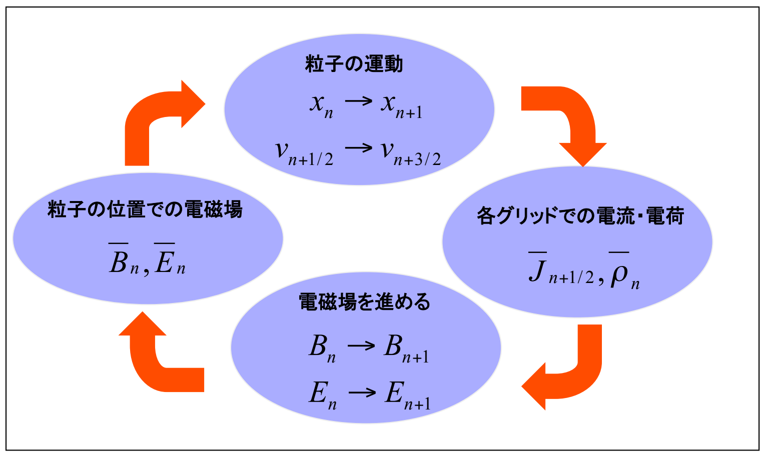
Today's topic

- Ion-scale properties in a reconnection outflow



- 2D particle-in-cell (PIC) simulations: m_i/m_e=100, N=10^9, 10^5 steps

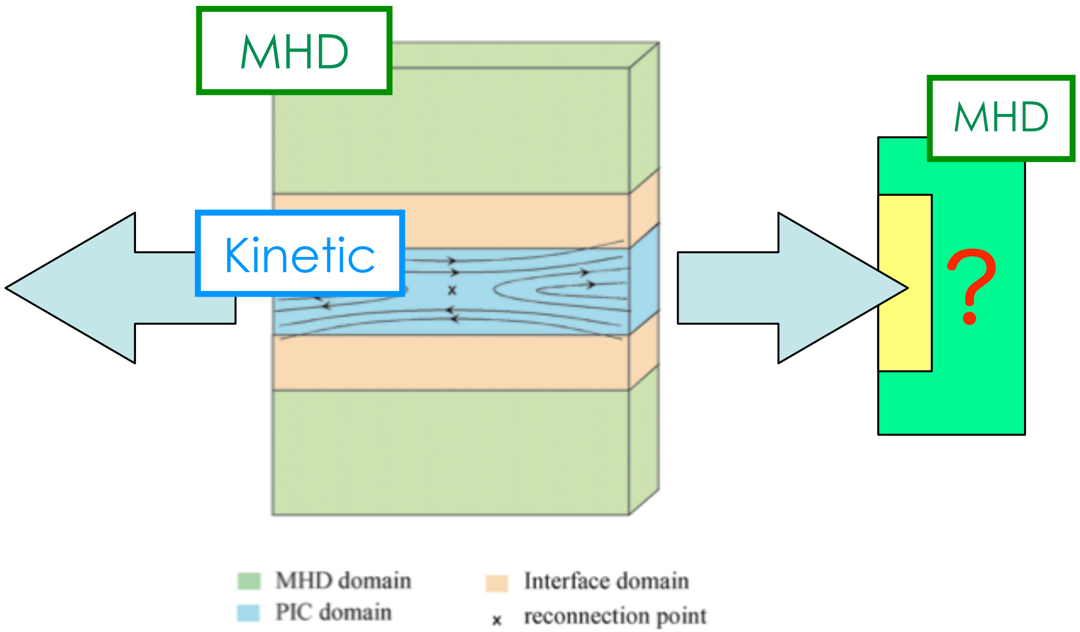


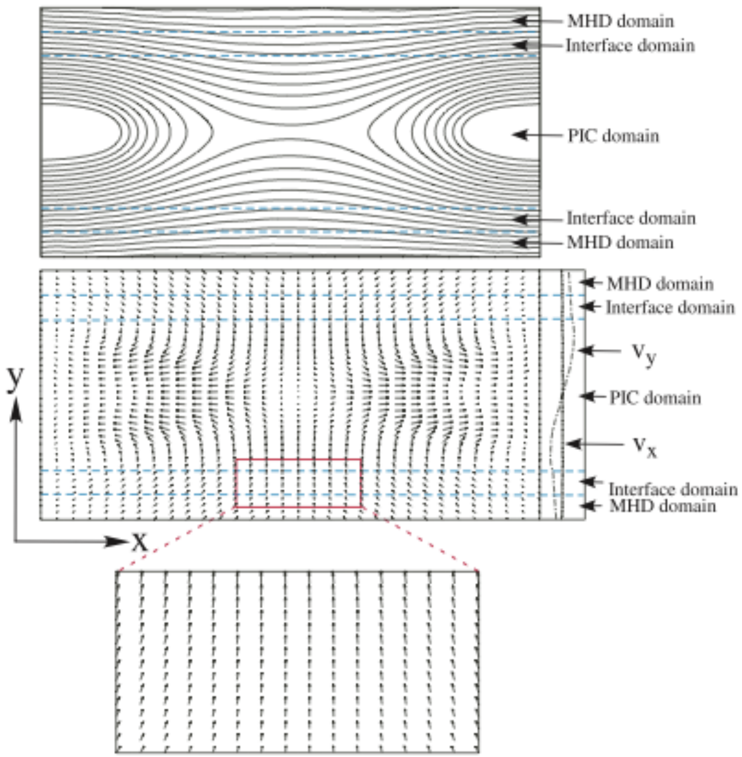


Multi-hierarchy simulation model

- Under development by NIFS (2006~)
- As of 2012, only implemented in the inflow direction.

$$\boldsymbol{E} + (\boldsymbol{v}_i/c) \times \boldsymbol{B} \neq 0$$



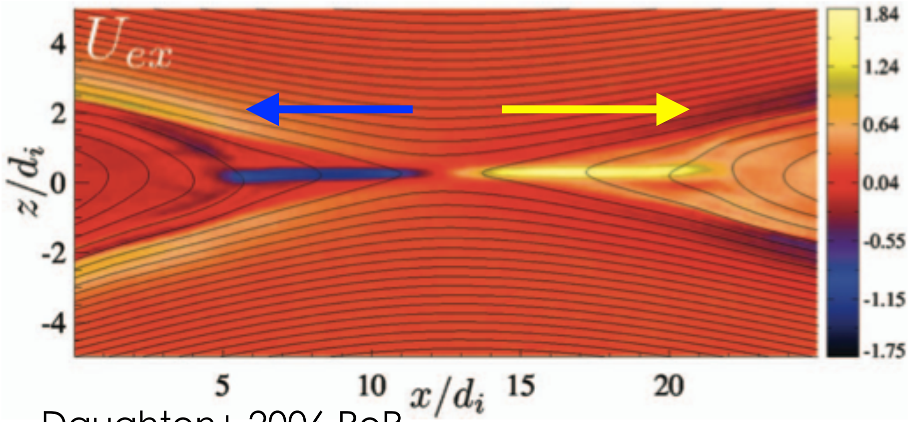


Usami+ 2009 PFR

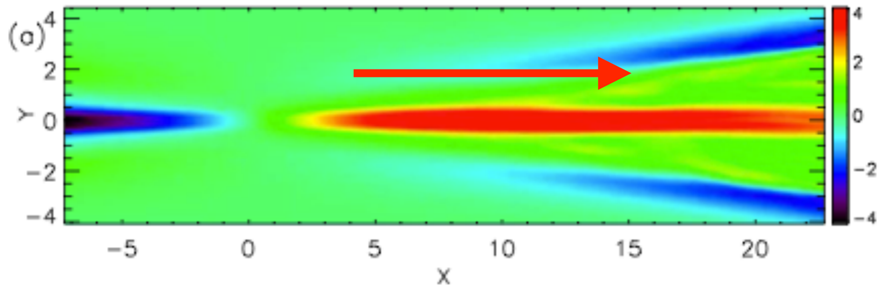
1. Electron-scale structure

“Super-Alfvénic electron jet”

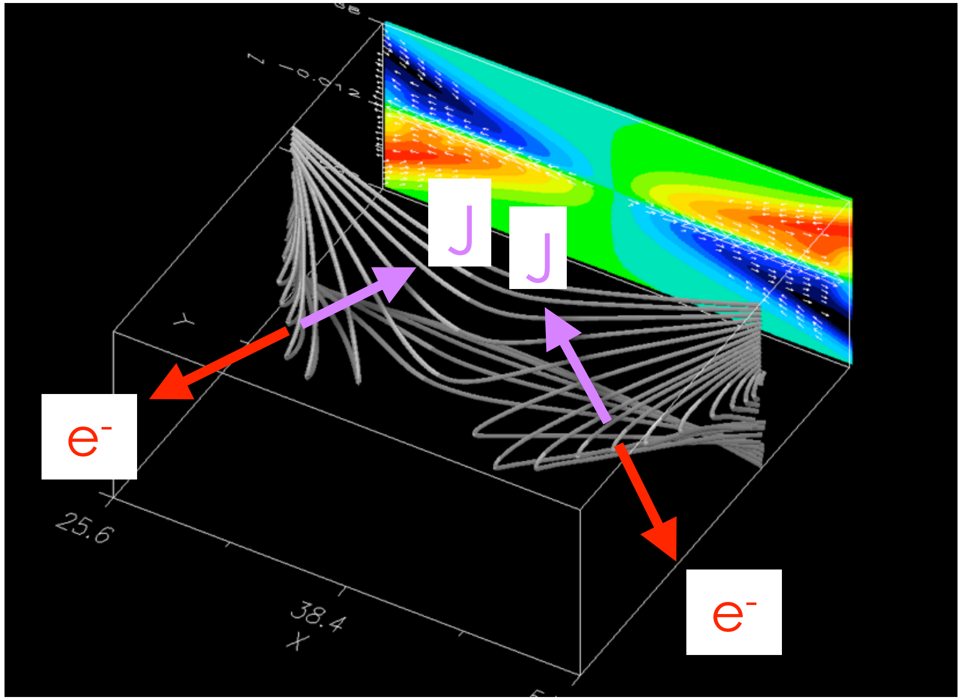
- Hot topic since 2006
- Oblique projection of an electron current sheet



Daughton+ 2006 PoP

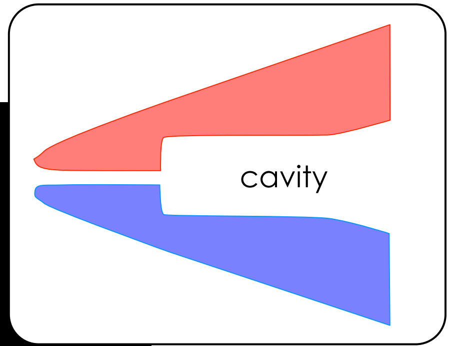


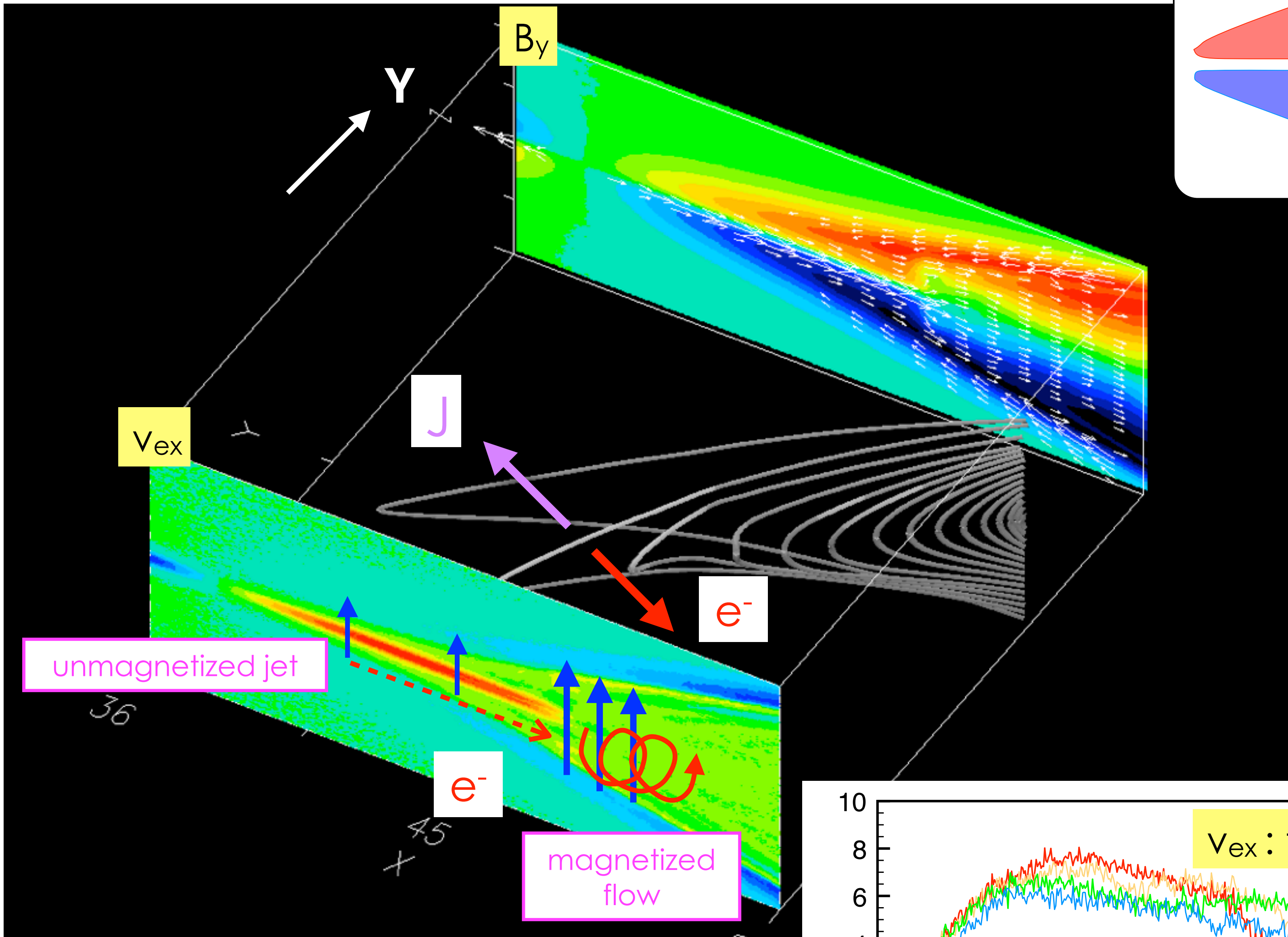
Shay+ 2007 PRL

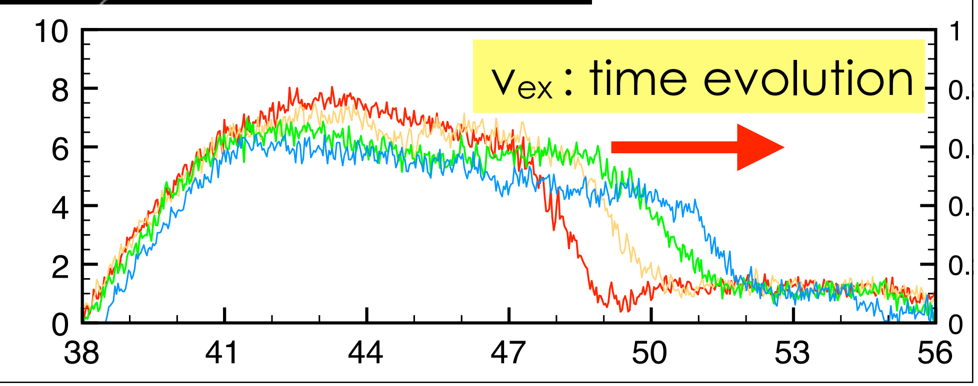


Hesse+ 2008 PoP (data from SZ+ 2011 PoP)

Electron shock

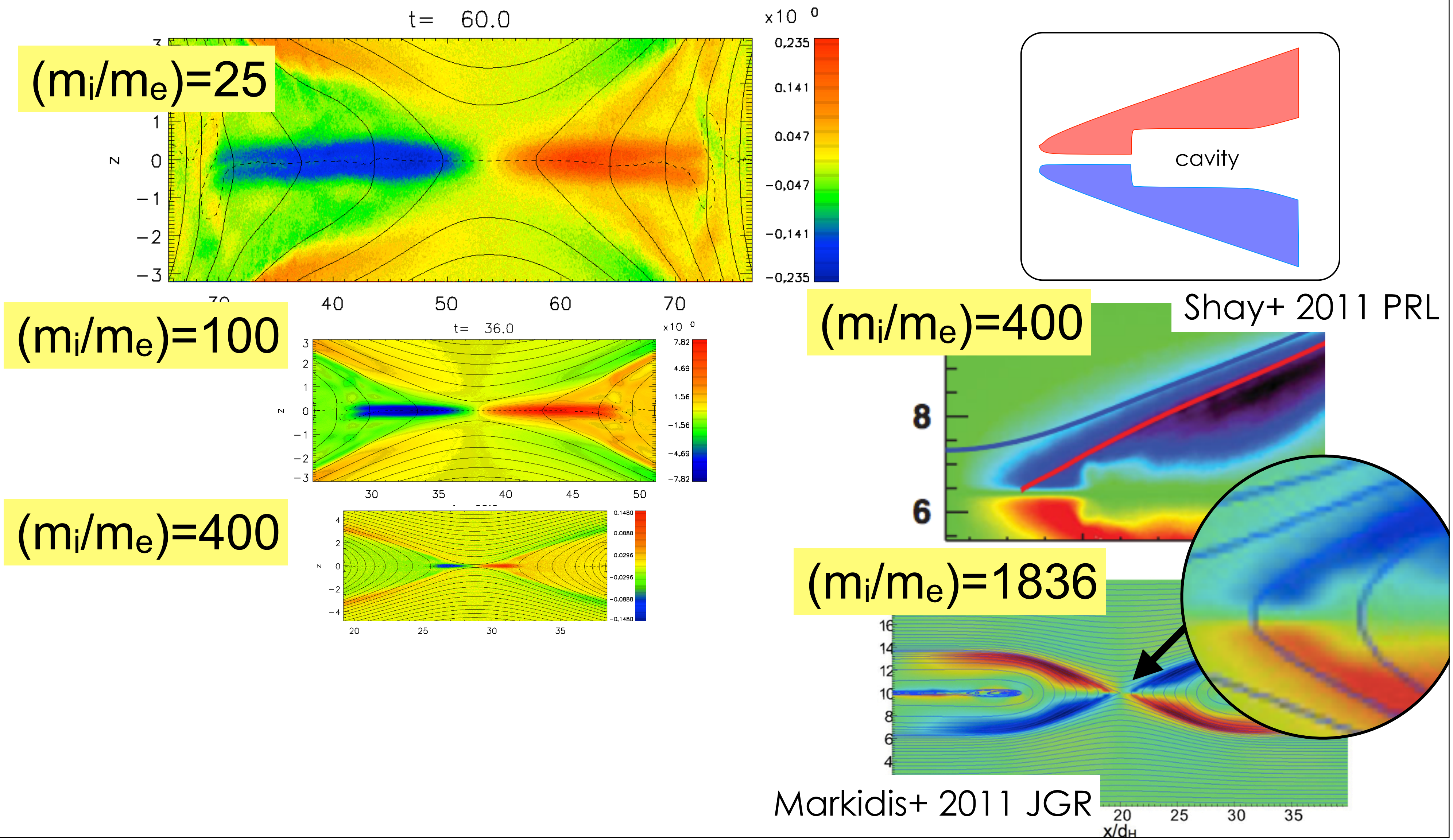






Dependence to m_i/m_e

- Shocks & cavities are clear at high mass ratio (m_i/m_e)
- Low occurrence in the Earth's magnetosphere



2. Boundary layer

Boundary layer (separatrix)

- Boundary between the outflow exhaust and the upstream plasma
- Nonideal layer that could control reconnection process
- Energy conversion site (Petschek picture)

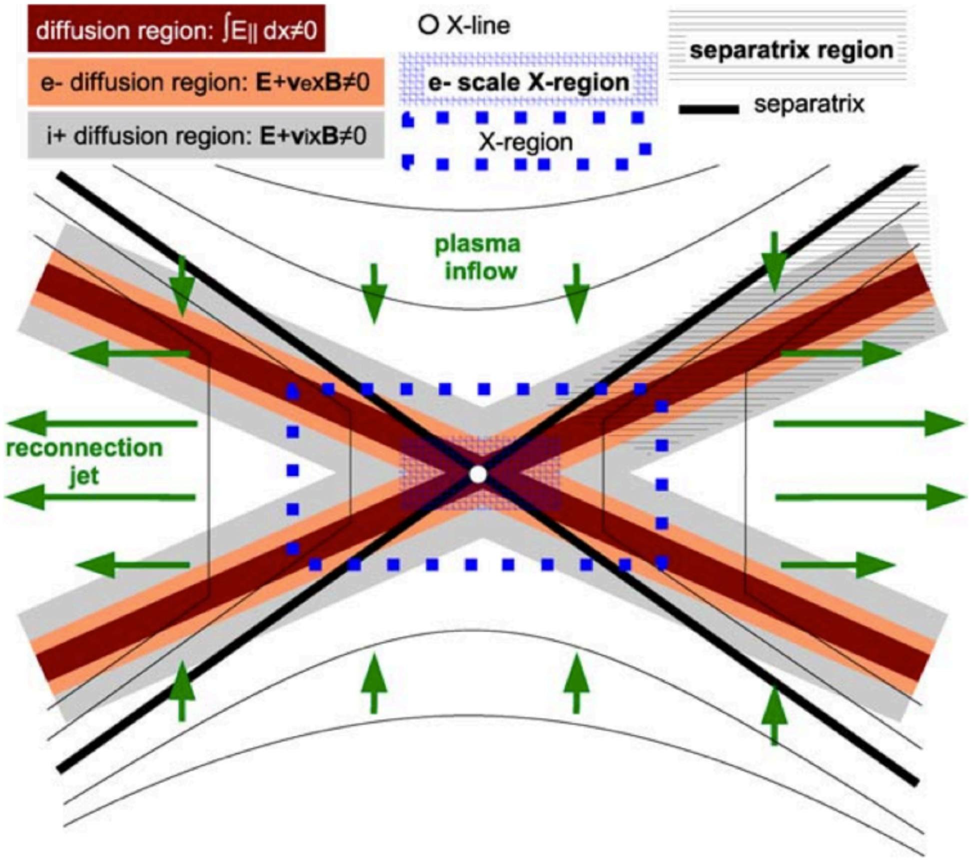
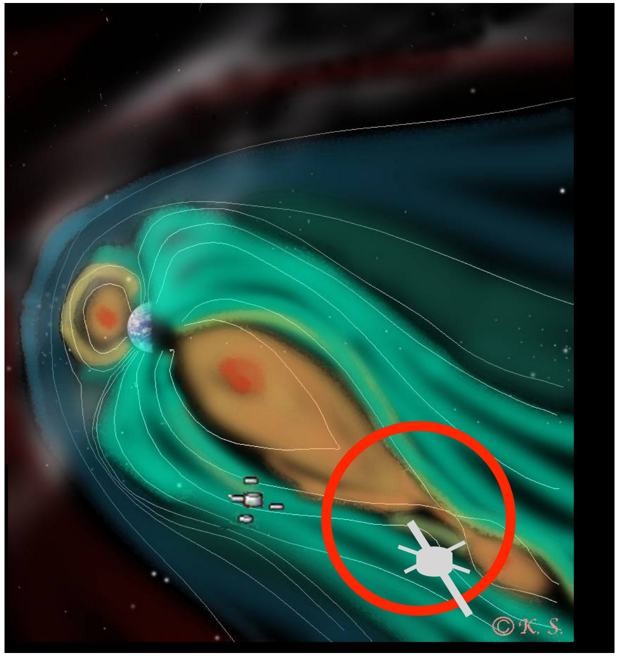


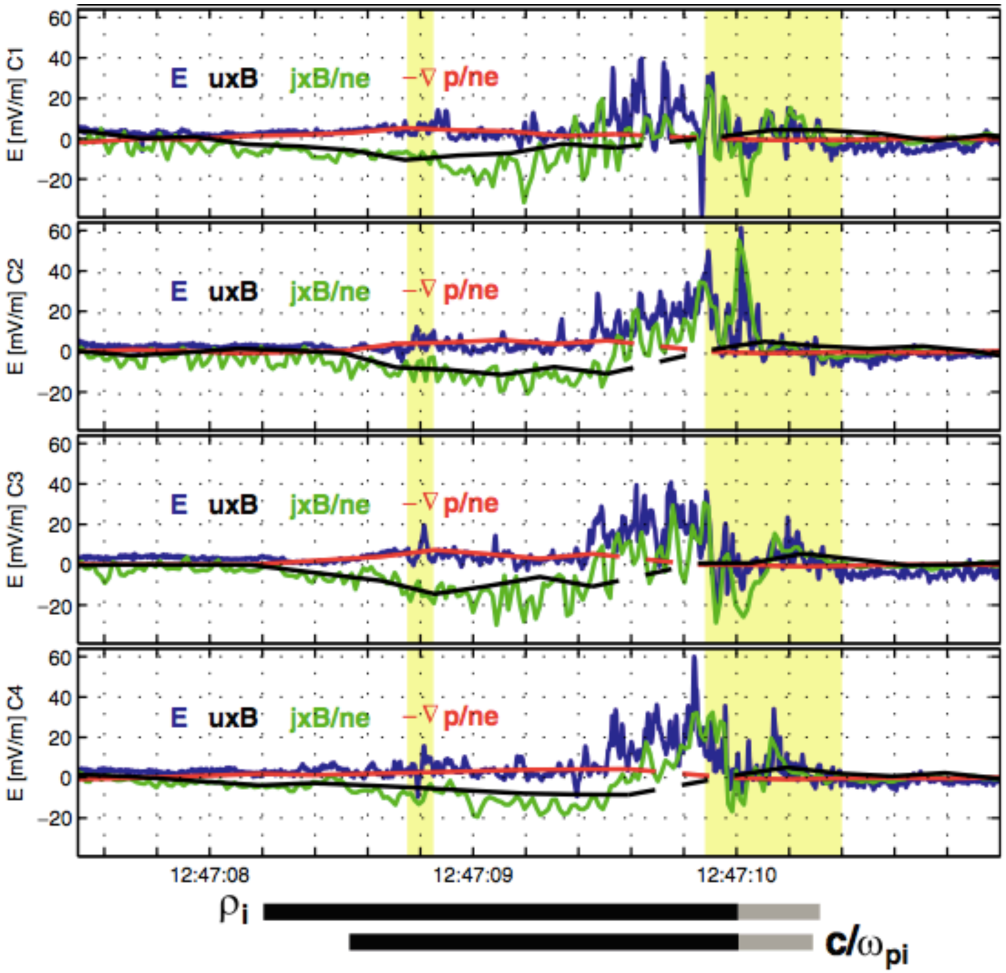
Figure 2. Sketch of all main regions of interest for microphysics of reconnection.

$$\boldsymbol{E} + (\boldsymbol{v}_i/c) \times \boldsymbol{B} \neq 0$$

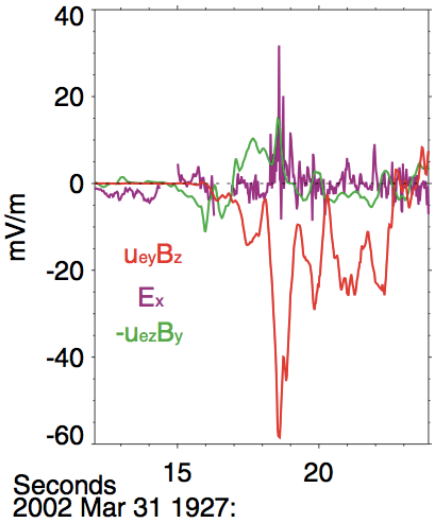
Vaivads 2006 Space Sci. Rev.

Extensive observations in the Earth's M'sphere





Khotyaintsev+ 2006 PRL

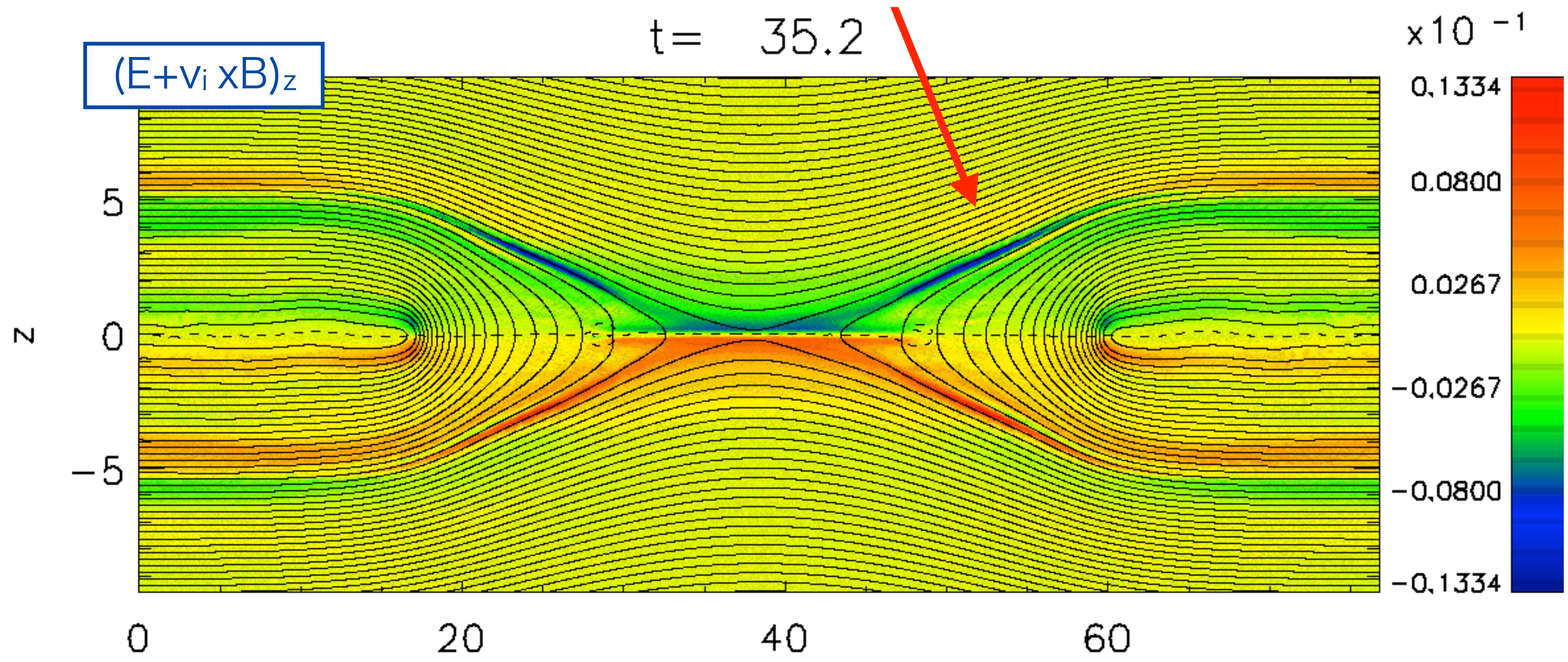


Mozer+ 2003 PRL

$$\boldsymbol{E} + (\boldsymbol{v}_i/c) \times \boldsymbol{B} \neq 0$$

PIC simulations - Nonideal Results

$$\boldsymbol{E} + (\boldsymbol{v}_i/c) \times \boldsymbol{B} \neq 0$$



- Ideal condition violated

MHD equations

- Basic equations

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \boldsymbol{V}) = 0,$$

$$\frac{\partial \rho \boldsymbol{V}}{\partial t} + \nabla \cdot \left(\rho \boldsymbol{V}\boldsymbol{V} + (p + \frac{B^2}{8\pi})\boldsymbol{I} - \frac{1}{4\pi}\boldsymbol{B}\boldsymbol{B} \right) = 0,$$

$$\frac{\partial \mathcal{E}}{\partial t} + \nabla \cdot \left((\mathcal{E} + p)\boldsymbol{V} \right) + \frac{\boldsymbol{j} \times \boldsymbol{B}}{c} \cdot \boldsymbol{V} - \boldsymbol{j} \cdot \boldsymbol{R} = 0,$$

Energy

$$\frac{\partial}{\partial t}\frac{B^2}{8\pi} + \frac{c}{4\pi}\nabla \cdot \left(-\frac{\boldsymbol{V} \times \boldsymbol{B}}{c} \times \boldsymbol{B} + \boldsymbol{R} \times \boldsymbol{B} \right) - \frac{\boldsymbol{j} \times \boldsymbol{B}}{c} \cdot \boldsymbol{V} + \boldsymbol{j} \cdot \boldsymbol{R} = 0,$$

Nonideal energy dissipation

$$\frac{\partial \boldsymbol{B}}{\partial t} + c\nabla \times \boldsymbol{E} = 0,$$

- Closures
  - EoS
  - Ohm's law

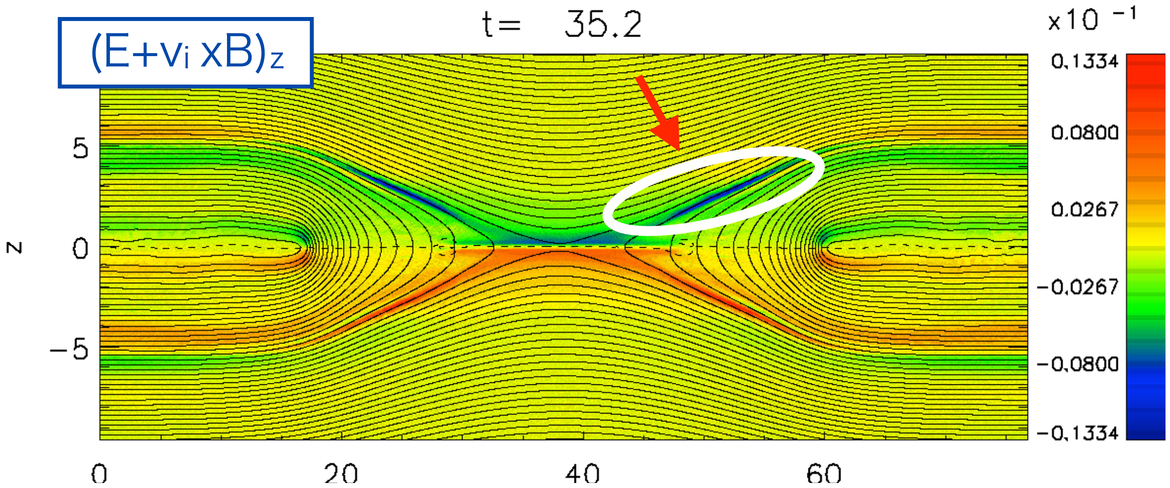
$$\boldsymbol{E} + (\boldsymbol{V}/c) \times \boldsymbol{B} = \boldsymbol{R}$$

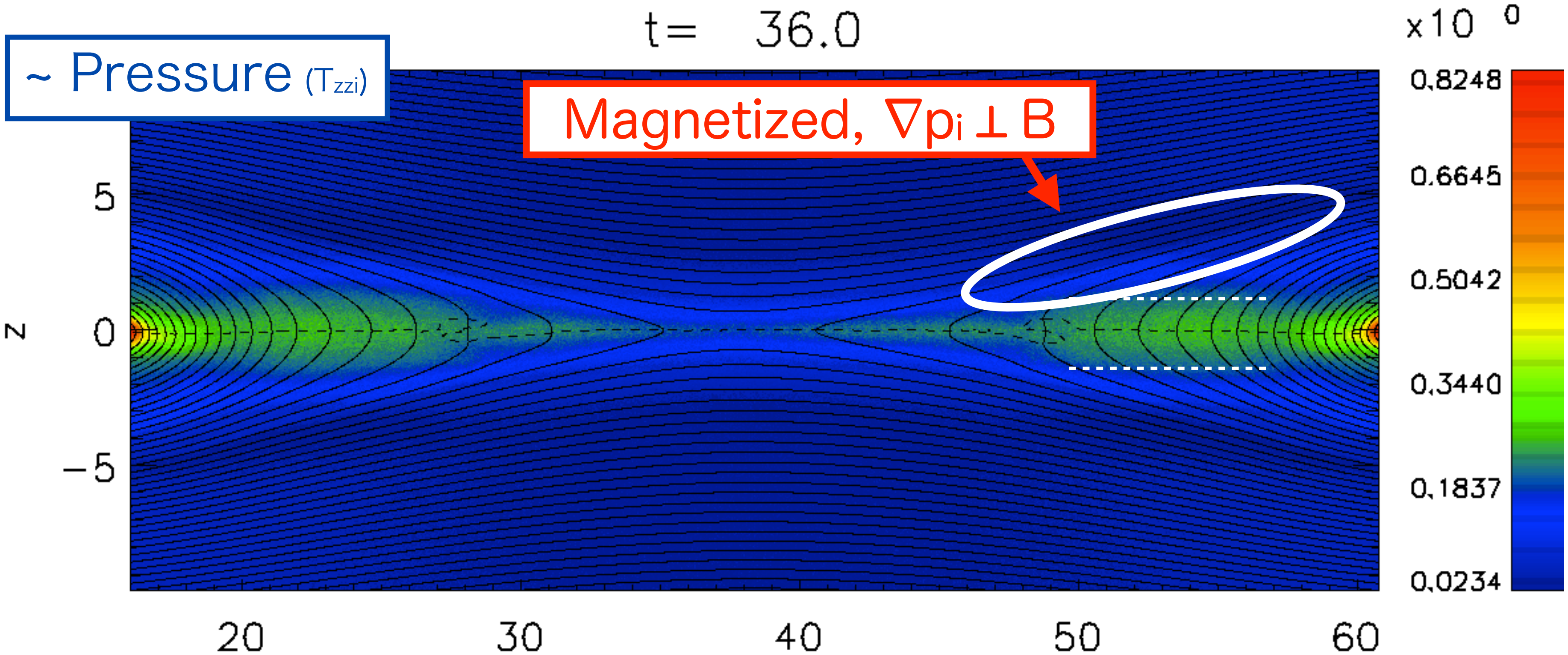
Topology

Flux freezing

$$\boxed{\frac{\partial}{\partial t}\boldsymbol{B} - \nabla \times (\boldsymbol{V} \times \boldsymbol{B}) + c\nabla \times \boldsymbol{R} = 0}$$

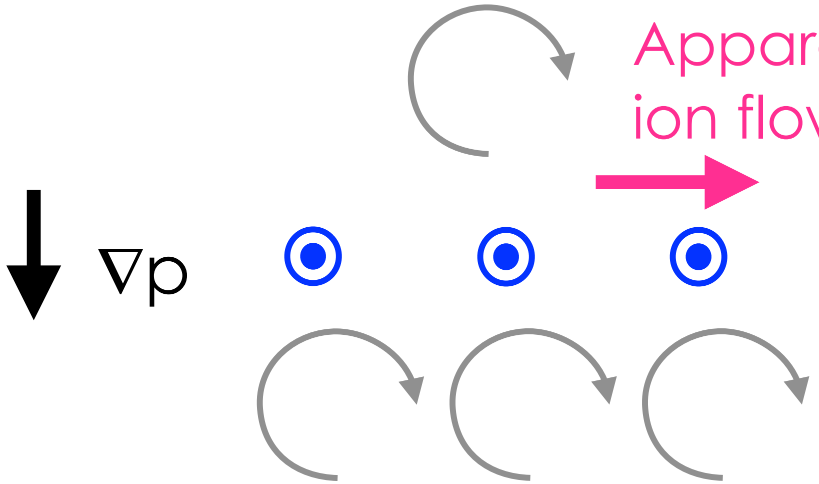
PIC simulations - pressure gradient





Diamagnetic effect

- Apparent flow due to density/pressure gradient



$$\boldsymbol{E} + (\boldsymbol{v}_i/c) \times \boldsymbol{B} = -\frac{1}{e n_i} \nabla p_i \neq 0$$

Topology
(※ barotropic case)

$$\nabla \times \boldsymbol{R} = 0$$

- Energy transfer remains quasi-ideal:

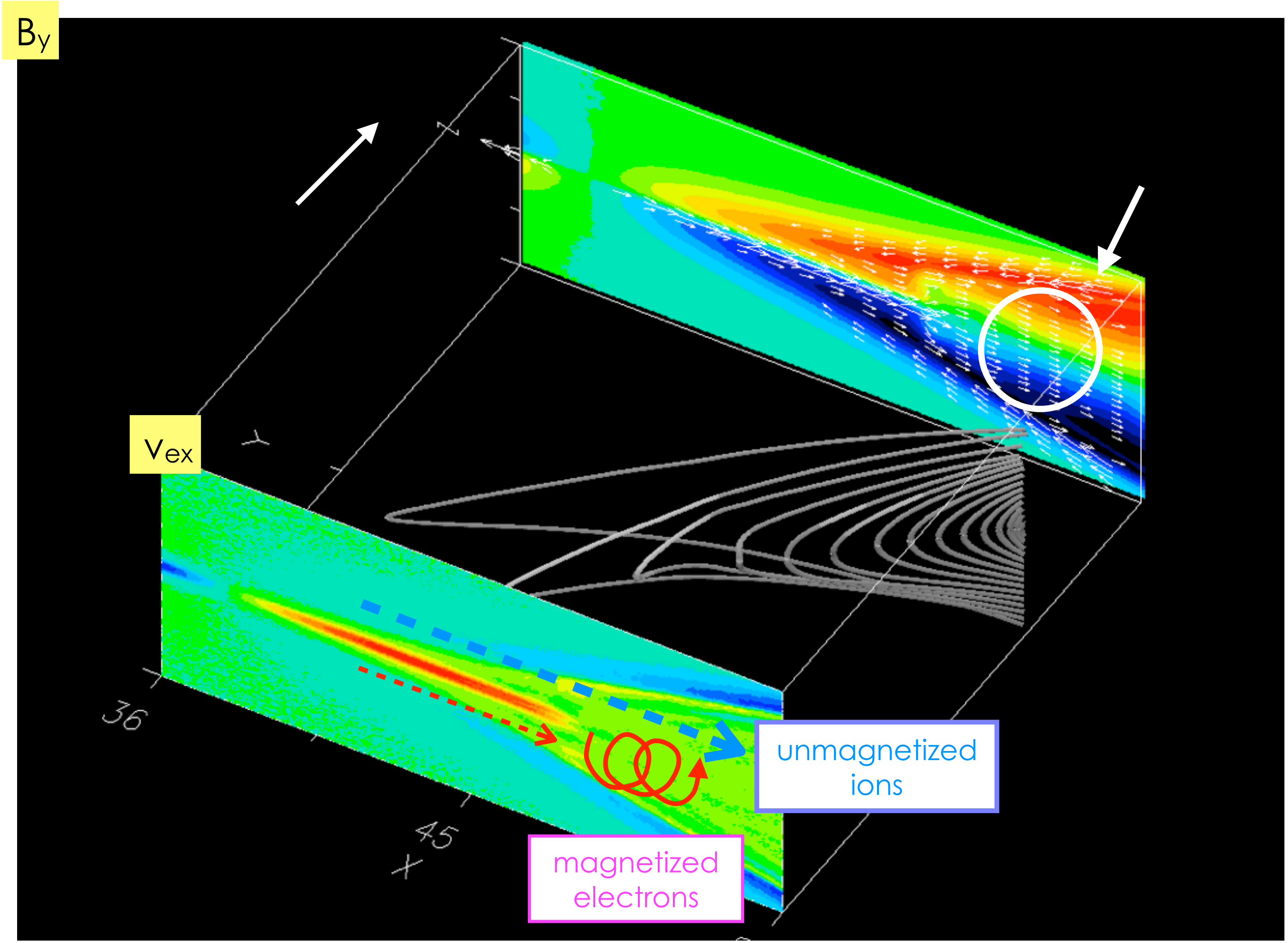
$$\boldsymbol{j} \cdot \boldsymbol{R} = \boldsymbol{j}_{diamag} \cdot \boldsymbol{R} = \frac{\boldsymbol{B} \times \nabla p}{B^2} \cdot \nabla p_i \approx 0$$

Energy

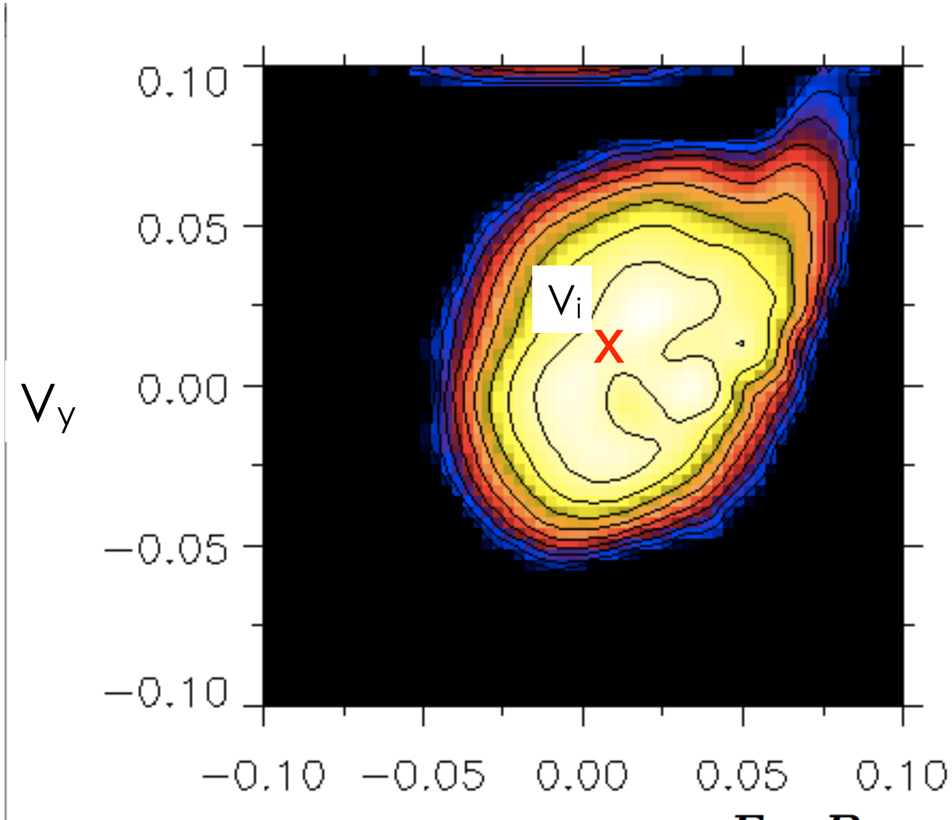
3. Ion current layer

Ion current layer

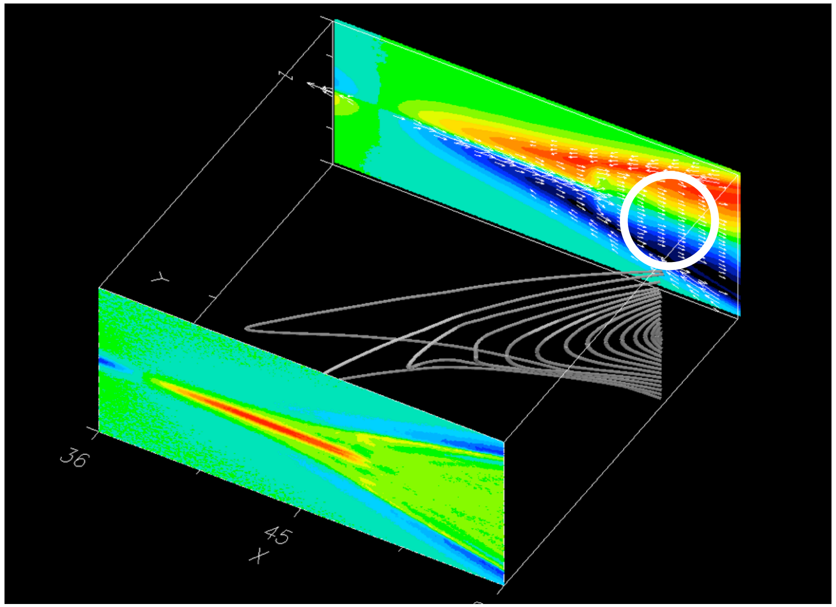
- Electrons are magnetized: only ions can cross the field line



Kinetic motion



$$\boldsymbol{v}_{\rm HT} = \frac{c\boldsymbol{E}\times\boldsymbol{B}}{B^2} \neq \boldsymbol{v}_i$$



Topology

$$\nabla \times \boldsymbol{R} = 0$$

Energy

$$\boldsymbol{j}\cdot\boldsymbol{R} = en(\boldsymbol{v}_i - \boldsymbol{v}_{\rm HT})\cdot[\boldsymbol{E} + (\boldsymbol{v}_i/c)\times\boldsymbol{B}] \approx 0$$

Summary : Ion-scale Outflow

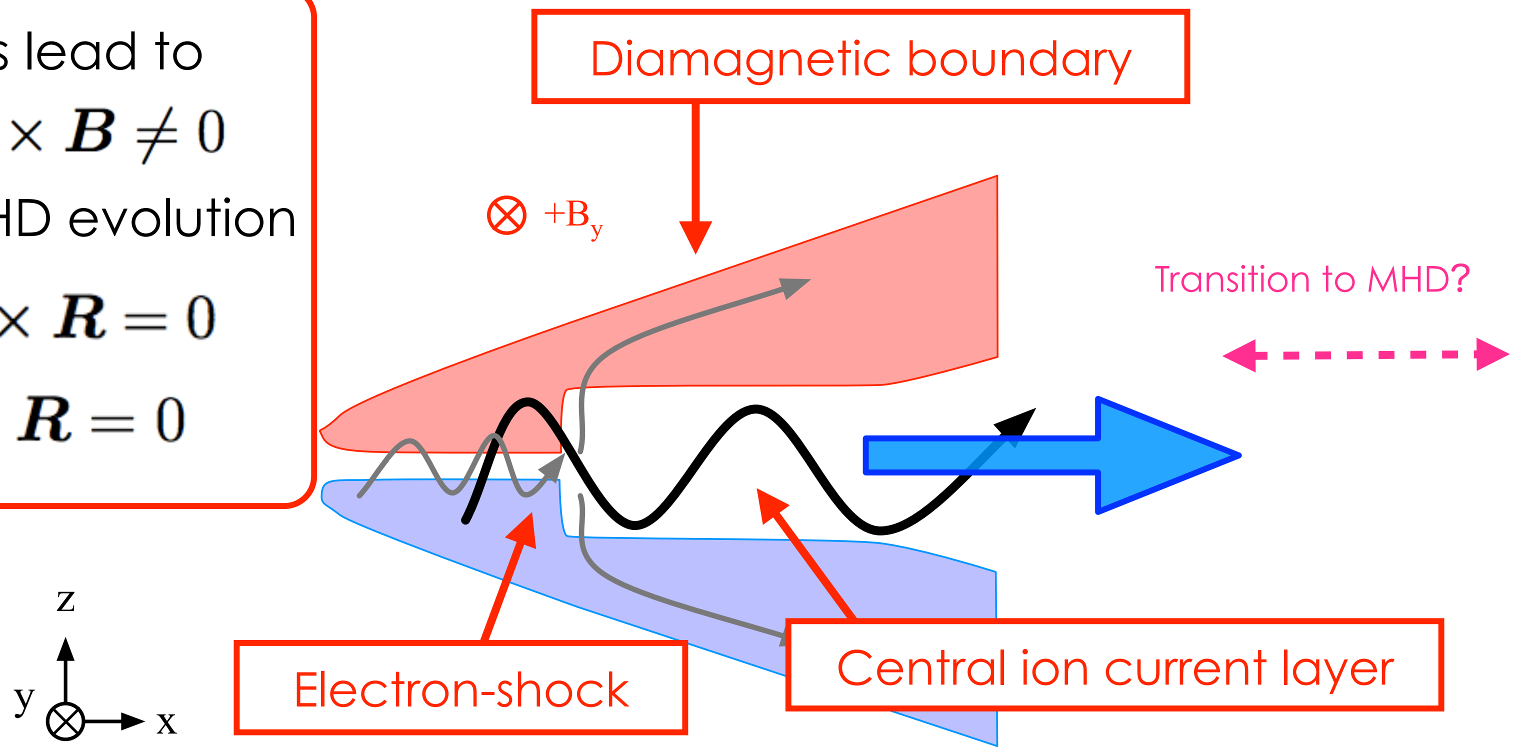
- Kinetic motions lead to

$$\boldsymbol{E} + (\boldsymbol{v}_i/c) \times \boldsymbol{B} \neq 0$$

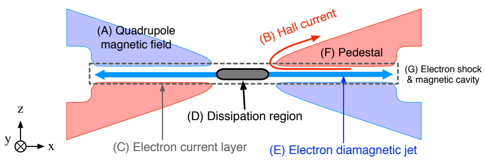
- Quasi-ideal MHD evolution

Topology $\nabla \times \boldsymbol{R} = 0$

Energy $\boldsymbol{j} \cdot \boldsymbol{R} = 0$



Electron kinetic physics (2000s ~)

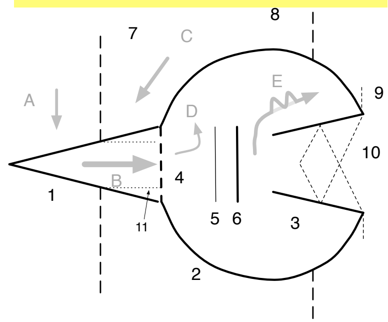


SZ+ 2011d PoP

Comprehensive understanding of 2D reconnection structure

Add'l players: anisotropy, turbulence, 3D

MHD (1970s ~)



SZ+ 2011a PoP