M23a

プラズマ中の磁気拡散と磁気リコネクションへの応用

Some remarks on the diffusion regions in magnetic reconnection

Seiji Zenitani

National Astronomical Observatory of Japan

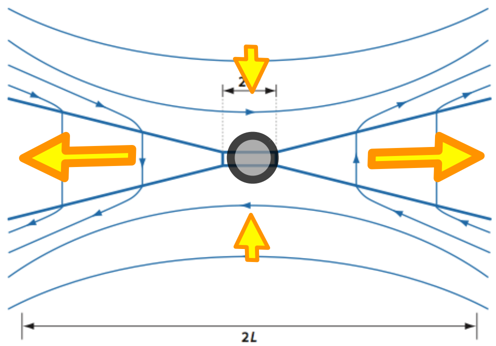
Takayuki Umeda

Nagoya University

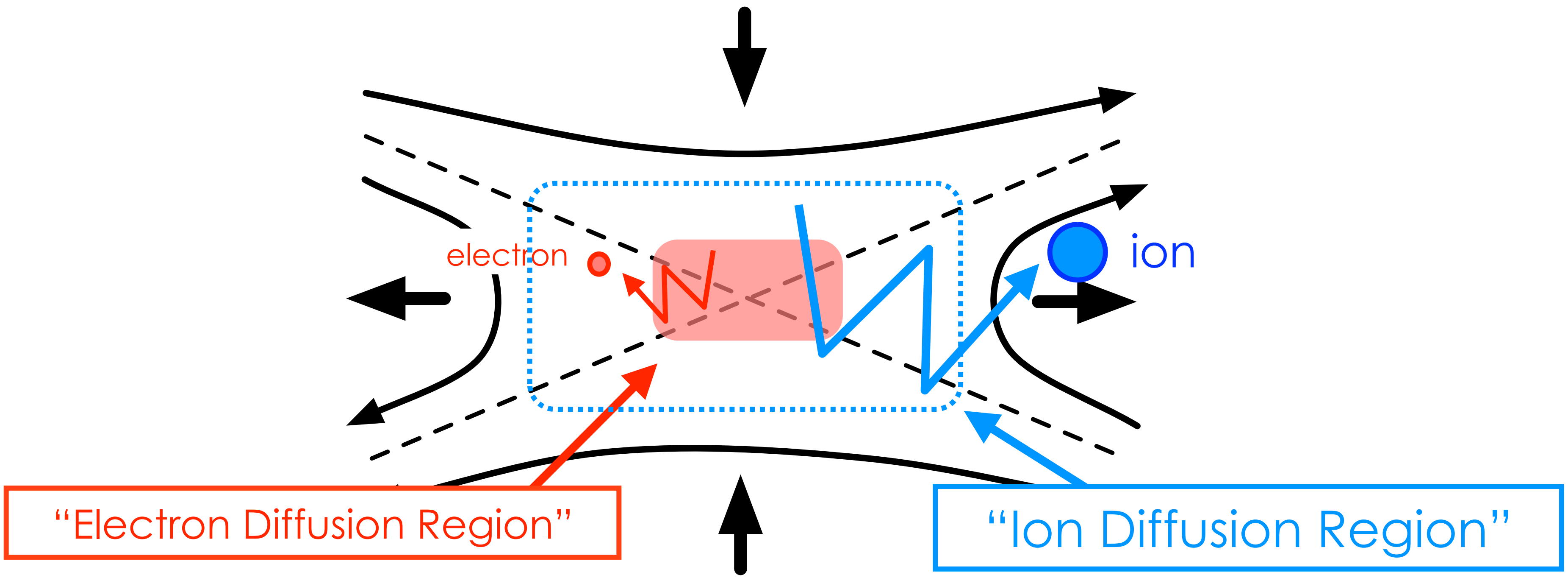
Zenitani & Umeda, *Phys. Plasmas*, **21**, 034503 (2014)

Diffusion region

- Central engine of magnetic reconnection



- Kinetic plasma: two-scale diffusion regions



Diffusion region?

- Plasma nonidealness

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

- Maximum flow speed, $v_{e,max}$ (Daughton+ 2006, Fujimoto 2006...)
- Electric current, J
- Parallel electric field $E_{||} \neq 0$
- Plasma inertial effect (Klimas+ 2010)

$$E_y^* = -\left[\frac{1}{en_e}\nabla \bullet \mathbf{P}_e + \frac{m_e}{e}\mathbf{v}_e \bullet \nabla \mathbf{v}_e\right]_y > 0$$

- Energy transfer in the electron's moving frame (Zenitani+ 2011, Birn & Hesse 2005)

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

- Agyrotropy in velocity distribution function and GCT parameters (Scudder & Daughton 2008)
  - Thermal Mach number
  - Ratio of the forces on the fluid

Dog?

Dog!

Diffusion region?

- Plasma nonidealness

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

- Maximum flow speed, $v_{e,max}$ (Daughton+ 2006, Fujimoto 2006...)

= The place where **magnetic diffusion** takes place.

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

- Agyrotropy in velocity distribution function and GCT parameters (Scudder & Daughton 2008)
  - Thermal Mach number
  - Ratio of the forces on the fluid

Question:

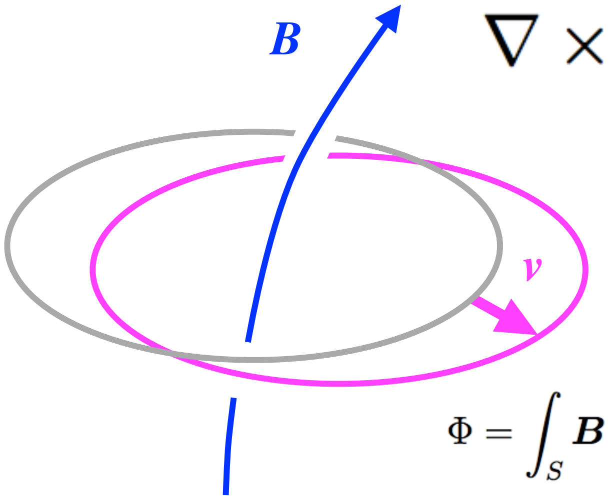
What is magnetic diffusion?

Magnetic diffusion

- Ohm's law

$$\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B} = \boldsymbol{R}$$

Frozen-in condition
(Flux preservation)



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

$$\Phi = \int_S \boldsymbol{B} \cdot d\boldsymbol{A}$$

Magnetic diffusion

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

$$\boldsymbol{R} = \eta \boldsymbol{j}$$

$$\frac{\partial}{\partial t}\boldsymbol{B} - \nabla \times (\boldsymbol{v} \times \boldsymbol{B}) - \frac{\eta}{\mu_0}\Delta \boldsymbol{B} = 0$$

Newcomb 1958, Stern 1966

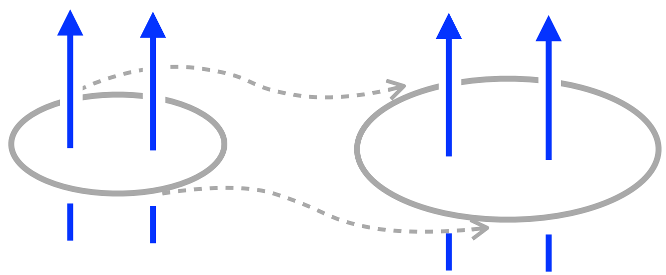
Finite frozen-in term relaxes to zero $\nabla \times \boldsymbol{R} \to 0$
(relaxation to the frozen-in state)

Violation of the frozen-in condition

$$\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B} = \boldsymbol{R}$$

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

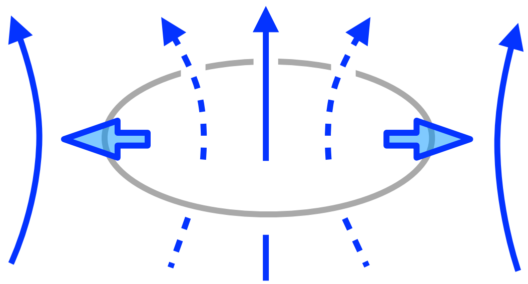
(a) $\nabla \times \boldsymbol{R} = \boldsymbol{0}$



Frozen-in condition
(Flux preservation)

Newcomb 1958
Stern 1966

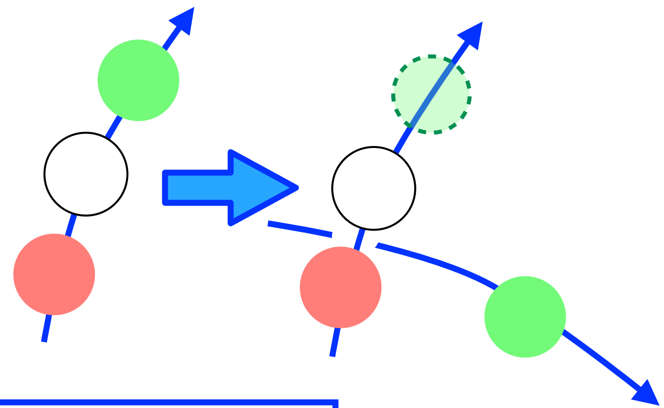
(b) $\boldsymbol{b} \cdot (\nabla \times \boldsymbol{R}) \neq 0$



Magnetic loss or gain

SZ & Umeda 2014

(c) $\boldsymbol{b} \times (\nabla \times \boldsymbol{R}) \neq \boldsymbol{0}$



Disconnection
(Line preservation)

Newcomb 1958

Diffusion region

- Induction equation

$$\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B} = \boldsymbol{R}$$

b ·

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

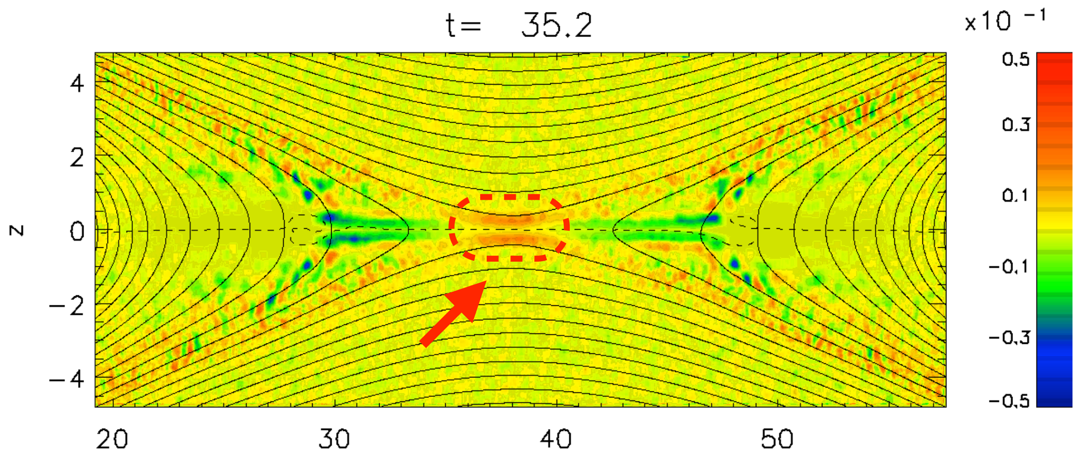
$$\frac{\partial}{\partial t}\boldsymbol{B} - \nabla \times (\boldsymbol{v} \times \boldsymbol{B}) - \alpha_{\mathrm{eff}} \Delta \boldsymbol{B} = 0$$

- Ad-hoc diffusion coefficient

$$\alpha = -\frac{\boldsymbol{b} \cdot (\nabla \times \boldsymbol{R})}{\boldsymbol{b} \cdot \Delta \boldsymbol{B}}$$

- **Generalized magnetic diffusion**

$$\alpha > 0$$



2D PIC simulations

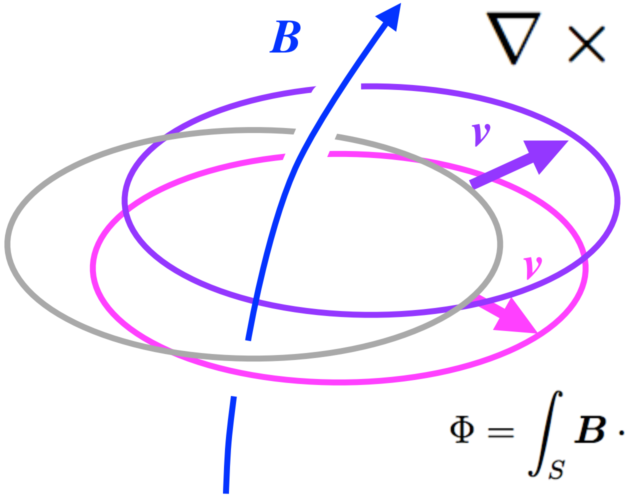
Again, frozen-in

- Arbitrary Ohm's law

$$\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B} = \boldsymbol{R}(\boldsymbol{v})$$

Frozen-in condition
(Flux preservation)

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



$$\Phi = \int_S \boldsymbol{B} \cdot d\boldsymbol{A}$$

Frozen-in and all other concepts are relative concepts that depend on a reference velocity field ***v***

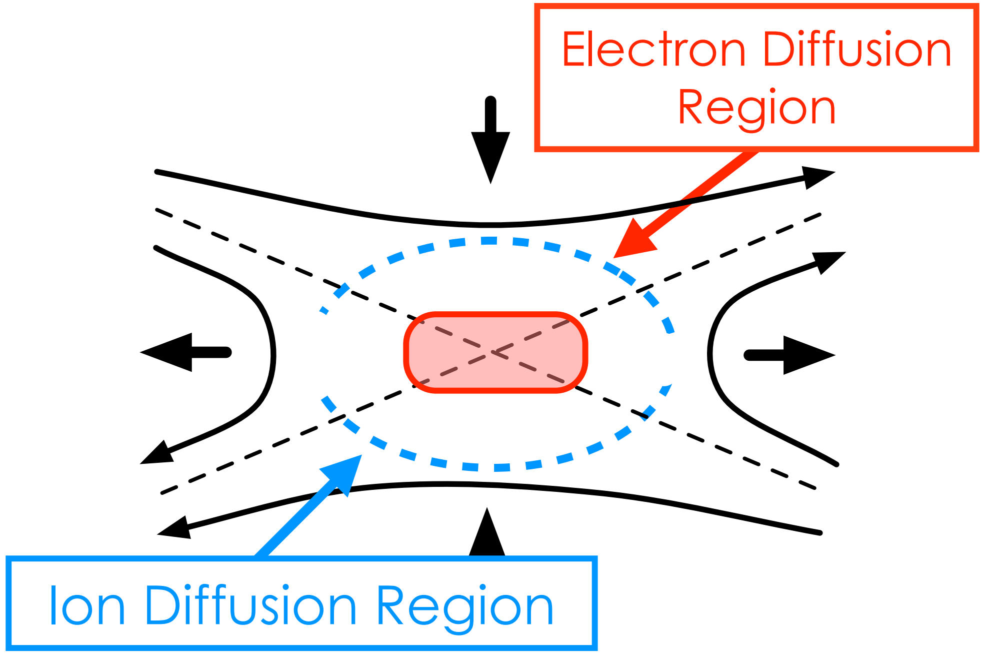
Two-scale diffusion regions

$$\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B} = \boldsymbol{R}$$

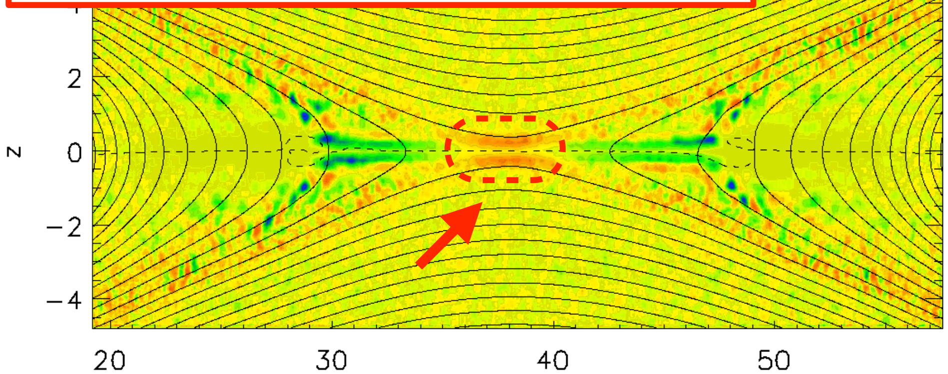
b ·

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

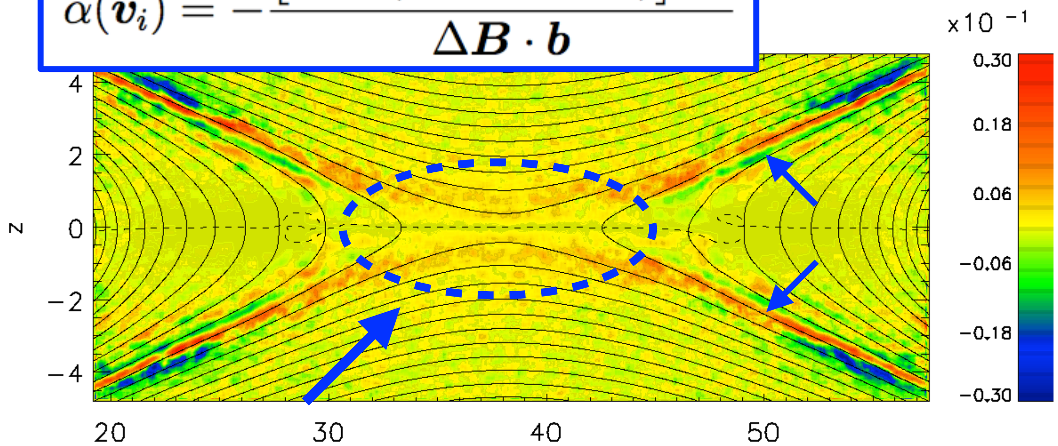
$$\frac{\partial}{\partial t}\boldsymbol{B} - \nabla \times (\boldsymbol{v} \times \boldsymbol{B}) - \alpha_{\mathrm{eff}} \Delta \boldsymbol{B} = 0$$



$$\alpha(\boldsymbol{v}_e) = -\frac{[\nabla \times (\boldsymbol{E} + \boldsymbol{v}_e \times \boldsymbol{B})] \cdot \boldsymbol{b}}{\Delta \boldsymbol{B} \cdot \boldsymbol{b}}$$



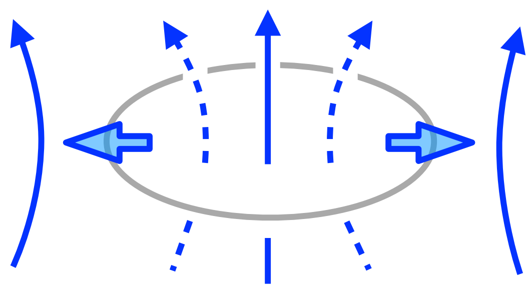
$$\alpha(\boldsymbol{v}_i) = -\frac{[\nabla \times (\boldsymbol{E} + \boldsymbol{v}_i \times \boldsymbol{B})] \cdot \boldsymbol{b}}{\Delta \boldsymbol{B} \cdot \boldsymbol{b}}$$



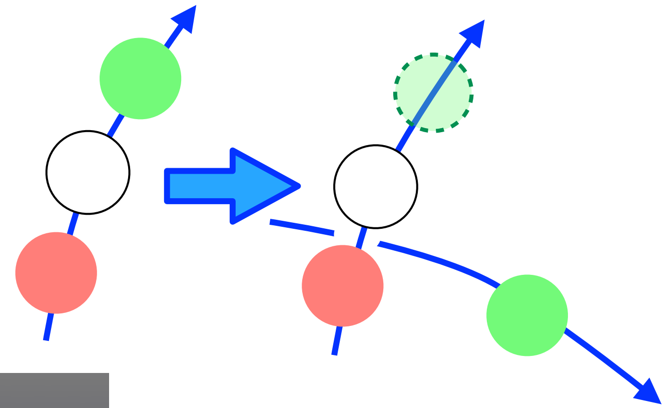
2D PIC simulations

Discussion (1/2): Is the diffusion region essential for reconnection?

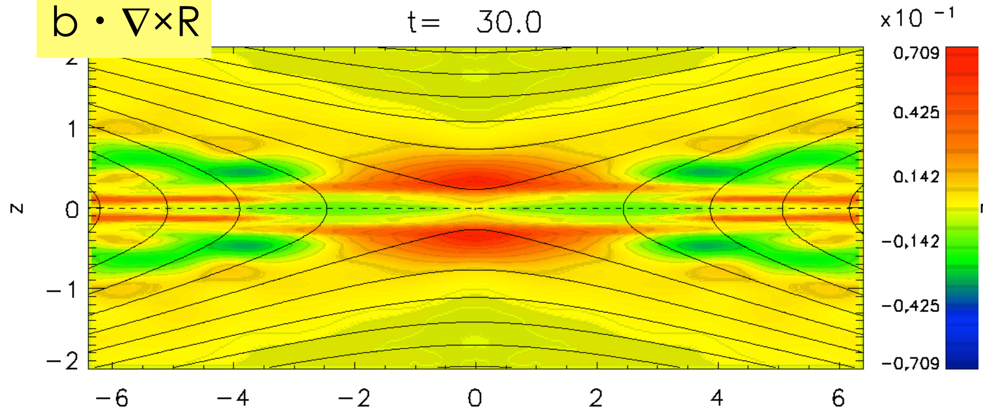
(b) $\boldsymbol{b}\cdot(\nabla\times\boldsymbol{R})\neq 0$

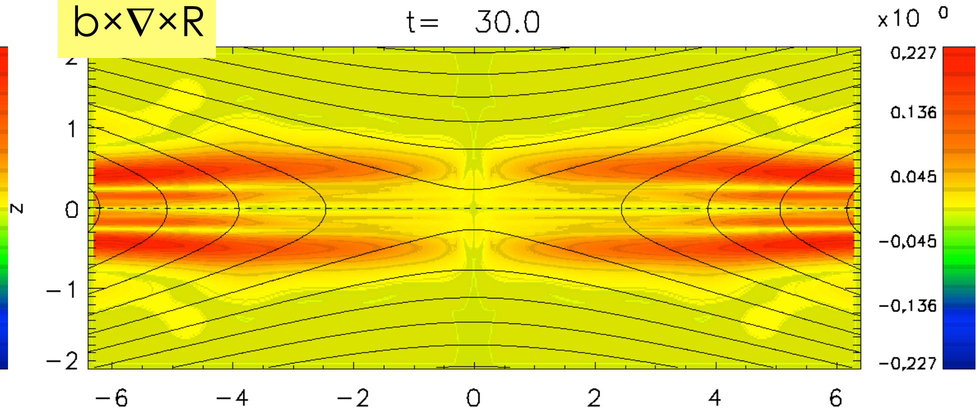


(c) $\boldsymbol{b}\times(\nabla\times\boldsymbol{R})\neq \boldsymbol{0}$



- Totally unclear





Vlasov simulations

Discussion (2/2): ambipolar diffusion

$$\frac{\partial B}{\partial t} = \nabla \times [V_n \times B - \frac{J \times B}{e n_e} + \frac{(J \times B) \times B}{c \nu_{ni} \rho_n} - \frac{4\pi\eta}{c} J]$$

Advection Hall Ambipolar Resistive

(Ve-Vi) (Vn-Vi)

from Isobe-san's slide

- Is it magnetic diffusion?
  - **No**. No guarantee.
- Is it diffusion?
  - **Yes**. Diffusion of charged-particles takes place.

Summary

- Generalized magnetic diffusion
  - Field-aligned component of the flux frozen-in term
- Diffusion region
  - Can be defined, but unclear role in reconnection

- Fundamental concepts
  - Ohm's law $\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B} = \boldsymbol{R}$
  - Idealness $\boldsymbol{R}$
  - Flux frozen-in $\nabla \times \boldsymbol{R}$
  - Line preservation $\boldsymbol{b} \times (\nabla \times \boldsymbol{R})$

new Magnetic loss $\boldsymbol{b} \cdot (\nabla \times \boldsymbol{R})$

new Magnetic diffusion $\nabla \times \boldsymbol{R} \to 0 \quad \alpha > 0$

other work Magnetic dissipation $D_e \approx \boldsymbol{j} \cdot \boldsymbol{R} \gtrsim 0$