Impact of diffusion processes on magnetic reconnection

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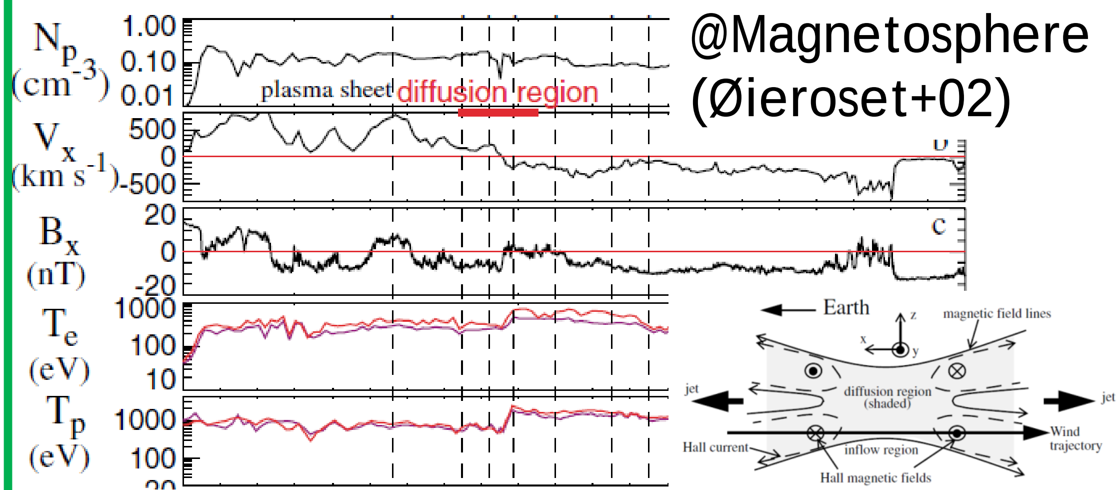
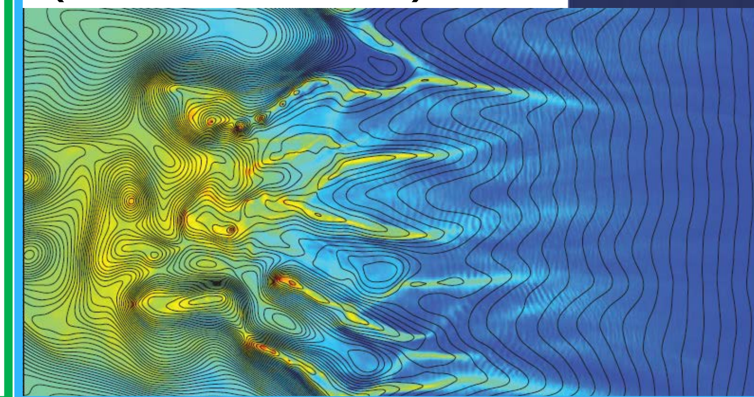
"Boosting magnetic reconnection by viscosity and thermal conduction", TM, T. Miyoshi, and S. Imada, *Physics of Plasmas* **23**, 072122 (2016)

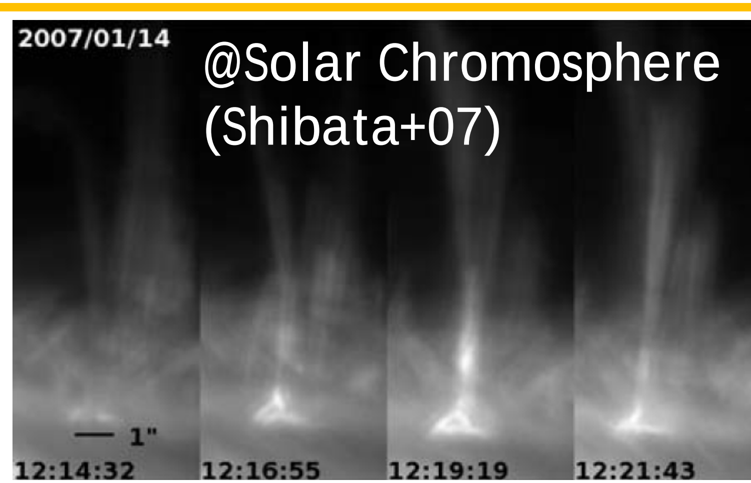
Magnetic Reconnection in Space

@Magnetosphere
(Øieroset+02)



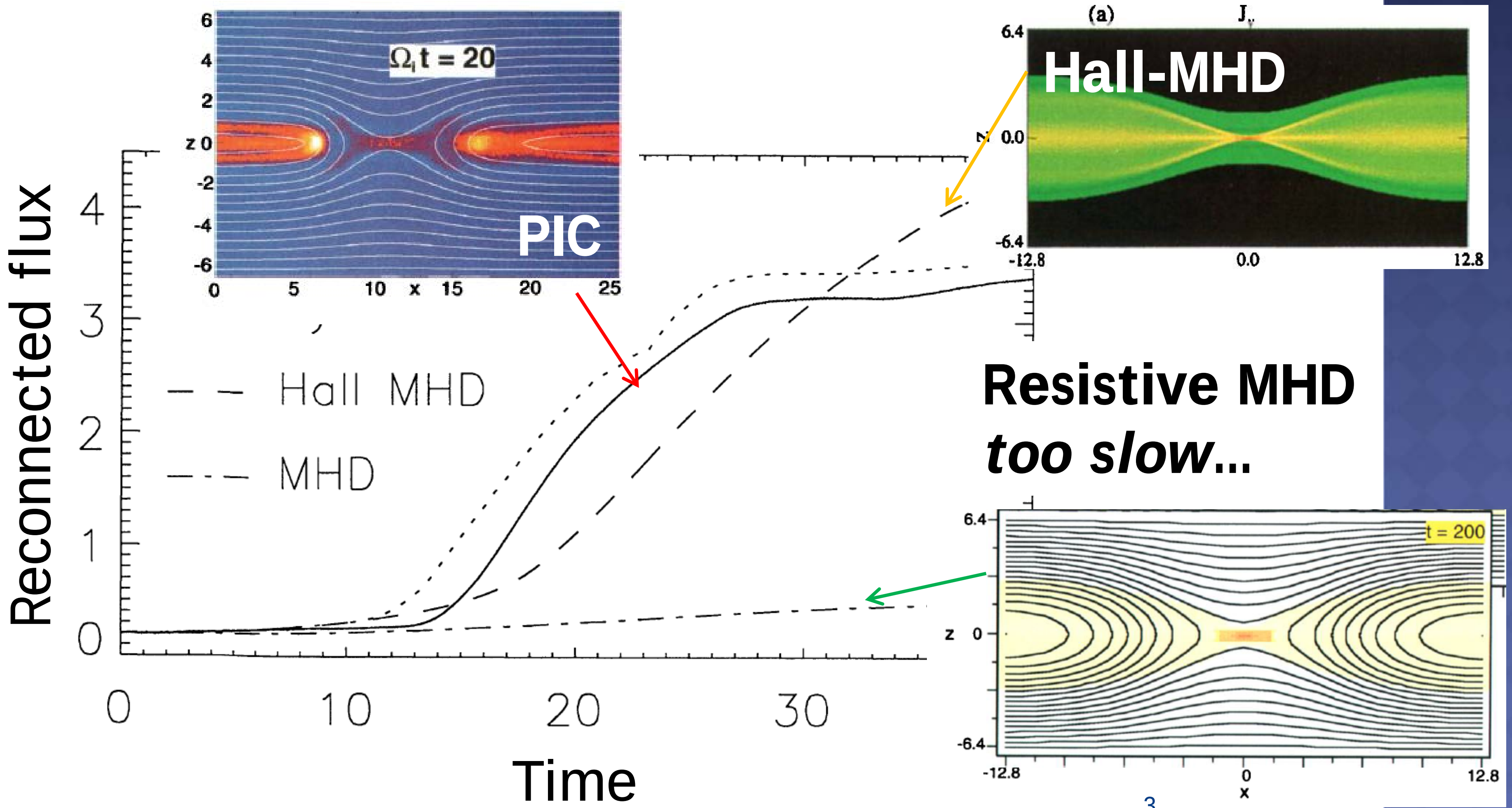
@Shock
(Matsumoto+15)



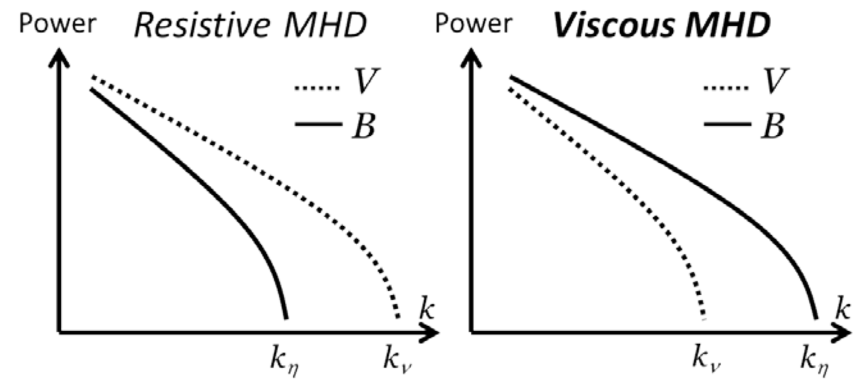


Plasma Hierarchy in MRX

- GEM Magnetic Reconnection Challenge (Birn+01)

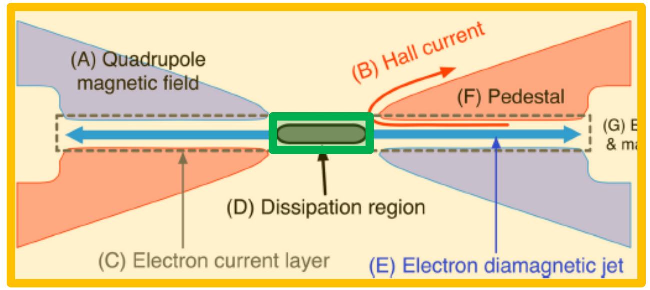


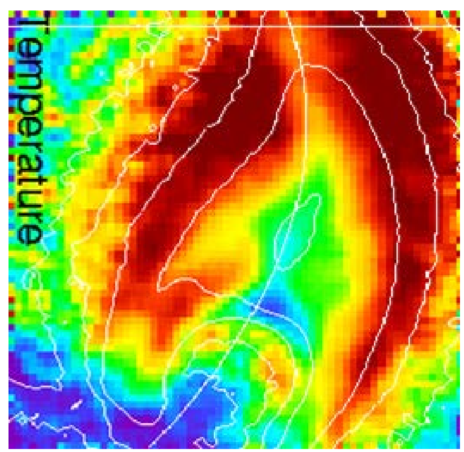
Diffusion in Fluid

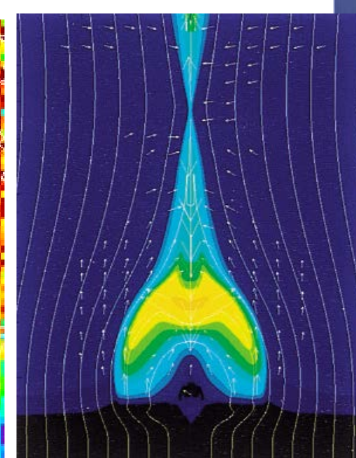


- ***Viscosity***
  - Turbulence, Dynamo (Schekochihin+04; Lesur+07; Brandenburg14; TM+15)
  - Related to *ion diffusion*?
- ***Heat transfer***
  - Field aligned beams (Hoshino+01; Fujimoto+06;)
  - Thermal conduction (Tsuneta+96; Yokoyama+97;)
  - Compressible effect (e.g., Birn+11,12)

Ion + ele. diff. region (e.g., Zenitani+11)







Prandtl Numbers

- **Resistivity** η
- **Kinematic viscosity** ν
- **Temperature conductivity** α
- **Prandtl number** $Pr = \nu / \alpha$
- **Magnetic Prandtl number** $Pr_m = \nu / \eta$
- $Pr \sim 10^{-3}$, $Pr_m \sim 10^{-5}\, T^4 / n >> 1$ (Spitzer62)

Table 1
Some Examples of Magnetized Plasmas in Space and Their Order-of-magnitude Parameters in cgs Units (Tenerani+15)

Plasma Environment	n	T	B	P	$P_{\parallel}$
Solar corona	10^9	10^6	50	10^{-2}	10^9
Solar flares	10^{10}	10^6–10^7	100	$10^{-2} - 10^{-1}$	10^8–10^{12}
Solar wind	5	$(35–23) \times 10^4$	$(20–100)\ \mu$	3–50	$10^{16} - 10^{15}$
ISM (ionized)	0.2–0.006	10^4–10^6	$(1–10)\ \mu$	10–100	$10^{11} - 10^{20}$
Intracluster medium	10^{-3}	10^8	$(0.1–1)\ \mu$	10^5–10^3	10^{29}

Dissipative MHD MRX

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

$$\frac{\partial (\rho \boldsymbol{u})}{\partial t} + \nabla \cdot \left[\rho \boldsymbol{u}\boldsymbol{u} + \left(P + \frac{B^2}{2} \right) \mathbf{I} - \boldsymbol{B}\boldsymbol{B} \underline{- \rho \nu \mathbf{S}} \right] = 0,$$

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

$$\frac{\partial e}{\partial t} + \nabla \cdot \left[\left(\frac{\rho u^2}{2} + \frac{\gamma P}{\gamma - 1} \right) \boldsymbol{u} + \boldsymbol{E} \times \boldsymbol{B} \underline{- \rho \nu \mathbf{S} \cdot \boldsymbol{u}} \underline{- \boldsymbol{\kappa} \cdot \nabla \frac{P}{\rho}} \right] = 0,$$

$$\boldsymbol{E} = -\boldsymbol{u} \times \boldsymbol{B} \underline{+ \eta \boldsymbol{j}}, \boldsymbol{j} = \nabla \times \boldsymbol{B},$$

$$P = (\gamma - 1) \left(e - \frac{\rho u^2}{2} - \frac{B^2}{2} \right),$$

$$\mathbf{S} = \sum_{i,j} \sigma_{ij} \boldsymbol{e}_i \boldsymbol{e}_j, \sigma_{ii} = \frac{2}{3} \left(2 \frac{\partial u_i}{\partial x_i} - \frac{\partial u_j}{\partial x_j} \right), \sigma_{ij} = \sigma_{ji} = \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right)$$

$$\boldsymbol{\kappa} = \frac{\alpha \rho}{\gamma - 1} \sum_{i,j} \frac{B_i B_j}{|\boldsymbol{B}|^2 + \epsilon} \boldsymbol{e}_i \boldsymbol{e}_j,$$ Anisotropic conduction

$R_e = \frac{V_A \delta}{\nu}$: Reynolds number

$R_m = \frac{V_A \delta}{\eta}$: Mag. Reynolds number

δ : Current sheet width

$Pr = \frac{\nu}{\alpha}$: Prandtl number

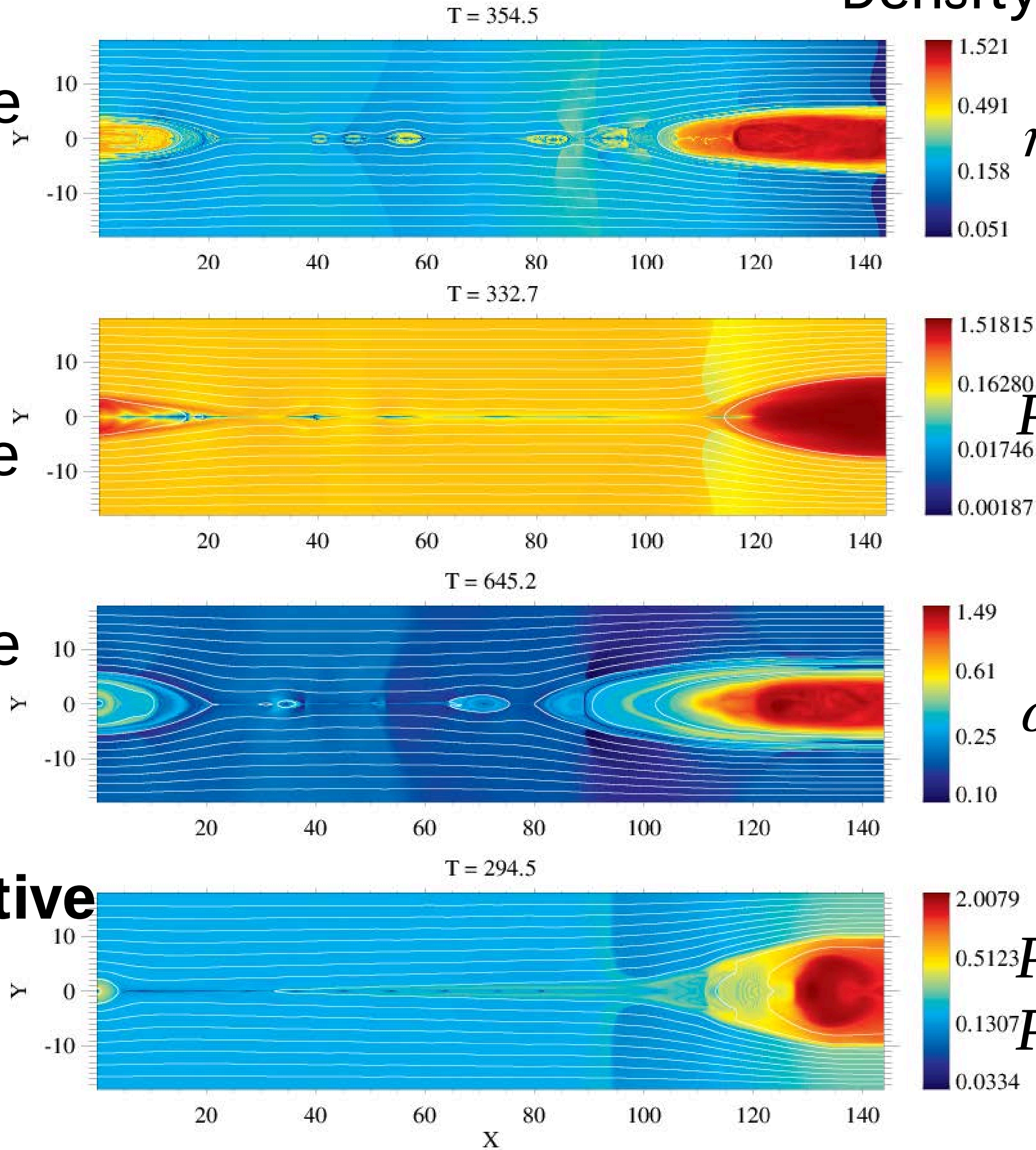
$Pr_m = \frac{\nu}{\eta}$: Mag. Prandtl number

$\beta = 0.2, \gamma = 5/3$

- Harris current sheet with localized perturbation
- $\eta=10^{-3}$(fixed), ν, α are constant and uniform

XC-B 648 cores
10-20 jobs/model

Density



Resistive — η=10^{-3}

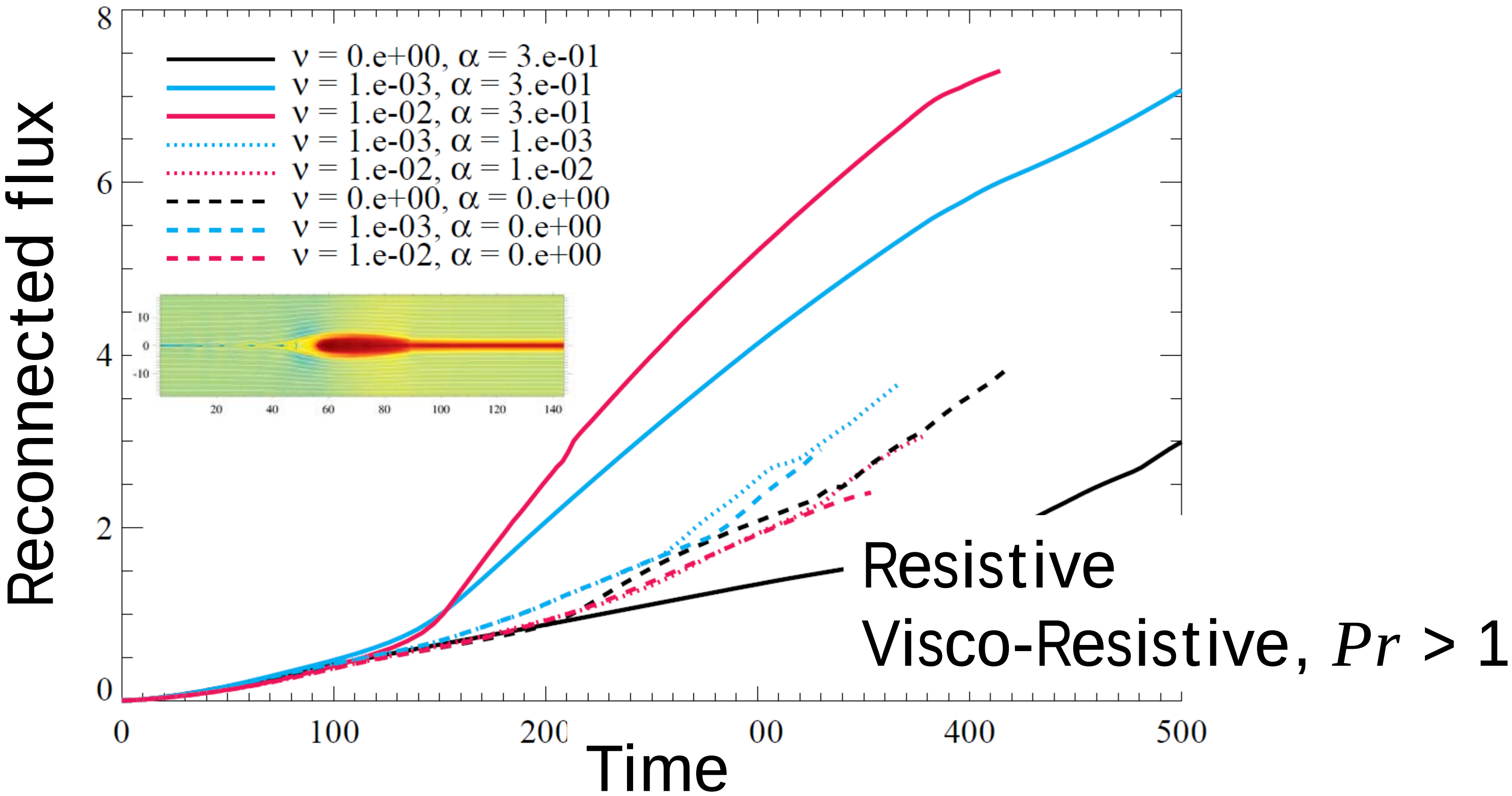
Visco-resistive — Pr_m=10

Resistive +cond. — α=0.3

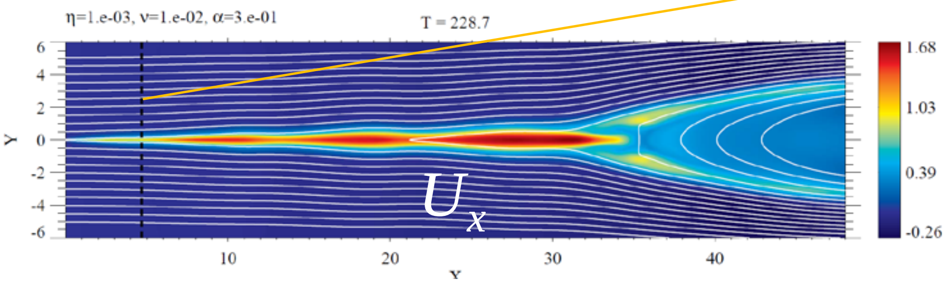
Dissipative — Pr_m=10, Pr=1/30

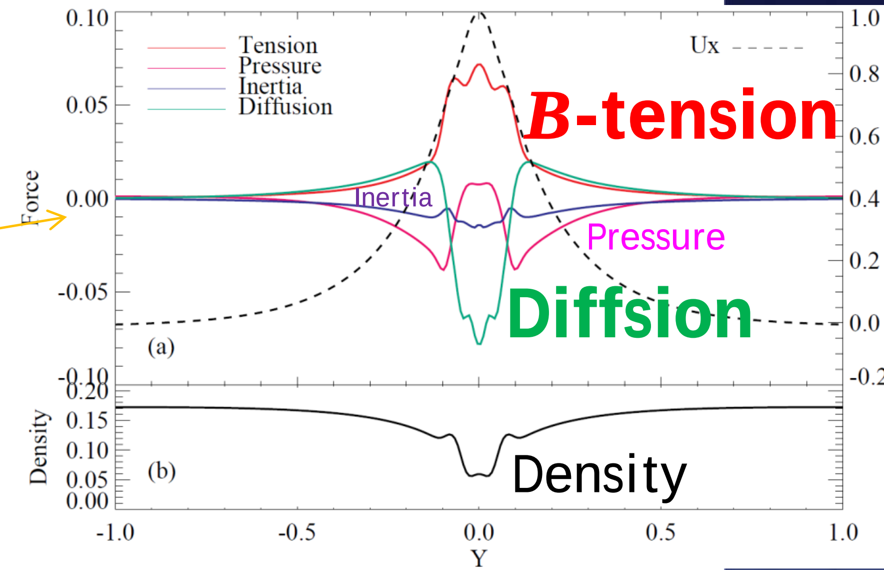
Reconnected Flux @ X-point

$Pr_m > 1$ & $Pr < 1$



Outflow Dynamics





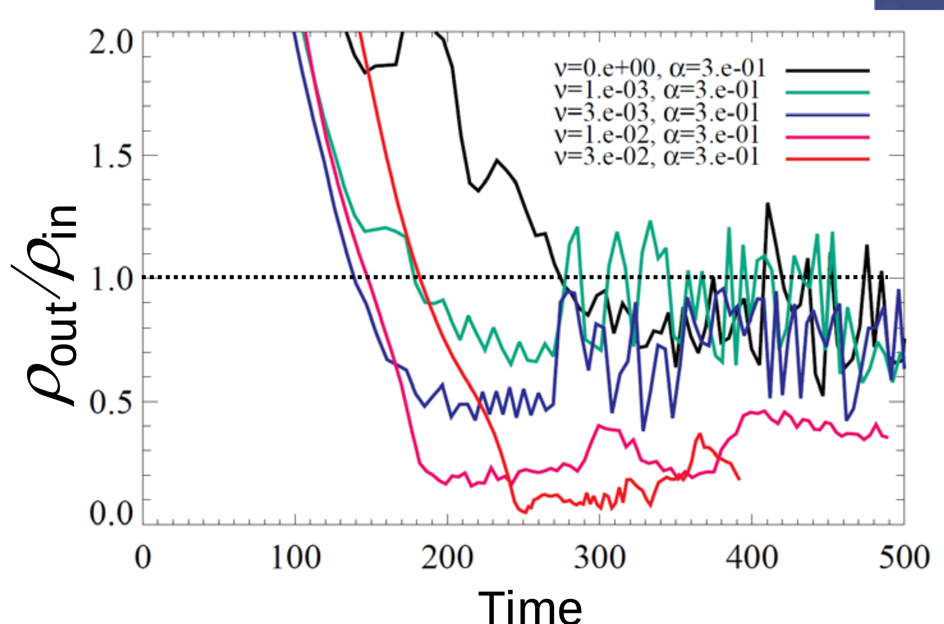
- **Magnetic tension** = **Viscous diffusion**

$$B_{in}B_{out} = \nu\rho_{out}u_{out}/\delta,$$

$$u_{in}B_{in} = u_{out}B_{out} = \eta B_{in}/\delta,$$

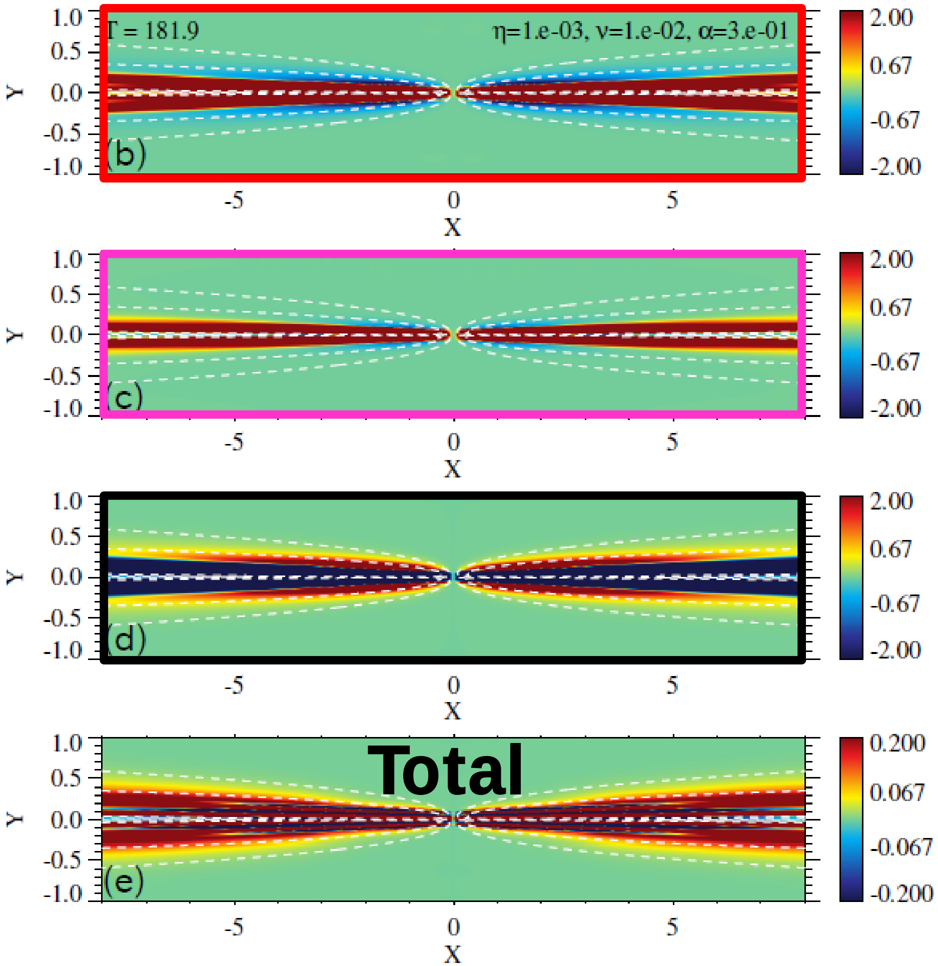
$$\rho_{in}u_{in}L = \rho_{out}u_{out}\delta,$$

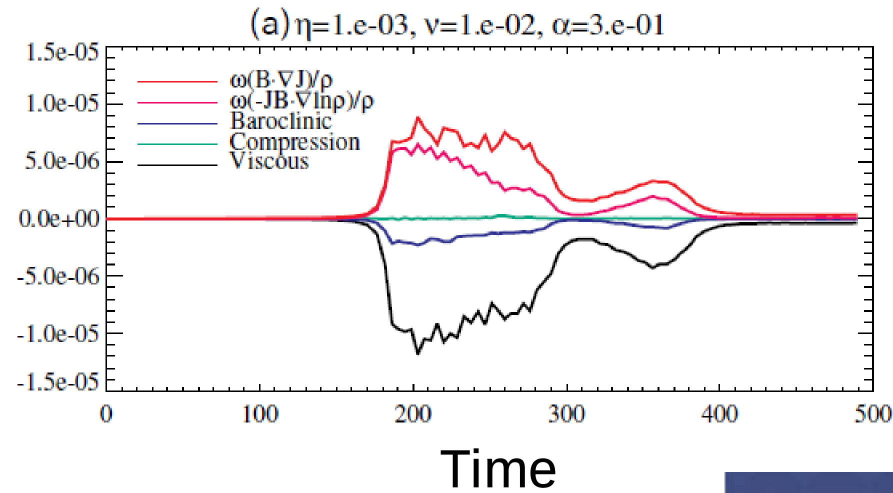
$$\Rightarrow \frac{\rho_{out}}{\rho_{in}} \propto Pr_m^{-1}.$$



Enstrophy

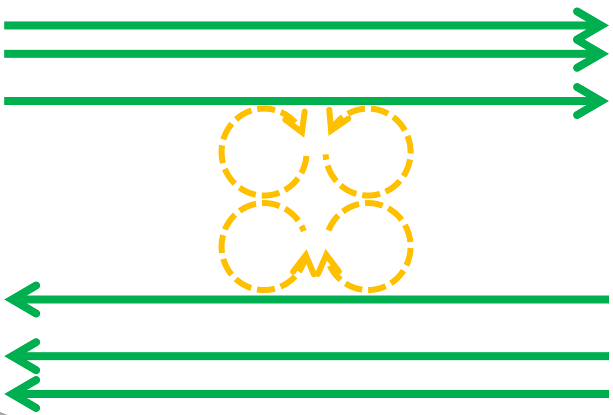
$$\frac{\partial Q}{\partial t} = -\left[\nabla\cdot(\boldsymbol{u}Q) + Q(\nabla\cdot\boldsymbol{u})\right] + \left[\frac{\boldsymbol{\omega}}{\rho}\cdot(\boldsymbol{B}\cdot\nabla)\boldsymbol{j} - \frac{(\boldsymbol{\omega}\cdot\boldsymbol{j})}{\rho^2}(\boldsymbol{B}\cdot\nabla\rho)\right]$$
$$-\frac{\boldsymbol{\omega}}{\rho^2}\cdot(\nabla P\times\nabla\rho) + \boldsymbol{\omega}\cdot\nabla\times\left(\frac{1}{\rho}\nabla\cdot\rho\nu\mathbf{S}\right).$$ (2D, in-plane B)



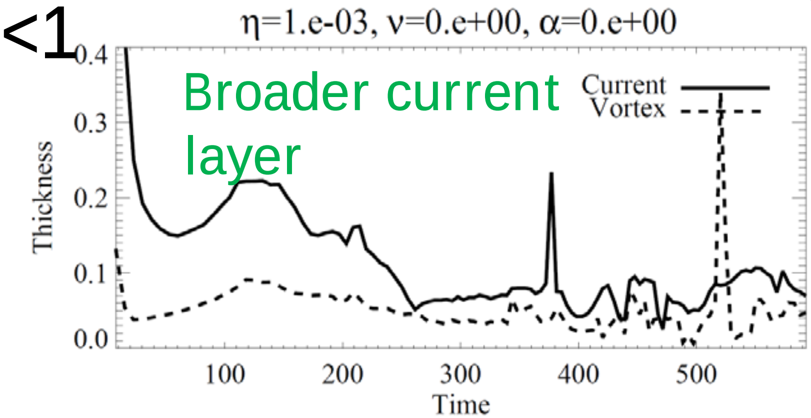


- C) Excitation by decreasing density
- D) Upstream transport
- E) Excitation even outside of CS

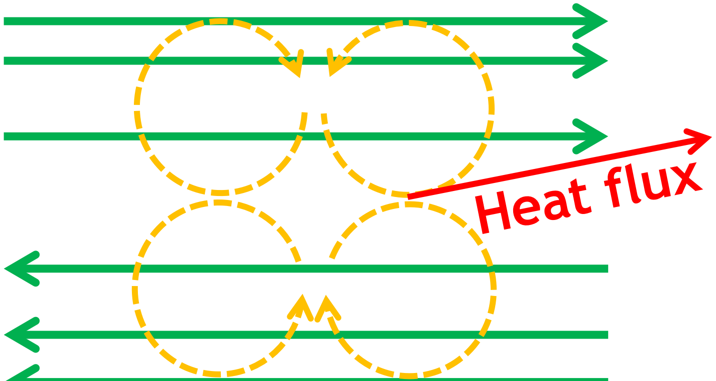
Role of Viscosity

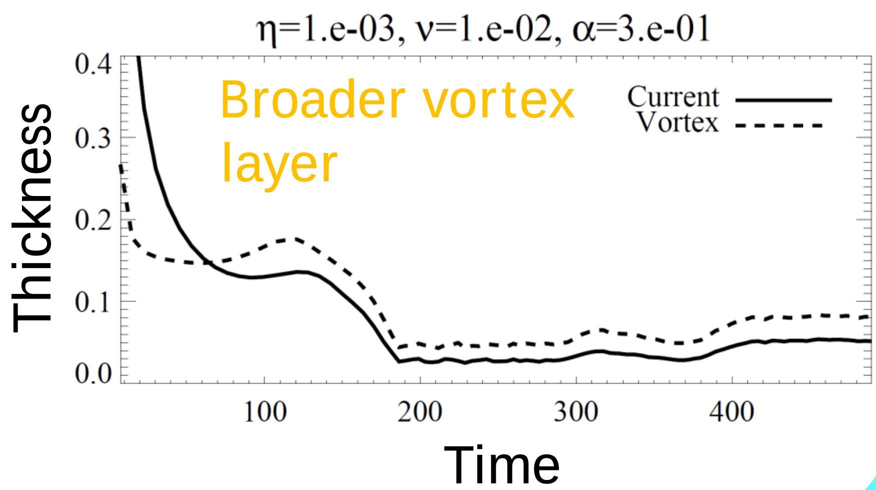


$Pr_m < 1$

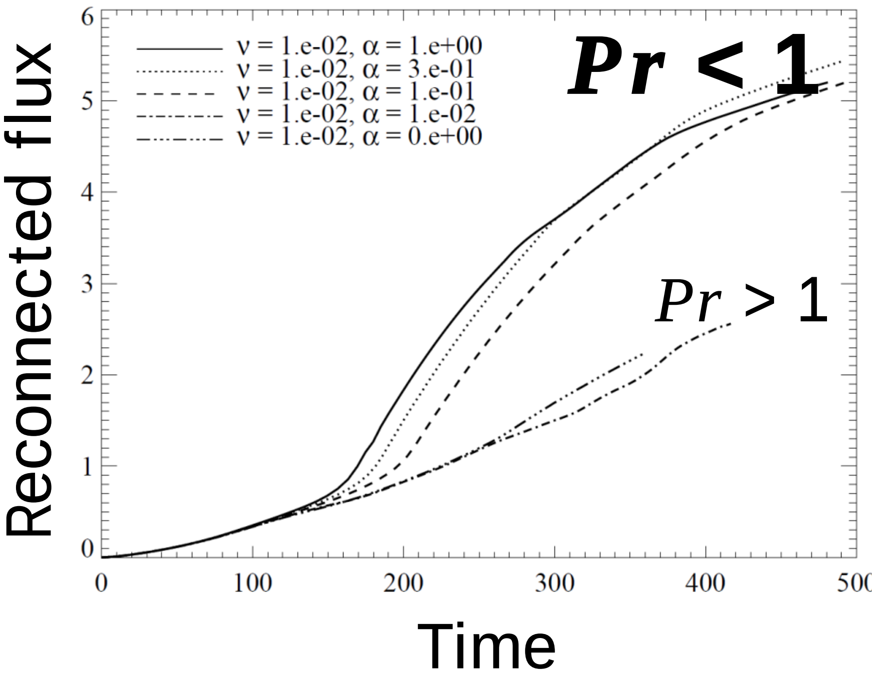


$Pr_m > 1$ & $Pr < 1$

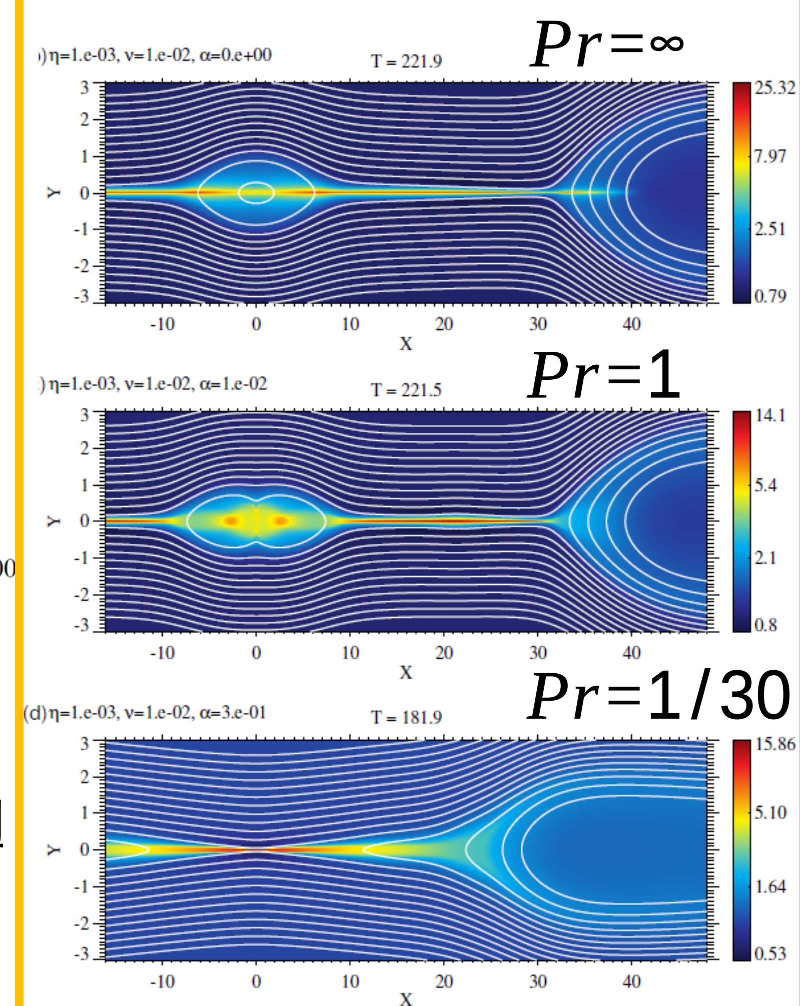




Role of Thermal Conduction



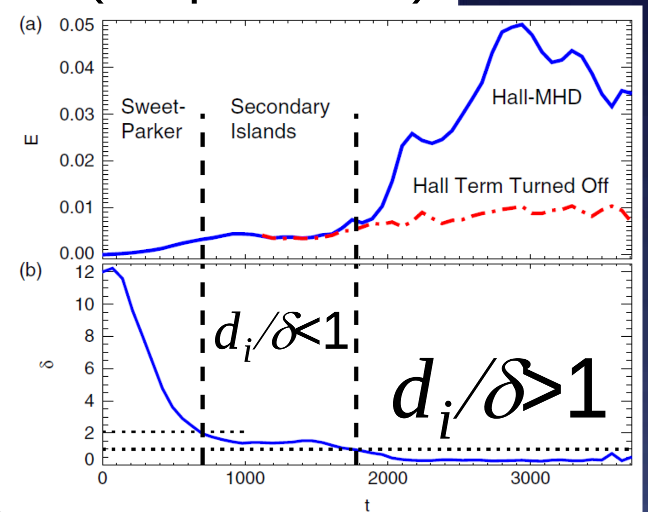
Temperature profile



- Heat flux required to <u>remove viscous heating</u>

Analogy to kinetic MRX

(Shepherd+10)



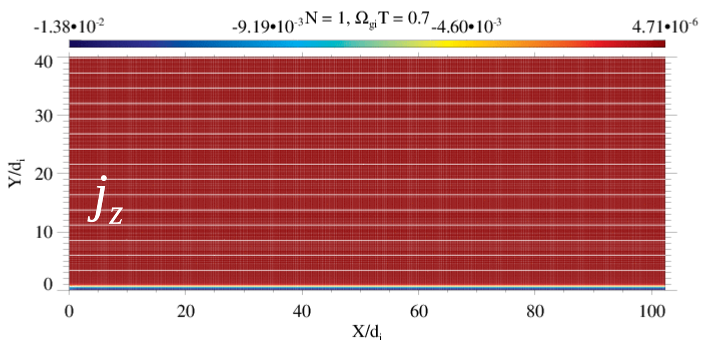
- *Effective* diffusion coefficients

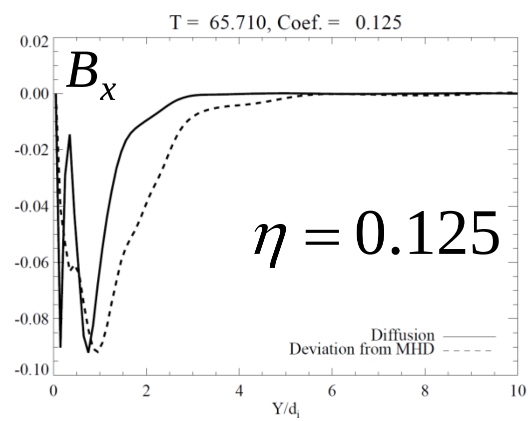
$$\begin{cases} \nu_{eff} \sim V_{A,in} d_i \left(d_i / L \right), \\ \eta_{eff} \sim V_{A,in} d_i \left(\delta / L \right), \end{cases} \Rightarrow Pr_{m,eff} \sim d_i / \delta$$

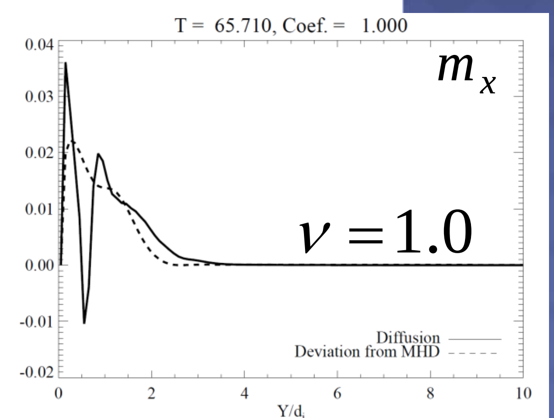
d_i=Ion inertia length

- Evaluate MHD eqs. from **kinetic solution**

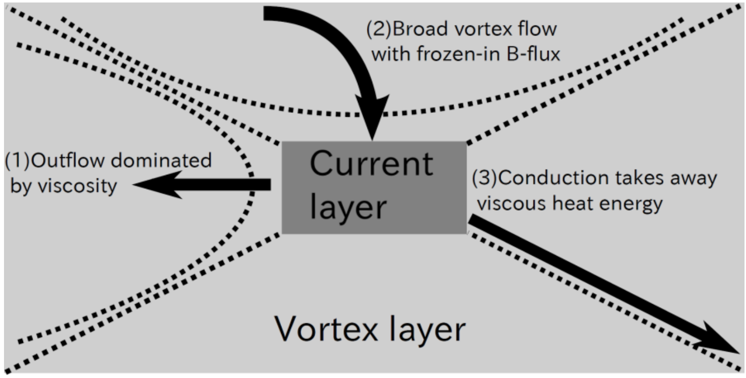
Vlasov simulation on K computer







Summary



- Viscosity and thermal conduction control MRX when $\boldsymbol{Pr_m > 1}$ **&** $\boldsymbol{Pr < 1}$
  - Decrease in plasma density inside a current sheet
  - Enstrophy excitation, feedback to upstream
  - Heat flux removes viscous heating
- Reasonable condition in actual plasmas
- Analogy to kinetic features, e.g, effective Pr_m >1 for two-scale diffusion region
- Resistive MHD => **Dissipative MHD**
  - Control Prandtl numbers