MAX-PLANCK-INSTITUT FÜR KERNPHYSIK

# 電磁場優勢プラズマにおける乱流磁気リコネクション


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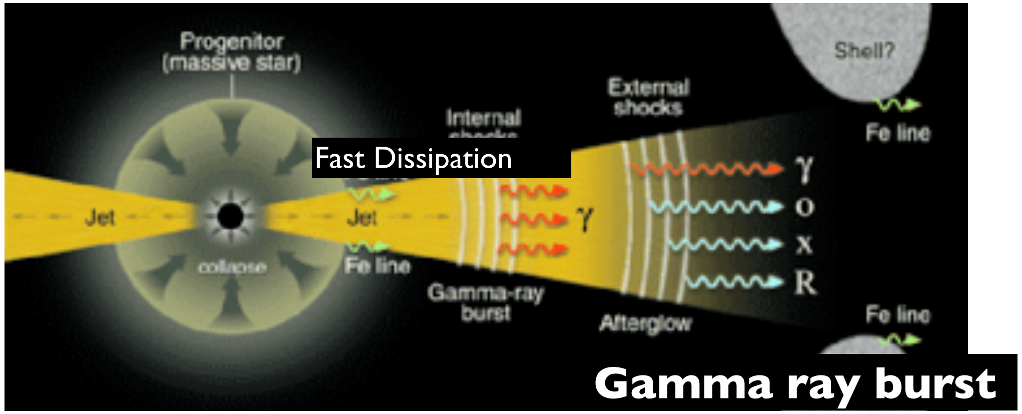
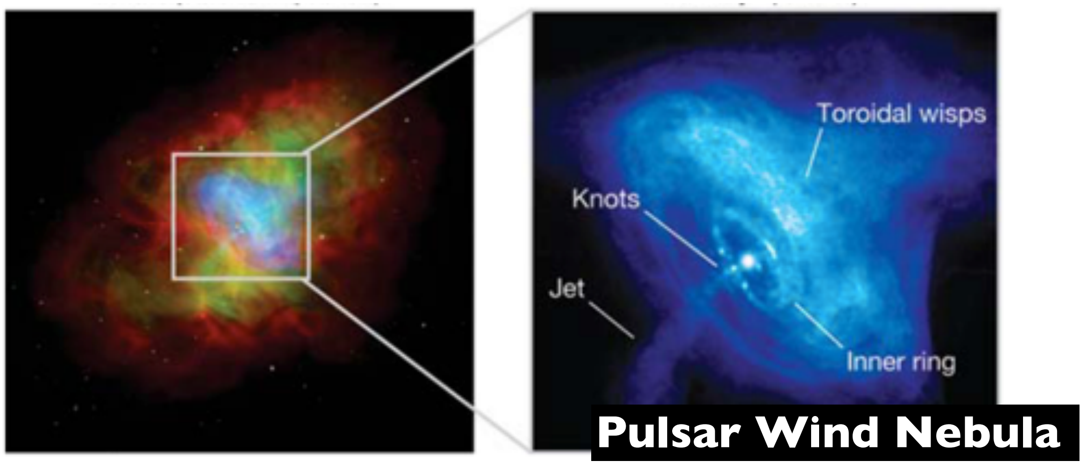
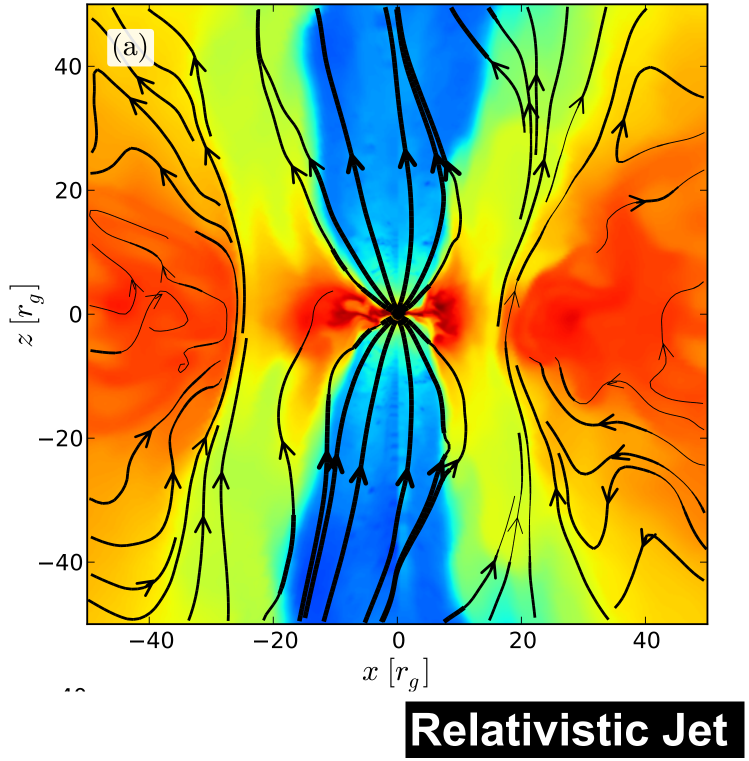
# 1. Poynting Dominated Plasma of Astrophysical Phenomena




ref ) Tchekhovskoy, McKinney, Narayan (2012), JphCS,372.

# 2. Magnetic Reconnection & Sweet-Parker model

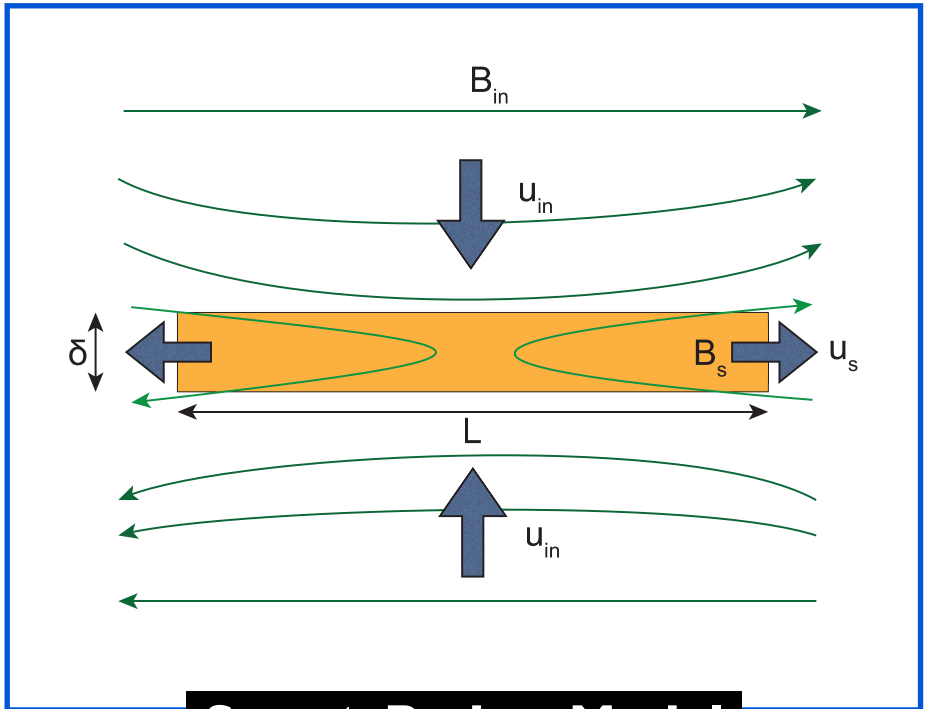
ref) Sweet, (1958)
Parker, (1957; 1963)

**Sweet-Parker model**

= steady reconnection model with uniform resistivity

Reconnection rate:

$$\begin{cases} u_{in} \sim c_A / \sqrt{S} \\ S = L\, c_A / \eta \end{cases}$$




Sweet-Parker Model

In many astrophysical objects,

$$S = L\, c_A / \eta >> 1$$

$$\Rightarrow u_{in} \sim c_A / \sqrt{S} << c_A$$

very slow ....

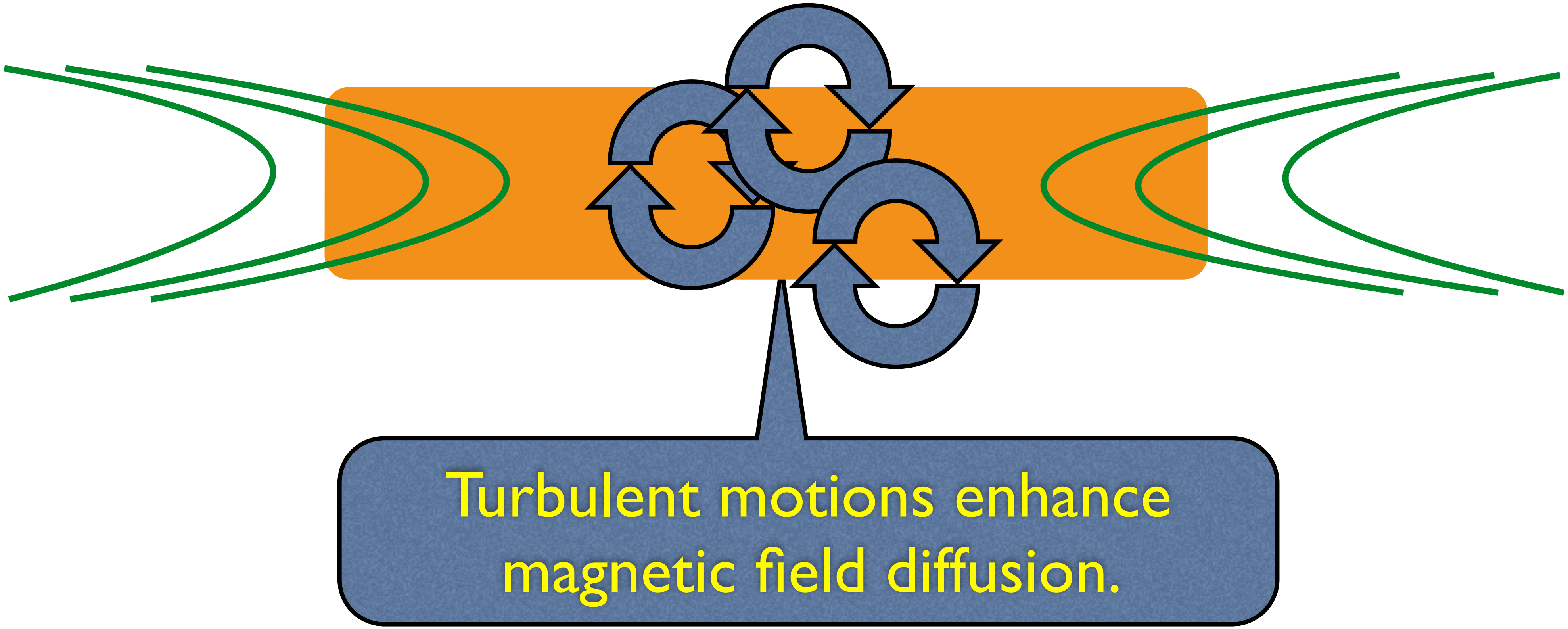
$\delta/L = 1/\sqrt{S}$ ⟷ too thin…

# 3D Turbulent Effects

# 3. Turbulent Sheets

ref ) Lazarian & Vishniac, (1999), ApJ, 517, 700.
Kowal et al. (2009), ApJ, 700, 63.

$$\frac{v_{\mathrm{in}}}{c_A} = \frac{\rho_{\mathrm{out}}}{\rho_{\mathrm{in}}}\frac{v_{\mathrm{out}}}{c_A}\frac{\delta}{L}$$



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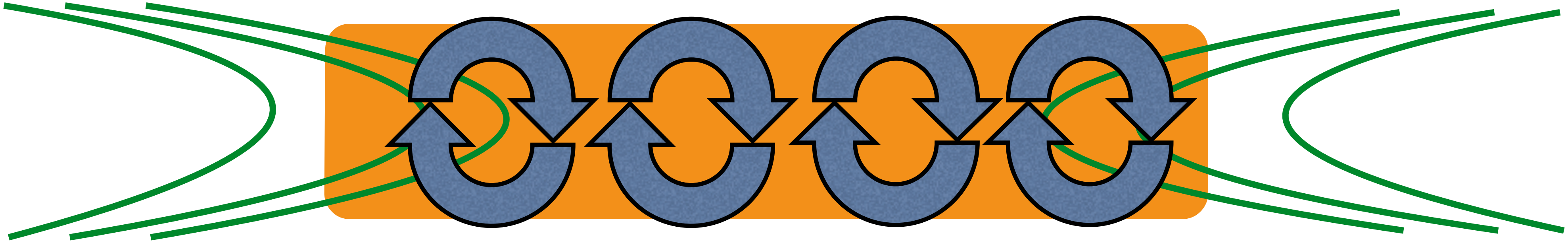
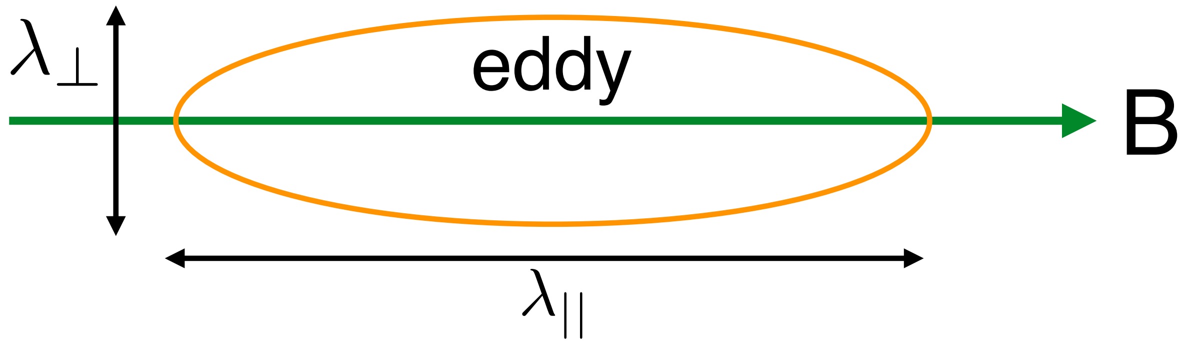


broadened by turbulent eddies
=> faster ! ($v_R/c_A$ is independent of resistivity)

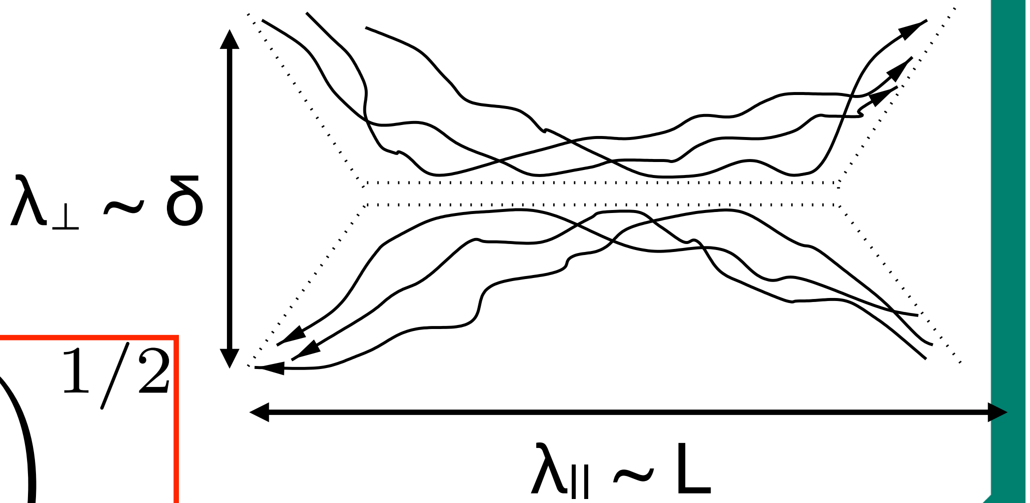
# 4. Theoretical Explanation



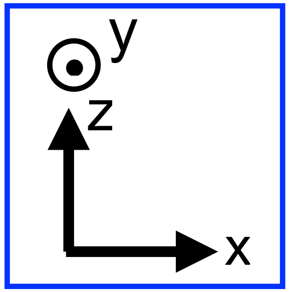

$$\frac{\lambda_{||}}{l} \sim \left(\frac{\lambda_\perp}{l}\right)^{2/3} \left(\frac{v_l}{c_A}\right)^{-4/3}$$ : MHD turbulence

$$\frac{v_{\rm in}}{c_A} = \frac{\delta}{L} \sim \frac{\lambda_\perp}{\lambda_{||}}$$

$$\sim \left(\frac{v_l}{c_A}\right)^2 \left(\frac{l}{L}\right)^{1/2}$$



# Simulation Setup



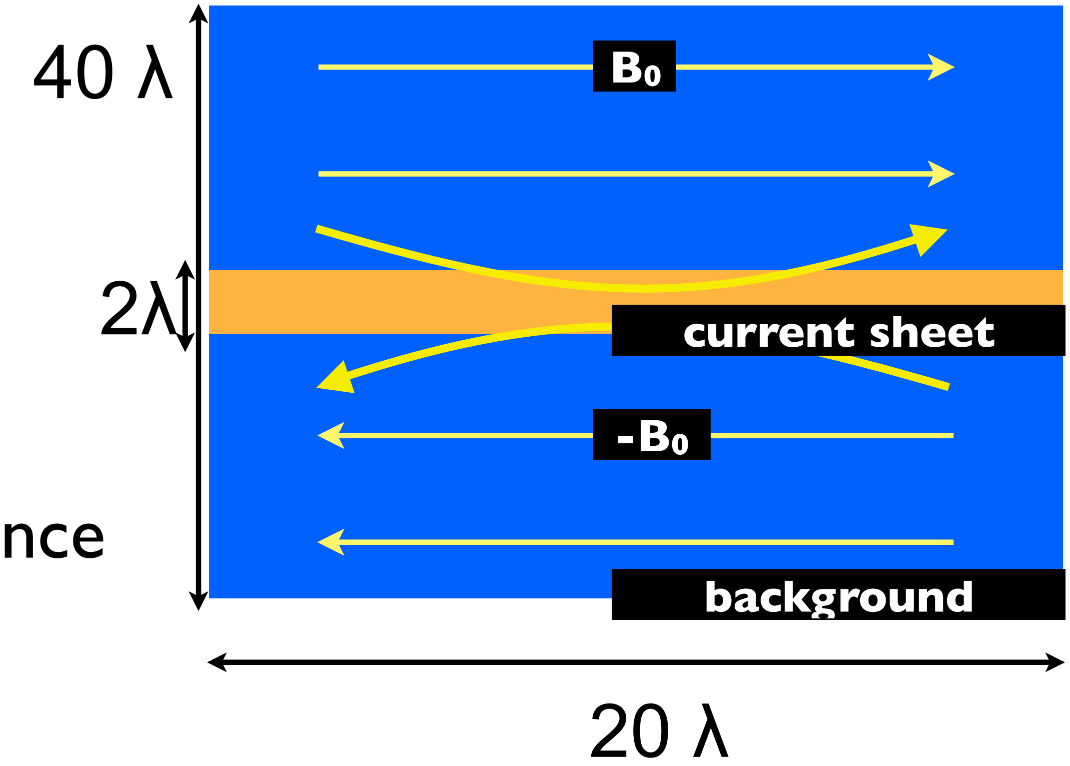

Initial condition:

- Harris Current Sheet
- mesh number:
  512*512*1024
  (resolving MHD turbulence)
- parameters:

1)injection velocity of turbulence

2)σ-parameter

3)resistivity



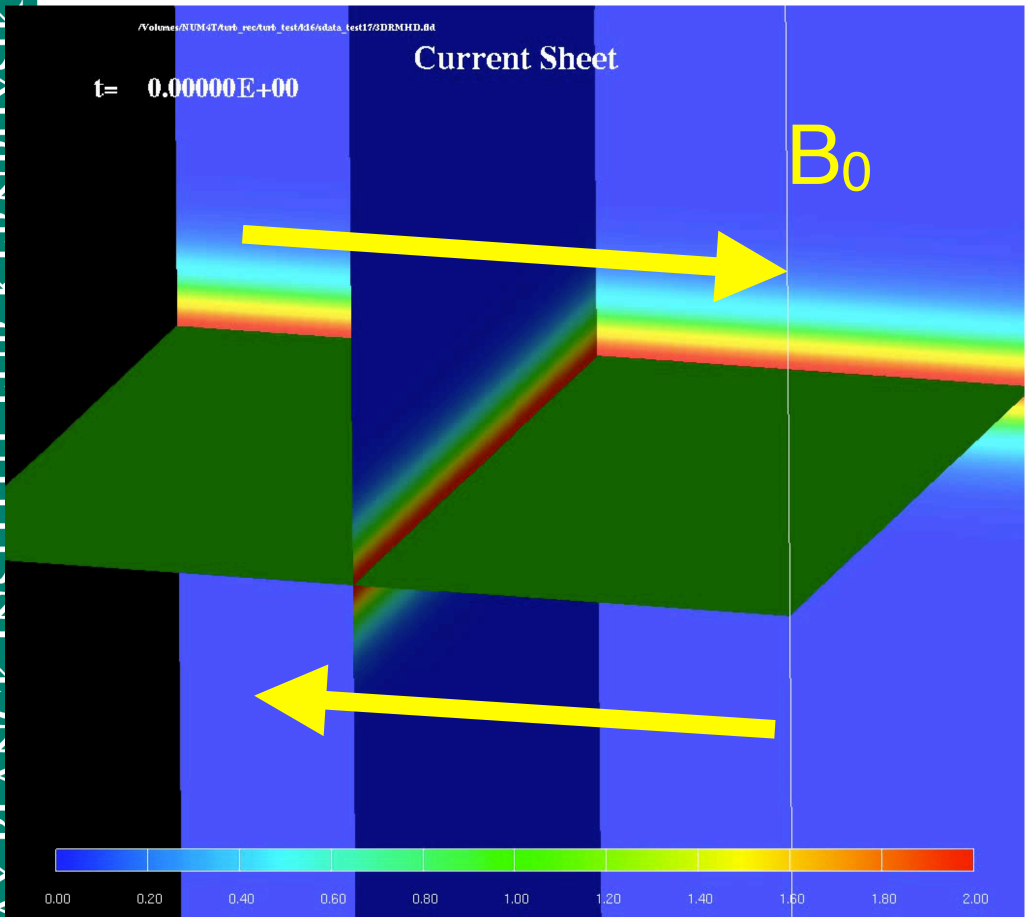

- Resistive Relativistic MHD approximation

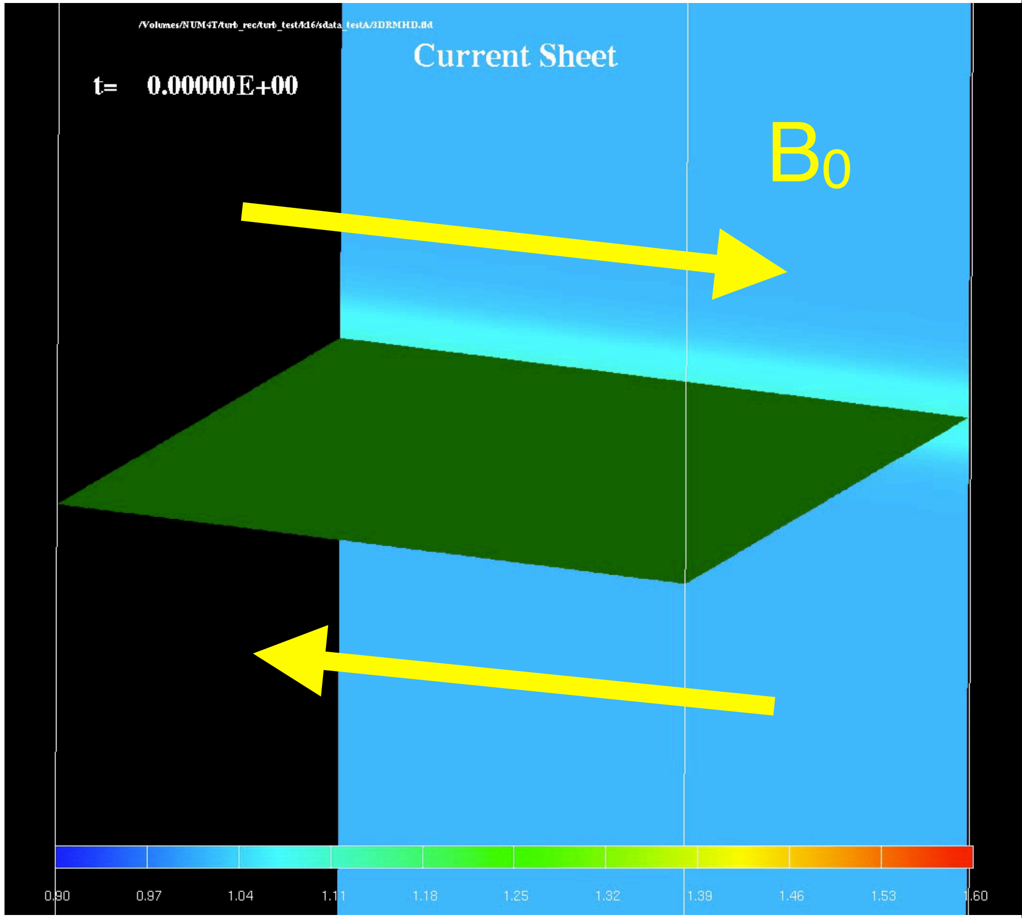
ref ) Takamoto & Inoue, (2011), ApJ ,735, 113

# 5. Turbulent Reconnection

$\sigma = 5$

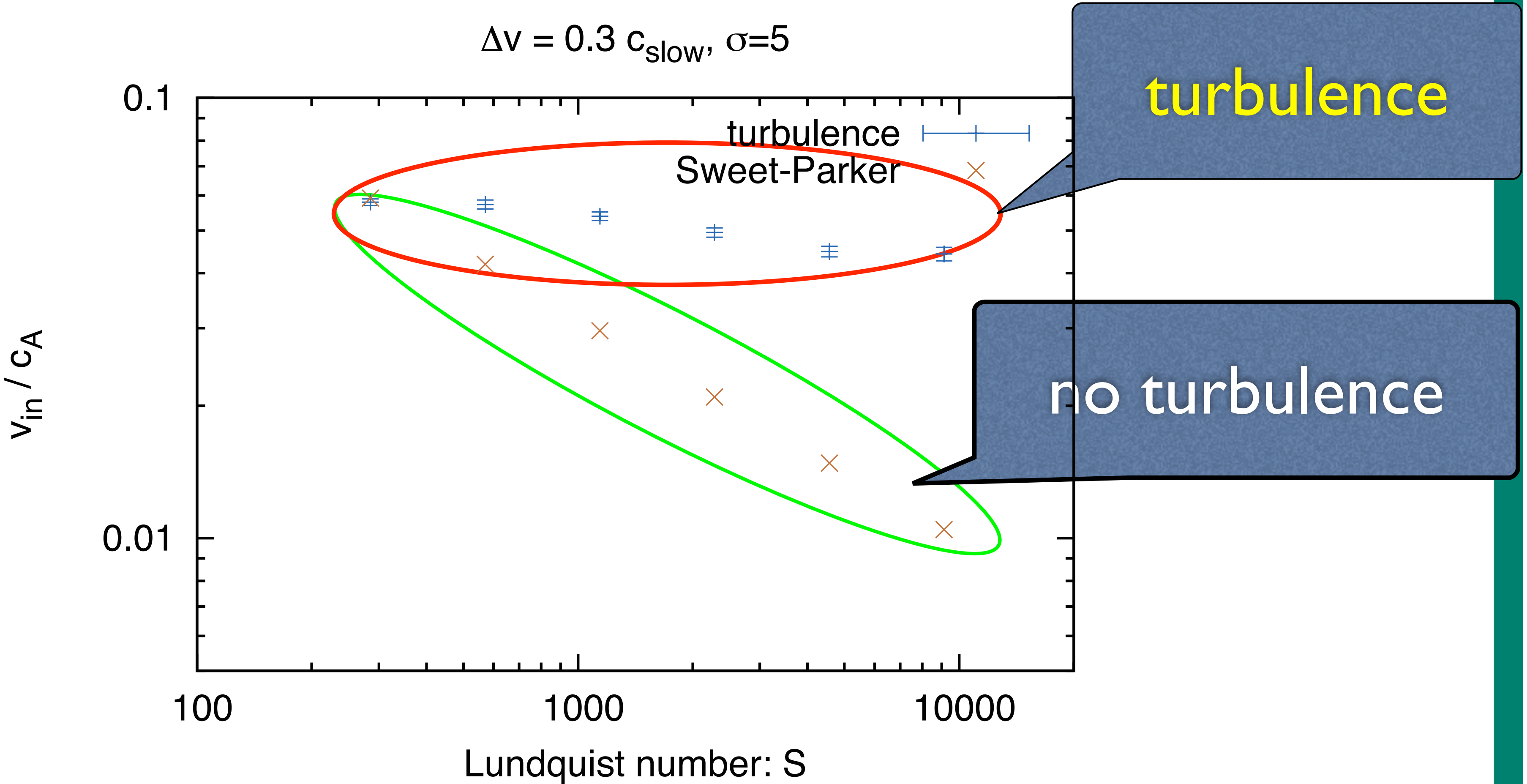
$\sigma = 0.04$



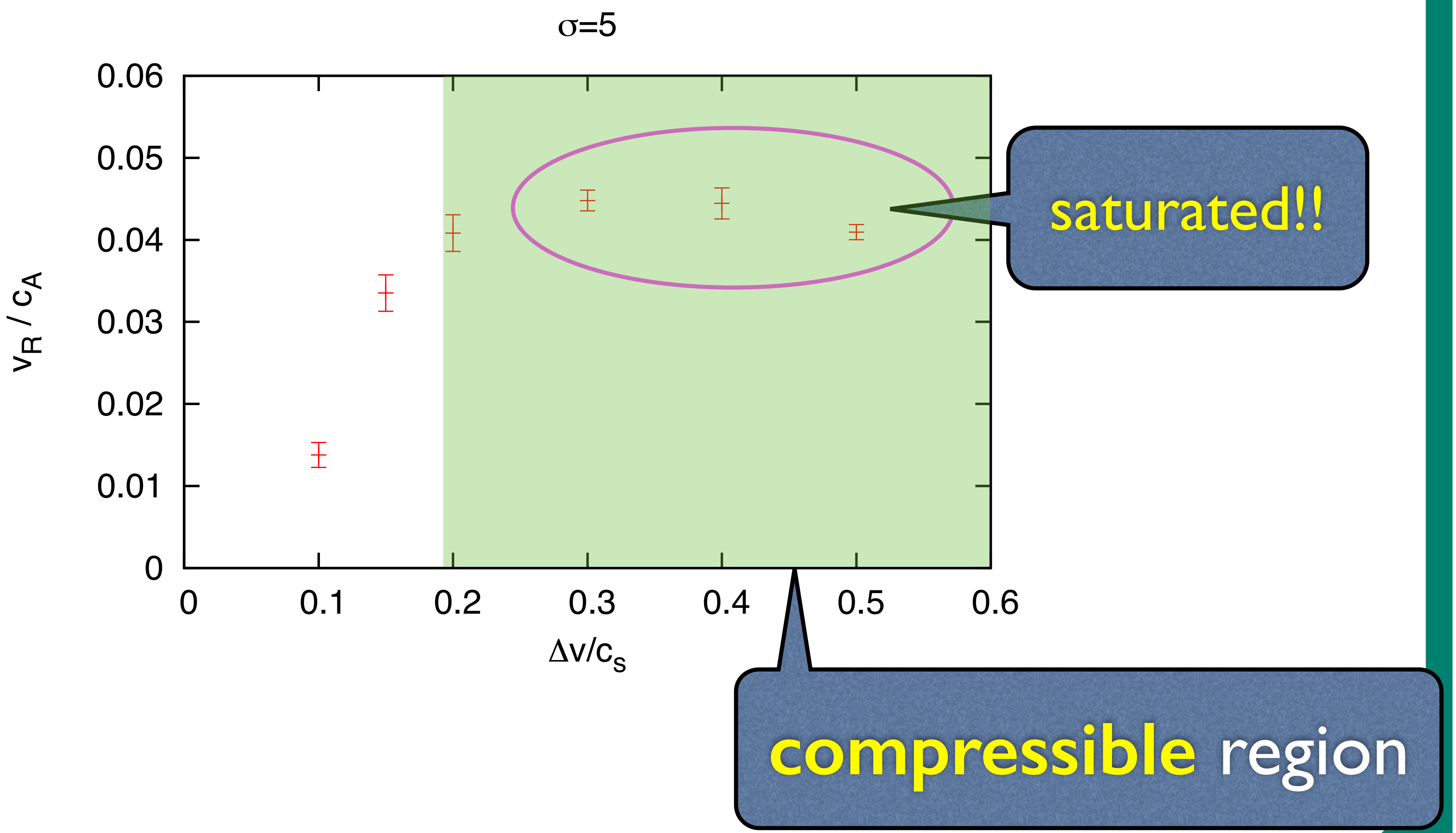

- $k_B T/mc^2 = 1$
- **driven** turbulence
  injected around central region

# 6. Lundquist Number Dependence

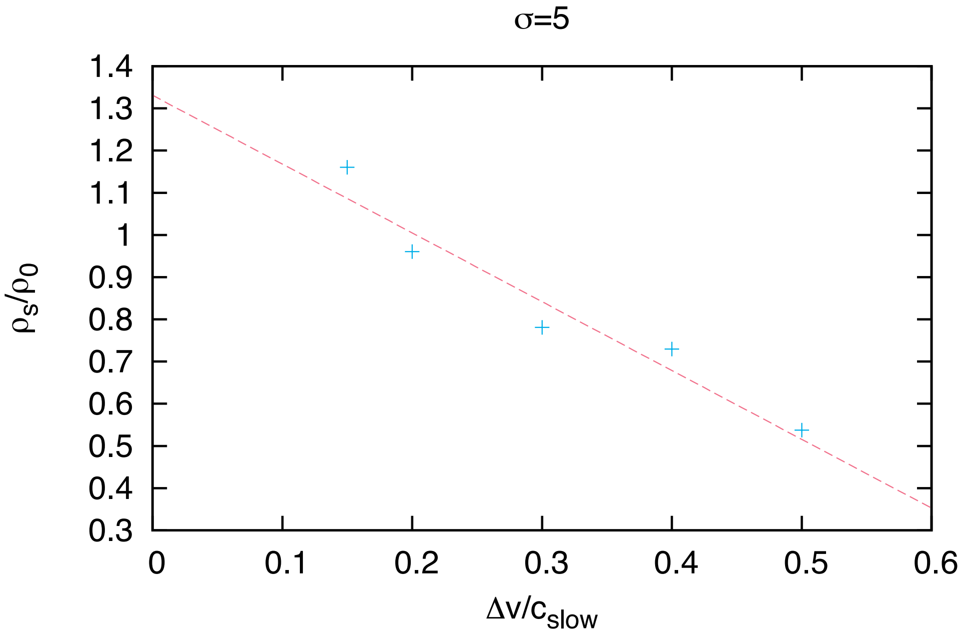


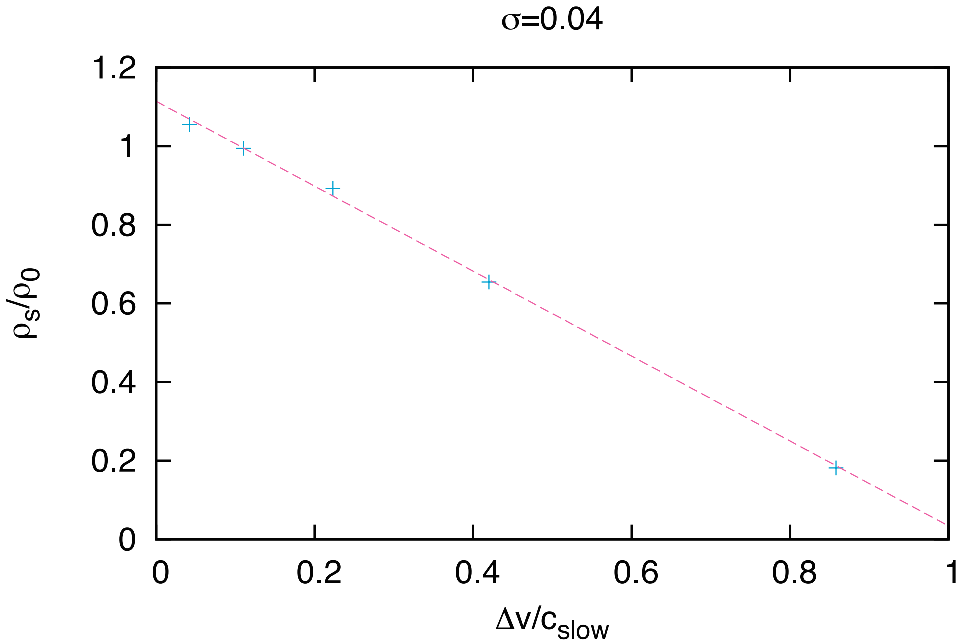

**fast & resistivity independent mechanism**

# 7. Too Strong Turbulence Effects



# 8. Compressible Effects: I




$$\frac{v_{\rm in}}{c_A} = \frac{\rho_{\rm out}}{\rho_{\rm in}} \frac{v_{\rm out}}{c_A} \frac{\delta}{L}$$

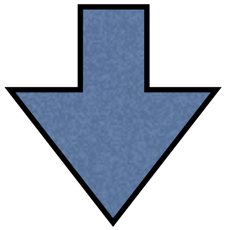
$$\frac{\rho_{\rm s}}{\rho_{\rm in}} = \frac{1}{1+\sigma}\left[\left(4+\frac{1}{\Theta_{\rm s}}\right)\frac{\sigma}{2}\frac{\gamma_{\rm s}^2}{\gamma_{\rm in}^2}\frac{v_{\rm s}}{c_A} - C_1 C_2 \frac{\rho_*}{\rho_{\rm in}} \frac{l_x}{c^2 h_{\rm in}\gamma_{\rm in}^2 \Delta t_{\rm inj}} \Delta v\right]$$

# 9. Compressible Effects: 2

$$\frac{v_{\rm in}}{c_A} = \frac{\rho_{\rm out}}{\rho_{\rm in}} \frac{v_{\rm out}}{c_A} \frac{\delta}{L}$$

**Incompressible:** (LV99)

$$\frac{\delta}{L} \simeq \min\left[\left(\frac{L}{l}\right)^{1/2}, \left(\frac{l}{L}\right)^{1/2}\right] \left(\frac{v_l}{c_A}\right)^2$$



**compressible:**

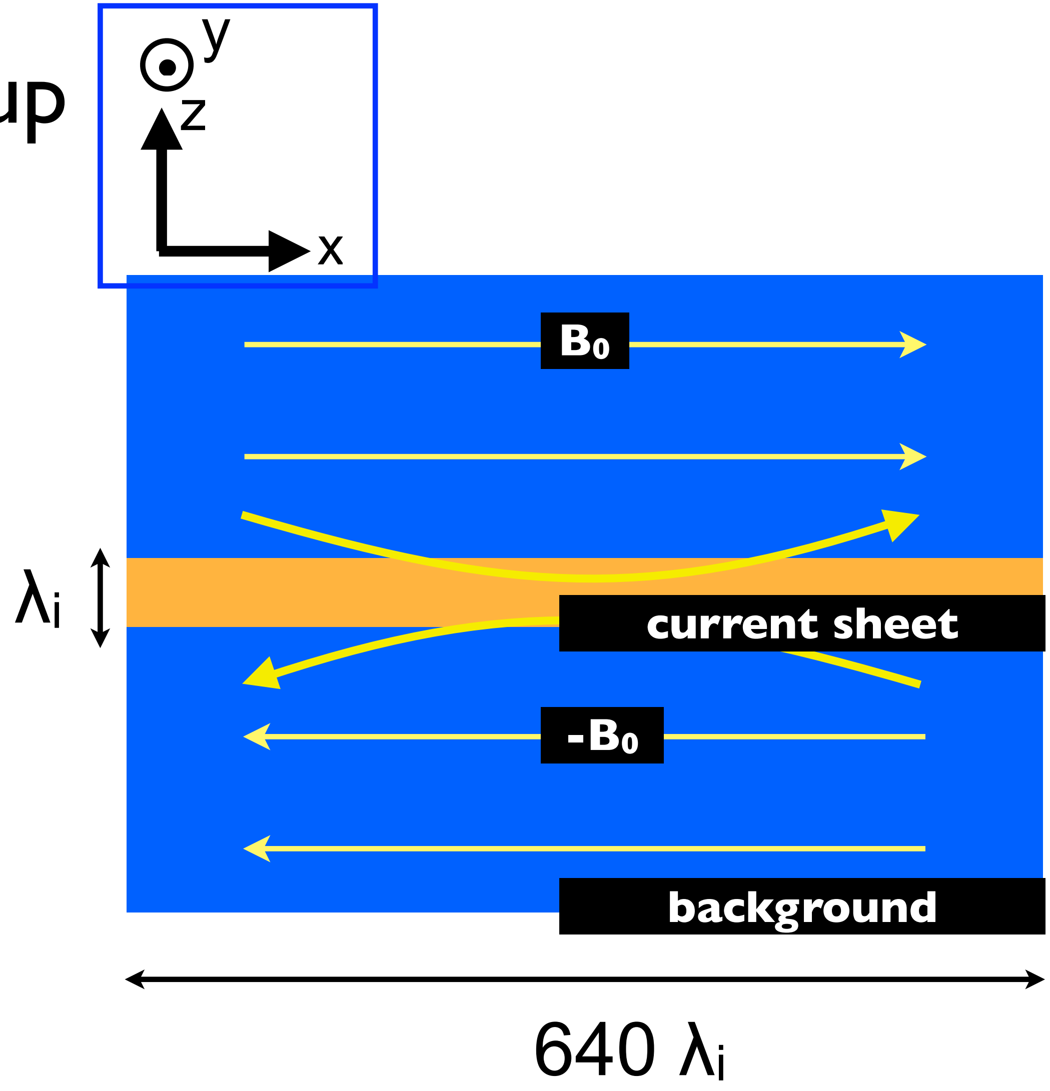
$$\frac{\delta}{L} \simeq \min\left[\left(\frac{L}{l}\right)^{1/2}, \left(\frac{l}{L}\right)^{1/2}\right] \left[\left(\frac{v_l}{c_A}\right)^2 - C\left(\frac{v_l}{c_A}\right)^4\right]$$

# 2D Kinetic Reconnection

# 10. PIC Simulation Setup

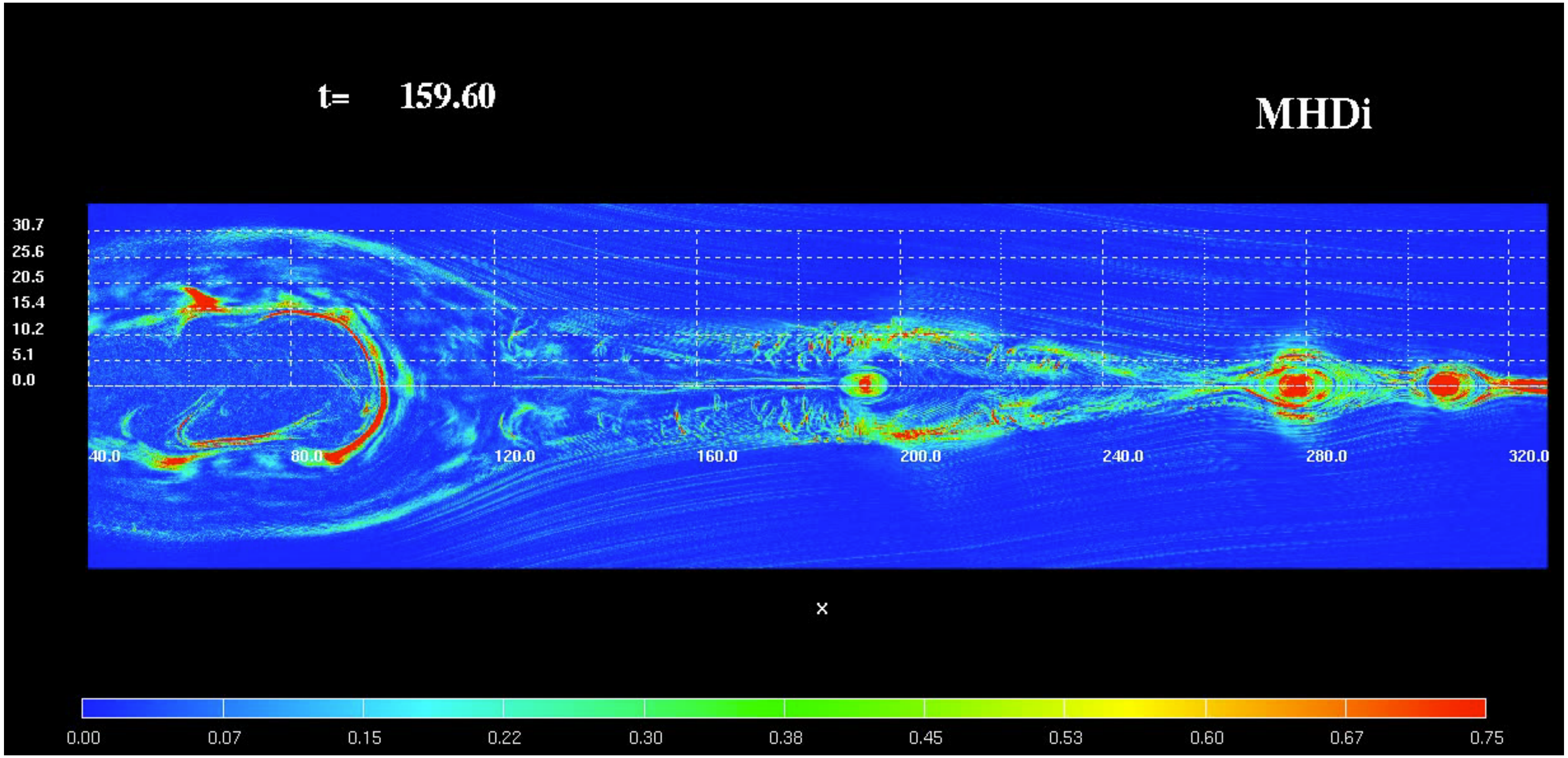
Initial condition:

- Harris Current Sheet  
  ($B_x$=$B_0$ tanh[z/λ],  
  n = $n_0$/$\cosh^2$[z/λ]  
  λ = $\lambda_i$ / 2 )
- total number of particles  
  =$10^{10}$
- $M_i$ / $m_e$ = 100
- $n_{background}$ /$n_{sheet}$ = 0.0875
- plasma β = 0.02
- 1024MPI*6OpenMP=6144core
- 2D AMR-PIC code




ref ) Fujimoto & Machida, (2006), JCP, 214, 550-566.  
Fujimoto, (2011), JCP, 230, 8508-8526.

# 11. Reconnection in Kinetic Region



# Summary

- We investigated various kinds of relativistic reconnection in Poynting-dominated plasma
- We found that the reconnection rate is highly enhanced ( dissipation time ~ **20 - 30 Alfvén crossing time** )
  —Turbulent Reconnection : vR/cA ~ 0.05
- Reconnection rate becomes **independent** of the Lundquist number (resistivity)
- Too strong turbulence **reduces** reconnection rate because of the **compressibility**!!