相対論的磁気リコネクションが駆動する乱流

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1 Magnetic Reconnection

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

<u>Assumptions</u>: steady flow and uniform resistivity
(Sweet-Parker model)

Re... ction rate:

u_{in} ... $/ S$

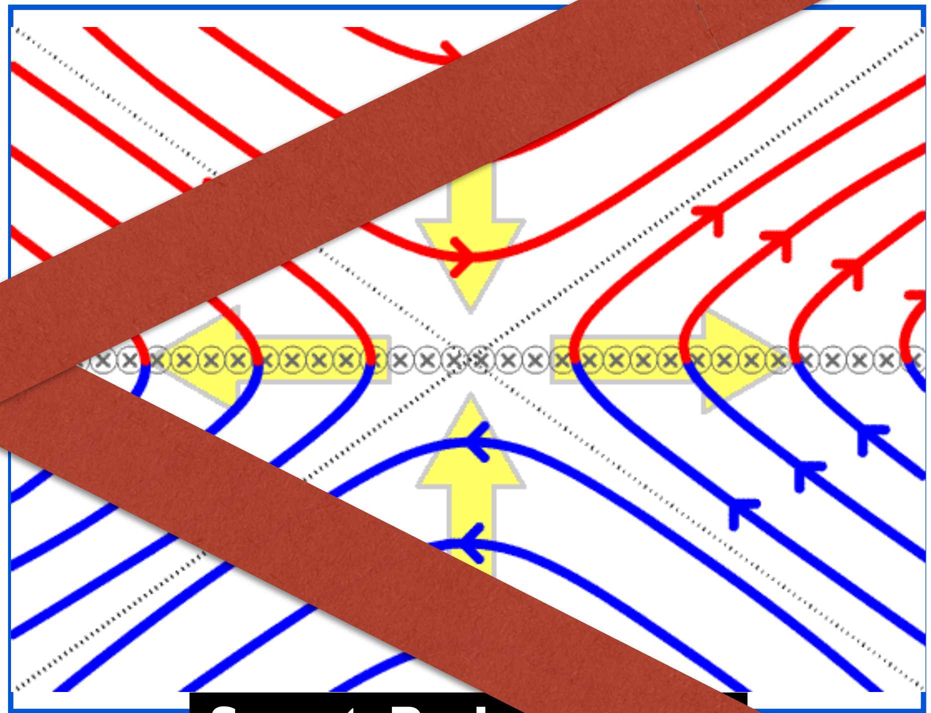
$S = L\, c_A$ ...

In many astrophysical ob...

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

... $A / \sqrt{S} << c_A$

very slow ....



Sweet-Parker

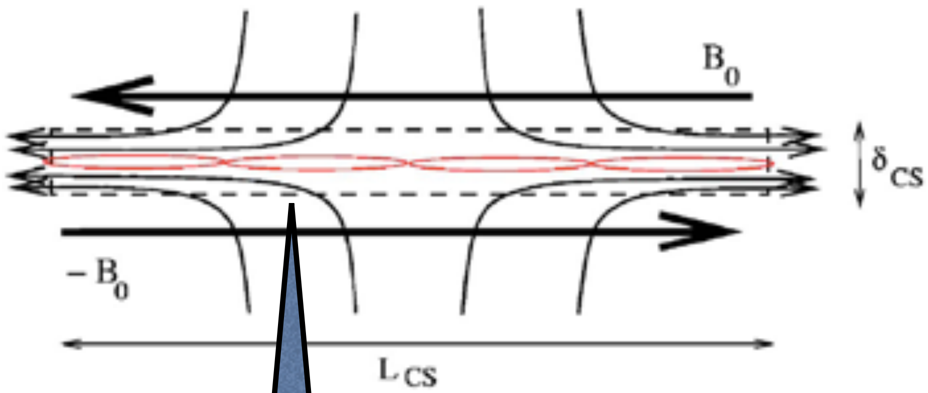
$\delta/L = 1/\sqrt{S}$ ⟷ too thin…

2. Plasmoid-Chain

ref) Shibata & Tanuma, 2001, EPS, 53, 473
Loureiro et al. 2007, Phys. Plasmas 14, 100703
Bhattacharjee et al., 2009, Phys. Plasmas 16, 112102
Takamoto, 2013, ApJ 775, 50.

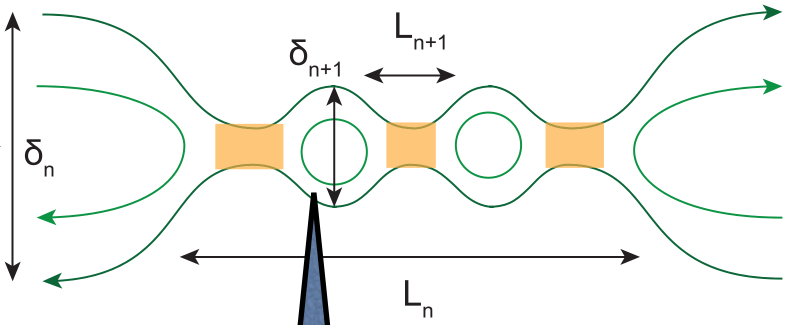
superposition of critical sheets ($S_c \sim 10^4$)

Sweet-Parker sheet



sheet shrinks!
=> unstable for tearing instability

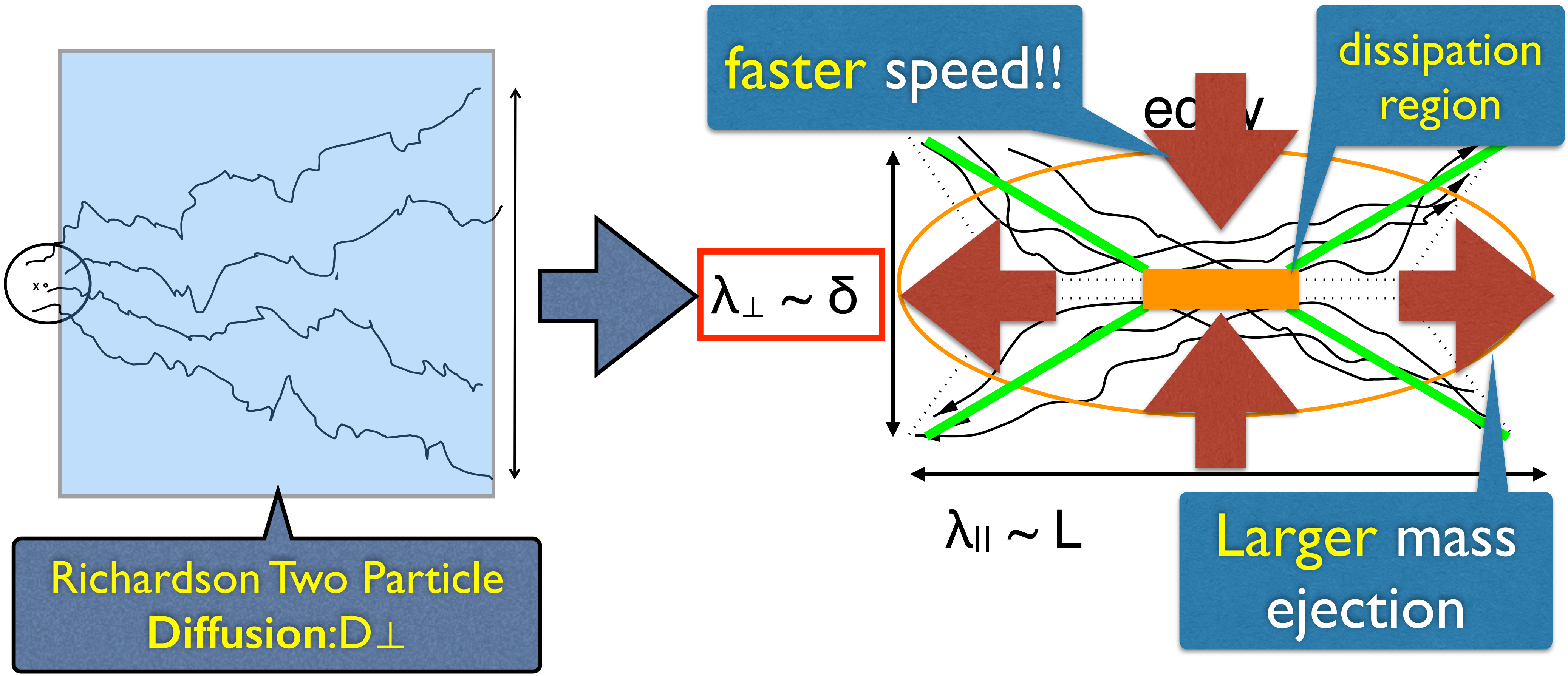
Plasmoid-Chain



secondly-tearing instability

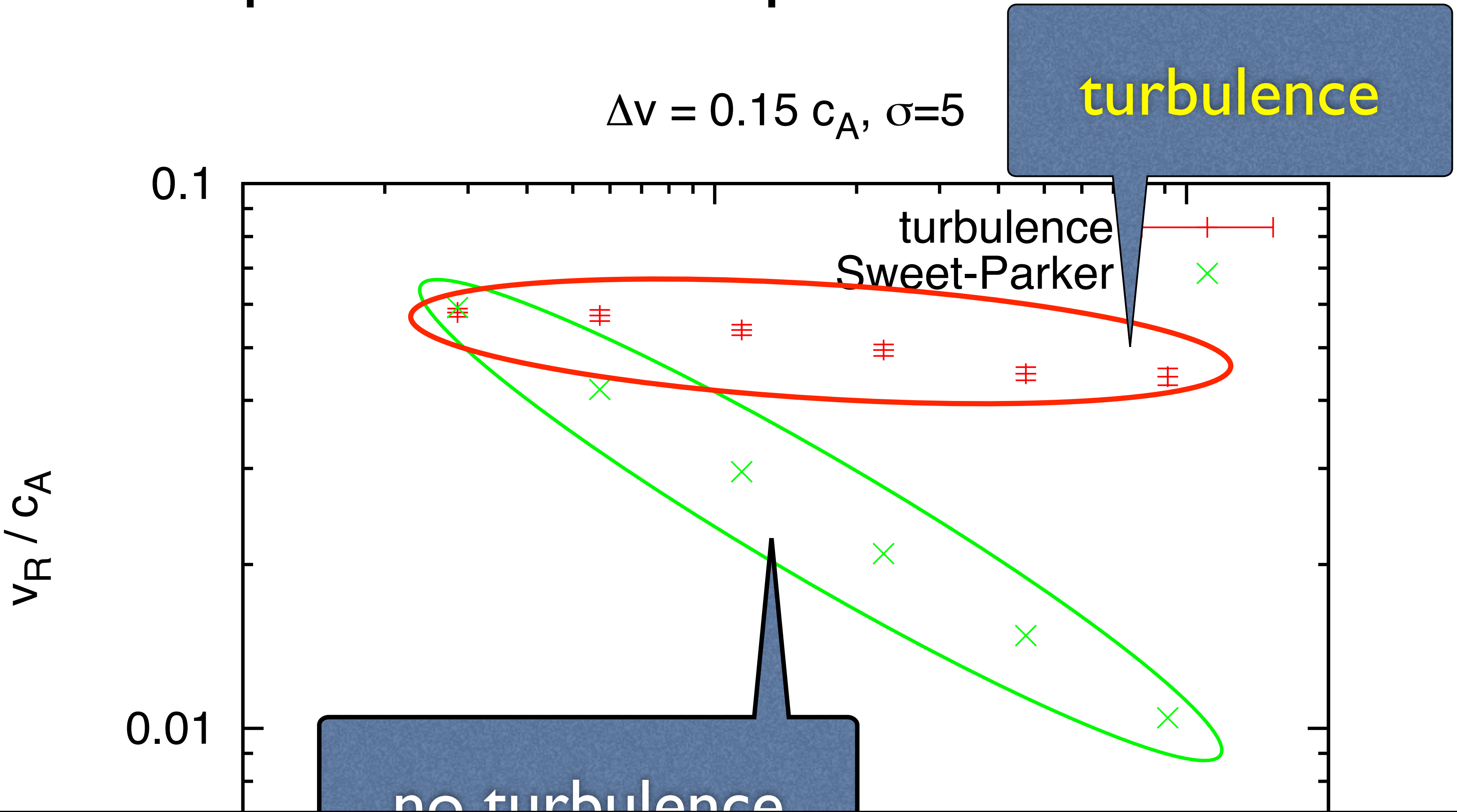
3. 3D Turbulent Sheet

ref) Lazarian & Vishniac (1999), ApJ, 517,700
Eyink, Lazarian, Vishniac, (2011), ApJ, 743, 51.



$$\frac{\delta}{L_x} = \boxed{M_A^2}\min\left\{\left(\frac{L_x}{L_i}\right)^{1/2}, \left(\frac{L_i}{L_x}\right)^{1/2}\right\}$$

4. Lundquist Number Dependence



fast & resistivity independent
mechanism

5.Necessary Turbulence Energy in Poynting-Dom. Plasma

3-Mach Number

if we set: $\boxed{\dfrac{v_{\rm turb}}{c_{\rm A}} \equiv \alpha}$

$$\boxed{\frac{\epsilon_{\rm turb}}{\epsilon_{\rm B}} \equiv \frac{\rho_0 h v_{\rm turb}^2/2}{B_0^2/8\pi} = \frac{\alpha^2}{1\boxed{+\sigma}}}$$

$$\left(c_{\rm A} \equiv c\sqrt{\frac{\sigma}{1+\sigma}}, \quad \sigma \equiv \frac{B^2}{4\pi\rho_0 h c^2 \gamma^2} = \frac{B_0^2}{4\pi\rho_0 h c^2} \right)$$

if we assume: $v_{\rm turb}/c_{\rm A} = 0.3$, $\sigma = 10$,

$$\varepsilon_{\rm turb}/\varepsilon_{\rm B} \sim 0.01$$

just **1%** of magnetic field energy is **sufficient**!!

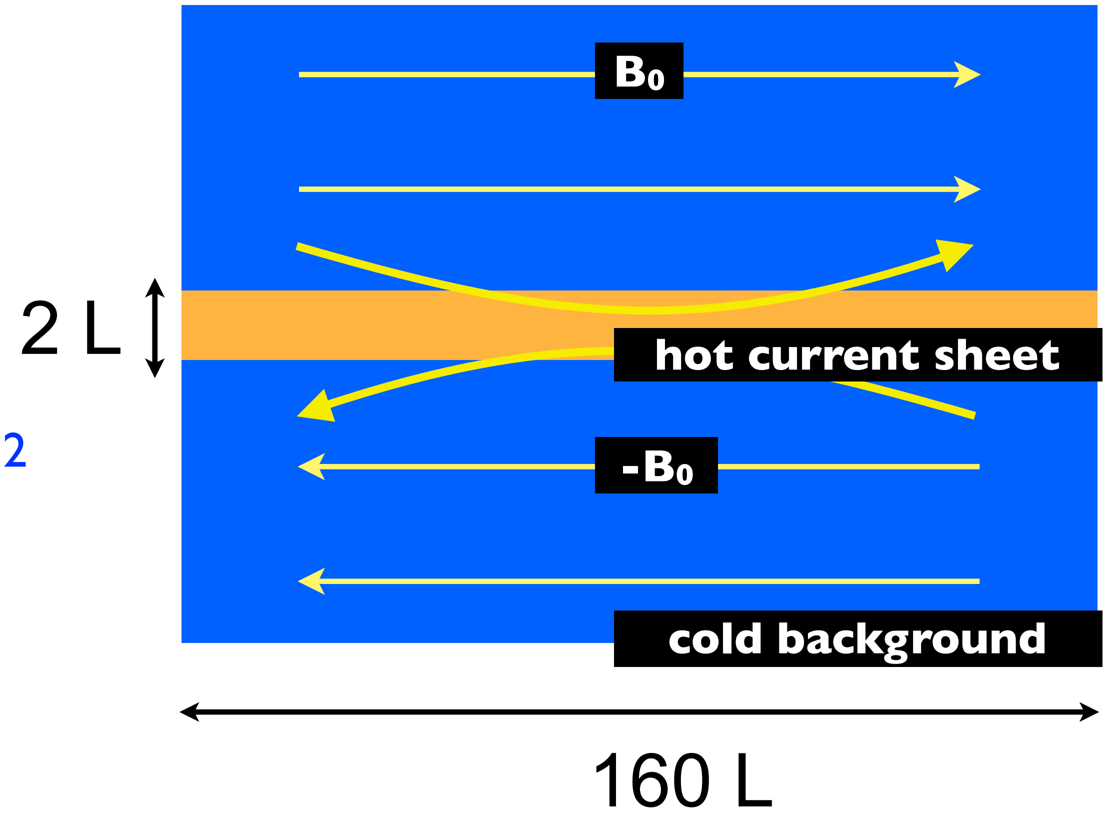
6. initial condition for self-generated turbulence

Initial condition:

- Harris current sheet
  => calculated until t=60L/c
  via 2D simulation
- uniform temperature: $T = mc^2$
- Box size: $160L \times 20L \times 40L$
- mesh size:

$\Delta_x, \Delta_y, \Delta_z, \sim 0.04L, 0.02L, 0.02L$

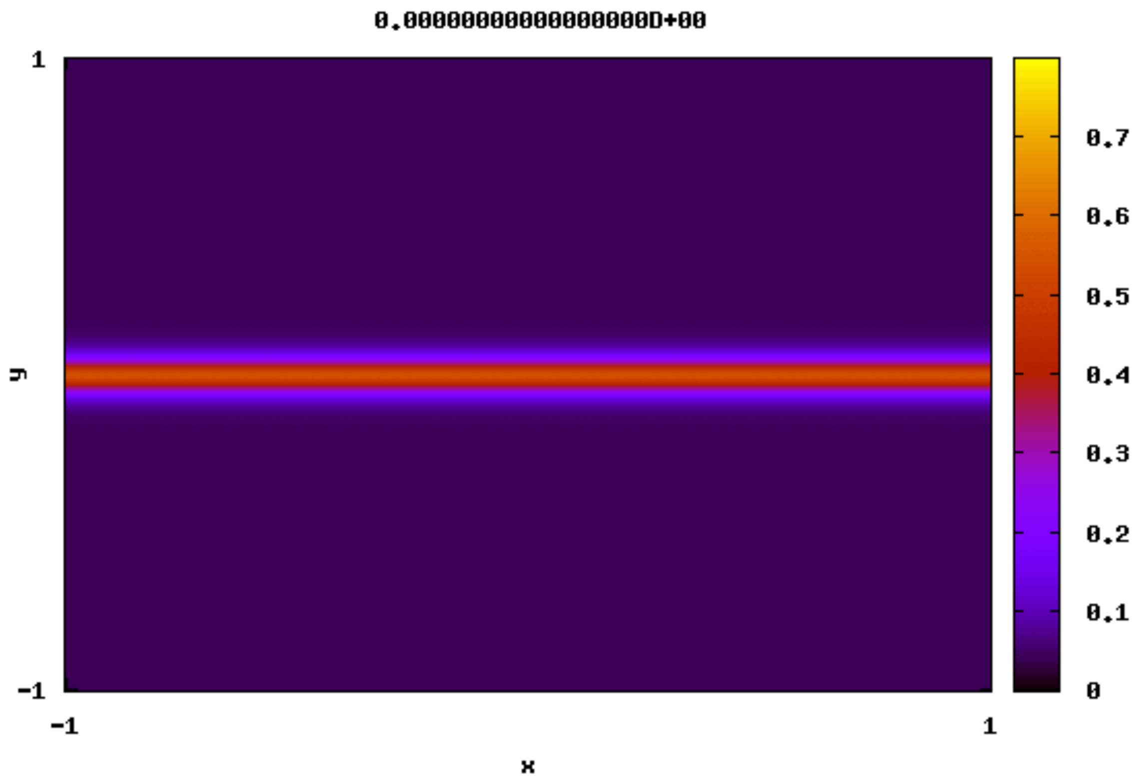
- 4096 MPI processes
- uniform resistivity
- Large Lundquist number:
  $S_L \sim 10^5$
- Poynting dominated :
  $\sigma = 5$



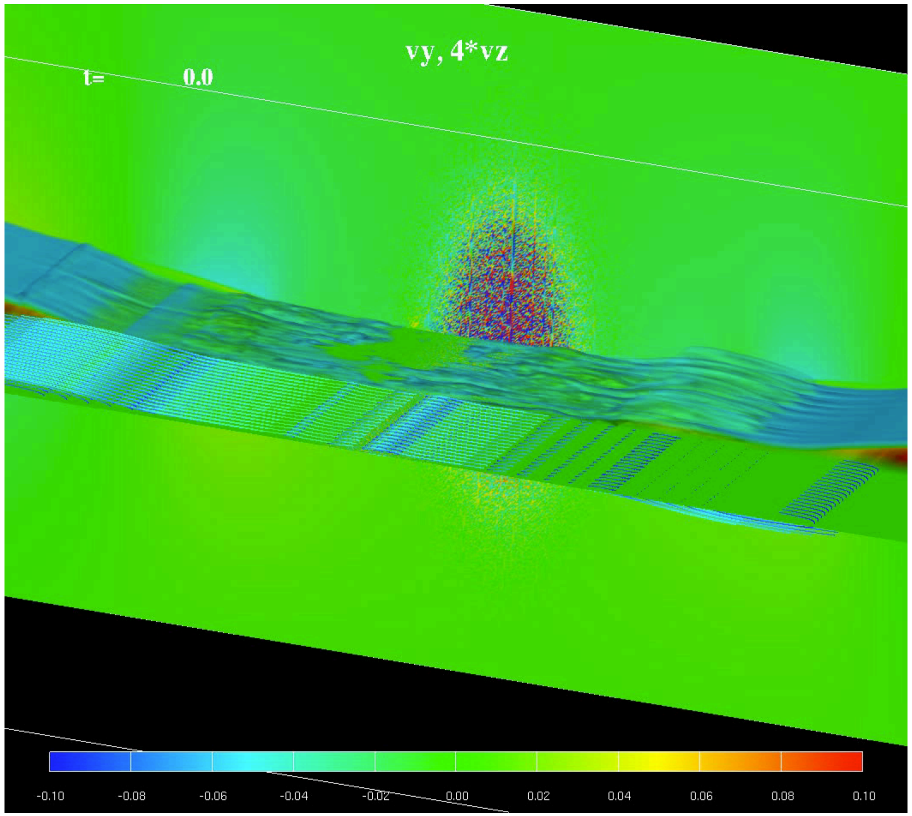
$$\sigma \equiv \frac{[\mathbf{E} \times \mathbf{B}c/4\pi]}{\rho h c^2 \gamma^2 v}$$

7. Relativistic Self-Generated Turbulence in Sheets

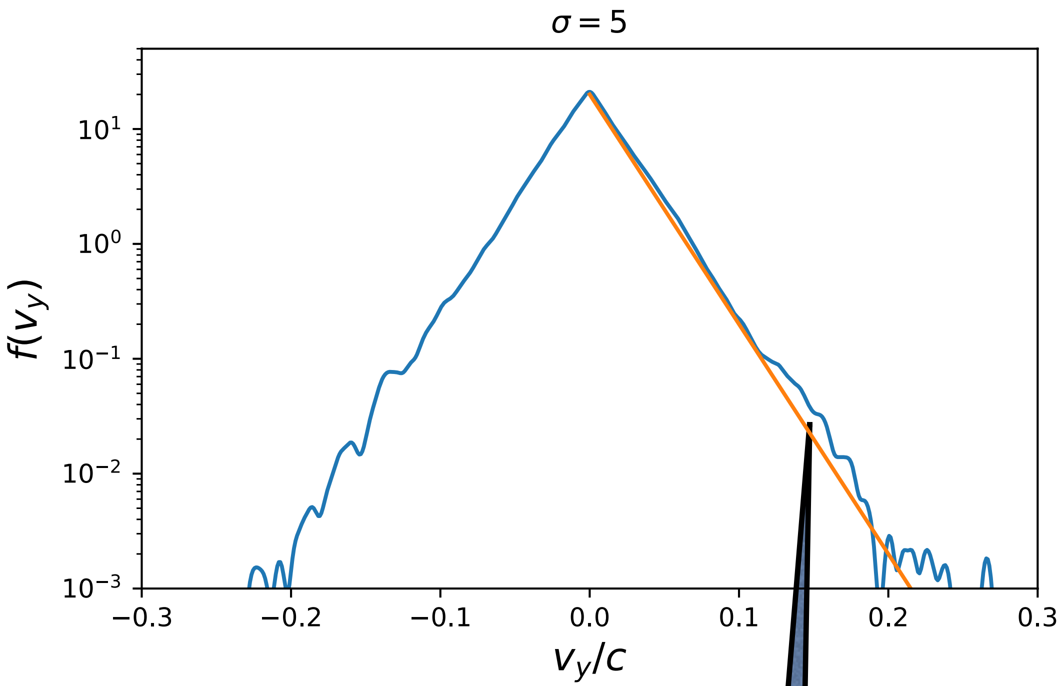
2D simulation

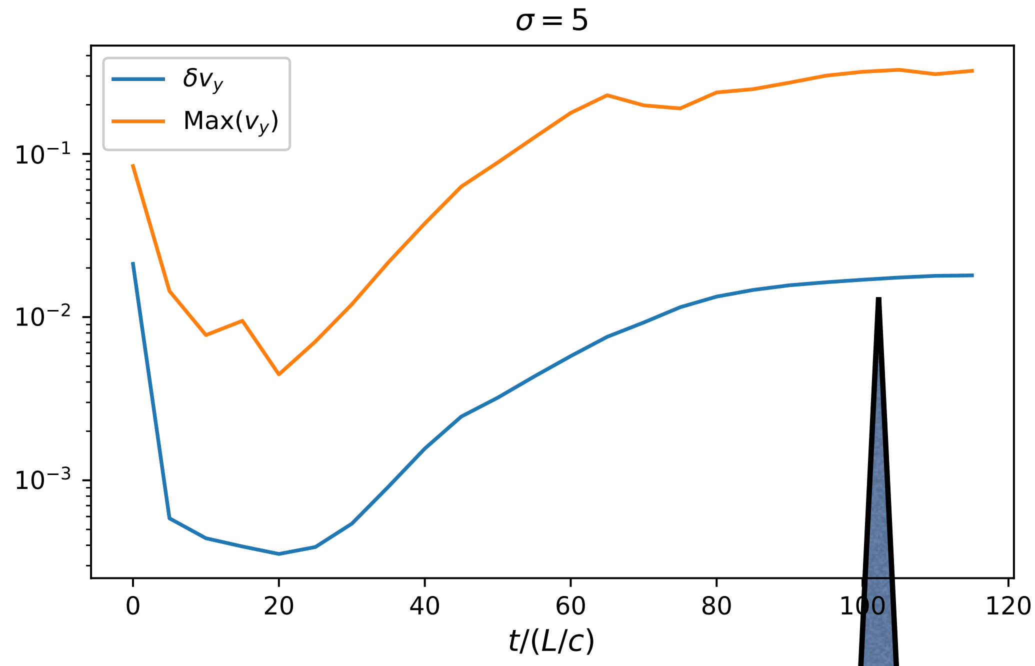


3D simulation



8. Temporal Evolution of Velocity Dispersion





exp[-|vy|/0.0217c]

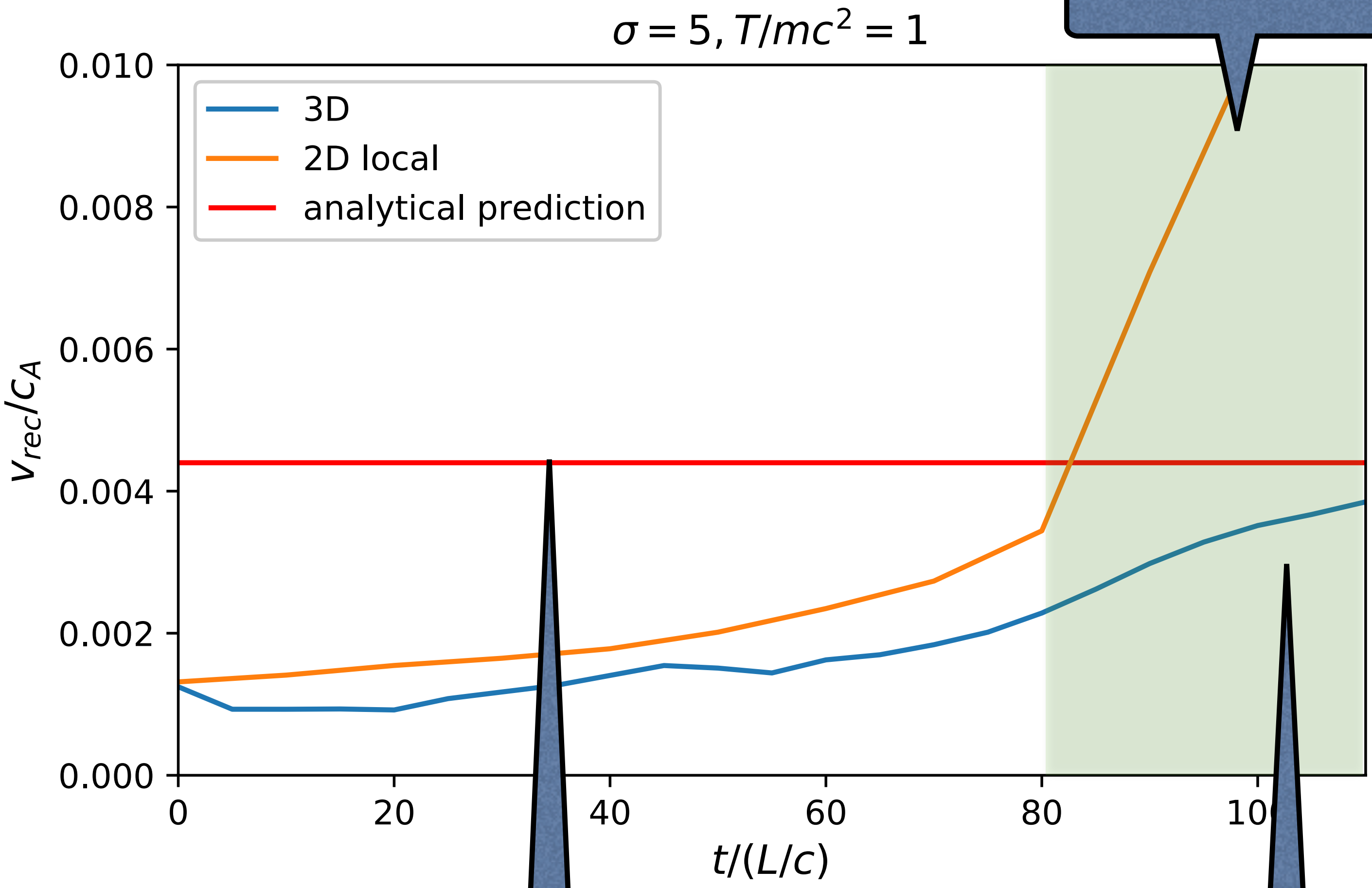
indicating a saturation around

$\delta v_y \sim 0.02c$?

$\Longleftrightarrow \varepsilon_{turb}/\varepsilon_B \sim 1.2\times10^{-4}$

9. Reconnection Rate

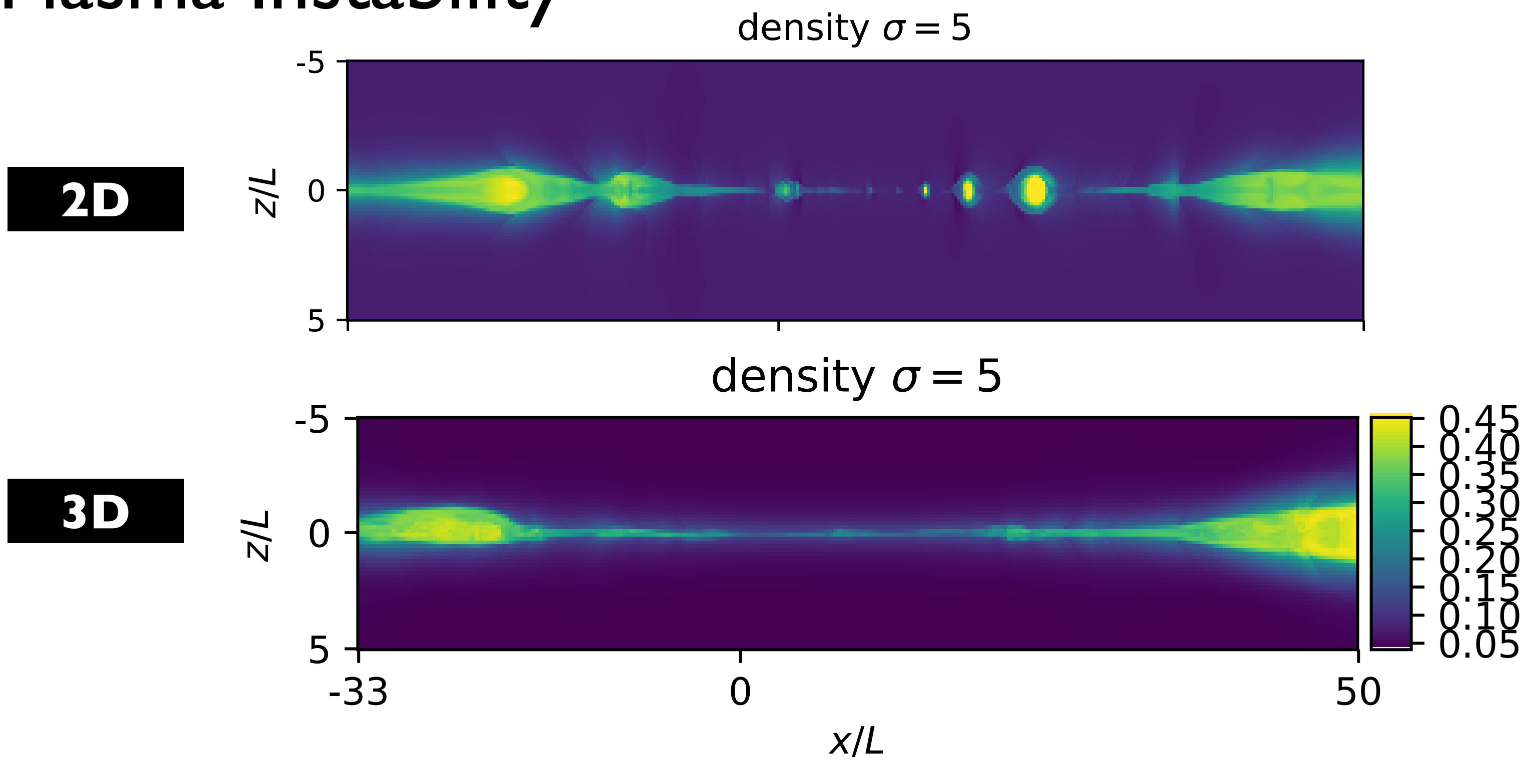
plasmoid-chain



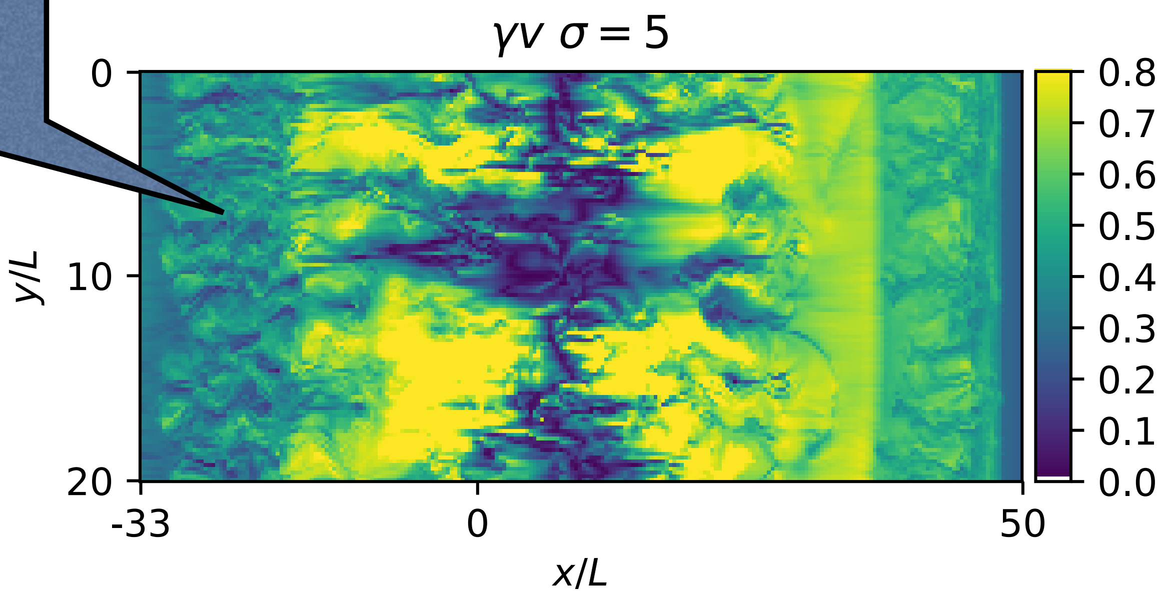
approximately reconnection rate can be described by TIL2015

3D turbulence reduces rec. rate

10. Plasma Instability



RT finger

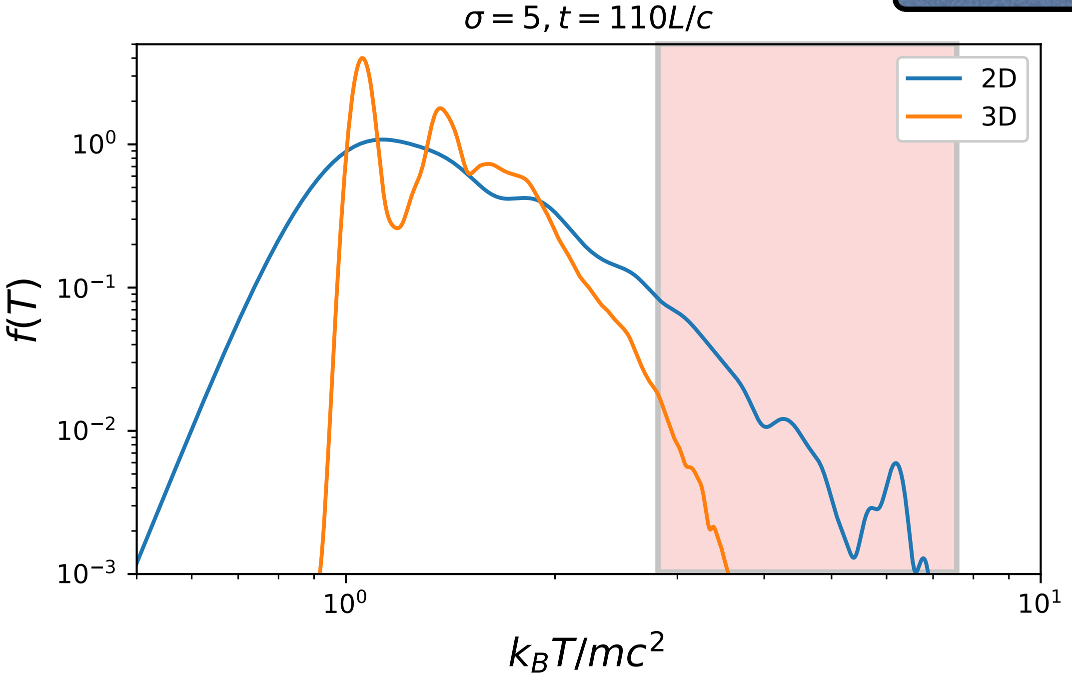


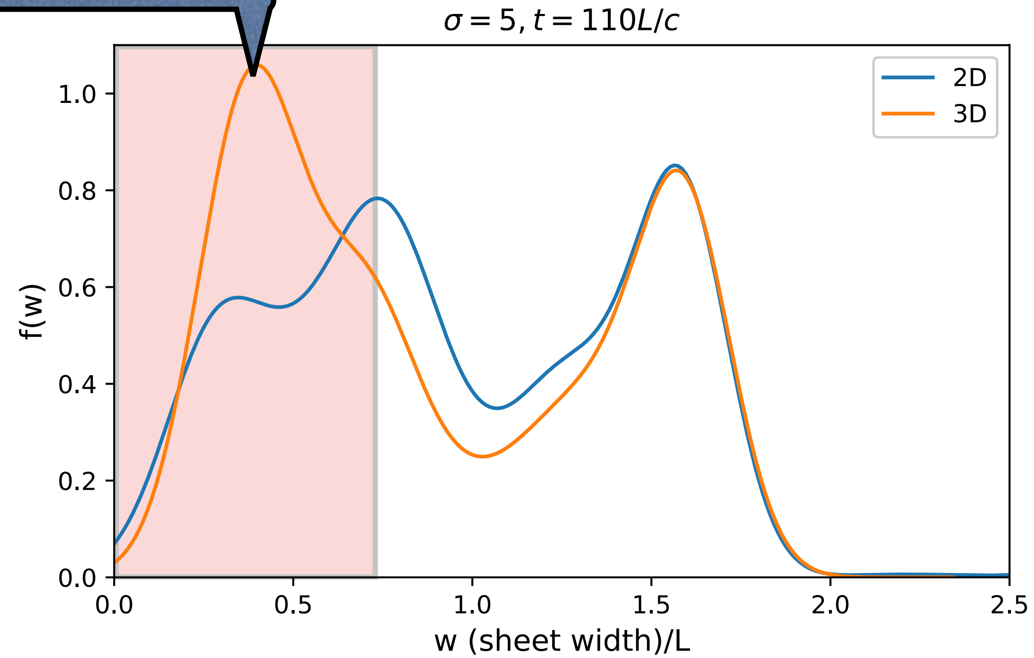
11. Temperature Distribution

Temperature distribution

turbulent sheet width?

sheet width distribution





アテルイを使っていての感想

- 計算のデータ量が増えた事でI/Oに時間がかかるようになってきた？
  ＝＞８時間ではI/Oに圧迫されて効率が悪い
  (２４時間くらいが適当？)

- たまに出力データに欠損が生じる？

- 4000コアを超えると急激にjobが走らなくなり、計算がどこまで実行出来るかについて予測が立てられない
  ＝＞XC-Aについてはノード時間で募集を行い、
  計算時間を確保出来るようにするべき？

Summary

- We investigated turbulence resulted from relativistic reconnection in Poynting-dominated plasma

- We found that the resulting turbulence is very weak: ~ 0.02c, inducing turbulent reconnection : $v_R/c_A \sim 0.004$

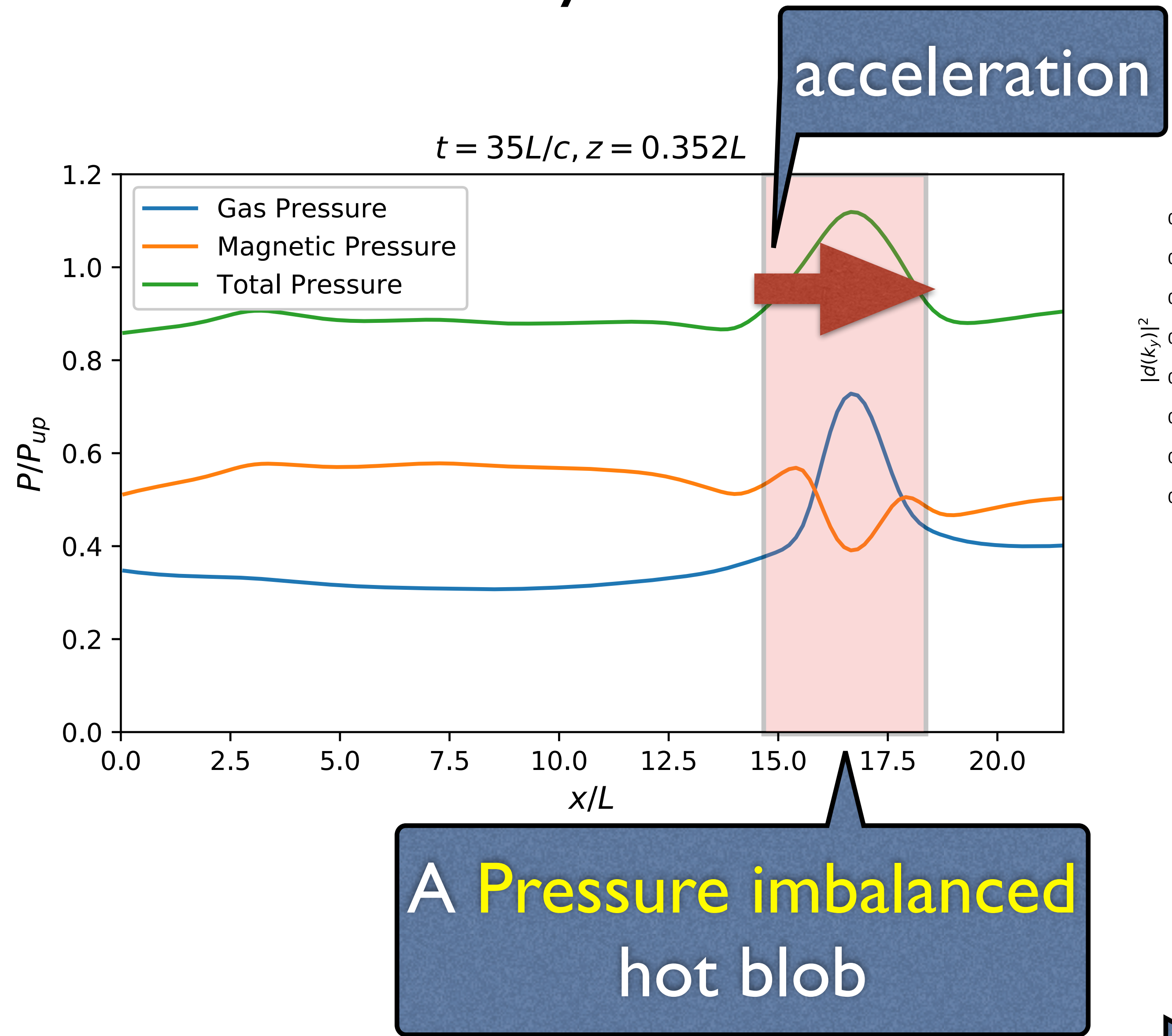
- turbulence prohibits appearance of plasmoid-chain, but the reconnection rate can be explained by analytical theory by TIL2015.

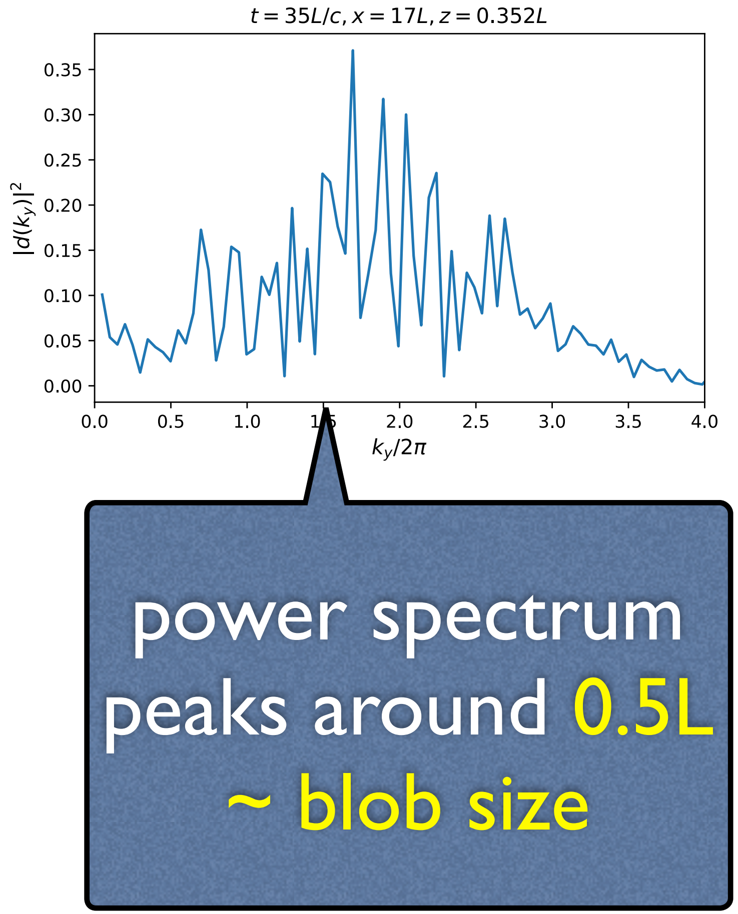
- origin of turbulence seems RT-type instability, but it still remains unclear.

- Turbulent sheet is less active than Plasmoid-chain.

O Ma Ke

11. Plasma Instability—2



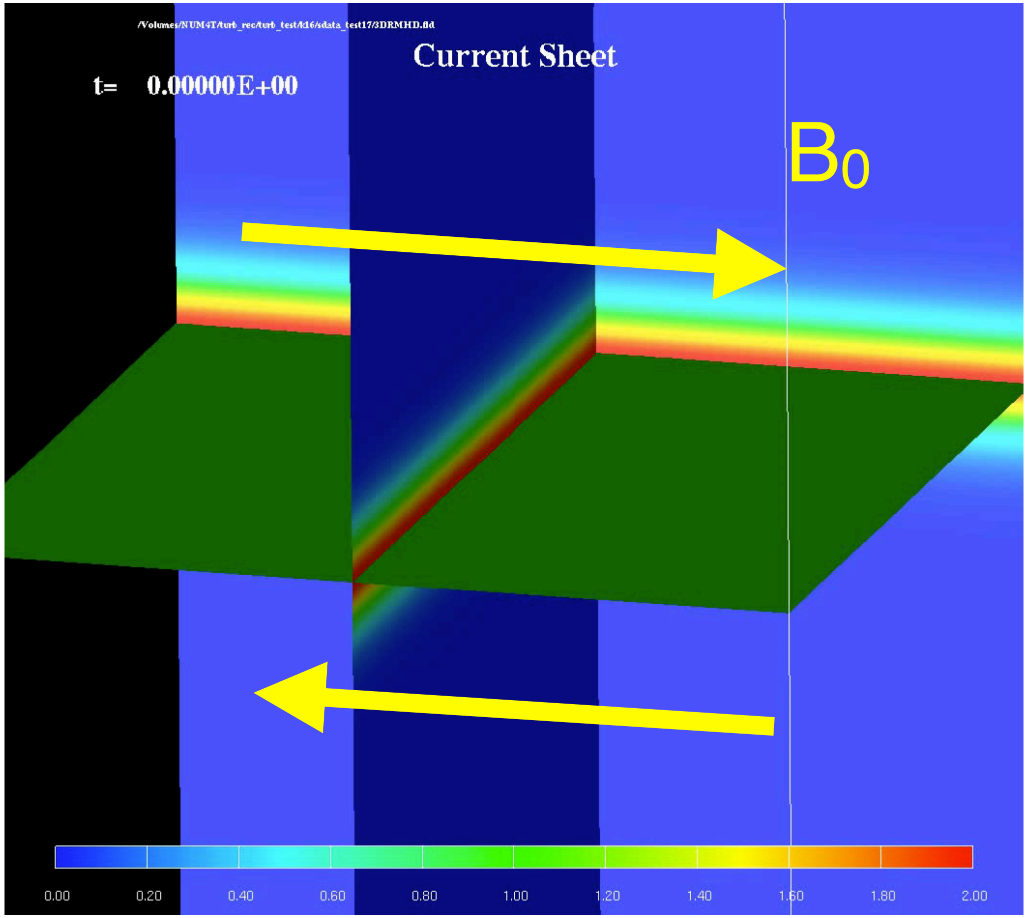


$$v_{RT} \sim \delta v_{\mathrm{y,turb}}$$

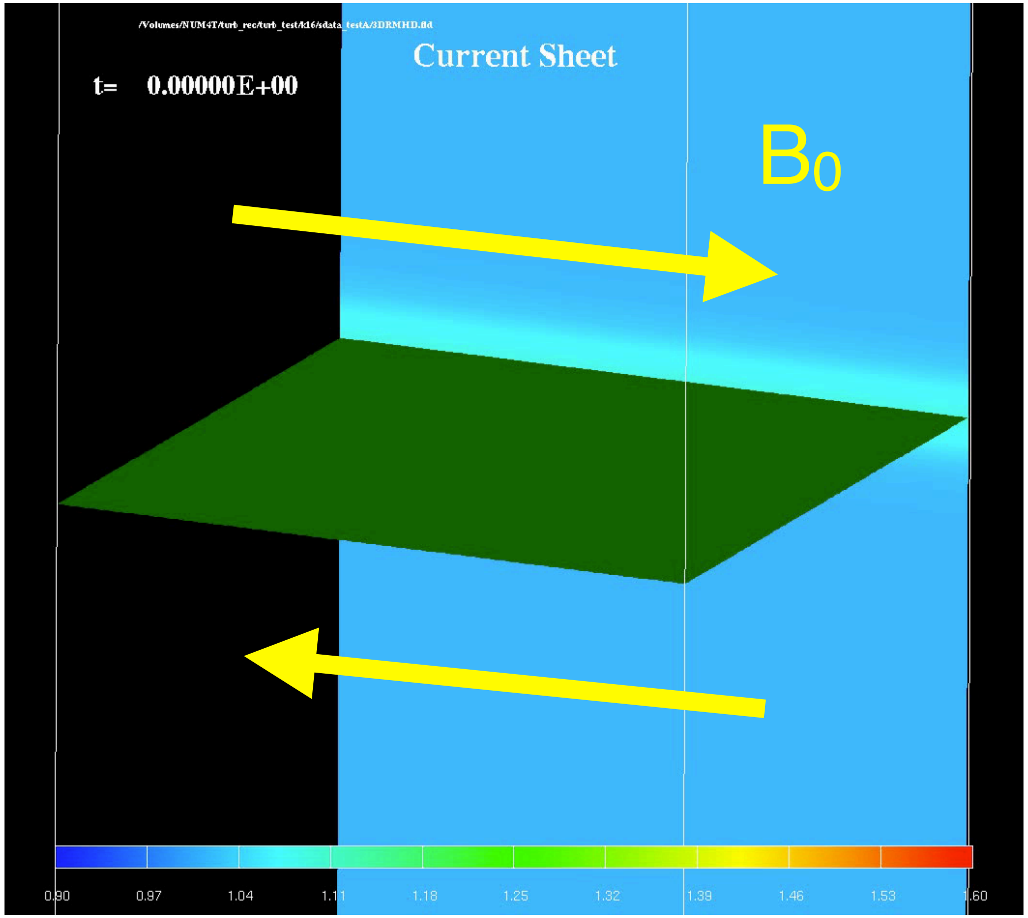
4. Relativistic Turbulent Reconnection

ref) Takamoto+ (2015), ApJ, 815, 16.

Poynting Dominated(σ = 5)



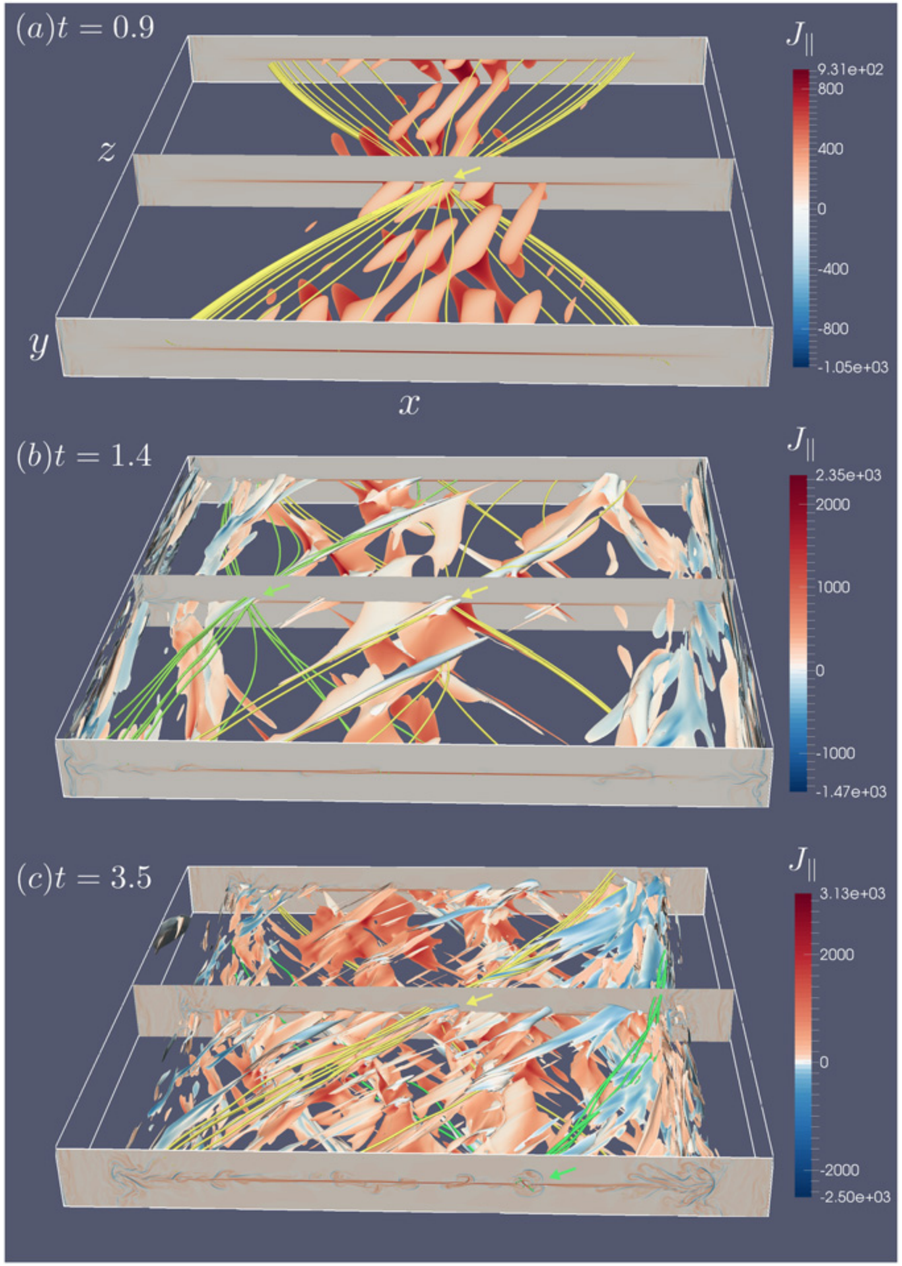
Matter dominated(σ =0.04)

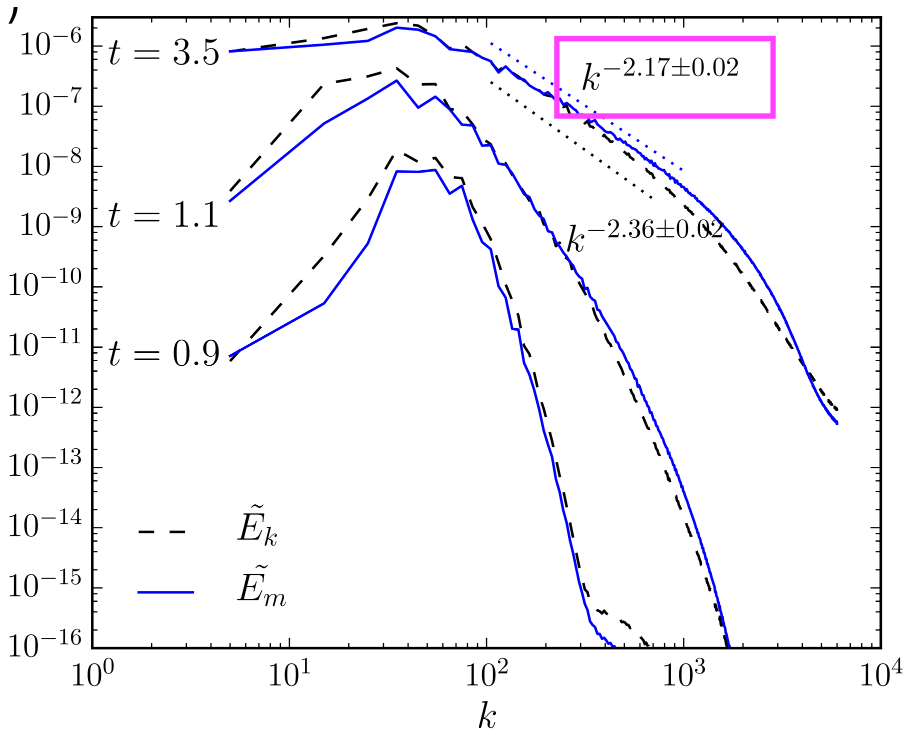


- $k_B T/mc^2 = 1$
- **driven** turbulence
  injected around central region

3.8. Self-Generated Turbulence in Sheets?

ref) Huang & Bhattacharjee (2016), ApJ 818





different turbulent law
caused by
different injection mechanism
and non-trivial background?

2.3. Relativistic Effects on Reconnection

ref) Lyutikov&Uzdensky 2003, ApJ 589, 893
Lyubarsky, (2005), ApJ, 358, 113.
Zenitani etal, (2009), ApJ 696, 1385.

density= $\rho_0\ \gamma$
transfer more matter
elocity

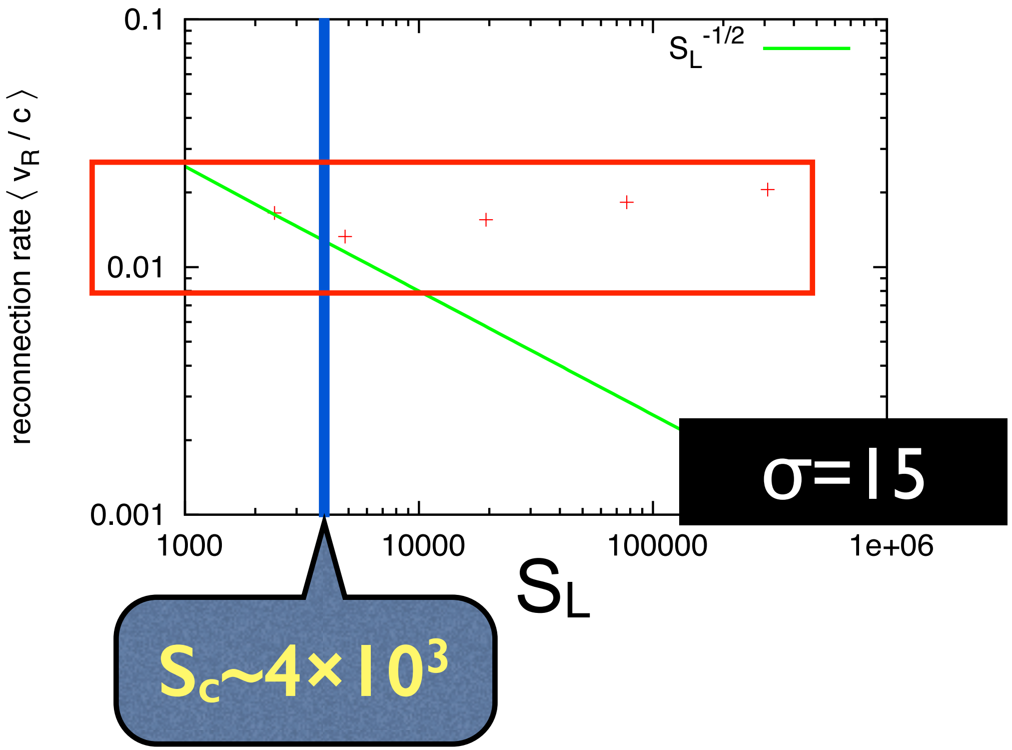
Maximum SP Rate

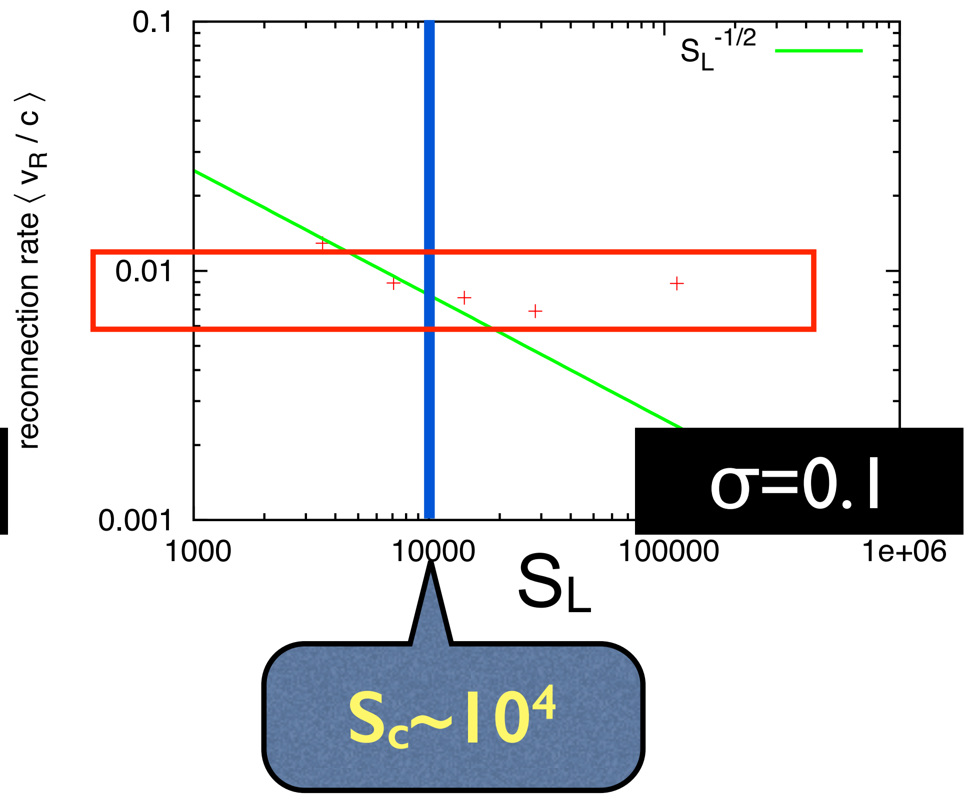
$$\frac{\gamma_{\rm in} v_{\rm in}}{\gamma_{\rm A} c_{\rm A}} \simeq \sqrt{\frac{2}{S_{\rm L}}} \left(\frac{\sqrt{c_{\rm A}}}{\gamma_{\rm A}} \right) \boxed{\gamma_{\rm out} \sqrt{v_{\rm out}}}$$

$k_B T/mc^2 > 1, \gamma > 1$
= large inertia
strong beaming
=>decelerate…
thin sheet…

3.2. Lundquist Number Dependence

ref) M.Takamoto, 2013, ApJ, 775, 50.





Reconnection Rate becomes
independent of Lundquist number S_L

when S_L > $S_{L,C}$: critical value
at which Plasmoid instability occurs

2.1. Relativistic Magnetohydrodynamics

Basic equations of RMHD:

$$\left\{\begin{aligned}
&\partial_t(\rho\boxed{\gamma}) + \partial_i(\rho\boxed{\gamma}v^i) = 0,\\
&\partial_t(\rho\boxed{h_{tot}\gamma^2}v^j - \boxed{b^0 b^j}) + \partial_i(\rho\boxed{h_{tot}\gamma^2}v^i v^j + p_{tot}\delta^{ij} - b^i b^j) = 0,\\
&\partial_t(\rho\boxed{h_{tot}\gamma^2} - p_{tot} - \boxed{(b^0)^2}) + \partial_i(\rho\boxed{h_{tot}\gamma^2}v^i - \boxed{b^0 b^i}) = 0,\\
&\partial_t B^j + \partial_i(v^i B^j - B^i v^j) = 0, \quad \partial_i B^i = 0.\\
&\qquad h_{tot} = 1 + \epsilon + \boxed{\frac{b^2}{\rho}}, \quad p_{tot} = p_{gas} + \frac{b^2}{2}
\end{aligned}\right.$$

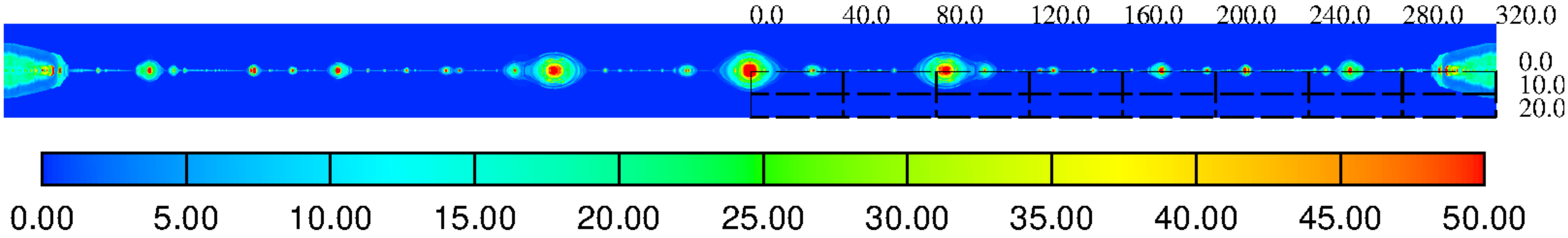
<u>features:</u>

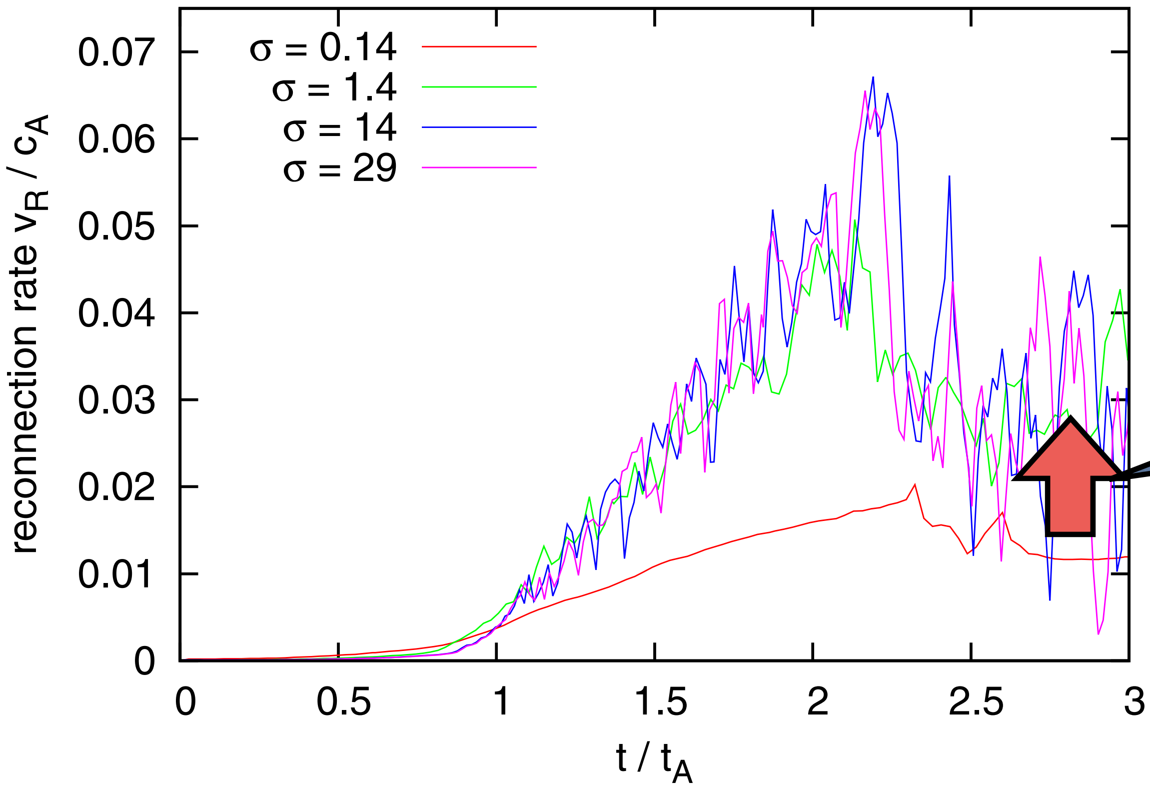
- correction from Lorentz factor and inertia of energy
- tension and pressure from magnetic field

2.4. Relativistic Plasmoid-Chain

ref) Takamoto, (2013), ApJ 775, 50.

p_{gas}, σ=20





reconnection rate increase with σ

3.4. Turbulence-Strength Dependence