高レイノルズ数磁気リコネクション シミュレーション

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Outline

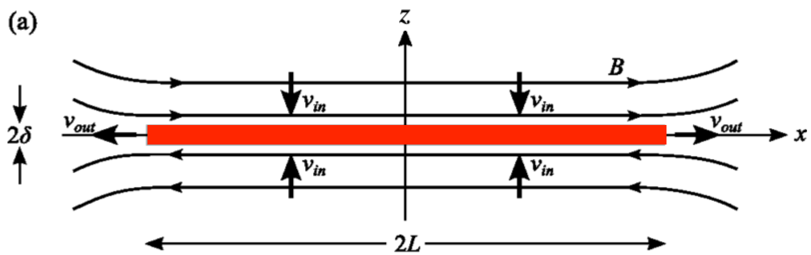
- Introduction
  - Classical steady models
  - Single X-point and Multi X-point reconnection
- 2D-MHD simulation of large system with uniform resistivity
  - Appearance of Petschek-type shocks
- 3D-MHD simulation of turbulent magnetic reconnection
  - Growth of oblique tearing mode
  - Interaction of 3D plasmoid structure
  - Structure of diffusion region

Steady state reconnection models

Figures from Comisso et al. 2014
See Kulsrud 2001

Sweet-Parker model

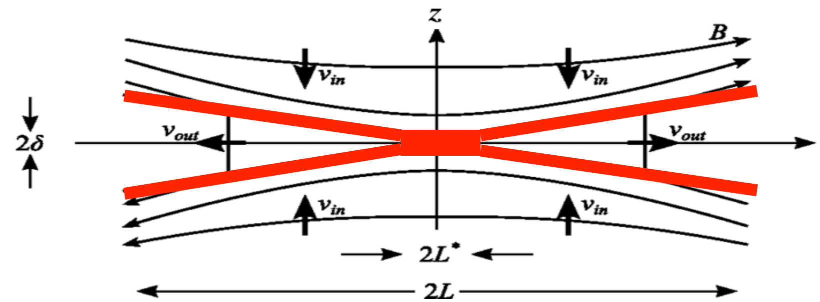
(Sweet 1958, Parker 1957)



Slow in coronal plasma $S = \frac{\mu L V_A}{\eta}$

Petschek model

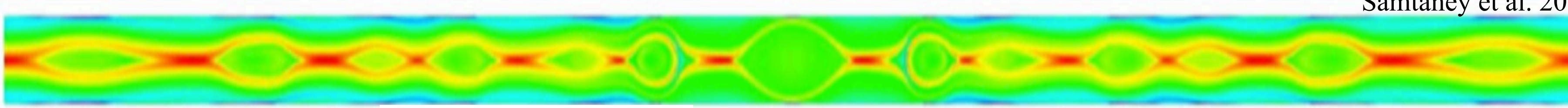
(Petschek 1964)

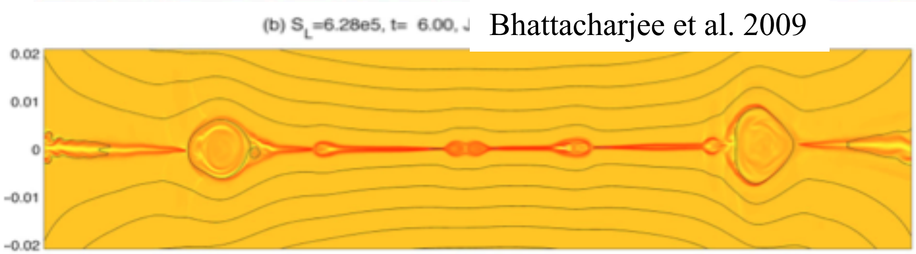


Impossible in uniform resistivity

Non-steady Sweet-Parker reconnection model

Samtaney et al. 2009

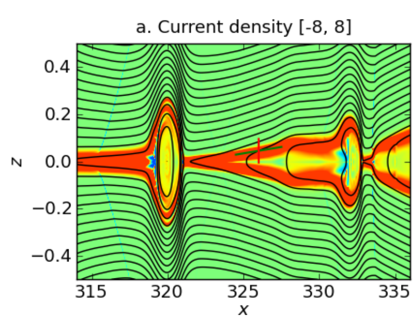




Bhattacharjee et al. 2009

Realize fast reconnection with diffusion regions between plasmoids. They have shorter length and smaller local Lundquist number S.

Non-steady Petschek reconnection

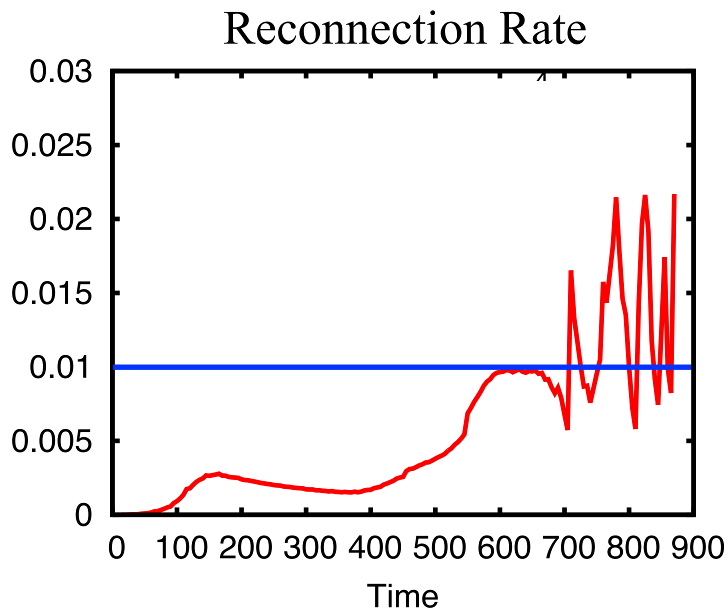


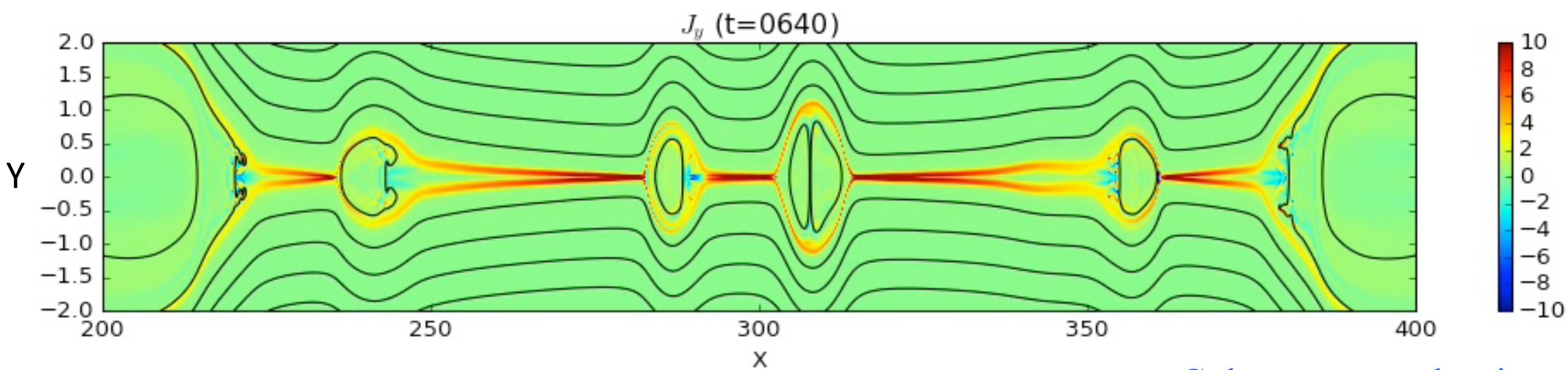
Petschek-type diffusion region forms even with uniform resistivity in higher S.

Shibayama et al. 2015

S-P → Plasmoid → Current bifurcation

- Reconnection rate goes up ~ 0.01
- Resistive 2D MHD with uniform resistivity
- Harris current sheet without forcing
- Lundquist number using current sheet length is $S \sim 10^6$



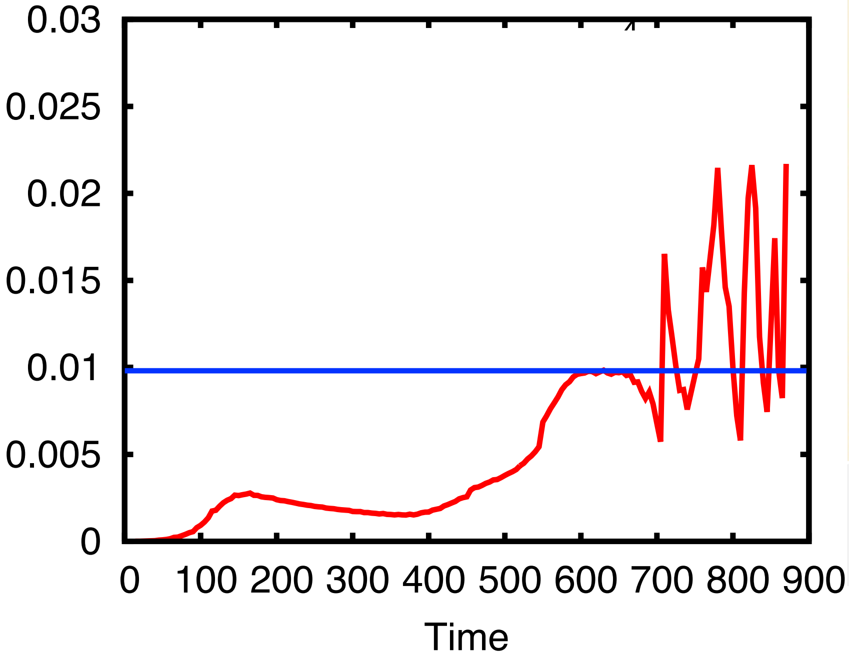


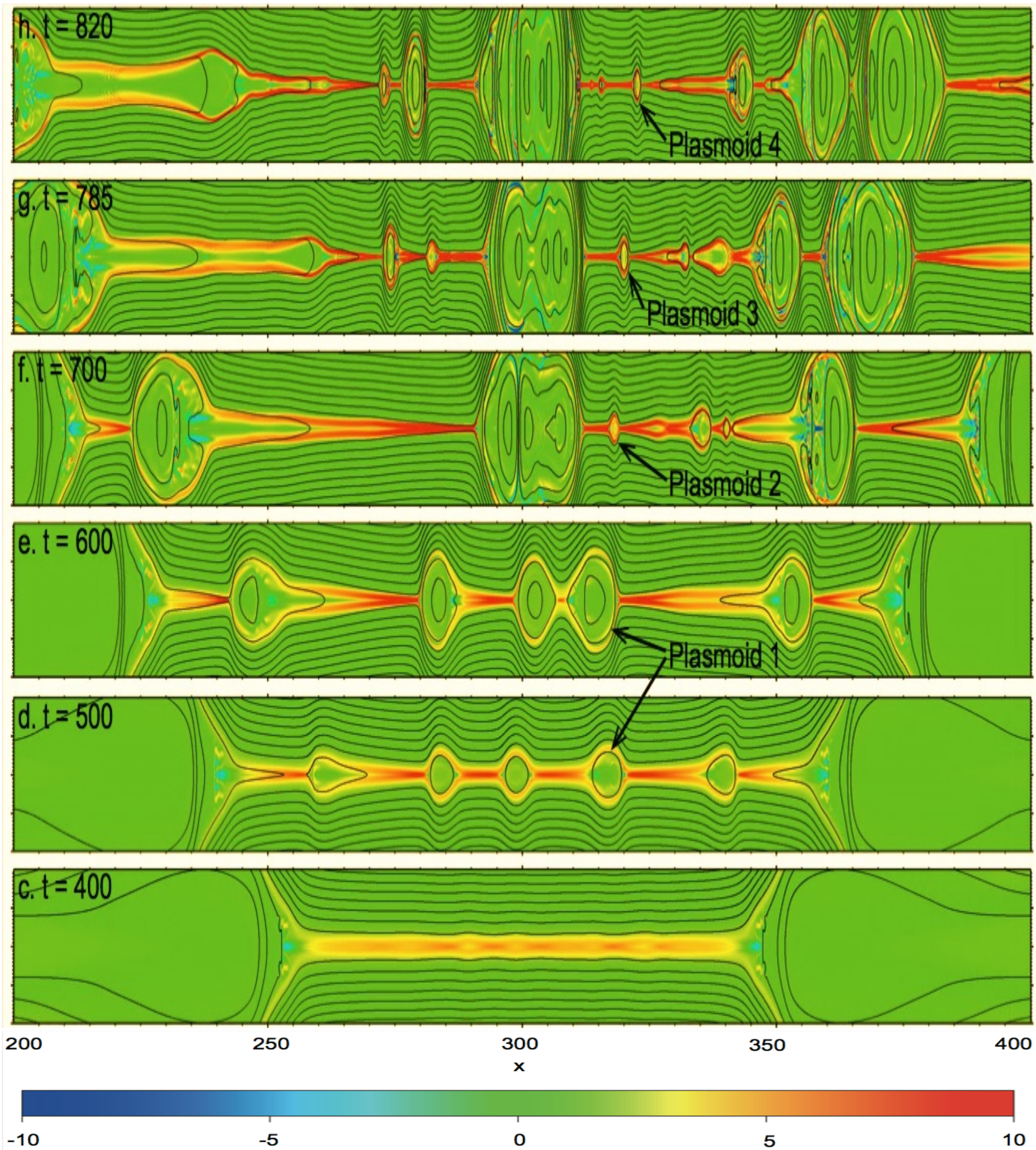
Color : current density

Repeated formation of bifurcated current

Reconnection is enhanced by plasmoid formation and bifurcated current structure.

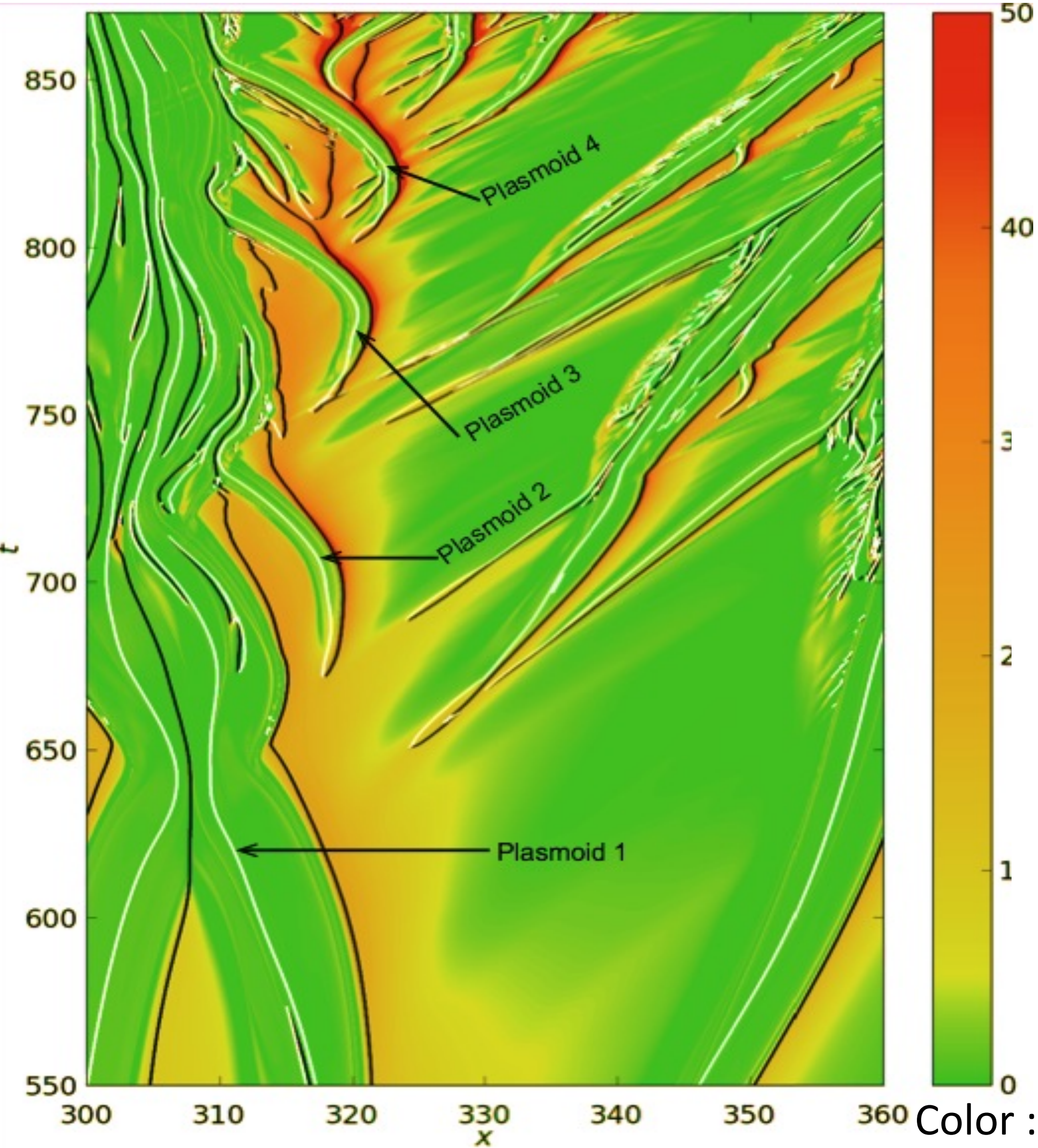
Reconnection rate





Color : current density

Variation of Reconnection rate



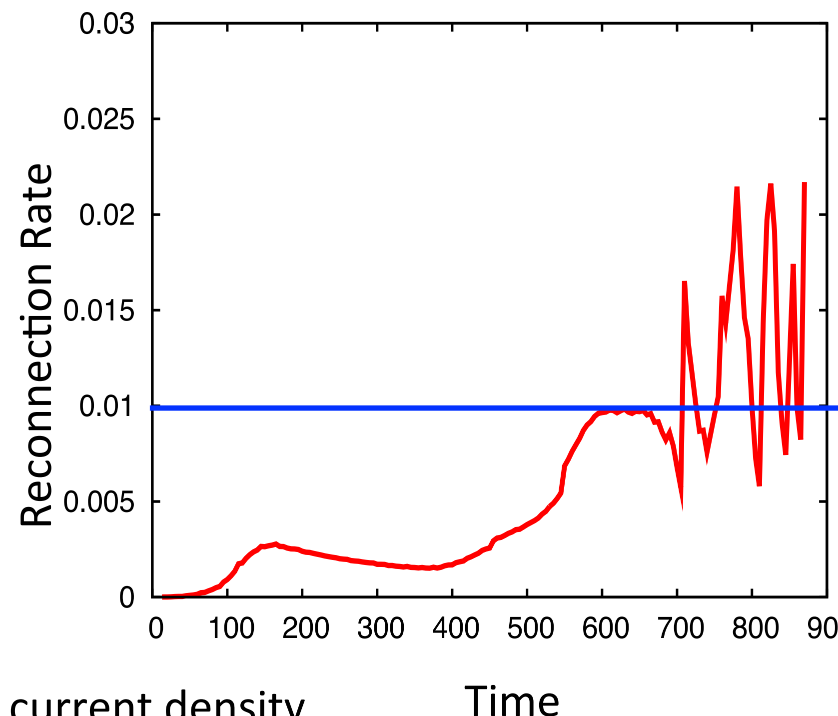
Color : current density

Out flow pushes plasmoid

-> Plasmoid is ejected

-> Current sheet elongation

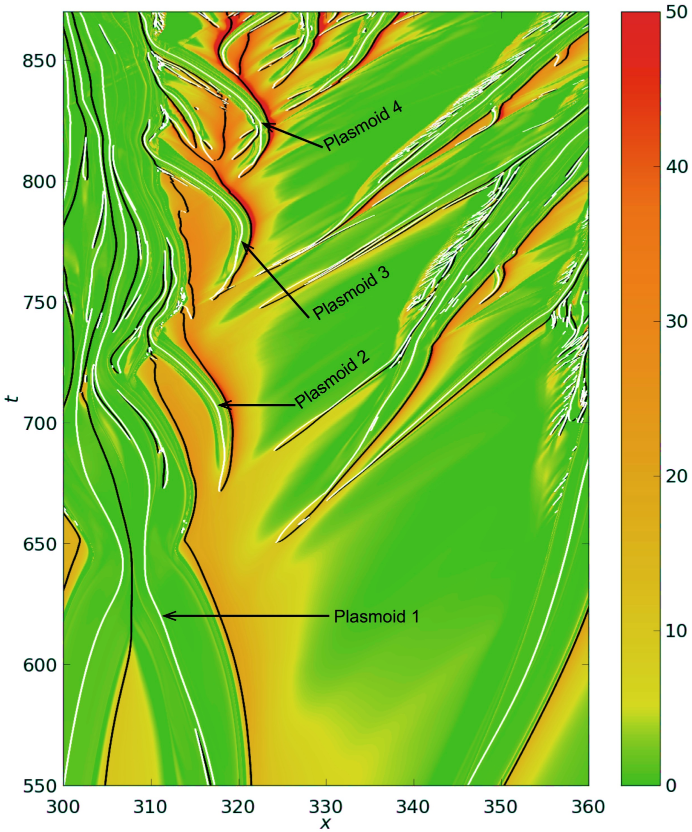
-> MR slows down



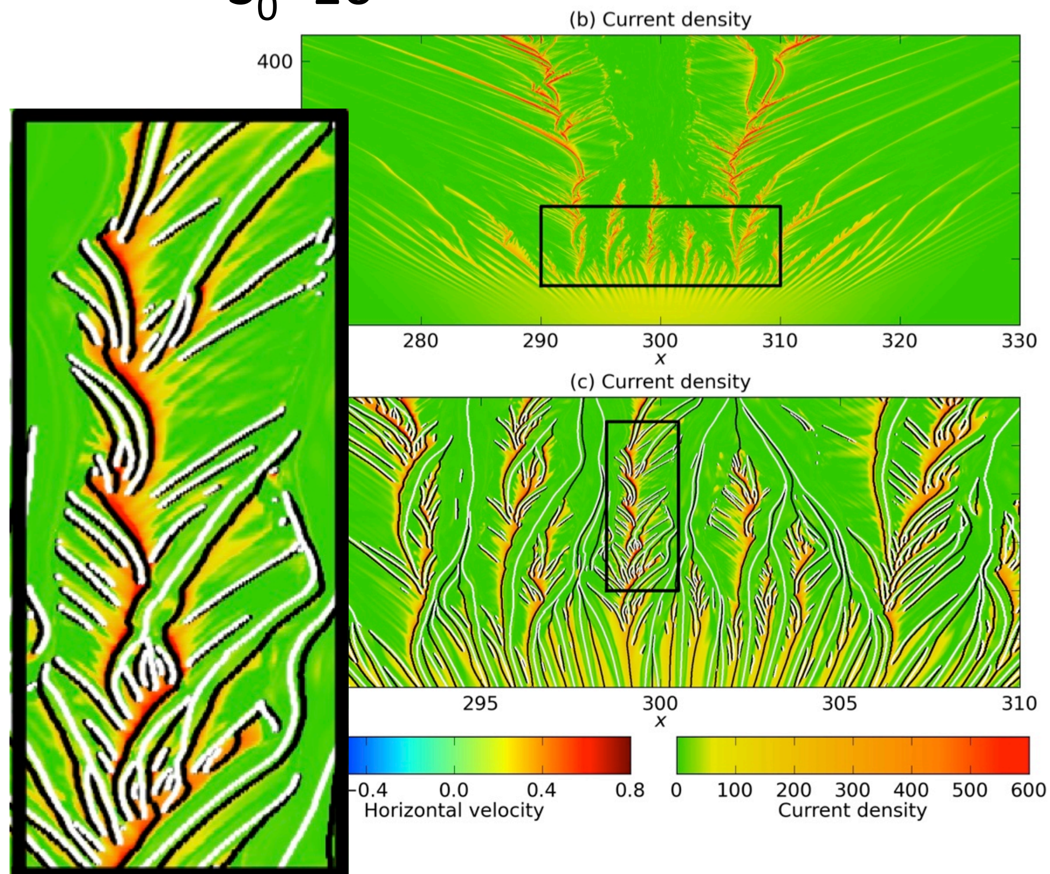
Similarity in Small-scale

Similar plasmoid motion and current concentration also occur in $S=10^6$. This may explain the weak dependence of reconnection rate on Lundquist number

$S_0=10^4$

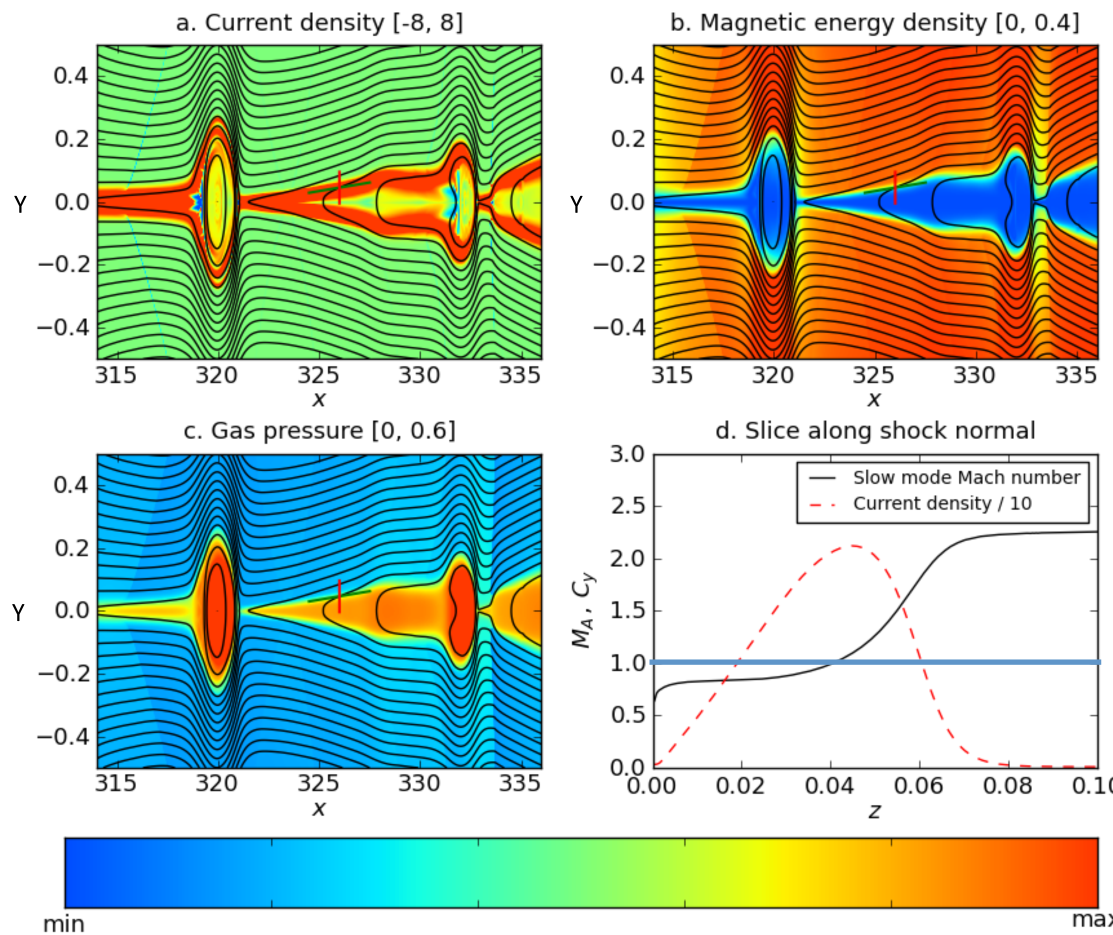


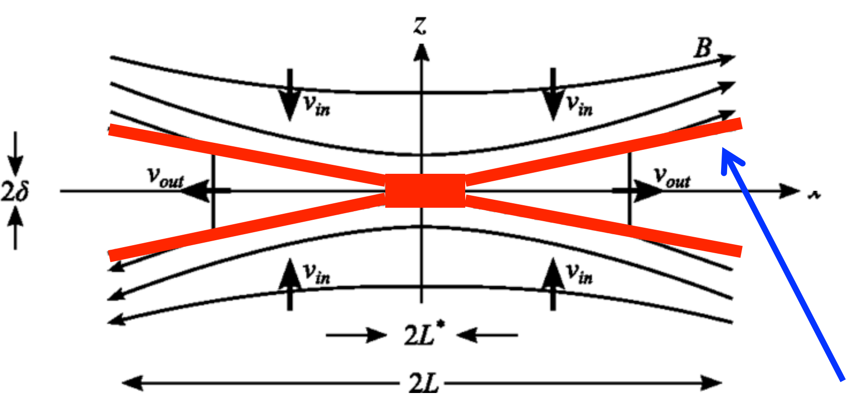
$S_0=10^6$



Petschek type diffusion region with uniform resistivity

- Bifurcated current structure is identified as a pair of slow mode shocks.
- This suggests non linear evolution of plasmoids can help localization of diffusion region.





Petschek model

Slow mode MHD shock

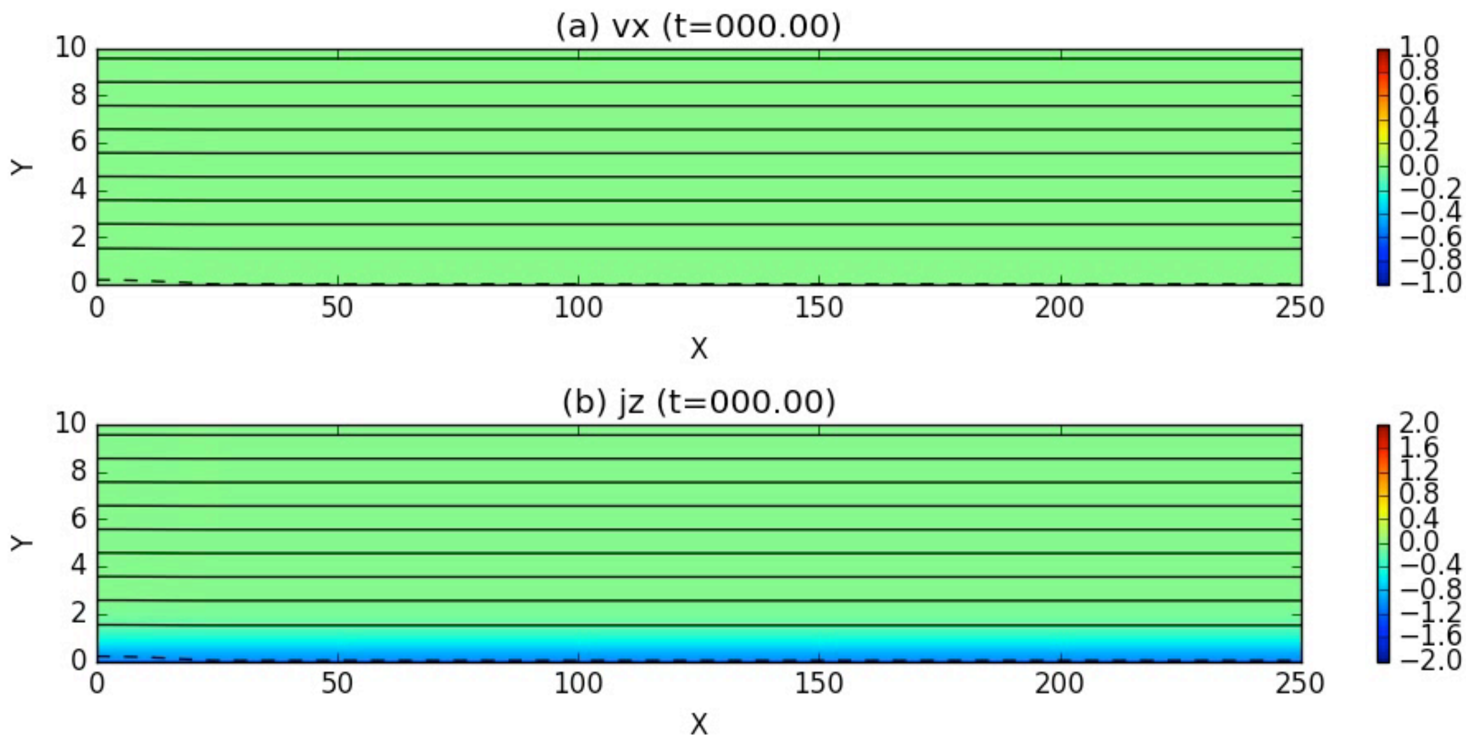
Petschek-type forms spontaneously even with uniform resistivity.

→Dynamical Petschek Reconnection

What is the mechanism to form Petschek-type?

Isolated plasmoid is the simplest model of Petschek-type.

(cf. Murphy et al. 2010)



- X-point is initially put at x = 20.
- Left reflecting boundary fixes a plasmoid.
- Right and top boundaries are far.

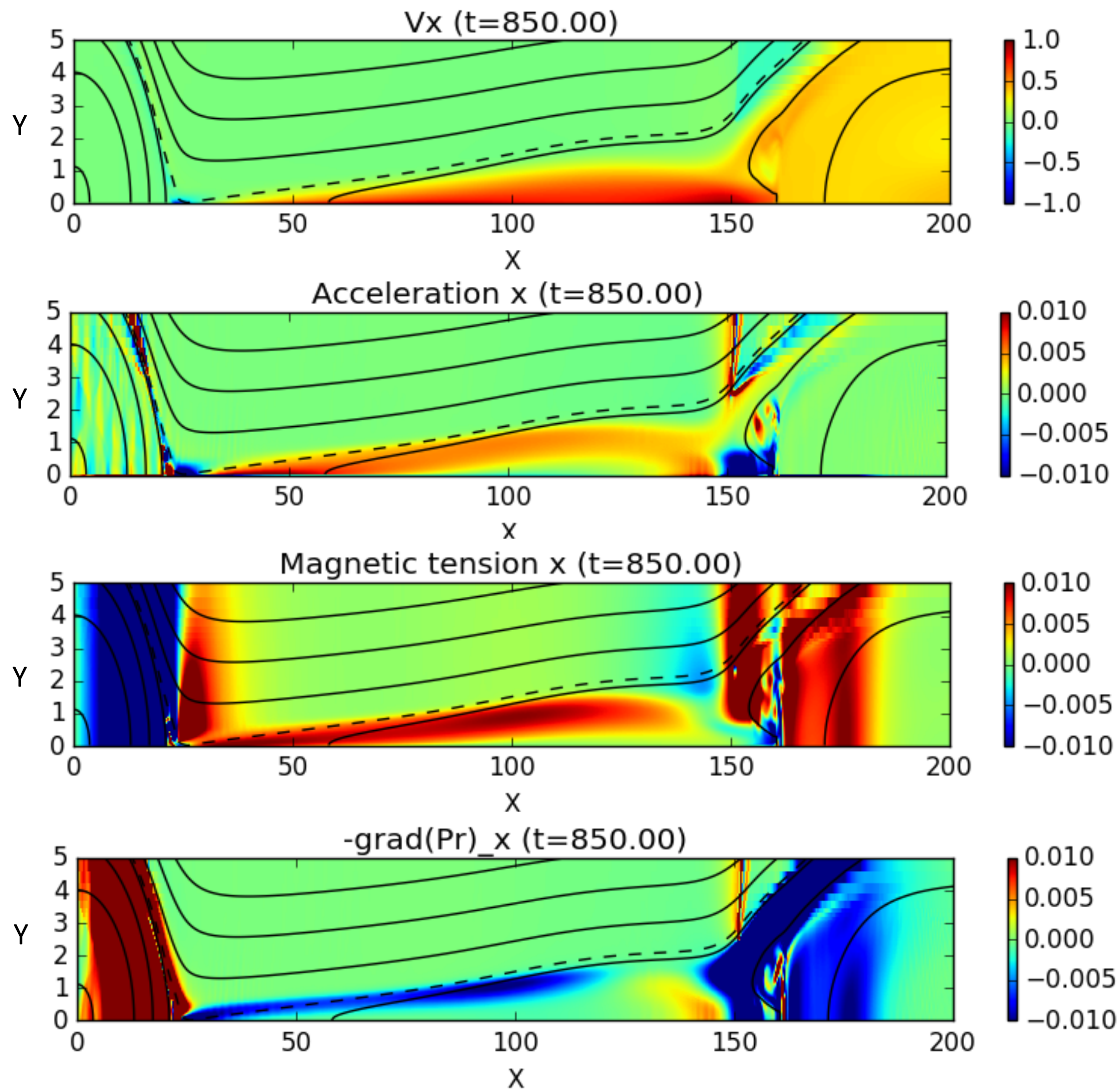
Out flow is accelerated by magnetic tension force

Vx

Acceleration x component

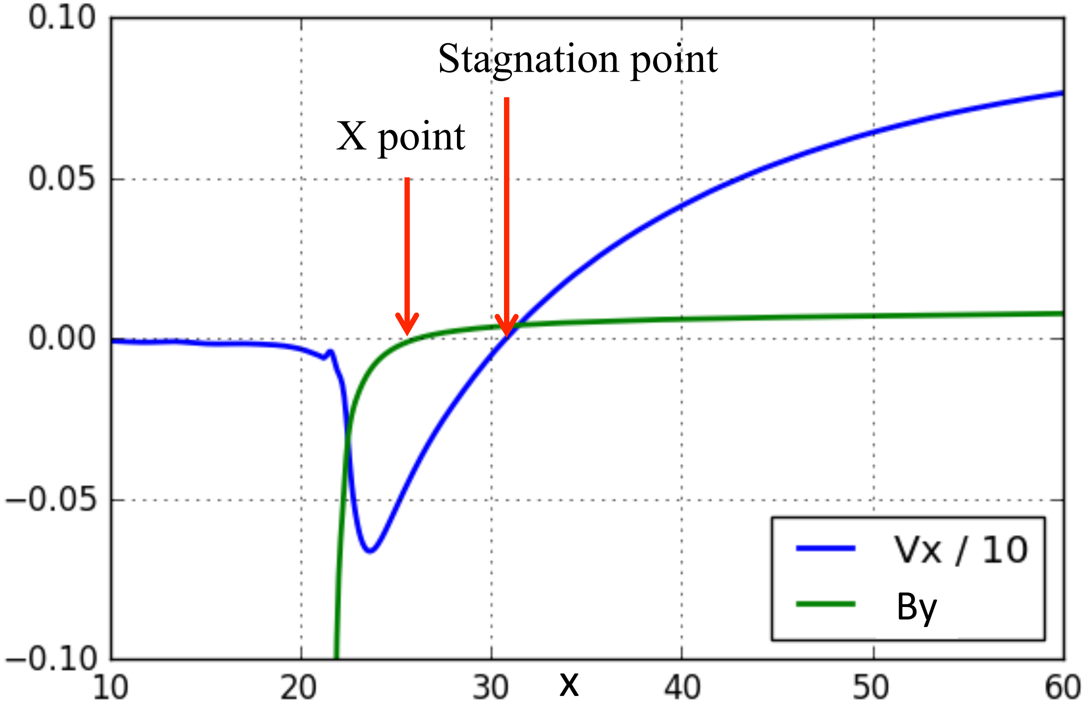
Lorentz force x component

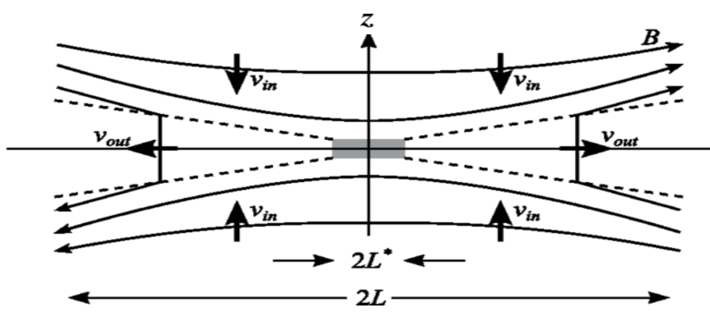
Pressure grad force x component



Acceleration to rightward is Petschek like, leftward is Sweet-Parker like

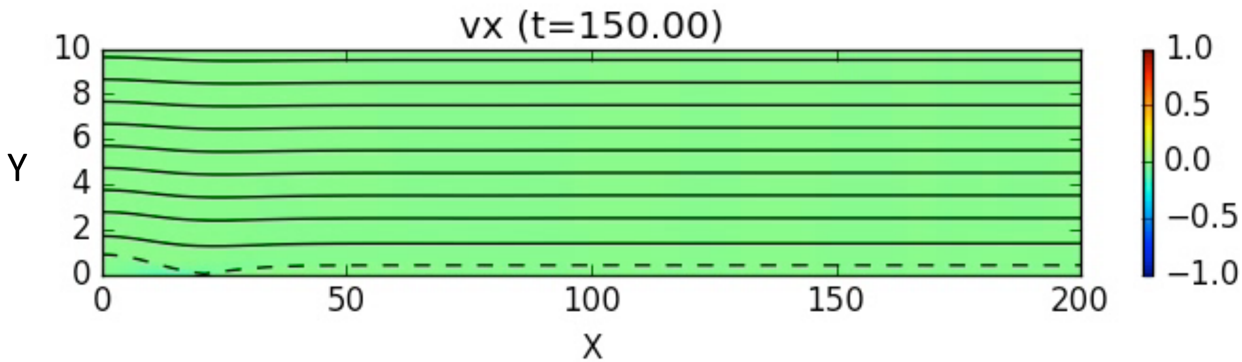
Why diffusion region is localized ?





Plasmoid breaks symmetry and X and stagnation point decouple.

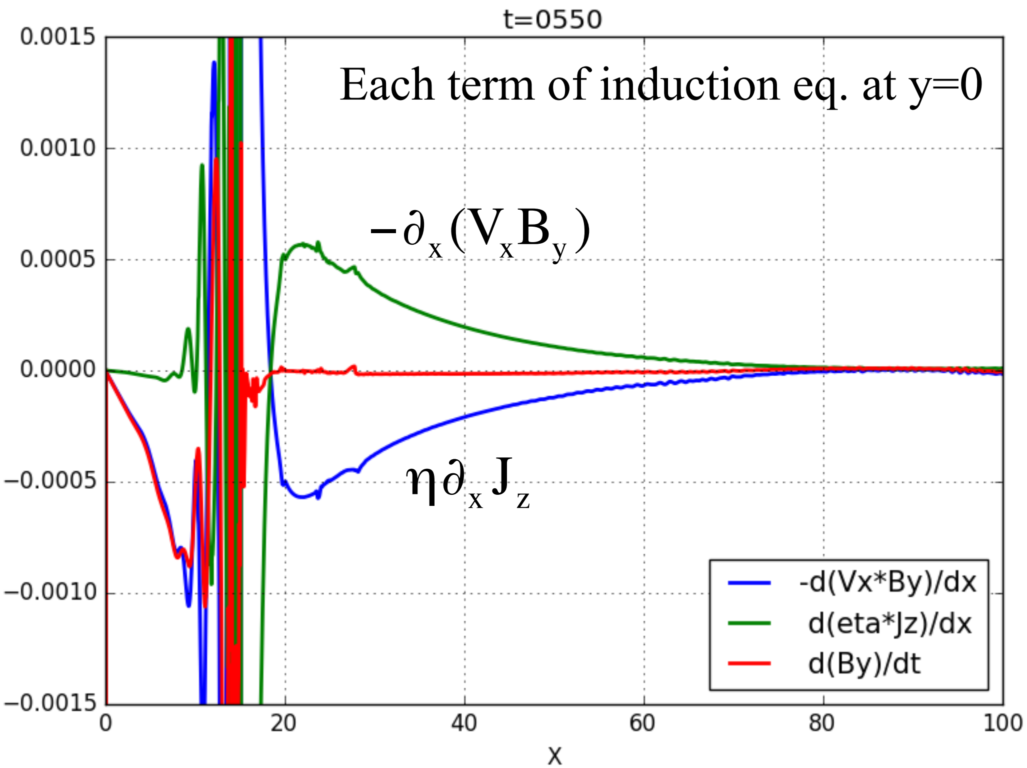
X point is in the down flow of $0.5V_A$

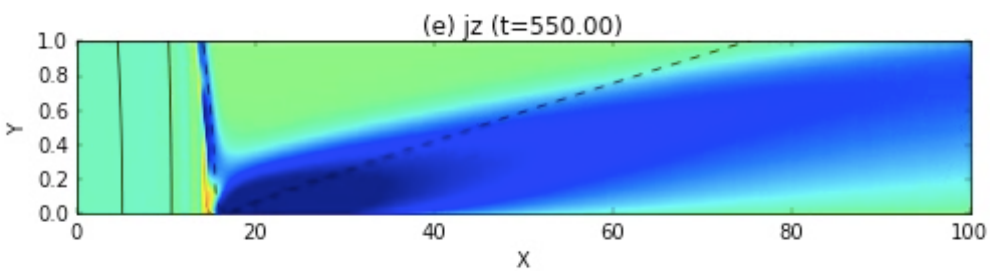


Velocity of X point

$$\frac{dx_{\mathrm{x}}}{dt} = V_x - \frac{\eta}{\partial_x B_y} \partial_y^2 B_y$$

Steady state is almost satisfied





Induction equation is almost in balance in the simulation.

$$\frac{\partial B_y}{\partial t} \cong -\partial_x(V_x B_y) + \eta\partial_x J_z \sim 0$$

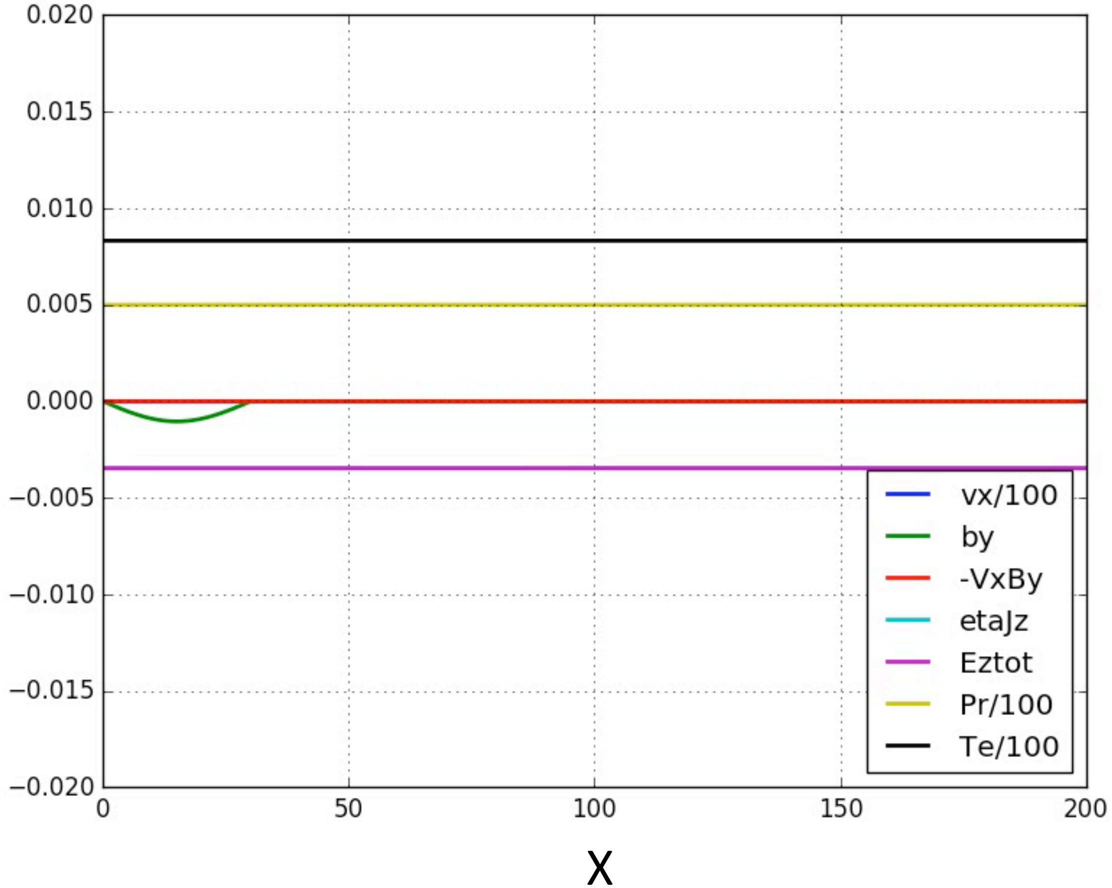
In Kulsrud2001, Petschek RX is impossible in steady state

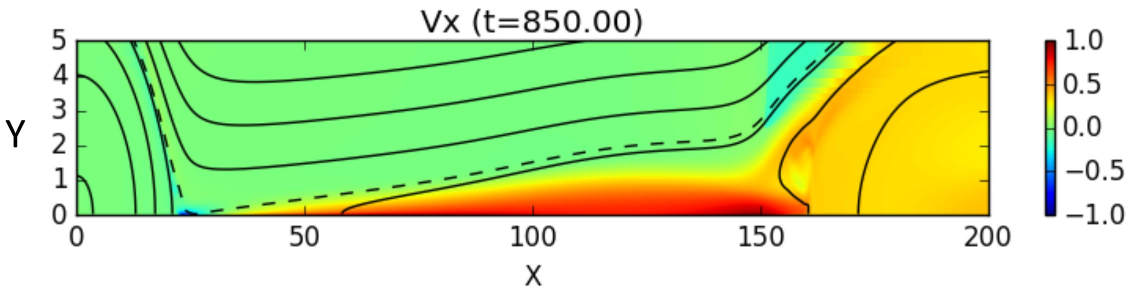
$$\frac{\partial B_y}{\partial t} \cong \partial_x(V_x B_y) + \eta\partial_x J_z$$

$$\sim -\frac{V_A}{L'}B_y + \frac{V_R}{L'}\frac{L'^2}{L^2}B_0$$

Profile of reconnecting Bx field is different from their assumption.

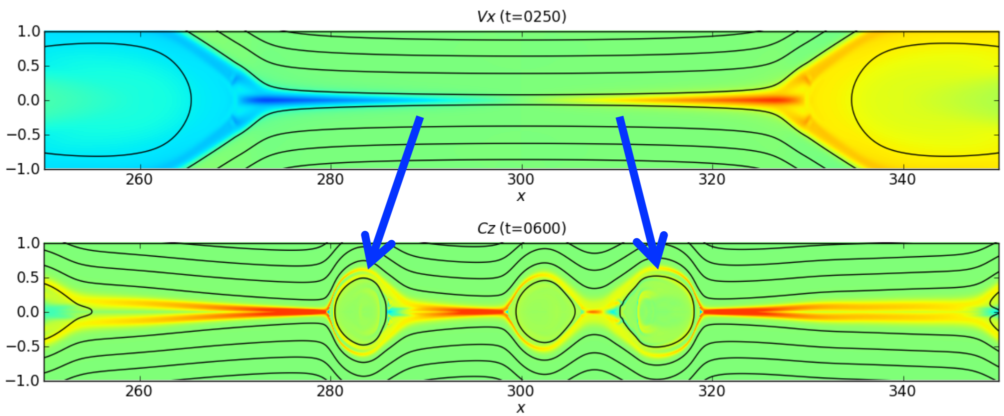
Self-similar-like expansion



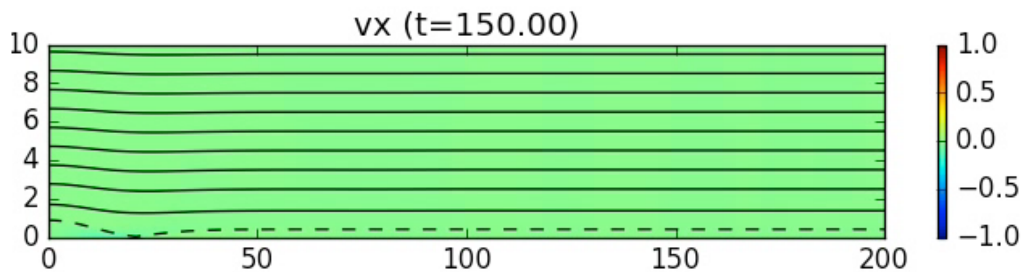


- Re-normalize length scale so that X point is fixed.
- Self-similar-like evolution is observed when Petschek-type structure is formed.
- Nitta2007 discusses similar self-similar solution of MHD.

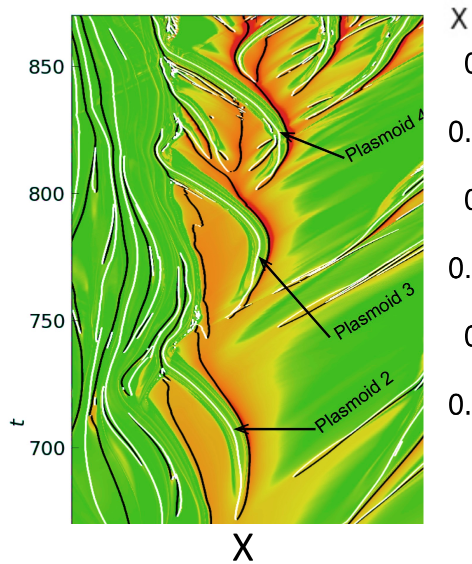
Our Scenario

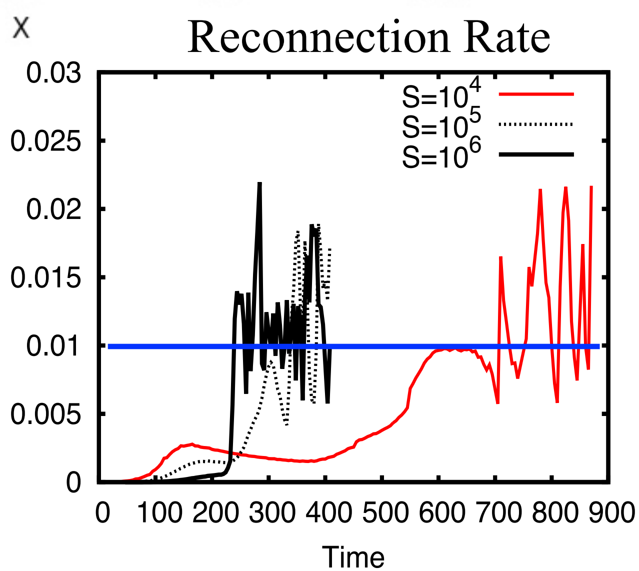


Secondary or tertiary plasmoid evolve in asymmetry of outflow.



Diffusion region goes to steady self similar solution of dynamic Petschek RX.





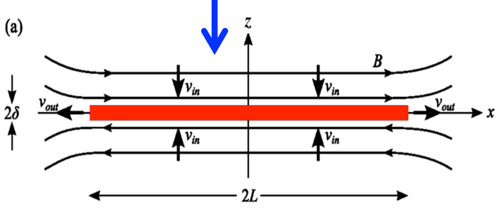
This process is repeated and fast reconnection goes on. Independent on Lundquist number S because of similarity in diffusion scale.

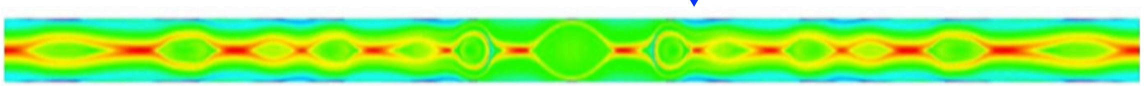
Summary of dynamical Petschek reconnection

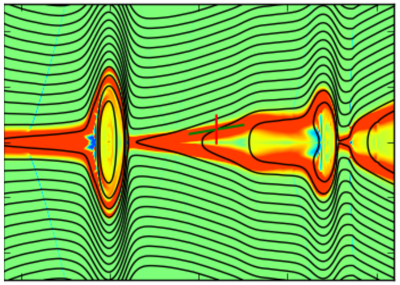
- Petschek-type reconnection spontaneously realizes in uniform resistivity.
- Isolated plasmoid break symmetry of diffusion region.
- Reconnection rate is determined by self-similar like Petschek solution not by Sweet-Parker model
- Dynamical Petschek reconnection is new reconnection regime in higher Lundquist number.

Sweet-Parker → Plasmoid MR → Dynamical Petschek

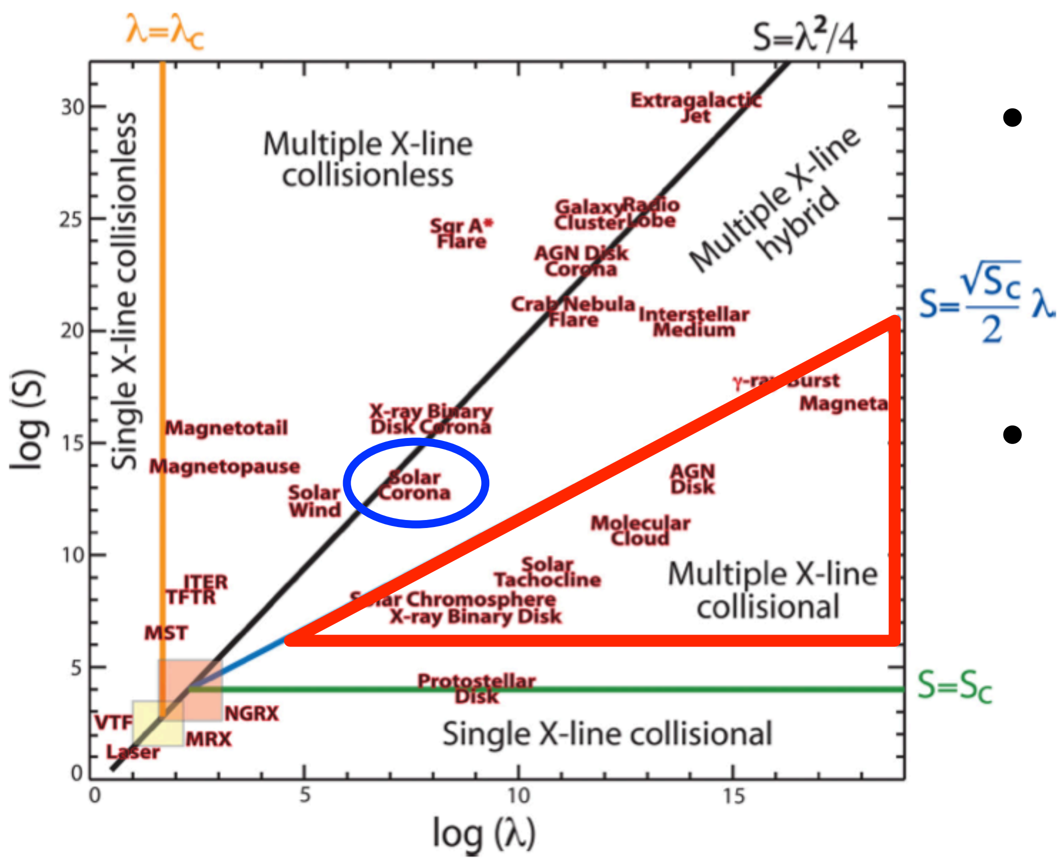
$S < 10^4$ $10^4 < S < 10^6$ $10^6 < S$







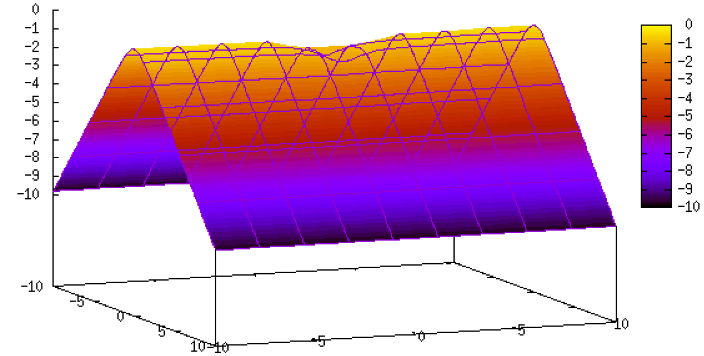
Dynamical Petschek Reconnection in the Phase diagram



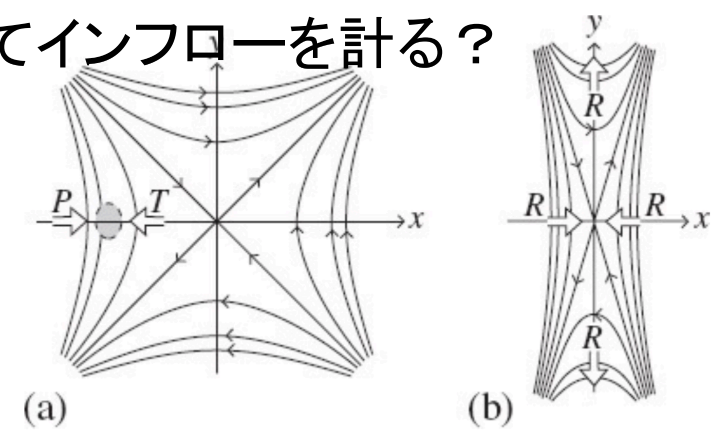
- Dynamical Petschek reconnection is in the red triangle (just speculation).
- Our mechanism cannot fully explain the fast reconnection in the solar corona.

Reconnection phase diagram (Ji & Daughton, 2011)

2DでのSwirl Tensorに関して



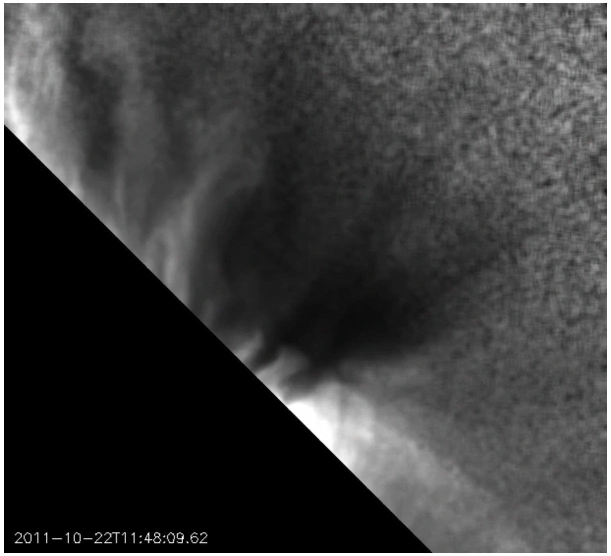
- ベクトルポテンシャル(Flux function)の形状解析が微分的にできる
- X点の検出
  - 2Dではベクトルポテンシャルの鞍点
- リコネクションの強さの指標になるか
  - 定常モデルでは90度で交わる磁力線はリコネクションしていない
  - X点での電場を見る
  - X点の“向き”(鞍点の谷方向)を判定してインフローを計る？



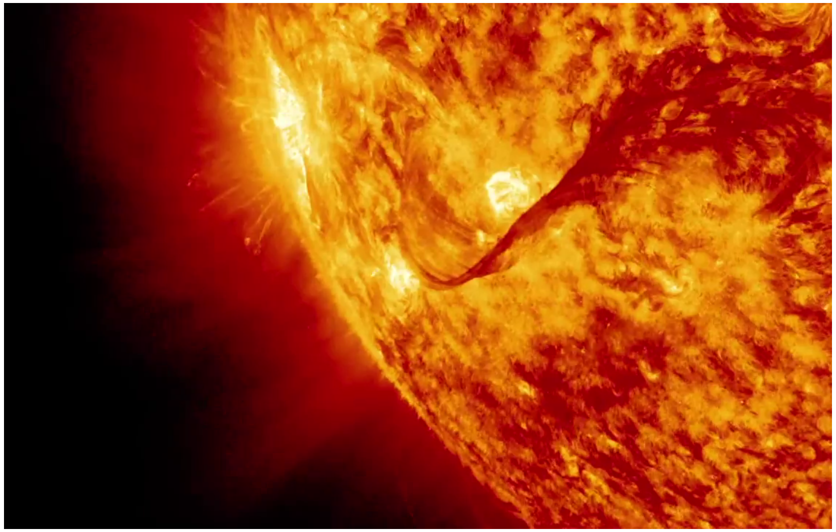
Priest, MHD of the Sun

フラックスロープはどうやってできるのか？

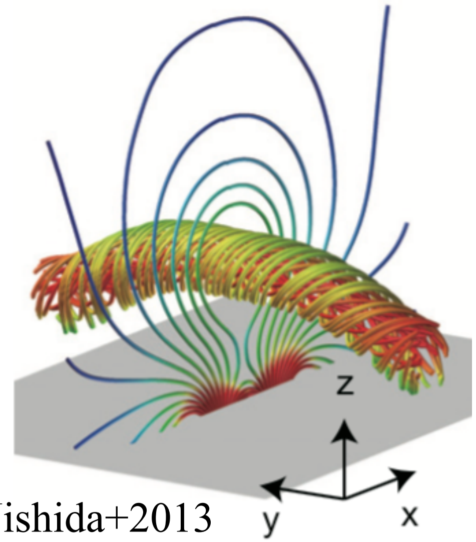
- フラックスロープ ≒ 3次元プラズモイド
- 2次元では出てこなかった不安定性
  - キンク、斜めテアリング、乱流
- 観測では大規模なフラックスロープが見られる



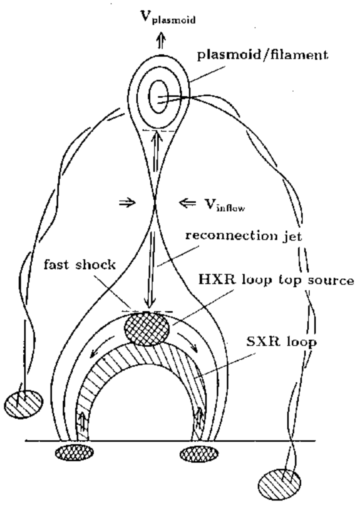
McKenzie+ 2013



SDO/AIA



Nishida+2013

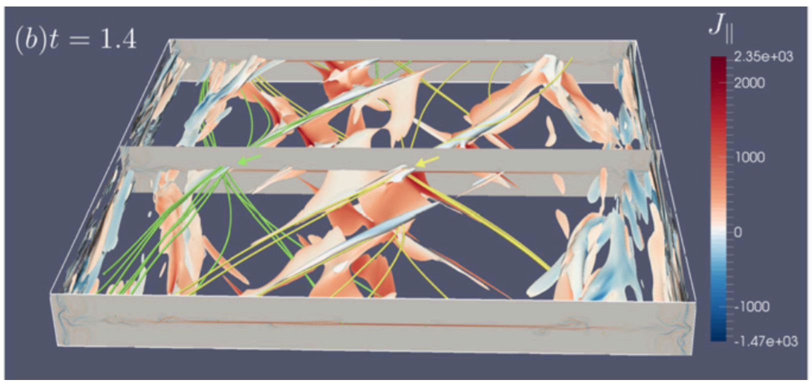


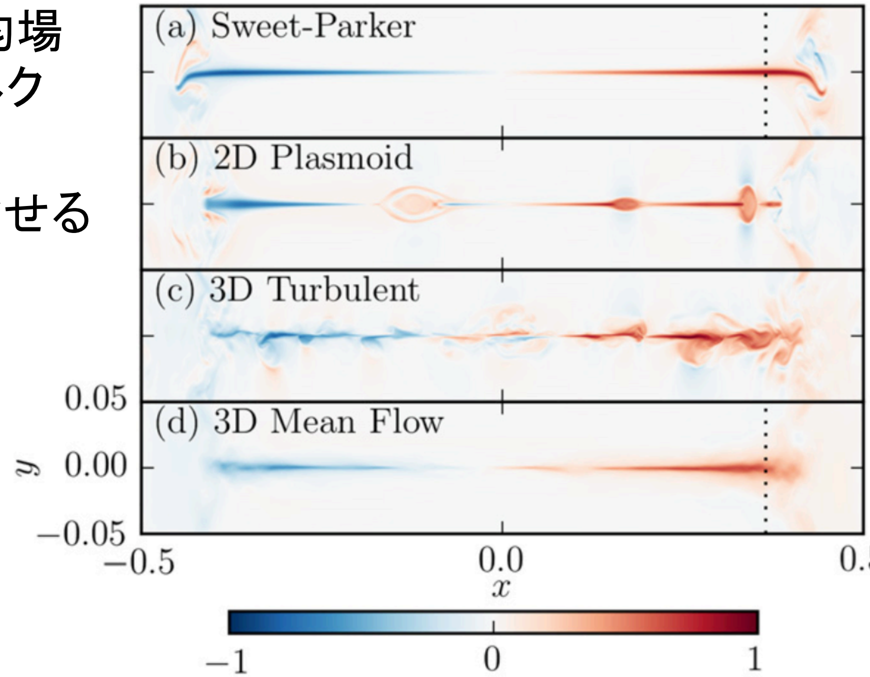
Shibata et al. 1995

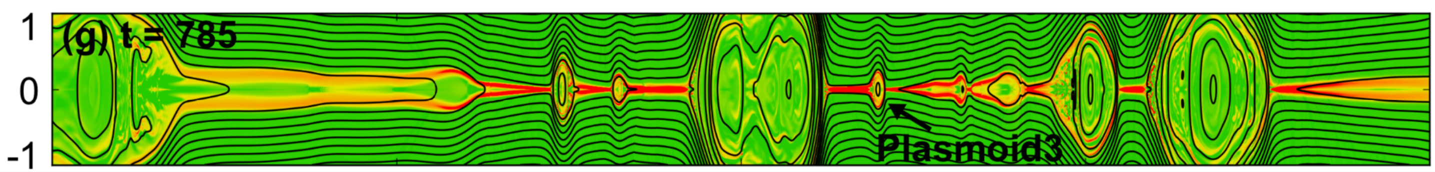
3D平均場構造 は 2D S-P構造 に類似

Huang et al. 2016

- 乱流によりアウトフロー幅が拡張され平均場は(電気抵抗の大きな)Sweet-Parkerリコネクションに相当する。
- 巨視的には電気抵抗を上げているとみなせる







リコネクション率:

$$\frac{\partial \phi}{\partial t} = E_z|_X = \eta J_z|_X$$

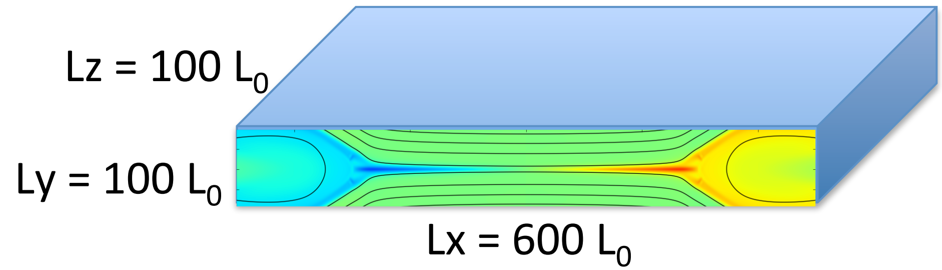
2次元では・・・

- ηが小さい時にJzが大きくなる理由を考えていた。
- プラズモイドやPetschek型でJ_zを大きくする。
- その結果巨視的なアウトフロー幅は大きくなる。

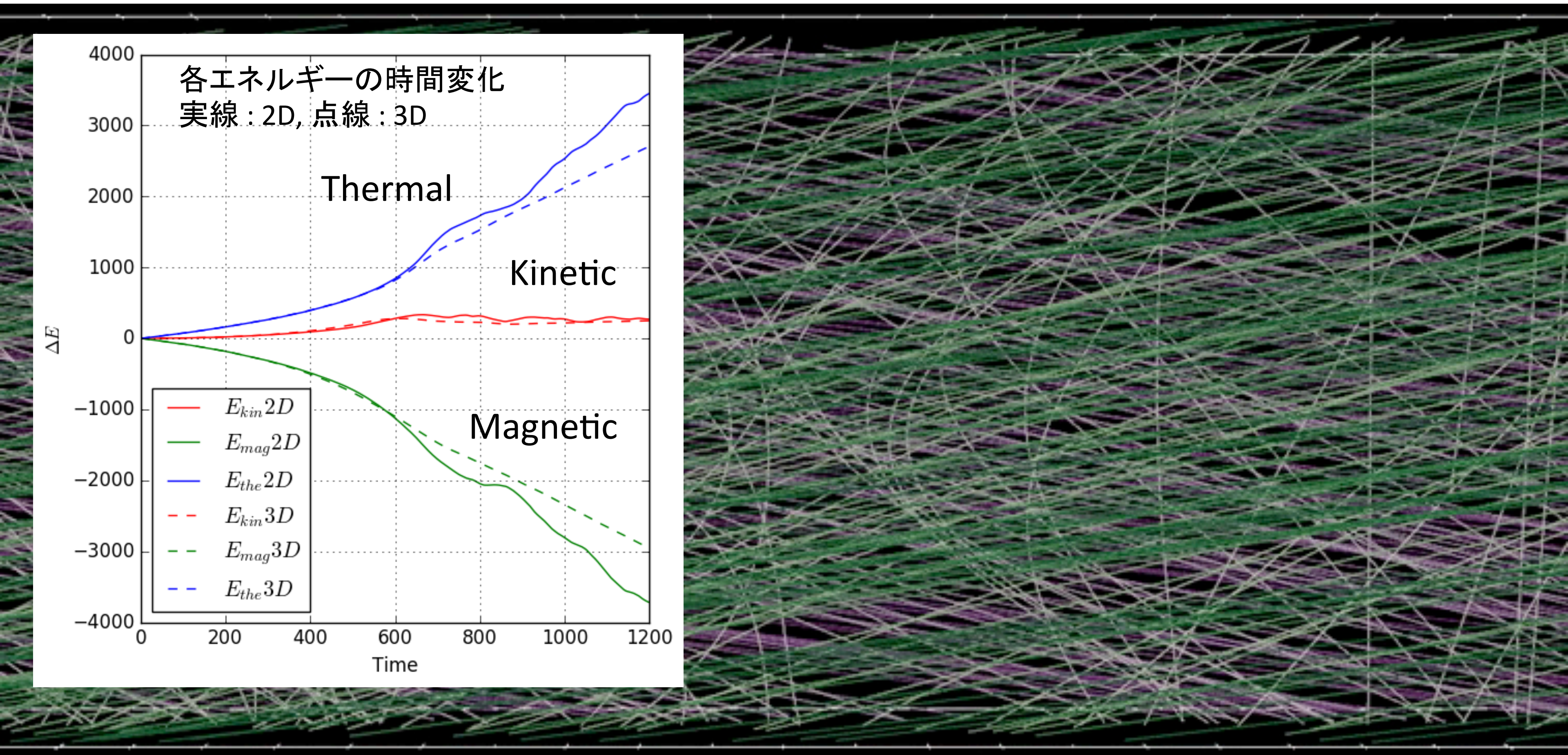
3D シミュレーション

- 3D 抵抗性 MHD 方程式
- HLLD + Flux-CT
- (Lx, Ly, Lz) = ($600L_0$, $100L_0$, $100L_0$)
- 弱いガイド磁場(0.1 Bx)
- Lundquist数 ~ 10^5

下の動画は真上から見た図



Volume : Vx(アウトフロー), 磁力線の色 : Bx

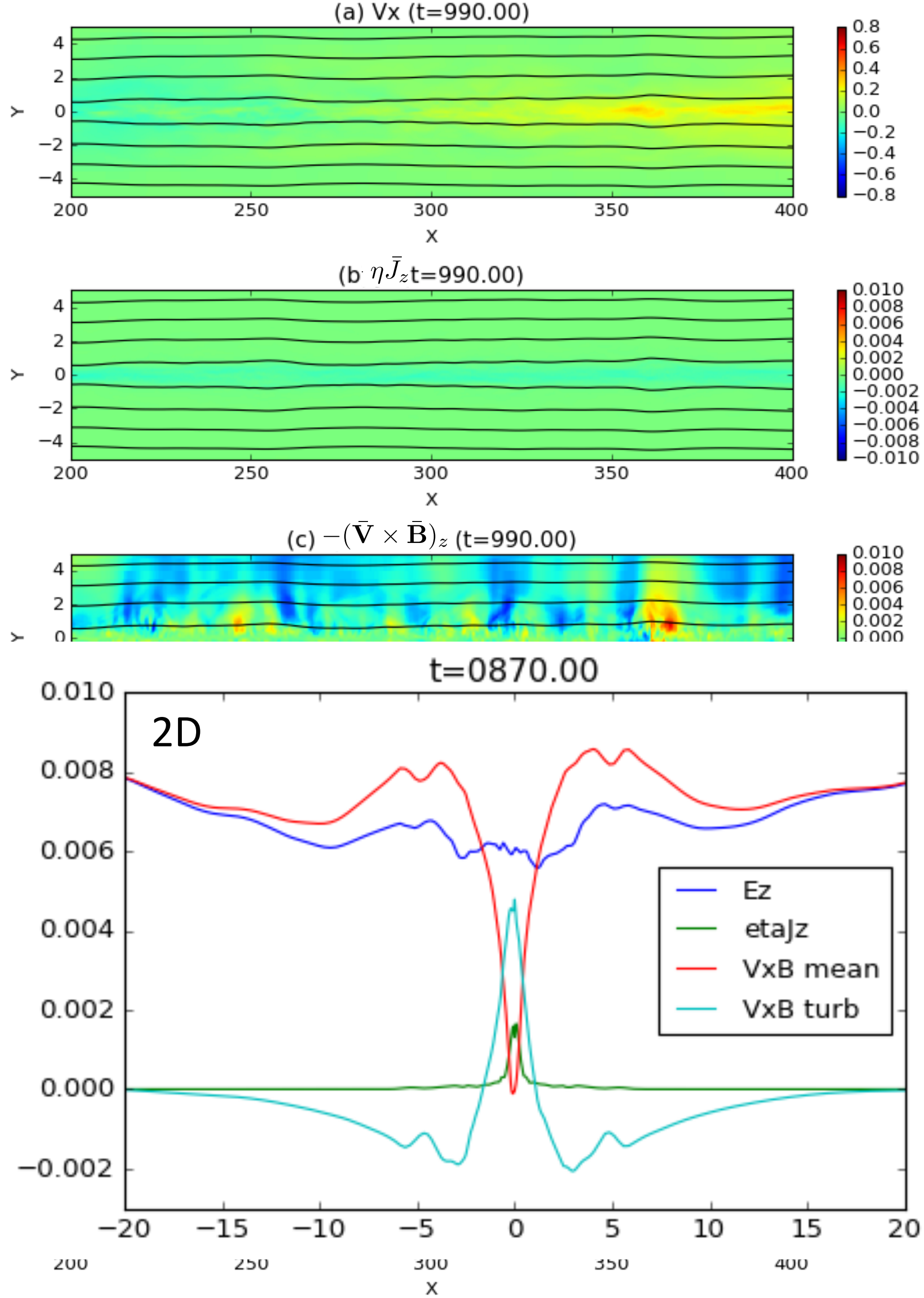


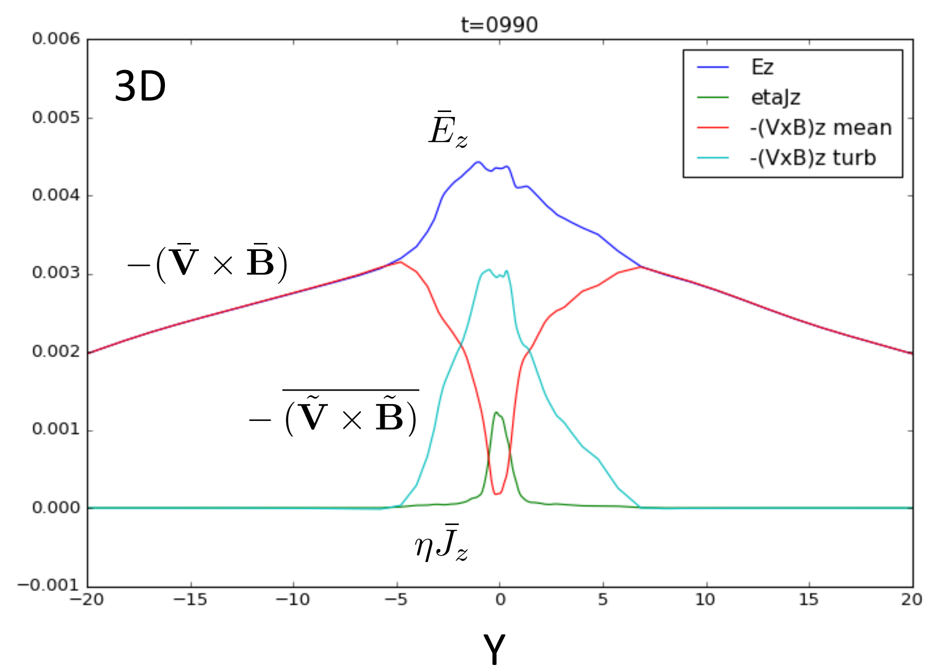
平均場電場

- 斜め構造がZ方向に平均されるのでほとんど乱流電場になってしまう

$$E_z = -(\mathbf{V}\times\mathbf{B})_z + \eta J_z$$

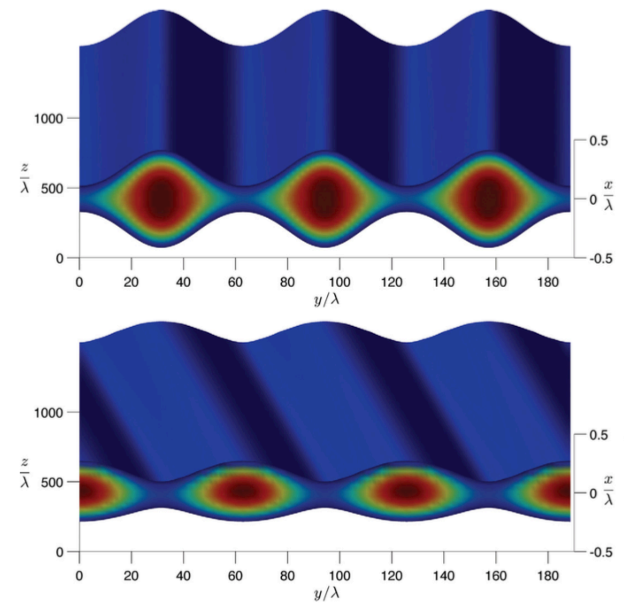
$$\bar{E}_z = -(\bar{\mathbf{V}}\times\bar{\mathbf{B}})_z - \overline{(\tilde{\mathbf{V}}\times\tilde{\mathbf{B}})}_z + \eta\bar{J}_z$$



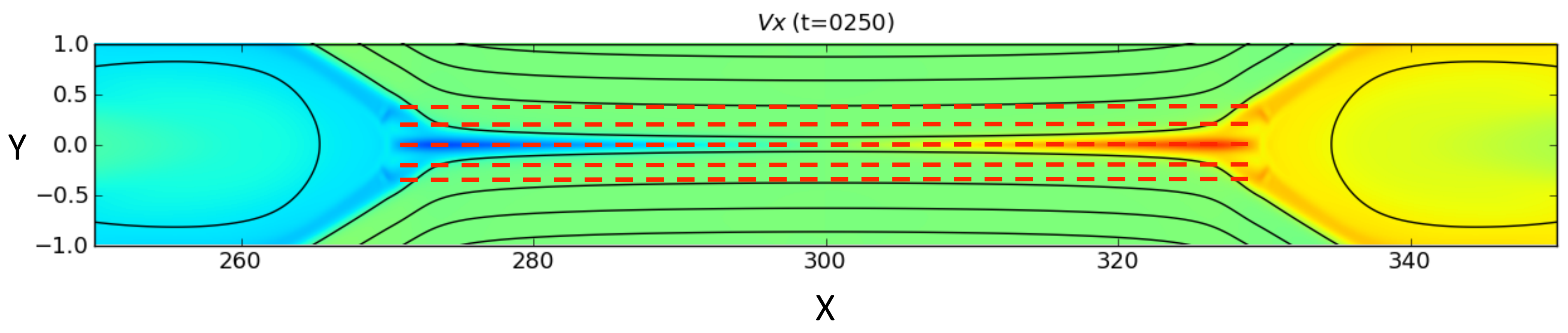


3次元では斜めテアリングモードが卓越

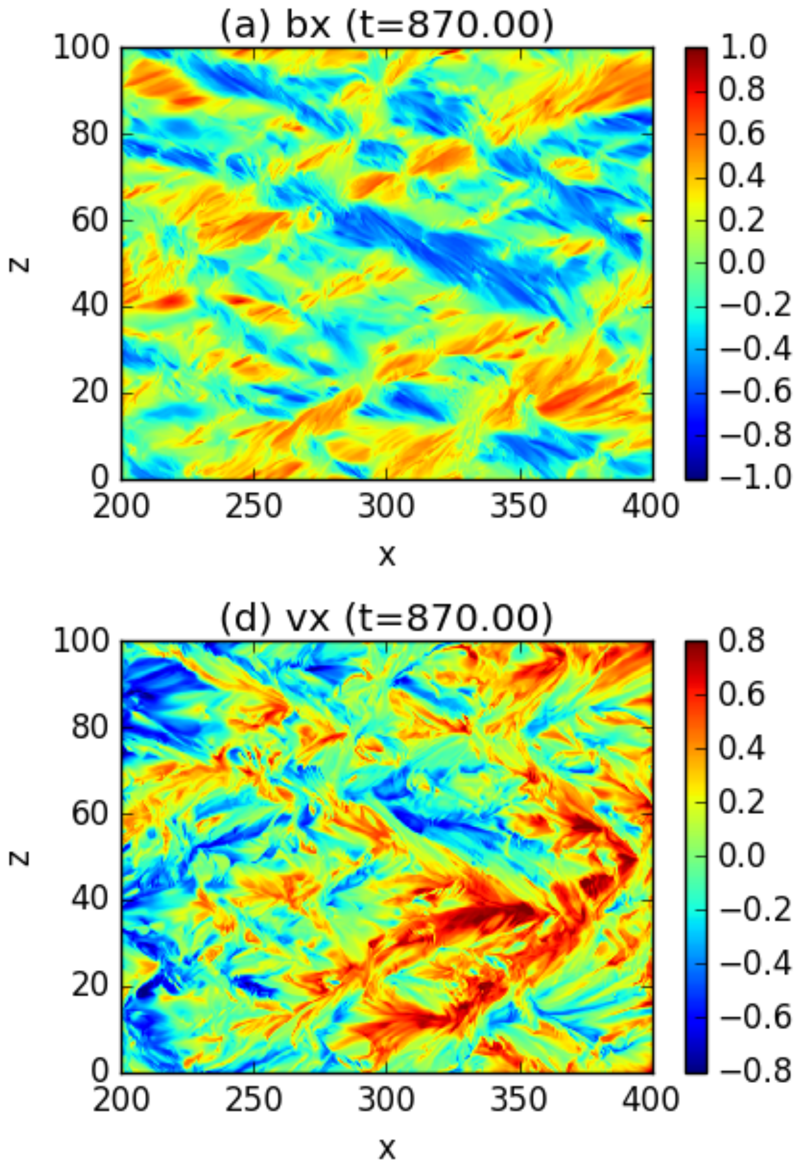
Baalrud et al. 2012



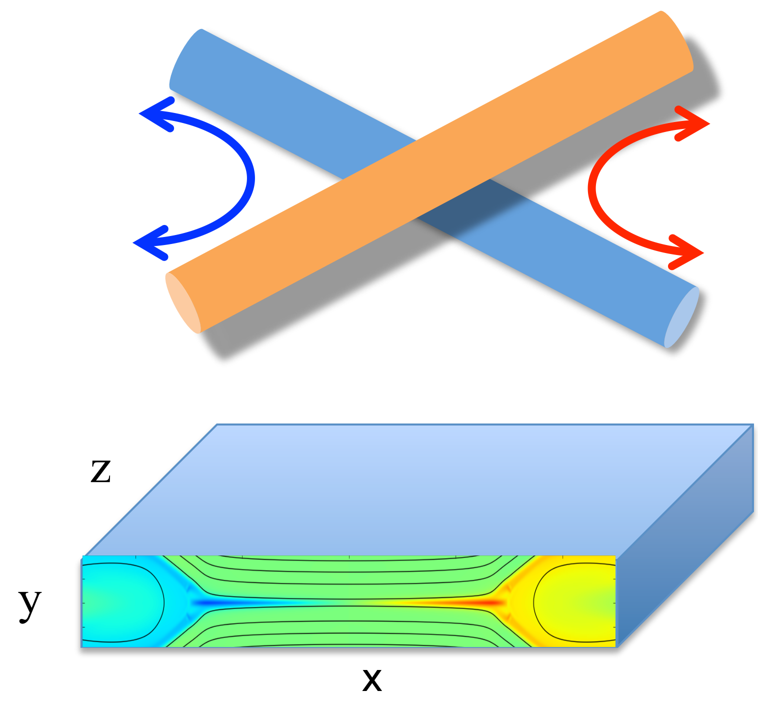
- 2次元ではz方向に一様な構造しか現れない(∂/∂z = 0)。
- 3次元では斜めテアリングモードがより大きな成長率を持つことがある。
- 斜めプラズモイドはその場の磁場に沿った構造を持ち、複数レイヤに形成する(k･B=0)。



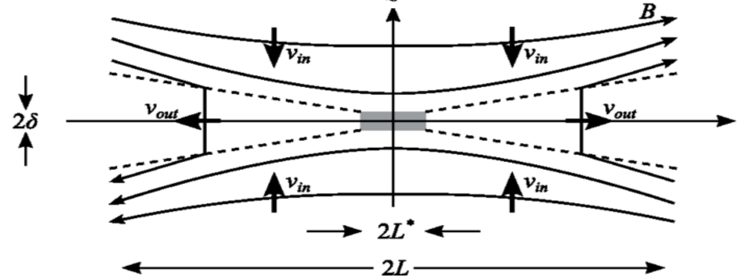
上下2レイヤで斜めプラズモイドが成長

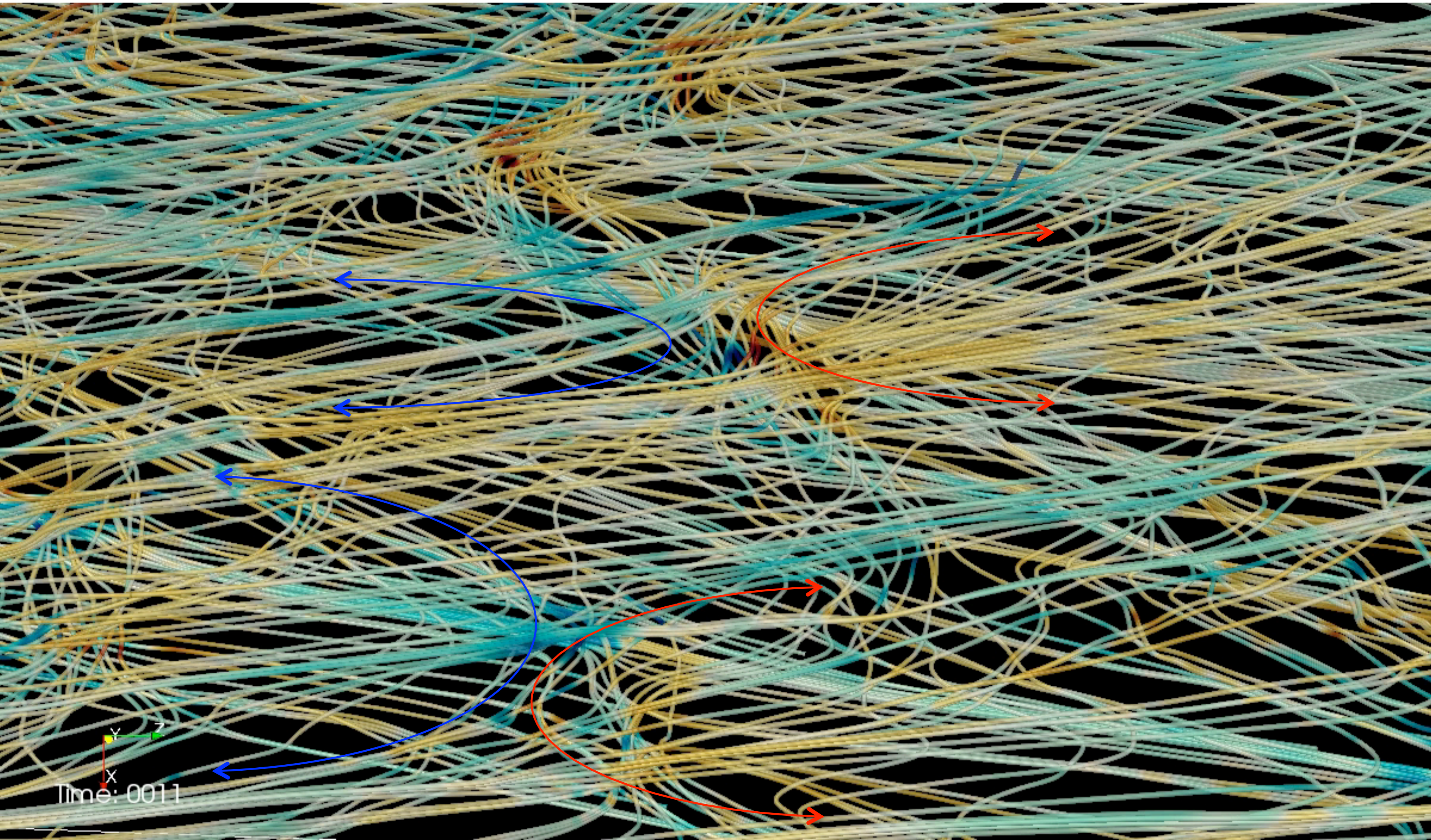


- 斜めプラズモイドが成長することで初期中性面で衝突、相互作用する。
- 斜めプラズモイドに沿ってアウトフローが形成



リコネクション領域とアウトフロー

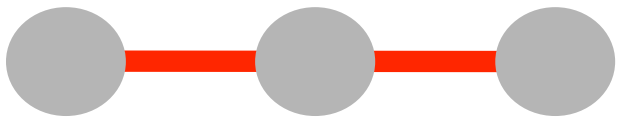




2次元と3次元の本質的な違い

2次元の場合

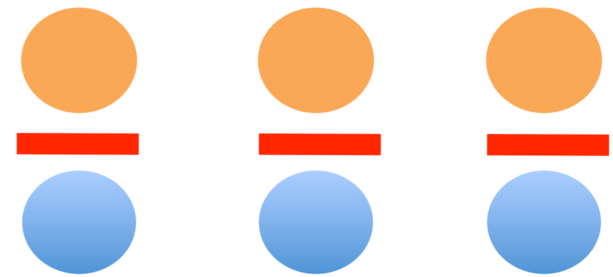
Side view



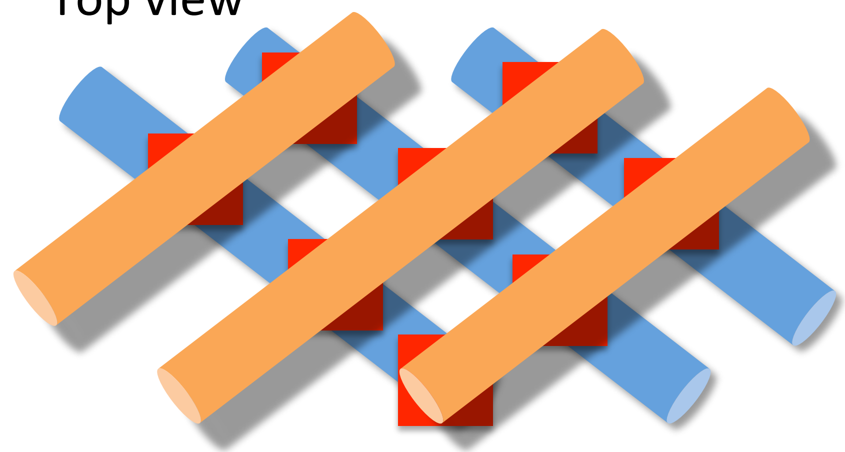
Top view

3次元の場合

Side view



Top view



- 2次元プラズモイドはリコネクションが終わった後の”掃き溜め”
- 3次元ではプラズモイド同士のリコネクションが本質的
- 2次元に比べてフィリングファクターが下がる
- プラズモイドスケーリングも見直しが必要