Universality of Fast Turbulent Magnetic Reconnection under High Landquist Number

Liping Yang[1,2,3], Hui Li[2], Fan Guo[2], Xiaocan Li[2], Shengtai Li[2], Lei Zhang[1], and Xueshang Feng[1,3]

[1]SIGMA Weather Group, State Key Laboratory for Space Weather, National Space Science Center, Chinese Academy of Sciences, 100190 Beijing, China

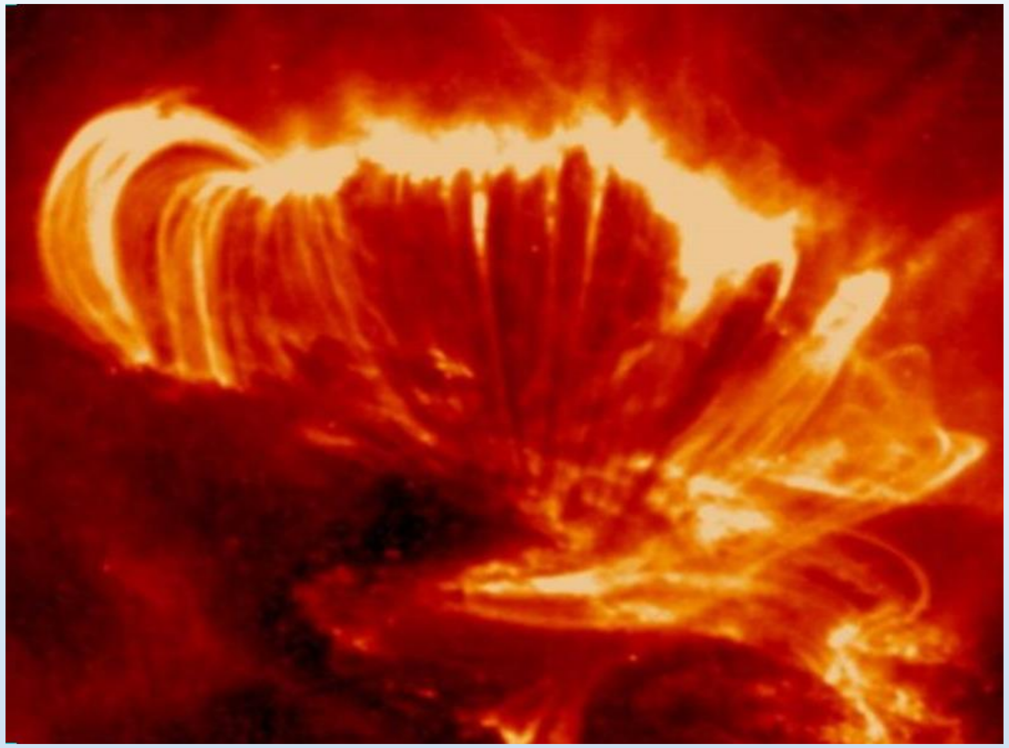
[2]Theoretical Division, MS B284, Los Alamos National Laboratory, Los Alamos, NM 87545, USA

[3]HIT Institute of Space Science and Applied Technology, 518055, Shenzhen, China

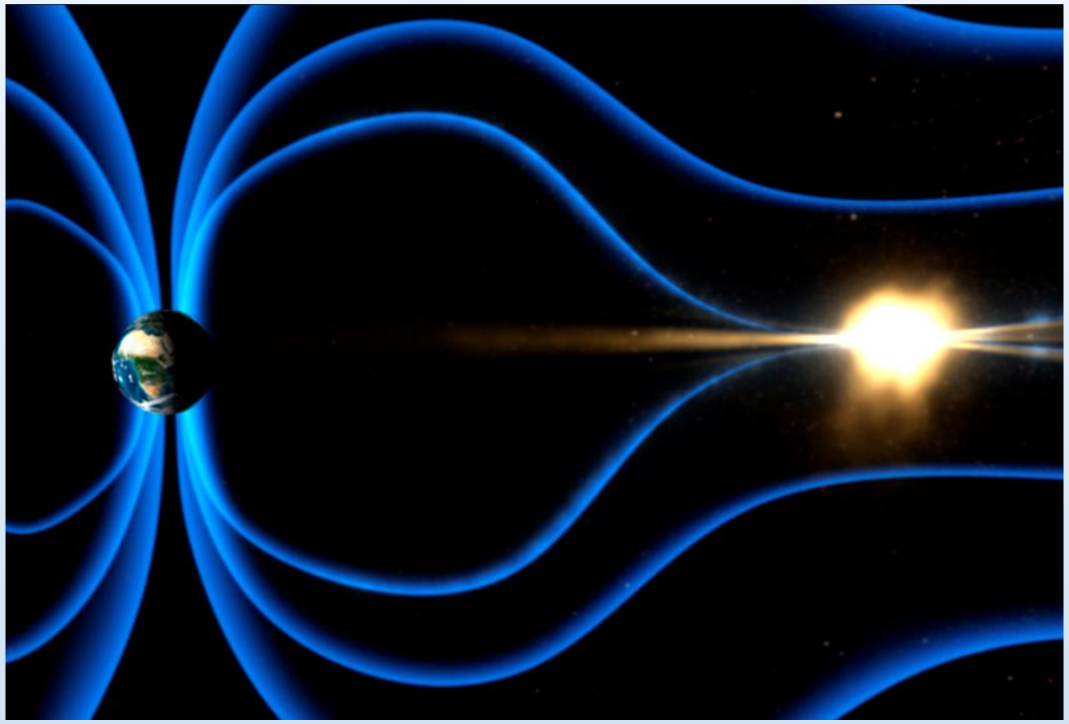
Main Content

- Introduction
  - Turbulent magnetic reconnection
  - Motivation
- Numerical Methods
  - MHD modeling
  - Measurement of rate
- Numerical results
  - Current sheet (CS) evolution
  - Reconnection features
  - Variation of rate with turbulence level and S
  - Turbulence anisoptropy
- Conclusion

Magnetic reconnection



solar flares



substorms

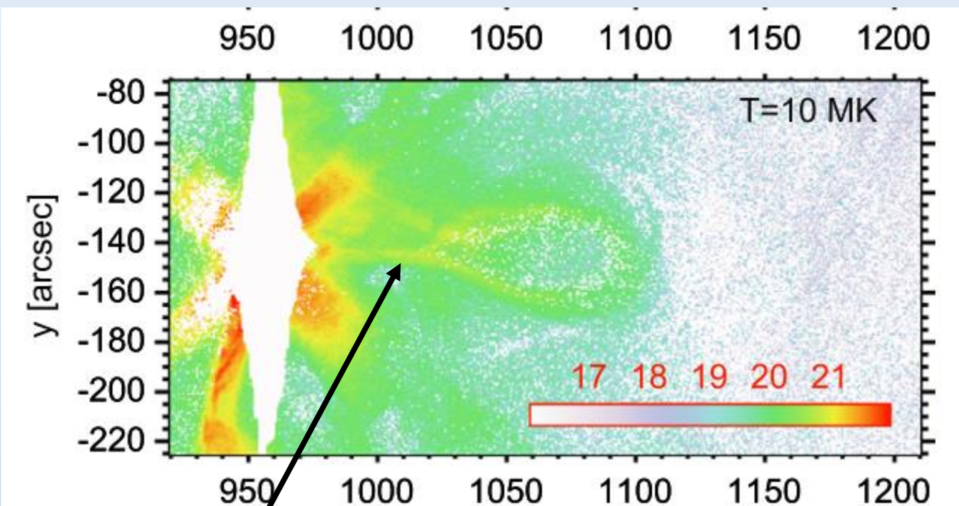
- A fast energy release is usually observed in solar flares and substorms in the magnetosphere of Earth.
- A likely mechanism behind these spectacular space- and astrophysical phenomena is magnetic reconnection.
- The rate that reconnection proceeds is required to be fast to explain the time scales of flares and substorms, usually in the range 0.01 ~ 0.1.

How to produce fast reconnection, especially in MHD scale?

Turbulent magnetic reconnection

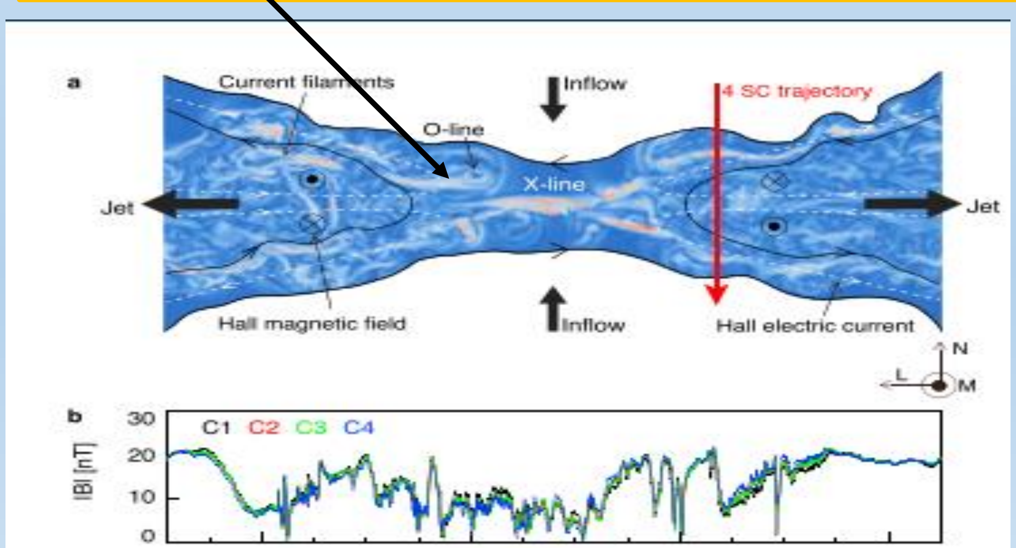
Since space plasma flows are generically chaotic, turbulence has been thought as a candidate to make reconnection fast (Matthaeus+1986; Lazarian+1999; Fan+2004; Kowal+2009; Loureiro+2009; Eyink+2011; Huang+2012; Oishi+2015; Huang+2016; Beresnyak 2017; Kowal+2017; Fu+2017; Huang+2017; Cheng+2018; He+2018, etc).

Observations



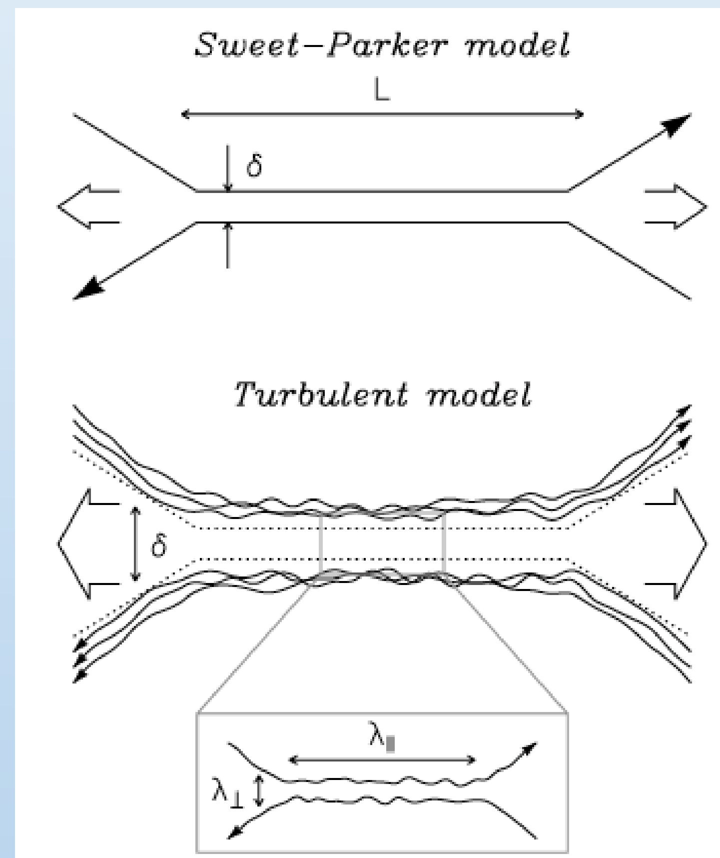
Chen et al. 2018

fragmented and turbulent nature of magnetic reconnection



Fu et al. 2017

Theory



Ohmic diffusion

super-diffusion of turbulent magnetic field

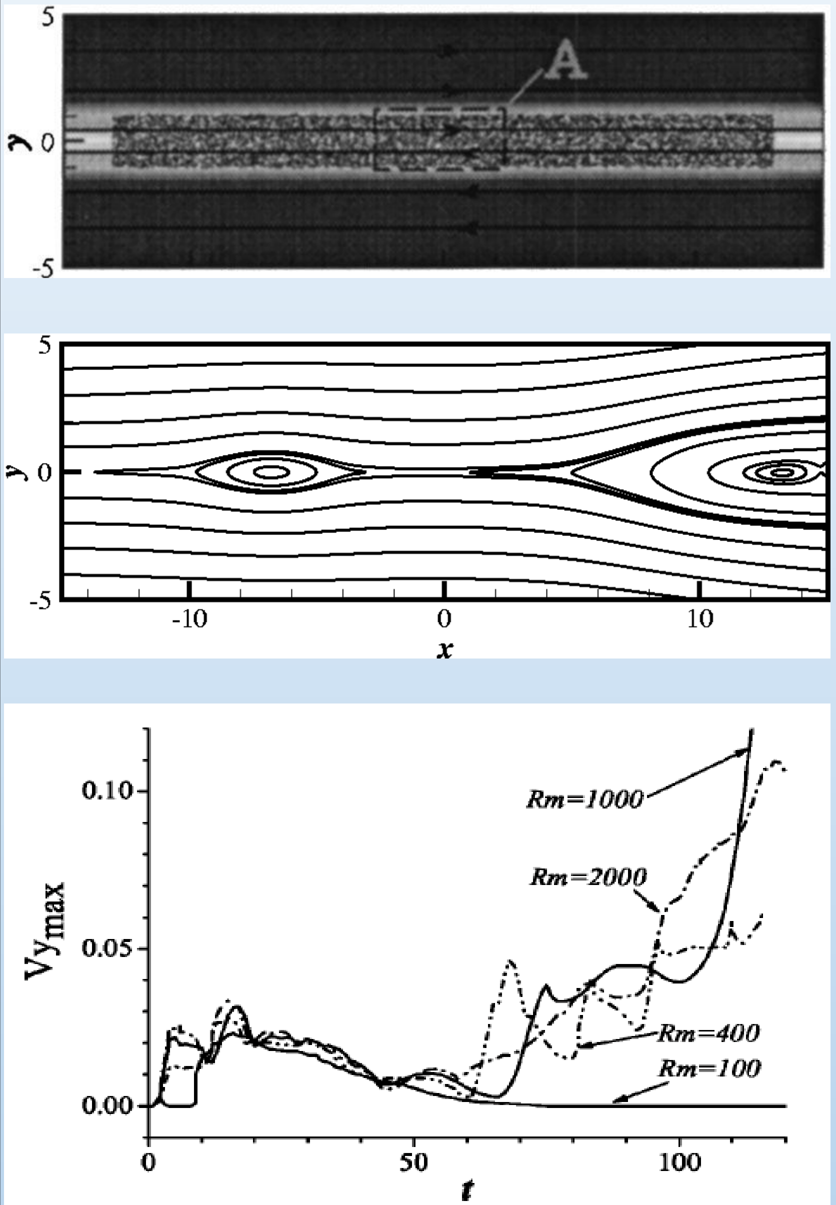
$$V_{\rm rec} < V_{\rm A} \min\left[\left(\frac{L_x}{l}\right)^{1/2}, \left(\frac{l}{L_x}\right)^{1/2}\right]\left(\frac{v_l}{V_{\rm A}}\right)^2$$

fast reconnection

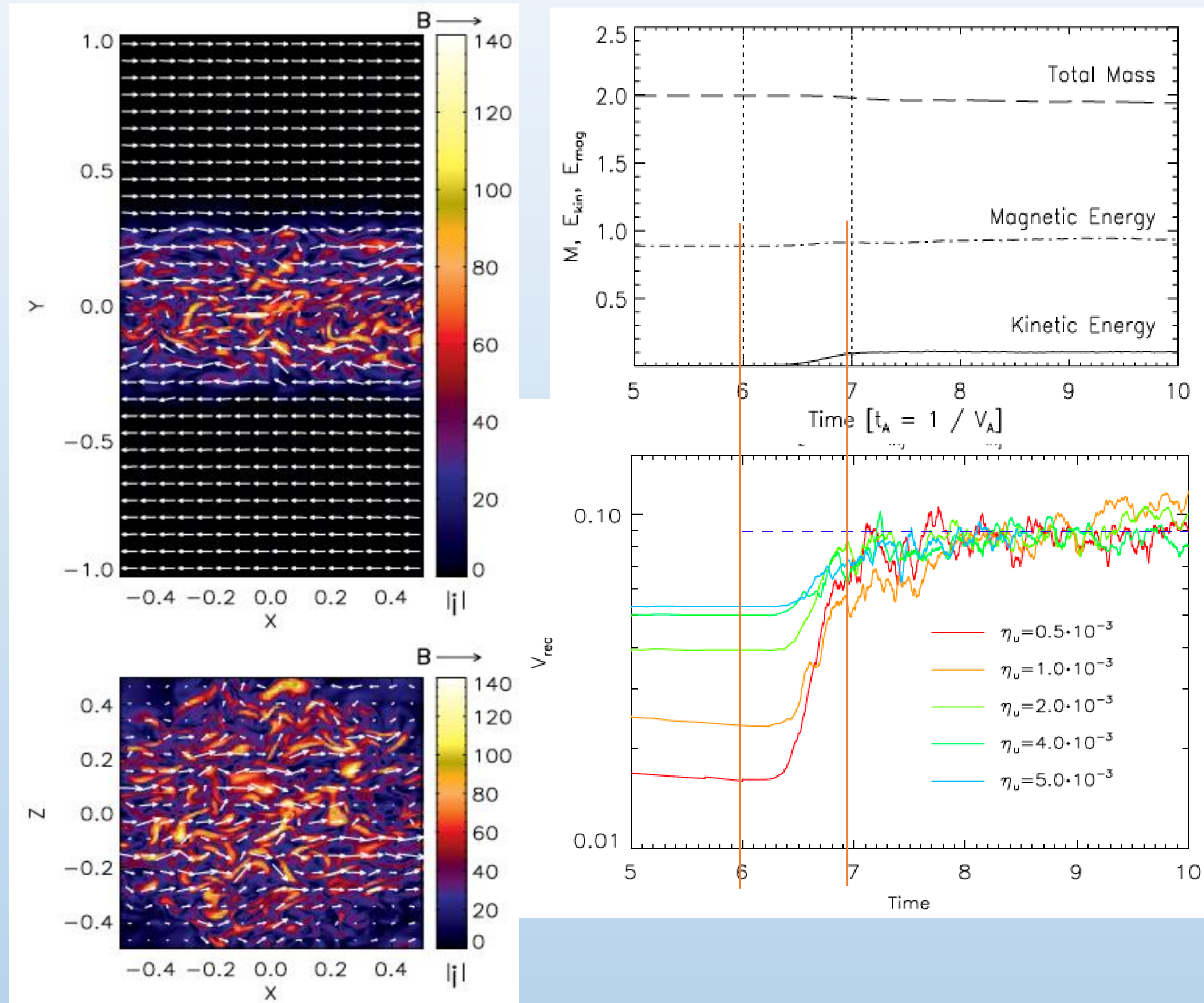
Lazarian &Vishniac 1999, Eyink et al. 2011

Turbulent magnetic reconnection ——— numerical works

2D runs (Fan, Feng, & Xiang 2004)



3D runs (Kowal & Lazarian 2009)



More works needed to be done:

1) clear coherence reconnection structures (outflow, energy convision, etc)
2) high Lundquist number S
3) mechanism behind turbulent reconnection (plsamoid instability or super-diffusion?)
4)…

Numerical MHD model

- Equations: 3D resistive MHD equations with driven forces:

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

$$\frac{\partial \rho \mathbf{u}}{\partial t} + \nabla \cdot \left[\rho \mathbf{u}\mathbf{u} + (p + \frac{1}{2}\mathbf{B}^2)\mathbf{I} - \mathbf{B}\mathbf{B} \right] = \nu \nabla^2 \mathbf{u} + \rho \mathbf{f}_v \ ,$$

$$\frac{\partial \mathbf{B}}{\partial t} + \nabla \cdot (\mathbf{u}\mathbf{B} - \mathbf{B}\mathbf{u}) = \eta \nabla^2 \mathbf{B} \ .$$

$$\frac{\partial s_1}{\partial t} + \nabla \cdot (s_1 \mathbf{u}) = 0 \ ,$$

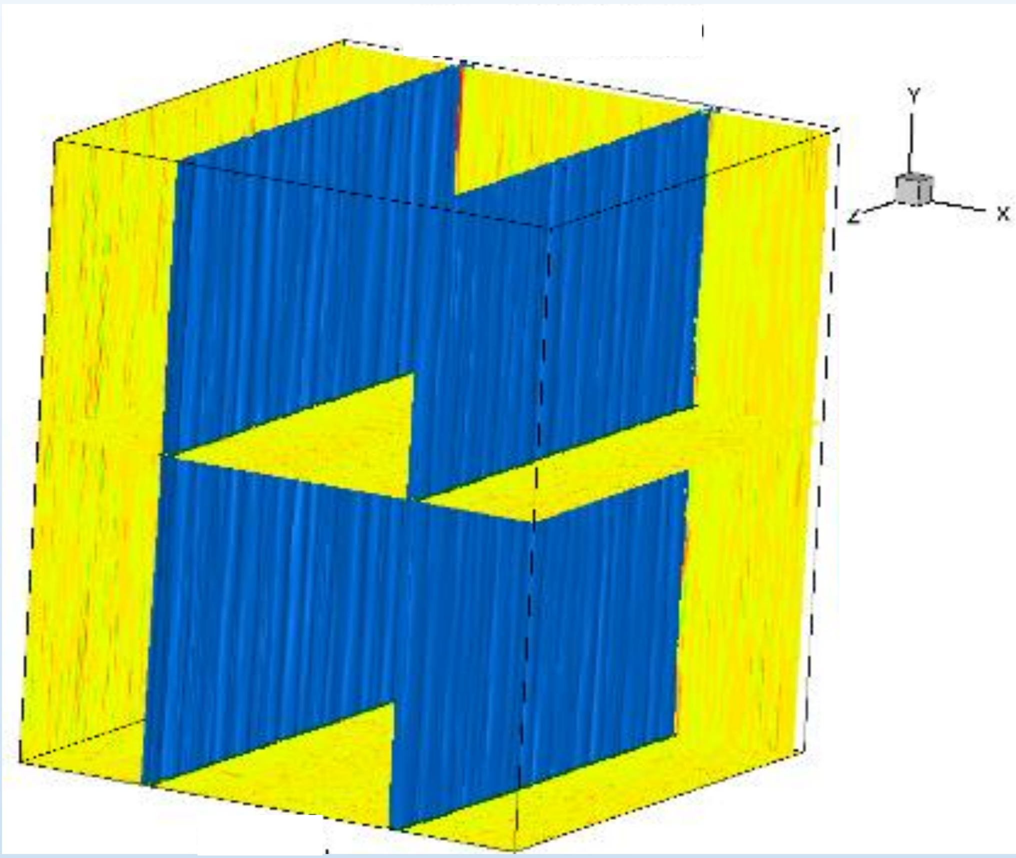
$$\frac{\partial s_2}{\partial t} + \nabla \cdot (s_2 \mathbf{u}) = 0 \ ,$$

s1 and s2 are the density of the traced mass.

- Scheme: Godunov finite volume method
  - a third-order piecewise parabolic and the approximate Riemann solver HLLD is implemented.
  - CT algorithm is applied for ensuring the divergence-free state of the magnetic field.

Yang et al. (2017, 2018, 2019)

- Initial condition:



- two thin Harris current sheets with no guide field
- uniform total (thermal plus magnetic) pressure is assumed.
- the initial plasma β is about 0.1

- Driven forces:

- fv is a large-scale force.
- It is defined with components with 2 ≤ k ≤3.5, and the maximal amplitudes of the components occurs at k ≈ 2.5.
- The phase angle is random.
- It satisfy ∇ · fv = 0.

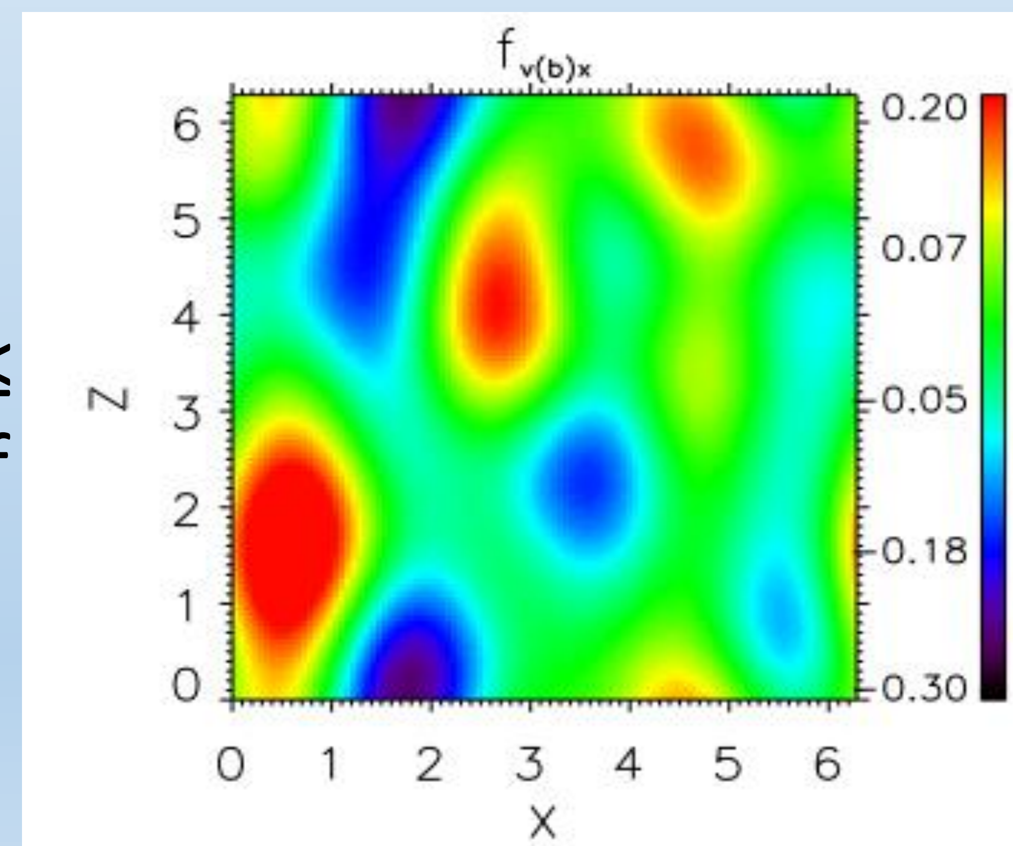


Table 1: Reconnection MHD Experiments

Run	N^3	S	M_A	f_v	CS
A1	2048^3	2.3e5	0.322	0.30	Yes
A2	1024^3	6.3e4	0.305	0.30	Yes
A3	1024^3	1.5e4	0.304	0.30	Yes
A4	512^3	4.8e3	0.302	0.30	Yes
B1	2048^3	2.3e5	0.192	0.10	Yes
B2	1024^3	6.3e4	0.185	0.10	Yes
B3	1024^3	1.5e4	0.183	0.10	Yes
B4	512^3	4.8e3	0.180	0.10	Yes
C1	2048^3	2.3e5	0.098	0.01	Yes
C2	1024^3	6.3e4	0.092	0.01	Yes
C3	1024^3	1.5e4	0.089	0.01	Yes
C4	512^3	4.8e3	0.084	0.01	Yes
D1	2048^3	2.3e5	0.072	0.00	Yes
D2	1024^3	6.3e4	0.067	0.00	Yes
D3	1024^3	1.5e4	0.060	0.00	Yes
D4	512^3	4.8e3	0.056	0.00	Yes
E	1024^3	6.3e4	0.421	0.30	No

- 17 MHD experiments are run with the Lundquist number S ranging from (4.8×10^3 to 2.3×10^5) and the module of large-scale driving force fv from 0.30 to 0.00.

- For Run D1-D4, a initial velocity is seeded with a random noise of amplitude 10^{-3} .

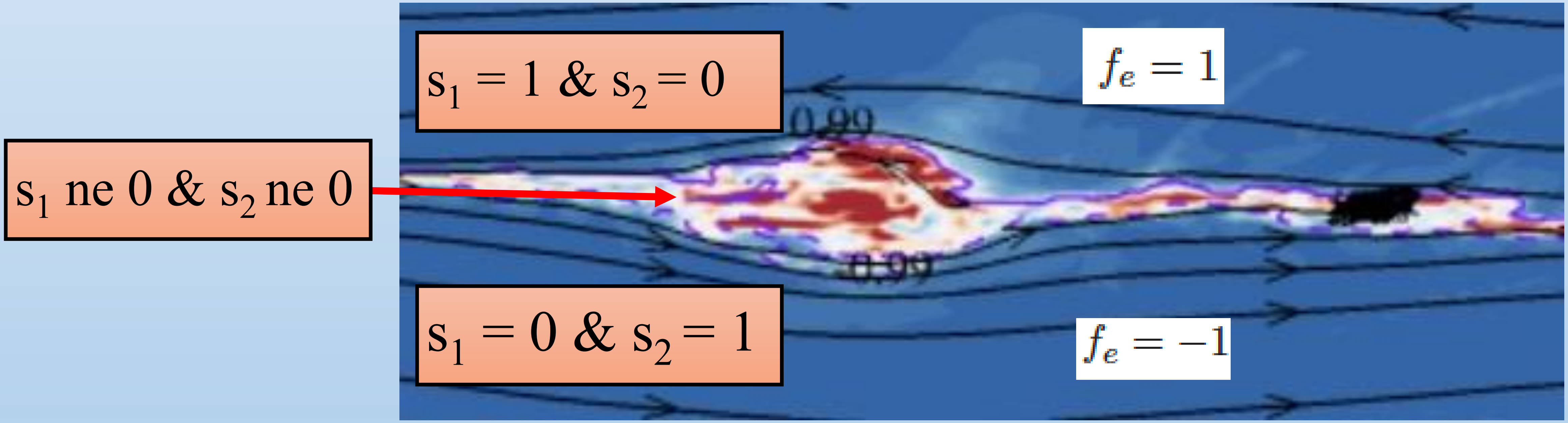
- For Run E, a uniform magnetic field, instead of Harris current sheets, is applied.

Measurement of reconnection rate

Reconnection rate R: $R = \frac{1}{B_0 V_A L_y} \frac{d\Phi}{dt}$, Φ is unreconneted magnetic flux.

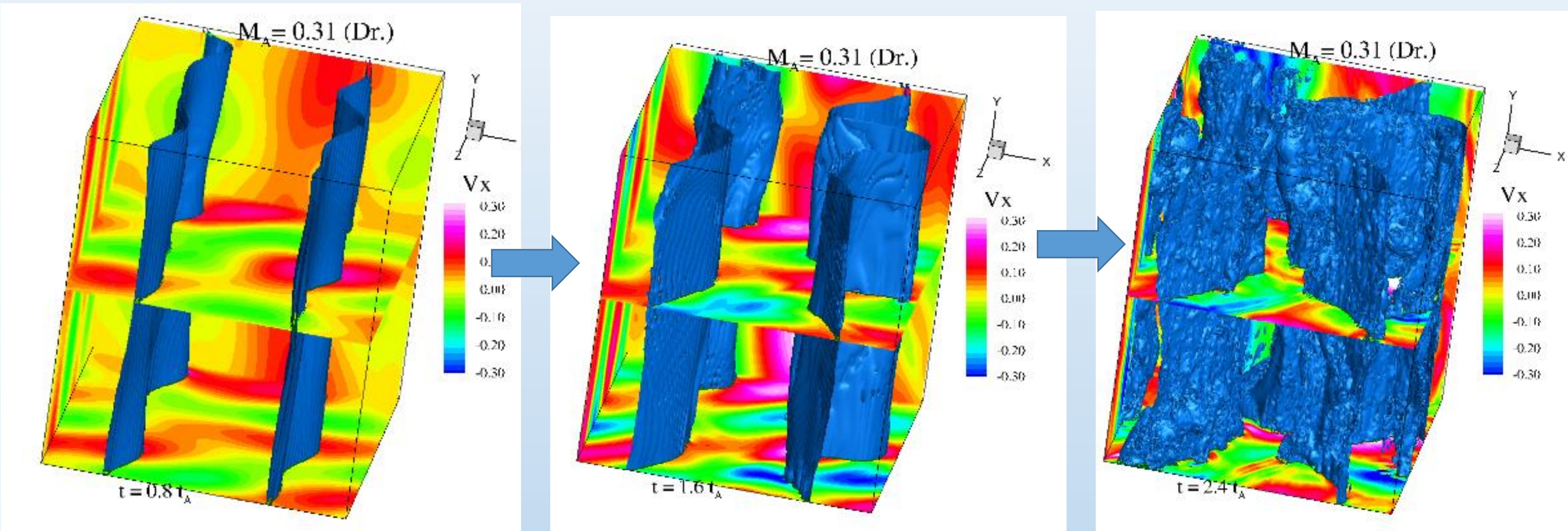
to calculate rate → identify separatrix surface → mixing of traced populations s_1 and s_2

mixing function: $f_e = \frac{|s_1| - |s_2|}{|s_1| + |s_2|}$



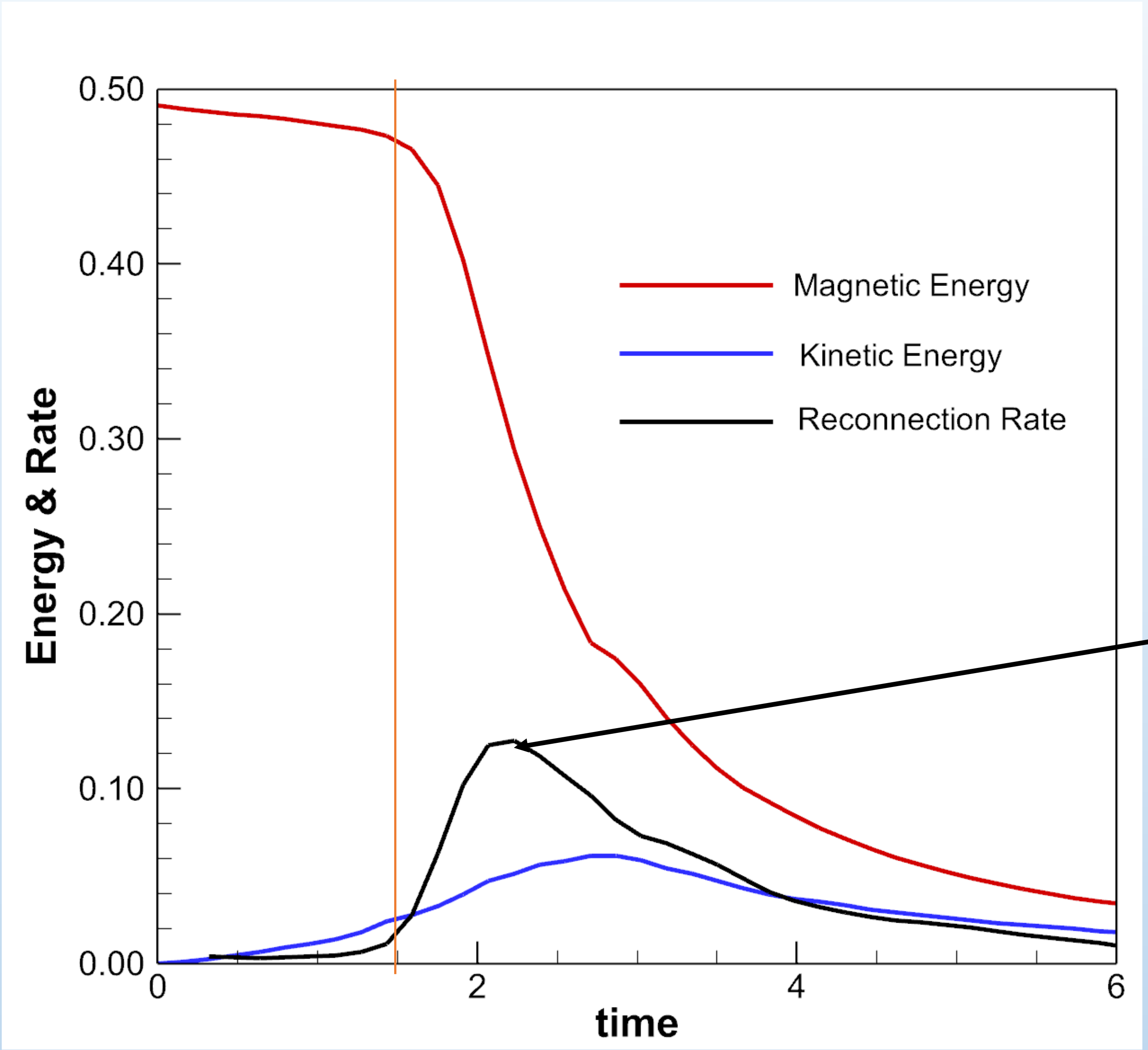
Purple contour lines of fe=0.99 and -0.99 wrap up reconnection region very well, nearly perfectly marking separatrix surfaces.

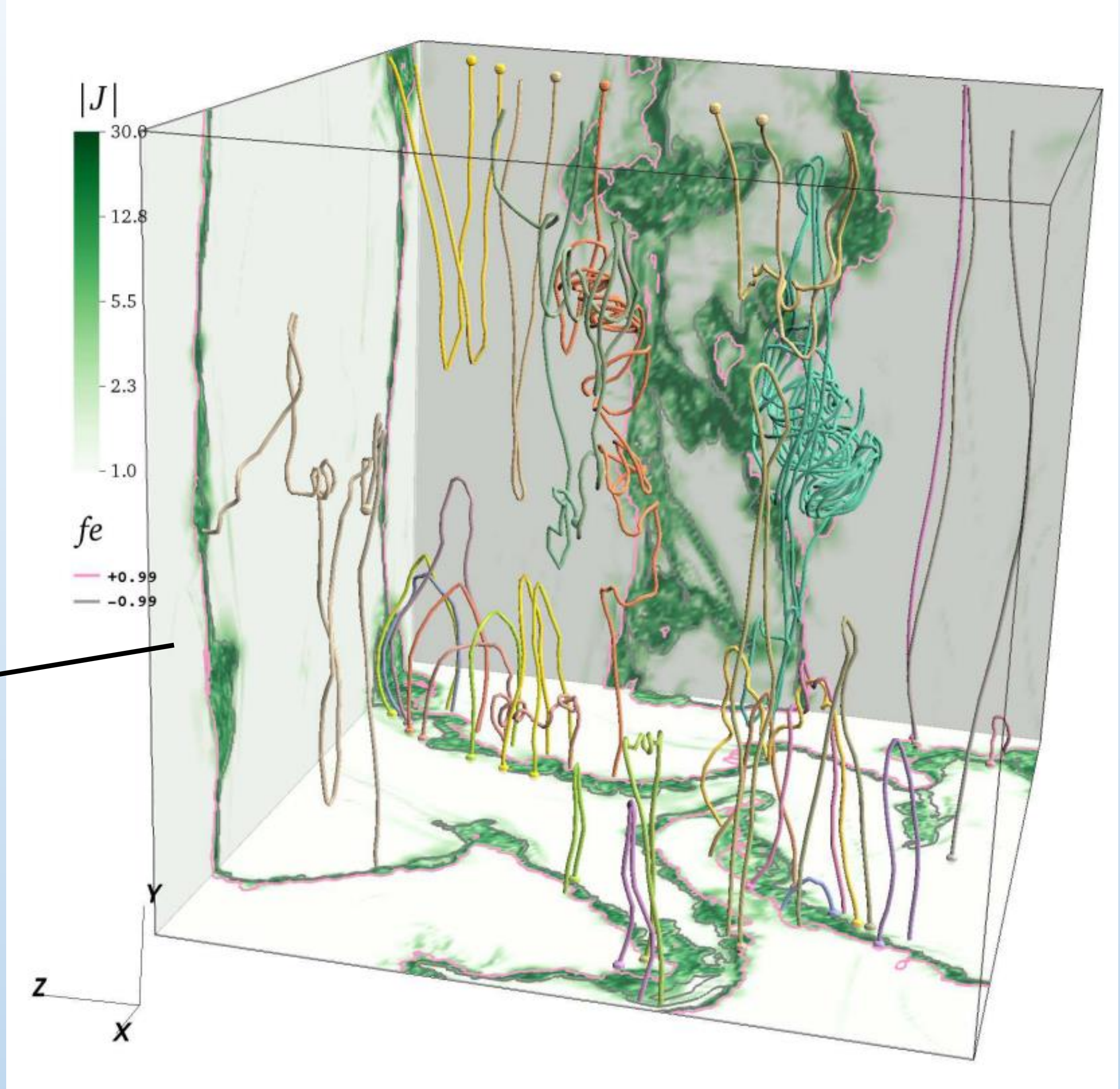
Numerical Results ------ CS evolution under external turbulence



Blue surfaces denote current sheets.
Colors show the velocity in x-direction (Vx).
Magnetic fields is at y-direction.
CSs are well preserved, but heavenly deformed in the third direction.

Reconnection features





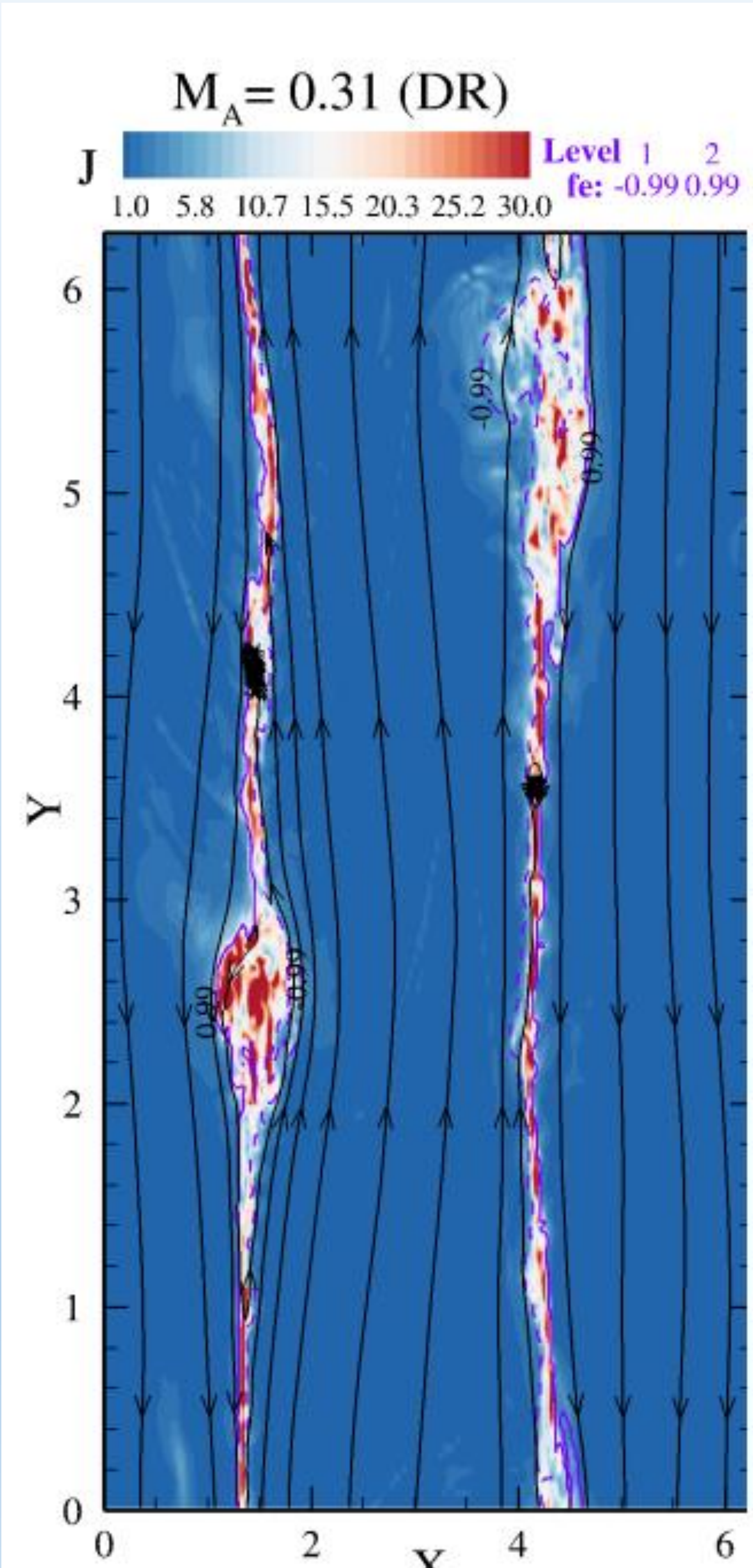
Energy：

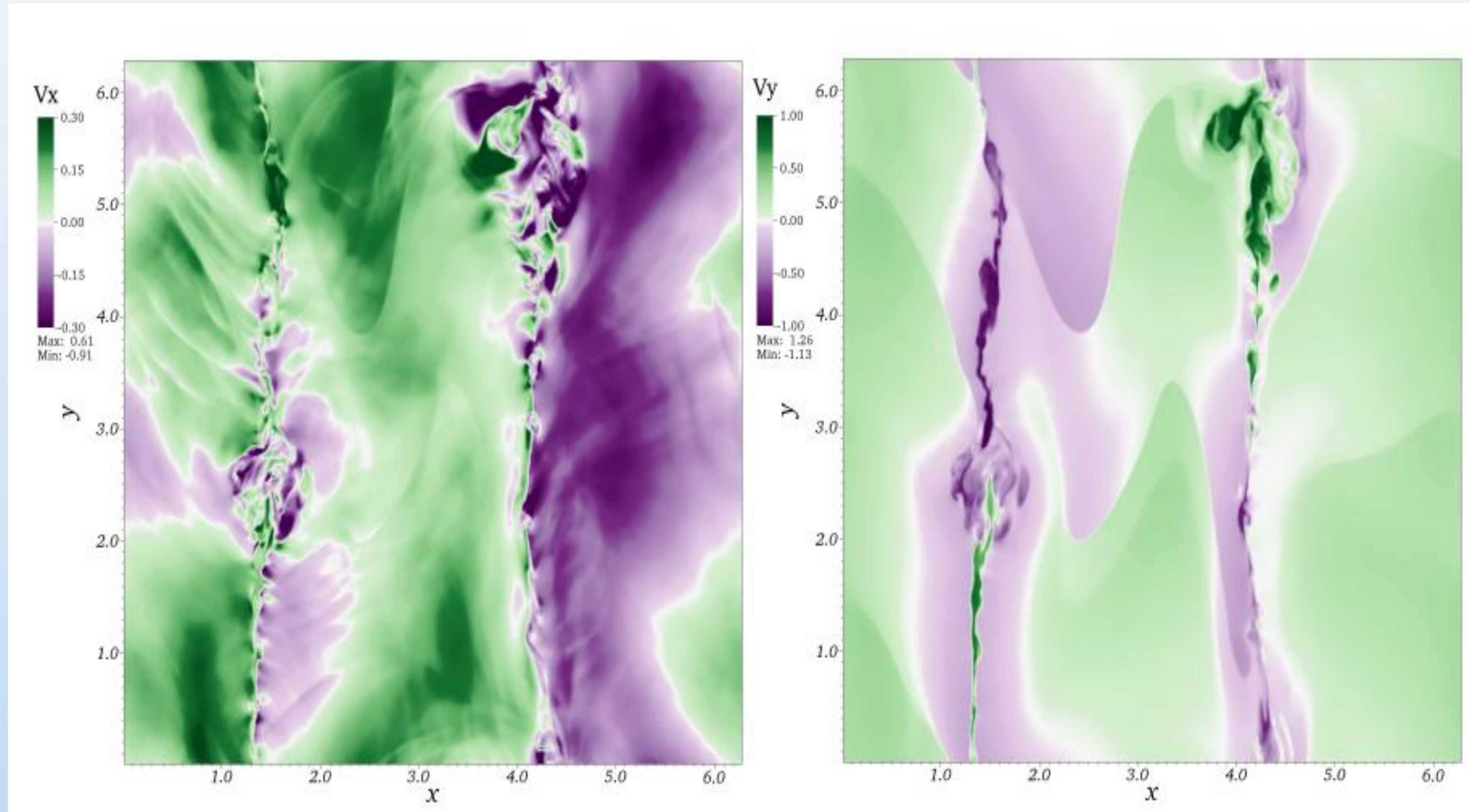
1) abrupt release of magnetic energy
2) increase of kinetic energy
3) sharp increase of Rate (0.13)
4) consistent onset time

Magnetic field lines：

1) Substantial field lines break
2) X−points with large opening angles form
3) magnetic flux ropes across or along deformed CSs

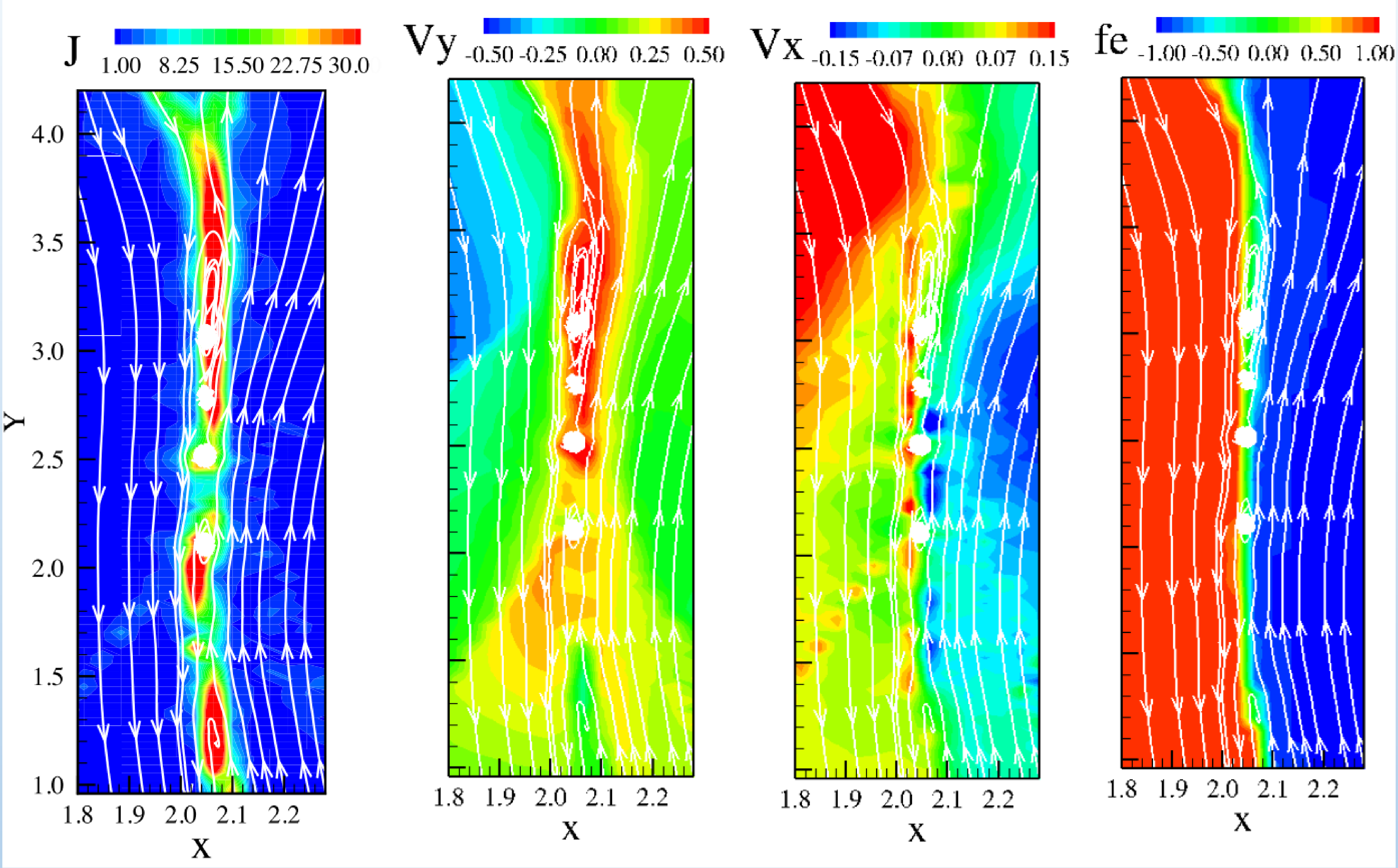
Reconnection features———classic X-point inflow/outflow





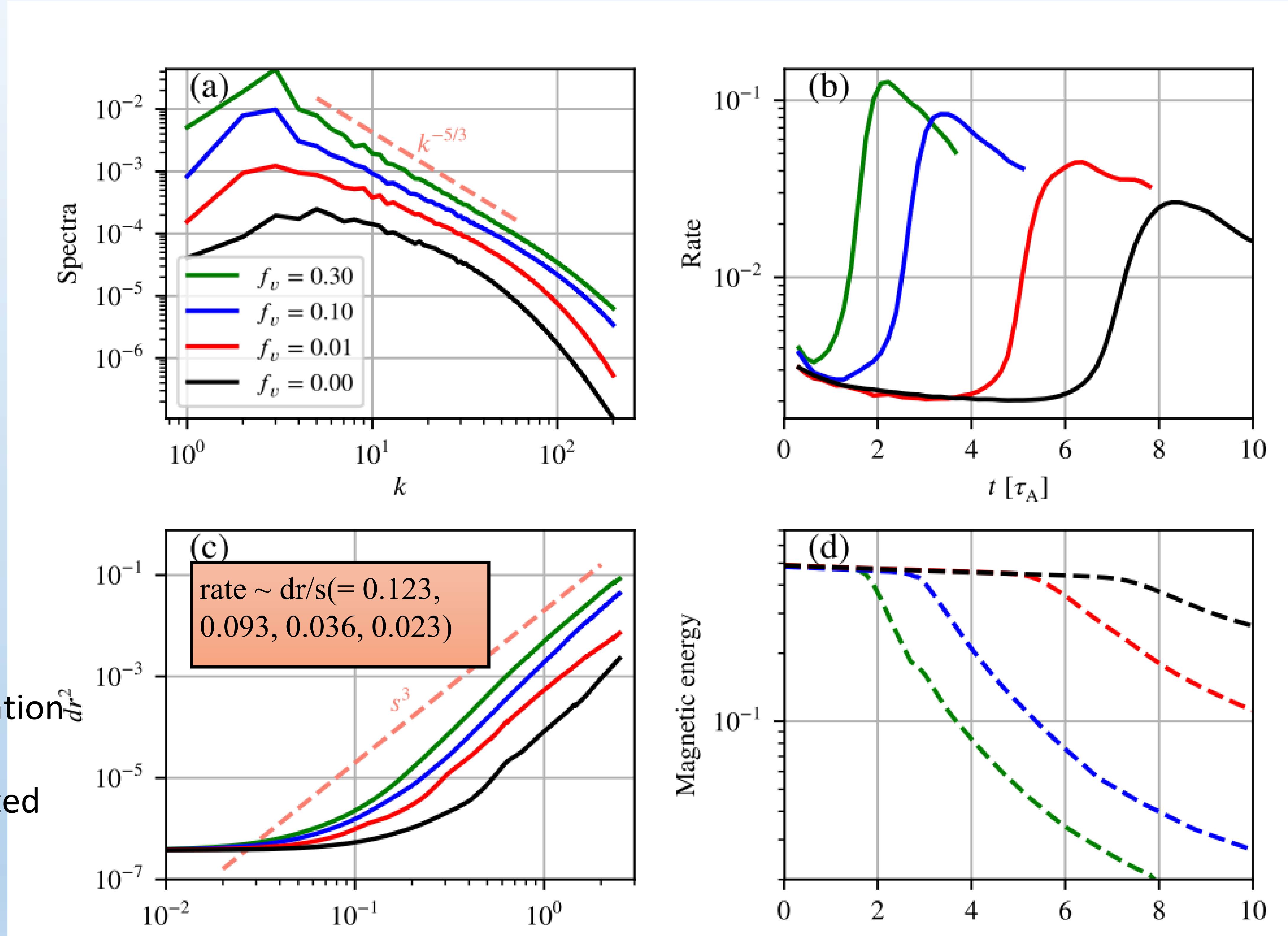
1) an inflow speed of about 0.15 V_A
2) outflows with the values of about 1 or −1 V_A
3) the rate got from inflow/outflow is about 0.15, consistent with that from mixing.

Local spots on the x – y plane



Blob-like structures, similar to plasmoids in 2D, are frequently produced.

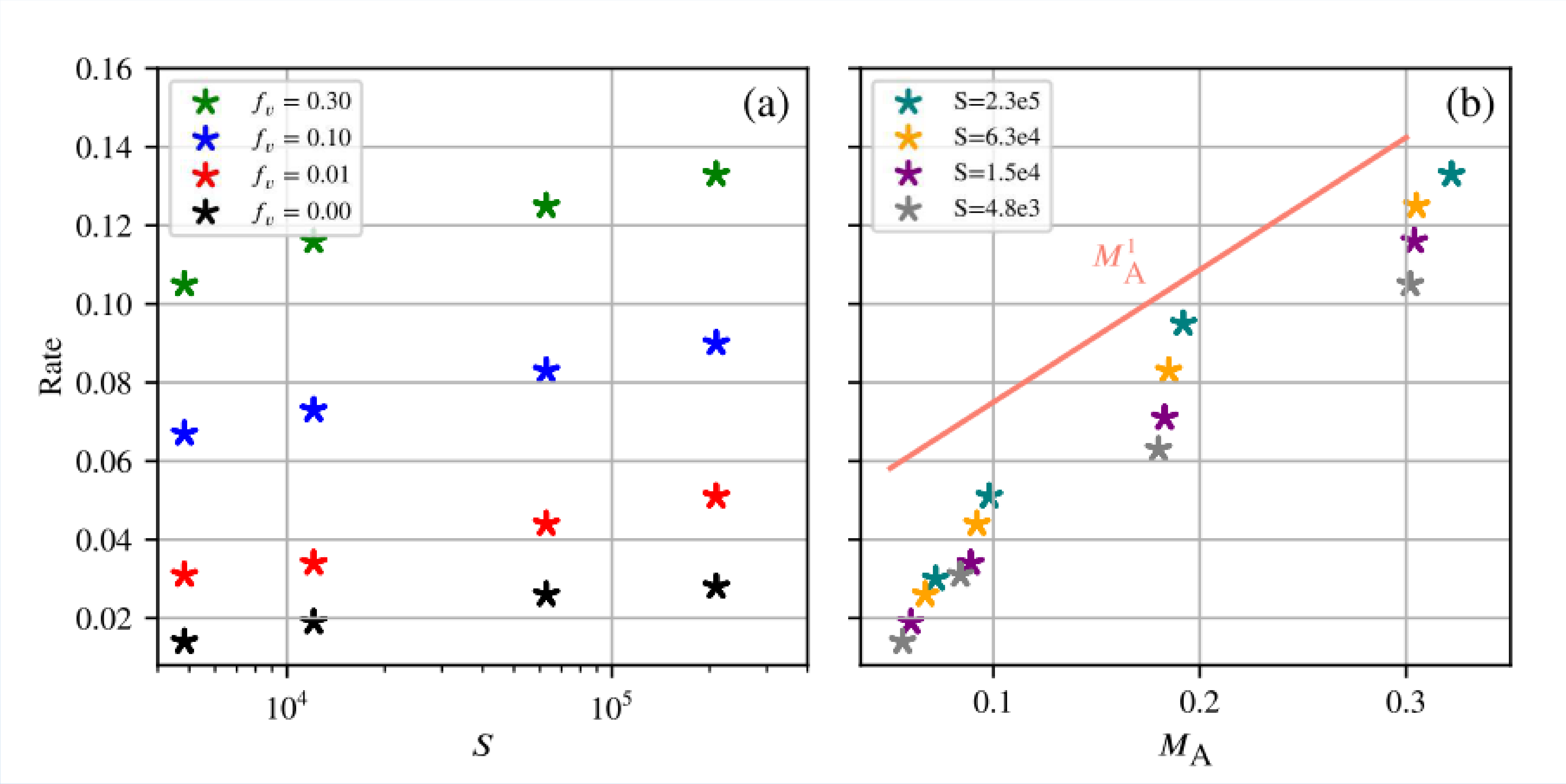
Variation of rate with turbulence level



dr:separation of two reconnected field lines

s:distance along field lines

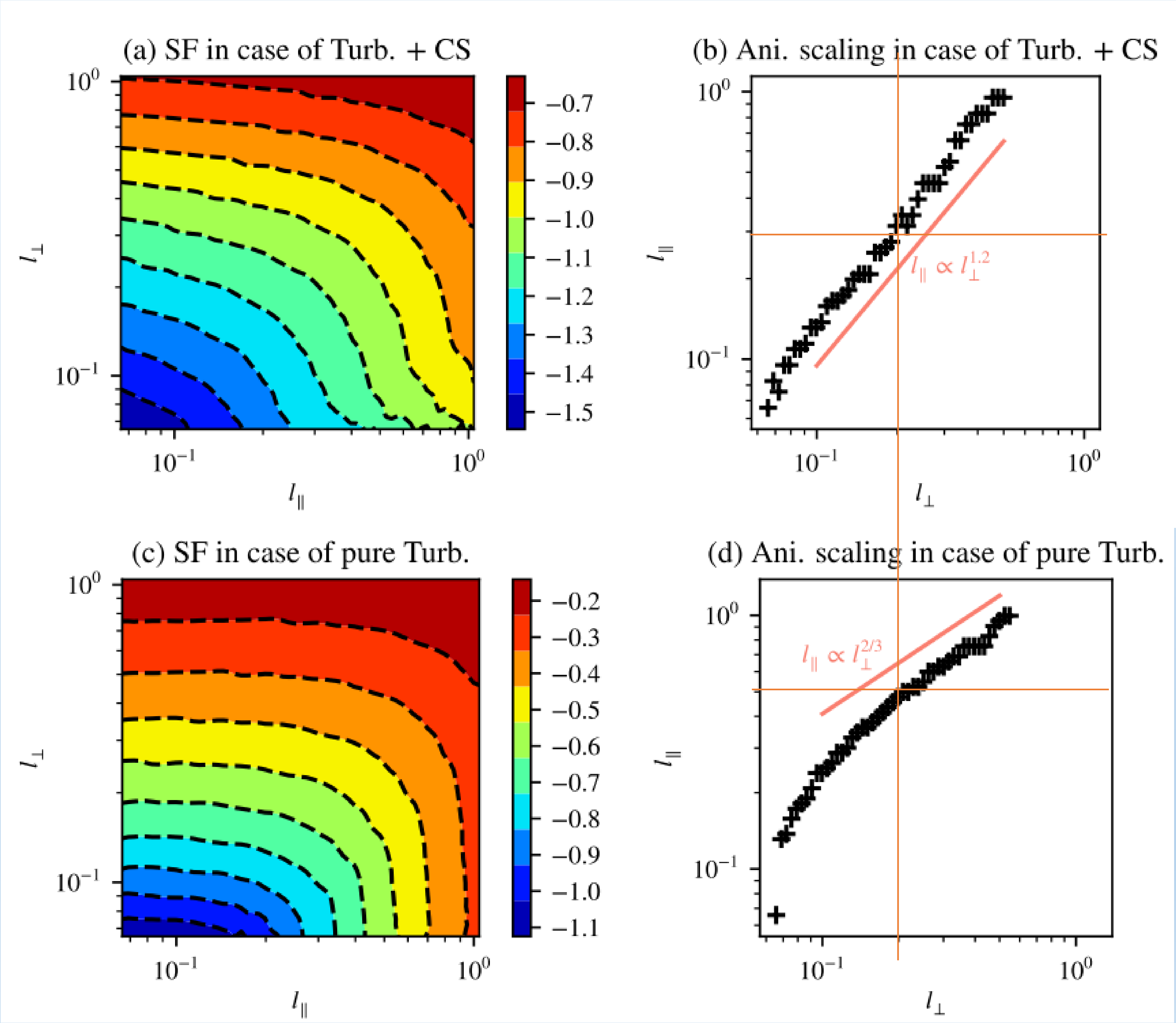
Variation of rate with Lundquist number S and Alfven Mach number M_A



little dependence of the reconnection rate on S, but a strong dependence of M_A, consistent with LV99 model

Anisotropy of the fully developed turbulence

2D structure functions in local reference frame



Weaker anisotropy than that of turbulence withour CS

Summary

(1) the normalized global reconnection rate can be about $0.02 - 0.1$, with the driver ranging from 0 to moderate value.

(2) the rate is nearly independent on Lundquist number, proving that occurs fast turbulent reconnection

(3) classic X-point inflow/outflow picture is preserved and magnetic flux ropes (plasmoids in 2D) are hierarchically formed and ejected.

(4) the reconnected magnetic field lines follows a super-diffusion, from which the rate is nearly the same values as that obtained from the mixing of traced populations.

(5) large opening angle induced by the super-diffusion of turbulent field lines seems to make reconnection fast, although flux ropes are frequently produced.

Thanks for your attention!