Extended Magnetic Reconnection in Kinetic Plasma Turbulence

Tak Chu Li[1], Yi-Hsin Liu[1], and Yi Qi[2], and Muni Zhou[3]

[1]Dartmouth College

[2]LASP, U Colorado Boulder

[3]IAS, Princeton

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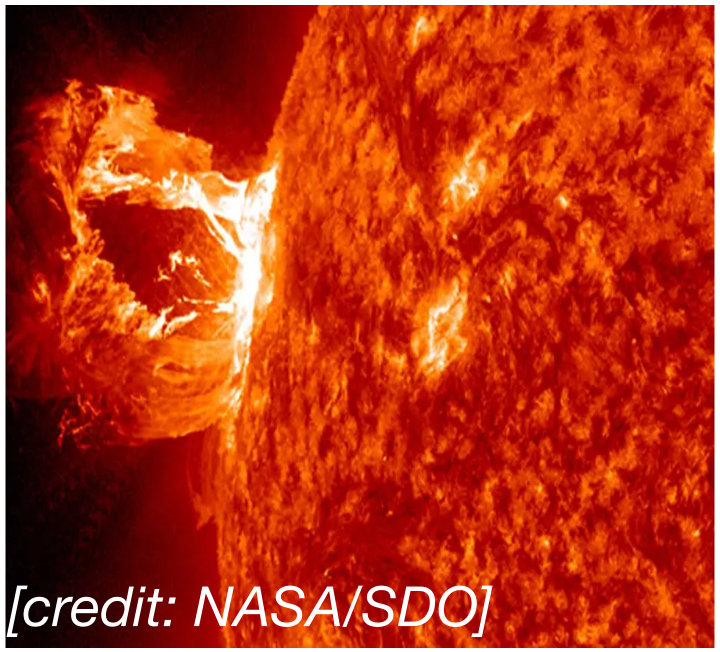
tak.chu.li@dartmouth.edu

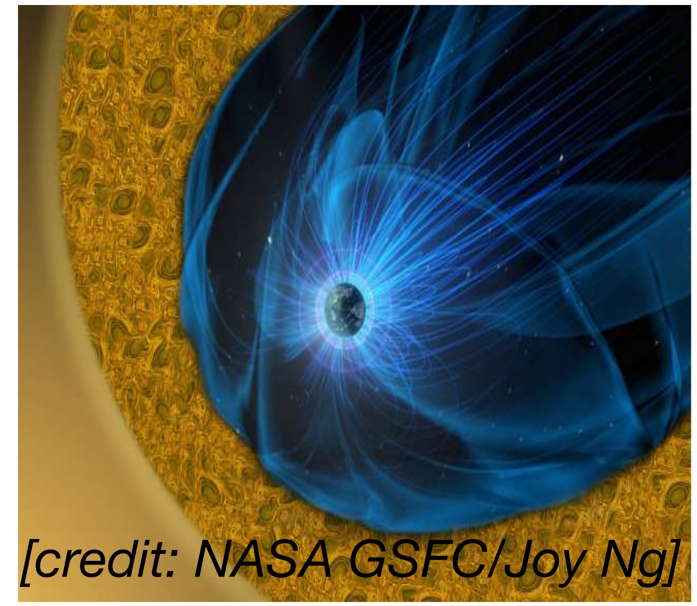
Reconnection and turbulence are ubiquitous in the universe

Solar corona



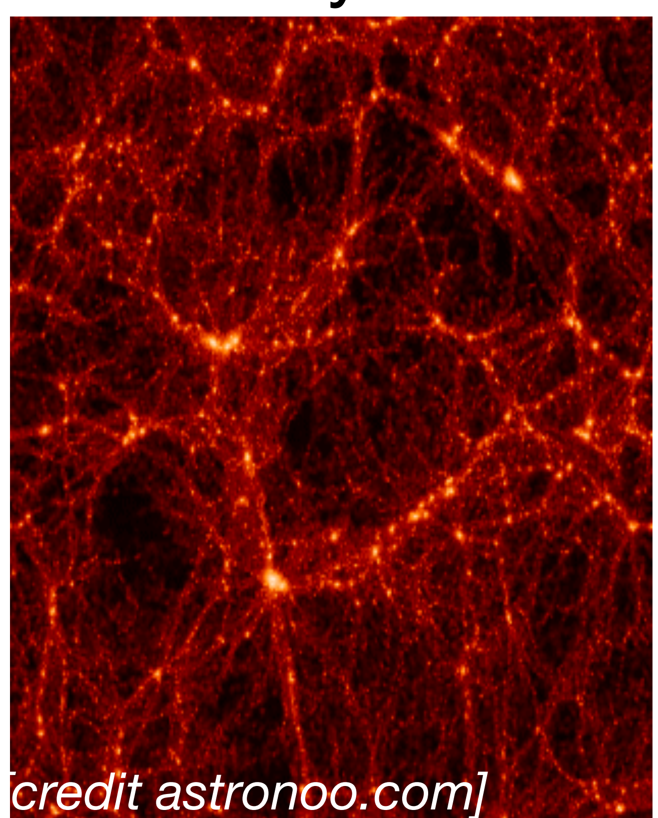
Solar wind

Earth's magnetosheath

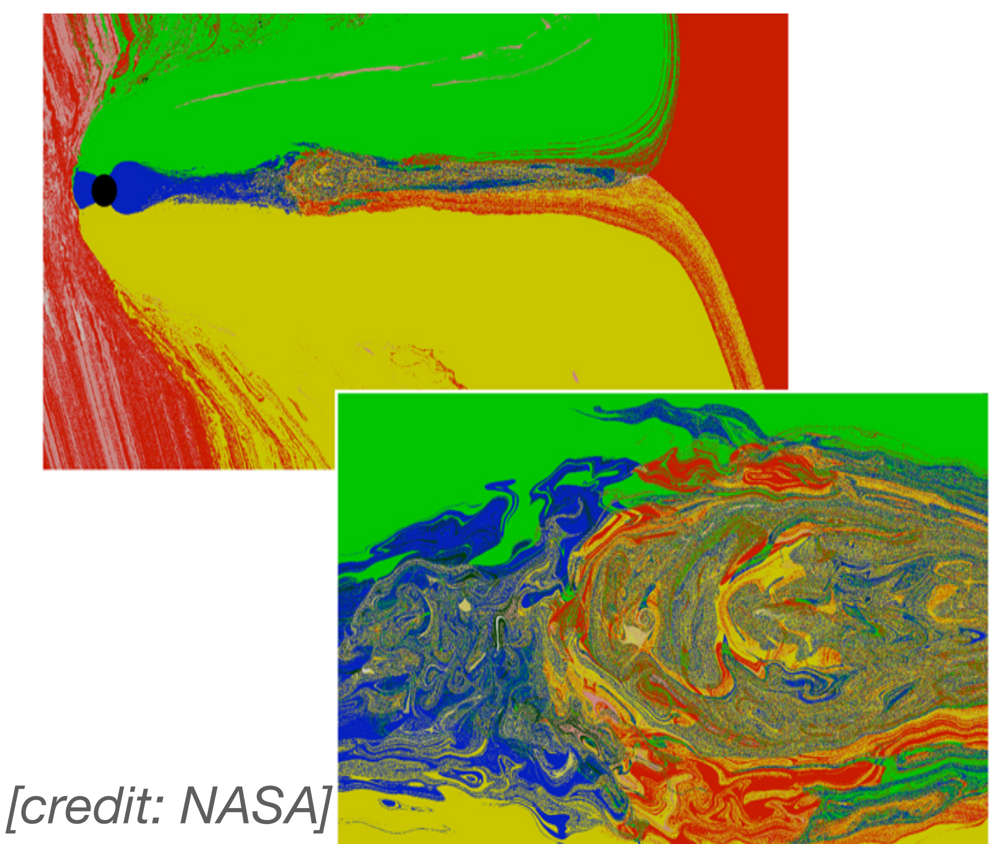


Supernova remnant

Galaxy cluster



Earth's magnetotail



[credit: NASA]

Magnetic reconnection in turbulence

- The general problem of reconnection in magnetized turbulence is a topic of extensive research, particularly in large scale systems [*Lazarian et al 2020*]
- Here we focus on the small scale limit of this problem, where fundamental properties of reconnection are largely unknown.

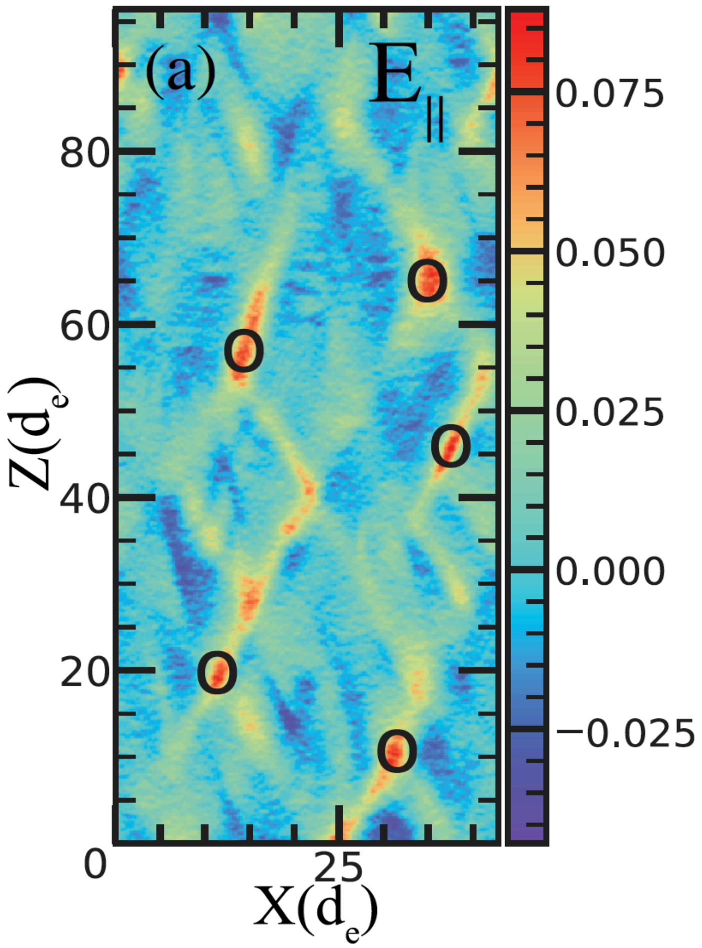
Spatial distribution of reconnection in turbulence

- At **Large scales**, reconnection associated with interplanetary CMEs can be extended over 10^4 ion gyroradii [*Phan et al, 2006, 2009, Eastwood et al 2021*]

- At **Kinetic scales**, an abundance of current sheets was observed by PSP and Wind, consistent with generation by a turbulent cascade [*Vasko et al, ApJL 2022, Lotekar et al, ApJ, 2022*]. Reconnection detection was limited by instrument resolution.

- At **Electron scales,** 3D kinetic simulation [*Pyakurel et al, PRL 2021*] indicated patchy electron reconnection X-lines with extents limited to ~10 electron gyroradii in laminar plasmas.

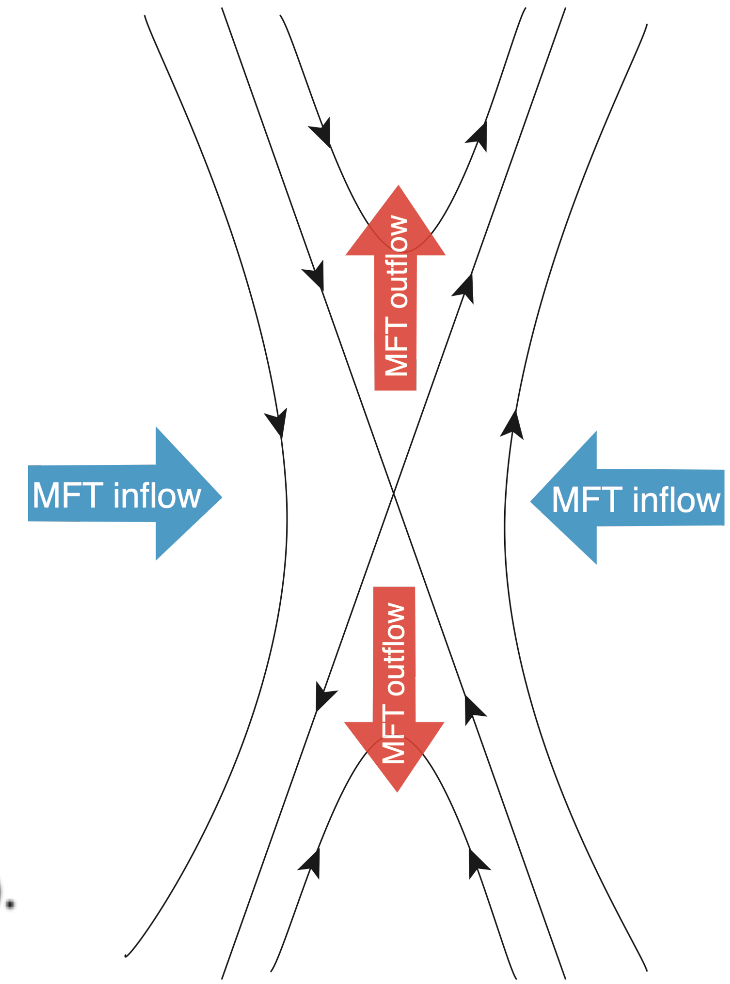
Electron reconnection



The spatial distribution of reconnection in kinetic-scale turbulence and the underlying physics are currently unknown.

Using the Magnetic Flux Transport (MFT) Method to identify active reconnection

Inflow & outflow of magnetic flux defines reconnection *[Vasyliunas 1975]*



Magnetic field given by an in-plane and out-of-plane component in quasi-planar reconnection:

$$\mathbf{B} = \hat{z} \times \nabla\psi + B_0\hat{z}$$

Faraday's law

Electron momentum equation

Advection equation of magnetic flux

Then the **flux transport velocity** is:

$$\mathbf{U}_\psi \equiv \underbrace{\mathbf{v}_{ep} - (\mathbf{v}_{ep}\cdot\hat{b}_p)\hat{b}_p}_{\text{perpendicular in-plane electron flow}} - \underbrace{\frac{cE'_{ez}}{B_p}(\hat{b}_p \times \hat{z})}_{\text{slippage due to non-ideal E field}} \;\Rightarrow\; \boldsymbol{U}_\psi = \frac{cE_z}{B_p}(\hat{\boldsymbol{z}} \times \hat{\boldsymbol{b}}_p).$$

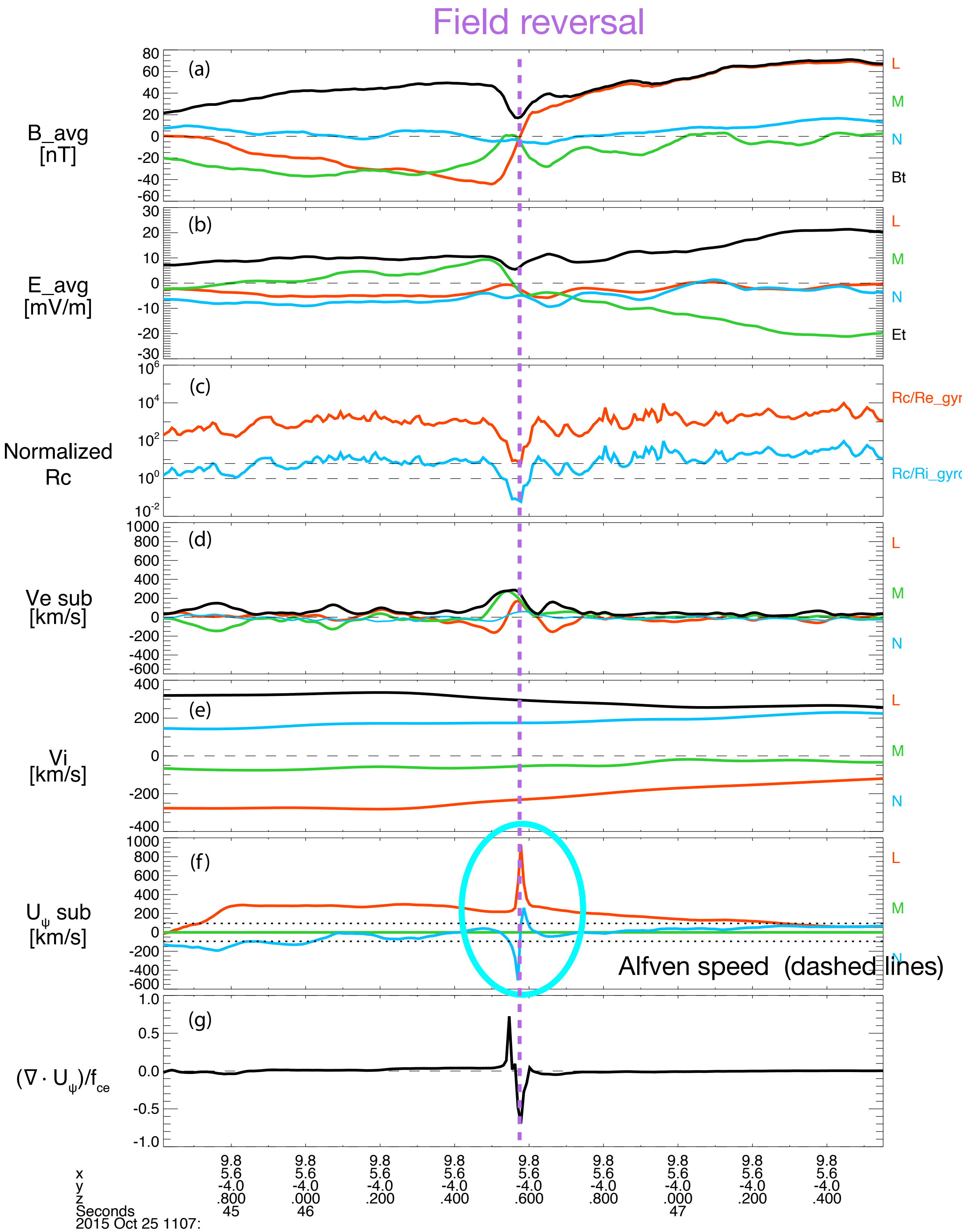
perpendicular in-plane electron flow   slippage due to non-ideal E field

$$B_p \equiv \sqrt{B_x^2 + B_y^2} \qquad \hat{b}_p \equiv \mathbf{B_p}/B_p$$

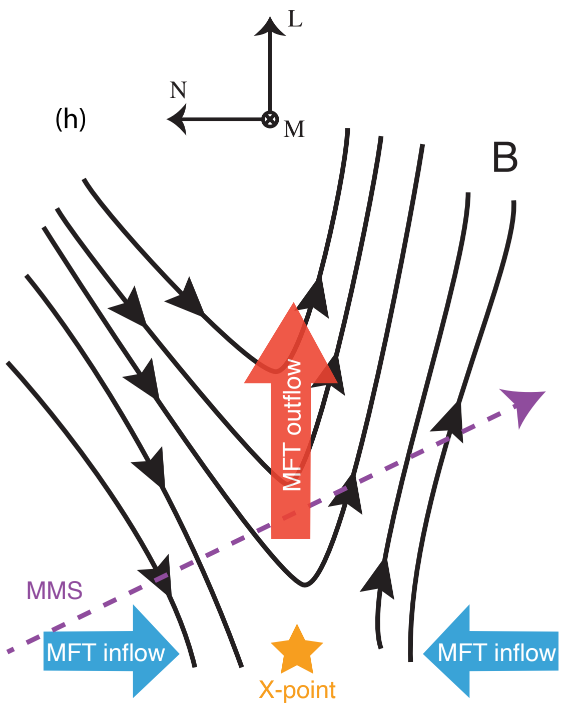
Liu et al., 2018

MFT demonstrated in simulations *[Li et al 2021, Ng et al 2022]* and observations *[Qi et al 2022, Wang et al 2023]*

Example of of a successfully identified reconnection site



- 2015 Oct 25 event (Eriksson et al 2018) in the turbulent magnetosheath
- Interpreted as reconnection in an extended current sheet
- (f) Bi-directional inflow MFT jets and super-Alfvenic outflow jet
- (g) Divergence of MFT ~ order Ω_{ce}
- Result consistent with simulation



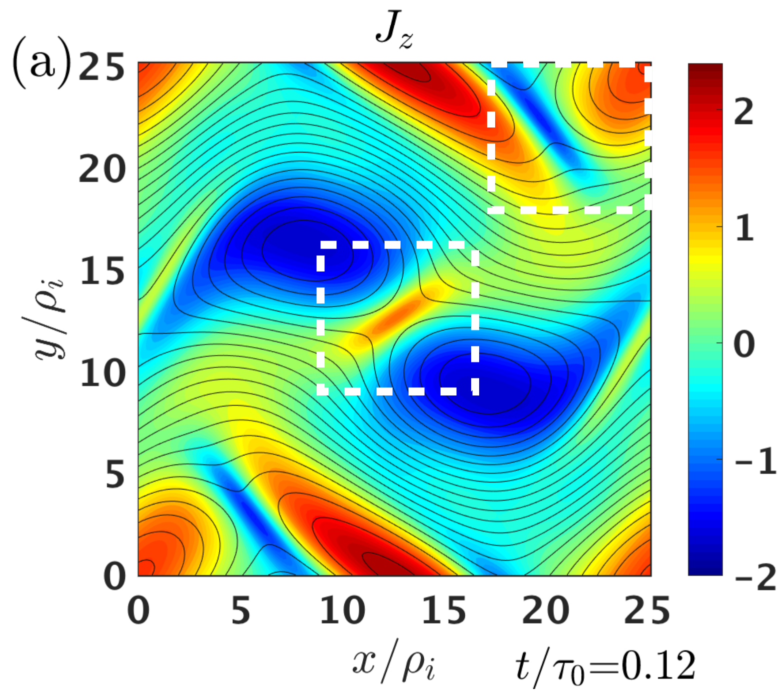
Demonstrated the capability of the MFT method in observations

Yi Qi et al, ApJL, 2022

Simulation setup

- 3D generalization of the classic 2D Orszag-Tang Vortex (OTV) problem
- This 3D setup consists of counter-propagating Alfvén waves along the background magnetic field **B** = $B_0\hat{z}$
- Details of setup and parameters given in *Li et al, ApJL,2016*
- Plasma beta = 0.01, m_i/m_e = 25, T_i/T_e = 1
- Dynamic range: $0.25 \leqslant k_\perp \rho_i \leqslant 10.5$ or $0.05 \leqslant k_\perp \rho_e \leqslant 2.1$
- Gyrokinetic: B_0 >> fluctuations (strong guide field limit)
- Normalization: ion gyroradius, electron thermal speed, domain turnaround time
    - Divergence of MFT normalized to $v_{te}/\rho_e = \Omega_{ce}$

2D OTV



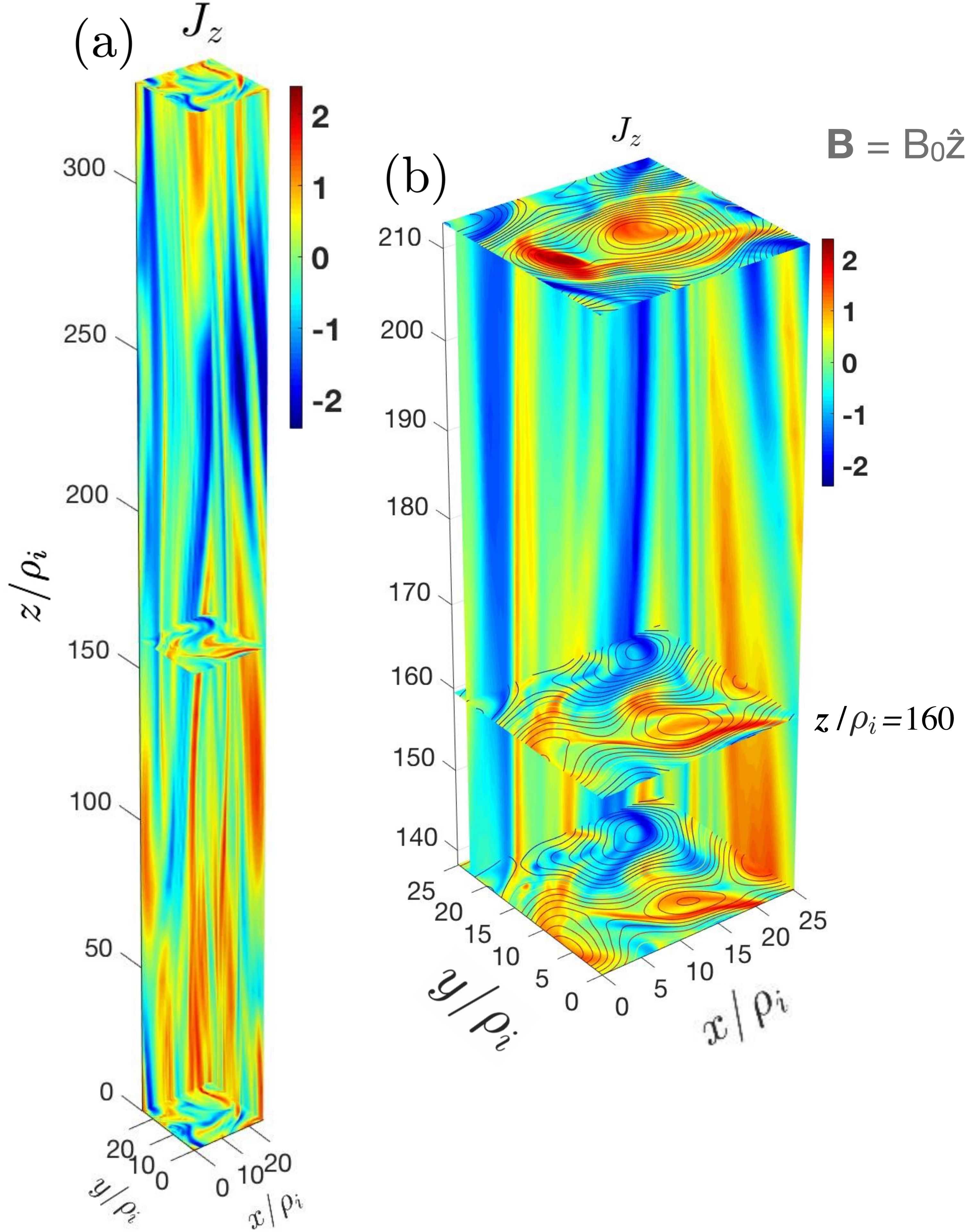
[Li et al 2021]

Reconnection Identification

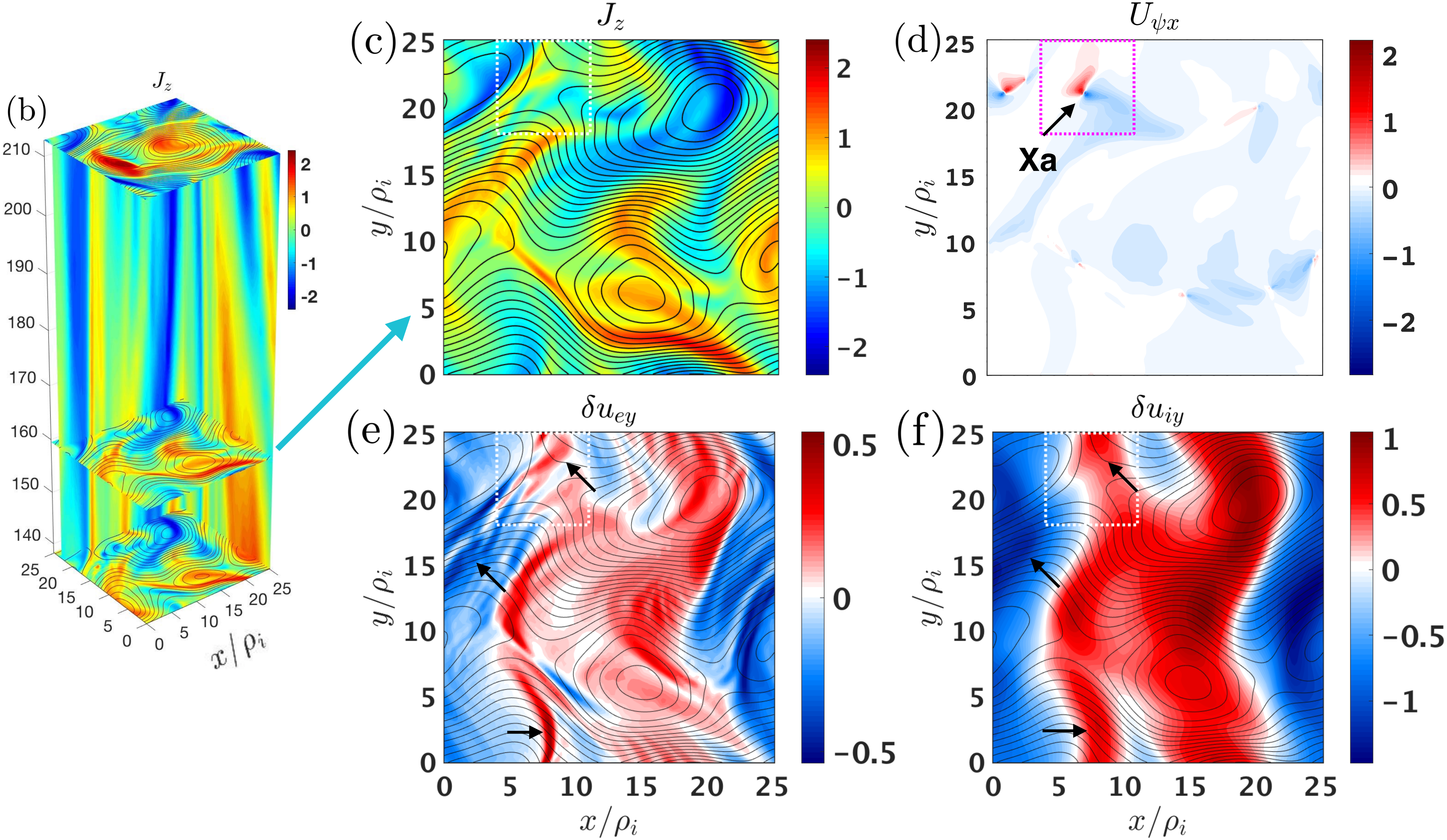
J_z at t = 0.34: a time of strong reconnection activity and energy dissipation.

A turbulent cascade at kinetic scales of $k_\perp \rho_i > 1$ has developed.

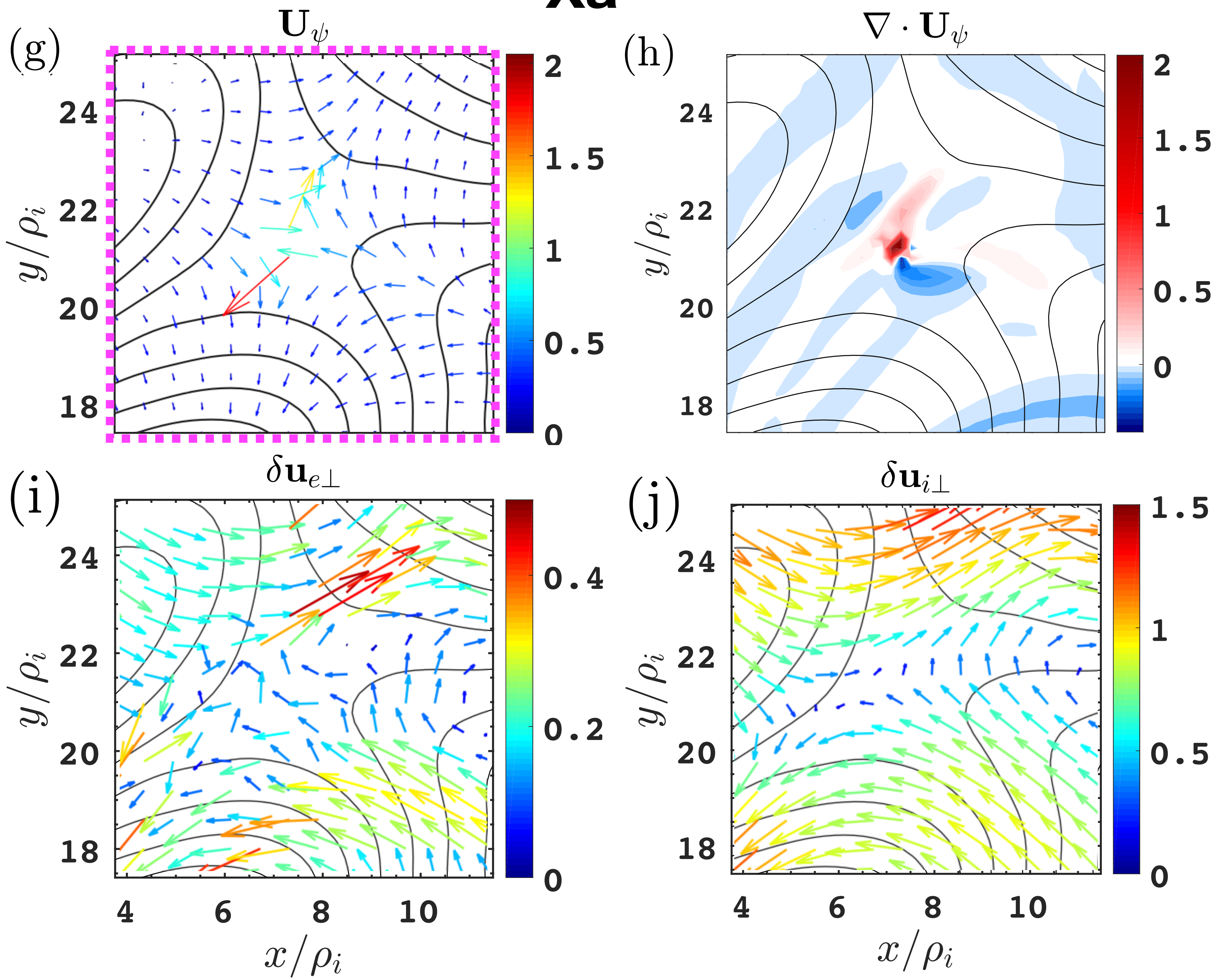
Elongated current channels consistent with turbulent anisotropy.



Reconnection Identification

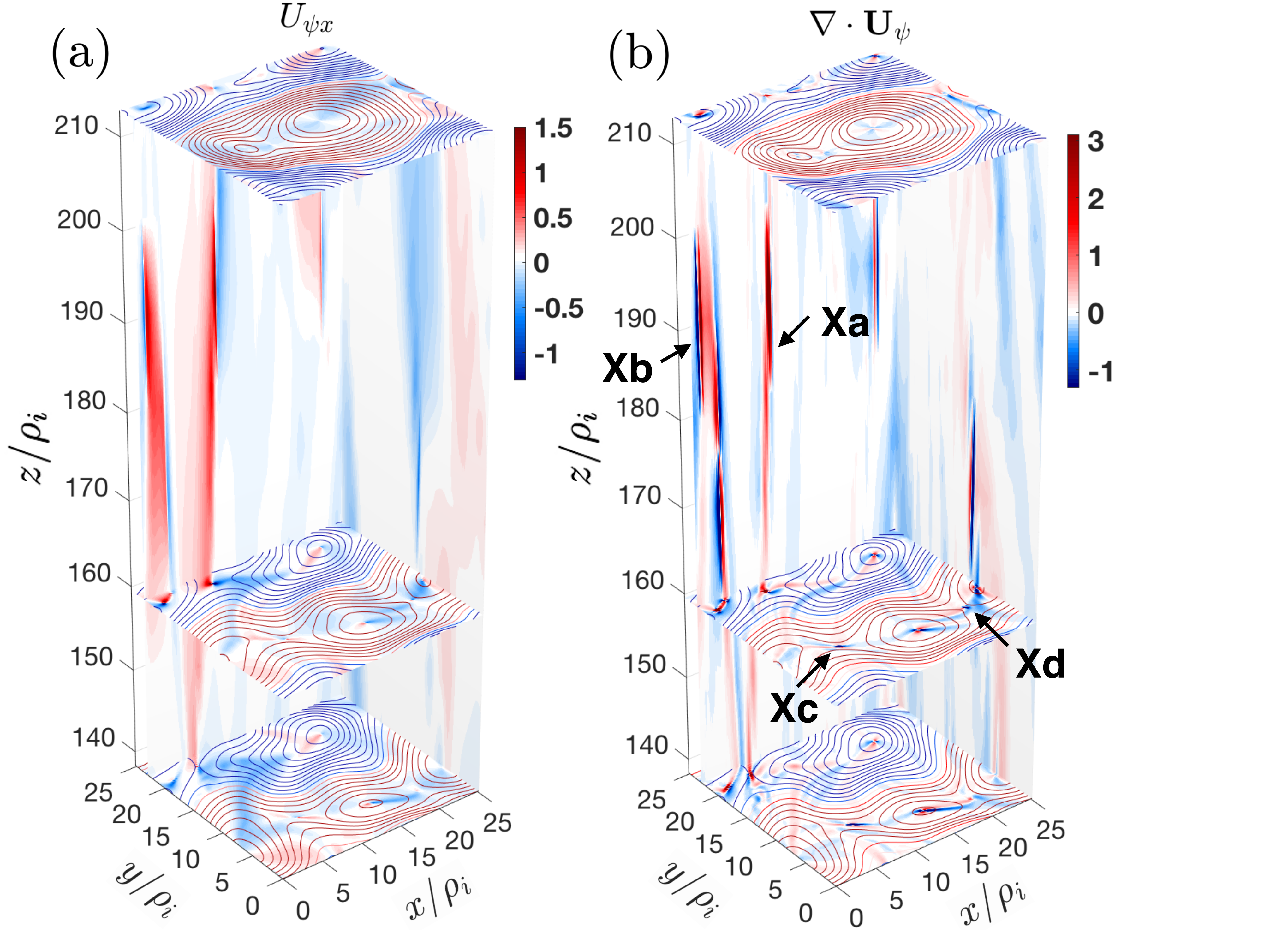


Xa



- (g-h) $\mathbf{U}_\psi$: clear MFT inflows and outflows, and $\nabla \cdot \mathbf{U}_\psi$: localized positive and negative peaks, as reconnection signature.
- Magnitude consistent with 2D simulation and MMS observations *[Li et al, 2021, Qi et al, 2022]*

Extended reconnection at kinetic scales



Application of MFT to the 3D domain reveals extended reconnection X-lines in kinetic turbulence.

Extended reconnection at kinetic scales

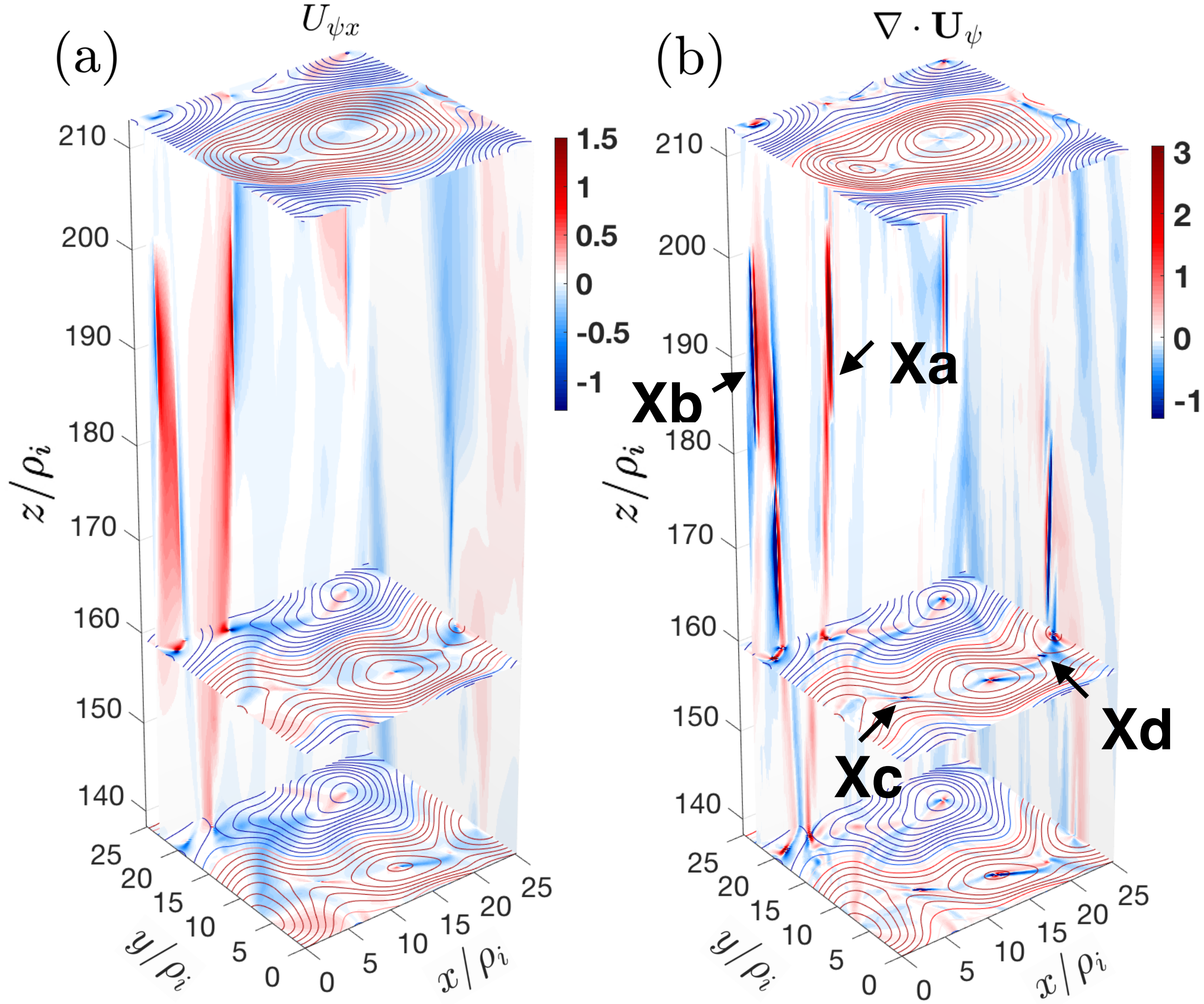


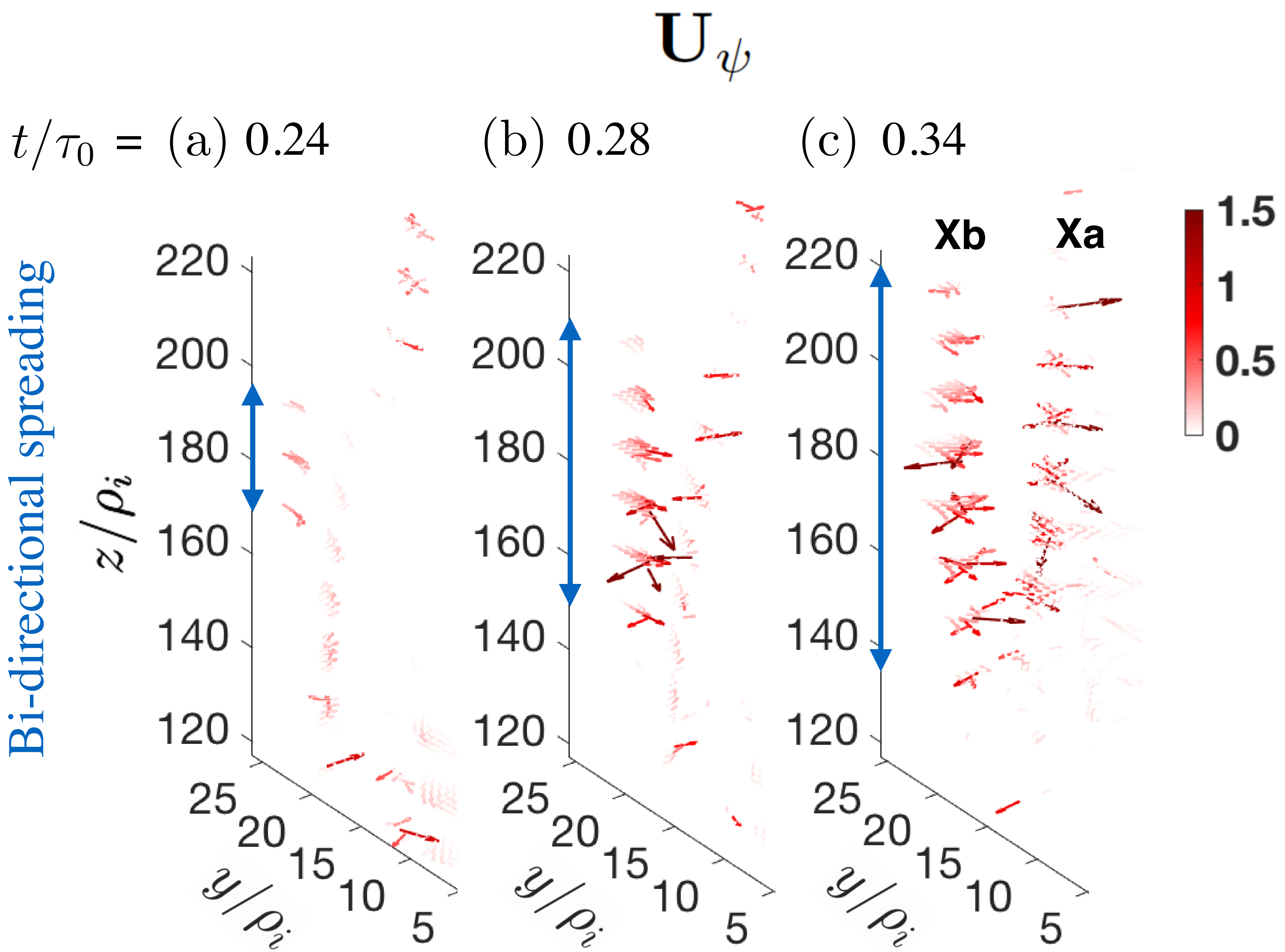
TABLE I. Reconnection X-line extents

X-line	z_{lower}	z_{upper}	Extent (ρ_i)
Xa	130	210	80
Xb	140	200	60
Xc	110	170	60
Xd	130	220	90

We estimate the X-line extents along z from their lower to upper z-ends based on MFT signatures.

How do extended reconnection X-lines develop in kinetic-scale turbulence?

Bidirectional reconnection spreading



Initially localized X-lines develop into extended X-lines through bidirectional reconnection spreading.

Bidirectional reconnection spreading

- Speed of spreading of Xb is estimated to be ~ V_A
- This speed is much higher than the electron current speed of ~0.25 V_A or ion current speed of < 0.1 V_A
- Reconnection spreading was not observed in kinetic turbulence before.
- This result is consistent with with laminar reconnection spreading under a guide field *[Li et al 2020; Shepherd & Cassak 2012].*

Balance of parallel and perpendicular time scales

- Recent MHD simulation of merging (reconnecting) flux tubes shows agreement with critical balance (*Zhou et al, JPP, 2020*)
- **Critical balance**: a balance between parallel and perpendicular time scales of fluctuations in anisotropic turbulence (*Goldreich & Sridhar, 1995*)
- We compare the parallel and perpendicular time scales of Xa:
  - Parallel time scale based on X-line spreading: $\tau_{R\|} \sim 0.1\ \tau_0$
- Perpendicular time scale based on reconnection inflow given by upstream MFT velocity and radius of reconnecitng flux ropes: $\tau_{R\perp} \sim 0.1–0.2\ \tau_0$

$$\tau_{R\|} \sim \tau_{R\perp}$$

Critical balance is satisfied; similarly satisfied for a number of X-lines.

Reconnection X-lines in kinetic turbulence satisfy critical balance.

—> Coherent structures, with their parallel and perpendicular scales related

Summary

- Extended and bi-directionally spreading X-lines
  Our work shows first evidence for **extended magnetic reconnection X-lines in kinetic plasma turbulence**, and extended X-lines developing through **bidirectional reconnection spreading**, reaching extents on the same order of magnitude as the system size.

- Critical balance
  Reconnection in kinetic turbulence satisfies critical balance. This provides a way to predict the extent of reconnection X-lines at a given perpendicular scale.

- Our results present a picture of fundamentally extended reconnection in kinetic-scale turbulence.

Future work could explore

- How does reconnection distribute in electron-scale turbulence?
- How do the properties of reconnection change with turbulent conditions?
- What is the contribution of reconnection to turbulent heating?

References

- Tak Chu Li , Yi-Hsin Liu, and Yi Qi, "Identification of Active Magnetic Reconnection Using Magnetic Flux Transport in Plasma Turbulence," ApJL, 2021
- Yi Qi et al, "Magnetic Flux Transport Identification of Active Reconnection: MMS Observations in the Earth's Magnetosphere," ApJL, 2022
- Li et al, "Extended Magnetic Reconnection in Kinetic Plasma Turbulence," in press, PRL (arxiv.org/pdf/2303.08642)

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tak.chu.li@dartmouth.edu