New opportunities and insights on magnetic reconnection in turbulent plasmas

Tak Chu Li
Dartmouth College

Collaborators: Luca Bucilli, Yi-Hsin Liu, Yi Qi

2nd European Conference on MR in Plasmas
June 17, 2025

Supported by NSF

tak.chu.li@dartmouth.edu

Fundamentals of the Magnetic Flux Transport (MFT) method

Fundamentals of the Magnetic Flux Transport (MFT) method

Express the magnetic field in terms of a background and fluctuating components parallel and perpendicular to the background:

$$\mathbf{B} = B_0\hat{\mathbf{z}} + \delta\mathbf{B}_\perp + \delta B_{||}\hat{\mathbf{z}}$$

Assume $k_{||} \ll k_\perp$, wavenumber of length scale of variation parallel and perpendicular to the background field. Consider Guass Law:

$$\nabla \cdot \mathbf{B} = \nabla_\perp \cdot \delta\mathbf{B}_\perp + \partial_z \delta B_{||} = 0$$

$$\sim k_\perp \qquad \sim k_{||}$$

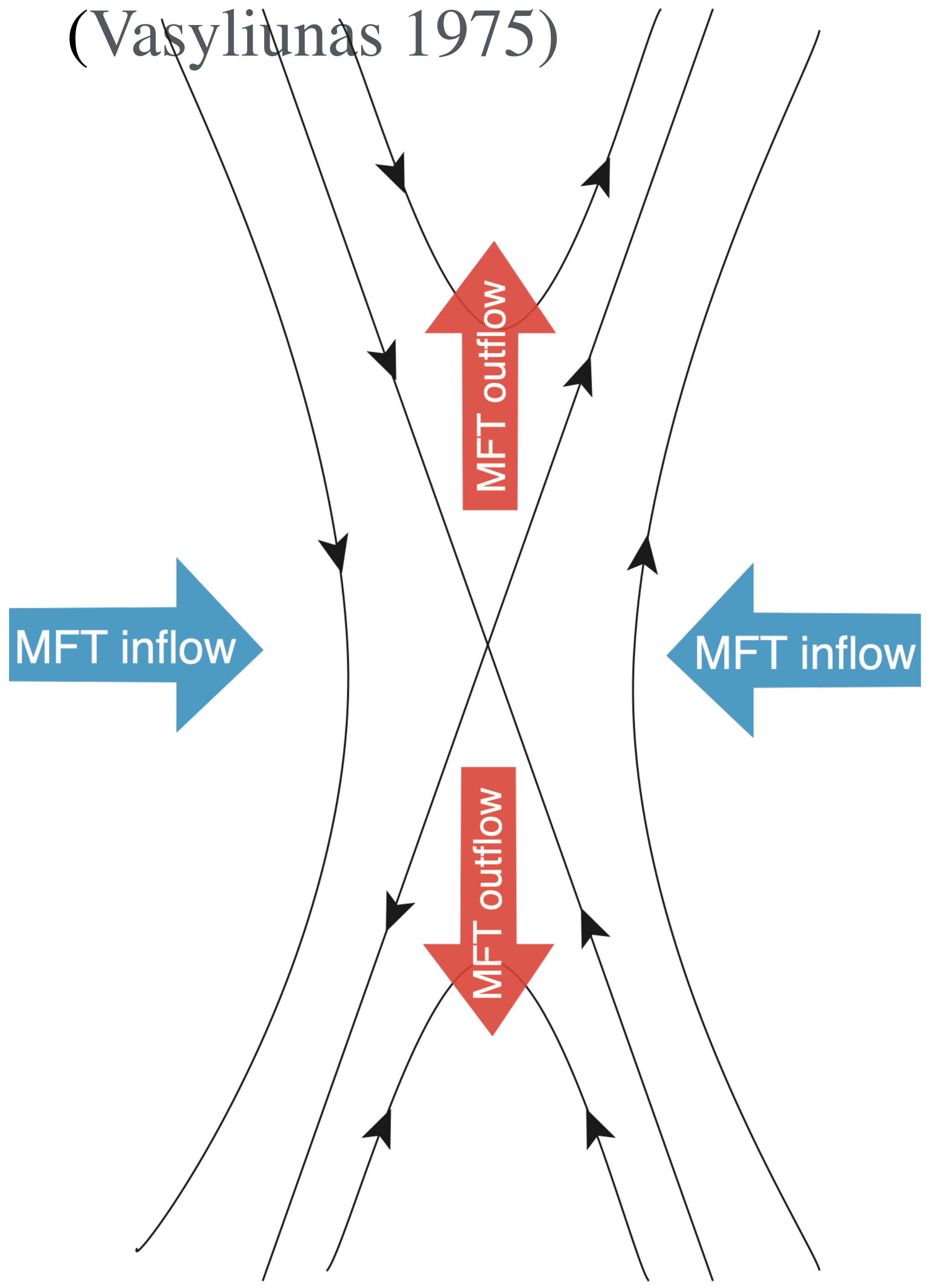
To the leading order, $\nabla_\perp \cdot \delta\mathbf{B}_\perp = 0$ —> 3D magnetic field is 2D solenoidal

Magnetic flux velocity is:

Then $\delta\mathbf{B}_\perp = \hat{\mathbf{z}} \times \nabla\psi$ → $\mathbf{U}_\psi = (\delta E_z/\delta B_\perp)(\hat{\mathbf{z}} \times \delta\hat{b}_\perp)$

$\delta\hat{b}_\perp \equiv \delta\mathbf{B}_\perp/\delta B_\perp$

Inflow & outflow of magnetic flux defines reconnection (Vasyliunas 1975)



Fluid quantity

Li+ 2025 ApJ, 2021 ApJL, 2023 PRL, Liu+ 2018 POP, Liu & Hesse 2016 POP

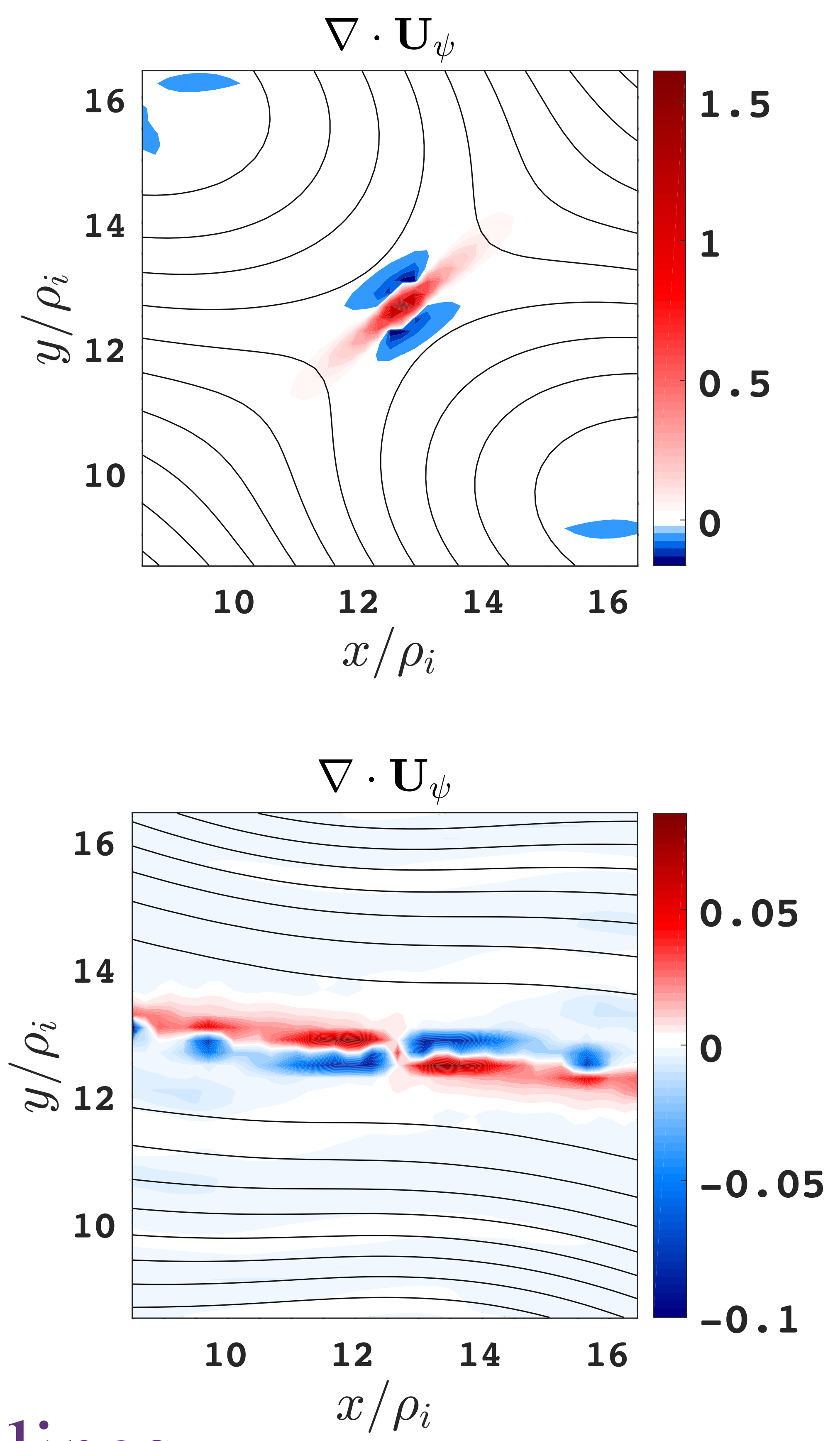
Signature for active reconnection in the divergence of MFT

$$\mathbf{U}_\psi = (\delta E_z/\delta B_\perp)(\hat{\mathbf{z}} \times \delta\hat{b}_\perp)$$

$$\nabla \cdot \mathbf{U}_\psi \begin{cases} < 0 \text{ (converging inflows)} \\ > 0 \text{ (diverging outflows)} \end{cases}$$

- Scalar defined on the perpendicular plane
- <u>Bipolarity at an X-line as signature for active reconnection</u>

Examples of $\nabla \cdot \mathbf{U}_\psi$ at reconnection X-lines



Positive and negative polarity in the divergence is present at reconnection X-lines. <u>Signatures in both the velocity and divergence of MFT coexist</u>. Either one can identify reconnection.

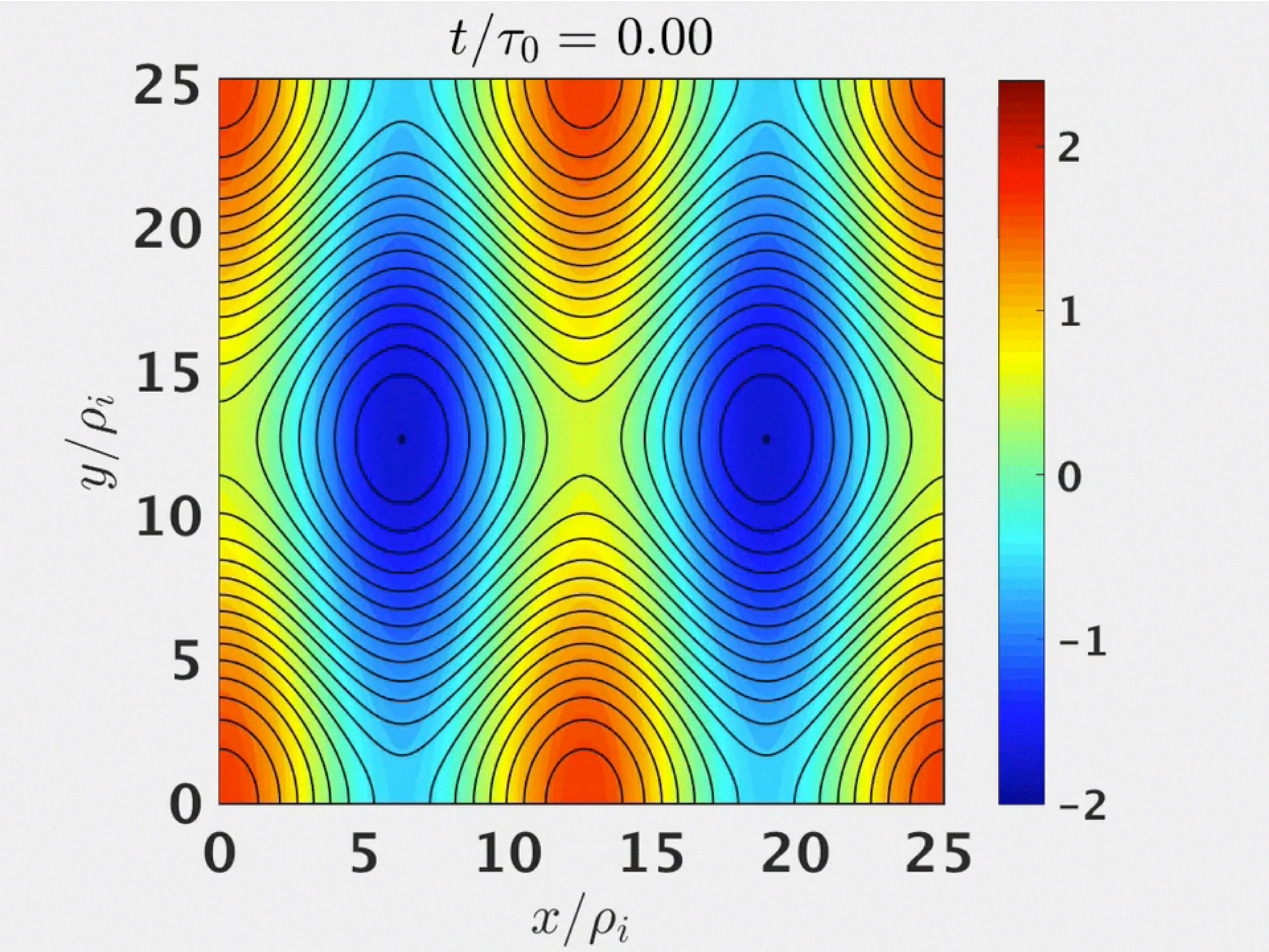
Li+ 2021 ApJL

Reconnection in 2D kinetic turbulence

Orszag-Tang Vortex

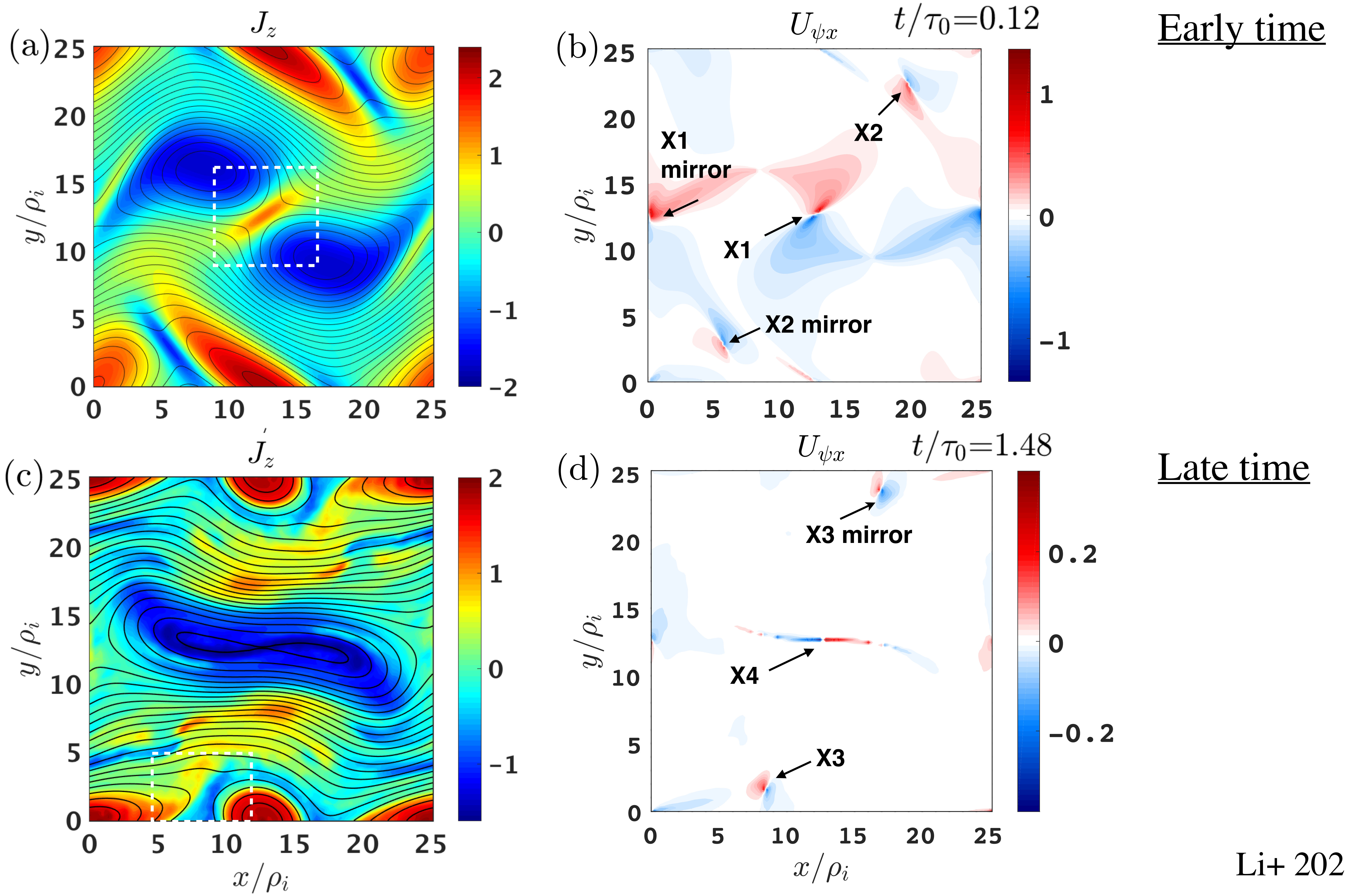
Plasma beta = 0.01

dB << B_0



Li+ 2021 ApJL

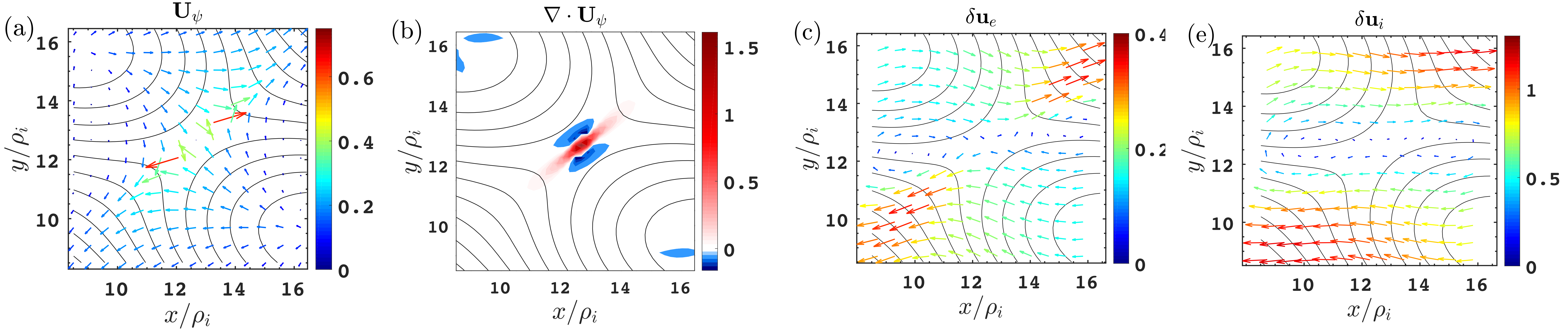
Reconnection in 2D kinetic turbulence



Li+ 2021 ApJL

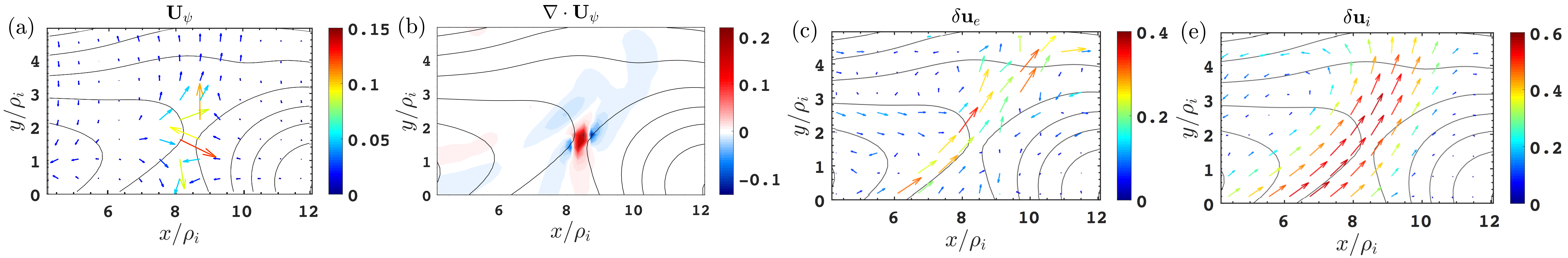
Examples of MFT signatures for active reconnection in 2D simulation

X1: Symmetric reconnection



Clear MFT signatures for reconnection. Electron jets present. Ion jets are obscured by shear flows.

X3: Asymmetric reconnection with only unidirectional ion and electron outflow jet

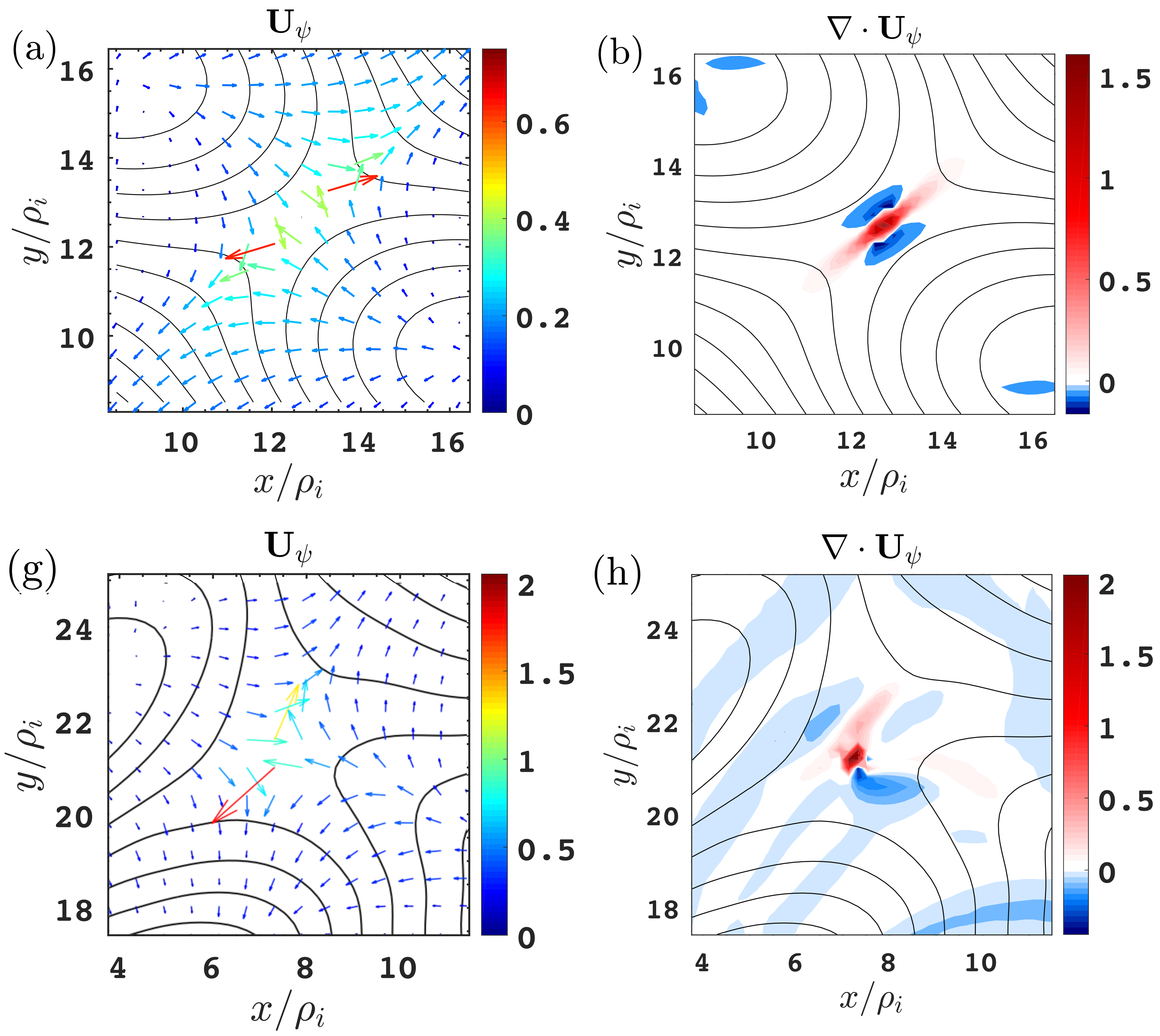


Clear MFT signatures for reconnection. Bidirectional ion or electron outflow jets are suppressed.

MFT signatures in 2D and 3D turbulence

2D

3D



Li+ 2023 PRL

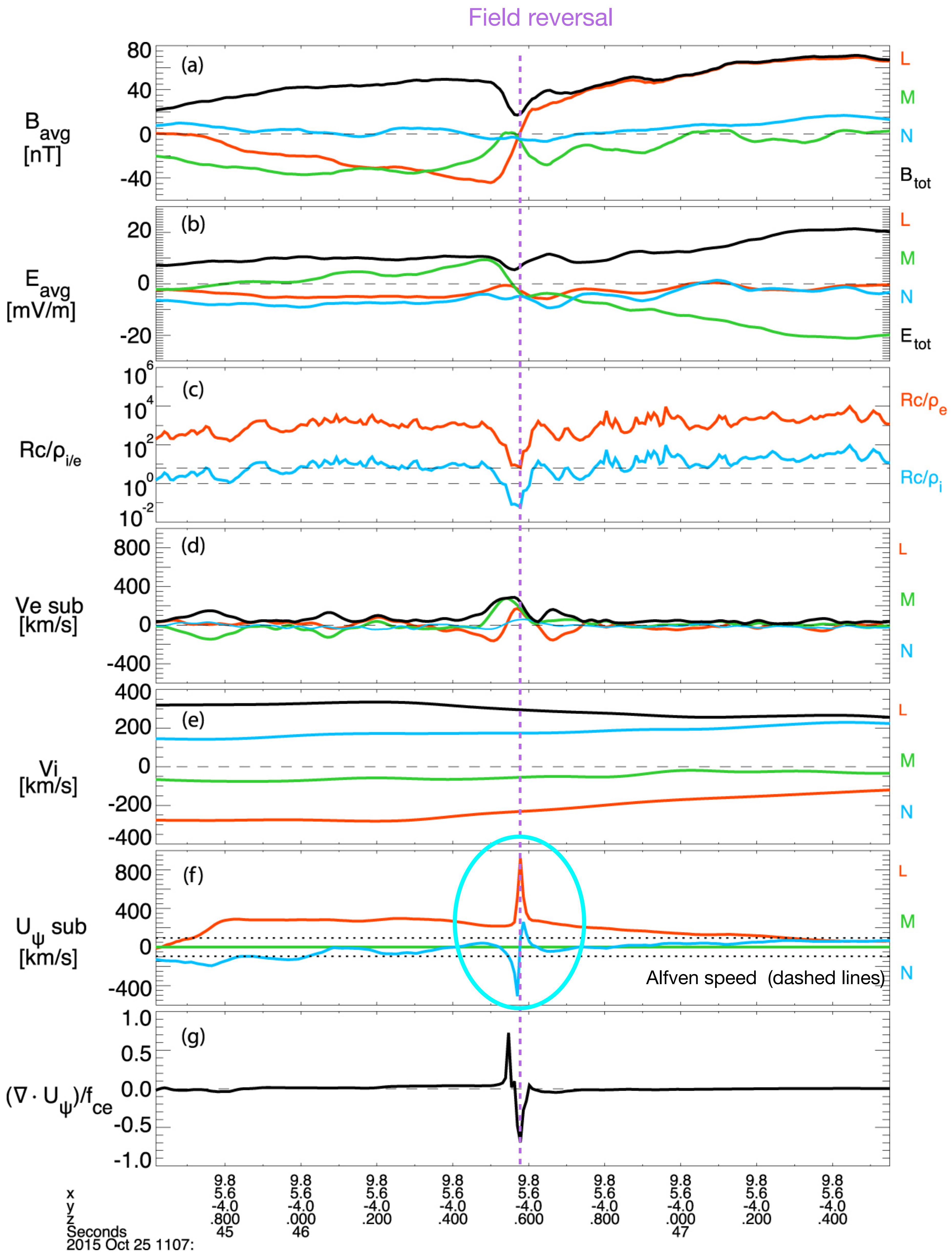
Similar MFT signatures for reconnection in both quantities in 2D and 3D

More irregular in 3D as expected

Consistent magnitude of the divergence of MFT in 2D and 3D

Divergence normalized to $v_{te}/\rho_e = \Omega_{ce}$

Verifying MFT signatures in space observations

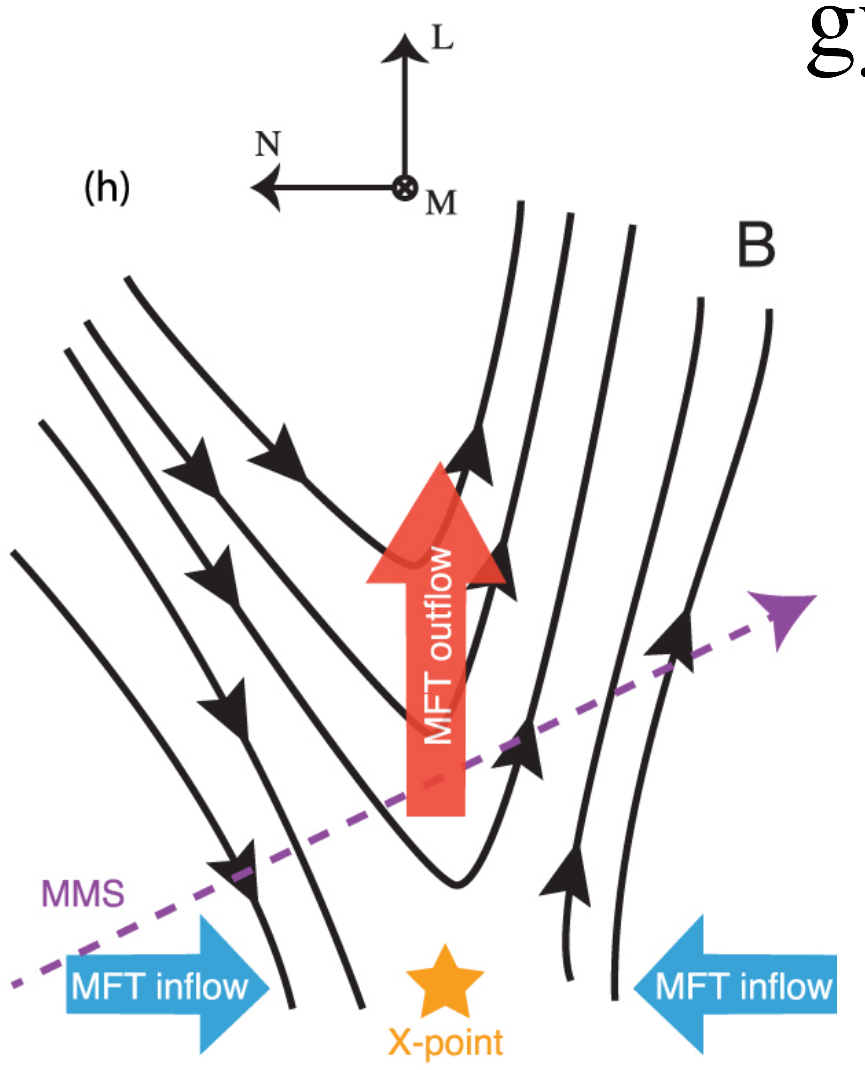


MMS observation in magnetosheath turbulence

MFT signatures measured in a reconnection event in the turbulent magnetosheath (Eriksson+ 2018)

(f) Bi-directional MFT inflow jets and uni-directional outflow jet

(g) Divergence of MFT ~ order electron gyro frequency



Qi+ 2022 ApJL, Hasegawa+ 2024 SSR

Measurements of 37 reconnection events in the magnetosphere under varied conditions

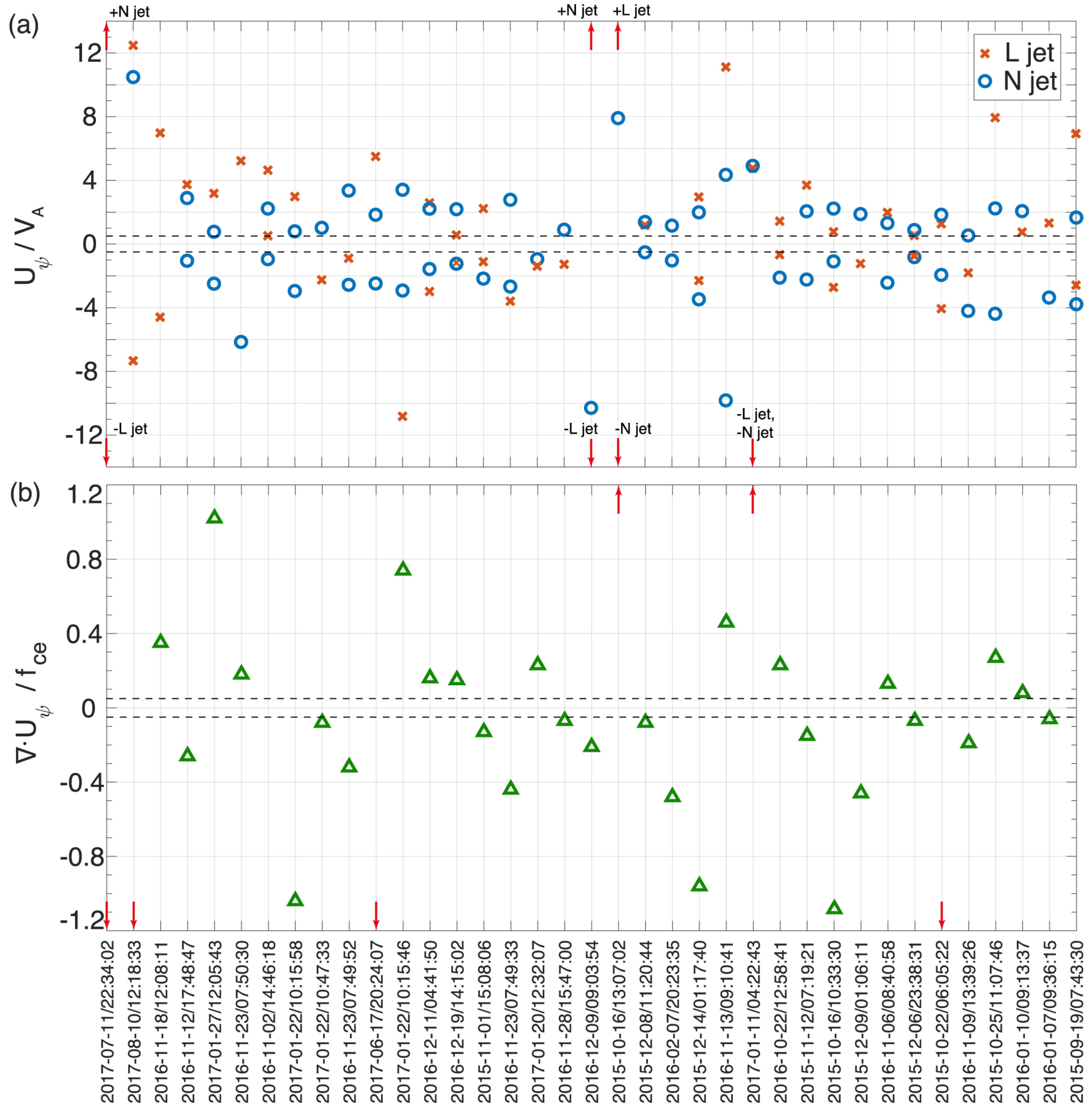
Table 1
Event List of EDR/Reconnection-line Crossings

Date and time	Location	Guide Field	Type	Spacecraft Separation [de]	Reference
2015-10-16 13:07:02	Day side	$\sim$0	Classic	$\sim$6	Burch et al. (2016)
2015-12-08 11:20:43	Day side	$\sim$1	Classic	$\sim$6	Burch & Phan (2016)
2015-12-06 23:38:31	Day side	$\sim$0.2	Classic	$\sim$10	Khotyaintsev et al. (2016)
2015-10-25 11:07:46	Sheath	$\sim$0.5	Classic	$\sim$20	Eriksson et al. (2018)
2016-12-09 09:03:54	Sheath	$>$5	Electron-only	$\sim$5	Phan et al. (2018)
2016-11-09 13:39:26	Shock transition region	$\sim$0	Classic	$\sim$16	Wang et al. (2019)
2017-07-11 22:34:02	Tail	$\sim$0	Classic	$\sim$1	Torbert et al. (2018)
2017-06-17 20:24:07	Tail	$\sim$0	Electron-only	$\sim$4	Lu et al. (2020)
2017-08-10 12:18:33	Tail	$\sim$0.1	Classic	$\sim$2	Zhou et al. (2019)
31 EDRs	Day side	varying	Classic	2-70	Webster et al. (2018)

Qi+ 2022 ApJ

Sample includes weak-to-strong guide fields, varied locations, and electron-only reconnection events.

Magnitude of MFT velocity and divergence



Median of +-L jets is +3.1/−2.3 V_A,
Median of +-N jets is +2.0/−2.5 V_A,

Typical MFT jets are **super-Alfvenic**.

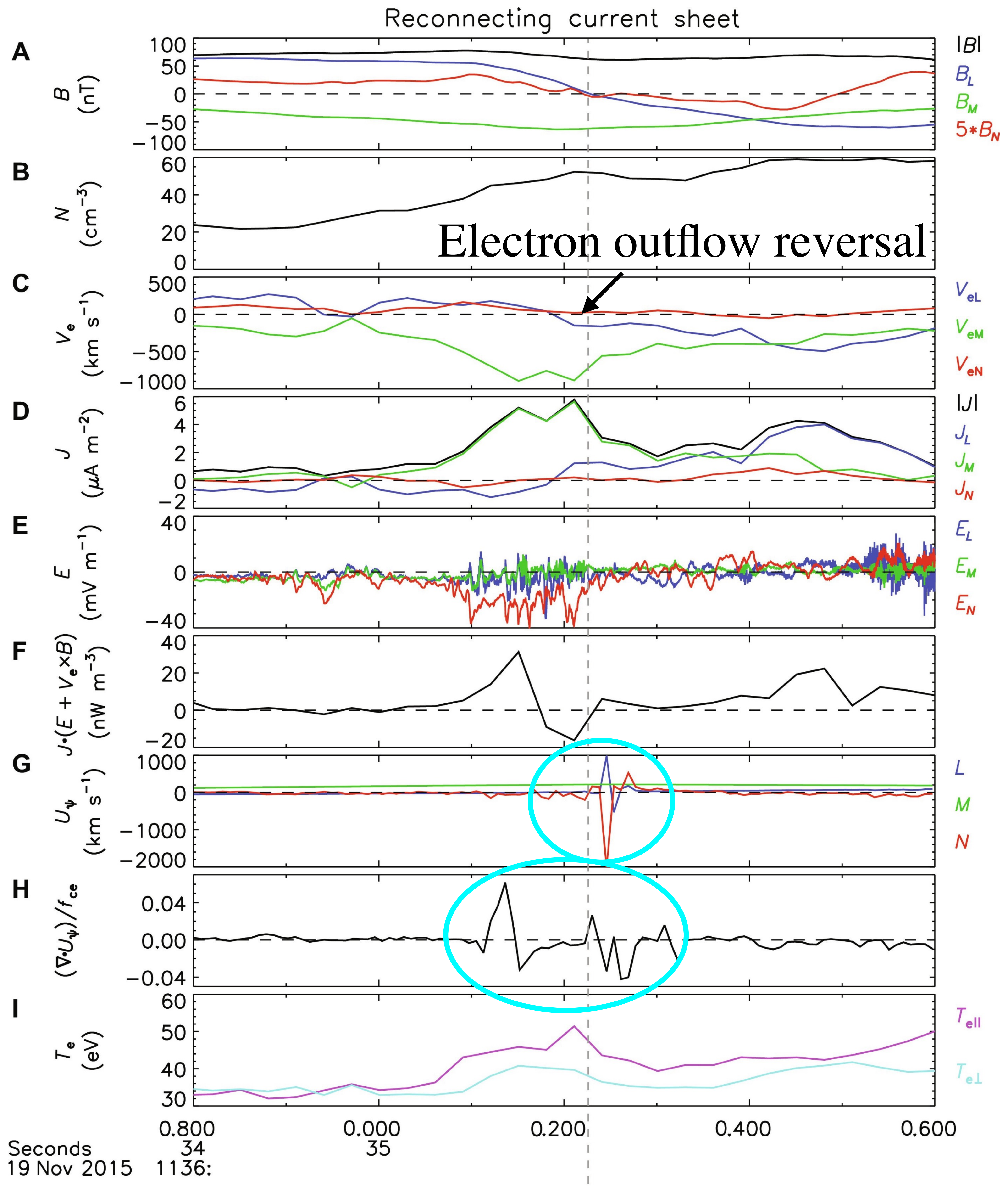
Median of the divergence is 0.3 f_{ce}.

Typical divergence ~ O(0.1) f_{ce} or higher.

The observations are in agreement with 2D and 3D simulations (Li+ 2021, 2023).

New opportunities to decipher reconnection in turbulent plasmas

Direct application to in-situ observations



MMS observation in magnetosheath turbulence

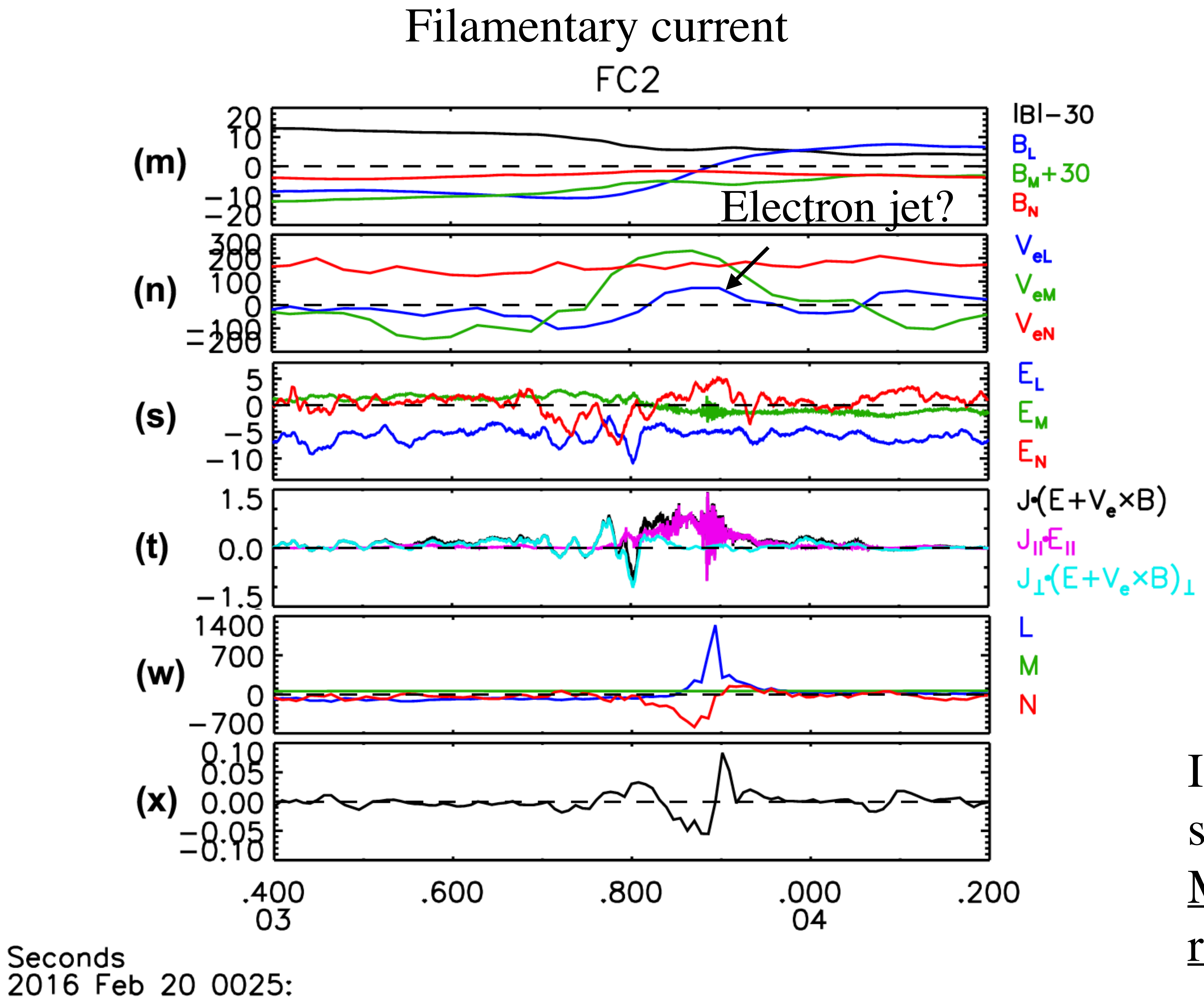
G. Super-Alfvenic MFT inflow and outflow jets

H. Bipolar divergence of MFT ~ 0.05 f_{ce}

In recent observations that links the formation of downstream current sheets to upstream waves across the bow shock, <u>MFT provided secondary evidence for active reconnection.</u>

Wang+ 2024 Sci Adv

Direct application to in-situ observations



MMS observations in magnetic flux ropes

(n) Inconclusive electron jet due to shear flow

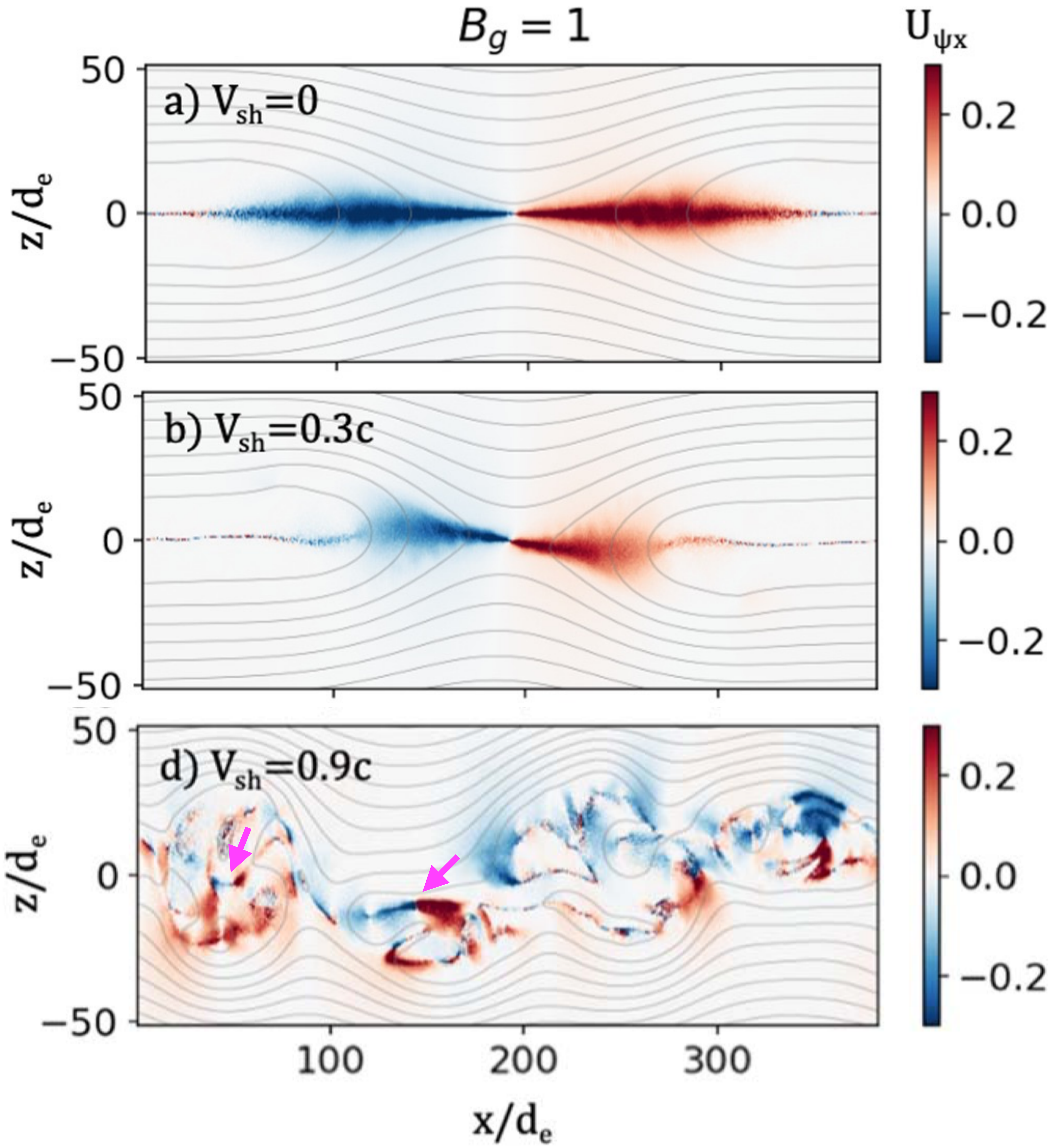
(w) Super-Alfvenic MFT inflow and outflow jets

(x) Bipolar divergence of MFT ~ 0.1 f_{ce}

In a recent work that studies electron acceleration in sub-ion-scale filamentary currents inside flux ropes, MFT provided primary evidence for active reconnection.

Wang+ 2023 GRL

Direct application to kinetic and fluid simulations



Example of an application to PIC

2D simulation of shear-flow reconnection in pair-plasma.

(a, b) For weak shear flows, a single reconnection X-line forms.

(d) For sufficiently strong shear flows, the single X-line is suppressed. Instead, secondary reconnection X-lines form in vortices induced Kelvin-Helmholtz instability.

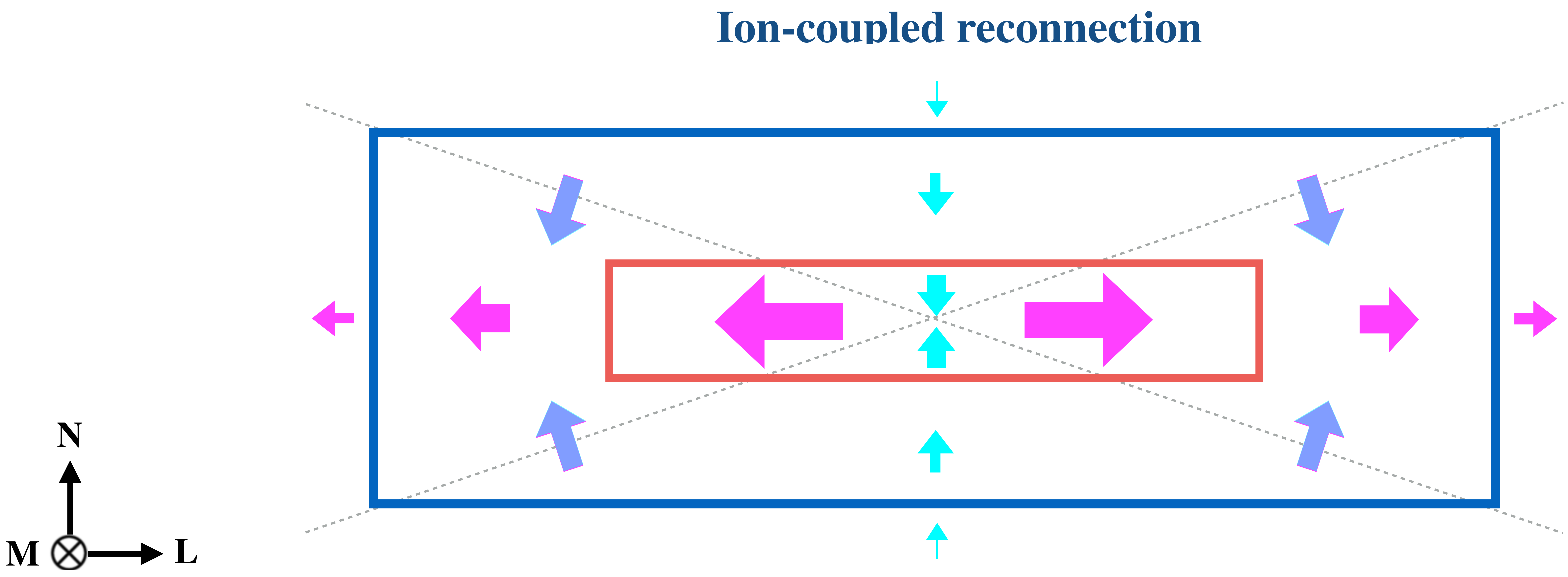
The MFT velocity is much clearer than the electron outflows that are obscured by shear flows.

Peery+ 2024 ApJ

New capability to identify electron-only reconnection

New capability to identify electron-only reconnection

Magnetic field-plasma flow coupling in the diffusion region



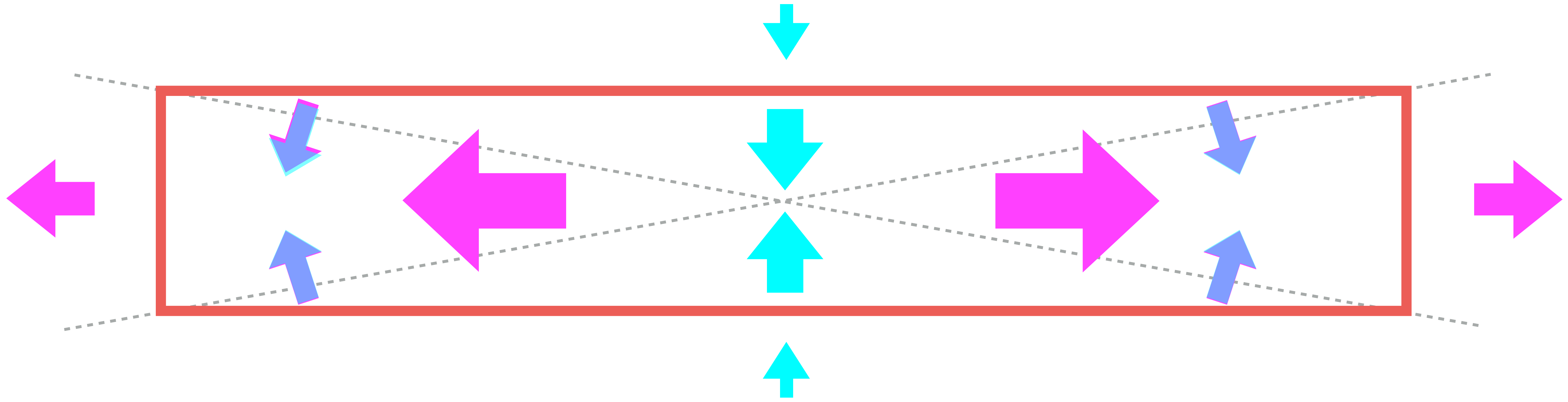
- Decoupling/recoupling of the magnetic field motion with the ion (electron) flow in the IDR (EDR) results in an increase/decrease in the MFT velocity over ion (electron) scale.
- The result is a two-scale structure in the MFT velocity along the normal (N) direction.

Li+ 2025 ApJ

New capability to identify electron-only reconnection

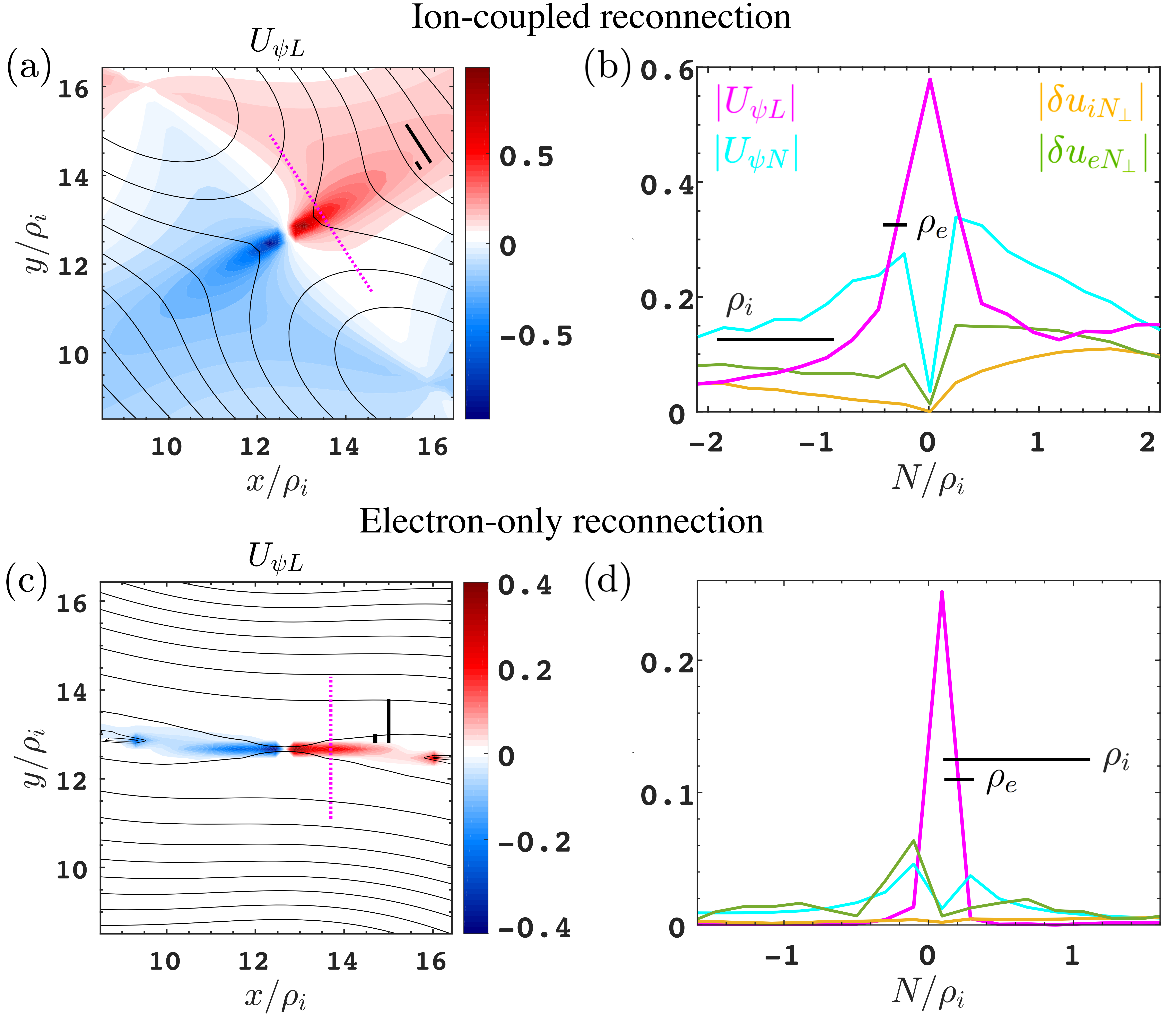
Magnetic field-plasma flow coupling in the diffusion region

Electron-only reconnection



- Similarly, coupling of the magnetic field motion with the electron flow in the EDR will result in an electron-scale structure in the MFT velocity.

Scale of MFT outflow in the diffusion region

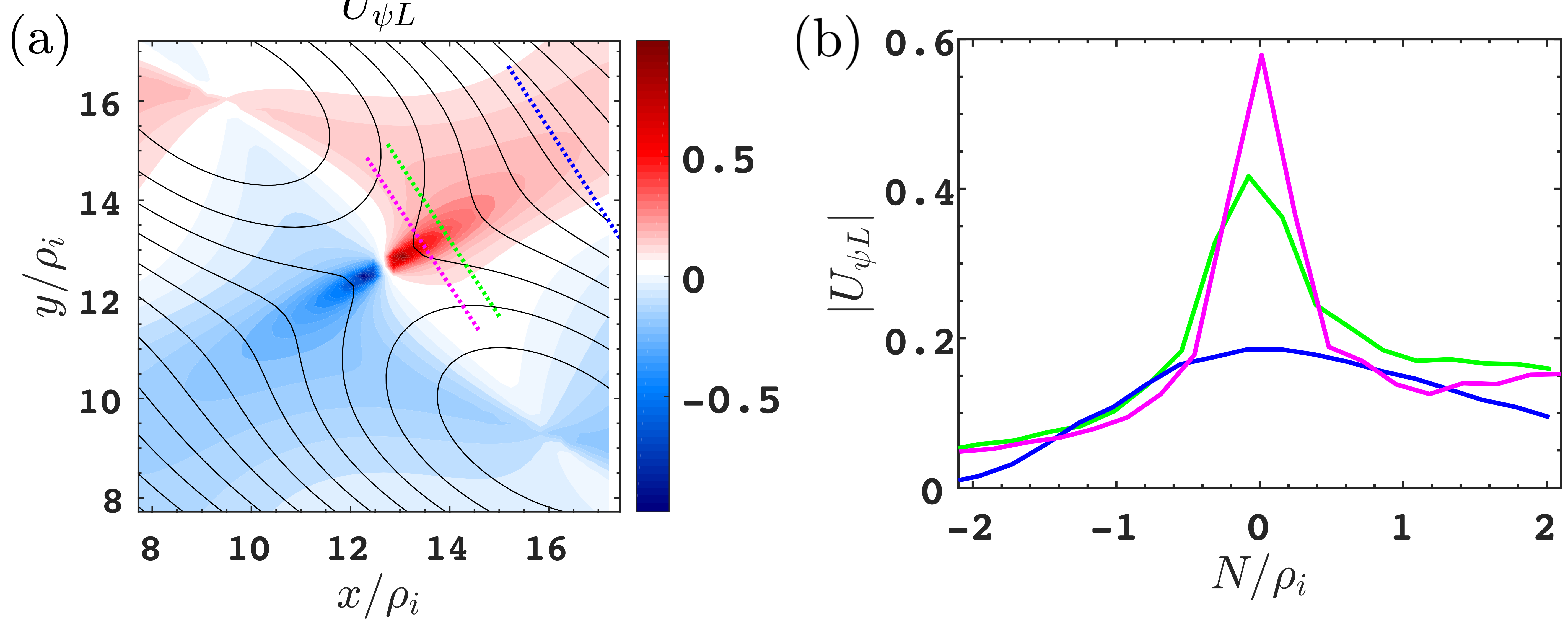


- MFT outflow shows a *two-scale* structure
- Inner-electron-outer-ion scale
- IDR: ion inflow decouples from MFT inflow
- EDR: electron inflow decouples from MFT inflow

- No ion response
- EDR: electron inflow deviates from MFT inflow
- Only *electron-scale* MFT outflow in EDR

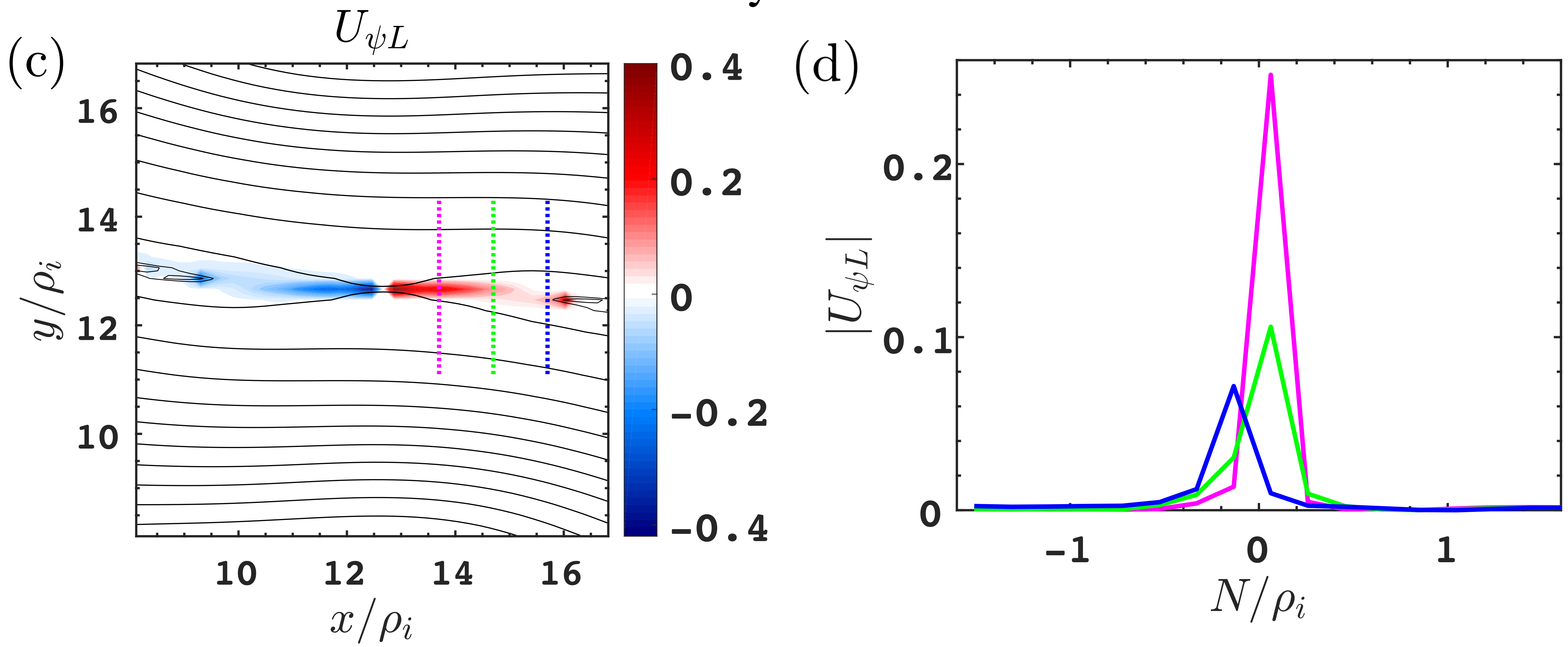
Downstream distance dependence of MFT outflow

Ion-coupled reconnection



Moving downstream from the X-line, the two-scale MFT outflow evolves into a single ion-scale structure, consistent with moving from EDR into IDR.

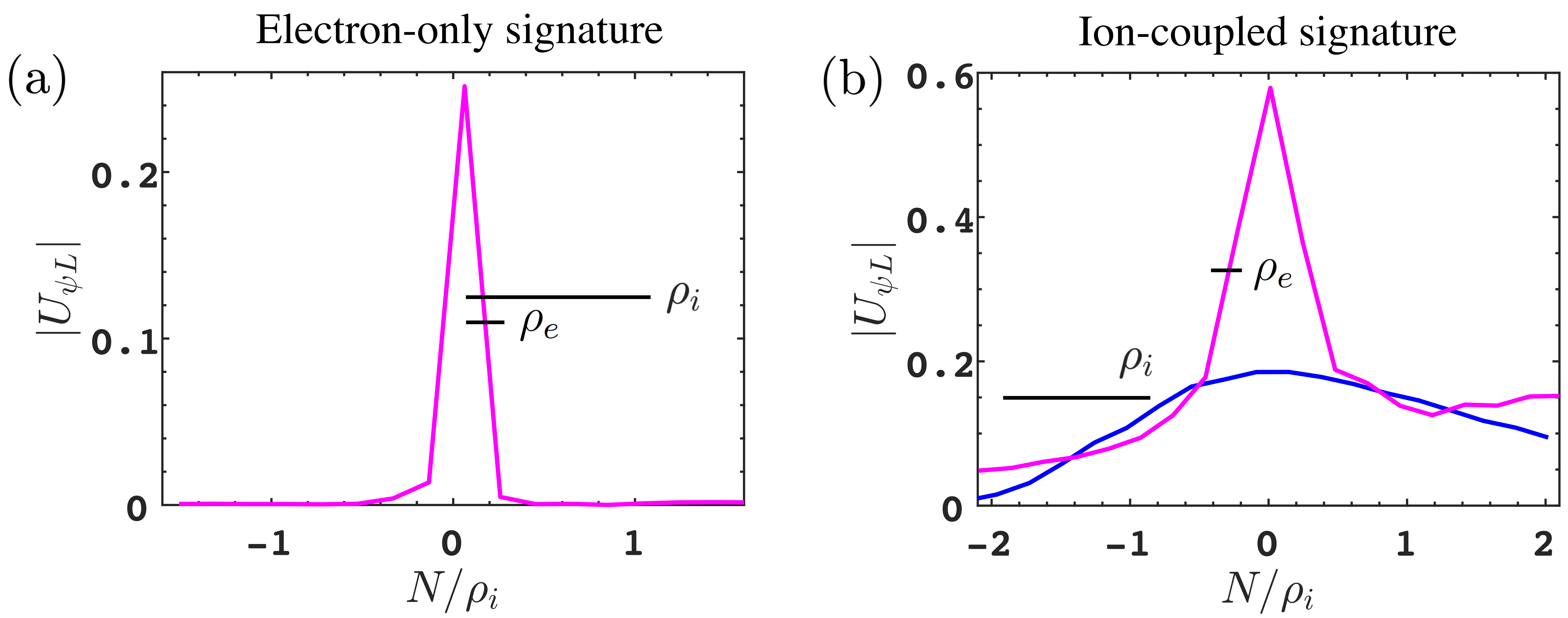
Electron-only reconnection



MFT outflow remains electron-scale for a few ion gyro radii downstream from the X-line.

Li+ 2025 ApJ

Specific MFT signatures for electron-only and ion-coupled reconnection



The electron-only signature is *only* an electron-scale MFT outflow along the normal direction.

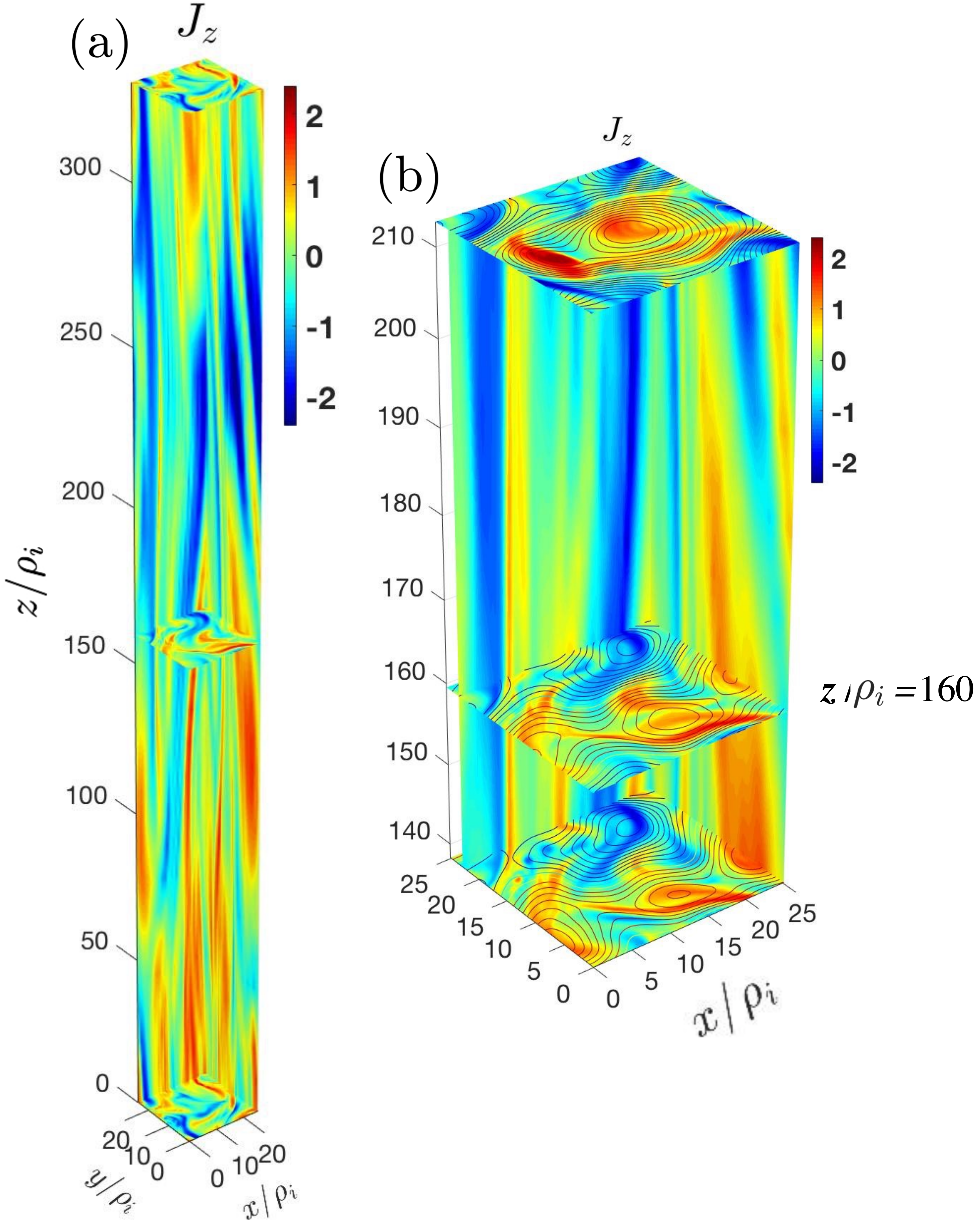
The ion-coupled signature is a two-scale, inner-electron-outer-ion-scale MFT outflow in the EDR, which evolves into an ion-scale MFT outflow in the IDR.

This new capability to identify electron-only reconnection is independent of electron outflows. It has direct application to simulations, and potential application to observations.

Li+ 2025 ApJ

New insights on the evolution of reconnection in turbulence

New insights on the evolution of reconnection in turbulence

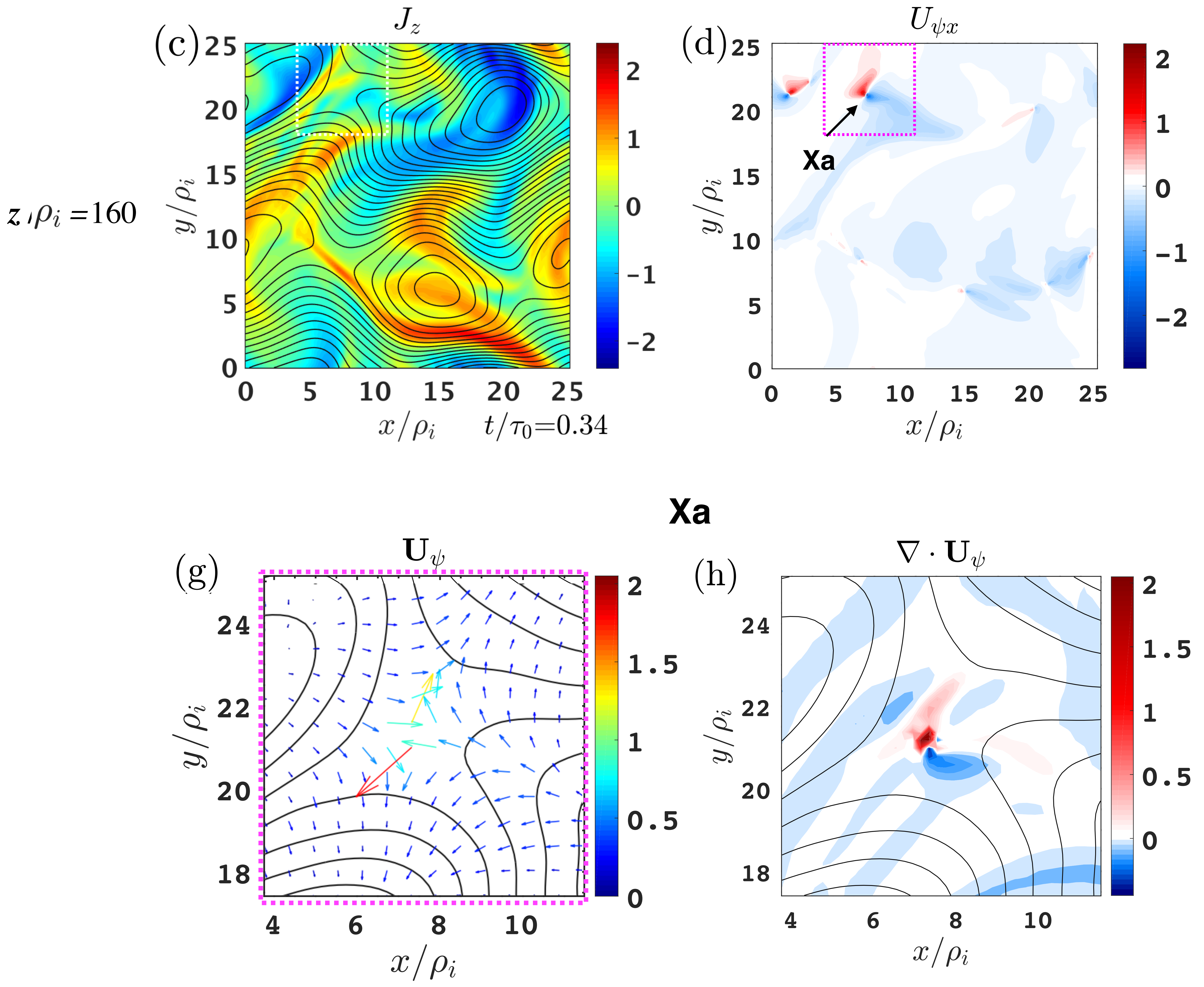


3D simulation of kinetic Alfven wave turbulence

- Plasma beta = 0.01
- Dynamic range: $0.25 \leqslant k_\perp \rho_i \leqslant 10.5$
- Gyrokinetic simulation: dB << B_0
- 3D generalization of the Orszag-Tang Vortex (Li+ 2016 ApJL)
- Normalization: ion gyroradius, electron thermal speed

Li+ 2023 PRL

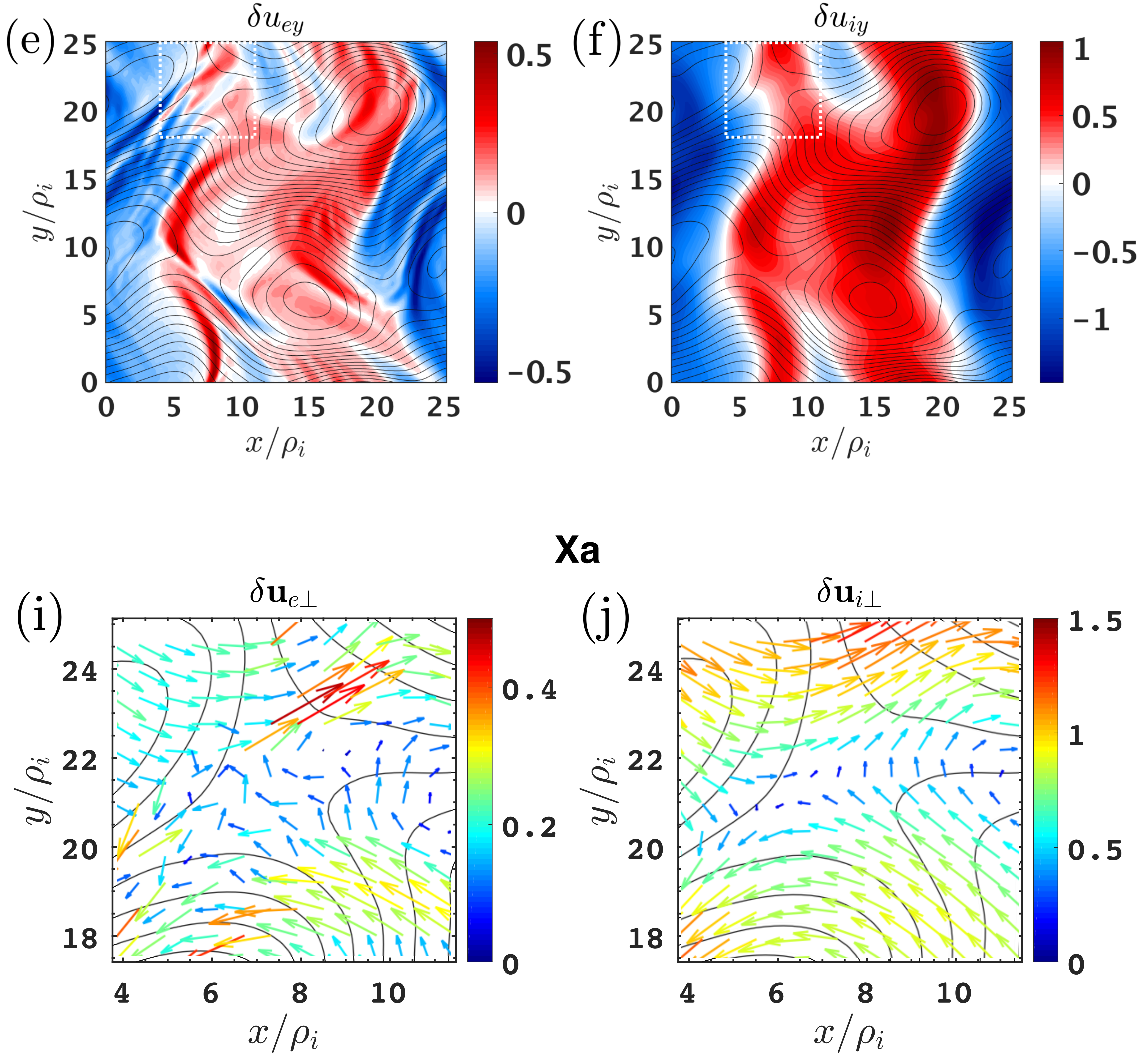
Identifying reconnection in 3D turbulence



Li+ 2023 PRL

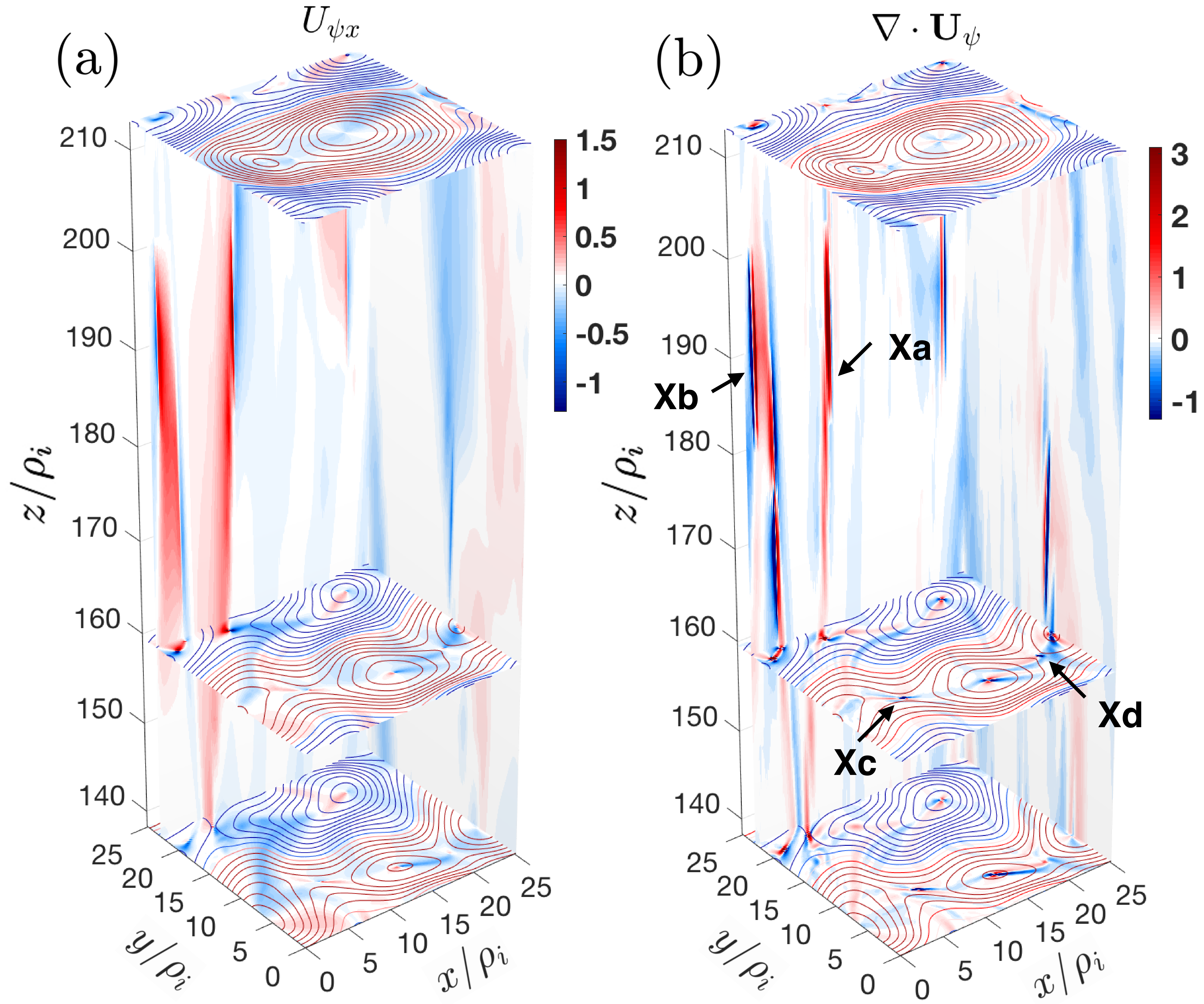
Comparison with ion and electron flows

$z/\rho_i = 160$



Li+ 2023 PRL

Discovery of extended reconnection X-lines in kinetic turbulence



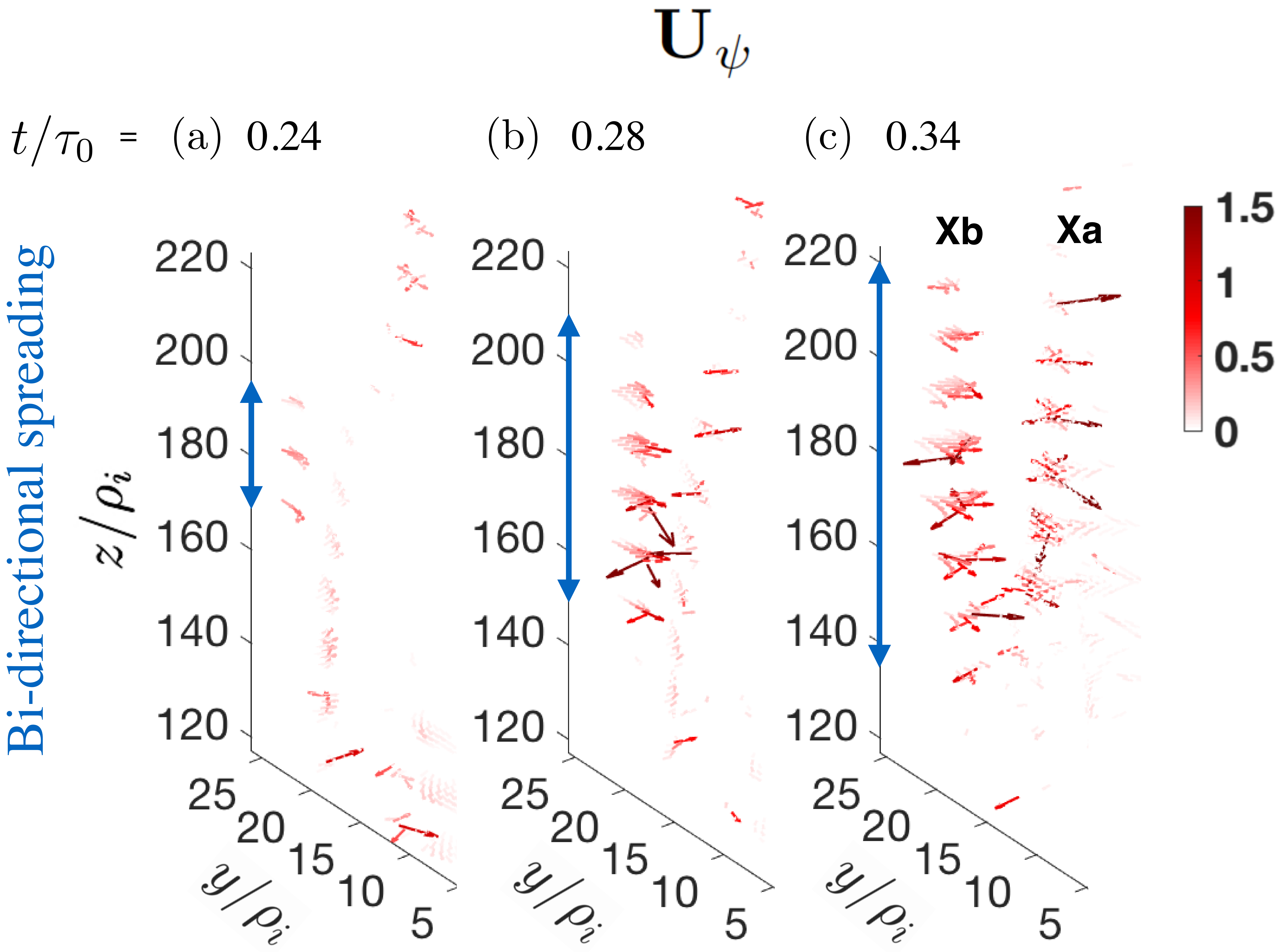
Highly extended reconnection X-lines in the 3D domain.

~ 100 ion gyroradii.

First evidence for extended reconnection in kinetic turbulence.

Li+ 2023 PRL

How do extended reconnection X-lines form?



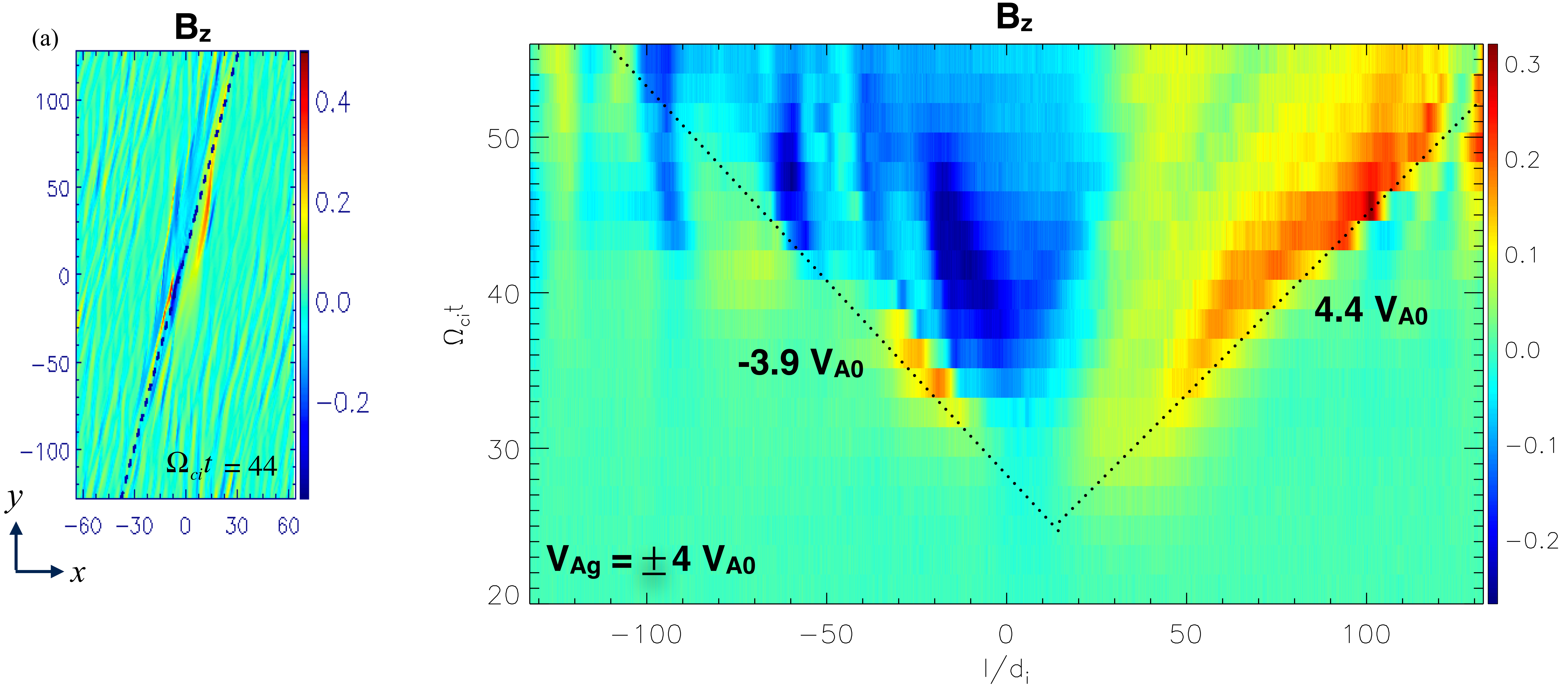
Reconnection starts in localized regions, and spreads bidirectionally at the Alfven speed to form extended X-lines.

Consistent with counterpropagating kinetic Alfven waves mediating the spreading of reconnection X-lines.

Strikingly similar to spreading of laminar reconnection under a guide field (Li+ 2020, Shepherd & Cassak 2012)

Li+ 2023 PRL

Evolution of guide-field reconnection in laminar plasmas

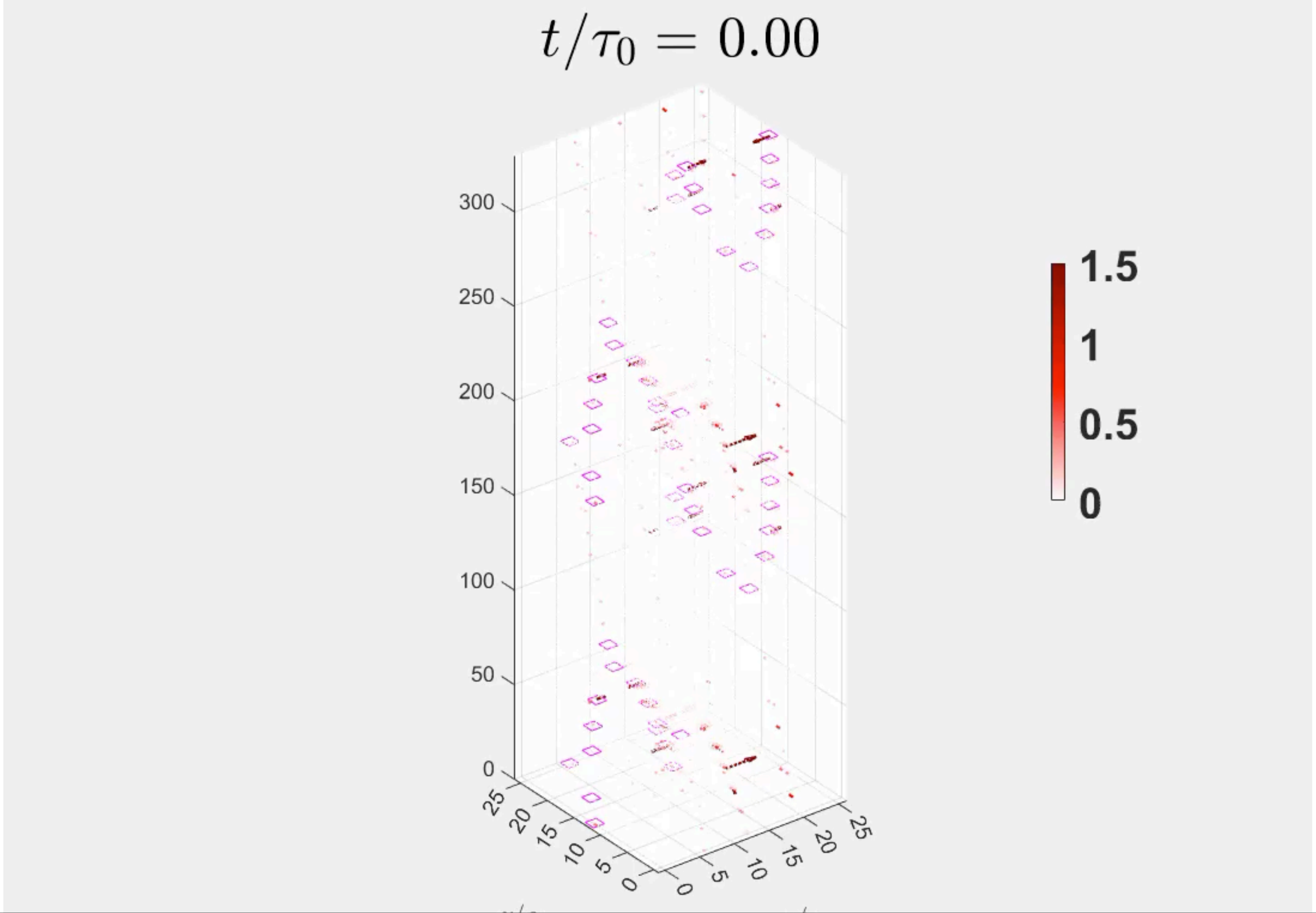


Li+ 2020 JGR

3D evolution of reconnection in turbulence is strikingly similar to those in laminar plasmas.

Automatic reconnection identification procedure with MFT

- Select saddle points with Hessian matrix (Servidio+ 2009 PRL)
- Impose thresholds on the divergence of MFT to identify active reconnection X-lines

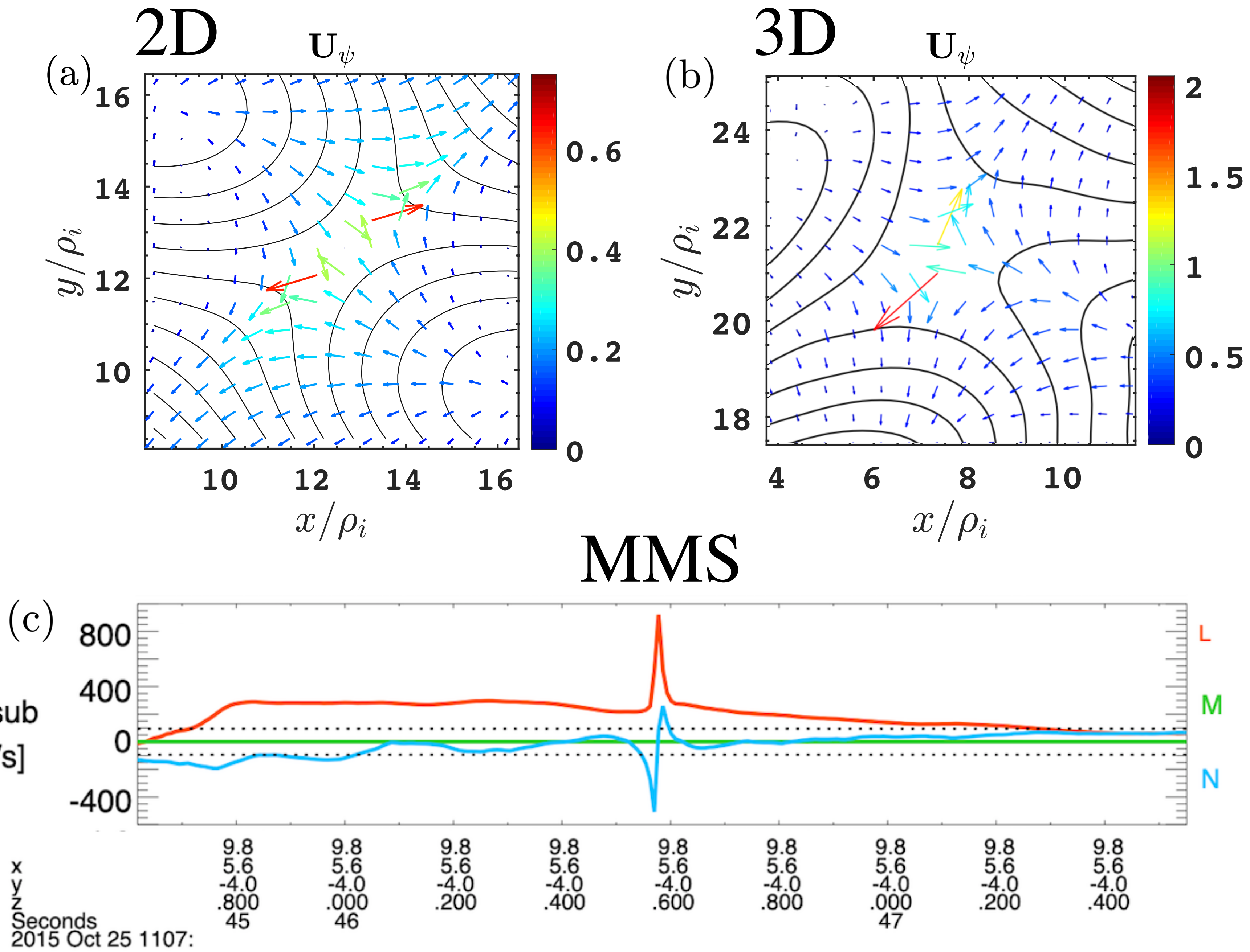


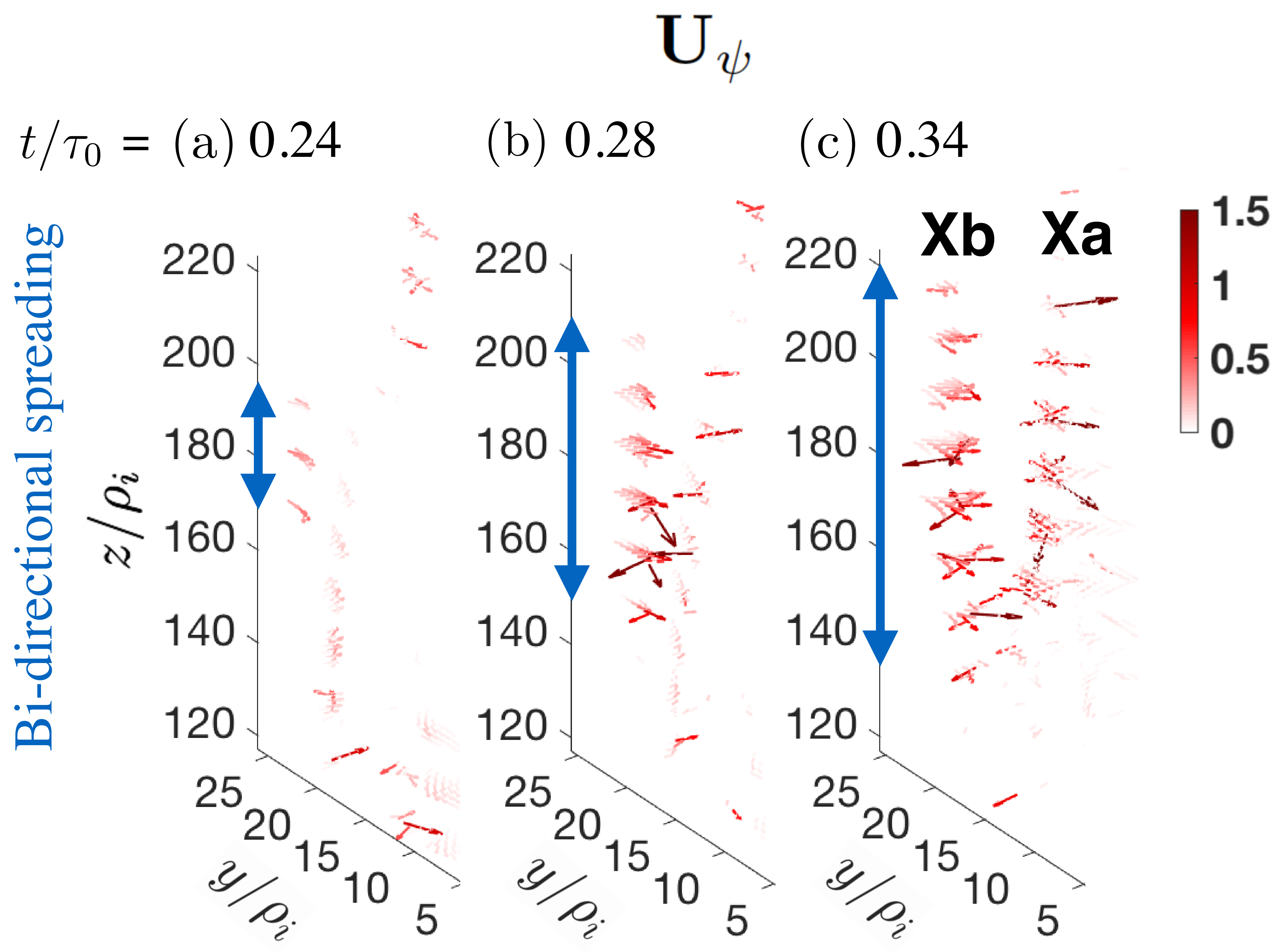
Summary

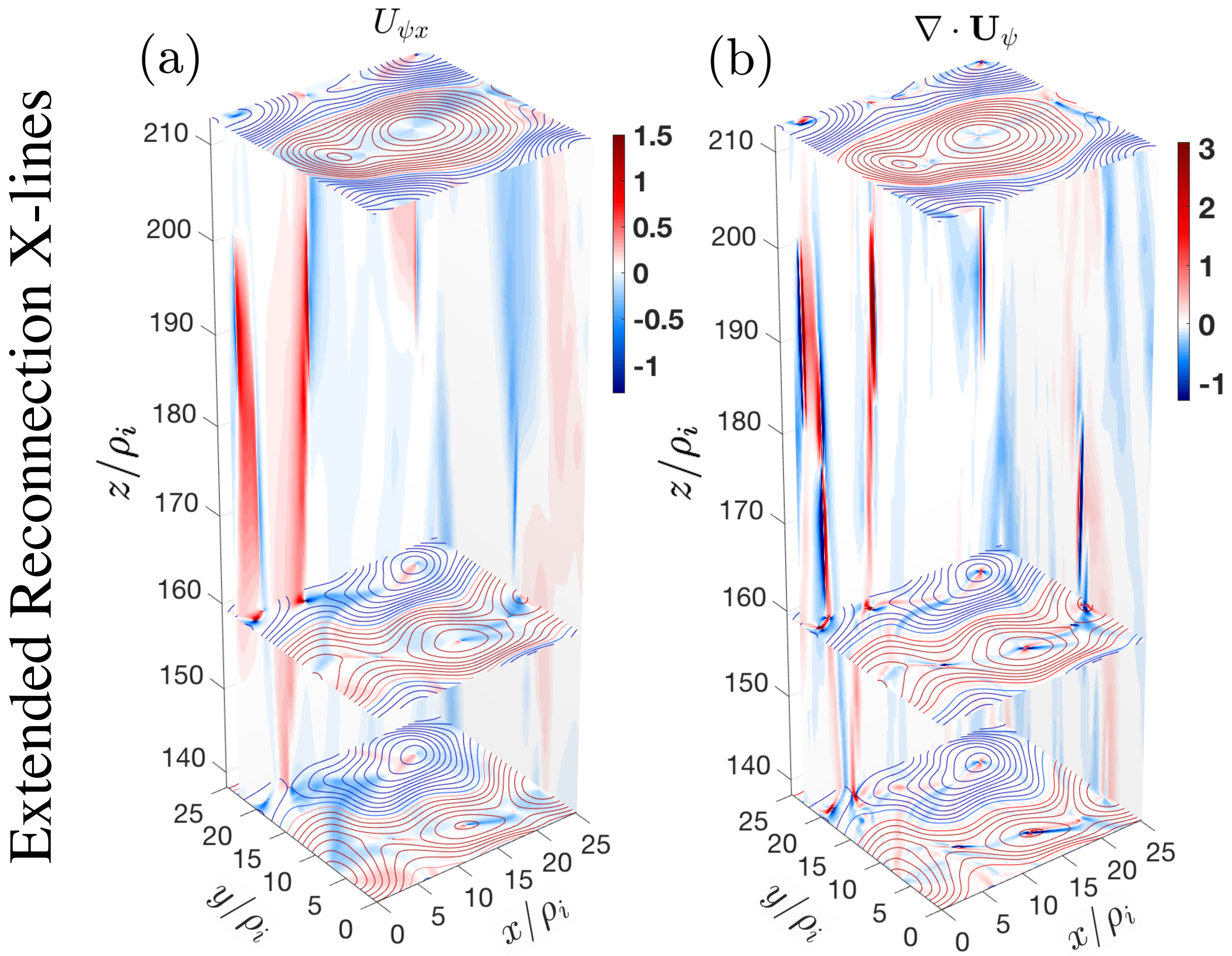
- The MFT method is an innovative method to identify reconnection in turbulent plasmas independent of complex plasmas flows.
- It has direct application to in situ observations, kinetic and fluid simulations.
- A new capability identifies electron-only reconnection independent of electron outflows.
- New insights on reconnection in 3D turbulence reveals extended reconnection X-lines in kinetic turbulence, which evolve in strikingly similarly to laminar reconnection under a guide field.
- An automatic procedure is underway for investigating reconnection activity statistically.

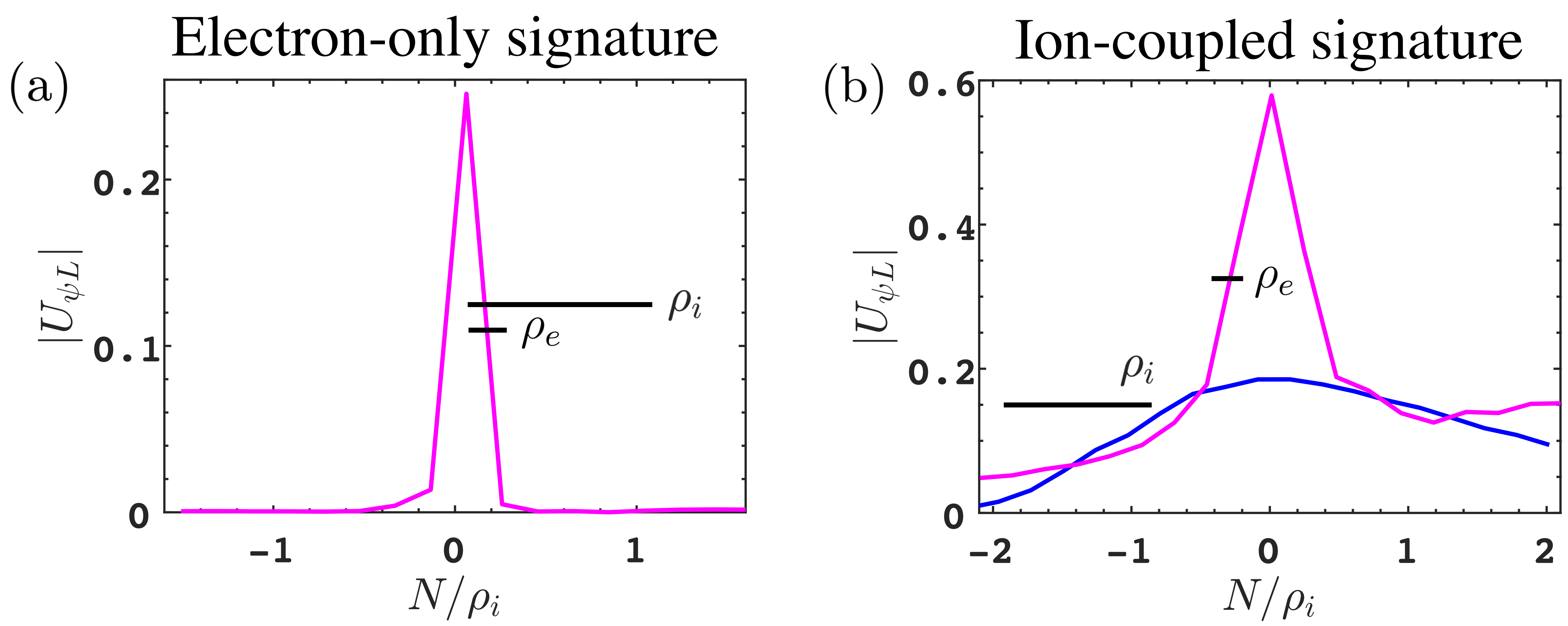
Supported by NSF

tak.chu.li@dartmouth.edu


2D
3D
$\mathbf{U}_\psi$
(a)
(b)
x/ρ_i
y/ρ_i
MMS
(c)
U_ψ sub [km/s]
L
M
N
2015 Oct 25 1107:


$\mathbf{U}_\psi$
t/τ_0 = (a) 0.24
(b) 0.28
(c) 0.34
Bi-directional spreading
Xb
Xa
z/ρ_i
y/ρ_i


Extended Reconnection X-lines
(a) $U_{\psi x}$
(b) $\nabla \cdot \mathbf{U}_\psi$
z/ρ_i
y/ρ_i
x/ρ_i


(a) Electron-only signature
(b) Ion-coupled signature
$|U_{\psi L}|$
N/ρ_i
ρ_i
ρ_e

References

1. Li et al, "Identification of Active Magnetic Reconnection Using Magnetic Flux Transport in Plasma Turbulence," ApJL, 2021
2. Qi et al, "Magnetic Flux Transport Identification of Active Reconnection: MMS Observations in the Earth's Magnetosphere," ApJL, 2022
3. Li et al, "Extended Magnetic Reconnection in Kinetic Plasma Turbulence," PRL, 2023
4. Hasegawa et al, "Advanced Methods for Analyzing In-Situ Observations of Magnetic Reconnection," Space Sci. Rev. 2024 (Section 3.1.5 MFT method)
5. Li et al, "Magnetic flux transport signatures of electron-only and ion-coupled magnetic reconnection in plasma turbulence", ApJ, 2025

Supported by NSF

tak.chu.li@dartmouth.edu