Electron-Only Reconnection: Overview of Simulations

Prayash Pyakurel
Space Sciences Laboratory
University of California, Berkeley

Collaborators:
T. D. Phan, M. A. Shay, J. F. Drake P. A. Cassak

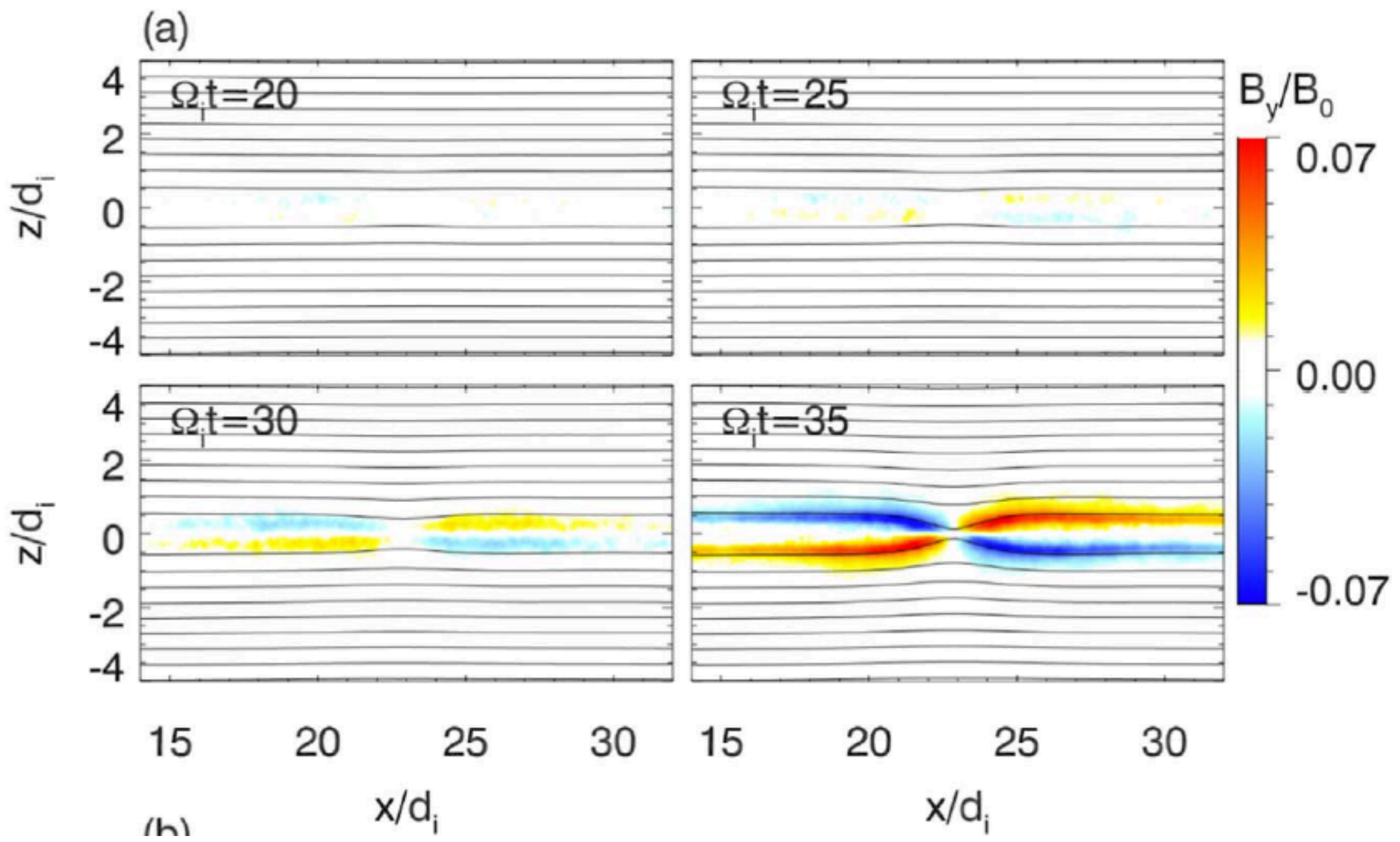
2D Reconnection Simulation: Electron-Only Onset

Spontaneous Onset of Collisionless Magnetic Reconnection on an Electron Scale

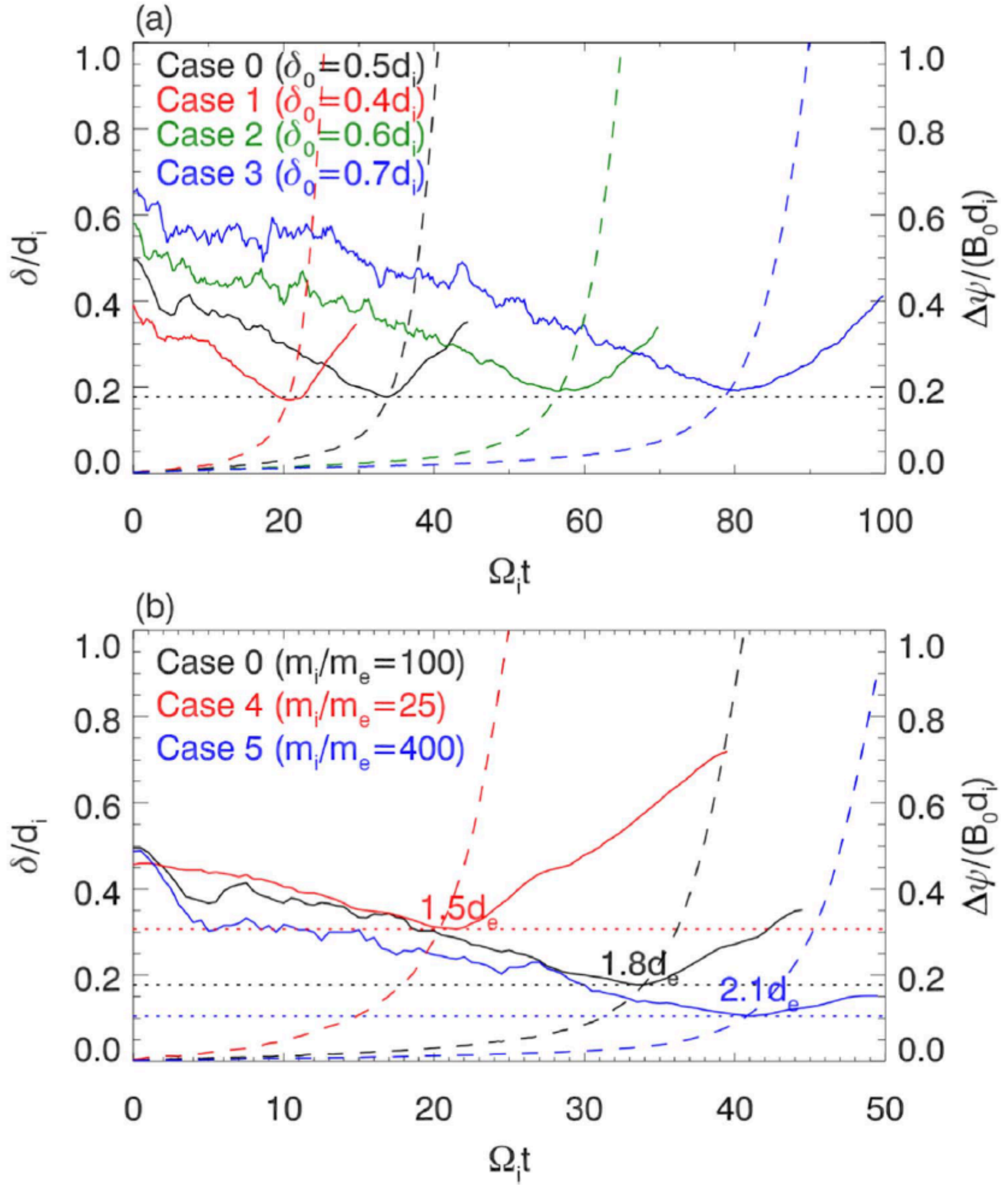
Key Points

- Reconnection onset due to tearing mode instability.
- Current sheet thins spontaneously and reaches a limit
  $\sim$2 d_e.
- Flux pile up in the upstream region during the onset
  compresses the current sheet.
- During reconnection, aspect ratio stays more or less constant, which increases the width.
- Electron kinetics govern spontaneous onset of collisionless magnetic reconnection.

Simulation in time



Evolution of current sheet width



Liu et al, 2020, ApJL

2D Reconnection Simulation: Electron-Only in the Magnetotail

Simulation evolution in time

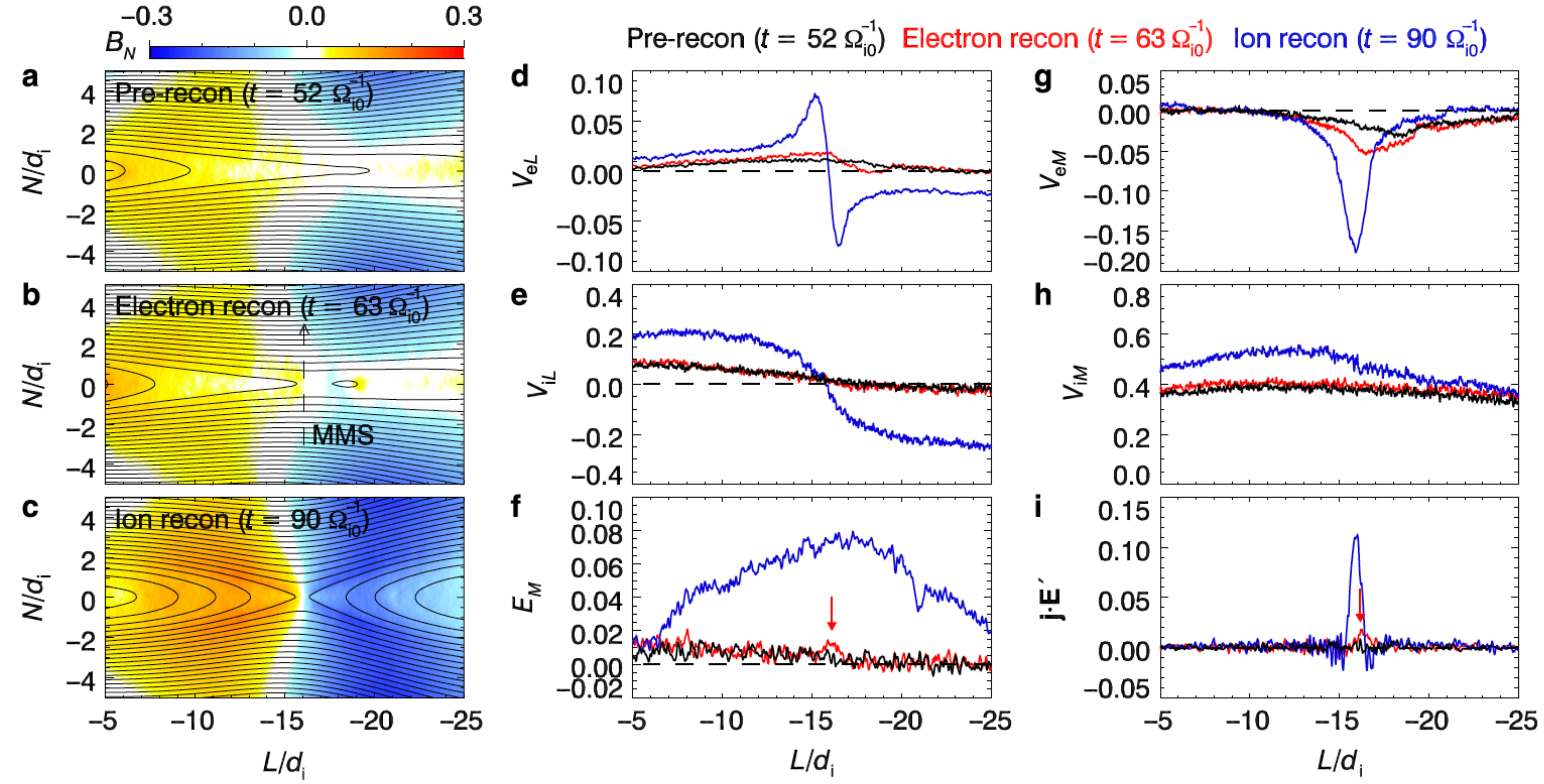
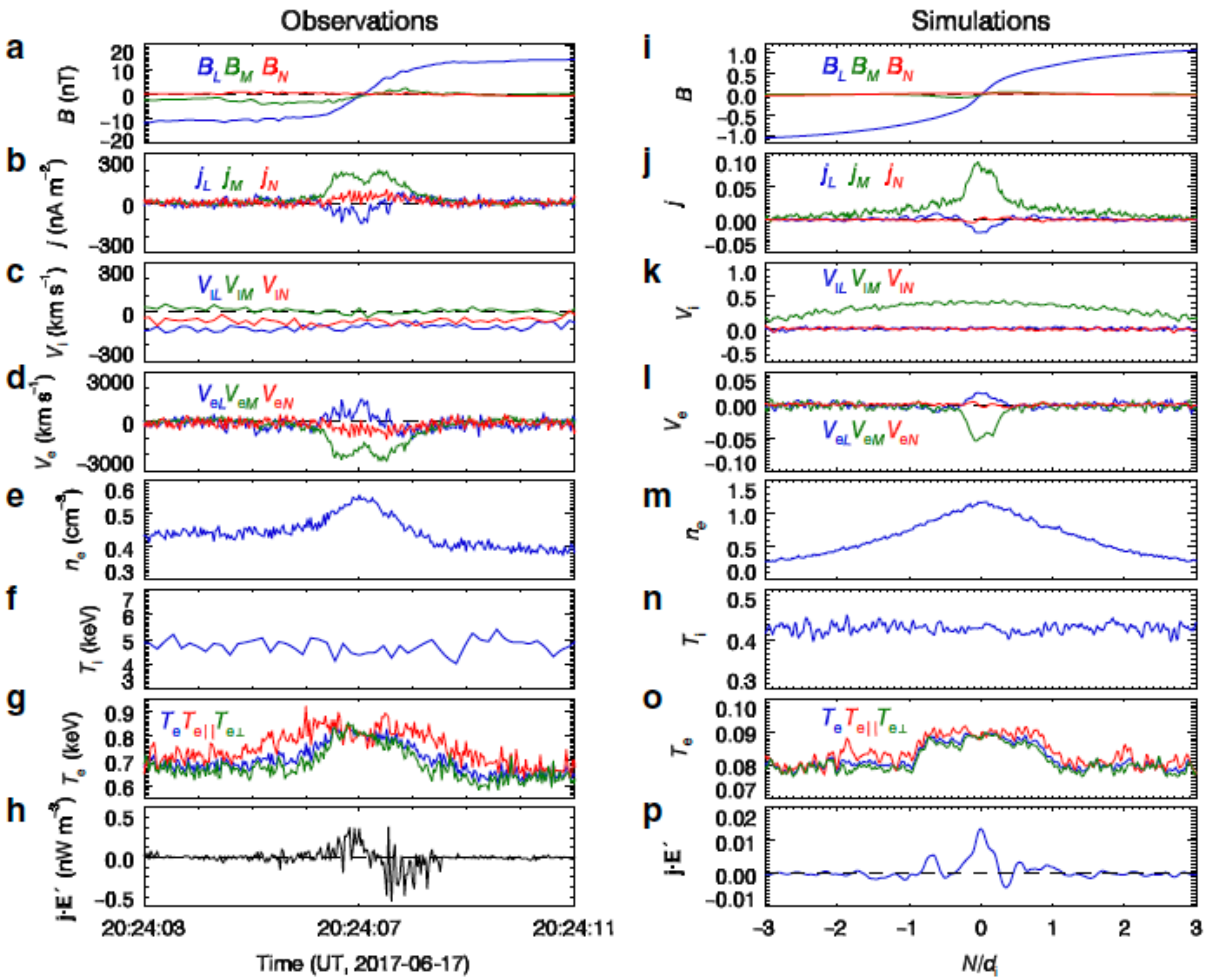


Fig. 3 PIC simulations of strongly externally driven onset of magnetotail reconnection. a–c Colors show the normal magnetic field B_N (in unit of B_0) in the L–N plane at pre-reconnection phase ($t = 52\Omega_{i0}^{-1}$), electron reconnection phase ($t = 63\Omega_{i0}^{-1}$), and ion reconnection phase ($t = 90\Omega_{i0}^{-1}$), respectively. The black curves represent the magnetic field lines in the reconnection plane. **d–i** Profiles, along $N = 0$, of V_{eL} (in unit of V_{eA}), V_{iL} (in unit of V_A), E_M (in unit of $V_A B_0$), V_{eL} (in unit of V_{eA}), V_{iL} (in unit of V_A), and $\mathbf{j} \cdot \mathbf{E}'$ (in unit of $en_0 V_A^2 B_0$) at pre-reconnection phase ($t = 52\Omega_{i0}^{-1}$, black curves), electron reconnection phase ($t = 63\Omega_{i0}^{-1}$, red curves), and ion reconnection phase ($t = 90\Omega_{i0}^{-1}$, blue curves). The dashed line with an arrow in **b** represents the virtual trajectory of the MMS spacecraft across the electron reconnection region, along $L = -16.1d_i$ at $t = 63\Omega_{i0}^{-1}$. The red arrows in **f, i** mark the location of the electron reconnection site.

Key Points

- Electron tearing mode responsible for onset.
- Simulation starts with electron scale with no ion coupling.
- Electron-only reconnection grows into ion coupled reconnection.
- Simulations are in agreement with EDR signatures without bursty reconnection signatures.

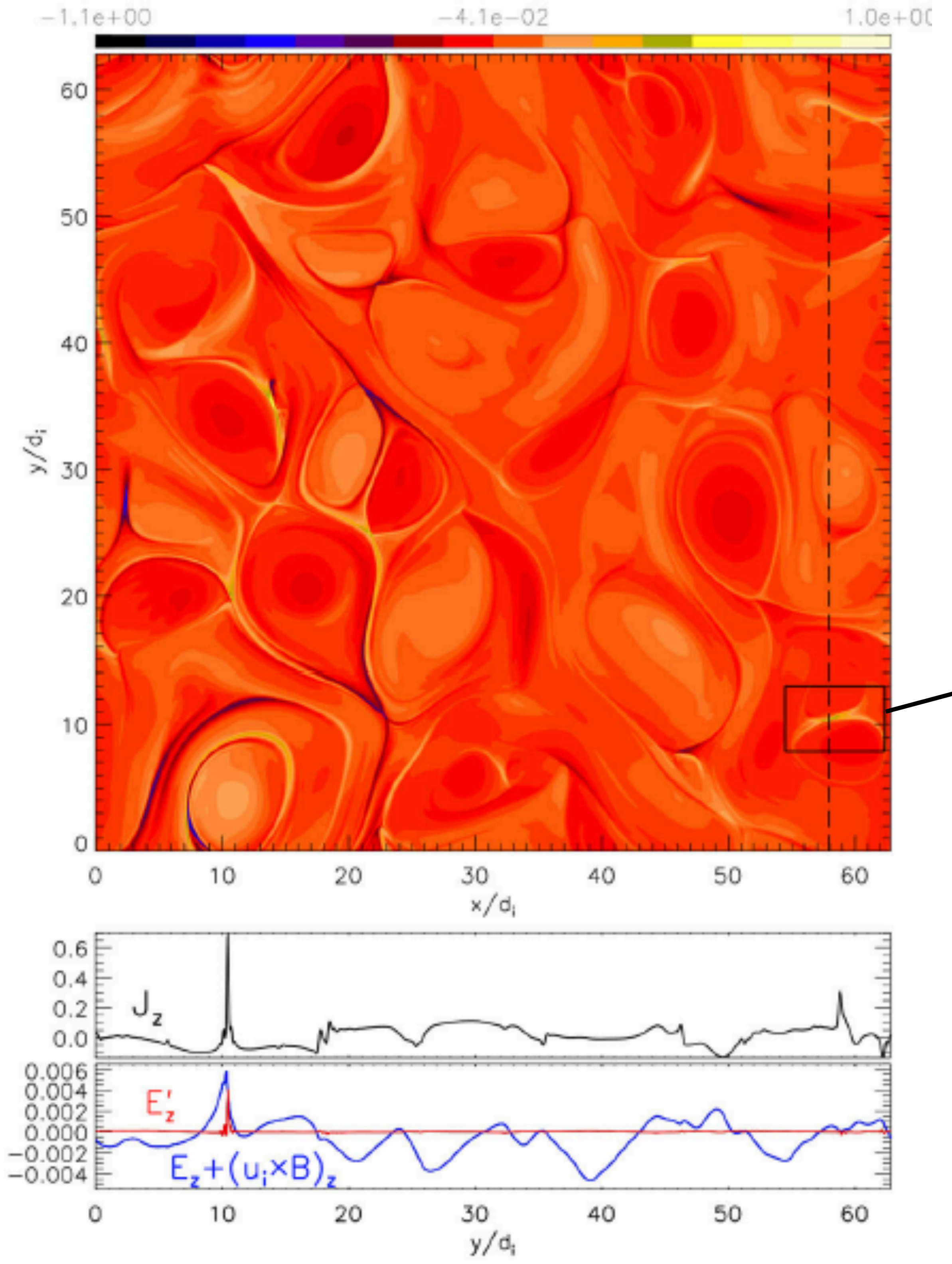
Magnetotail reconnection onset caused by electron kinetics with a strong external driver



Lu et al, 2020, Nature Comm

2D Turbulence Simulation: Electron-Only Identified in Thin Current Sheets

Fully developed turbulence simulation



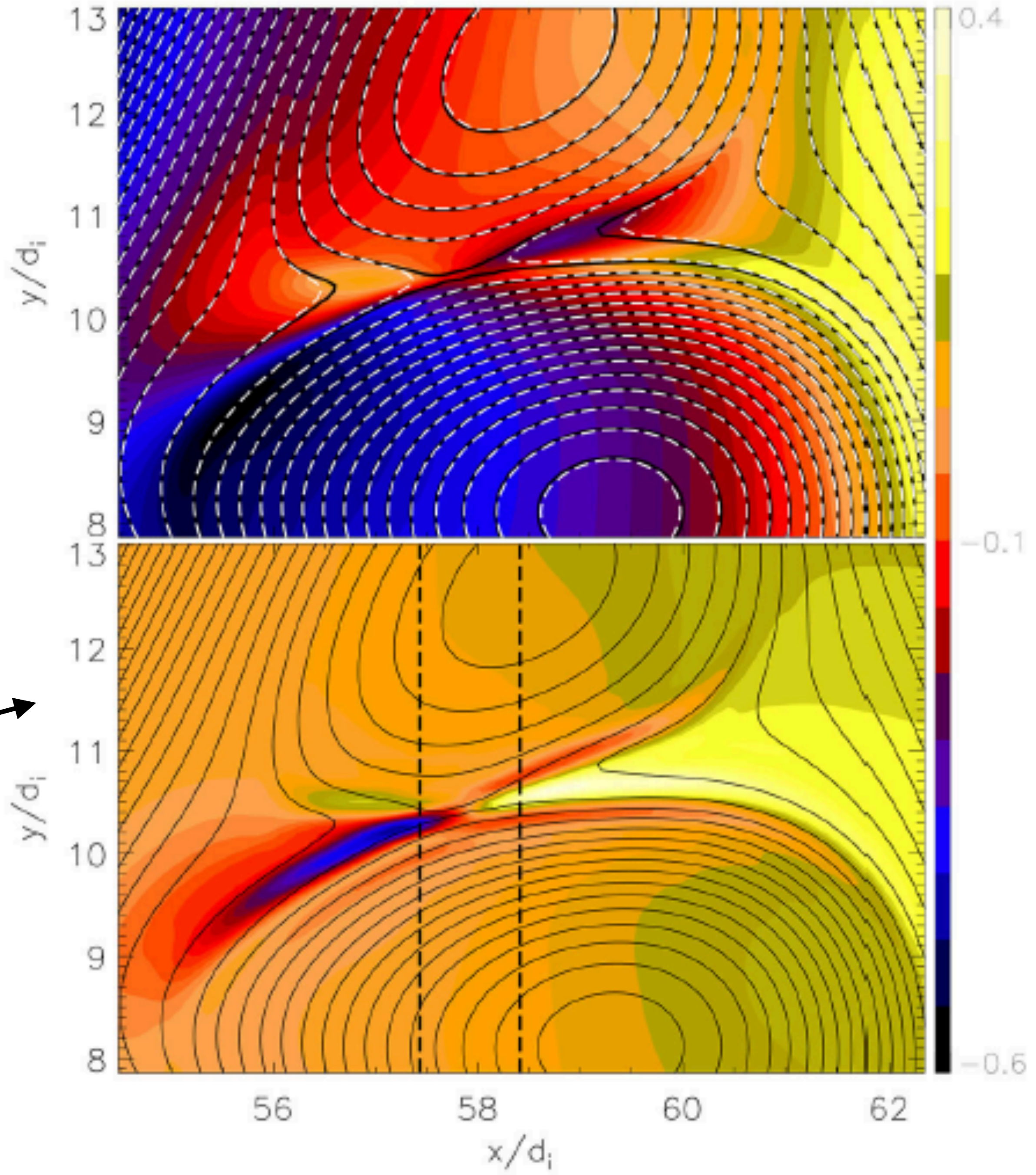


FIGURE 2 | From sim.A. Zoom-in on CS1 at $t = 42.5\Omega_i^{-1}$. **(Top)** Shaded iso-contours of the out-of-plane magnetic field B_z with superposed iso-contours of ψ (dashed white) and F (black). **(Bottom)** Shaded iso-contours of the x-component of the electron flow, $u_{e,x}$, and of ψ (solid black lines). Dashed vertical lines trace the two virtual spacecraft trajectories shown in the two columns of **Figure 3**.

Key Points

- Two injection scale: (A) $0.1 \leq k_\perp d_i \leq 0.6$ (ion scale)
  (B) $0.1 \leq k_\perp d_i \leq 0.3$

(A) No traditional reconnection observed. Only electron-only reconnection.

(B) Both kinds of reconnection observed.

Electron-Only Reconnection in Plasma Turbulence

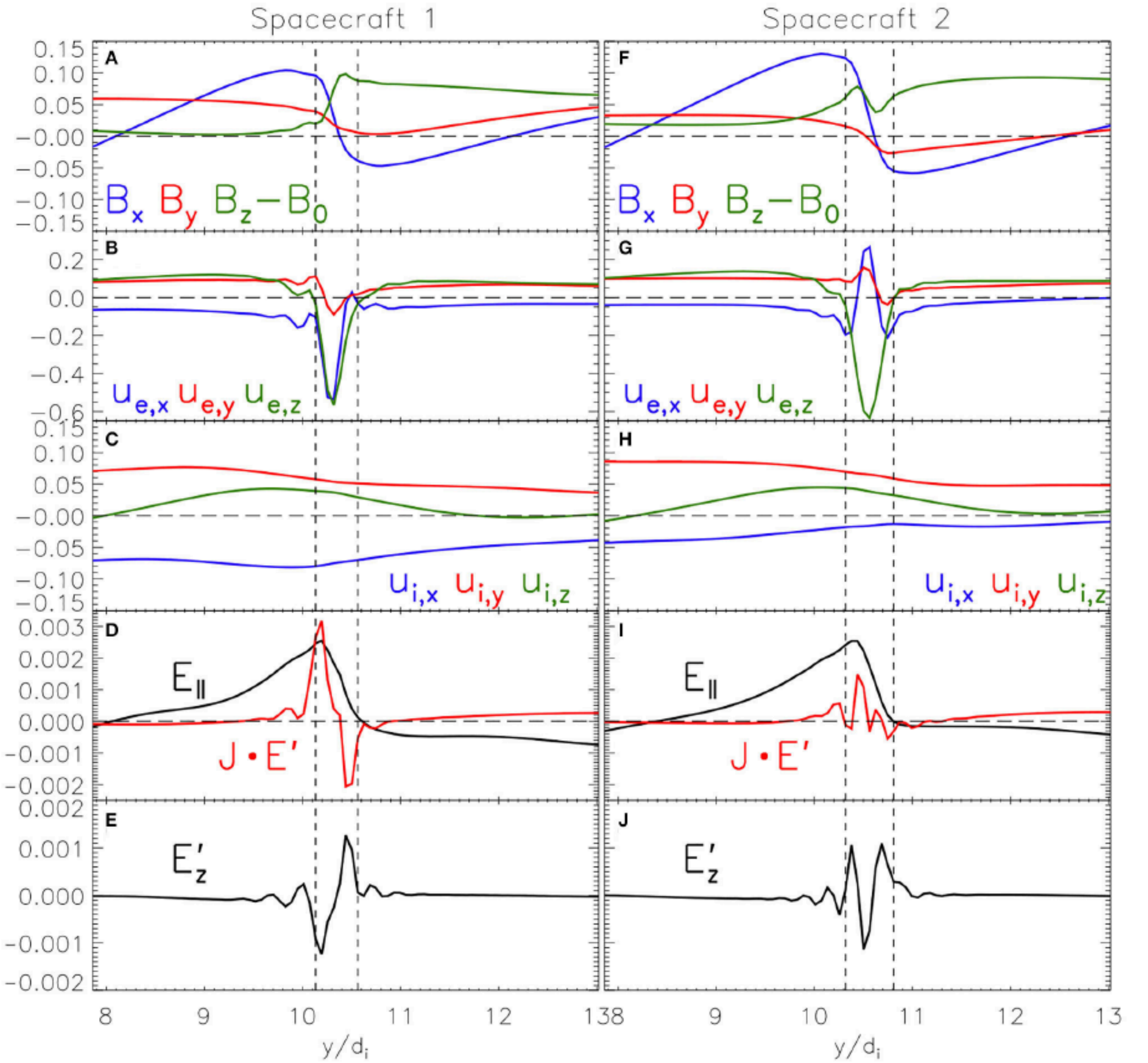


FIGURE 3 | **(A–J)** Display different physical quantities along the trajectories of virtual satellites dubbed as spacecraft 1 and 2, respectively. From sim.A. Data taken by two virtual spacecraft passing through CS1 along the paths traced by the vertical dashed lines in **Figure 2** ("Spacecraft 1" at $x \simeq 57.4d_i$, left column; and "Spacecraft 2" at $x \simeq 58.4d_i$, right column). The vertical dashed lines represent the local boundaries of the CS given by the condition $|J_z| > J_z^{rms}$.

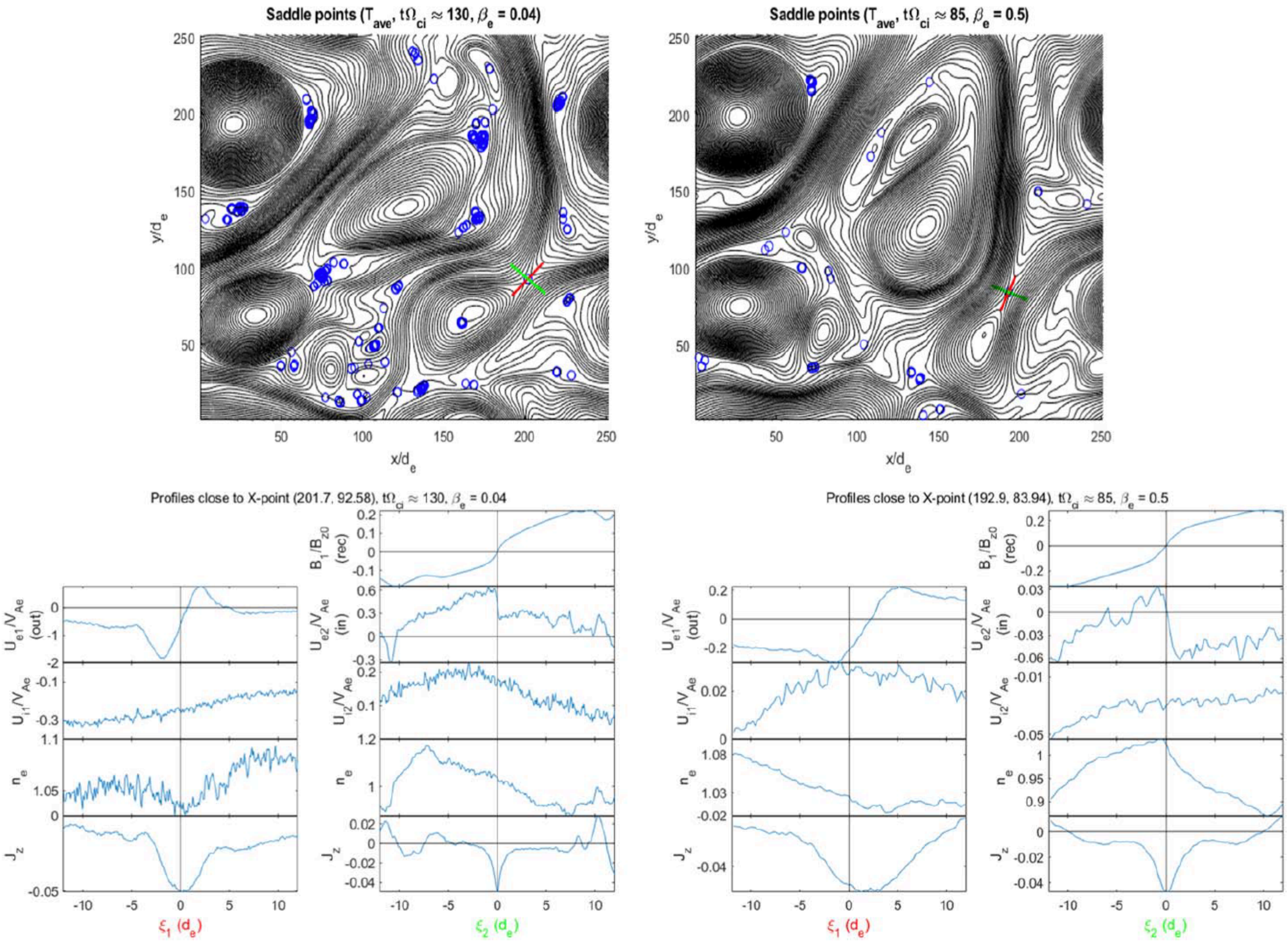
Califano et al, 2020, Frontiers in Physics

2D Turbulence Simulation: Electron-Only Identified in Thin Current Sheets

Key Points

- Kinetic-Alfven turbulence (sub-proton) responsible for generating electron-only reconnection.
- Both low and high β_e and β_i regimes are expected to populate electron-only reconnection in turbulence.

Electron-Only Reconnection in Kinetic-Alfven Turbulence



Saddle points (T_{ave}, $t\Omega_{ci} \approx 130$, $\beta_e = 0.04$)

Saddle points (T_{ave}, $t\Omega_{ci} \approx 85$, $\beta_e = 0.5$)

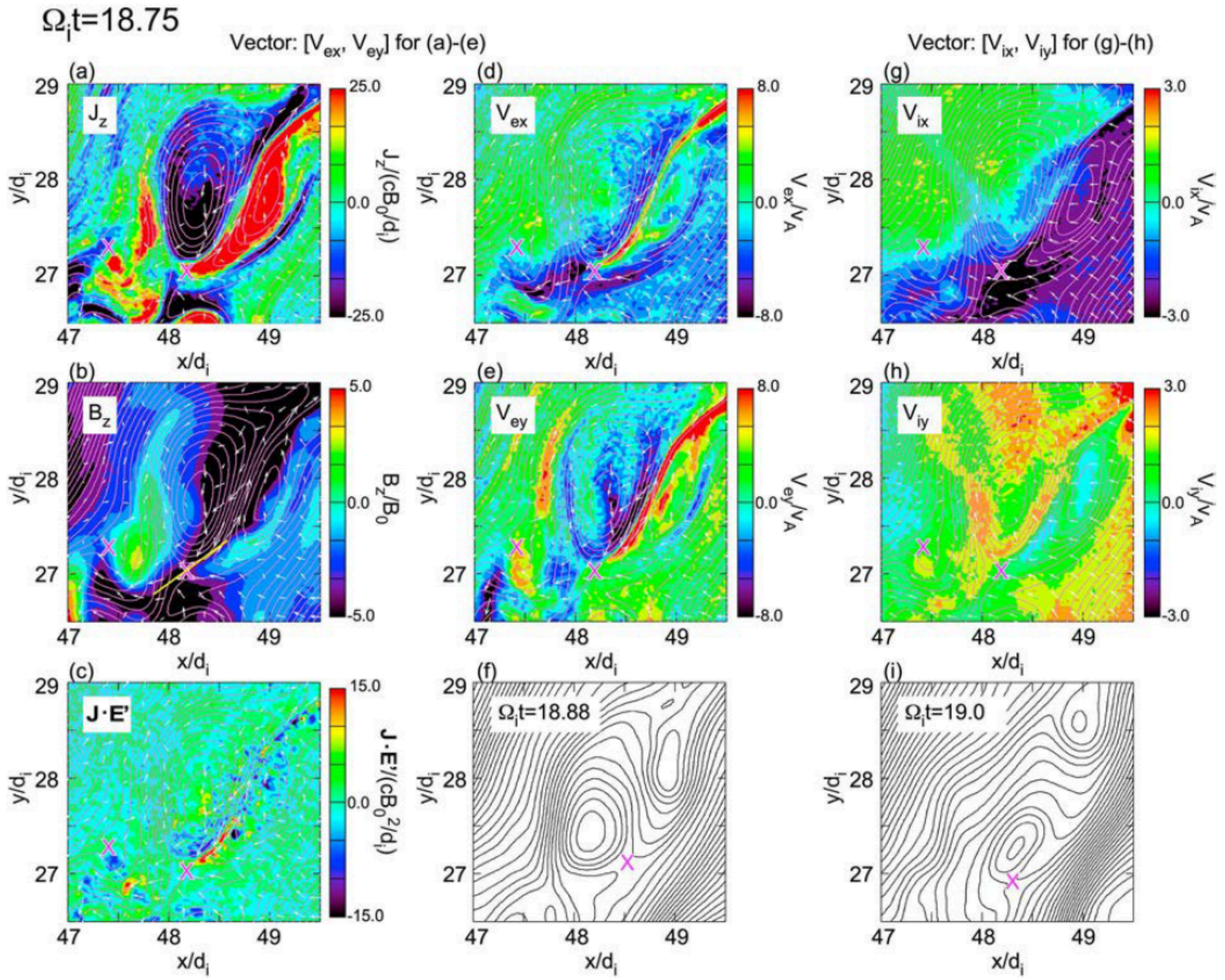
Profiles close to X-point (201.7, 92.58), $t\Omega_{ci} \approx 130$, $\beta_e = 0.04$

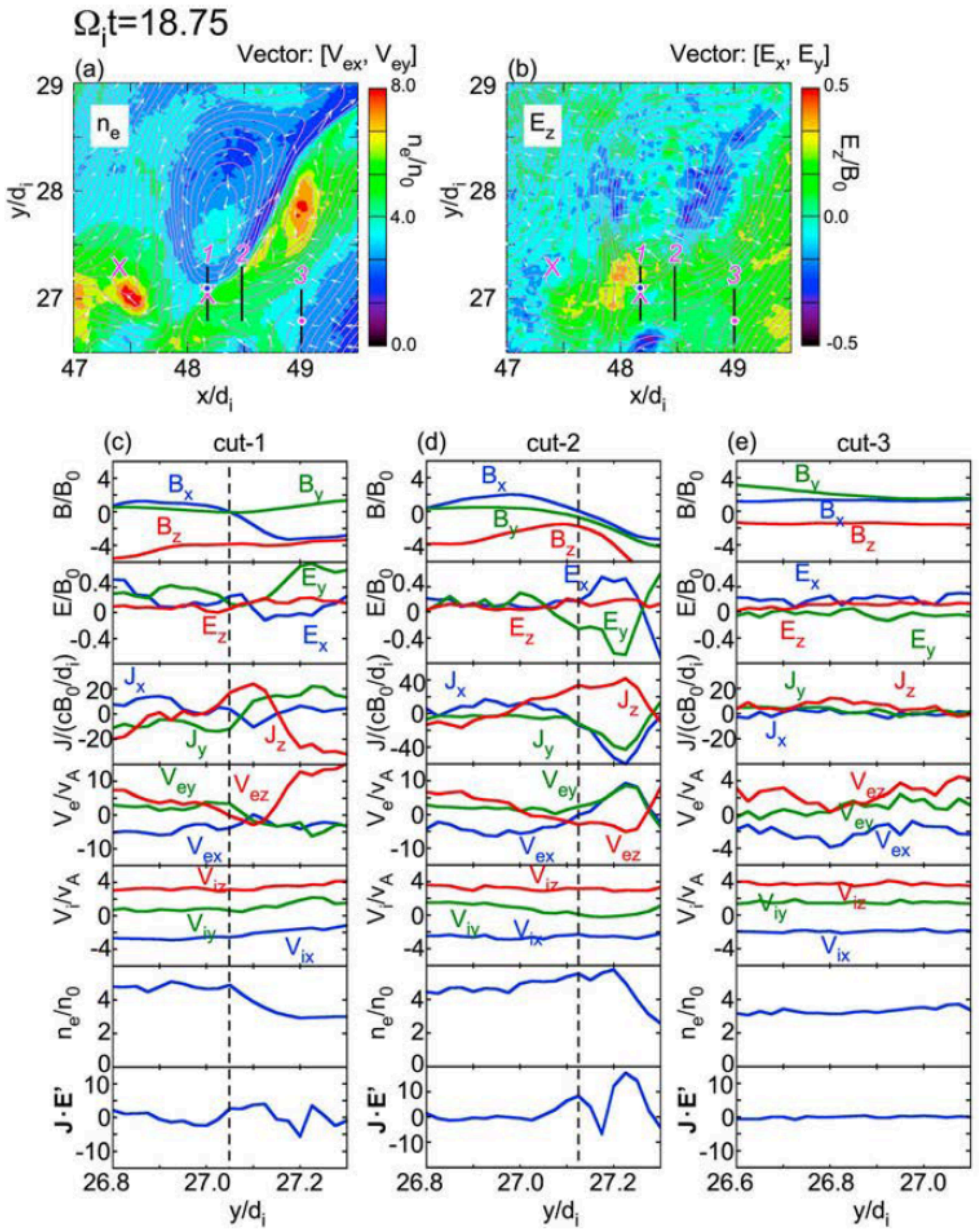
Profiles close to X-point (192.9, 83.94), $t\Omega_{ci} \approx 85$, $\beta_e = 0.5$

Vega et al, 2020, ApJL

2D Shock Simulation: Electron-Only Identified in the Shock Transition Region

Magnetic Reconnection in a Quasi-Parallel Shock: Two-Dimensional Local Particl-in-Cell Simulation





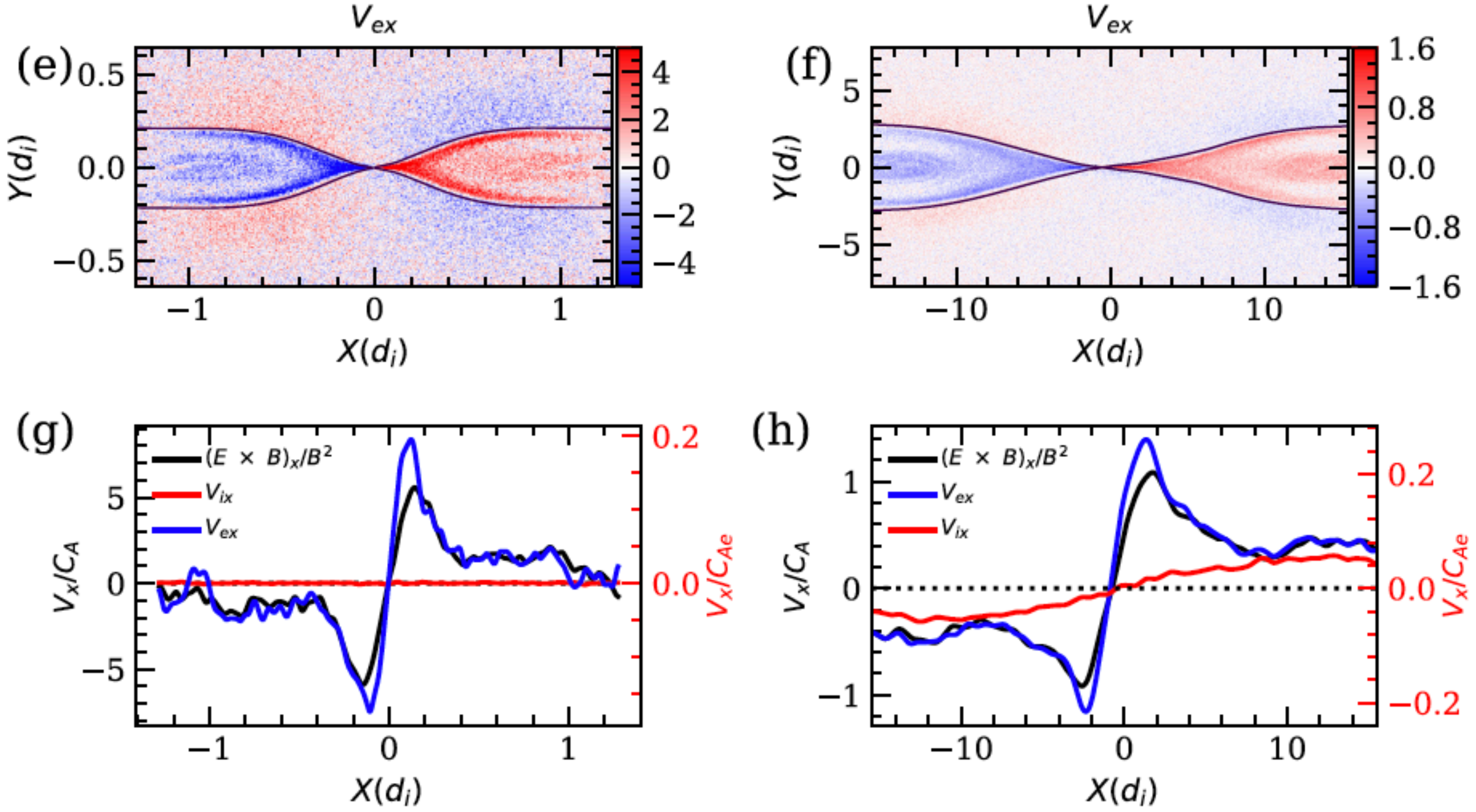
Key Points

- 2D PIC simulation of quasi-parallel shock simulation demonstrate reconnection.
- Both traditional ion-coupled and electron only reconnection are identified.
- Guide field electron-only reconnection has few d_e thickness.

Bessho et al, 2019, GRL

Canonical 2D Reconnection Simulation: Transition from Ion-Coupled to Electron-only Reconnection

Electron-only vs. ion coupled



Reconnection in turbulence

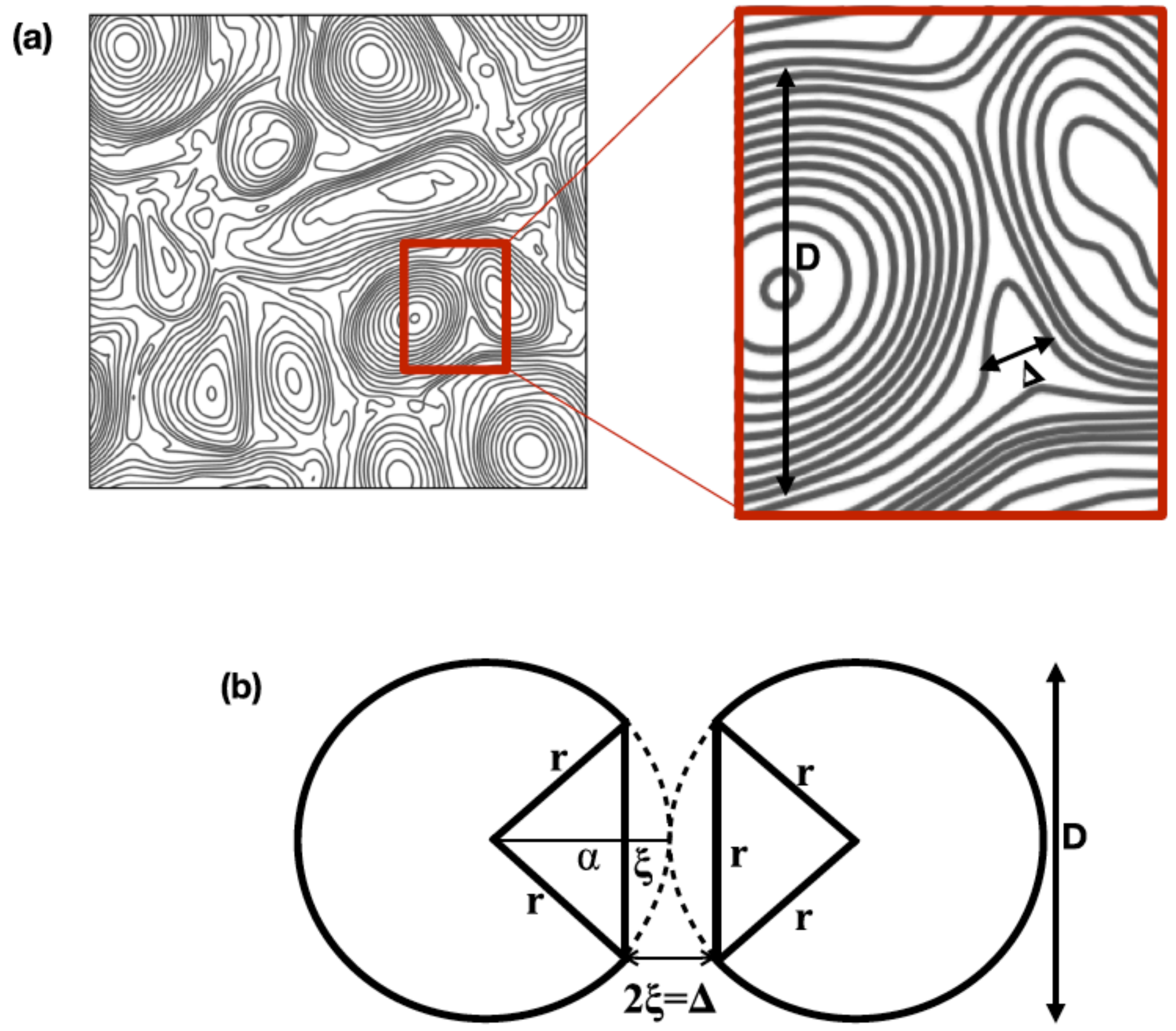


FIG. 1. (a) Schematic of magnetic field lines adapted from Ref. 6 showing an enlargement in the vicinity of a magnetic reconnection region. Shown are the approximate exhaust width Δ from the reconnection of a magnetic bubble roughly of size D. (b) Geometrical interpretation: two flux bubbles interact with a radius r with a separation distance Δ. The figure is an illustration of bubble size threshold for the ions to respond to the reconnected field lines in magnetic reconnection.

Gradual coupling of ions

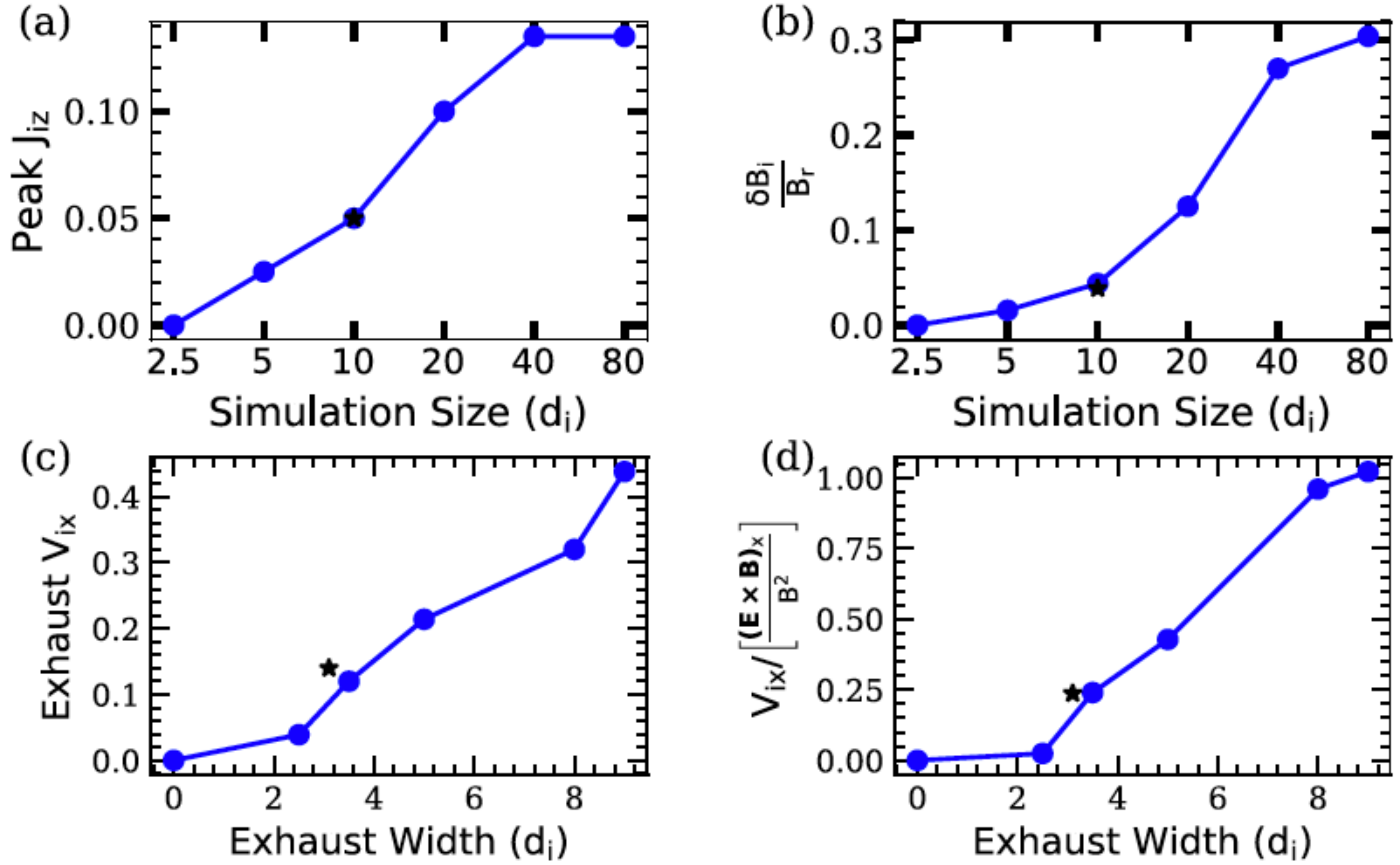


FIG. 9. All runs: each point represents a simulation and (∗) represents run C2. (a) Peak J_{iz} gradually increases and plateaus at a simulation size of 40 d_i. (b) Reduction in the inflowing reconnecting magnetic field for given simulations. (c) The peak ion exhaust velocities are plotted against the exhaust widths for given simulations. A gradual increase is seen. (d) The ion exhaust speeds normalized to E × B drift velocity for each simulation are plotted against the exhaust width.

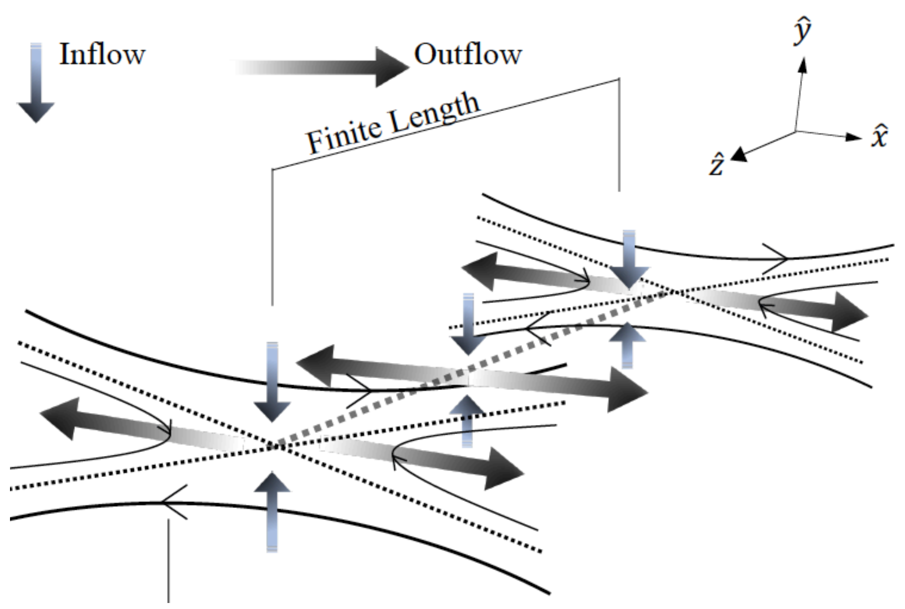
Key Points

- Scale D is the approximate scale length associated with reconnection.
- Constraint on magnetic bubble size.
  - For smallest discernible ion flows r ~ 8 d_i.
  - Fully ion-coupled r~30 d_i.

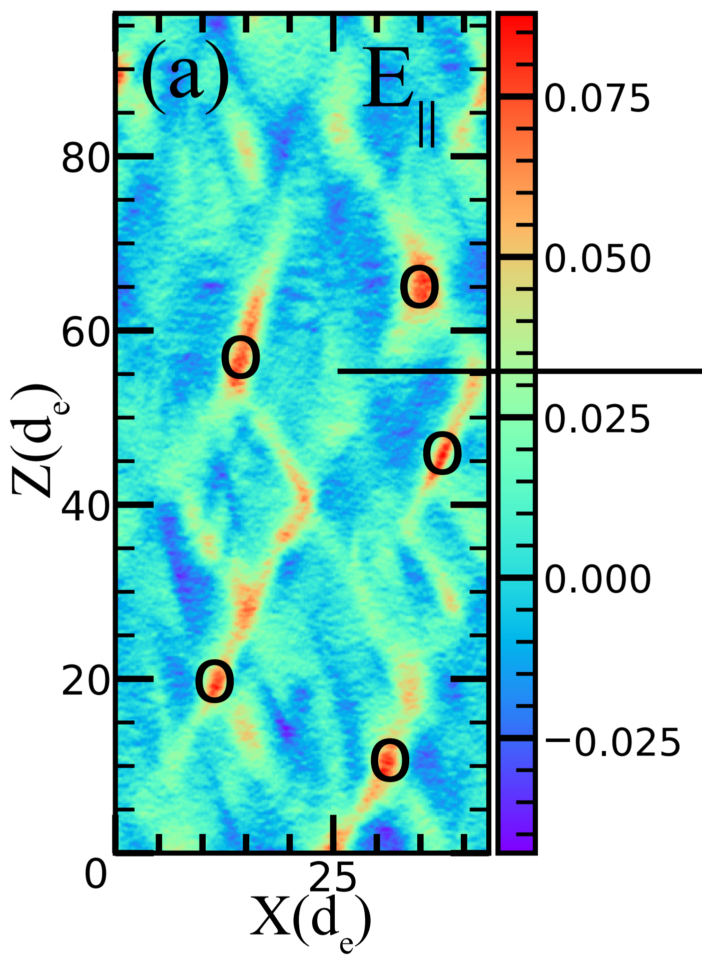
Pyakurel et al, 2019, POP

3D Electron-Only Reconnection: Finite Length X-line

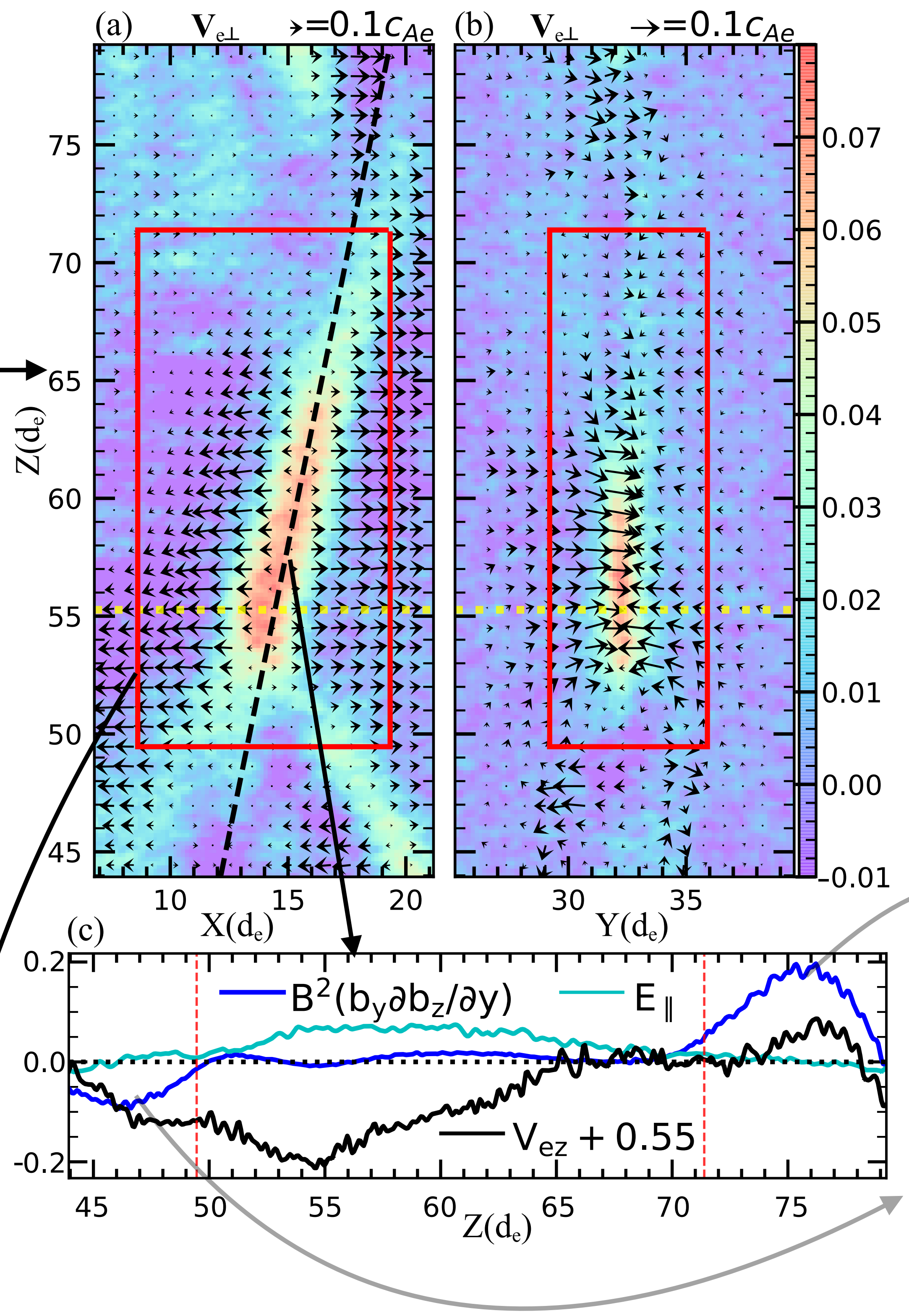
3D Geometry



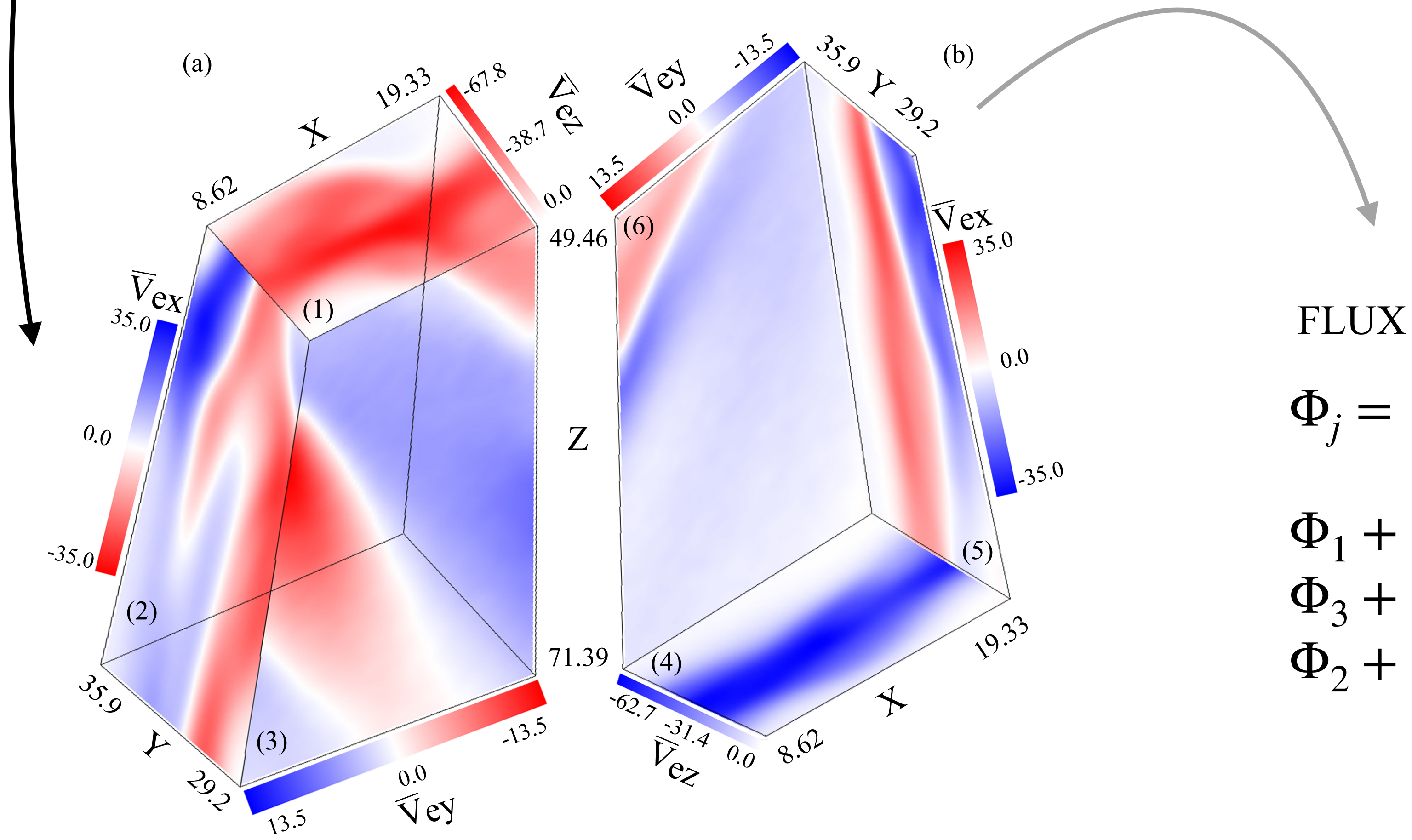
Spontaneous generation of many finite length X-lines in 3D.



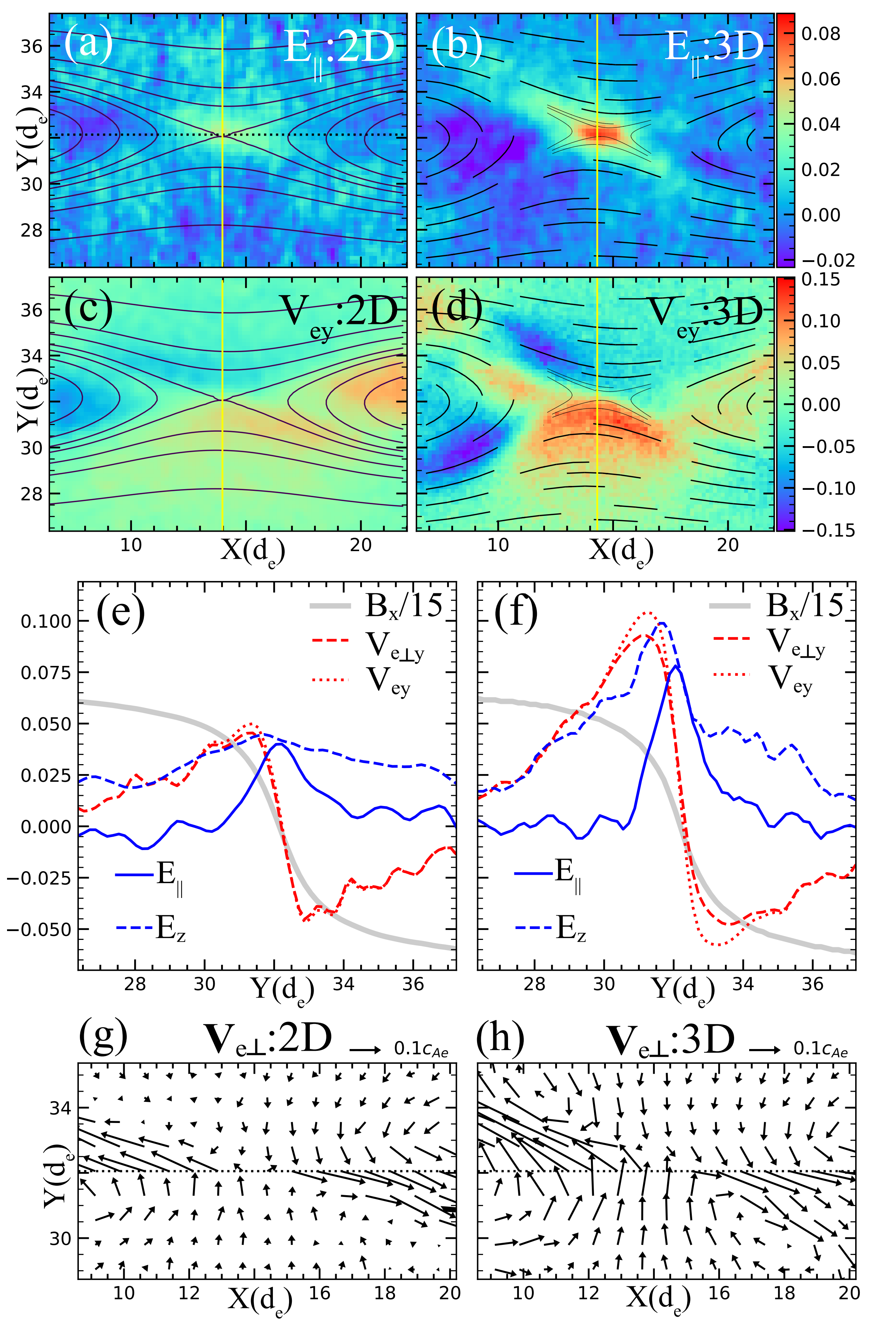
Analyzing one finite X-line in 3D



1. Curvature force term enhanced and depressed outside the diffusion region.
2. Out of plane Vez flows respond to this tension force.



2D vs. 3D



Key Points

- 3D Electron-only reconnection spontaneously develops where the magnetic X-line is localized in the out-of-plane (z) direction.
- The consequence is an enhancement of the reconnection rate compared with 2D, which results from differential mass flux out of the diffusion region along z, enabling a faster inflow velocity and thus a larger reconnection rate.
- This outflow along z is due to the magnetic tension force in z just as the conventional exhaust tension force, allowing particles to leave the diffusion region efficiently along z unlike 2D configuration
- Upper limit of reconnection rate in 3D electron-only reconnection?

FLUX IN = FLUX OUT

$$\Phi_j = \sum_{l,m} [V_{e,j}(l,m) \,.\, \hat{n}_j]\Delta^2$$

$\Phi_1 + \Phi_4 = 2.72$ → z direction

$\Phi_3 + \Phi_6 = -5.61$ → y direction

$\Phi_2 + \Phi_5 = 2.72$ → x direction

Summary

- Many simulation studies of electron-only reconnection in different regions of the magnetosphere has been conducted.

- Electron reconnection may play a key role in dissipation of turbulence energy at kinetic scales.

- Is the onset mechanism of electron-only reconnection fully understood?

- 3D reconnection at electron scales is fundamentally different than standard 2D reconnection.

- Unknowns
  - Upper limit of reconnection rate in 3D electron scale reconnection - 3D picture indicate larger than standard reconnection rate.

  - Heating in electron-only reconnection.

  - Effects of varying guide field and temperature.

  - What else?

Questions, comments and suggestions!