Energy transport during 3D small-scale reconnection driven by anisotropic turbulence using PIC simulations

Jeffersson Andres Agudelo Rueda
jeffersson.agudelo.18@ucl.ac.uk

Co-authors Verscharen D., Wicks R. T., Owen C. J., Nicolaou G., Walsh A. P., Zouganelis I., Germaschewski K.; Vargas Dominguez S.

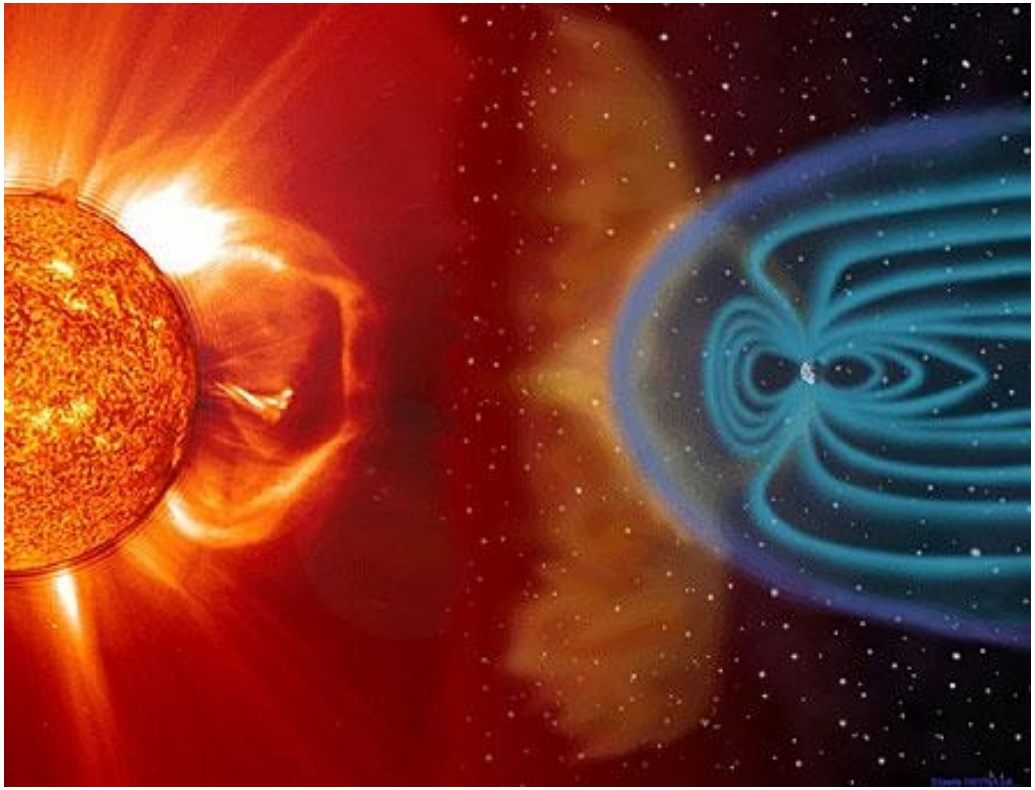
vEGU21, EGU21-8544, 15:48–15:50

This project is funded by ESA and ICETEX (Colombia)

Motivation

- Solar wind heating;
- Nearly collisionless plasma;
- Energy dissipation;
- Turbulence and magnetic reconnection;

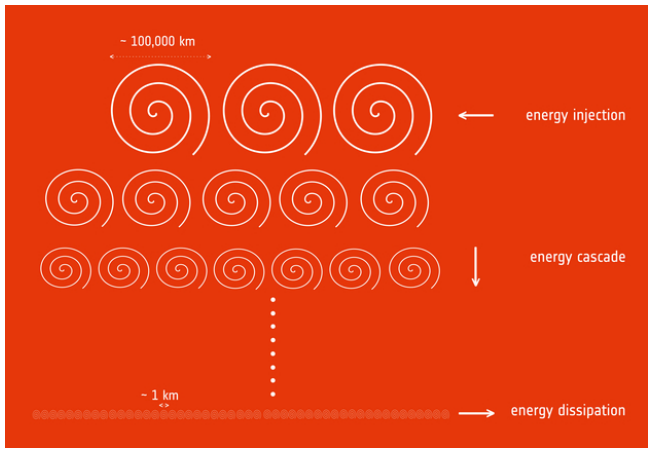
(Image taken from NASA)

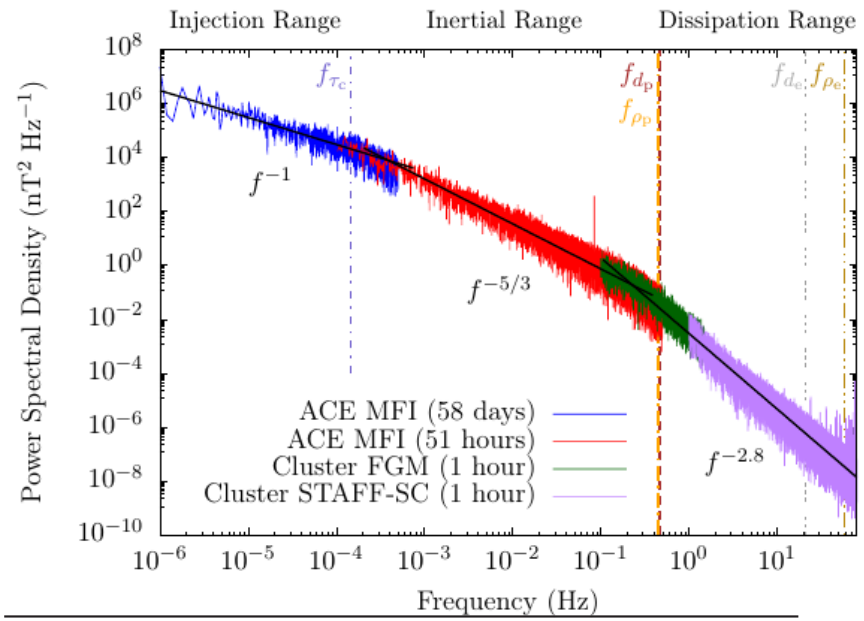


What is the link between turbulence and reconnection at small scales?

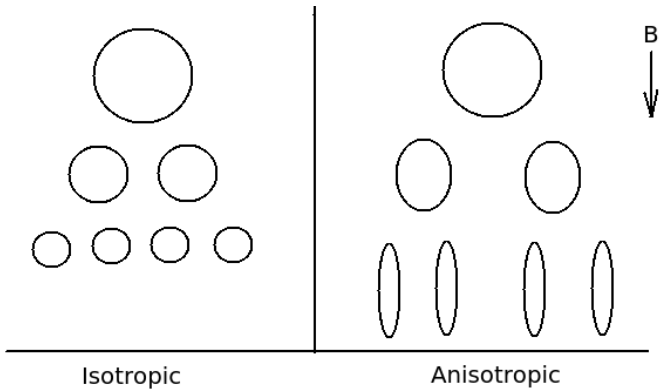
Plasma Turbulence

Top (ESA),Bottom (Verscharen et al., 2019)





- Anisotropy.



In the inertial range[1], $E \sim k_{\perp}^{-5/3}$, $E \sim k_{\parallel}^{-2}$;CB: $k_{\parallel} \sim k_{\perp}^{2/3}$.
In the kinetic range[2], $E \sim (k_{\perp}^{-2.3} - k_{\perp}^{-2.8})$, $E \sim (k_{\parallel}^{-3.5} - k_{\parallel}^{-5})$;

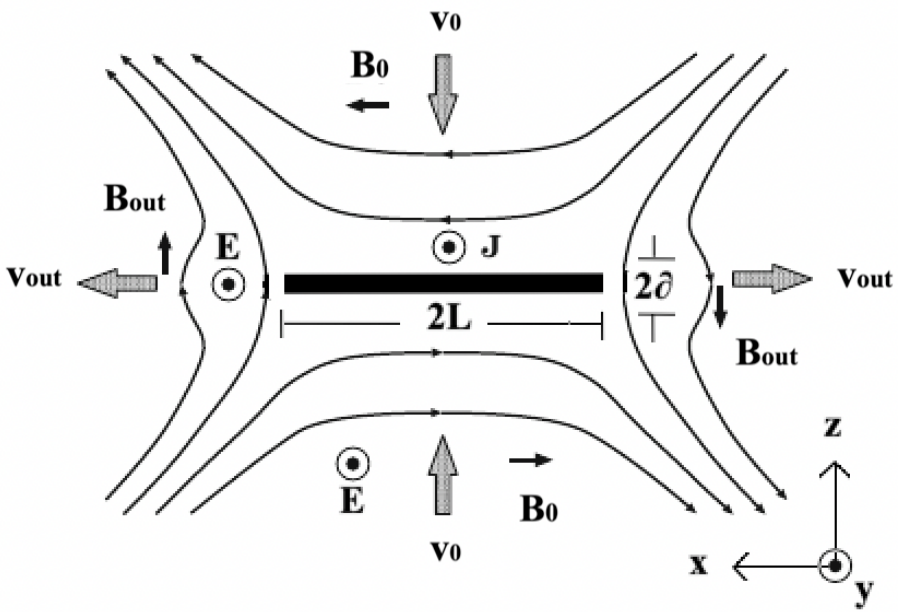
[3] Horbury et al, 2008; Alexandrova et al., 2009; Wicks et al., 2010; Goldreich & Sridhar, 1995.

[4] Chen C.H.K. et al., 2010, 2011, 2012; Alexandrova et al, 2013; Cho & Lazarian, 2004; Boldyrev & Perez, 2012.

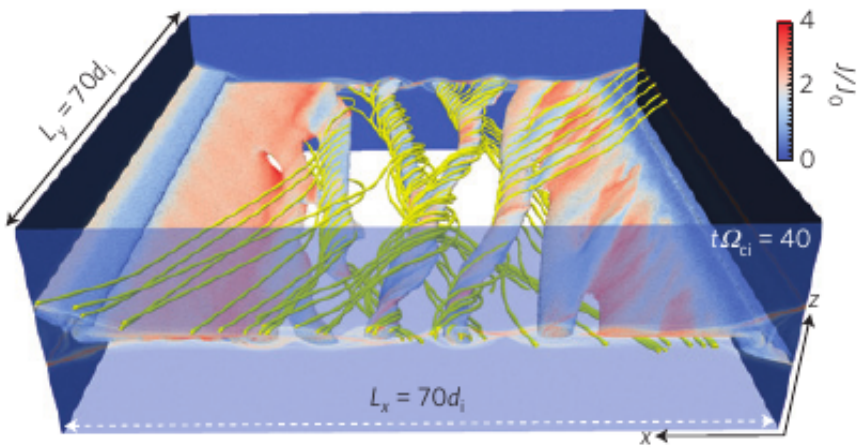
Magnetic reconnection is not 2D

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{u} \times \mathbf{B}) + \frac{\eta}{\mu_0} \nabla^2 \mathbf{B},$$

Adapted from Somov,(2012)

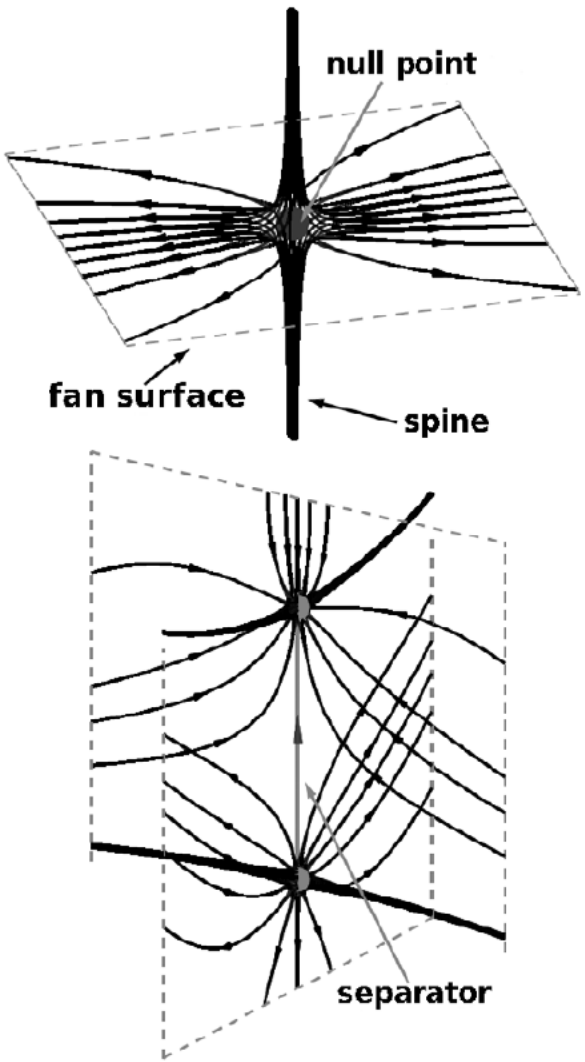


Adapted from Daughton et al. (2011)

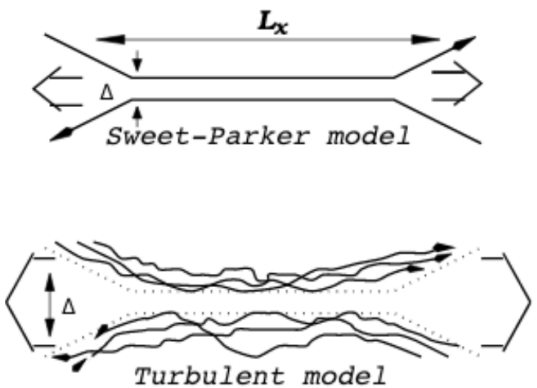


Reconnection is more complex

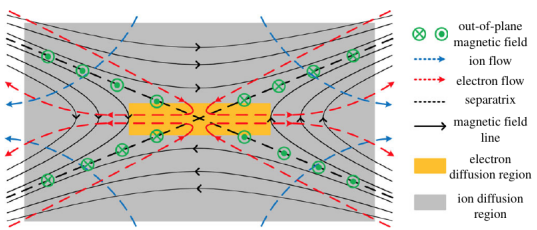
Adapted from Pontin, (2011)



Adapted from Lazarian et al. (2019)

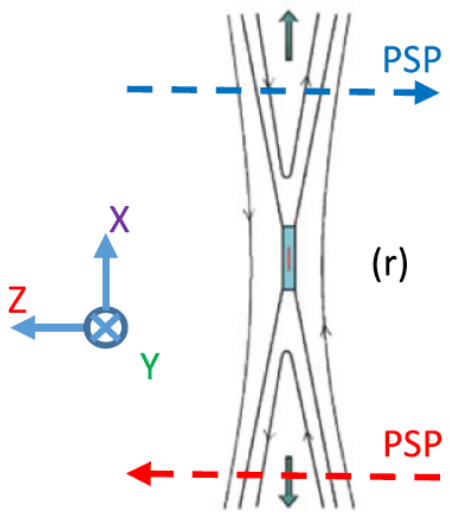


Adapted from Zweibel & Yamada, (2016)



A 2D model is our best guest with observations

Adapted from Phan et al. (2020)



Turbulence in reconnection

Disruption of current sheets and speeding up of reconnection rate.

Reconnection in turbulence

Dissipation channel of turbulent energy.

Is turbulence dissipated by small-scale reconnection in the solar wind?

Questions to answer

1. Does reconnection occur from an anisotropic turbulent cascade?
2. How do we identify 3D magnetic reconnection?
3. What does 3D small-scale reconnection look like?
4. How does reconnection dissipate energy?

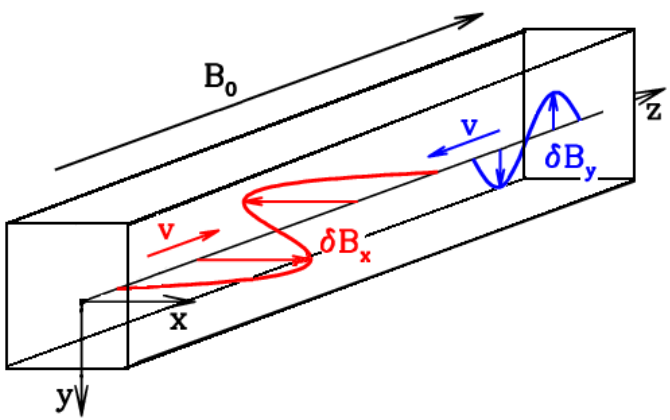
What do we need for addressing these questions?

1. Turbulence $\longrightarrow$ 3D geometry;
2. Small scales $\longrightarrow$ Kinetic simulations;
3. Kinetic effects at subproton scales $\longrightarrow$ Full Particle In Cell (PIC);
4. Identify occurrence of reconnection in 3D $\longrightarrow$ Define a set of indicators;

Simulating anisotropic Alfvénic turbulence

PIC code, Plasma simulation code (Germaschewski, et al. 2016). Periodic boundary conditions. $\mathbf{B}_0 = B_0\hat{z}$.

$$\frac{\delta \mathbf{v}_m^\alpha}{v_A} = \mp \frac{\delta \mathbf{B}_m^\alpha}{B_0};$$
$$k_{m,\parallel} d_i = C\left(|\mathbf{k}_{m,\perp}| d_i\right)^{2/3}.$$

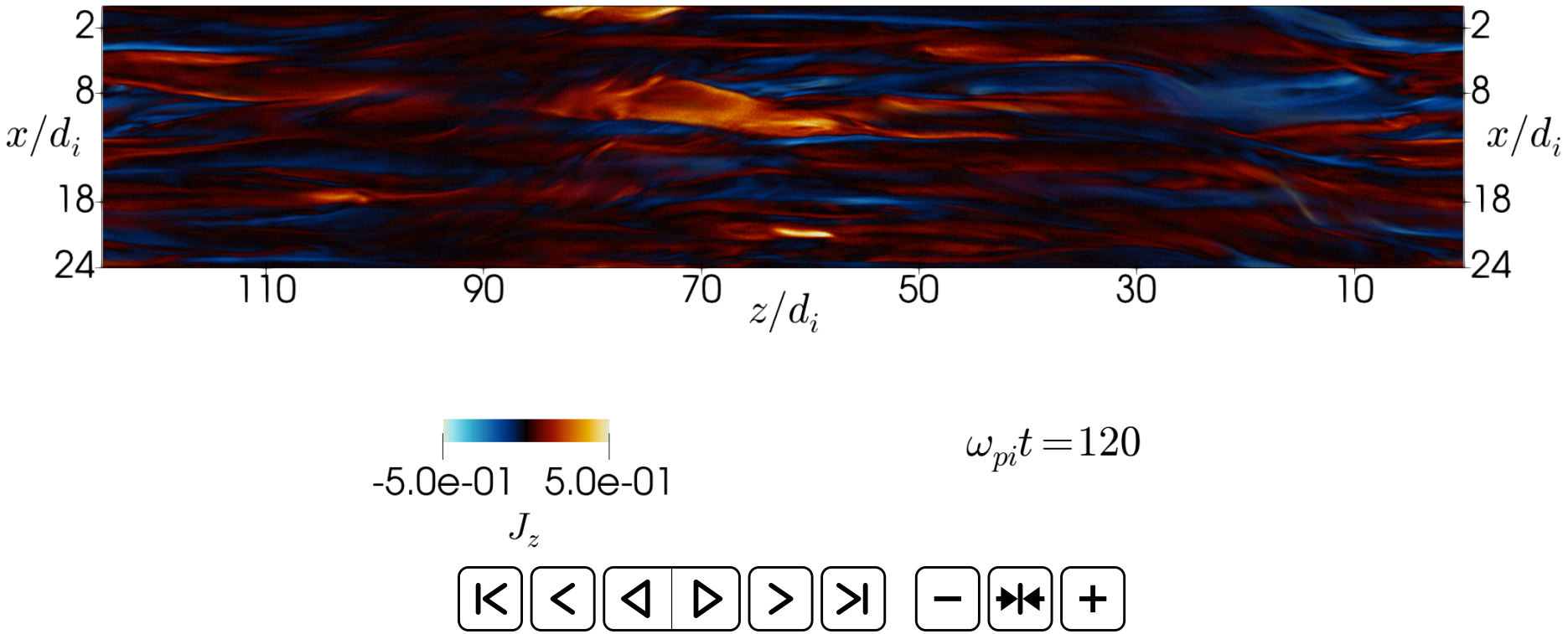


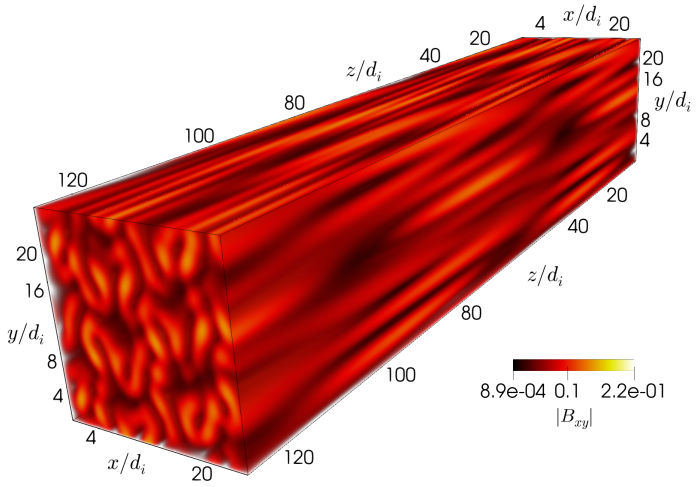
V	$24d_i \times 24d_i \times 125d_i$
Δr	$0.06d_i$
Δt	$0.06/\omega_{pi}$
m_i/m_e	100
V_A/c	0.1
$n_i; n_e$	1
$N_i; N_e$	100
$\beta_i; \beta_e$	1
$T_{i;\perp}/T_{i,\parallel}, T_{e,\perp}/T_{e,\parallel}$	1

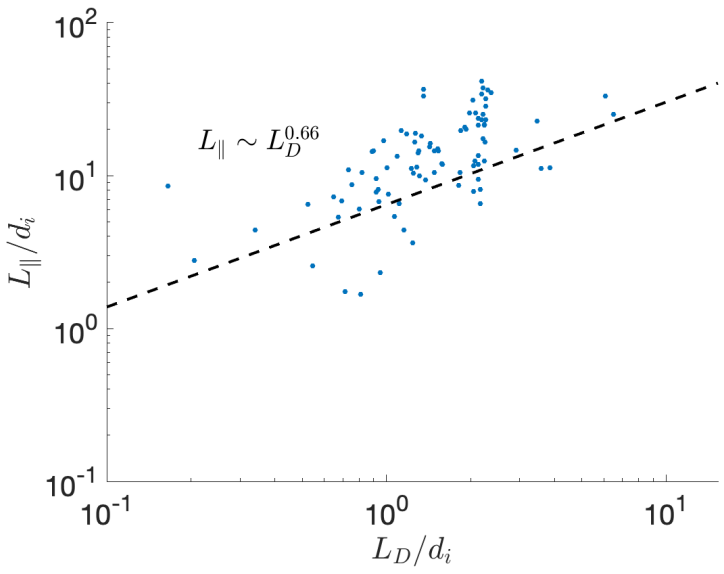
Table: Simulation parameters

Simulations performed at DiRAC DIaL. For details, see Agudelo et al., (JPP accepted 2021)

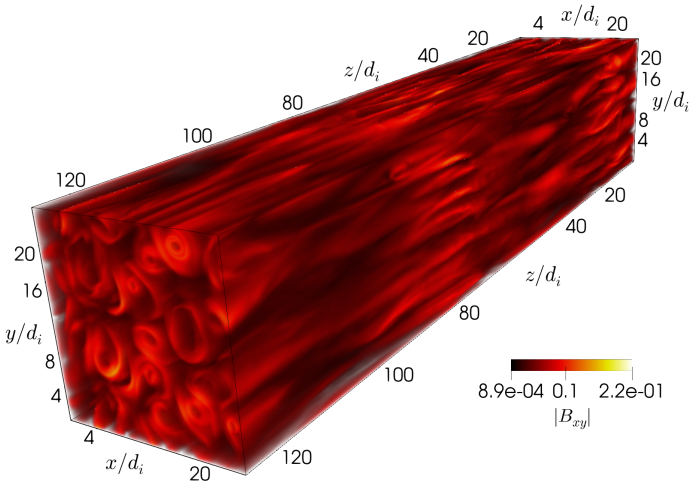
Highly dynamic system.

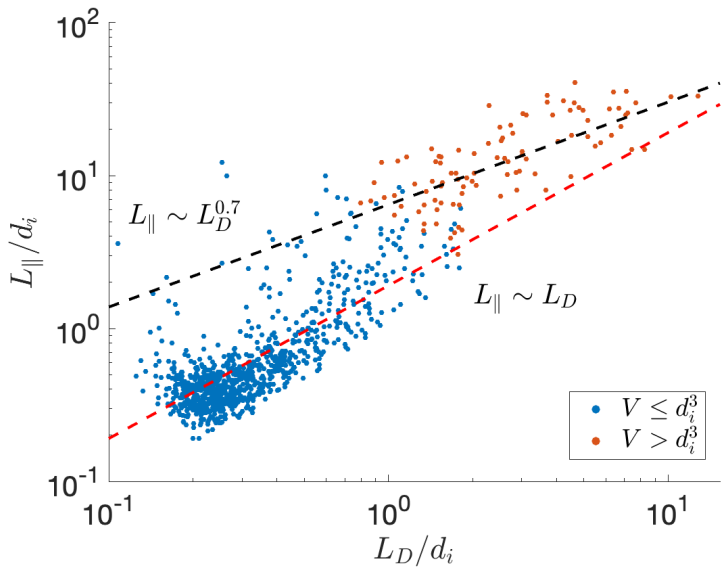



x/d_i
z/d_i
y/d_i
8.9e-04 0.1 2.2e-01
$|B_{xy}|$


$L_\parallel \sim L_D^{0.66}$
$L_\parallel/d_i$
L_D/d_i

(a) $t = 0$


x/d_i
z/d_i
y/d_i
8.9e-04 0.1 2.2e-01
$|B_{xy}|$


$L_\parallel \sim L_D^{0.7}$
$L_\parallel \sim L_D$
$V \leq d_i^3$
$V > d_i^3$
$L_\parallel/d_i$
L_D/d_i

(b) $t = t_R$

Formation of current structures.

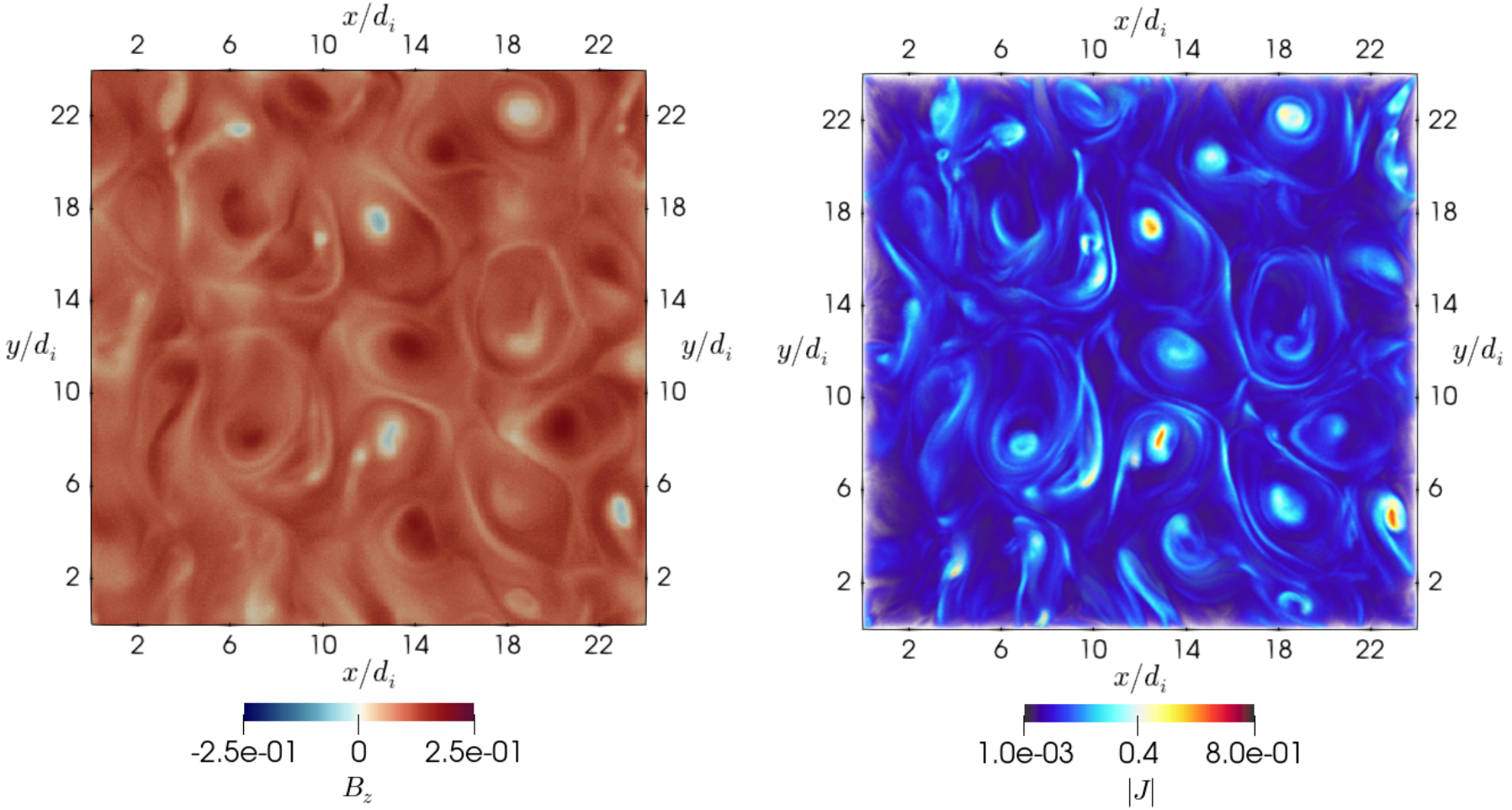
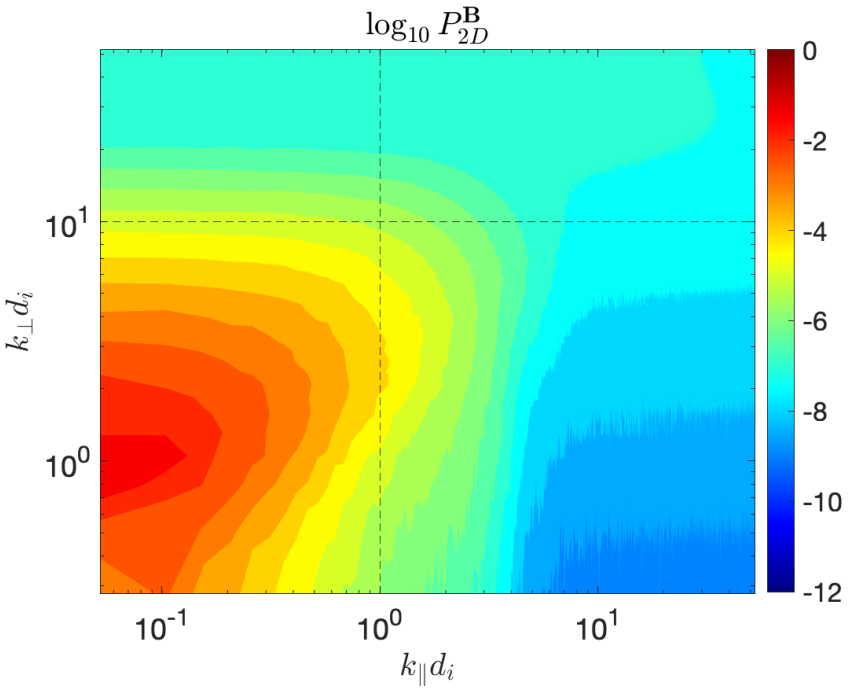
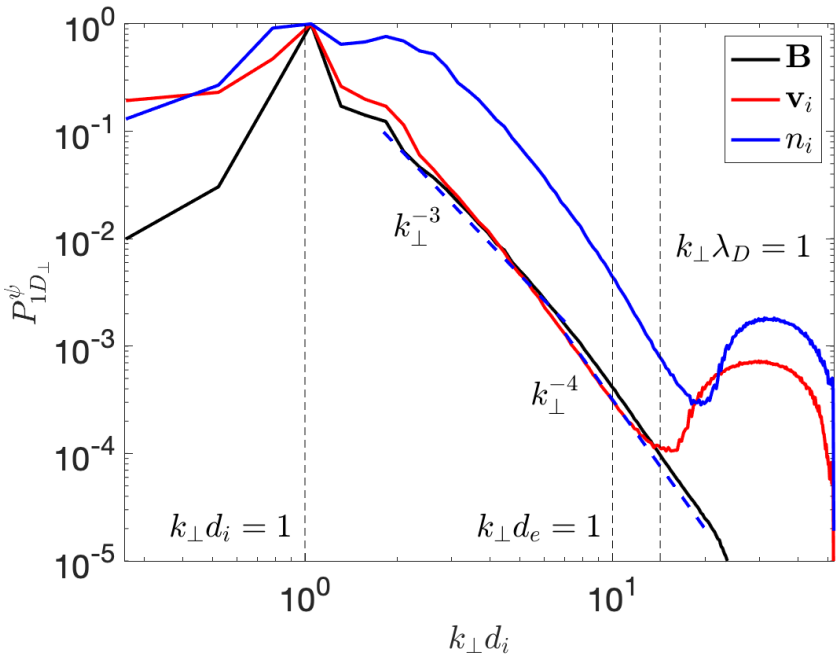


Figure: Snapshots at $\omega_{pi}t = 120$ over the front face of the simulation box. The background magnetic field is directed out of the plane.

Evidence of turbulence in the simulation domain. Anisotropic cascade



(a)



(b)

Isocontours of the reduced 2D PSD in the $(k_\parallel, k_\perp)$-plane for the magnetic field (a) and reduced 1D perpendicular PSD (b) at $\omega_{pi} t = 120$.

Finding reconnection sites

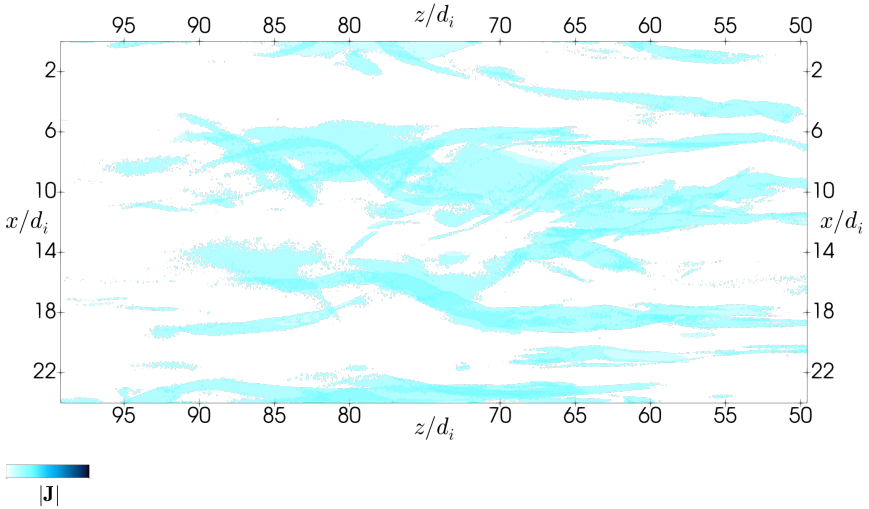
Indicators of magnetic reconnection

- C1 Current-density structures, $|\mathbf{J}| \geqslant \langle|\mathbf{J}|\rangle + N_{th}(|\mathbf{J}|)^{rms}$
- C2 Fast ions and electrons, $|\mathbf{v}_{i,e}| \geqslant \langle|\mathbf{v}_{i,e}|\rangle + N_{th}(|\mathbf{v}_{i,e}|)^{rms}$;
- C3 Heated particles, $T_{i,e} \geqslant \langle T_{i,e}\rangle + N_{th}(T_{i,e})^{rms}$;
- C4 Energy exchange particles-fields, $|\mathbf{J}\cdot\mathbf{E} - \langle|\mathbf{J}\cdot\mathbf{E}|\rangle| \geqslant N_{th}(|\mathbf{J}\cdot\mathbf{E}|)^{rms}$;
- C5 Non-zero parallel electric fields, $|E_{\parallel} - \langle|E_{\parallel}|\rangle| \geqslant N_{th}(|E_{\parallel}|)^{rms}$, where $E_{\parallel} = \mathbf{E}\cdot\mathbf{B}/|\mathbf{B}|$ [3];

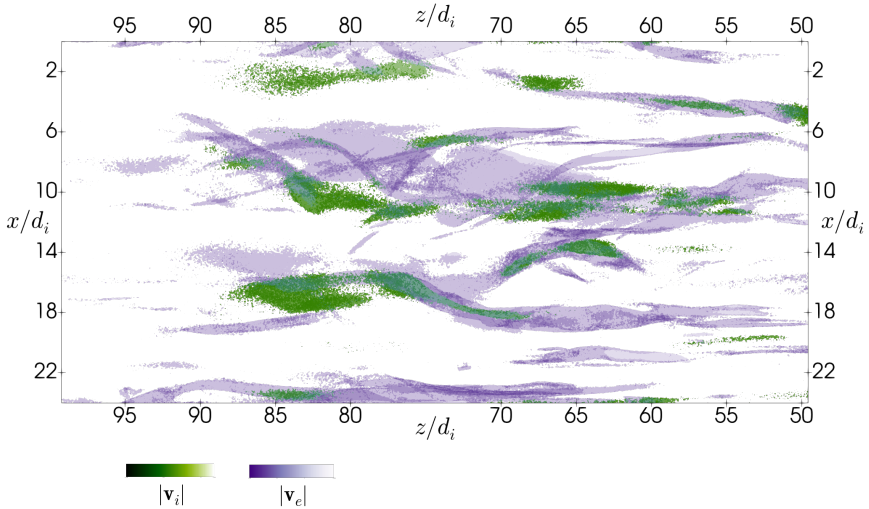
(Agudelo et al., JPP, accepted 2021). Scan →



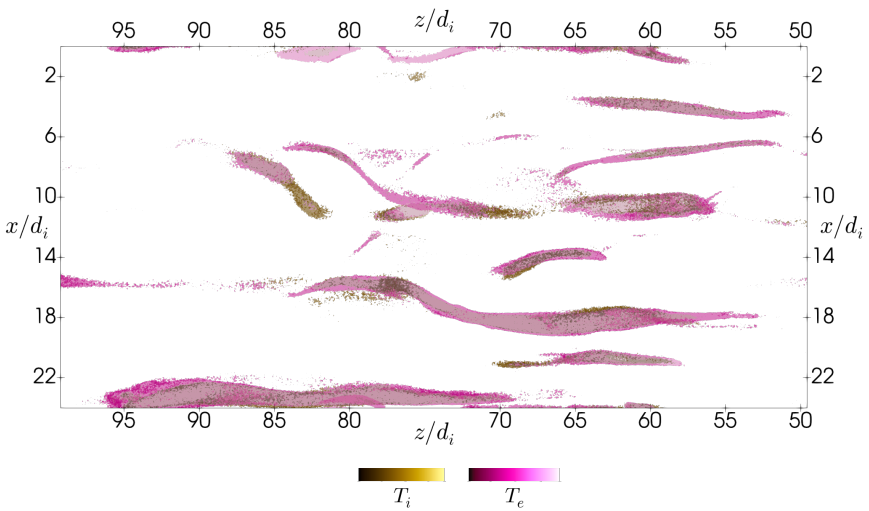
[3] The particle noise affects the applicability of this indicator


z/d_i
95 90 85 80 70 65 60 55 50
x/d_i
2 6 10 14 18 22
$|\mathbf{J}|$

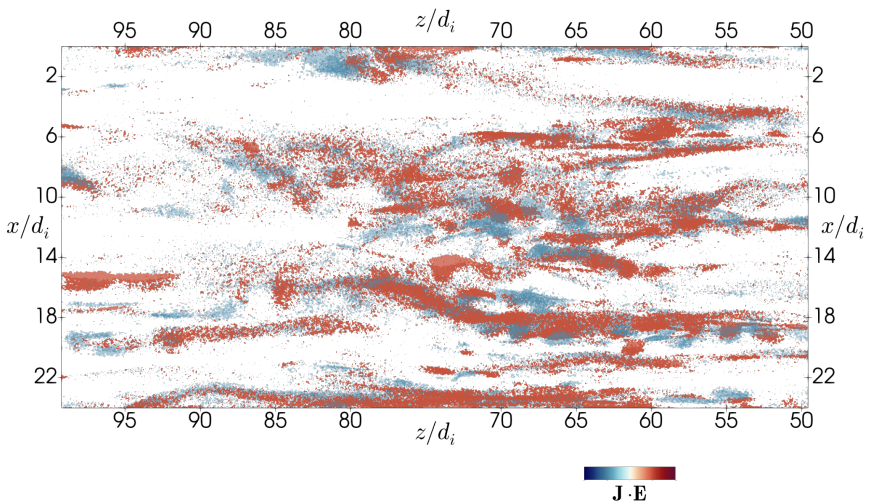
C1


z/d_i
95 90 85 80 70 65 60 55 50
x/d_i
2 6 10 14 18 22
$|\mathbf{v}_i|$
$|\mathbf{v}_e|$

C2


z/d_i
95 90 85 80 70 65 60 55 50
x/d_i
2 6 10 14 18 22
T_i
T_e

C3

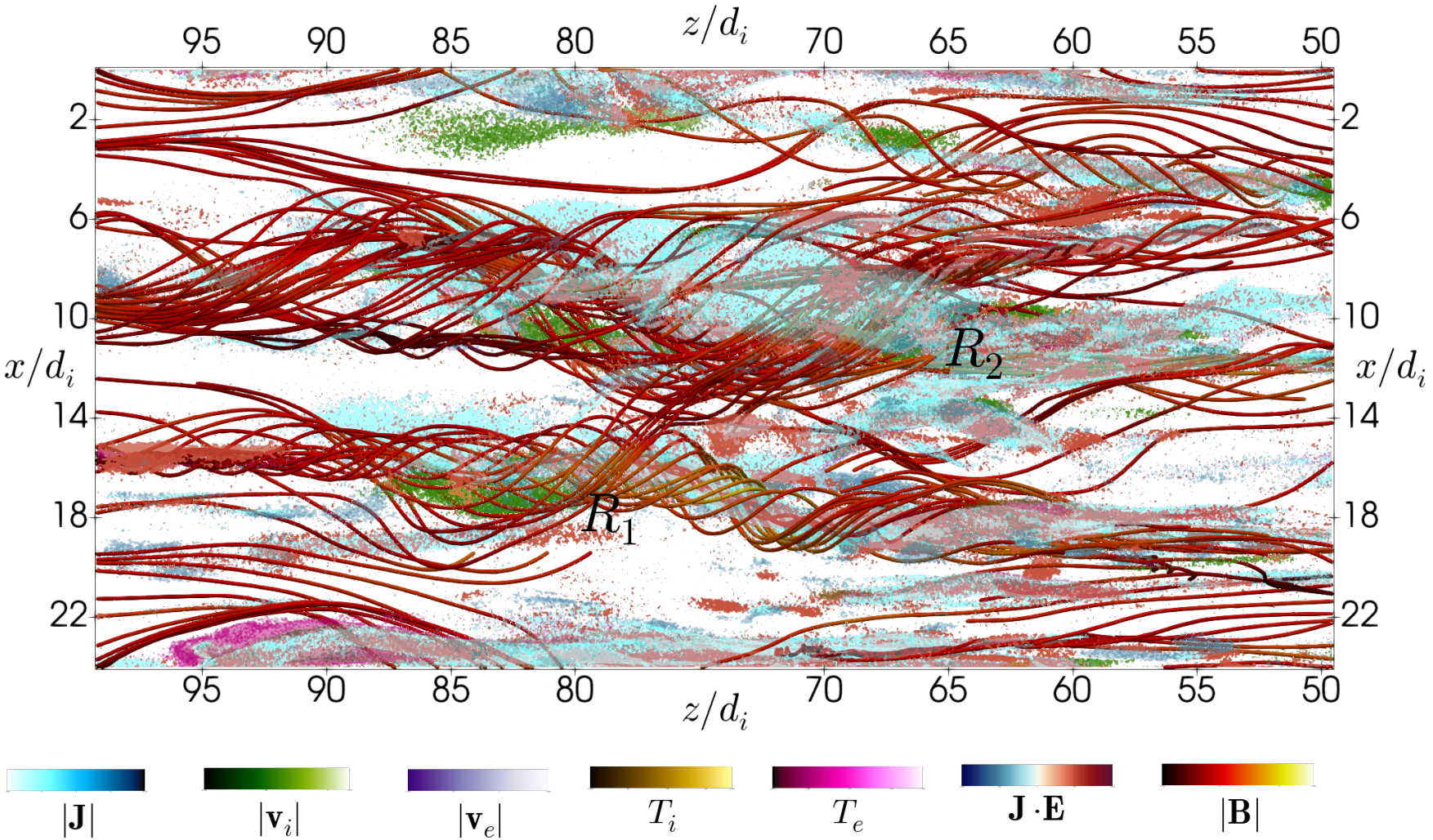

z/d_i
95 90 85 80 70 65 60 55 50
x/d_i
2 6 10 14 18 22
$\mathbf{J}\cdot\mathbf{E}$

C4

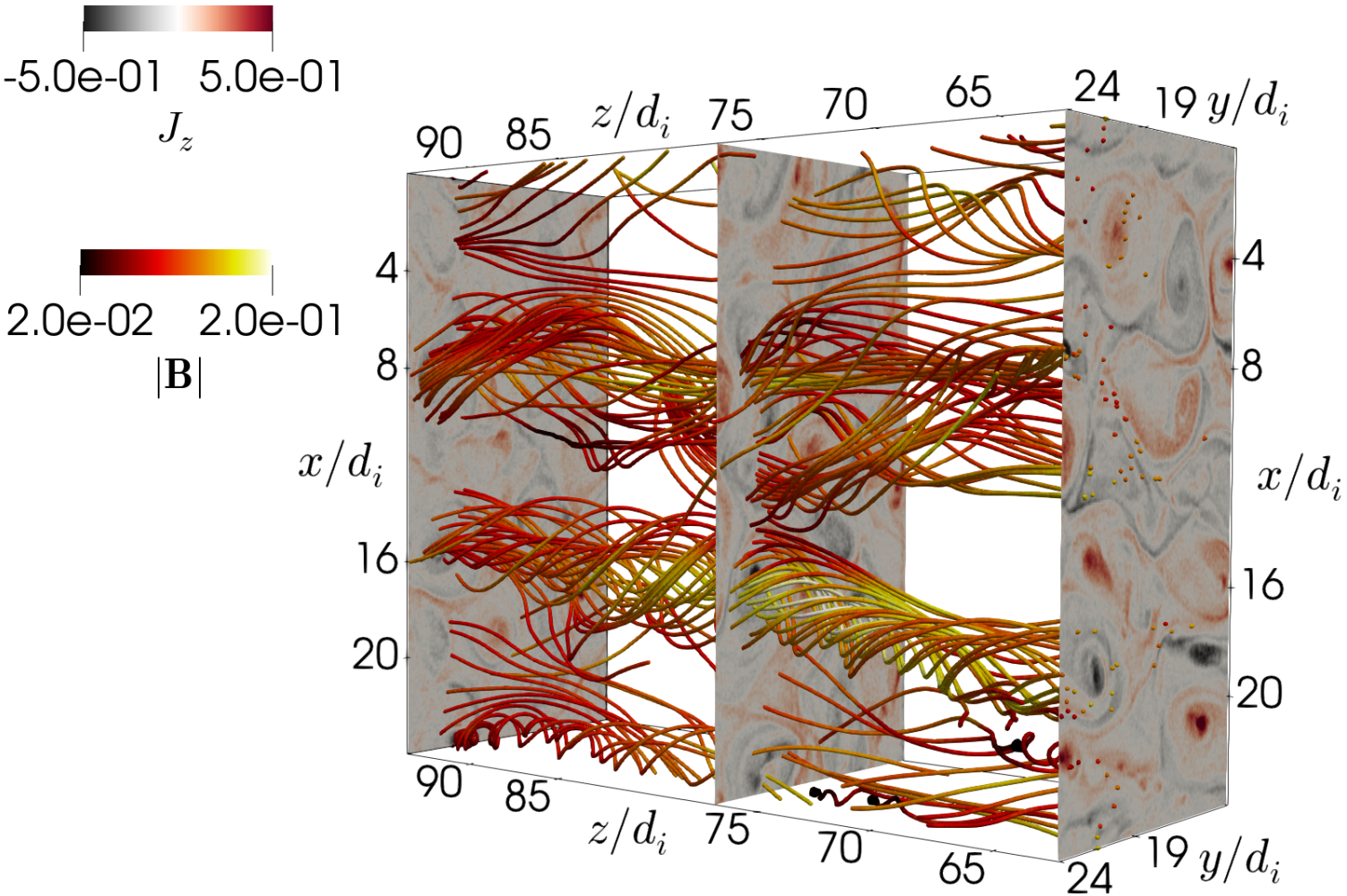
N_{th}	C1	$C2_e$	$C2_i$	$C3_e$	$C3_i$	$C4_+$	$C4_-$	$C5_+$	$C5_-$
3	149	144	77	92	82	68	77	0	0
4	97	92	29	50	39	23	17	0	0

N_{th}	C1 and $C2_{i,e}$	C1 and $C3_{i,e}$	C1-$C3_{i,e}$	C1-$C4_-$	C1-$C4_+$
3	34	55	24	3	3
4	9	27	6	6^*	6^*

Table: Number of events in our simulation domain at time $t = t_R$ fulfilling each condition

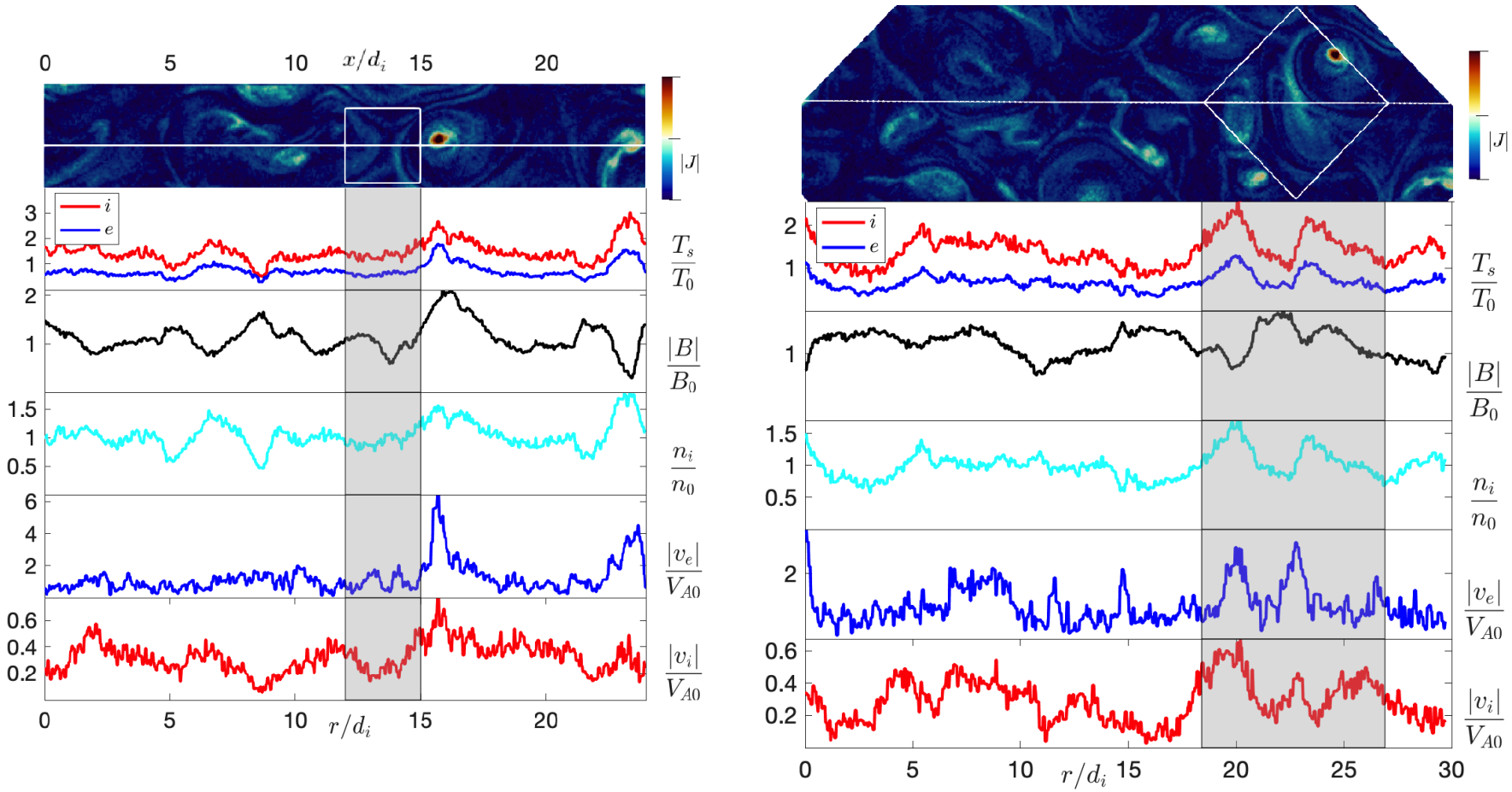


Set of indicators and magnetic field lines



$\omega_{pi}t = 120$

1D trajectories across the simulation box

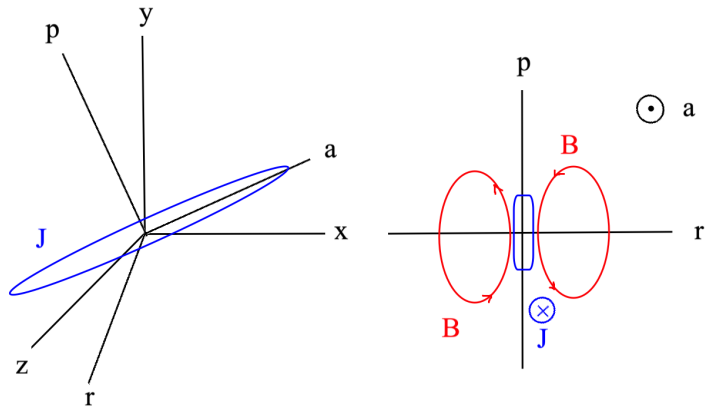


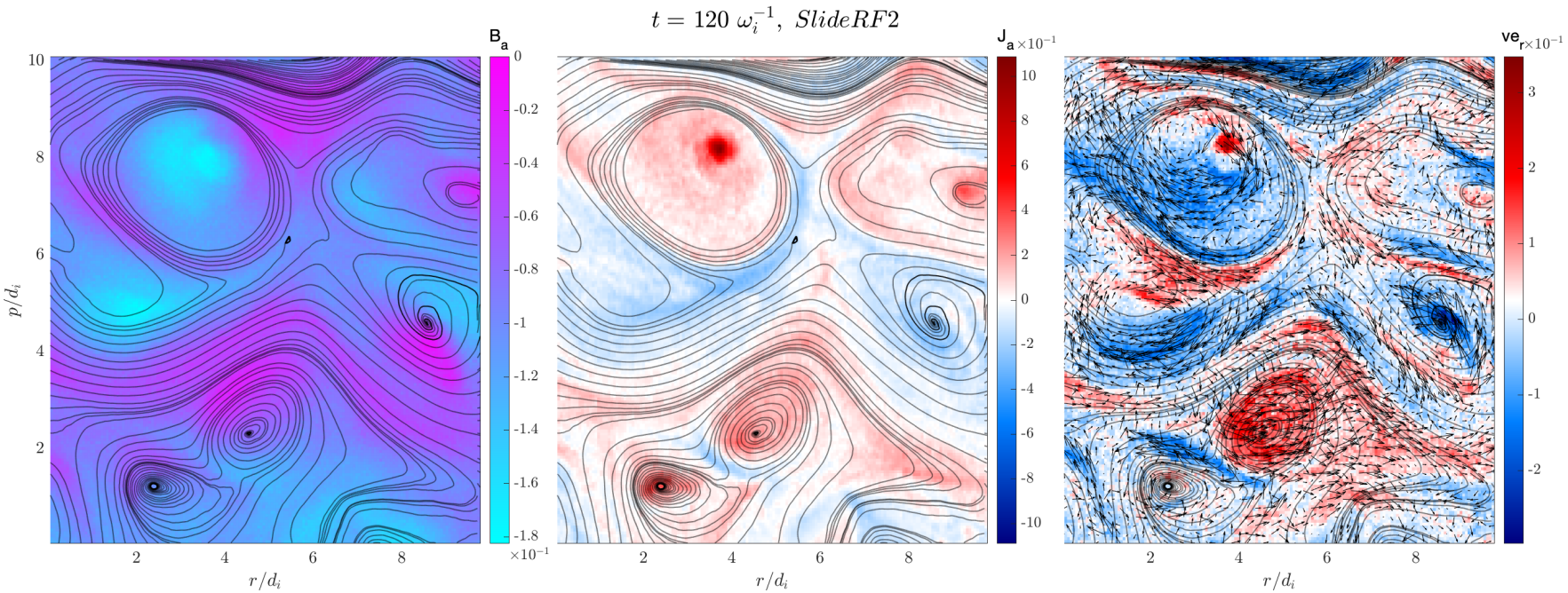
Small-scale features. Direct comparison with Parker Solar Probe and Solar Orbiter.

Energy distribution in the reconnection region

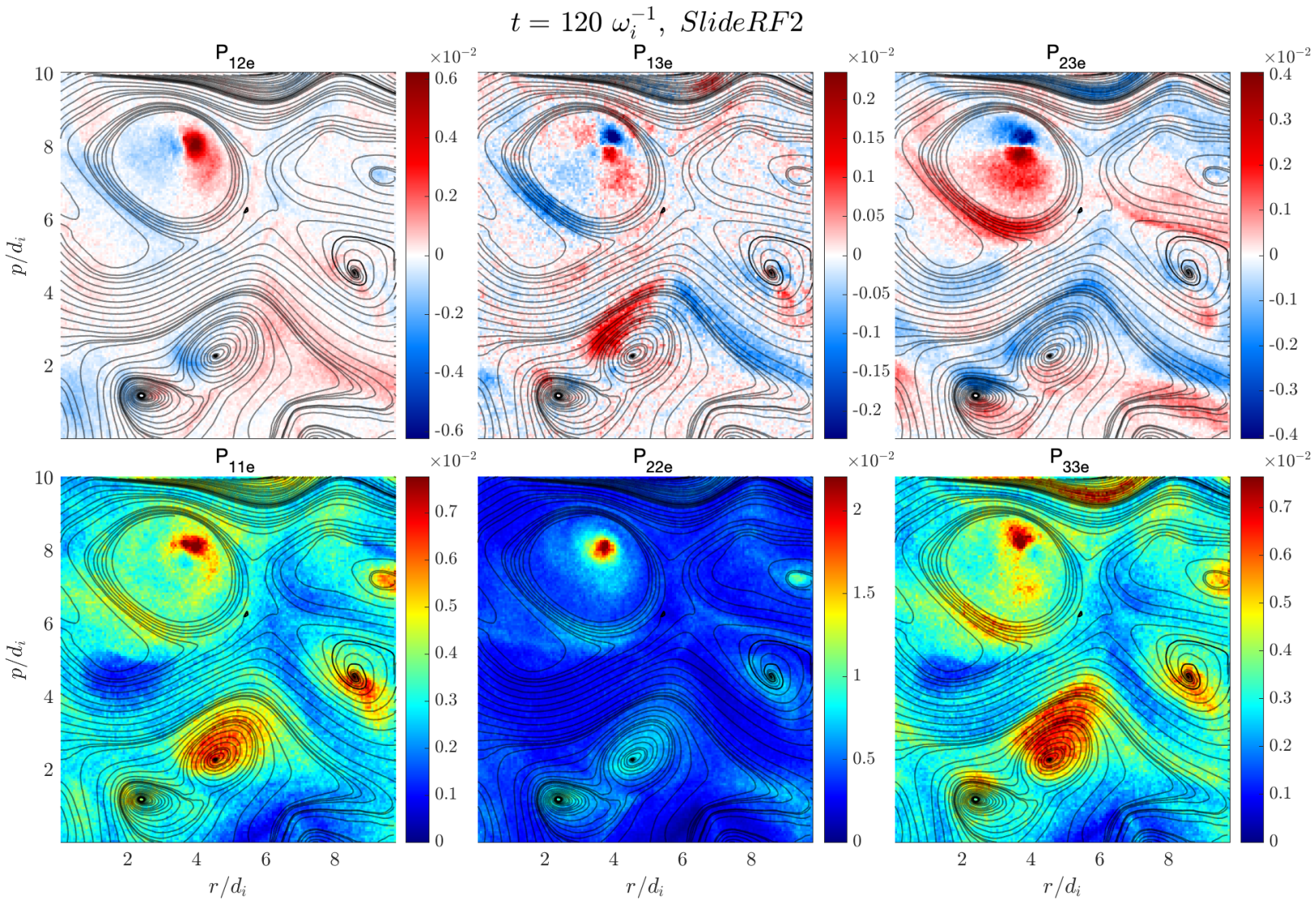
Coordinate transformation to the current-aligned reference frame

$x, y, z \longrightarrow p, a, r$

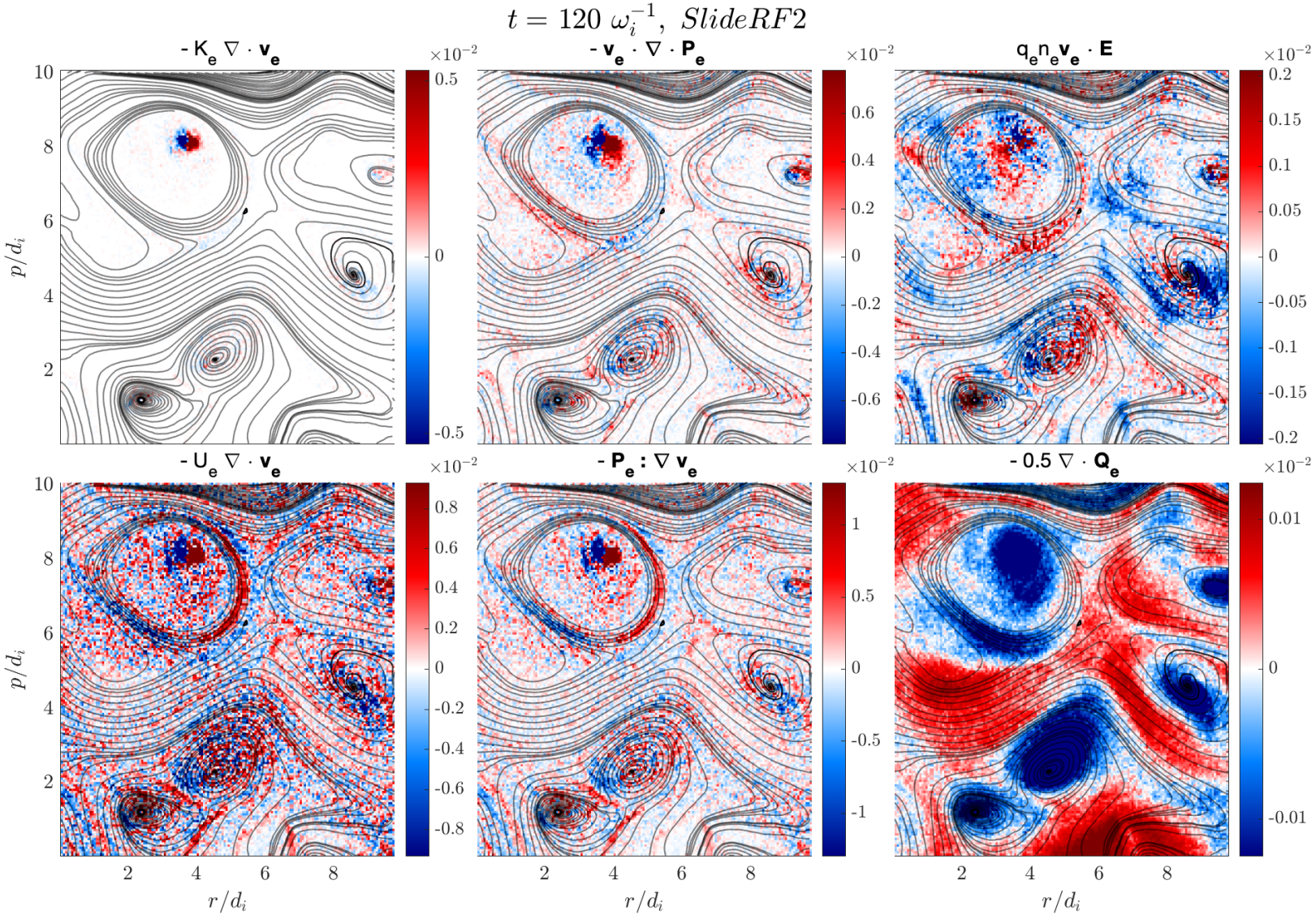




Electron pressure



Kinetic (K) and internal (U) energy structures



Conclusions and take-away points

- We set up anisotropic turbulence and observe the occurrence of magnetic reconnection;
- We propose a set of indicators to identify magnetic reconnection events in 3D PIC simulations.
- The observed reconnection event is asymmetric and complex;
- Particle heating and acceleration are associated with current filaments and flux ropes in our simulation. Research is Ongoing.

