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Free energy sources in current sheets formed in collisionless plasma turbulence

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Collisionless Plasma Turbulence

- Space and astrophysical plasmas are usually collisionless and in turbulent state.
  - Earth's magnetosphere, Solar wind, ISM, star atmosphere etc.

- Turbulence acts to dissipate energy into heat by transferring it to dissipation scales.
  - Slower-than-adiabatic-cooling of the solar wind is accounted for by its turbulent heating.

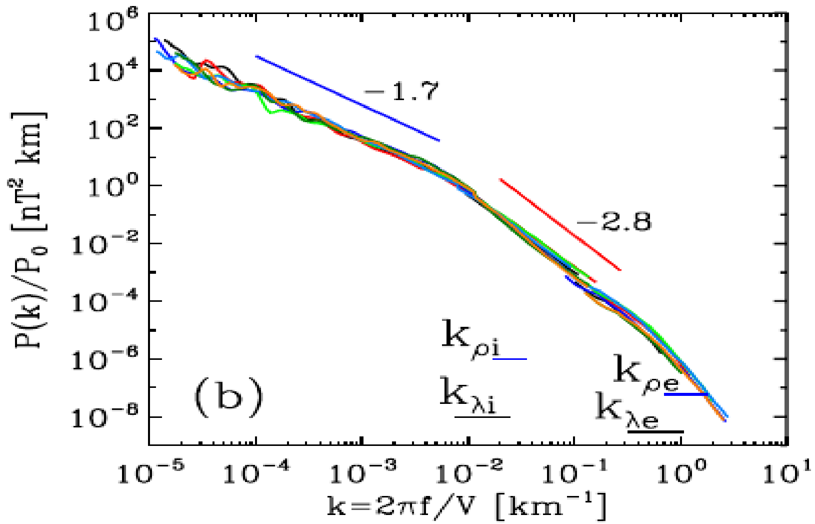
- In space and astrophysical plasmas with rare collisions,
  - Collisional dissip. scale << kinetic scales (gyro-radius, inertial length)

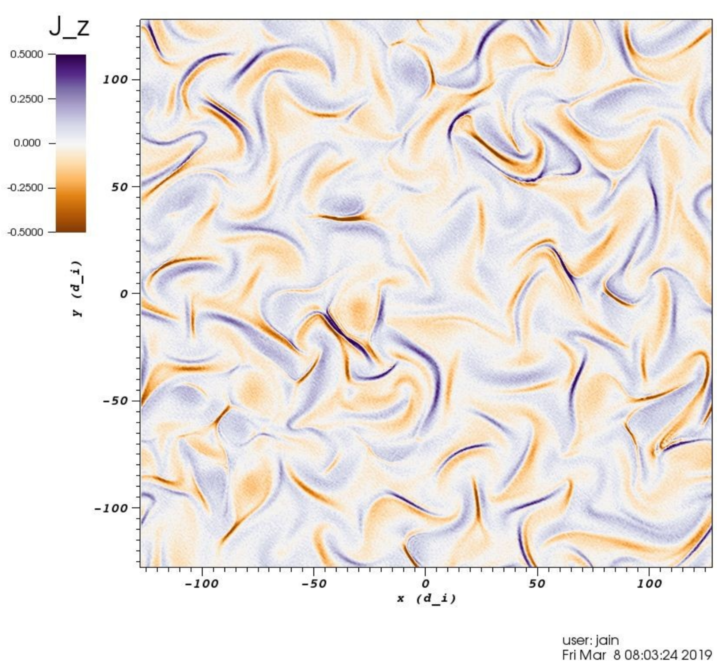
- Energy cascades down all the way to kinetic scales before hitting collisional dissipation scale.

What happens at kinetic scales?

Spectral breaks forms in energy spectrum at kinetic scales.

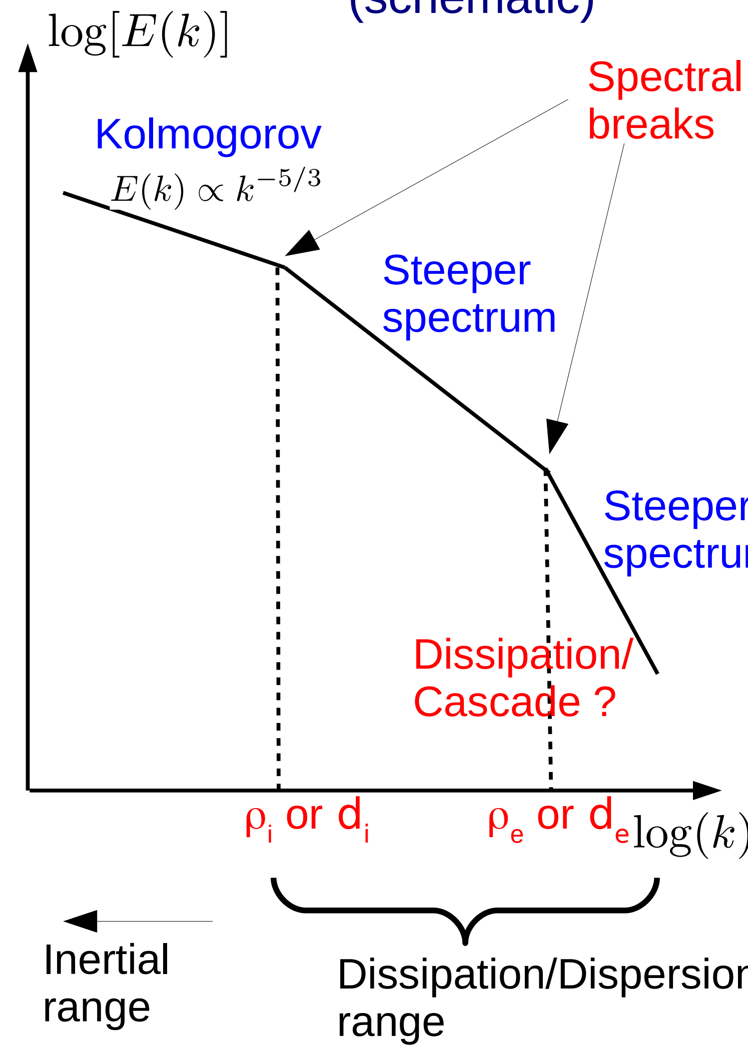
Solar wind obs. at 1 AU
[Alexandrova et al. (2009)]





CS forms at kinetic scales

Kinetic scale energy spectrum (schematic)

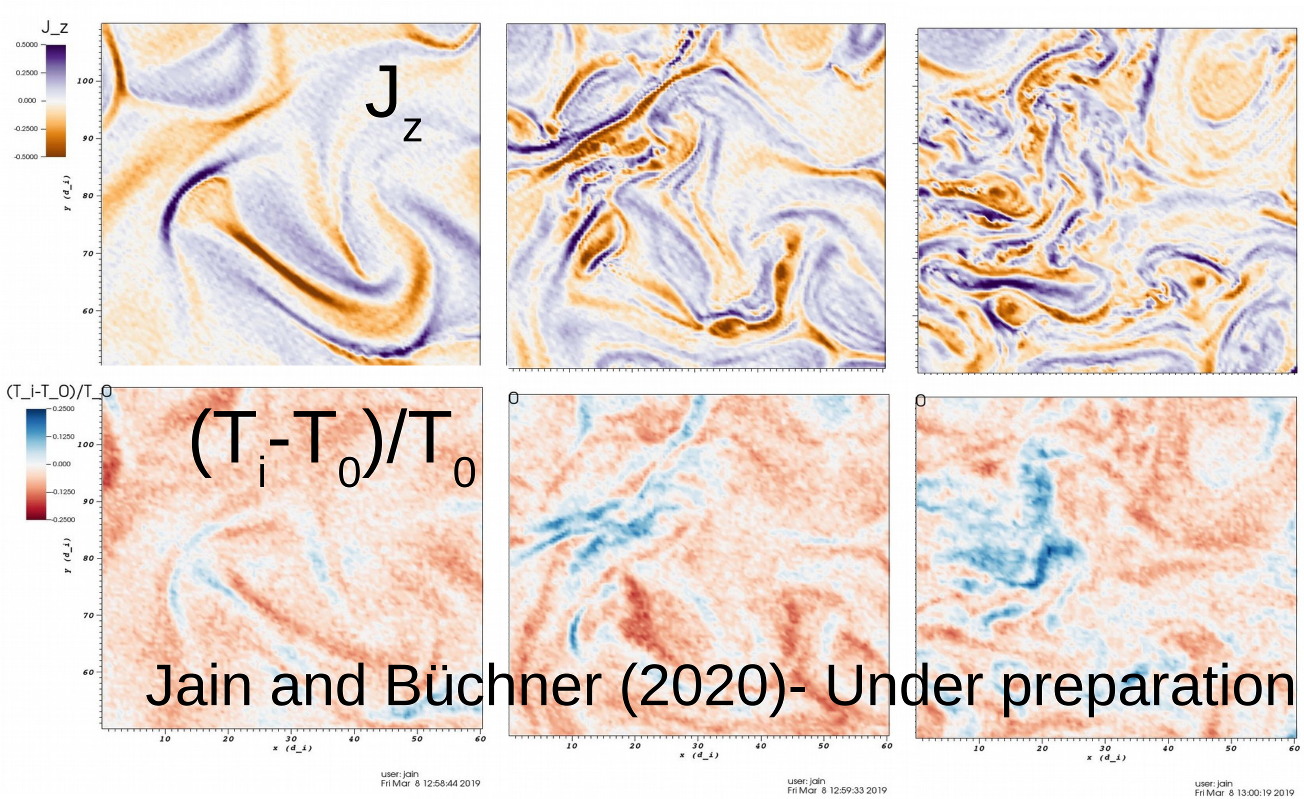


What about dissipation?

Dissipation takes place in and around kinetic scale current sheets formed in collisionless plasma turbulence.

- Current sheets form self-consistently at kinetic scales. [Franci et al. (2015), Servidio et al. (2014)]
- Simulations and space observations show that the dissipation is concentrated in and around these current sheets [Matthaeus et al. (2015)].

Time evolution



Jain and Büchner (2020)- Under preparation

What are the physical processes responsible for dissipation?

Kinetic plasma processes responsible for dissipation in current sheets are not well understood.

Several processes were considered.

- Magnetic reconnection
  - generates parallel electric field which can accelerate particles
  - In plasma turbulence basically a time-dependent tearing-like instability process
- Fermi acceleration:
  - energization by multiple bounces in contracting magnetic islands
  - magnetic islands are generated by magnetic reconnection
- Stochastic acceleration:
  - energization by chaotic orbits of ions for large enough fluctuation amplitudes
  - plasma instabilities can influence fluctuation amplitudes
- Plasma instability in CS:
  - can produce anomalous dissipation by generating their own turbulence
  - can generate plasma waves which participate in dissipation and/or cascade

Plasma instabilities in CS directly or indirectly influence the dissipation/cascade and resulting spectral behavior of plasma turbulence.

Free energy sources in CS

- Plasma instability are driven by free energy sources.
  - Spatial gradients of fluid variables
  - non-Maxwellian features of the distribution function

- Free energy sources in current sheets formed in collisionless plasma turbulence need to be characterized to understand the the role of plasma instabilities in collisionless dissipation.

- In a current sheet, current density, $J=e\, n\, (u_i-u_e)$, is confined in small thickness.
  - Gradients in at least one of n, u_i and u_e are present in current sheets. (Focus of this talk)
  - In addition non-Maxwellian features, like, temperature anisotropy can also be present. (Work under progress)

We carry out hybrid simulations to address physics near ion-kinetic scales.

- 2-D (x-y plane) hybrid simulations by A.I.K.E.F. code [Mueller et al, 2011]
  - – Ions as particles and electrons as inertialess fluid

- Initial conditions:
  - – A uniform plasma ($\beta_i = \beta_e = 0.5$)
  - – random phased equal amplitude Alfvenic fluctuations in the range

    $k_{min}\, d_i < k\, d_i < 0.2 < k_{break}\, d_i \approx 1$
  - – An external magnetic field (B_0) perpendicular to the 2-D simulation plane.

- Periodic boundaries.

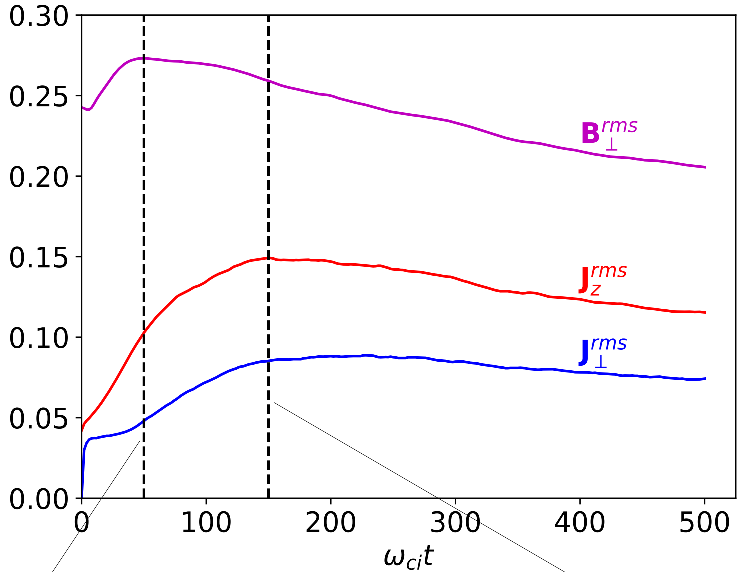
- Simulation parameters:
  - – box size: $256\, d_i \times 256\, d_i$
  - – Grid points: up to 2048×2048
  - – Particles per cell: 500

- Normalization:
  - – length by d_i
  - – time by ω_{ci}^{-1}
  - – Magnetic field by B_0

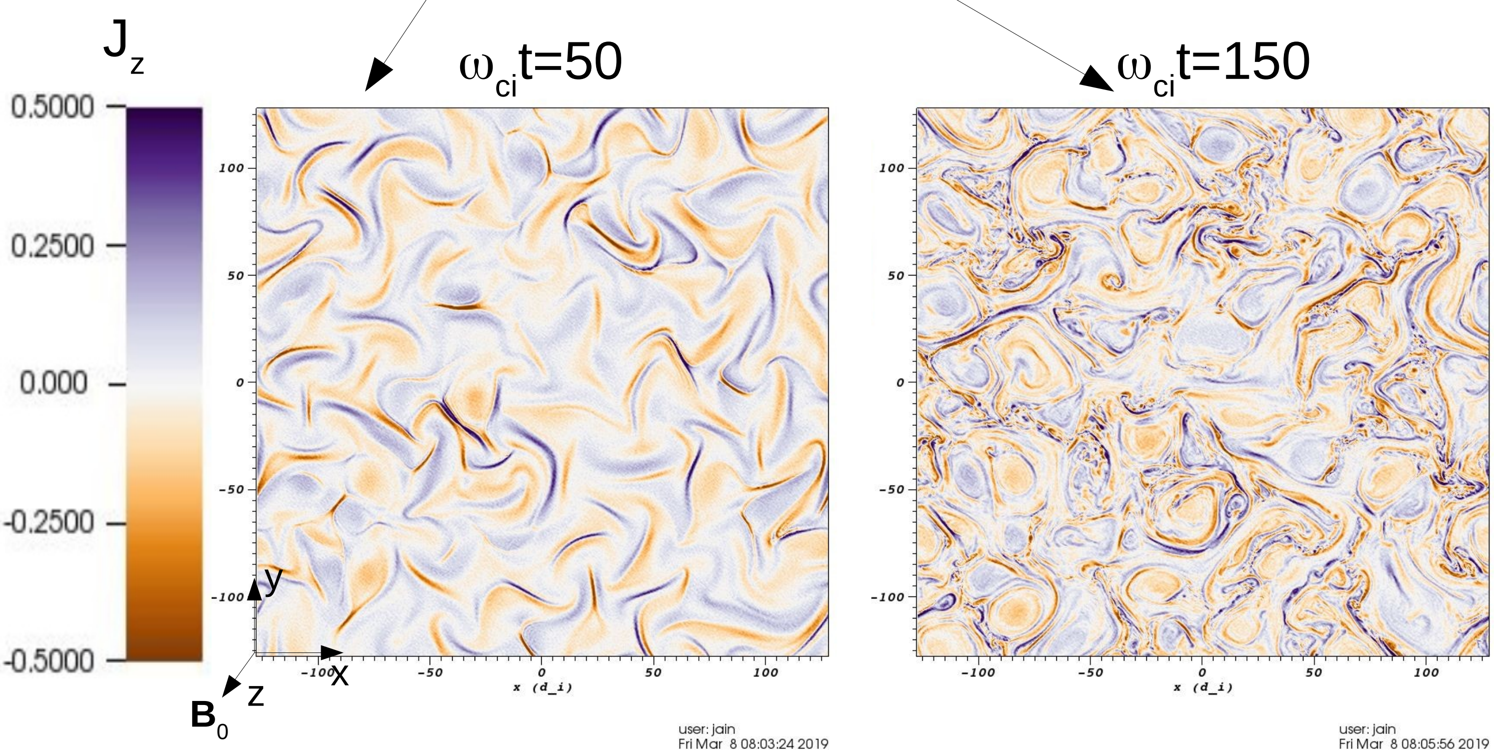
Initial random fluctuations evolve into current sheets (CS) which later disintegrate.

Jain and Büchner (2020) (*under preparation*)

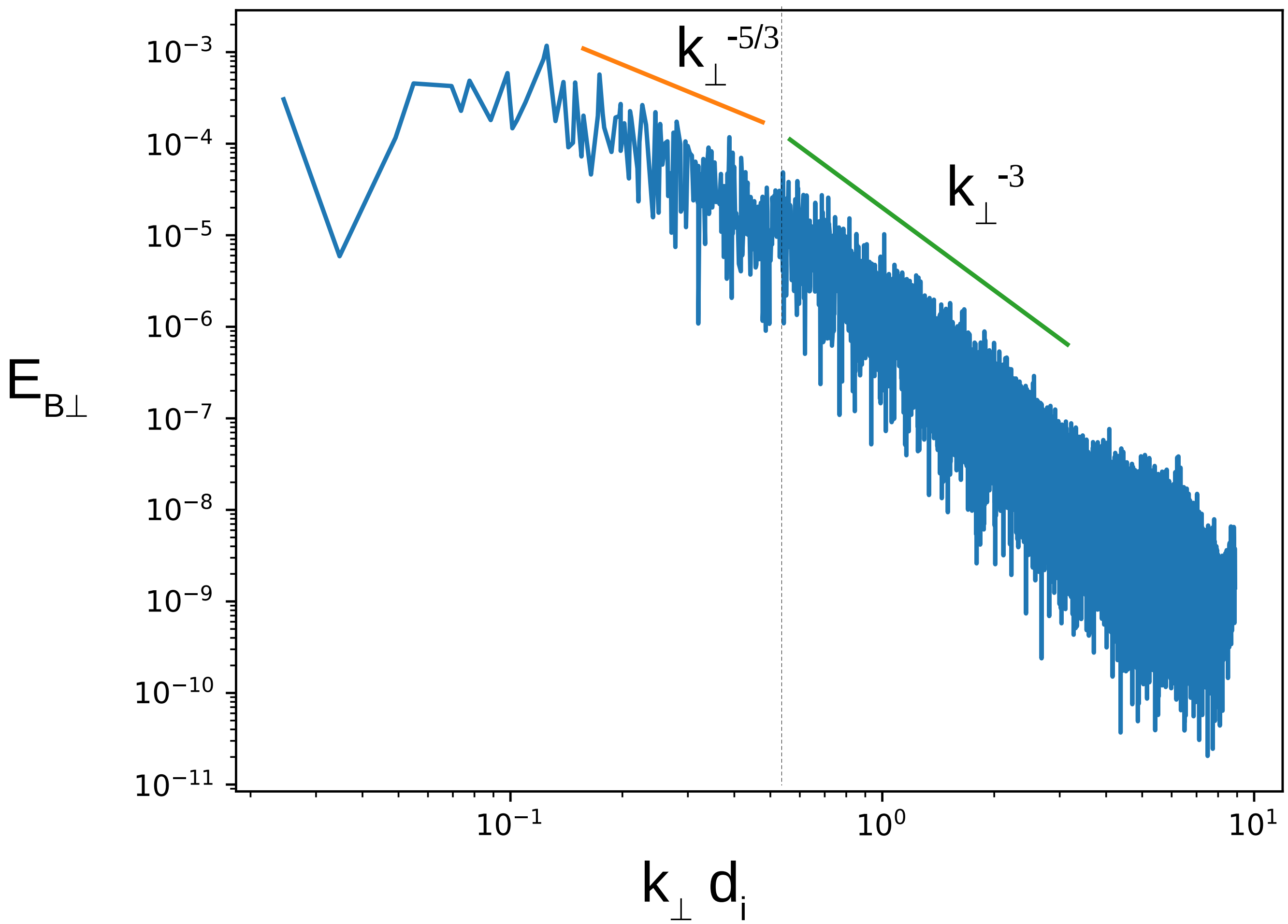
J_z evolution



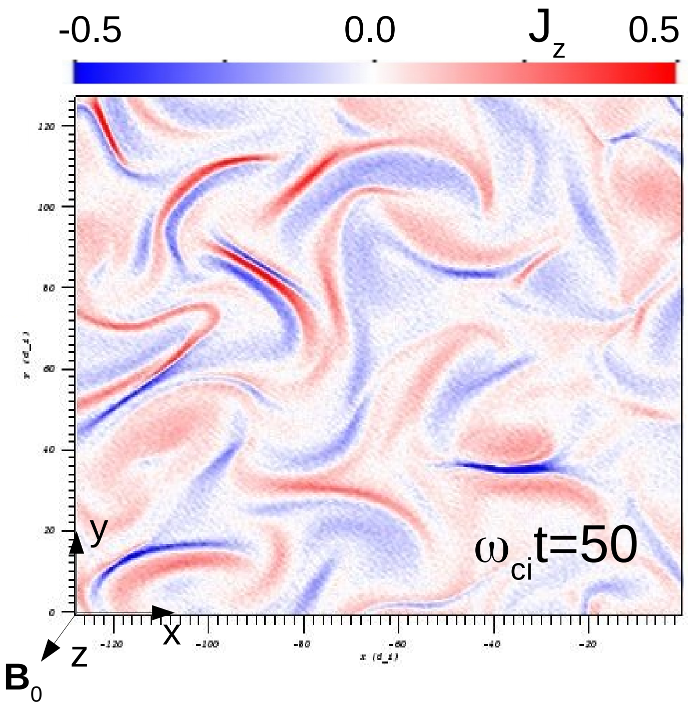
In order to identify free energy sources in current sheets, we analyze them at $\omega_{ci}t$=50 before they disintegrate.



Spectrum of simulated turbulence develops an ion-scale break.



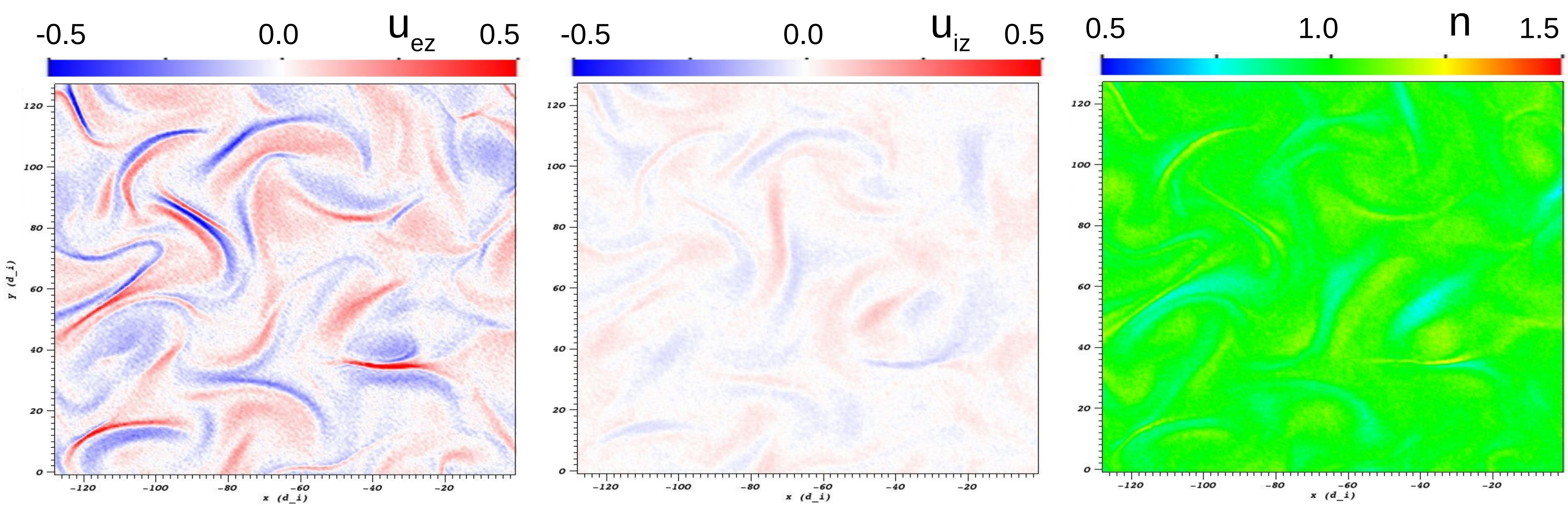
Current sheets are primarily due to electron shear flow.



$$J_z = n\,(u_{iz} - u_{ez})$$

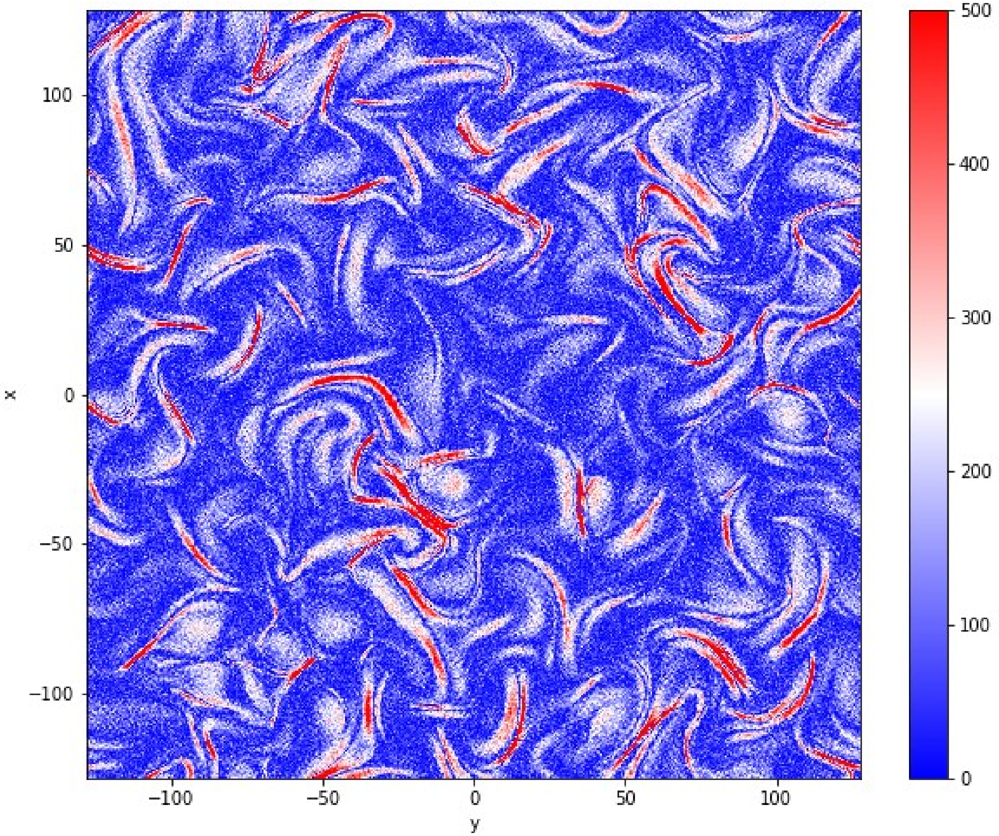
Contributions of u_{ez}, u_{iz} and n?

Results are shown on a quarter of the simulation domain.



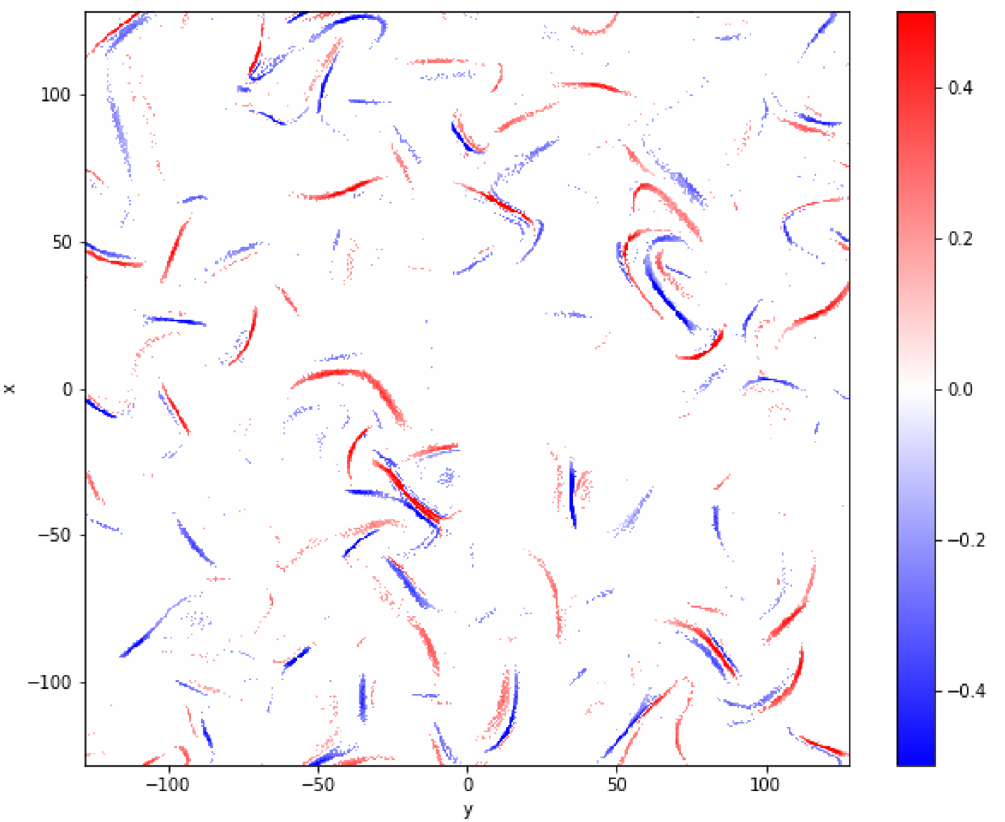
$|u_{ez}|/u_{iz,rms}$ has large value ~ 300 in current sheets.

$|u_{ez}|/u_{iz,rms}$



Masked J_z:

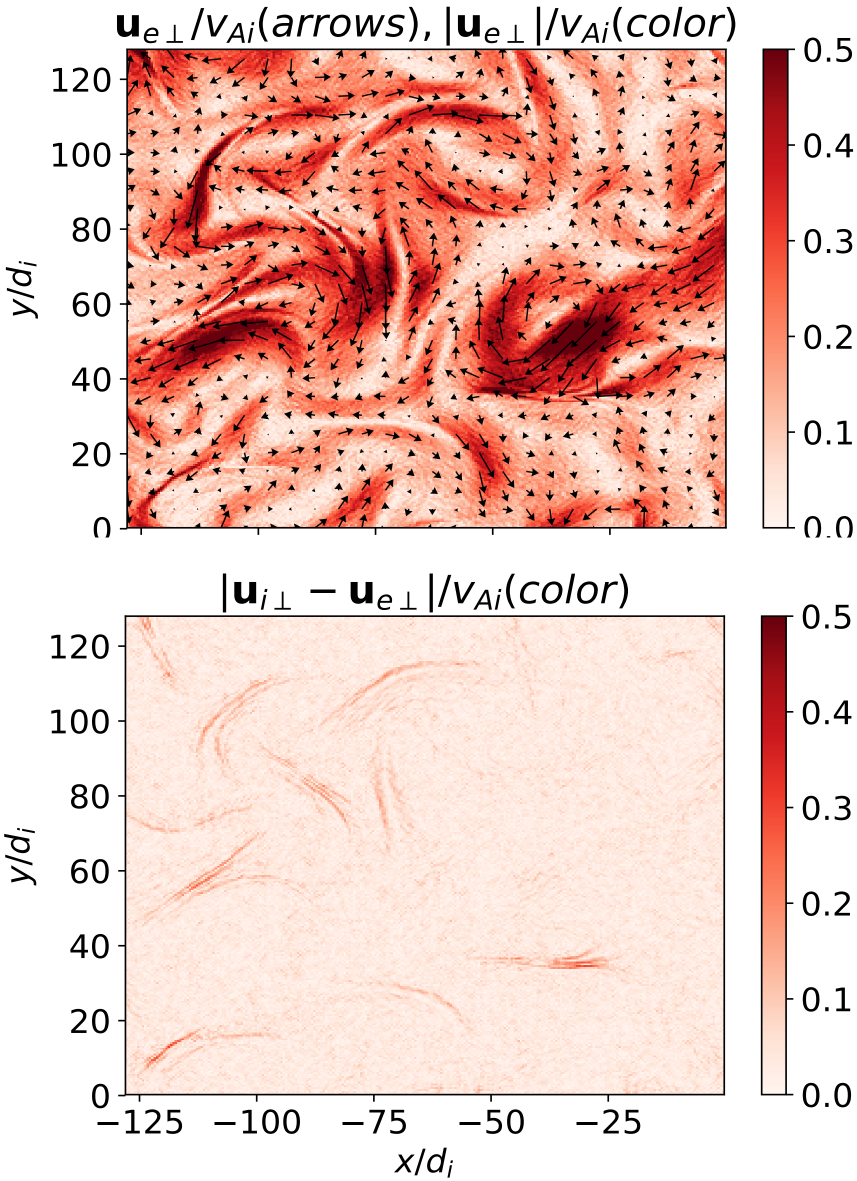
$J_z\ [|u_{ez}|/u_{iz,rms}<300]=0$



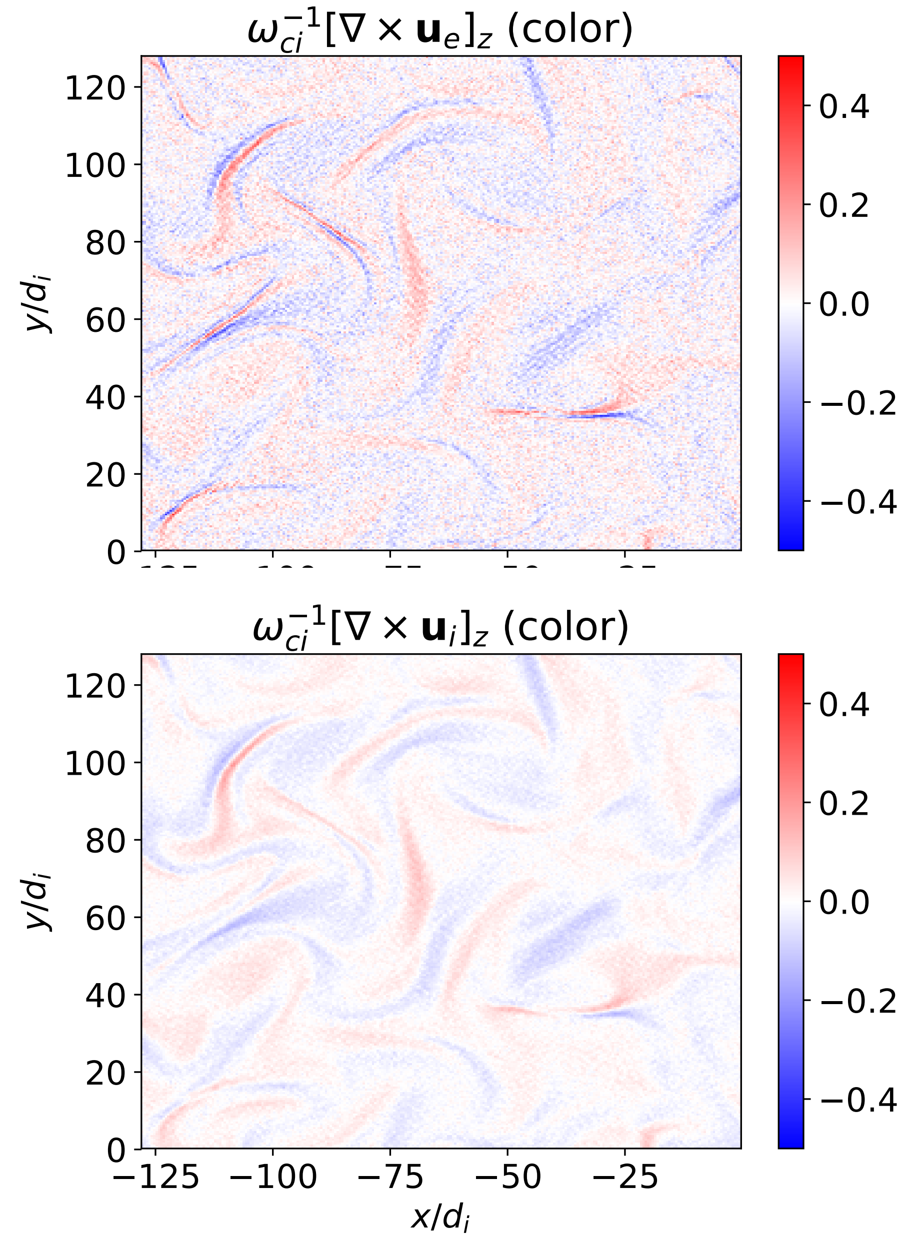
We have used large value of $|u_{ez}|/u_{iz,rms}$ as condition in numerical algorithm developed for the identification and characterization of CS in turbulence.

Perpendicular flows

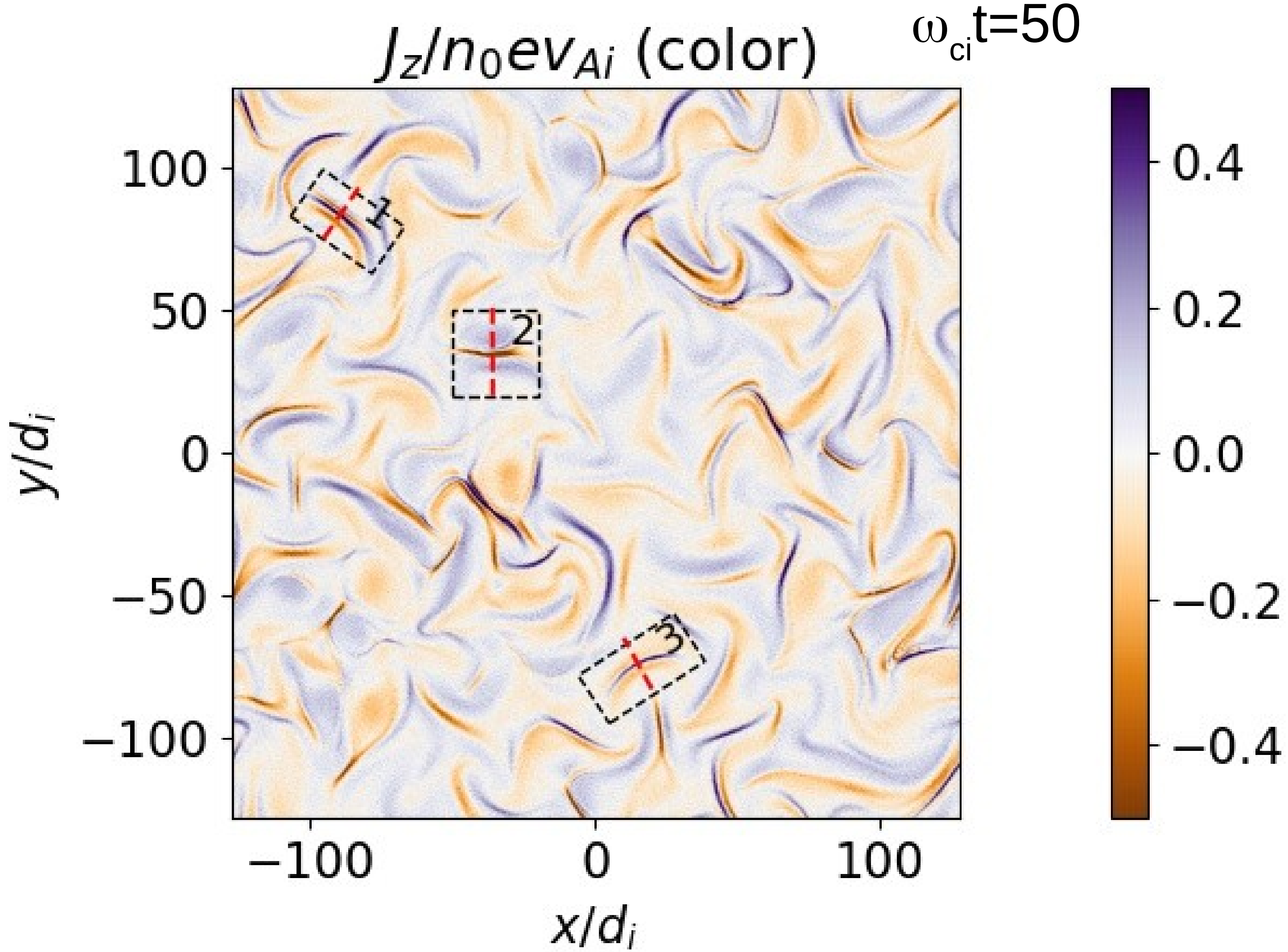
$\mathbf{u}_{i\perp} \approx \mathbf{u}_{e\perp}$ except at few locations



Perpendicular flows have shear

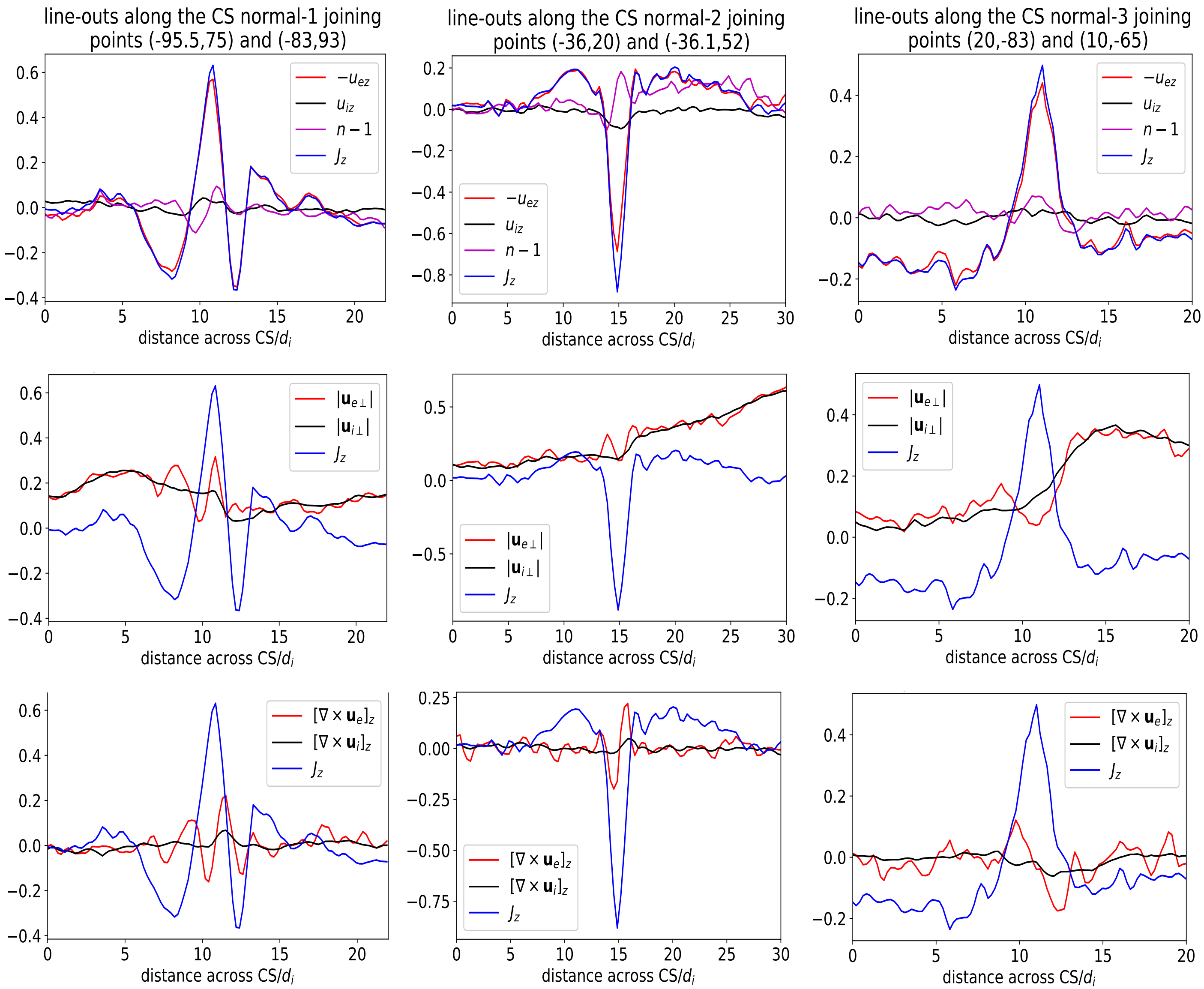


We select manually from the full simulation domain three current sheets for a closer inspection.



Line-outs across current sheets

Jz: Blue line,
electron quantities: red line,
ion quantities: black line



J_z dominated by u_{ez}

$\Delta n/n \sim 0.1$

Return current

$|\mathbf{u}_{i\perp}| \approx |\mathbf{u}_{e\perp}|$ outside CS

$|\mathbf{u}_{e\perp}|$ differs from $|\mathbf{u}_{i\perp}|$ and varies faster inside CS

electron vorticity larger than ion vorticity,

Changes sign at center, peaks at edges of CS

Theoretical estimates support simulation results.

At the ion scales, magnetic field is pushed around by turbulent electron flows generating a parallel inductive electric field E_z which accelerate ions.

At the scales of current sheet ~ $d_i = 2^{1/2} \rho_i$, ions are approx. unmagnetized.

$$\frac{\partial u_{iz}}{\partial t} = \frac{e}{m_i} E_z$$

Neglecting convective derivative

Electron velocity adjusts to satisfy Ampere's law time derivative of which gives,

$$\frac{\partial u_{ez}}{\partial t} = \frac{e}{m_i} (E_z - d_i^2 \nabla^2 E_z)$$

Not electron mom. eq.

Theoretical estimates support simulation results.

The two eq. gives,

$$\frac{|u_{ez}|}{|u_{iz}|} \sim \left|1 - \frac{d_i^2}{L^2}\right|$$

For CS thickness L=0.5 d_i,

$$|u_{ez}|/|u_{iz}| \sim 3$$

Consistent with simulations

For L << d_i,

$$|u_{ez}|/|u_i z| \sim d_i^2/L^2 >> 1$$

Thinner the CS, more dominating is parallel electron flow

In hybrid models, $\mathbf{u}_{e\perp}$ is always ExB drift. When strongly magnetized $\mathbf{u}_{i\perp}$ is also ExB drift. In current sheets, $\mathbf{u}_{i\perp}$ differ from $\mathbf{u}_{e\perp}$ as ions are unmagnetized.

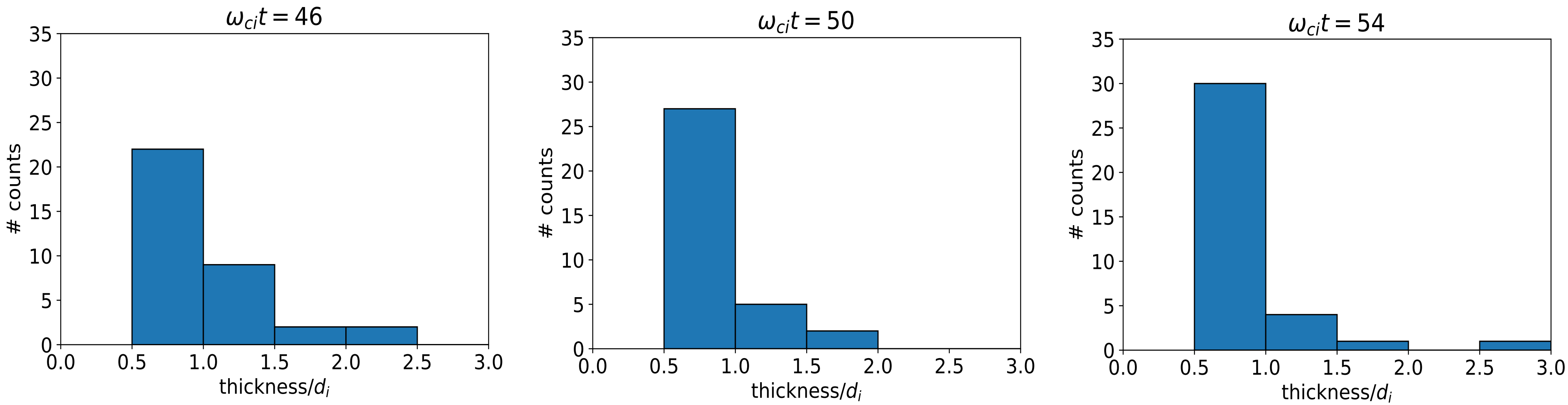
Characterization of current sheets

- Gradient driven instabilities depend on scale lengths.
- Need of statistical characterization of CS in terms of thickness, length, aspect ratio
- Developed a python code implementing the Zhdankin et al (2013) algorithm of CS detection and characterization.
- CS detection depends on algorithm parameters.
- Varying the parameters give results statistically independent of them.

Distribution of CS half-thickness

Chatraee, Jain, and Büchner (2020)
(*under preparation*)

- Current sheets thin down to grid scales.



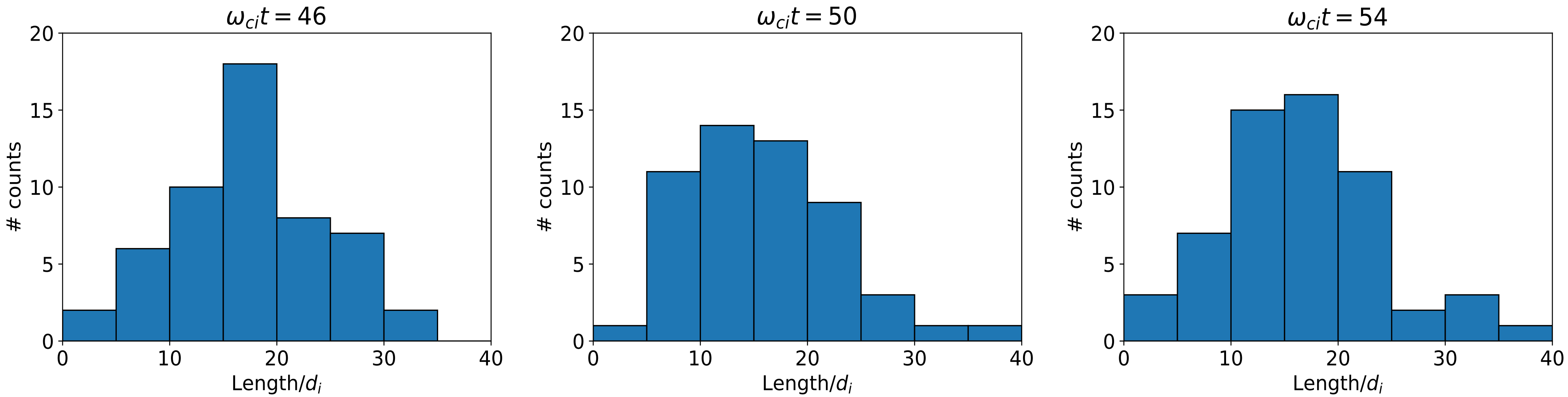
- Increasing grid resolution leads to thinner current sheets.

- Hybrid plasma model w/o electron inertia is not sufficient to address the physics of current sheets.

- Next step: Hybrid plasma simulations with electron inertia using a code CHIEF recently developed in our group.

Distribution of CS length

- Distribution of CS length peaks around 15 d_i.



- Expected half-thicknesses $L_{CS} << d_i$
- Aspect ratio: Length/half-thickness >> 15.
  - Condition $k L_{CS} < 1$ of gradient driven instabilities is easily satisfied.

Summary

- 2-D hybrid simulations of kinetic plasma turbulence show formation of current sheets which thins down to grid scale.
- Current sheets are formed mainly due to electron shear flow.
- In a current sheet:
  - parallel electron flow velocity dominates ion flow velocity
  - parallel electron vorticity is larger than ion vorticity
  - gradients in plasma density are weak (~ 10 % variation).
  - Theoretical estimates support simulation results.
- Instabilities driven by parallel and perpendicular electron shear flow can grow in current sheets of collisionless plasma turbulence.
- Hybrid simulations including electron inertia are required to address the physics of the current sheets and instabilities therein.