

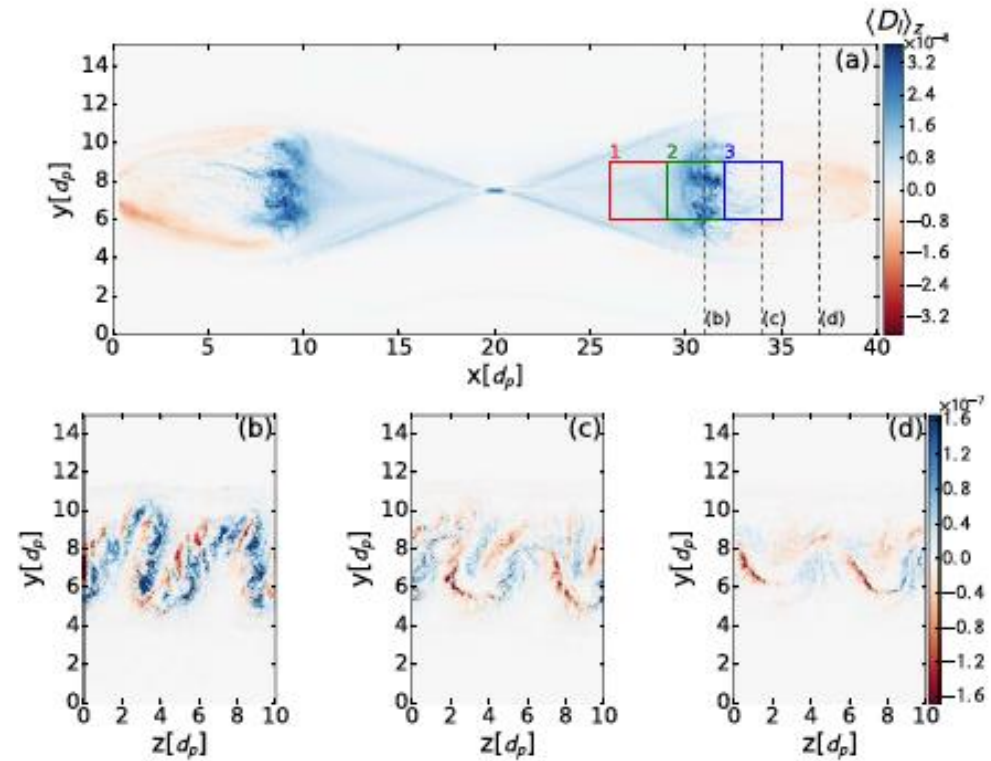
Anomalous electric fields in magnetic reconnection

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**Synergies Between Astrophysical, Space, Laboratory, and Fusion Plasma Physics, Nordita,
Stockholm, Sweden, 2026**

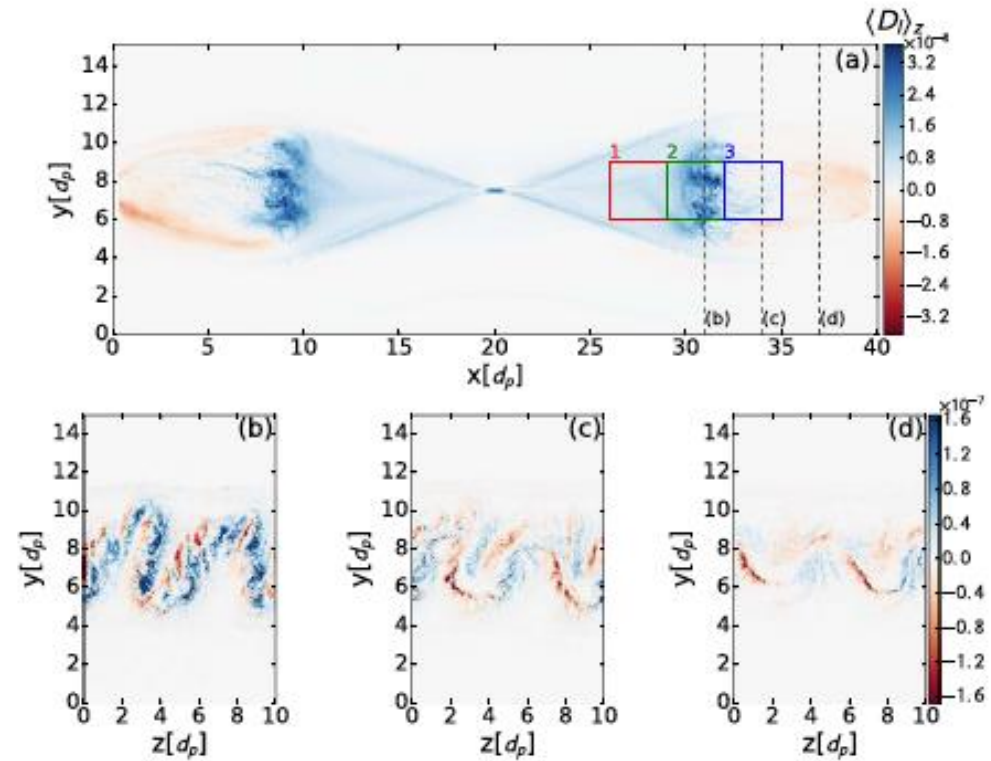
Turbulence and reconnection

Turbulence in reconnection regions.



Turbulence and reconnection

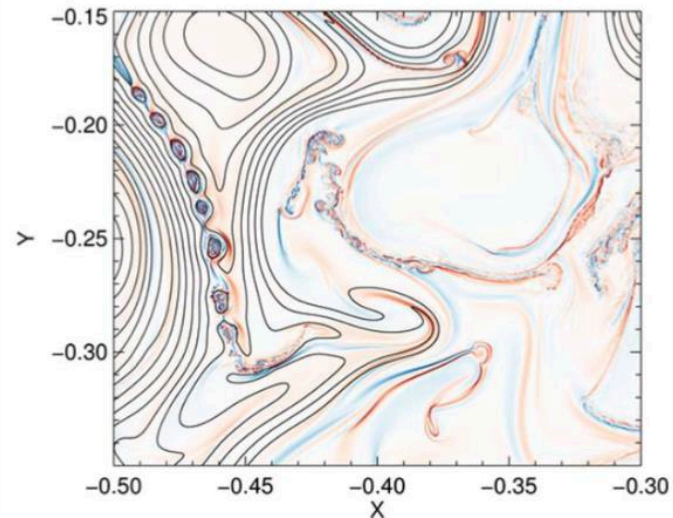
Turbulence in reconnection regions.



Pucci et al, ApJ, 2017

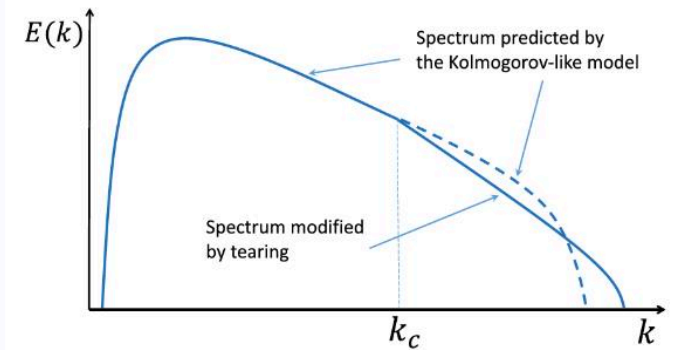
Reconnection as part of the turbulent cascade

Adapted from Borgogno et al, 2022



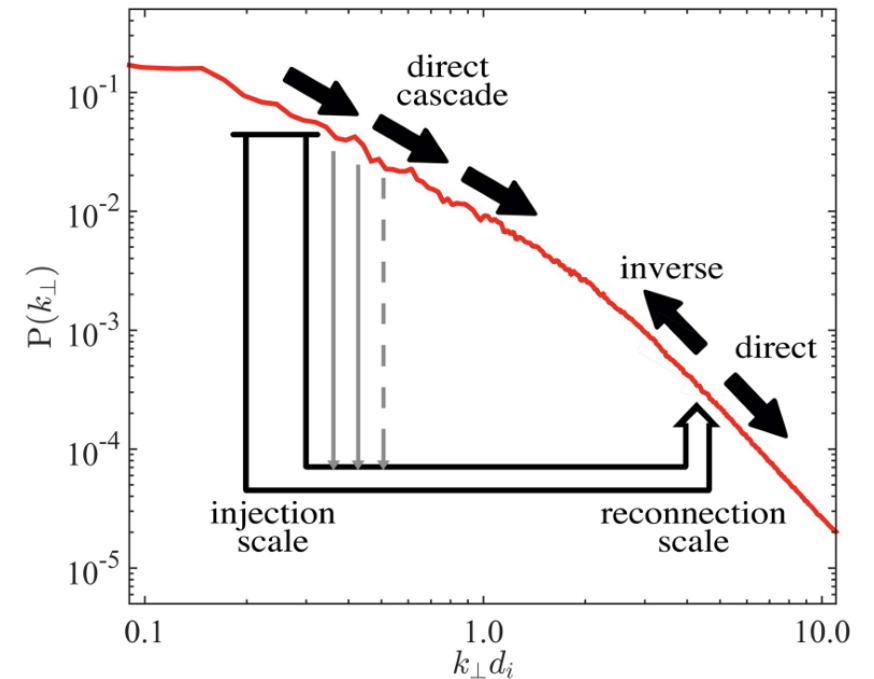
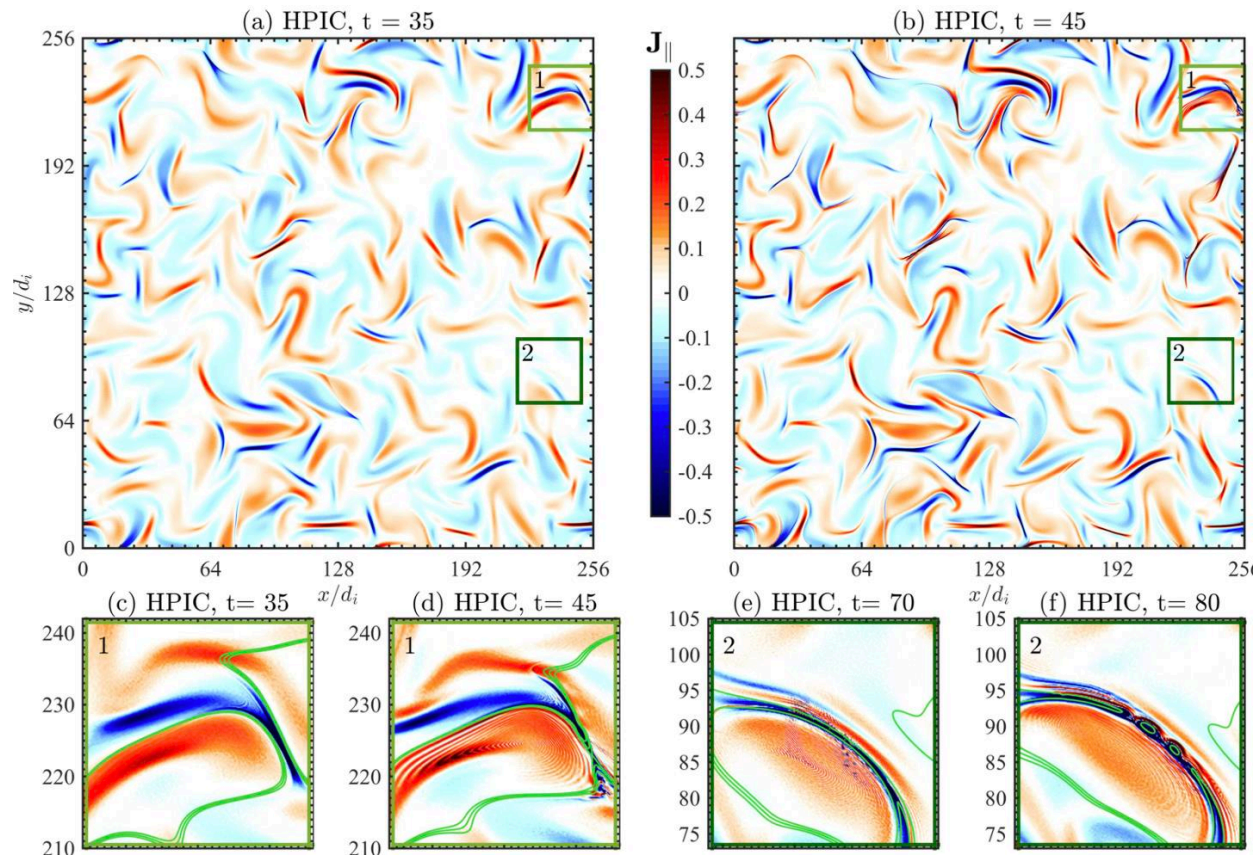
Modified energy spectrum.

Adapted from Boldyrev & Loureiro et al. 2020



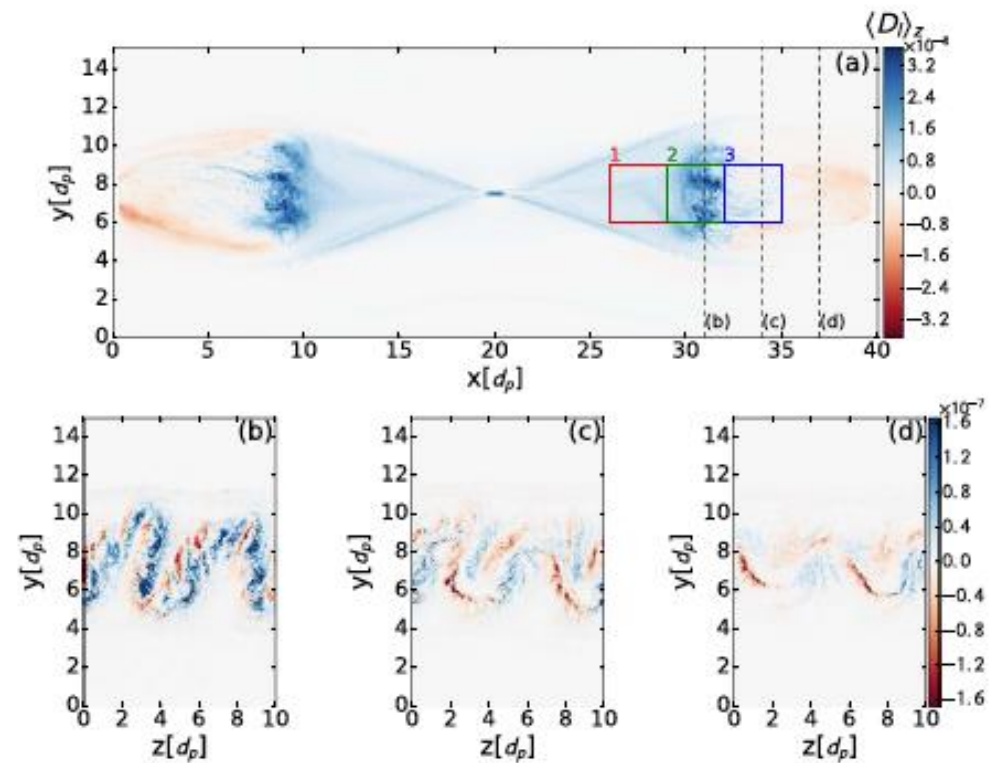
Turbulence and reconnection

Reconnection as part of the turbulent cascade



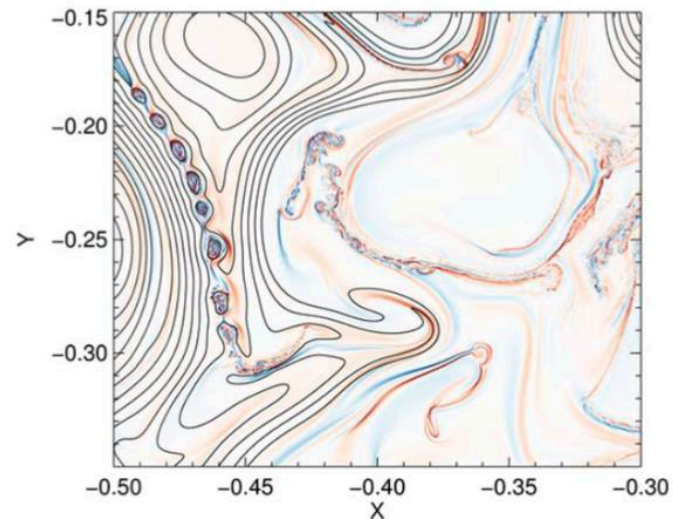
Turbulence and reconnection

Turbulence in reconnection regions.

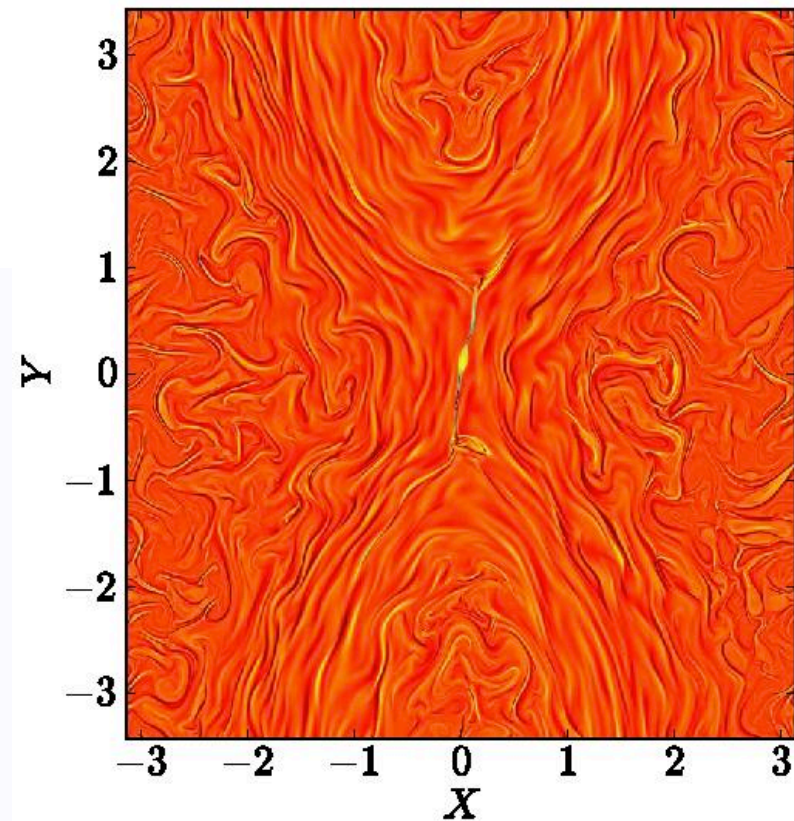


Pucci et al, ApJ, 2017

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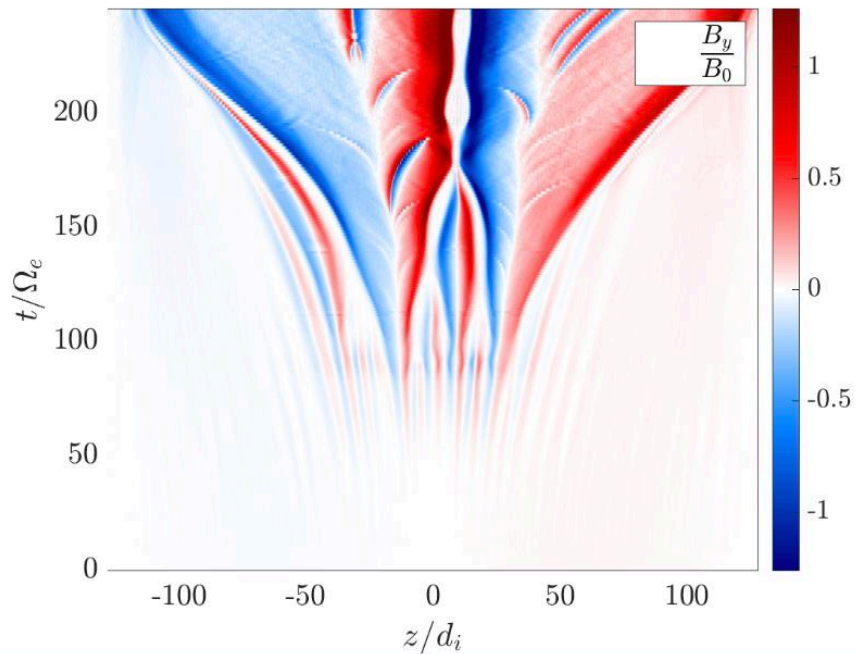
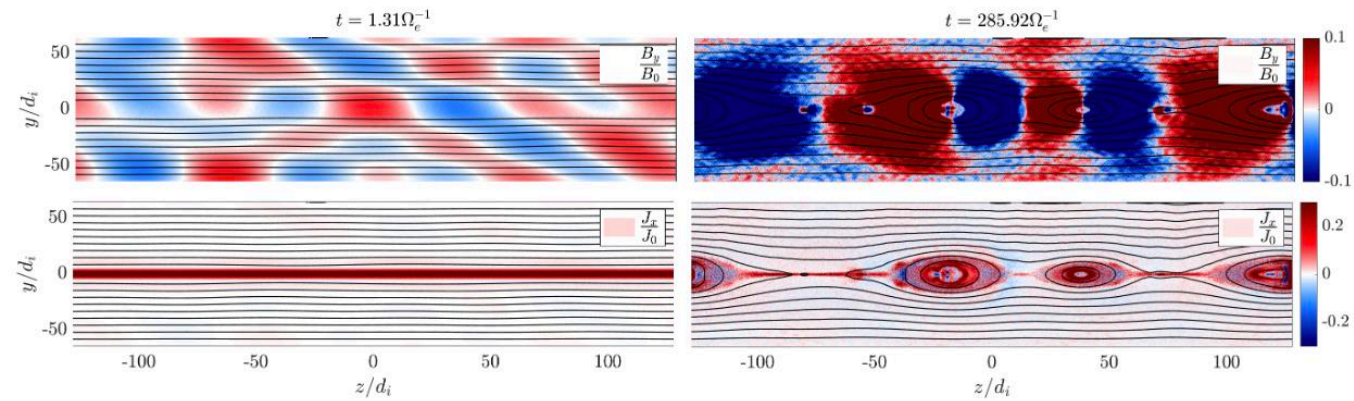
Loureiro +, 2009



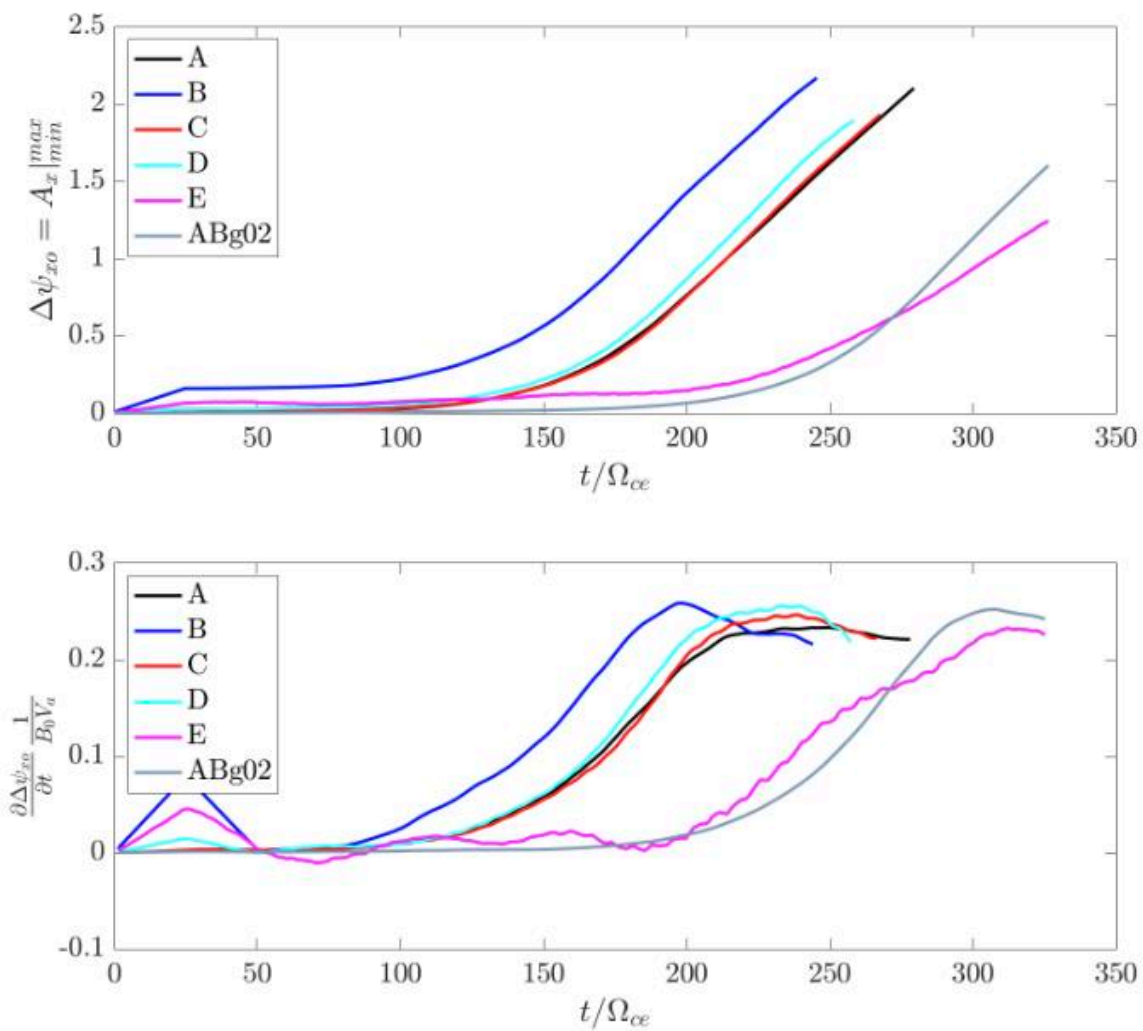
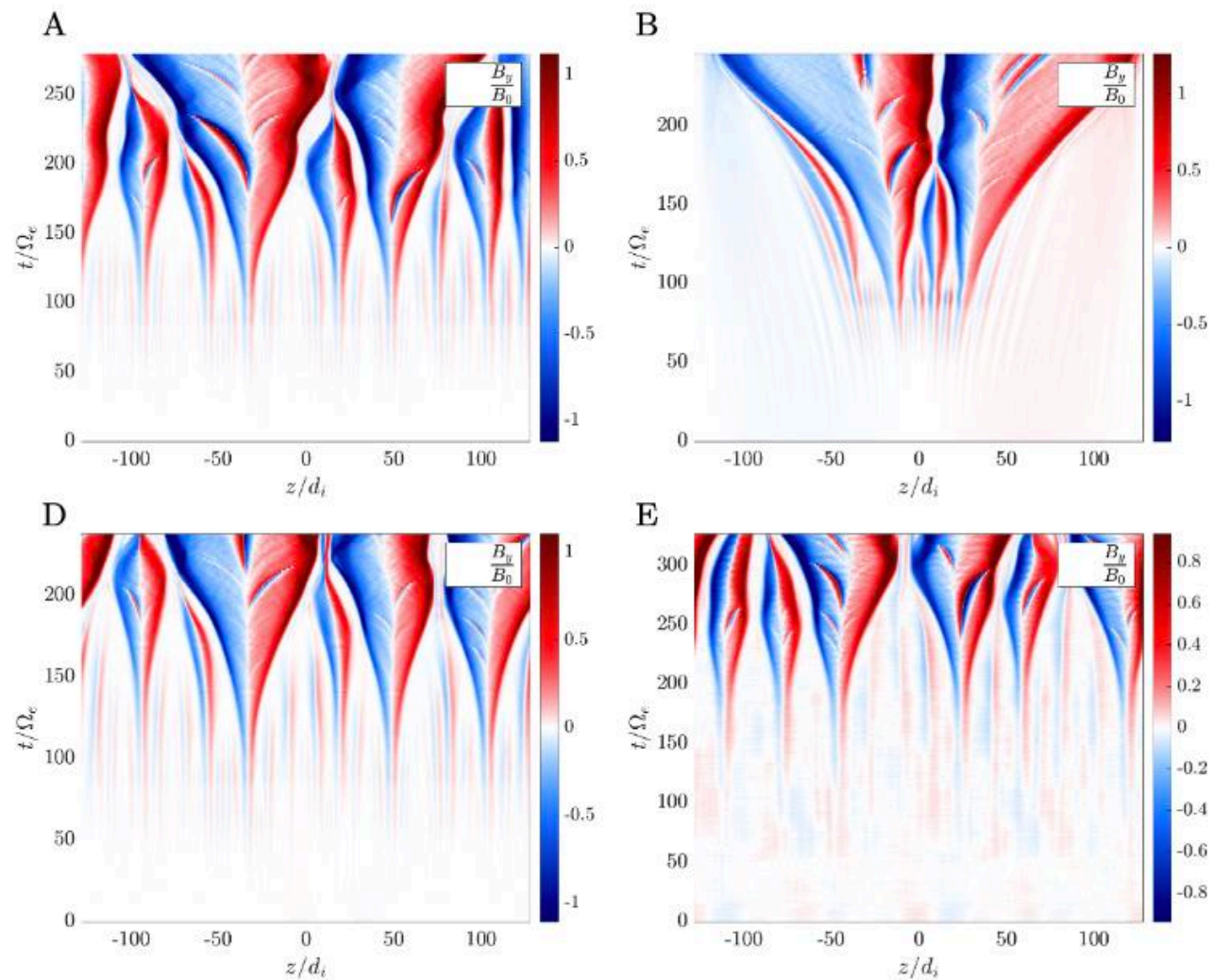
Large-scale reconnection in the presence of turbulence

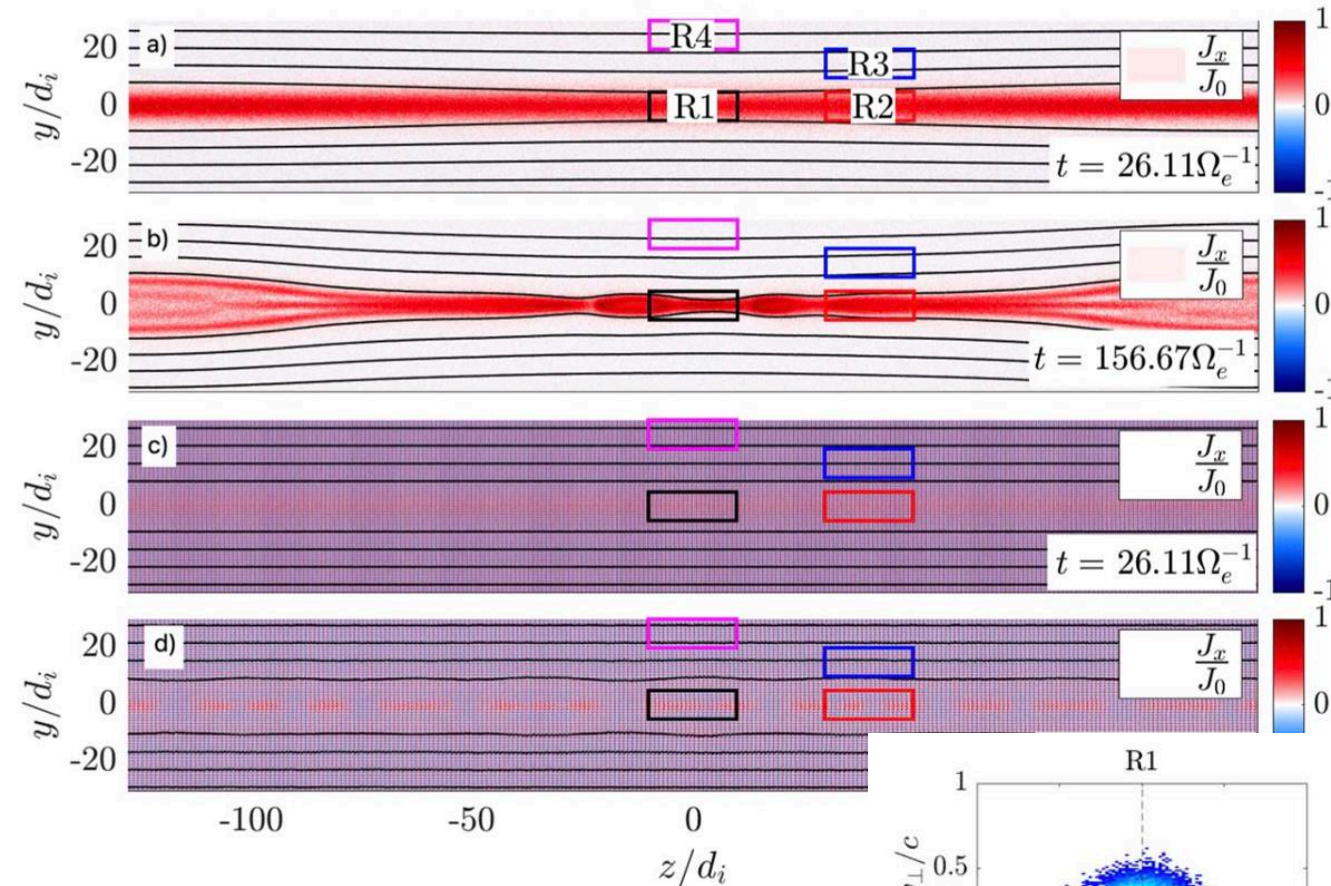
Harris current-sheet + forcing turbulent fluctuations

Non-relativistic pair plasma, PIC.



The presence of turbulence can slow down the nonlinear phase

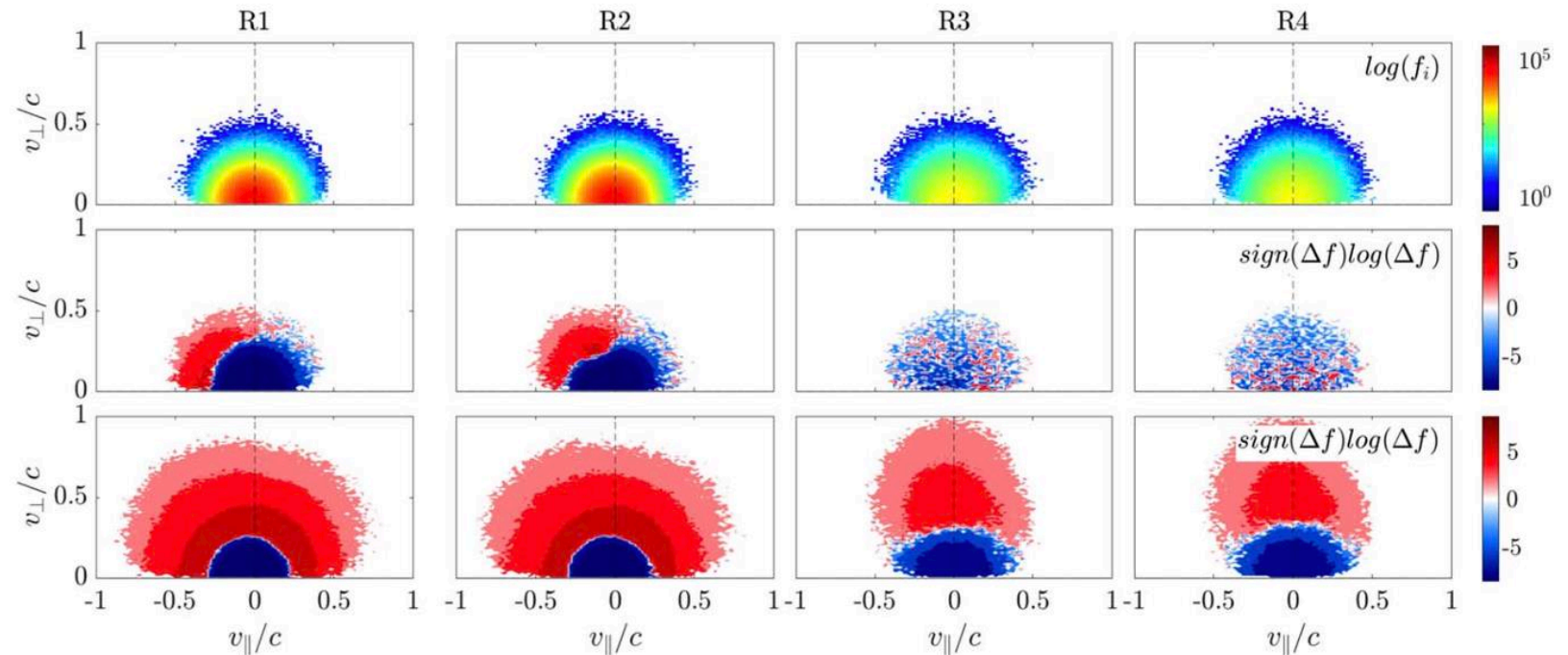


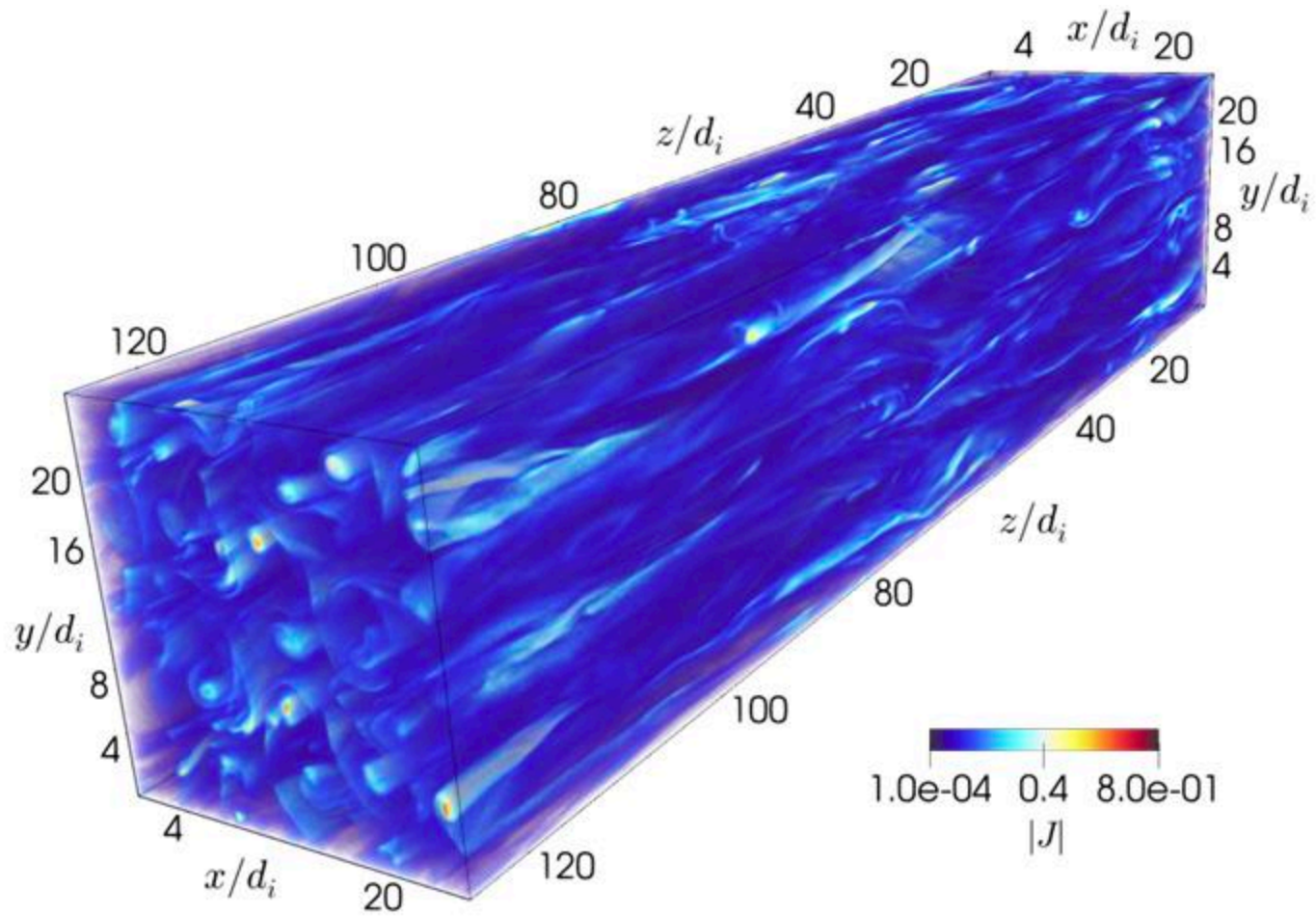


What happens with the VDFs?

Strong kinetic scale fluctuations heat the particles preferentially in the perpendicular

Fragmentation of the current-sheet





Current structures in 3D turbulence

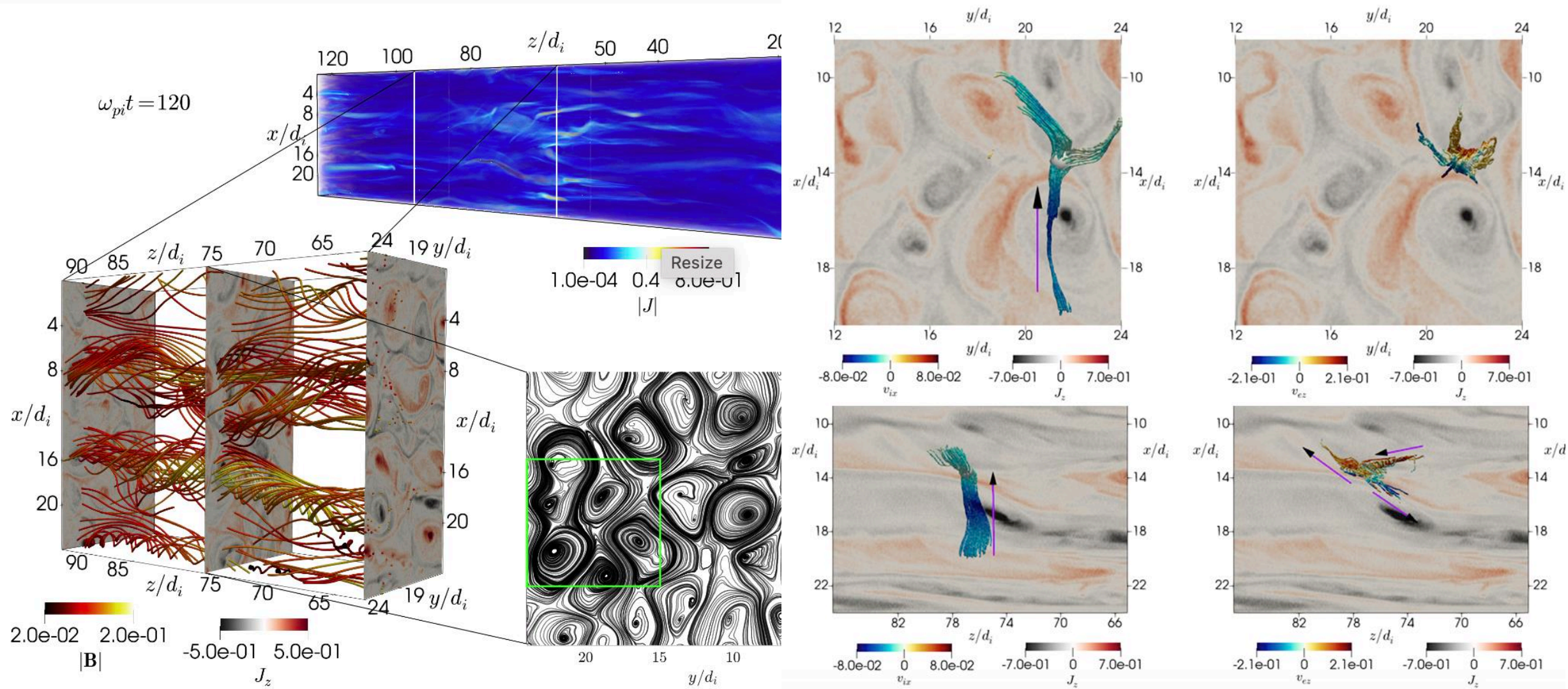
From 3D ion-electron plasma turbulence, PIC

Thin current sheets,
Strong current filaments,

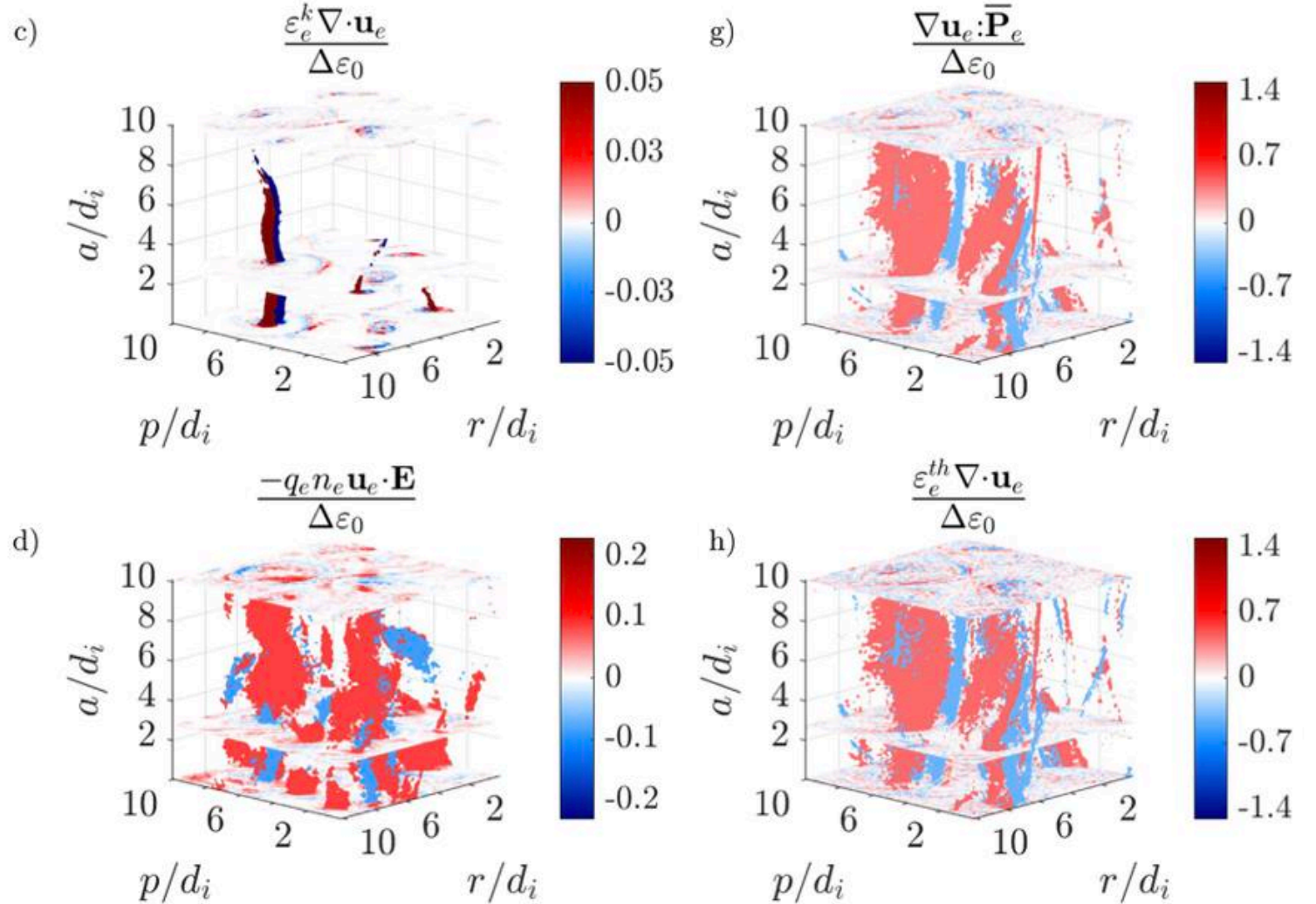
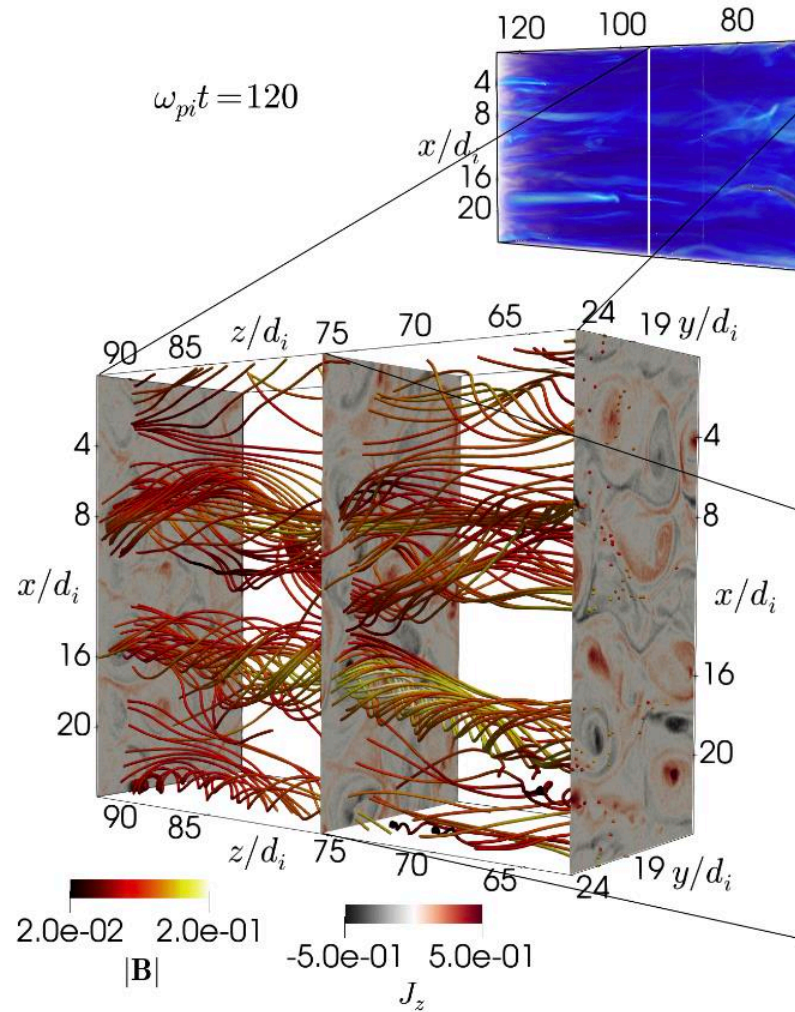
Both can reconnect (helical kink instability)

Reconnection in 3D turbulence is complex,

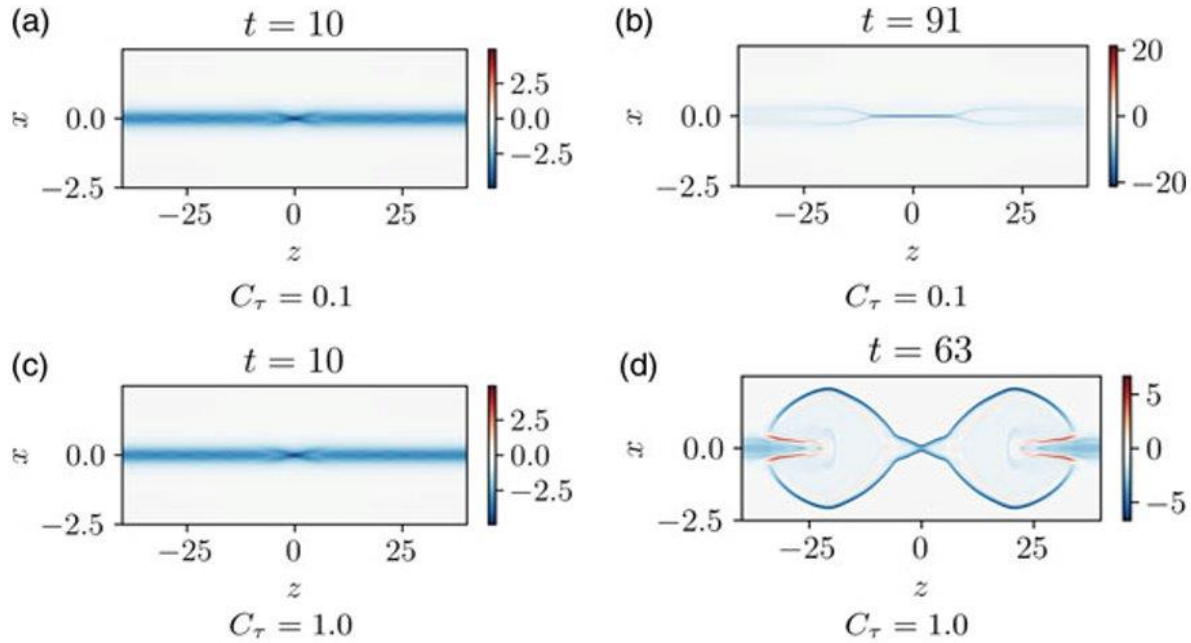
Usual signatures of reconnection may be hidden in the turbulent dynamics



Energy conversion channels are active at different regions

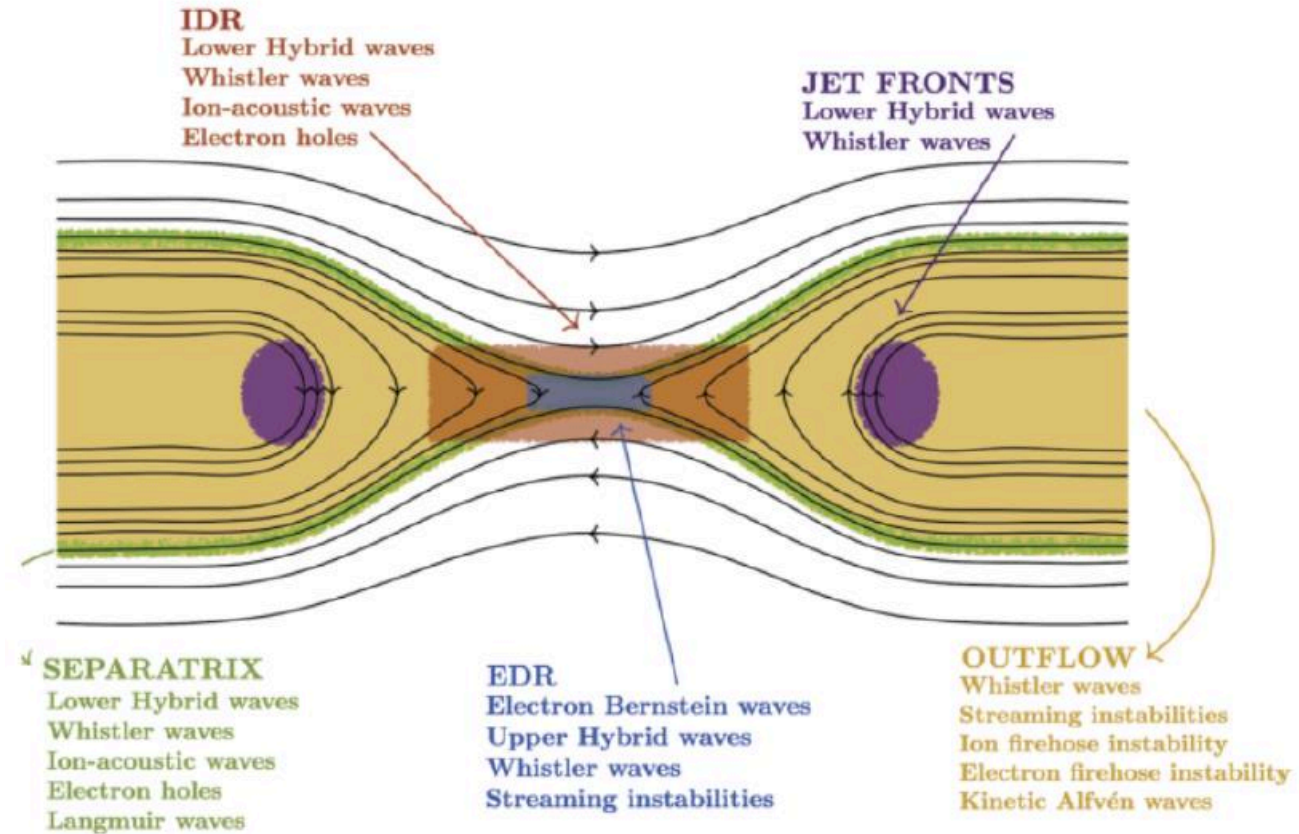


Turbulence in reconnection as a source of anomalous electric fields



Stanish & MacTaggart, JPP 2025

Kinetic modes in reconnection regions



Graham et al, Space Sci. Rev., 2025

$$\mathbf{E} = -\mathbf{u}_i \times \mathbf{B} + \frac{\mathbf{J} \times \mathbf{B}}{ne} + \frac{m_e}{m_i ne} \nabla \cdot \mathbb{P}_i - \frac{1}{ne} \nabla \cdot \mathbb{P}_e + \frac{m_e}{ne^2} \nabla \cdot \left(\mathbf{u}_i \mathbf{J} + \mathbf{J} \mathbf{u}_i - \frac{\mathbf{J} \mathbf{J}}{ne} \right) + \frac{m_e}{ne^2} \frac{\partial \mathbf{J}}{\partial t},$$

$$\mathbf{E} = -\mathbf{u}_i \times \mathbf{B} + \frac{\mathbf{J} \times \mathbf{B}}{ne} + \frac{m_e}{m_i ne} \cancel{\nabla \cdot \mathbb{P}_i} - \frac{1}{ne} \nabla \cdot \mathbb{P}_e + \frac{m_e}{ne^2} \nabla \cdot \left(\mathbf{u}_i \mathbf{J} + \mathbf{J} \mathbf{u}_i - \frac{\mathbf{J} \mathbf{J}}{ne} \right) + \frac{m_e}{ne^2} \frac{\partial \mathbf{J}}{\partial t},$$

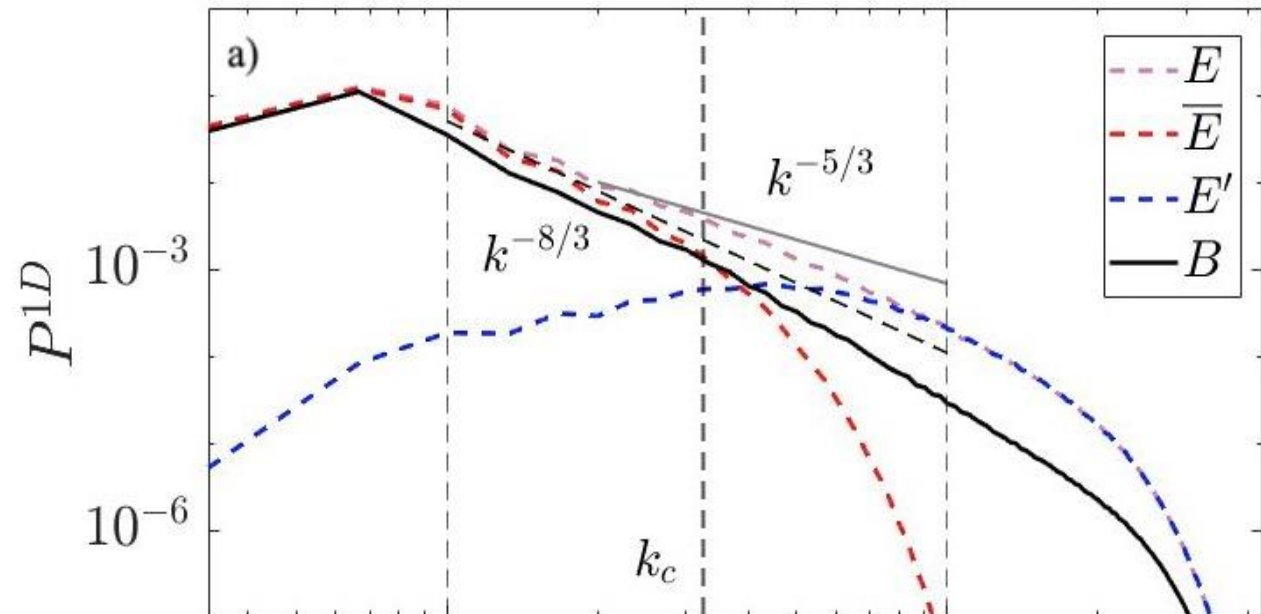
$$\mathbf{E} = \underbrace{-\mathbf{u}_i \times \mathbf{B}} + \frac{\mathbf{J} \times \mathbf{B}}{ne} - \frac{1}{ne} \nabla \cdot \mathbb{P}_e + \frac{m_e}{ne^2} \left[\nabla \cdot \left(\mathbf{u}_i \mathbf{J} + \mathbf{J} \mathbf{u}_i - \frac{\mathbf{J} \mathbf{J}}{ne} \right) + \frac{1}{\mu_0} \nabla^2 \mathbf{E} \right],$$

Decomposing between mean and residual

$$\mathbf{f} = \langle \mathbf{F} \rangle + \mathbf{f}'$$

Using a gaussian filter as a proxy

$$\mathbf{f} = \text{filtered}(\mathbf{f}) + \mathbf{f}'$$



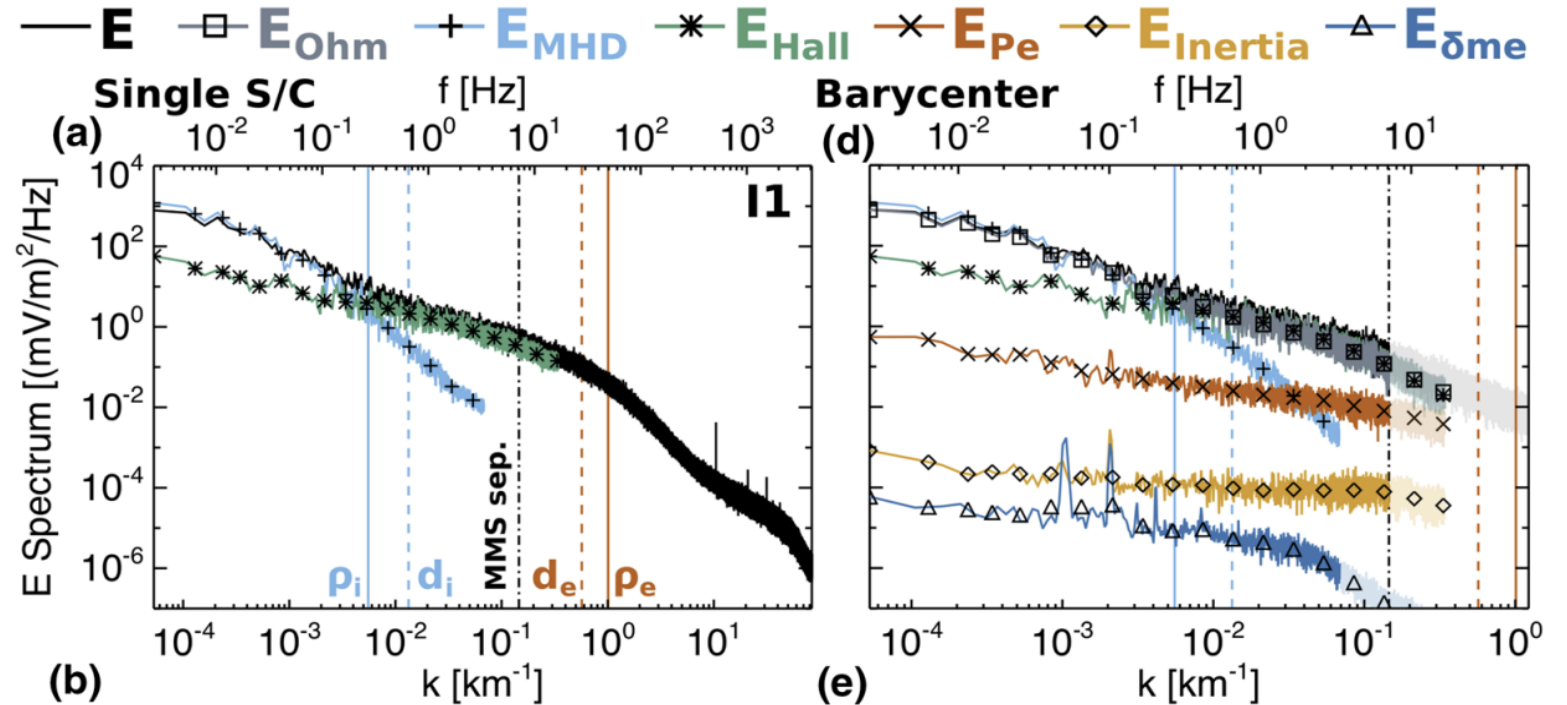
$$\bar{\mathbf{E}} = - \bar{\mathbf{u}}_i \times \bar{\mathbf{B}} + \frac{\bar{\mathbf{J}} \times \bar{\mathbf{B}}}{\bar{n}e} - \frac{1}{\bar{n}e} \nabla \cdot \bar{\mathbf{P}}_e + \frac{m_e}{\bar{n}e^2} \left[\nabla \cdot \left(\bar{\mathbf{u}}_i \bar{\mathbf{J}} + \bar{\mathbf{J}} \bar{\mathbf{u}}_i - \frac{\bar{\mathbf{J}} \bar{\mathbf{J}}}{\bar{n}e} \right) + \frac{1}{\mu_0} \nabla^2 \bar{\mathbf{E}} \right]$$

$$- \boldsymbol{\tau}_{nE} - \boldsymbol{\tau}_{nu_i \times B} + \boldsymbol{\tau}_{J \times B} + \boldsymbol{\tau}_{Ine},$$

$$\bar{\mathbf{E}} = - \bar{\mathbf{E}}_{MHD} + \bar{\mathbf{E}}_{Hall} - \bar{\mathbf{E}}_{Pe} + \bar{\mathbf{E}}_{Ine} - \boldsymbol{\tau}_{nE} - \boldsymbol{\tau}_{nu_i \times B} + \boldsymbol{\tau}_{J \times B} + \boldsymbol{\tau}_{Ine},$$

$$\boldsymbol{\tau}_{nE} = (\overline{n\mathbf{E}} - \bar{n}\bar{\mathbf{E}})/\bar{n}, \quad \boldsymbol{\tau}_{nu_i \times B} = (\overline{nu_i \times B} - \bar{n} \bar{u}_i \times \bar{B})/\bar{n},$$

$$\boldsymbol{\tau}_{J \times B} = (\overline{\mathbf{J} \times \mathbf{B}} - \bar{\mathbf{J}} \times \bar{\mathbf{B}})/\bar{n}e, \quad \Sigma \boldsymbol{\tau} = -\boldsymbol{\tau}_{nE} - \boldsymbol{\tau}_{nu_i \times B} + \boldsymbol{\tau}_{J \times B} + \boldsymbol{\tau}_{Ine}$$



MMS results: Stawarz +, 2021

$$\bar{\mathbf{E}} = - \bar{\mathbf{u}}_i \times \bar{\mathbf{B}} + \frac{\bar{\mathbf{J}} \times \bar{\mathbf{B}}}{\bar{n}_e} - \frac{1}{\bar{n}_e} \nabla \cdot \bar{\mathbb{P}}_e + \frac{m_e}{\bar{n}_e^2} \left[\nabla \cdot \left(\bar{\mathbf{u}}_i \bar{\mathbf{J}} + \bar{\mathbf{J}} \bar{\mathbf{u}}_i - \frac{\bar{\mathbf{J}} \bar{\mathbf{J}}}{\bar{n}_e} \right) + \frac{1}{\mu_0} \nabla^2 \bar{\mathbf{E}} \right]$$

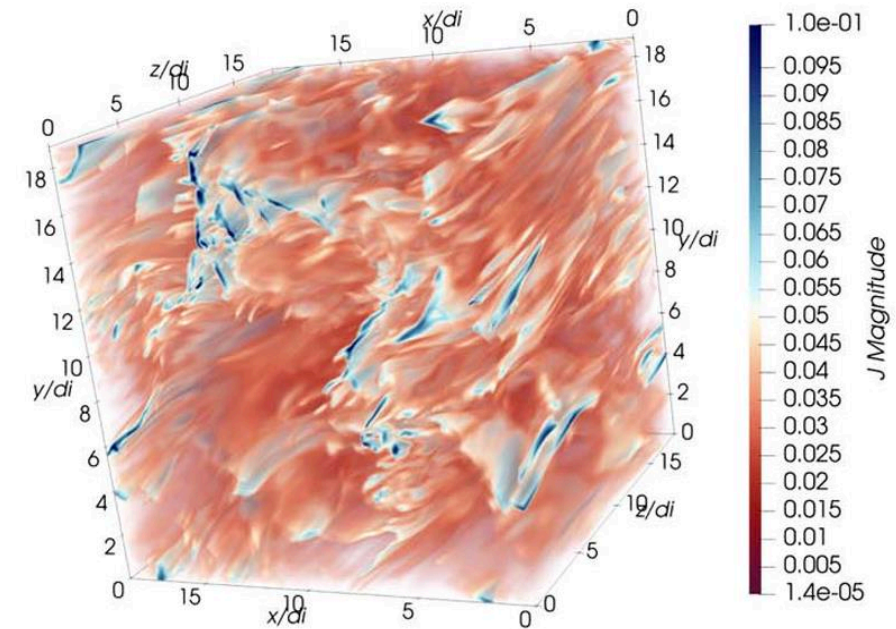
$$- \boldsymbol{\tau}_{nE} - \boldsymbol{\tau}_{nu_i \times B} + \boldsymbol{\tau}_{J \times B} + \boldsymbol{\tau}_{Ine},$$

$$\bar{\mathbf{E}} = - \bar{\mathbf{E}}_{MHD} + \bar{\mathbf{E}}_{Hall} - \bar{\mathbf{E}}_{Pe} + \bar{\mathbf{E}}_{Ine} - \boldsymbol{\tau}_{nE} - \boldsymbol{\tau}_{nu_i \times B} + \boldsymbol{\tau}_{J \times B} + \boldsymbol{\tau}_{Ine},$$

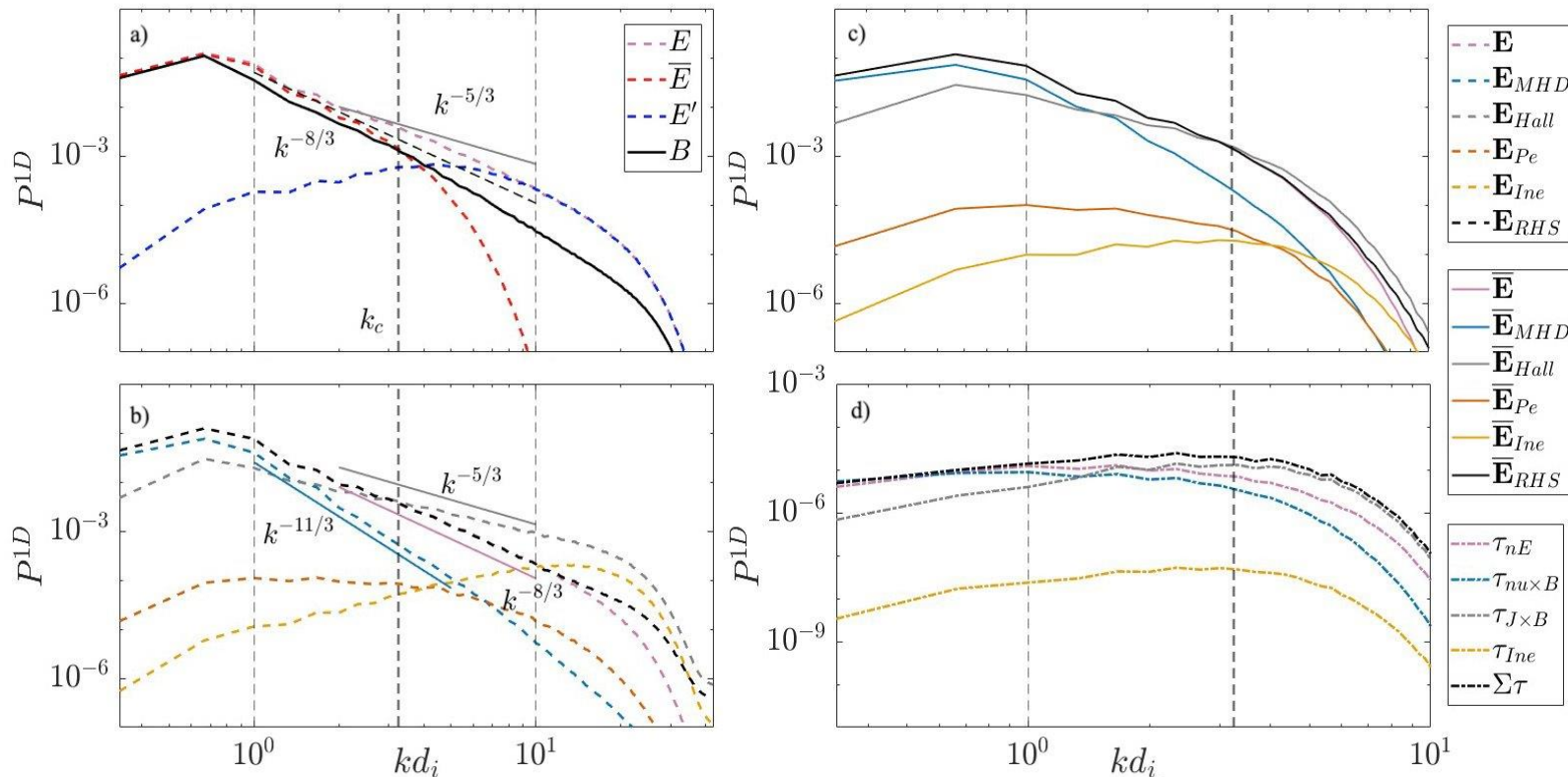
$$\boldsymbol{\tau}_{nE} = (\overline{n\mathbf{E}} - \bar{n}\bar{\mathbf{E}})/\bar{n}, \quad \boldsymbol{\tau}_{nu_i \times B} = (\overline{nu_i \times \mathbf{B}} - \bar{n} \bar{\mathbf{u}}_i \times \bar{\mathbf{B}})/\bar{n},$$

$$\boldsymbol{\tau}_{J \times B} = (\overline{\mathbf{J} \times \mathbf{B}} - \bar{\mathbf{J}} \times \bar{\mathbf{B}})/\bar{n}_e, \quad \Sigma\boldsymbol{\tau} = -\boldsymbol{\tau}_{nE} - \boldsymbol{\tau}_{nu_i \times B} + \boldsymbol{\tau}_{J \times B} + \boldsymbol{\tau}_{Ine}$$

3D Hybrid-Vlasov turbulence,
Earth's magnetosheath-like



Granier, Cerri & Jenko, 2024



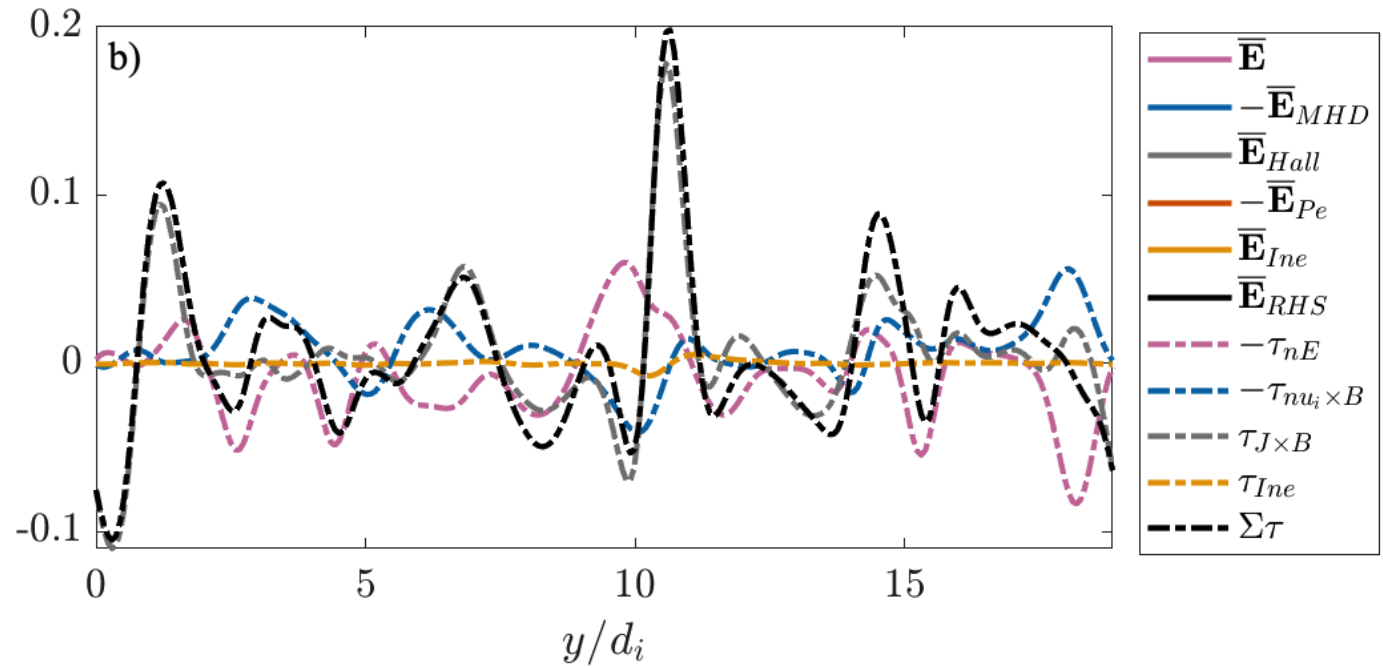
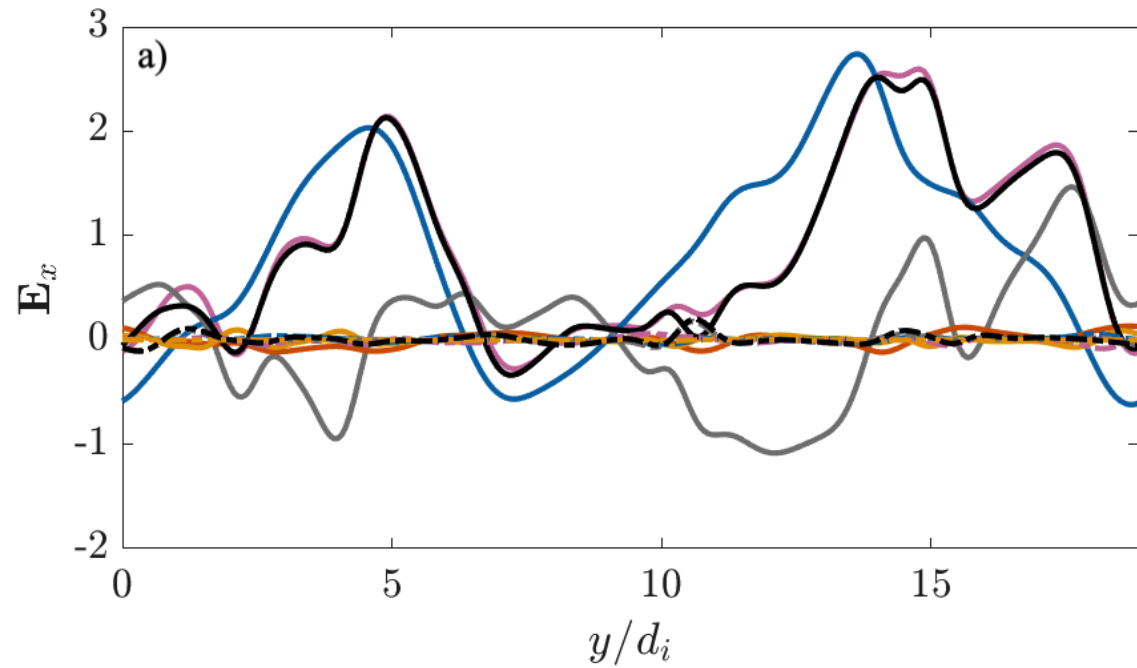
$$\bar{\mathbf{E}} = - \bar{\mathbf{u}}_i \times \bar{\mathbf{B}} + \frac{\bar{\mathbf{J}} \times \bar{\mathbf{B}}}{\bar{n}e} - \frac{1}{\bar{n}e} \nabla \cdot \bar{\mathbb{P}}_e + \frac{m_e}{\bar{n}e^2} \left[\nabla \cdot \left(\bar{\mathbf{u}}_i \bar{\mathbf{J}} + \bar{\mathbf{J}} \bar{\mathbf{u}}_i - \frac{\bar{\mathbf{J}} \bar{\mathbf{J}}}{\bar{n}e} \right) + \frac{1}{\mu_0} \nabla^2 \bar{\mathbf{E}} \right]$$

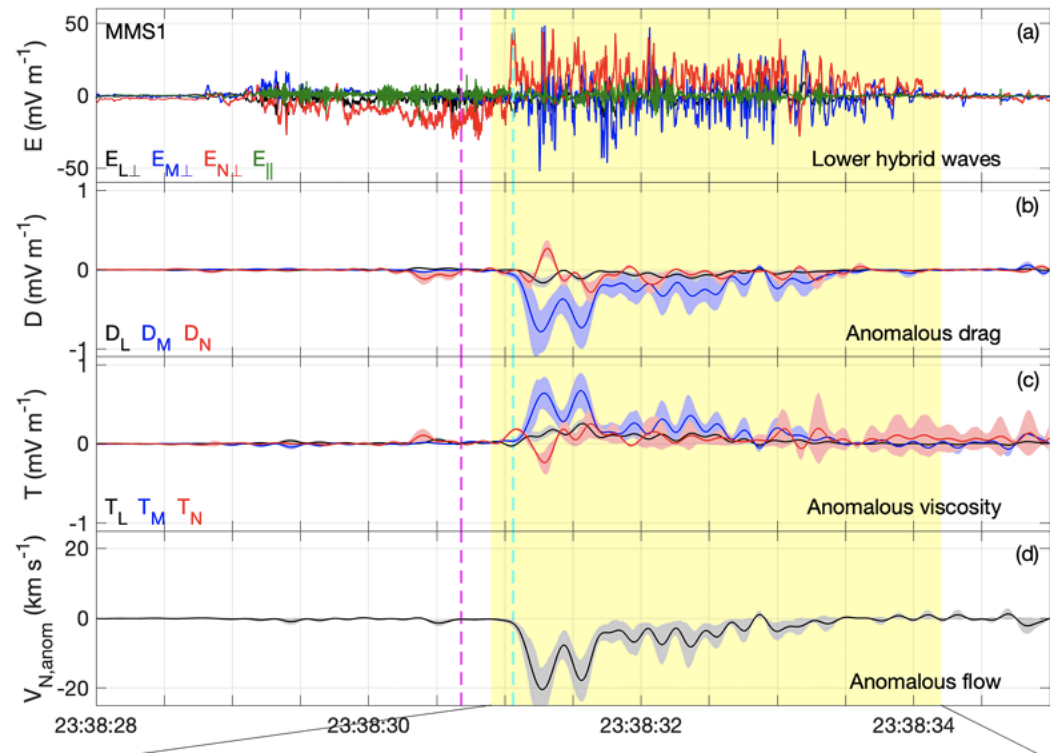
$$- \tau_{nE} - \tau_{nu_i \times B} + \tau_{J \times B} + \tau_{Ine},$$

$$\bar{\mathbf{E}} = - \bar{\mathbf{E}}_{MHD} + \bar{\mathbf{E}}_{Hall} - \bar{\mathbf{E}}_{Pe} + \bar{\mathbf{E}}_{Ine} - \tau_{nE} - \tau_{nu_i \times B} + \tau_{J \times B} + \tau_{Ine},$$

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$$\tau_{J \times B} = (\bar{\mathbf{J}} \times \bar{\mathbf{B}} - \bar{\mathbf{J}} \times \bar{\mathbf{B}})/\bar{n}e, \quad \Sigma\tau = -\tau_{nE} - \tau_{nu_i \times B} + \tau_{J \times B} + \tau_{Ine}$$

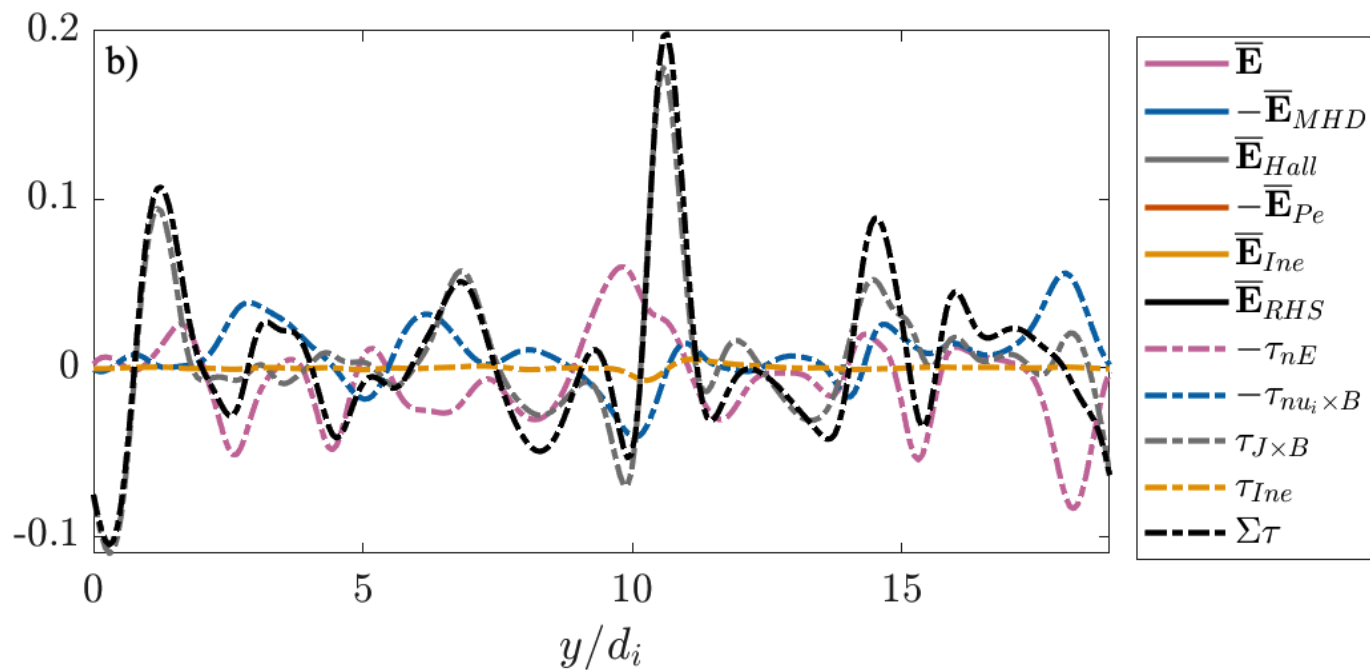




Graham et al, Nat.Comm., 2022

$$\mathbf{D} = -\frac{\langle \delta n_e \delta \mathbf{E} \rangle}{\langle n_e \rangle},$$

$$\mathbf{T} = -\frac{\langle n_e \mathbf{V}_e \times \mathbf{B} \rangle}{\langle n_e \rangle} + \langle \mathbf{V}_e \rangle \times \langle \mathbf{B} \rangle,$$



$$\mathbf{E} = -\mathbf{u}_i \times \mathbf{B} + \frac{\mathbf{J} \times \mathbf{B}}{ne} - \frac{1}{ne} \nabla \cdot \mathbb{P}_e + \frac{m_e}{ne^2} \left[\nabla \cdot \left(\mathbf{u}_i \mathbf{J} + \mathbf{J} \mathbf{u}_i - \frac{\mathbf{J} \mathbf{J}}{ne} \right) + \frac{1}{\mu_0} \nabla^2 \mathbf{E} \right],$$

$$\begin{aligned} \mathbf{E} &= -\mathbf{u}_i \times \mathbf{B}, \\ \overline{\mathbf{E}} &= -\overline{\mathbf{u}_i \times \mathbf{B}}, \\ \overline{n\mathbf{E}} &= -\overline{n\mathbf{u}_i \times \mathbf{B}}, \end{aligned}$$



$$\begin{aligned} \tau_{nE} &= (\overline{n\mathbf{u}_i \times \mathbf{B}} - \overline{n\mathbf{u}_i} \times \overline{\mathbf{B}}) / \overline{n} + \overline{\mathbf{u}_i \times \mathbf{B}} - \overline{\mathbf{u}_i} \times \overline{\mathbf{B}} \\ \tau_{nE} &= -\tau_{n\mathbf{u}_i \times \mathbf{B}} + \tau_{\mathbf{u}_i \times \mathbf{B}}, \end{aligned}$$

By construction, the anomalous terms will cancel in the absence of non linear correlations between \mathbf{u}_i and \mathbf{B}

$$\tau_{nE, EMHD} = -\tau_{n\mathbf{u}_e \times \mathbf{B}} + \tau_{\mathbf{u}_e \times \mathbf{B}},$$

Same for the electron MHD case

Anomalous electric fields in the turbulent Earth's magnetosheath: insights from 3D hybrid simulations. Agudelo Rueda, et al., in prep.

How do each of the anomalous terms contribute to the total electric field?

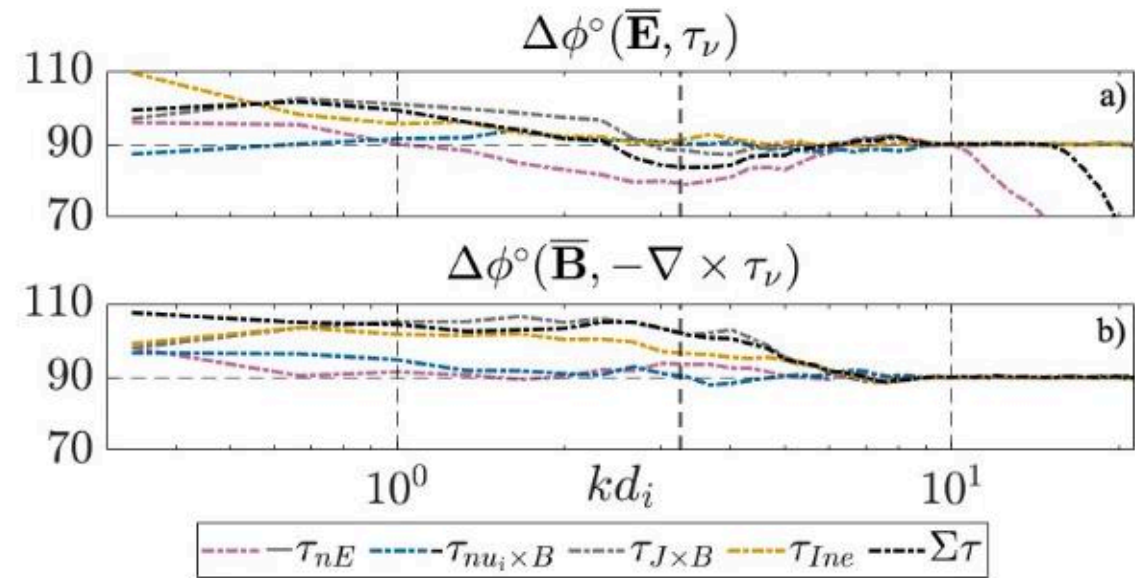
Can the collisionless physics be modelled to be used at large scales?

Stay tune for next week.

$$\frac{\partial \bar{\mathbf{u}}}{\partial t} + \nabla \cdot (\bar{\mathbf{u}} \bar{\mathbf{u}} - \bar{\mathbf{B}} \bar{\mathbf{B}}) = -\nabla P_M + \nabla \cdot \mathbf{R} + \nu \nabla^2 \bar{\mathbf{u}},$$

$$\frac{\partial \bar{\mathbf{B}}}{\partial t} = \nabla \times (\bar{\mathbf{u}} \times \bar{\mathbf{B}} + \mathbf{E}_M) + \lambda \nabla^2 \bar{\mathbf{B}}$$

$$\mathbf{E}_M = \overline{\mathbf{u}' \times \mathbf{B}'} = -\beta \bar{\mathbf{J}} + \alpha \bar{\mathbf{B}} + \gamma \bar{\mathbf{\Omega}},$$



Anomalous electric fields in the turbulent Earth's magnetosheath: insights from 3D hybrid simulations. Agudelo Rueda, et al., in prep.

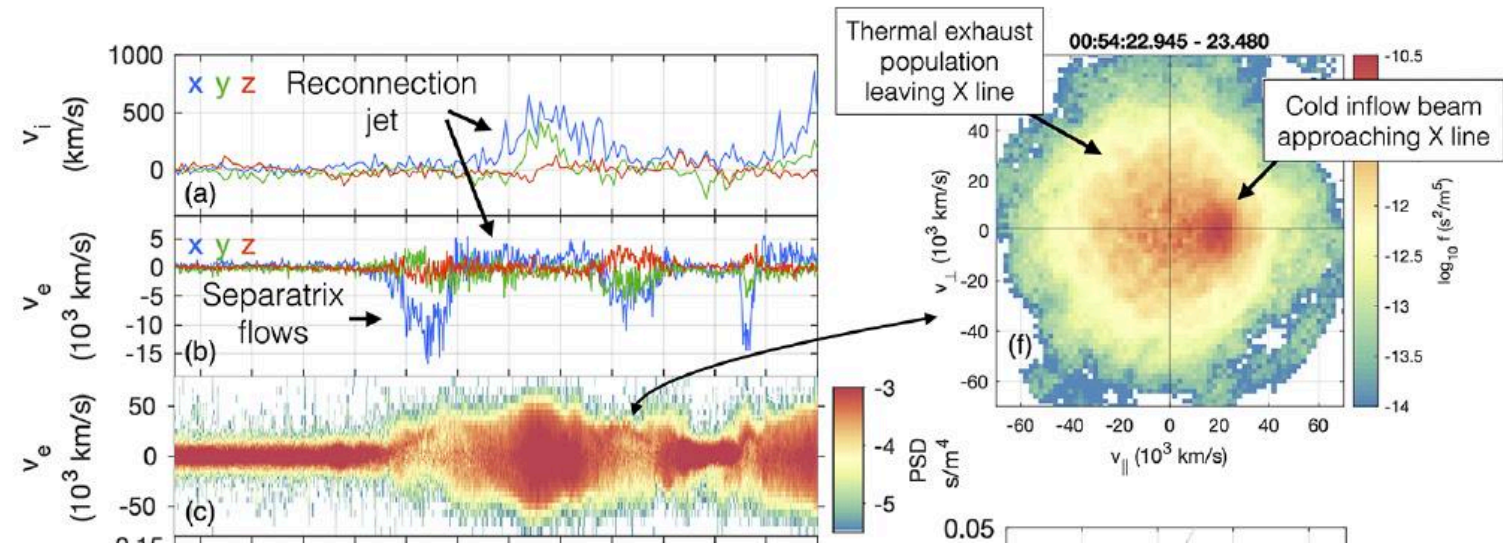
Anomalous electric fields, VDFs and kinetic instabilities

Future project addressing questions of interest around.

Effects of anomalous electric fields in the context of magnetic reconnection, under several conditions (anti-parallel, guide-field, asymmetric)

Sources of anomalous electric fields in the context of reconnection

Question: can the presence of non-thermal distributions modify the generation of instabilities that trigger kinetic scale modes that contribute to the anomalous electric field?



Norgen et al, Space Sci. Rev, 2025

Graham et al, Space Sci. Rev., 2025

