Evolution of current and vorticity sheets in collisionless plasma turbulence

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in collaboration with

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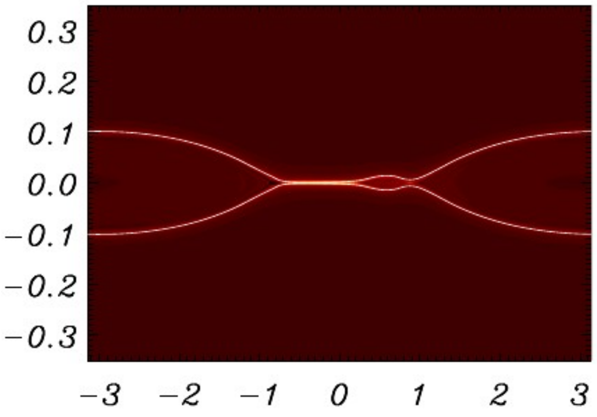
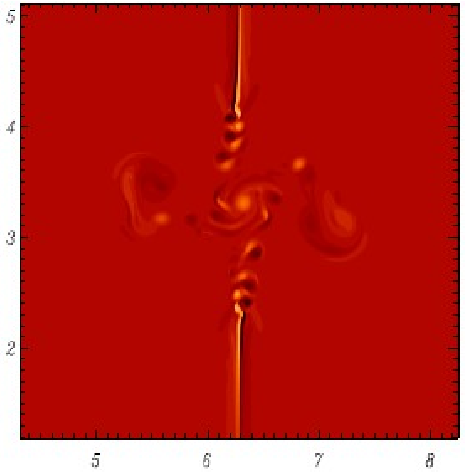
Introduction





- Current and vorticity sheets can be thought of as fingerprints of magnetic reconnection and turbulence respectively

- Magnetic reconnection is ubiquitous in several astrophysical environments where, due to high Reynolds numbers, the transition to turbulence is unavoidable

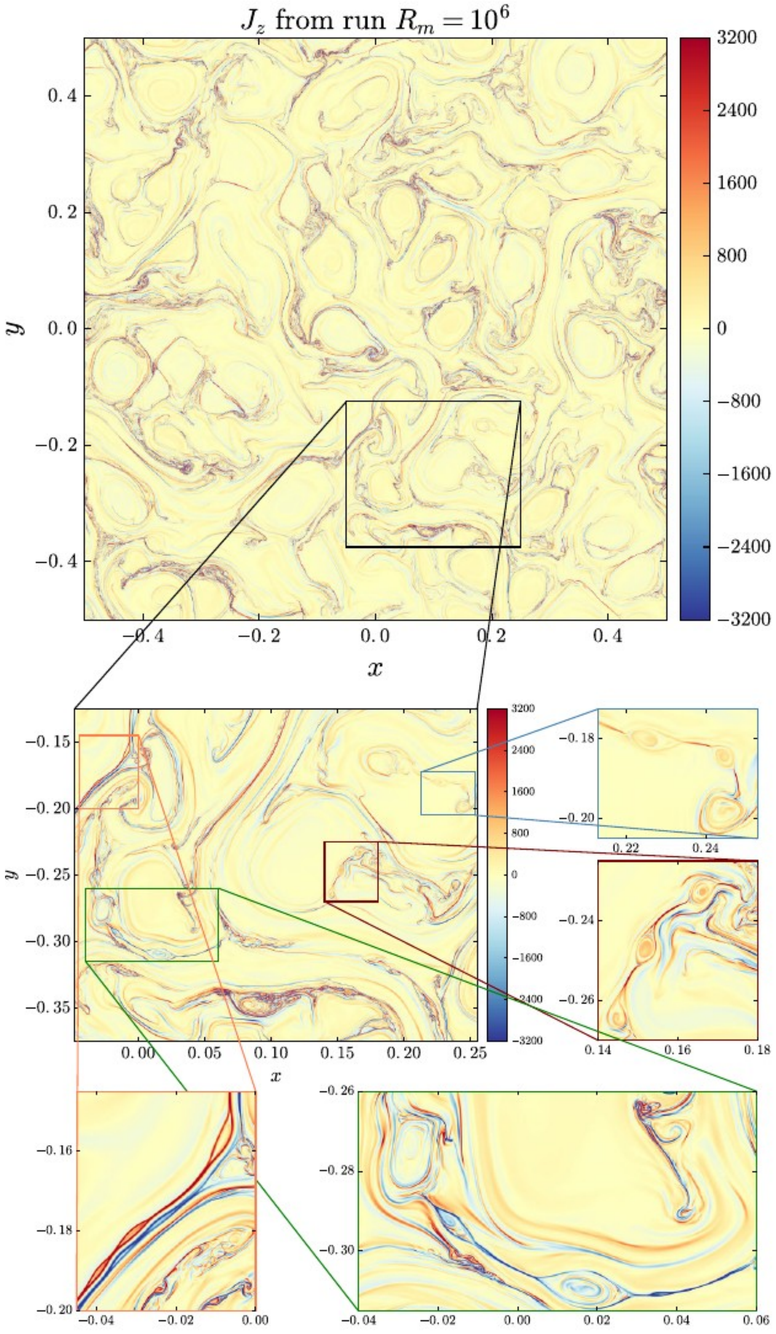
- In the presence of strong turbulence in the medium, magnetic field line reconnection is continuously met along the flow

- Both processes involve energy cascades towards small scales

- This makes magnetic reconnection an intrinsic element of the turbulent cascade and vice versa

Introduction

- Many works have analyzed the turbulent cascade in RESISTIVE MHD, defining under which conditions the plasmoid instability influences the energy cascade
- Most of the time space and astrophysical plasmas are collisionless
- Here we analyze the development of plasmoids in a turbulent collisionless plasma where the reconnection mechanism is provided by the electron inertia
- We find a much more complex situation in which, due to the presence of strong velocity shears, the typical plasmoid formation, has to coexist and compete with the Kelvin–Helmholtz (KH) instability



Dong et al. PRL 121, 165101,2018

Outline

- The collisionless model
- Linear digression: shear flow effects on the reconnecting instability
- The numerical setup for turbulence studies
- CS disruption via plasmoid instability
- CS disruption via KH instability
- Plasmoid mediated turbulence regime
- Energy spectra
- Comparison with a resistive case
- Conclusions and future perspectives

Borgogno et al ApJ 929:62, 2022

The collisionless model

- In order to compare our results with the reduced resistive MHD studied in Dong 2018 and to reduce the problem to a few essential ingredients we adopt the two fluid 2D reduced model of MR, accounting for both resistivity and electron inertia

$$\boxed{\begin{aligned} \frac{\partial \psi}{\partial t} + [\varphi, \psi] &= -d_e^2 \frac{\partial J}{\partial t} - d_e^2 [\varphi, J] - \eta (J - J_{\mathrm{eq}}), \qquad (1) \\ \frac{\partial U}{\partial t} + [\varphi, U] &= [J, \psi] + \nu \nabla^2 U, \qquad (2) \end{aligned}}$$

$$\boxed{J = -\nabla^2 \psi}$$

$$\boxed{U = \nabla^2 \varphi}$$

$$\boxed{d_e = c/\omega_{\mathrm{pe}}}$$

$$\boxed{\boldsymbol{B} = B_0 \boldsymbol{e}_z + \nabla \psi \times \boldsymbol{e}_z}$$

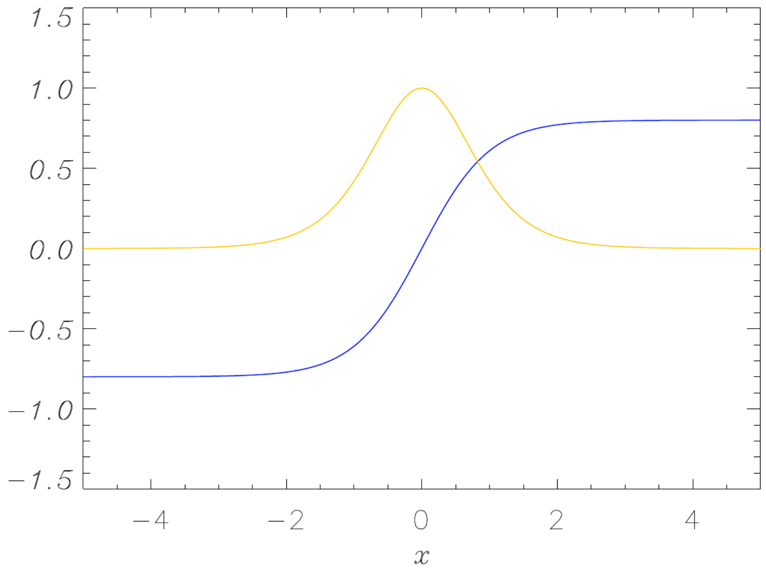
$$\boxed{|B_0| >> 1}$$

$$\boxed{\boldsymbol{v} = \boldsymbol{e}_z \times \nabla \varphi}$$

- Equations are integrated by the numerical solver SCOPE3D: a pseudospectral, explicit in time, MPI parallelized code

Linear digression:

shear flow effects on the reconnecting instability



- We analyze the growth rate of reconnection and KH instabilities for a current-sheet-like equilibrium
- Following Biskamp (2000) we consider a Bickley jet embedded in a sheared magnetic field

$$B_{\mathrm{eq}}(x) = B^0_{\mathrm{eq}} \tanh(x),$$

$$V_{\mathrm{eq}}(x) = \frac{V^0_{\mathrm{eq}}}{\cosh^2(x)}.$$

$$B^0_{\mathrm{eq}} = 0.8$$

$$V^0_{\mathrm{eq}} = 1.0$$

- The linear solution of our model equations assuming this equilibrium configuration, leads to two classes of eigenmodes:

$$\phi_1 = \phi(x) \exp\{ik(y - ct)\}$$

φ even (Kelvin-Helmoltz kink mode) and ψ odd
φ odd (pinch mode) and ψ even

- In the case of an ideal plasma with $d_e = \eta = 0$ the numerical solution of the linearized equations shows the stabilizing effect of the magnetic field on both the classes of solutions

Linear digression:

shear flow effects on the reconnecting instability

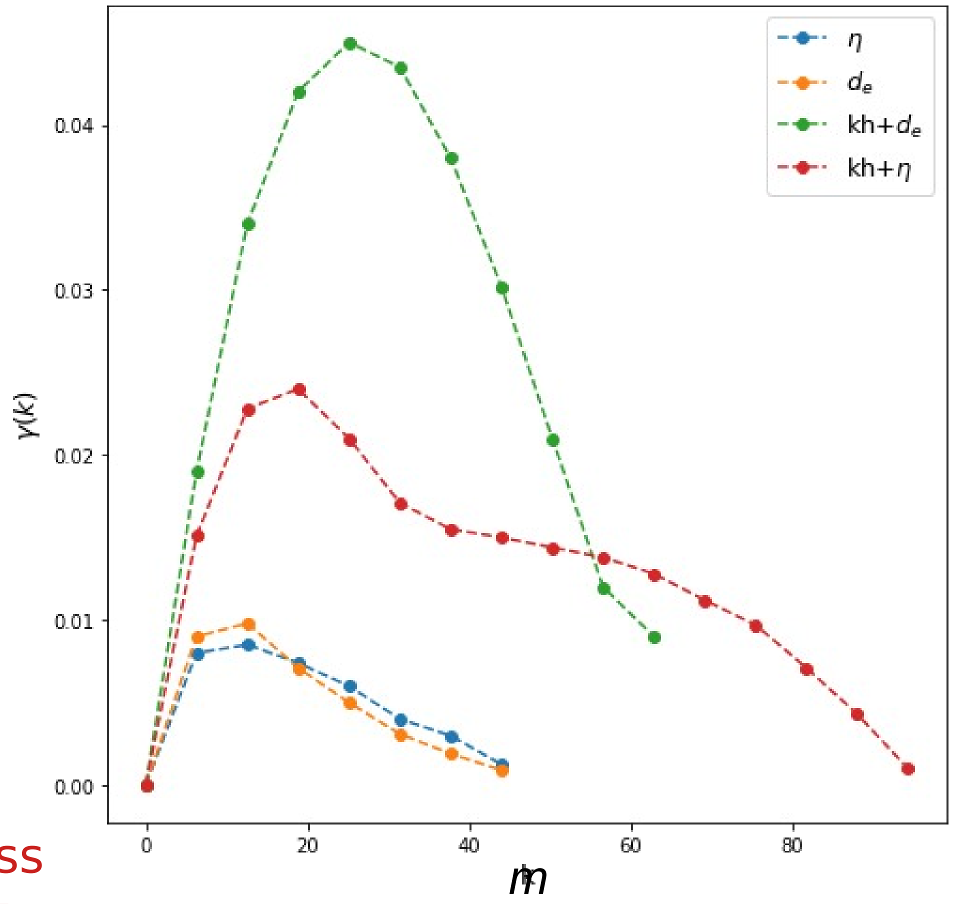
- In presence of non-ideal contributions in the plasma Ohm’s law the reconnecting modes are strongly affected by the presence of the shear flow

- The figure shows the linear growth rates of the pinch modes for $\eta=0.0003$ and $d_e=0.188$

- The combined action of a sheared velocity field together with the sheared magnetic field causes in both the regimes:
  - i) broadening of the spectrum of unstable modes
  - ii) increase of the growth rate
  - iii) shift of the peak values towards higher k.

- Differences between collisionless and resistive regimes:
  - i) the spectrum of unstable modes broadens less
  - ii) the growth rate are much higher

- These results already suggest that in a turbulent collisionless environment the reconnection instability will receive a boost



Numerical setup

- Freely decaying turbulence problem as in Dong (2018)
- Equations (1)–(2) are solved in the domain $-1/2 < x, y < 1/2$
- For the collisionless runs: $\eta = 0$, $\nu = 10^{-6}$, $d_e = 5 \times 10^{-4}$
- Initial condition: 10x10 uncorrelated, equipartitioned ψ and φ fluctuations in Fourier harmonics:

$$\psi = -\sum \psi_{0mn} \sin(k_m x + \xi_{1mn}) \sin(k_n y + \xi_{2mn}),$$
$$\varphi = \sum \varphi_{0mn} \sin(k_m x + \xi_{3mn}) \sin(k_n y + \xi_{4mn}),$$

$$k_m = 2\pi m/L$$

ξ_i with *i*=*1*,..,*4* are random phases

- Energy is initialized in the range m,n=0,...,10, with:

$$l_{\min} \leqslant (m^2 + n^2)^{1/2} \leqslant l_{\max}$$

$$l_{\min} = 1,\ l_{\max} = 10$$

$$\varphi_0 = \psi_0 \simeq 2$$

$$\psi_{0mn} = \psi_0 \Big/ 2\pi\sqrt{(m^2 + n^2)(l_{\max}^2 - l_{\min}^2)},$$
$$\varphi_{0mn} = \varphi_0 \Big/ 2\pi\sqrt{(m^2 + n^2)(l_{\max}^2 - l_{\min}^2)}.$$

$$E = \frac{1}{2}\langle \boldsymbol{v}^2 + \boldsymbol{B}^2 \rangle \simeq \frac{1}{8}(\varphi_0^2 + \psi_0^2) \simeq 1$$

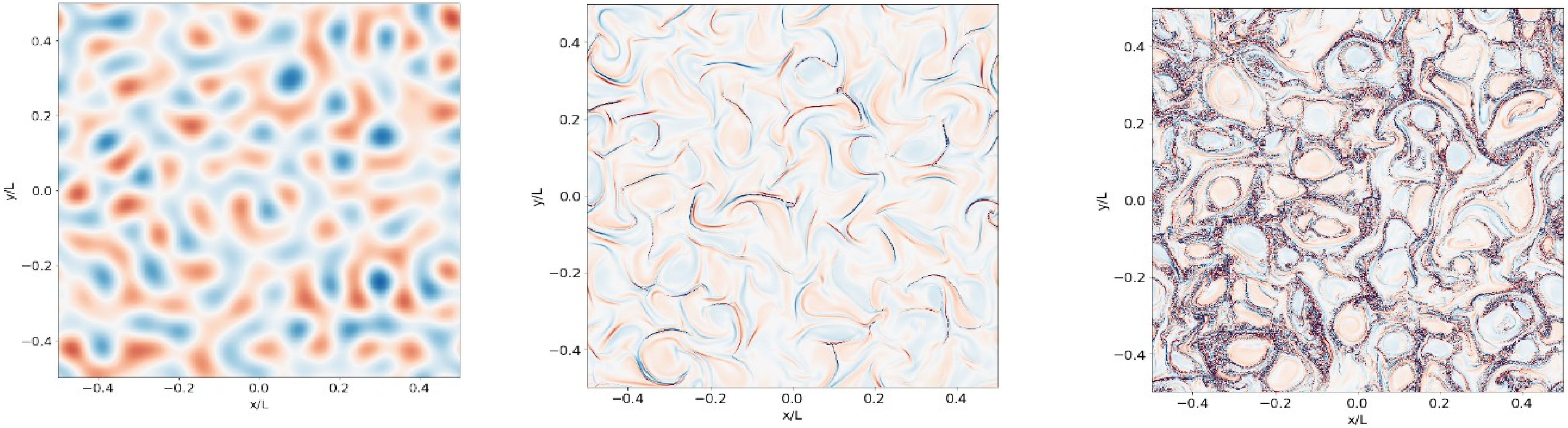
Numerical setup

- This condition is convenient both to achieve early an adequate state of turbulence and to have thin and elongated current sheets with a high aspect ratio

$$\boxed{l_{\mathrm{cs}}/d_e \sim 200}$$

necessary for the onset of the plasmoid instability (Comisso & Sironi 2018, 2019)

nx=ny=
9600,
19040,
38080

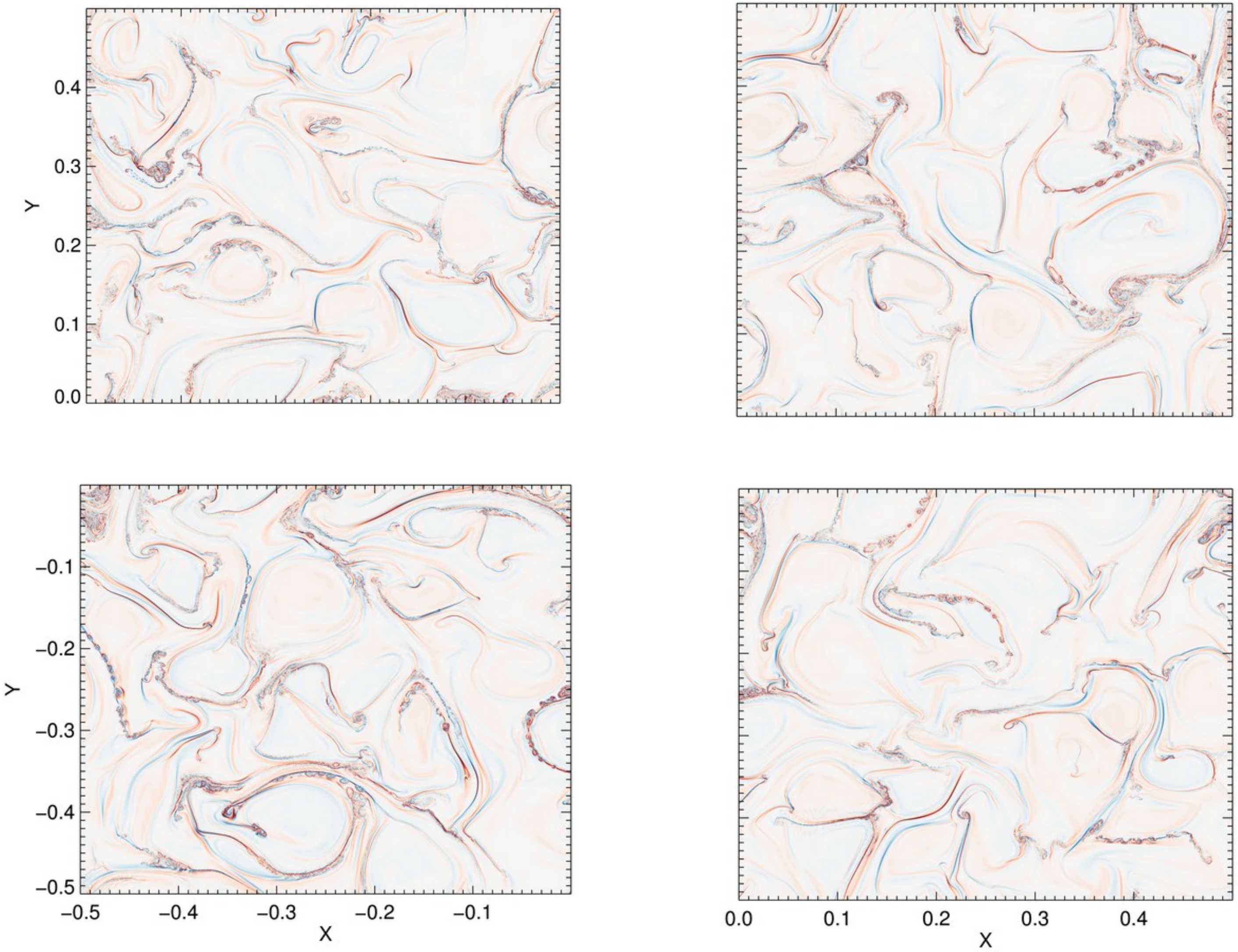


- The plasmoid activity starts well in advance respect the reaching of the maximum turbulent activity, measured by the maximum of the rms value of the current density

CS evolution

- The initial eddies merge, giving rise to the formation of thin and elongated current sheets, which are analogous for the vorticity

- In each subdomain is possible to see CS evolving in plasmoid chains, as well as CS dominated by the KH instability

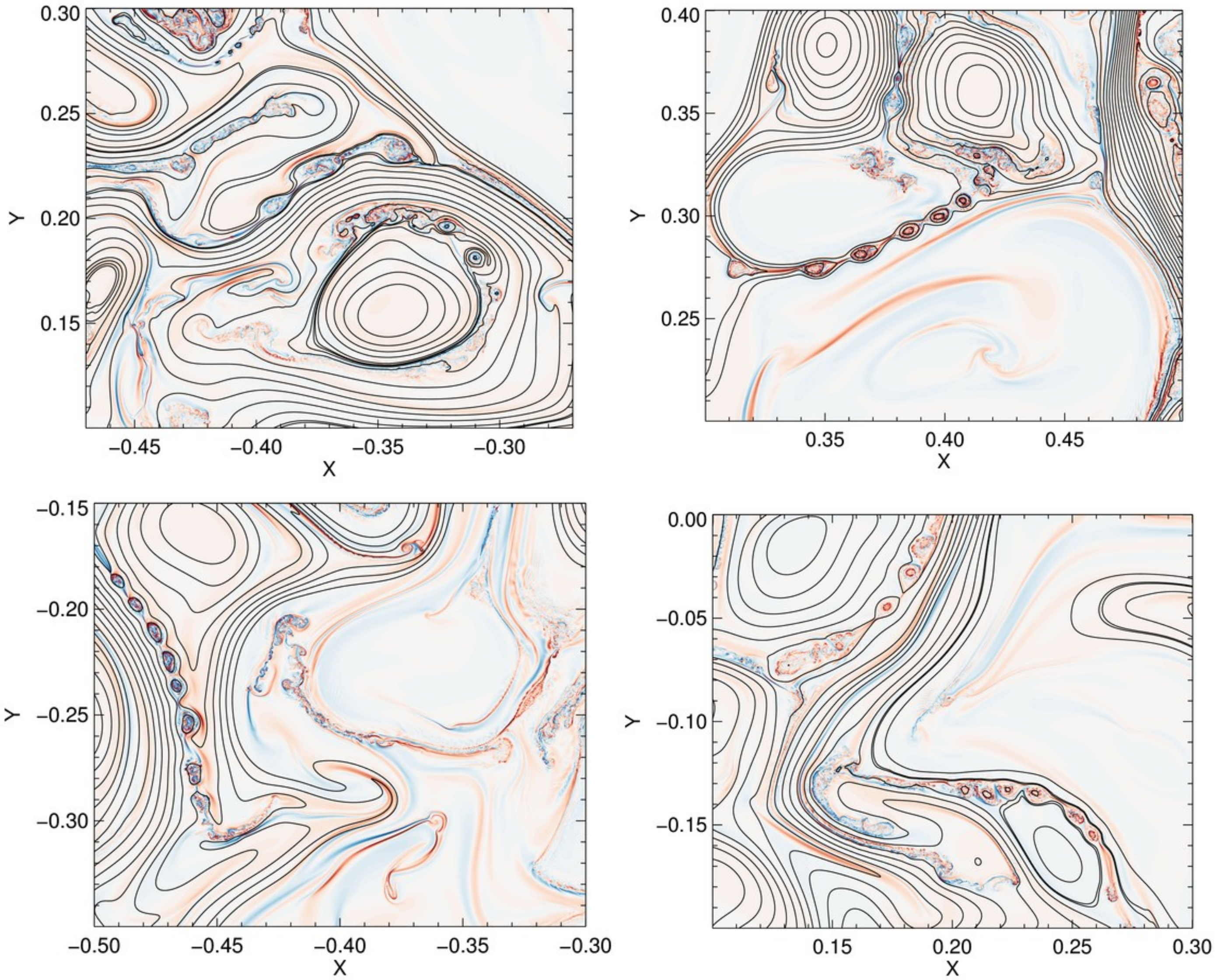


CS evolution

- Current density distribution with overplotted the magnetic surfaces

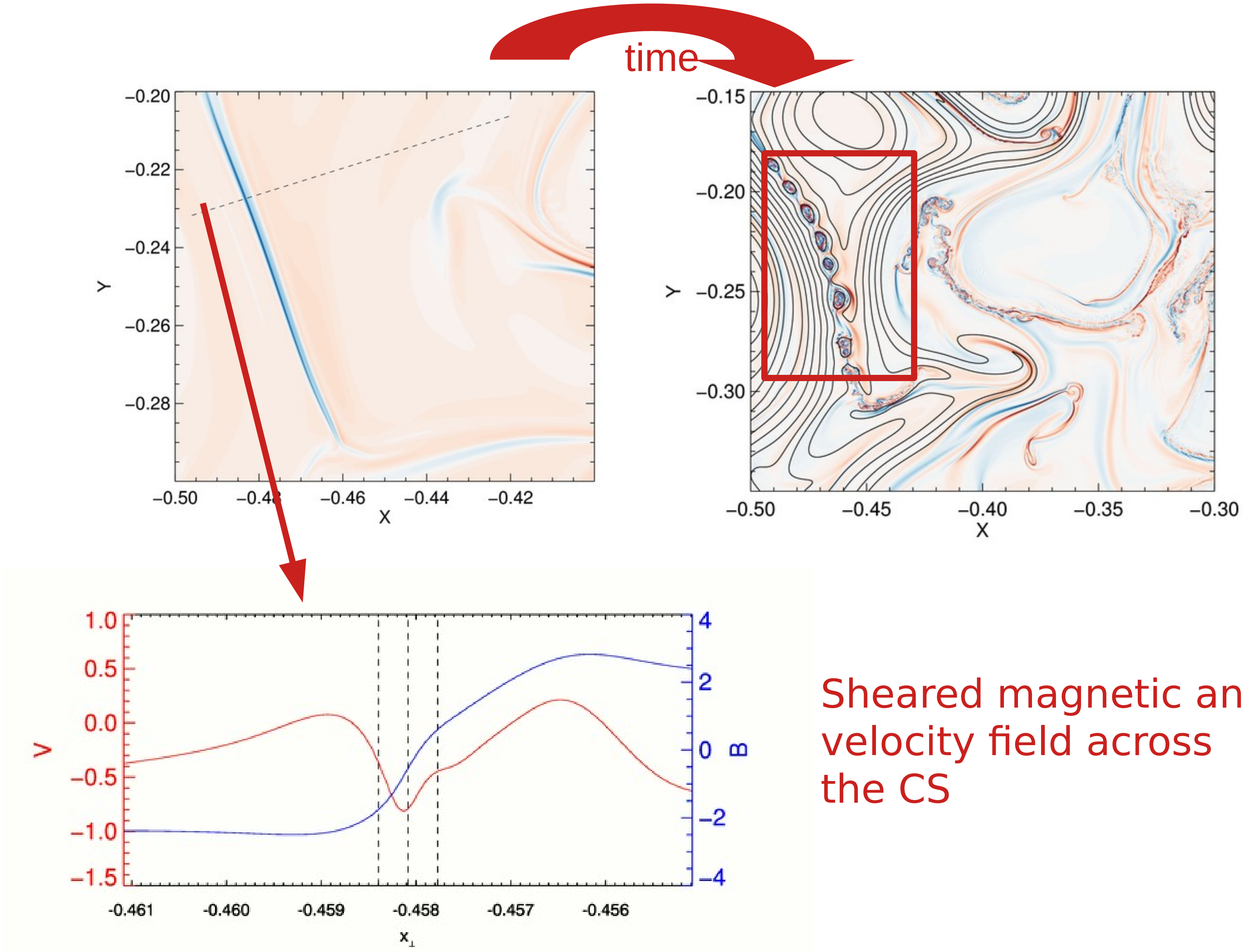
- Plasmoids are clearly identified by magnetic structures

- Turbulent and laminar structures coexist localized where the magnetic field is weaker



CS disruption via plasmoid instability

- Stabilizing role of the magnetic field
- KH suppressed when |B| ≥ |V| .
- Plasmoid chain formation via the reconnection of the magnetic field lines

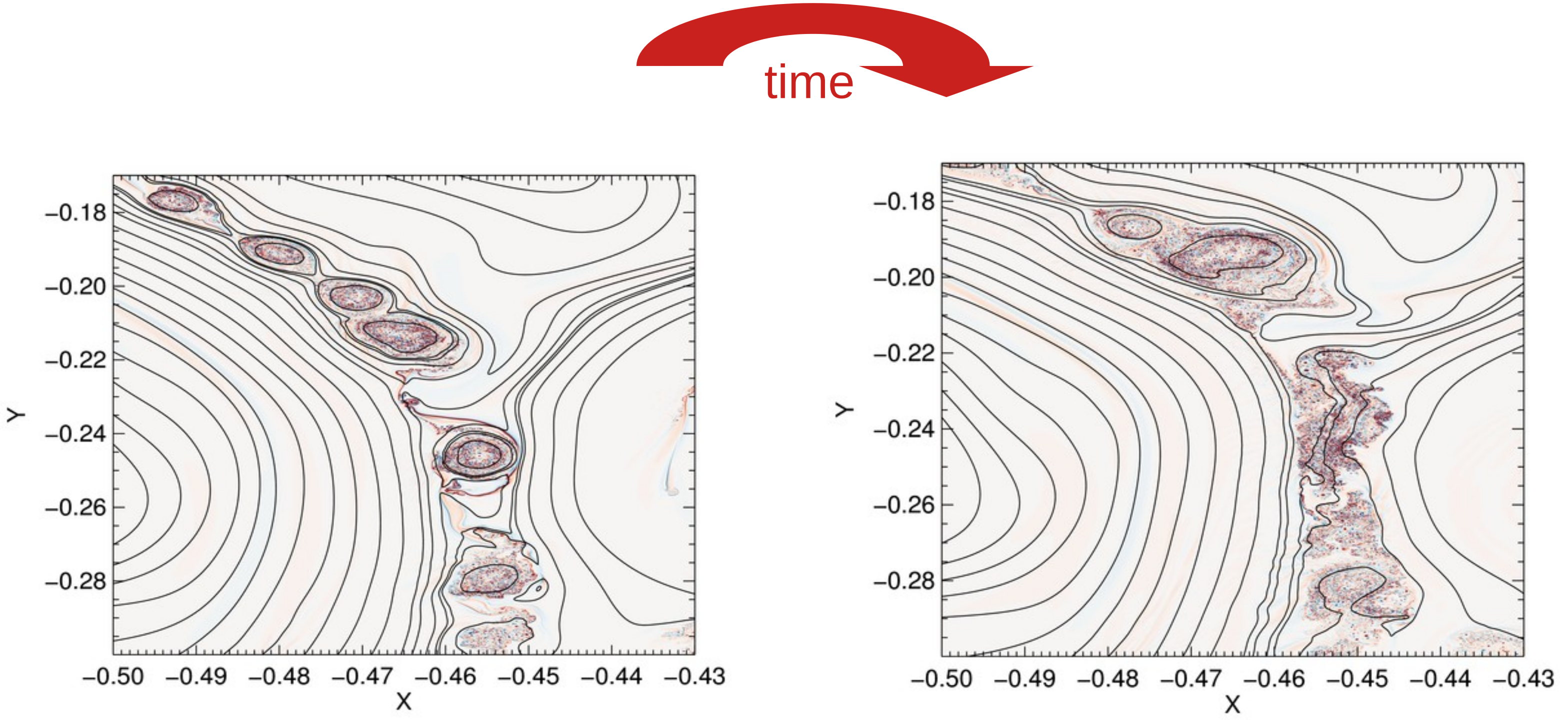


Sheared magnetic and velocity field across the CS

CS disruption via plasmoid instability

In this model J and U are bounded by the same dynamics

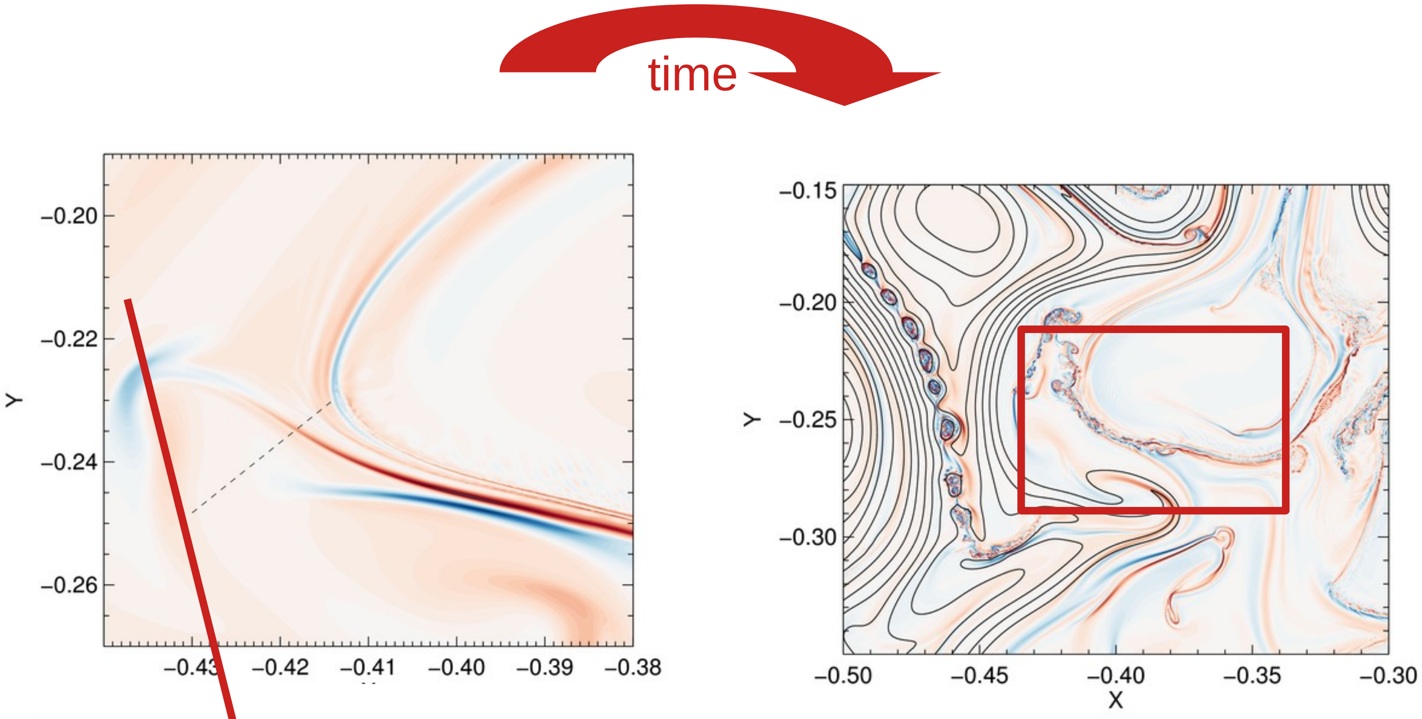
Vorticity layers behave as the current density ones

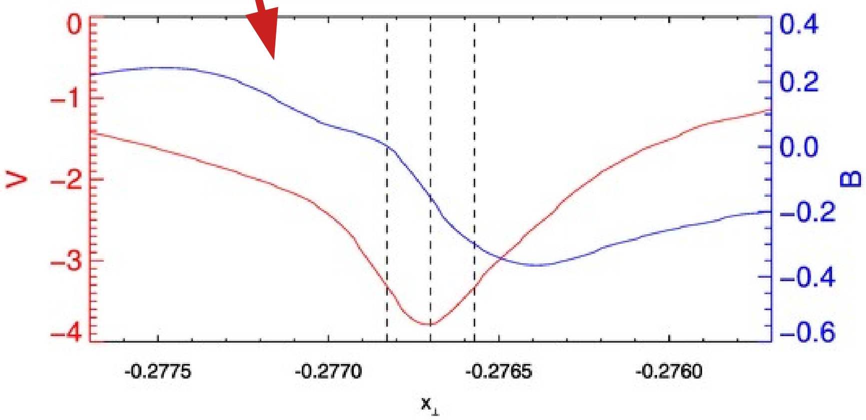


- In the case of plasmoid chain formation turbulence is bounded inside the magnetic structures, where the vorticity and current density exhibit small scale vortexes
- When the plasmoids become larger, their mutual interaction leads to the coalescence between the magnetic structures that belong to the same island chain
- This results in large turbulent regions where the magnetic structures eventually disappear
- The magnetic connections between the nearby turbulent regions finally drive the appearance of macroscopic turbulent domains
- KH dominated current sheets never show plasmoid formation

CS disruption via KH instability

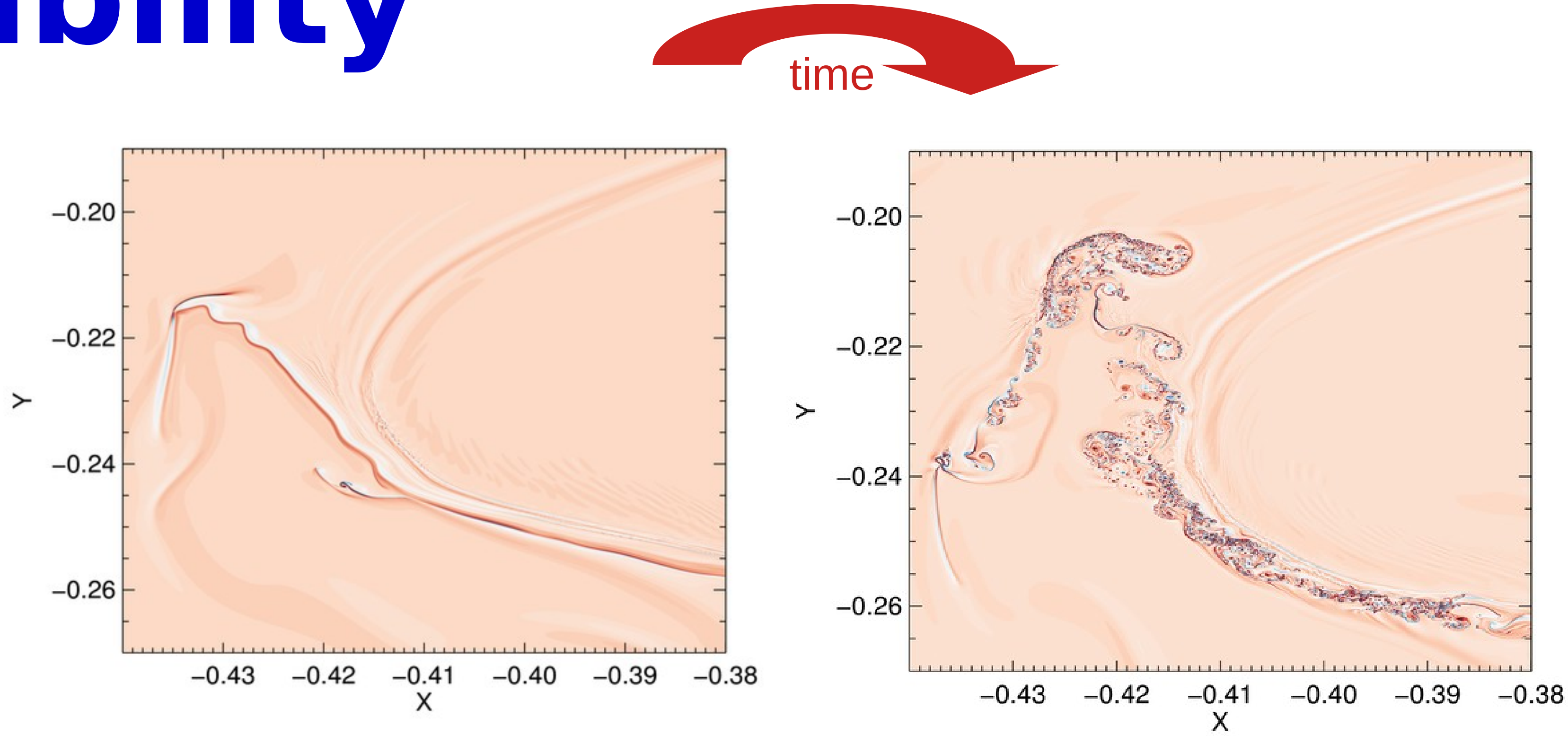
- Destabilizing role of the velocity field
- KH dominates when |V| ≥ |B| .
- CS evolves directly into a turbulent regime
- KH dominated current sheets never show plasmoid formation





Sheared magnetic and velocity field across the CS

CS disruption via KH instability



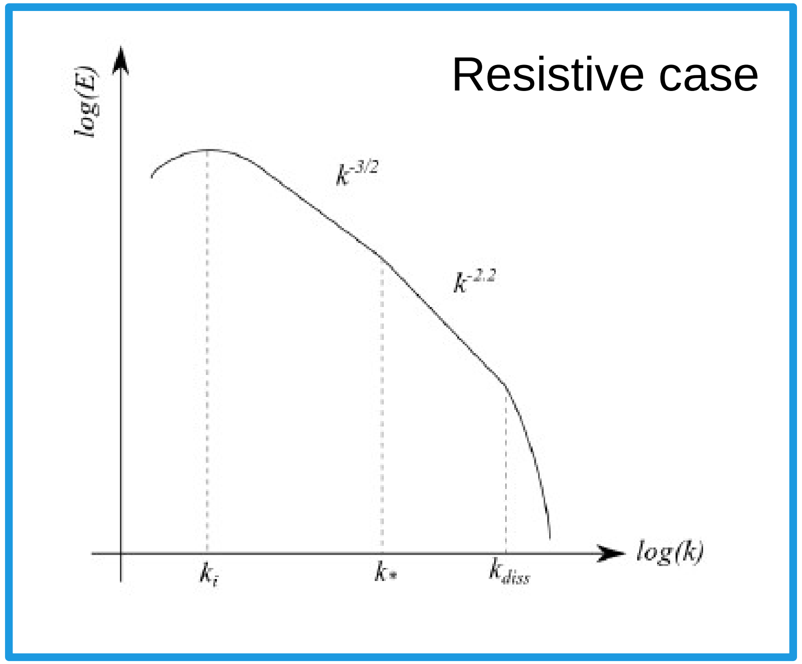
Vorticity

- The vorticity layers start to develop the KH instability that leads to its complete disruption in many small vortexes
- The layers examined are representative of many ones that form and disrupt according to either the plasmoid or the KH instability depending from the relative magnitude of the B and V fields
- Although distinguishing between these two evolution paths may be difficult, their coexistence is crucial in explaining the energy cascade

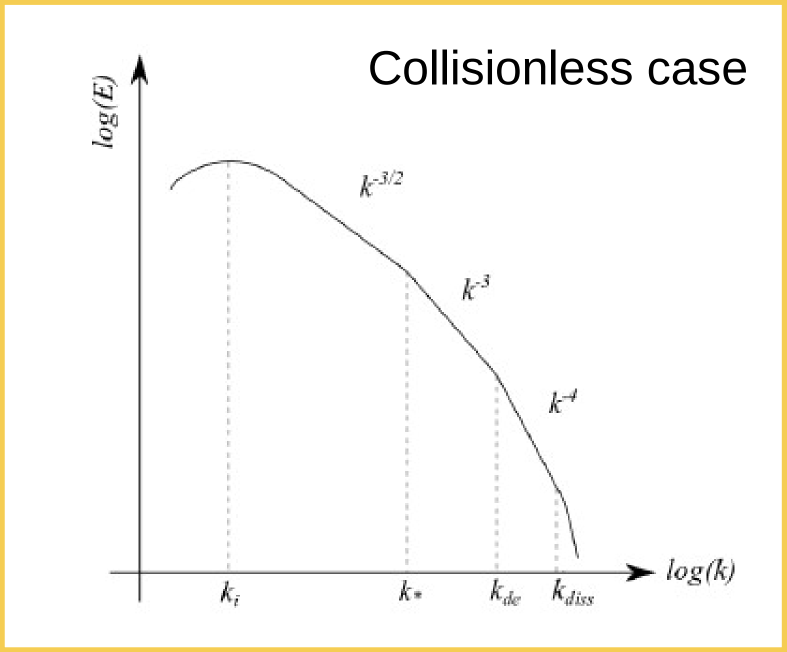
Plasmoid mediated turbulence

- In resistive regimes the onset of the plasmoid instability produces a steepening in the slope of the energy spectra (Comisso et al., Phys. Plasmas 2016)

$$E(k) \propto k^{-2.2}$$


Resistive case

$K_* \longrightarrow$ Plasmoid onset


Collisionless case

- We extend this result to collisionless regimes and find at zeroth order:

$$E(k) \propto k^{-3}$$

- The plasmoid dominated regime ends at the available kinetic scale:

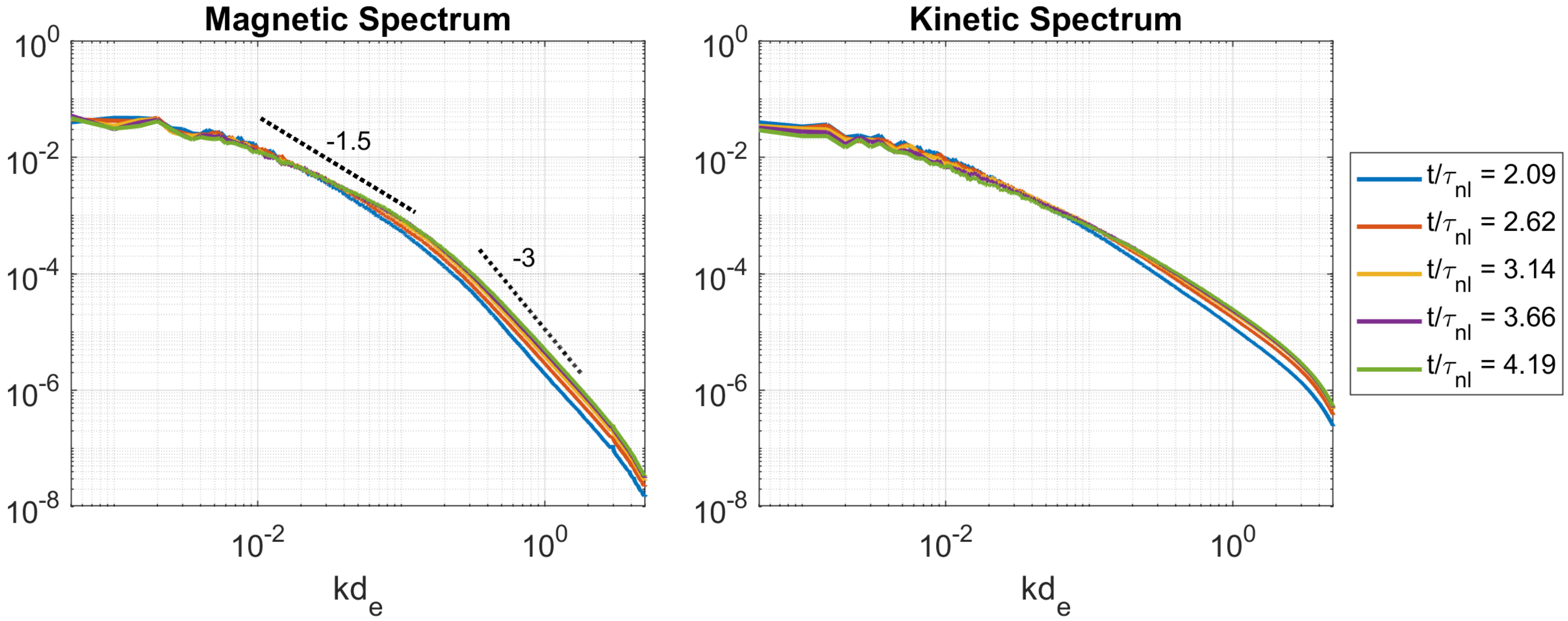
$$K_{de} = 2\pi / d_e \longrightarrow \text{kinetic scale}$$

Energy spectra

τ_{nl} → nonlinear eddy turnover time

- Magnetic and kinetic energy spectra at four times, after plasmoid formation

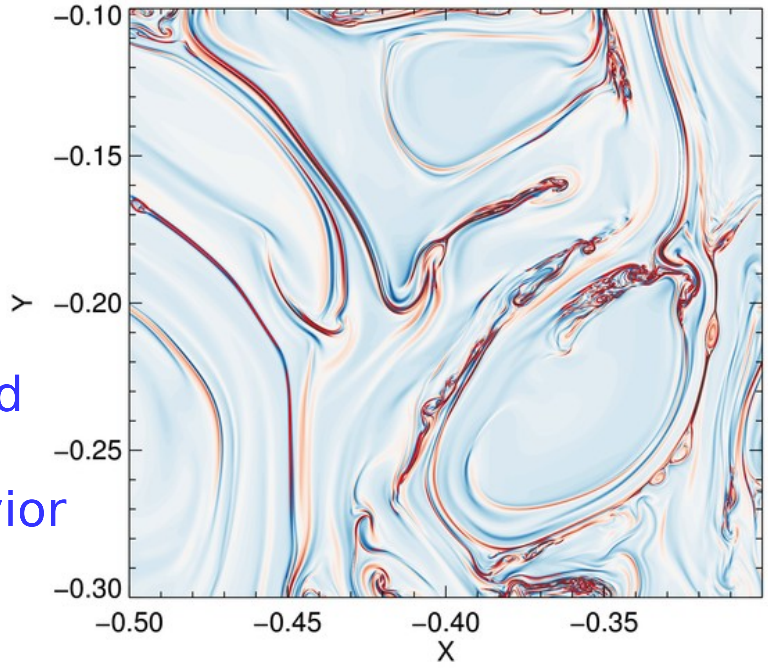
- The change in the slope occurs at
  $kd_e \sim 0.1$
- Corresponding to
  $w_{pl} \sim 0.1 l_{cs} \sim 20 d_e$



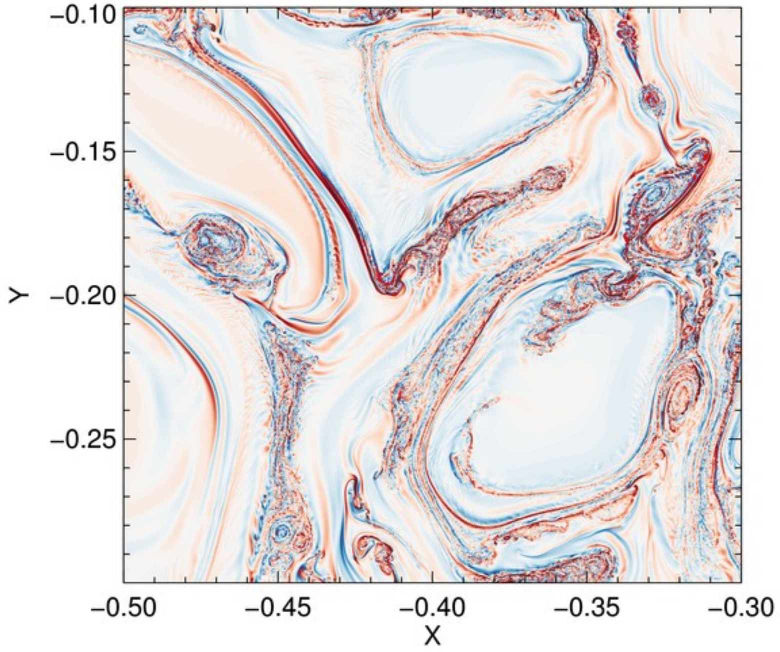
- We find smoother slopes than theoretical predictions
- The magnetic energy spectrum tends to flatten, consistently with the observation that the fully plasmoid mediated regime is somehow inhibited by the presence of a turbulence dominated by the KH instability
- Kinetic spectrum decoupled from the magnetic one
- No abrupt change in the slope: kinetic energy dominated by KH instability

Collisionless vs. resistive

- The structures are similar
- Resistive CS are less sensitive to disruption and evolve following a laminar behavior



$\eta = 5 \times 10^{-6}$, $d_e=0$

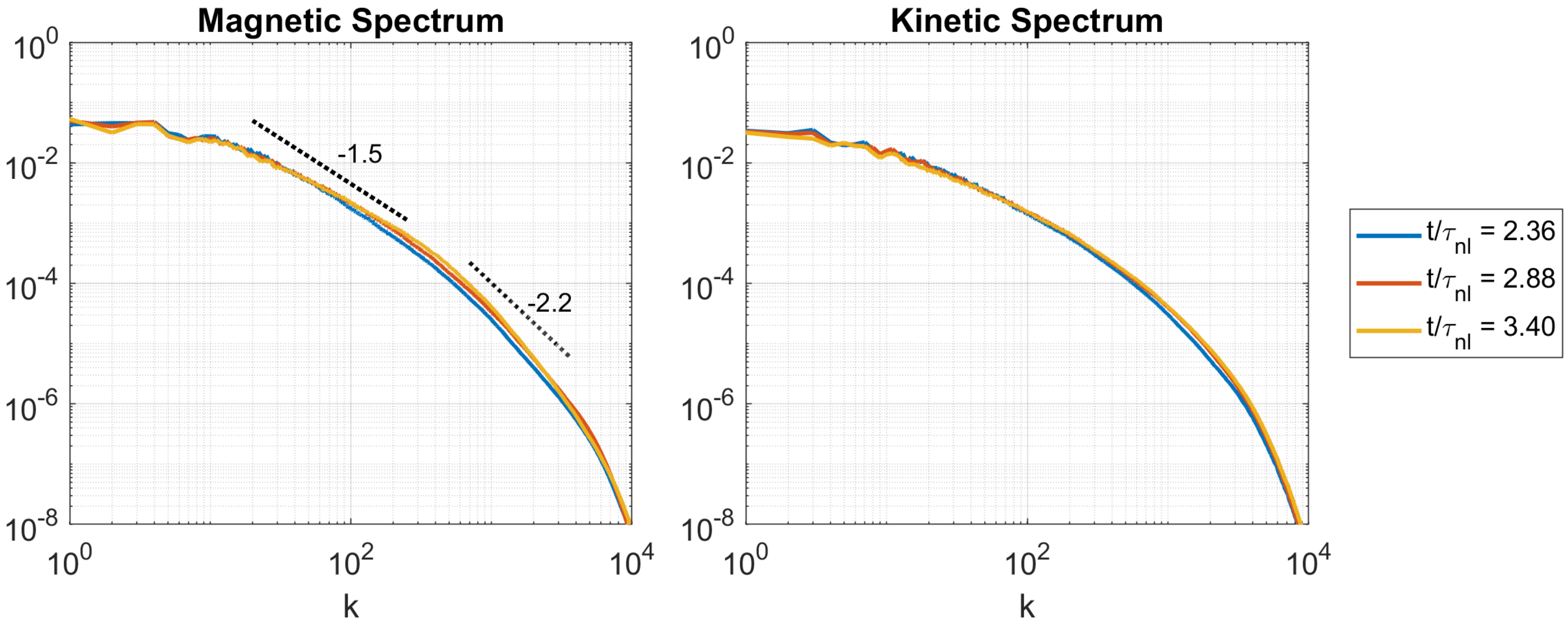


$\eta = 0$, $d_e= 5 \times 10^{-4}$

- The number of plasmoids in the resistive regime significantly increases as we follow the turbulence evolution and we get closer to the turbulent activity peak
- From linear analysis we expect the impact of a velocity shear on the growth rate of reconnecting modes to be greater in the collisionless regime
- The number of unstable modes increases as well as their growth rate
- Hence, it is reasonable to find that the plasmoid instability starts earlier in the collisionless case
- In the resistive regime, the current and vorticity sheets are not affected by the KH instability

Collisionless vs. resistive

Energy spectra in the resistive regime



- At this time of the resistive simulation we have not reached yet the plasmoid mediated regime
- Plasma collisions make the kinetic and magnetic spectrum comparable
- The values of resistivity, affecting the current density, and that of the viscosity, affecting the vorticity, are comparable in our simulation, thus determining the same dissipation length scale for J and U

Conclusions

We addressed the problem of turbulent cascade in the collisionless regime with a different perspective focused on the interaction between the magnetic and fluid instabilities

- Do plasmoids form in collisionless plasmas?

  The plasmoid instability develops also in collisionless plasmas under appropriate choice of parameters

- If they do form, how do they affect the turbulent energy cascade?

  The energy spectrum of turbulence in the plasmoid mediated regime has a different slope

  Magnetic and kinetic spectra are decoupled

- How do plasmoids interact with Kelvin-Helmholtz instability?

  The plasmoid instability is enhanced by the shear flow instability

Perspectives

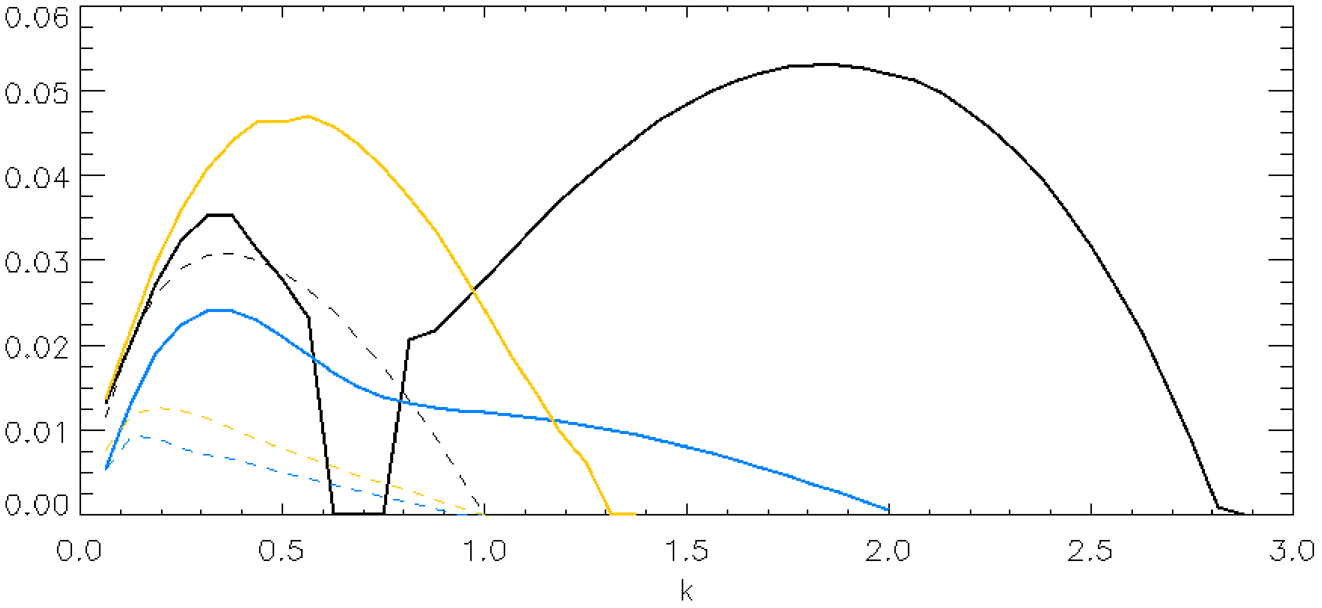
Physics:

- role of electron temperature linear analysis of KH on top of reconnection

black curves

- 3D: effect of magnetic chaos

Technique: transition to GPU



Grasso & Borgogno in Plasma Modeling IOP (second edition) 2022

Thank you