Generation of turbulence in magnetic reconnection: numerical solutions of the Vlasov-Maxwell system and observations

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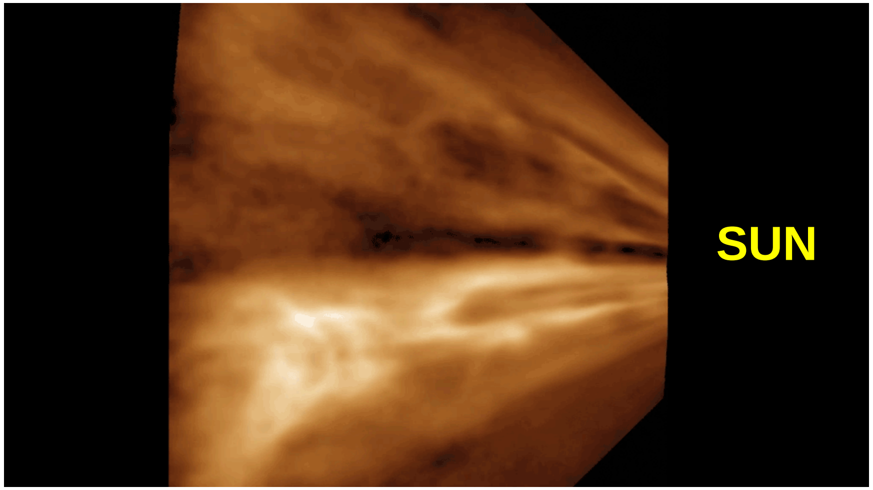
Outline

- Introduction: reconnection in turbulence, turbulence in reconnection
- The semi-implicit particle in cell method for the solution of the Vlasov equation
- Two numerical studies:

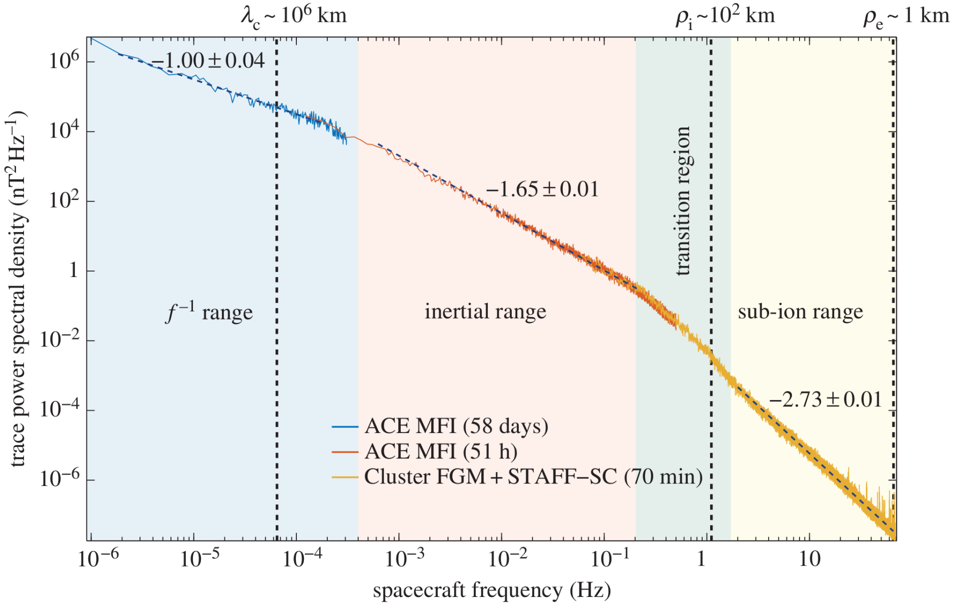
  - turbulence in non iteracting reconnection outflows

  - turbulence colliding reconnection jets
- Conclusions

Introduction: Observation of turbulence in the solar wind



Observation of turbulence at Solar Wind source (De Forest et al. 2018). Credits:NASA

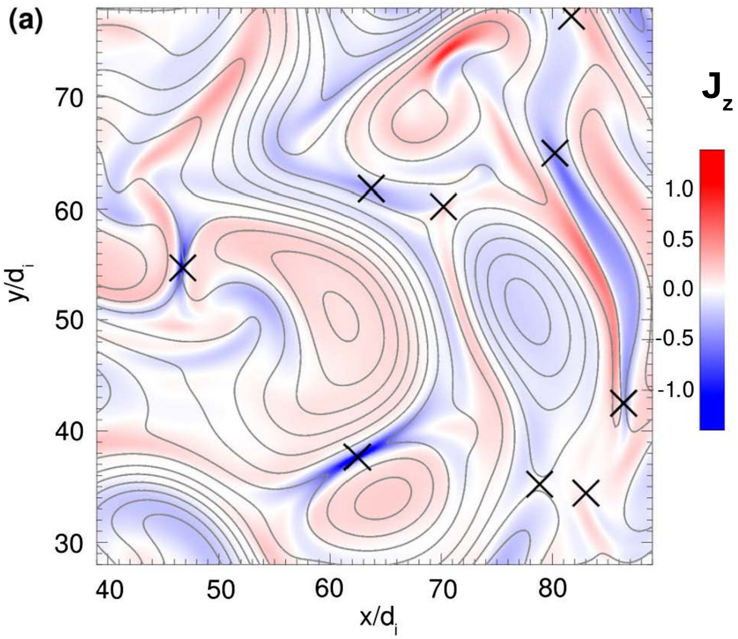


Spectrum of magnetic fluctuations in the solar wind (Kiyani et al. 2015)

- The solar wind is filled with magnetic fluctuations at different scales
- The range of scale involved is estensive

Introduction: magnetic reconnection in turbulence

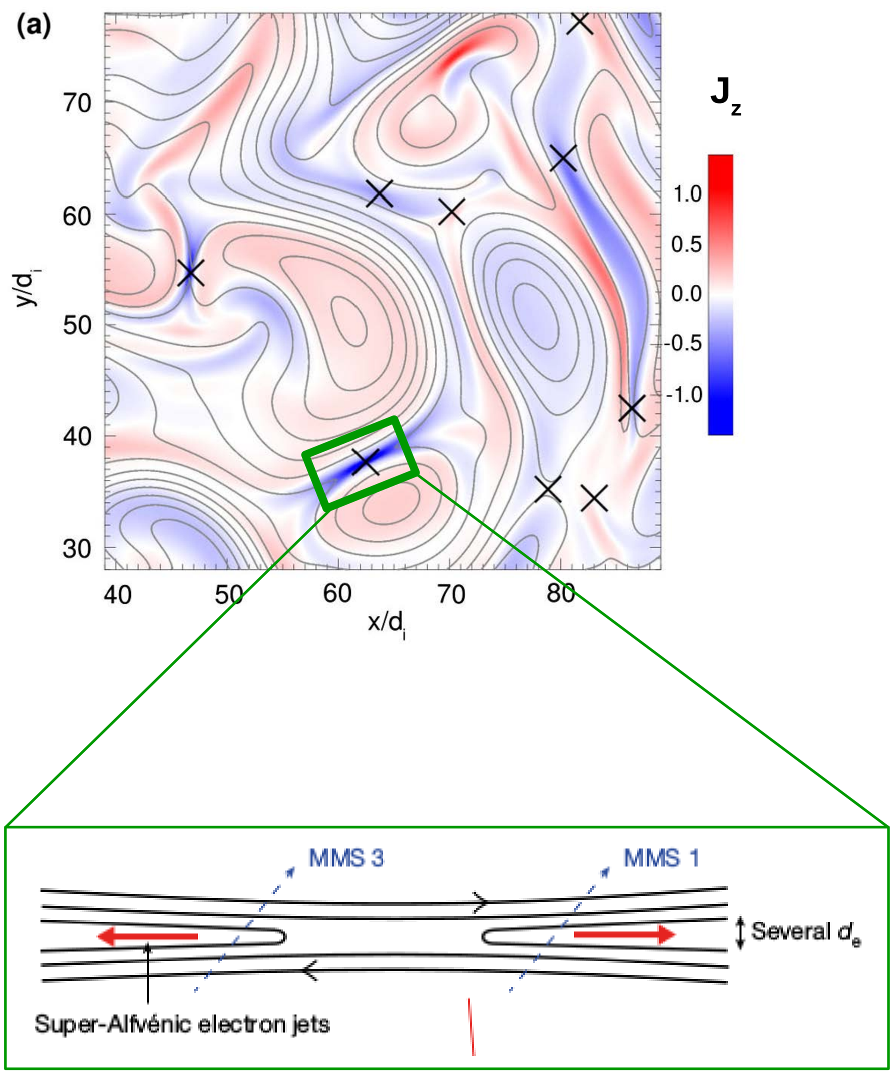
NUMERICAL SIMULATIONS



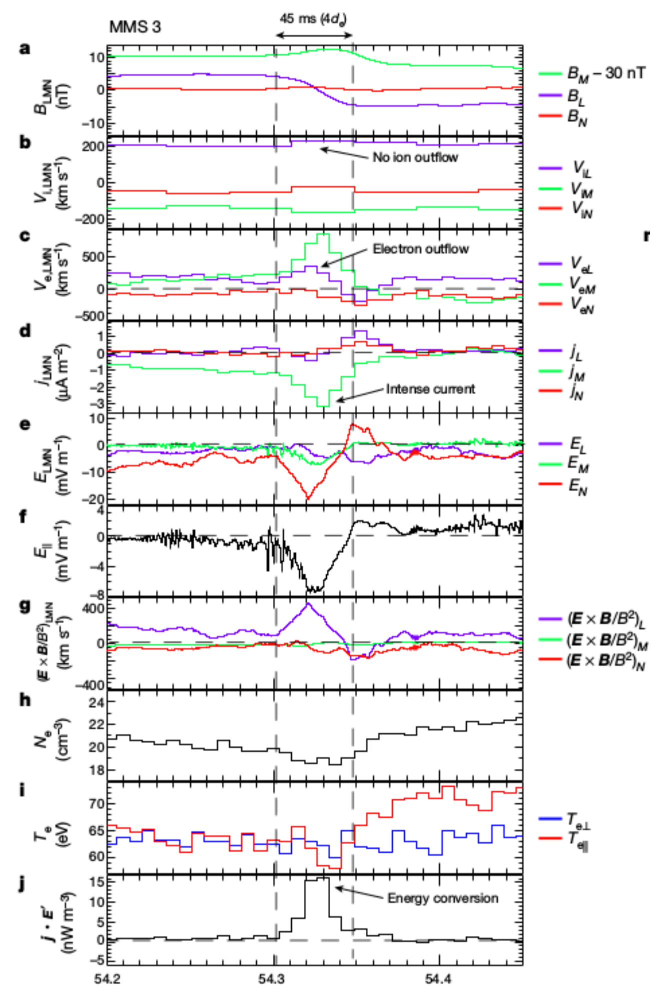
Out of plane current in simulation of decaying turbulence. (Servidio et al. 2012)

Introduction: magnetic reconnection in turbulence

NUMERICAL SIMULATIONS



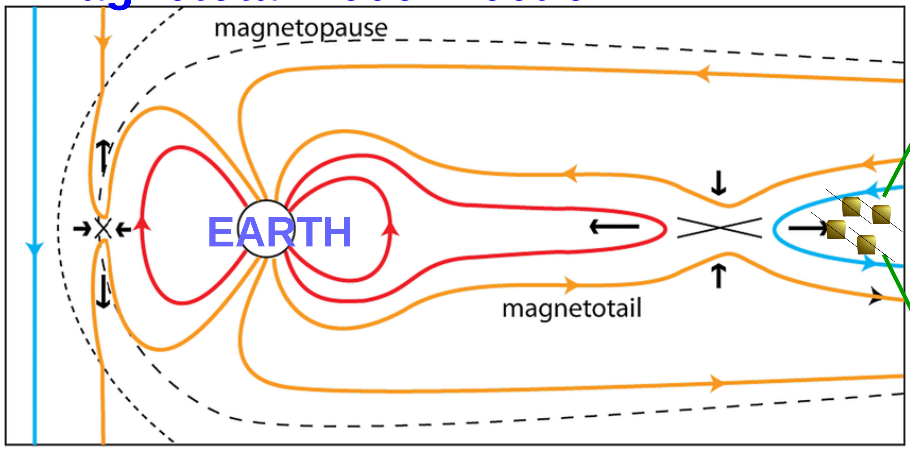
OBSERVATIONS



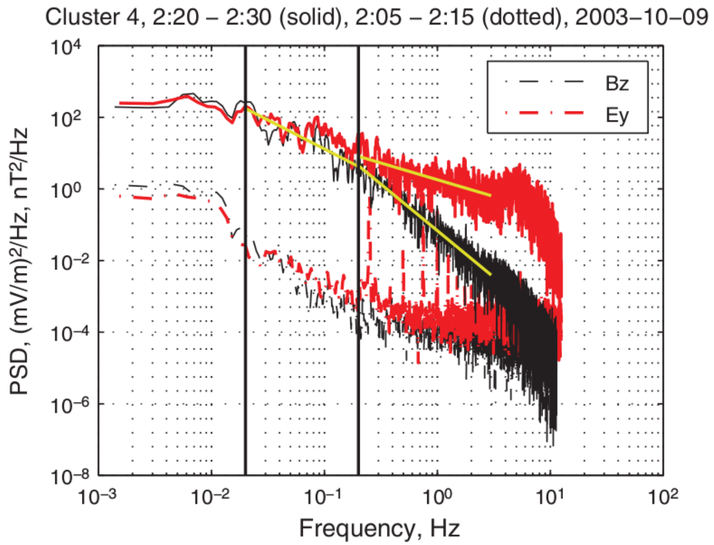
Observation of electron scale reconnection in turbulence by MMS. Phan et al. 2019

Introduction: turbulence in magnetic reconnection

Magnetotail reconnection



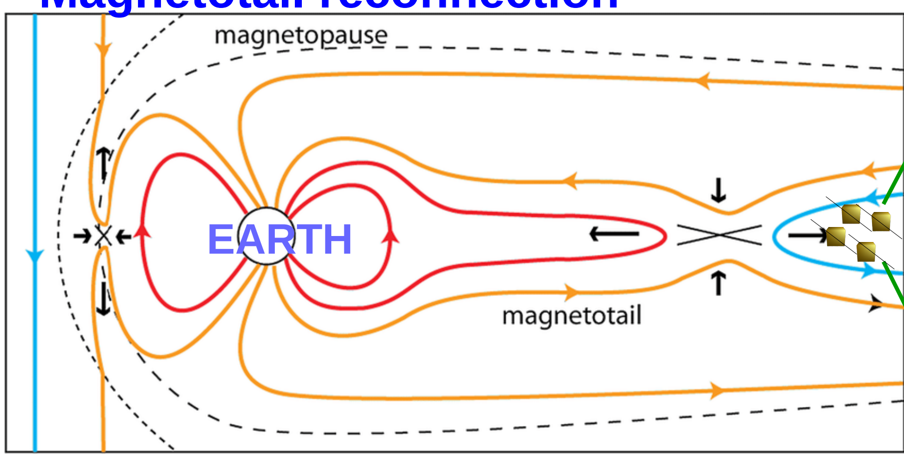
Observations by Cluster



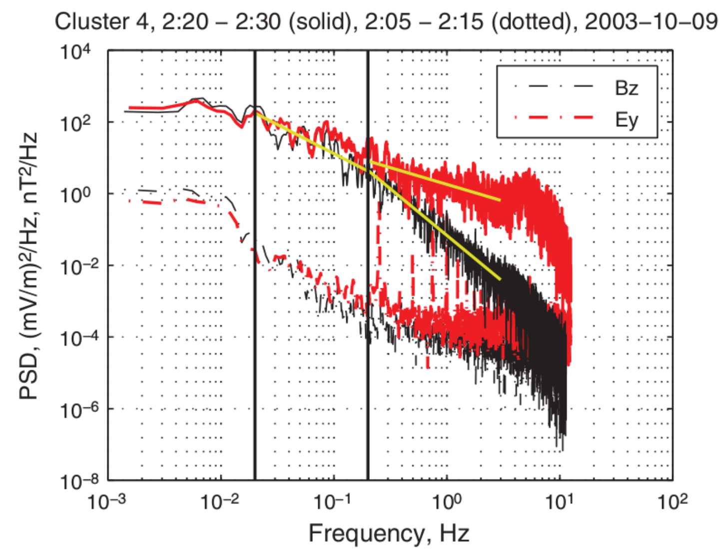
Electric and magnetic spectra of turbulence produced in reconnection outflows (Eastwood et al. 2009).

Introduction: turbulence in magnetic reconnection

Magnetotail reconnection



Observations by Cluster

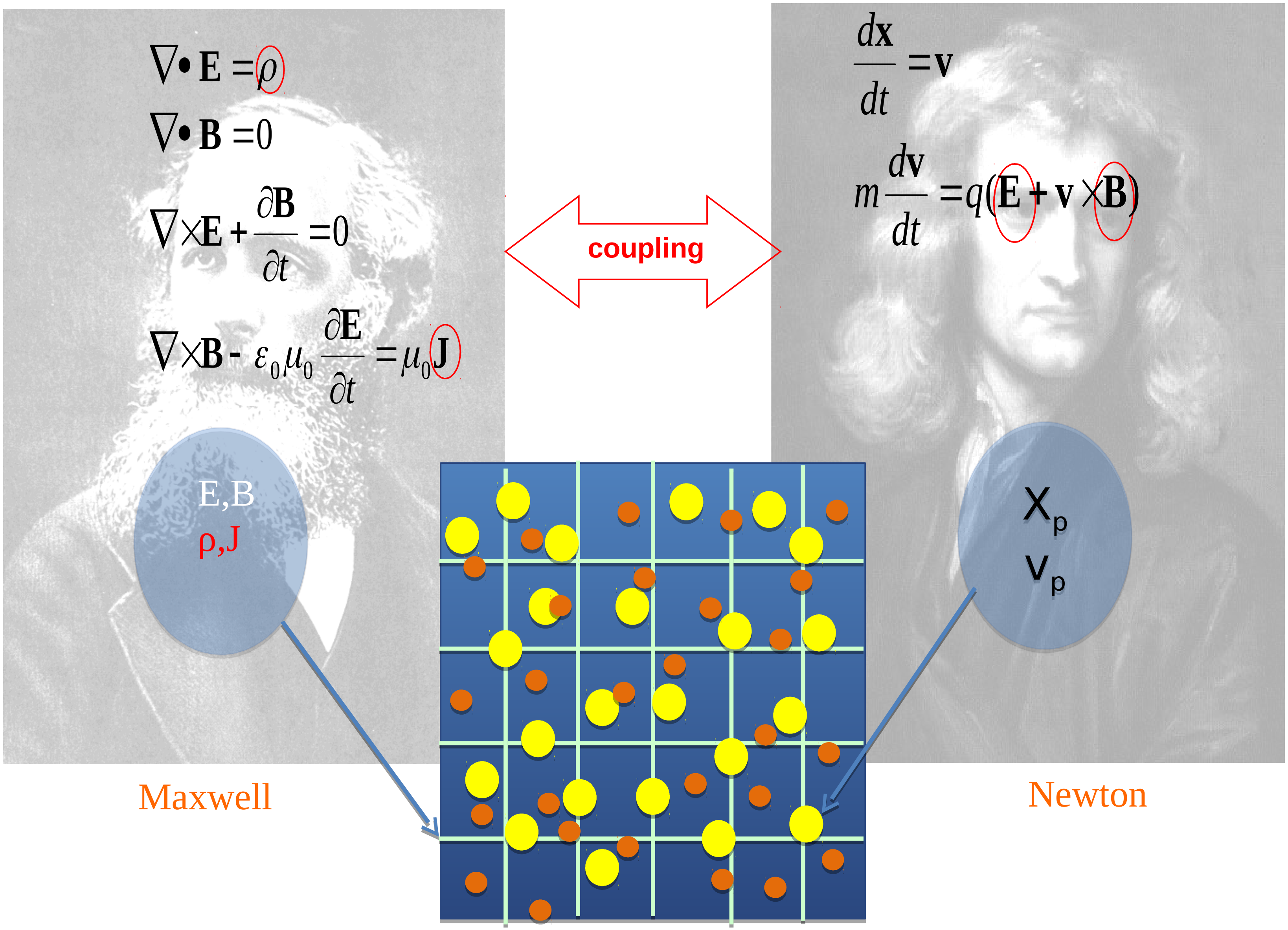


Electric and magnetic spectra of turbulence produced in reconnection outflows (Eastwood et al. 2009).

- Is it possible to recover the observed properties of turbulence produced by reconnection with numerical solution of the Vlasov equations?
- What can we learn from simulations and their comparison with observations?

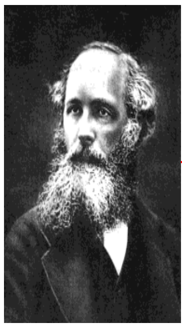
The semi implicit particle in cell method for the solution of the Vlasov-Maxwell system of equations

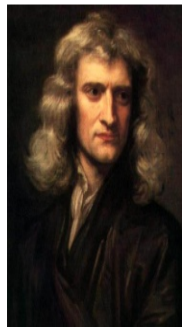
Kinetic Particle in Cell



Explicit computational approach

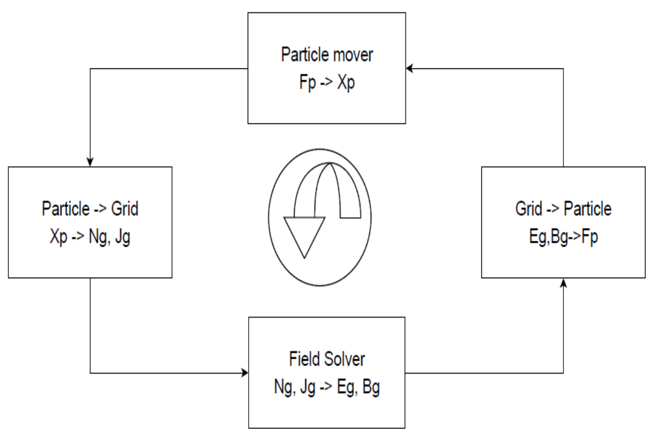
T=0 | T=Δt | T=2Δt





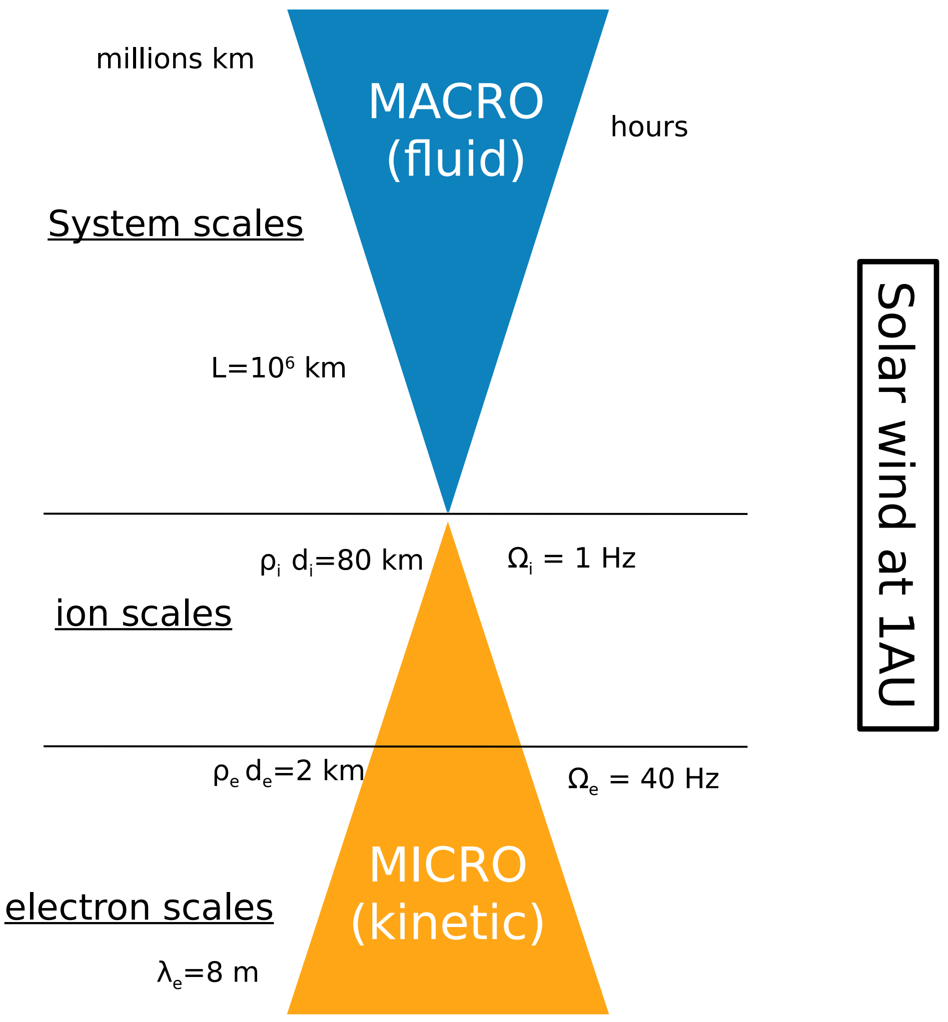
Operations:

- Solve Newton equations in previous electromagnetic fields
- Solve Maxwell equations with previous particle positions



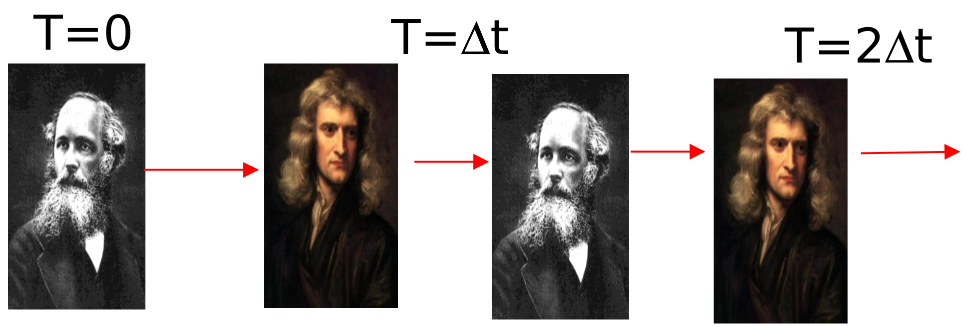
Limits of the explicit method

- Explicit mover : $\omega_{pe} \Delta t < 2$
- Explicit Particle- Grid coupling: $\Delta x < 3 \lambda_{De}$
- Explicit Maxwell solver: $c \Delta t < \Delta x$



Explicit and implicit Computational approaches

EXPLICIT



Operations:

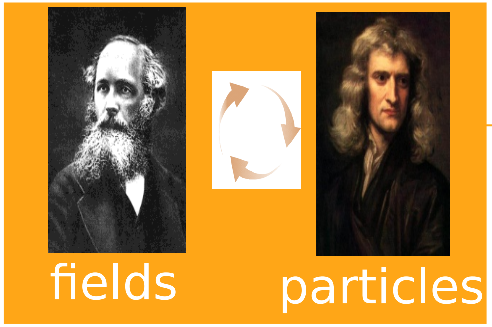
- Solve Newton equations in previous electromagnetic fields
- Solve Maxwell equations with previous particle positions

IMPLICIT

Over each time step, iteratively solve the two coupled equations until convergence

Can we avoid the non-linear iteration? Semi-implicit methods

T=0



T=Δt

IMPLICIT

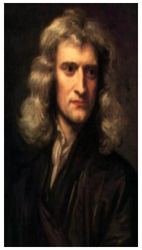
Non-linear Newton- Krylov iteration

Chapman-Enskog linearization of the plasma response:
Moment implicit: Taylor series expansion in Celeste and iPic3D

Langdon et al, 1983; Brackbill, Forslund, 1985; Lapenta, Ricci, Brackbill, 2005

T=0

T=Δt



particles

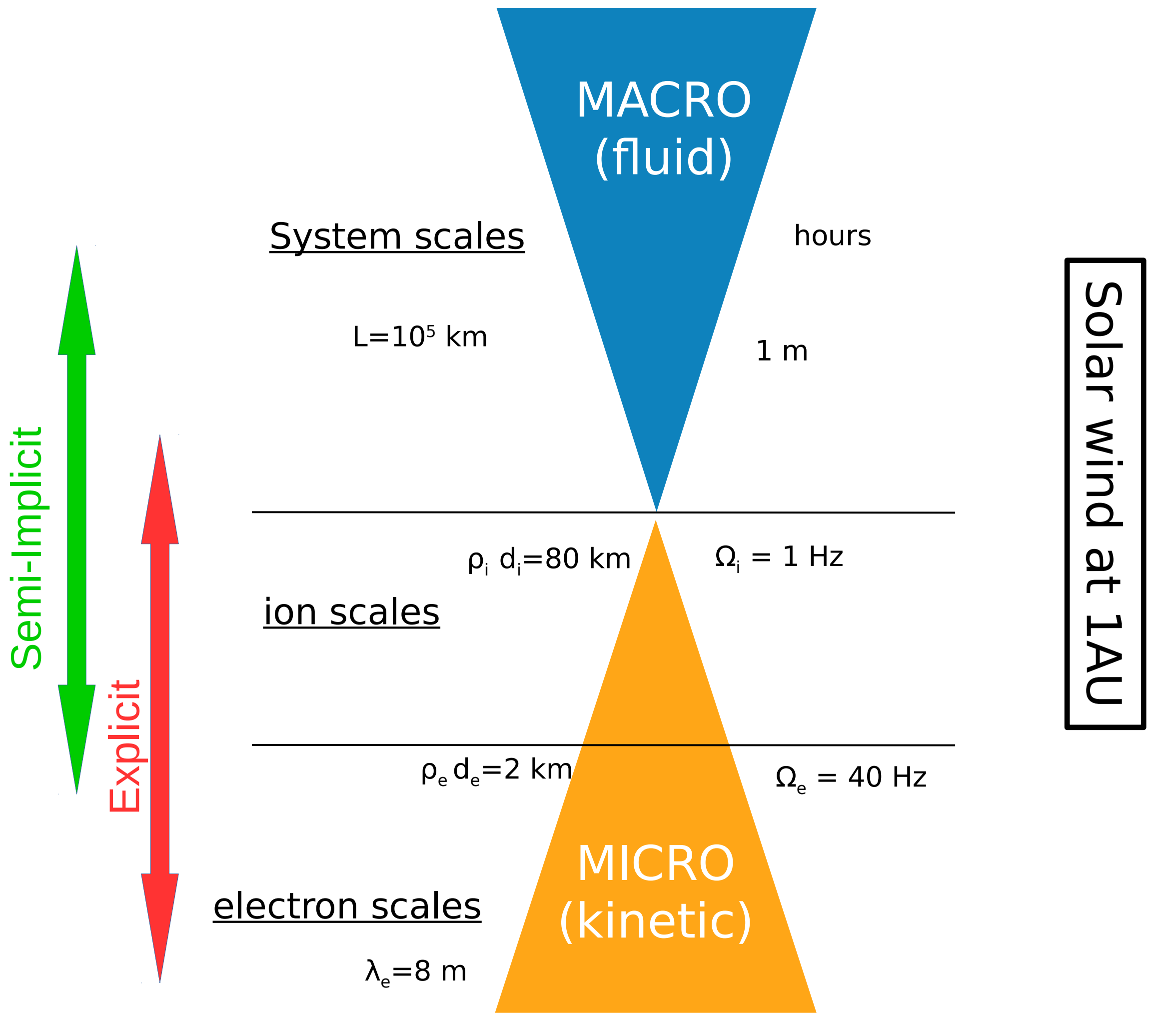
IMPLICIT MOMENT

iPic3D

$v_{th,e}\,\Delta t < \Delta x$

Linear GMRES Solver

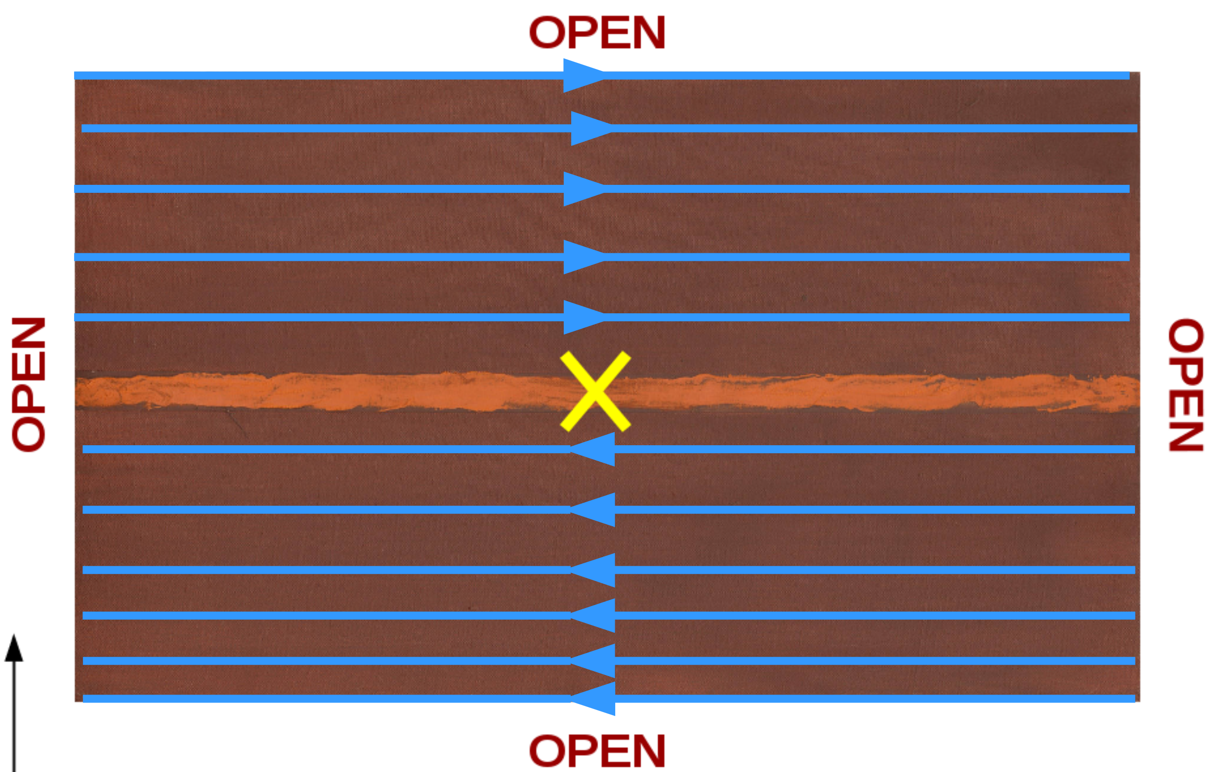
The challenge in modelling space plasmas: multiple scales

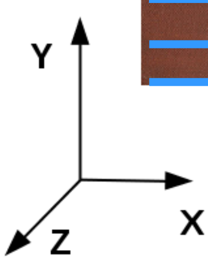


- Intermediate scales are resolved
- Electron kinetic effects are retained (contrary to hydrib)

First study: turbulence in non mutually interacting reconnection outflows

Simulation set up





Adapted from Newman, Onement I, 1948, MoMA, New York

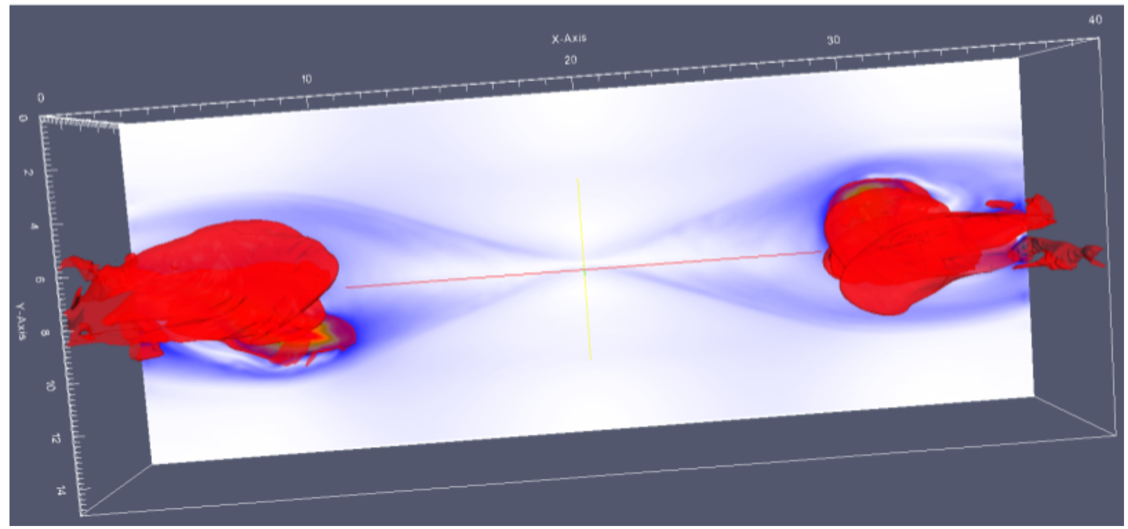
- $B_{0z} = B_{0x}/10$
- $40 \times 15 \times 10\ d_i^3$
- $m_i/m_e = 1836$
- $\Delta x = d_i/18 \sim 2\ d_e$
- $\Delta t \sim 2\pi/4\ \Omega^{-1}_{ce}$
- $T_i/T_e = 5$
- $\beta_i = 0.8$, $\beta_e = 0.2$
- $c_A/c = 0.01$, $\omega_{pe}/\Omega_{ce} = 2.4$
- 125 ppc
- Open in x-y, periodic in z

- The Vlasov-Maxwell system of equations is solved with a semi-implicit particle in cell method (iPic3D code).
- Ions and electrons distribution functions are represented by macro-particles.

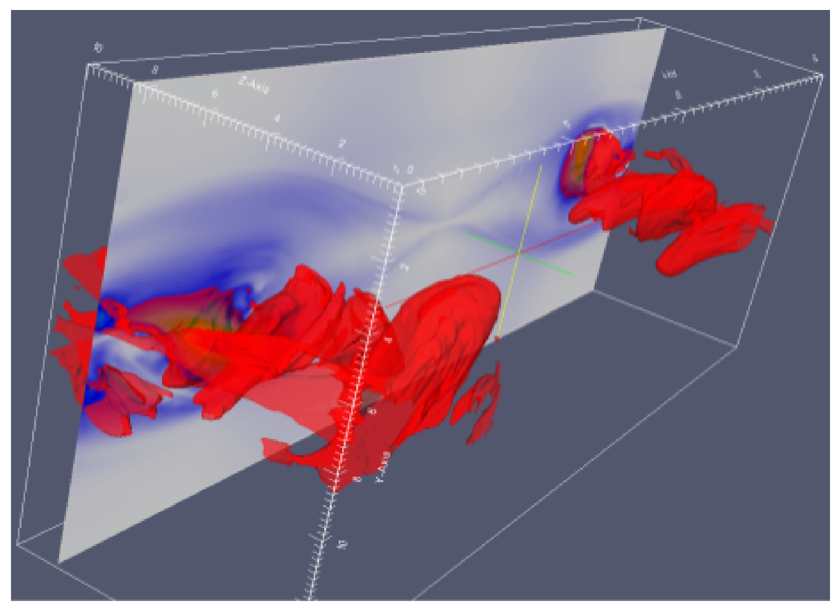
Magnetic fluctuation energy

We extract the magnetic field fluctuations, subtracting average fields:

$$b_x = B_x - B_{x0}(y)$$
$$b_y = B_y - B_{y0} = B_y$$
$$b_z = B_z - B_{z0}$$



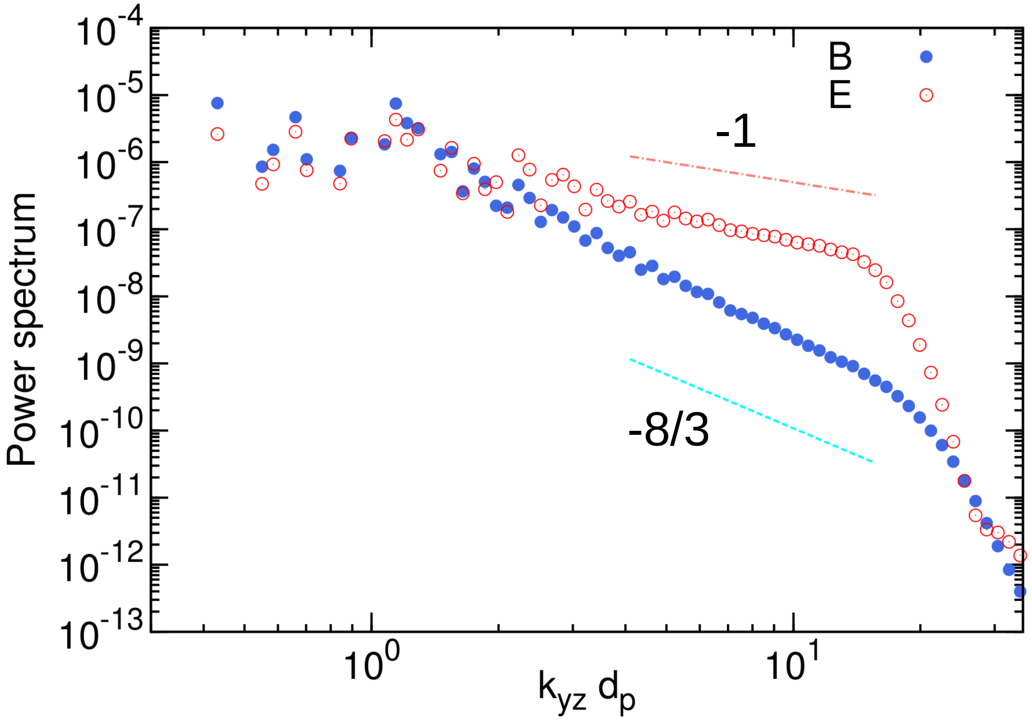
$$E_b(x, y, z) = |\boldsymbol{b}|^2$$



How the spectra of these fluctuations looks like?

Magnetic and electric spectra produced by reconnection

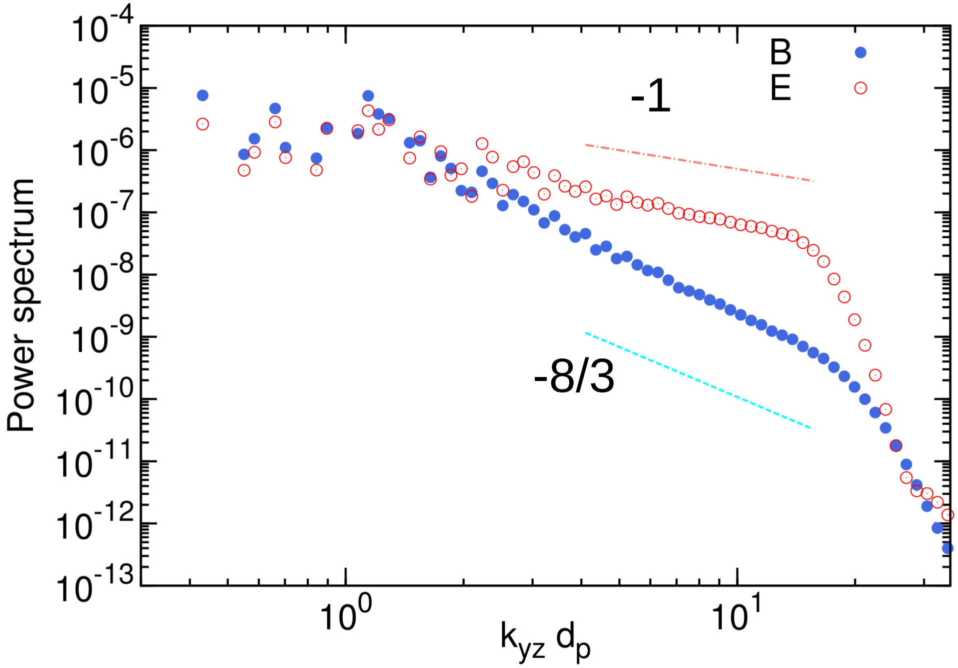
- The spectra are using fourier transform in the plane perpendicular to the outflow.
- Periodicity is obtained by eliminating the large scale Harris-background and using windowing tecnique.
- The full box is considered (both outflows).



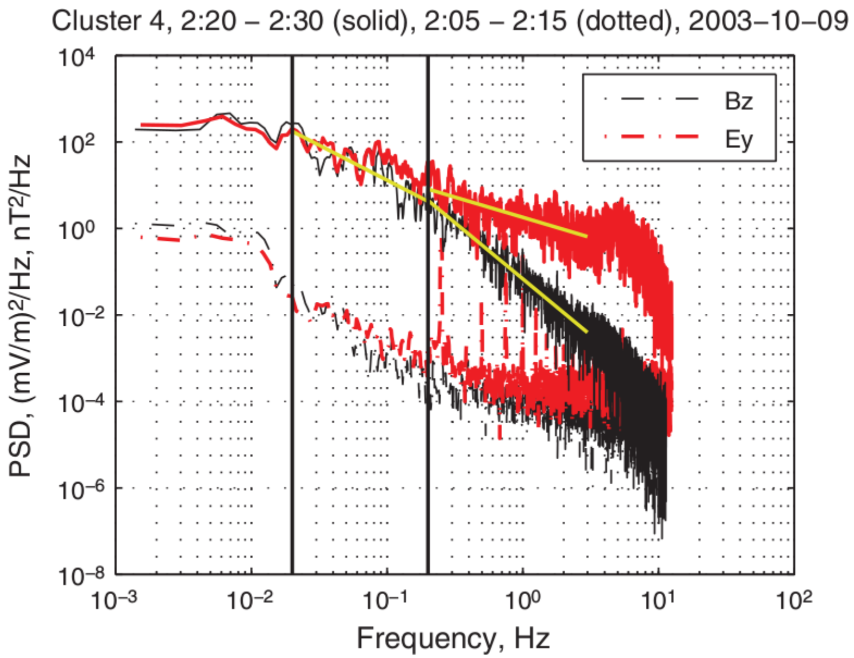
Magnetic and electric spectra in reconnection outflows (Pucci et al. 2017).

Magnetic and electric spectra produced by reconnection

NUMERICAL SIMULATIONS



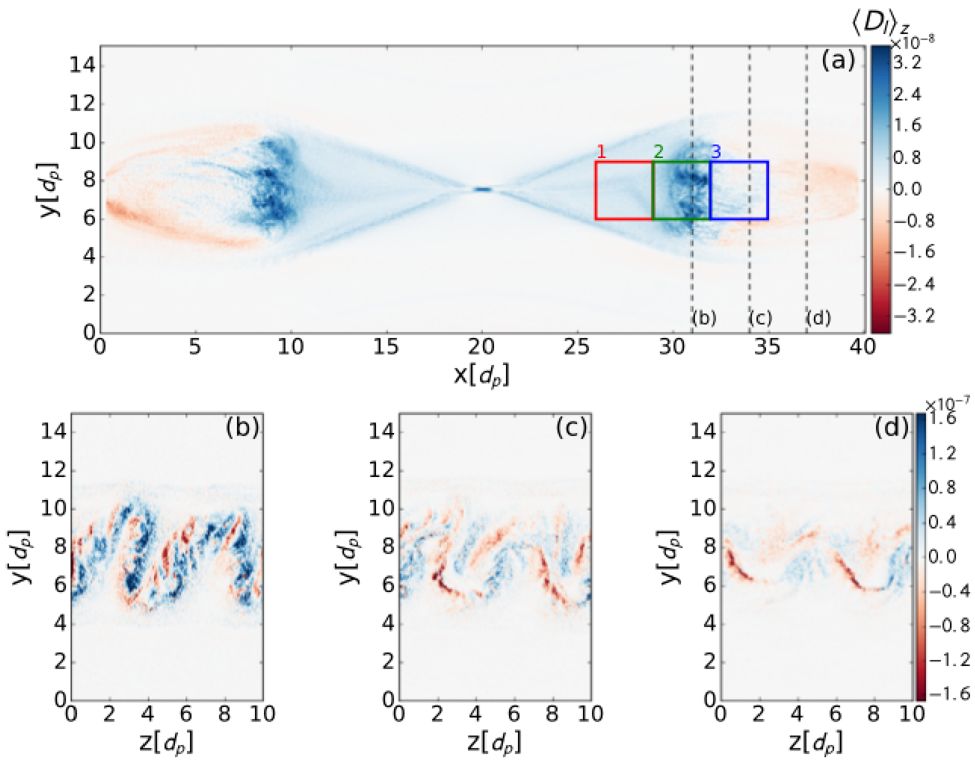
OBSERVATIONS



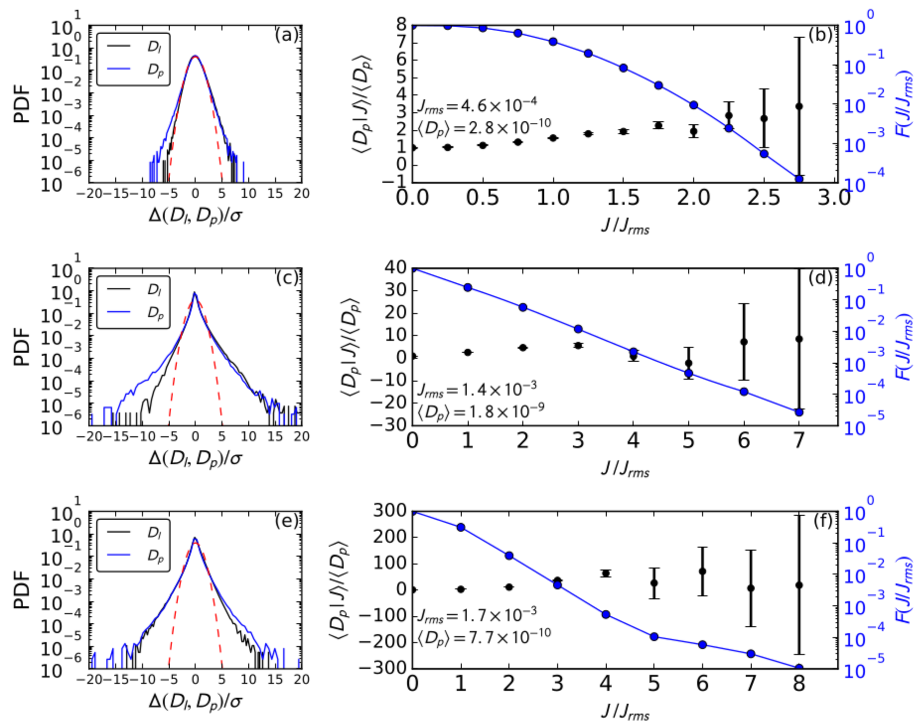
Spatial magnetic and electric spectra at sub-proton scales in simulations are comparable with frequency spectra from observations

Energy exchange between fields and particles

$$D_l = \mathbf{J} \cdot \mathbf{E}$$



$$D_p = \mathbf{J} \cdot (\mathbf{E} + \mathbf{v}_p \times \mathbf{B})$$

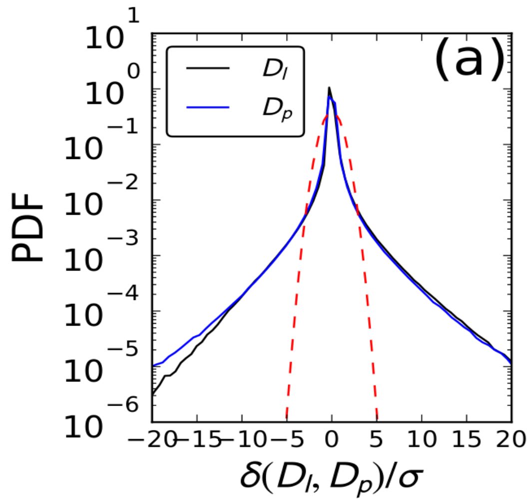


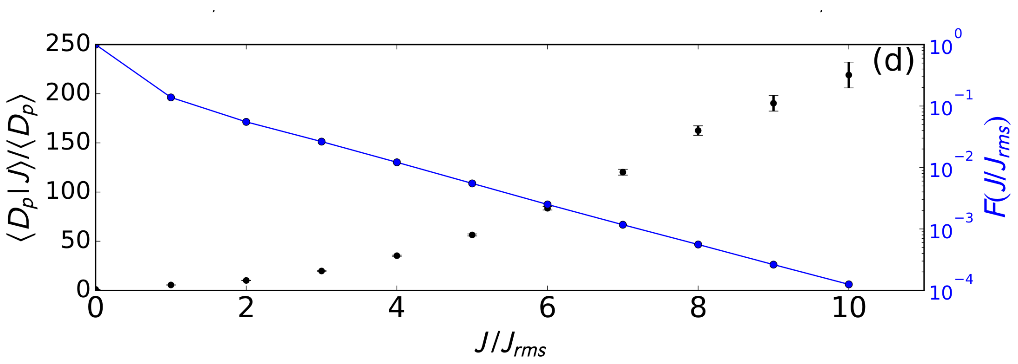
Highest values of the dissipation proxy D_l are found at the interface between the outflows and the ambient plasma

The properties of turbulence vary with the distance. The level of intermittency increase moving away from the X-line.

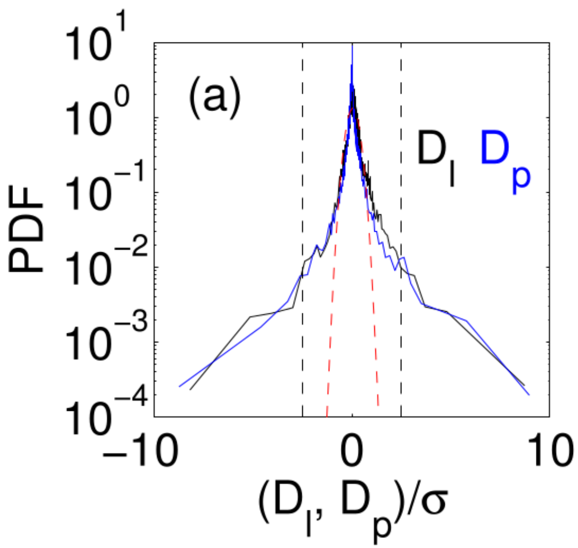
Energy exchange: comparison with observations

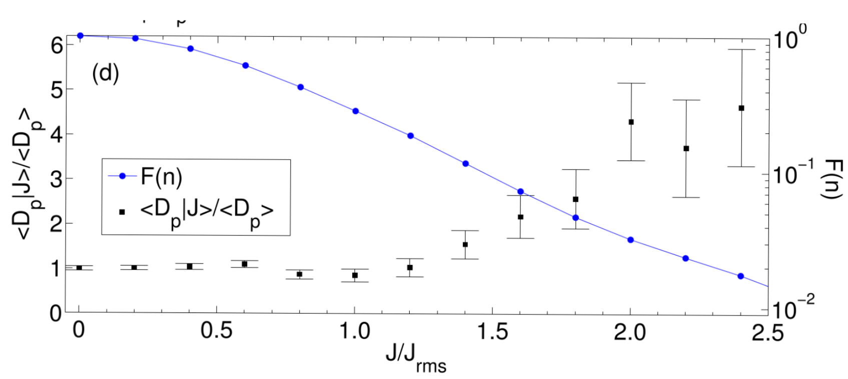
NUMERICAL SIMULATIONS





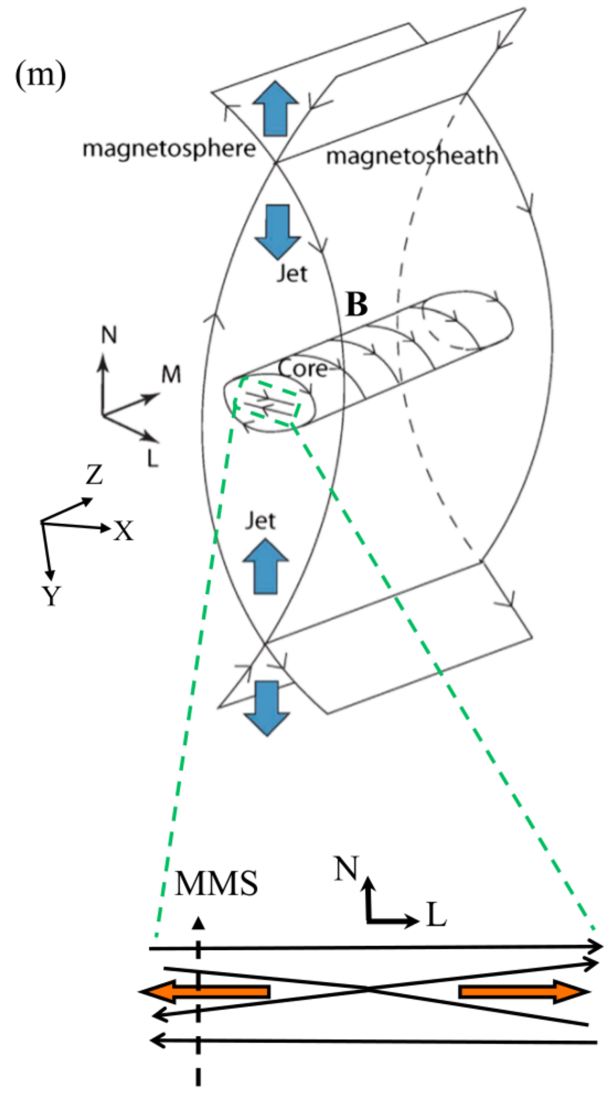
OBSERVATIONS





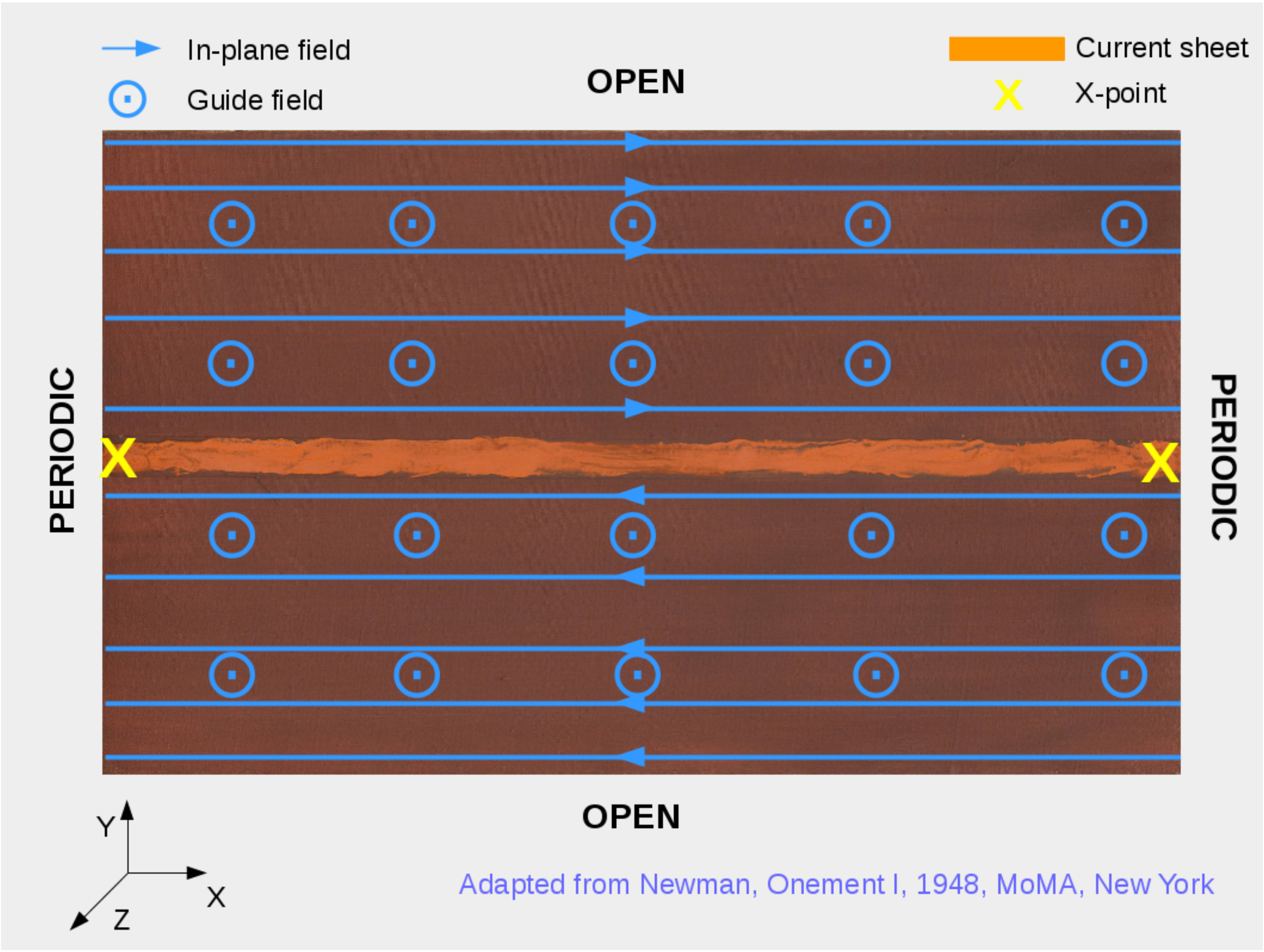
Second study: turbulence produced by the collision of reconnection jets

Observation of collision of reconnection jets



First MMS observation of secondary reconnection in reconnection jets collision (Oieroset et al. 2016).
Other observations of jets collision, e. g. (Alexandrova et al. 2016).

Numerical set up

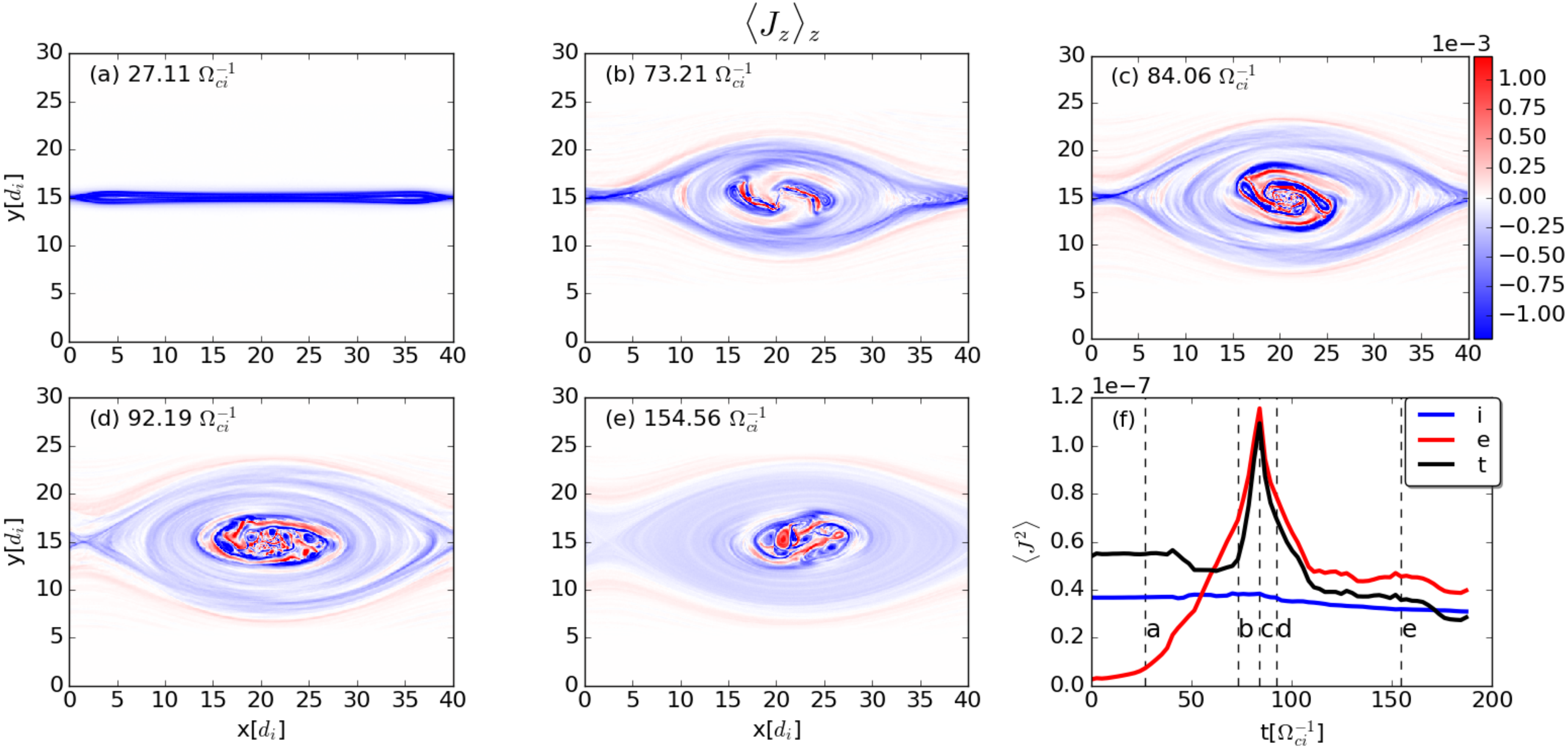


$$\mathbf{B} = B_{0x}\tanh(y/\delta)\mathbf{e_x} + B_{0z}\mathbf{e_z}$$

$$n = n_b + \frac{n_0}{\cosh^2(y/\delta)}$$

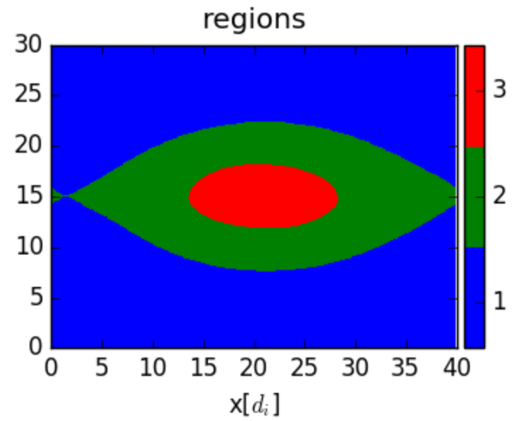
- $B_{0z} = B_{0x}/10$
- $40 \times 30 \times 10\ d_i^3$
- $m_i/m_e = 256$
- $\Delta x = d_i/13 \sim 1.25\ d_e$
- $\Delta t \sim 2\pi/10\ \Omega^{-1}_{ce}$
- $T_i/T_e = 5$
- $\beta_i = 0.2$, $\beta_e = 0.04$
- $c_A/c = 0.02$, $\omega_{pe}/\Omega_{ce} = 2.9$
- 125 ppc
- Open in y, periodic in x-z

Dynamical evolution of jets collision

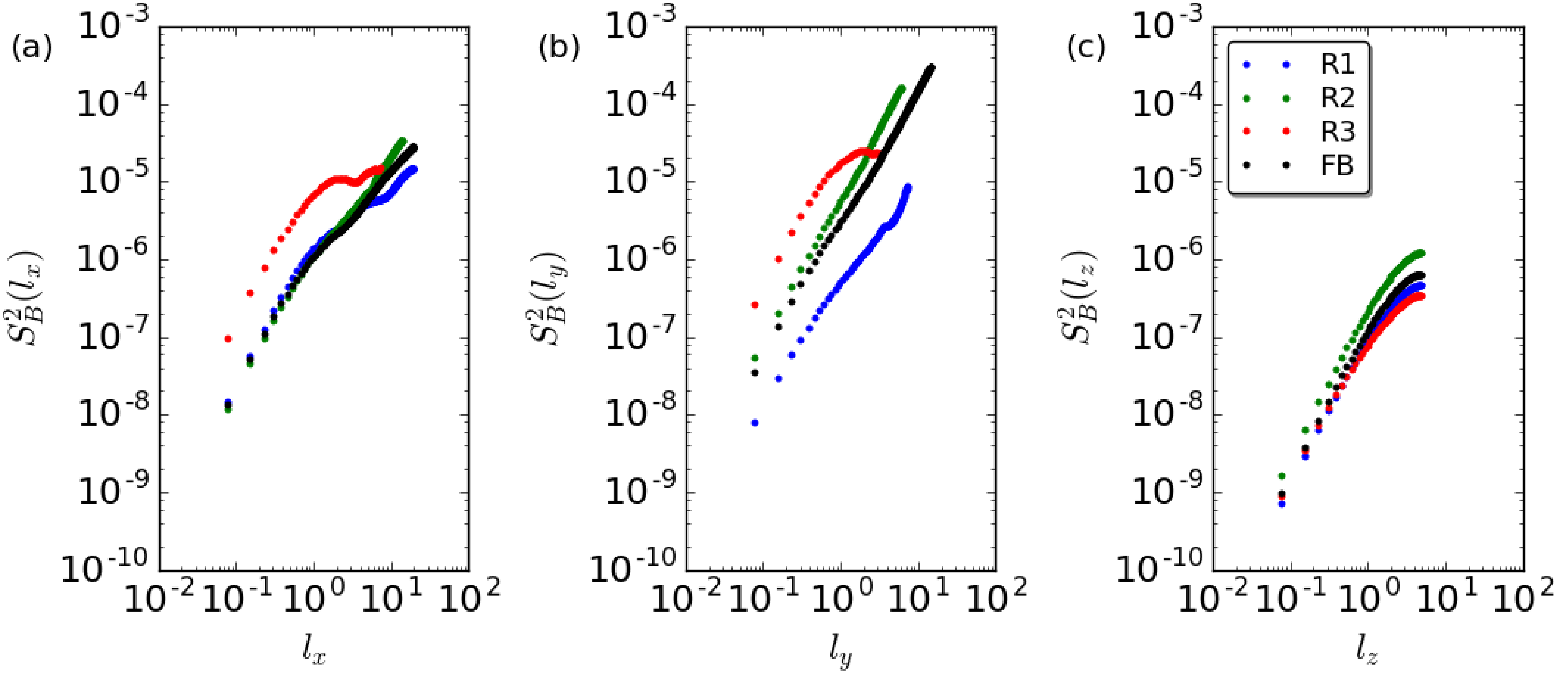


The peak of current intensity is reached when jets collides. After the collision several current sheets at different scales forms in the central region given rise to a turbulent phenomenology.

Magnetic 2nd order structure functions in regions

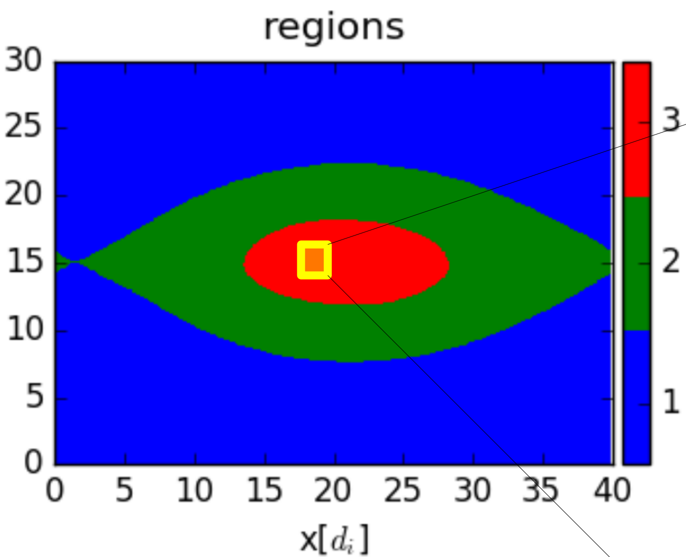


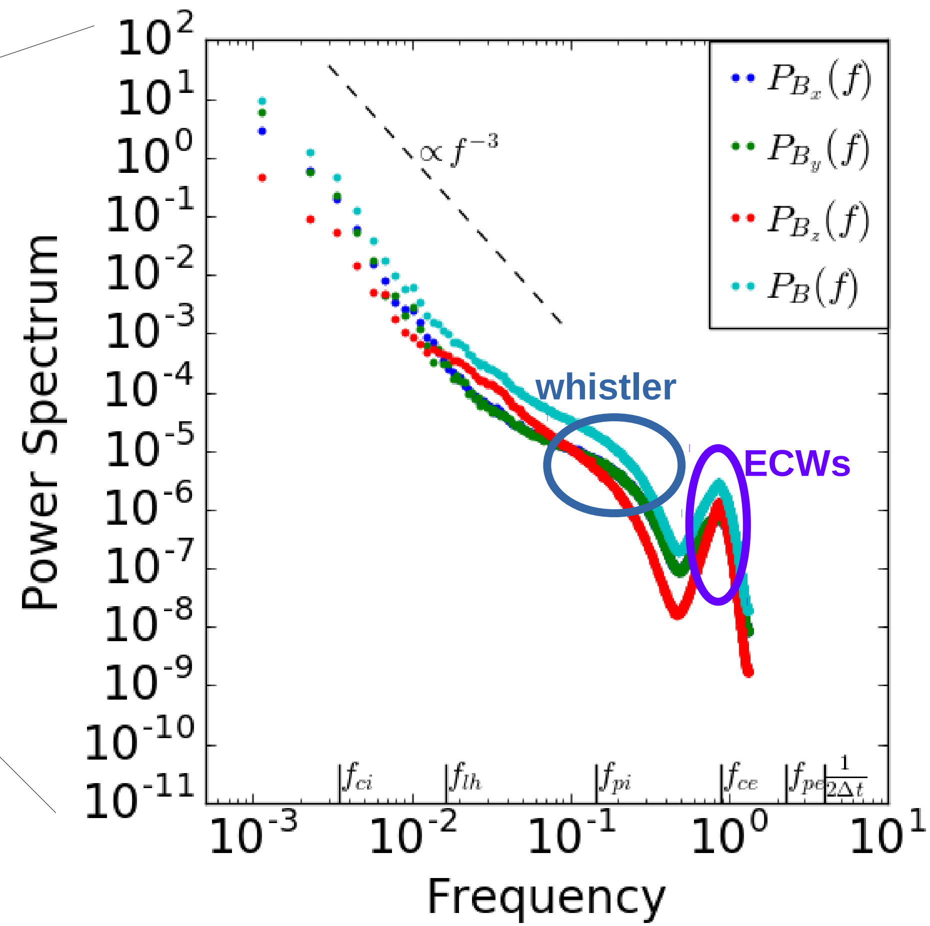
$$S_B^2(\ell_i) = \frac{1}{V}\int |\mathbf{B}(\mathbf{x}+\ell_i\hat{\mathbf{e}}_i) - \mathbf{B}(\mathbf{x})|^2 d^3x$$



In the central region (red) the magnetic fluctuations with in-plane wavevector are stronger at small scales.

Eulerian frequency spectra from virtual satellites



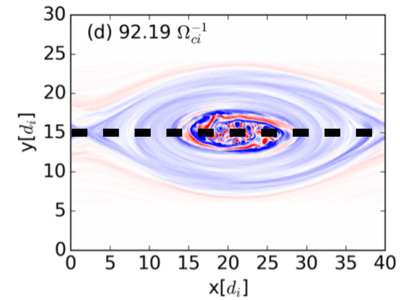


We use virtual probes to compute the Eulerian frequency spectra

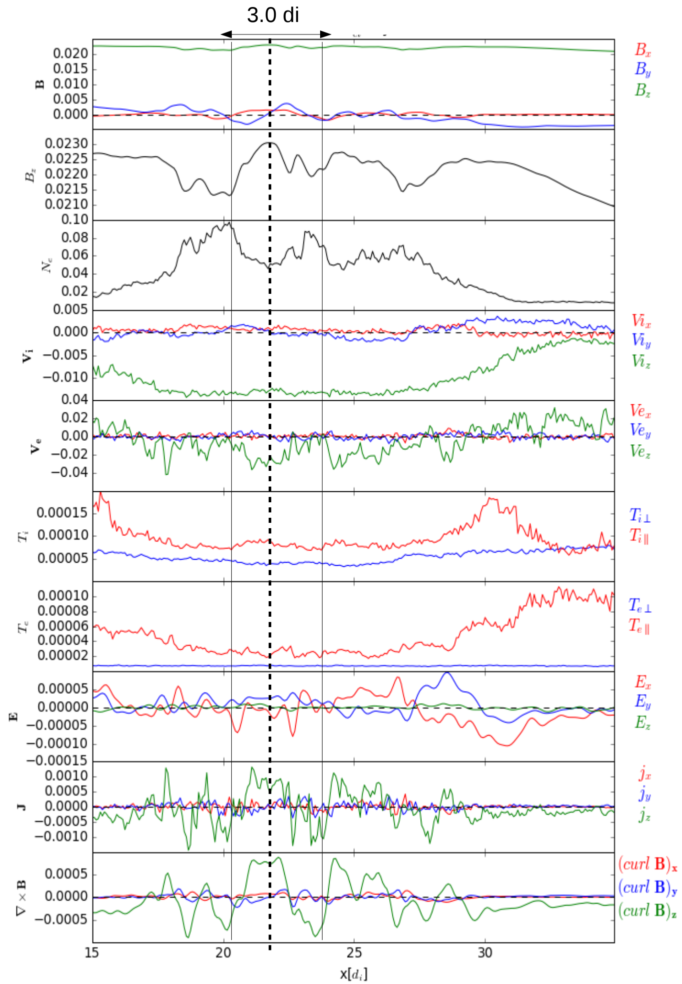
The frequency spectra shows:

- A bump of energy between ion and electron cyclotron frequency due to whistler (Alexandrova et al. 2016)
- A peak at the electron cyclotron frequency (ECWs)

Comparison of simulation with observations

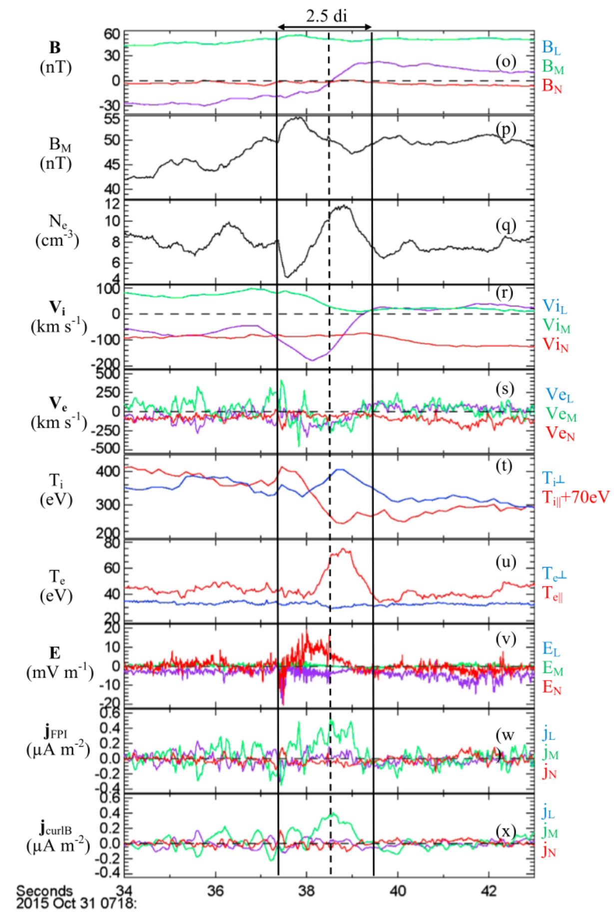


simulation



Virtual satellite trace of turbulence in reconneciton jets (Pucci et al 2018).

observations



MMS observation of reconnection jets collision (Oieroset et al 2016).

Conclusions

- Previous numerical and observational works have shown that turbulence and reconnection are two interlinked phenomena in space plasmas.
- These two phenomena involve a broad range of scale. An exaustive study of them in non collisional plasmas involve the solution of the Vlasov-Maxwell system of equations across the scales of interest.
- The semi-implicit particle in cell method allows to resolve a range of scale going from fluid to kinetic at a convient computational cost. The method retains the kinetic effects for both ions and electrons.
- The numerical results of simulations of magnetic reconnection conducted with the semi-implicit moment method show that reconnection is able to produce turbulence, also starting with different boundary conditions.
- The numerical results are in accordance with the observations and help to figure out the spatial picture of the reconnection event observed by the spacecraft.