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# Interpreting and predicting spacecraft observations of plasma turbulence with high-resolution hybrid simulations


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*in collaboration with*

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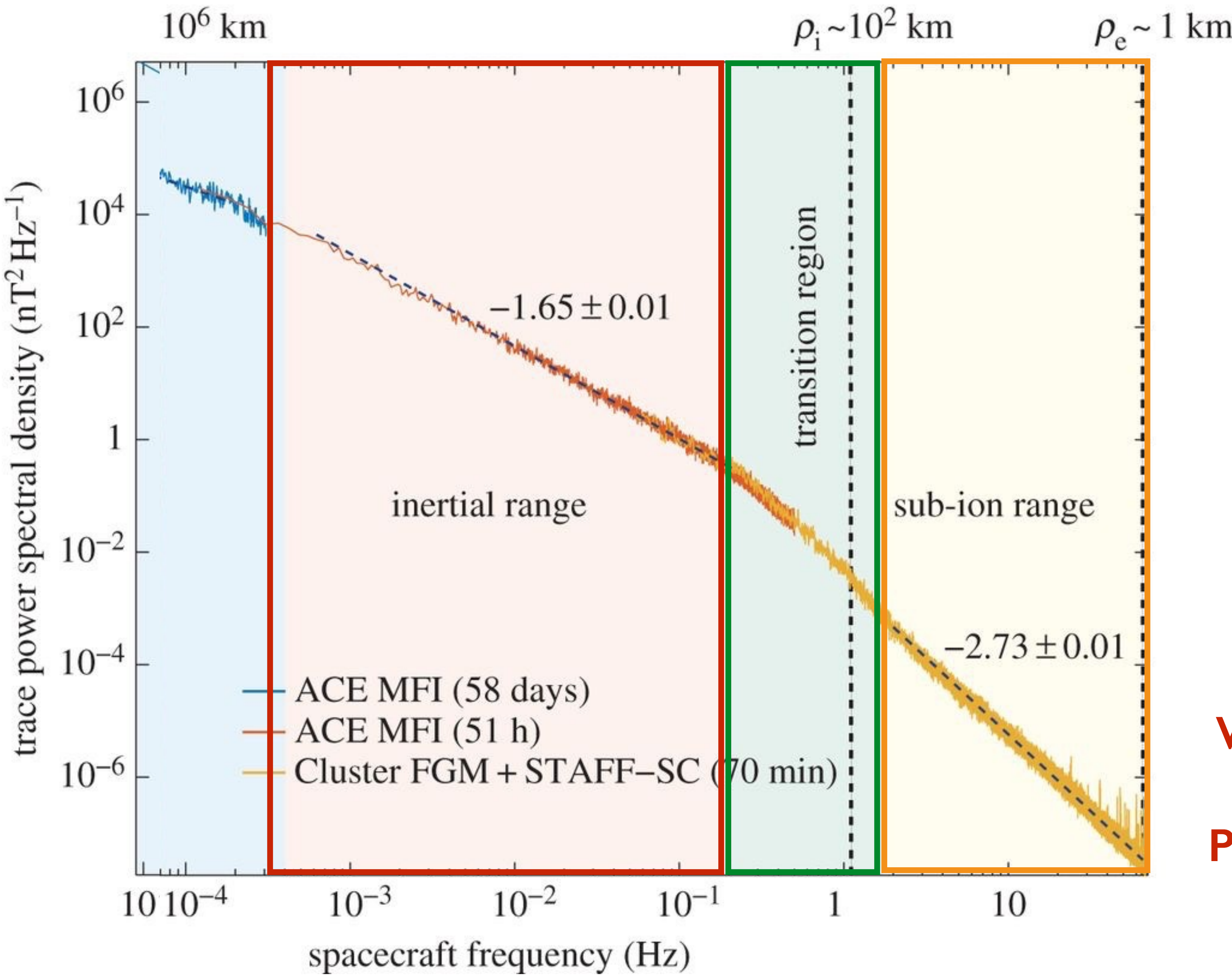
# Observations in the solar wind

In situ measurements of the solar wind plasma and electromagnetic fields show **spectra with a power-law scaling spanning several decades in frequency**




- **In the MHD inertial range:** dominated by $k_\perp$ fluctuations, Kolmogorov power law ~ $k^{5/3}$

- **Transition region:** more or less sharp spectral break around ion-scales **?**

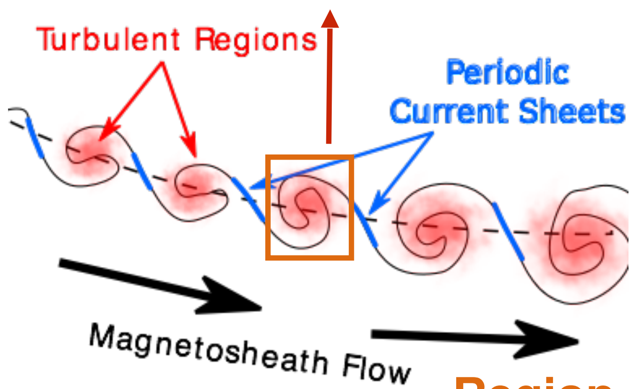
- **At sub-ion scales:** small-scale inertial range, spectrum ~ $k^{-2.8}$ **?**

**What is going on close to ion and sub-ion scales?**
**Physical mechanism(s) responsible for the steepening?**

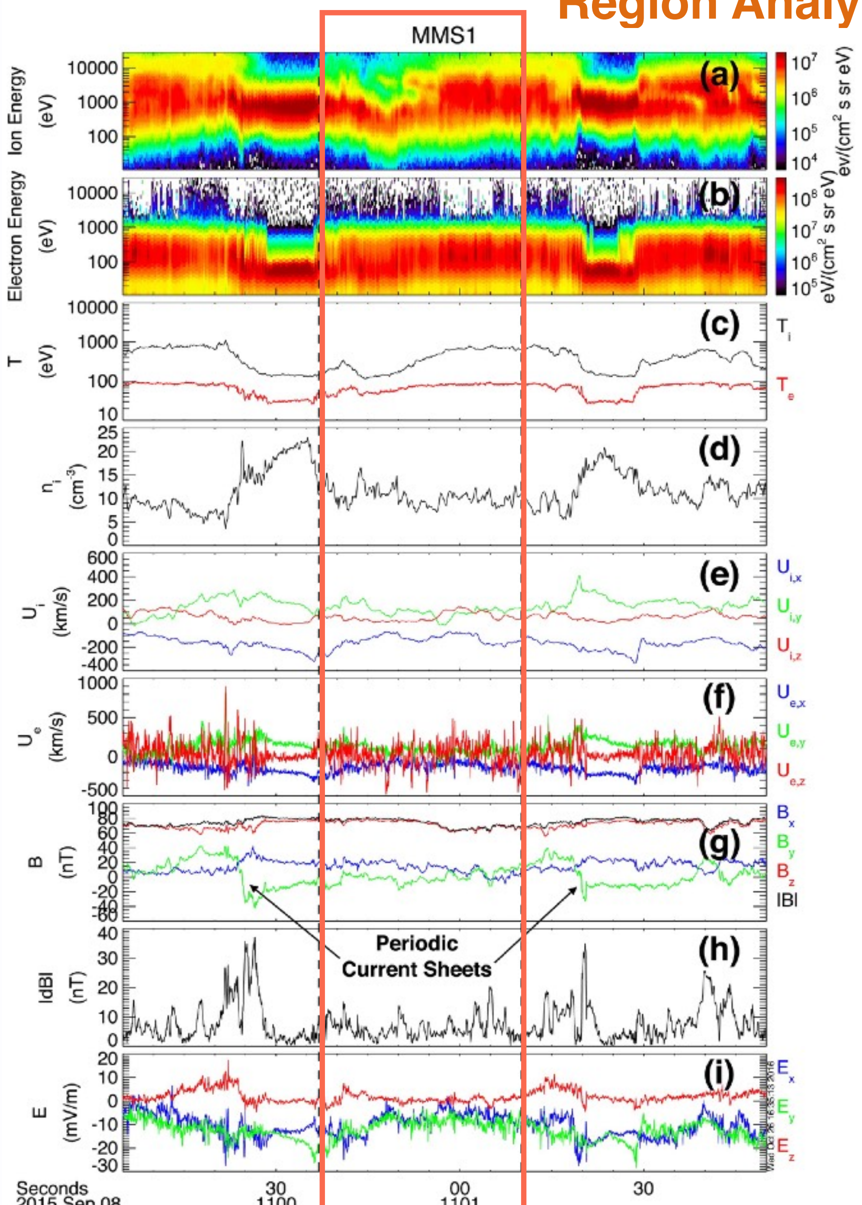
Power-laws support an **interpretation in term of turbulent fluctuations**, although the rich variety of spectral features is not easily explained in the framework of known turbulent theories

# MMS observations in the magnetosphere

Region Analysed

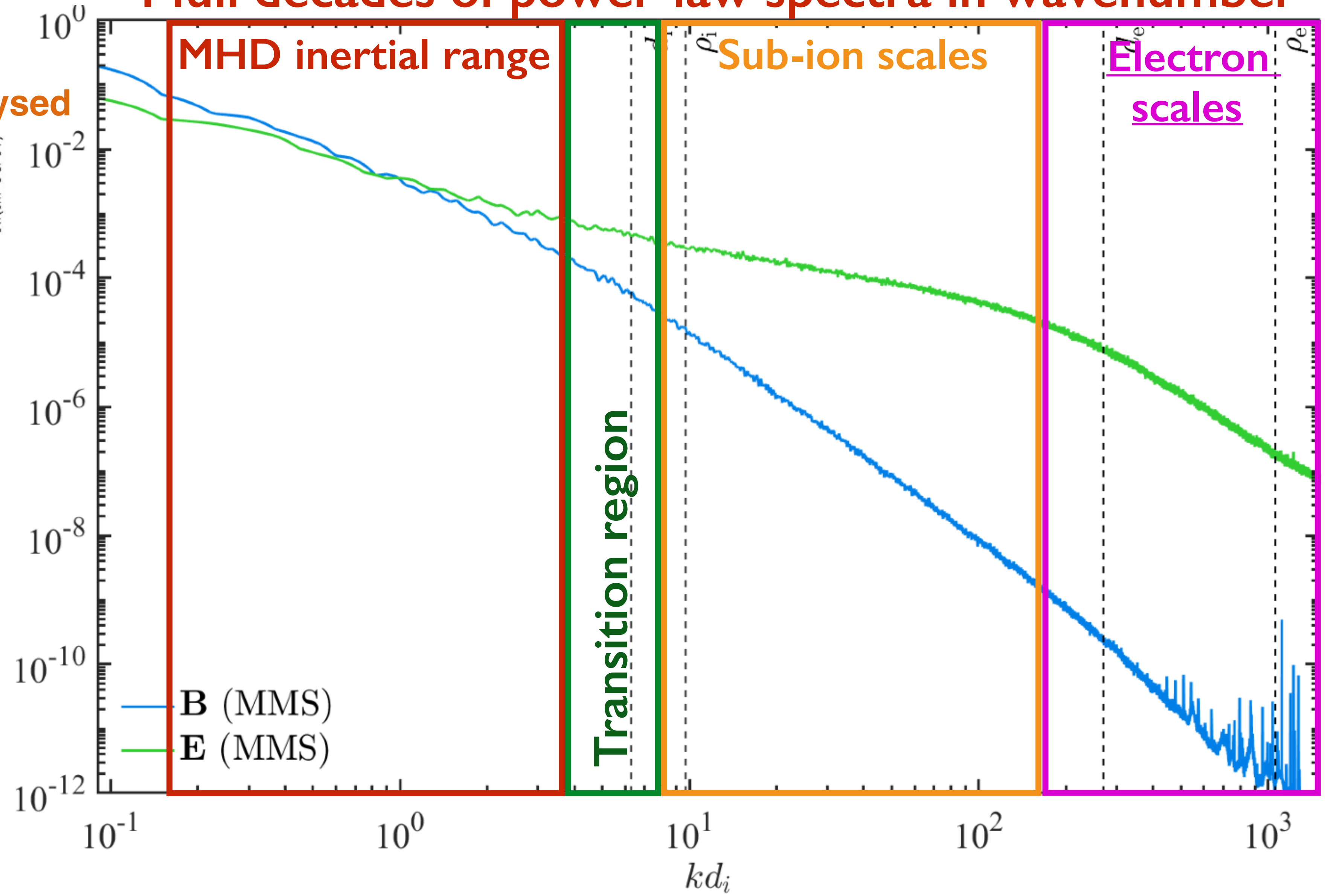



Region Analysed




Plasma turbulence generated by a **Kelvin-Helmholtz** (KH) instability event **on 8 September 2015**
Observations by the MMS spacecraft in the magnetopause
***(Stawarz et al. JGR 2016)***

**4 full decades of power-law spectra in wavenumber**




**At electron scales:**
both the magnetic and the electric field spectrum further steepen?

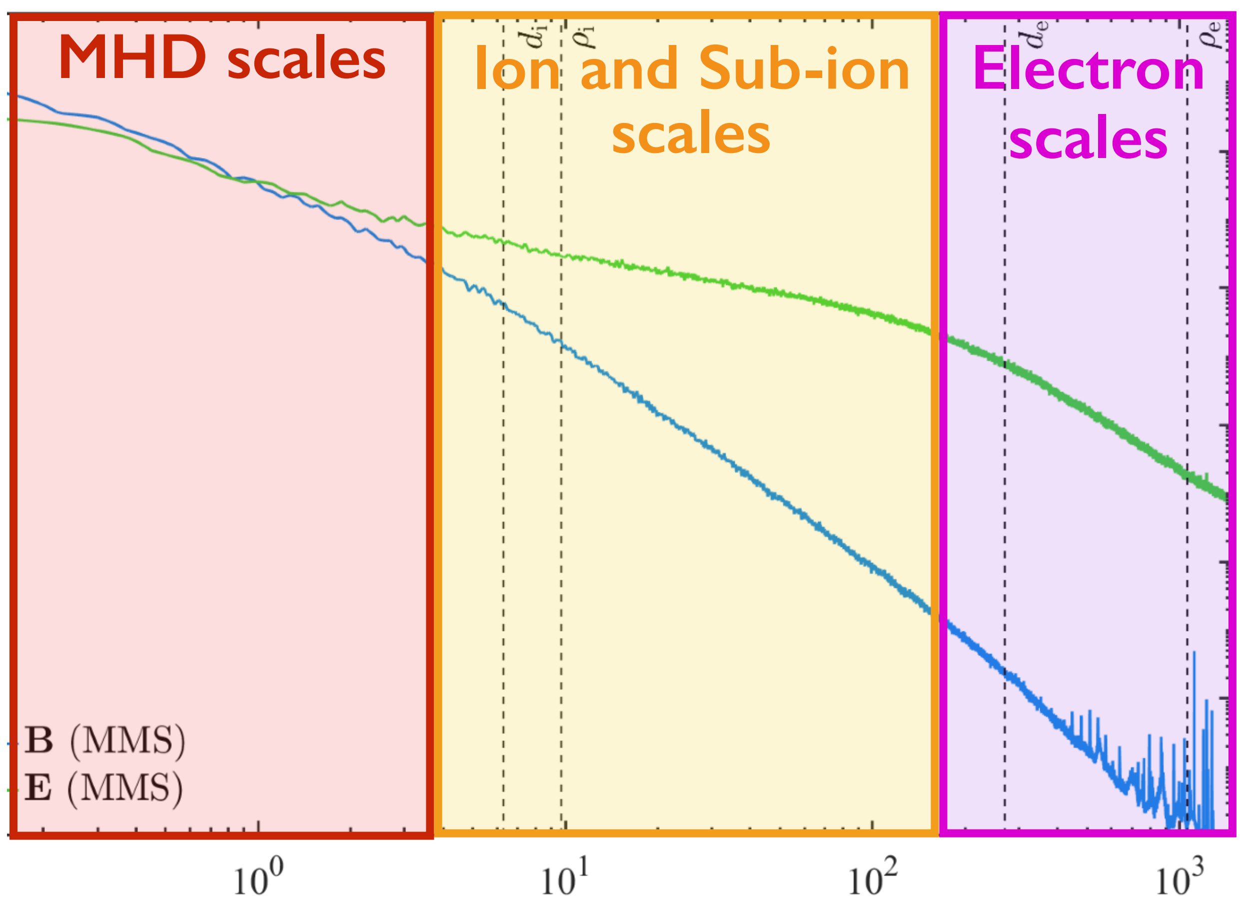
# Theoretical modelling with simulations

Comparing observations with theoretical models through **numerical simulations** is fundamental to:

- **interpret observational data** and understand physical processes at work
- **provide predictions** on important physical parameters for future space missions

The dissipation of turbulent fluctuations operates at scales where particle kinetics dominates

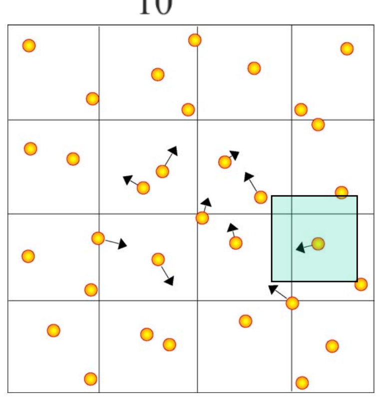
**We need to go beyond a magnetohydrodynamics (MHD) model to account for kinetic effects**




A full kinetic model is extremely computationally expansive and/or not always accurate (e.g., small resolution, small number of particles)

| both ions and electrons treated as a fluid | fluid electrons, kinetic ions | both ions and electrons treated as particles |
| --- | --- | --- |
| **MHD MODEL** | **HYBRID MODEL** | **FULL PIC MODEL** |

→ **richness of physical processes**
**computational requirements**

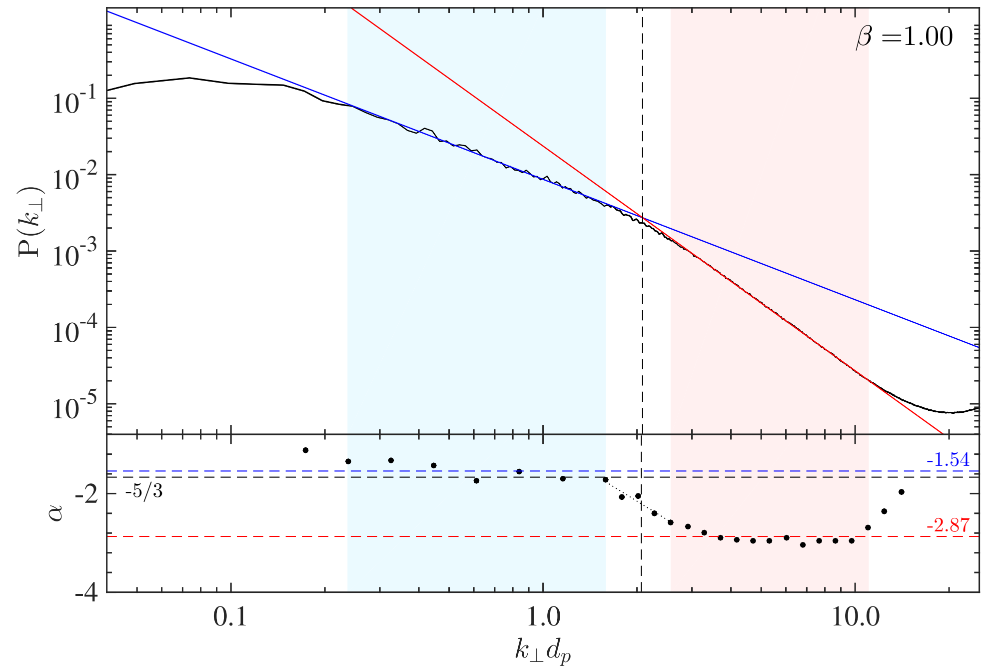


## PARTICLE-IN-CELL (PIC)

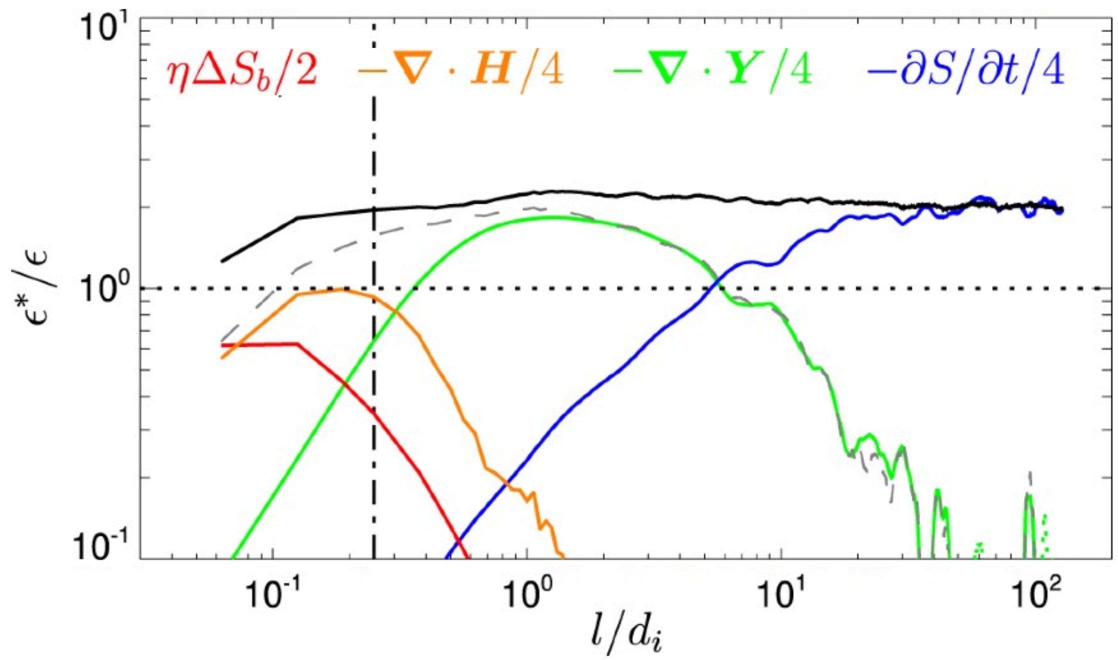
- "finite-size" particles are advanced by a Boris' scheme and individual trajectories are tracked in continuous phase space
- moments are collected and interpolated in each grid cell

# Results from 2D hybrid simulations

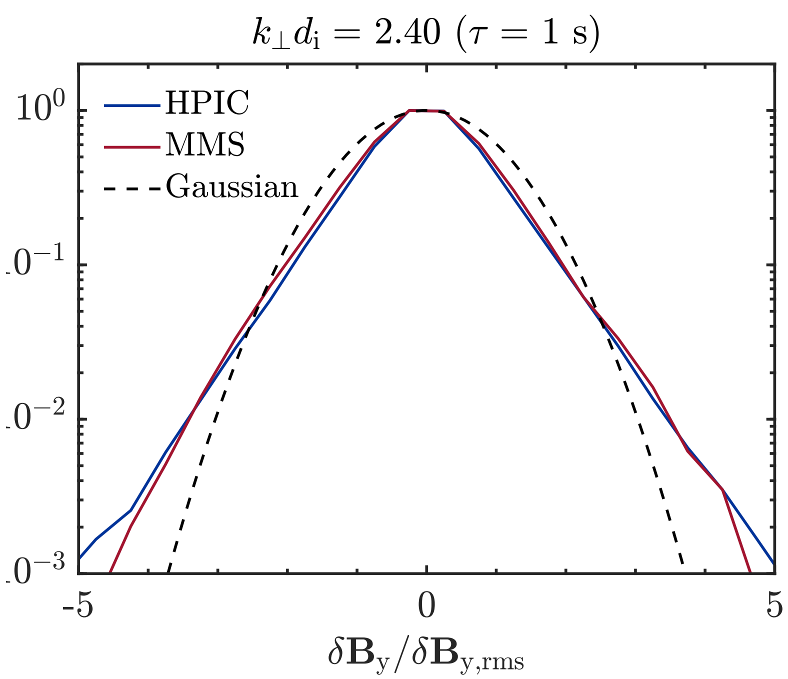
## Power spectra of fluctuations (e.g., level, slopes)



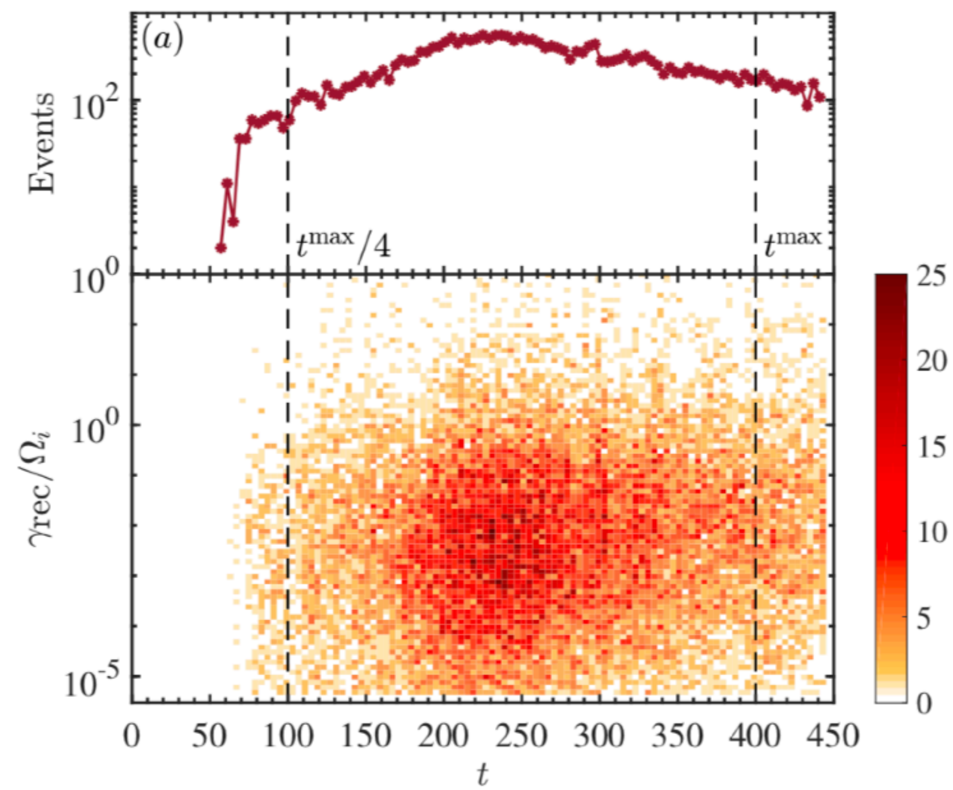

## Turbulent cascade rate




## Intermittency (e.g., PDFs of fluctuations, kurtosis)




## Magnetic reconnection (e.g., nº of events, rate)




**+ time evolution, particle heating, temperature anisotropy, spectral anisotropy, wave polarization…**

# 2D numerical setup and initial conditions

Units

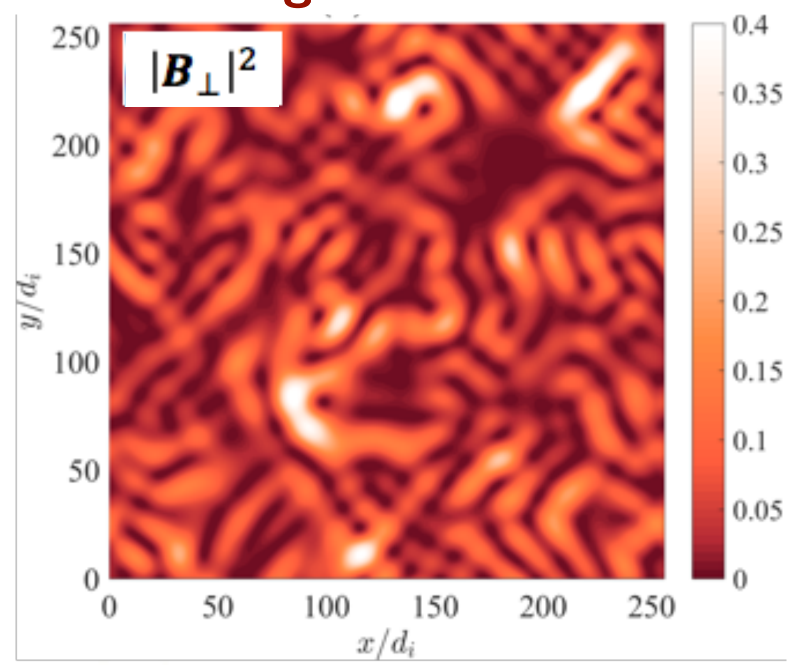
time: $\Omega_i^{-1}$ *inverse ion gyrofrequency*

space: $d_i = v_A / \Omega_i$ *ion inertial length*

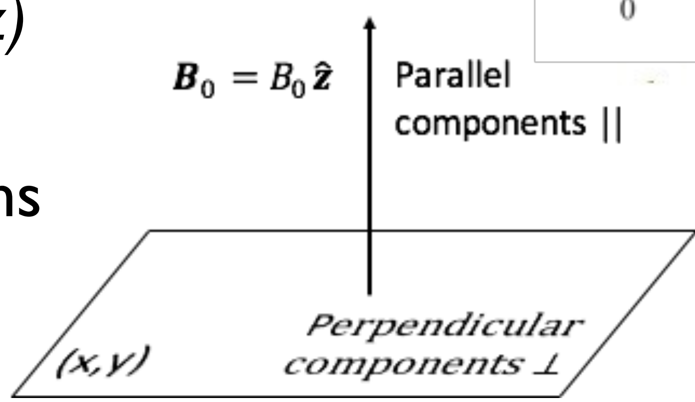
Initialization

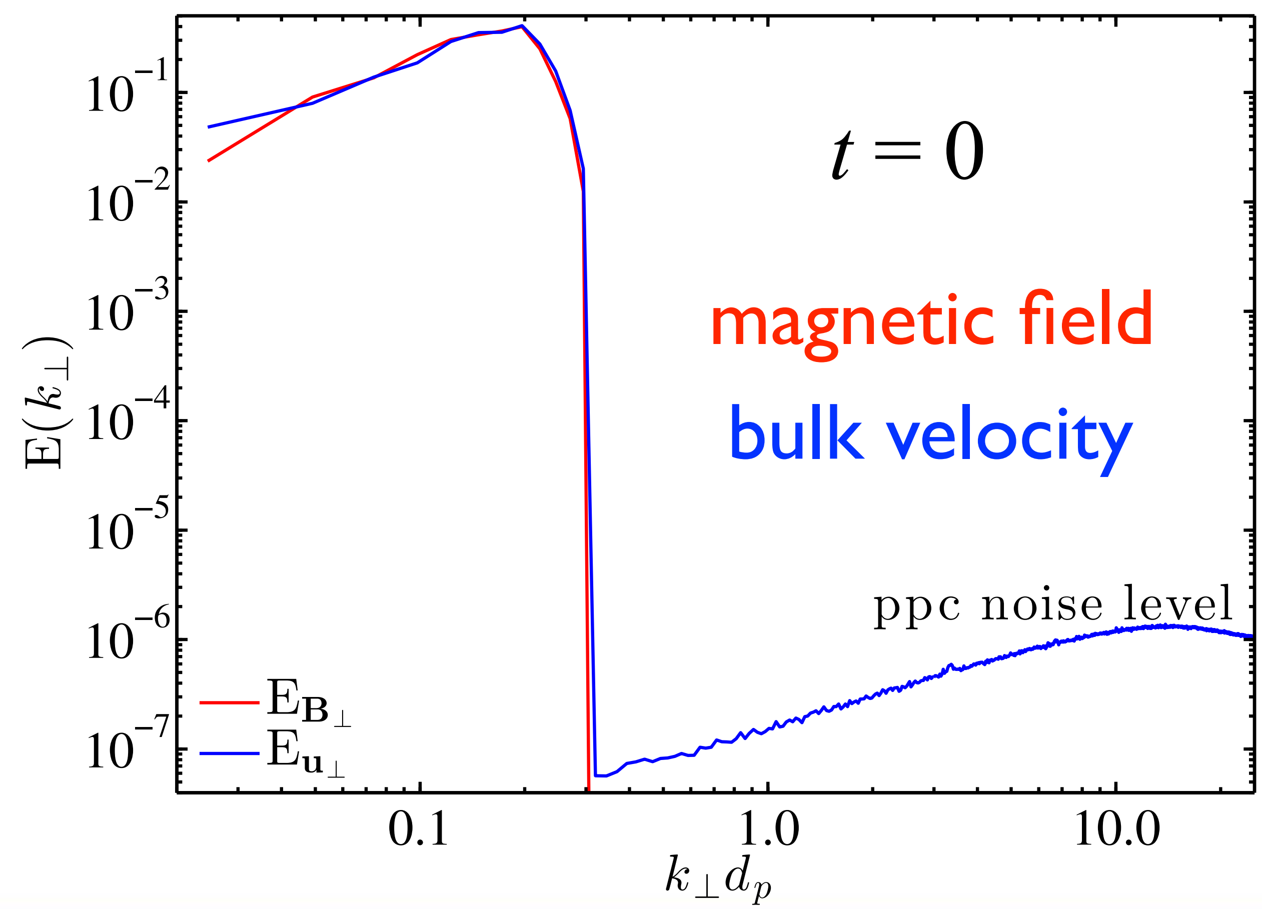
- Homogeneous plasma defined on a 2D domain *(x,y)*
- **Out-of-plane mean magnetic field** *(along z)*
- Initial perpendicular Alfvénic-like fluctuations
- Energy equipartition between kinetic and magnetic fluctuations
- No initial density fluctuations (in the limit of numerical noise)
- Freely-decaying evolution (no forcing)

Initial magnetic fluctuations



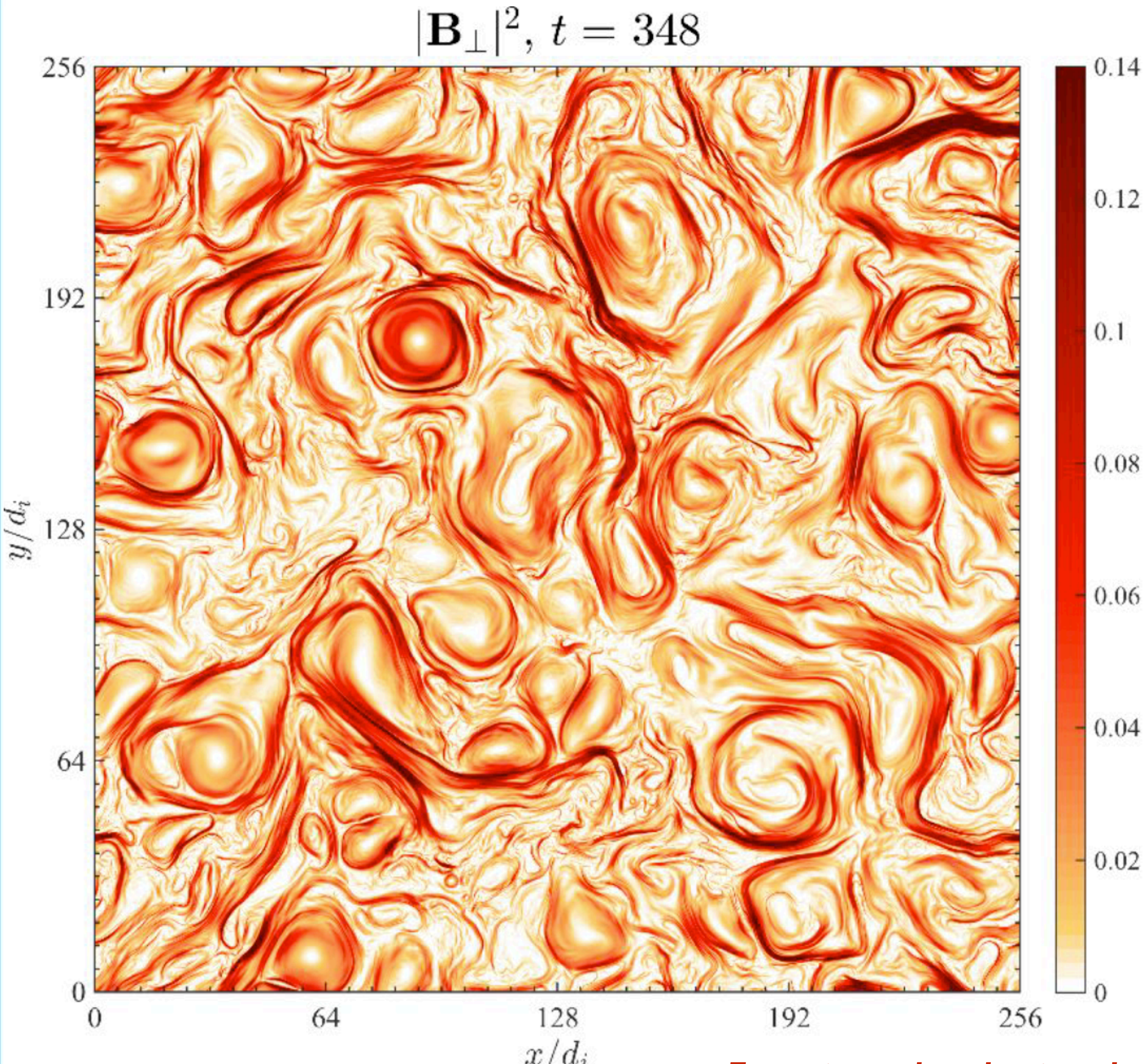

+ similar ion bulk velocity fluctuations (with different random phases)



# Ad-hoc 2D hybrid simulation

*We set __just 3__ fundamental physical parameters to the values measured by the MMS mission*

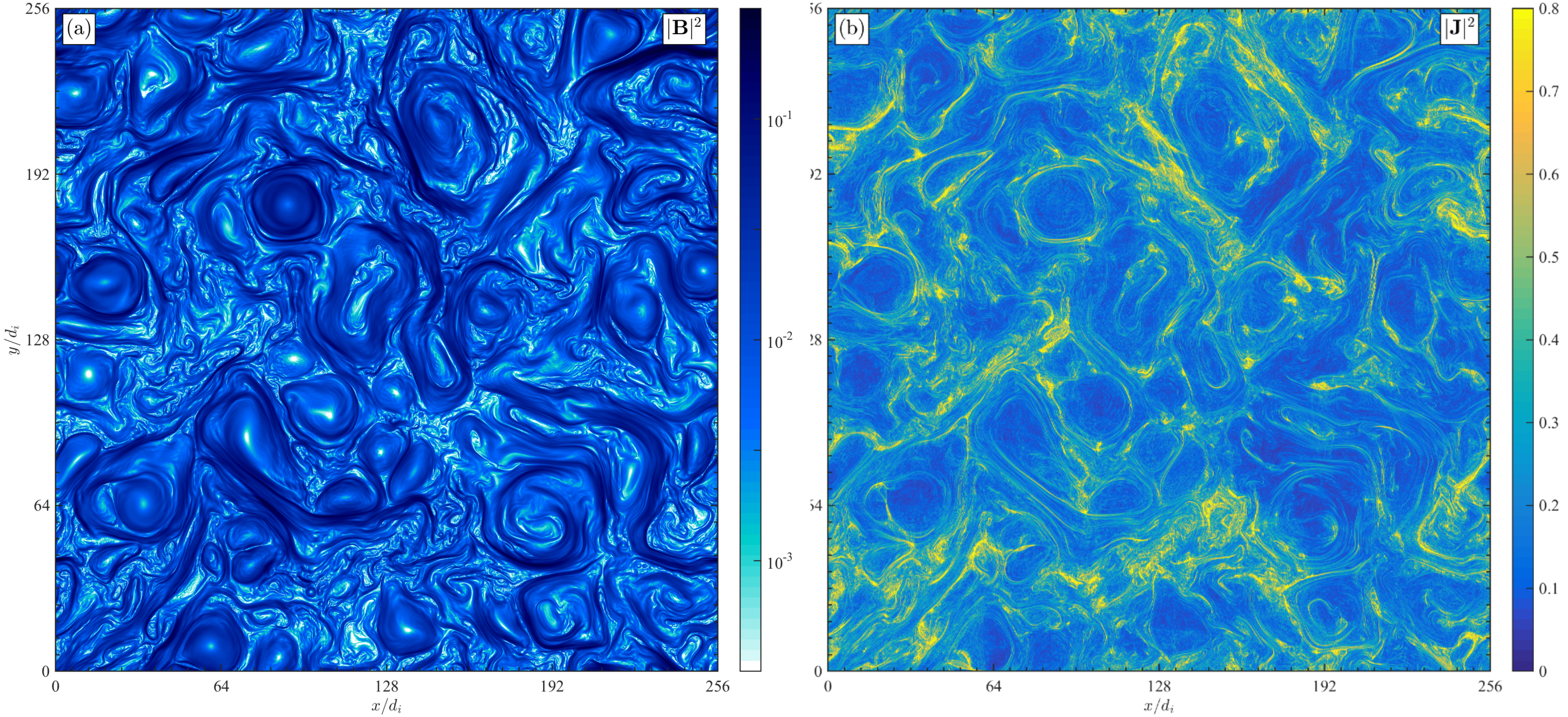



| NUMERICAL PARAMETERS | |
|---|---|
| grid points | $4096^2$ |
| spatial resolution | $d_i/16$ |
| box size | $256\ d_i$ |
| particle-per-cell | 16384 |
| total particles | $\sim 2.7 \times 10^{11}$ |

| PHYSICAL PARAMETERS | |
|---|---|
| $B^{rms}/B_0$ | 0.14 |
| ion plasma beta $\beta_i$ | 0.42 |
| electron beta $\beta_e$ | 0.065 |
| AS IN THE 8 SEP 2015 EVENT | |

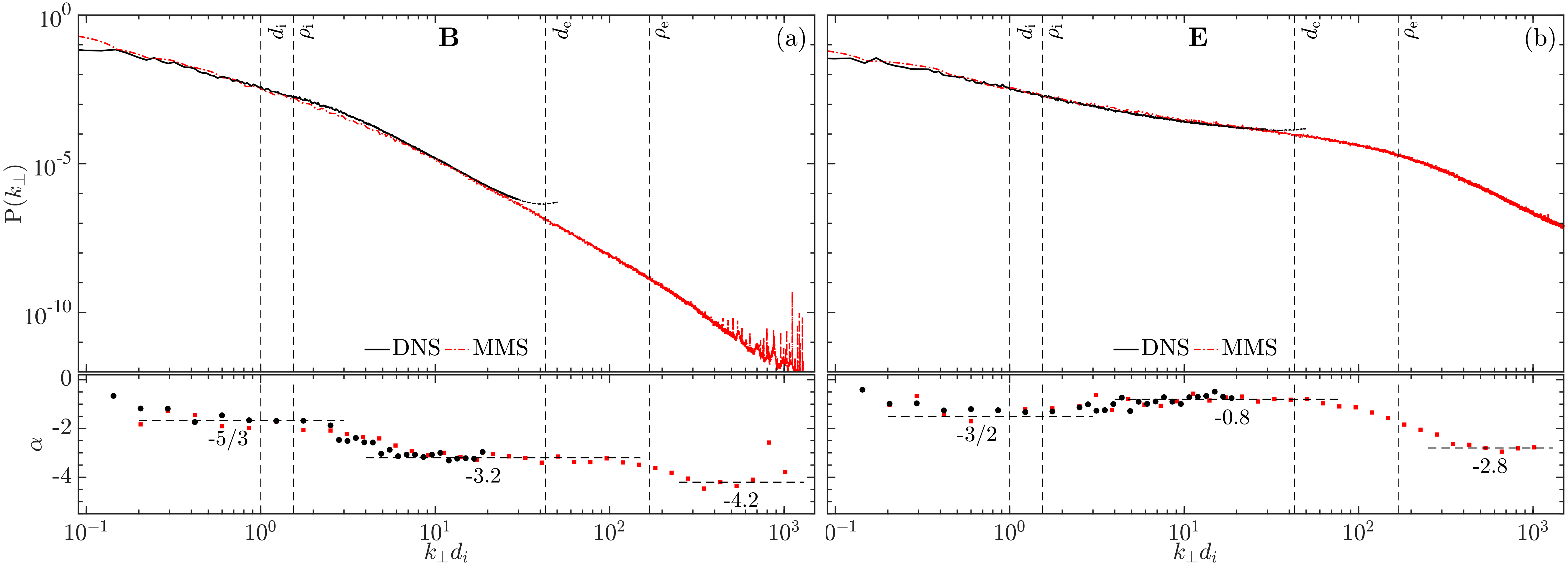
*Franci et al. submitted*

# Magnetic and current structures




Contour plots of the magnitude of the magnetic fluctuations (a)
and of the current density (b) in the whole simulation domain at the final time

# Spectra of electromagnetic fluctuations

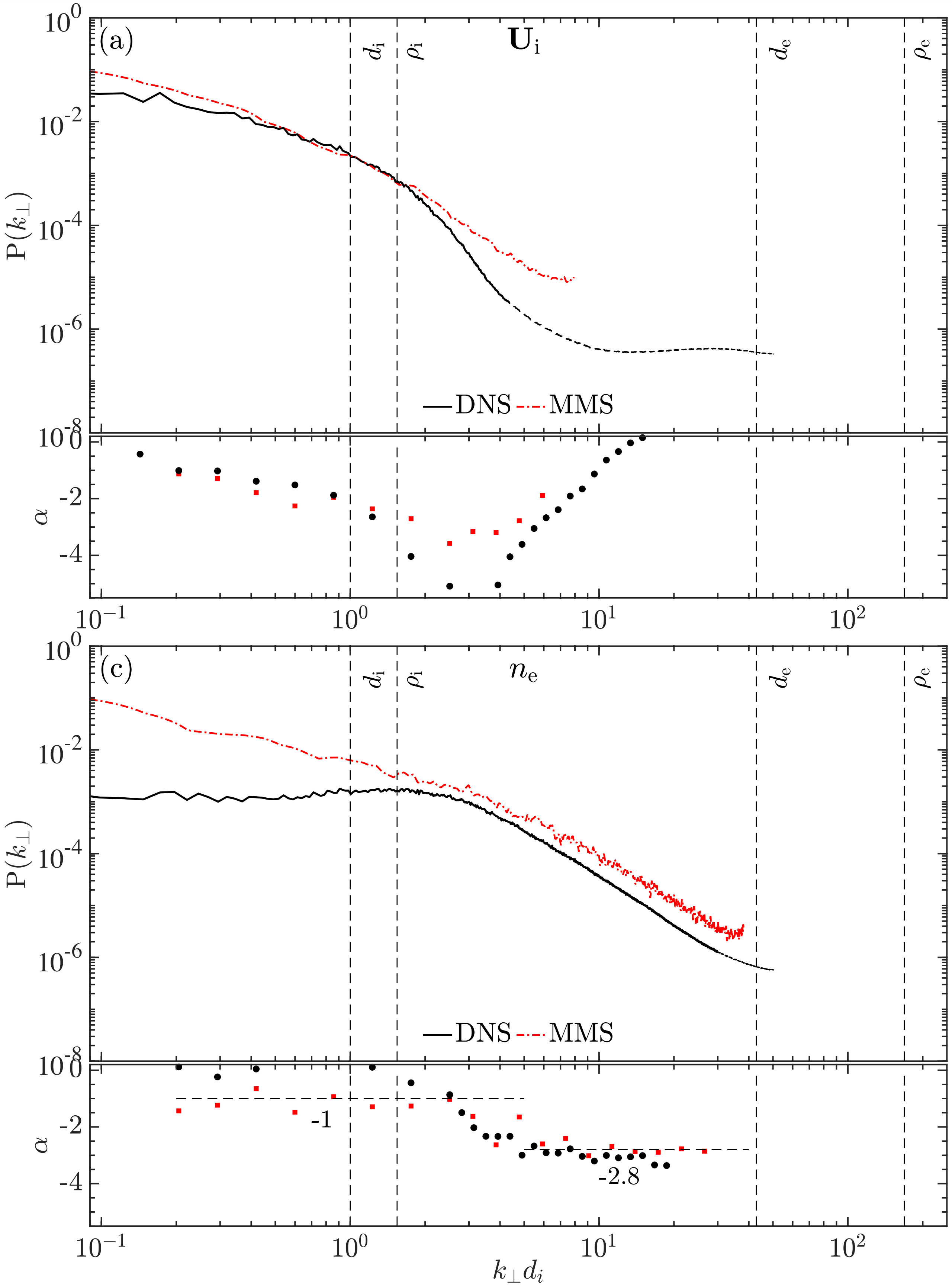


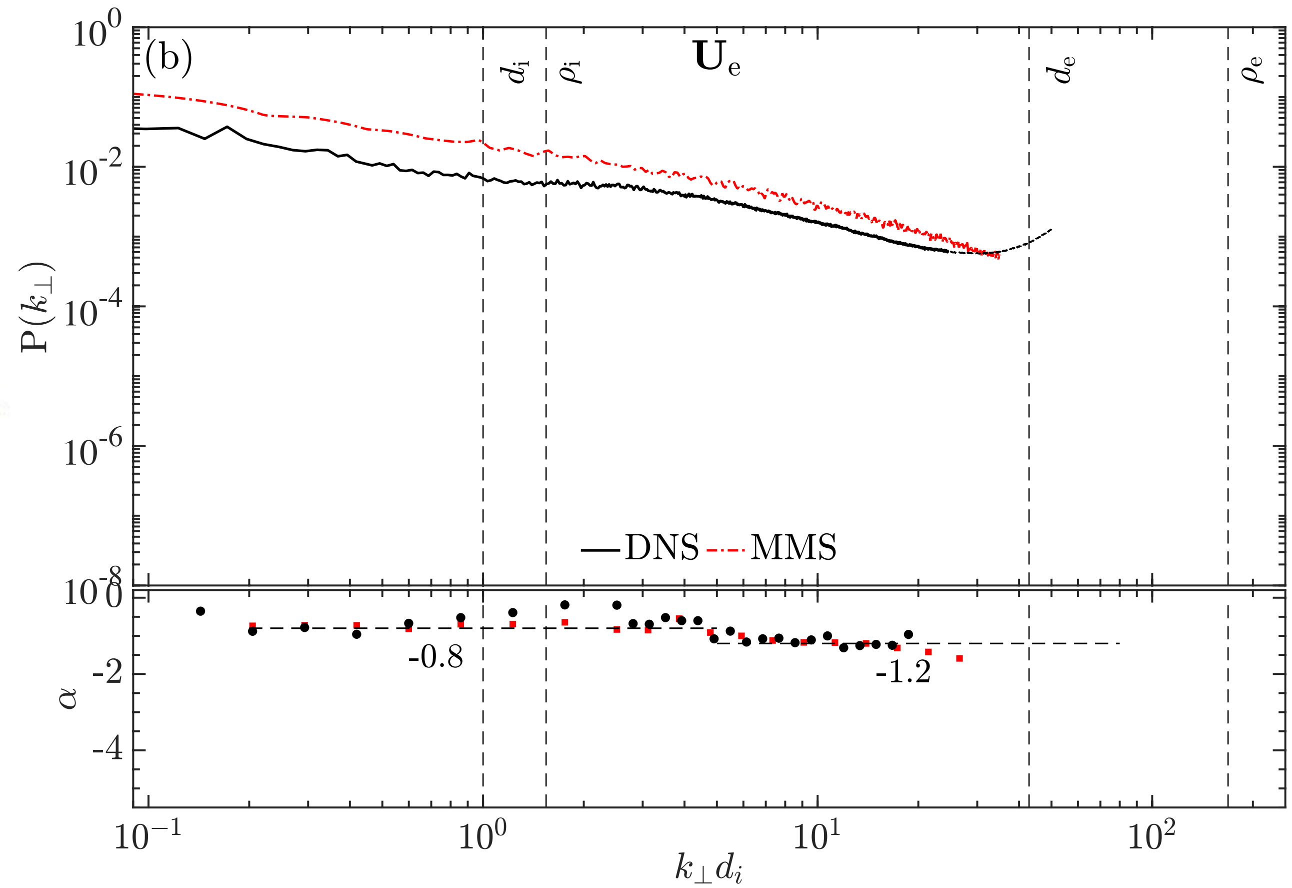

Spectral properties of the electromagnetic fluctuations: magnetic field (a) and electric field (b).
Upper panels: 1D MMS and DNS spectra. Bottom panels: local slope, α.

- Kolmogorov-like slope -5/3 over a full decade
- Spectral break around ion scales (around $kd_i$ ~3)
- Spectral slope ~ -3.2 below $d_i$ over a full decade
- Hint of a second spetral break at ~$d_e$ followed by a third, steeper slope

- Slope closer to -3/2 ( as in $\mathbf{u}_i$ )
- Spectral break around ion scales S
- pectral slope ~ -0.8 below $d_i$ (generalized Ohm law)
- Evidence of second break at ~$d_e$ and third slope -2.8

# Spectra of plasma fluctuations

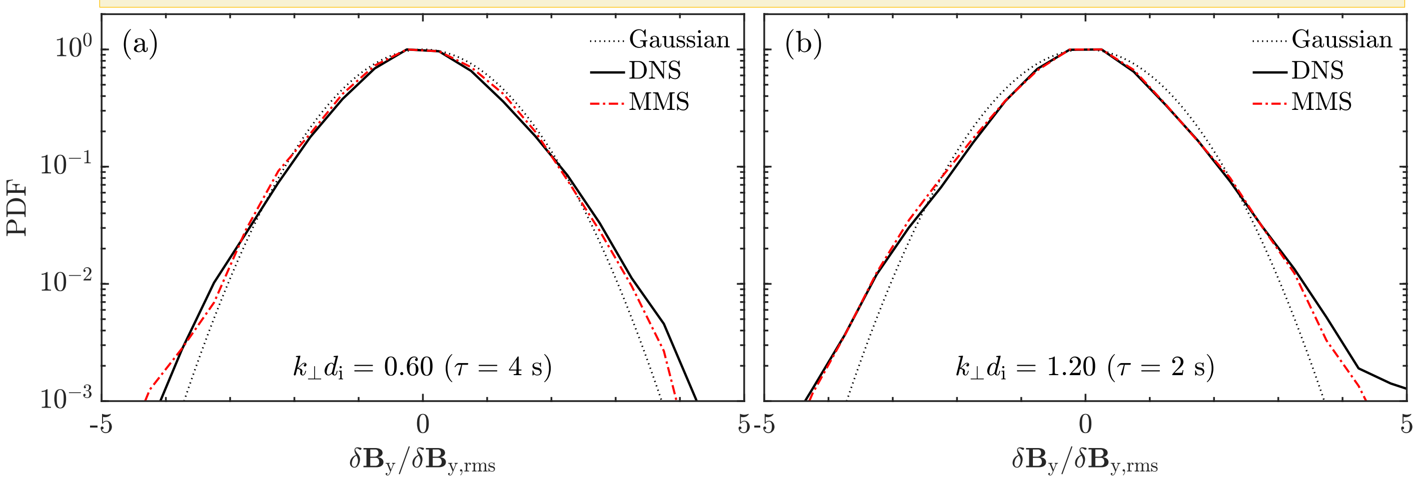


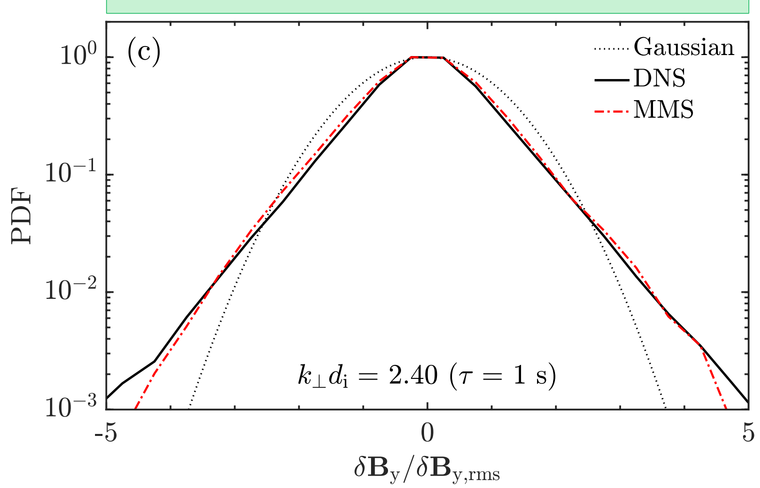

Spectral properties of the plasma fluctuations: ion (a) and electron velocity (b), and electron density (c).

# Intermittency (PDFs and kurtosis)

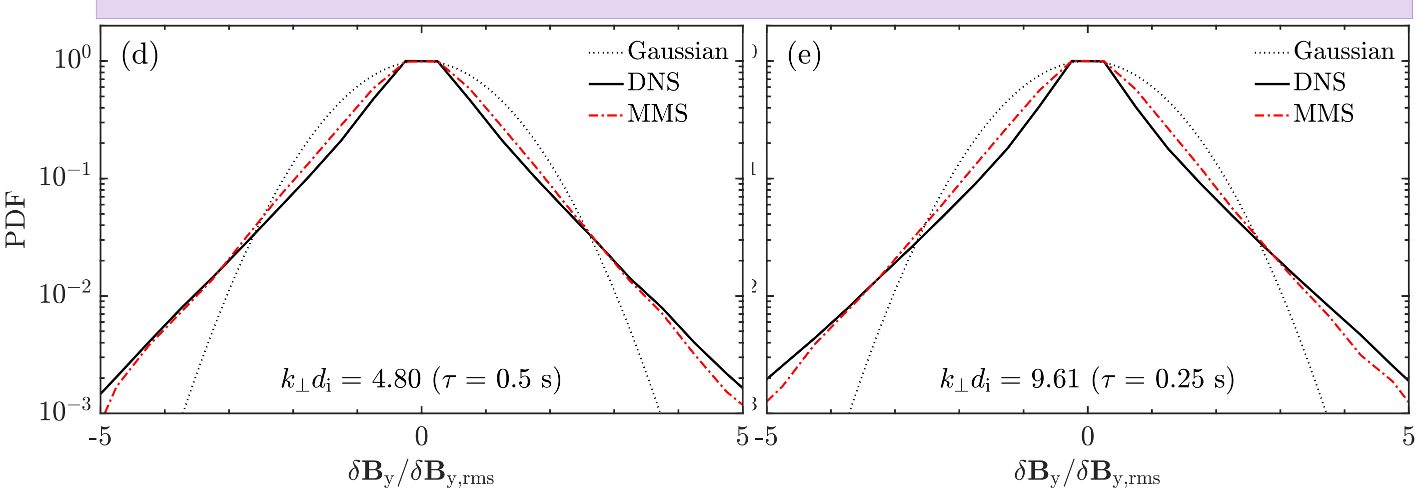
## MHD scales



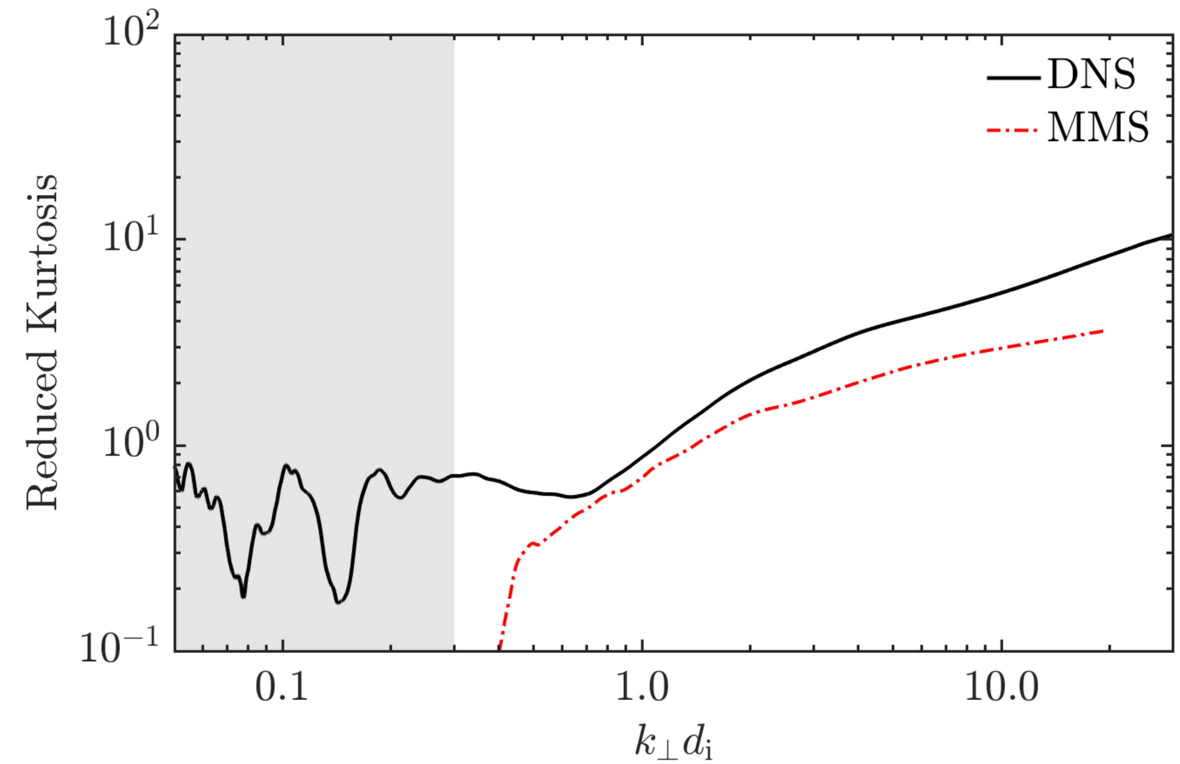

## Break scale




## Kinetic scales




Normalized probability distribution functions (PDFS) of magnetic field increments at different wavenumbers, corresponding to different temporal lags



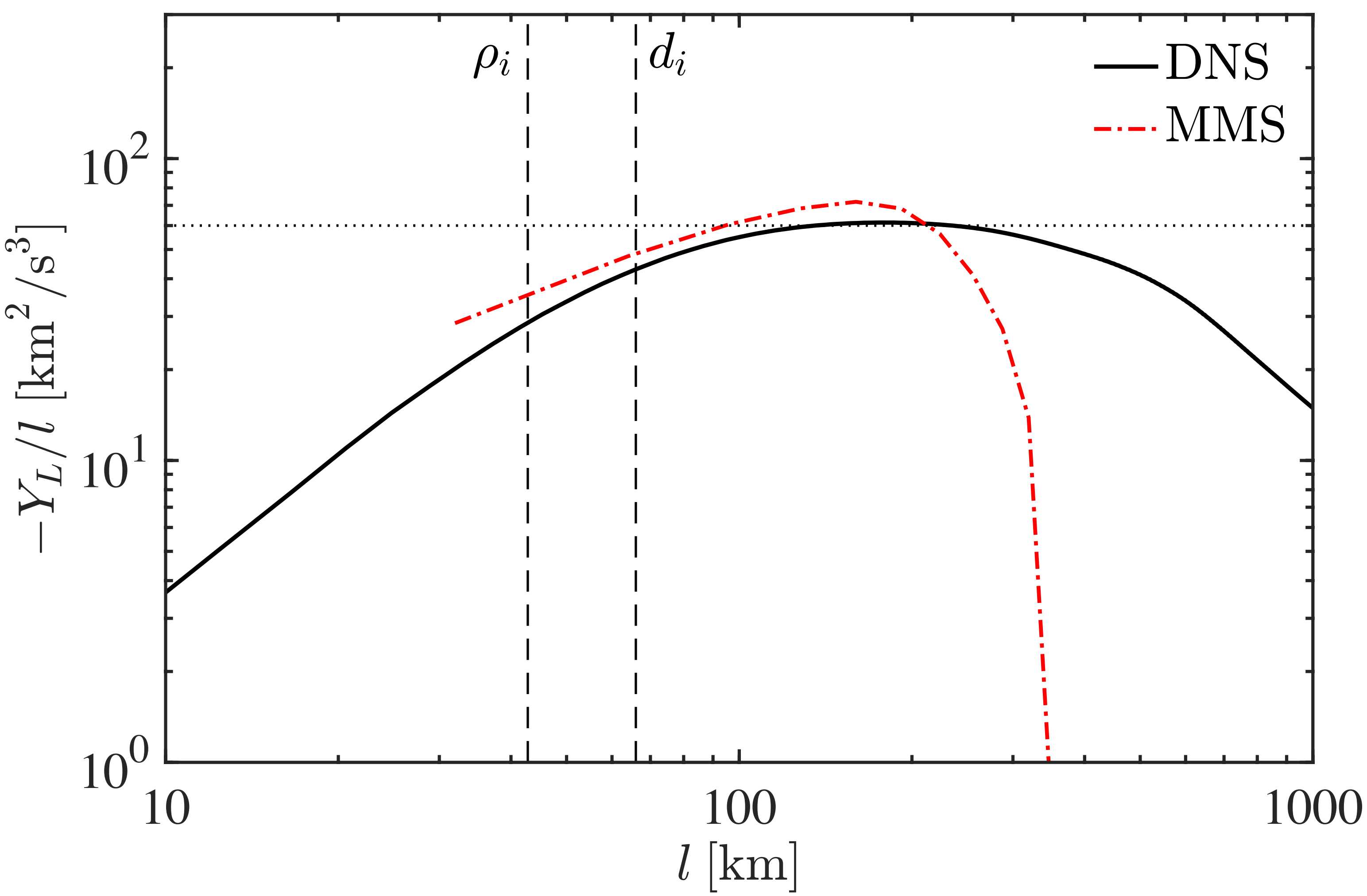

Excess kurtosis of magnetic field increments. The grey shaded area marks the range of scales where energy is initially injected in the simulation

At both extremes of the range of scales here investigated, the intermittency properties differ from what typically observed in the solar wind, where the kurtosis is larger at MHD scales and exhibits a plateau or a decrease at sub-ion scales

# Cascade rate

The cascade rate properties can be investigated by using the statistical von Karman-Howarth/ Politano-Pouquet law (de Karman & Howarth 1938; Politano & Pouquet 1998) for the mixed 3rd-order structure function

$$\boldsymbol{Y} = \left\langle \delta\boldsymbol{U}\left|\delta\boldsymbol{U}\right|^2 + \delta\boldsymbol{U}\left|\delta\boldsymbol{b}\right|^2 - 2\delta\boldsymbol{b}\left(\delta\boldsymbol{U}\cdot\delta\boldsymbol{b}\right)\right\rangle$$




MHD structure function from generalized third-order law, −Y , divided by the spatial lag, l, versus l in km.

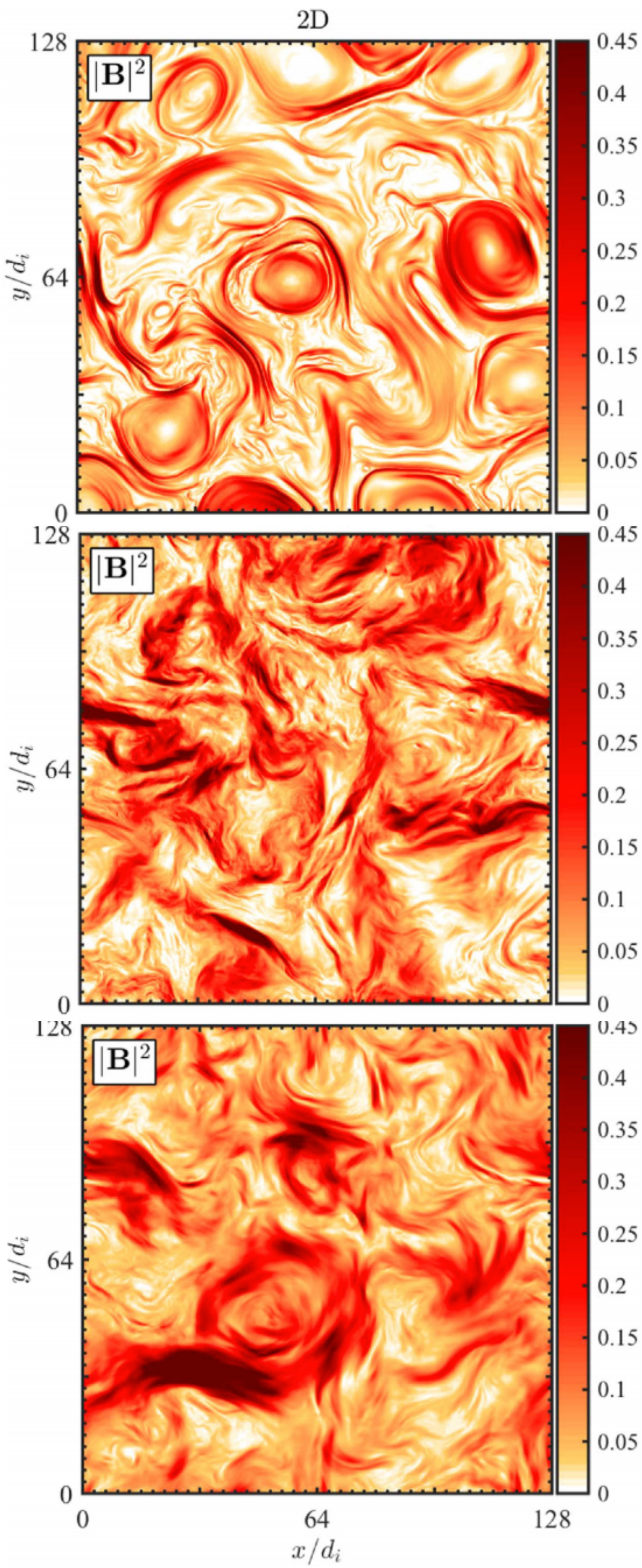
- In both MMS observations and the simulation the inertial ranges is quite small and a change in the nature of the fluctuations is observed at ion scales
- This is where the MHD approximation of the 3rd-order exact law stops to hold and Hall and kinetic effects need to be taken into account
- The KH instability-driven turbulence is observed to be much stronger than the ambient magnetosheath turbulence (the cascade rate is ~ 10 times larger)

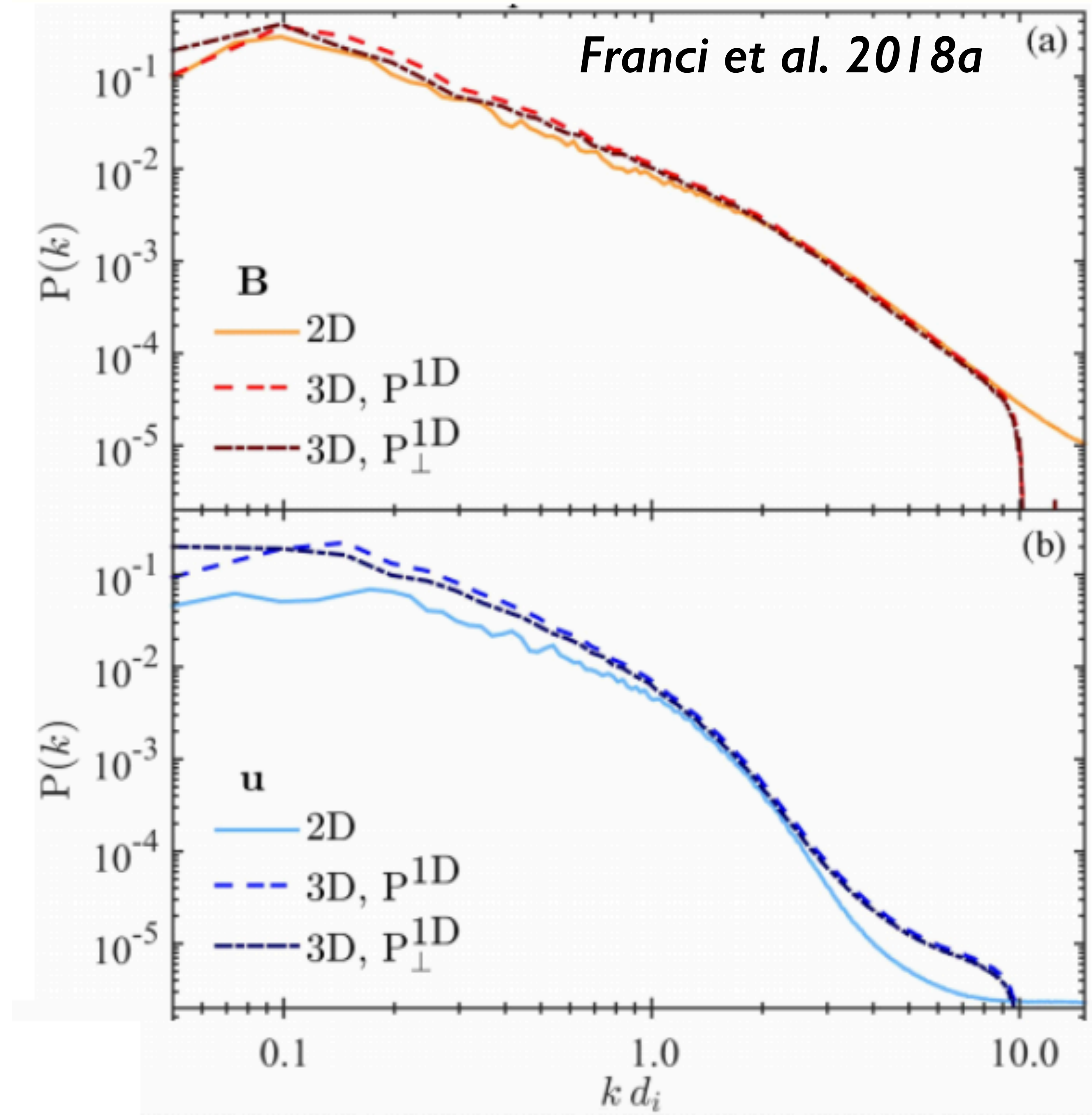
# 2D vs. 3D simulation in real and Fourier space

**2D**
(subset)
$2048^2$
8000 ppc

**3D**
(2D cut
$\perp$ to $\mathbf{B}_0$)
$512^3$
2000 ppc

**3D**
(averaged
over 16 $d_i$)
$512^3$
2000 ppc



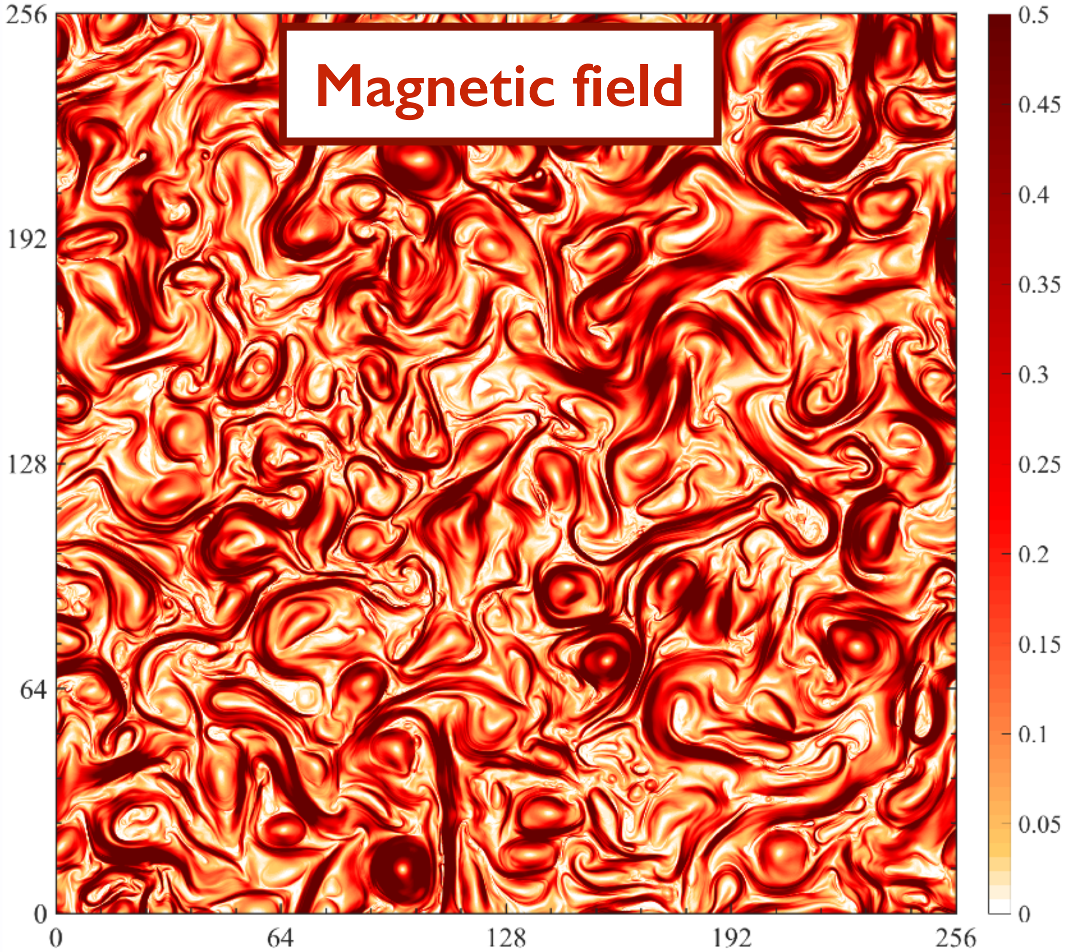



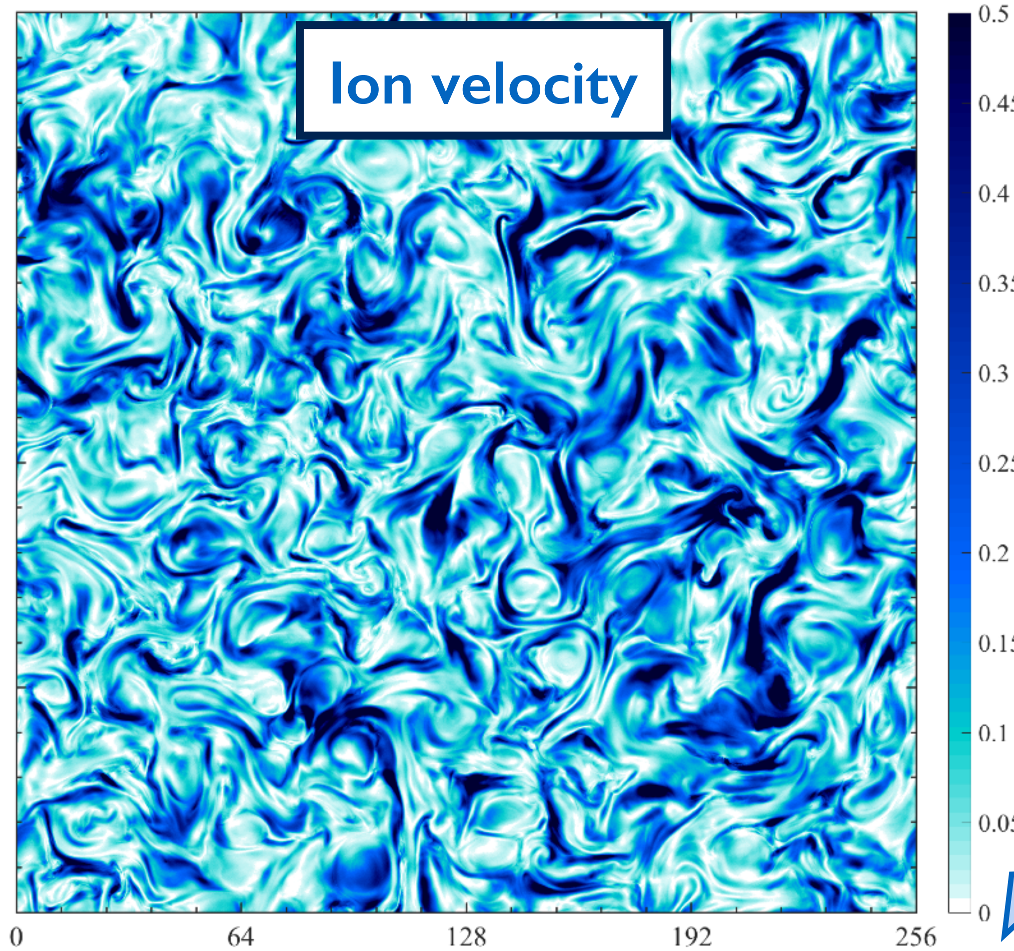

- Different shapes of structures in real space determine very similar spectral properties
- The main spectral properties are not affected by the reduced geometry

$\longrightarrow$ **validation of 2D results**

# 2D simulation with PSP parameters

We ran a simulation setting the 2 fundamental physical parameters to the **values measured by Parker Solar Probe (PSP) during its first perihelion on 5 November 2018**




ion beta = 0.2

electron beta = 0.5

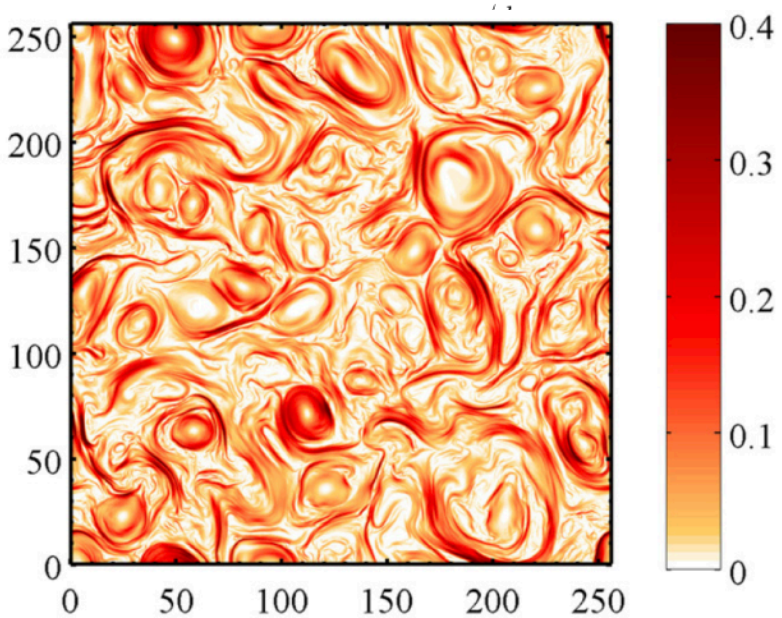
higher level of fluctuations than usual (~ 0.5 $B_0$)

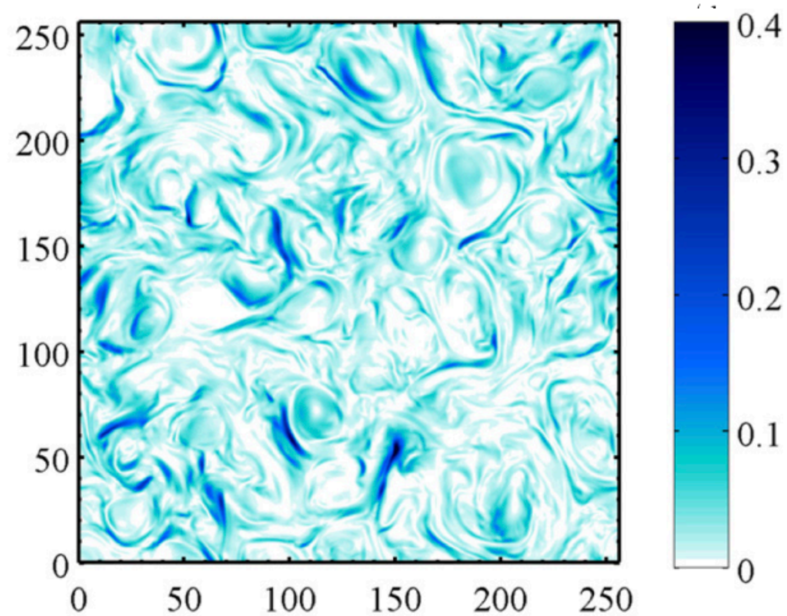
4096x4096

1024 ppc

~ 20 billion particles

*Franci et al., in prep.*





The ion velocity fluctuations are much stronger than in previous simulations with similar but still different parameters

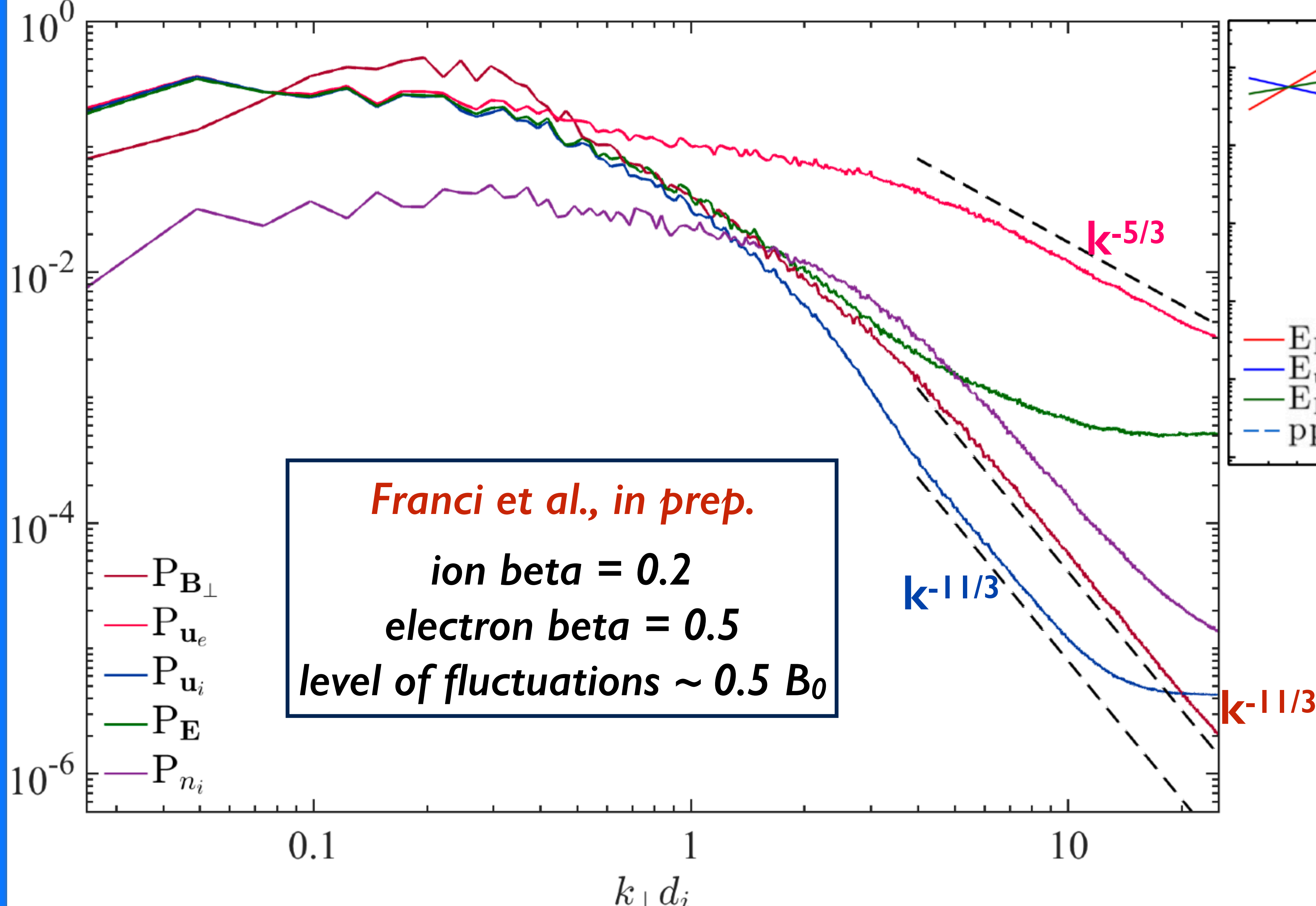
*Franci et al., ApJ 2015*

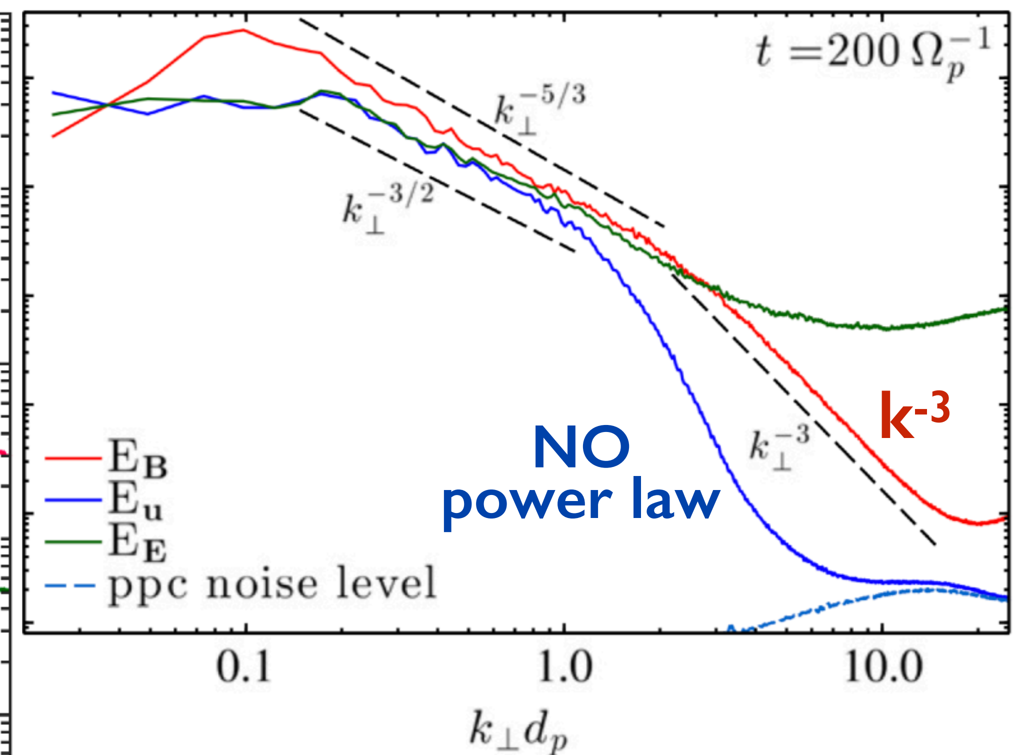
*ion beta = 0.5, electron beta = 0.5*

*level of fluctuations ~ 0.25 $B_0$*

# 2D simulation with PSP parameters

**The spectra of electromagnetic and plasma fluctuations show hints of a newly-observed regime**




*Franci et al., ApJ 2015*

*ion beta = 0.5*

*electron beta = 0.5*

*level of fluctuations ~ 0.25 $B_0$*

The spectrum of the magnetic fluctuations is much steeper than usual **(slope of -11/3 vs. -3)**

The spectrum of ion velocity fluctuations shows a **power law, with the same slope**

The spectrum of the electron velocity fluctuations shows a **-5/3 Kolgomorov-like slope**

**(hint of an electron-MHD regime dominated by the electron dynamics?)**

# Conclusions

*The physical implications of the comparison between MMS observation and our simulation are:*

- the KH instability-driven turbulence in the magnetopause has similar spectral and intermittency properties compatible with Alfvenic turbulence from MHD scales down to sub-ion scales;
- the plasma dynamics is controlled by a few fundamental plasma parameters, and the injection scale is more important than the nature of the driving mechanism itself, hinting at a certain universality;
- the main properties of the fluctuations (e.g., compressibility) at ion and sub-ion scales are independent on the inertial range, possibly suggesting a certain universality of the kinetic cascade;
- electron kinetic processes (e.g., electron Landau damping) are not observed to have significant effects on the properties here compared at scales larger than the electron characteristic scales, in the particular investigated regime (intermediate ion beta and low electron beta);
- fluctuations at ion and sub-ion scales are likely low-frequency;
- our simulation results represent a good model for the particular observed KH event, compatible with a quasi-2D nature of the turbulent cascade;
- the inertial-range intermittency is smaller than in the pristine solar wind, consistent with a smaller correlation length of the turbulence due to energy injection at scales closer to the ion scales;
- the kurtosis does not saturate at sub-ion scales in the magnetopause, possibly due to a significant contribution from coherent structures;
- the larger cascade rate than the one measured in the ambient magnetosheath suggests that the turbulence we are observing is indeed driven by the KH event rather than pre-existing turbulence.

*Our preliminary numerical attempt of modelling PSP observations during its first perihelion show:*

- a qualitative agreement with observed spectra of magnetic fluctuations
- a possible hint of an electron-MHD regime dominated by the electron dynamics