This presentation participates in OSPP

EGU

Outstanding Student & PhD candidate Presentation contest

KU LEUVEN

Università di Pisa

Giuseppe Arrò[1,2], Francesco Califano[2], Giovanni Lapenta[1]

[1]Department of Mathematics, KU Leuven, Leuven, Belgium, EU

[2]Dipartimento di Fisica, Università di Pisa, Pisa, Italy, EU

Spectral features and energy cascade of kinetic scale plasma turbulence

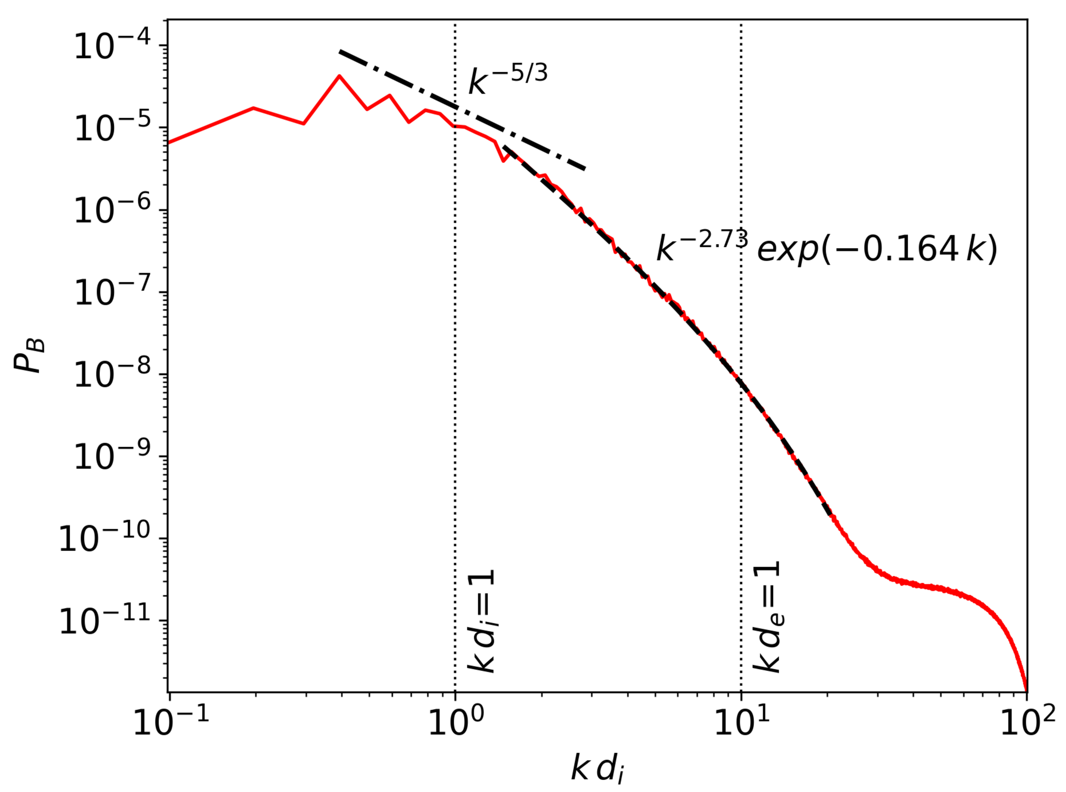
Context

Turbulence in collisionless magnetized plasmas is a complex process involving the transfer of energy from large magnetohydrodynamic (MHD) scales to small ion and electron kinetic scales. The multi-scale nature of plasma turbulence is reflected in the properties of the turbulent spectra that have different shapes in different ranges of scales. Satellite observations show that at MHD scales the magnetic field spectrum follows a power-law that breaks at ion scales, where a steeper power-law develops. A second break and steepening is observed towards electron scales but the shape of the spectrum in this range is still under debate and it is not clear if it follows a new power-law or if an exponential falloff develops.

Simulations setup

We investigate the spectral properties of sub-ion scales turbulence by means of a fully kinetic particles-in-cell simulation of freely decaying turbulence:

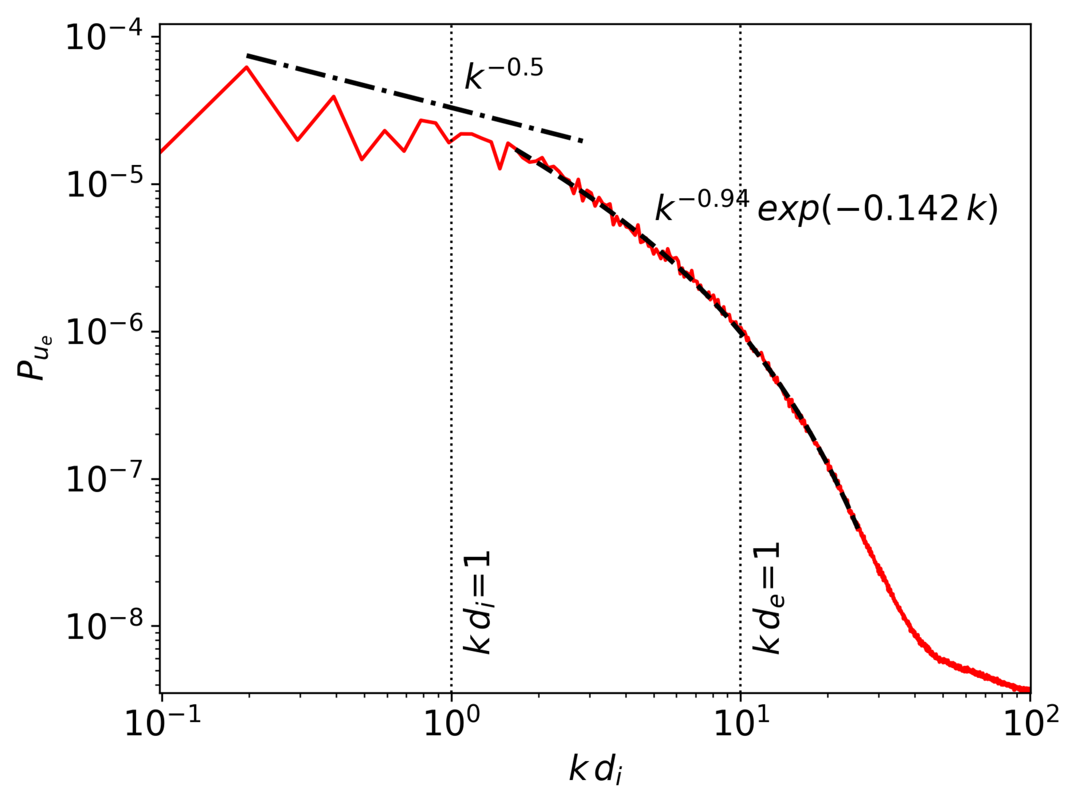
- 2D square periodic box with $L=64\,d_i$, 2048^2 cells and 5000 particles per cell (for both ions and electrons);
- Maxwellian ions and electrons with uniform density, uniform and isotropic temperature, $\beta_i=8$, $\beta_e=2$ and $m_e=m_i/100$;
- An homogeneous guide field B_0 is present and the turbulence is triggered by random, isotropic magnetic field and velocity fluctuations with wavenumber $1\leqslant k/k_0\leqslant 4$ ($k_0=2\pi/L$) and amplitudes $\delta B_{rms}/B_0\simeq 0.9$ and $\delta u_{rms}/c_A\simeq 3.6$.

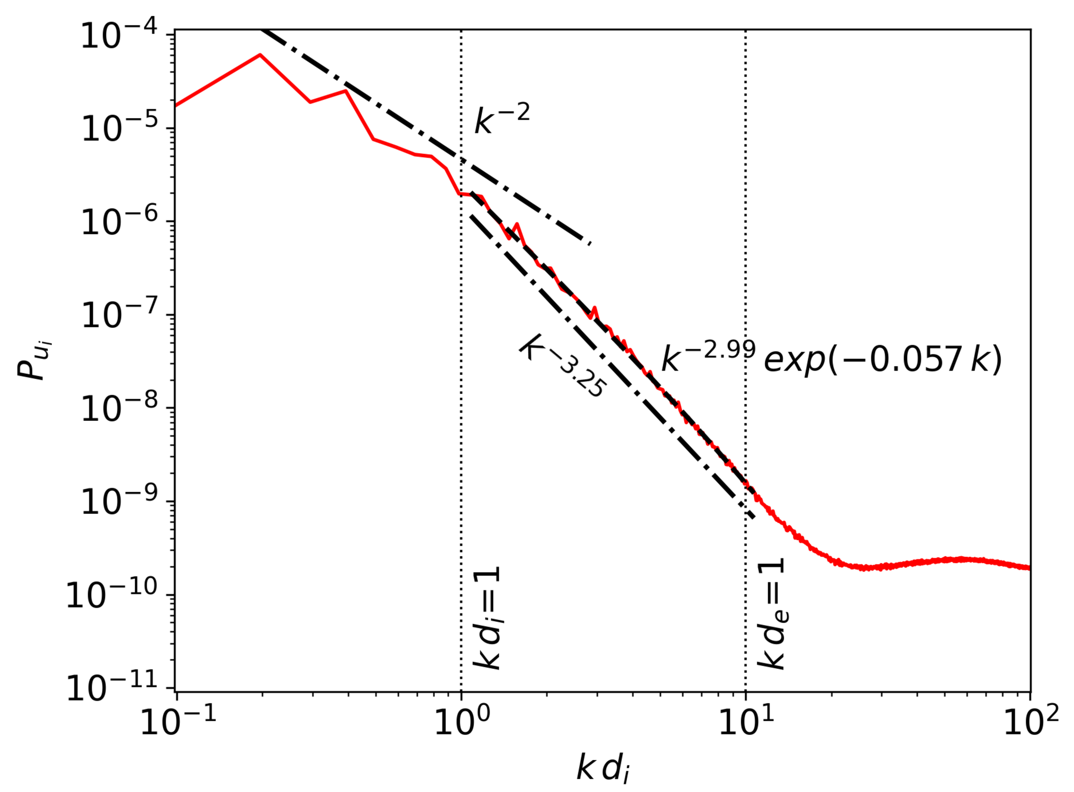


Magnetic field

Spectral shapes

At sub-ion scales, the magnetic field and electron velocity spectra follow the *power exp* model $\sim k^{-\alpha}\,exp(-\rho_e\,k)$ while the ion velocity spectrum drops as a steep power-law.





Electron (top) and ion (bottom) velocities

Scale filtered energy transport

We analyze the filtered energy transport equations to investigate the development of the turbulence at sub-ion scales:

$$\partial_t \widetilde{E}^f_s + \nabla\cdot\mathbf{J}^u_s = -\Pi^{uu}_s + \overline{\mathbf{P}}_s:\nabla\widetilde{\mathbf{u}}_s + \overline{\mathbf{J}}_s\cdot\widetilde{\mathbf{E}} \qquad\qquad W_s = \mathbf{J}_s\cdot\mathbf{E} - \overline{\mathbf{J}}_s\cdot\widetilde{\mathbf{E}}$$

$$\rightarrow$$

$$\partial_t \overline{E}^m + \nabla\cdot\mathbf{J}^b = -\sum_s \Pi^{bb}_s - \sum_s \overline{\mathbf{J}}_s\cdot\widetilde{\mathbf{E}} \qquad\qquad PS_s = (-\mathbf{P}_s:\nabla\mathbf{u}_s) - (-\overline{\mathbf{P}}_s:\nabla\widetilde{\mathbf{u}}_s)$$

with $\bar{\cdot}$ indicating the low-pass filtering, while $\tilde{\cdot}$ is the density-weighted filtering ($\widetilde{q}=\overline{nq}/\overline{n}$ for a quantity q, where n is the density).

We consider the high-pass filtered electromagnetic (e.m.) work W_s and pressure-strain interaction PS_s, defined as the difference between the corresponding unfiltered quantities and the low-pass filtered ones.

Sub-ion scales energy transfer

By comparing the evolution of the energies contained in the magnetic field and electron velocity exponential ranges (Fig.A) we see that their development is correlated in time. Two phases can be distinguished, a growth phase for $t<500\,\Omega_e^{-1}$ and a saturation phase when the turbulence is fully developed. Fig.B shows the time evolution of the box-averaged W_s, PS_s and the total e.m. work $W=\sum_s W_s$, filtered at sub-ion scales $r=1\,d_i$. $\langle W\rangle$ is negative during the growth phase and turns positive in the saturation phase. This means that the plasma is feeding energy to the magnetic field at sub-ion scales during the growth phase but at fully developed turbulence it starts to oppose the magnetic field cascade and the exponential range saturates. The main contribution to $\langle W\rangle$ comes from $\langle W_e\rangle$ while $\langle W_i\rangle$ does not show any response at the transition from the growth to the saturation phase. Hence, most of the energy subtracted to the magnetic field by $\langle W\rangle$ goes into electron kinetic energy when the turbulence is fully developed. This energy is finally dissipated by the electron $\langle PS_e\rangle$ that follows the same evolution of the energies contained in the exponential ranges [arXiv:2112.12753].

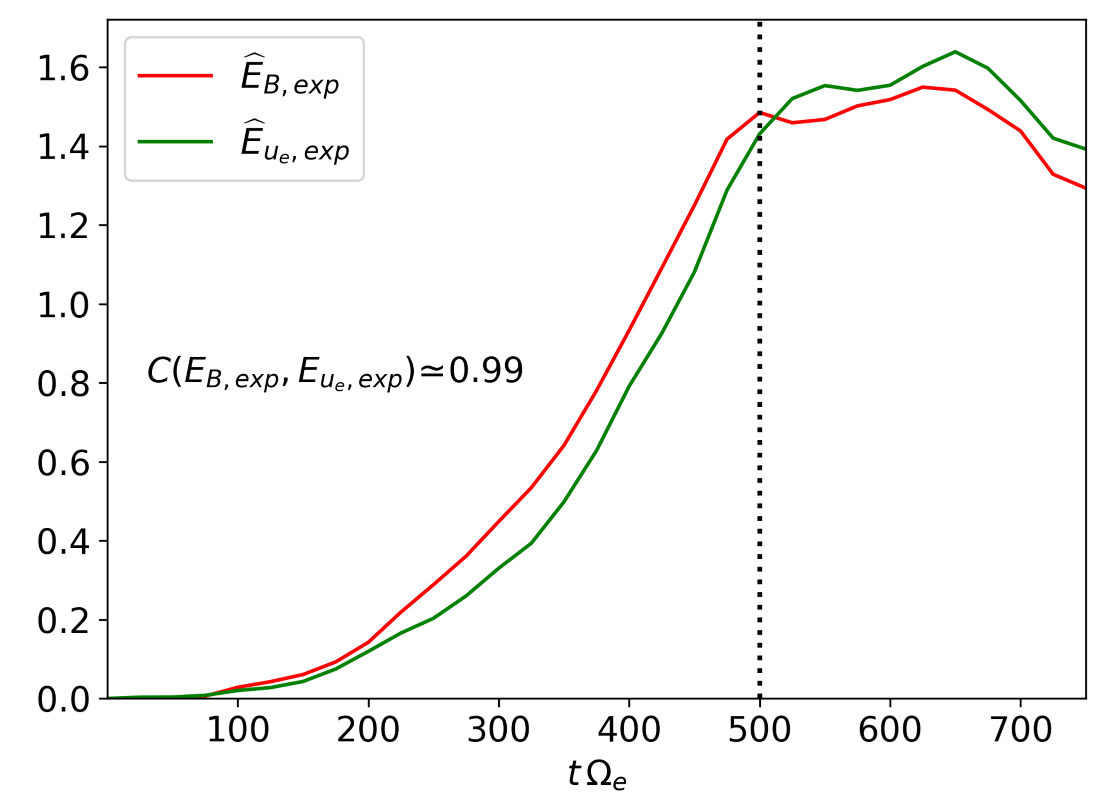


Fig.A: Magnetic and electron exponential range energies

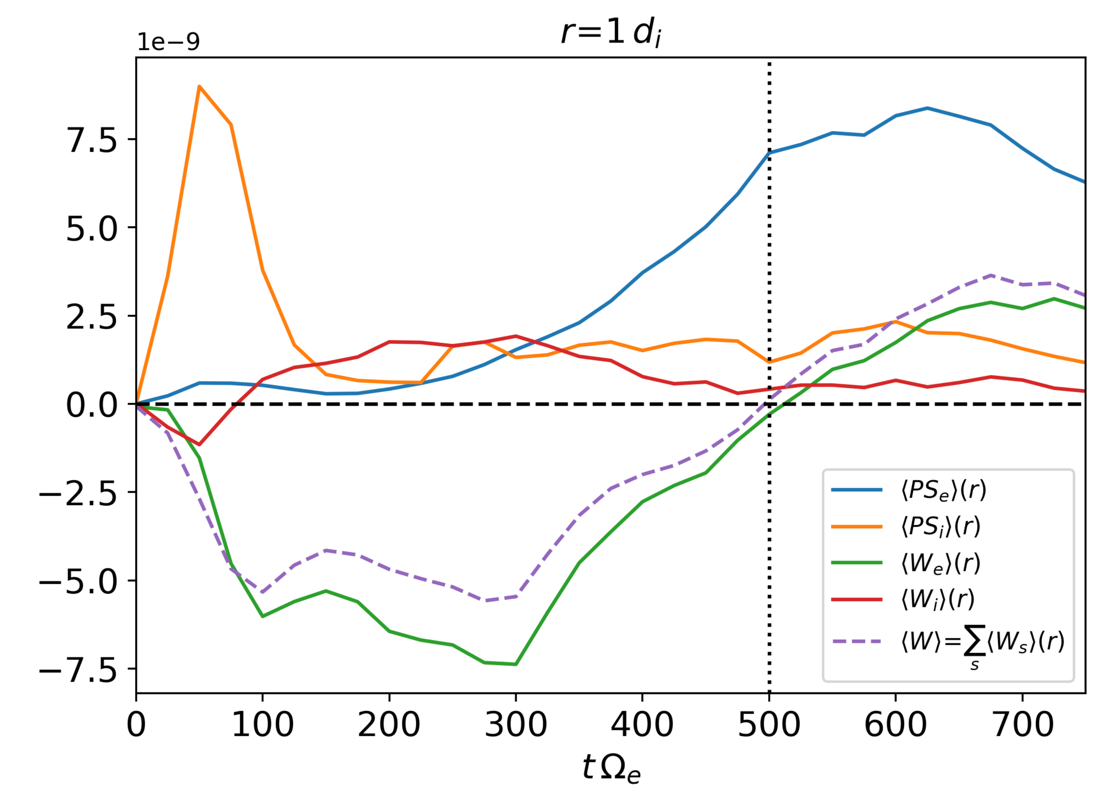


Fig.B: Energy conversion channels