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Sounding plasma turbulence at sub-ion scales with Fast Iterative Filtering in space and time.

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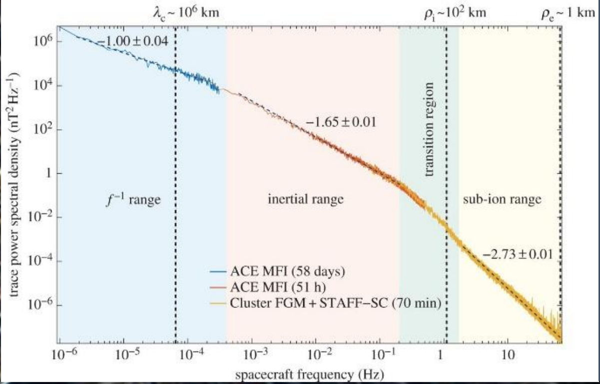
THE NEED FOR A MULTISCALE STUDY OF PLASMA TURBULENCE

- There is a long standing debate about what causes the turbulent energy cascade at sub-ion scales.
- Kinetic-Alfvén-wave interactions (or other wave-like non-linear interactions) may continue the turbulent cascade below d_i. Indeed, several observational studies suggest the presence of wave-like perturbations in the solar wind [2,3].
- But the intermittency observed in both simulations and observations [4], together with the measure of enhanced dissipation in localized structures [5], puts doubts on the validity of such models .

- A full space-time analysis can indeed help to shed light on this relatively long-standing problem,

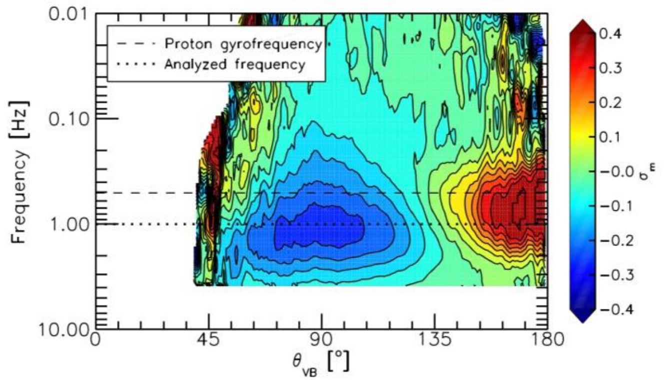
HOWEVER…

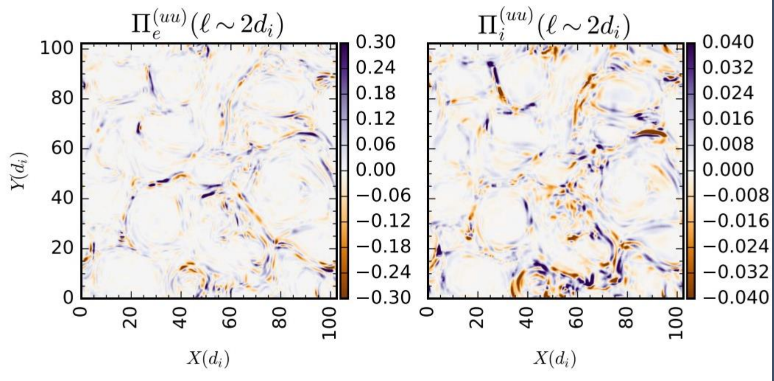
- The intrinsic nature of turbulence (**nonlinearity**, **nonstationarity**, presence of **impulsive events**) makes difficult to use standard techniques that rely on linearity and/or stationarity of the signal to be analyzed.



Power spectrum of magnetic fluctuations shows the multiscale turbulence of the solar wind. In particular, the well-known -5/3 MHD inertial range, and the transition to the sub-ion range. (from ref. [1])

Measure of the reduced magnetic helicity in the solar wind. The signature consistent with KAW (right-hand polarization) is found between $\sim 70°$ and $\sim 120°$. (from ref [2])





Contour plot of fluid flow electron's and ion's energy transfer across scales $\ell \sim 2d_i$, which shows the spatial localization of enhanced dissipation. (from ref [5]).

FAST ITERATIVE FILTERING

A. Cicone, Numerical Algorithms 85, 811, (2020)

Fast Iterative Filtering (FIF) [6] is an adaptive technique for the analysis of non-stationary non-linear signals similar to the Empirical Mode Decomposition [7].

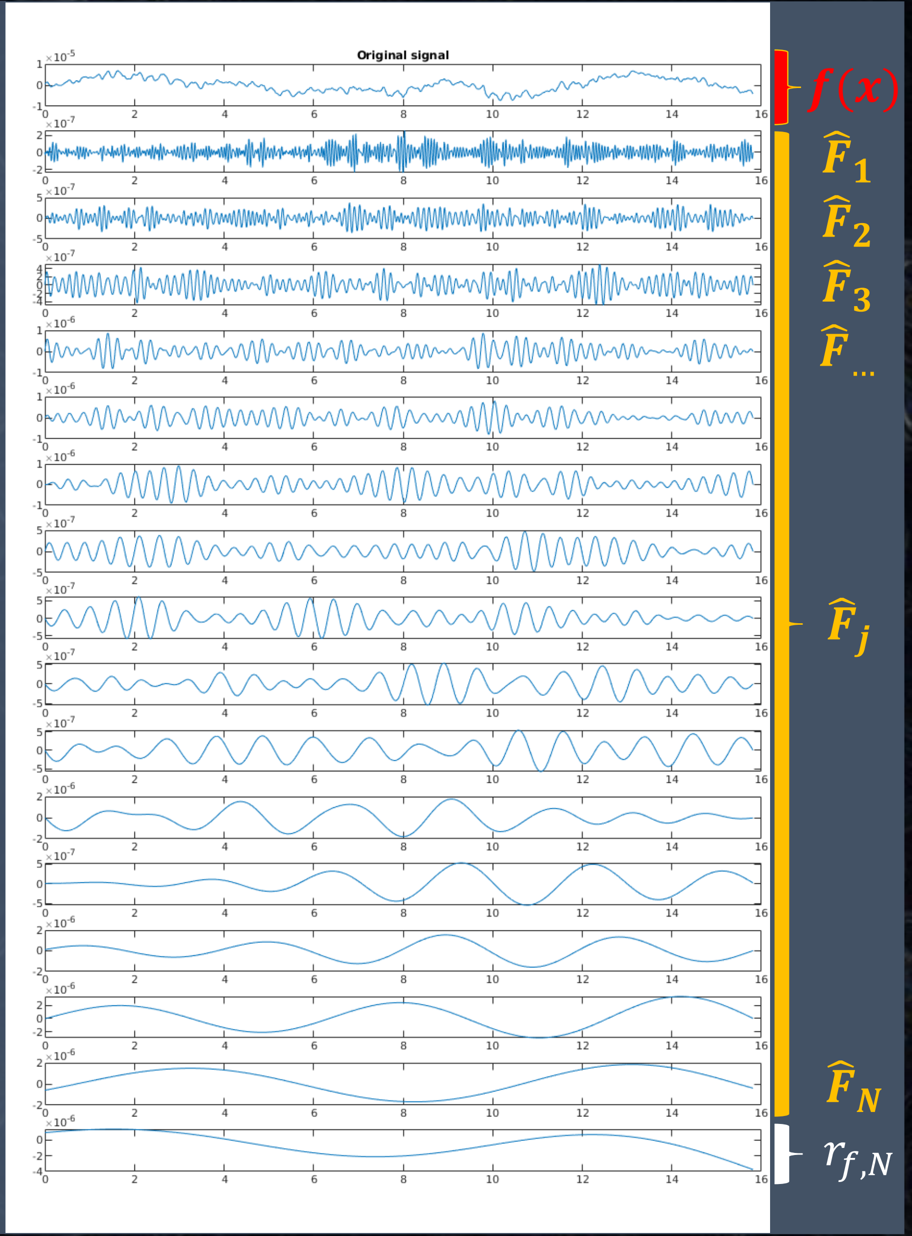
- A given signal, $f(x)$ (e.g. a time series) is decomposed into a finite number N of Intrinsic Mode Components $\widehat{F}_j(x)$ (IMCs) (whose average frequency is well behaved) plus a residual $r_{f,N}(x)$:

$$f(x) = \sum_{j=1}^{N} \widehat{F}_j(x) + r_{f,N}(x),$$

- Each IMC $\widehat{F}_j(x)$ is the result of an iterative procedure that, by using a low-pass filter $w_{\lambda_j}(t)$, isolates a high-frequency fluctuating component whose frequency is well-behaved:

High-pass filter operator: $S_{\lambda_j}[s(x)] = s(x) - \int_{-\lambda_j}^{\lambda_j} s(x+t) w_{\lambda_j}(t) \mathrm{d}^k t,$

IMC definition: $\widehat{F}_j(x) = \lim_{n\to\infty} S_{\lambda_j}^n \left[f(x) - \sum_{l=1}^{j-1} \widehat{F}_l(x) \right]$

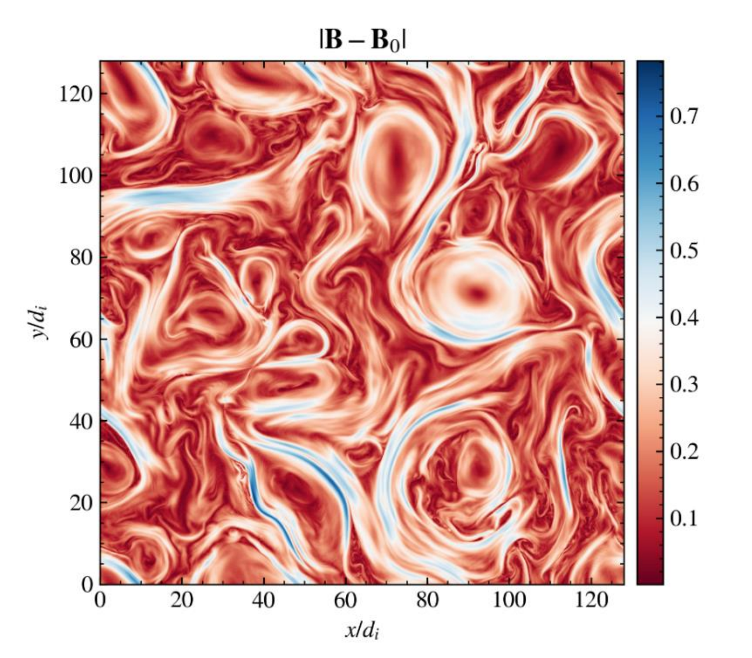


MULTISCALE ANALYSIS IN SPACE AND TIME WITH FTFIF

Submitted to PRL

NUMERICAL DATASET

- Periodic 2D Hall-MHD simulation with **1024^2** grid points and a box size of **$128\ d_i$**.
- **Freely-decaying turbulence** in presence of a mean out-of-plane magnetic field B_0 (plasma $\beta = 2$).
- Alfvénic-like fluctuations with b_{rms}: 0.24 B_0 are introduced, at large scales ($k_\perp d_i < 0.3$).



SPACETIME ANALYSIS

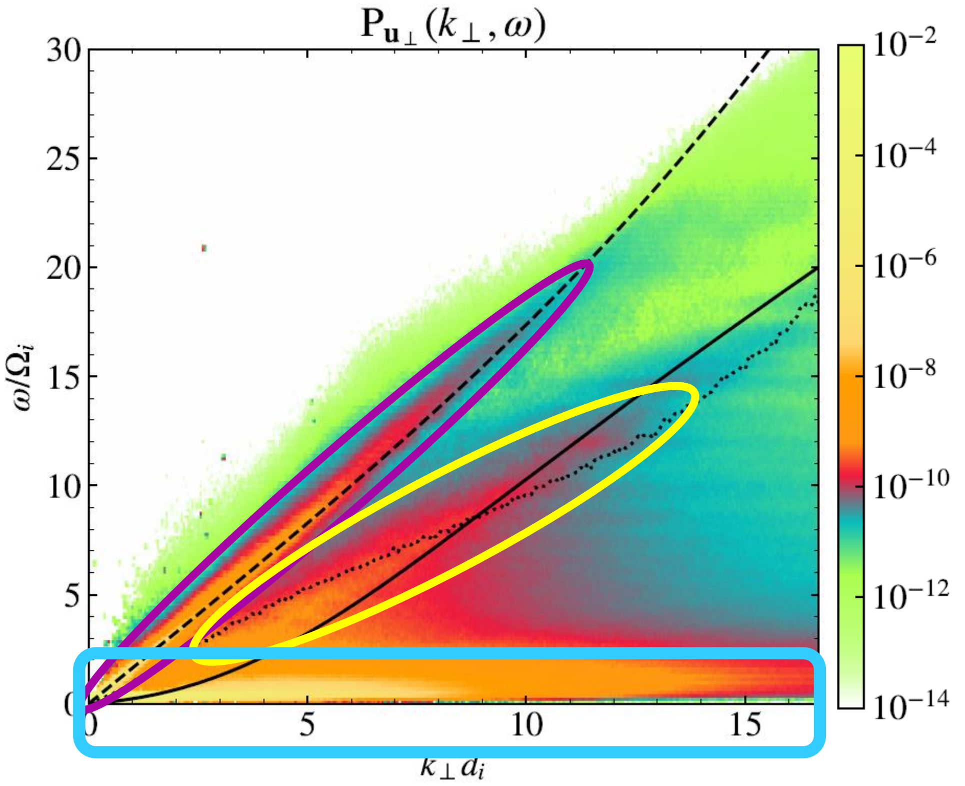
Buiding a $k\omega$-power spectrum of fully developed turbulence

We use Fourier Transform (FT) in space and Fast iterative Filtering (FIF) in time to measure the distribution of magnetic energy in wavenumber-frequency ($k\omega$) space.

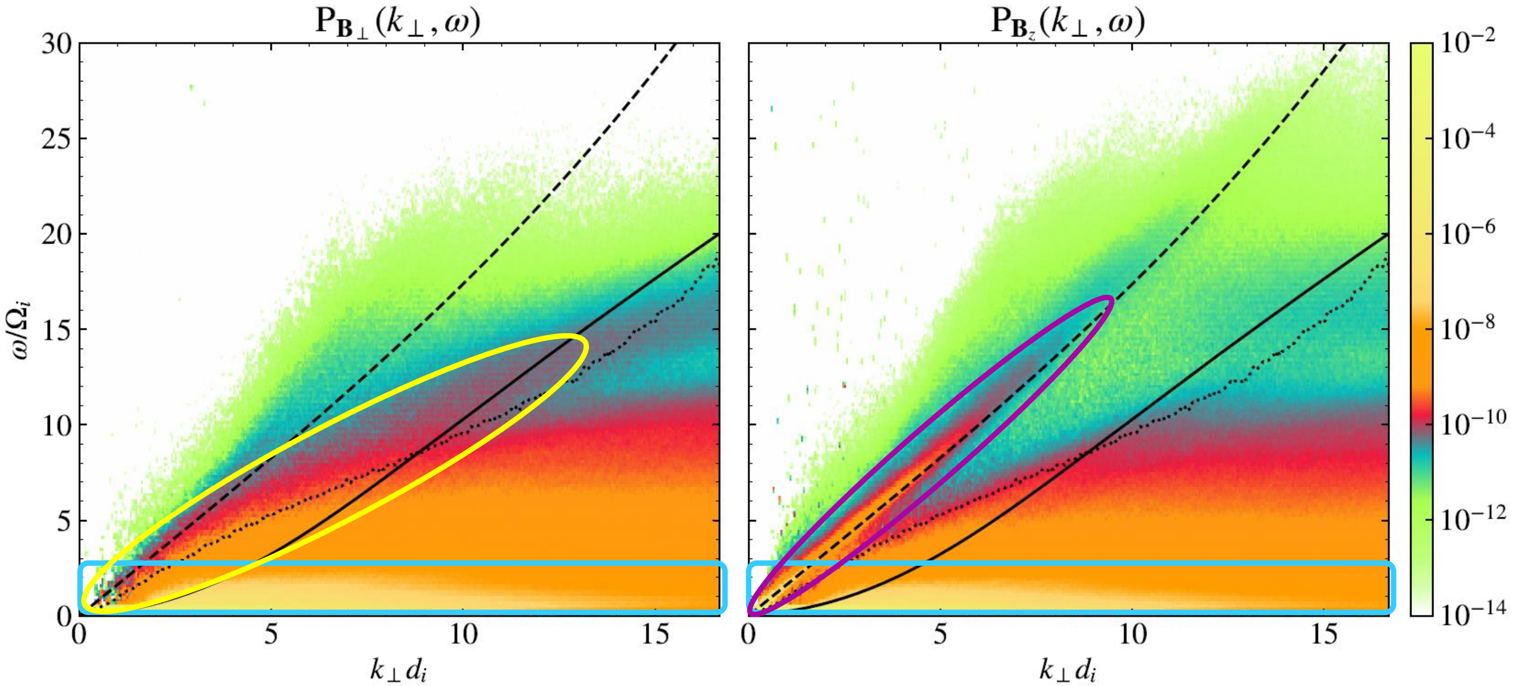
1. At the maximum of turbulent activity and for each quantity (e.g. B_z), we take a datacube of 1024^2x2001 points and with a resolution of $0.125d_i \times 0.125d_i \times 0.01\Omega_i^{-1}$.
2. We perform a 2D FFT to obtain $B_z(k_x,k_y,t)$.
3. For each pair (k_x,k_y), we perform a FIF decomposition and calculate average frequency and amplitude of each IMC.
4. We Interpolate the corresponding power to a (k, ω) grid and sum up the power over all found frequencies **(~2.000.000 complex IMFs found per field)**.

$k\omega$-POWER SPECTRA OF VELOCITY AND MAGNETIC FIELD

Submitted to PRL



kω-diagram of the power spectrum obtained from the FTFIF decomposition of the perpendicular component of the ion-fluid velocity (left) and magnetic field (bottom) at the maximum of turbulent activity. Superimposed is the dispersion relation for Fast/Whistler (FW) (dashed) and Alfvén/Kinetic Alfvén waves (A/KAW) (solid). The dispersion relation is calculated using the mode (84.9°) and the mean (79.3°) of the distribution of the angle between the magnetic field and the simulation plane, where the *k* vectors lie.



1. Clear signature of fast/whistler branch.
2. The signature of KAW activity is seen better in velocity (top).
3. In all the fields, most of the energy is at low frequencies, not clearly related to wave activity.

POWER SPECTRA IN k-SPACE: WAVES ENERGETICS

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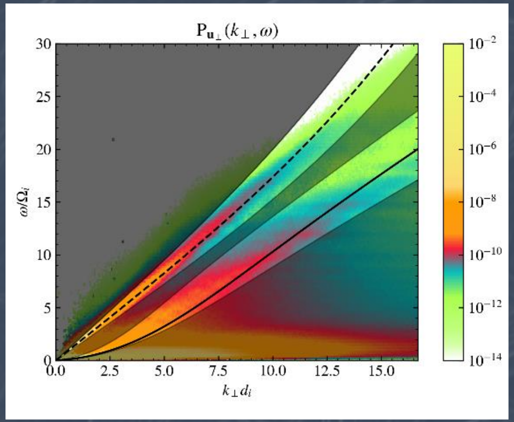


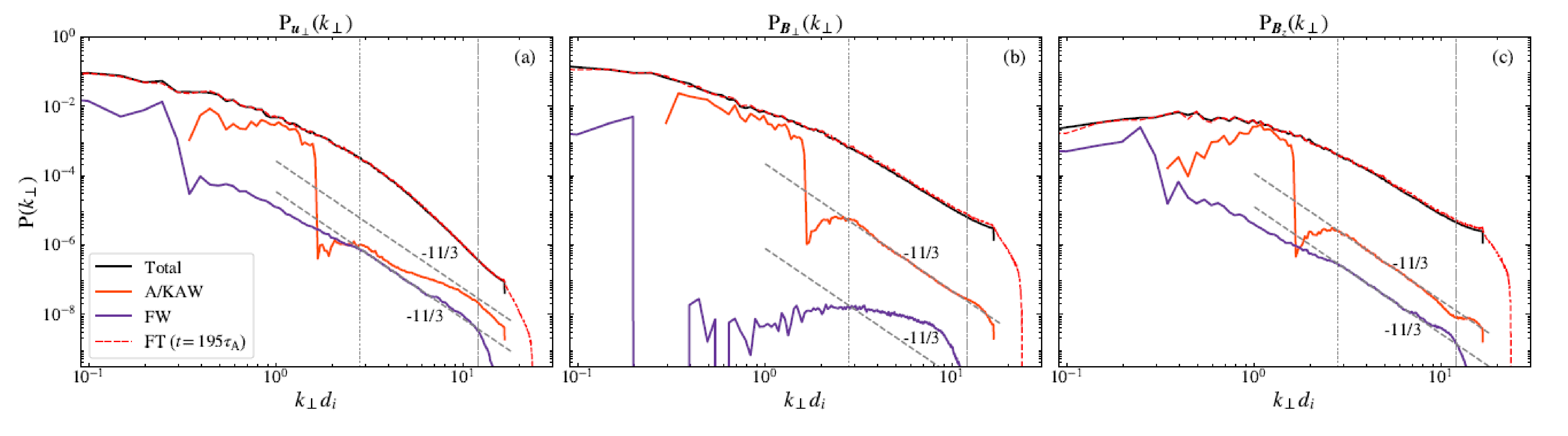
The energetic contribution from wave branches and from low-frequencies is measured by integrating in frequency over selected areas of the $k\omega$-space (see left figure).

Bottom: FW (violet curve) and A/KAW (orange curve) k-power spectra are obtained, together with the spectrum obtained by integrating in ω over the whole area (black solid curve), which correspond to the classic Fourier 1D spectrum (dashed red curve).

THE CONTRIBUTION FROM WAVE BRANCHES IS ENERGETICALLY IRRELEVANT!

But…

The energy at low frequencies could still come from slow/Ion-Cyclotron (S/IC) activity and/or low-frequency almost perpendicular KAWs.



ASSESSING THE NATURE OF LOW-FREQUENCY FLUCTUATIONS

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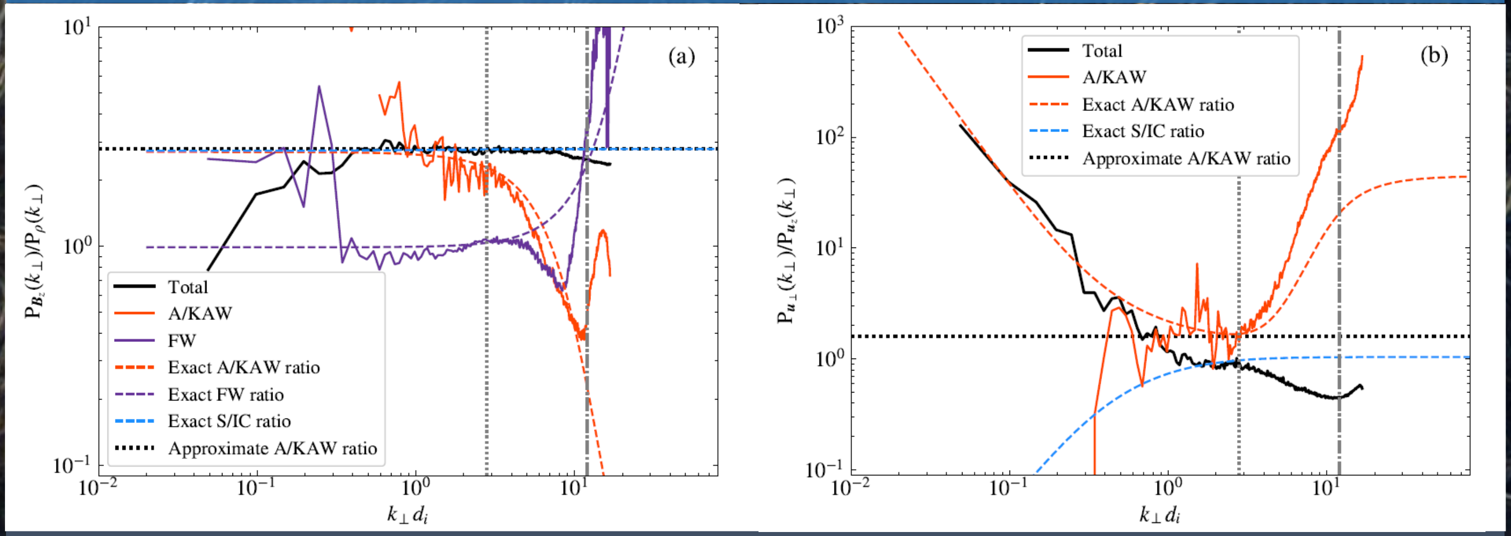
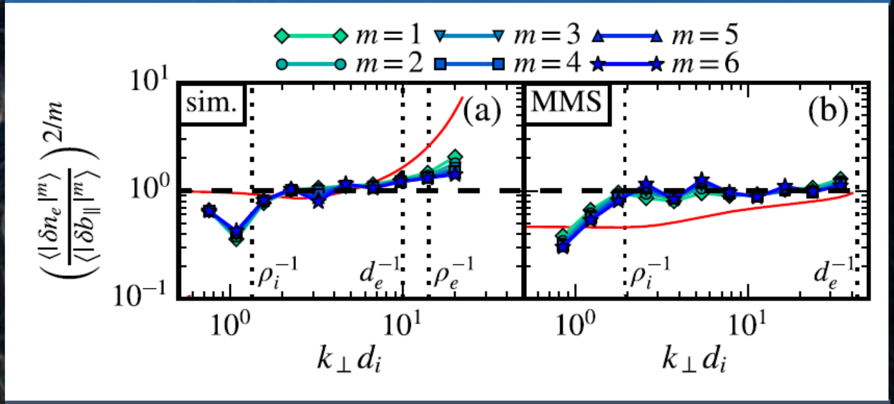
$\delta B_{||}^2/\delta\rho^2$ $\qquad$ $\delta u_{\perp}^2/\delta u_z^2$



The ratios of the power spectra from the wave branches (violet and orange) confirm that they are of wave origin. The ratio $\delta B_{||}^2/\delta\rho^2$ (panel a) of the total spectra (black solid curve) matches with the approximate KAW ratios [8] and with the S/IC ratio from the parallel magnetic spectrum. HOWEVER, the ratio for the velocity fluctuations (panel b) does not match. This, together with the fact that $\delta B_{||}^2/\delta\rho^2$ is not a good proxy for KAW [8], rules out any wavelike energetic contribution at low frequencies.

Grošelj et al. 2019 [9]



The ratio of the total spectra (black solid line of panel a in the left plot) are in agreement with the KAW ratios measured both in 3D FULL-PIC simulations and observations (top right figure). This strongly suggests that our results may hold also in more realistic numerical models, as well as in space plasma environments.

CONCLUSIONS: sub-ion scales turbulence is more structure-*like* than wave-*like*!

REFERENCES

1. K. Kiyani *et al.*, Phil.Trans.R.Soc.A 373: 20140155 (2015).
2. D. Telloni and R. Bruno, MNRAS, 463 L79 (2016).
3. L. Woodham *et al.*, Astrophys. J. 856, 49 (2018).
4. R. Bruno, *Earth and Space Science*, 6:5, pp. 656-672 (2019).
5. Y. Yang *et al.,* Phys. Plasmas 24, 072306 (2017).
6. A. Cicone, Numerical Algorithms 85, 811, (2020).
7. Huang *et al.,* Proceedings of the Royal Society of London Series A 454: 1971, (1998).
8. C. H. K. Chen *et al.*, Phys. Rev. Lett., 110, 225002 (2013).
9. D. Grošelj *et al.,* Phys. Rev. X 9, 031037 (2019).