Multiscale analysis of Hall-MHD and Hybrid-PIC simulations of plasma turbulence: structures or waves?

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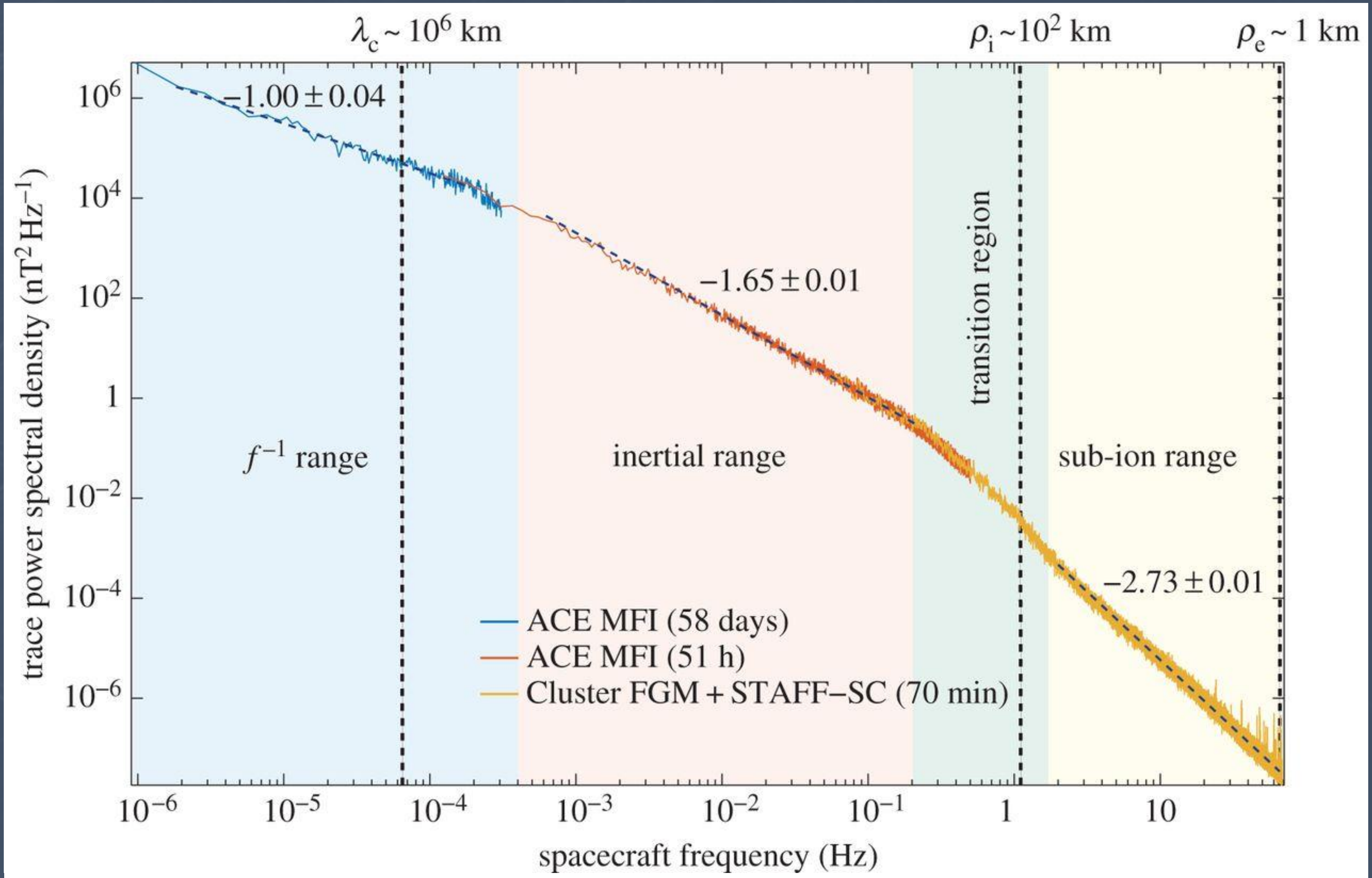
THE NEED FOR A MULTISCALE ANALYSIS OF PLASMA TURBULENCE

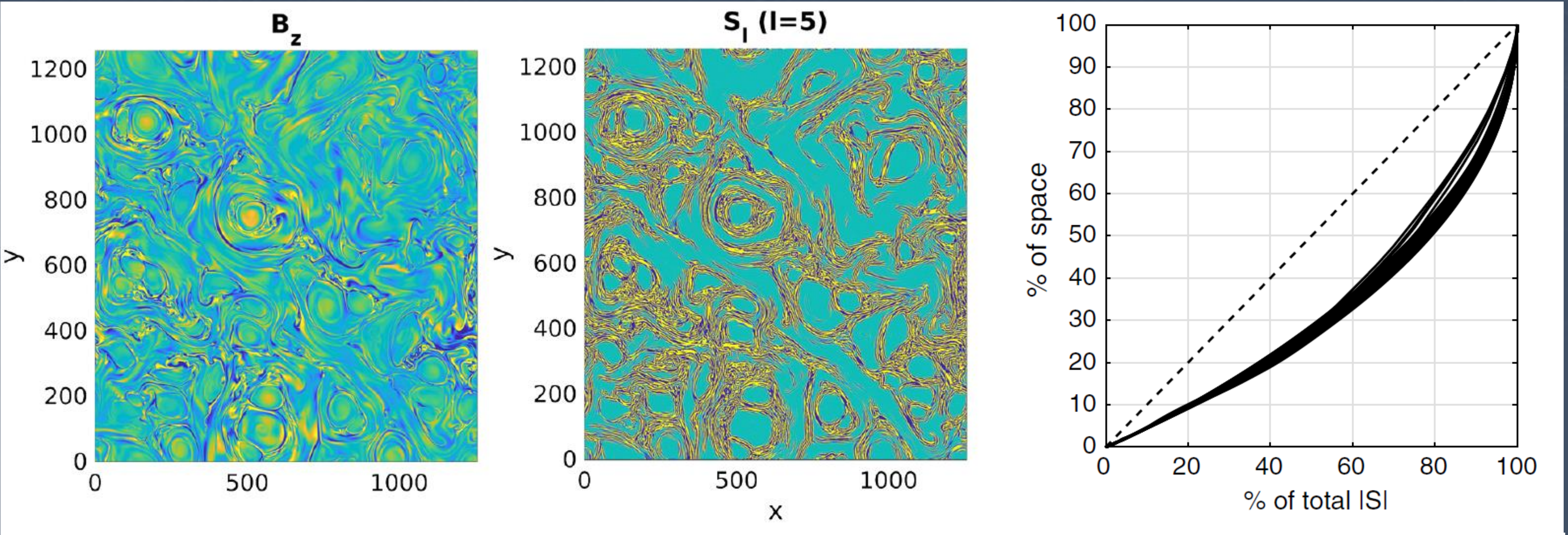
- There is a long standing debate about what causes the kinetic cascade at sub-ion scales.



Kiyani et al. (2015)

THE NEED FOR A MULTISCALE ANALYSIS OF PLASMA TURBULENCE

- There is a long standing debate about what causes the kinetic cascade at sub-ion scales.
- Kinetic-Alfvén-wave interactions (or other wave-like non-linear interactions) may continue the turbulent cascade below d_i. However, the intermittency observed in both simulations and observations, together with the measure of enhanced dissipation in localized structures (**reconnection**), puts doubts on such models.



Camporeale et al., PRL, 120, 125101 (2018)

THE NEED FOR A MULTISCALE ANALYSIS OF PLASMA TURBULENCE

- There is a long standing debate about what causes the kinetic cascade at sub-ion scales.
- Kinetic-Alfvén-wave interactions (or other wave-like non-linear interactions) may continue the turbulent cascade below d_i . However, the intermittency observed in both simulations and observations, together with the measure of enhanced dissipation in localized structures (**reconnection**), puts doubts on 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 stationarity of the signal to be analyzed.

- In what follows, we use **ITERATIVE FILTERS** (and Fourier transforms) to do a space-time analysis of plasma turbulence simulations.

ITERATIVE FILTERS

ITERATIVE FILTERS: A NEW APPROACH TO INVESTIGATE PLASMA TURBULENCE

Cicone, Liu, and Zhou, *Appl. Comput. Harmon. A.*, 41 (2016).

Iterative Filtering (IF) is a new approach for the analysis of non-stationary non-linear signals (1D, 2D,…) similar to the Empirical Mode Decomposition (EMD, Huang et al. 1998).

IF decomposes a (multidimensional) signal, $f(\boldsymbol{x})$, into a finite number N of Intrinsic Mode Functions (IMFs):

$$f(\boldsymbol{x}) = \sum_{j=1}^{N} \mathrm{IMF}_j(\boldsymbol{x}) + r_{f,N}(\boldsymbol{x}), \qquad \boldsymbol{x} \in \mathbf{R}^{\boldsymbol{k}}$$

- Each IMF is the result of an iterative procedure that, by using a low-pass filter $w_j(\boldsymbol{t})$, isolates a fluctuating component whose frequency is well-behaved:

$$\mathrm{IMF}_j(\boldsymbol{x}) = \lim_{n\to\infty} S_{j,n}(r_n), \text{ where}$$

$$S_{j,n}(r_n) = r_{j,n} - \int r_{j,n}(\boldsymbol{x}+\boldsymbol{t}) w_j(\boldsymbol{t}) \mathrm{d}^k t, \qquad r_{j,n} = S_{j,n-1}(r_{j,n-1}),$$

- IF methods **give a convergent solution for any L^2 signal, also in presence of noise.**
- Iterative filters have already been applied to the analysis of geomagnetic data (Piersanti et al. 2018).

MULTISCALE ANALYSIS OF TURBULENCE IN SPACE

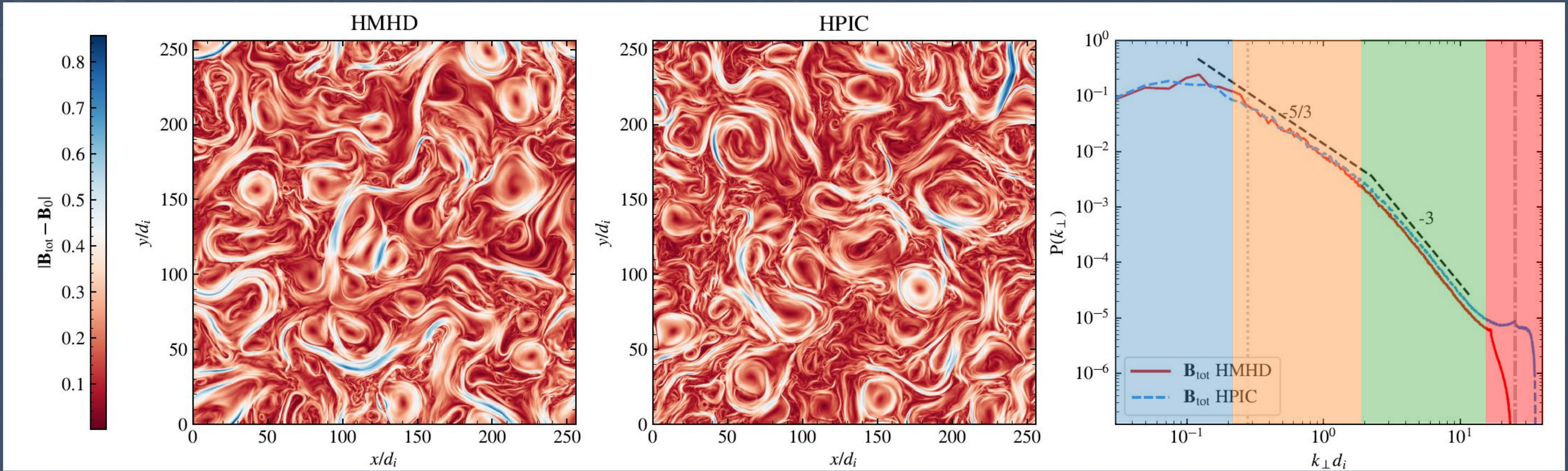
Papini et al. 2020 arXiv:2004.10040

INVESTIGATING PLASMA TURBULENCE WITH MULTIDIMENSIONAL ITERATIVE FILTERING

Papini et al. 2020 arXiv:2004.10040

Our dataset consists of a Hall-MHD (HMHD) and a Hybrid particle-in-cell (HPIC) high-resolution 2D numerical simulations of plasma turbulence. Turbulent properties are thoroughly characterized by **Papini et al., ApJ, 870, 52 (2019)**.

- We performed a multiscale analysis at the peak of the turbulent activity

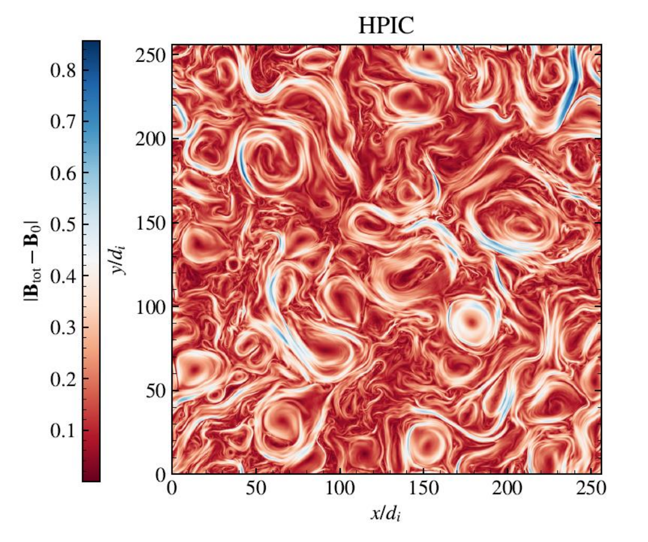


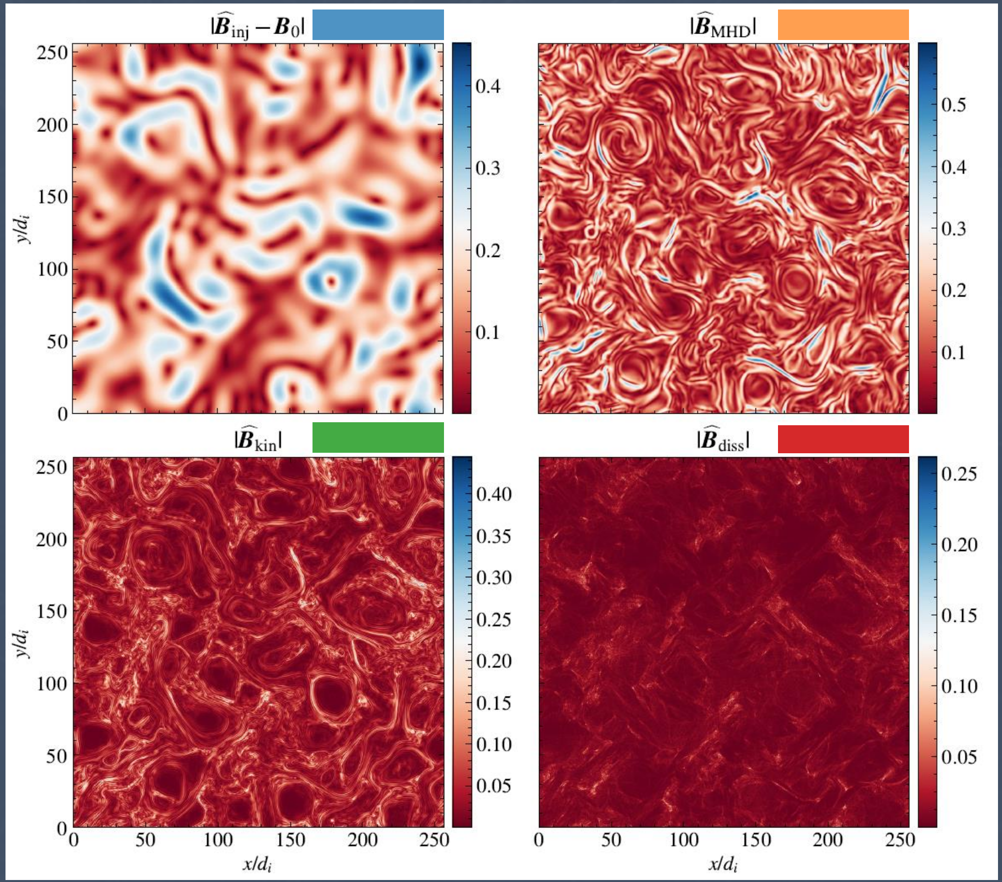
- In the power spectra, we can see four different relevant scales: Injection scales (**inj**), the inertial range scales (**MHD**), ion-kinetic scales (**kin**) and dissipation scales (**diss**).
- Thanks to MIF, we successfully separated the contribution of magnetic features at those scales!

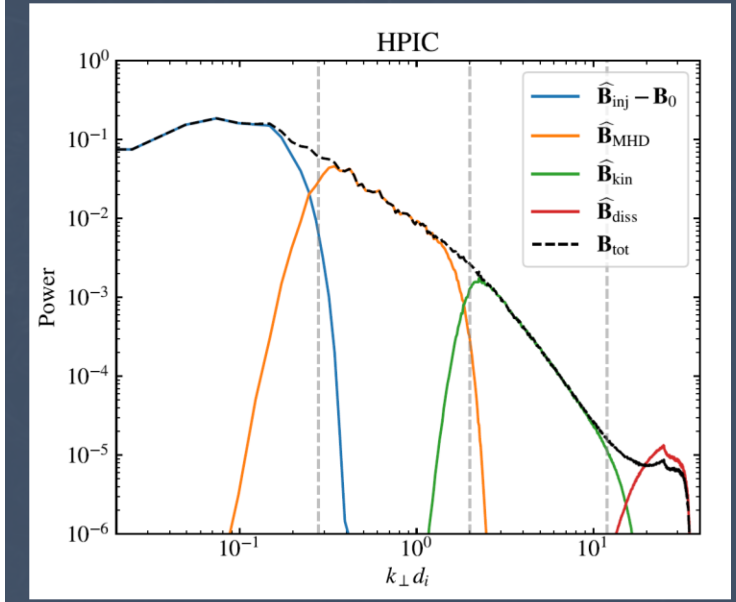
INVESTIGATING PLASMA TURBULENCE WITH MULTIDIMENSIONAL ITERATIVE FILTERING

Papini et al. 2020 arXiv:2004.10040, submitted to JPP

- We performed a multiscale analysis at the peak of the turbulent activity (only HPIC results are shown):





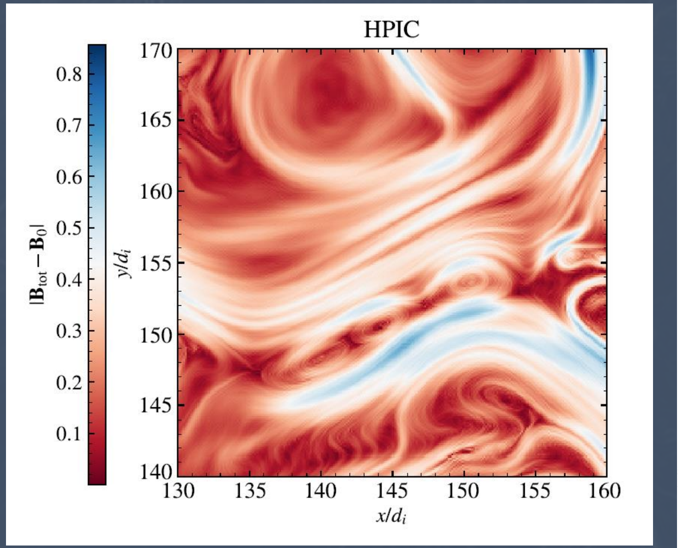


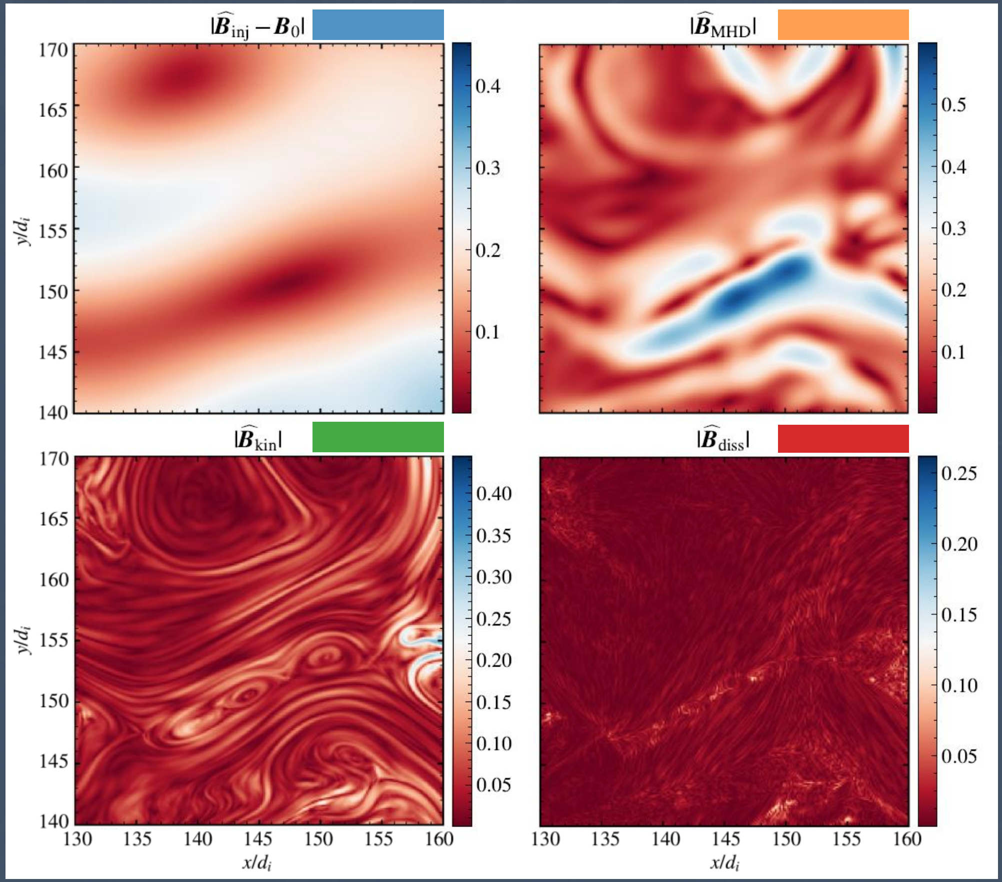
- Sub-ion scales are organized in a filamented network where dissipation is enhanced.
- Morphological and physical multiscale properties of reconnection are nicely separated (see next slide).

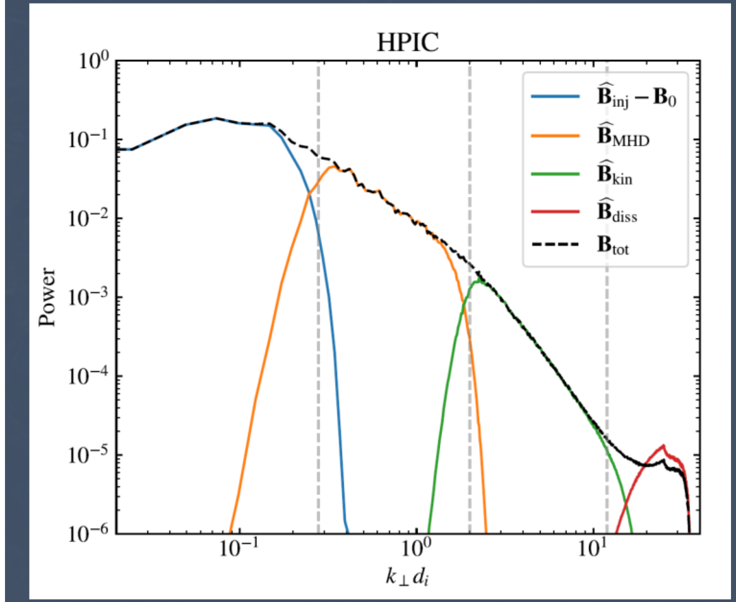
INVESTIGATING PLASMA TURBULENCE WITH MULTIDIMENSIONAL ITERATIVE FILTERING

Papini et al. 2020 arXiv:2004.10040, submitted to JPP

- Zooming to a sub-region where plasmoid reconnection is taking place (3 plasmoids are visible):



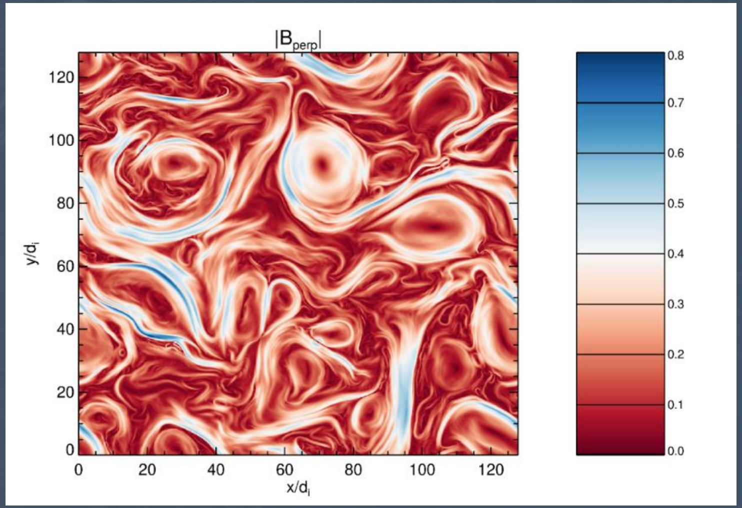
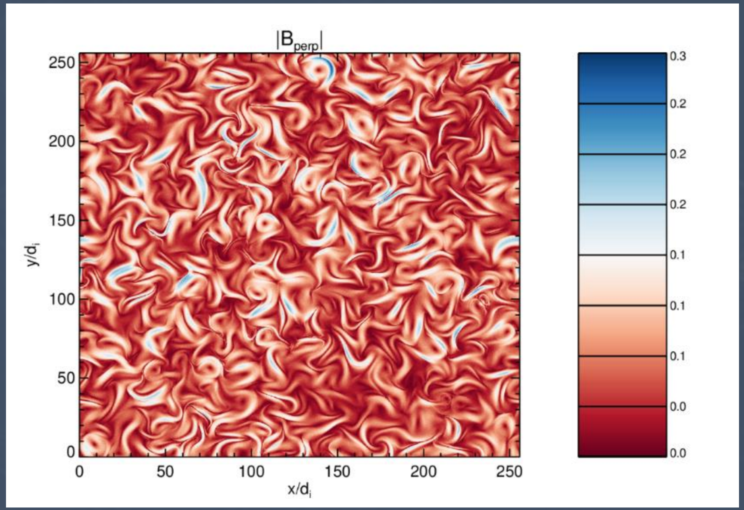




- **Morphological** (plasmoid chain in $|\widehat{B}_{\rm kin}|$) and **physical** (enhanced dissipation at the X-points in $|\widehat{B}_{\rm diss}|$) multiscale properties of **reconnection** are nicely separated and identified.

UNRAVELING SPACETIME TURBULENCE

NUMERICAL SETUP

HMHD	HPIC
	

HMHD

- Periodic 2D domain:
  Grid: **1024^2** Resolution Δx: $d_i/8$ Box size: **$128\ d_i$**
- **B_0** mean field out of plane, along the z direction.
- **Freely-decaying turbulence:** Alfvénic-like fluctuations.
- b_{rms}: 0.24 B_0 .
- Initial energy-containing scale $k_\perp d_i < 0.3$.
- Plasma beta: β = 2.
- Magnetic resistivity: $\eta = 10^{-3}$ $\rightarrow$ $S \approx 4{\cdot}10^4$, $\nu/\eta = 1$
- Maximum of turbulent activity at **$t = 195t_A$**.

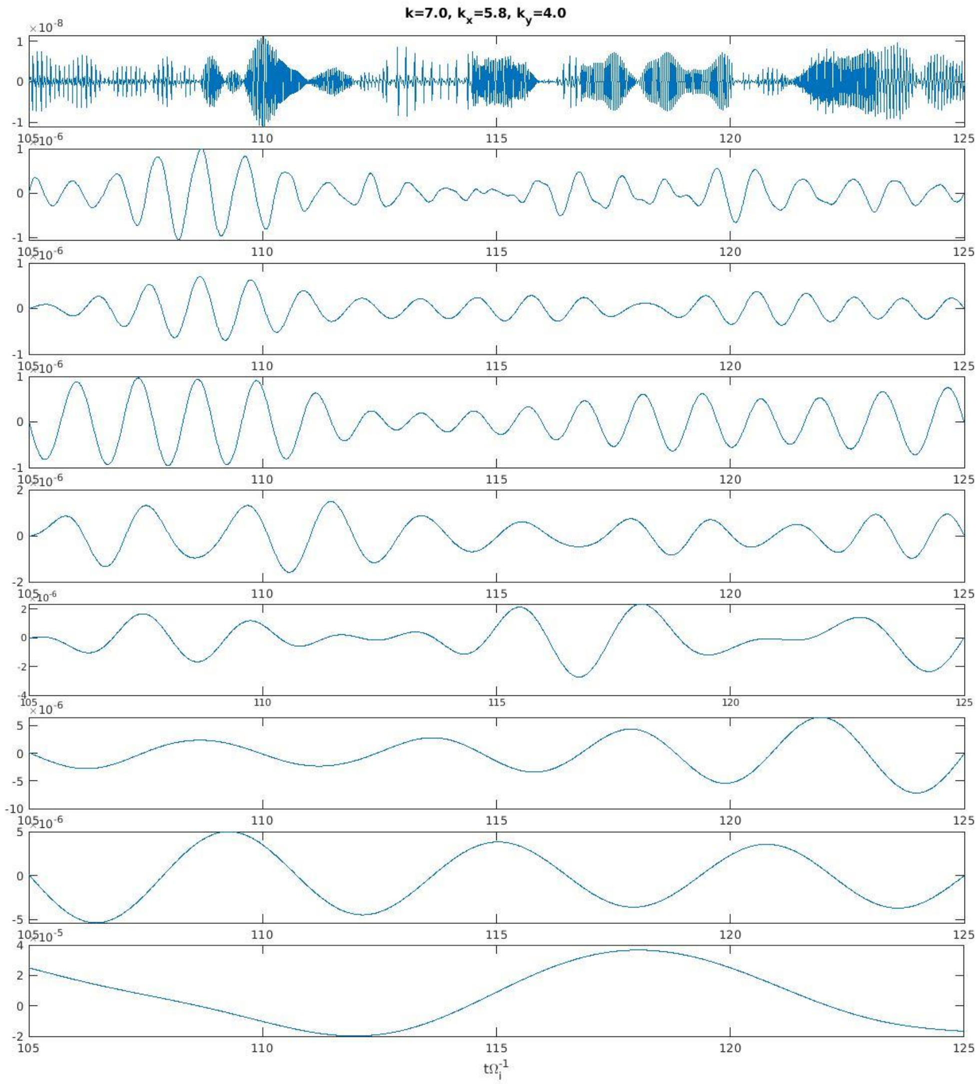
HPIC

- Periodic 2D domain:
  Grid: **2048^2** Resolution Δx: $d_i/8$ Box size: **$256\ d_i$**
- **B_0** mean field out of plane, along the z direction.
- **Freely-decaying turbulence:** Alfvénic-like fluctuations.
- b_{rms}: 0.25 B_0 .
- Initial energy-containing scale $k_\perp d_i < 0.6$.
- Ion (electron) plasma beta: β_i = 0.5 (β_e = 0.5)
- Magnetic resistivity: $\eta = 5{\cdot}10^{-4}$ $\rightarrow$ $S \approx 8{\cdot}10^4$, $\nu/\eta = 1$
- Maximum of turbulent activity at **$t = 105t_A$**.

Units and normalizations: space: $d_i = V_A/\Omega_i$, time: $\tau_A = \Omega_i^{-1}$, magnetic field: B_0 (ambient field)

TIME FREQUENCY ANALYSIS WITH ITERATIVE FILTERING

Example of IF decomposition of $v_y(kx=5.8,ky=4.0,t)$

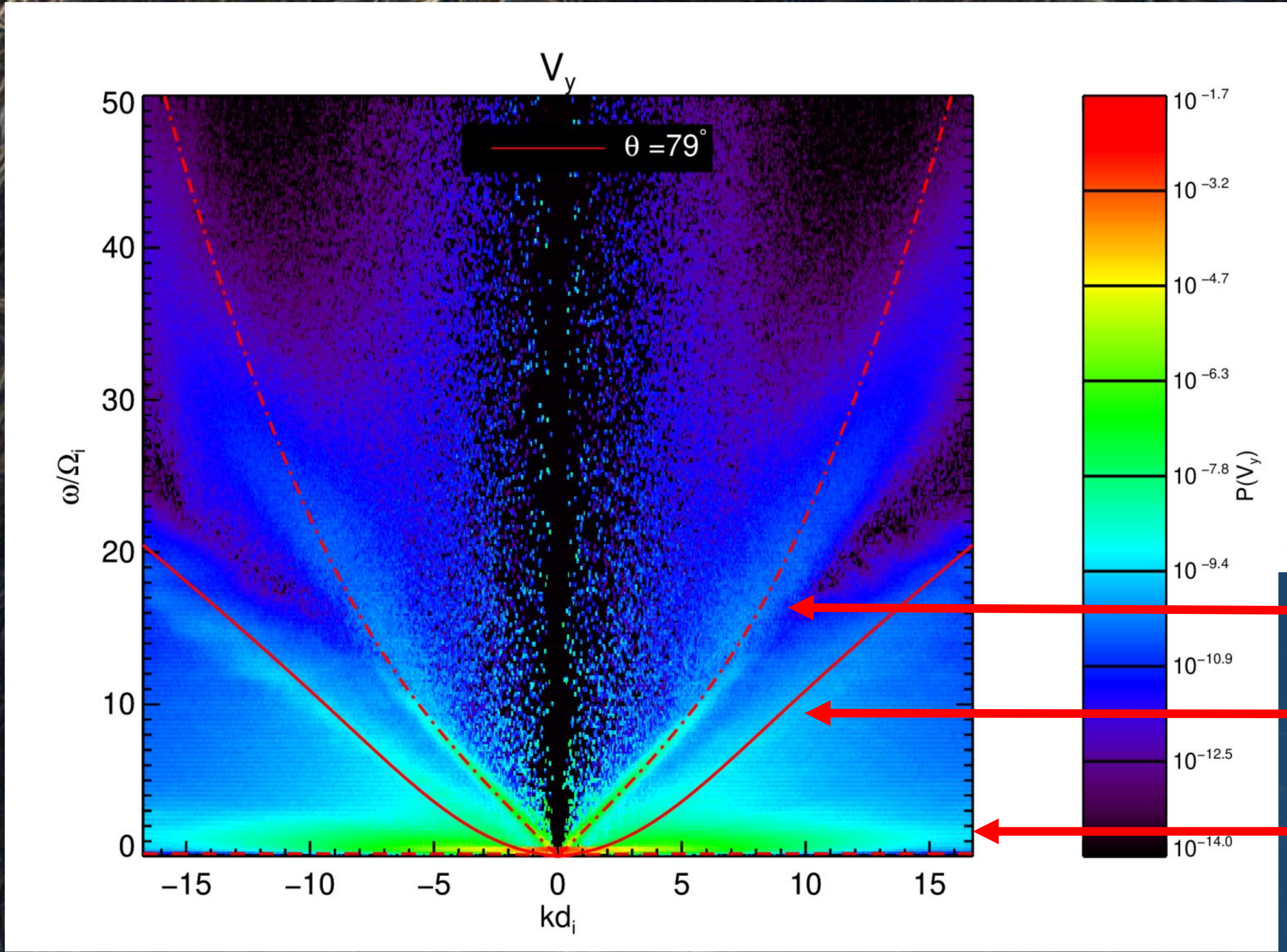


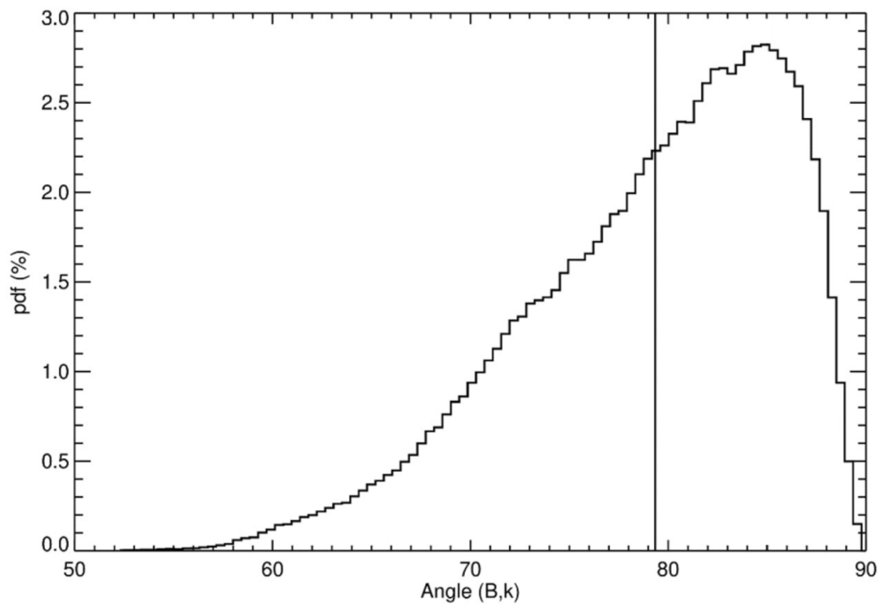
DATASET PREPARATION AND ANALYSIS PROCEDURE

1. We let the plasma dynamics evolve (up to $t=300t_A$ in HMHD and to $t=150t_A$ in HPIC) run, in order to correctly identify the maximum of turbulent activity (around $t=195t_A$ and $t=105t_A$).
2. We then restart the simulation at that time and run it up to $t=215t_A$ ($125t_A$) with an output of cadence $0.01t_A$ (Ω_i^{-1}).
3. We take a field component, say $B_z(x,y,t)$.
4. We perform a 2D FFT to obtain $B_z(k_x,k_y,t)$.
5. For each pair (k_x,k_y) we perform a IF decomposition and calculate average frequency and amplitude of each IMF.
6. We interpolate the corresponding power to a k,ω grid and sum up over all found frequencies and powers.

Done for all the fields!

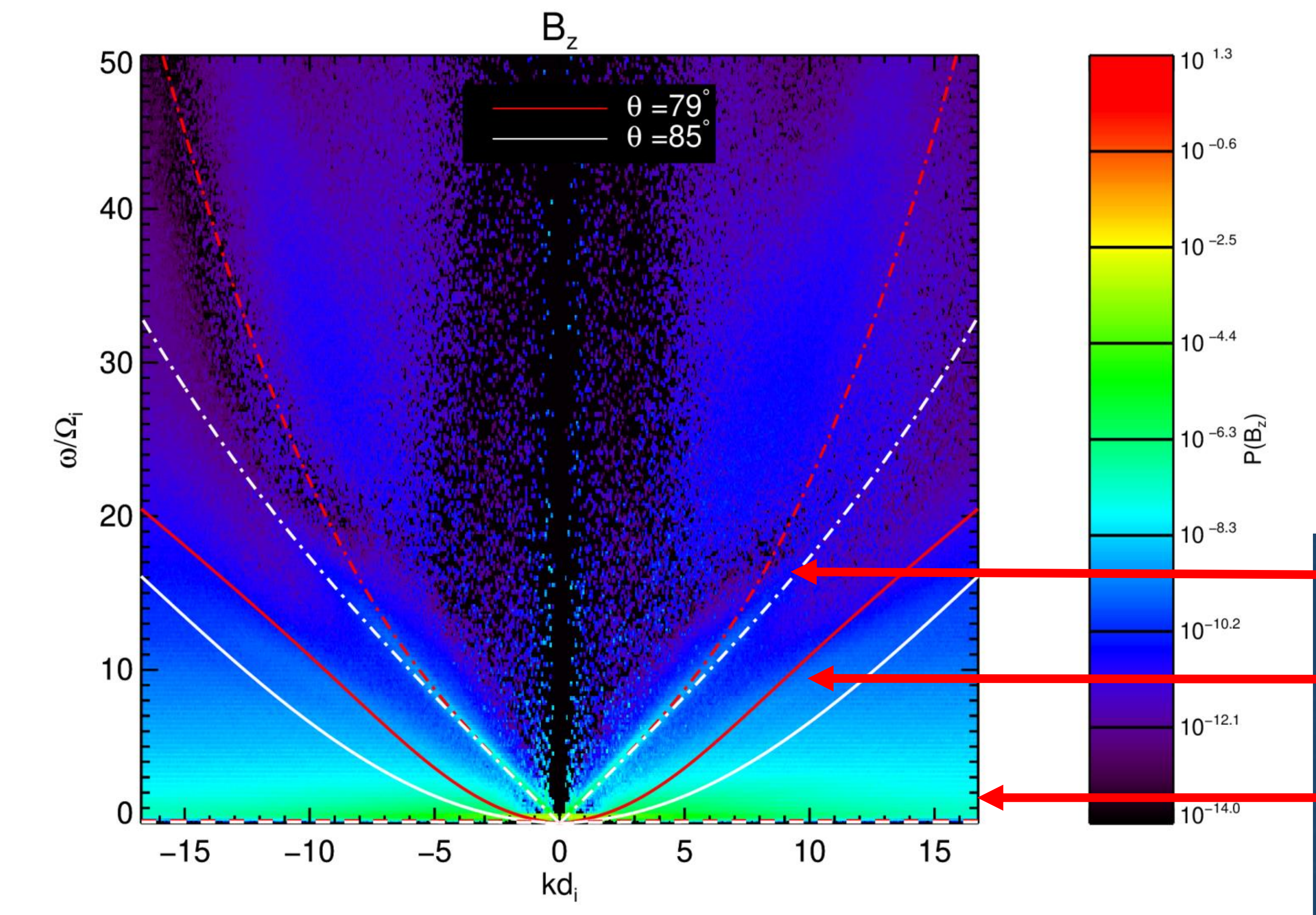
k-ω DIAGRAM: VELOCITY FIELD (IN-PLANE) HMHD

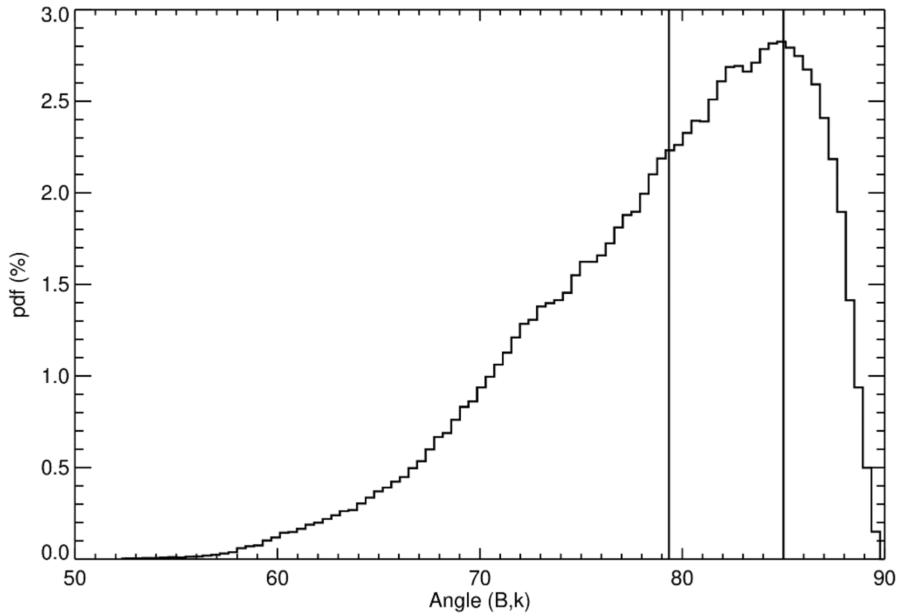




1. Clear signature of fast/whistler branch.
2. The signature of (K)AW activity is seen better in velocity (see next slide for B).
3. Most of the energy is at low frequencies, not clearly related to wave activity.

k-ω DIAGRAM: MAGNETIC FIELD (OUT-OF-PLANE) HMHD

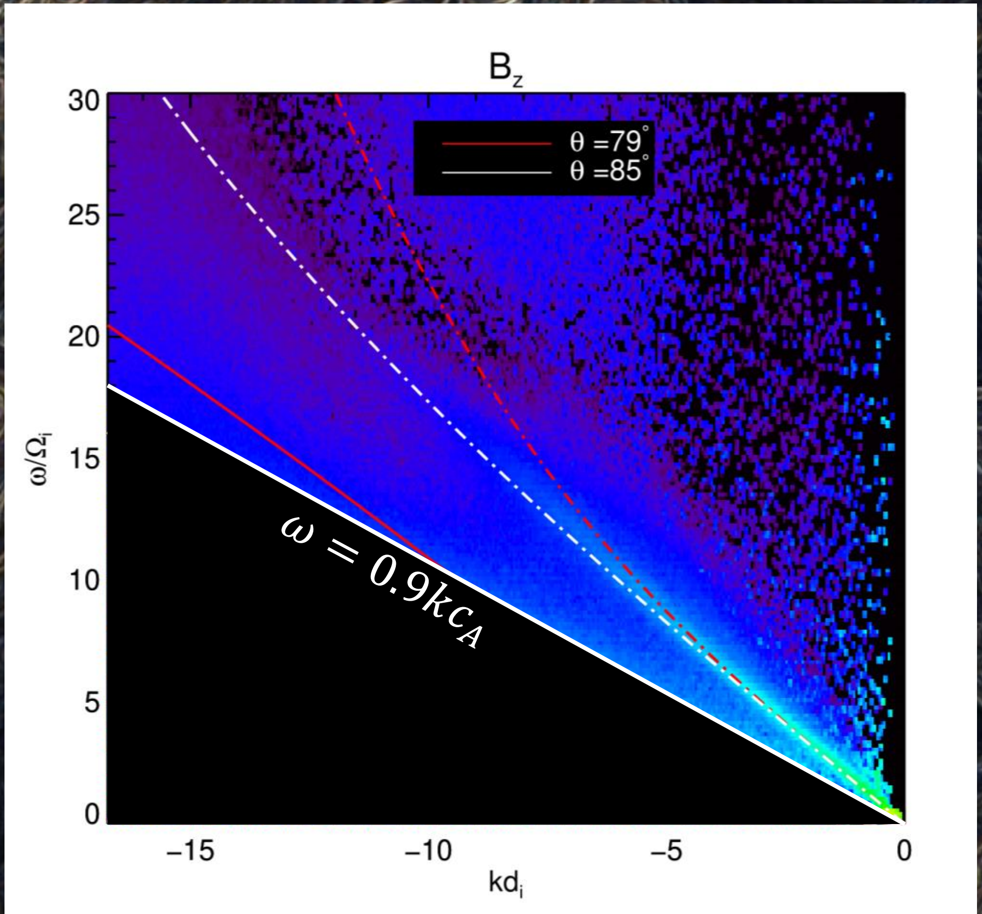


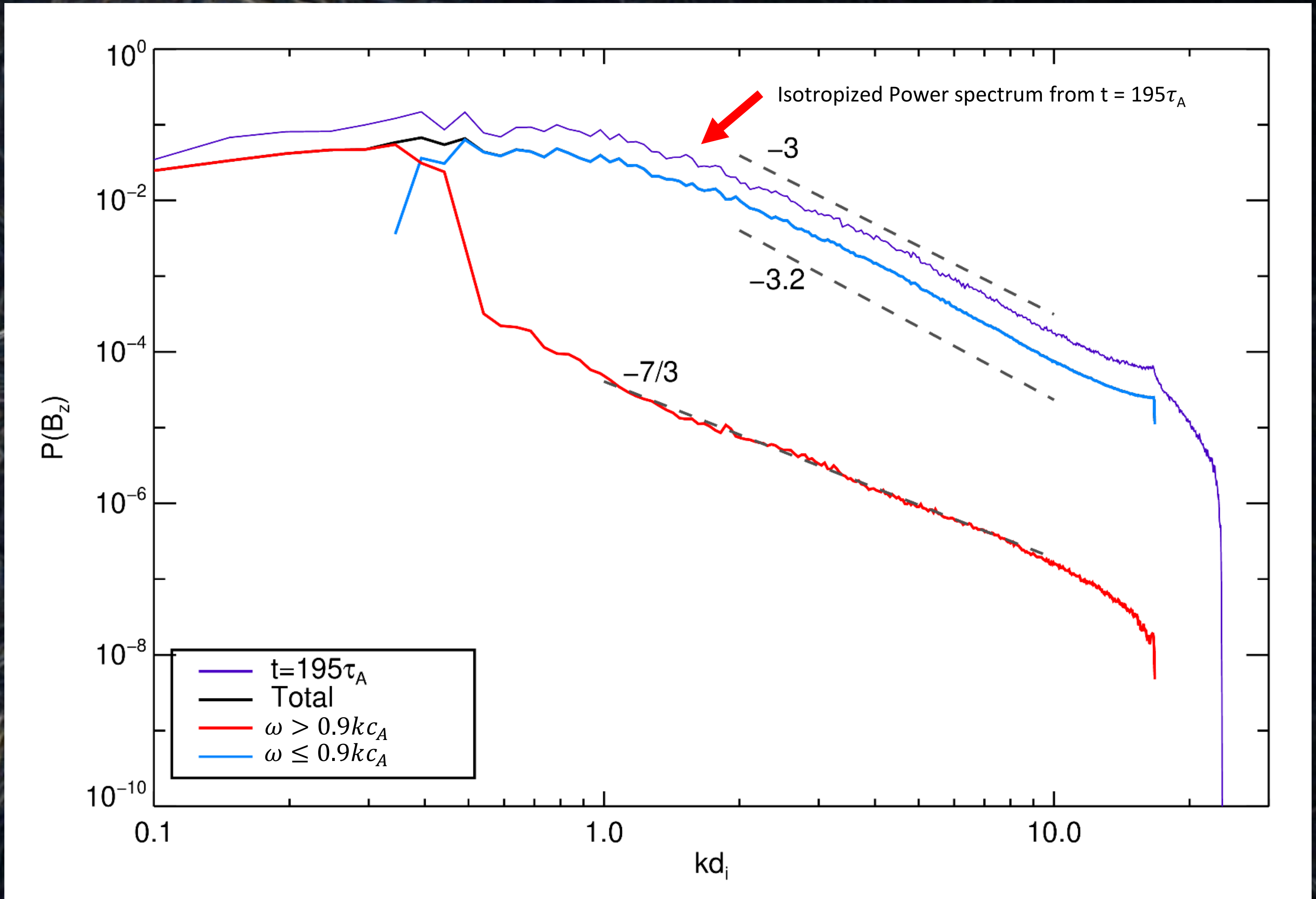


1. Clear signature of fast/whistler branch.
2. Hints of (K)AW activity (but not as clean as in velocity).
3. Most of the energy is at low frequencies, not clearly related to wave activity.

HOW DOES THE K-SPECTRUM LOOK LIKE?

POWER SPECTRUM: WAVES CONTRIBUTION HMHD



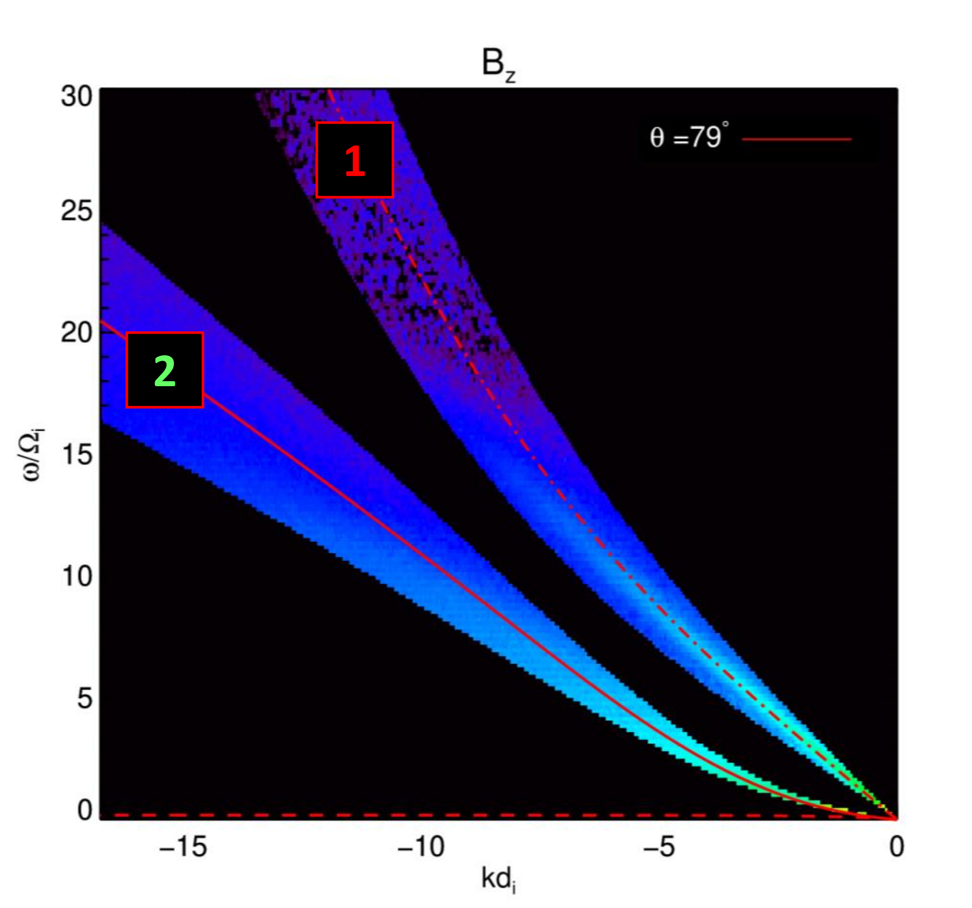


NICE -7/3 SLOPE, BUT …

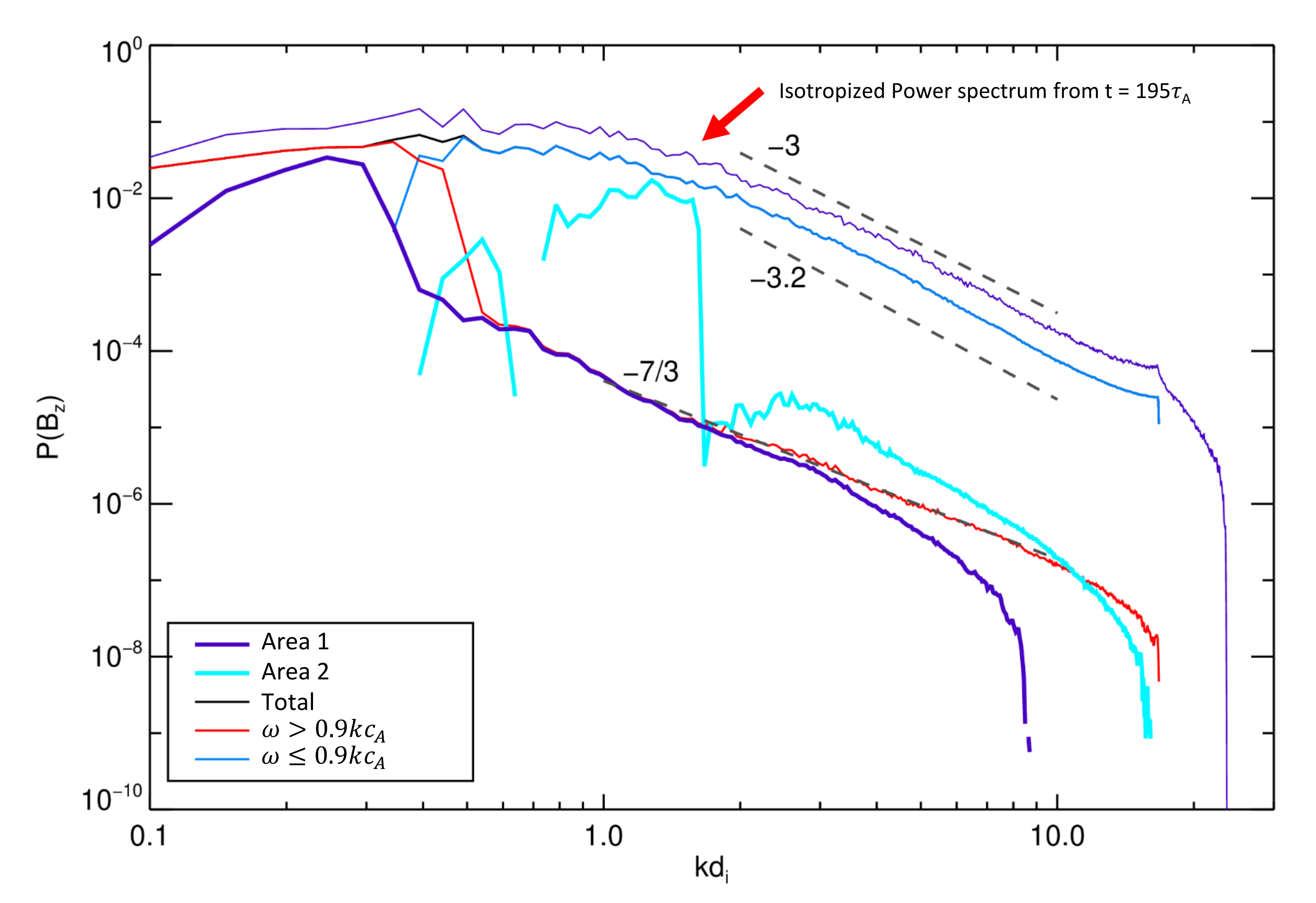
ENERGETICALLY IRRELEVANT!

Spectra obtained by integrating over ω in selected areas of the k-ω diagram. The violet curve is the 1D Isotropized Power spectrum at t = $195\tau_A$.

POWER SPECTRUM: WAVES CONTRIBUTION HMHD



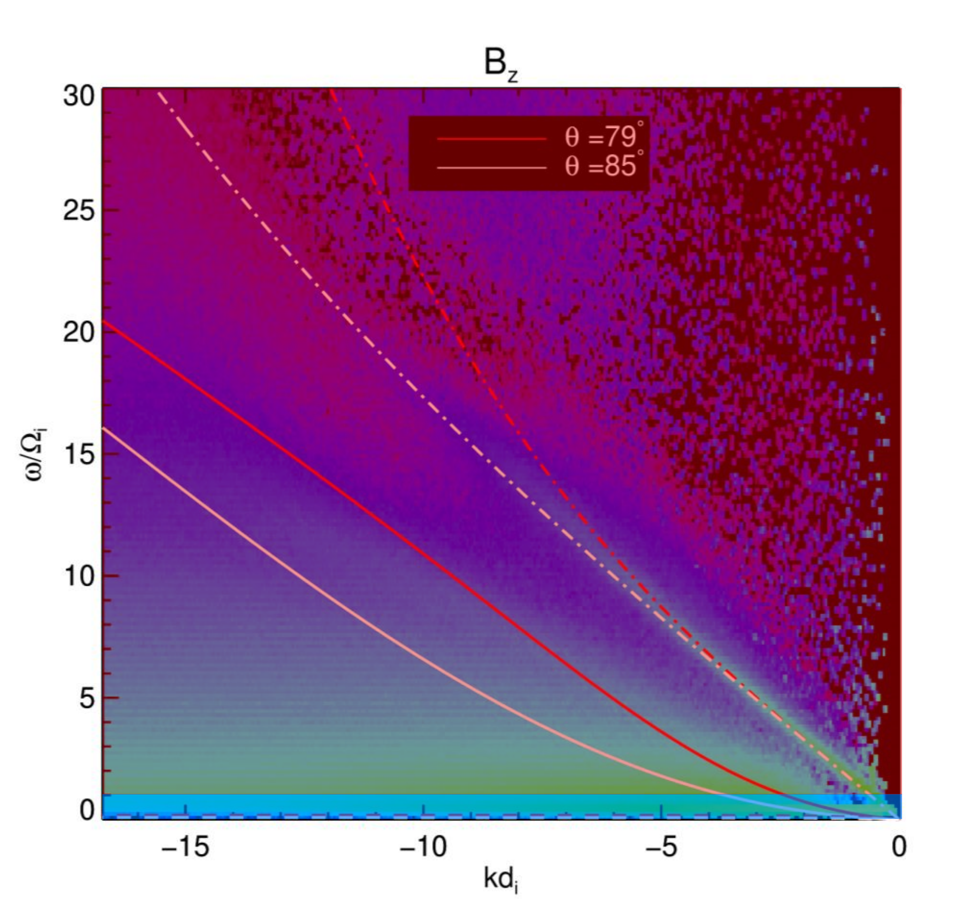
Area 1 and 2 cover the whistler and KAW dispersion relation, within a tolerance in frequency (with *k* fixed) of 25%.

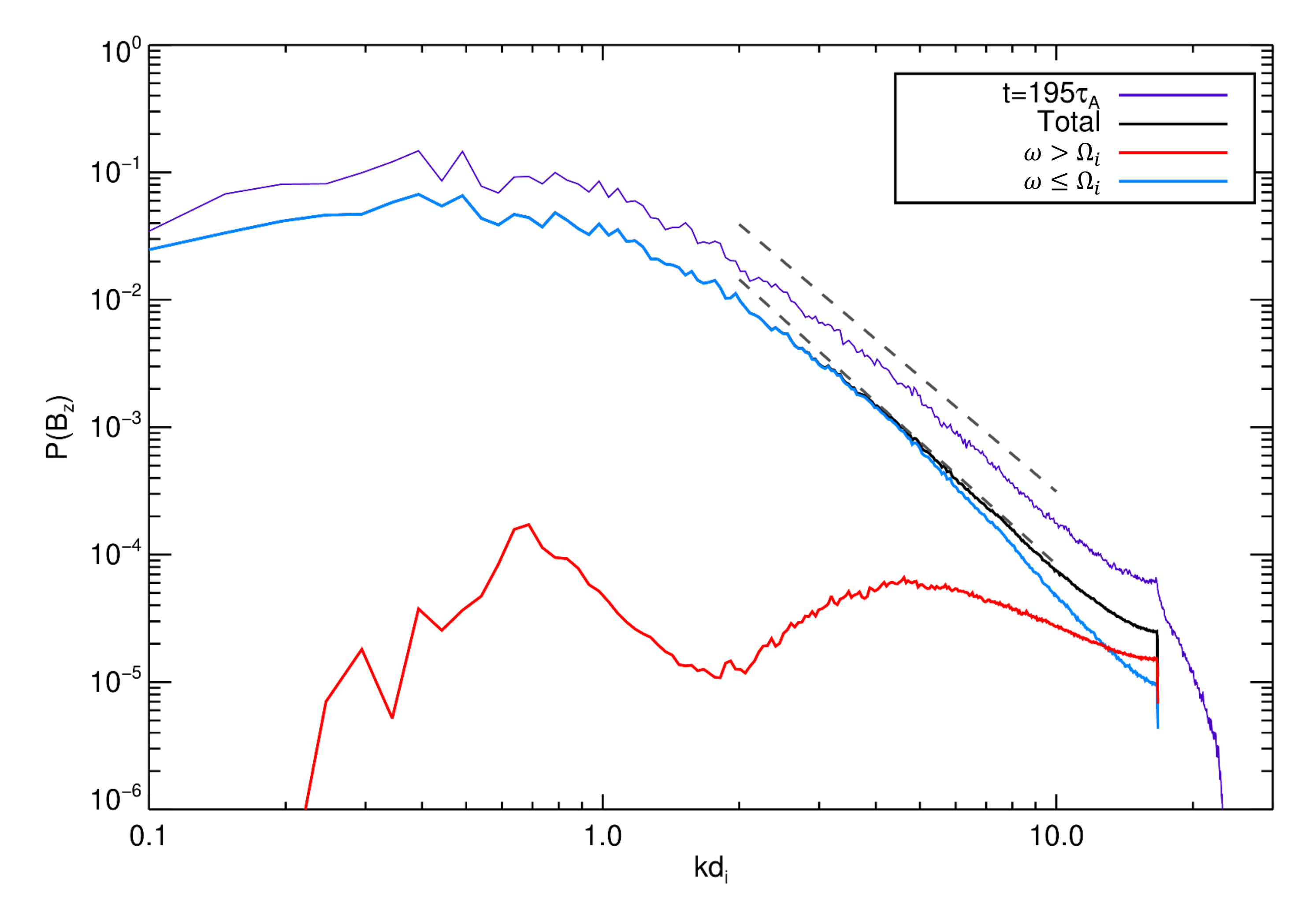


Spectra obtained by integrating over ω in selected areas of the k-ω diagram. The violet curve is the 1D isotropized Power spectrum at t = $195\tau_A$.

WAVES OR STRUCTURES?: ω > Ω$_i$

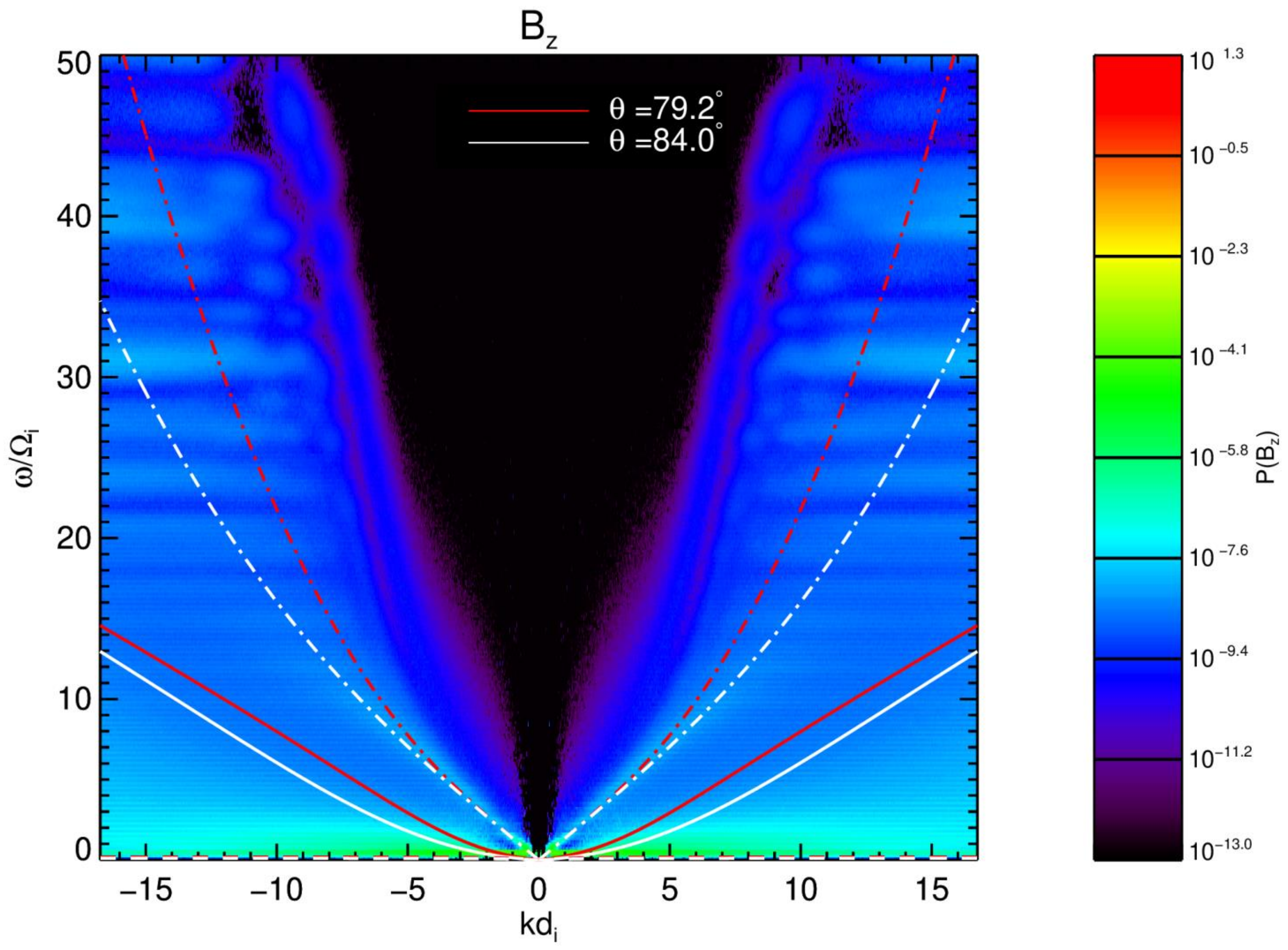
HMHD

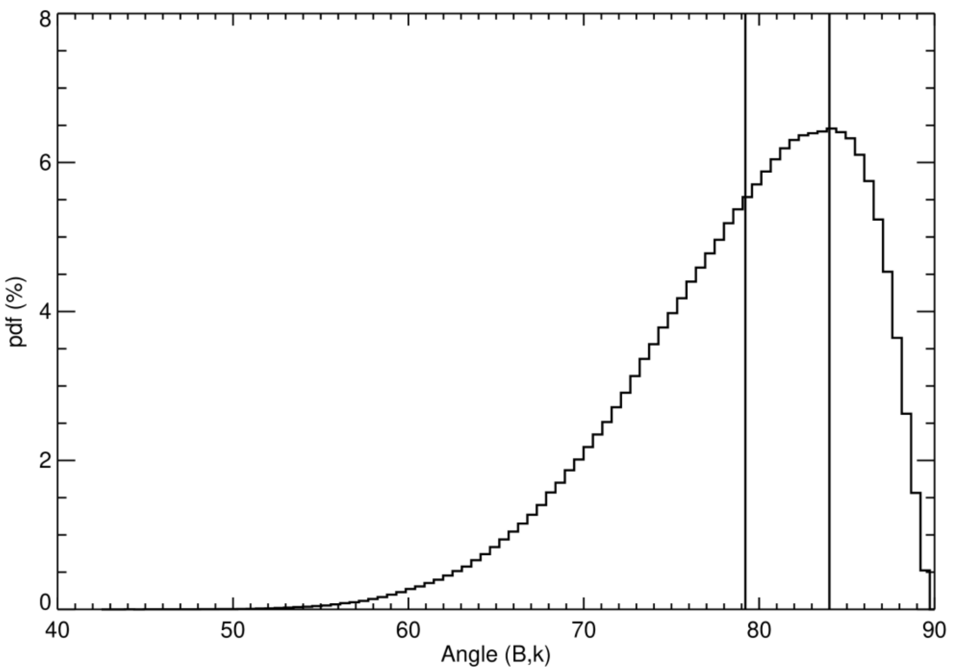




Spectra obtained by integrating over ω in selected areas of the k-ω diagram. Almost all the power is at $\omega \leq \Omega_i$ (blue curve) and likely due to structures.

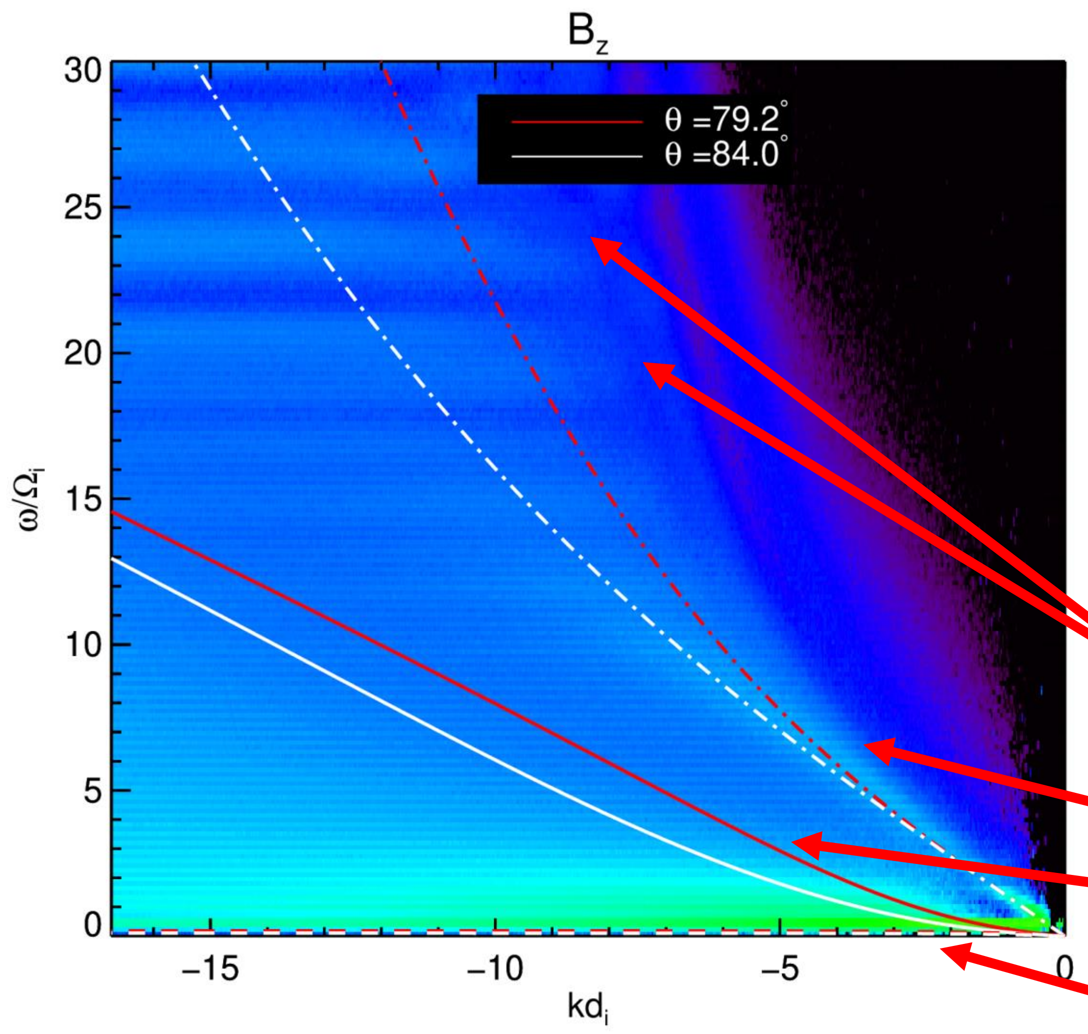
k-ω DIAGRAM: MAGNETIC FIELD (OUT-OF-PLANE) HPIC



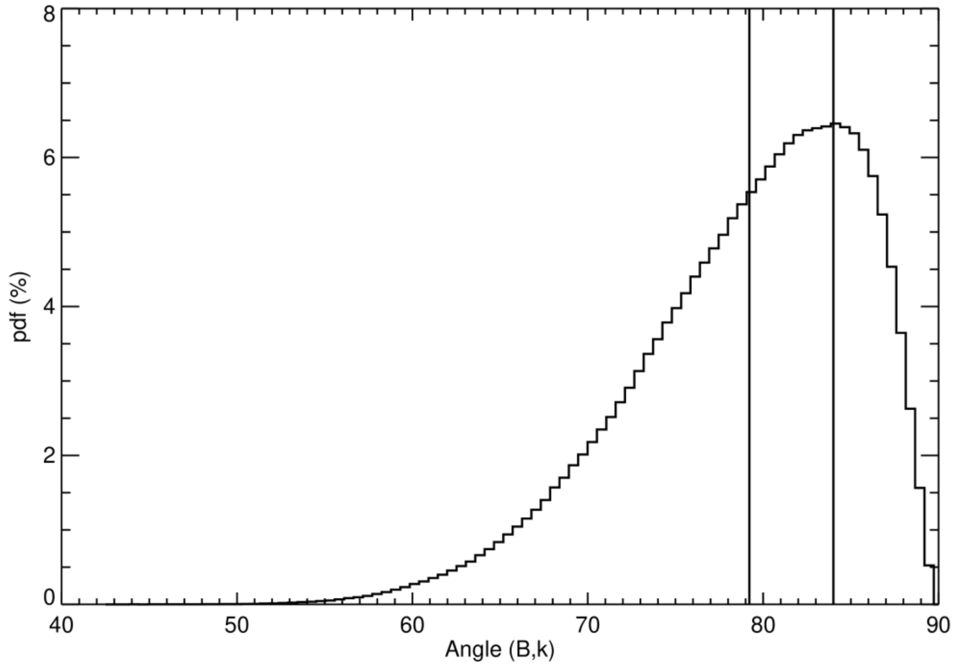


1. Horizontal bands of activity, possibly from ion-Bernstein waves?
2. Signature of fast/whistler waves.
3. No clear (K)AW dispersion relation (B, ion velocity, density, …).
4. Most of energy is at low frequencies, not clearly related to wave activity.

k-ω DIAGRAM: MAGNETIC FIELD (OUT-OF-PLANE) HPIC



Zoom of ***k***-ω diagram from previous slide.



1. Horizontal bands of activity, possibly from **ion-Bernstein** waves?
2. Signature of **fast/whistler** waves.
3. **No clear (K)AW** dispersion relation (B, ion velocity, density, …).
4. Most of energy is **at low frequencies**, not clearly related to wave activity.

WRAPPING UP…

- Iterative Filtering offers many potential applications in the analysis of both observation and simulation datasets. **(Papini et al. 2020 arXiv:2004.10040)**
- IF methods are able to separate the contribution of wave-like perturbation and coherent structures, and show that **the spectrum is mainly shaped by low frequency/slowly evolving features**.
- KAW/WHISTLER activity is present in the Hall-MHD data, but **energetically unimportant**.
- WHISTLER activity can be spotted in the HPIC data, no sign of kaw dispersion relations. Hints for the presence of ion Bernstein modes (to be verified), However…
- … **Recall that HPIC and HMHD simulations are different (e.g., in the injection scales and plasma beta)!**
- Need to go 3D to confirm this picture.
- Overall, IF methods arise as ideal candidates for the analysis of both simulation datasets and have many potential applications for the analysis of spacecraft data from, e.g., Parker Solar Probe, Solar Orbiter, and the Magnetospheric Multiscale (MMS) Mission.

Ion-kinetic scales turbulence is structure-*like*, not wave-*like*!

DISENTANGLING WHISTLER WAVES IN SPACETIME

SHOOT ME A PHOTO

WHISTLER BRANCH

QR-1

Movie of the evolution of the filtered fast magnetosonic/whistler branch of B_z (x,y,t) from t=195 t_A to t = 215 t_A.

DOI: 10.13140/RG.2.2.19332.68482

ALL THE REST

QR-2

Movie of the evolution of B_z (x,y,t) with the fast magnetosonic/whistler branch filtered out from t=195 t_A to t = 215 t_A .

DOI: 10.13140/RG.2.2.22688.12809