Young solar wind coherent structures from inertial to sub-ion range

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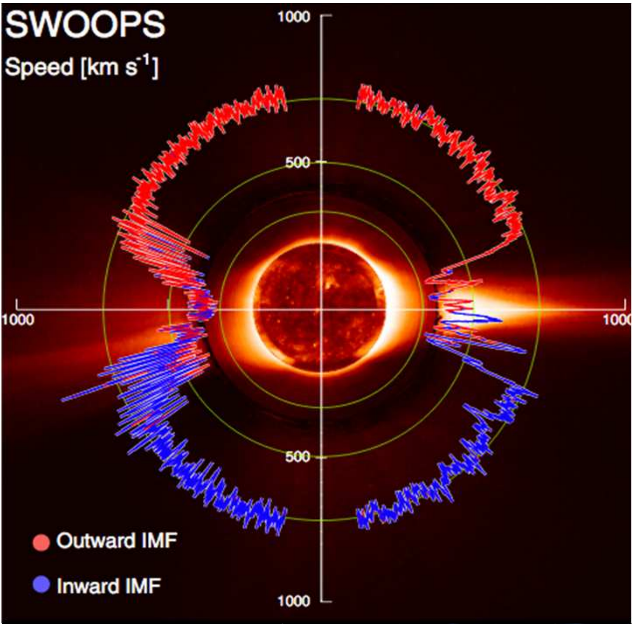
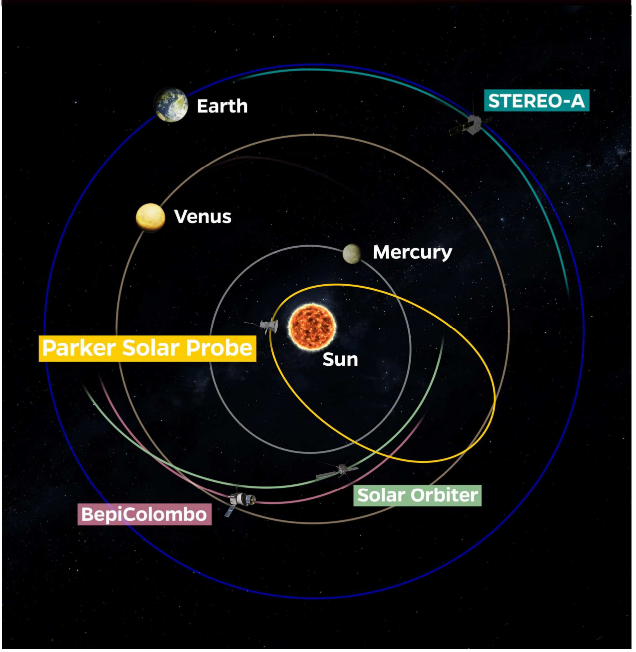
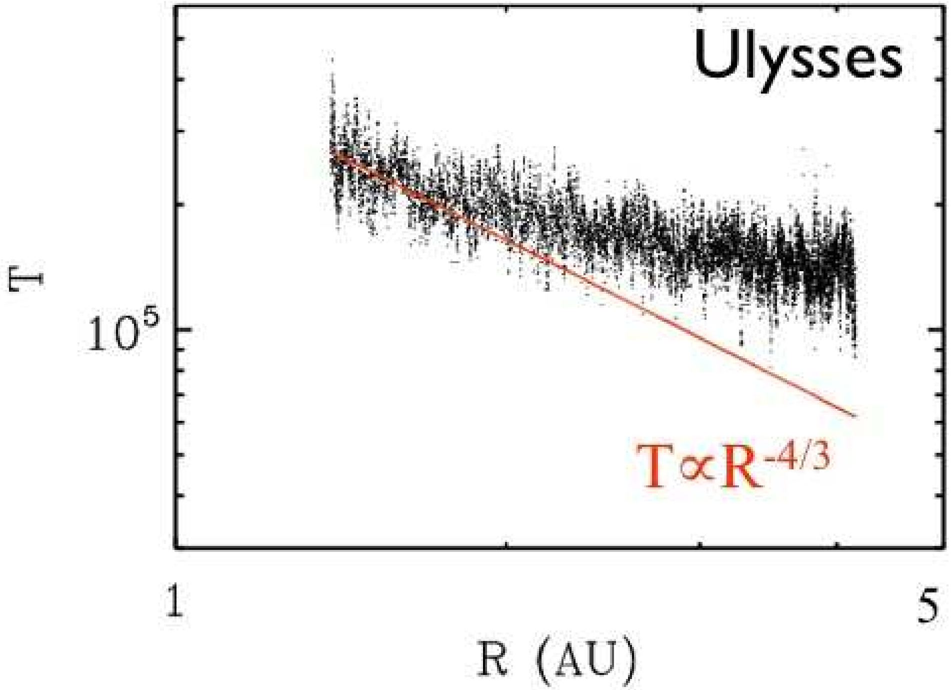




The solar wind

Wind temperature (T_{ions}) decays less than adiabatic ($\sim R^{-4/3}$)

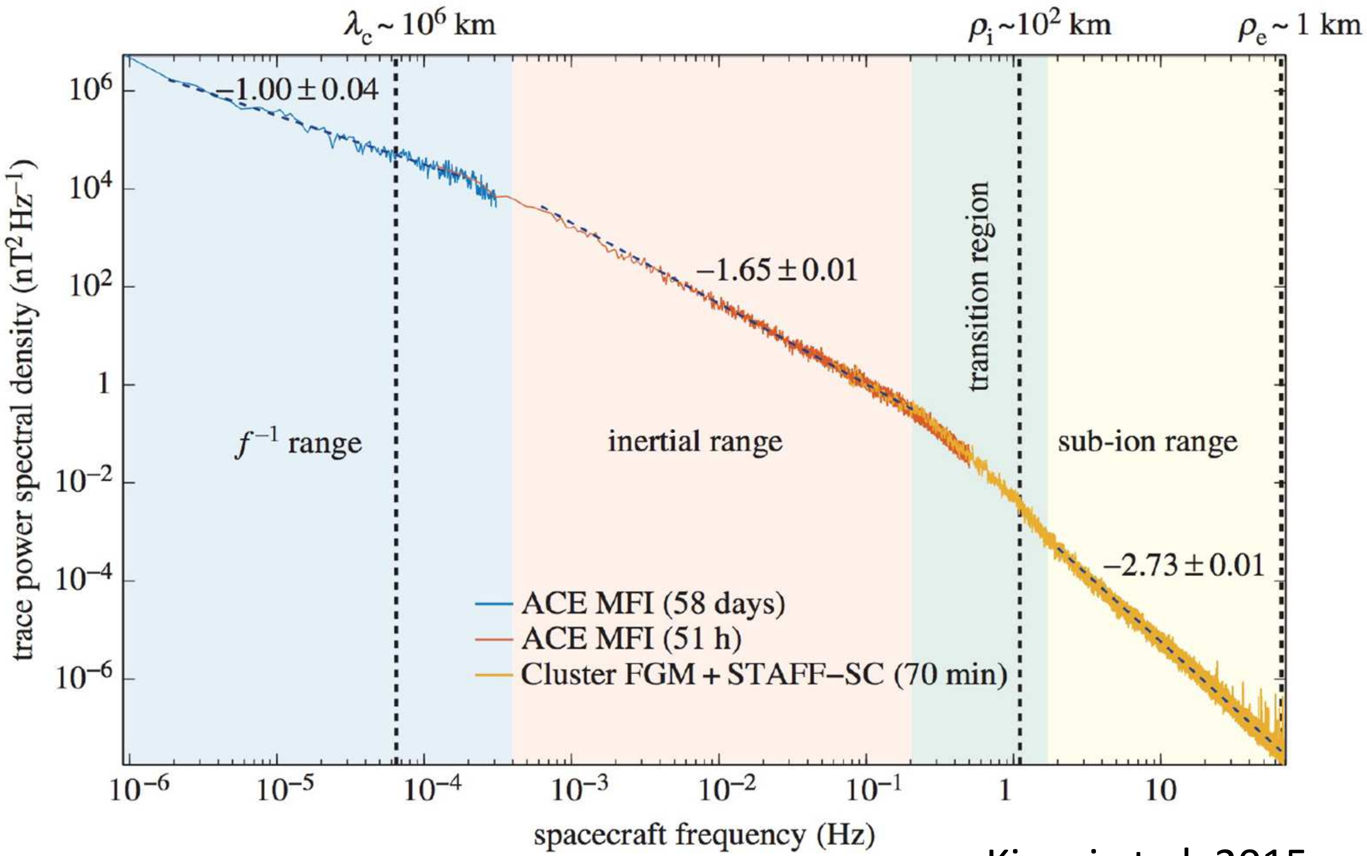


[Image credit: Lorenzo Matteini]

- Non-adiabatic plasma expansion
- Heating problem
- Turbulent fluctuations could be the energy source

Solar wind turbulence: Introduction

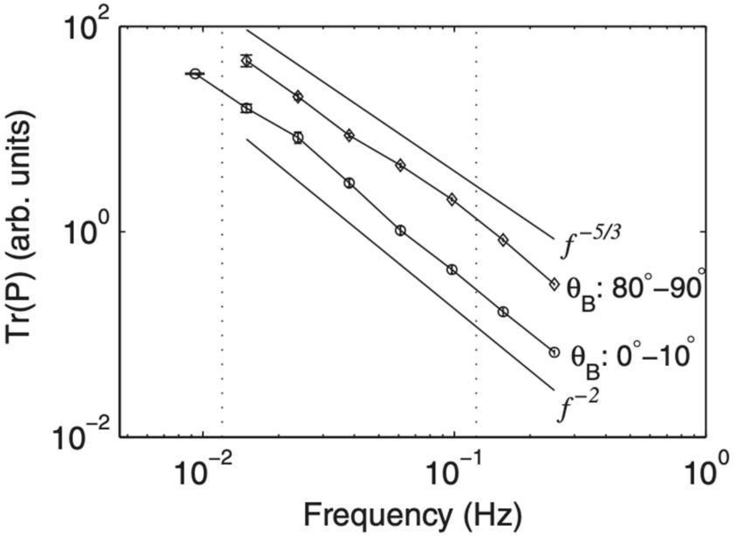
- Power low spectrum
- Spectral break at ion scales
- Intermittency
- Dissipation

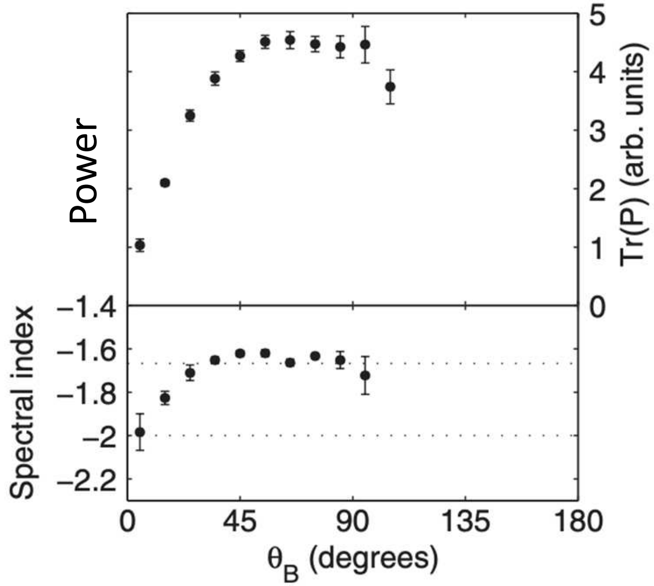


Kiyani et al. 2015

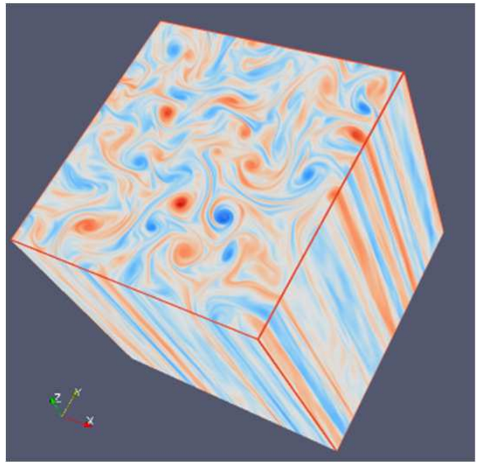
Observations of k-anisotropy in the solar wind

Horbury, T. S., Forman, M., and Oughton, S., "Anisotropic Scaling of Magnetohydrodynamic Turbulence", *Physical Review Letters*, 2008.





Vorticity component aligned along the mean magnetic field, from a MHD simulation.

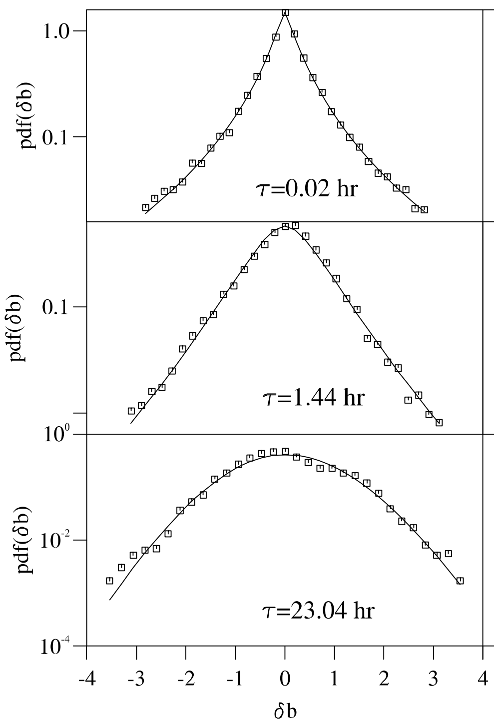


Alexakis, A. and Biferale, L., "Cascades and transitions in turbulent flows", *Physics Reports*, 2018

- 2D turbulence dominates
- Spectral indices are in agreement with critical balance (CB) model
- But δV-spectra in the solar wind are not the same as δB-spectra => problem with CB… not resolved.

$$\mathcal{P}(f;\theta_B) = C_{\text{slab}} f^{-\gamma_{\text{slab}}} |\cos\theta_B|^{\gamma_{\text{slab}}-1} + C_{\text{2D}} f^{-\gamma_{\text{2D}}} |\sin\theta_B|^{\gamma_{\text{2D}}-1},$$

Intermittency in space plasma turbulence



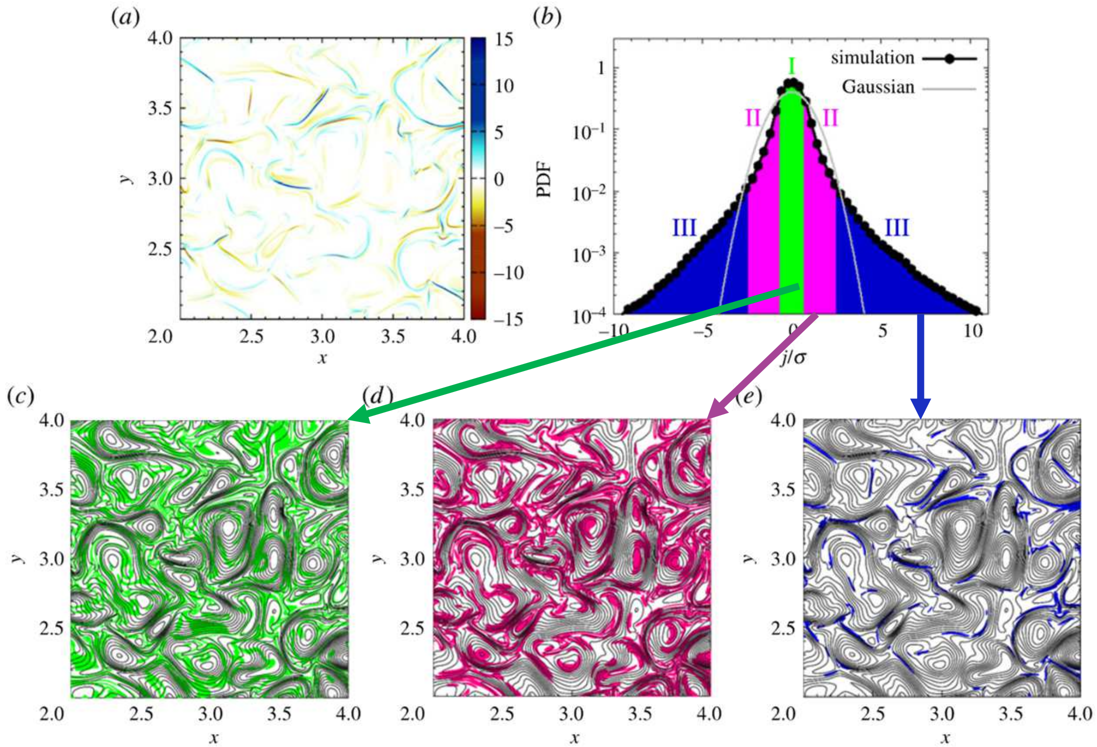
- Intermittency is scale-dependent deviation of the fluctuation distribution function from gaussianity.

$$|\Delta \mathbf{b}| = |\mathbf{b}(s+\Delta s) - \mathbf{b}(s)|$$

[Sorriso-Valvo et al. 1999]

- Intermittency is due to appearance of coherent structures

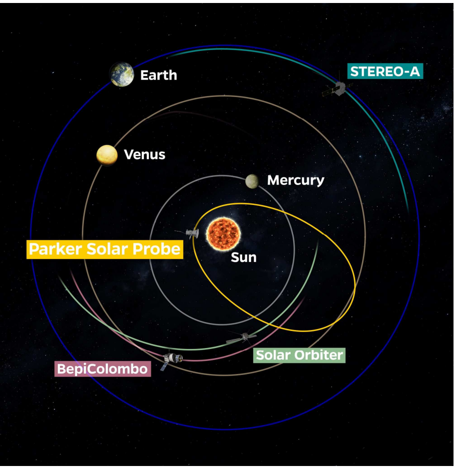
2D MHD simulations: current density:

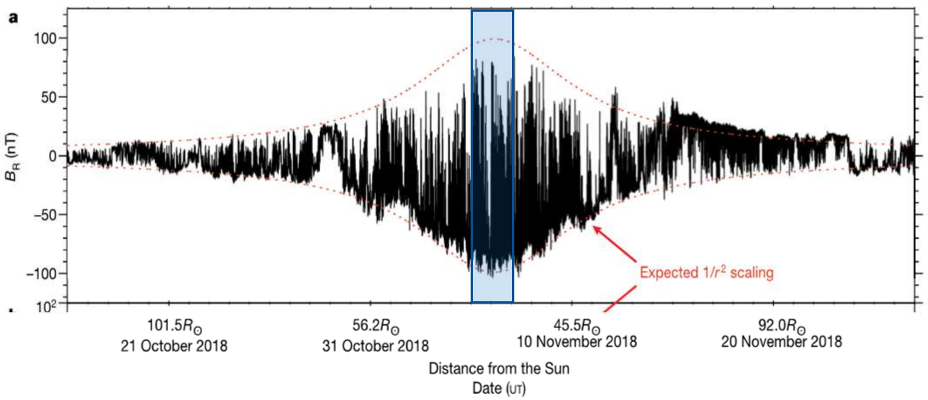


Matthaeus W.H. et al, "Intermittency, nonlinear dynamics and dissipation in the solar wind and astrophysical plasmas." *Phil. Trans. R. Soc. A,* 2015.

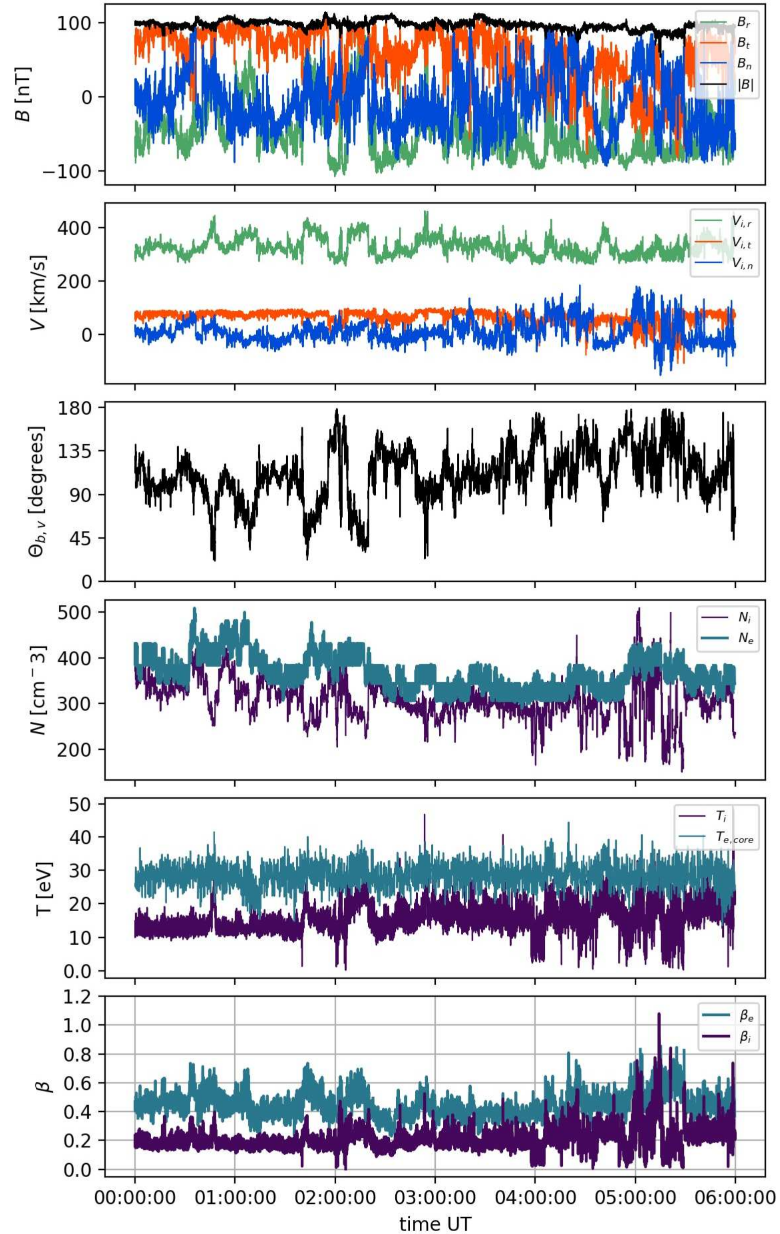
Parker Solar Probe First encounter 2018-11-06

- <u>The main goal of our investigation is to characterize solar wind coherent structures at multiple ranges of scales.</u>
- We use merged (SCM and fluxgate magnetometer) data with 3.413 ms resolution in the satellite frame
- Radial distance R~25*10^9 m~0.17 a.u.





Bale et al., 2019, Nature



Parker Solar Probe at 0.17 AU
Spectral properties

- To investigate the multi-scale nature of the magnetic fluctuations we define the following frequency ranges:

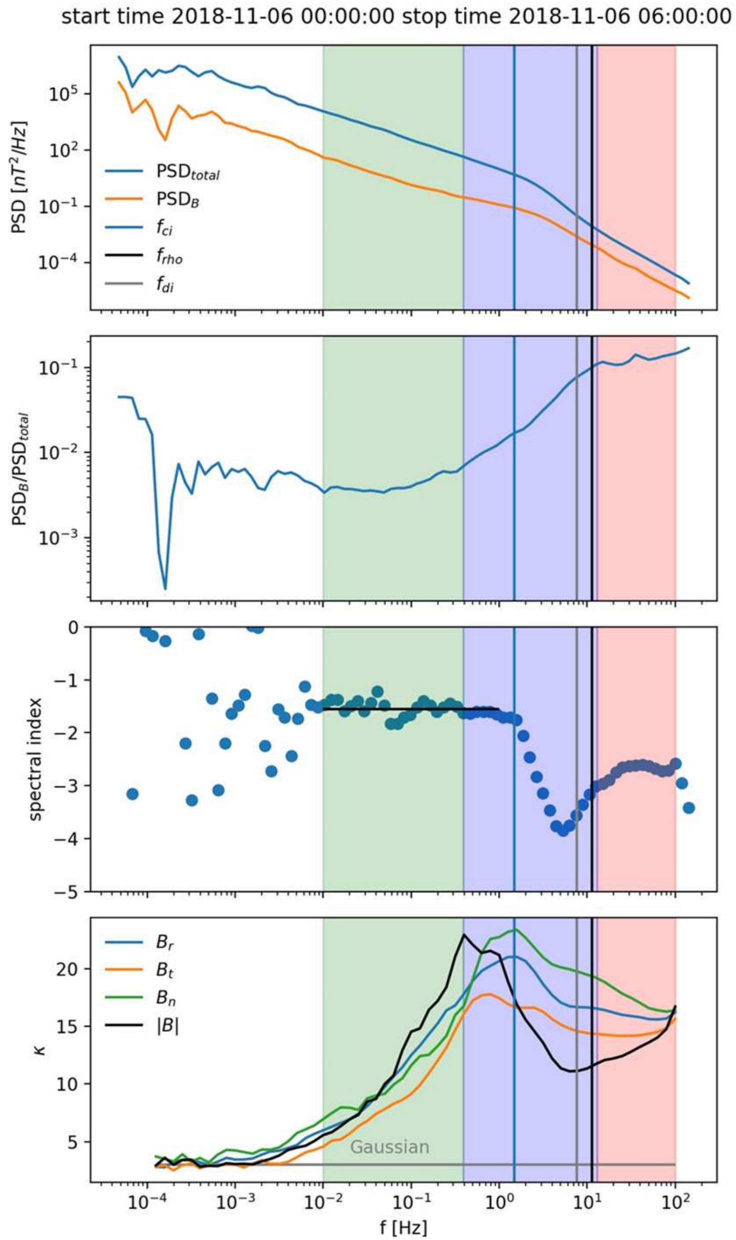
1. Low frequency MHD scales 10^{-4} Hz $< f < 10^{-2}$ Hz (Fig. 2 in white)
2. Inetrial range MHD scales 10^{-2} Hz $< f <$ 0.4Hz (Fig. 2 in green)
3. Ion scales 0.4 Hz $< f <$ 12 Hz (Fig. 2 in blue)
4. Sub-ion scales 12 Hz$< f <$ 100 Hz (Fig. 2 in red)

Increment

$$\delta B(t, \Delta t) = |B(t + \Delta t) - B(t)|$$

Kurtosis is the fourth normalized moment (at the bottom panel), defined as :

$$\kappa(\Delta t) = \frac{E[\delta B(\Delta t)^4]}{(E[\delta B(\Delta t)^2])^2}$$



Detection of coherent structures in turbulent signal

Wavelet transform of a magnetic filed component:

$$\hat{B}_r\ (t,\tau)\ = \sum_{j=0}^{N-1} B_r(t_j)\psi^*\left[\frac{t_j - t}{\tau}\right]$$

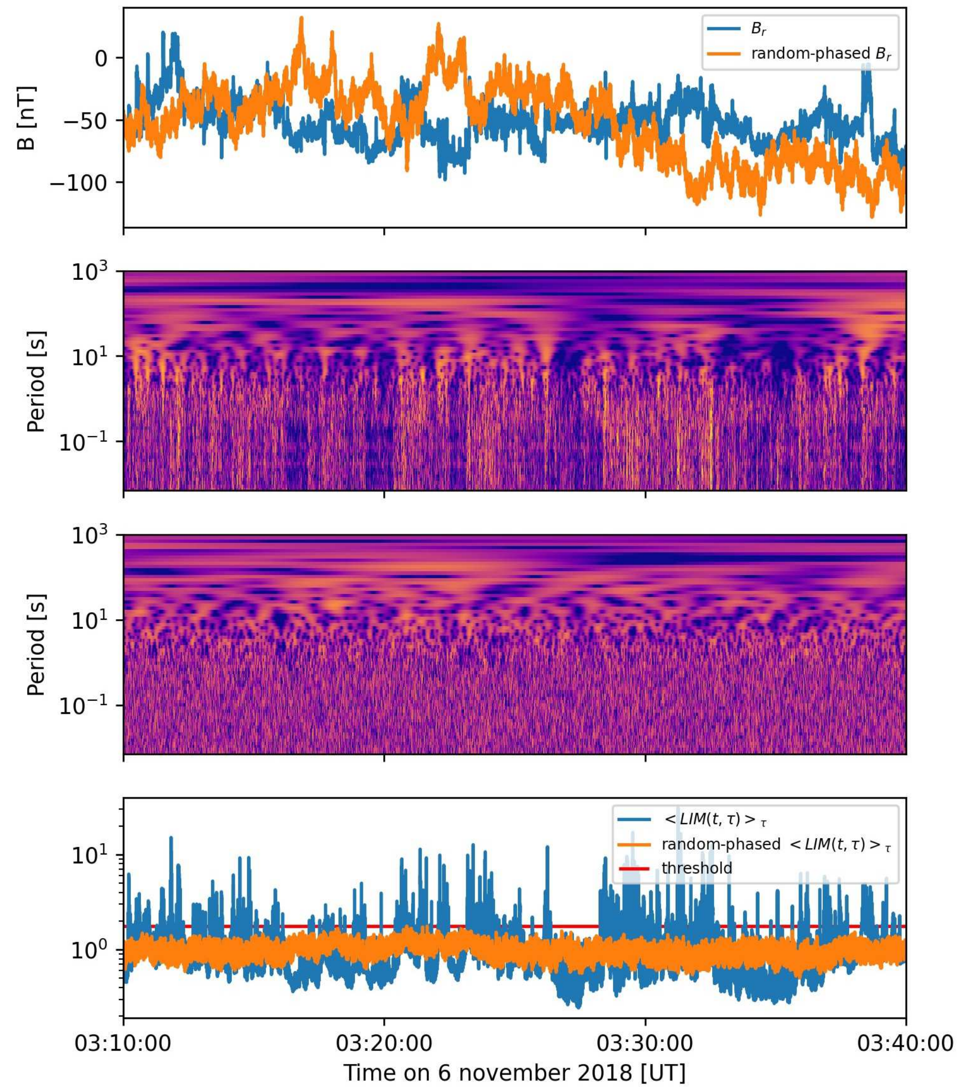
Morlet basis function:

$$\psi(t) = \pi^{-1/4}e^{-i\omega t}e^{-\frac{t^2}{2}}$$

Local Intermittency Measure (LIM) [Farge 1990]:

$$LIM_r = \frac{\hat{B}_r^2(t,\tau)}{< \hat{B}_r^2(t,\tau) >_t}$$

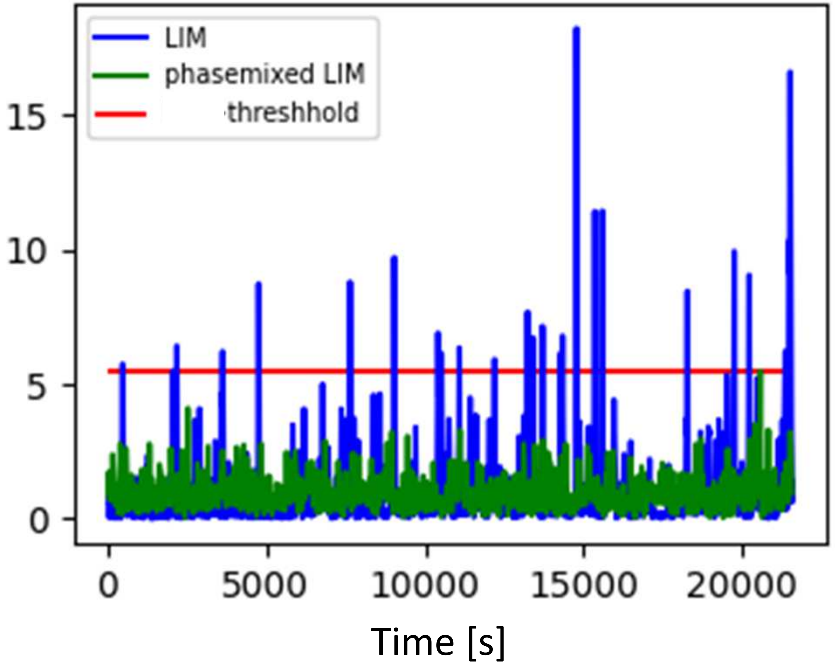
- **Scale-by-scale vs all-scales-methodology**

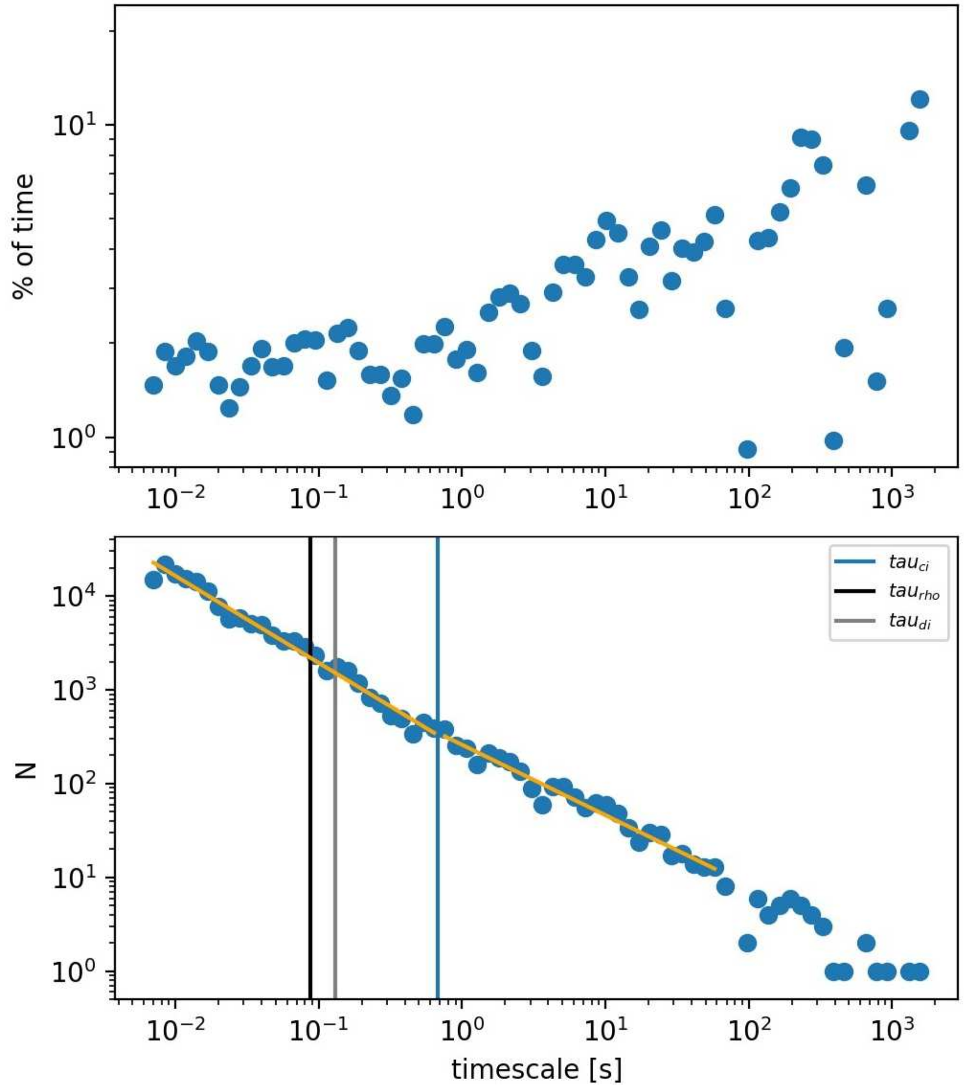


Structures filling factor at different scales

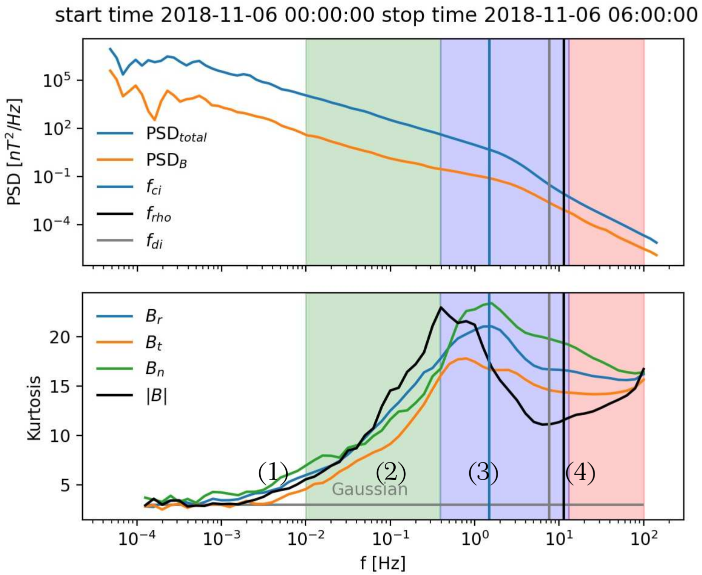
- Scale-by-scale methodology

Example for ∼20 sec time-scale:





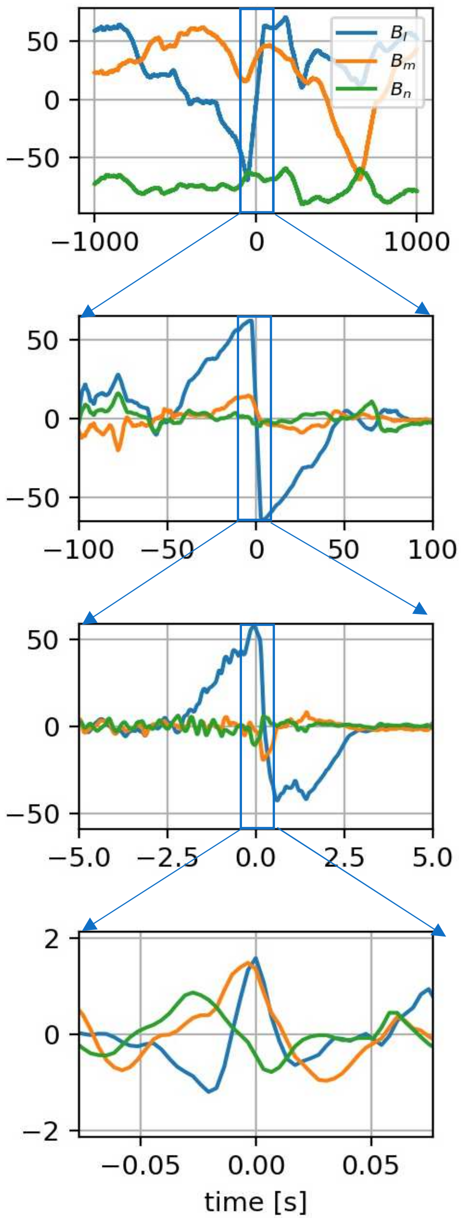
Example-1



To define fluctuations within a frequency range, we apply a band-pass filter $f \in F_j$:

$$\delta \boldsymbol{B}_{f \in F_j} = \left\langle \boldsymbol{B} - \langle \boldsymbol{B} \rangle_{\max(\tau_j)} \right\rangle_{\min(\tau_j)}$$

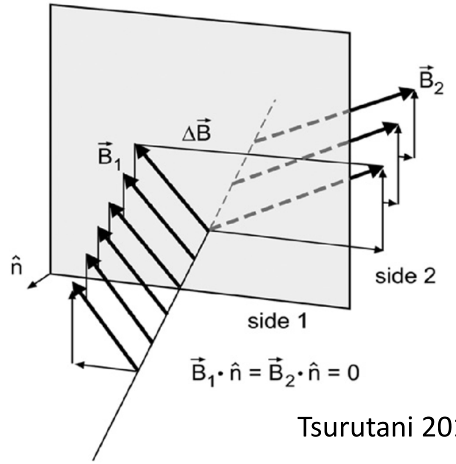
$\min(\tau_j)$, $\max(\tau_j)$ – minimum and maximum timescales corresponding to F_j frequency range



(1) Frequency range (1): reversal in one component. A current sheet with a mean field ?

Frequency ranges (2) and (3): the same current sheet as in (1) ?

(2)

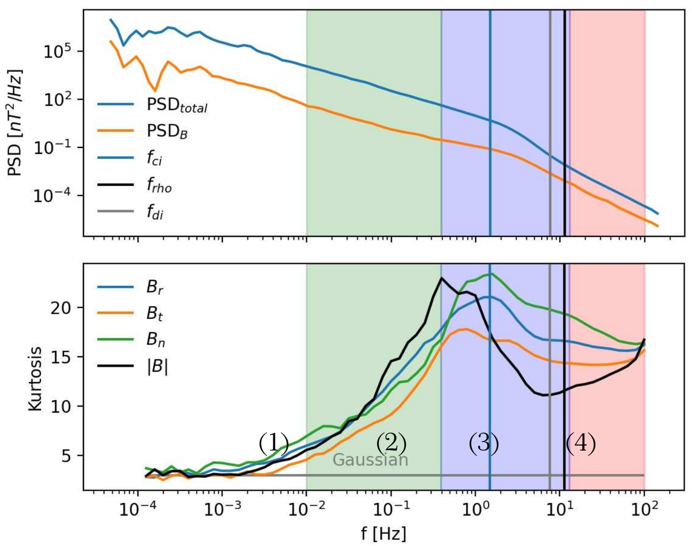


Tsurutani 2011

(3)

(4) Range (4): small scale vortex?

Example-2



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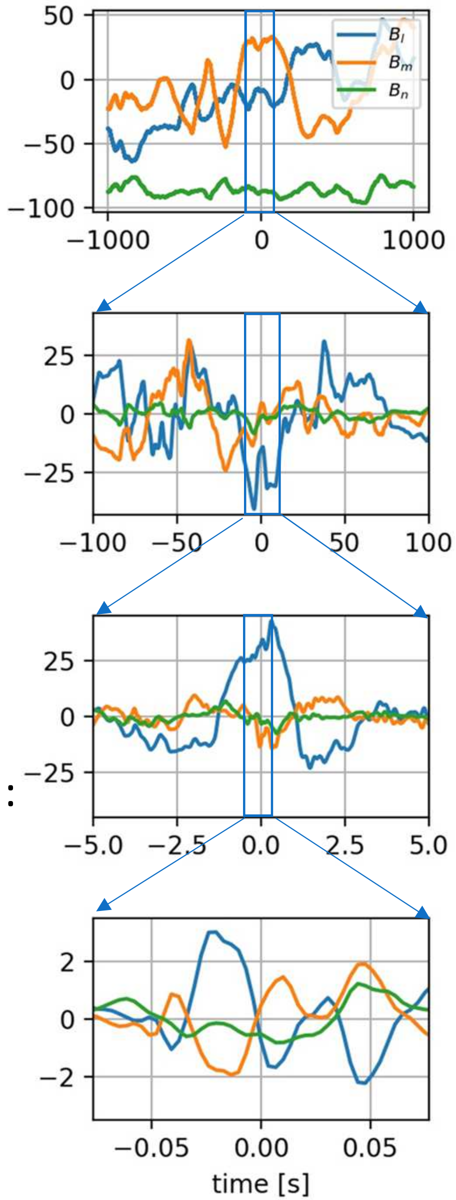
$\min(\tau_j)$, $\max(\tau_j)$ – minimum and maximum timescales corresponding to F_j frequency range



(1)

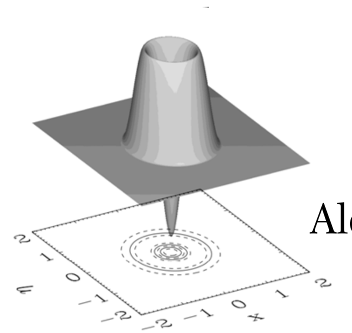
(2)

(3)

(4)

Frequency range (1): flux rope/vortex ?
Frequency ranges (2): the same a vortex?

Frequency ranges (3): more clear
signature of an Alfven vortex at

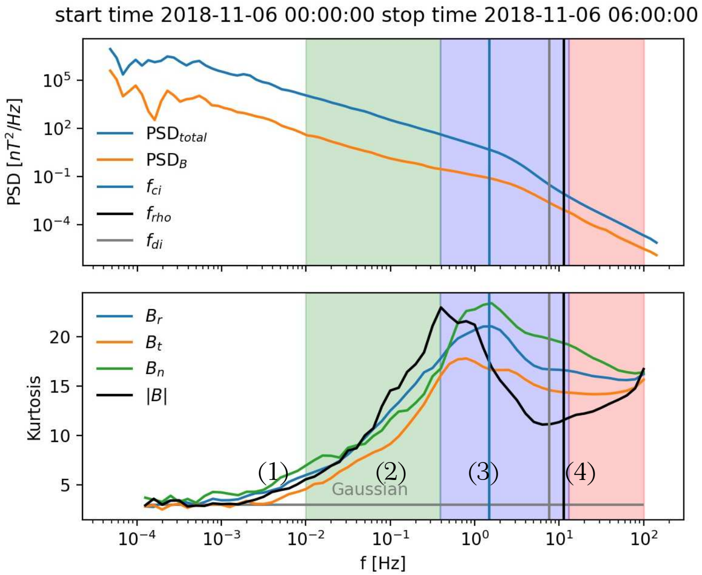


Alexandrova 2008

- Incompressible MHD vortex model: Petviashvilli & Pokhotelov 1992;
- Compressible MHD + Ion-scales vortex model: Jovanovic et al. 2020;

Range (4): small scale vortex?

Example-3



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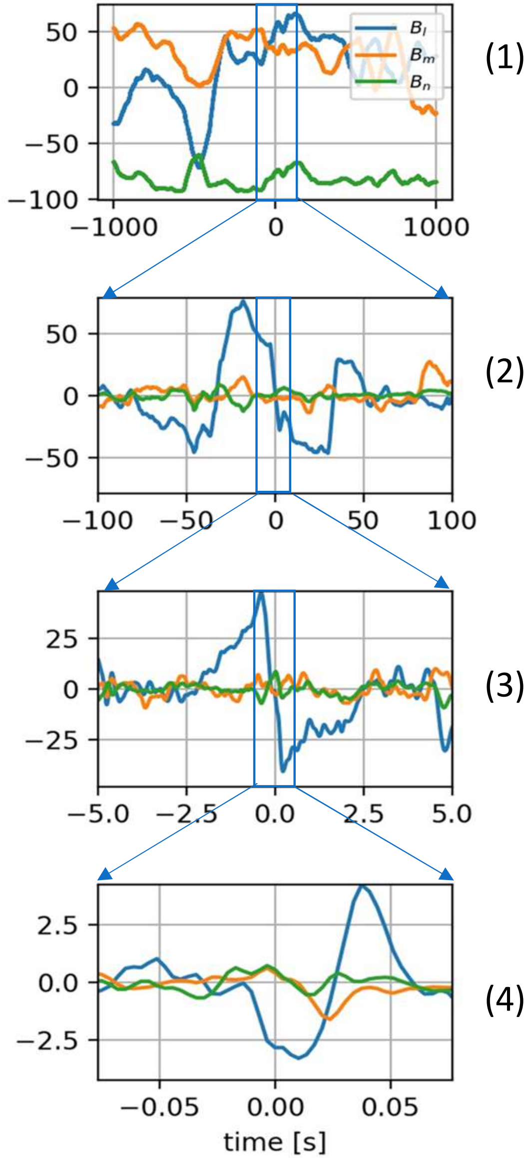
$$\delta \boldsymbol{B}_{f\in F_j} = \left\langle \boldsymbol{B} - \langle \boldsymbol{B}\rangle_{\max(\tau_j)} \right\rangle_{\min(\tau_j)}$$

$\min(\tau_j)$, $\max(\tau_j)$ – minimum and maximum timescales corresponding to F_j frequency range



Frequency range (1) ?

Frequency ranges (2): Series of MHD discontinuities or a vortex at 10^2s scale ?

Frequency ranges (3): signatures of a current sheet at ~1 s scale.

Range (4): small scale vortex?

Conclusion

- We detected statistics of high-intermittency events
- Analized them at different ranges of scales (from MHD inertial to sub-ion scales)
- Classified/found them as structures (vortex, discontinuity)
- Plasmoid-mediated turbulence (Tearing mode instability in the current sheets)
- Clustering/embedding of the structures
- Structures occurence rate and filling factor

Open questions

- Several new structures with explicit/specific features lack obvious interpretation
- How these structures interact with ions and electrons?
- Can they explain the non-thermal particles distributions and solar wind heating?