XVIth Hvar Astrophysical Colloquium

International Study of Earth-affecting Solar Transients

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THE FEATURES OF PLASMA TURBULENCE ASSOCIATED WITH SOLAR TRANSIENTS

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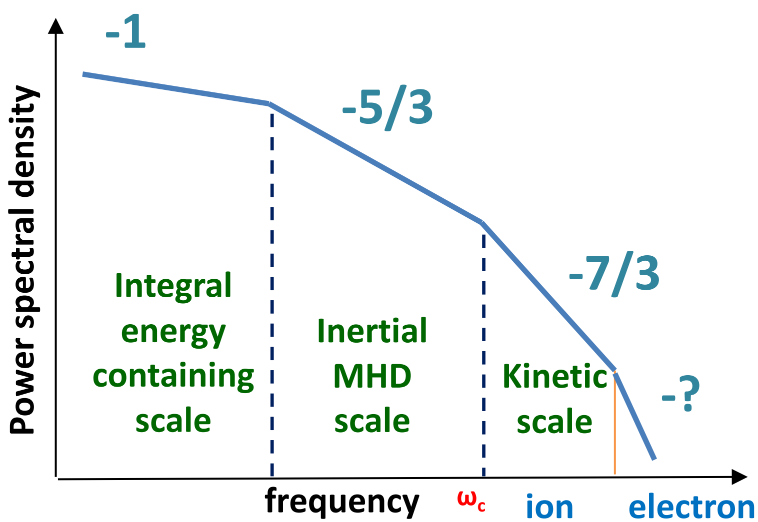
Turbulence in the solar wind

Is turbulence only in the sheath regions as a result of shocks?

NOT!

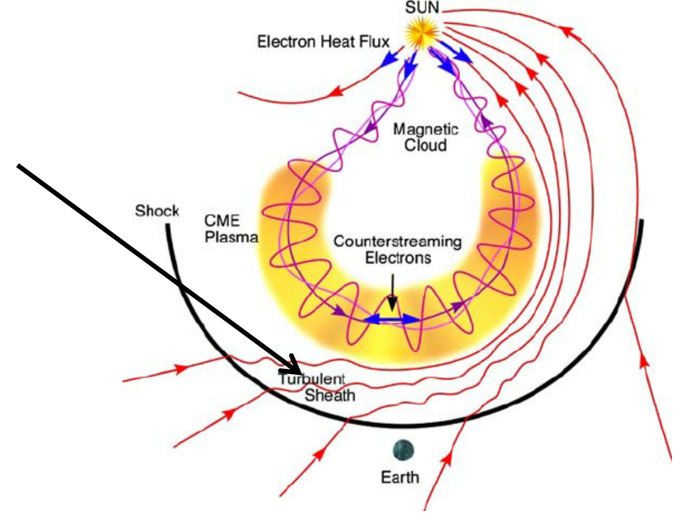
The turbulence is present through all solar wind!

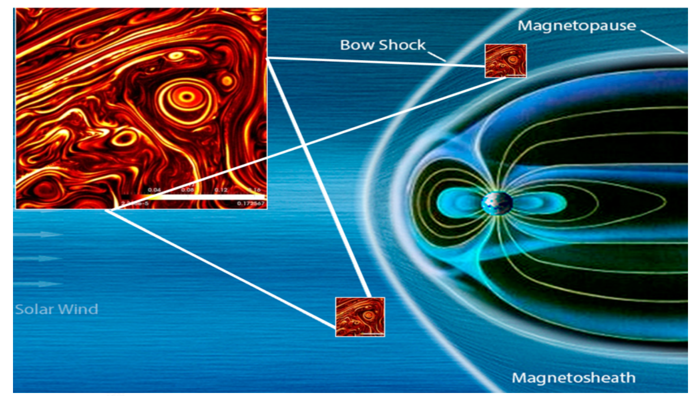
The properties of turbulence can be different in different large scale solar wind structures!

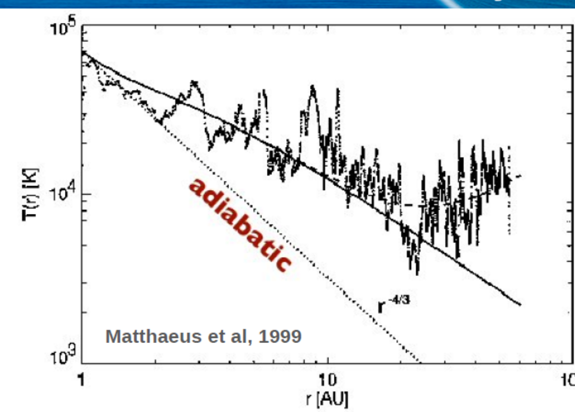


Schematic cascade of plasma turbulence

- **problem of energy exchange between the structures of different time and spatial scales.**
- **problem of solar wind dissipation and heating.**
- **problem relevant for energetic particle transport and acceleration!**



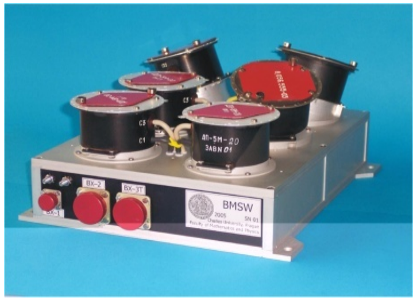




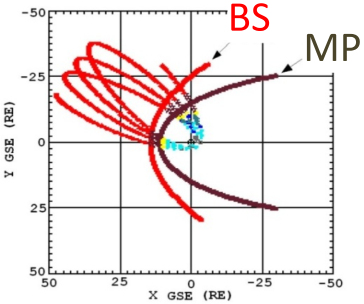
solar wind temperature decreases radially less than expected from adiabatic expansion

BMSW instrument (experiment PLASMA-F, spacecraft SPEKTR-R)

- Highly elliptical orbit
- Data are available from August 2011 - present time
- Measurements:
  - -F (ion Flux vector) (31 ms)
  - -N_p, V_p, V_{thp}, N_α, V_α (3 s - sweeping mode)
  - -N_p, V_p, V_{thp} (31 ms –adaptive mode)



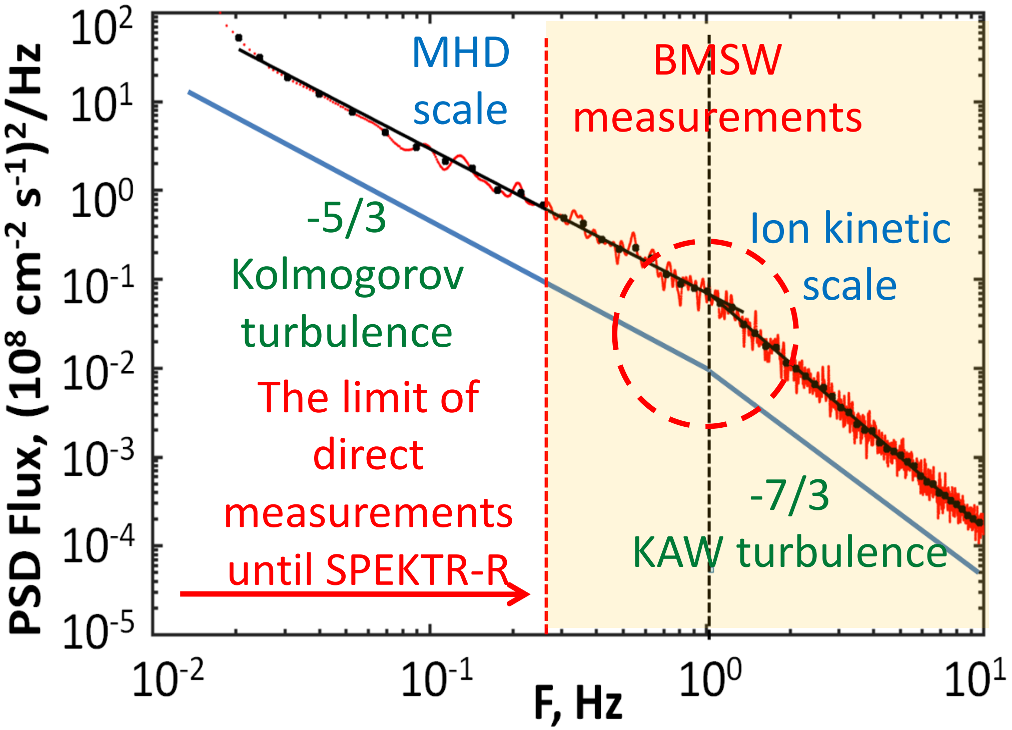
BMSW instrument



BMSW is a unique instrument for the investigation of turbulence properties at the large range of scales including kinetic scales!

- The analysis of turbulent characteristics of plasma at high frequencies:

✓In the solar wind(Safrankova et al., 2013,2015,2016; Chen et al., 2014; Riazantseva et al.,2015, 2016, 2017)
✓In magnetosheath (Riazantseva et al., 2016; Rakhmanova et al., 2016, 2017)
✓Near the interplanetary shocks in the solar wind (Pitna et al.,2016) and magnetosheath (Prakhmanova et al. 2017,2018)



Motivation:

The turbulence in the solar wind is traditionally considered as freely developing in space, however actually its development is limited by natural boundaries creating by different large scale dynamic structures associated with Solar transients. Velocity shear near these boundaries can play a critical role on the formation of turbulent cascade, especially at the dissipation scale and in the region of transition between inertial and dissipation scale.

The main goal of the study:

To reveal the relation between the type of large scale solar wind structures and the characteristics of plasma turbulence observed inside them.

We present:

•The analysis of the ion flux fluctuation spectra at scales 0.01-10 Hz on base of high resolution plasma measurements at BMSW instrument on board of SPECTR-R astrophysical mission during 2011-2015.

•The selection of large scale solar wind types using catalogue of Yermolaev (Yermolaev et al., 2009) during the investigated period .

•Collection of the large statistic evenly distributed in the selected large-scale solar wind structures .

•Comparison of the properties of plasma turbulence in different large-scale solar wind streams especially associated with Solar transients.

The measurements of solar wind ion flux by BMSW instrument (SC SPEKTR-R) with time resolution 31 ms for the period 2011-2015

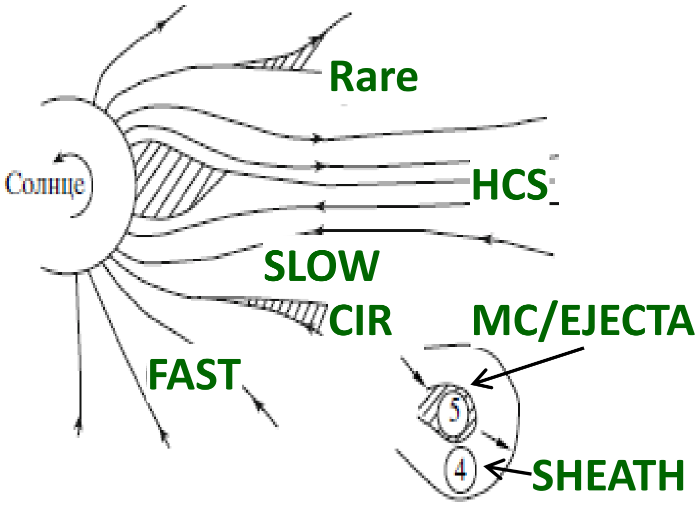
+

Solar wind type selection: catalogue of Yermolaev (Yermolaev *et al.*, 2009) fttp://ftp.iki.rssi.ru/pub/omni/catalog/

DATA selection

	SW slow	SW fast	EJECTA	SHEATH EJECTA	MC	SHEATH MC	CIR
N	1241	301	717	185	292	197	329
N,%	38.0	9.2	22.0	5.7	9.0	6.0	10.1
Vp, km/s	368	471	420	412	483	446	359
Np, $см^{-3}$	10.4	8.1	9.6	10.4	8	16	20.6
Tp, eV	6.1	12.1	2.9	9.1	5.0	12	7.9
Na/Np	3.5	2.5	3.8	3.1	8.5	3.2	3.1
|B|, nT	7.6	7.7	6.5	7.03	8.5	9.2	10.3
beta_p	0.72	0.93	0.54	0.96	0.57	0.97	0.61

Full number of analyzed intervals = 3262



SW slow - pristine solar wind

SW fast - fast solar wind

EJECTA - interplanetary Coronal Mass Ejection

MC - Magnetic cloud

SHEATH - compression region before EJECTA or MC

CIR - compression region before high-speed streams

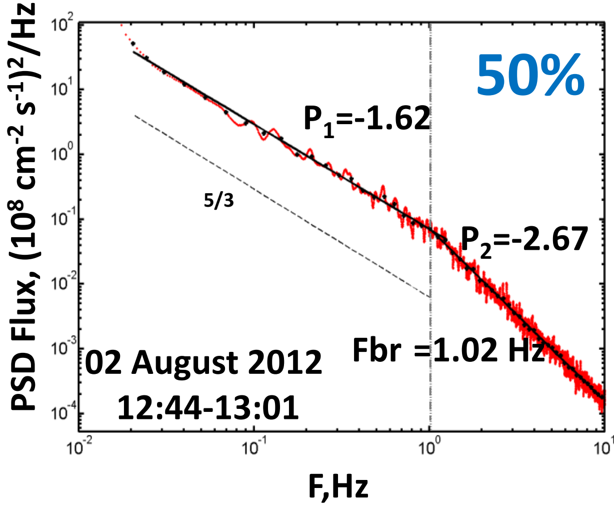
IS – Interplanetary shocks are excluded

Variety of shapes of the fluctuation spectra in the solar wind

The Spectra of plasma and magnetic field fluctuations with two characteristics slopes (Bruno et al. 2013; Alexandrova et al., 2013) are observed in the solar wind only in 50% of cases. The other 50% are distributed by different spectral shapes (Riazantseva et al. JPP 2017)

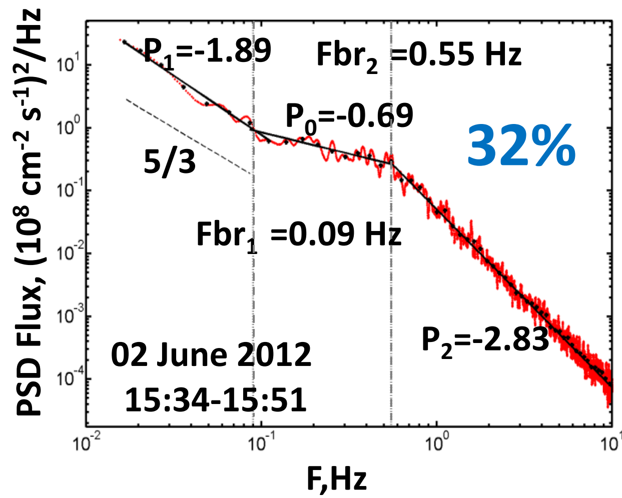
Spectra with two slopes and one break

Bruno et al. 2013, Alexandrova et al., 2013; by SPEKTR-R Safrankova et al., 2013 Riazantseva et al. 2015

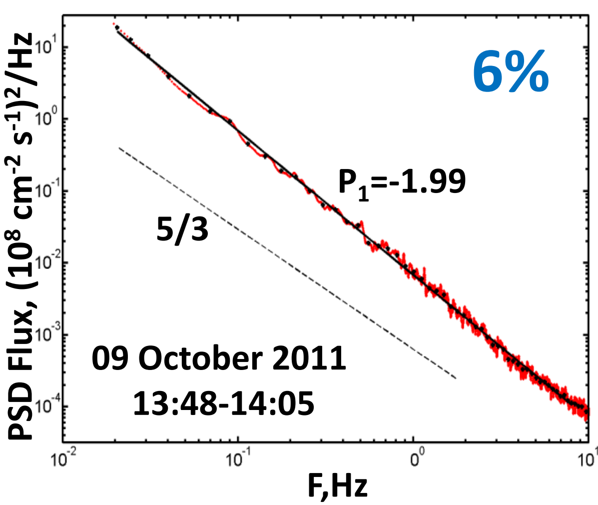


Spectra with flattening in the vicinity of the break

Unti et.al., 1973.; Celnikier et.al., 1987; Chen et.al.,. 2012. by SPEKTR-R Safrankova et.al., 2015

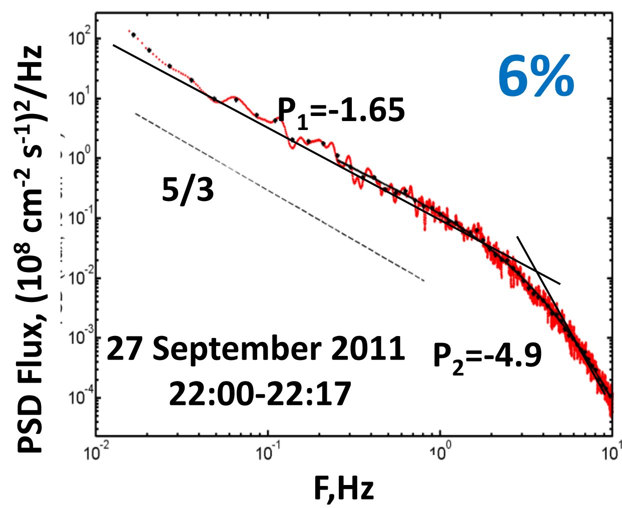


Spectra without steepening in the kinetic range



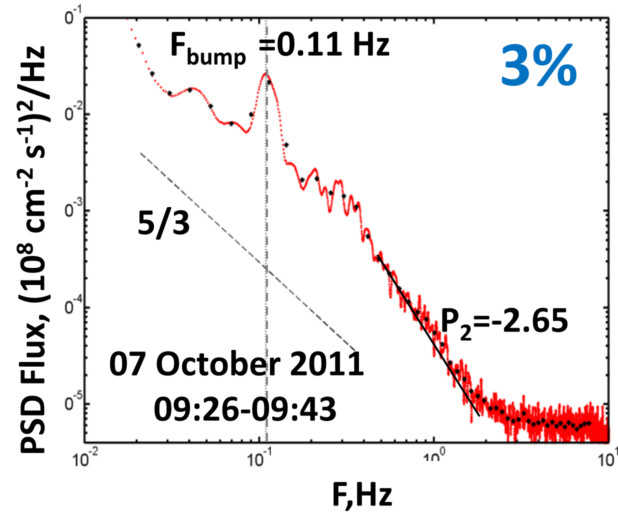
Spectra with nonlinear steepening in the kinetic range

Pitna et al., 2016

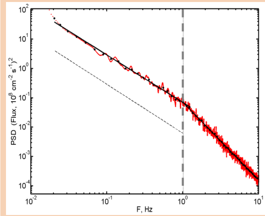
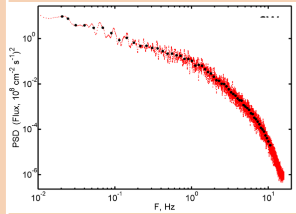
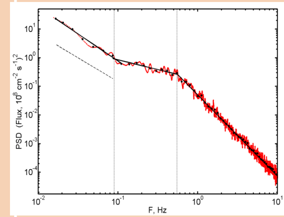
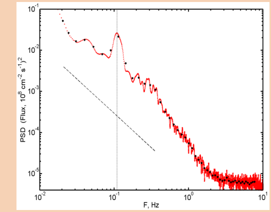
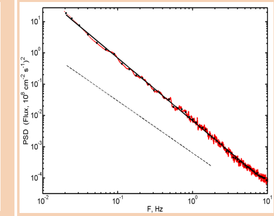


Spectra with bump in the vicinity of the break

often in magnetosheat *Alexandrova et. al., 2004, 2006; Rakhamonova et al. 2016*.



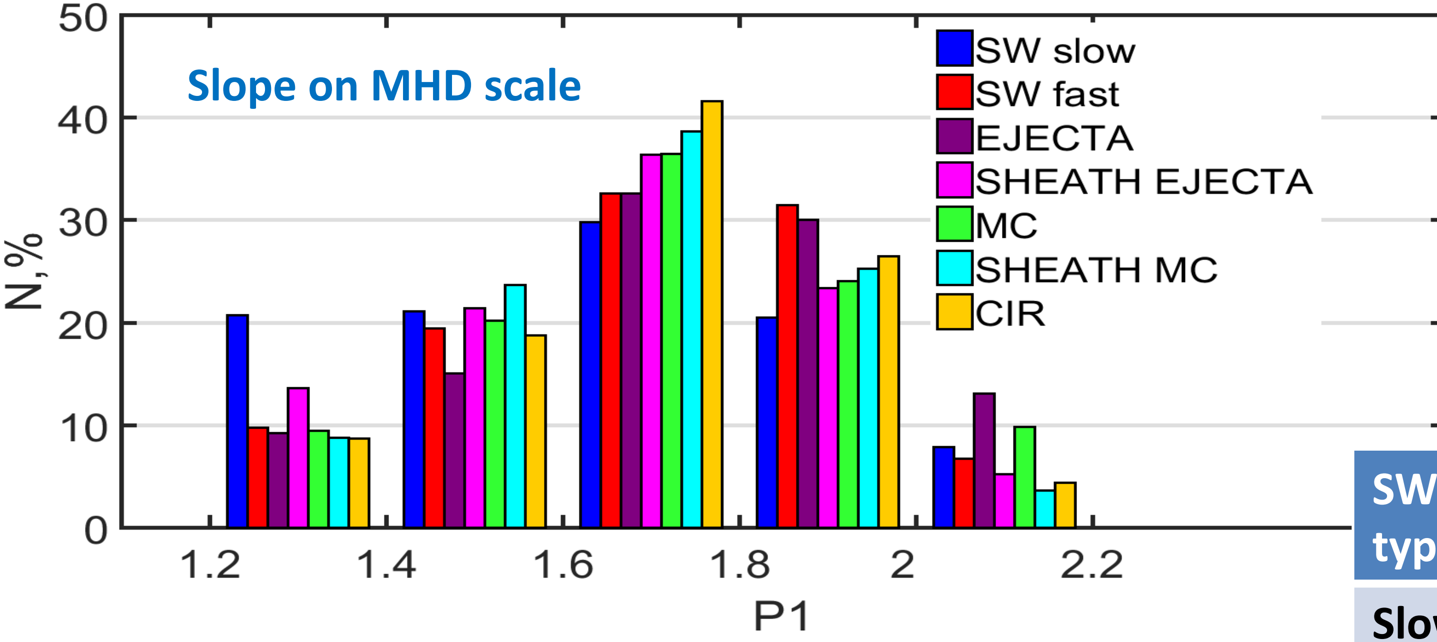
The distributions of the ion flux fluctuations spectra with various shapes in different large scale SW streams

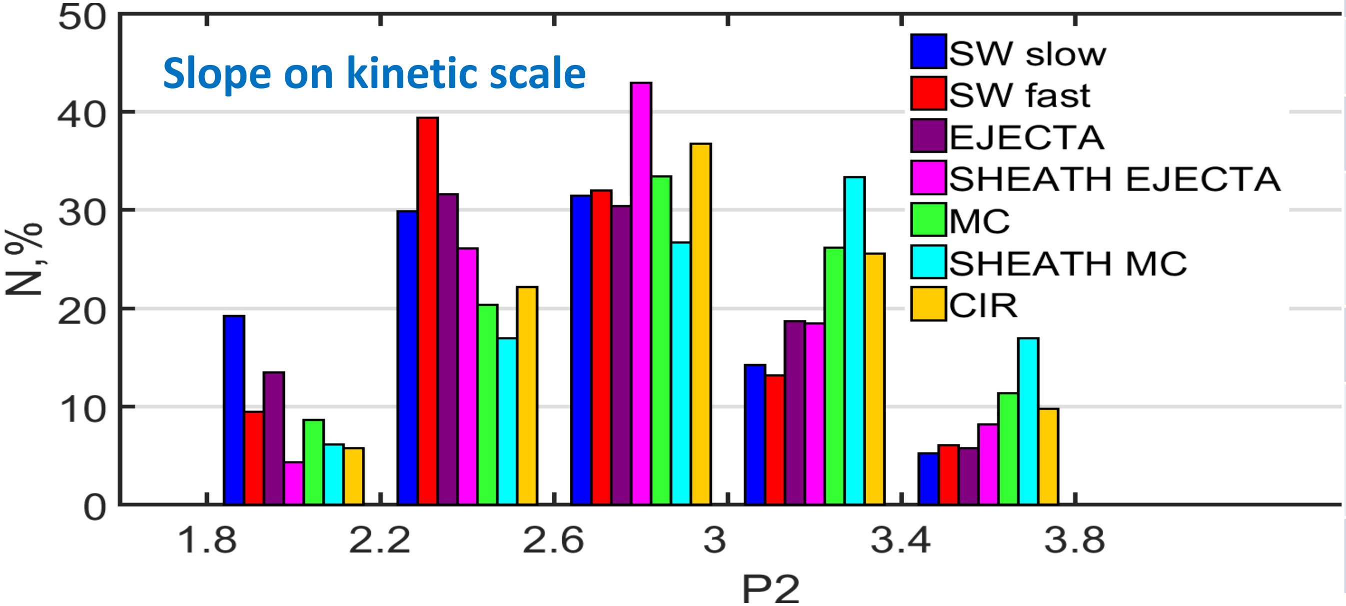
Types of the SW streams	The relative amounts of intervals					
SW SLOW	38%	42.3 %	16.6 %	21.8 %	13.5 %	5.9 %
SW FAST	9%	28.8 %	21.7 %	36.1 %	8.7 %	4.7 %
EJECTA	22%	31.2 %	27.5 %	24.4%	6.3 %	10.3 %
SHEATH EJECTA	6%	42.5 %	22%	23.1 %	9.1 %	3.2 %
MC	9%	20.8 %	42.9 %	15.3 %	16.3 %	4.8 %
SHEATH MC	6%	32.1%	54.6%	11.7%	0.5%	1%
CIR	10%	31.6%	41.3%	22.8%	2.4%	1.8%

- **Spectra with two slopes are more frequent in slow SW and SHEATH, whereas the spectra with flattening are more frequent in the non disturbed fast solar wind.**

- **The distribution of the spectral shapes for MC, SHEATH before MC and CIR is strongly differed from other – the anomalously large number of spectra with**

The characteristics of ion flux fluctuation spectra in different large scale solar wind structures

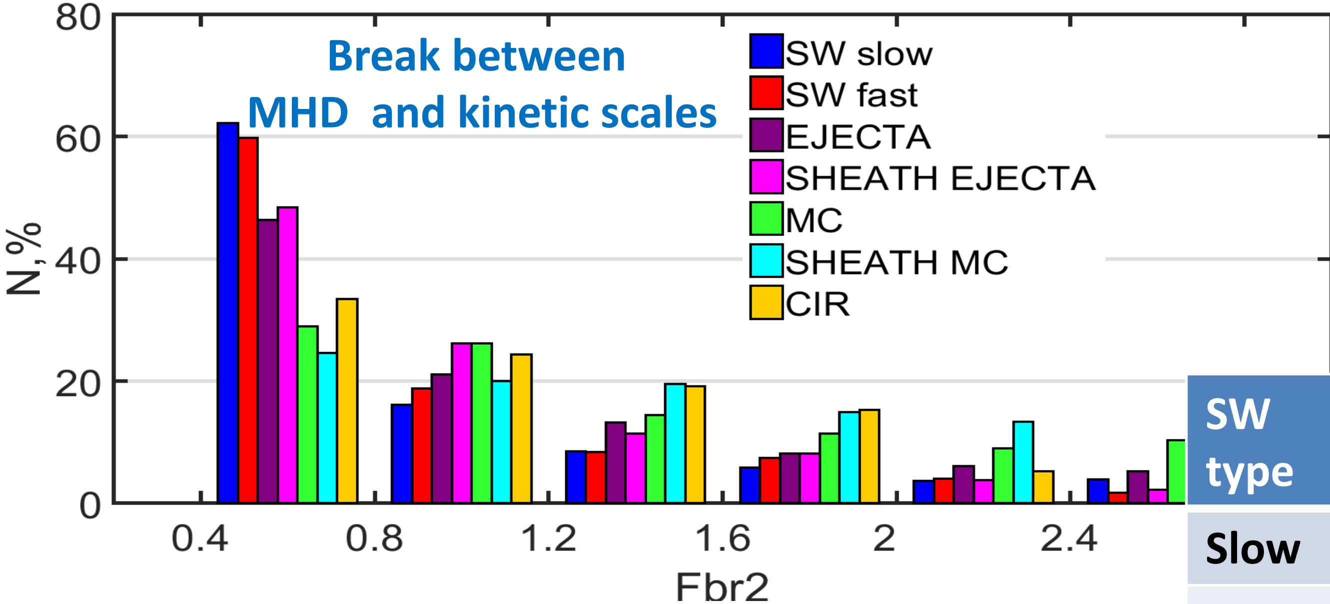


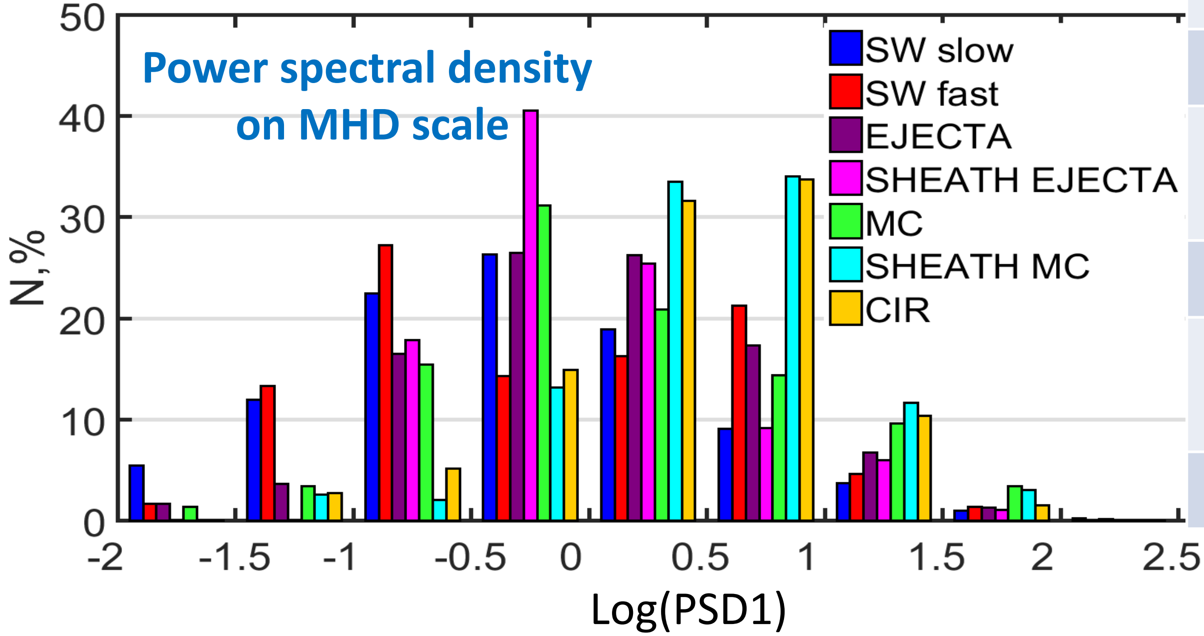


Selection of spectra with two slopes and one break, spectra with flattening and spectra with steepening at the kinetic range N= 2759.

SW type	<P1>	<P2>
Slow	1.6	2.67
Fast	1.66	2.7
EJECTA	1.69	2.78
SHEATH EJECTA	1.61	2.86
MC	1.64	2.92
SHEATH MC	1.66	2.97
CIR	1.64	2.94

The characteristics of ion flux fluctuation spectra in different large scale solar wind structures

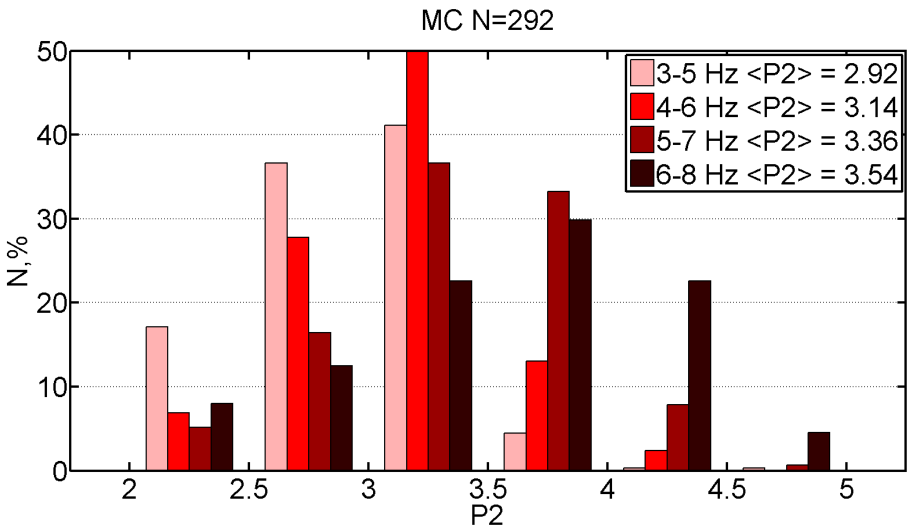


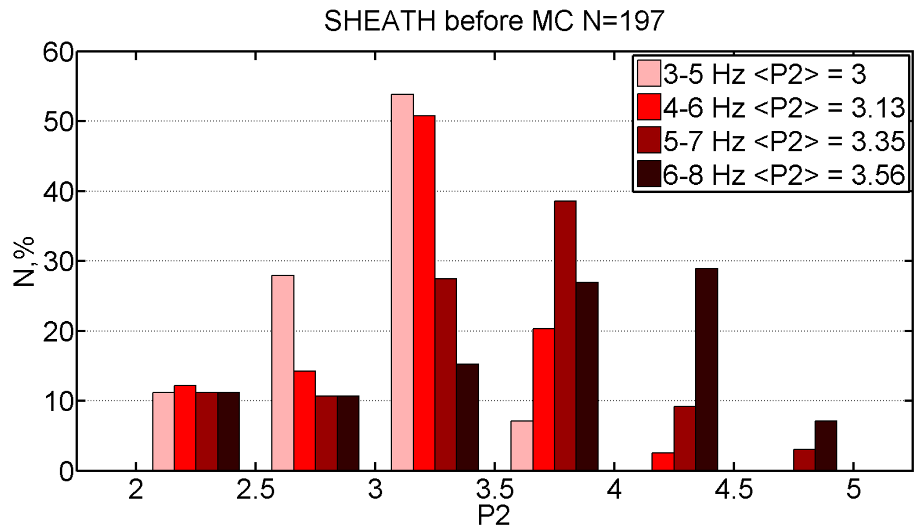


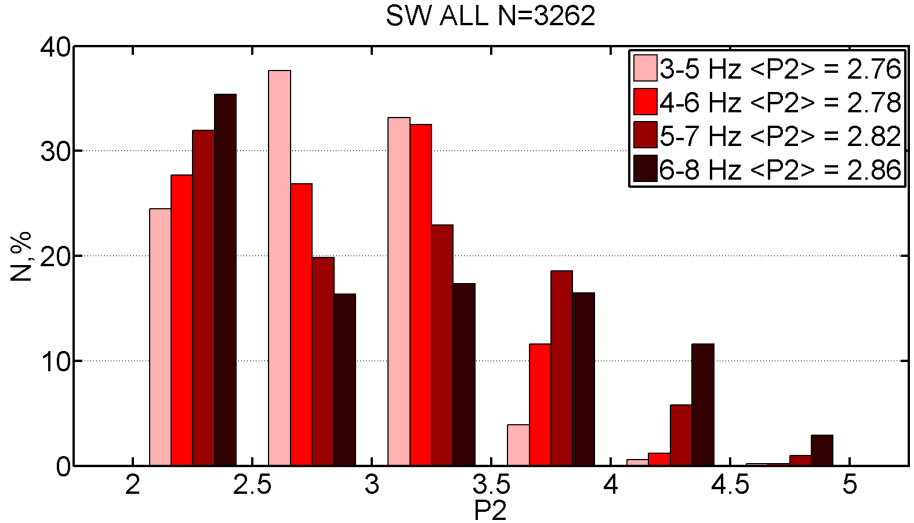
PSD2 (the average spectral density at the kinetic scale) have a similar distribution as PSD1 (at the MHD scale) but with 3 order lower of power density value.

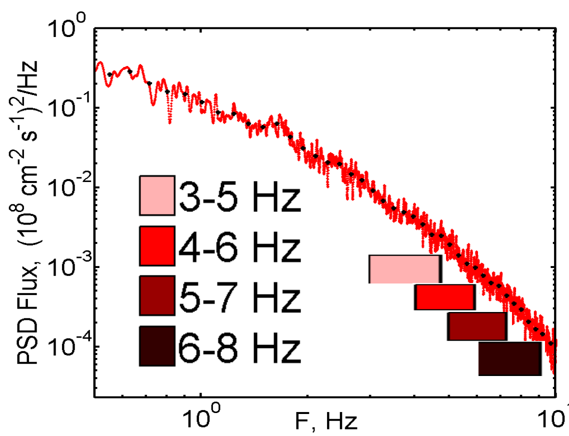
SW type	F_{br}, Hz	$<PSD_1>$	$<PSD_2>$
Slow	0.94	3.1	$0.52 \cdot 10^{-3}$
Fast	1.04	2.8	$0.57 \cdot 10^{-3}$
EJECTA	1.16	3.7	$0.81 \cdot 10^{-3}$
SHEATH EJECTA	1.12	2.3	$0.39 \cdot 10^{-3}$
MC	1.45	5.3	$1.35 \cdot 10^{-3}$
SHEATH MC	1.48	6.6	$1.46 \cdot 10^{-3}$
CIR	1.2	4.7	$1.16 \cdot 10^{-3}$

The steepening of the ion flux fluctuation spectra at the kinetic scale in the Magnetic clouds and in the SHEATH region before MC







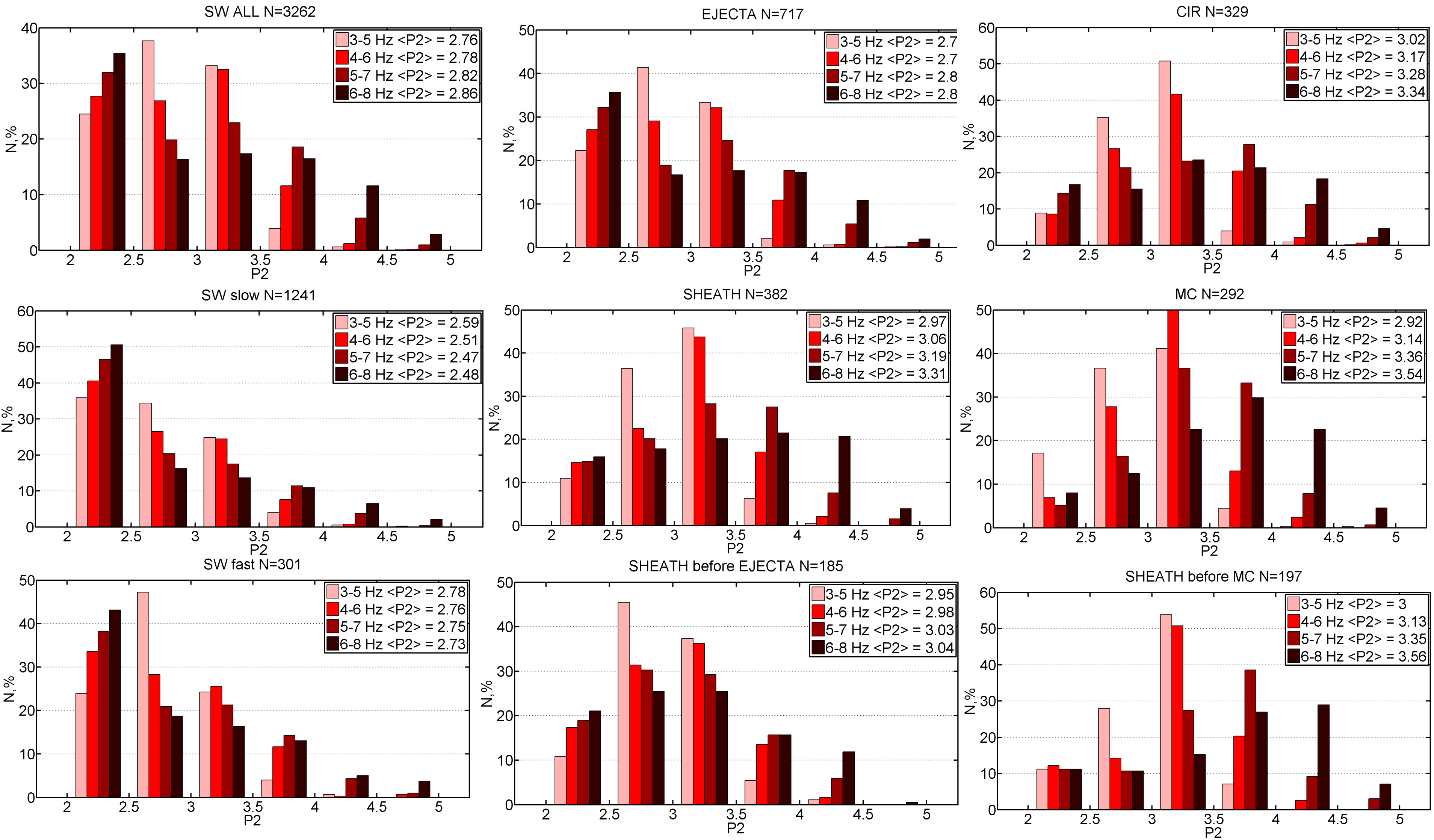


Extended statistic: 3262 spectra during 2011-2015.

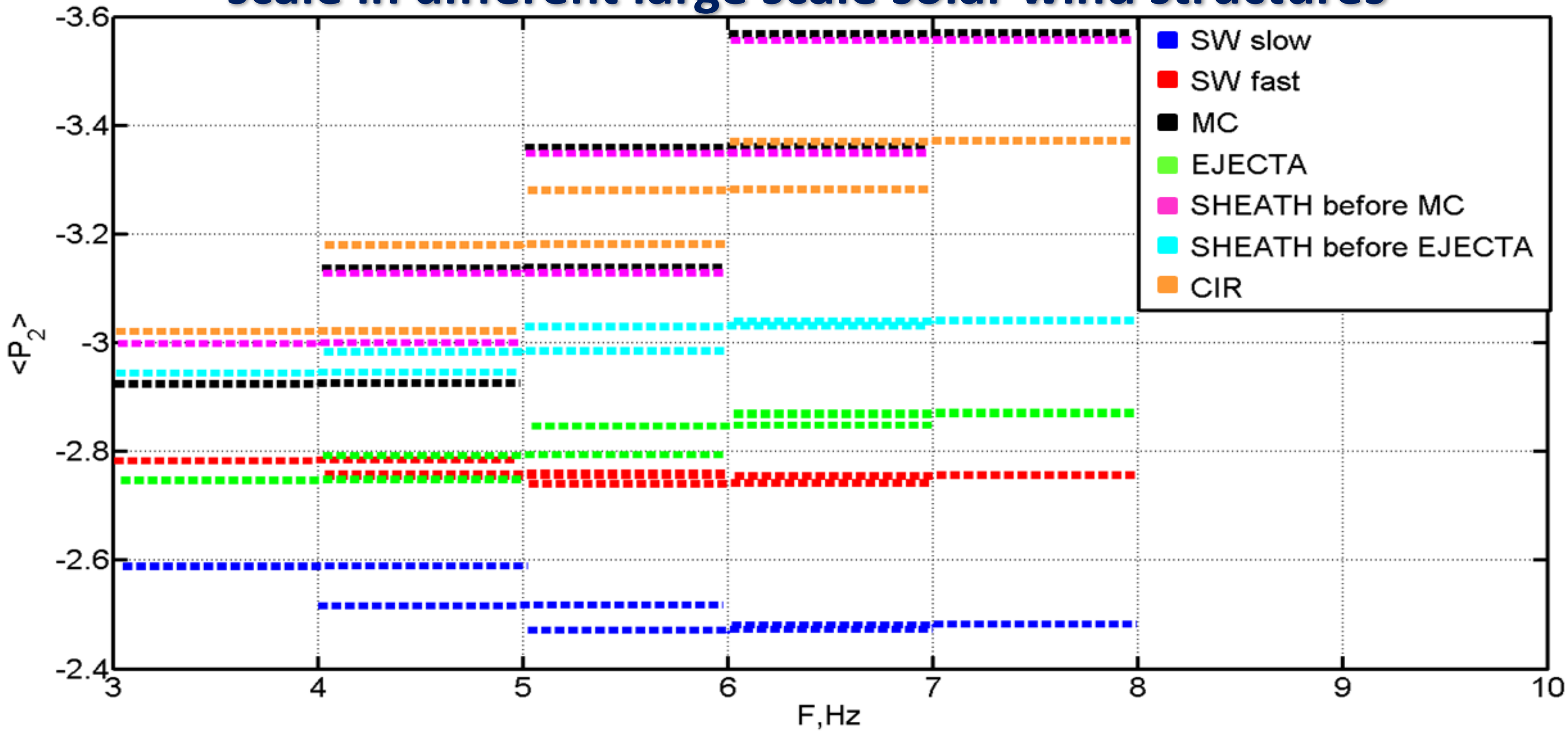
The distributions of the spectrum slopes for different high frequency ranges of the spectrum (4-5 Hz ; 4-6 Hz; 5-7 Hz ; 6-8 Hz)

The spectral steepening in high frequency range is observed clearly for MC and SHEATH before MC.

The steepening of the ion flux fluctuation spectra at the kinetic scale in different large scale solar wind structures

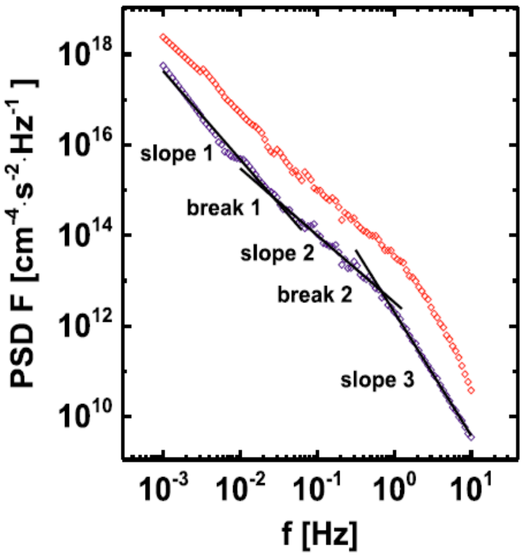


The steepening of the ion flux fluctuation spectra at the kinetic scale in different large scale solar wind structures

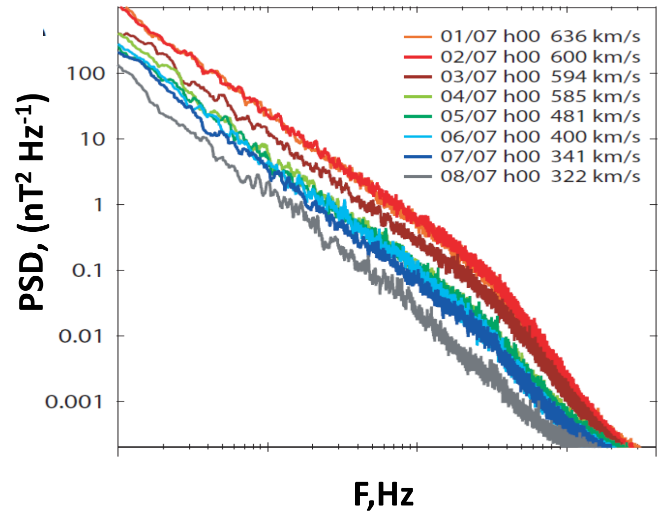


- The minimum spectral slopes -(2.4-2.6) are observed in the slow pristine solar wind and slightly decrease on higher frequencies;
- The slopes are higher in high speed solar wind streams ~(-2.8) and do not change with frequencies ;
- The slightly spectra steepening is observed for EJECTA and SHEATH before EJECTA, wherein the slopes are higher for the SHEATH region;
- The highest slopes and clear steepening are observed in MC and SHEATH before MC, the values of slopes are practically the same for both regions;
- High slopes and steepening are observed also for the CIR region, but the slopes change in wide range.

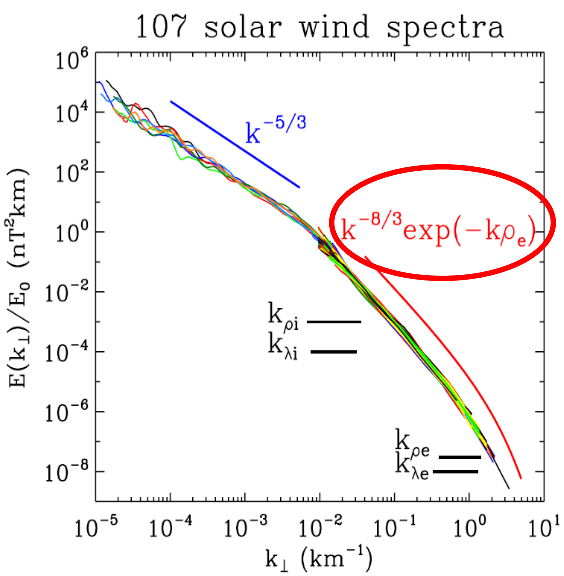
Spectra with steepening on kinetic scales



Such spectra can be observed for high speed streams in the SW, for example downstream the IP shocks (*Pitna et.al., APJ 2016*)



Bruno et al. (APJ 2014) show the dependence of spectral steepening on SW velocity, and suggested that the steeper spectra might be related to some dissipative mechanism, such as Landau damping and/or ion-cyclotron resonance.

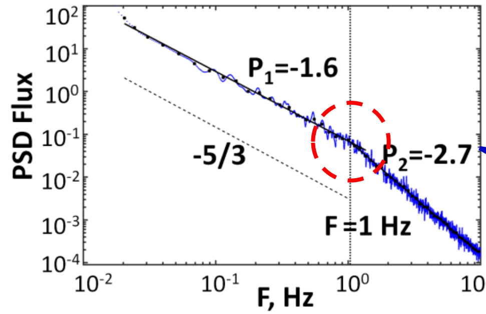


Spectra of interplanetary magnetic field fluctuations demonstrate the exponential character of descent on electron scales (*Alexandrova et al. 2012.)*

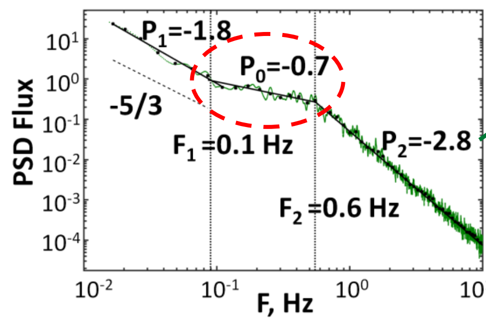
Voitenko et al (2016) argue that there this steepening is mainly nonlinear, due to collisions among co-propagating waves (co-collisions).

The shapes of turbulent spectra in different large scale SW structures.

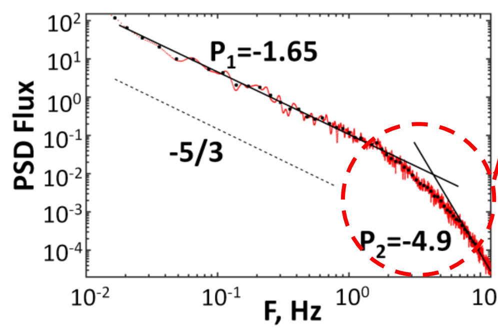
Spectra with two slopes and one break (classical framework):
in the pristine slow solar wind and inside SHEATHs regions.



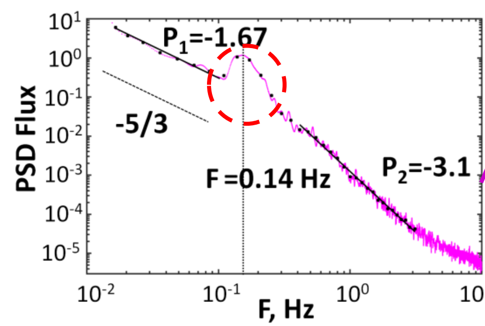
Spectra with flattening in the vicinity of the break
(predicted by Chandran et al. 2009 as a superposition of Alfvénic turbulence and Kinetic Alfvénic turbulence for low level of fluctuations):
in the not disturbed fast solar wind.

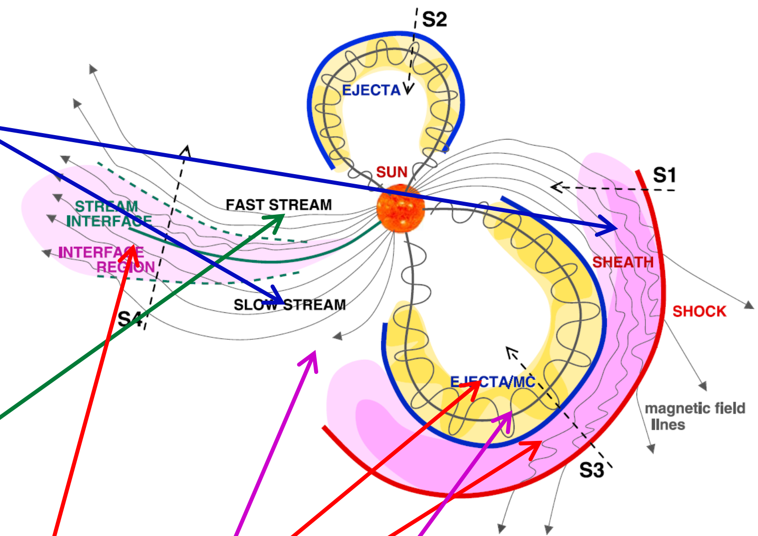


Spectra with fast nonlinear decay in the kinetic range, the slope up to -5!
(stronger damping, leading to sharper cutoff at ion scales):
in the magnetic clouds , SHEATHs before them, corotating interaction regions between fast and slow solar wind.



Spectra with bump in the vicinity of the break
(signature of instabilities or localized coherent structure):
in the slow solar wind, inside magnetic clouds but the statistic is poor.





The shape of density spectrum in KAW (kinetic Alfvenic wave) model is strongly controlled by the power of large-scale density fluctuations (Chandran et al., 2009)

(Riazantseva et al. JPP 2017, Rakhmanova et al. JGR 2018)

Conclusions:

- The spectra with two slopes and one break and spectra with flattening in the vicinity of the break are the most popular spectral shapes in the solar wind. However the spectra with two slopes and one break are more frequent in pristine slow SW and in SHEATH's regions, whereas the spectra with flattening in the vicinity of the break are more frequent in the non disturbed fast solar wind.

- The distribution of the shapes of the ion flux fluctuation spectra for MC and SHEATH before MC is strongly differ from the distributions for other large scale SW streams. The anomaly large amount of the spectra with nonlinear steepening at the kinetic scale is observed. The steepening can be also observed in the CIR region, but the statistic shows the rather wide range of the slopes.

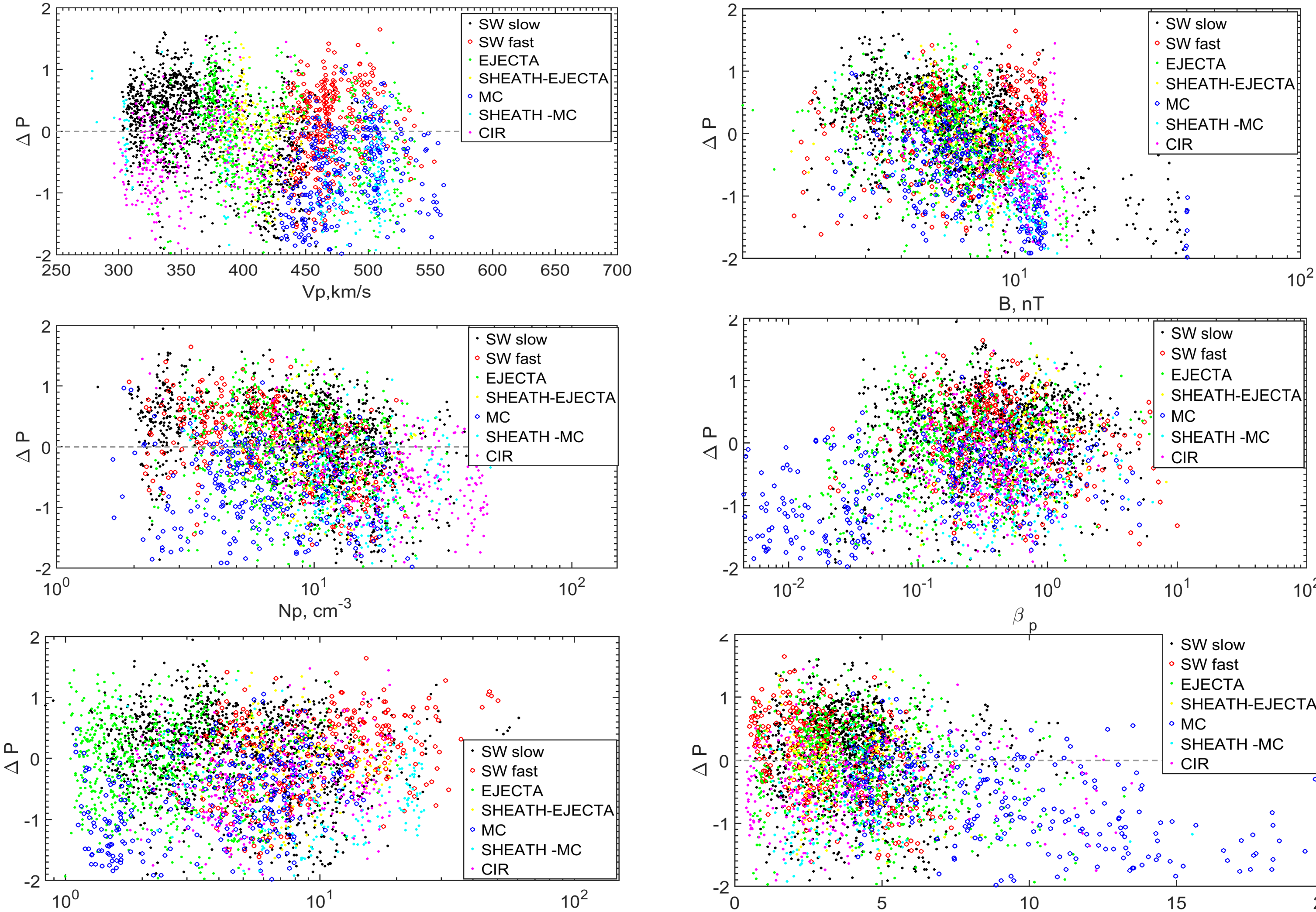
- The spectral steepening is rarely observed in the pristine slow solar wind , in EJECTA and in the SHEATHs before EJECTA.

- The spectral steepening is rarely observed in high speed streams not associated with dynamic events of Solar corona, so the key role play not the value of velocity, but the velocity shear near the boundaries of different large scale solar wind structures.

- The spectra with slope -5/3 (the slope following from Kolmogorov model of full developed isotropic turbulence) is typically observed at the MHD scale in the solar wind, however the flatter slopes can be observed also in slow pristine solar wind and SHEATH before EJECTA;

- The spectral slope closest to the theoretical model predictions at the kinetic scale ($P_2 \approx -2.67$) is observed only in the slow pristine solar wind. The spectral slope at the kinetic scale in high speed streams and in EJECTA is steeper $P_2 \approx -(2.7-2.8)$. This value is close to the typical slope of the interplanetary magnetic field fluctuation spectra published in literature. The steepest spectral slope at the kinetic scale $P_2 \approx -(2.8-3)$ is observed inside the MC and also inside the compression regions SHEATH and CIR.

The dependence of spectra steepening at high frequency vs solar wind parameters



There is not clear dependence between the spectral steepening at the kinetic scale and the value of local solar wind parameters. So the characteristics of the large scale solar wind streams as a whole play a critical role at the formation of turbulent cascade. The dependence of the value of the slope at the kinetic scale, shown earlier in Bruno et al.2014, can be observed only for high speed dynamic structures and do not observed for high speed streams from the coronal hole.