EGU 2020 Session ST1.7 - Zoom Meeting 09:00 CEST 6 May 2020

Characteristics of turbulence in transition regions near large-scale boundaries in the solar wind

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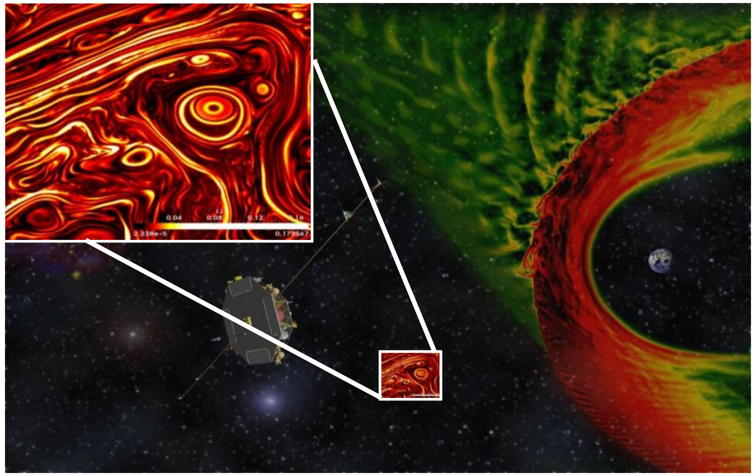
Motivation:

•The development of turbulence is limited by boundaries between streams of different speed and nature;

• Velocity shear near such large scale boundaries produce highly disturbed transition regions and can play a critical role in the formation of turbulent cascade;

•The models mainly predict properties of freely developing turbulence.



Objectives:

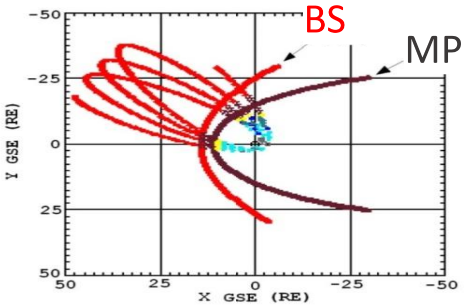
•The analysis of fluctuation spectrum changes during crossings of transition regions near large scale boundaries (compression regions SHEATH and CIR);

•The statistical comparison of turbulent properties in the solar wind transition regions and in the steady slow solar wind.

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

- Highly elliptical orbit
- Data are available from August 2011 - 2019
- 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



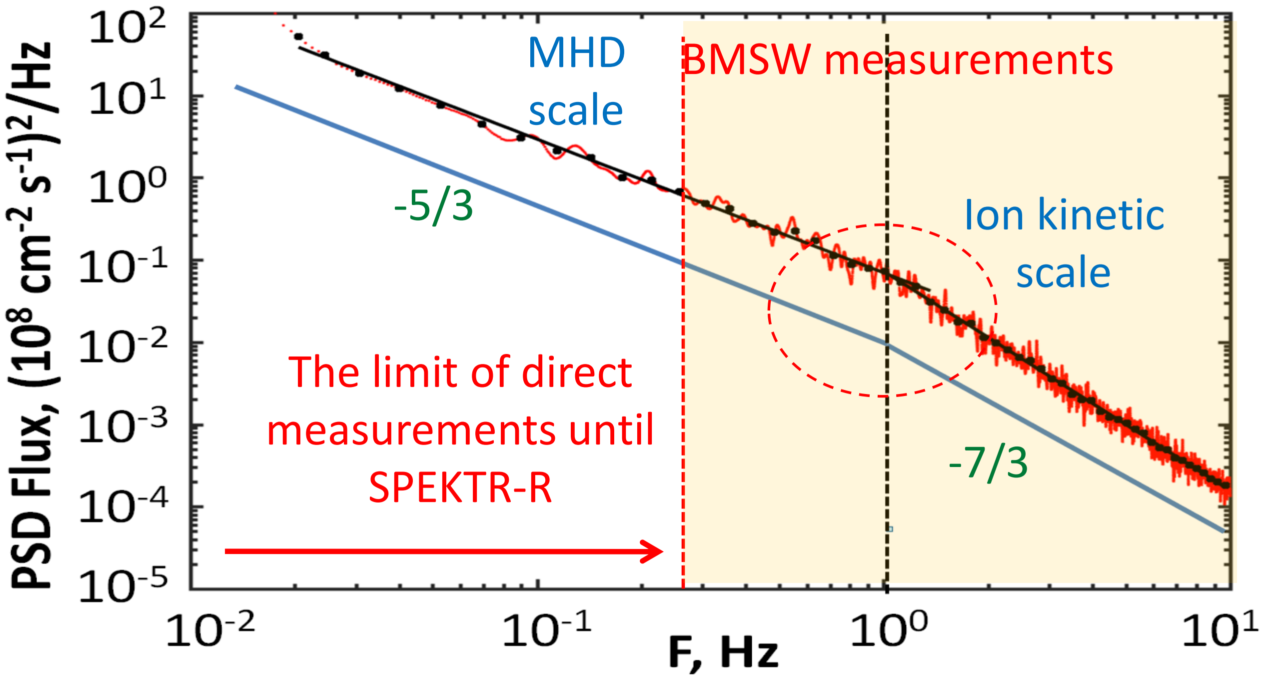
SPEKTR-R orbit

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:

Safrankova et al., 2013,2015,2016, 2019; Pitna 2017, 2019; Chen et al., 2014; Riazantseva et al.,2015, 2016, 2017a, 2017b, 2018, 2019)

✓In magnetosheath (Riazantseva et al., 2016; Rakhmanova et al., 2016, 2017a, 2017b, 2018a, 2018b, 2019)



DATA selection

The measurements of solar wind ion flux by BMSW instrument (SC SPEKTR-R) with time resolution 31 ms for the period 2011-2016

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WIND plasma and IMF measurements at http://cdaweb.gsfc.nasa.gov/

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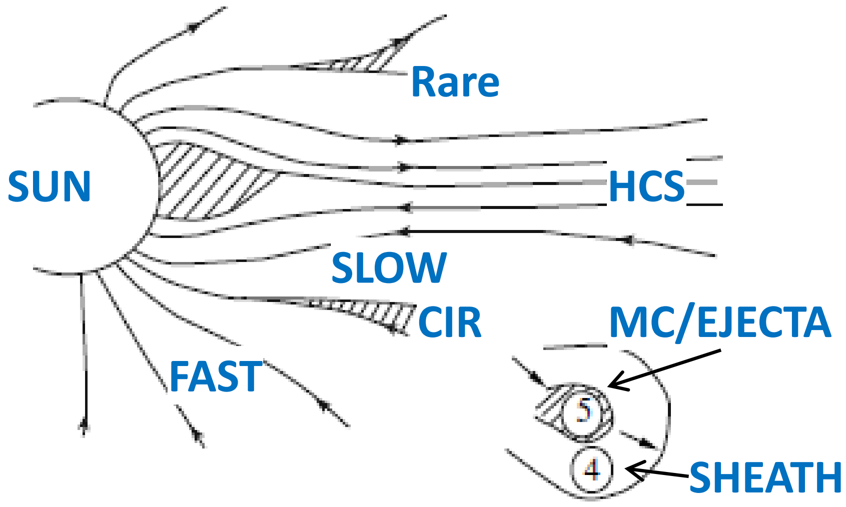
Solar wind type selection: IKI catalogue (Yermolaev *et al.,* 2009) ftp://ftp.iki.rssi.ru/pub/omni/catalog/

	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, cm^{-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 – steady slow solar wind

SW fast - steady fast solar wind

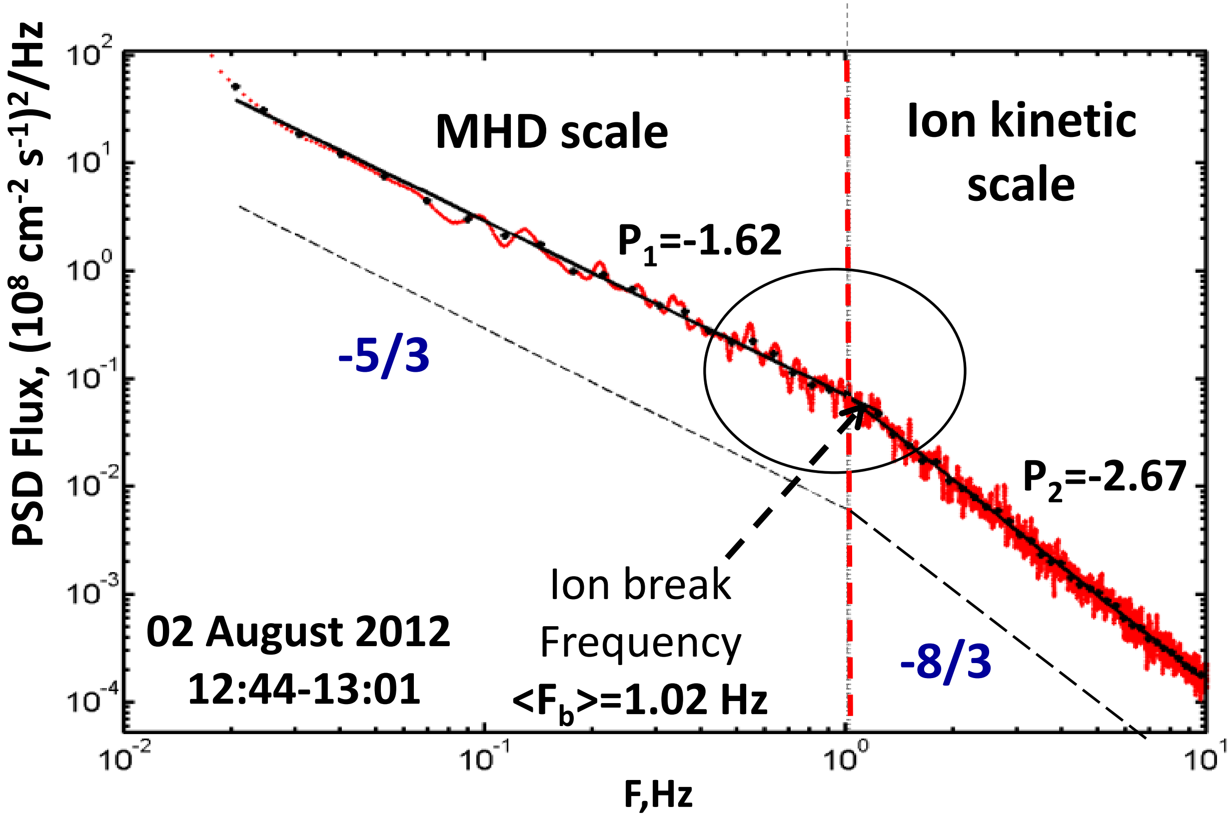
EJECTA - interplanetary Coronal Mass Ejection

MC - Magnetic cloud

SHEATH - compression region before EJECTA or MC

CIR - compression region before high-speed streams

Typical turbulent spectrum in BMSW measurements



Ion flux fluctuations turbulent spectra. Solar wind, BMSW

Shafrankova et al., 2013; *Riazantseva et al.., 2015.*

The similar spectra in magnetic field data: reviews (Bruno, Living., 2013 ; Alexandrova et.al.,2013) -

General view

Power law at the MHD scale:

- -5/3 (Kolmogorov slope) - strong turbulence, MHD Alfven waves (*Goldreich & Sridhar, 1995*)
- -3/2 - weak turbulence (*Kraichnan 1965*)

Power law at the kinetic scale:

- -7/3 - kinetic Alfvenic turbulence (KAW) (*Schekochihin et al., 2009*)
- -8/3 KAW + intermittent 2-D structures (*Boldyrev & Perez 2012*)

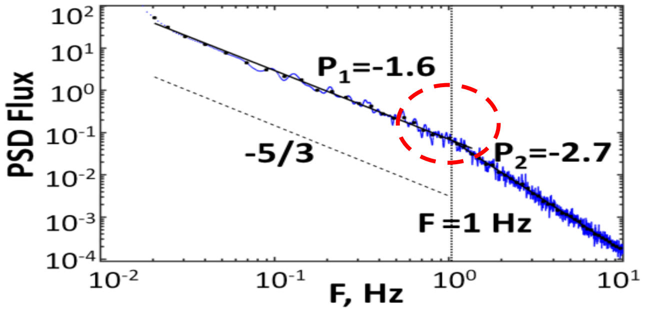
The break is controlled by:

- Ion cyclotron frequency $F_{ci} = q_i B_0 / 2\pi m_I$ (*Goldstein et al., 1995*)
- Ion thermal gyroradius $R_T = V_t / \omega_c$ (corresponding frequency $F_{\rho i} = V/2\pi R_T$) (*Schekochihin et al., 2009*)
- Ion inertial length $\lambda_i = c/\omega_p$ (corresponding frequency $F_{\lambda i} = V/2\pi\lambda_i$) (*Galtier, 2006*).

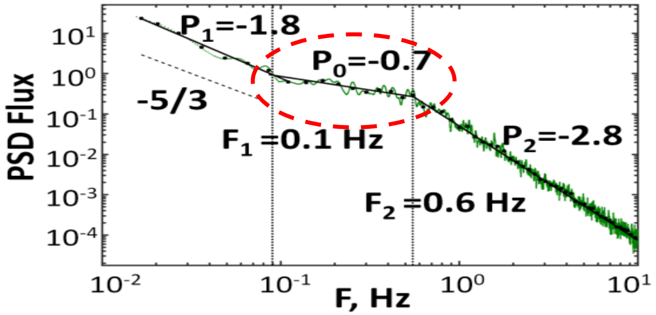
The shapes of turbulent spectra in different plasma locations

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

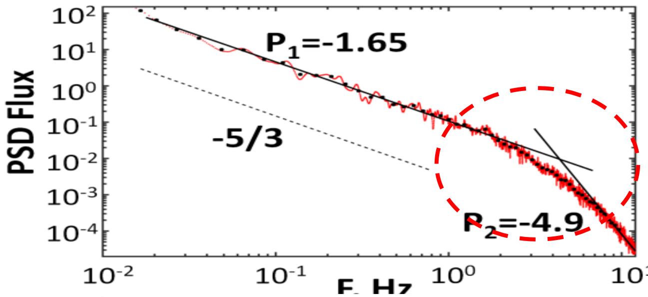
with two slopes and one break
(classical framework ~50%)



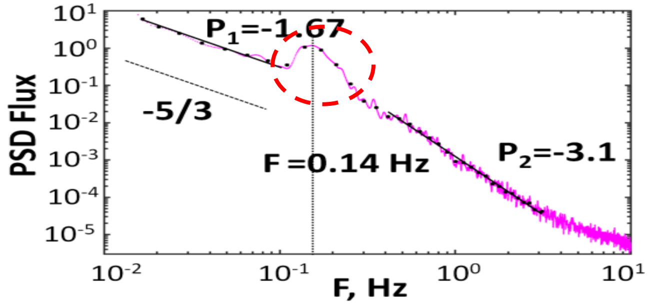
with flattening
(predicted by Chandran et al. 2009 as a superposition of Alfvénic and Kinetic Alfvénic turbulence)

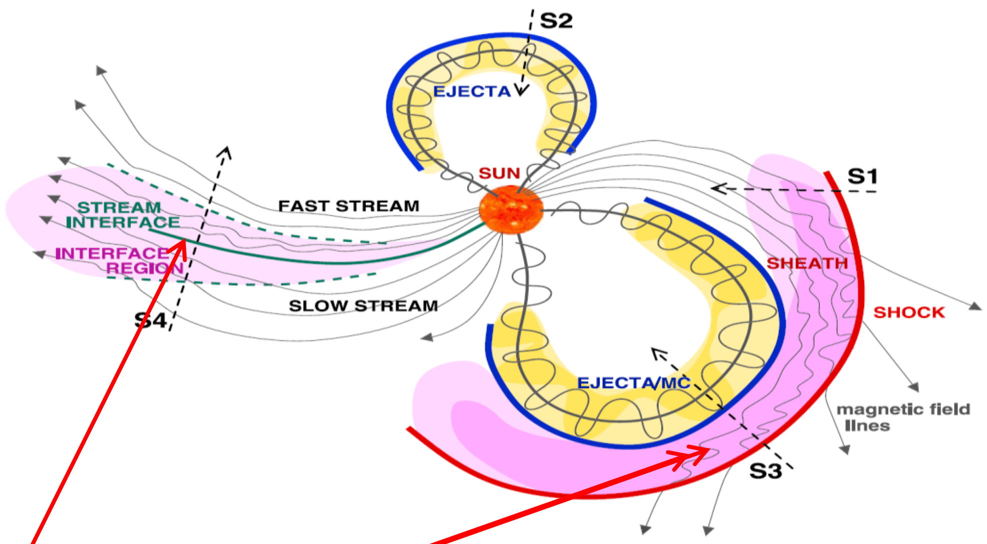


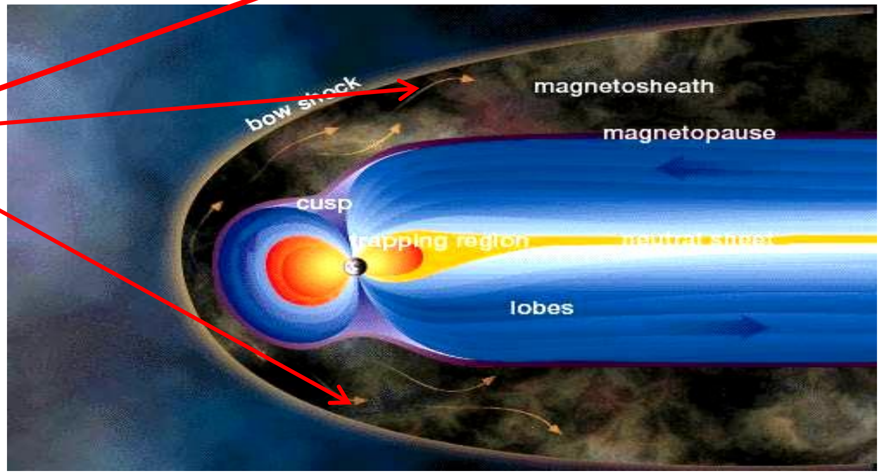
with fast nonlinear decay in the kinetic range, the slope up to -5!
(stronger damping)



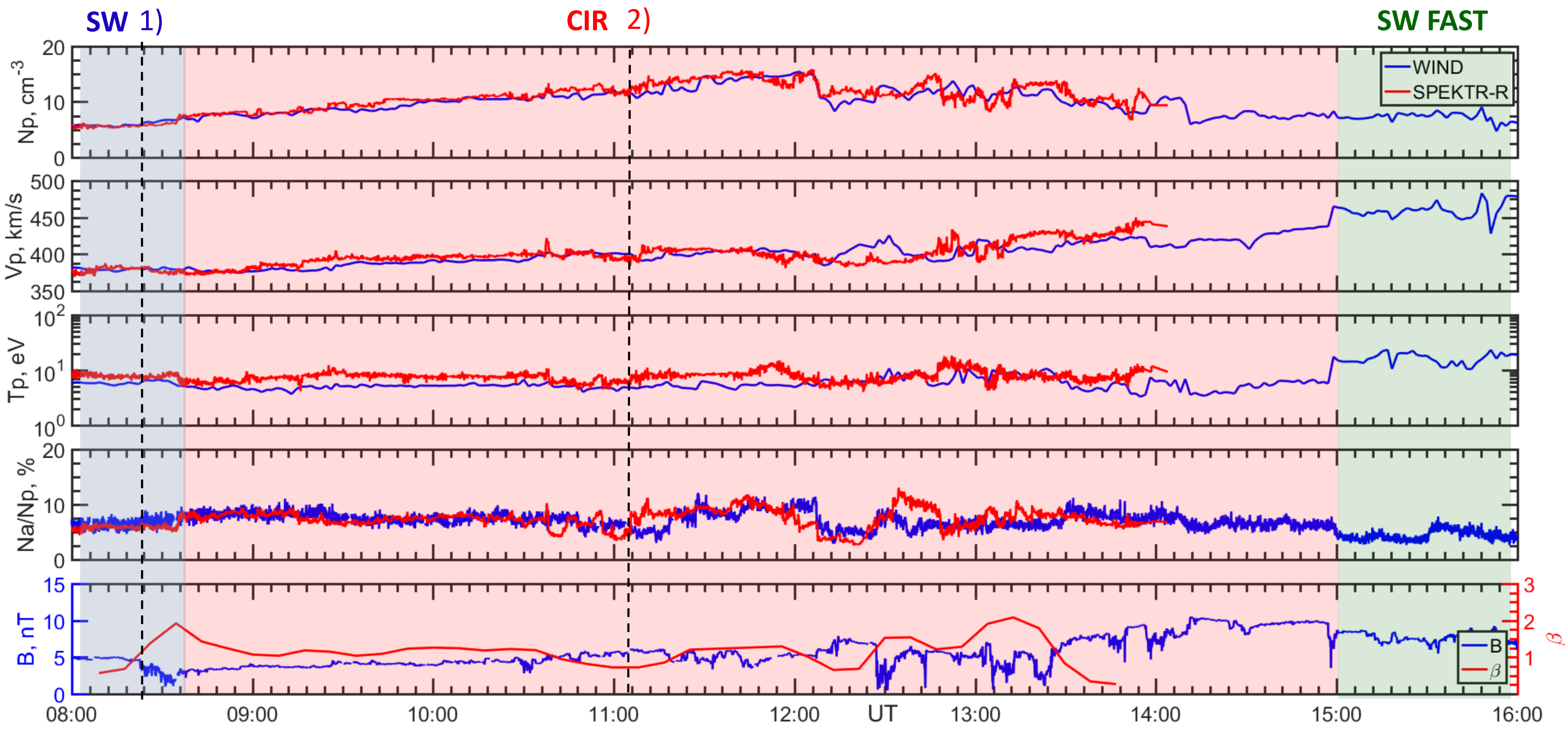
with bump
(signature of instabilities or localized coherent structure)





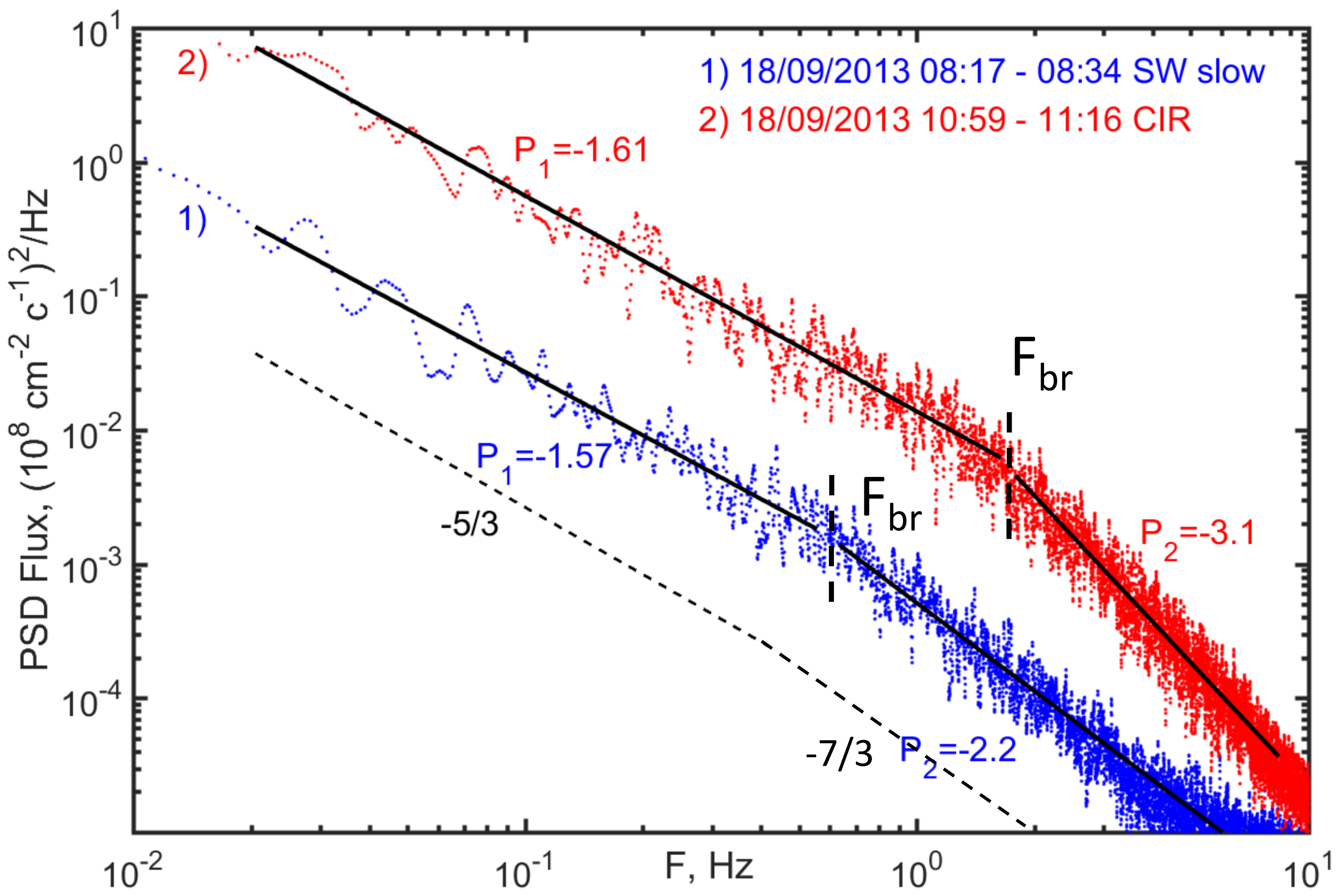


CIR crossing by SPEKTR-R & WIND



13-09-18 08:00 - 13-09-18 16:00; SPEKTR-R(24,-36,-26)Re; WIND(239,89,8)Re, Δ(t) =01:27

The comparison of ion flux frequency spectra in steady slow SW and CIR by SPEKTR-R



SW Type	SW	CIR
RSD, %	3	11
PSD_1	0.12	2.54
PSD_2	$0.28 \cdot 10^{-4}$	$6.01 \cdot 10^{-4}$
P_1	-1.57	-1.61
P_2	-2.2	-3.1
F_{br}, Hz	0.6	1.6
$F_{\rho i}$, Hz	0.7	1.1
$F_{\lambda i}$, Hz	0.6	1.0
F_{ci}, Hz	0.06	0.09
β	1.0	0.7

Steady slow SW - is similar to model predictions
(at MHD scale -5/3 – Kolmogorov theory,
at kinetic scale slope -7/3 - KAW turbulence theory)

CIR – higher power density, steeper spectrum at ion kinetic scale

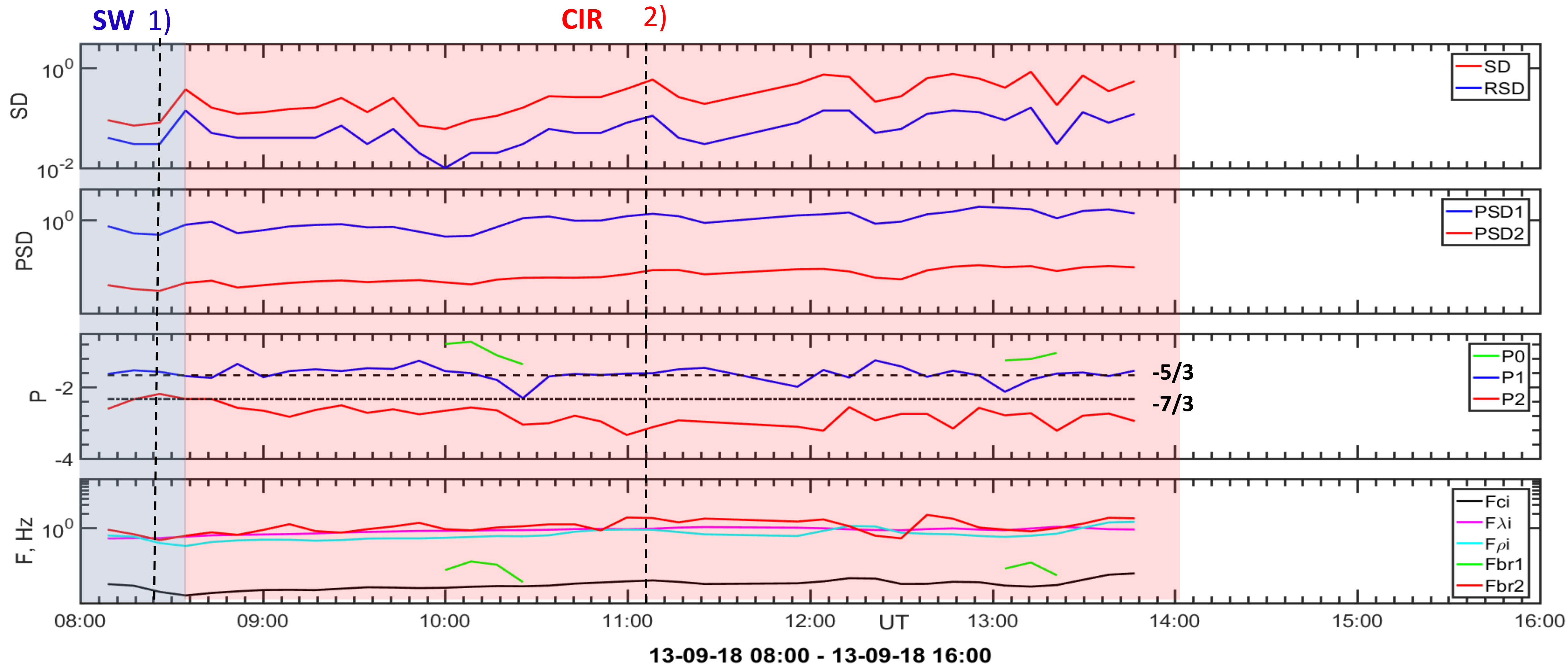
Characteristic scales:

$F_{\lambda i} = V/2\pi\lambda_i$, $\lambda_i = c/\omega_p$ - inertial length

$F_{\rho i} = V/2\pi R_T$, $R_T = V_t/\omega_c$ - proton thermal gyroradius

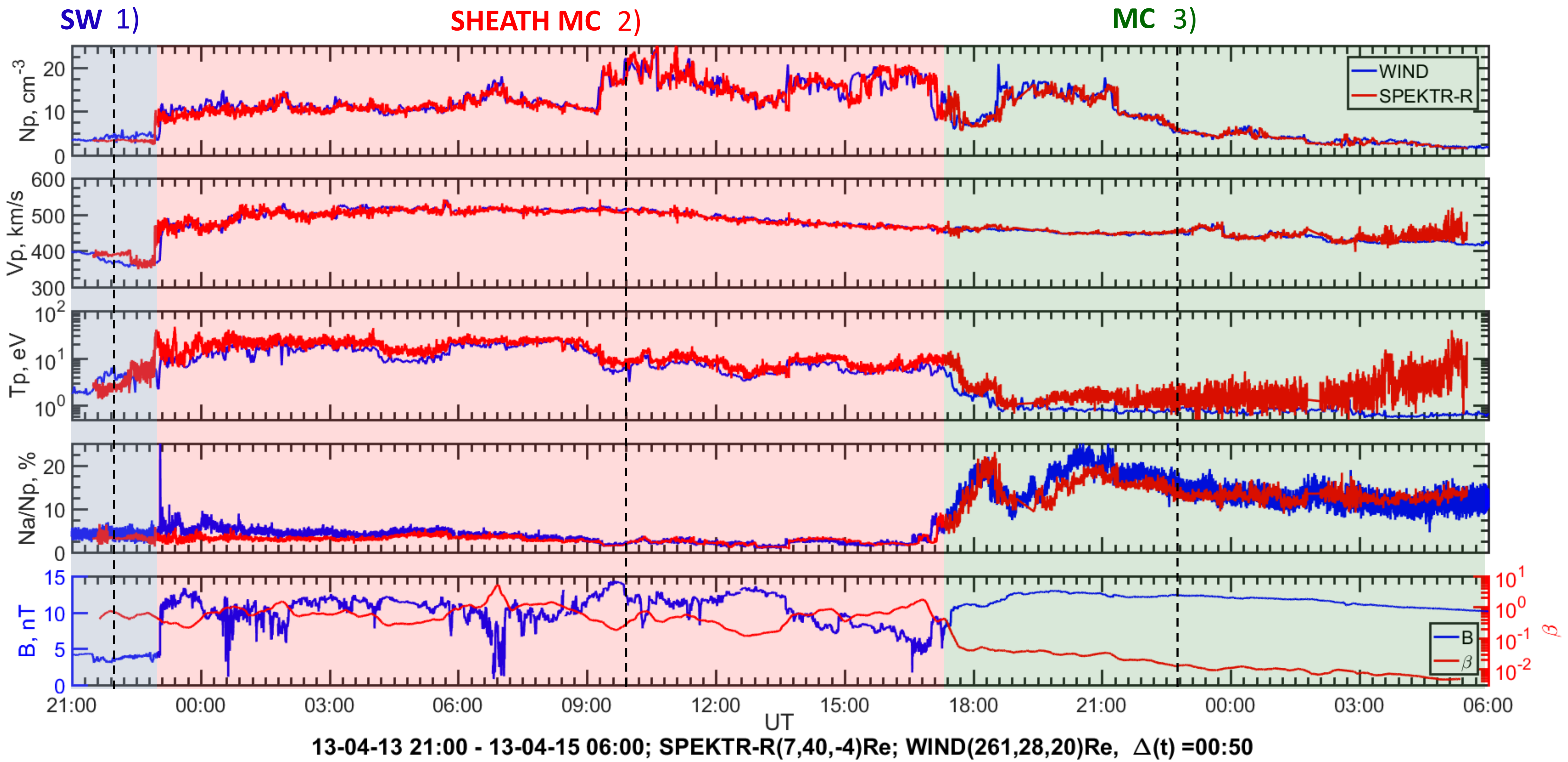
$F_{ci} = q_i B_0/2\pi m_i$ – ion cyclotron frequency

CIR crossing by SPEKTR-R & WIND: the evolution of spectral characteristics

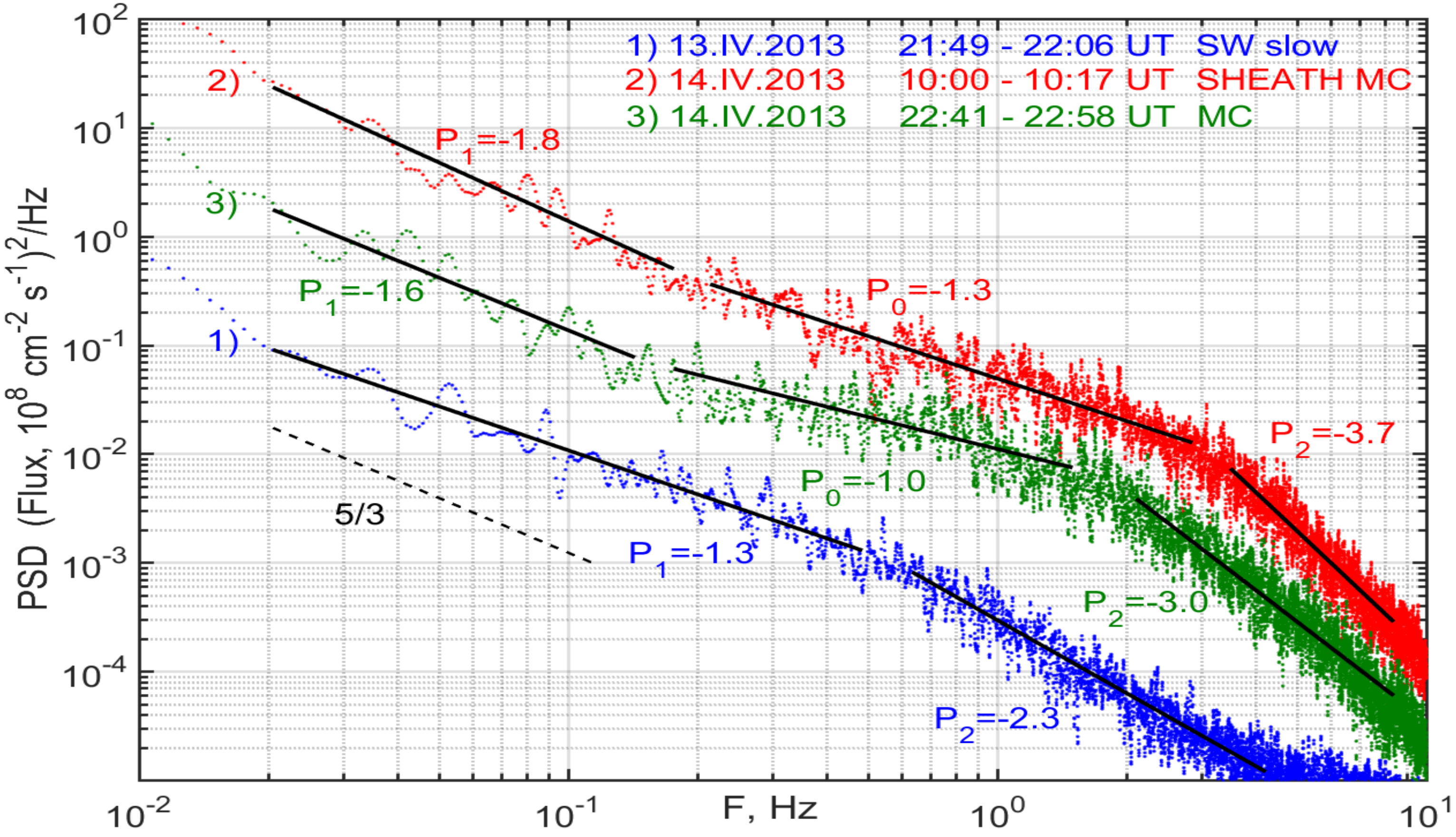


- MHD scale slope: variations around -5/3 (Kolmogorov) during all period ;
- Kinetic scale slope: close to -7/3 (KAW theory) in SW and increasing steepening during CIR crossing;
- Break frequency : close to the characteristic scales $F_{\rho i}$ and $F_{\lambda i}$ ($F_{\rho i} \approx F_{\lambda i}$ due to $\beta \approx 1$).

SHEATH MC crossing by SPEKTR-R & WIND



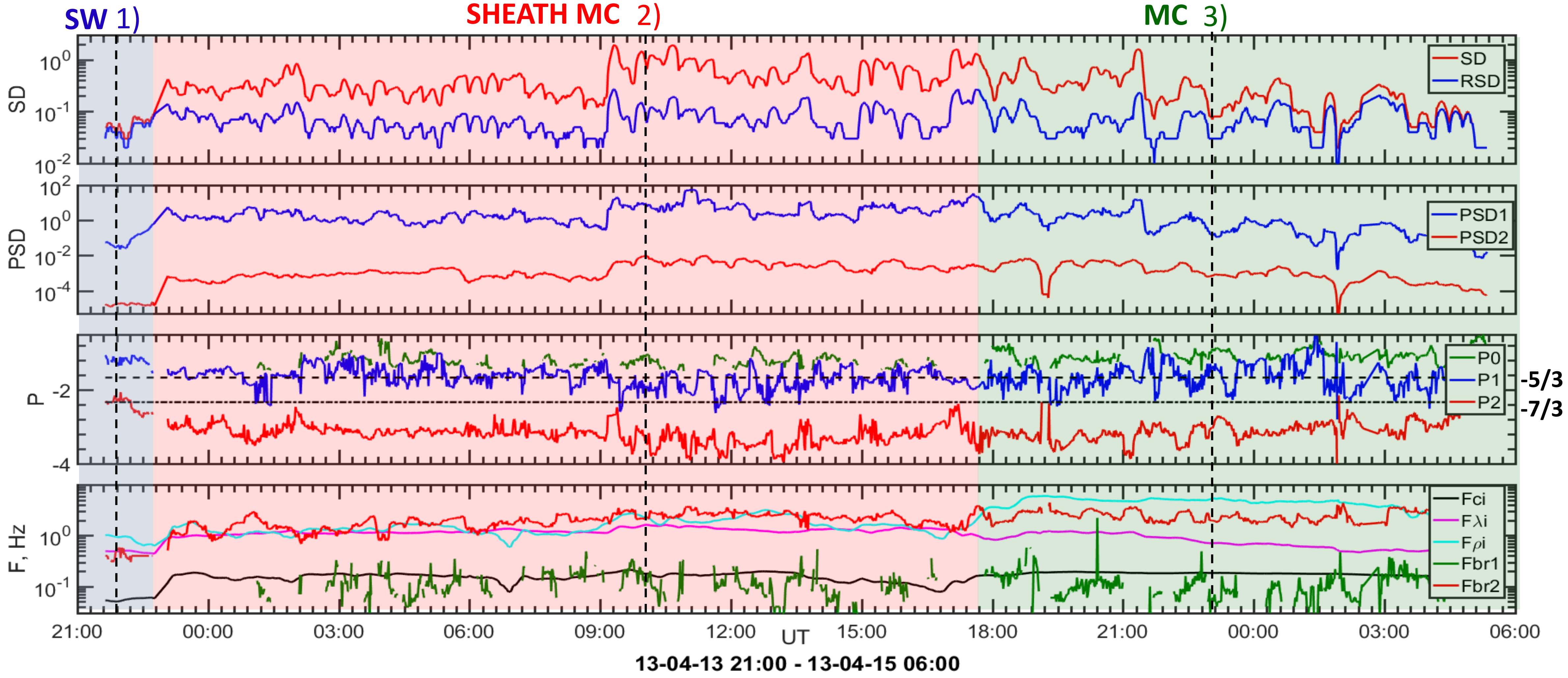
The comparison of ion flux frequency spectra in steady slow SW, SHEATH MC and MC by SPEKTR-R



SW type	SW	SHEATH MC	MC
RSD	0.04	0.12	0.09
PSD_1	0.035	6.92	0.61
PSD_2	$0.01 \cdot 10^{-3}$	$6.88 \cdot 10^{-3}$	$0.94 \cdot 10^{-3}$
P_1	-1.34	-1.79	-1.61
P_0		-1.3	-0.98
P_2	-2.23	-3.71	-3.02
Fbr_1		0.20	0.15
Fbr_{12}	0.57	3.12	1.80
$F_{\rho i}$, Hz	0.64	2.53	6.61
$F_{\lambda i}$, Hz	0.53	1.55	0.73
F_{ci}, Hz	0.05	0.18	0.19
β	0.71	0.39	0.01

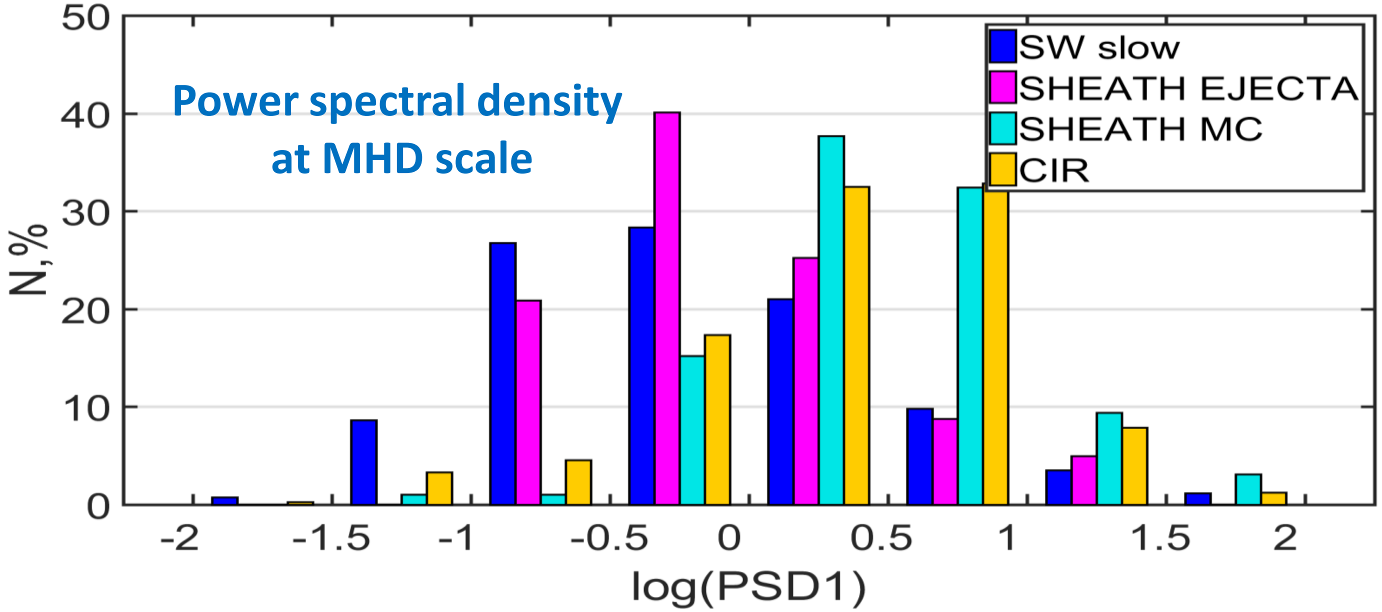
- The spectrum in slow SW is depleted – with lower values of spectral density and shallower spectral slopes.
- Highest spectral density (PSD) in the SHEATH MC , and the most steep spectrum at the kinetic scale.
- The plateau between MHD and kinetic scale is observed for SHEATH MC and MC regions - the result of superposition of Alfven and KAW turbulence more distinct for low plasma β (Chandran et al., 2009)

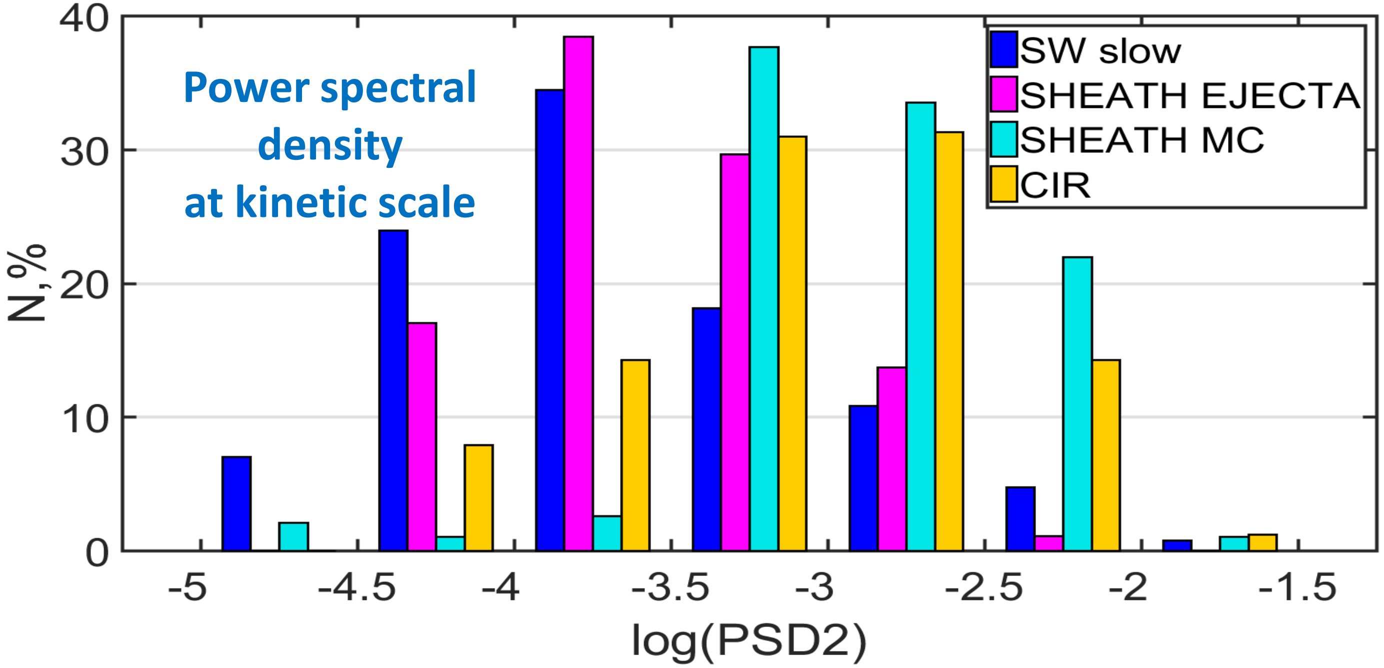
SHEATH MC crossing by SPEKTR-R & WIND: the evolution of spectral characteristics



- •MHD scale slope: strong variations around -5/3 during SHEATH and MC crossings, shallower slope for SW;
- •Kinetic scale slope: close to -7/3 (KAW theory) in SW and increasing steepening during SHEATH crossing ;
- •Break frequency: close to $F_{\lambda i}$ in SW, close to $F_{\rho i}$ in SHEATH. (The first break before flattening –close to F_{ci}).

The characteristics of ion flux fluctuation spectra in transition regions and in the steady slow SW

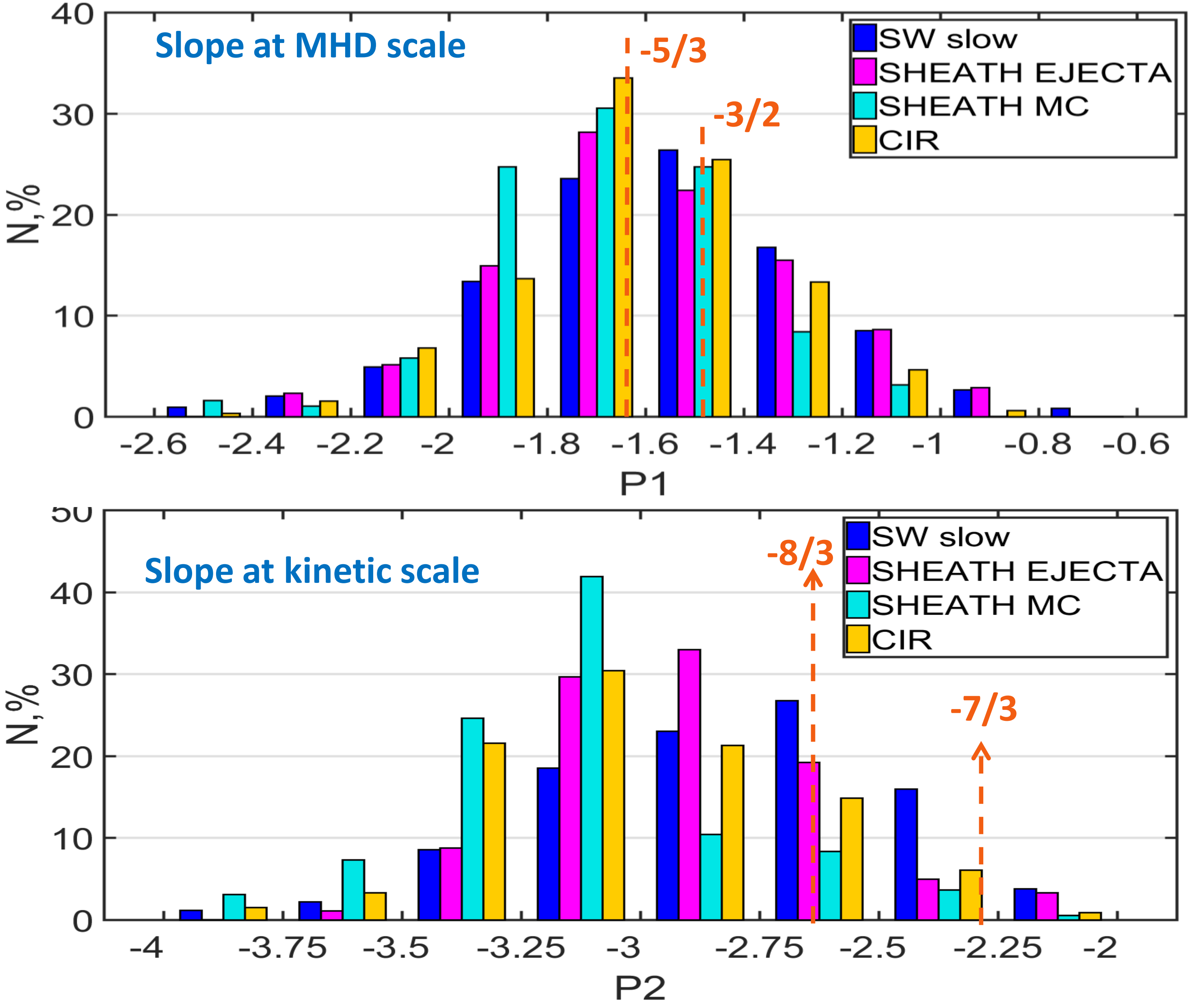




PSD_2 (the median spectral density at the kinetic scale) have a similar distribution as PSD_1 (at the MHD scale) but more than 3 order lower by power density value. The highest PSD_1 and PSD_2 are observed in SHEATH MC and CIR regions.

SW type	PSD_{1}, 10^{16} $cm^{-4}s^{-2}Hz^{-1}$	$PSD_{1\,norm}$, 10^{-2}	PSD_{2}, 10^{12} $cm^{-4}s^{-2}Hz^{-1}$	$PSD_{2\,norm}$, 10^{-5}
Slow	0.54	4.0	1.8	1.6
SHEATH EJECTA	0.6	4.9	2.6	2.4
SHEATH MC	2.9	7.4	11.6	3.6
CIR	2.5	6.3	9.4	2.5

The characteristics of ion flux fluctuation spectra in transition regions and in the steady slow SW

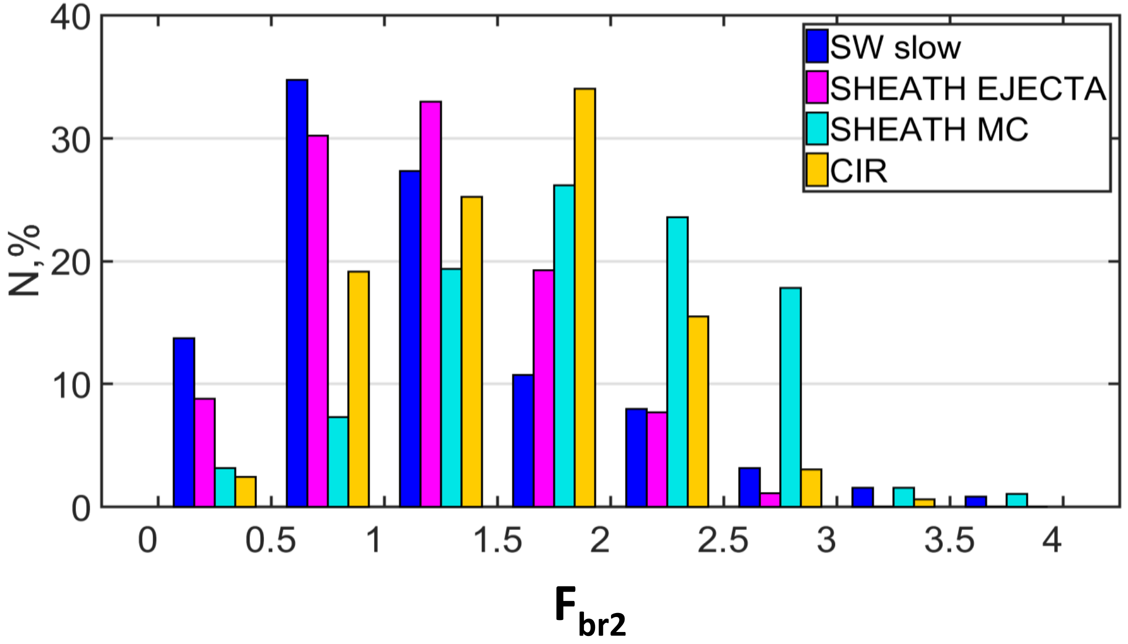


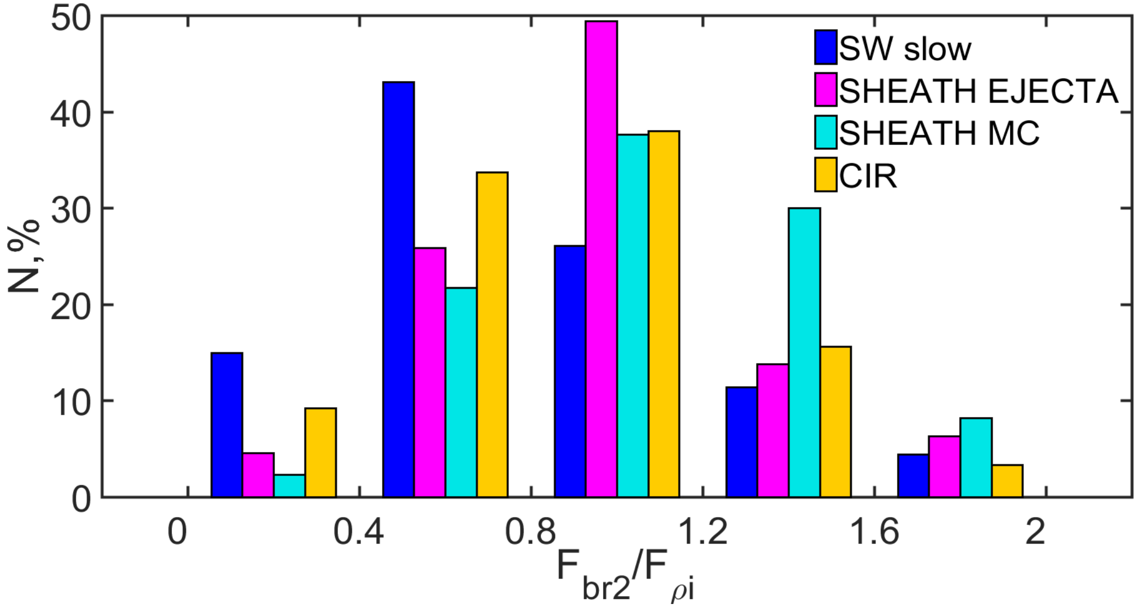
MHD scale: the maximums of distributions correspond to -5/3 for transition regions, and is slightly shallower for steady slow SW

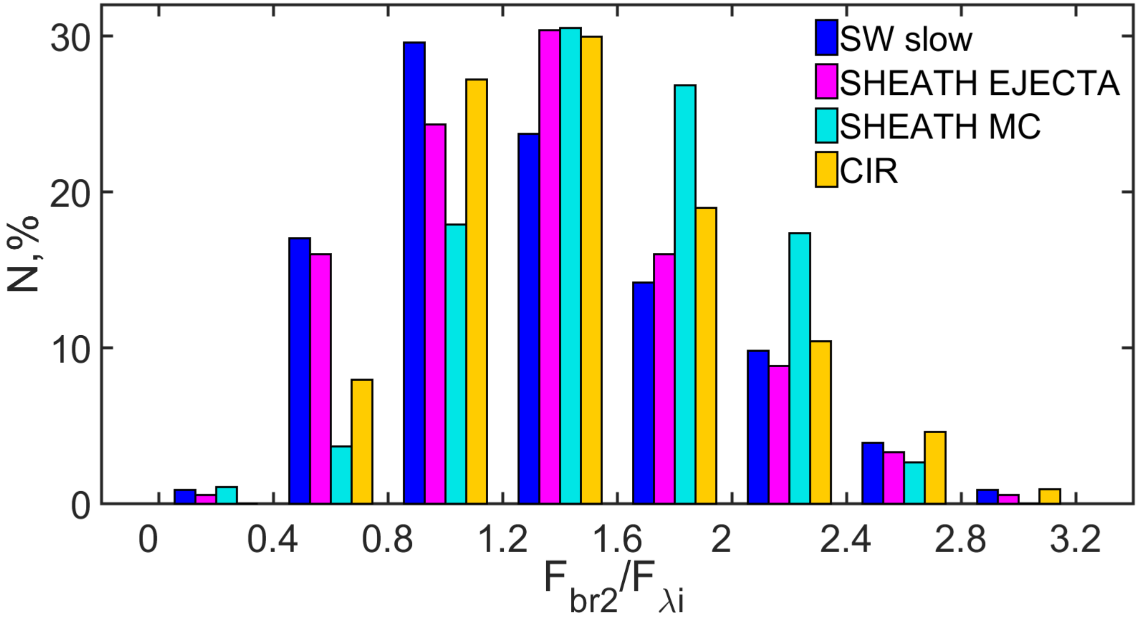
Kinetic scale: The maximum of distribution is close to -8/3 for steady slow SW and steeper for transition regions. The steepest spectra are observed in SHEATH MC and CIR

SW type	P_1	P_2
Slow SW	1.56	2.79
SHEATH EJECTA	1.6	2.9
SHEATH MC	1.68	3.17
CIR	1.63	3.08

The characteristics of ion flux fluctuation spectra in transition regions and in the steady slow SW







- The break frequency F_{br} significantly increases for transition regions;
- The break frequency in transition regions statistically correspond to frequency related to proton thermal gyroradius;
- The break frequency in steady solar wind statistically correspond to frequency related to the inertial length.

Characteristic scales:

$F_{\lambda i} = V/2\pi\lambda_i$, $\lambda_i = c/\omega_p$ - inertial length

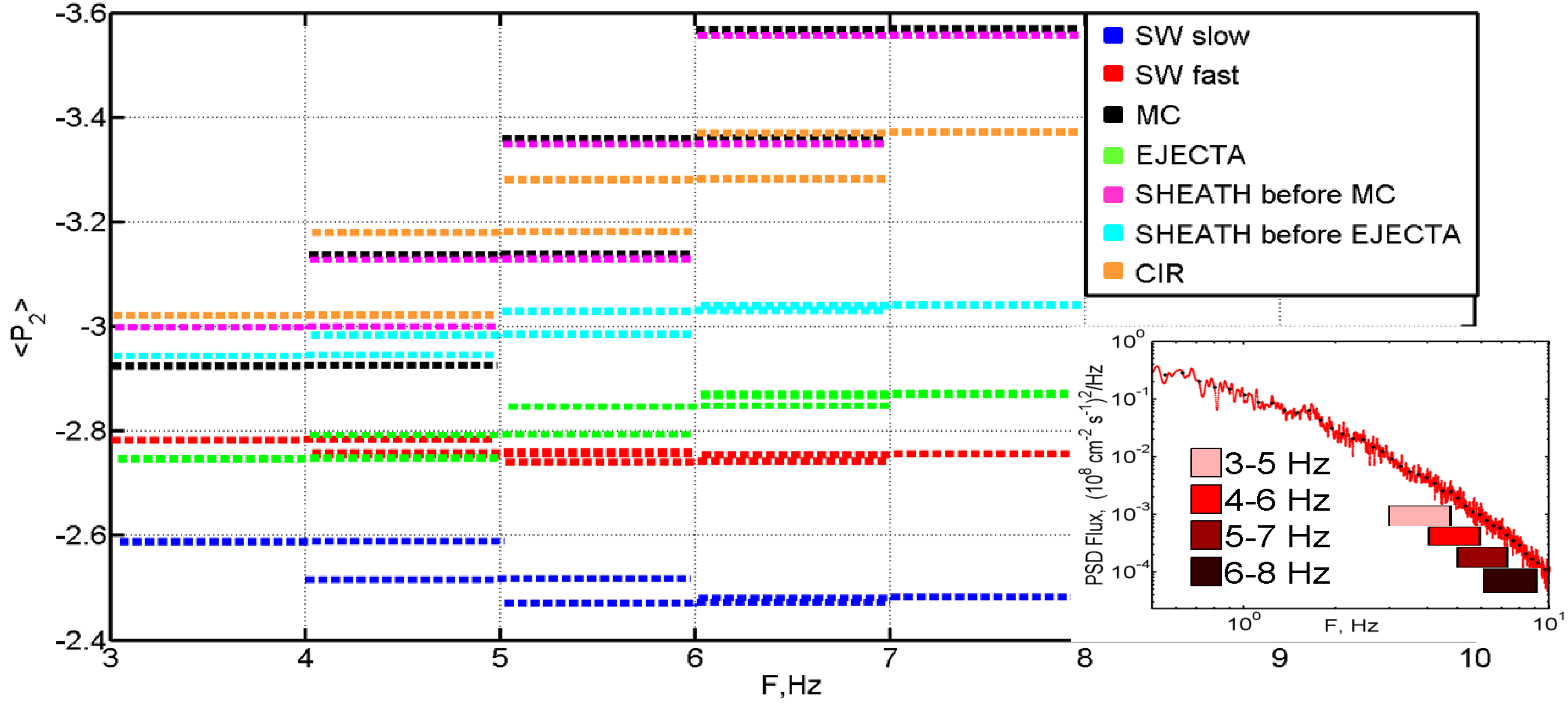
$F_{\rho i} = V/2\pi R_T$, $R_T = V_t/\omega_c$ - proton thermal gyroradius

The median characteristics of ion flux fluctuation spectra in compression transition regions and in the steady slow solar wind

SW Type	N	$\|P_1\|$	$\|P_2\|$	PSD_1 *normalized at flux value*	PSD_2 *normalized at flux value*	RSD, %	F_{br}, Гц	$F_{br}/F_{\rho i}$	$F_{br}/F_{\lambda i}$	V_p, km/s	N_p, cm^{-3}	F_{ion}, $10^8\ cm^{-2}\ c^{-1}$	T_p, eV	$\|B\|$, nTl	β
SW	1051	1.56	2.79	$4.0 \cdot 10^{-2}$	$1.6 \cdot 10^{-5}$	5	1.0	0.72	1.24	355	11.1	4.1	4.9	6.5	0.54
SHEATH EJECTA	182	1.6	2.9	$4.9 \cdot 10^{-2}$	$2.4 \cdot 10^{-5}$	5	1.2	0.96	1.35	409	9.5	4.1	8.2	6.9	0.79
SHEATH MC	191	1.68	3.17	$7.4 \cdot 10^{-2}$	$3.6 \cdot 10^{-5}$	7	1.9	1.07	1.53	477	14.1	6.9	9.5	10.0	0.76
CIR	329	1.63	3.08	$6.3 \cdot 10^{-2}$	$2.5 \cdot 10^{-5}$	7	1.6	0.86	1.38	350	17.8	6.5	6.6	10.7	0.51

- Spectrum at the MHD scale is practically the same in steady slow solar wind and in all types of transition regions, and roughly corresponds -5/3, but the statistical spread of slopes value is large;
- Spectrum at the kinetic scale is steeper, break frequency and spectral density (PSD) is higher for transition regions in comparison with steady slow SW ;
- The break frequency roughly corresponds to $F_{\rho i}=V/2\pi R_T$ for transition regions. For steady slow solar wind there are no good correspondence of the break to any characteristics scales but it is closer to $F_{\lambda i}=V/2\pi\lambda_i$.

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



- The spectral slopes in both slow and fast steady SW do not depend on frequency - spectra can be approximated by power law function
- The highest slopes and clear steepening are observed in MC and SHEATH before MC and CIR regions - spectra can not be approximated by power law function

Conclusions:

The plasma turbulence in the transition regions with plasma compression associated with velocity shear near large scale boundaries can be characterized by:

- **Higher spectral density (PSD) than in the steady slow solar wind;**
- **Slope close to -5/3 (Kolmogorov like spectrum) at the MHD scale;**
- **Slope ≈-3 (often with non linear descent) at the kinetic scale , steeper than in the steady slow solar wind and than predicted by models (-7/3 or -8/3);**
- **Higher break frequency than in the steady slow solar wind;**
- **clear relation of the break frequency with scale of the proton thermal gyroradius as predicted in KAW model (for steady slow solar wind – not!)**

These turbulent properties are typical for SHEATH MC and CIR, and are not so clear for SHEATH EJECTA due to the lack of statistic

The turbulent properties at the ion kinetic scale are strongly different from model predictions can be the signature of energy disbalance through the cascade, the intensification of dissipation processes and additional heating in transition regions.