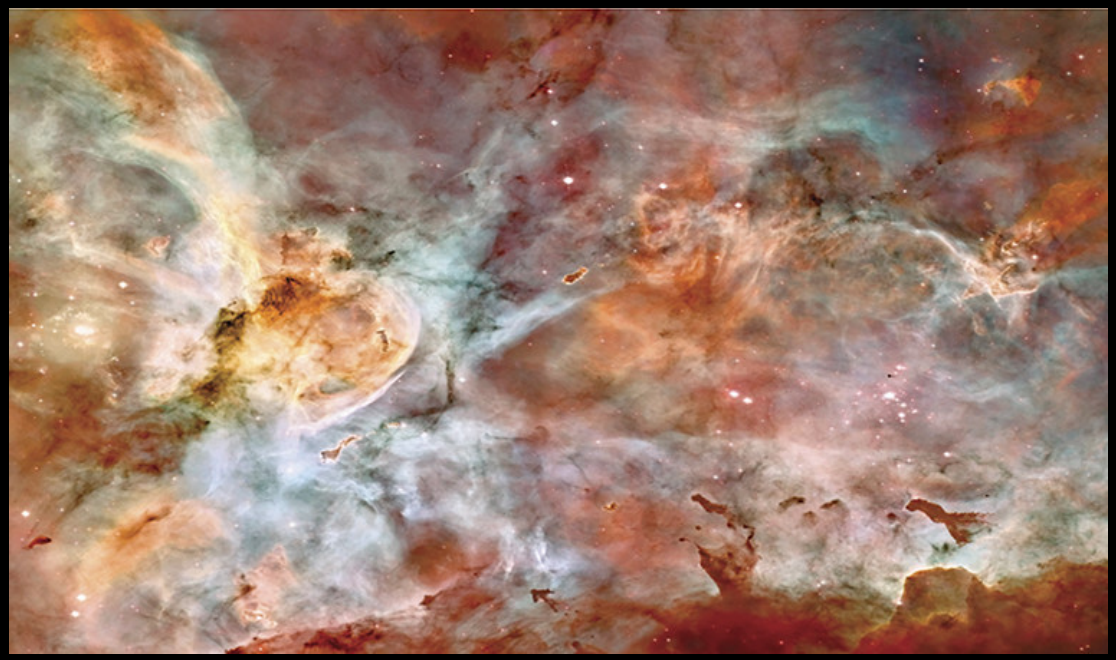
RPW & FILEDS workshop, 26-29 February 2024, Orleans, France

Coherent structures across the turbulent cascade in the solar wind at 0.17 au

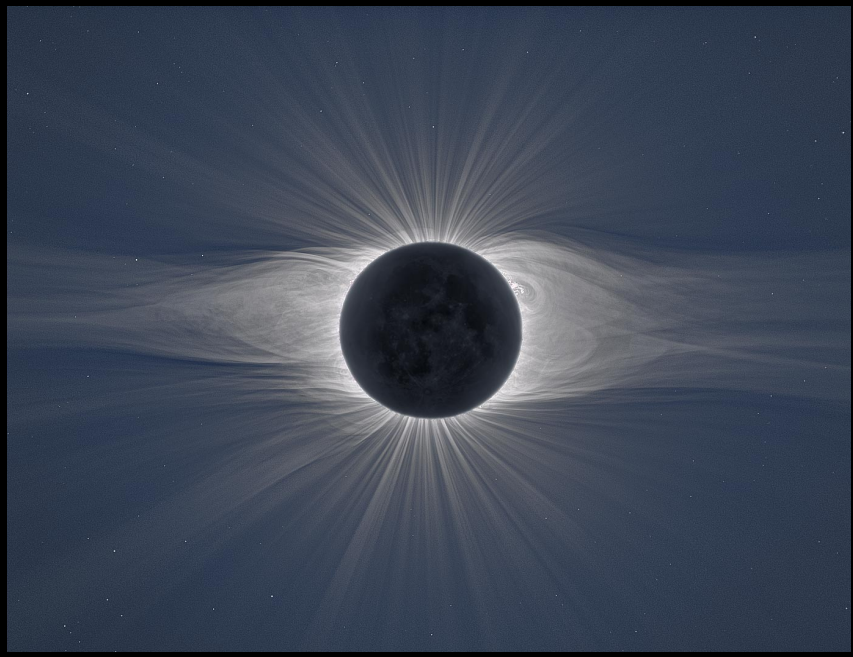
Olga Alexandrova, **A. Vinogradov (PhD thesis)**, P. Demoulin,
A. Artemyev, M. Maksimovic, A. Mangeney, S. Bale
LESIA, Observatoire de Paris

olga.alexandrova@obspm.fr

Atrophysical plasmas are generally turbulent



NASA, ESA, N. Smit (UC Berkley), HUBBLE Heritage team (STSCL/AURA), NOAO/AURA/NSF



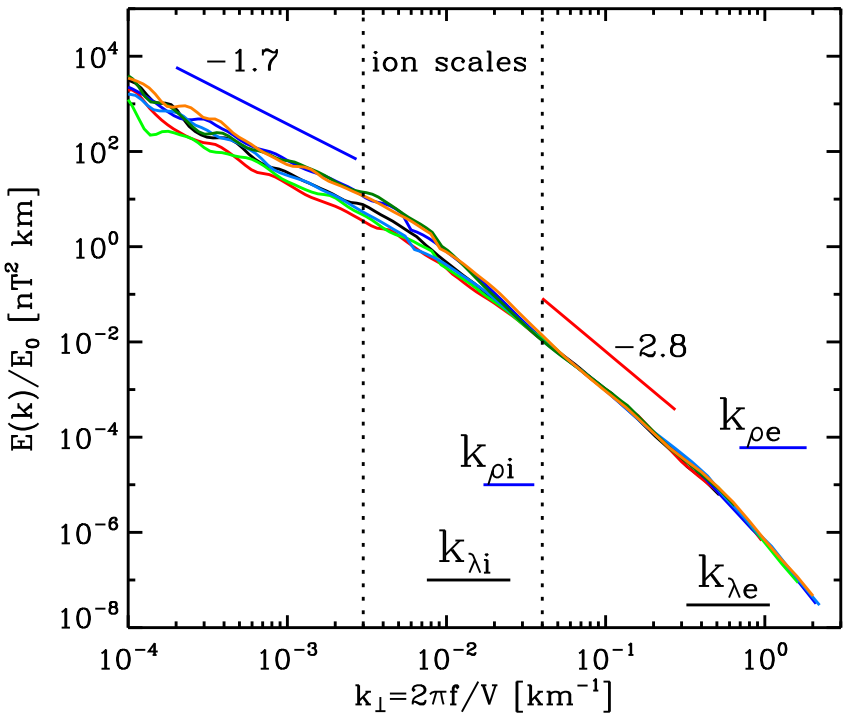
2019 Miloslav Druckmuller, Peter Aniol

Turbulence develops in any flow where energy is injected at scales L_0 >> the scale of dissipation L_d ($L_0/L_d = R_e^{3/4}$), i.e. for Reynolds numbers >> 1.

What kind of order emerges from this apparent chaos ?

Solar wind (odd) turbulence: spectrum and intermittency

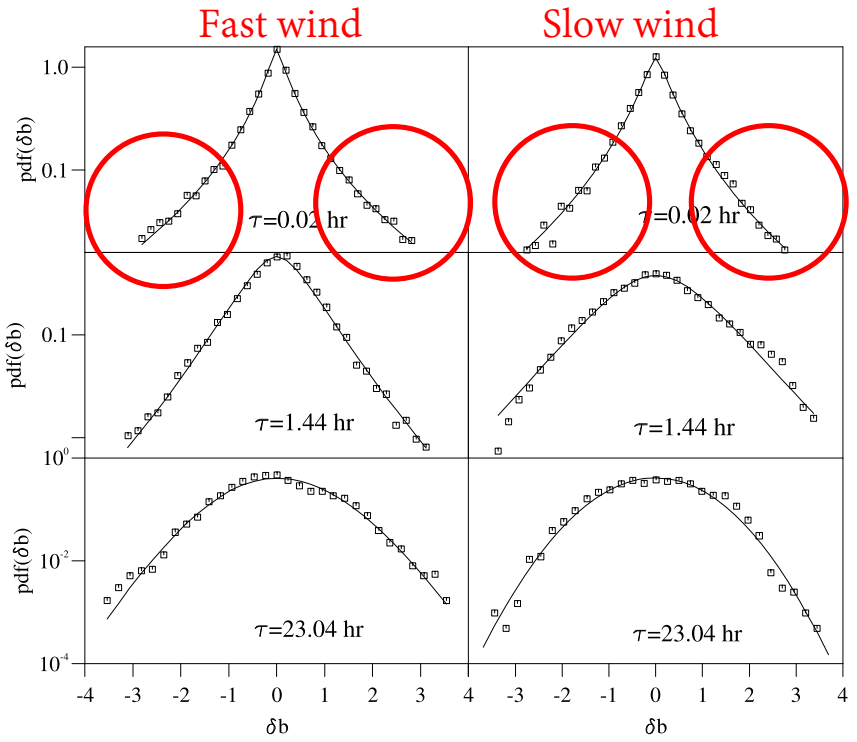
m.f.p.~ 1 AU= 1.5 10^8 km => cascade is at sub-collisional scales !



[Alexandrova et al. 2009 PRL, 2013 SSR]

$$\rho_e = \frac{V_{th,e}}{2\pi f_{ce}}$$

$$k_{\rho_e} = 1/\rho_e$$



[Sorriso-Valvo et al. 1999]

High tails : coherent structures (coupled phases)

Intermittent structures in solar wind turbulence

- **High B-increments => planar discontinuities (current sheets and magnetosonic shocks)**

[e.g., Veltri & Mangeney 1999, Veltri+2005, Servidio+2008, Greco+2009, 2012, 2014, Perri+2012]

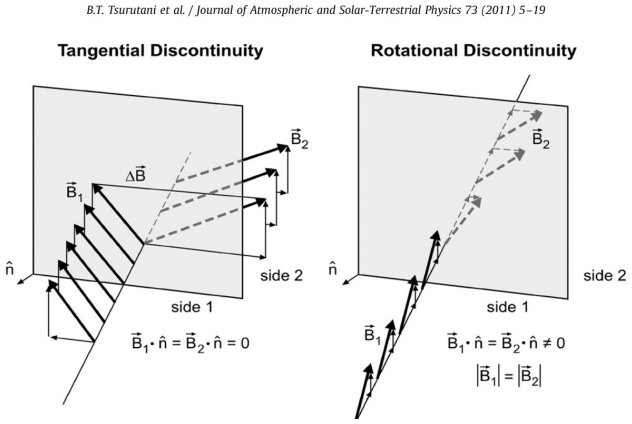
- **High Morlet wavelet coefficients => more complex topologies, such as Alfven vortices, magneric holes & magnetosonic solitons** [e.g., Lion+2016, Perrone+2016, 2017, 2020, Roberst+2016].

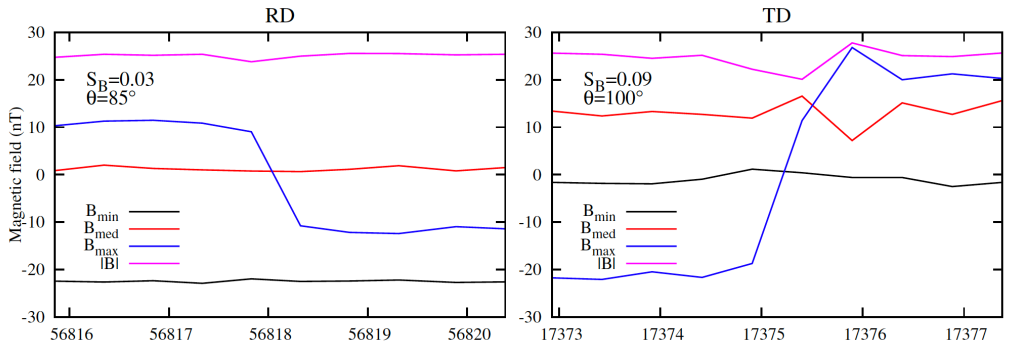
Most of literature:

End of the inertial range and ion scales.

Perri+12, Greco+16:

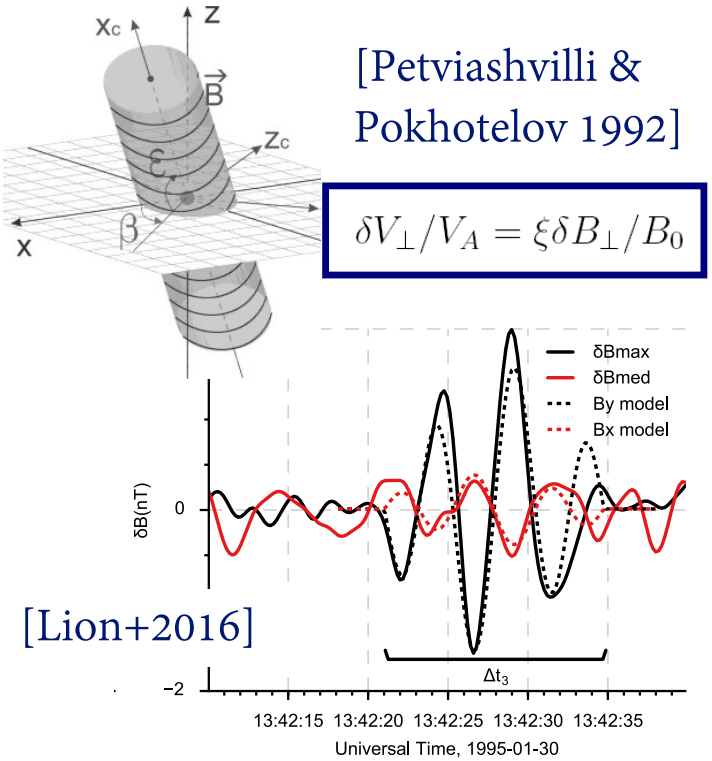
Current sheets @sub-ion scales





[Petviashvilli & Pokhotelov 1992]

$$\delta V_\perp / V_A = \xi \delta B_\perp / B_0$$



[Lion+2016]

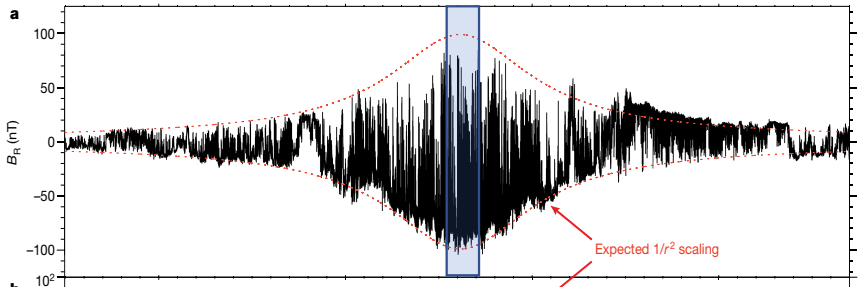
Parker Solar Probe first encounter, 0.17 au

2018-11-06, [00:00,05:00] UT

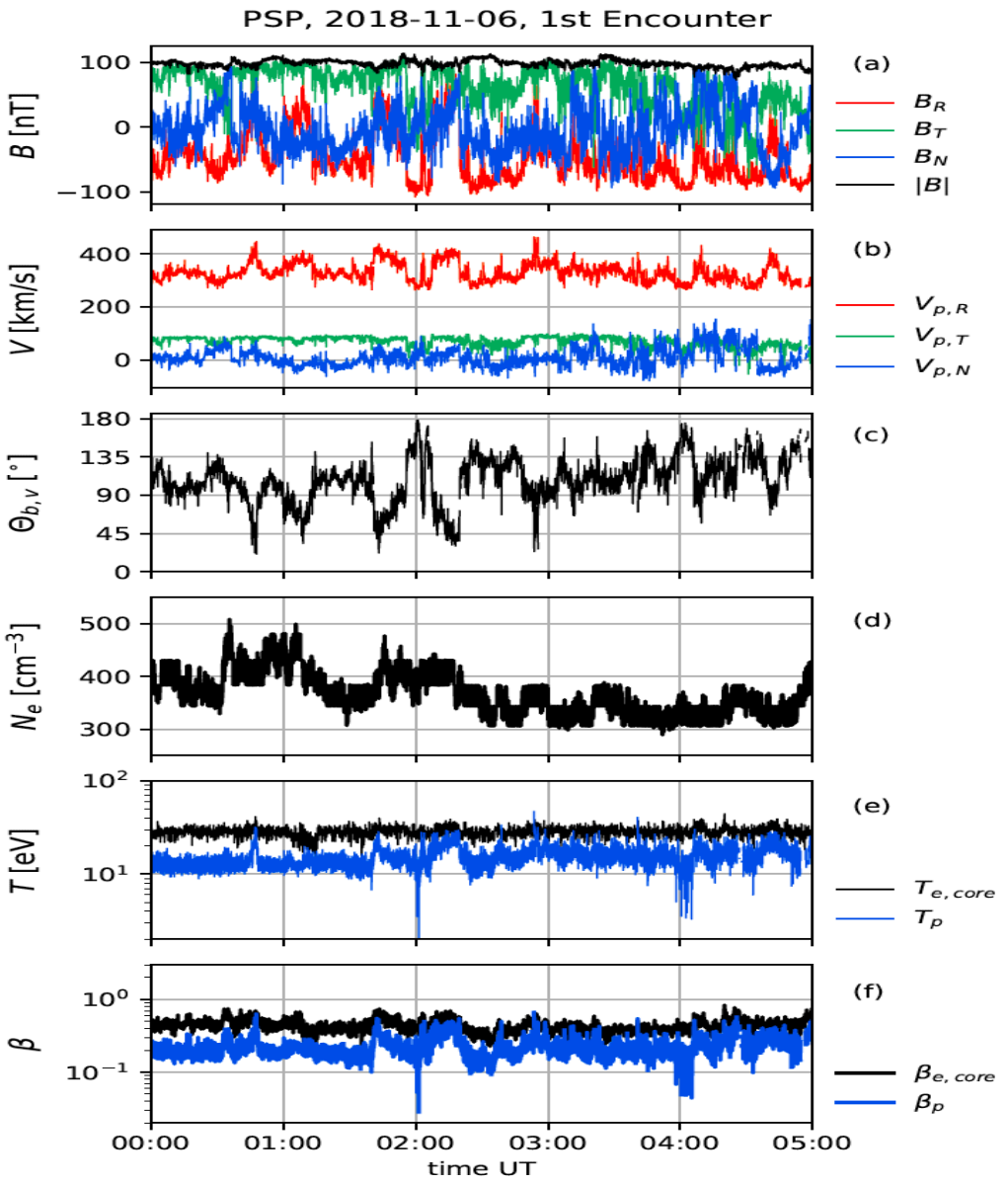
- highly perturbed interval

[Bale et al. 2019, Perrone et al. 2020]

FIELDS/MAG+SCM merged data



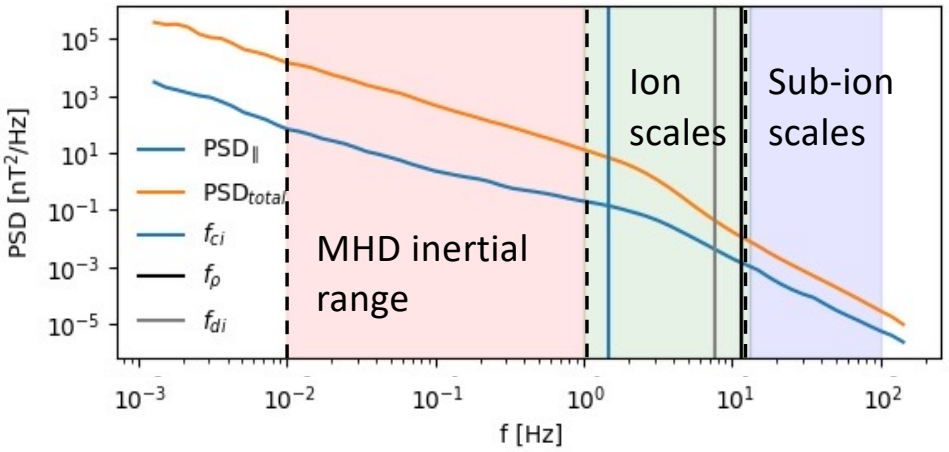
Bale et al., 2019, Nature



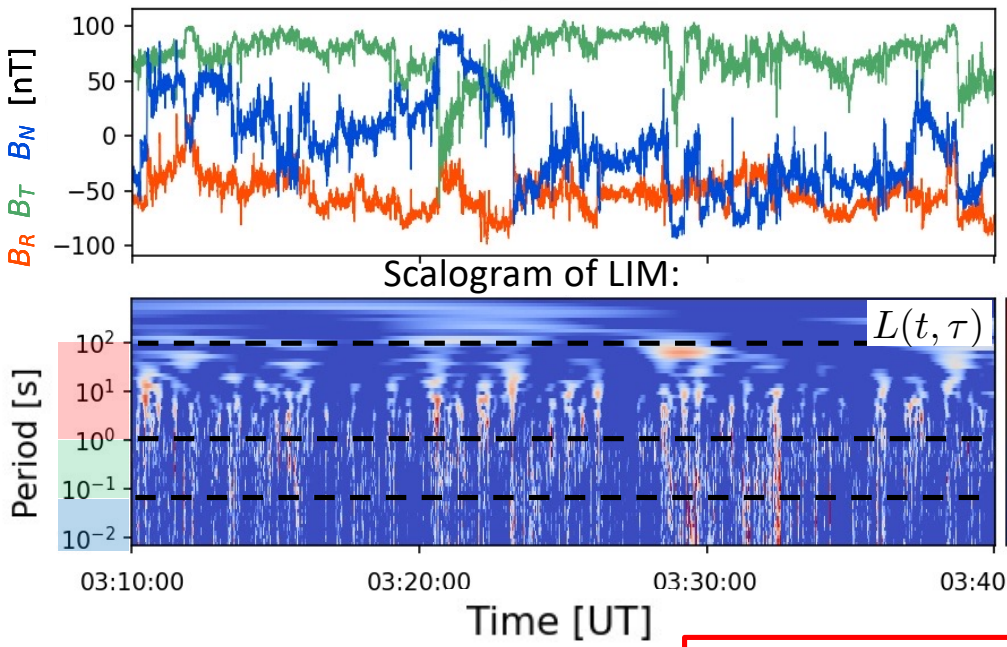
Detection of coherent structures at 0.17 au

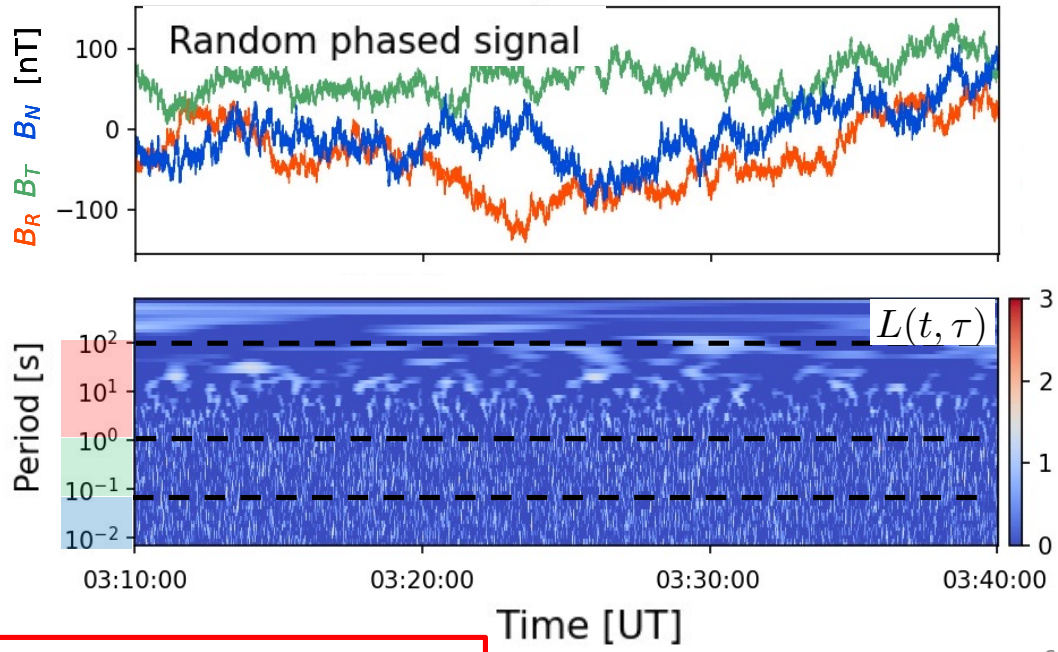
Local Intermittency Measure (***LIM***) [Farge 1992], with W[B_i] being Morlet wavelet coeff. of B_i:

$$L(t,\tau) = \frac{\sum_{i=R,T,N} |W[B_i](t,\tau)|^2}{\langle \sum_{i=R,T,N} |W[B_i](t,\tau)|^2 \rangle_{t \in T'}}$$



PSP/FIELDS



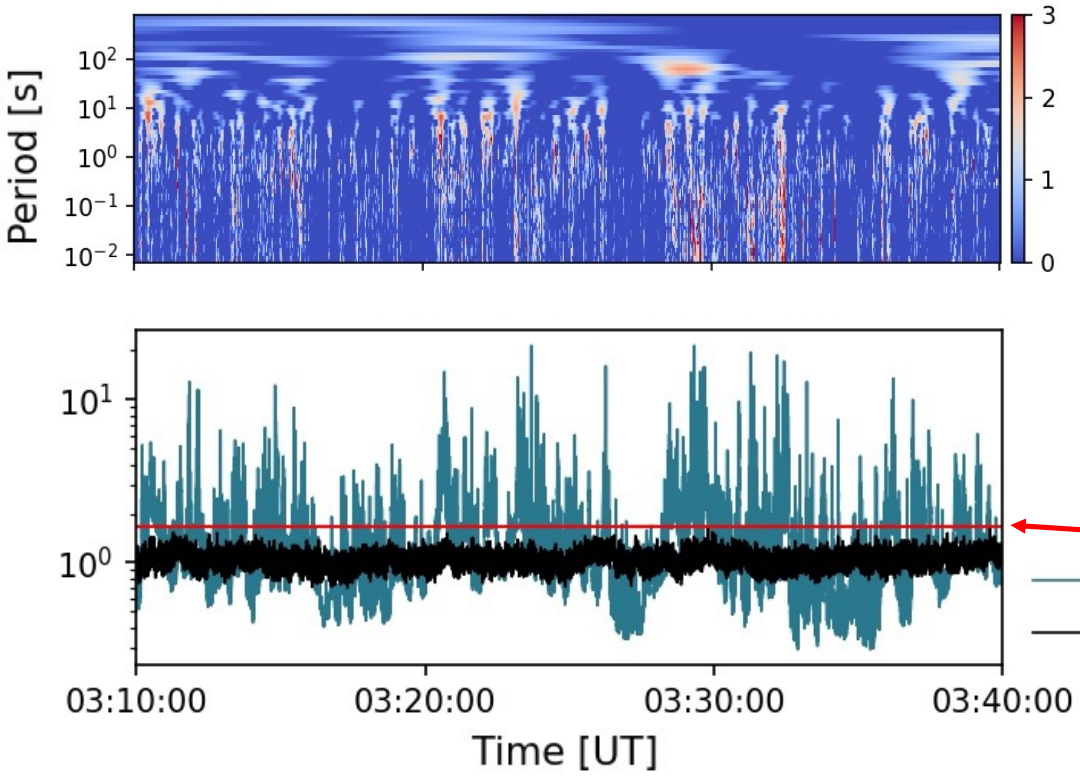


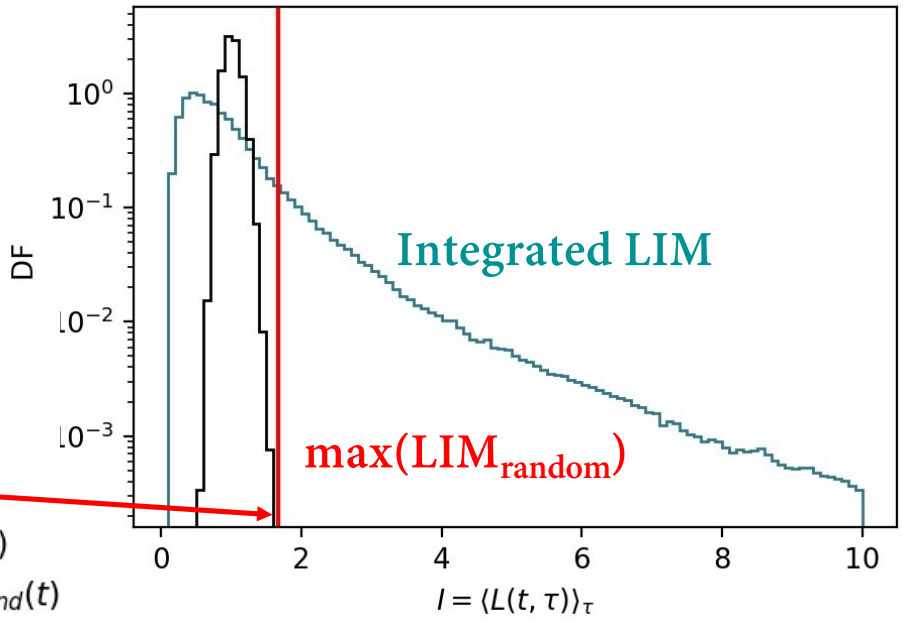
Vertical lines in the scalogram = coherent structures

Detection of coherent structures at 0.17 au

LIM: $L(t,\tau) = \frac{\sum_{i=R,T,N} |W[B_i](t,\tau)|^2}{\langle \sum_{i=R,T,N} |W[B_i](t,\tau)|^2 \rangle_{t \in T'}}$

Integrated LIM: $I(t) = \sum_{\tau \in \tau_{all}} L(t,\tau)$

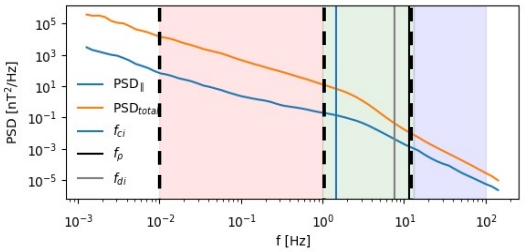


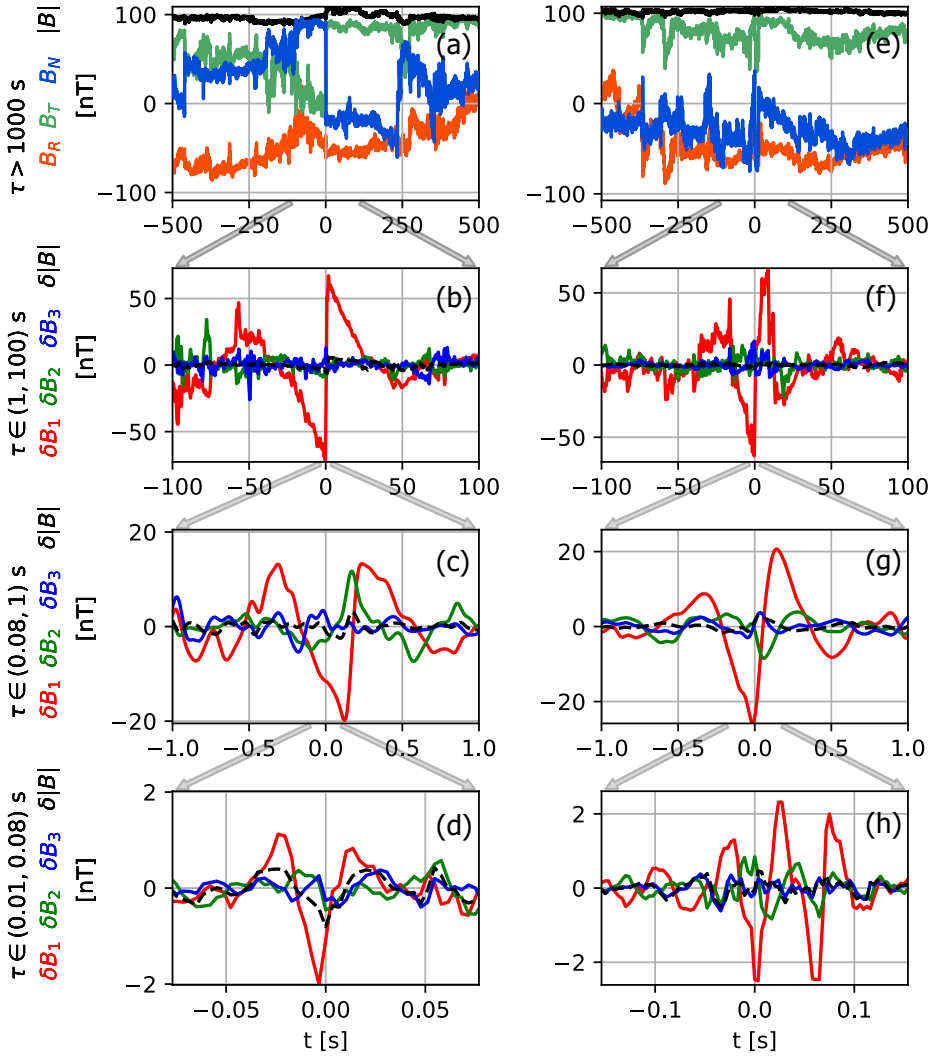


Central times of intermittent events covering all scales

In physical space: embedding of coherent structures

Examples around 2 central times





RAW data for B components

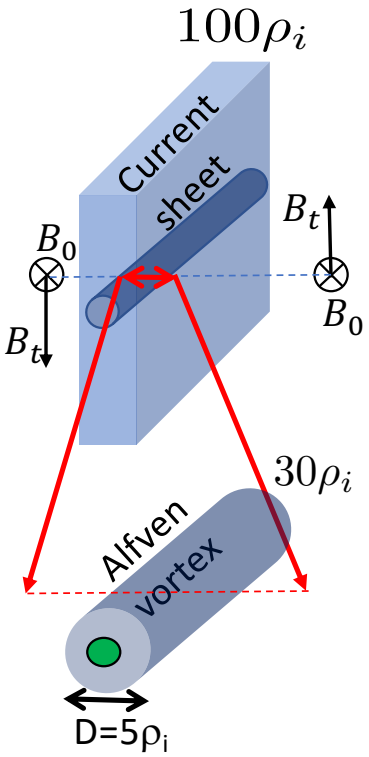
Band-pass filtered data at **MHD scales**

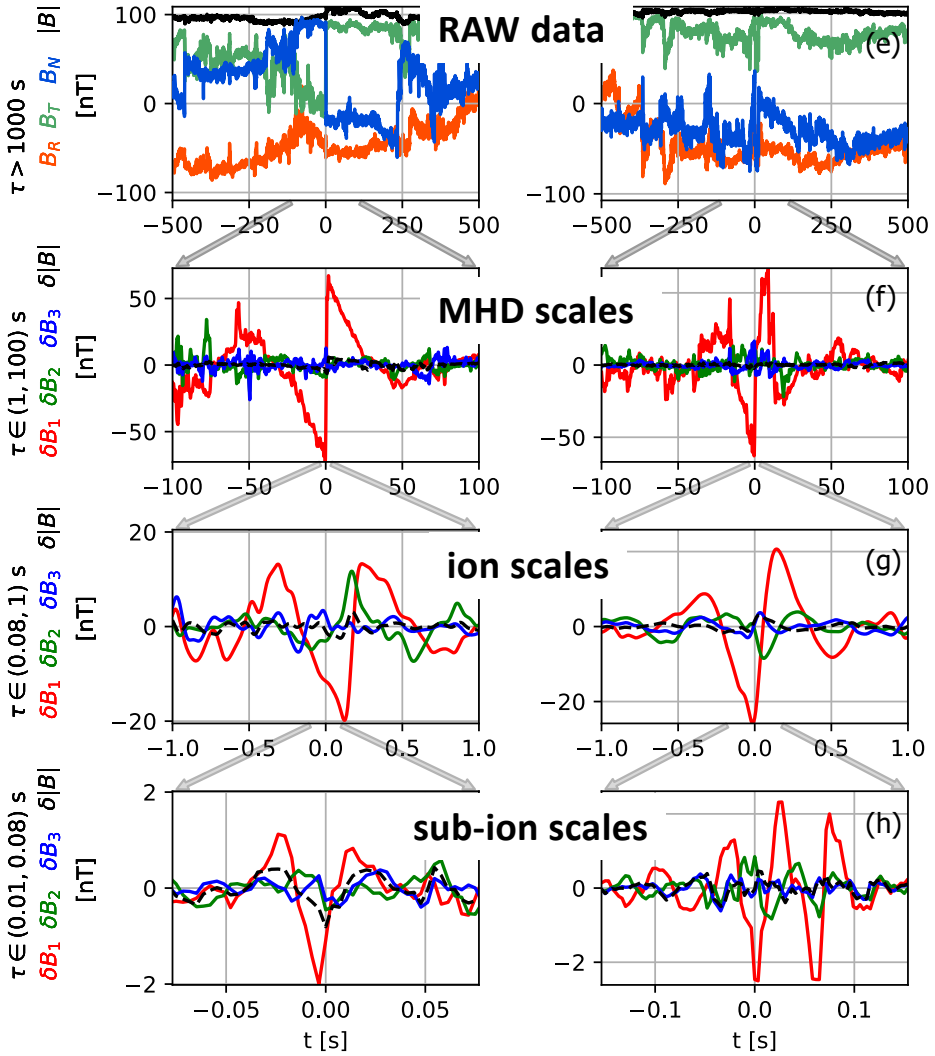
Band-pass filtered data at **ion scales**

Band-pass filtered data at **sub-ion scales**

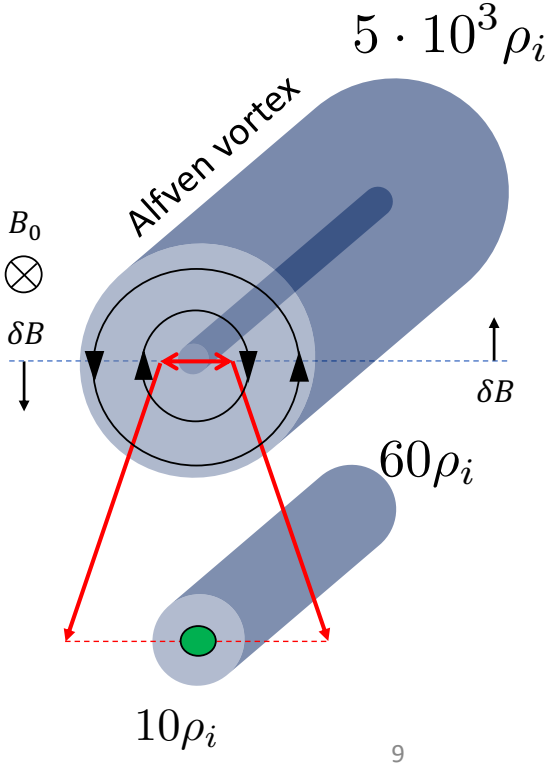
In physical space: embedding of coherent structures

Examples around 2 central times

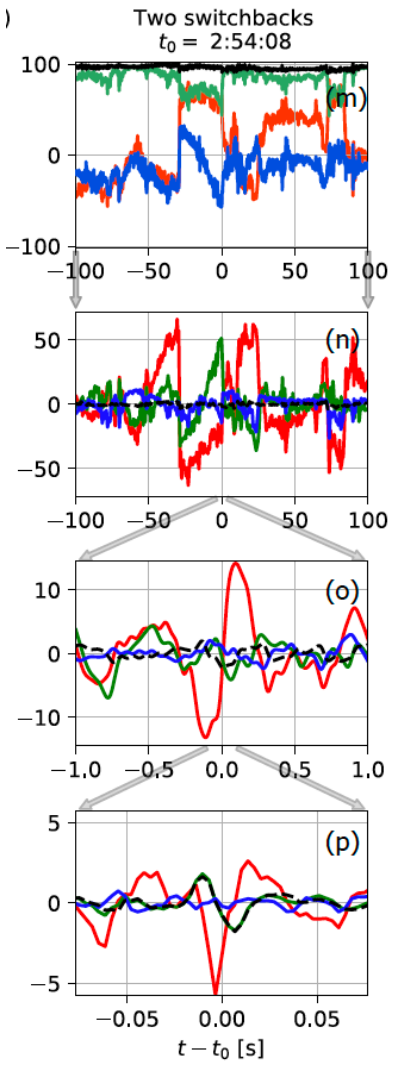


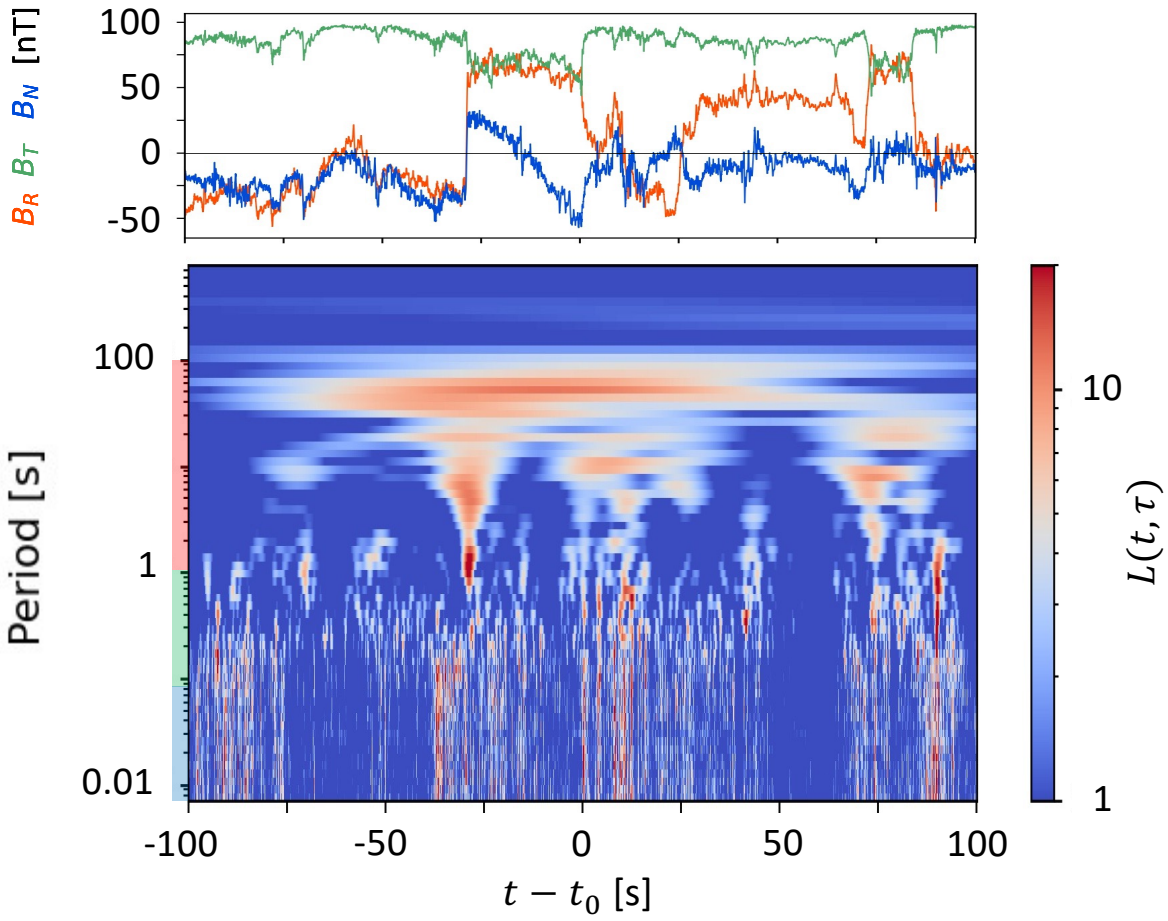


Alfven vortex models:
Petviashvilli & Pokhotelov, 1992
Jovanovic et al. 2020 (ion scales)

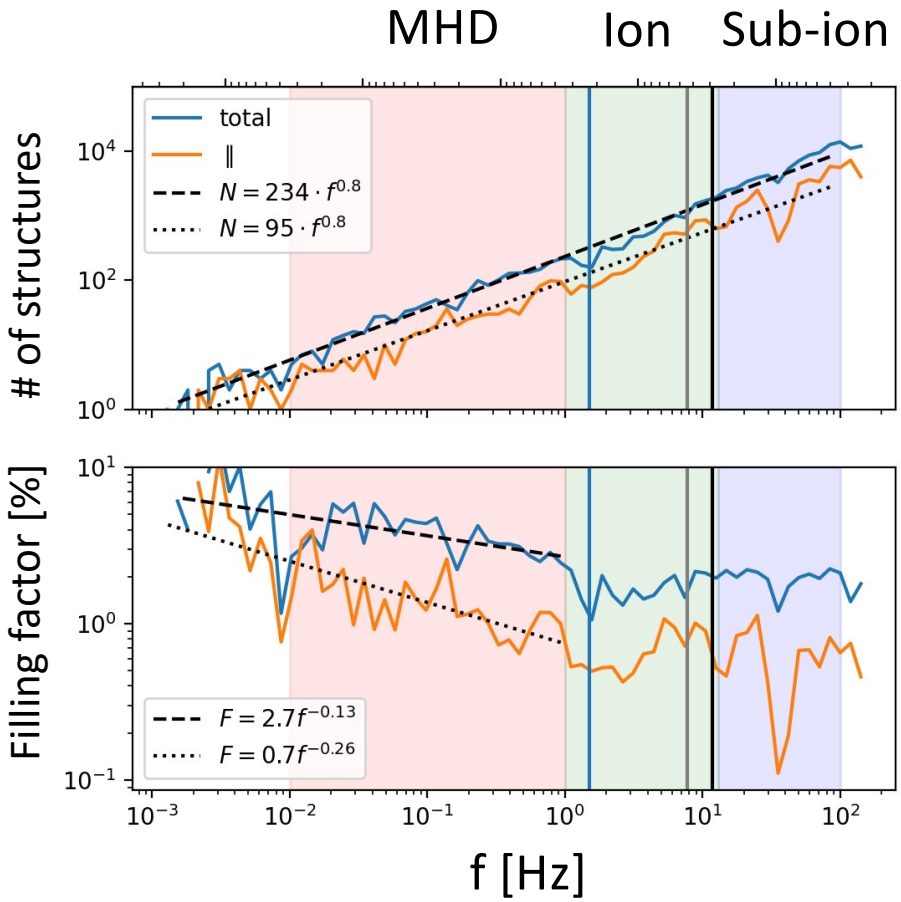


Sub-structure of switchbacks





Number of events and filling factor as a function of freq (or scale) for 5h time interval



If we integrate LIM at 3 bands of scales and take > max(LIM_{random}), we find:

1. MHD scales [1,100] sec => ~ 200 events
2. Ion scales [0.08,1] sec => more than 2.10^3 events
3. sub-ion scales <0.08 sec => more than 10^4 events

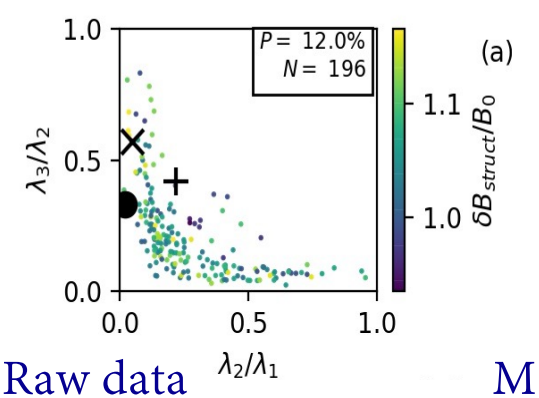
Statistics over all observed events: minimal variance analysis (MVA)

MVA ordering:

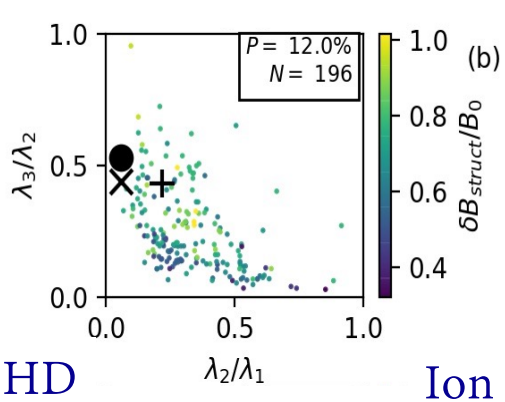
$$\lambda_1 > \lambda_2 > \lambda_3$$

$$M^B_{ii} = \langle B_i B_i \rangle - \langle B_i \rangle \langle B_i \rangle = \lambda_i$$

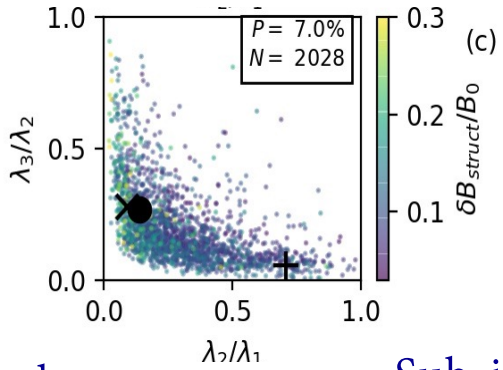
Observed events in δB anisotropy plane $(\lambda_2/\lambda_1, \lambda_3/\lambda_2)$



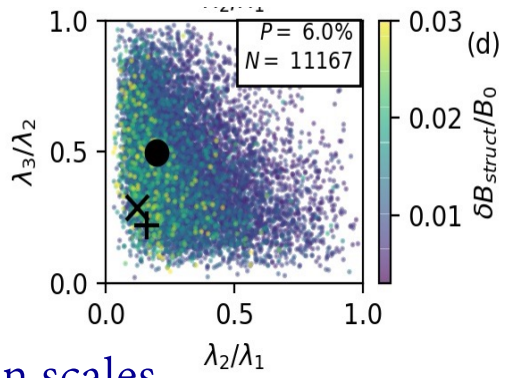
Raw data



MHD



Ion scales



Sub-ion scales

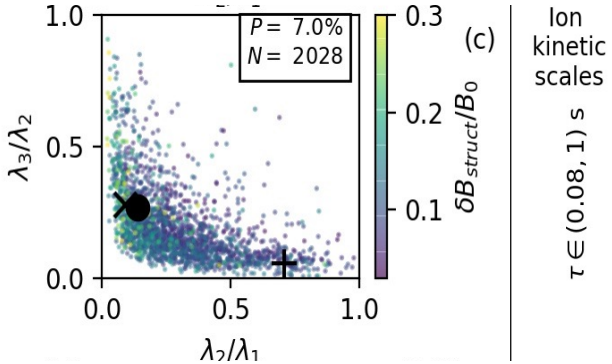
What does it mean ? Mixture of different type of structures ?

Model crossings and MVA results

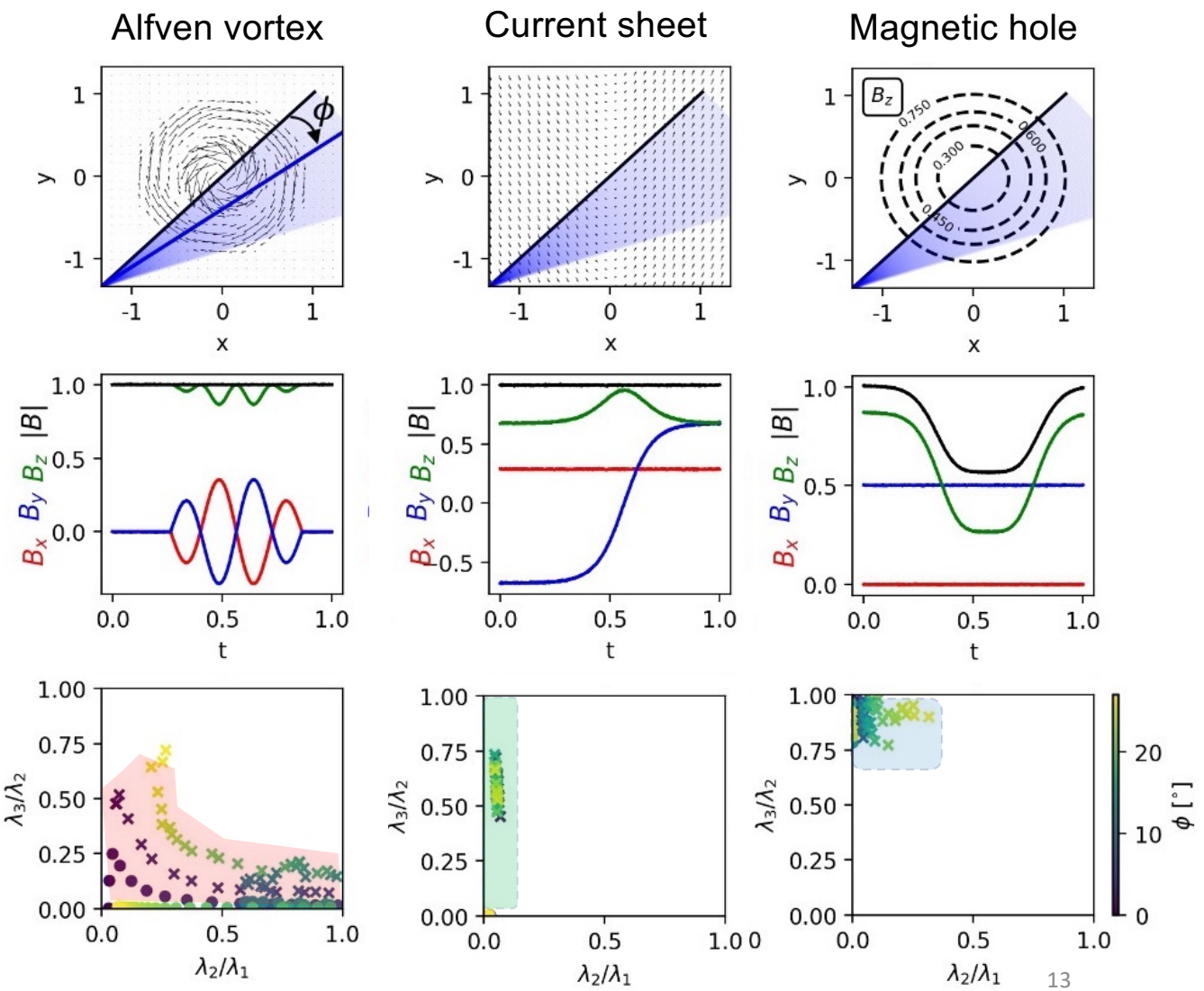
- Crossings along the set of trajectories (blue cone)

We consider

- Distributions of the MVA eigenvalue ratios
- Magnetic compressibility



The observation seems to be the combination of these different types of structures.

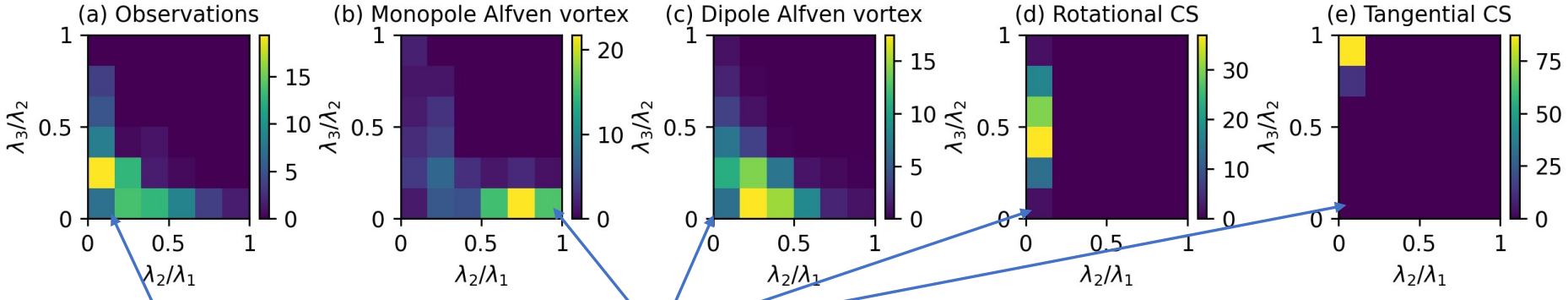


Estimating the probability of different types of structures

MHD scales

DATA

MODELS



$$\begin{cases} ||P_{obs}(\lambda_3/\lambda_2, \lambda_2/\lambda_1) - \sum_{model} p(\text{model})\, P(\lambda_3/\lambda_2, \lambda_2/\lambda_1|\text{model})|| \to 0 \\ \sum_{model} p(\text{model}) \leq 1 \\ p(\text{model}) \geq 0 \end{cases}$$

- Fit the observed distribution with the linear combination of the distributions from the models
- We obtain probability weights: $p(\text{model})$

The same fitting is done for ion and sub-ion scale distributions

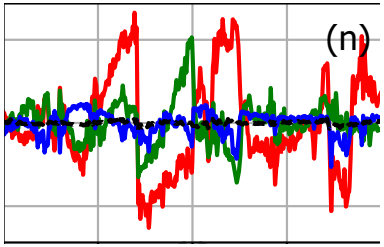
What are the proportions of the different structures?

	Alfvén vortex		Current sheet		Magnetic hole	None
	Monopole	Dipole	Rotational	Tangential		
RAWDATA MHD	0.04	0.86	0.1	<0.01	<0.01	<0.01
MHD	0.1	0.84	<0.01	<0.01	<0.01	0.06
Ion scales	0.15	0.85	<0.01	<0.01	<0.01	<0.01
Sub-ion	0.07	0.49	0.05	<0.01	0.05	0.39

Why so small number of CS? -> Visual examonation

	Alfvén vortex			Current sheet	
	Isolated	Multiple	Vortex+Current sheet	Isolated	Non-isolated
RAWDATA & MHD	0.28	0.23	0.35	0.02	0.11

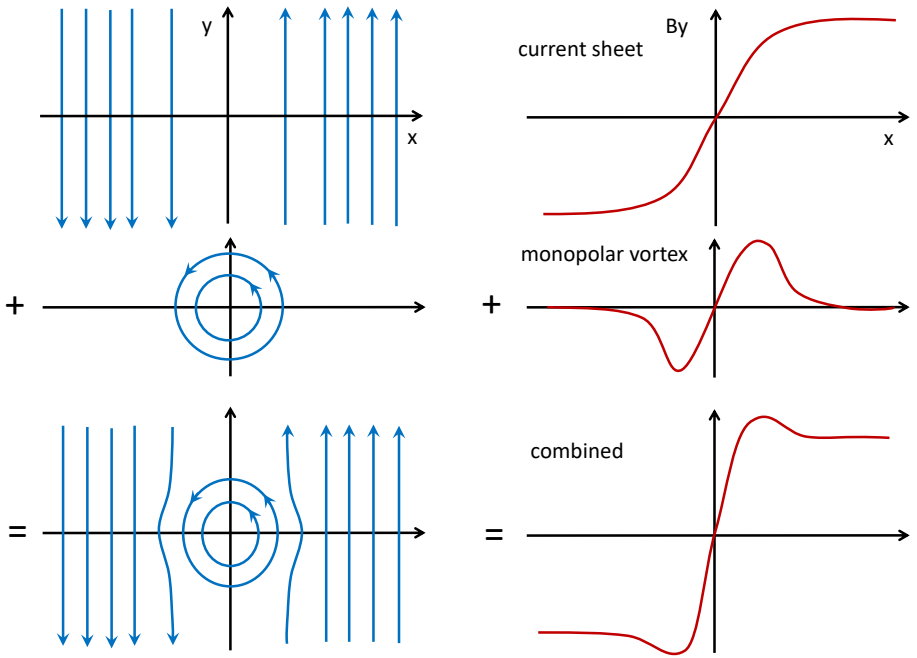
Ex. of a non-isolated current sheet: 2*SwB's



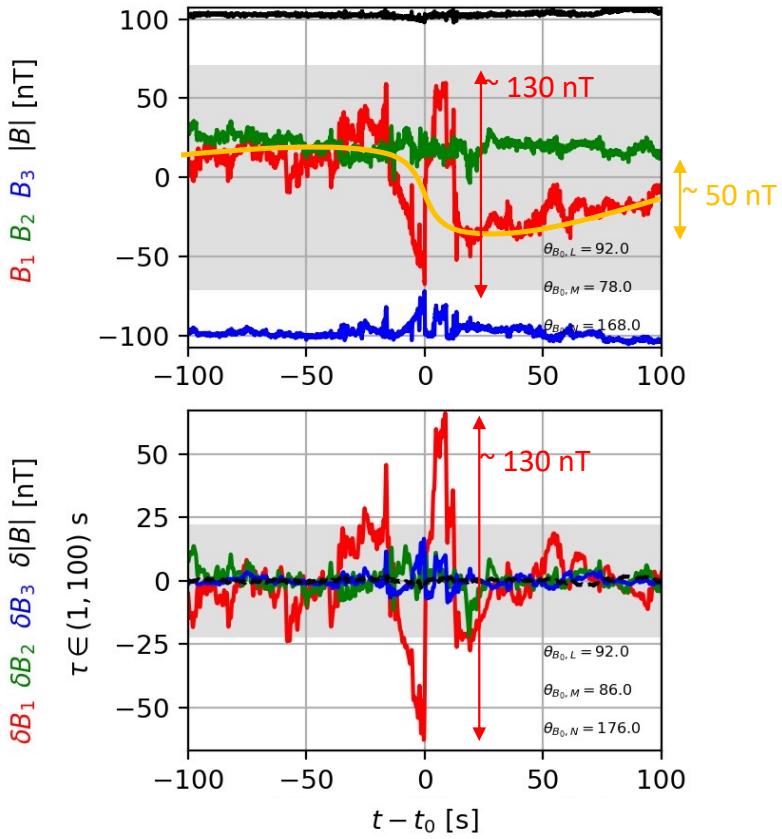
This multiscale classification of turbulent coherent structures in the solar wind is obtained here for the first time.

Example of a ‘vortex + CS’ at MHD scales

Generation of the vortex via magnetic reconnection ?



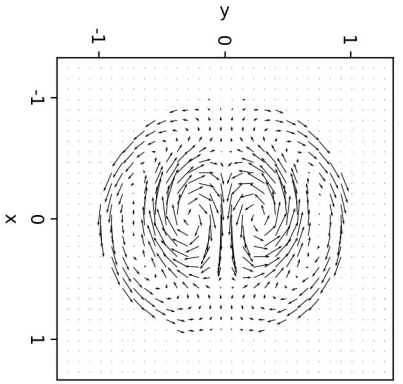
[Courtesy of Pascal Demoulin]

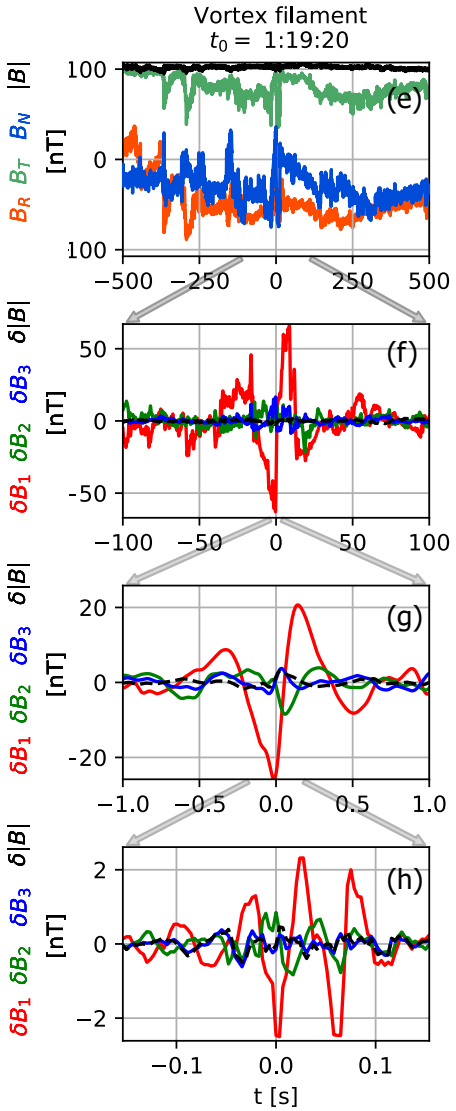


Conclusions

- We investigate turbulent coherent structures at 0.17 au
- We show embedding: one big includes many smaller scale structure, the number of structures is increasing as a power law from MHD to sub-ion scales.
- **Inertial range**: current sheets (including SB/SB-boundaries ~15%), Alfven vortices and their superposition.
- **Ion transition/sub-ion range**: mostly Alfven vortices
- Alfven Vortices are dominant at all scales.

=> Alfven vortices: building blocks of solar wind turbulence.



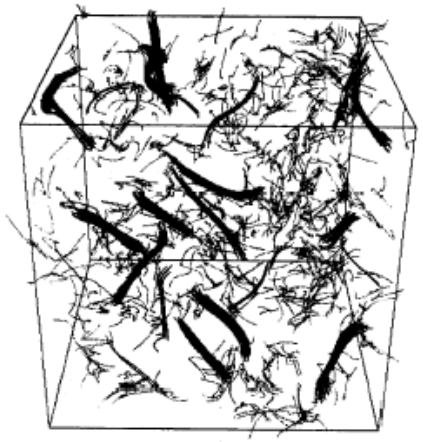


Vinogradov et al., 2023, arXiv:2307.10478

Vinogradov, et al., under review in APJ, PSP focus issue

Definition of a coherent structure

[She et al., 1991]



1. Farge & Schneider (2015): 'Everything that is not noise'

2. Inspired by Fiedler (1988) & Lesieur (1993)

- High amplitude event localized in space
- Delocalisation in Fourier space
- **Phase coupling over a large range of scales**
- Particular topology
- Life time ≫ life time of random fluctuations [at the smallest scale of the structure]

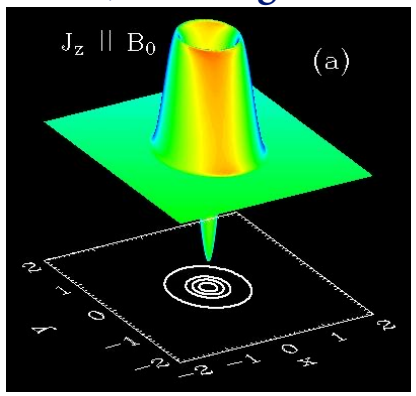
Alfven vortices : building blocks of solar wind turbulence ?

Vector potential, A, ~ to stream function ⇒ field lines || stream lines & current || vorticity [Petviashvilli & Pokhotelov, 1992]

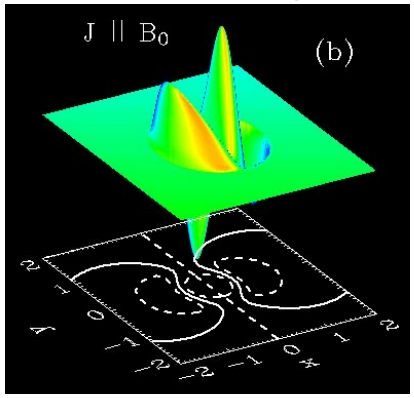
$$\frac{\partial_z}{\nabla_\perp} \sim \frac{\partial_t}{V_A \nabla_\perp} \sim \frac{\delta B_z}{\delta B_\perp} \sim \frac{\delta V_z}{\delta V_\perp} \sim \frac{\delta B_\perp}{B_0} \sim \frac{\delta V_\perp}{V_A} \sim \varepsilon.$$

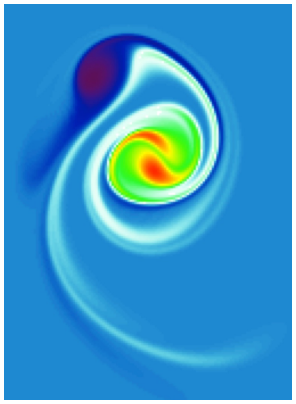
$$\boxed{\delta V_\perp / V_A = \xi \delta B_\perp / B_0}$$

Monopole ~ force free current, standing structure



Dipole ~ two inversed currents, propagates



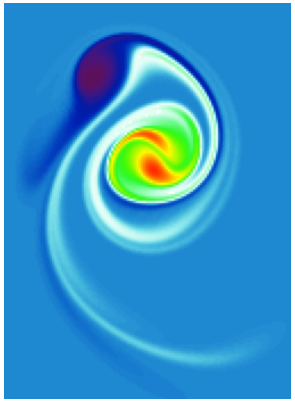


Alfven vortices ~ 2D incompressible HD vortices

Localized solutions of 2D incompressible Navier-Stokes equation

$$\partial_t \omega + (\delta \mathbf{V}_\perp \cdot \nabla)\omega = 0$$

[Lamb 1895, 1906]
[Chaplygin 1903]



ω - vorticity & Ψ - stream function

$$\omega = \nabla \times \delta \mathbf{V}_\perp = -\triangle \Psi \; ; \quad \delta \mathbf{V}_\perp = -\nabla \times \Psi$$

Particular case:
slow variations & vorticity is localized in a circle of the radius *a*

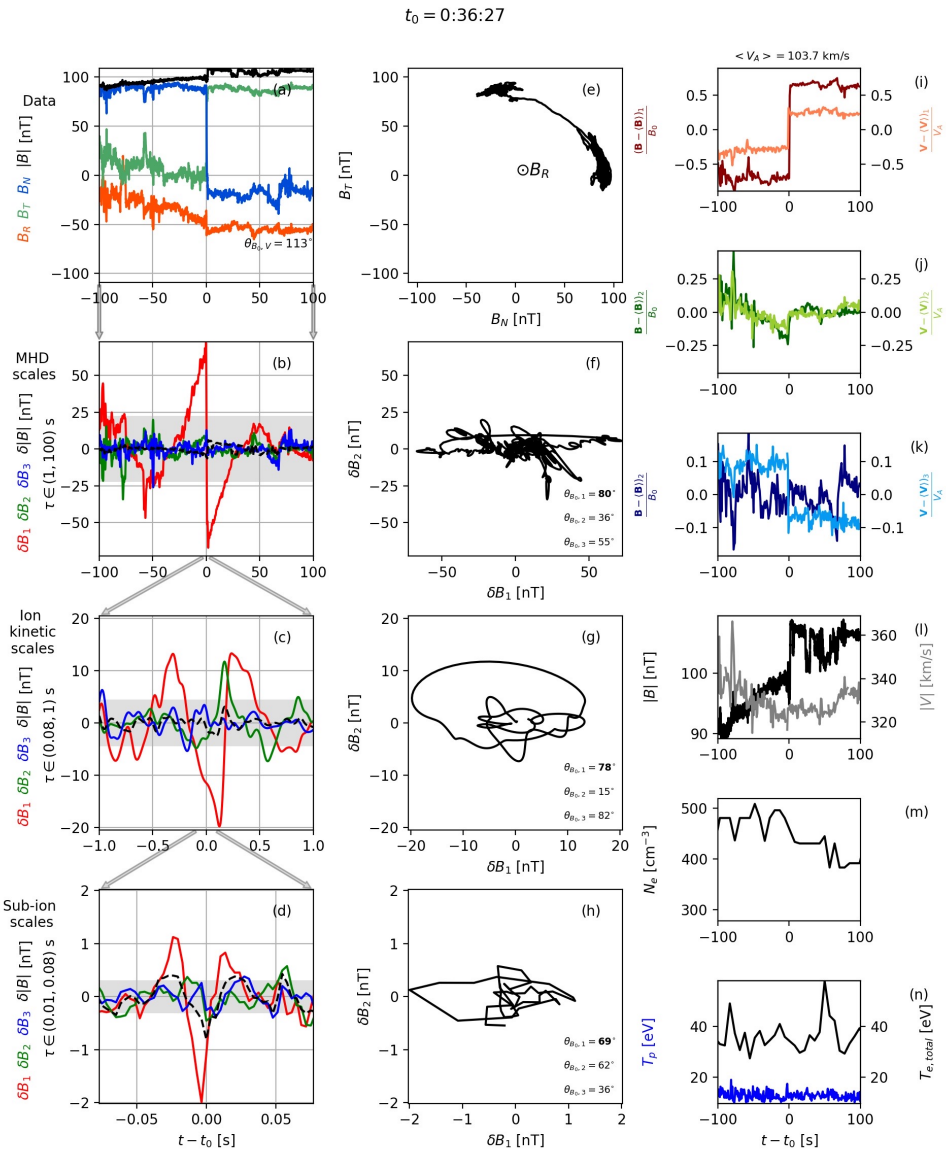
$$\begin{cases} \Delta\Psi + k^2\Psi + c = 0, & r < a \\ \Delta\Psi = 0, & r \geq a \end{cases}$$

- **Helmholtz's equation**
- **Laplace's equation**

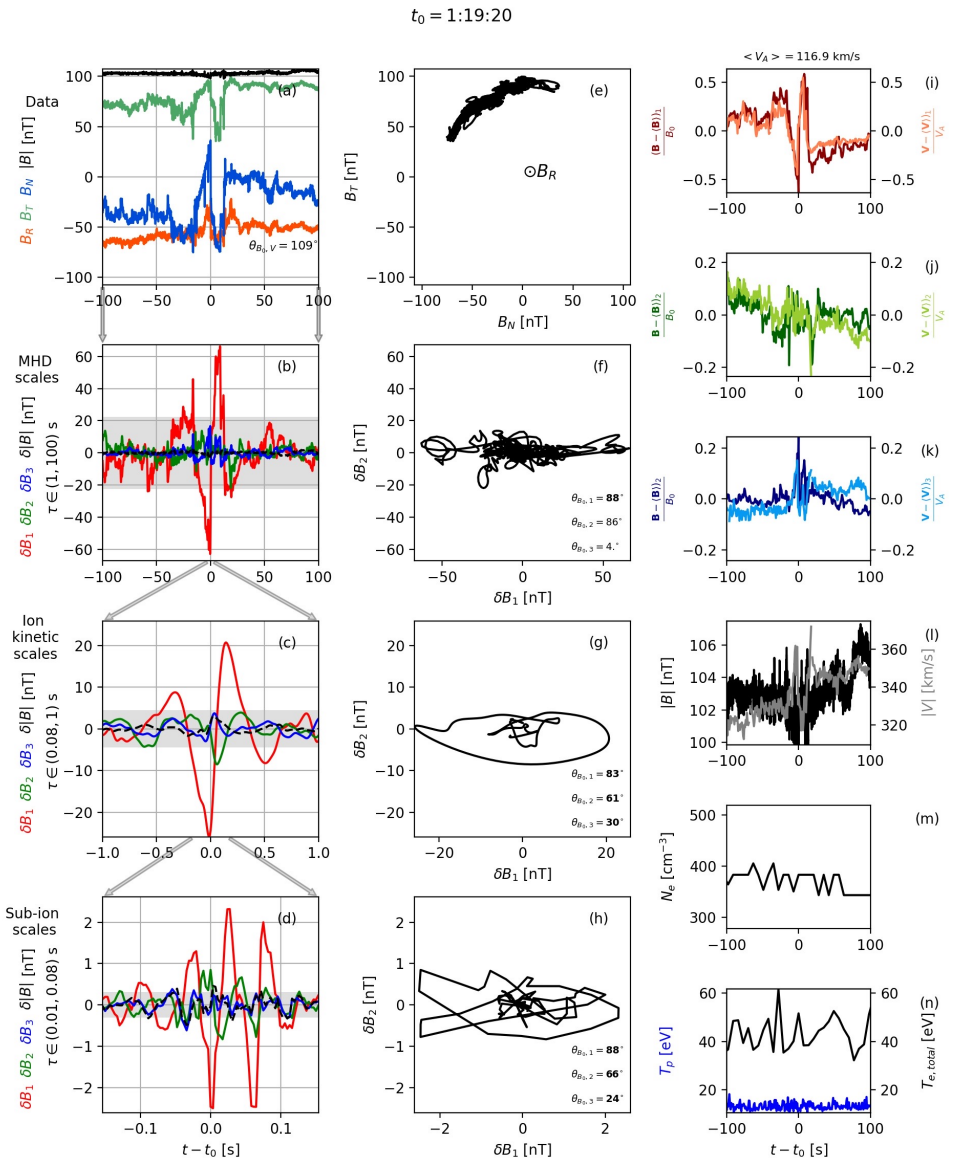
monopole

$$\begin{cases} \Psi = \Psi_0(J_0(kr) - J_0(ka)) + ux\left(1 - \dfrac{2}{kr}\dfrac{J_1(kr)}{J_0(ka)}\right), & r < a \\ \Psi = a^2 u \frac{x}{r^2}, & r \geq a. \end{cases}$$

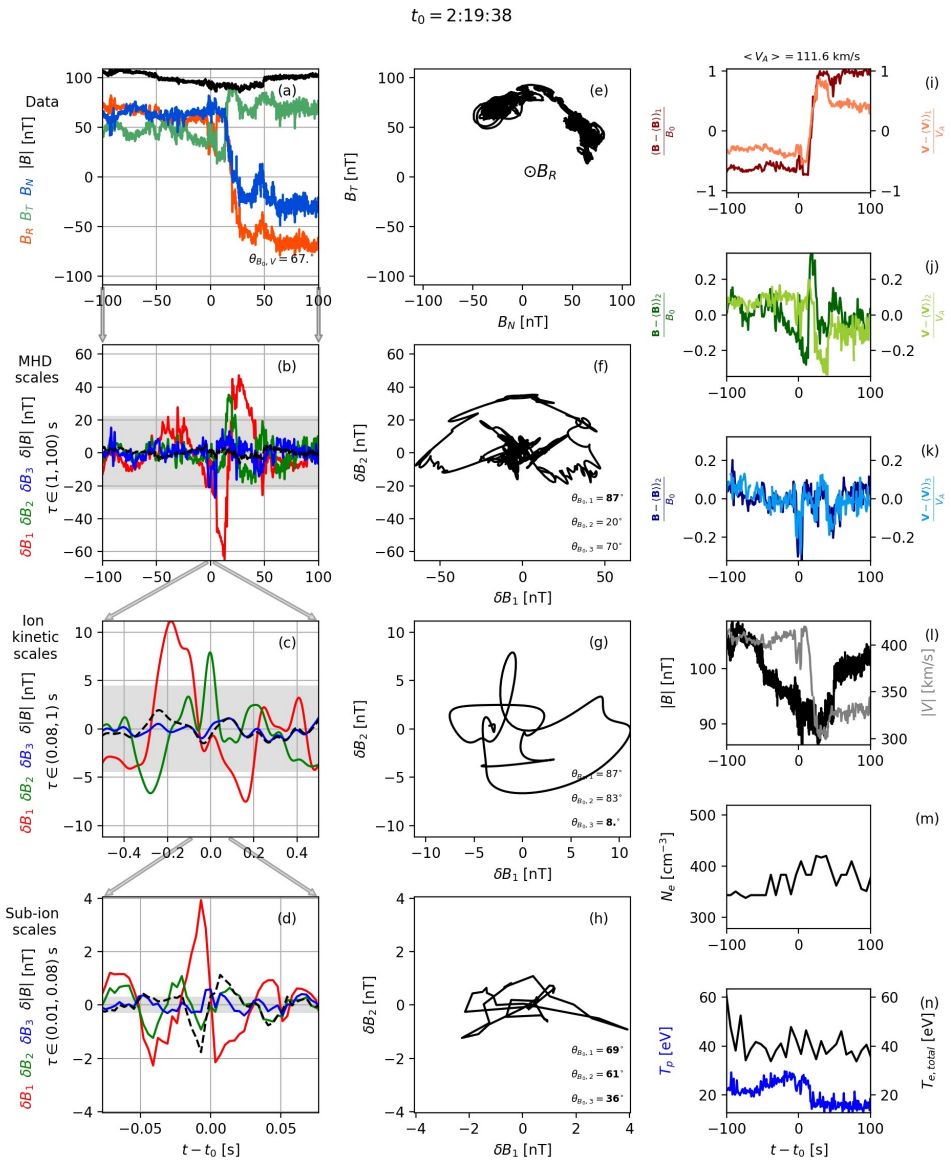
dipole


$t_0 = 0:36:27$
$< V_A > = 103.7$ km/s
Data
MHD scales
Ion kinetic scales
Sub-ion scales
B_R B_T B_N $|B|$ [nT]
δB_1 δB_2 δB_3 $\delta|B|$ [nT] $\tau \in (1, 100)$ s
$\tau \in (0.08, 1)$ s
$\tau \in (0.01, 0.08)$ s
$\theta_{B_0,V} = 113^\circ$
$\odot B_R$
$\theta_{B_0,1} = 80^\circ$
$\theta_{B_0,2} = 36^\circ$
$\theta_{B_0,3} = 55^\circ$
$\theta_{B_0,1} = 78^\circ$
$\theta_{B_0,2} = 15^\circ$
$\theta_{B_0,3} = 82^\circ$
$\theta_{B_0,1} = 69^\circ$
$\theta_{B_0,2} = 62^\circ$
$\theta_{B_0,3} = 36^\circ$
B_N [nT]
B_T [nT]
δB_1 [nT]
δB_2 [nT]
$t - t_0$ [s]
$|B|$ [nT]
$|V|$ [km/s]
N_e [cm^{-3}]
T_p [eV]
$T_{e,total}$ [eV]

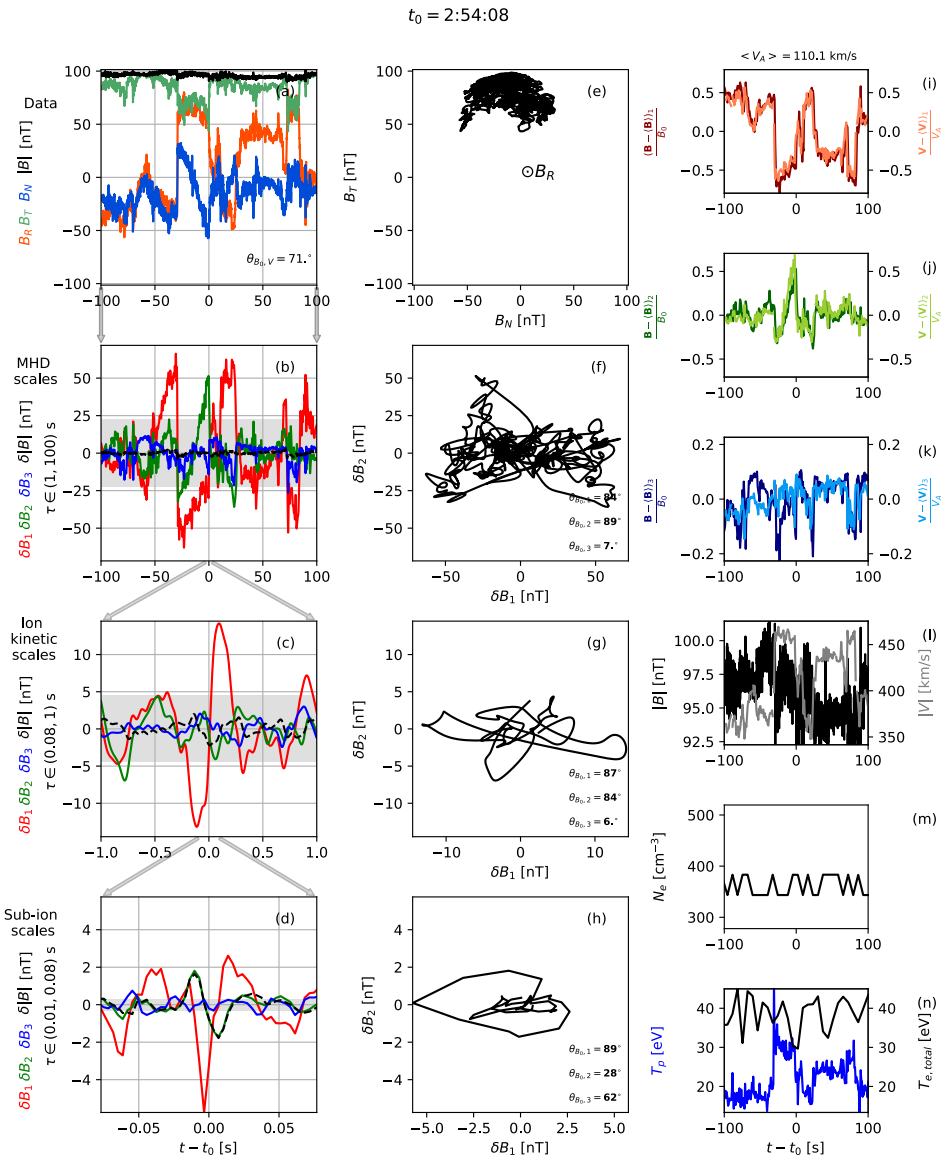
Event-1: TD



Event-2: Alfven vortex


$t_0 = 2{:}19{:}38$
$< V_A > = 111.6$ km/s
Data
MHD scales
Ion kinetic scales
Sub-ion scales
(a)
(b)
(c)
(d)
(e)
(f)
(g)
(h)
(i)
(j)
(k)
(l)
(m)
B_R B_T B_N $|B|$ [nT]
δB_1 δB_2 δB_3 $\delta|B|$ [nT] $\tau \in (1, 100)$ s
$\tau \in (0.08, 1)$ s
$\tau \in (0.01, 0.08)$ s
B_T [nT]
B_N [nT]
δB_2 [nT]
δB_1 [nT]
$t - t_0$ [s]
$|B|$ [nT]
$|V|$ [km/s]
N_e [cm^{-3}]
T_p [eV]
$T_{e,total}$ [eV]

Event-3: RD



Event-4: 2 switchbacks

Scale of the structure, d [km]

	Example1	Example2	Example3	Example4
MHD	480	2.4*10^4	1.4*10^4	4.2*10^4
Ion	160	290	150	160
subion	23	47	24	12

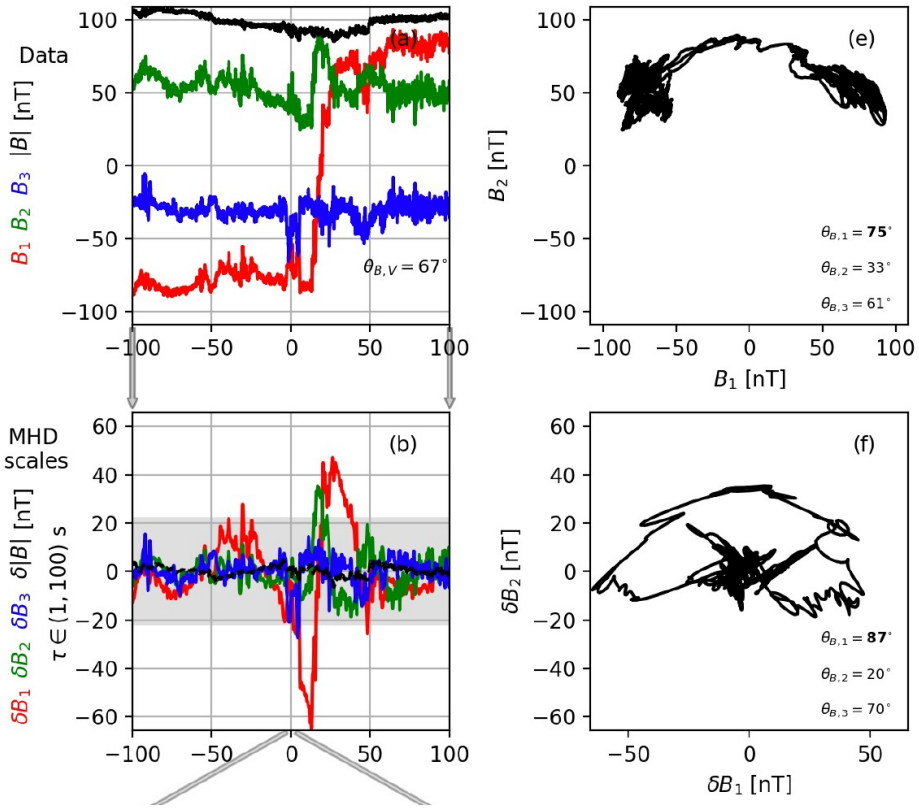
Scale of the structure, d/d_i

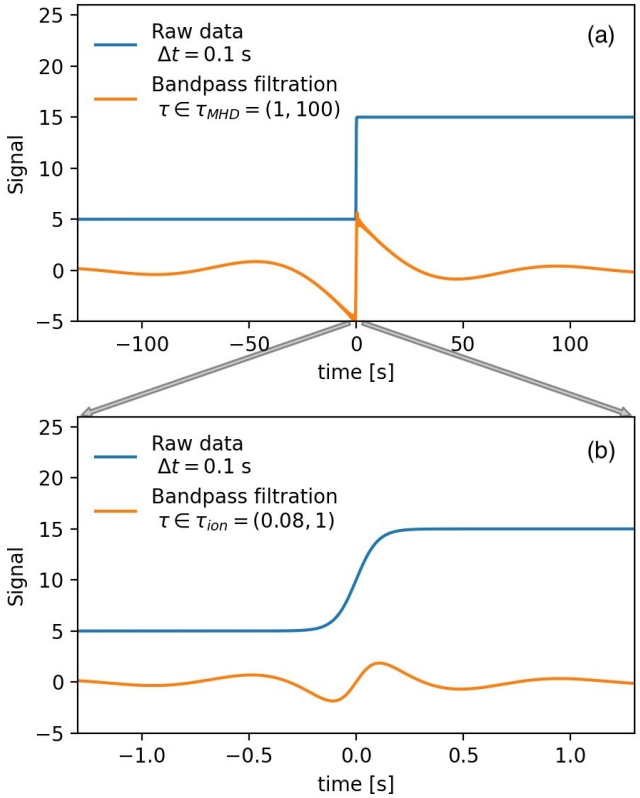
	Example1 d_i=12 [km]	Example2 d_i=11 [km]	Example3 d_i=12 [km]	Example4 d_i=12 [km]
MHD	40	2.2*10^3	1.2*10^3	4.2*10^4
Ion	13	26	12.5	13
subion	1.9	4	2	1

Scale of the structure, d/\rho_i

	Example1 \rho_i=5 [km]	Example2 \rho_i=5 [km]	Example3 \rho_i=6.5 [km]	Example4 \rho_i=7 [km]
MHD	96	4800	2000	6000
Ion	32	58	23	23
subion	4,6	9,4	3,7	1,7

SWB boundary in MVA frame. Filtering effect.





Here, 2 magnetic components fluctuat in MVA frame – not in agreement with a current sheet filtering effect