Turbulent Properties Of CME-driven Sheath Regions

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Motivation: Sheaths ahead of interplanetary coronal mass ejections (CMEs) are large-scale heliospheric structures. They share properties of both expansion and propagation sheath and accumulate gradually from inhomogeneous plasma and field as the CME propagates through interplanetary space. Sheaths have thus variable structure with plasma waves, discontinuities and reconnection exhausts embedded. There are however only a few studies of magnetic field fluctuations/turbulence and small-scale structures in CME sheaths. Increased knowledge helps to understand sheath formation and evolution and are also useful for space weather forecasting purposes. In addition, sheaths provide an interesting natural plasma laboratory to study turbulence in general.

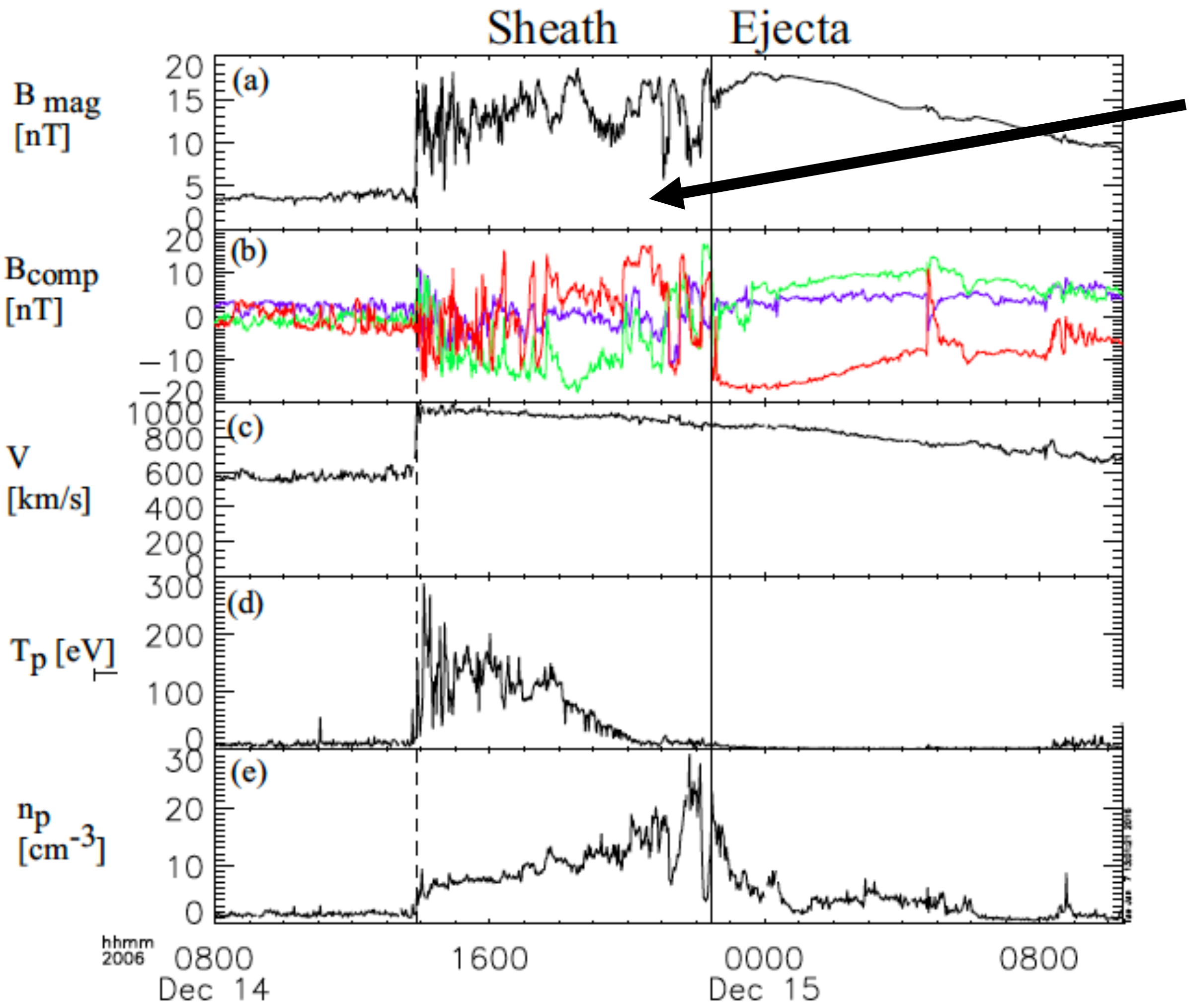
Results shows: We report here the results of our recent studies investigating in detail magnetic field fluctuations in CME-driven sheaths in the near-Earth solar wind (L1) using high-resolution magnetic field data. We have studied fluctuation power, spectral slopes both in kinetic and inertial range, intermittency and compressibility.

See also following EGU online presentations:

Ala-Lahti et al.: Spatial coherence of interplanetary coronal mass ejection-driven sheaths at 1 AU, EGU2020-13474

Good et al.: Radial evolution of magnetic field fluctuations in an ICME sheath, EGU2020-13664

CME sheath in interplanetary space



sheath: turbulent and compressed region with high solar wind dynamic pressure and variable magnetic field. Parameters can vary considerably from the shock to the ejecta leading edge. Also fluctuations likely generated in different manner close to the shock (compression, alignment, ..) and close to ejecta leading edge (field line draping, pile-up)

Kilpua, Fontaine et al., Space Weather, *2019*
Kilpua, Koskinen & Pulkkinen, Living Reviews in Solar Physics, 2017

Average sheath fluctuation properties

- 42 sheaths studied (from the list in *Masias-Meza et al.*, 2016) using ACE 1-second magnetic field data
- Fluctuation power, compressibility and anisotropy defined using Morlet wavelet analysis with 15-min sliding window in the range 20 sec - 7.5 min.

	Power [nT^2]	Anisotropy	Compressibility
Solar wind ahead	0.8 ± 1.0	10 ± 6	0.07 ± 0.04
Sheath	9.3 ± 10.8	5 ± 3	0.15 ± 0.08
Flux rope	1.0 ± 1.8	36 ± 23	0.02 ± 0.01

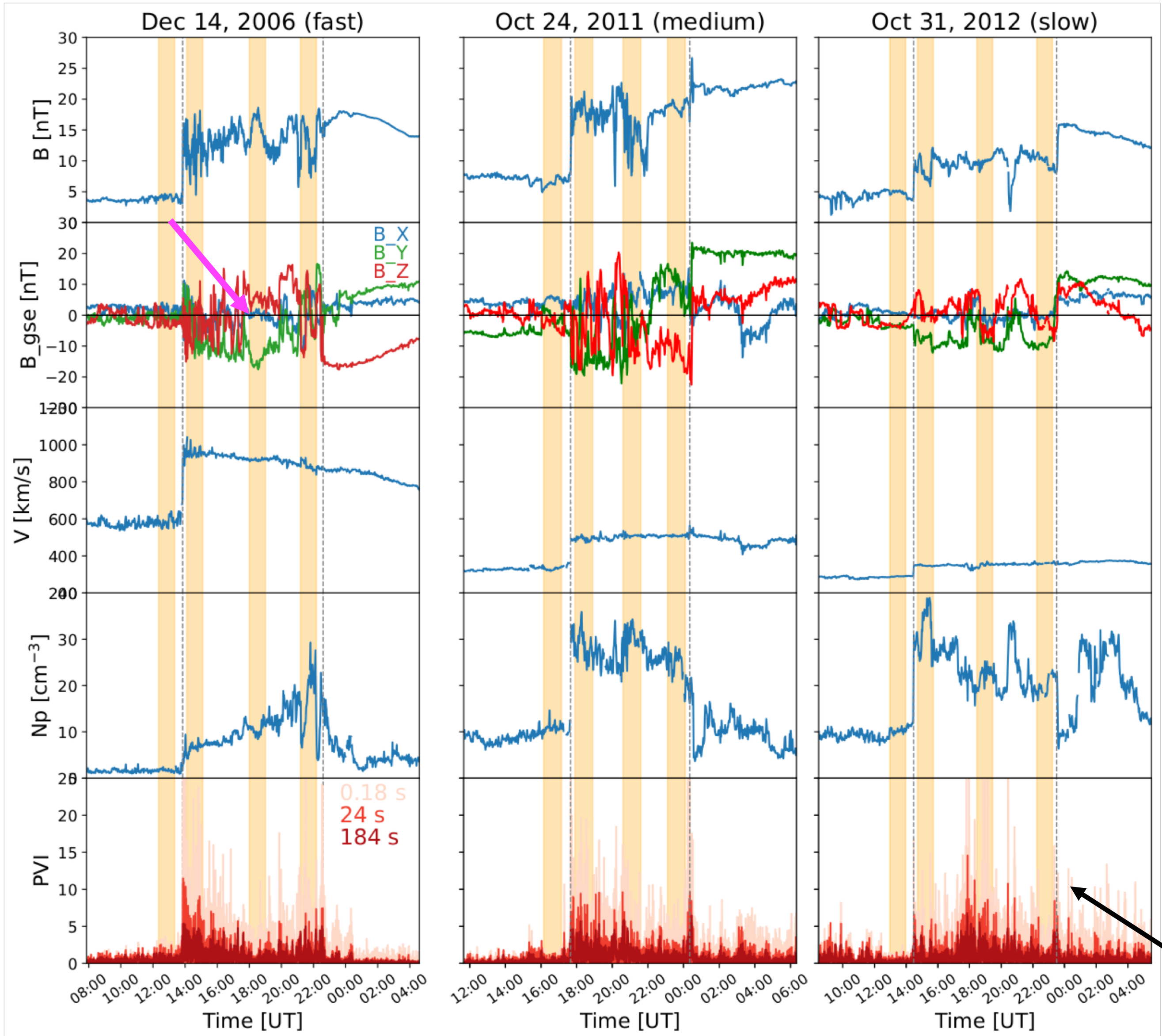
anisotropy $A = \frac{P_\perp}{2P_\parallel}$

compressibilty $\mathrm{C} = \frac{P_\parallel}{P_\perp}$

- The study also shows that sheaths of fast CMEs encountering turbulent solar wind and with high Mach number shocks have on average highest level of turbulence and lowest anisotropy in their fluctuations. For quasi-parallel shocks and high upstream beta the both turbulent energy and anisotropy were low

Moissard, Fontaine and Savoni, JGR, 2019

Three case studies: Overview



quasi-par ($\theta_{Bn} = 33°$) strong ($M_{ms} = 4.9$)

quasi-perp ($\theta_{Bn} = 64°$) strong ($M_{ms} = 2.5$)

~perp ($\theta_{Bn} = 86°$) strong ($M_{ms} = 1.8$)

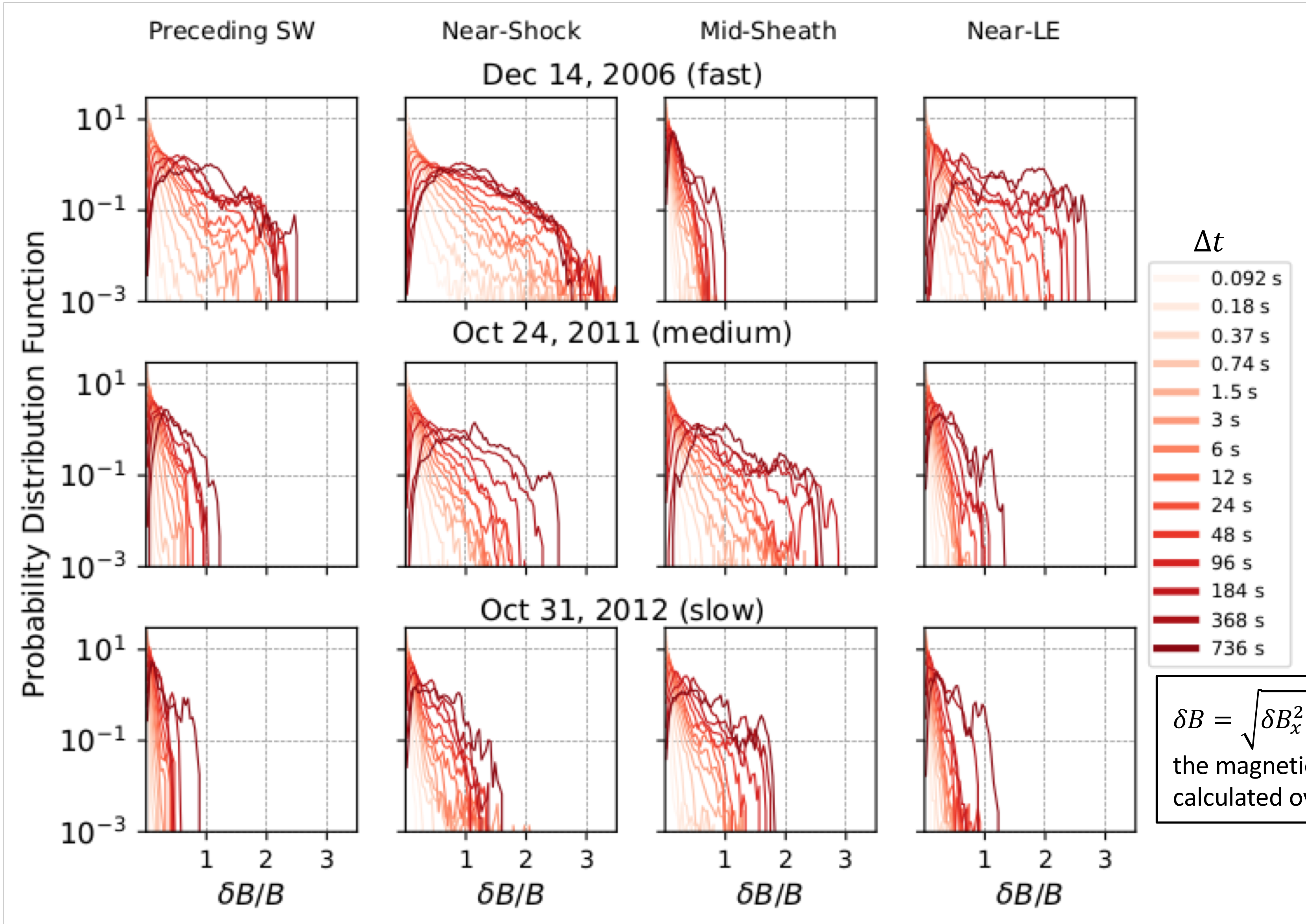
- Wind high resolution (0.092 s) magnetic field data used
- Three events selected from *Kilpua, Fontaine et al.*, Space Weather, 2019 list based on average speed in the sheath
- Fluctuations investigated over successive double values of 0.092 s
- Four separate regions investigated: Solar wind ahead, Near-Shock, Mid-Sheath and Near-LE (leading edge), each 1-h in duration

Partial Variance of Increment

$$PVI = \frac{|\Delta \mathbf{B}(t, \Delta t)|}{\sqrt{\langle |\Delta \mathbf{B}(t, \Delta t)|^2 \rangle}}$$

Kilpua, Fontaine et al., submitted Ann. Geophys.

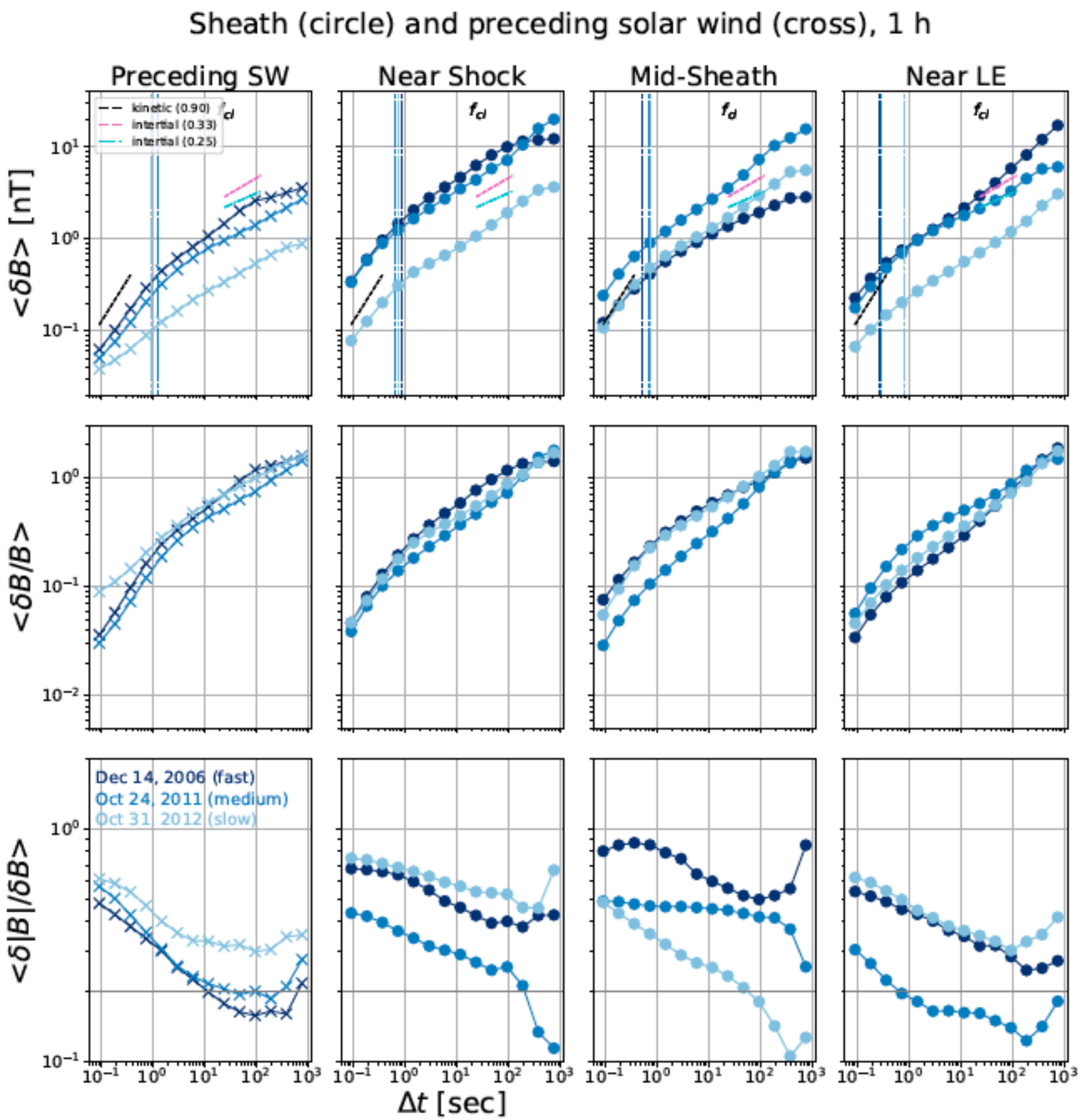
Normalized B fluctuations



$\delta B = \sqrt{\delta B_x^2 + \delta B_y^2 + \delta B_z^2}$ and B is the magnetic field amplitude calculated over the interval Δt

Kilpua, Fontaine et al., submitted Ann. Geophys.

Averaged fluctuations



Kilpua, Fontaine et al., submitted Ann. Geophys.

Spectral Indices

	Kinetic	Inertial	t_{ci} [sec]	κ
Fast				
Preceding SW	-2.47	-1.84	1.28	0.16
Near-Shock	-2.49	-1.67	0.87	0.17
Mid-Sheath	-2.23	-1.49	0.53	0.21
Near-LE	-2.27	-1.99	0.28	0.18
Intermediate speed				
Preceding SW	-2.29	-1.56	1.25	0.16
Near-Shock	-2.41	-1.71	0.62	0.28
Mid-Sheath	-2.42	-2.03	0.72	0.18
Near-LE	-2.44	-1.63	0.28	0.21
Slow				
Preceding SW	-1.72	-1.67	0.93	0.12
Near-Shock	-2.37	-1.84	0.77	0.15
Mid-Sheath	-2.56	-1.81	0.75	0.17
Near-LE	-2.15	-1.77	0.80	0.28

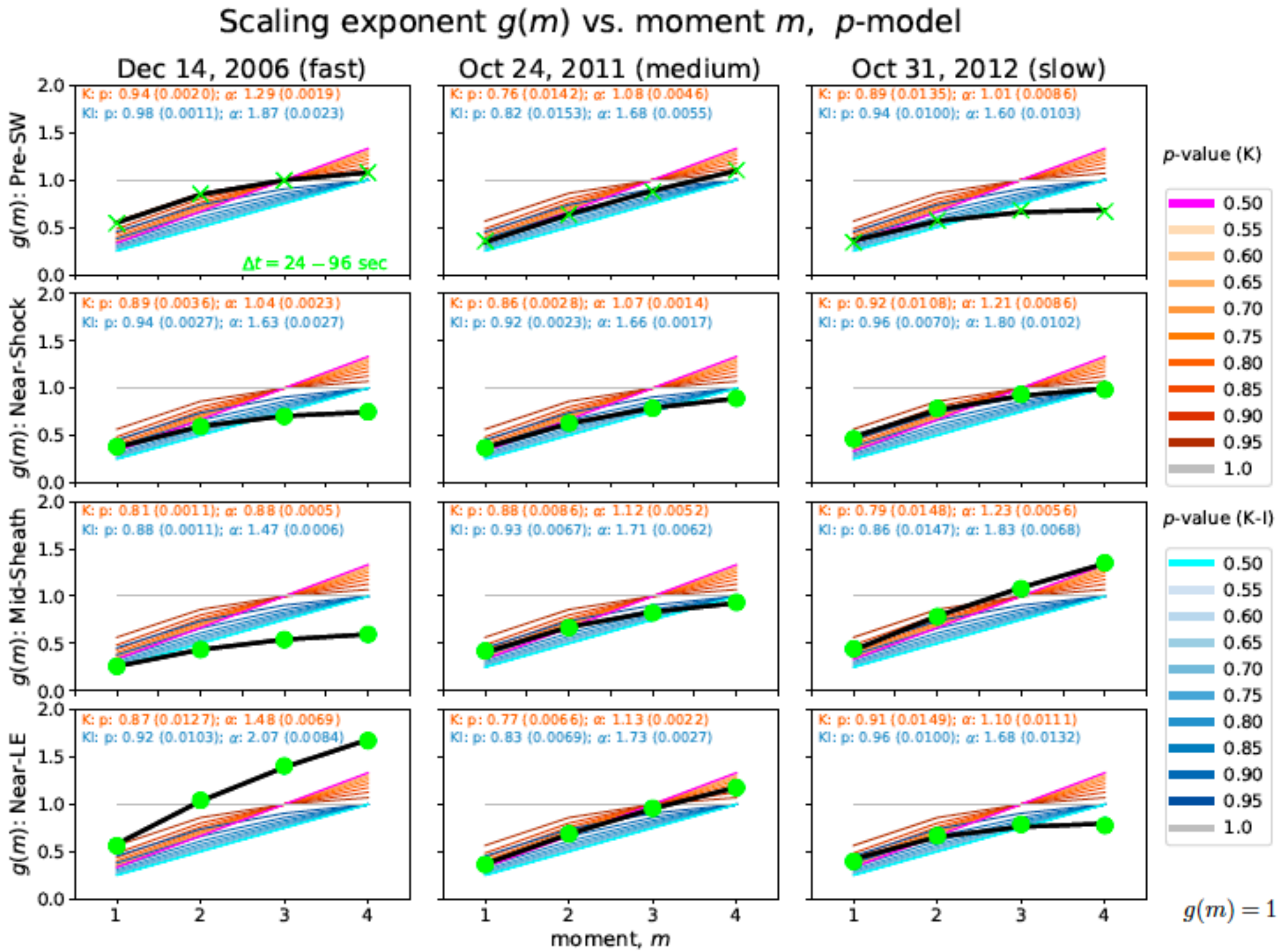
Kilpua, Fontaine et al., submitted Ann. Geophys.

t_{ci} is the ion cyclotron time scale and $\kappa = v_A/v$ tests the validity of Taylor hypothesis

Inertial range spectral index:
Kolmogorov's: -1.67
Kraichnan: -1.5

Kinetic range spectral index
Typical in solar wind: -2.8
(e.g., Bruno et al., 2017;
Huang et al., 2017;
Alexandrova, 20113)

Standard/Extended p-model



standard p-model

Kolmogorov
$(q = 3)$

Kraichnan
$(q = 4)$

$$g(m) = 1 - log_2[p^{m/q} + (1-p)^{m/q}]$$

black line: extended p-model (*Tu et al.*, 1996; *Marsch et al.*, 1997)
green dots: observed values

Kilpua, Fontaine et al., submitted Ann. Geophys.

Summary and discussion

- On average sheaths have higher fluctuation power, lower anisotropy and higher compressibility than the solar wind ahead or the following CME flux rope
- Turbulent properties can however vary strongly from the shock to the ejecta leading edge (also coherent structures)
- All sheaths, even slow sheath with ~quasi-perpendicular shock, had clear differences to solar wind ahead. In particular this was the case for the Near-Shock region.
- Near-LE region resembles most solar wind ahead
- Spectral indices are generally steeper than Kolmogorov's in sheath in the inertial range → higher intermittency?
- Extended p-model yields better results than the standard p-model → turbulence in sheath at 1 AU not yet fully developed
- Spectral indices in kinetic range were shallower → only small part of energy dissipated at ion scales (e.g., as suggested by *Sahraoui et al.*, 2009)