Multiscale Features of the Near-Hermean Environment as Derived by the Hilbert-Huang Transform

Tommaso Alberti[1,*], A. Milillo[1], M. Laurenza[1], S. Massetti[1], S. L. Ivanovski[2], A. Ippolito[3], C. Plainaki[3], E. De Angelis[1], V. Mangano[1], A. Mura[1], S. Orsini[1], R. Rispoli[1]

[1] INAF - Institute for Space Astrophysics and Planetology, Rome, Italy
[2] INAF - Astronomical Observatory of Trieste, Trieste, Italy
[3] ASI - Italian Space Agency, Rome, Italy

* tommaso.alberti@inaf.it

OUTLINE

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2. The Hilbert-Huang Transform (HHT)
3. MESSENGER Mercury flybys
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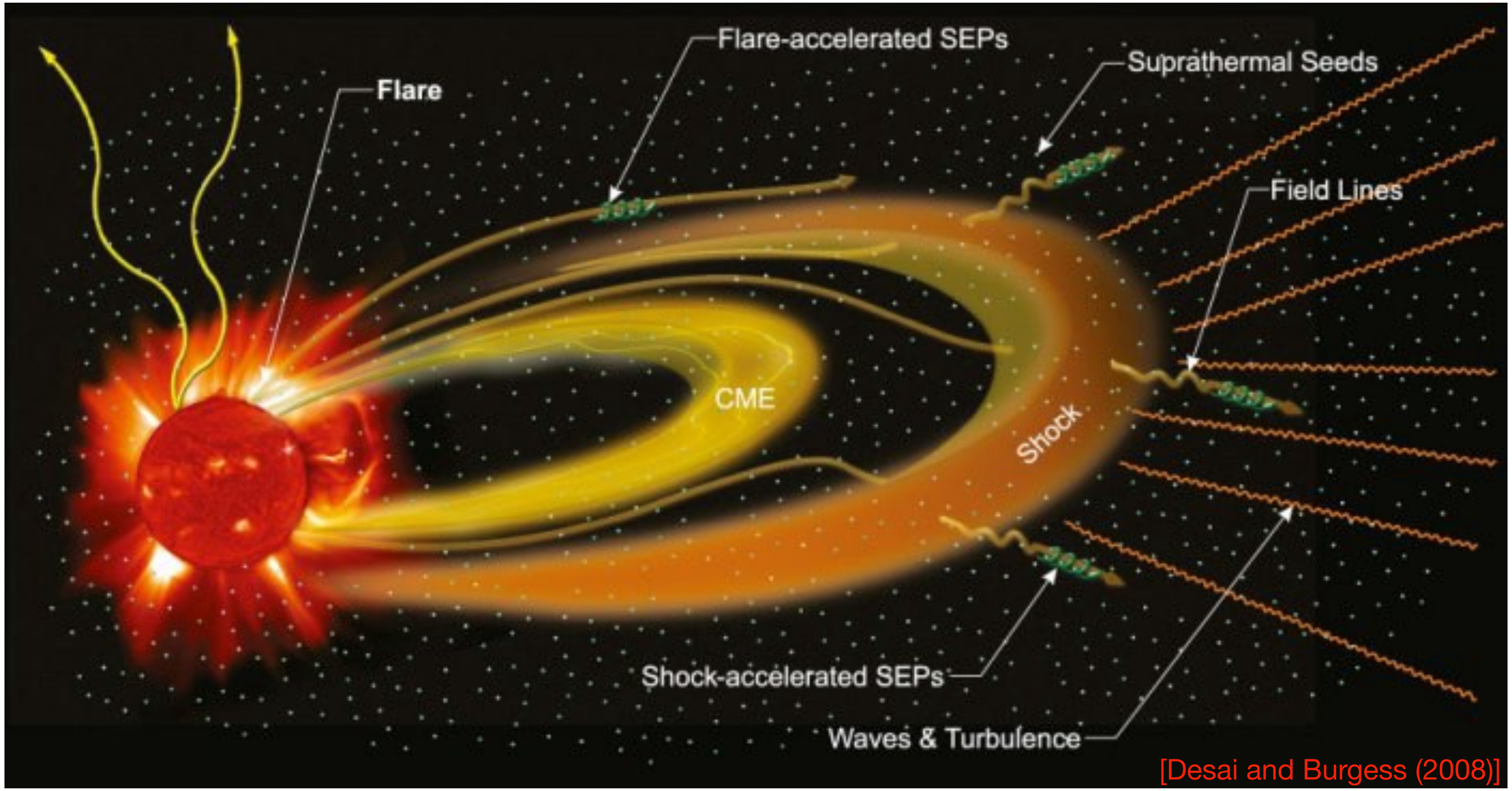
1. Interplanetary medium and the Hermean environment



[Desai and Burgess (2008)]

The interplanetary medium is

- complex system:
many interacting components

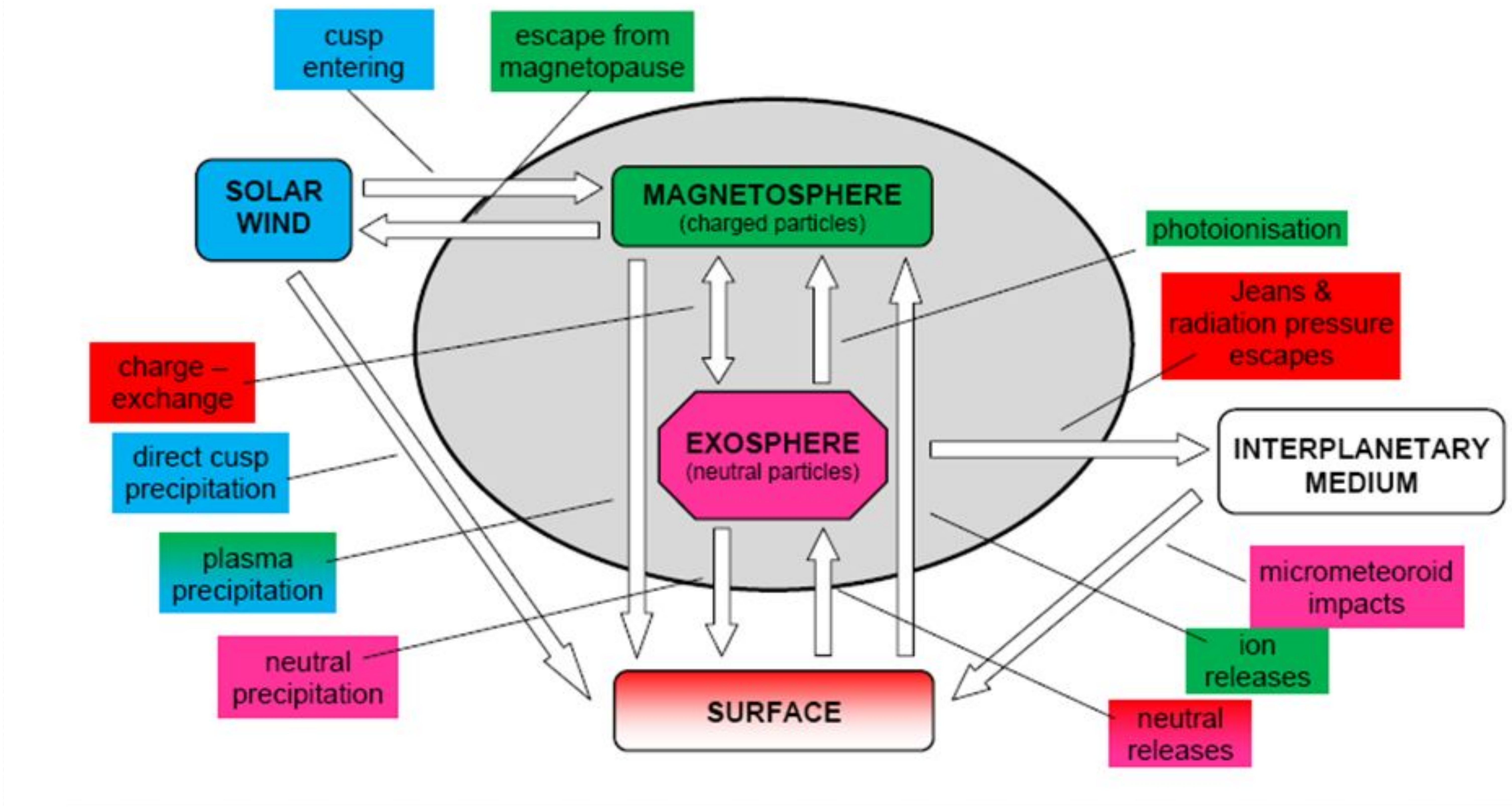
- multiscale system:
variability evolving over a wide range of spatial and temporal scales

- plasma:
ionized gas carrying out a magnetic field from the solar upper atmosphere

The interplanetary plasma parameters and magnetic field vary within the Heliosphere

$v \sim 250 - 750\,\text{km/s} \quad n_i \sim 10 - 400\,\text{cm}^{-3} \quad |B| \sim 10 - 200\,\text{nT}$

1. Interplanetary medium and the Hermean environment



[Milillo+ (2010)]

The Hermean environment

nteracts with the ambient solar wind

Can be seen as a “miniature” of the Earth’s magnetosphere

is characterized by many features as
Flux transfer events,
Kelvin-Helmholtz instability,
Photoionisation,
Particle precipitation,
Ion circulation,
…

2. The Hilbert-Huang Transform (HHT)

- a novel method of analysis to study non-stationary and nonlinear signals $f(t)$ containing oscillating modes, embedded structures, and trends
- based on two different steps

the Empirical Mode Decomposition (EMD)

1. define a zero-mean signal and find its local maxima and minima
2. define upper and lower envelopes via cubic spline interpolation
3. Evaluate the mean envelope and subtract from the signal
4. Is it an Intrinsic Mode Function (IMF)?
   Does it has (i) the same number of extrema and zero crossing and (ii) an average envelope with zero mean?

   4.1 YES -> store it as $\mathscr{C}_1(t)$ and repeat 1.-3. on the residual

   4.2 NO -> repeat steps 1.-3. until it is an IMF

At the end you can write

$$f(t) = \sum_k \mathscr{C}_k(t) + \mathscr{R}(t)$$

the Hilbert Spectral Analysis (HSA)

1. Define the Hilbert Transform of each empirical mode $\mathscr{C}_k(t)$

$$\tilde{\mathscr{C}}_k(t) \doteq \frac{1}{\pi} \mathscr{P} \int_{-\infty}^{\infty} \frac{\mathscr{C}_k(t)}{t - t'} dt' \quad \rightarrow \quad \mathscr{C}_k(t) = \mathscr{A}_k(t)\, e^{i\,\varphi_k(t)}$$

2. Define an Hilbert-based spectrogram known as **Hilbert-Huang Spectrum**

$$\mathscr{S}(t, \omega) = \int_{-\infty}^{\infty} \rho(\mathscr{A}, \omega)\, \mathscr{A}^2\, d\mathscr{A}$$

3. Define an its integrated version known as **Hilbert-Huang Power Spectral Density**

$$\mathscr{H}(\omega) = \frac{1}{\omega} \int_t \mathscr{S}(t, \omega)\, dt$$

[Huang+ (1998), Huang and Wu (2008)]

2. The Hilbert-Huang Transform (HHT)

Why to use the HHT?

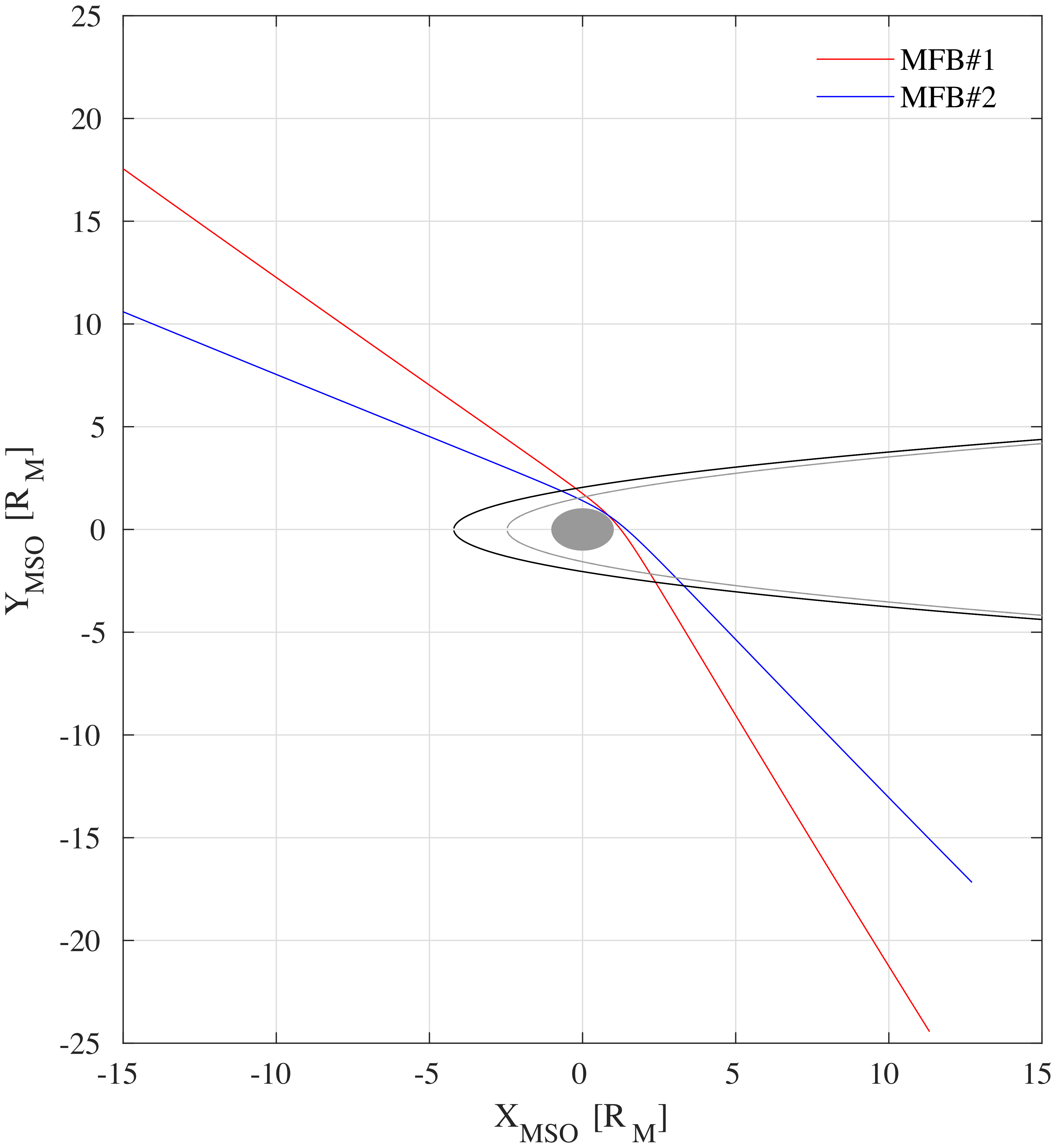
1. The EMD allows to extract local properties of oscillating modes and embedded structures without any *a priori* selected basis → useful for nonlinear signals

2. The HSA can be used, after the EMD, to investigate non-stationary features of each oscillating mode and/or embedded structure

3. A finite number of oscillating components are found (typically as the log of the number of time series points)

4. The HSA allows us to investigate local (in terms of time and frequency) properties and to filter out fluctuations in a specific range of frequencies

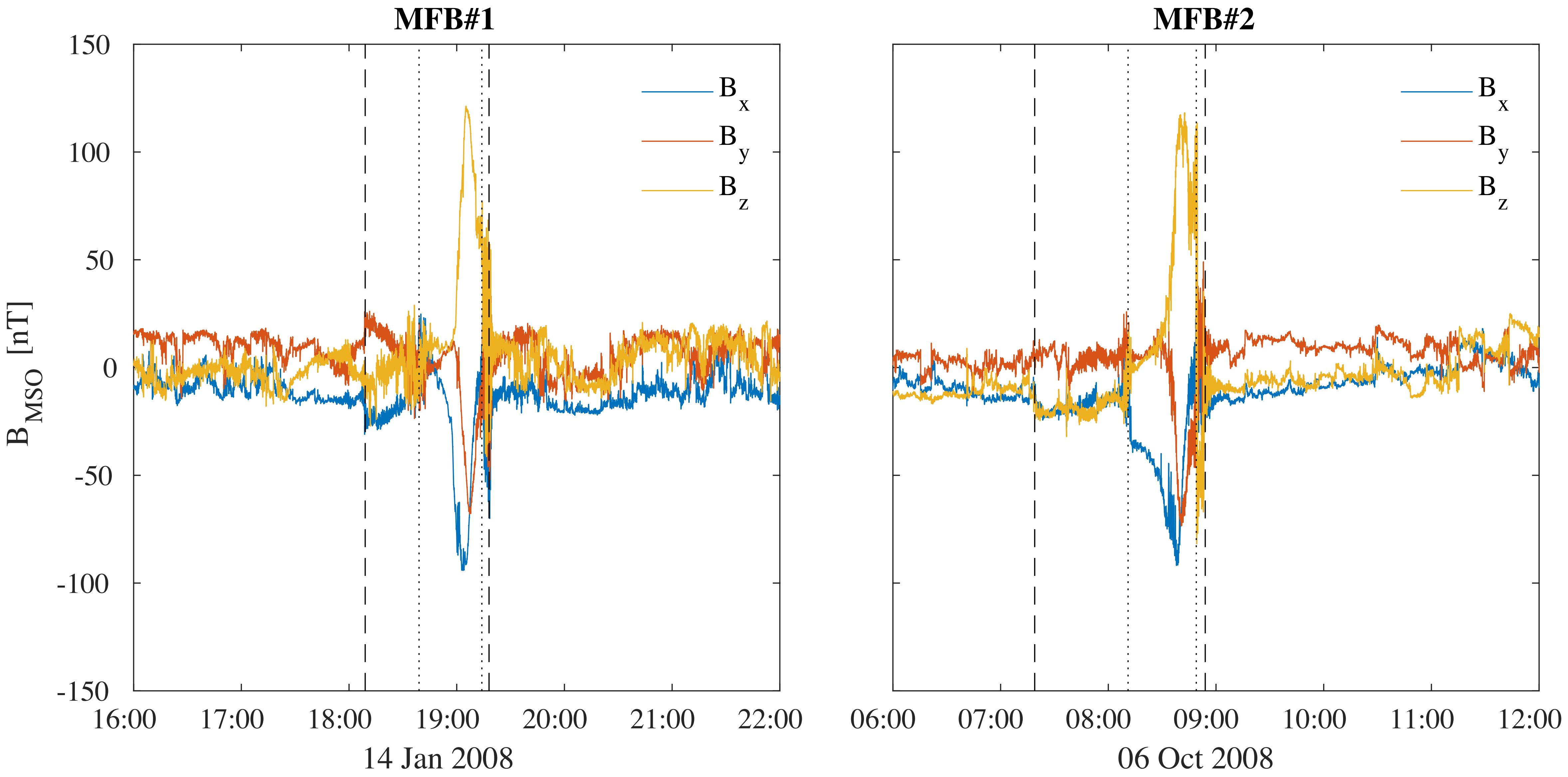
3. MESSENGER Mercury flybys



The first Mercury flyby (MFB#1) occurred on 14 January 2008

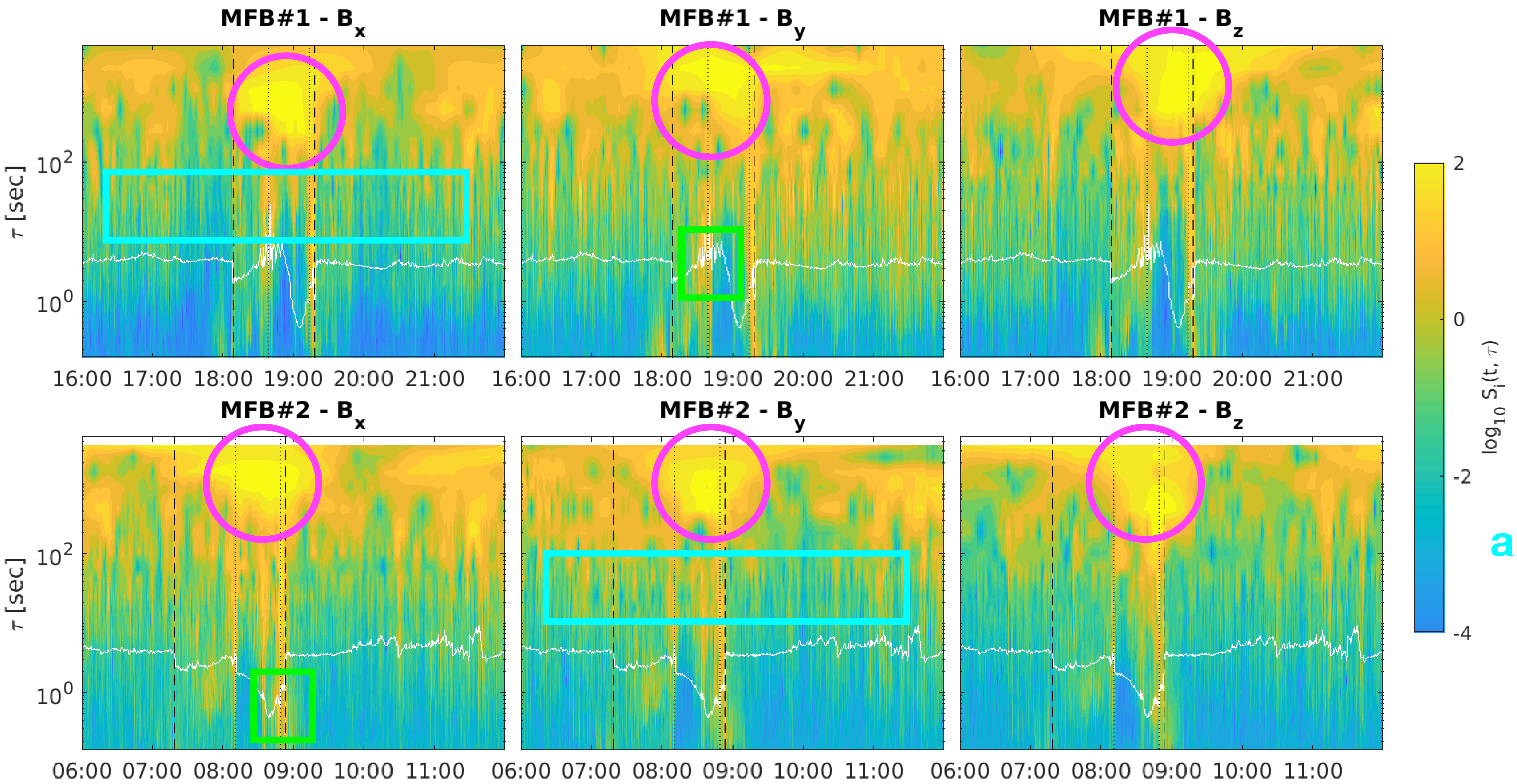
The second Mercury flyby (MFB#2) occurred on 06 October 2008

We used data collected by the magnetometer (MAG) at the highest resolution $\Delta f = 20$ Hz in the MSO coordinate system



3. MESSENGER Mercury flybys

Looking at the Hilbert-Huang spectrum $\mathscr{S}(t, \tau)$



highly non-stationary features

clear dependence on time across the whole scale range

energy increases as MESSENGER approached the inner magnetosphere, especially at large scales

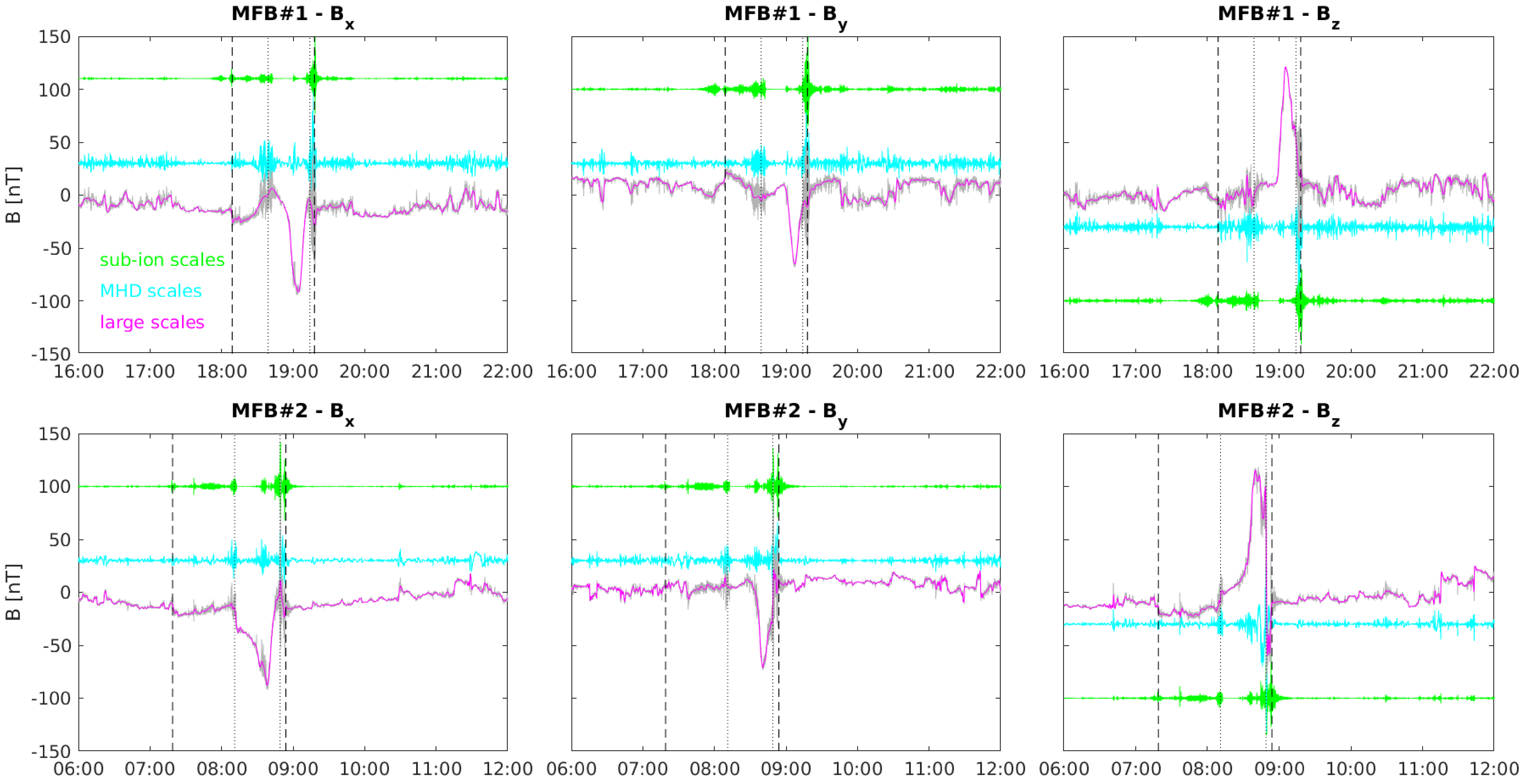
MHD-type processes both in the solar wind and in the Hermean environment

sub-ion processes in the magnetosheath

three different dynamical regimes: **large-scales**, **MHD**, and **sub-ion scales**

3. MESSENGER Mercury flybys

Looking at the three different dynamical regimes



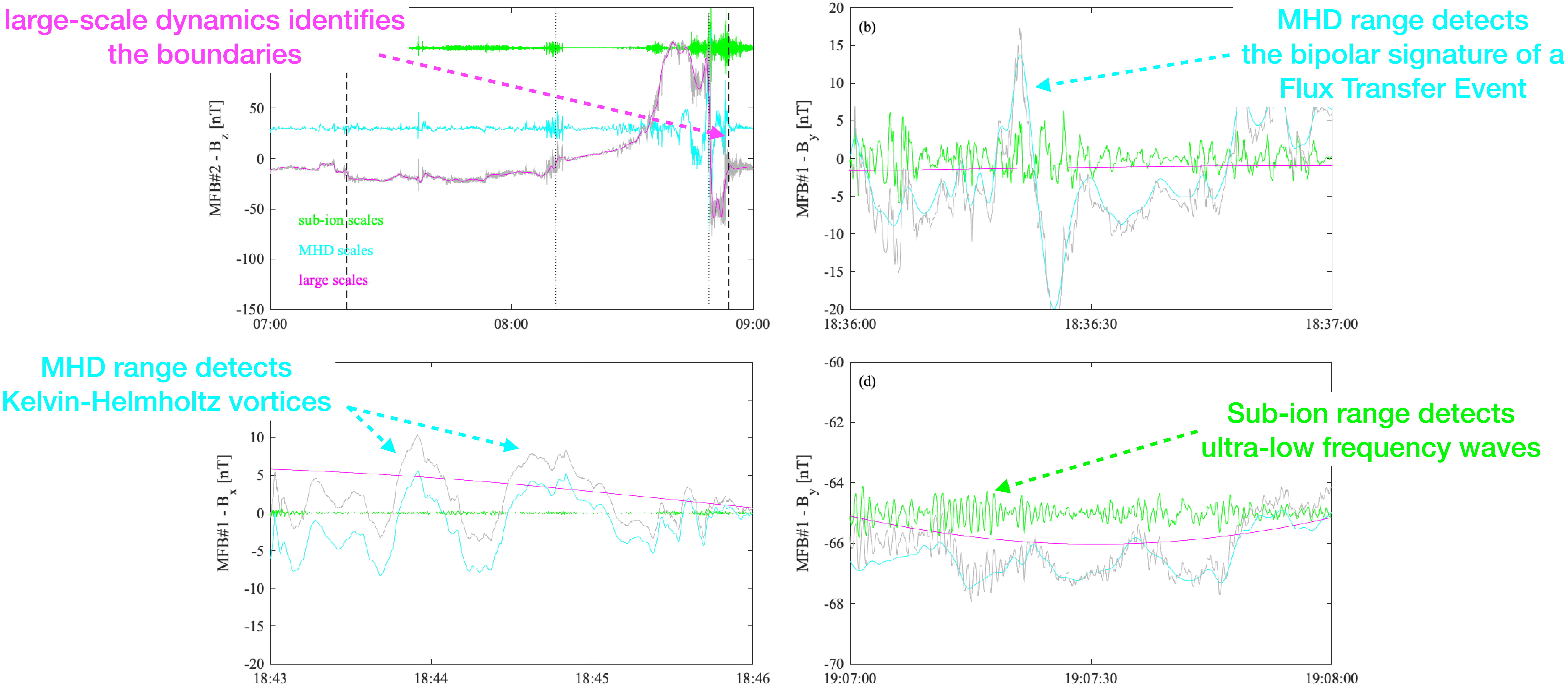
large-scale range allows us a very good characterization of the profile of the main magnetic field as well as to investigate and localize the boundaries

MHD range dynamics is characterized by localized fast amplitude enhancements, useful for turbulence and reconnection-driven processes

sub-ion range useful for studying kinetic processes occurring in the inner magnetosphere and surrounding regions

3. MESSENGER Mercury flybys

Zooming into localized processes



4. Tips & Conclusions

1. The HHT is useful for characterizing the **structure and dynamics** of the Hermean environment **at different scales**

2. It allows to identify **different dynamical regimes** that can be used for multiple purposes as **boundaries identification**, exploring **localized processes**, numerical **testing of main field simulations**, …

3. **Deeper investigations** are required **on different parameters** (particle distributions, plasma measurements, …)

4. BepiColombo could provide both **high-resolution measurements** and **particle distributions** as well as to compare the ambient solar wind with the near-Hermean environment

5. **Multi-spacecraft investigations** could be relevant for **simultaneously monitoring** the solar activity and planetary environments

Thanks for the attention