# CME Observations – from Sun to impact on Geospace


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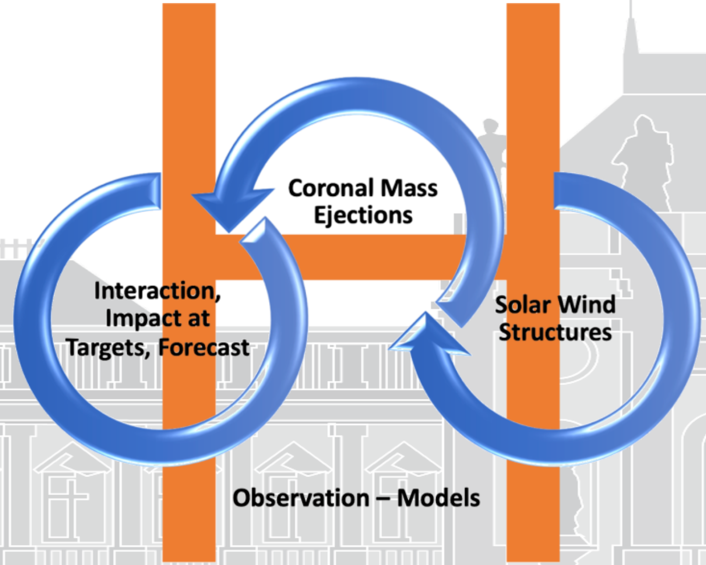
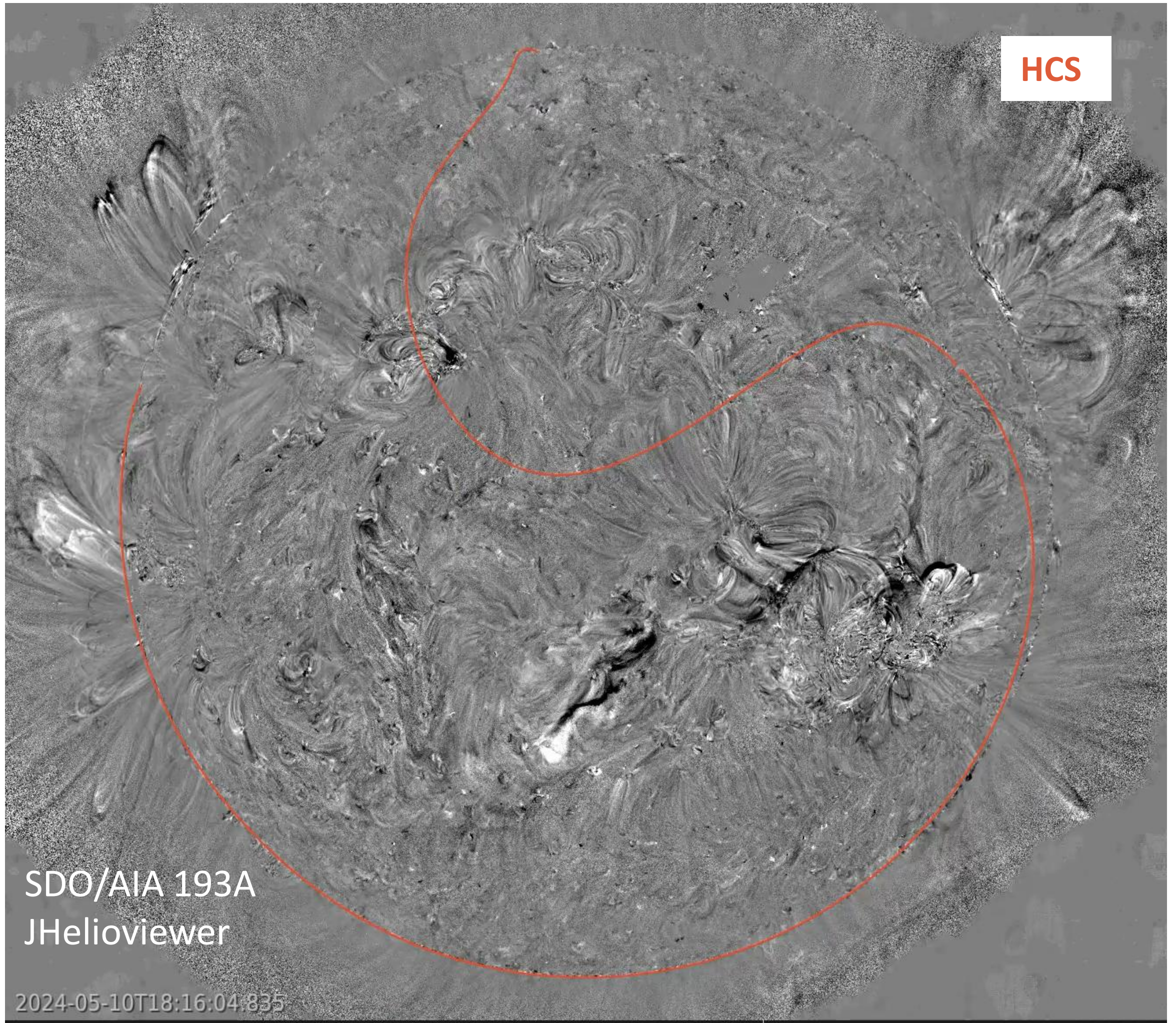
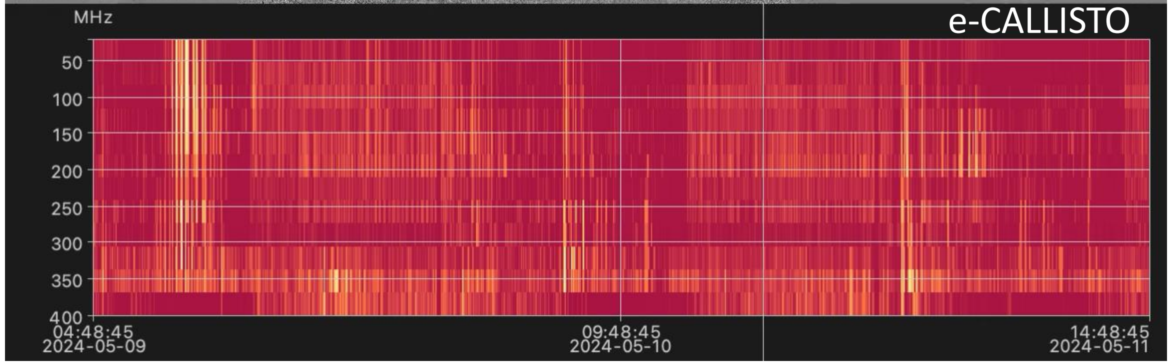


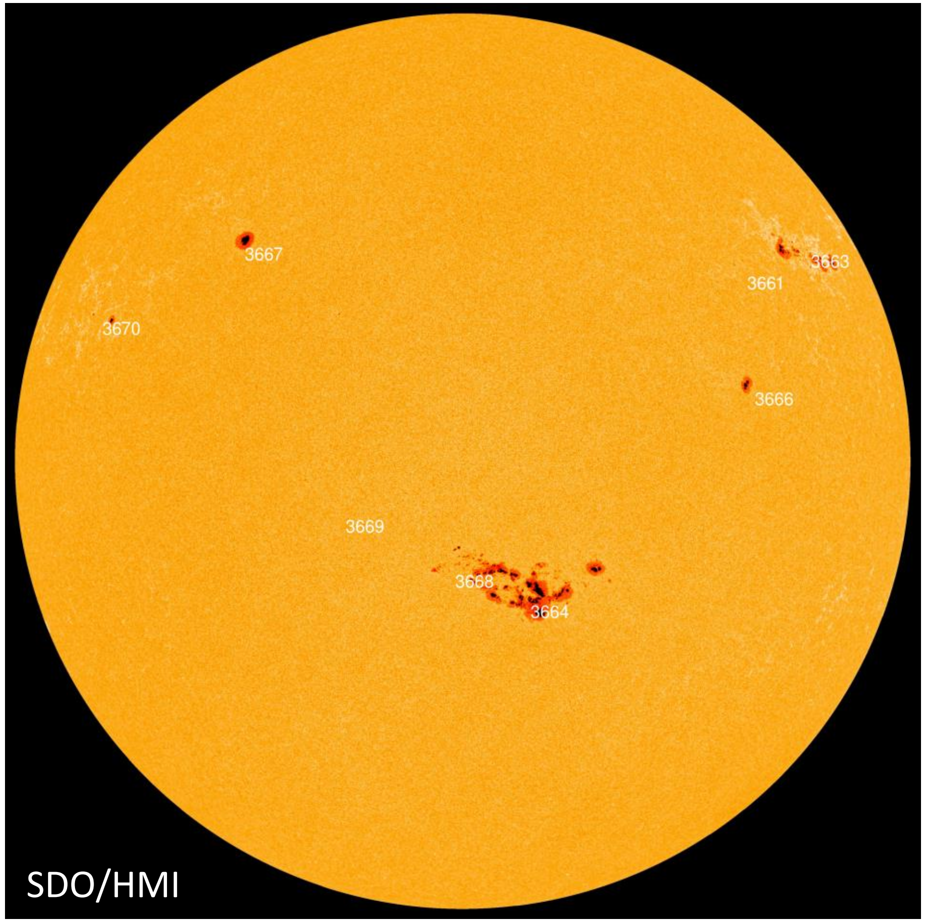

*"We study the physics of background solar wind, coronal mass ejections and their mutual interactions, with the aim to improve models and Space Weather forecasting abilities."*

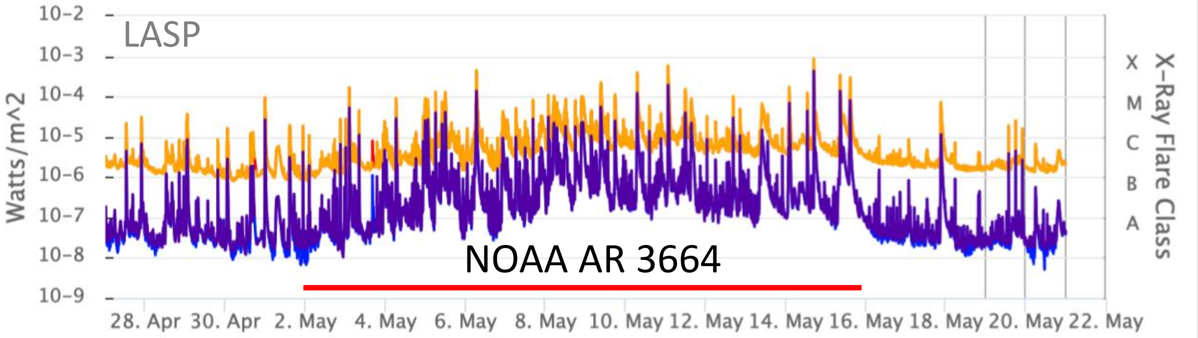
*UNOOSA / ISWI UN Workshop :: Neustrelitz June 10-14, 2024*

# Sun: May 8-11, 2024 X-class flares

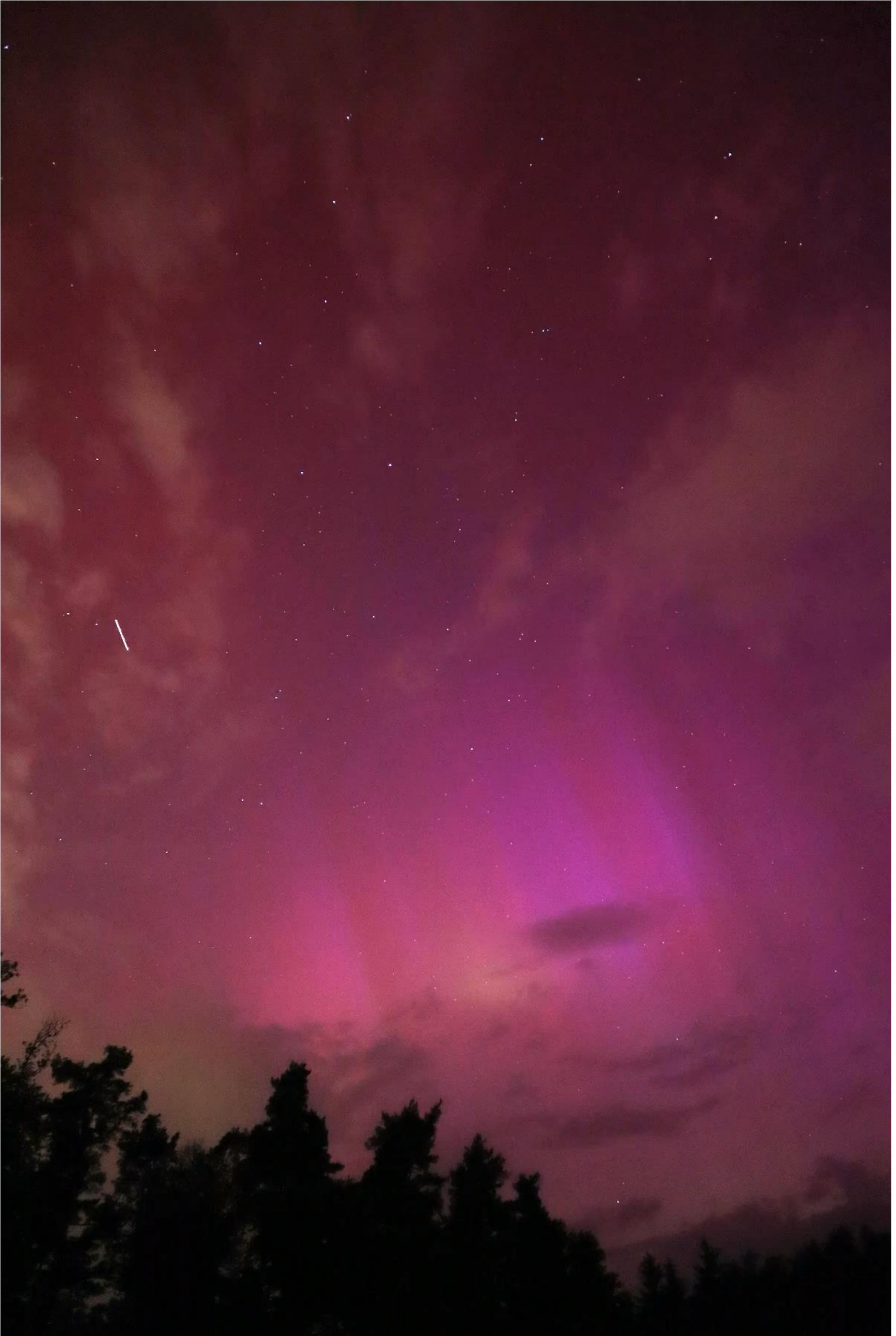


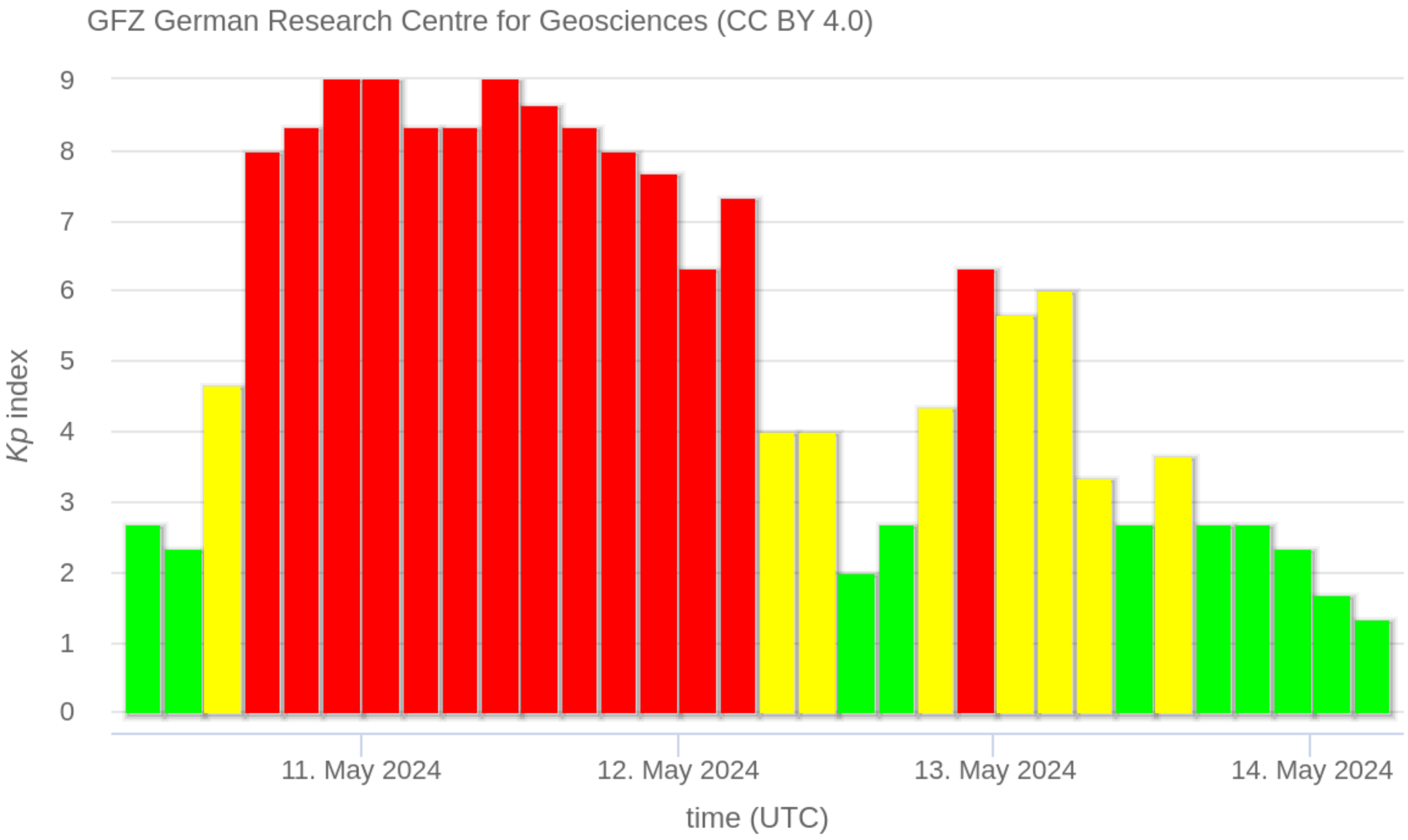



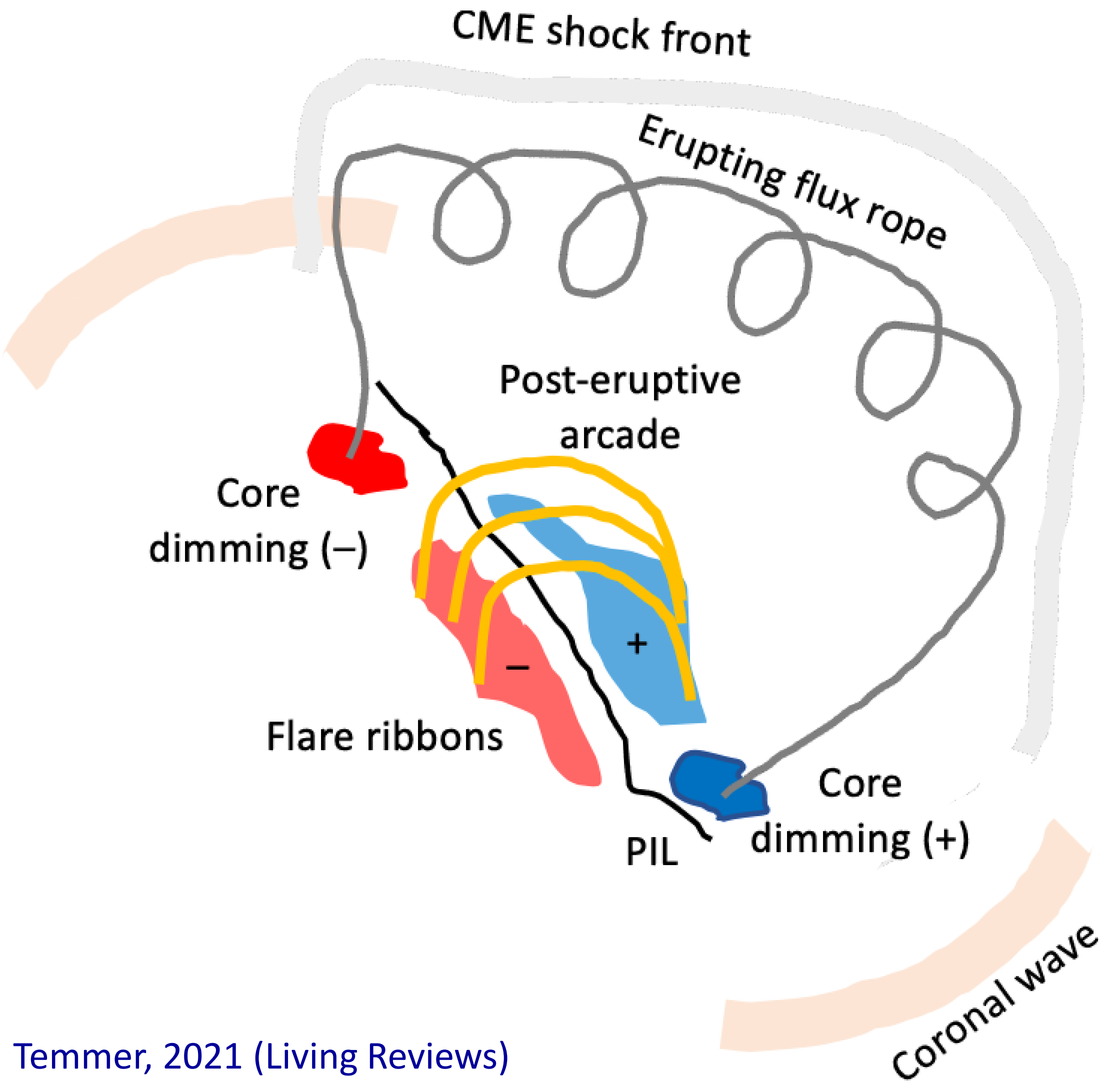
# Earth: May 10-11, 2024 event






Aurorae over Graz, May 11, 2024 © Florian Koller

# Solar surface phenomena related to an eruptive event

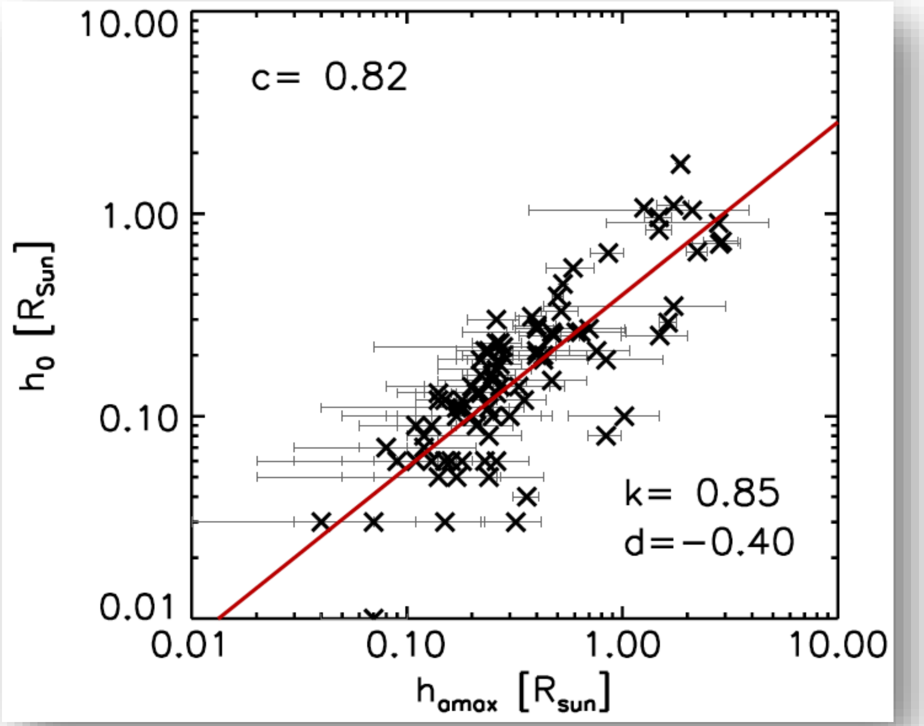



Temmer, 2021 (Living Reviews)

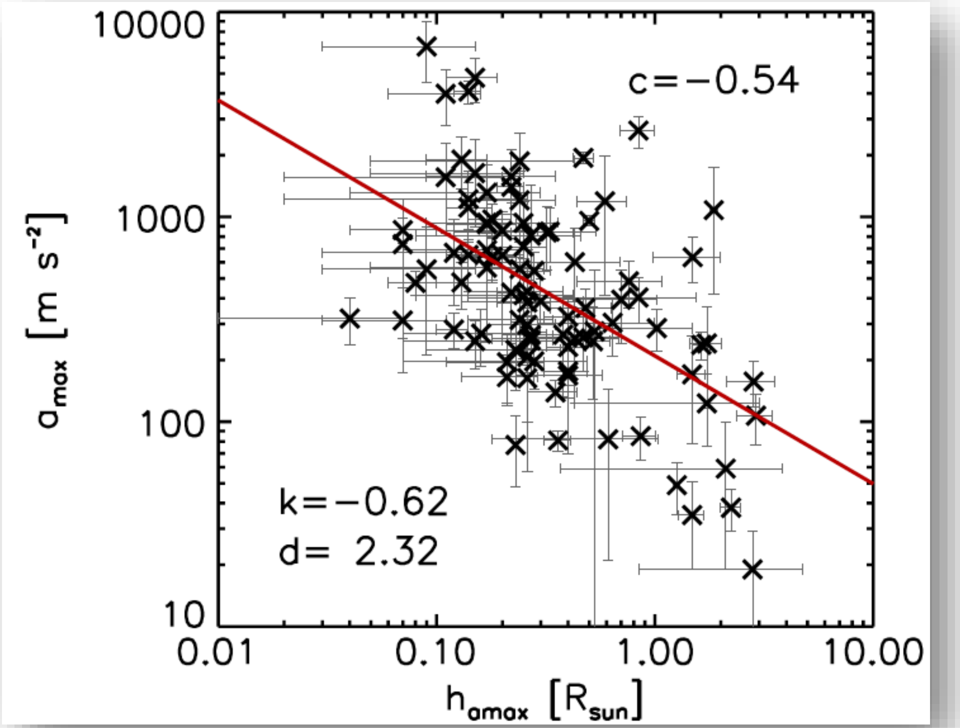
- **Flare** – bright H-alpha, EUV, SXR, HXR, white-light for strong events (e.g., Fletcher+ 2011)
- **Flare-reconnection-CME feedback:** HXR flare <=> CME acceleration; SXR flare <=> CME speed (e.g., Zhang+ 2001,2004; Chen & Krall, 2003; Maričić+ 2007; Temmer+ 2008,2010; Schmieder+ 2015)
- **Flux rope** – filament eruption and mass motion (e.g., Schmieder+ 2013)
- **Mass release** – EUV dimming regions (e.g., Hudson & Cliver, 2001; Mandrini+2007; Temmer+ 2017); dimming-CME speed relation see Dissauer+ 2018, 2019;
- **Propagating surface wave** due to lateral (over-)expansion of flux rope (e.g., Patsourakos+2010; Warmuth, 2015)
- **Post-eruptive arcades** – proxy for magnetic structure and reconnected flux (e.g., Green+ 2011, 2015; Gopalswamy+ 2017; Palmerio+ 2018; Tschernitz+ 2018; Scolini+ 2020).

# CME properties are set in low corona

*CMEs that start at lower heights also reach their peak acceleration at lower heights.*



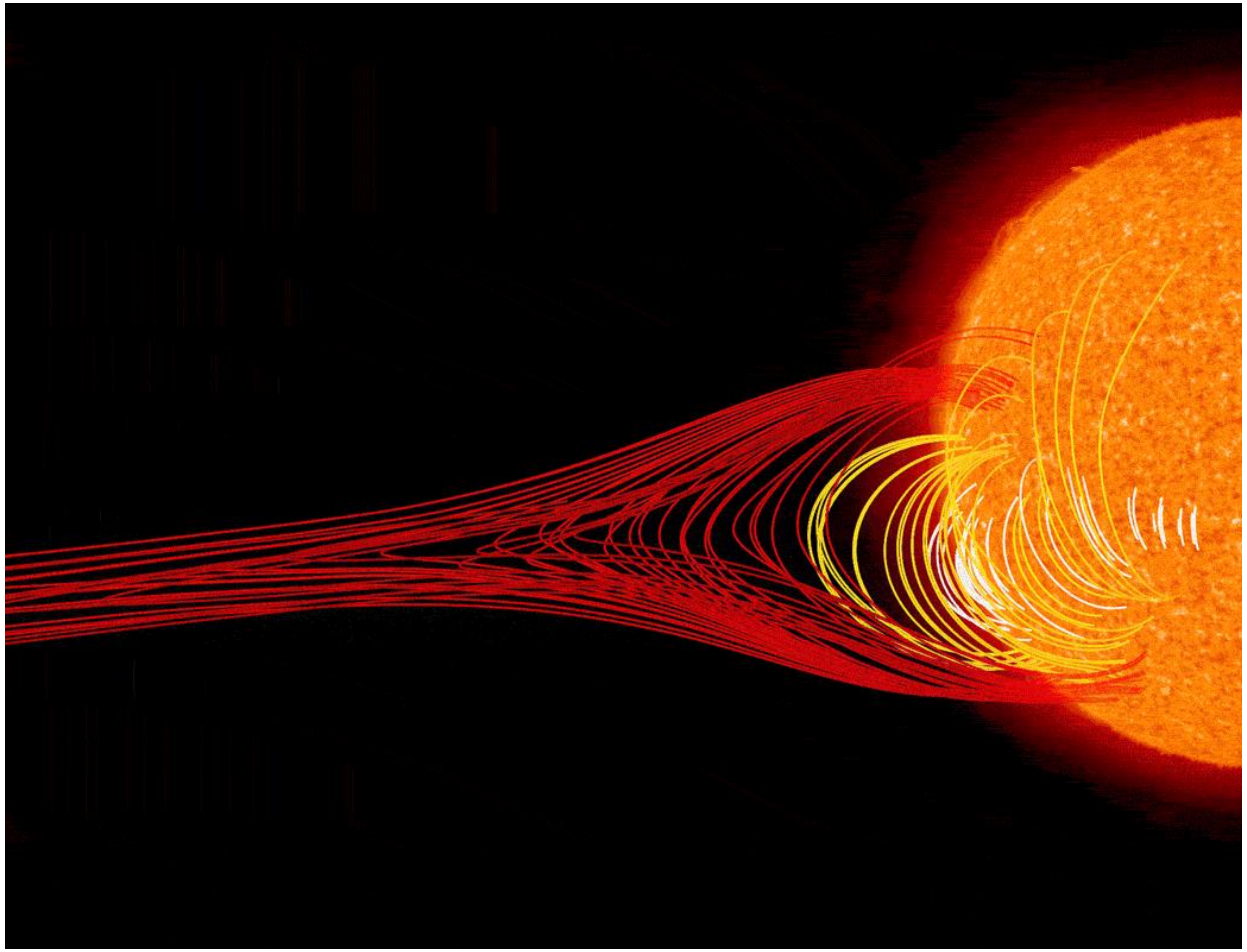

*CMEs that are accelerated at lower heights reach higher peak accelerations.*




Bein et al., 2011

Lower coronal heights :: stronger Lorentz force and shorter Alfvén time scales involved in the process (with stronger magnetic field and larger Alfvén speed; see Vršnak et al., 2007).

# The lower the starting height, the faster the CME



From Lynch+ 2017; model results based on event from Robbrecht+ 2009

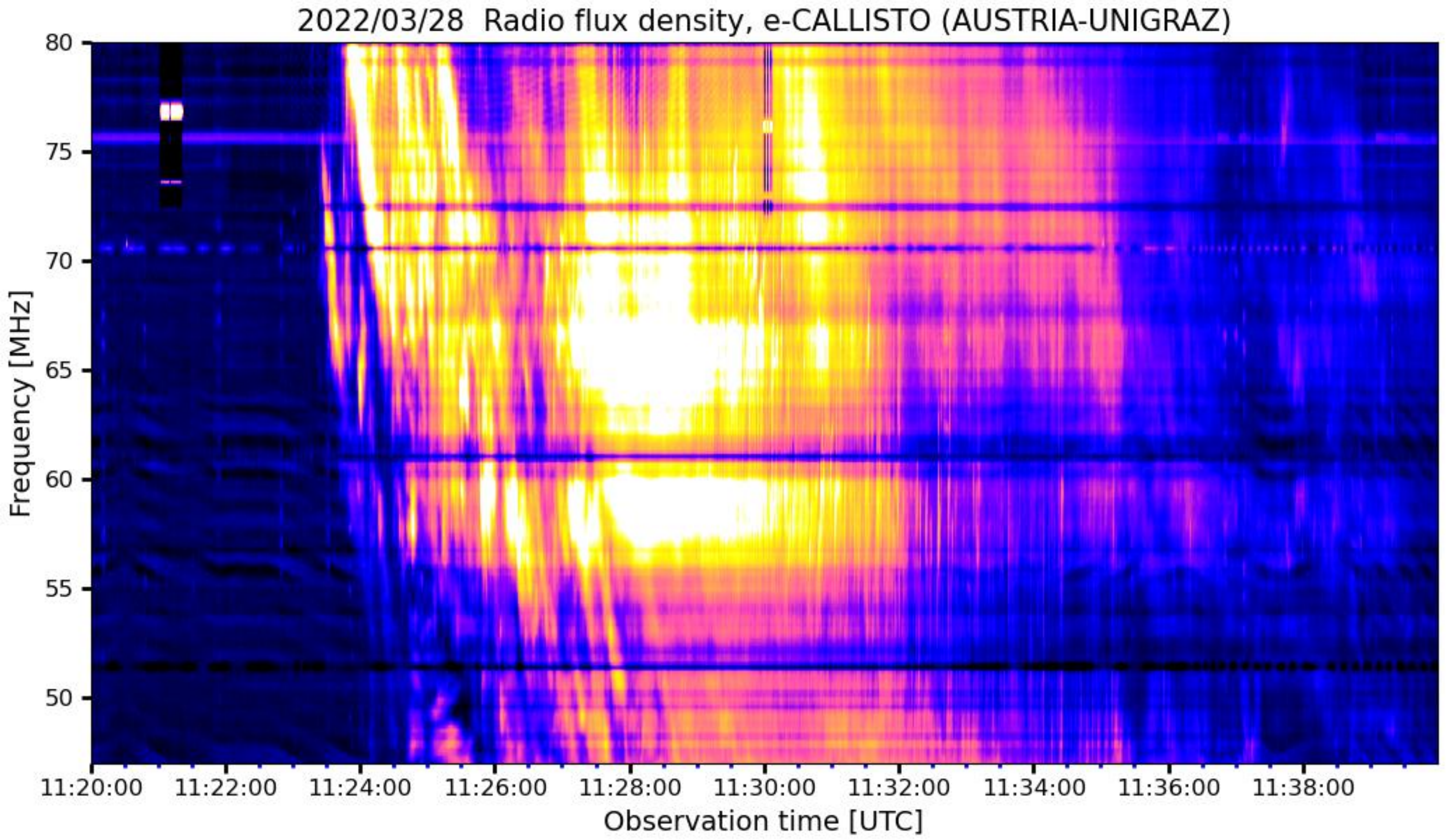
Distance at which reconnection or instability (disconnection) sets in, i.e., at which height the eruption starts, dictates how strongly CMEs are driven (Bein+ 2011).

Stealth CMEs typically go with the flow, but may produce shocks further out in IP space (e.g., Vrsnak & Lulic, 2000).

see also D'Huys+2014; Nitta & Mulligan 2017; Vourlidas & Webb 2018; Palmerio+2021

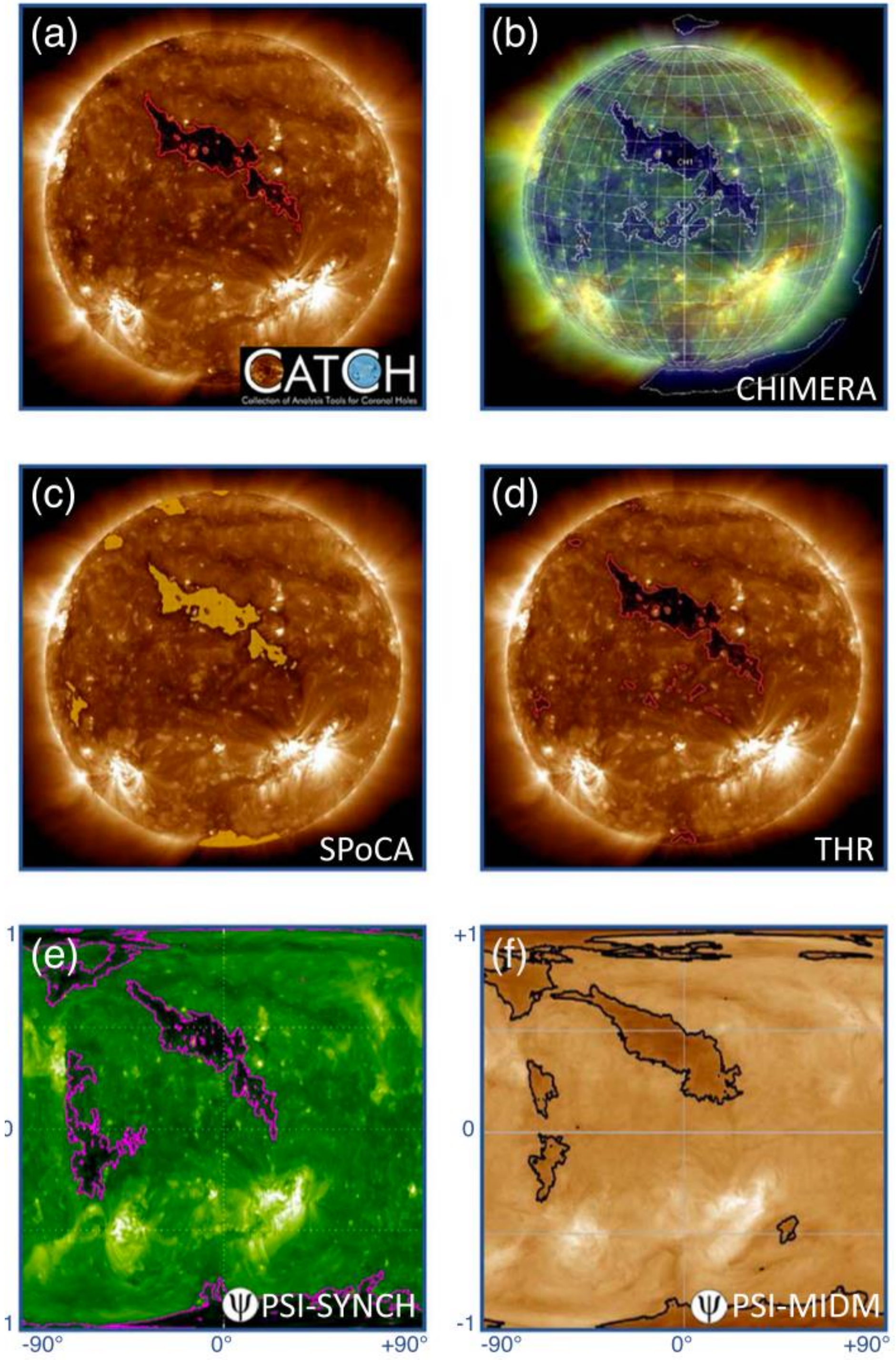
***Stealth CMEs** might cause „problem storms“ due to missed alarms.*
***Confined events** (flare: yes, CME: no) might cause false alarms.*
*Information support: Type III radio bursts*

# Radio signatures




- Type II: fast CMEs (multiple events – preconditioning effects – density depletion)
- Type III: eruptive flare

See more e.g., in Mann+ 1998; Gopalswamy+ 2001; Vrsnak+ 2002; Zucca+ 2018; Morosan+ 2020;

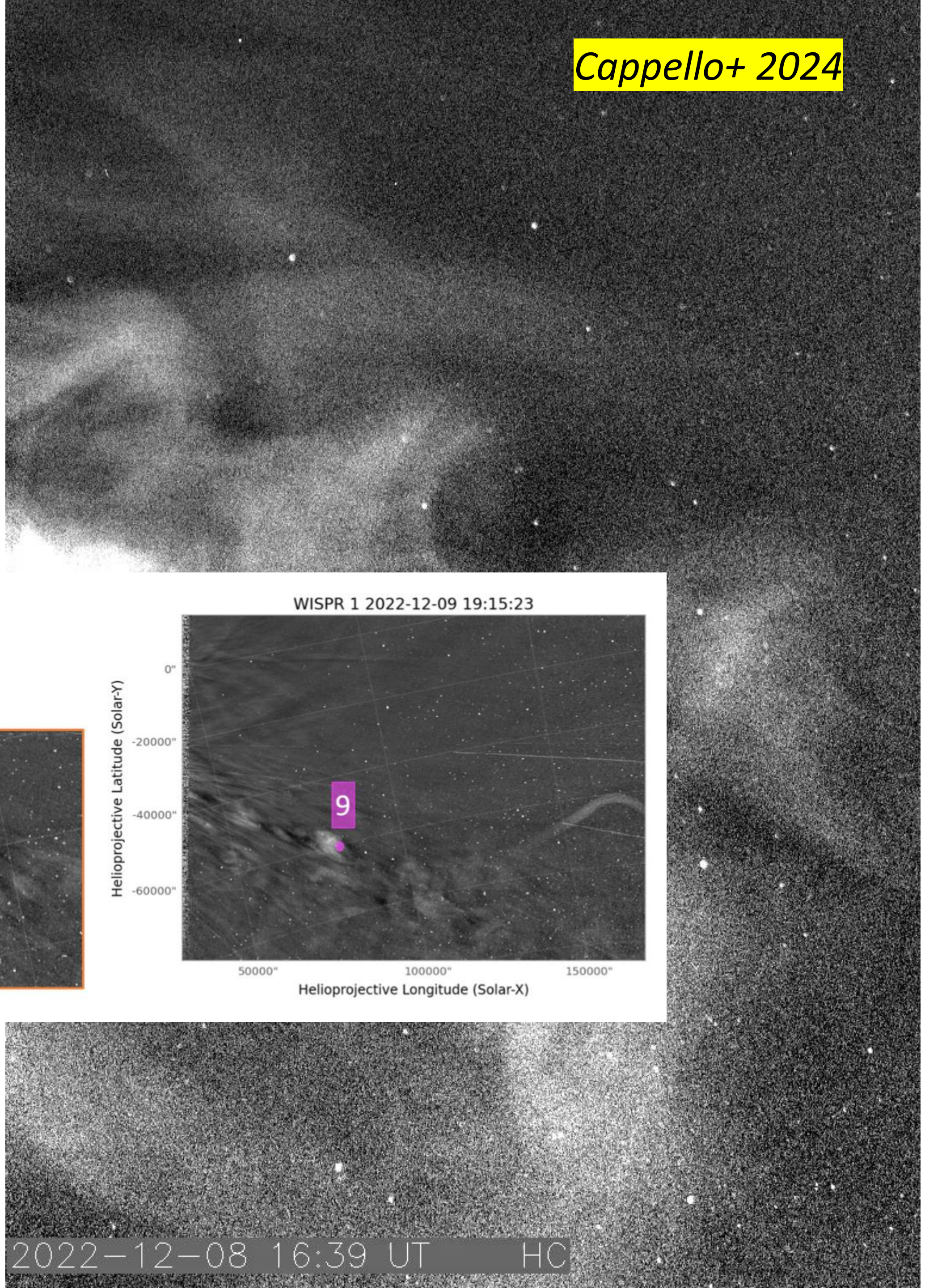


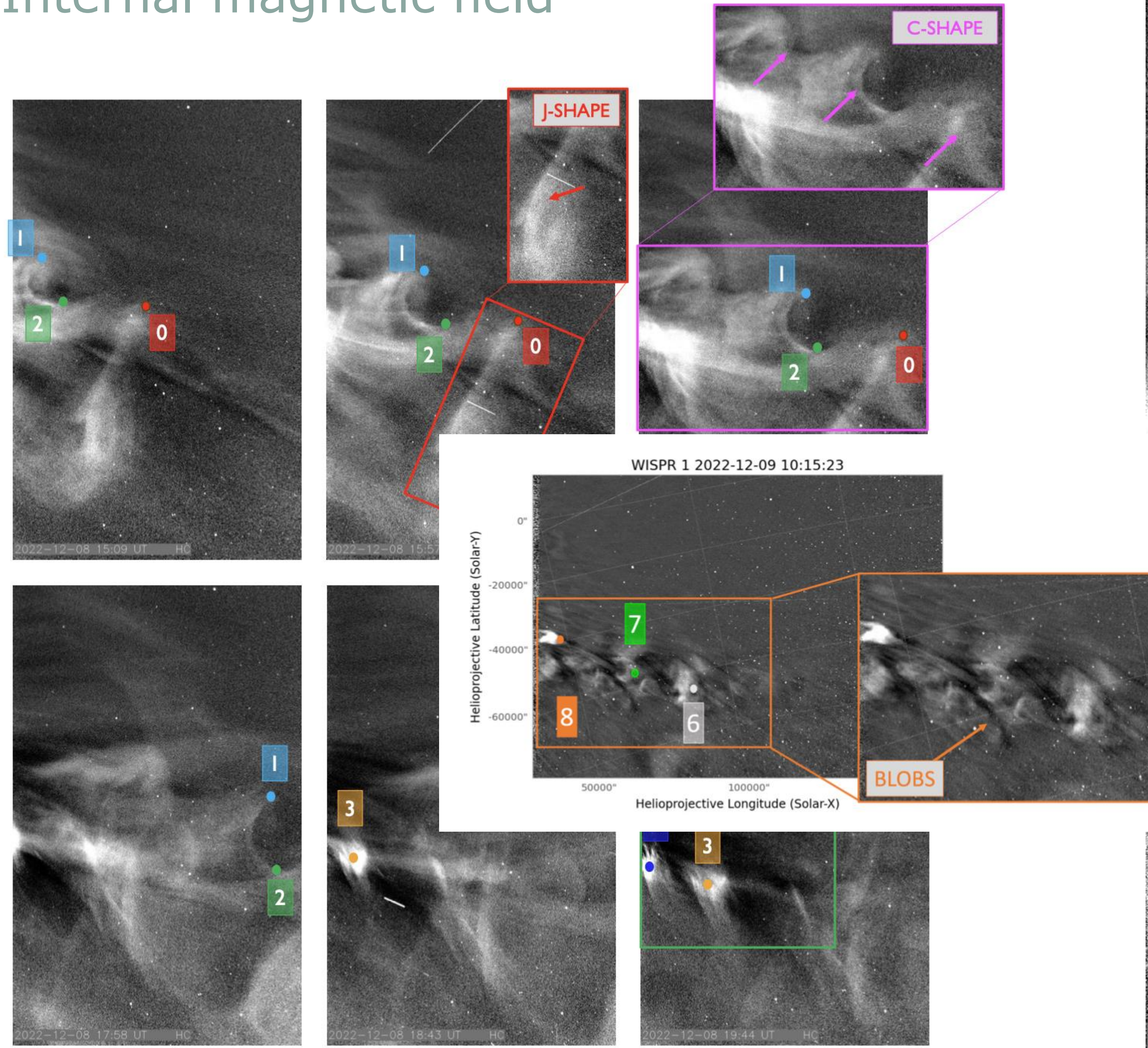
Linker+ 2021

# Structuring of IP space – magnetic "obstacles" for CMEs

- OMF „shapes" the heliosphere (HSS, forming SIRs/CIRs), magnetically connects the Sun to the planets, and dominates the motion of energetic particles (Frost+ 2022).
- CHs are assumed to mainly represent the OMF.
- Discrepancy between in-situ and magnetogram OMF estimates; OMF underestimed by factor 2, e.g., Arden, Norton & Sun, 2014; Linker+ 2017; Wallace+ 2019; Linker et al., 2021; Frost+ 2022; Linker+ 2021; Asvestari+ 2024;
- AR outflows might contribute to OMF (vanDriel+ 2012).
- OMF evolution correlates with CH open flux, but not with CH area evolution (Heinemann+ 2024).
- OMF variation might be related to vanishing remnant magnetic field at poles (Heinemann+ 2024) => cycle dependence!

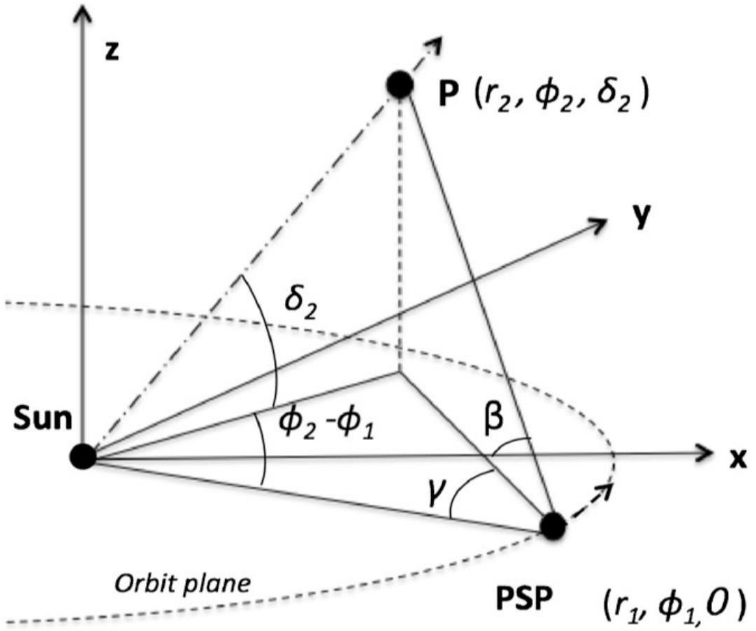
# Internal magnetic field



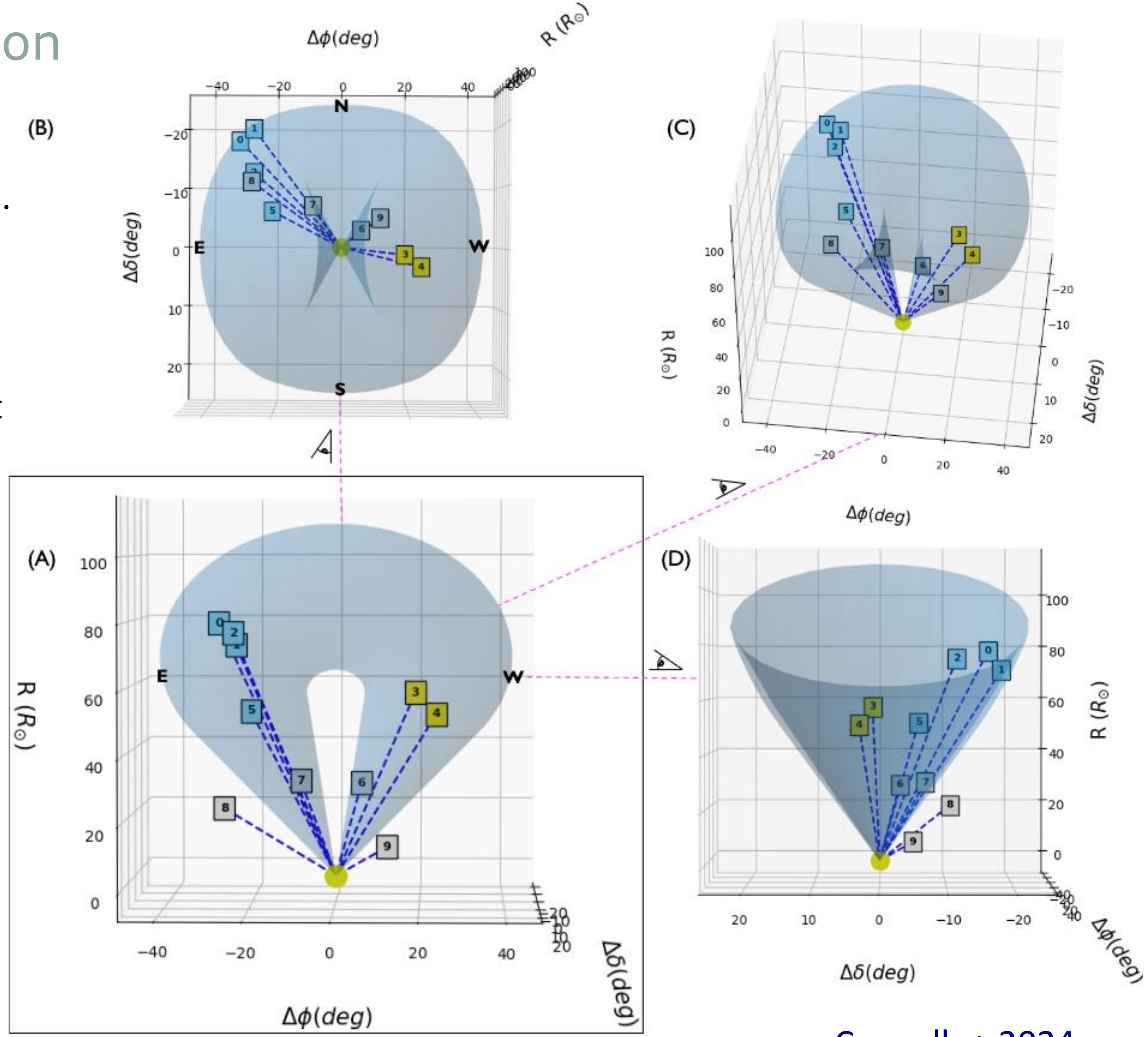



# Internal magnetic field distribution

- Small-scale density structures distributed in different regions of the CME (Cappello+ 2024).
- Blobs might refer to interaction of CME flanks/trailing edge with ambient SW (Cappello+ 2024).
- Global shape of CME from 1AU looks different (see also Howard+2022).

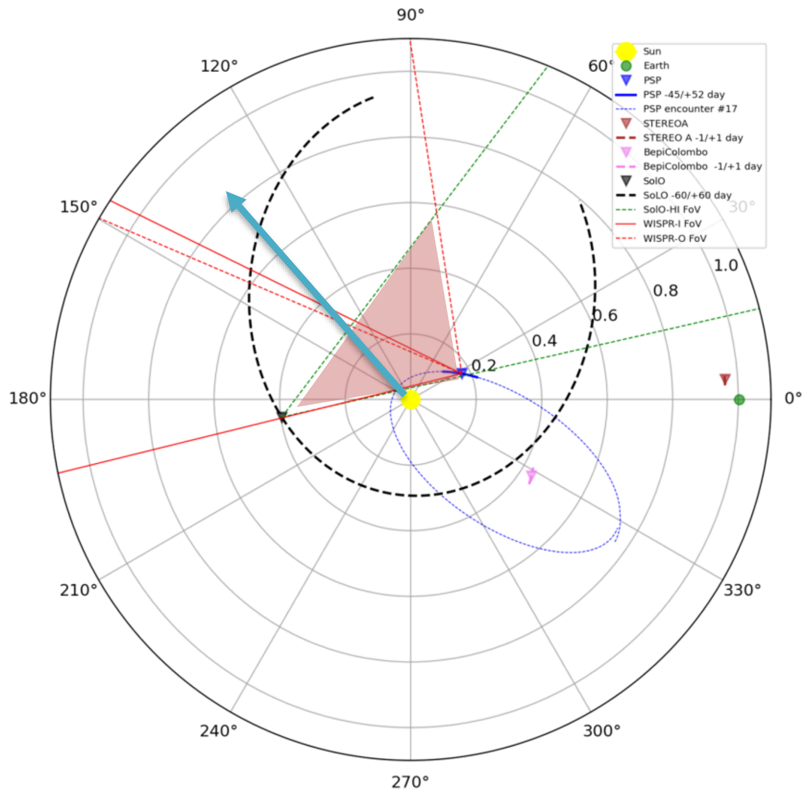


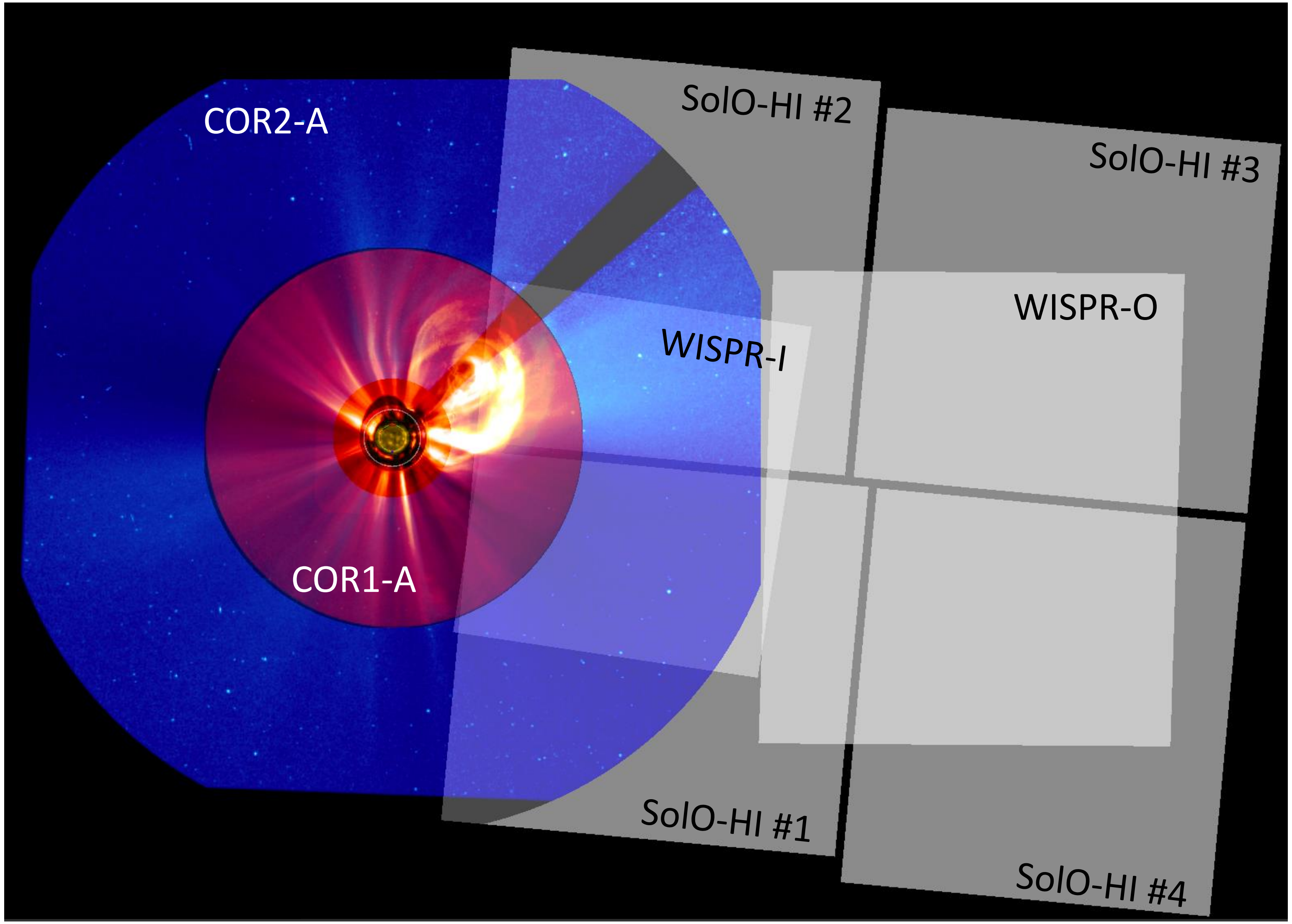

Liewer+ 2020




Cappello+ 2024

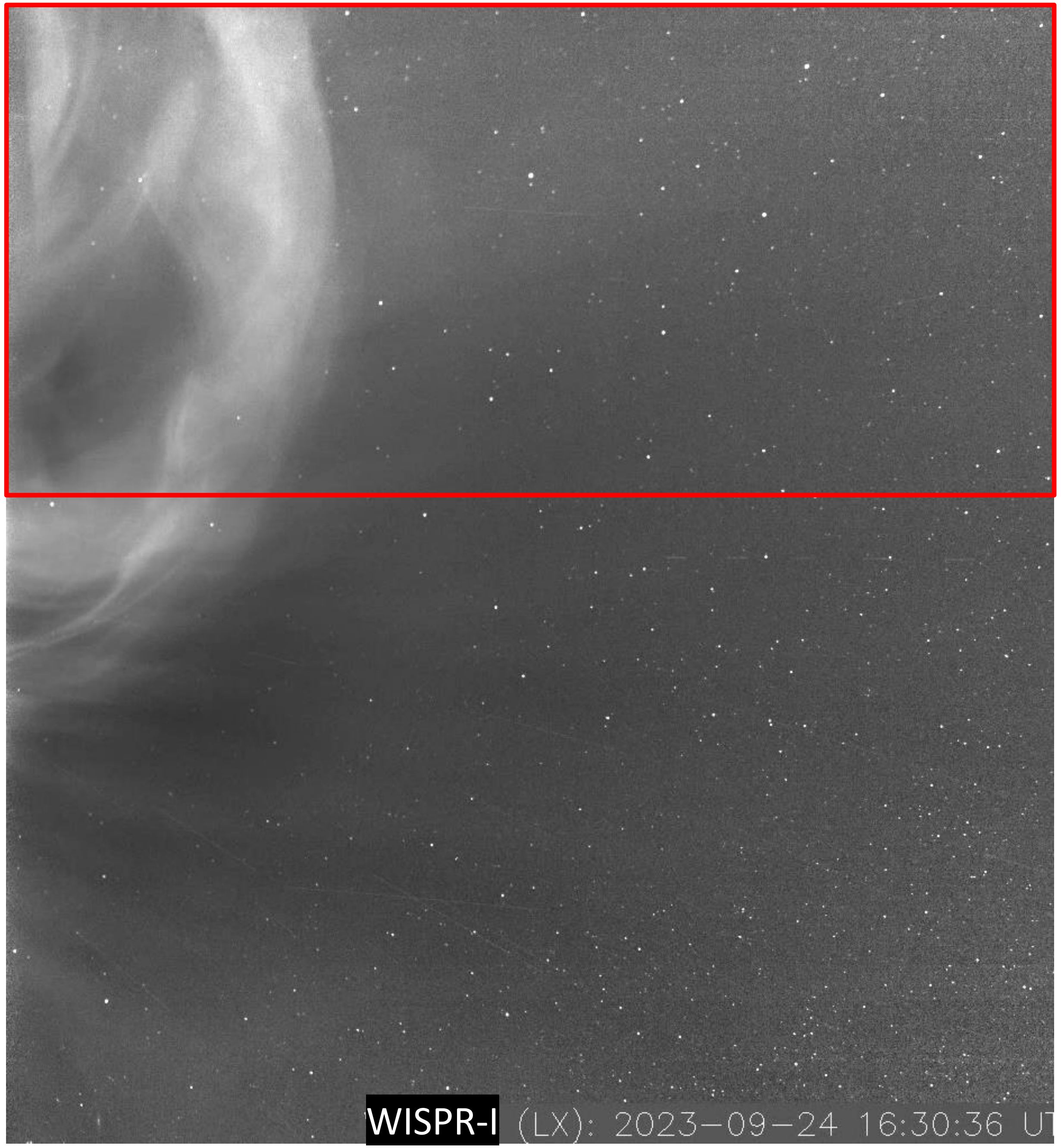
# HI data from SolO and PSP – line-of-sight integrated intensity over different distances

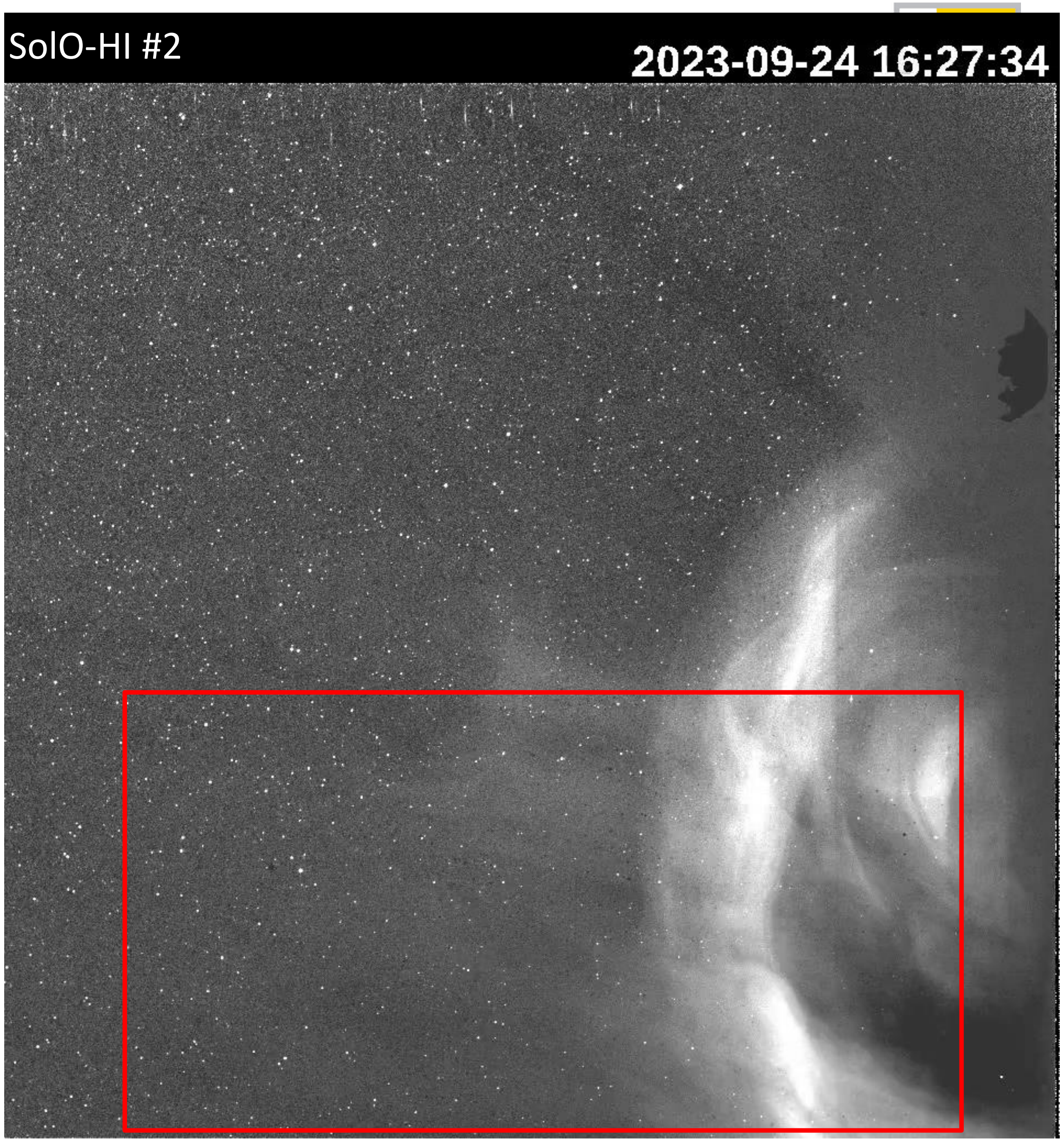



New data reveal the complexity of CME's internal magnetic field structure, see Cappello+ 2024, in prep.; Rouillard+ 2020; Hess+ 2020; Liewer+ 2021; Wood+; Braga & Vourlidas 2021; Howard+ 2022 …

Cappello+ 2024 (in prep.)

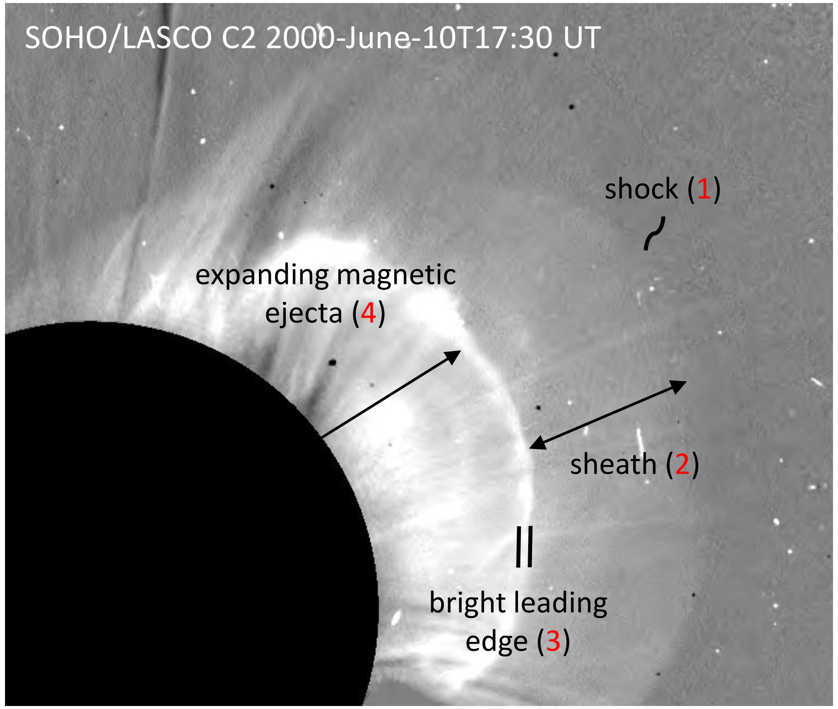

WISPR-I (LX): 2023-09-24 16:30:36 UT


SolO-HI #2
2023-09-24 16:27:34

# Local structures versus global appearance

- Space weather forecasting focus: arrival time and speed of shock-sheath and magnetic ejecta
- *Are we consistent in our understanding of different structures and their definitions?* See also ISSI team by C. Verbeke and L. Mays. (e.g., Verbeke+23)
- PSP/WISPR (Vourlidas+ 2016) enables comparative studies in-situ ⇔ high-resolution WL image data

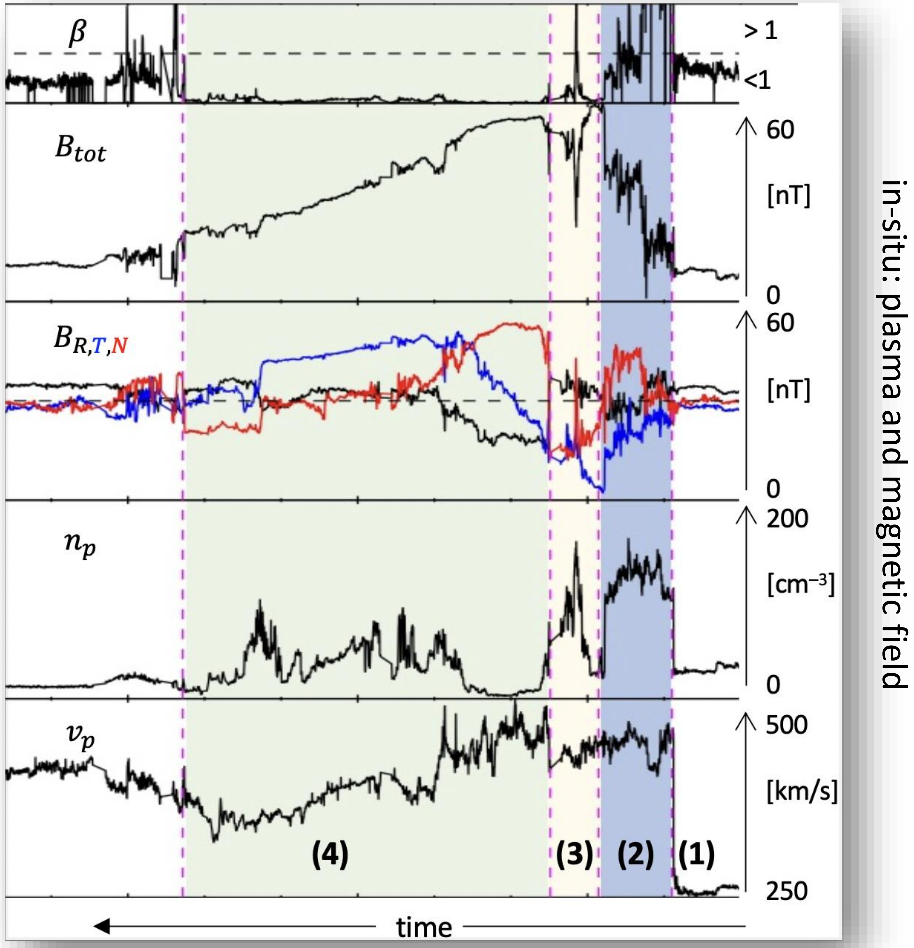
white-light image: density information




*global*

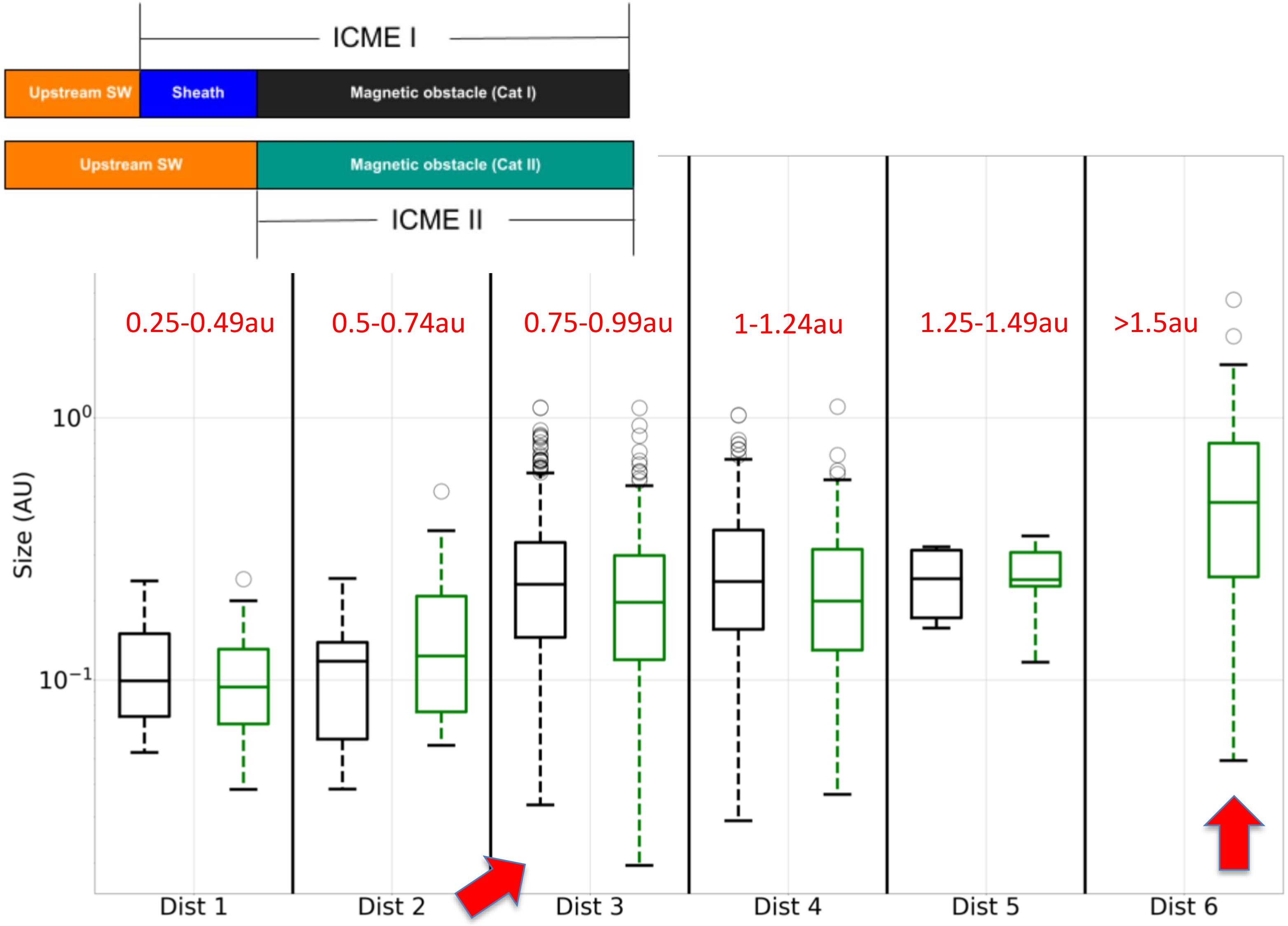
*local*

Temmer & Bothmer, 2022




*It needs further investigations and discussions about local vs. global properties and in-situ vs. remote sensing observations.*

# Expansion behavior of CMEs with and w/o driving clear sheaths



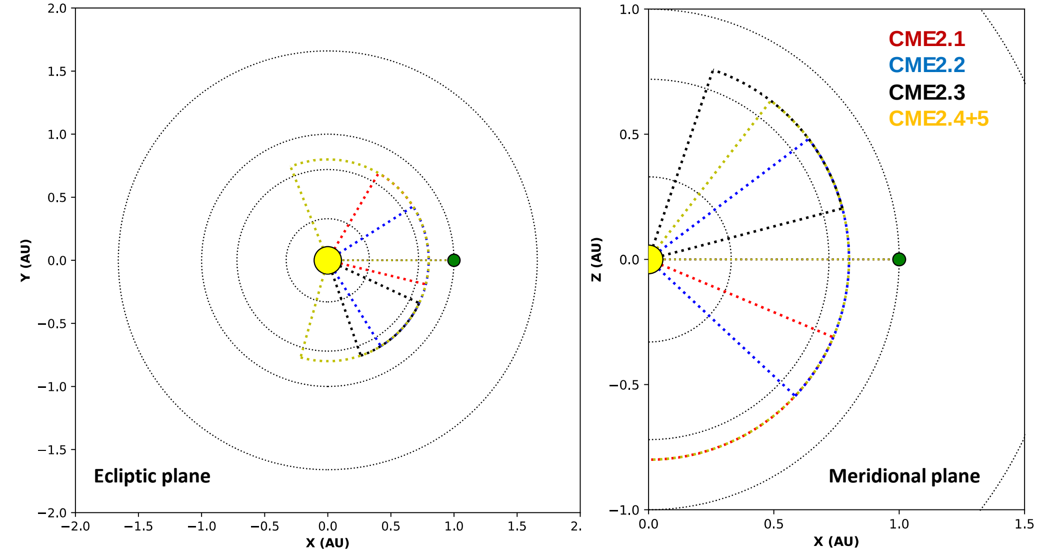

Larrodera & Temmer 2024

Sheath = high plasma-beta; implications for IMF draping and plasma accumulation (McComas+ 1998; Siscoe & Odstrcil, 2008);

From inner heliosphere to 1 AU both ME types increase in size by ~47%; at ca 0.75AU strongest size increase; no ICME I type >1.5AU (statistics from > 2000 CMEs, see Larrodera & Temmer 2024);

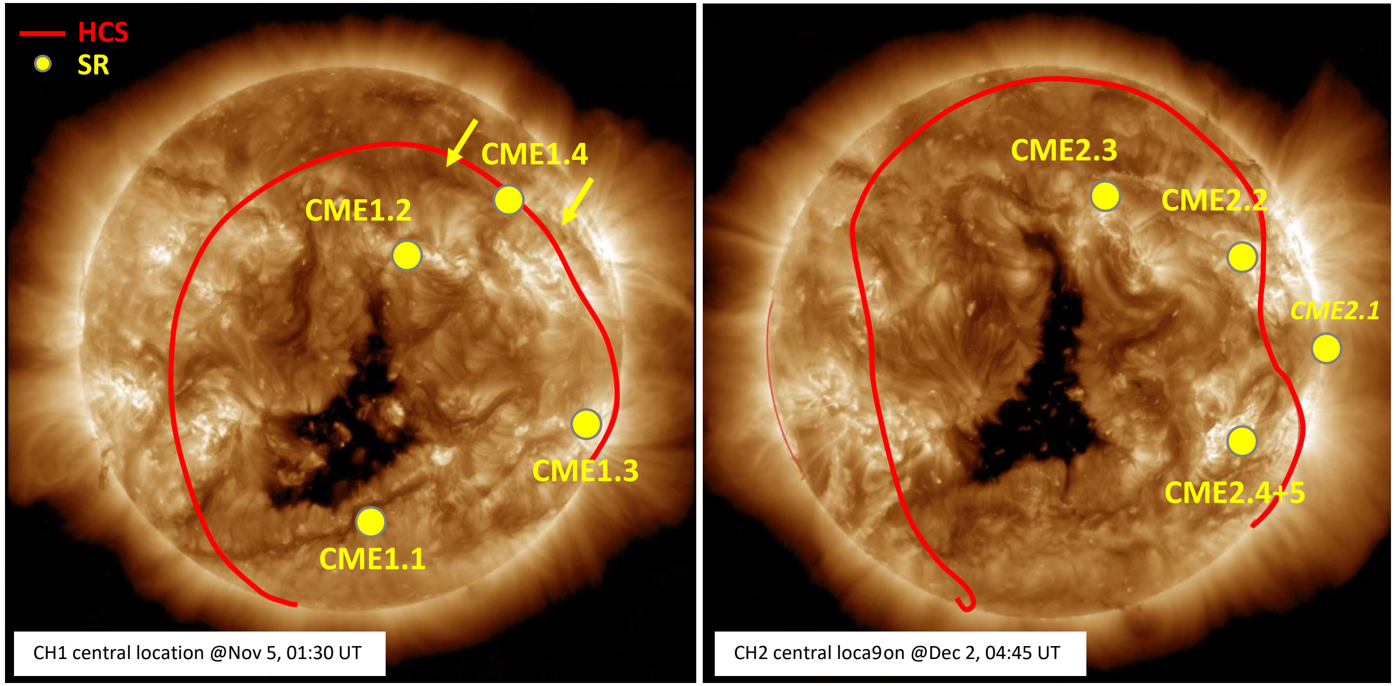
Other recent studies on CME sheath characteristics: e.g., Mitsakou & Moussas, 2014; Masias-Meza+ 2016; Janvier+ 2019; Lugaz+ 2020; Salman+ 2020, 2021; Temmer+ 2021; Temmer & Bothmer, 2022; […]
See review by Kilpua+ 2017

# Preconditioning and interacting structures




Nov/Dec 2023: Modulation effect related to HCS

Temmer+ 2024 (to be subm.)




- High solar activity: multiple CMEs.
- Decay phase: SIRs/CIRs dominate.
- HCS structure varies

Besides interactions, each CME generates perturbations in the smooth outflow of the slow solar wind (preconditioning duration 2-5 days: Temmer+2017).

Interactions (CME-CME, CME-SIR, *CME-HCS*) cause complex structures (e.g., Gopalswamy+ 2001; Burlaga+ 2002, 2003; Harrison+ 2012).

Interaction events cause most intense geomagnetic storms (e.g., Burlaga+ 1987; Farrugia+ 2006a,b; Xie+ 2006; Dumbović+ 2015)

CME-CME interaction review: Lugaz+2017

# Preconditioning and interacting structures (CME-CME, CME-SIR)

Temmer+ 2024 (iSWAT H1+H2 COSPAR Space Weather Roadmap paper)

**Past**

Check solar perspective 3-5 days back in time:

- Remote sensing EUV data, magnetograms, …
  - SR location of CME of interest and closeby ARs
  - Activity of SR or other ARs? Yes => derive CME properties for previous events and estimate interaction distance
  - check CH locations for possible deflection
- Eruptive event of interest:
  - SR longitude/latitude
  - check for coronal deflection due to CHs
  - Reconnected flux (FR)

**Present**

CME of interest at actual time (height ca 15-20Rs and beyond):

- Remote sensing white-light data and (3D) reconstruction methods/models, …
  - Speed
  - Propagation direction
  - Size and cross-section
  - Mass
  - Density

*If possible, use in-situ measurements at different locations in IP space and/or heliospheric image data and/or IPS radio data to update the parameters (DA).*

**Future**

SW perspective 2-4 days forward in time:

- Chose SW model (empirical, analytical, numerical)
  - Speed
  - Density
  - Presence of HSSs and possible interaction

*Validate your chosen SW model against others, to estimate uncertainty in the SW forecast. If possible, use in-situ measurements at different locations in IP space to update the parameters (DA).*

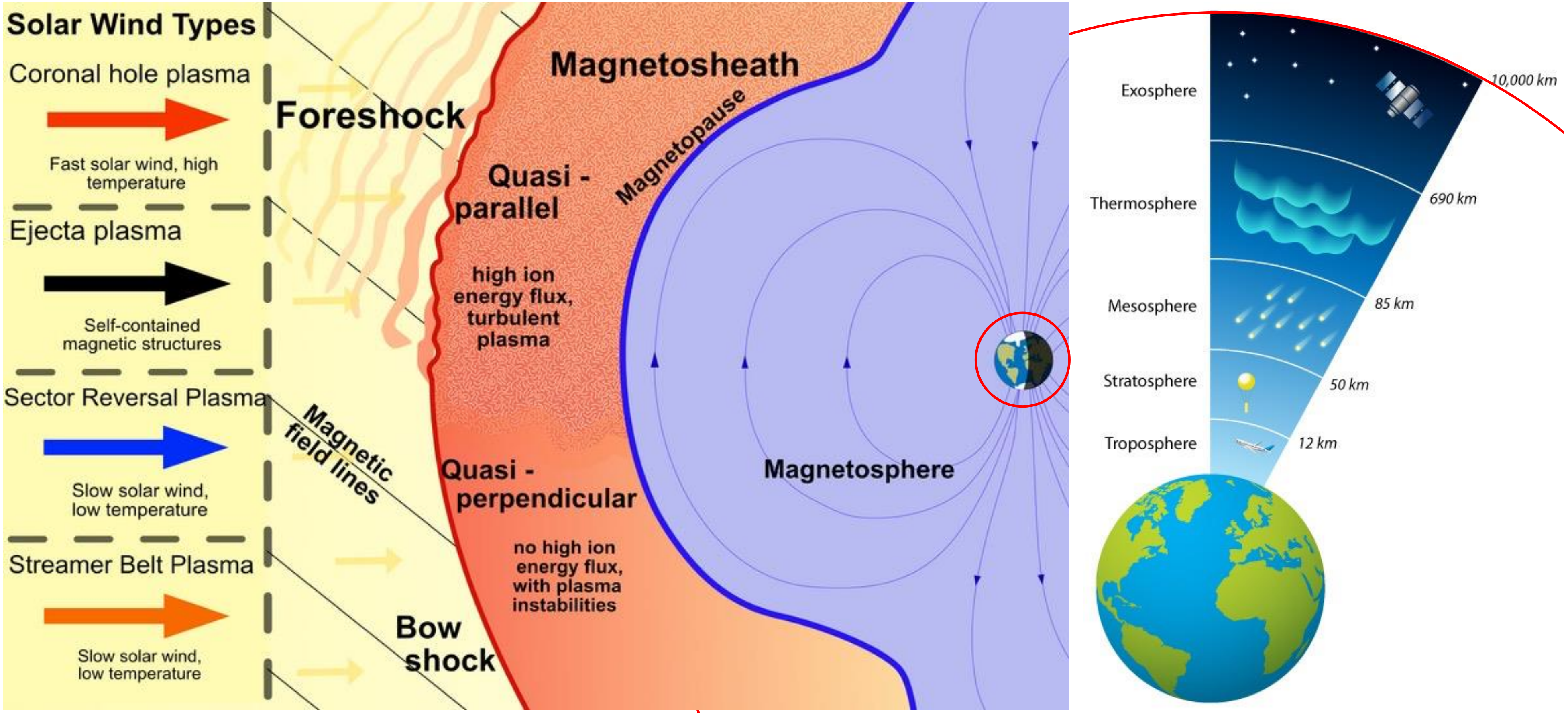
Input information for Space Weather models

Interacting magnetic structures cannot easily penetrate (frozen-in) => strong changes in CME physical properties:

- geometry and size (deformation, compression)
- propagation direction and orientation (rotation, deflection)
- kinematic properties
- magnetic structure and field (amplification, distortion, reconnection – erosion or flux injection, magnetic tension)
- plasma parameters, thermal properties

# Impact at Earth – interdisciplinary research

Cascade of reactions happen starting in the magnetosphere (opening of magnetic field, compression, substorms), with consequences for modern life – ionosphere (communication, navigation), thermosphere (satellite drag;e.g., Knipp+ 2004; Bruinsma+2006), GICs (power grids); see e.g., review by Tsurutani+ 2011; also, Dasso+ 2020;

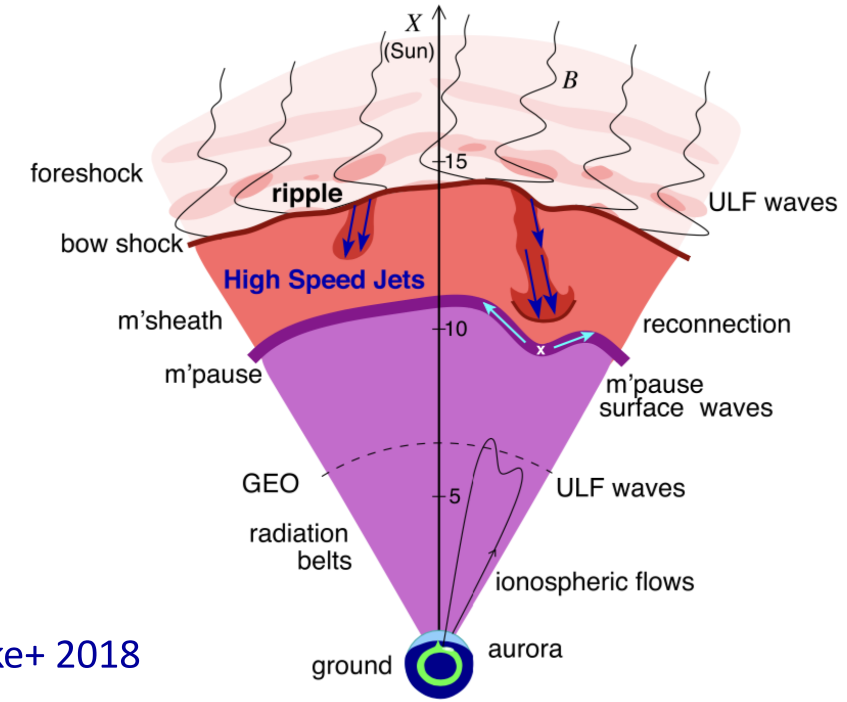



Adapted from Koller+ 2024

# Impact at Earth – interdisciplinary research

- **Magnetosheath jets** represent a significant coupling effect between SW and the Earth's magnetosphere (e.g. Hietala+2009; Plaschke+2018).
- Recent studies showed significant jet variation with large-scale SW structures SIRs and CMEs (Koller, Temmer+ 2022; Koller, Plaschke, Temmer+2023; Koller+2024).

**1st 'Heliophysics in Europe'** Workshop
(ESTEC, November 18 – November 22, 2024)




Plaschke+ 2018

- SODA tool: Empirical relation between IMF $B_z$, **thermospheric density** and satellite orbit decay (see papers by Krauss, Temmer+ 2015; 2018; Krauss+ 2020; Krauss+ 2024).
- Lead time: 20 hours (https://swe.ssa.esa.int/).