Solar-terrestrial research and modeling

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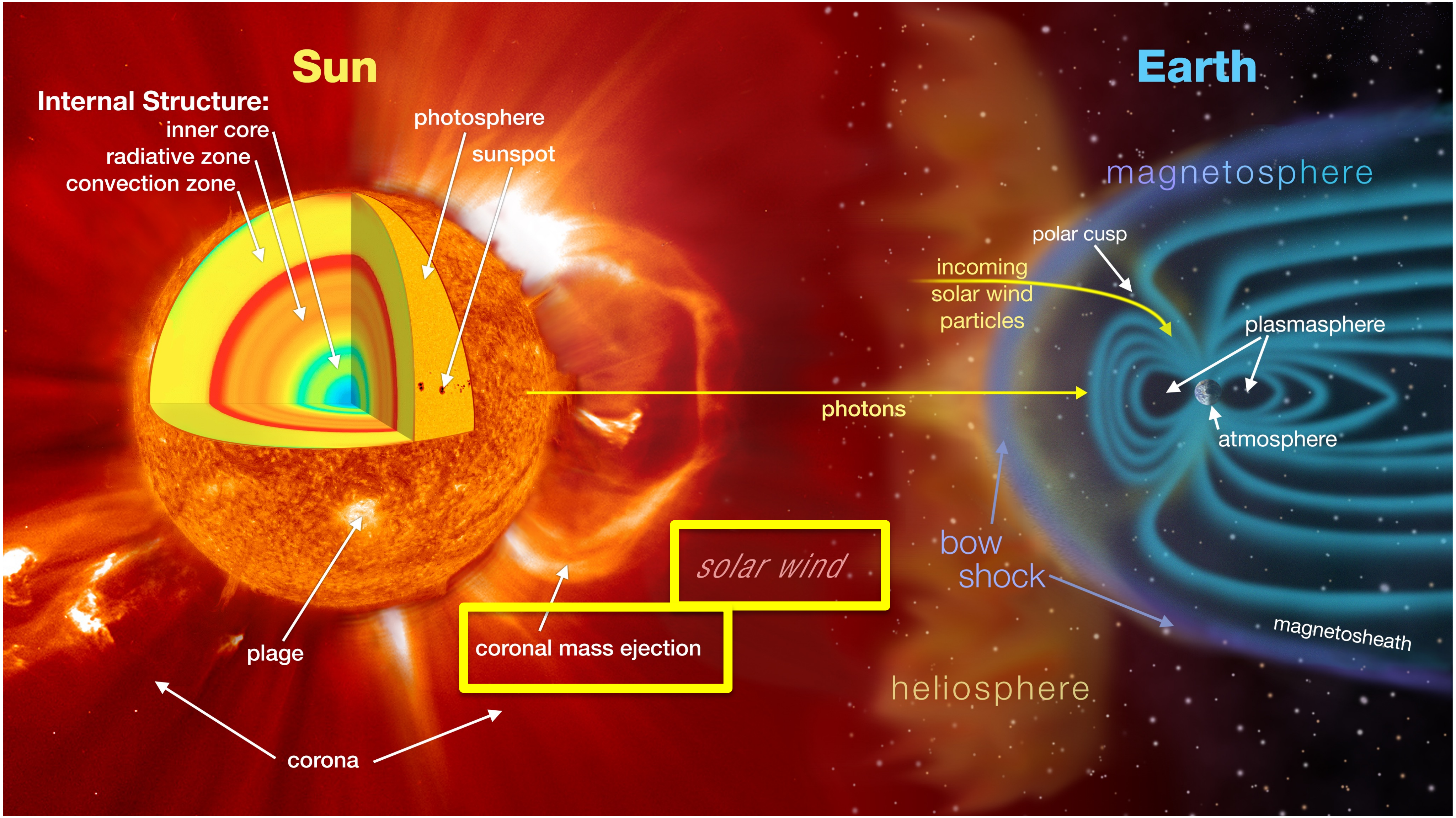
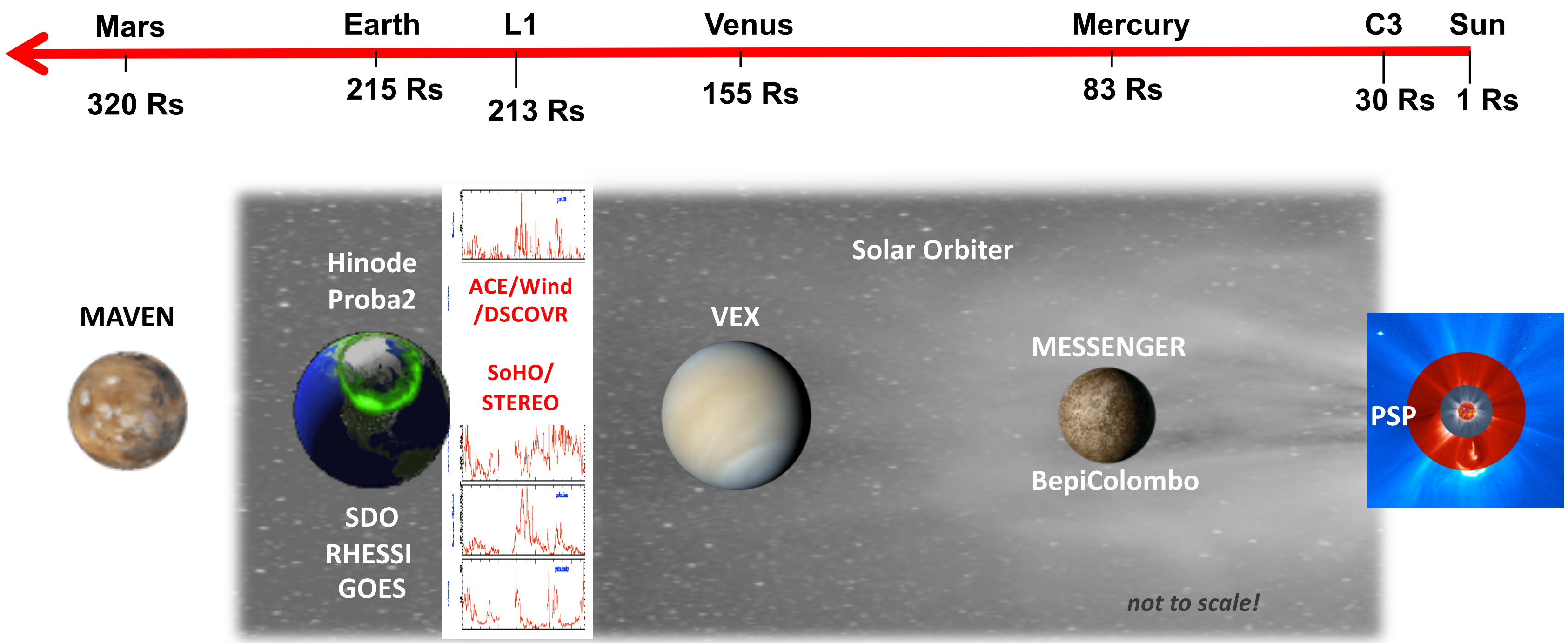
Solar-terrestrial physics

Solar physics -> Heliospheric physics -> Geospace (Magnetosphere, Ionosphere, Thermosphere, Surface)



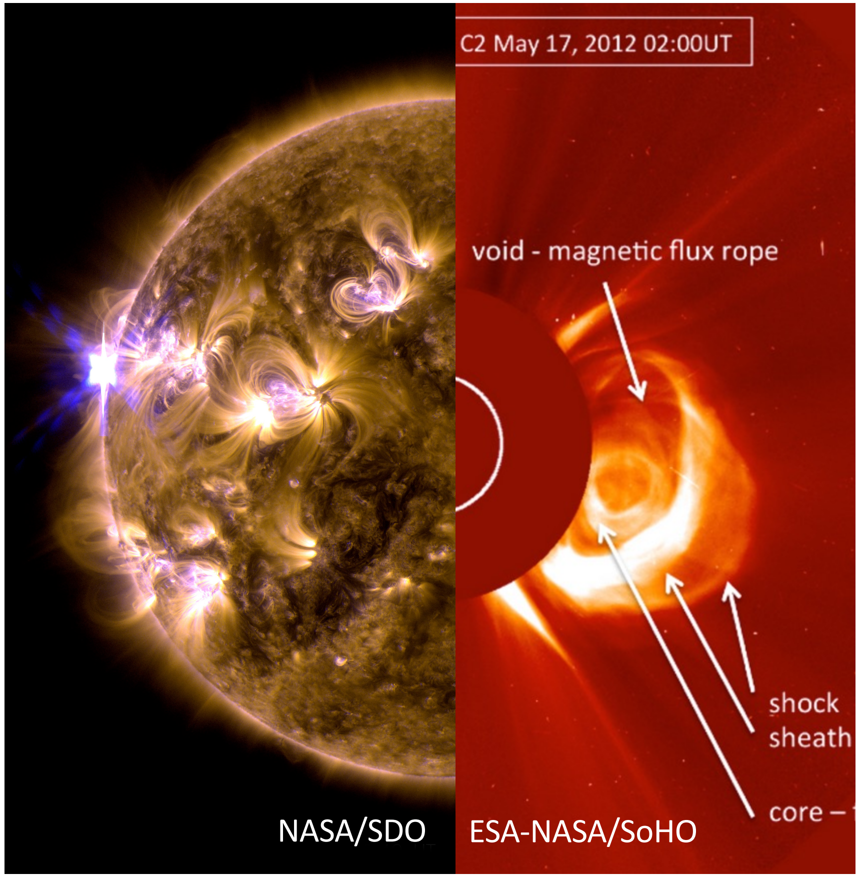
Remote-sensing and in-situ

- Remote data for observations of the solar surface and magnetic field
- Coronagraphs (SoHO since 1996, STEREO since 2006): FoV up to 30Rs, STEREO HI1+2 inner heliosphere
- ACE/Wind in-situ (since 1994), DSCOVR (since 2015) at L1
- In-situ instruments at planet's orbit (Venus Express (2005-2014), MESSENGER (2004-2015), MAVEN, BepiColombo)
- Variable distances and off-ecliptic: Parker Solar Probe (since 2018) and Solar Orbiter (since 2020)



Temmer, 2021 (Living Reviews)

Flares and coronal mass ejections



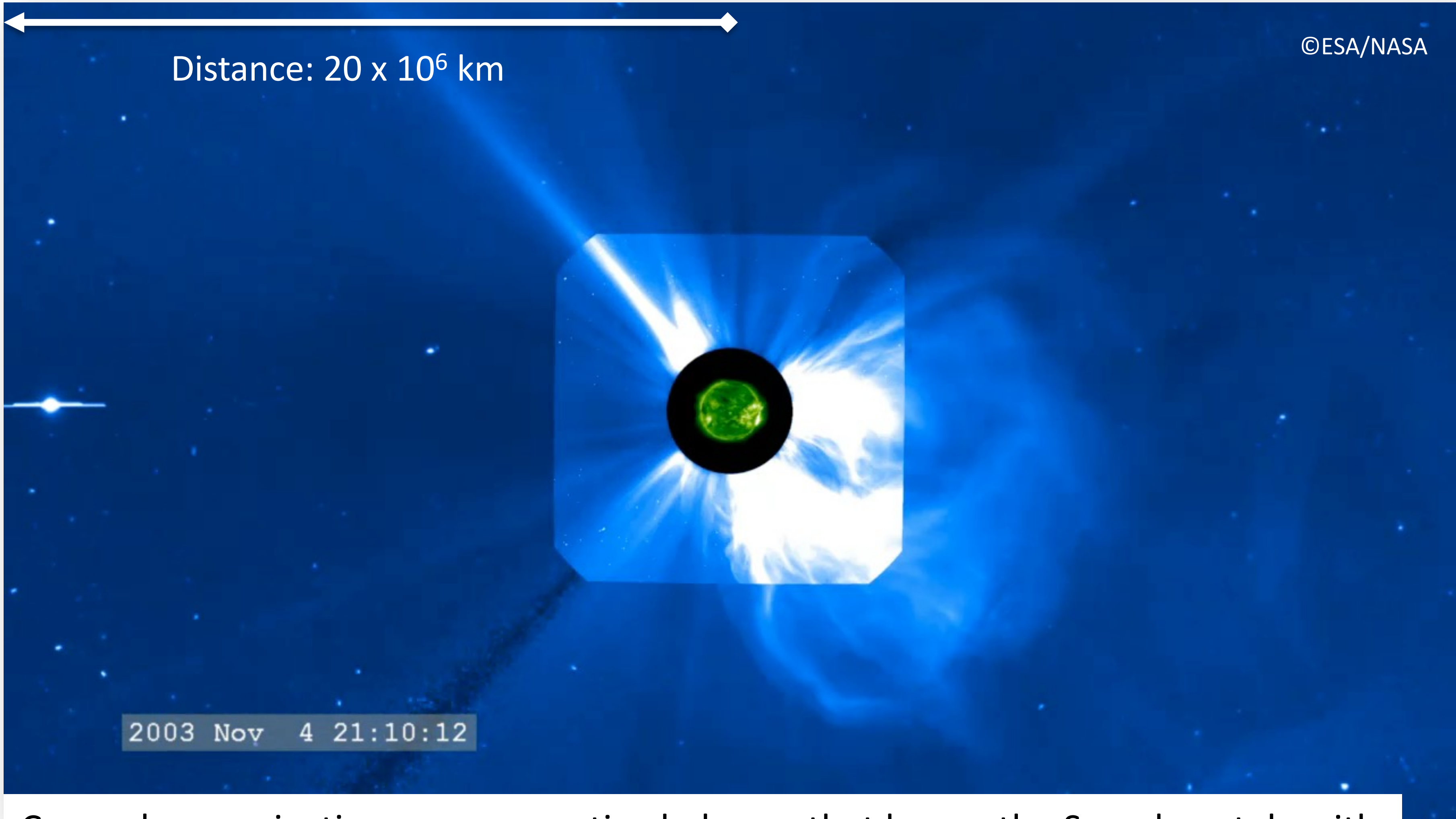
CMEs arise from usually complex, closed magnetic field structures. Some instability disrupts the equilibrium causing an eruption (e.g., Forbes 2000).

CMEs related to flares – magnetic reconnection strongly drives the CME.

CMEs erupting in high corona due to simple field reconfiguration ('stealth' CMEs, Robbrecht+ 2009; D'Huys+ 2014; Nitta & Mulligan, 2020).

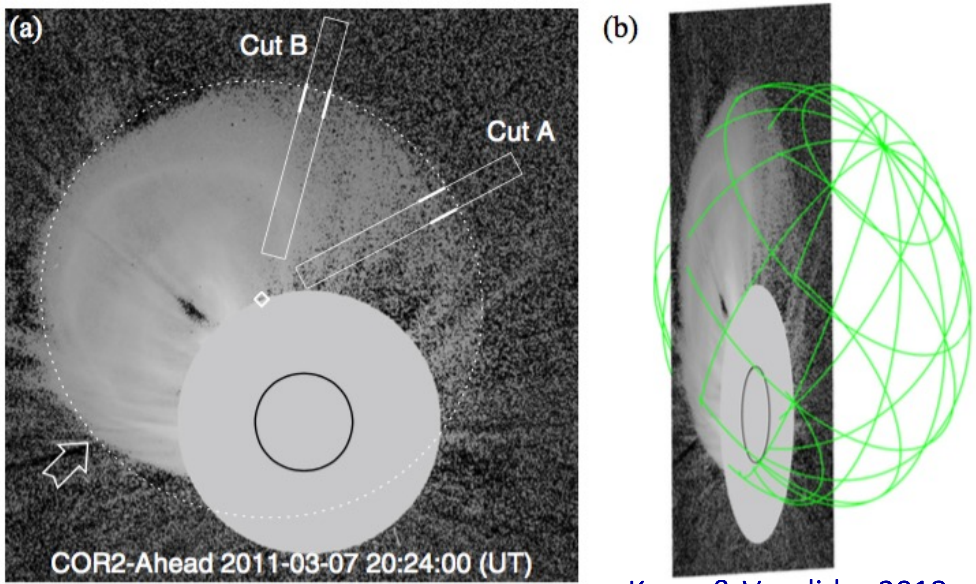
***Confined events** may show strong emission but no mass ejection (e.g., Sun+2015, Thalmann+ 2015).*

Eruptive events: coronal mass ejections

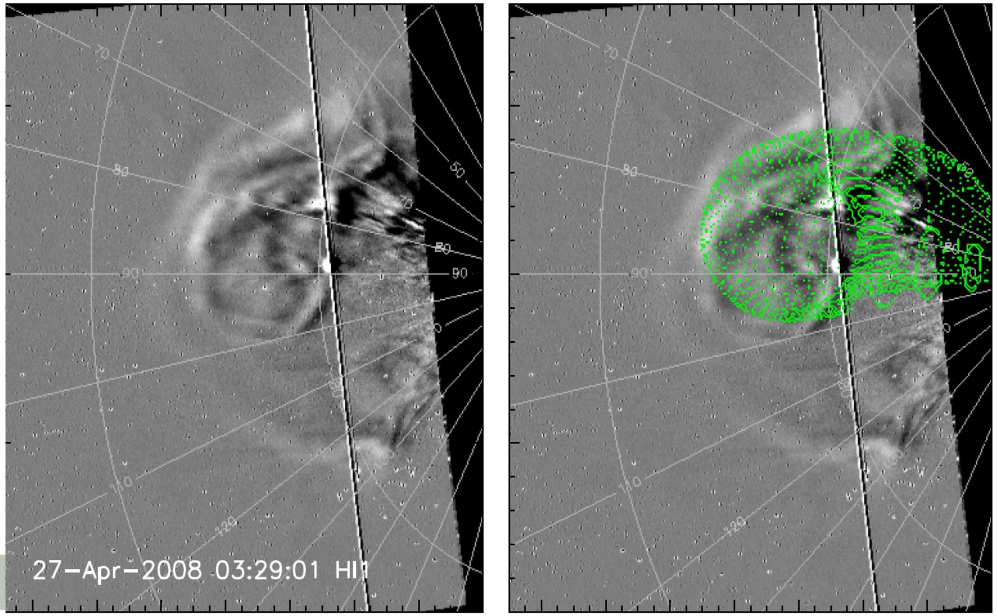


Coronal mass ejections are magnetized plasma that leaves the Sun abruptly with speeds from about 400 km/s up to 3000 km/s. Those disturbances propagate the Sun-Earth distance in ca. 1-4 days and may be geoeffective.

CMEs: what do we actually observe?



Kwon & Vourlidas 2018



Temmer+ in prep.

Shock (sheath)

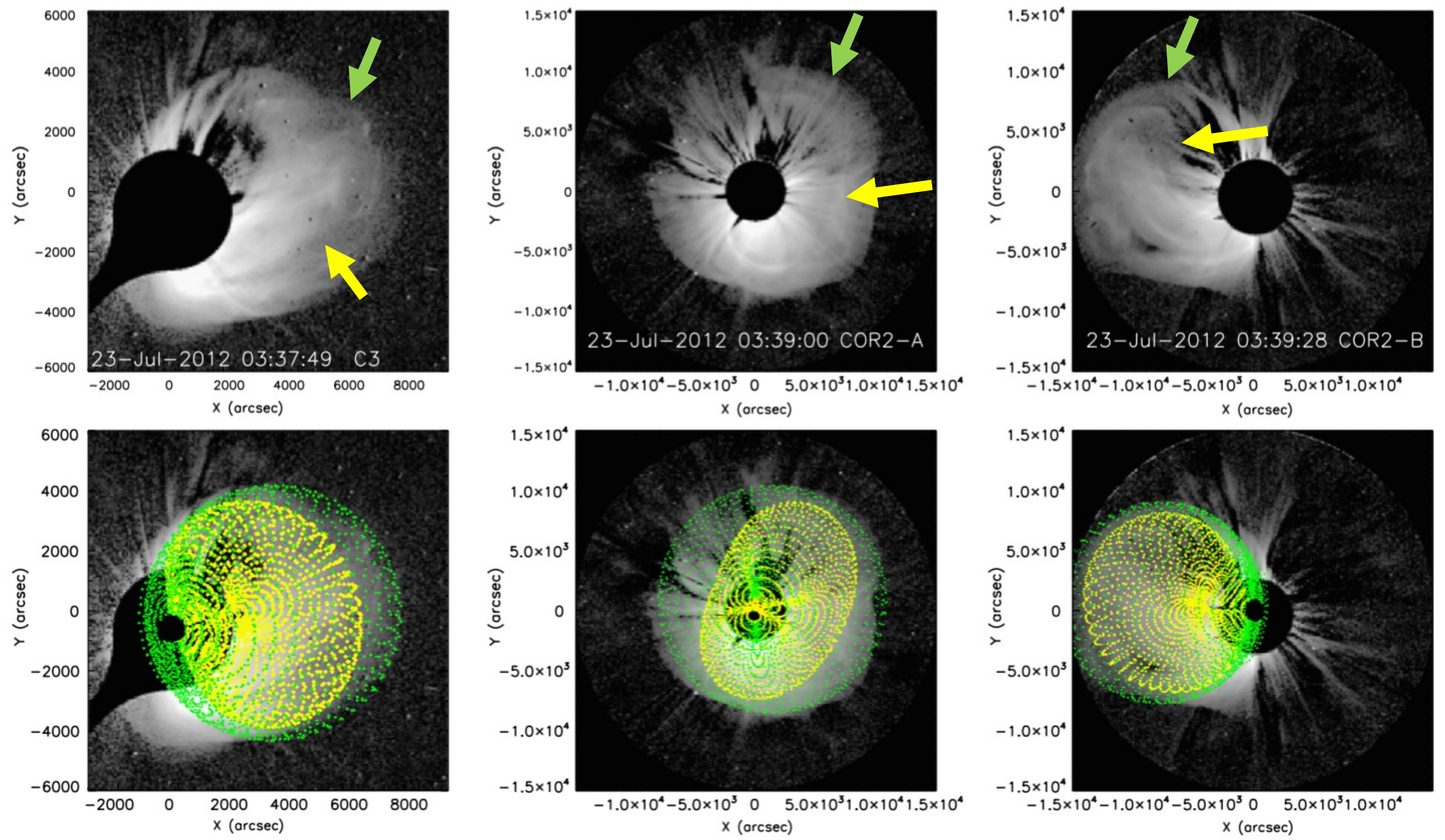
- CMEs are optically thin.
- Projection effects influence measurements severly.
- Compressed shock region, leading edge and magnetic driver (flux rope).
- Driver part: intense storms if strong negative B_z

(see e.g., Burkepile+2004; Cremades & Bothmer, 2004; Kwon+2015; Kilpua+2015).

Magnetic flux rope (driver)

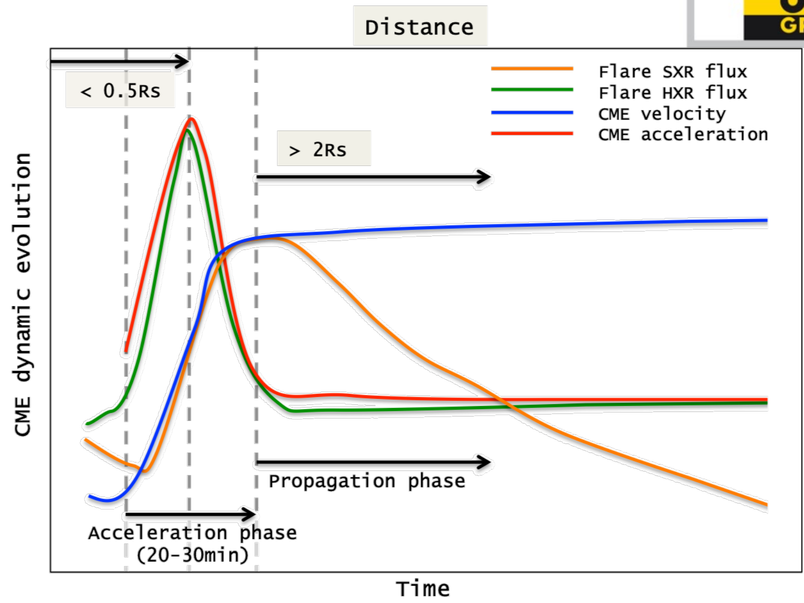
Modeling CMEs using multi-s/c data

Temmer and Nitta, 2015



Connecting flares+CMEs

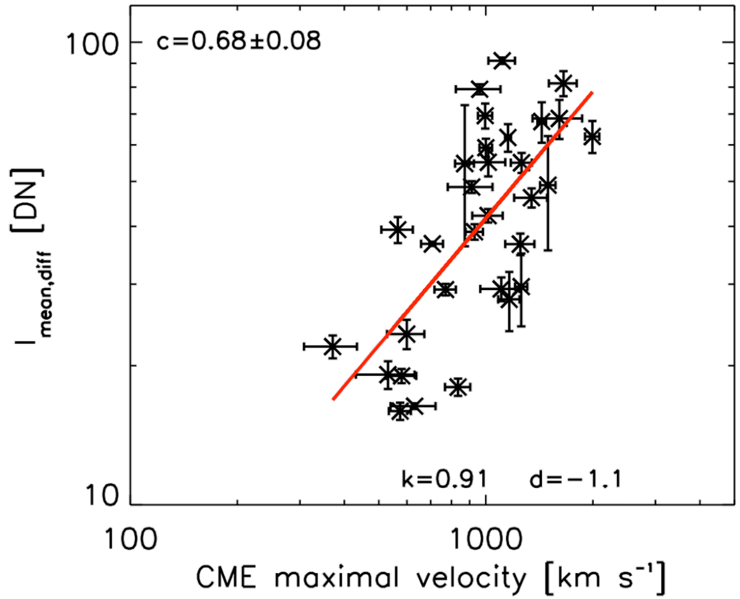
Flare-CME feedback relation:
HXR flare <=> CME acceleration
SXR flare <=> CME speed
(e.g., Zhang+ 2001, 2004;
Chen & Krall, 2003; Maričić+ 2007;
Temmer+ 2008, 2010).



Temmer 2016

Mass depletion is observed as dimming in EUV (e.g., Hudson & Cliver, 2001; Mandrini+2007).

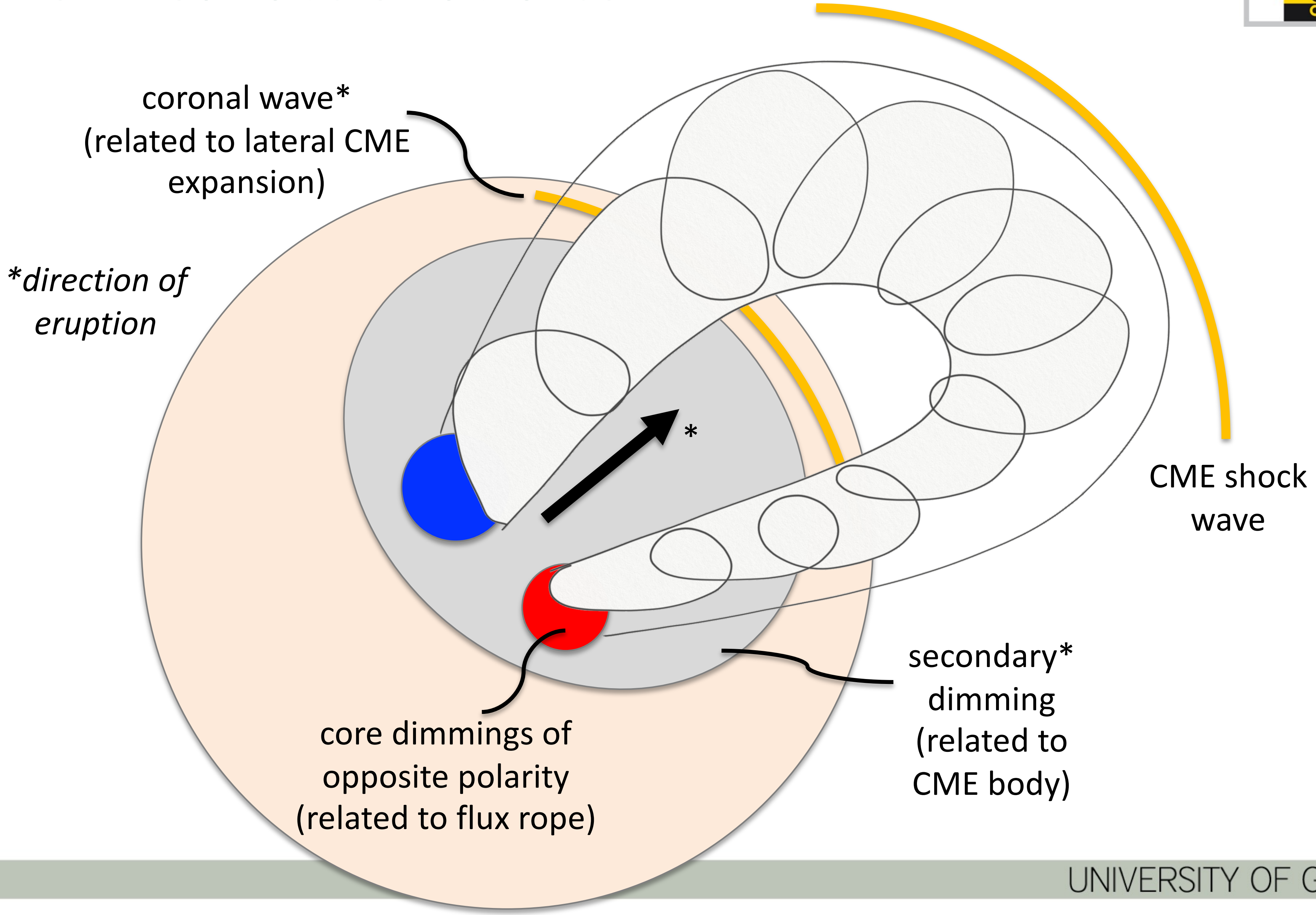
Core dimmings – CME footpoints (e.g., Temmer+2017).
Dimming intensity – CME speed relation (Dissauer+ 2018, 2019).



Dissauer+ 2019

CME-related surface parameters *can make a major contribution to detect CMEs and derive their characteristics before entering a coronagraph FoV.*

CME surface structures

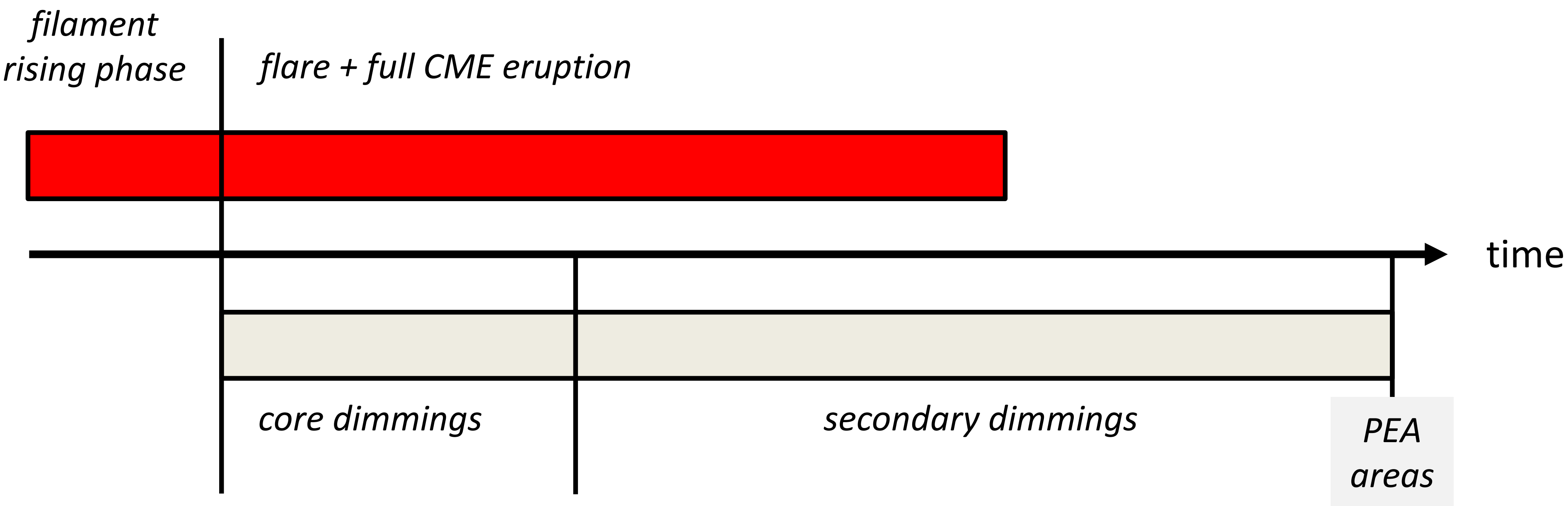


Total reconnected flux – input parameter for CME propagation models

Observational signatures of reconnection areas:

- ✓ filament eruption (timing)
- ✓ flare ribbon areas
- ✓ dimming regions (core and secondary)
- ✓ Post-eruptive arcades (PEA)

- Large uncertainties in deriving the reconnected flux. Results reveal ±50% of the measured value (Gopalswamy et al. 2017; Pal et al. 2017; Temmer et al. 2017; Dissauer et al. 2018a; Tschernitz et al. 2018).
- Empirical relations provide a fast and easy way to estimate the reconnected flux (see Scolini+2020).

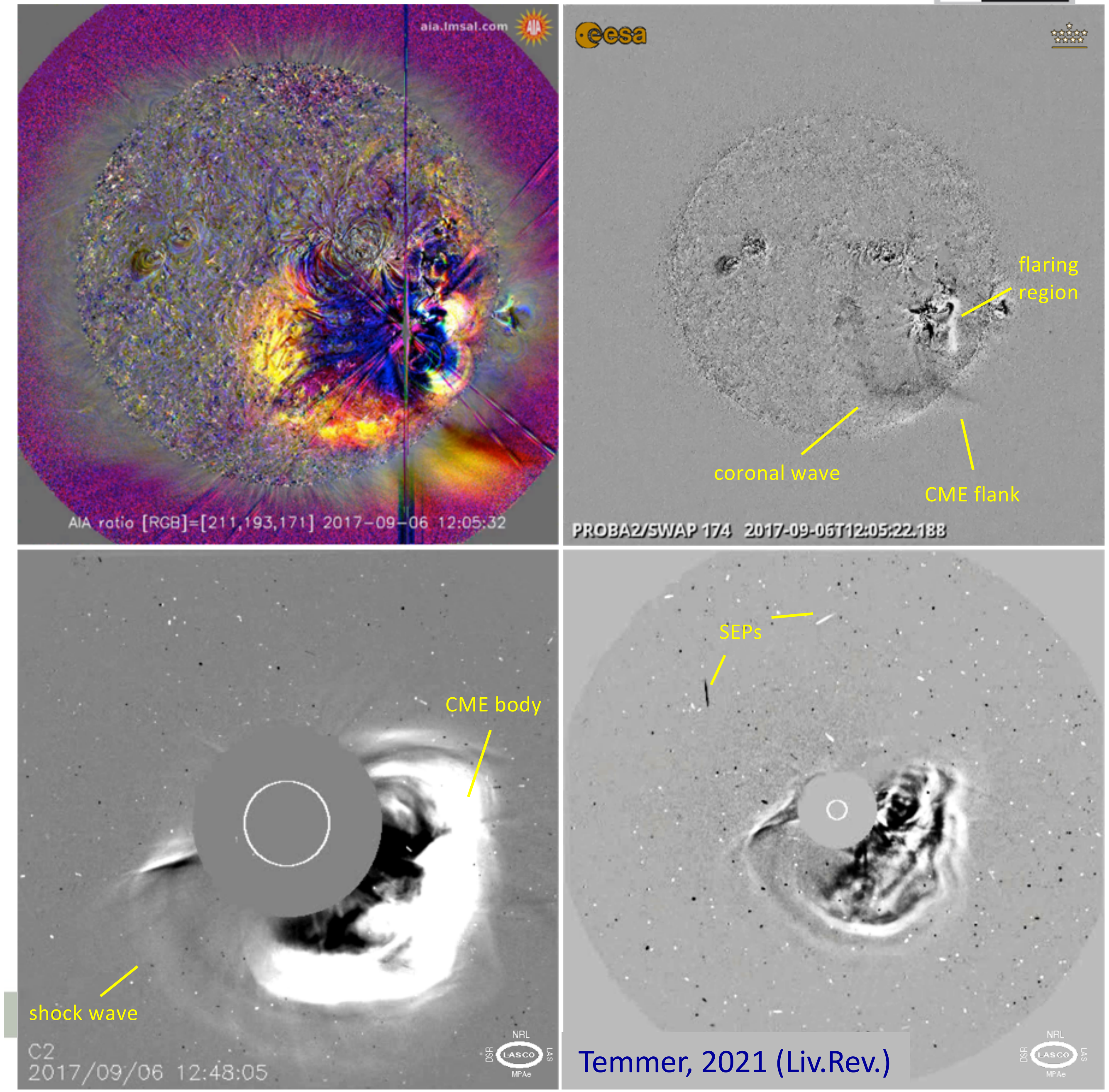


Flares, CMEs and SEPs – Sep 2017 events

EUV and LASCO/C2 and C3 coronagraph data showing the phenomena related to a strong eruptive flare-CME event

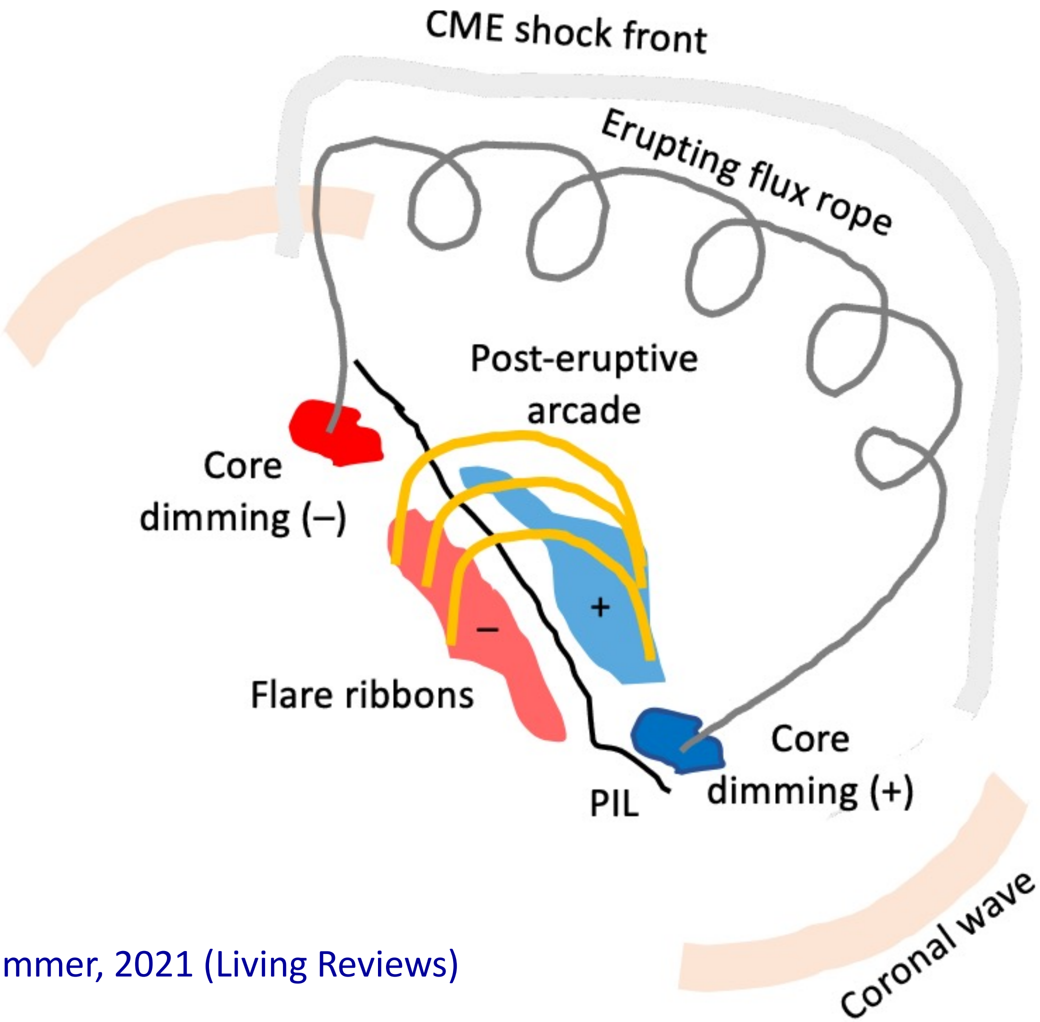
The generated SEPs are accelerated to relativistic speeds producing spikes in the image data (''snowstorm'' effect).

This event was the first flare event in a sequence of X-class flares on 6, 7, and 10 September 2017 causing strong disturbances at Earth and Mars. The most well documented Space Weather event from solar cycle 25.



Temmer, 2021 (Liv.Rev.)

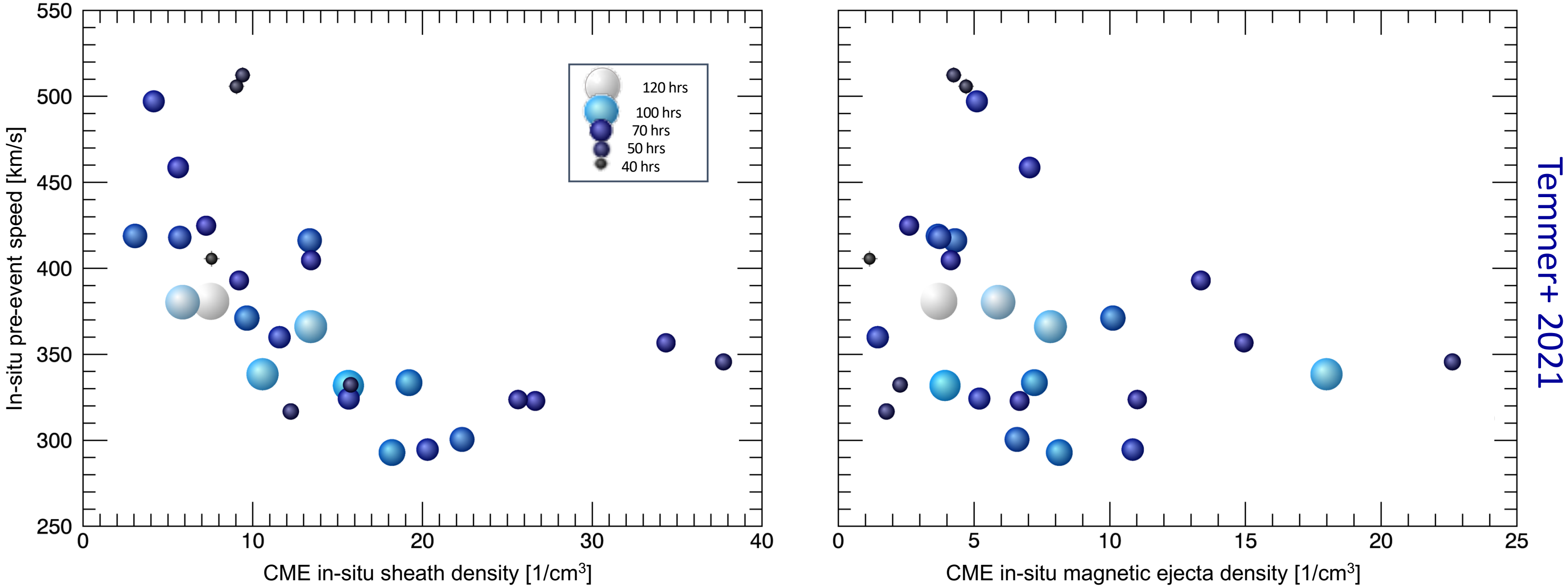
Solar surface phenomena related to an eruptive event



Temmer, 2021 (Living Reviews)

- **Flare** – bright H-alpha, EUV, SXR, HXR, white-light for strong events
- **Mass release** – EUV dimming regions, radio type III bursts
- **Flux rope formation** and lift off – filament eruption and mass motion
- **Propagating surface wave** due to laterally expanding shock

CME sheath region: mass

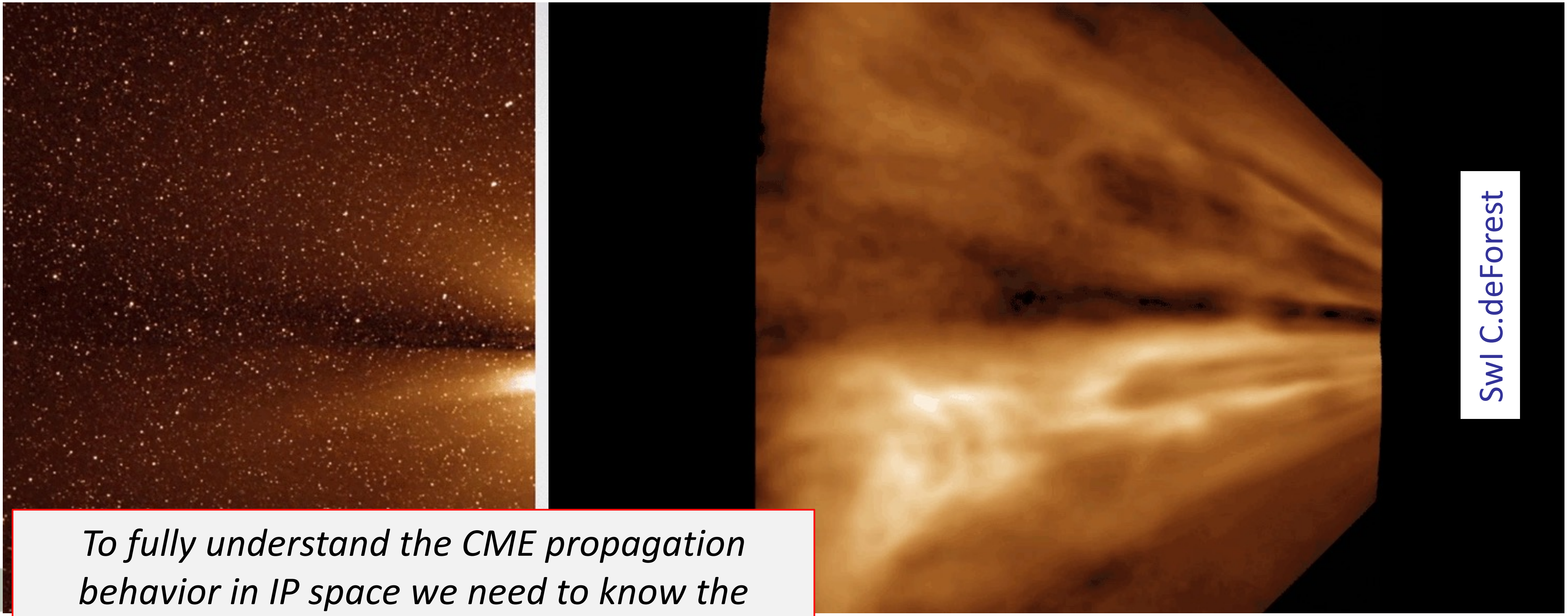


- CMEs increase in mass up to 20R_s coming from surface outflows (Bein+2013, Howard & Vourlidas2018)
- In IP space, sheath formation due to SW pile-up (e.g., deForest+2013; Kilpua+ 2017).
- Relation with the ambient solar wind speed (Temmer+2021); **sheath build up** might start around 13Rs (Helios1/2 data, Temmer&Bothmer2022 tbs, PSP will show more…stay tuned!).
- A change in mass/density relates to the effectiveness of the drag force. More massive CMEs show low deceleration –> analytical drag-based models (e.g., Vrsnak+2013)

$$F_D = C_D A \frac{\rho V^2}{2}$$

CME IP evolution

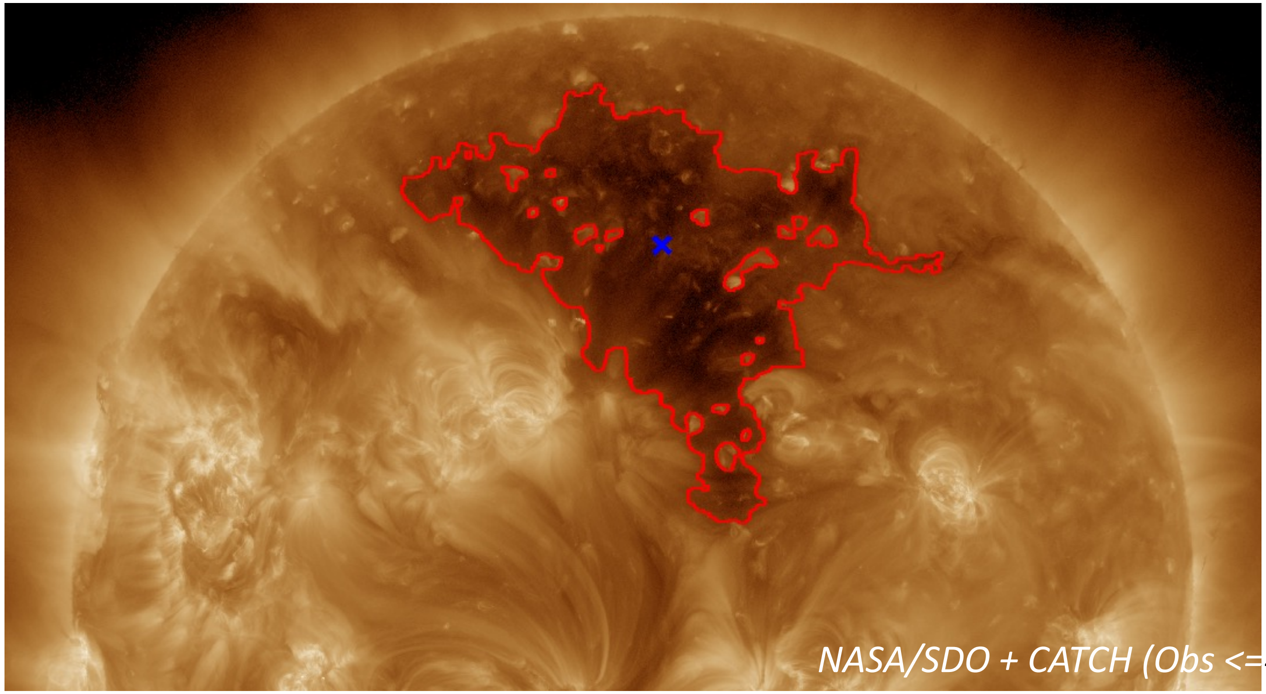
- CME rotation and adjustment to ambient magnetic field (pressure gradients) as well as flow speed (e.g., Yurchyshyn+ 2001; 2009; Vourlidas+ 2011; Isavnin+ 2014)
- Latitudinal/longitudinal deflection/channeling in corona (e.g. Bosman+ 2012; Panasenco+ 2013; Wang+ 2014; Möstl+ 2015; Harrison+ 2018)
- Location of coronal holes are important (Gopalswamy et al., 2009)

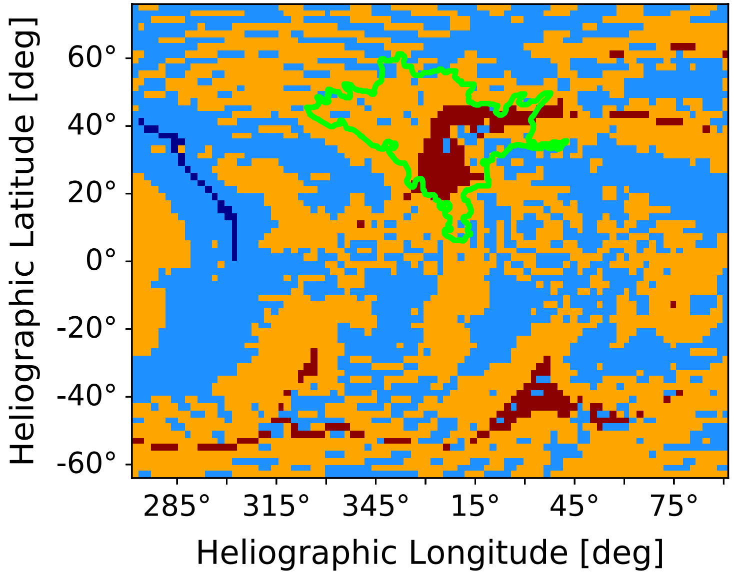


To fully understand the CME propagation behavior in IP space we need to know the ***spatial distribution of SW parameters.***

Sources of the solar wind

http://www.issibern.ch/teams/magfluxsol/





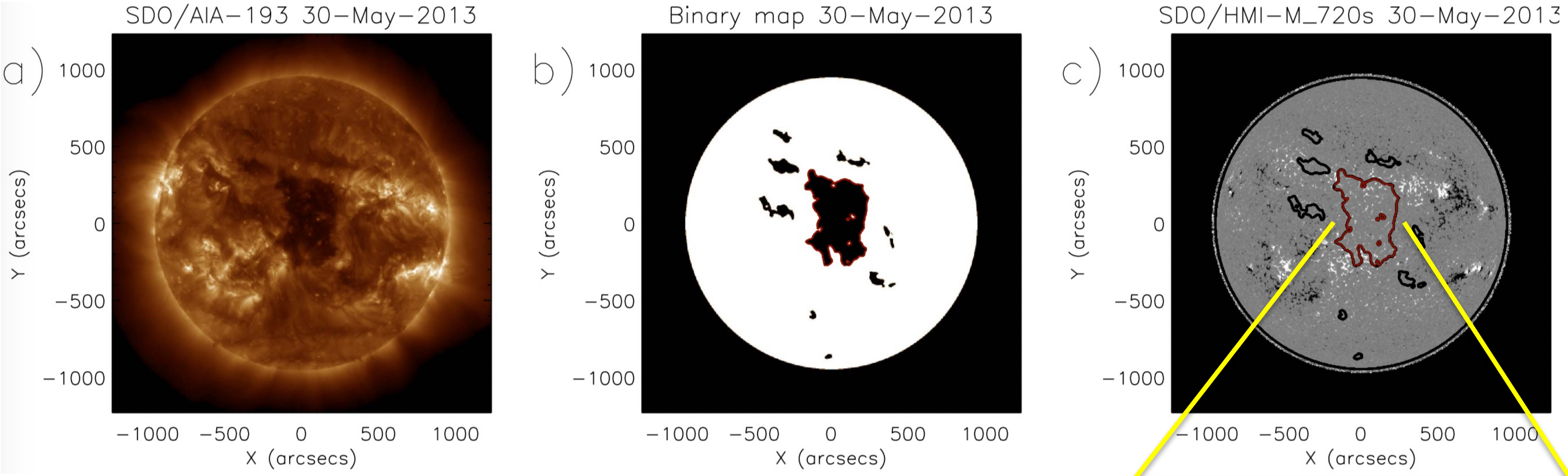
NASA/SDO + CATCH (Obs <==> Model) EUHFORIA

- Mixture of **open and closed magnetic field -** slow and fast wind. Their interaction structures IP space (SIR/CIR - HSSs).

➢ Studying coronal holes is important

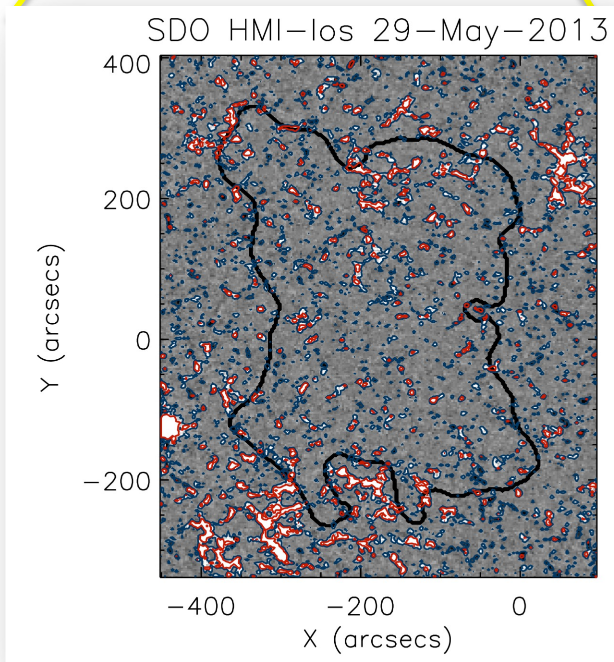
- Comparison to models may be poor: open flux - uncertainties ca. 25% (Linker+ 2021); switchbacks? (PSP: Tenerani+2020, Zank+2020)
- Model validation is key to improve understanding of large-scale structures in IP space and impact at planets (see iSWAT initative: https://iswat-cospar.org)

Coronal holes: fine structure



Open field predominantly concentrated in unipolar magnetic flux tubes inside CHs:

- 38% (81%) of the unbalanced magnetic flux of CHs arises from only 1% (10%) of the CH area with
- magnetic flux tubes of field strengths >50 G (10 G). See Hofmeister+ 2017, 2019; Heinemann+ 2018;



Evolution of CH boundaries and coronal bright points (Madjarska & Wiegelmann 2009).

CME-CME interaction events

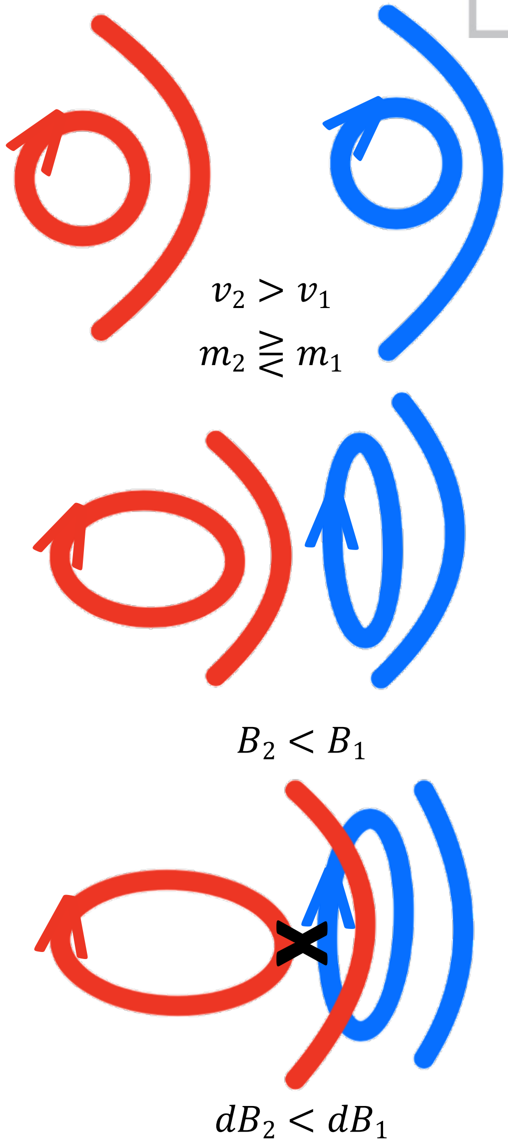
Merged CMEs form complex ejecta of single fronts (e.g., Gopalswamy+ 2001; Burlaga+ 2002, 2003; Harrison+ 2012).

Change in kinematics, deflection,…
(e.g., Farrugia & Berdichevsky, 2004; Temmer+ 2012, Lugaz+ 2015, Mishra+2018).

Increased *B* fluctuations and extended periods of neg. B_z (e.g. Wang+ 2003; Farrugia+ 2006; Scolini+ 2020).

⇒ **Most intense geomagnetic storms** (Burlaga+ 1987; Farrugia+ 2006a,b; Xie+ 2006; Dumbović+ 2015)

⇒ CME-CME interaction review by Lugaz, Temmer, Wang, Farrugia, in *Solar Physics* (2017)



Temmer et al., 2022 (in prep. for the COSPAR Space Weather Roadmap update H1+2 CLuster)

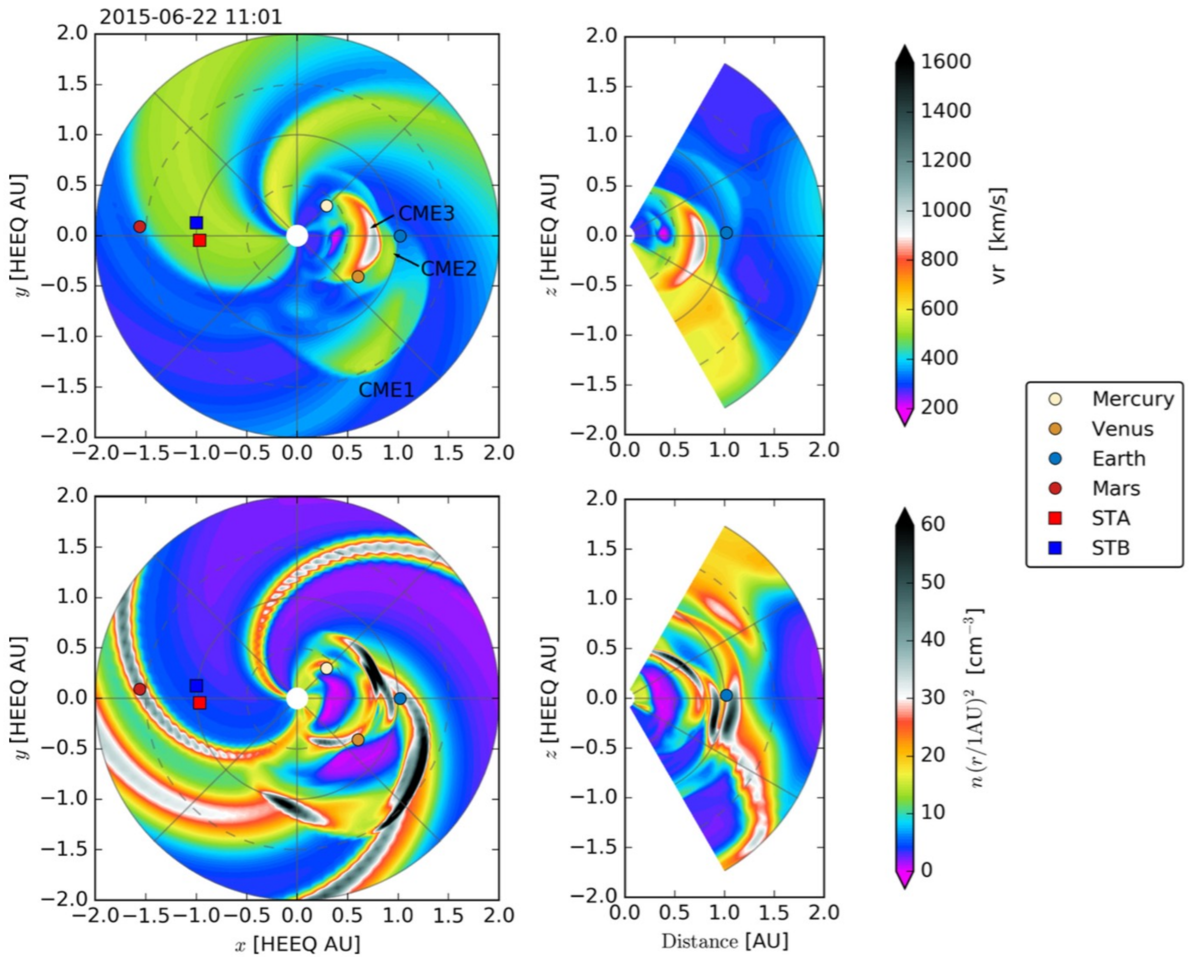
Preconditioning – rule or exception?

EUHFORIA (Pomoell & Poedts 2018); ENLIL (Odstrcil+ 2002)

CME occurrence rate: 2-3/w (solar min) to 4-5/d (solar max) (e.g., St. Cyr+ 2000, Gopalswamy+ 2006).

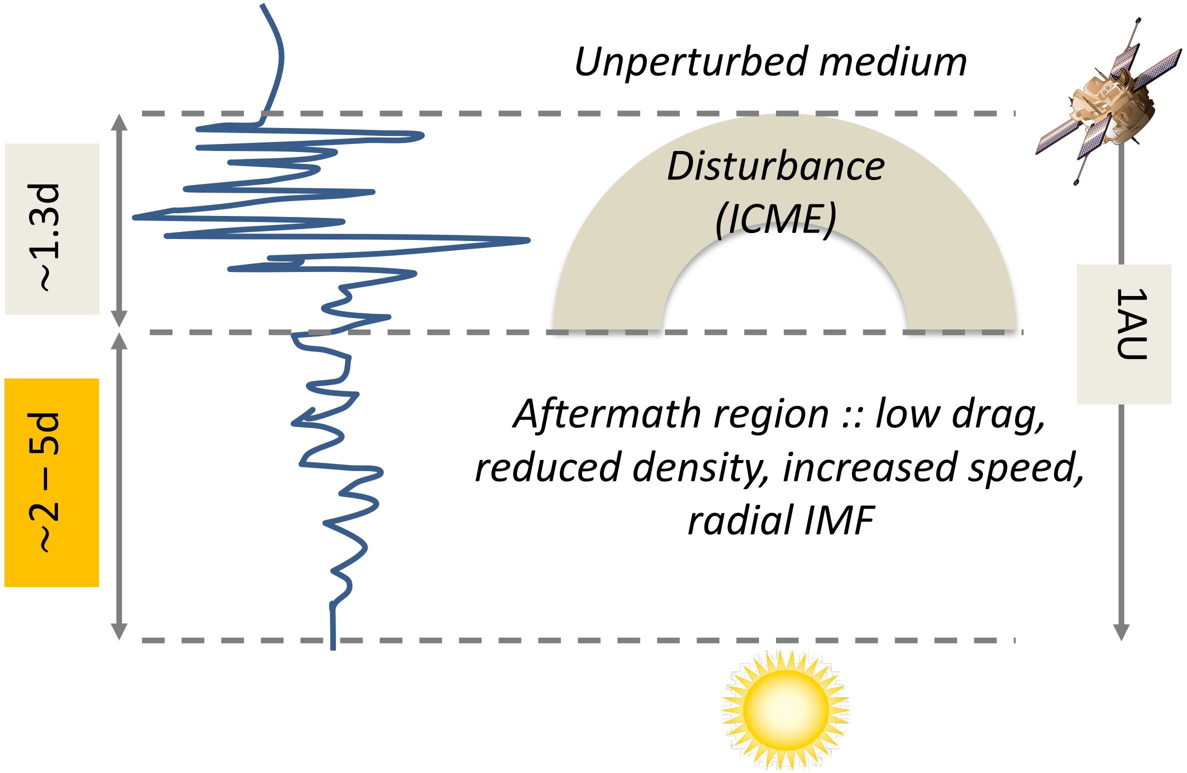
CME 1AU *tt*: 1 to 4 days (close to Sun: mean *v*: 500 km/s; max. *v* up to 3000 km/s).

2 – 20 CMEs within Sun-Earth sector, depending on solar cycle phase (Lugaz+ 2017).



During times of inreased solar activity, „CME-chains“ are assumed to happen frequently. Effects on model performance (Gressl+ 2014).

Preconditioning of IP space



- Drag might be lowered by factor of 10 due to preceding CME (Temmer & Nitta, 2015) and *B* is more radial (Liu+ 2014).
- September 4-6, 2017 events high impact due to CME-CME interaction close to Earth (Werner+ 2019; Scolini+ 2020)

IP space needs ca. **2-5 days** to „**recover**" from strong disturbances (Temmer+ 2017; Janvier+ 2019)

To improve models/predictions and to better understand, take into account ALL disturbances leaving Sun at least 2 days and up to 5 days before the actual event of interest.

Impact at Earth

Cascade of reactions in the magnetosphere (substorms), ionosphere (dB_z/dt), thermosphere (satellite drag), GICs, ...

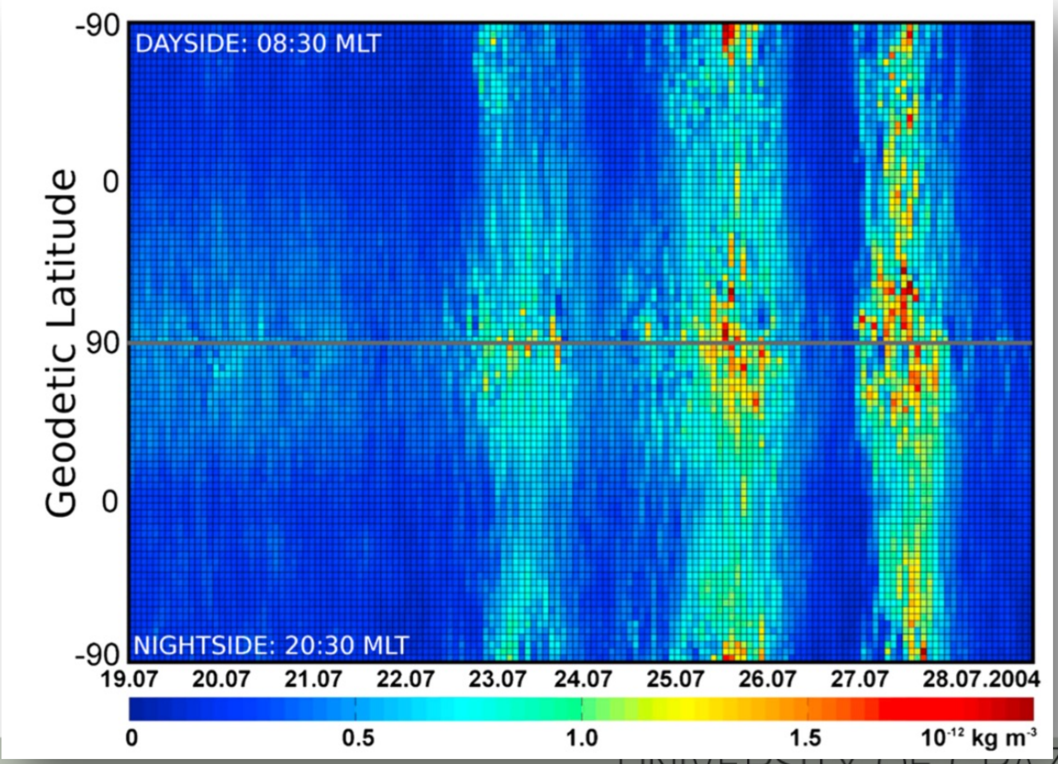
Significant differences in magnetospheric response between ICMEs and shock-sheath regions; most intense GICs during sheath (e.g., Huttunen+ 2005, 2008).

Differences between CME and CIR-driven storms (Borovsky+ 2006).

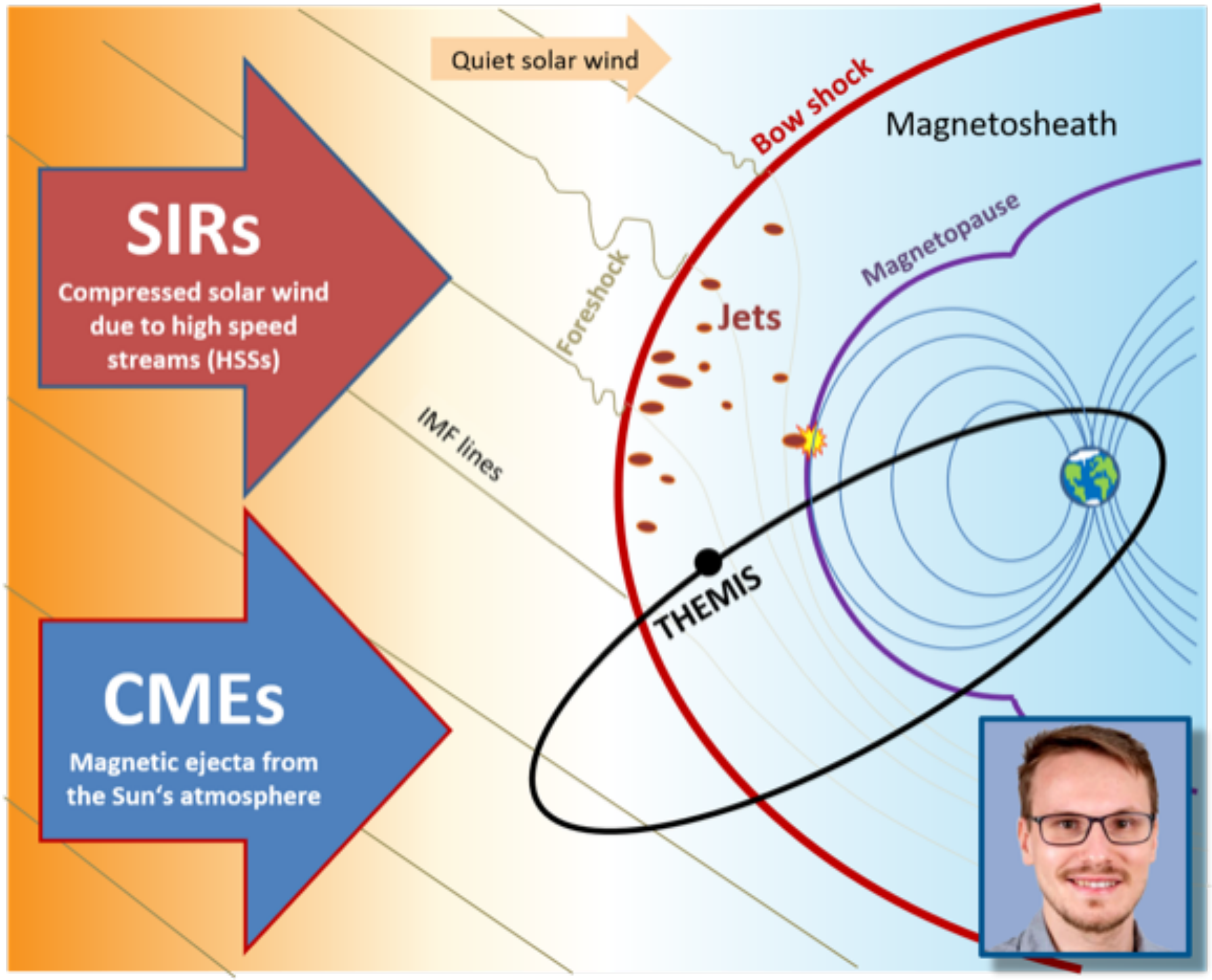
Thermosphere density response to solar ejecta (e.g., Knipp+ 2004; Bruinsma+2006; Krauss+ 2015, 2018, 2020).

Forecasting GICs based on proton flux and SW speed values, SSCs (see e.g., Bailey & Leonhardt 2016).

Krauss+ 2015

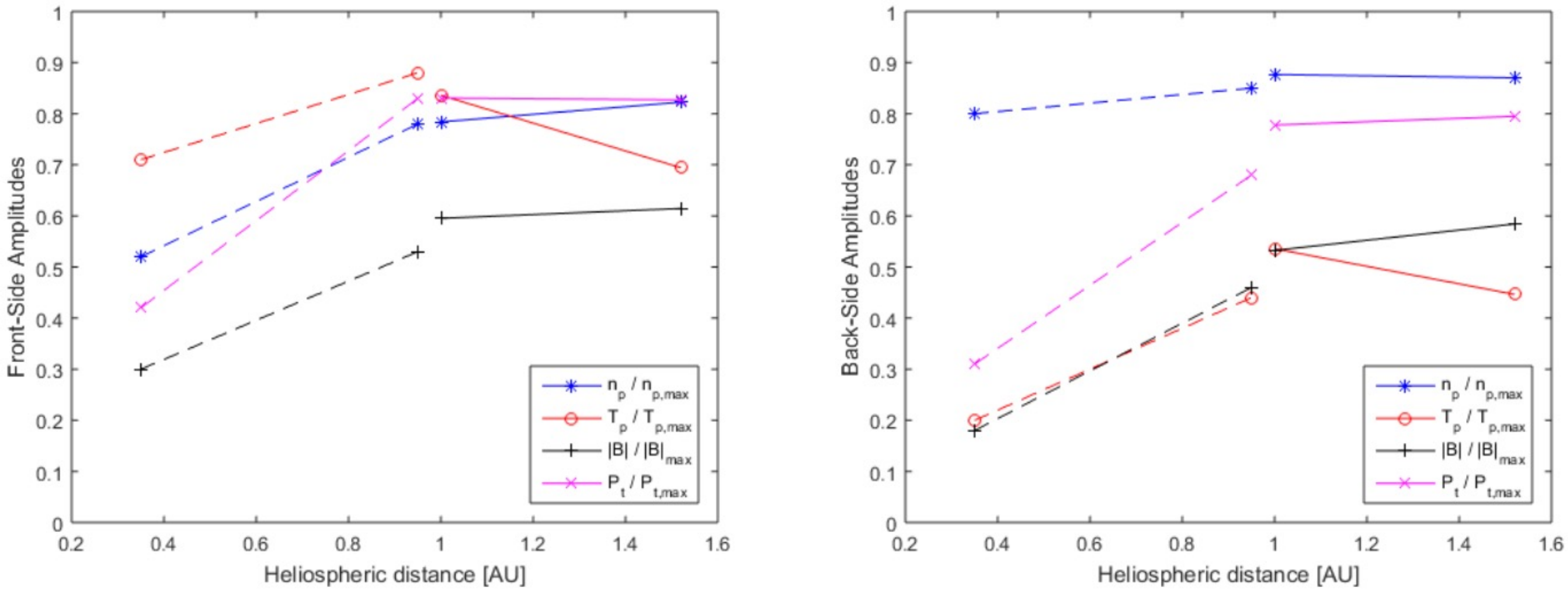


Impact at Earth



- Magnetosheath jets constitute a significant coupling effect between SW and the Earth's magnetosphere (e.g., Hietala+2009; Plaschke+2018).
- Recent studies showed a clear variation with imcoming large-scale SW structures SIRs and CMEs (Koller+ 2022).
- Effect on planetary atmosphere not fully understood

Impact of SIRs at Mars



Geyer+ 2021

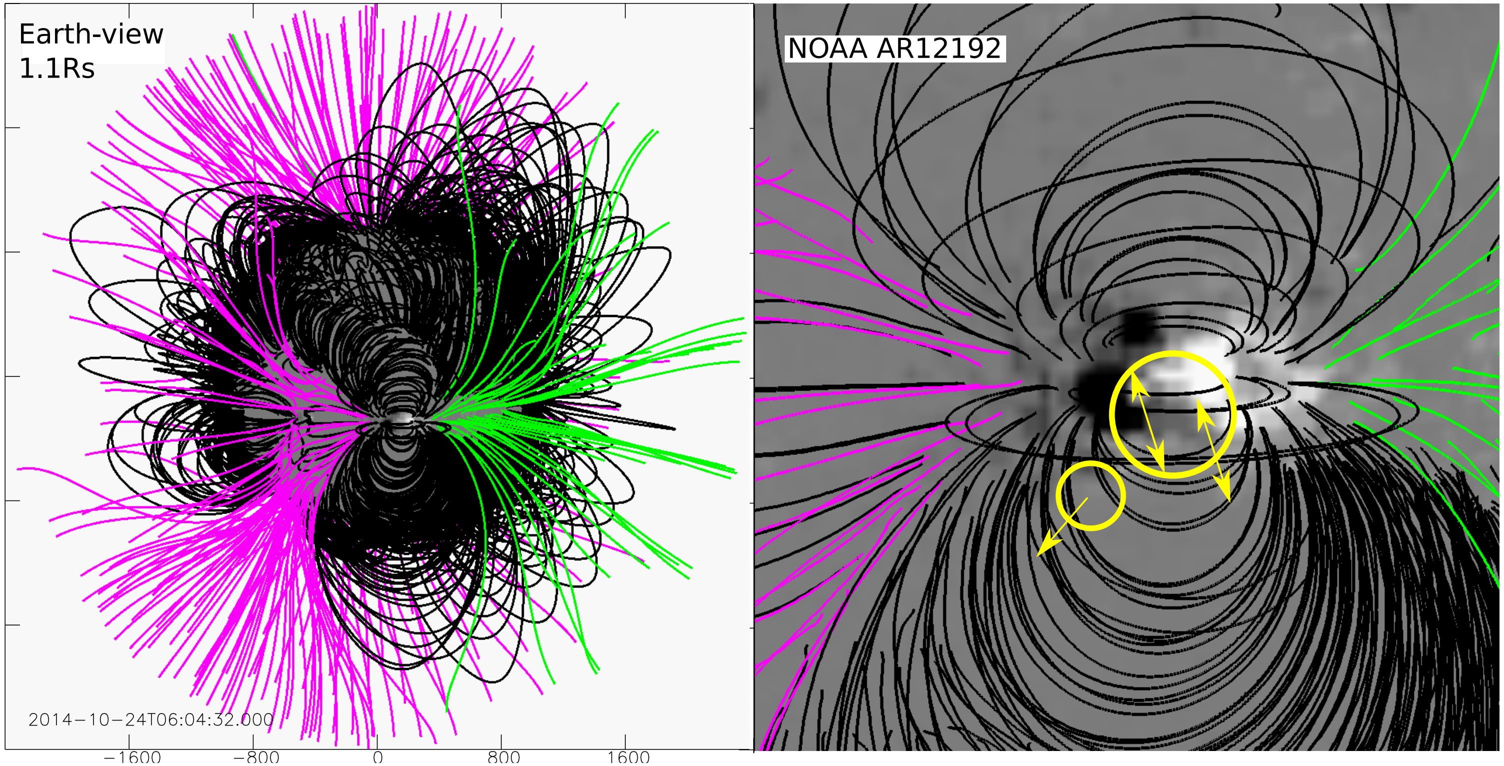
In comparison to Sun-Earth distance, SW streams shows less expansion from Earth to Mars. But: crest of the high speed stream profile broadens by about 17%, and the magnetic field and total pressure by about 45% around the stream interface (Geyer+2021).

In relation to the flow speed, density/magnetic field decreases over distance (Masters 2018). **Shock occurrence rate at Mars distance** increases by factor of 3 (Geyer+2021).

Shock type	Earth	Mars
FF only	6.7% (3)	20.0% (9)
FR only	6.7% (3)	6.7% (3)
FF and FR	0 % (0)	8.9% (4)
FF and/or FR	13.3% (6)	35.6% (16)

Solar-stellar connection

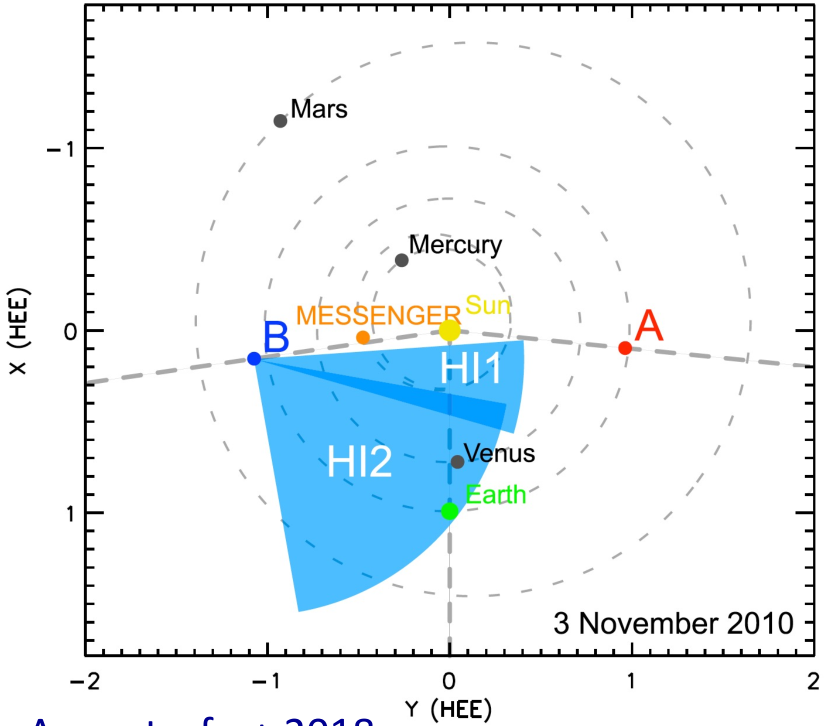
Thalmann+ 2015



- CMEs on stars are rare (Koller+2020, Veronig+2021)
- Are confined eruptions the norm at stars?
- Are strong overlying bipolar fields confining these eruptions?

Advantage of multiple views - L5 mission

- Constrain projection effects, increase surface coverage for magnetic field data
- L4/L5, off-ecliptic provide **continuous monitoring** of interplanetary space
- In-situ data separate **shock-sheath / magn. structure** (geo-impacts differ Kilpua+ 2017)
- However, hard to distinguish structures using image data
- Enable connecting large-scale structures in image data to small scale measured in-situ



Amerstorfer+ 2018

Event studies using STEREO-B close to L5 position (2009-2010) revealed advantages in the analysis and understanding.

Tracking of evolving structures over radial distance with VEX, MESSENGER, MAVEN, PSP, Solar Orbiter...

Summary and conclusions

- CME properties are set in the low corona -> source region characteristics, magnetic reconnection process linking flares, filaments, dimmings, CMEs
- Ambient magnetic field configuration controls CME onset (confined versus eruptive) and propagation behavior (magnetic pressure gradient)
- Propagation behavior of CMEs in IP space strongly affected by the characteristics of the ambient solar wind flow – structures (SIRs/CIRs)
- CME-CME interaction and precoditioning: extreme changes in CME dynamics; model efforts for better understanding the physics and forecasting purposes (ENLIL, EUHFORIA, SUSANOO, ElEvoHI, …)
- Challenge: input parameters for models (uncertainty assessment); open magnetic flux, magnetic properties of CMEs; *international teams*!
- Solar-stellar connection – solar and heliospheric physics adds important results

iSWAT – international Space Weather action teams where interdisciplinary research meets

https://www.iswat-cospar.org/

S: Space weather origins at the Sun	H: Heliosphere variability	G: Coupled geospace system	Impacts
			Climate
S1: Long-term solar variability	H1: Heliospheric magnetic field and solar wind	G1: Geomagnetic environment	Electric power systems/GICs
S2: Ambient solar magnetic field, heating and spectral irradiance	H2: CME structure, evolution and propagation through heliosphere	G2a: Atmosphere variability	Satellite/debris drag
S3: Solar eruptions	H3: Radiation environment in heliosphere	G2b: Ionosphere variability	Navigation/ Communications
	H4: Space weather at other planets/planetary bodies	G3: Near-Earth radiation and plasma environment	(Aero)space assets functions
			Human Exploration

Overarching Activities:
Assessment
Innovative Solutions
Information Architecture & Data Utilization
Education & Outreach