Exploring Coronal Mass Ejections: an Overview

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Content

CMEs: the general picture:

- sources,
- propagation into the corona,
- propagation into the interplanetary space,
- geoeffectiveness.

CMEs: visualization (image processing) and detection

CMEs: properties, observations, modeling

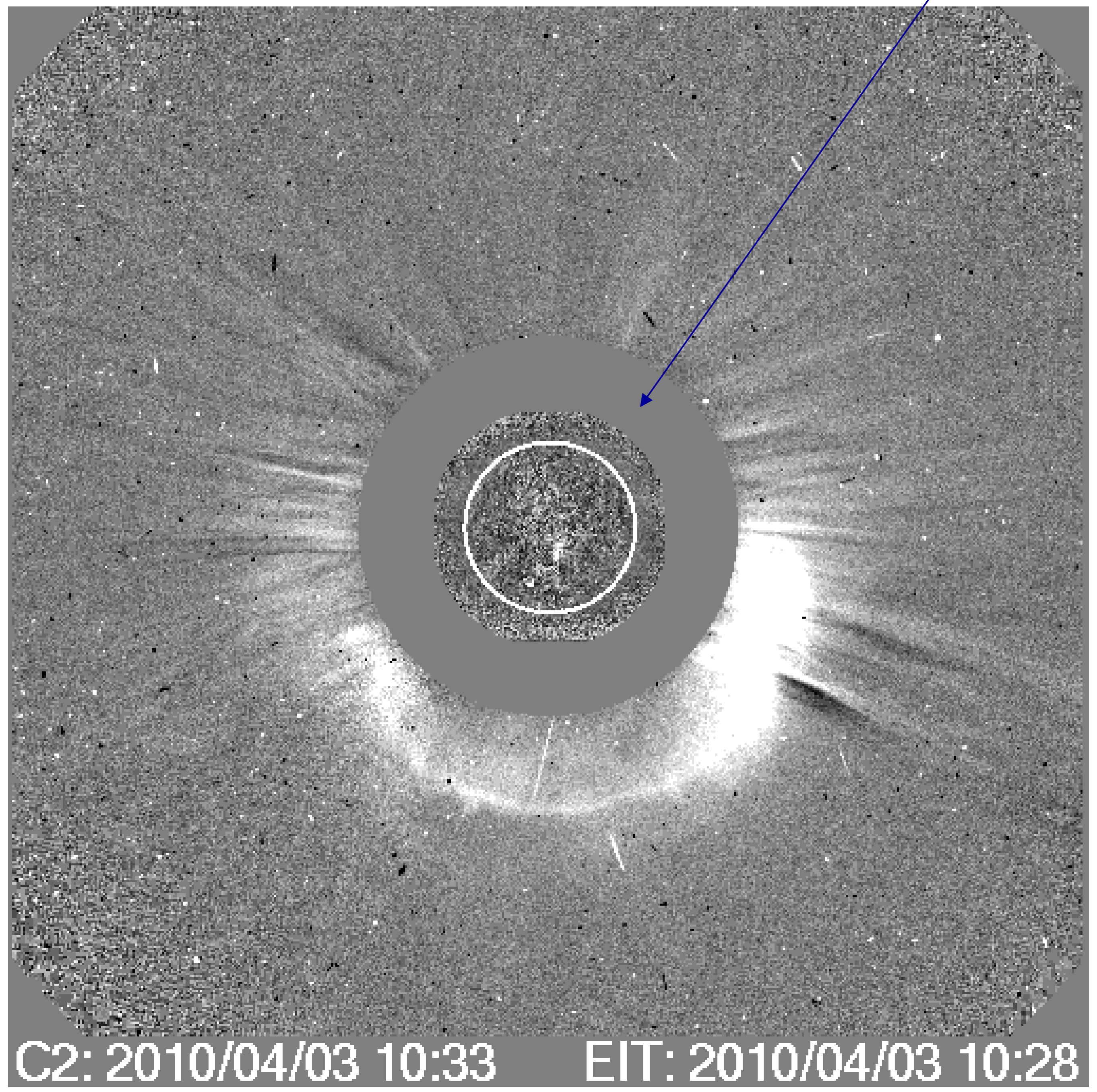
Eruptions observed by SolO/EUI/FSI

A detailed case study

What next?

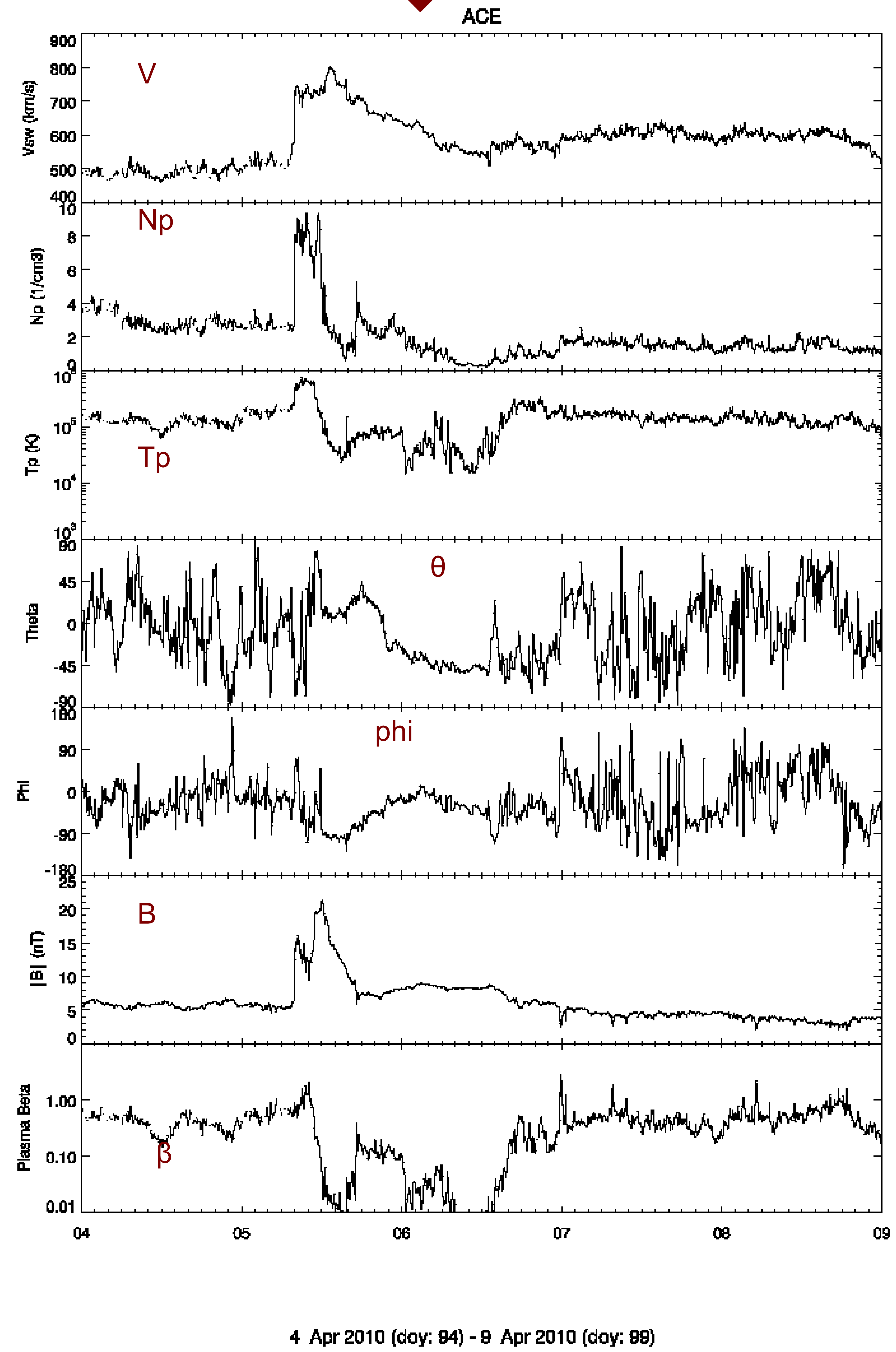
CMEs — **Scarce observations** — **ICMEs**

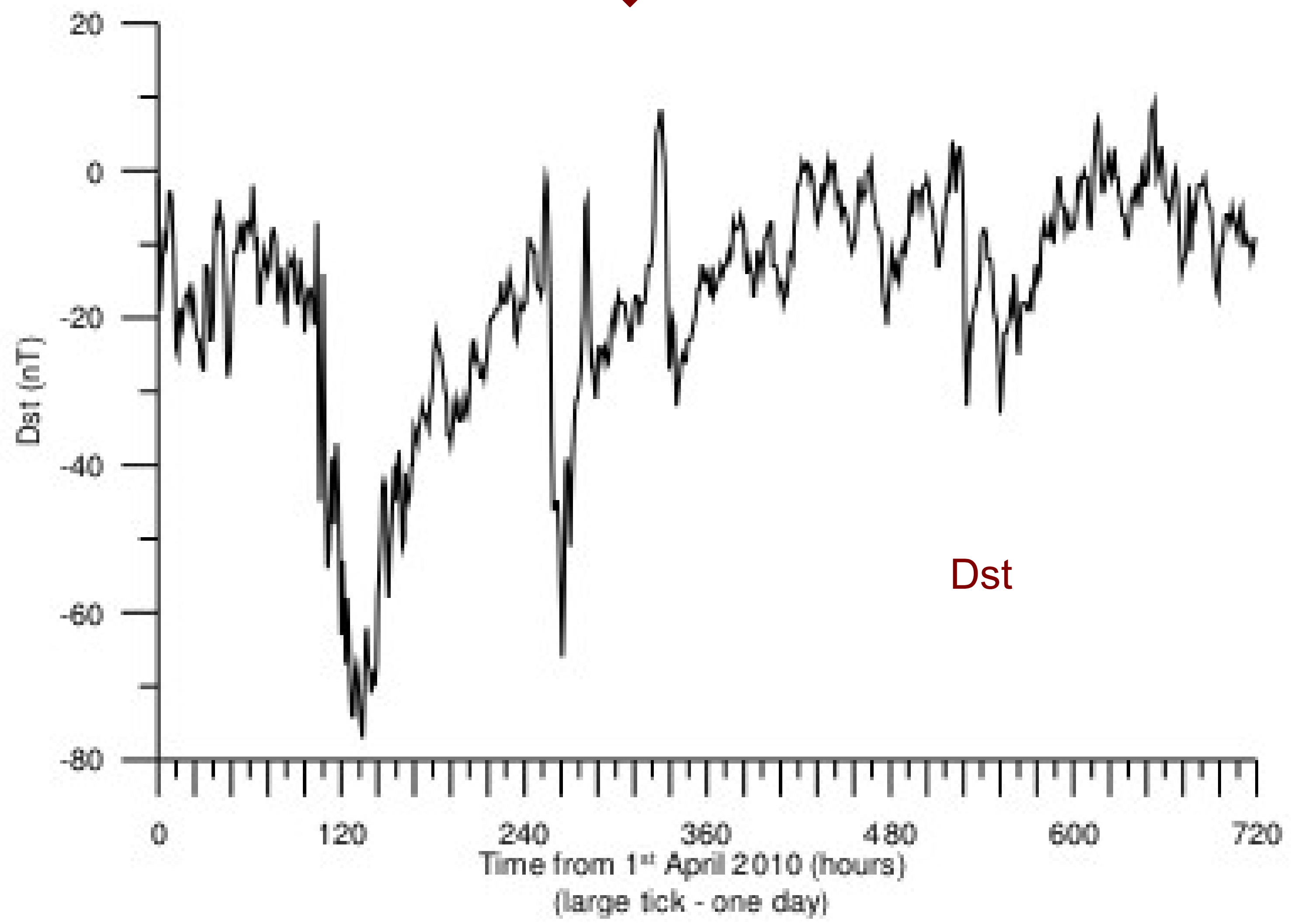
Geomagnetic Storms



From the Sun to the Earth the CMEs may:
- Deflect
- Rotate
- Get deformed

Manchester et al. 2014, 2017





Zuccarello et al. 2013

Transfer of energy from ICME to magnetosphere:

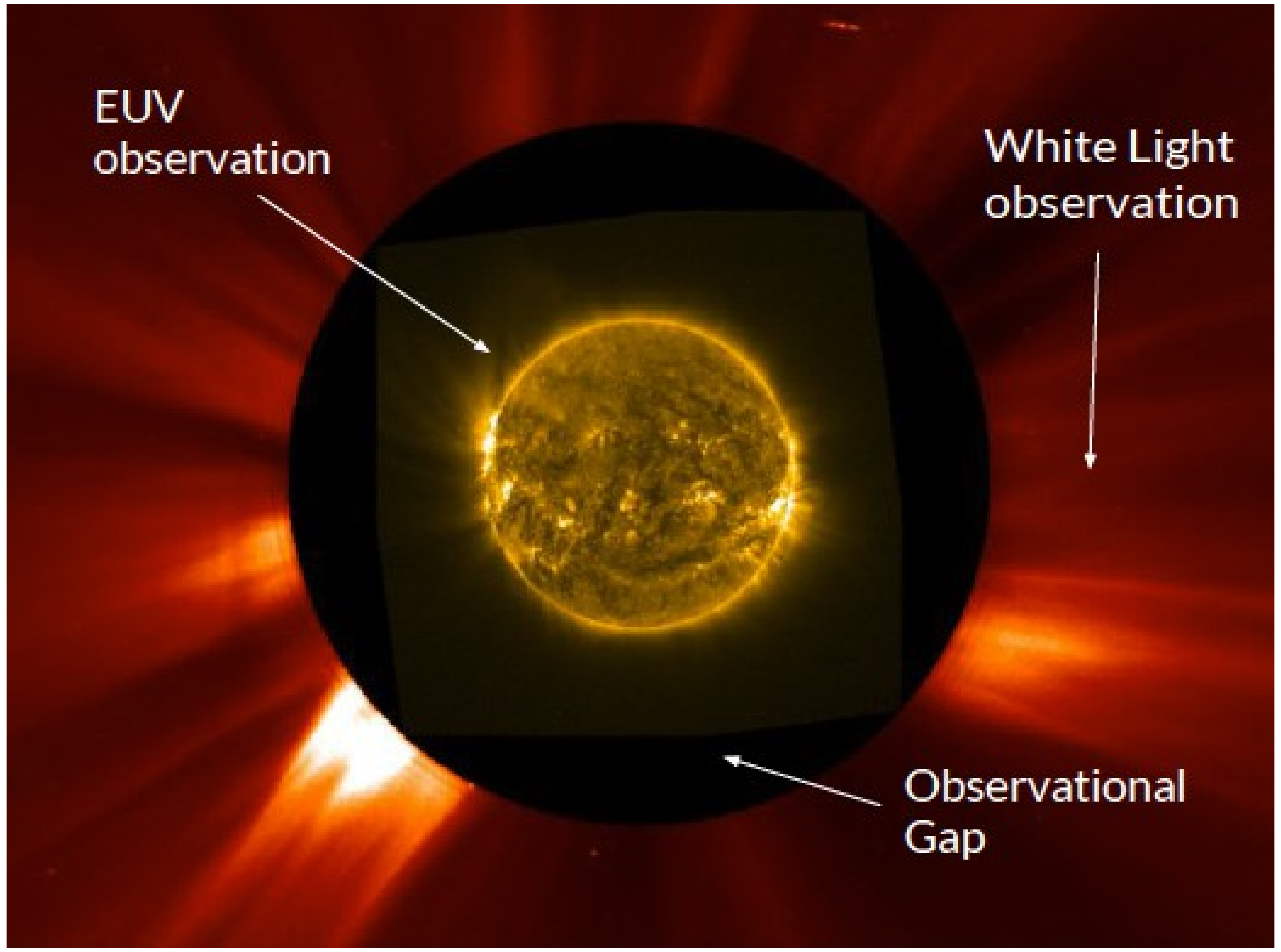
Akasofu (1983) function:

$$\varepsilon = 10^7\, V\, B^2\, l_0^2 \sin^4(\theta/2)\ \mathrm{(J/s)}$$

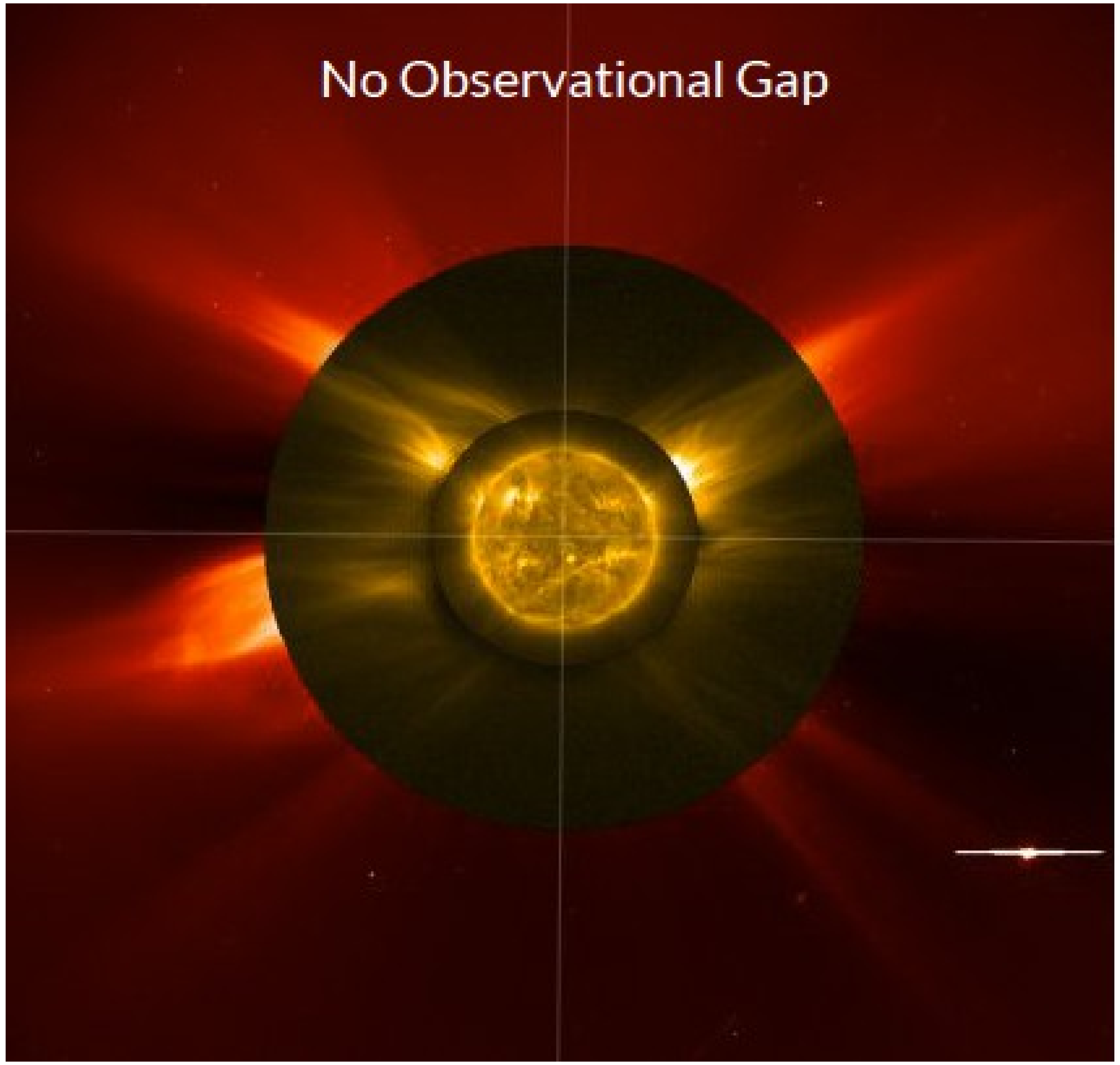
Wang et al. 2014:

$$E_{IN} = 3.78 \times 10^7\, n_{SW}^{0.24}\, V_{SW}^{1.47}\, B_T^{0.86}\, (\sin^{2.7}(\theta/2) + 0.25)\ \mathrm{[J/s]}$$

Filling the gap in the inner corona



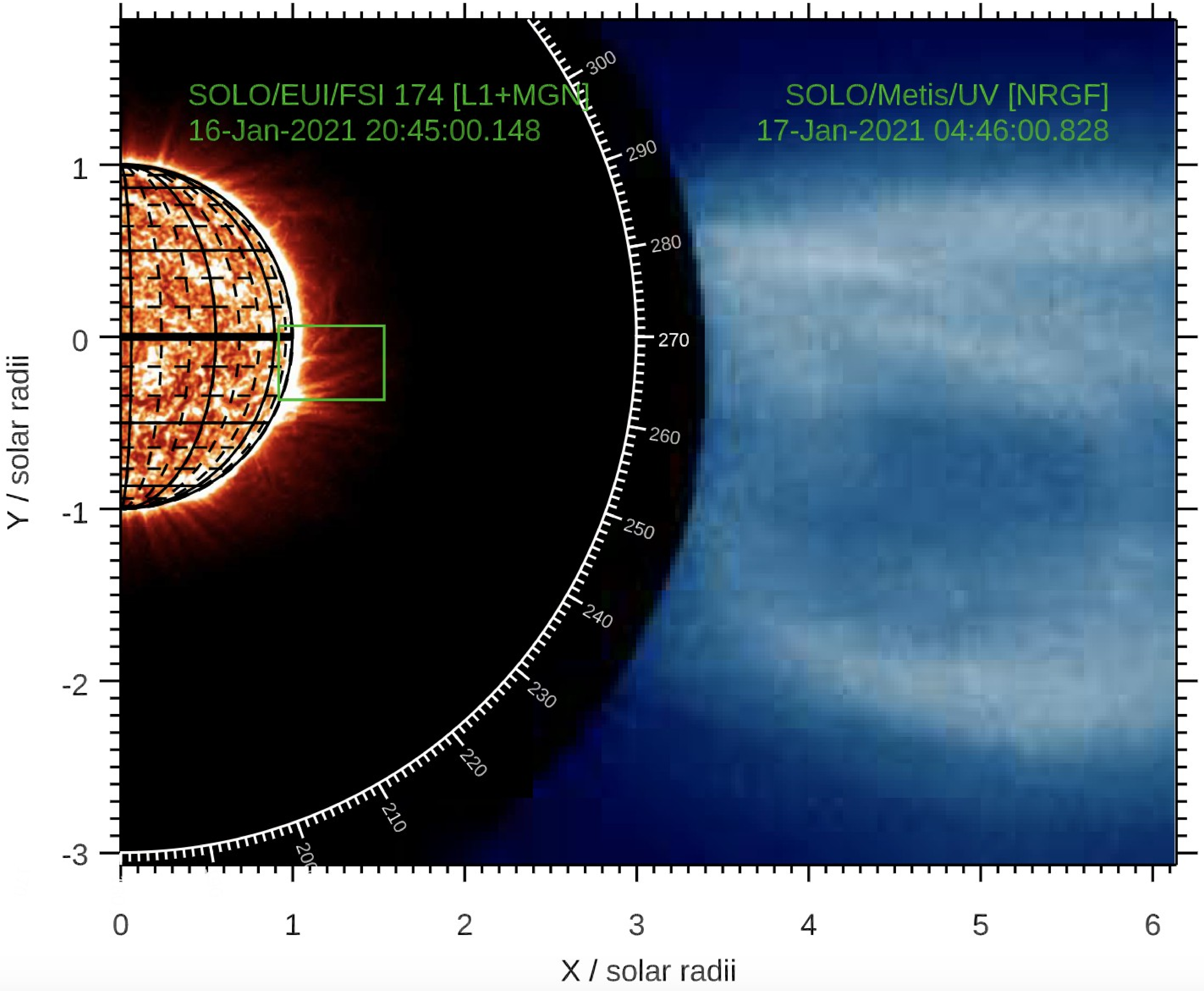
PROBA2/SWAP + SOHO/LASCO-C2



SolO/EUI/FSI + SOHO/LASCO-C2

Auchere et al. 2023

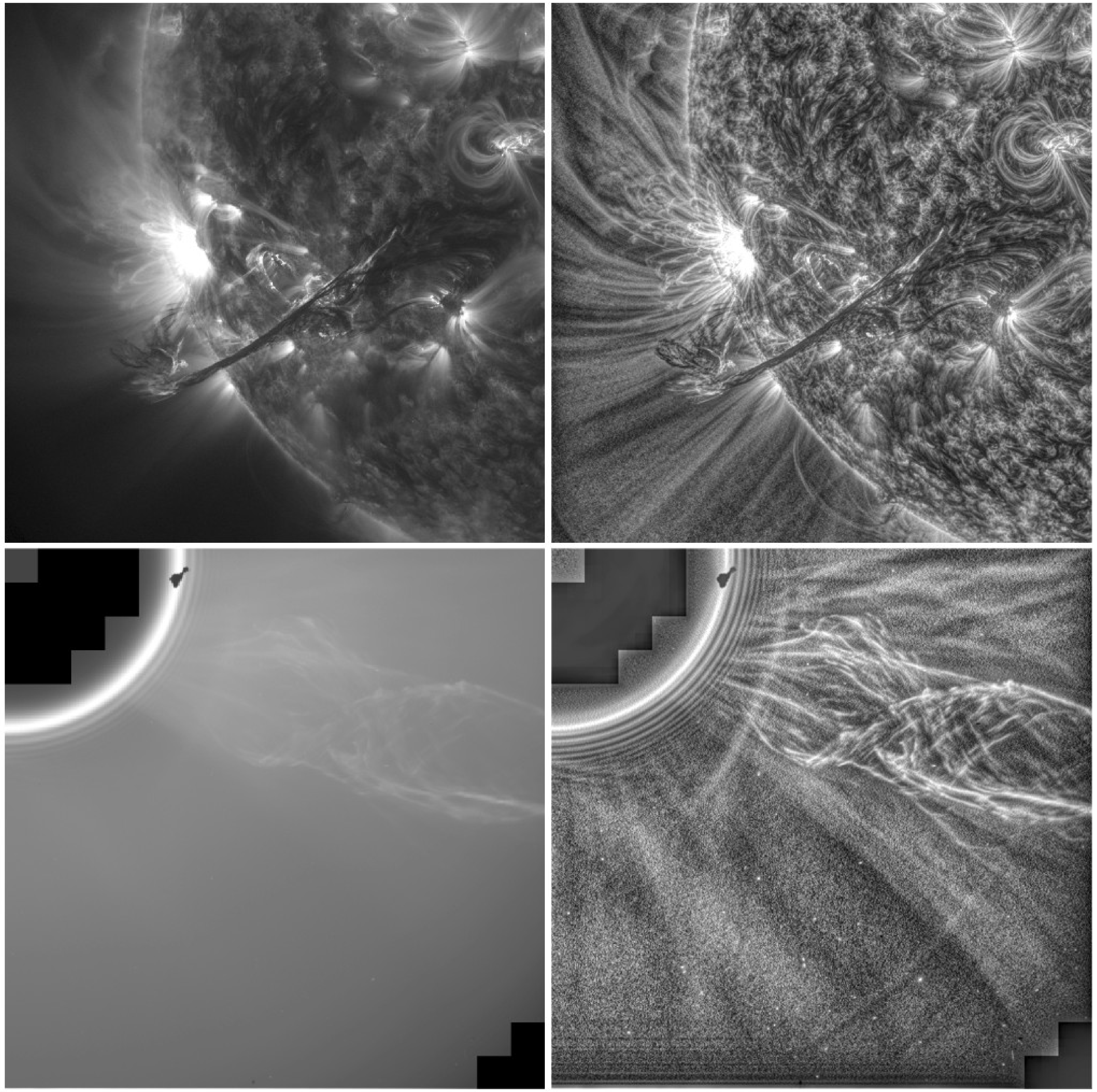
CME visualization - NRGF

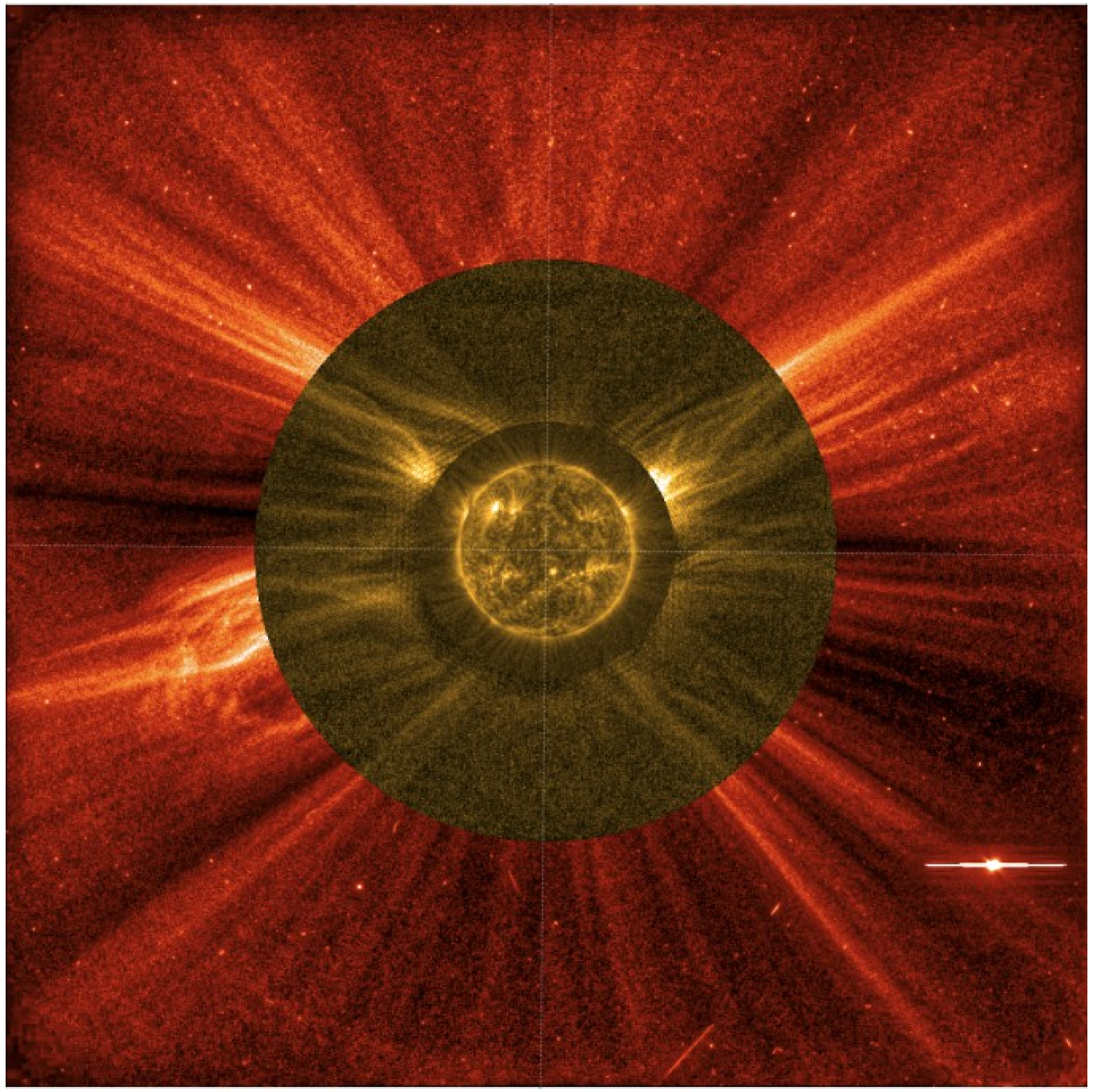


First CME observed by SolO/METIS

Andretta et al. 2021

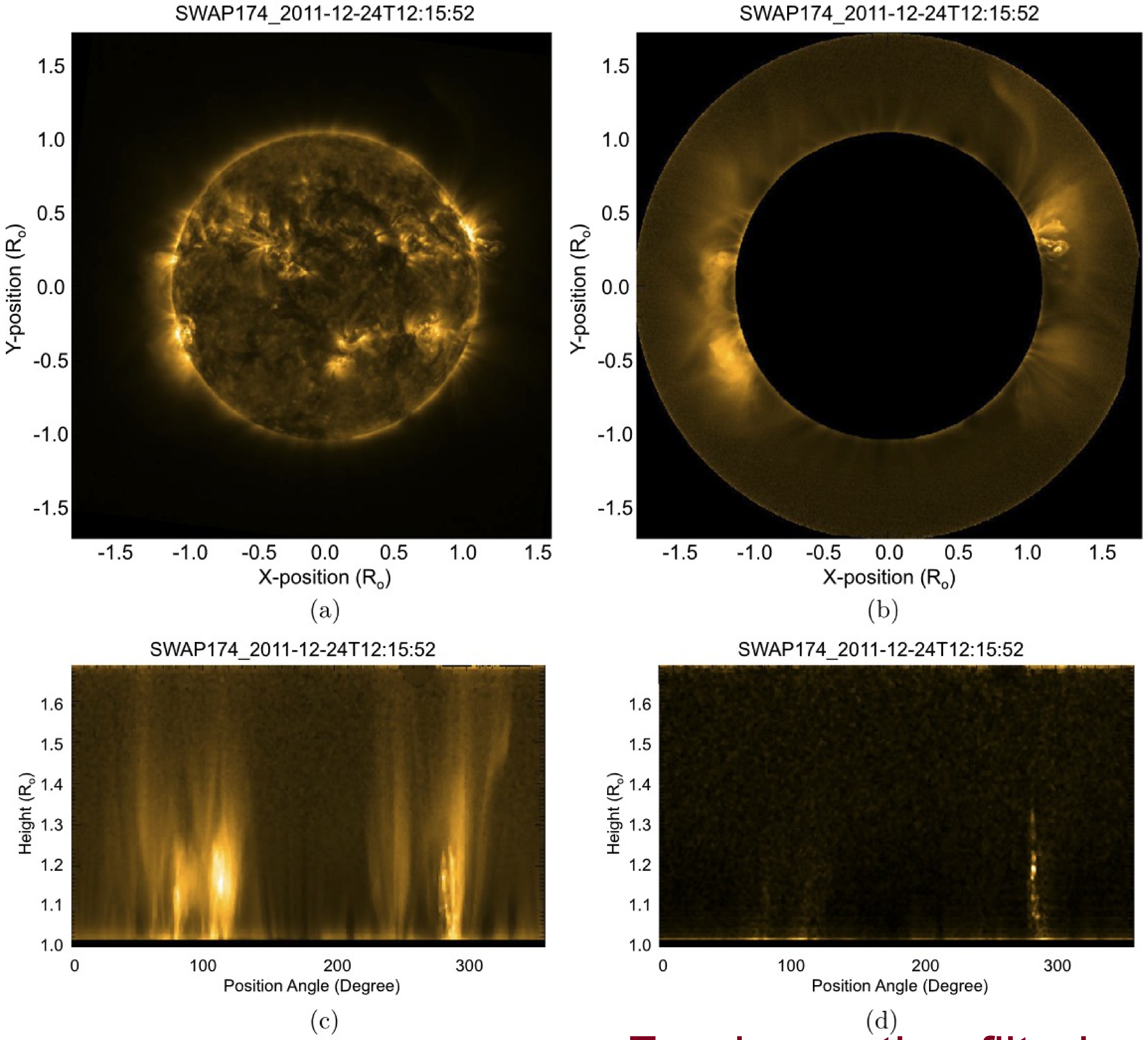
Wavelet-optimized Whitening (WOW)





Auchere et al. 2023a, 2023b

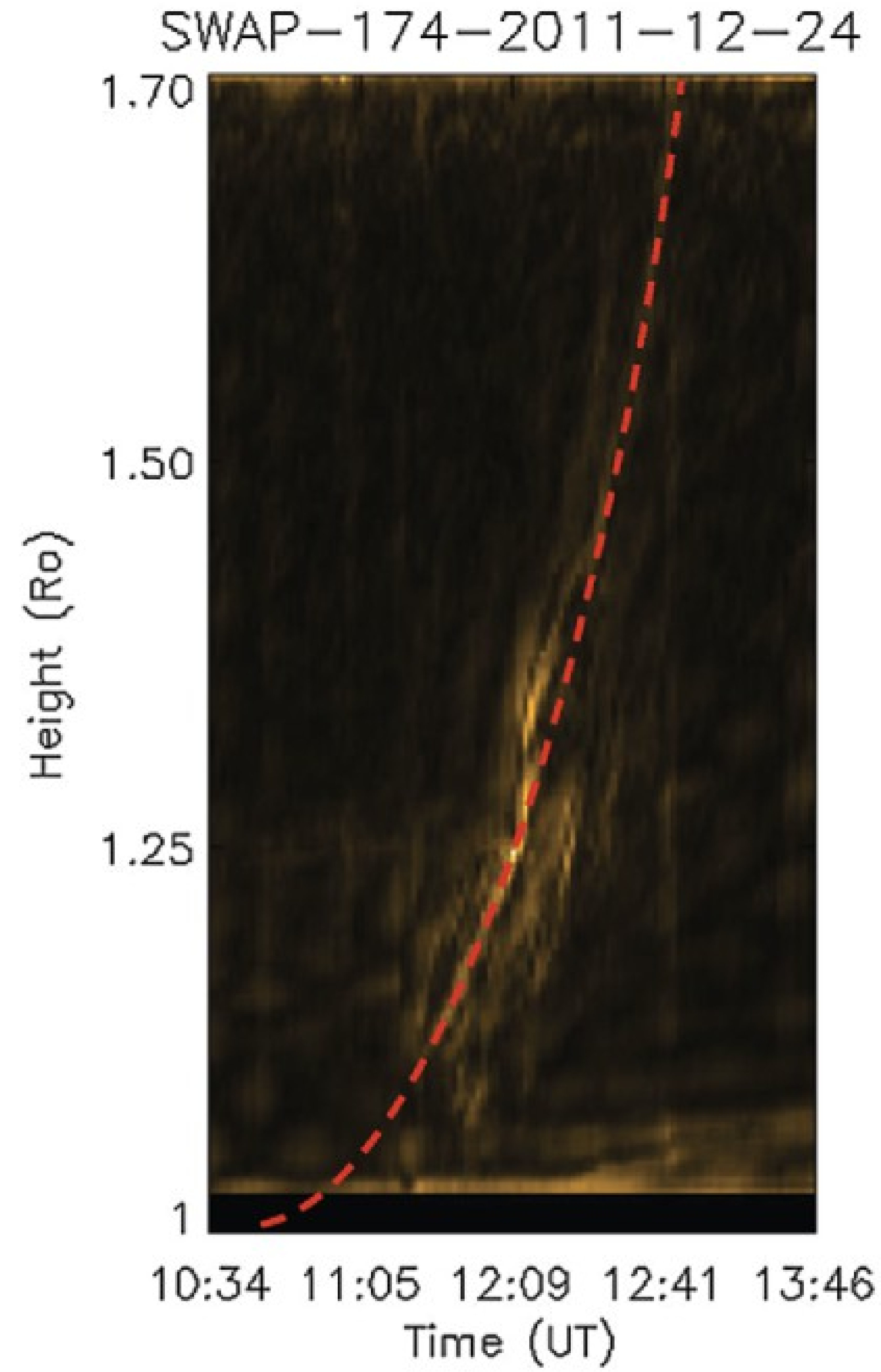
CME Detection - CIISCO



Polar Transformation

Fourier motion filtering

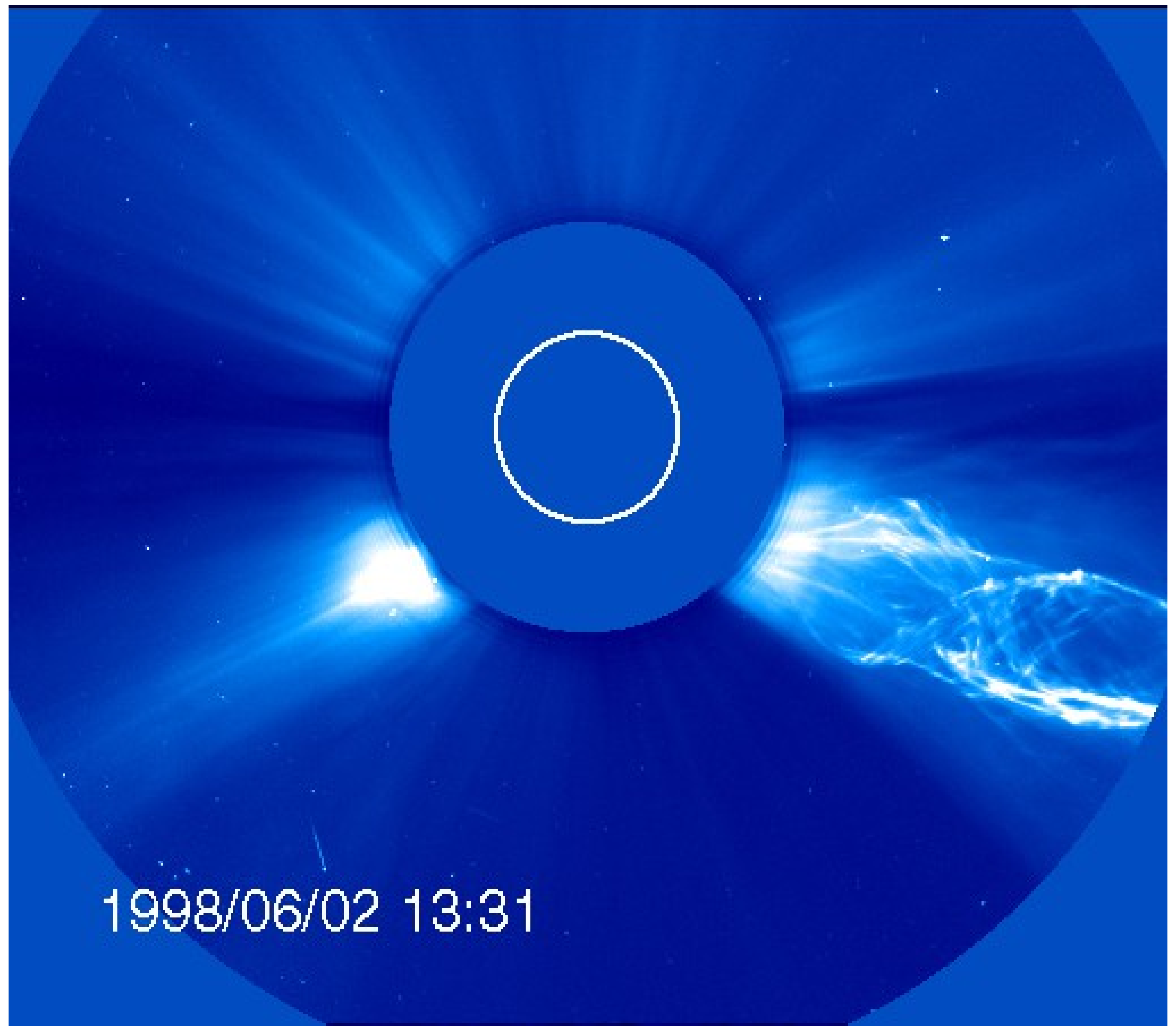
Parabolic Hough Transform

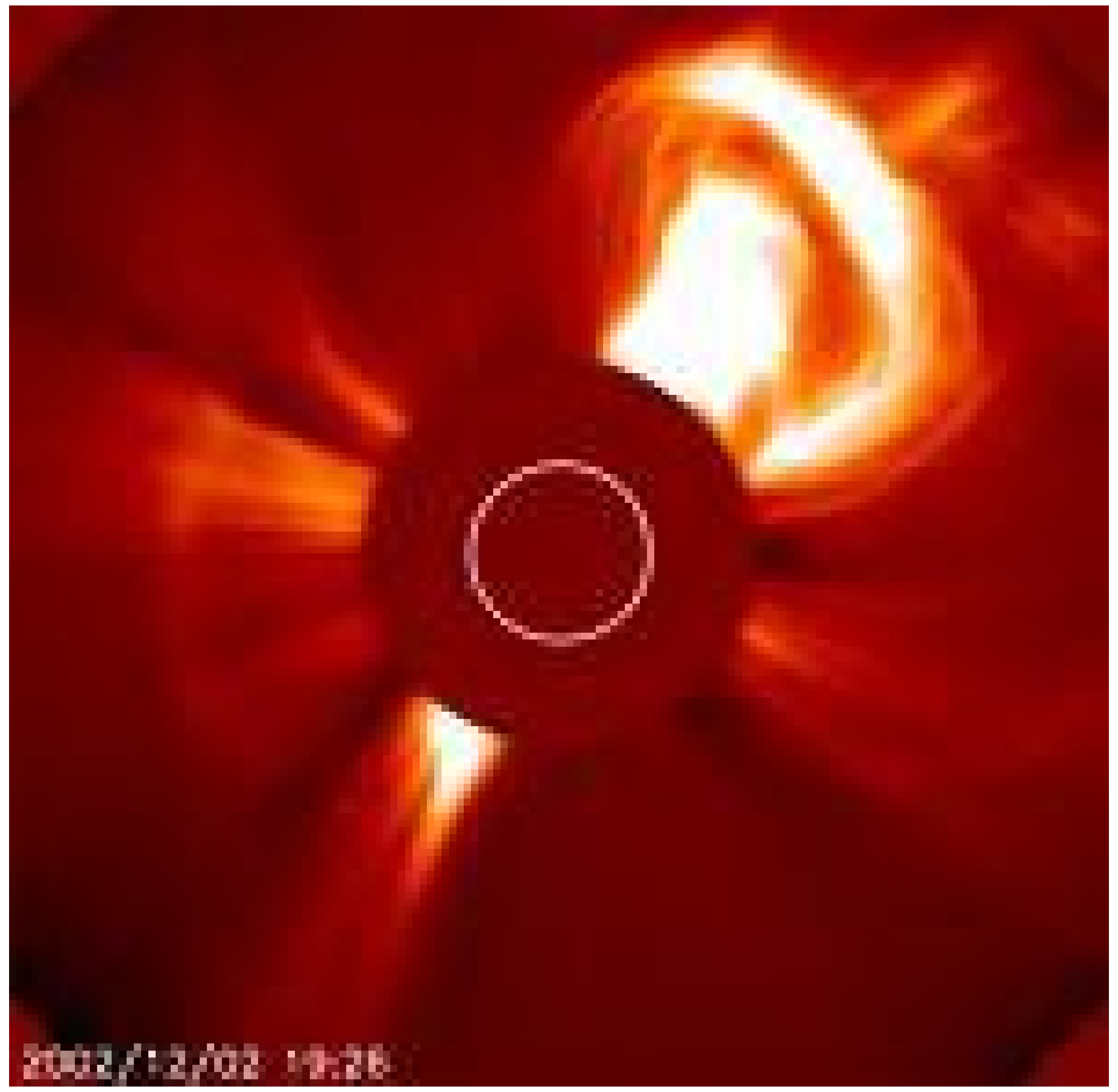


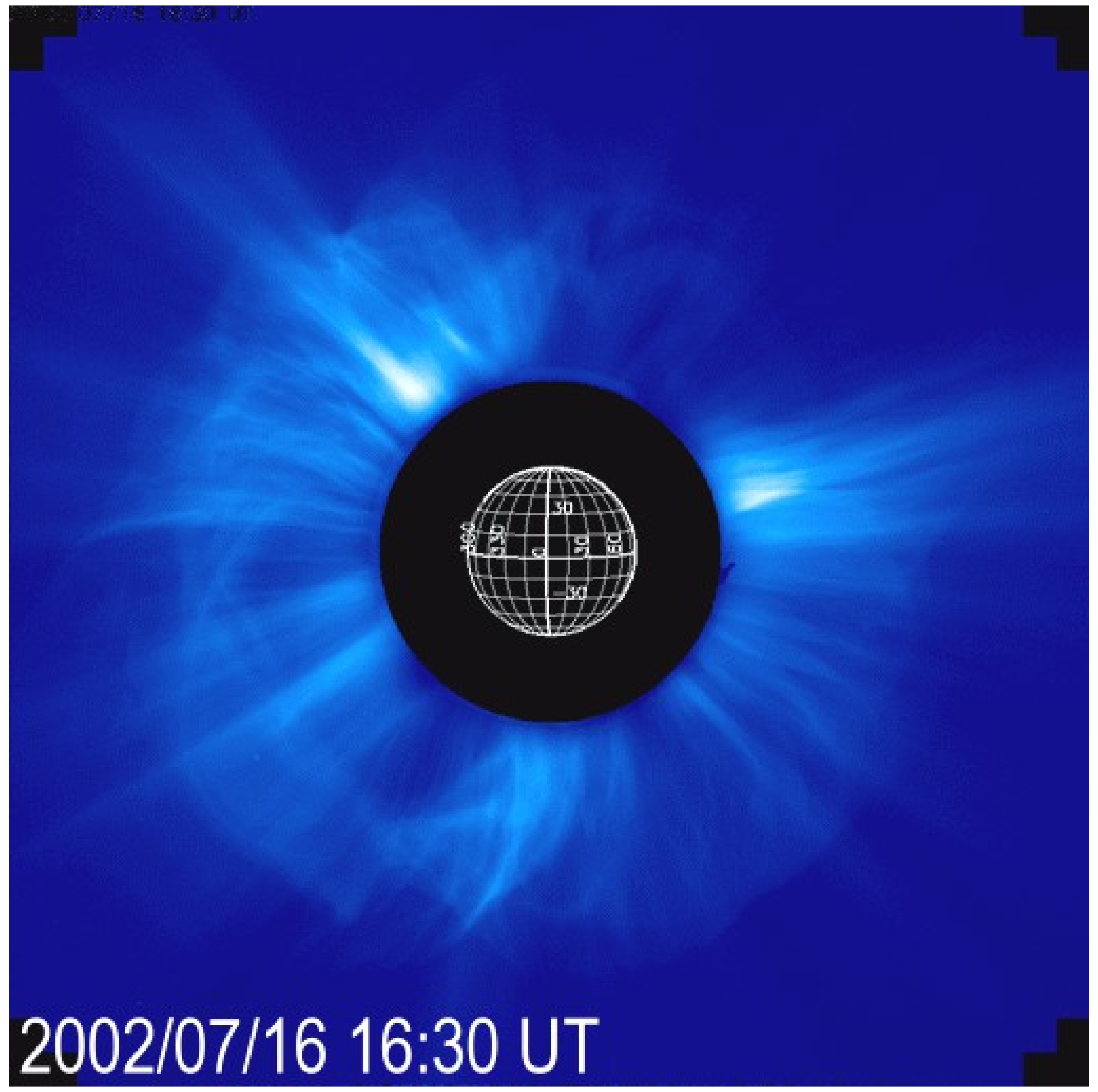
Patel et al. 2021

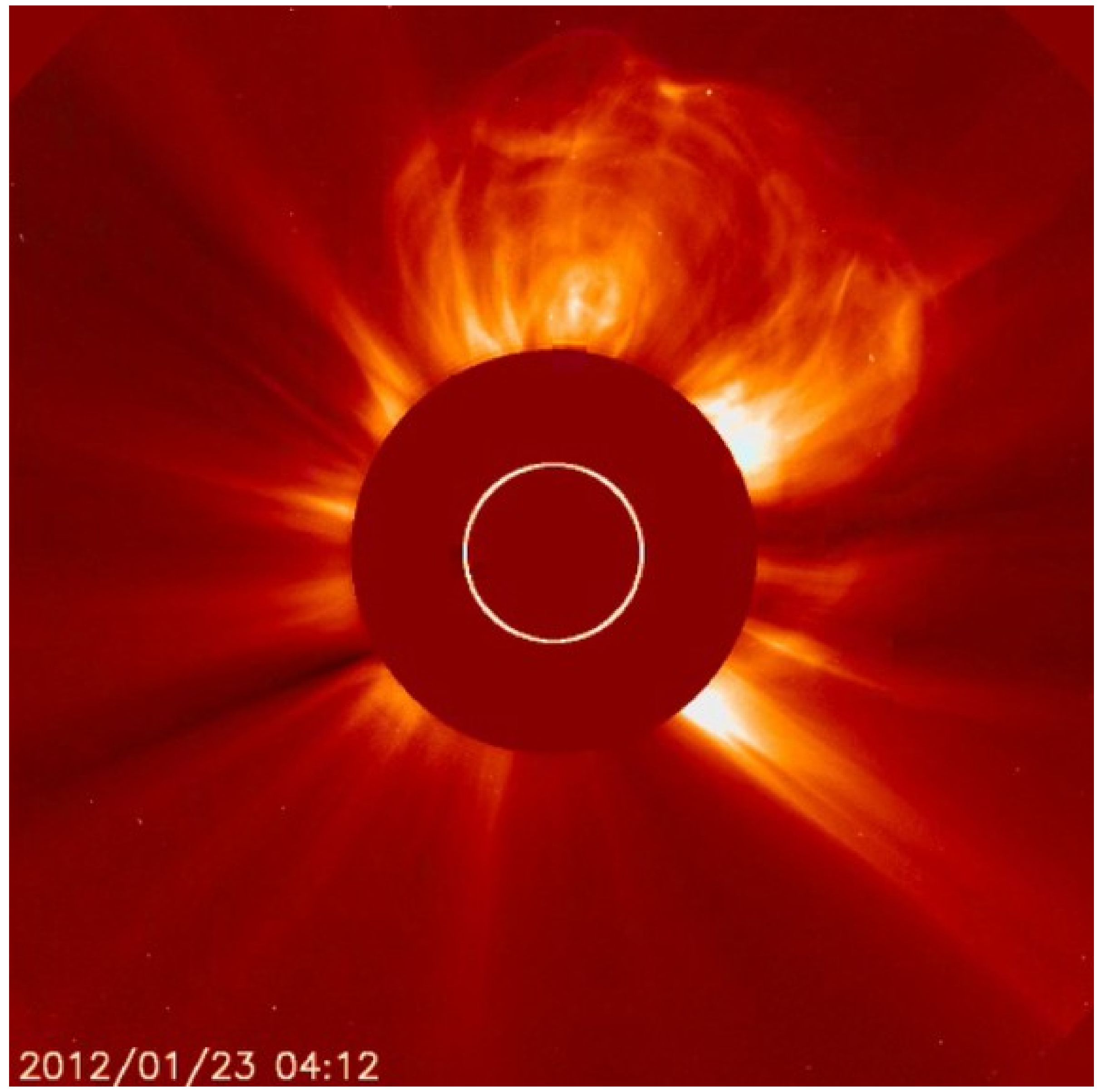
The Complexity of the CME Phenomena

- **large variety of apparent morphologies** in coronagraph images:
    - bubble-like shapes
    - flux-rope-like shapes etc.
- **highly-dynamic events:**
    - the global appearance may change from a frame to another

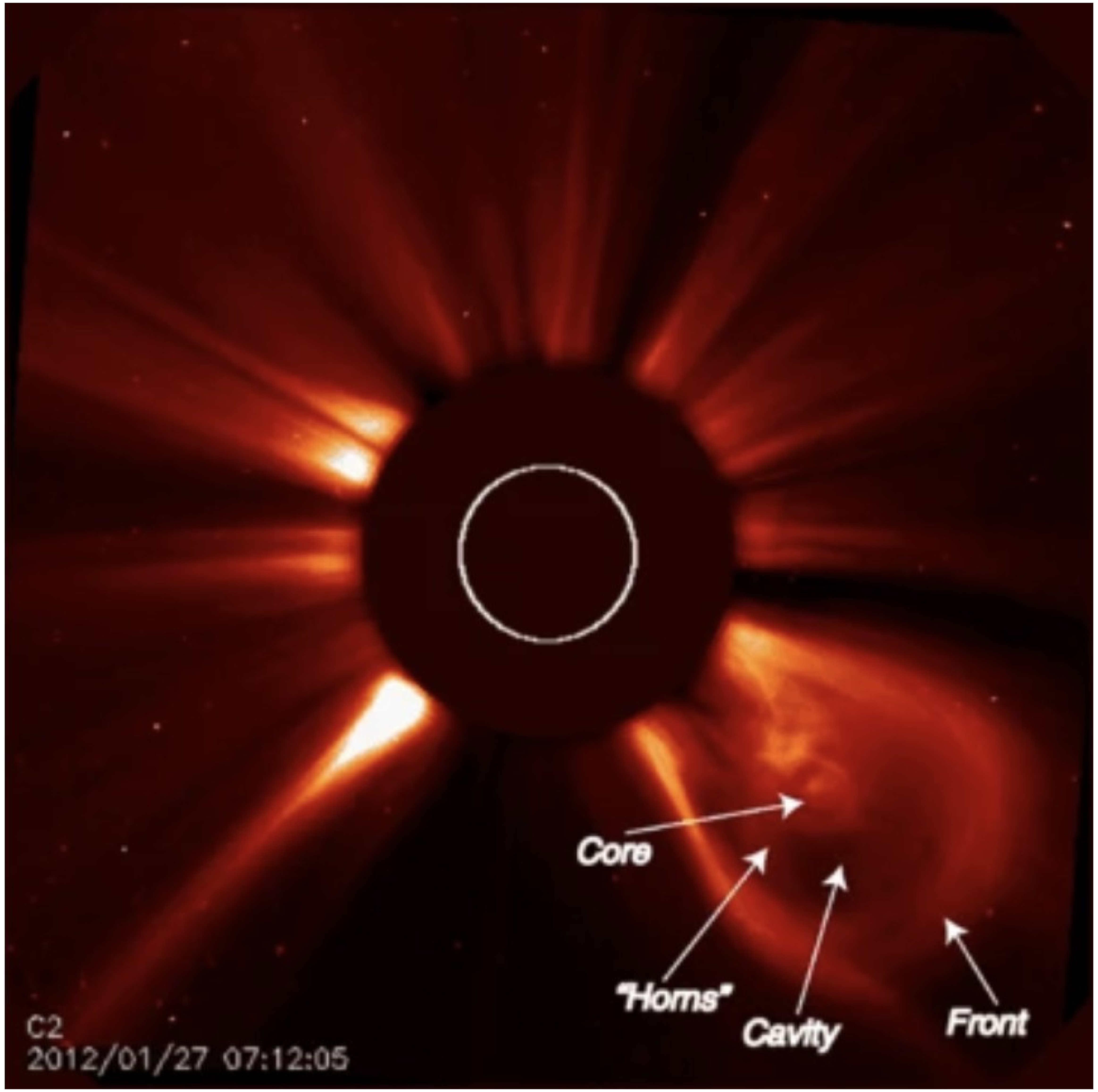




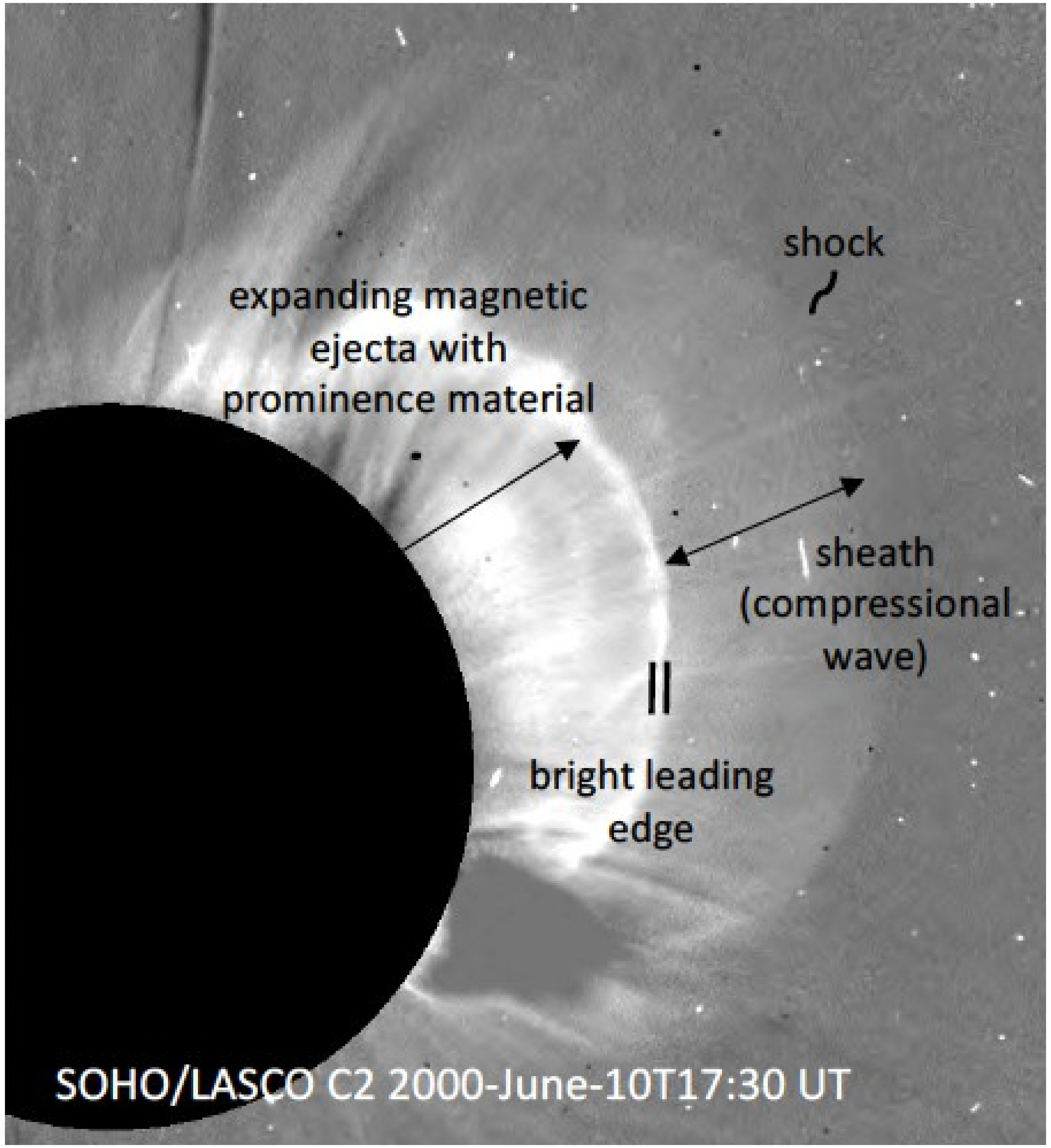




Classical Morphology



Vourlidas et al. 2013



Vourlidas et al. 2003, Temmer et al. 2022

Connecting WL with EUV Observations

Gibson&Fan 2006; Gibson et al. 2010; Rachmeler et al. 2013; Bąk-Stęślicka et al. 2019; Ruminska et al. 2022; Zhao et al. 2022

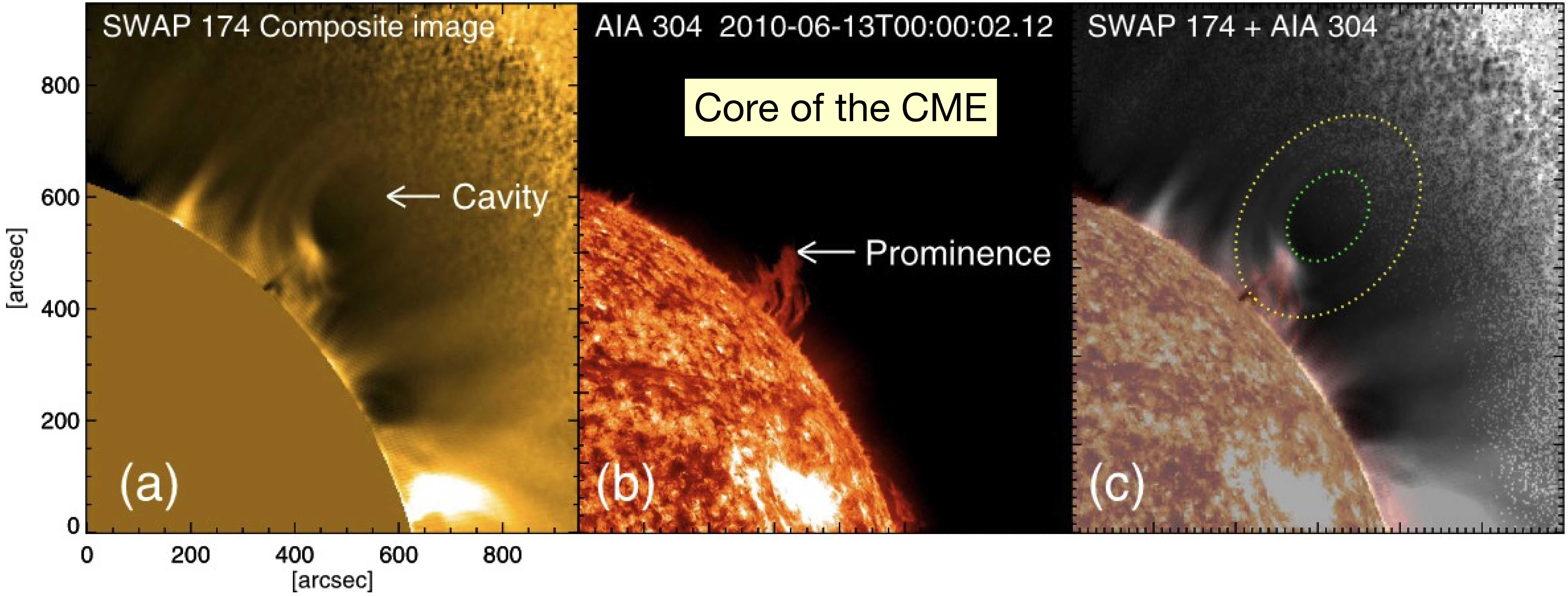
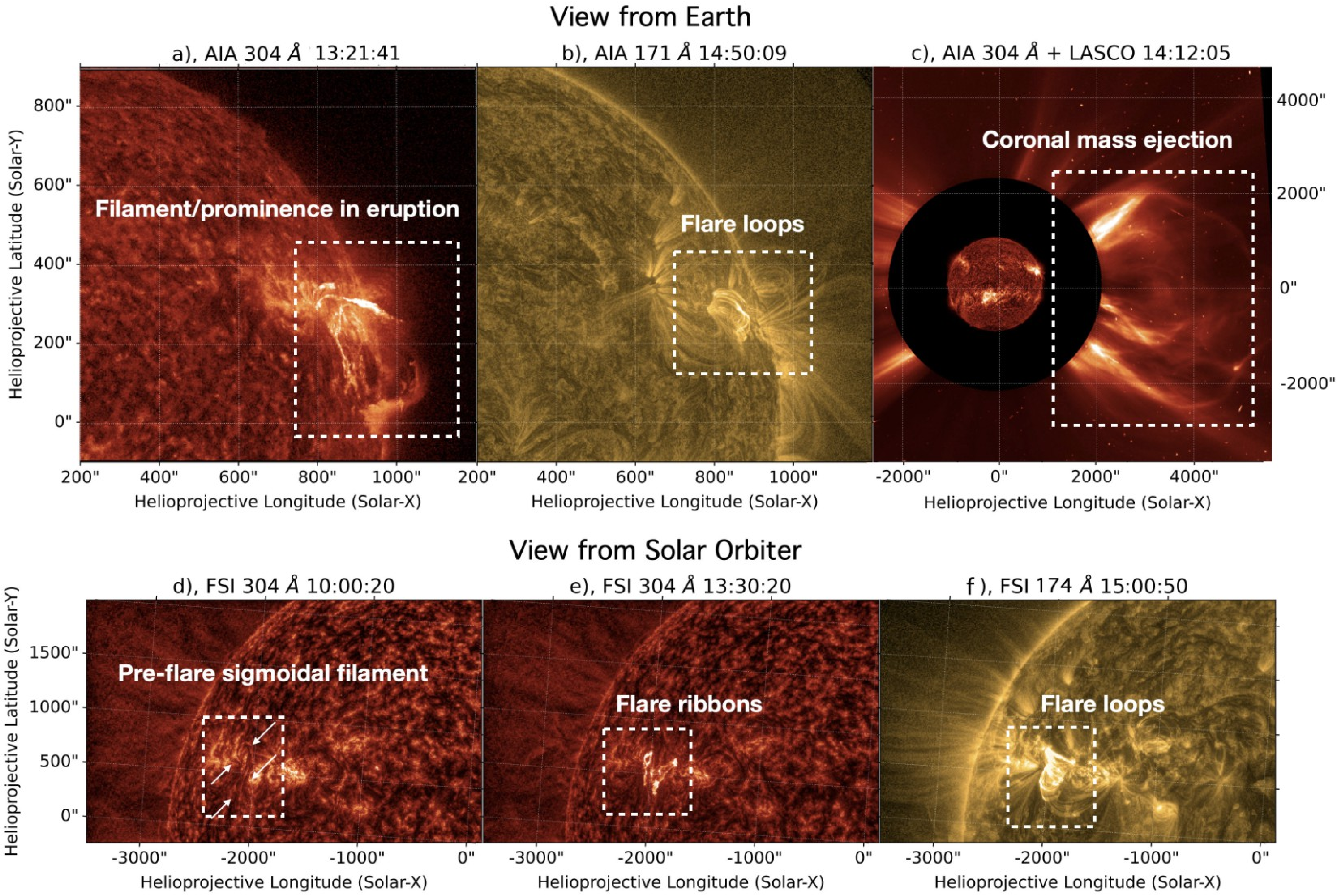


Figure from Sarkar et al. 2019

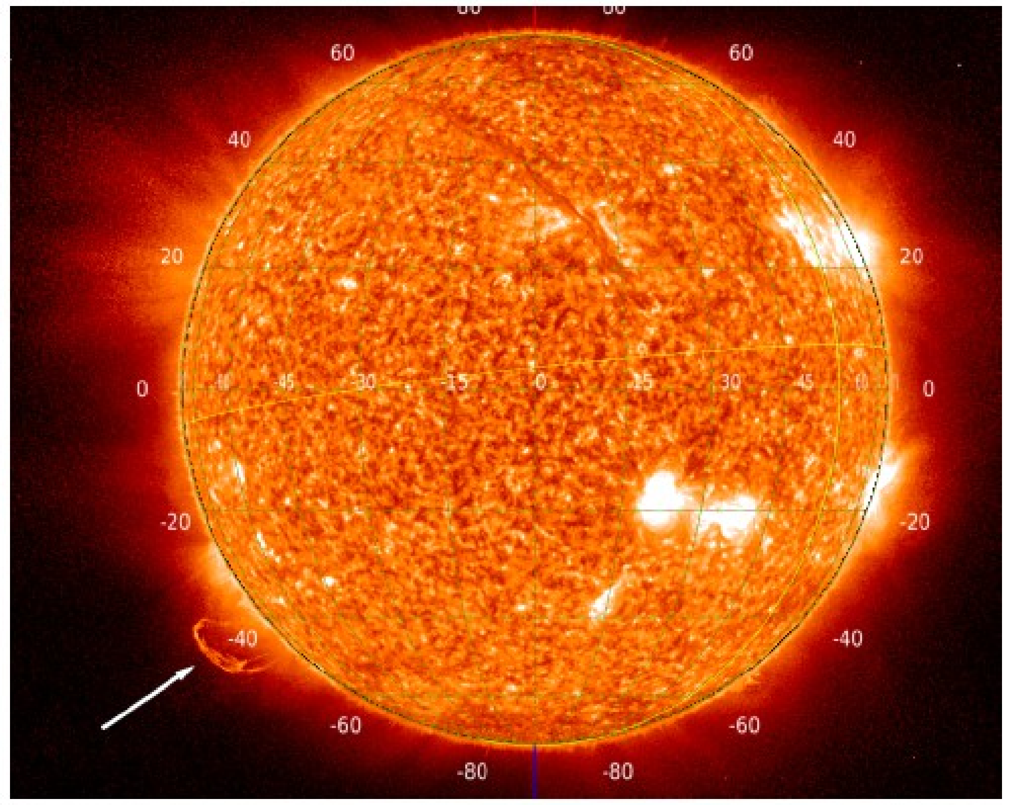
Signatures of CME origin



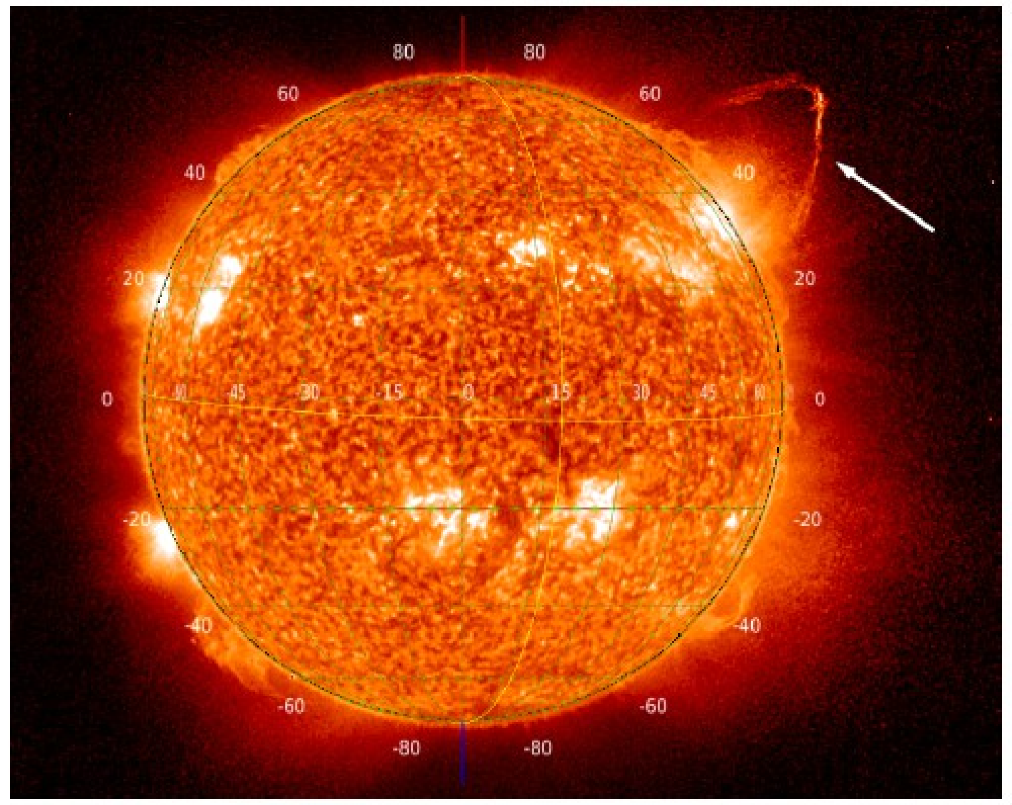
Janvier et al. 2023

Eruption mechanisms – SolO/EUI/FSI observations

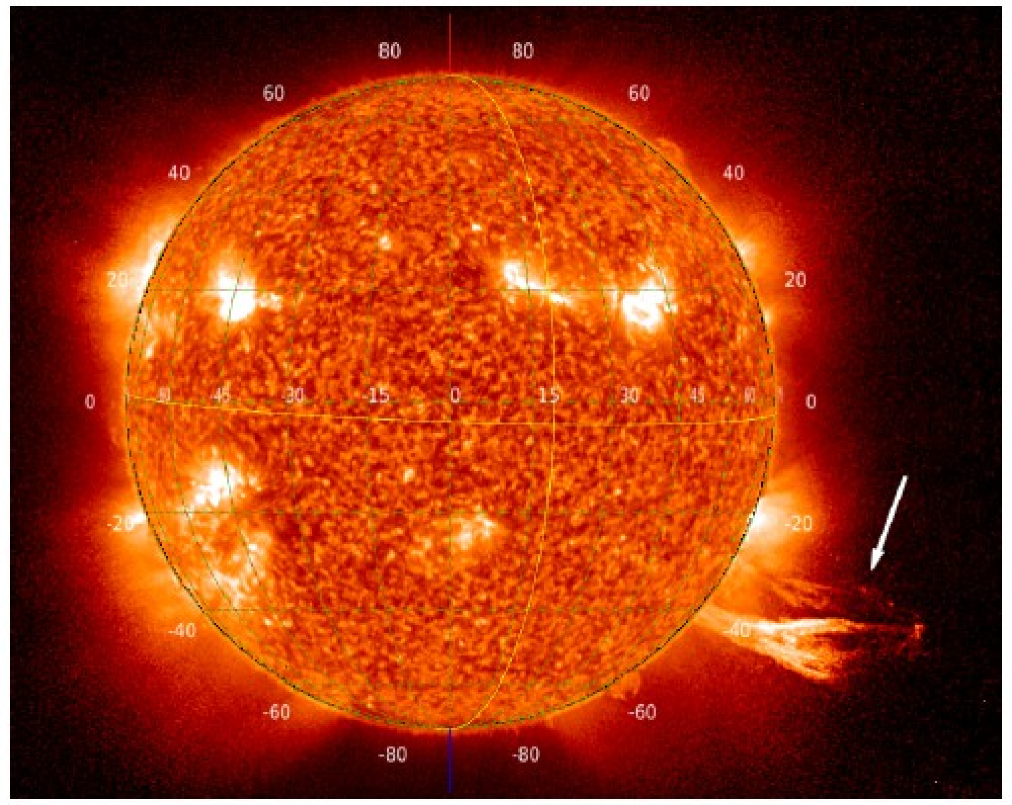
Six prominence eruptions observed at high cadence (2 to 6 minutes) by the FSI 304 instrument.



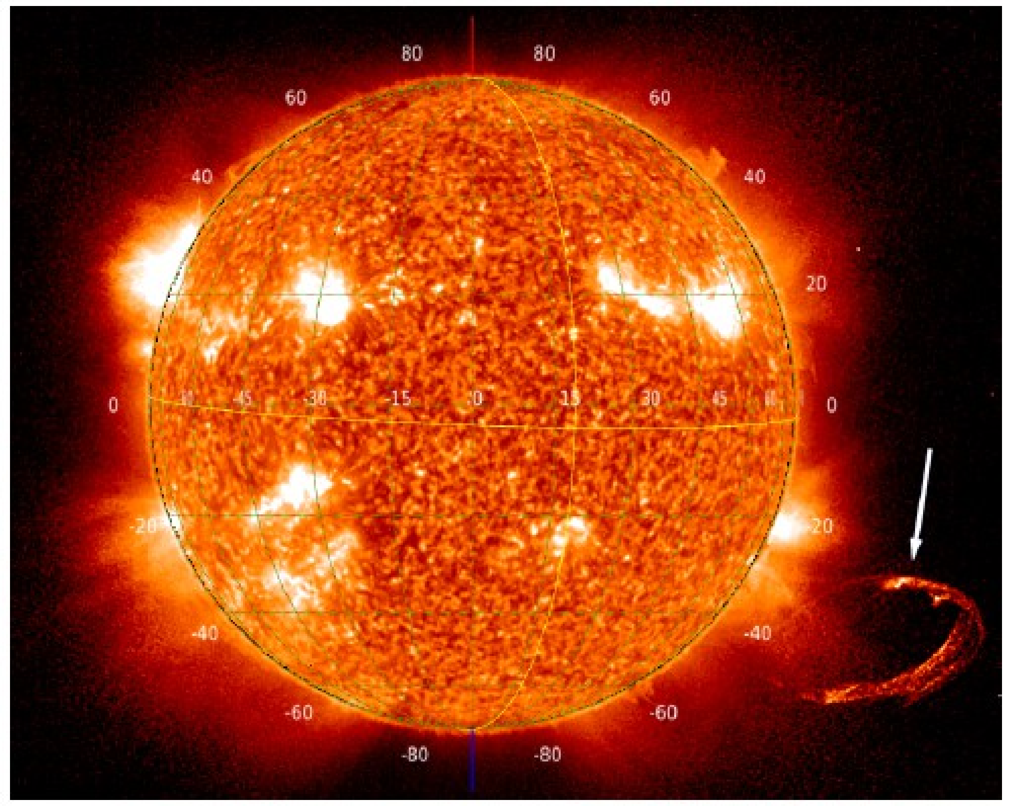
(a) 06-09-21 18:40:20 UTC



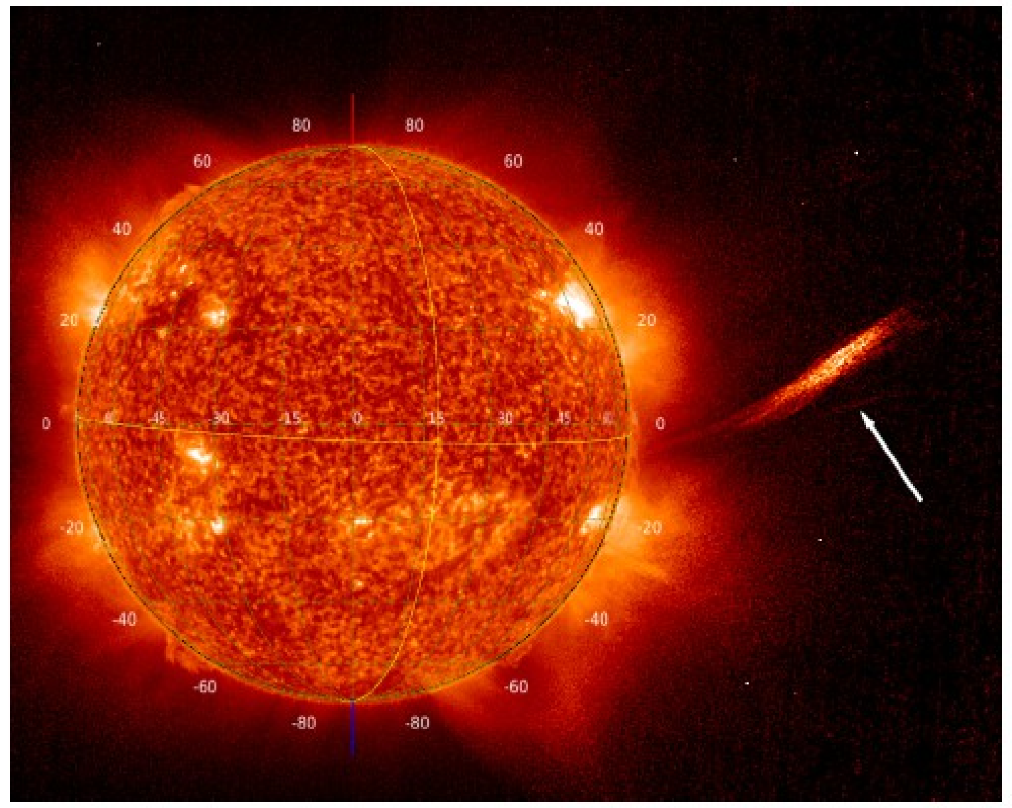
(b) 25-01-22 03:54:20 UTC



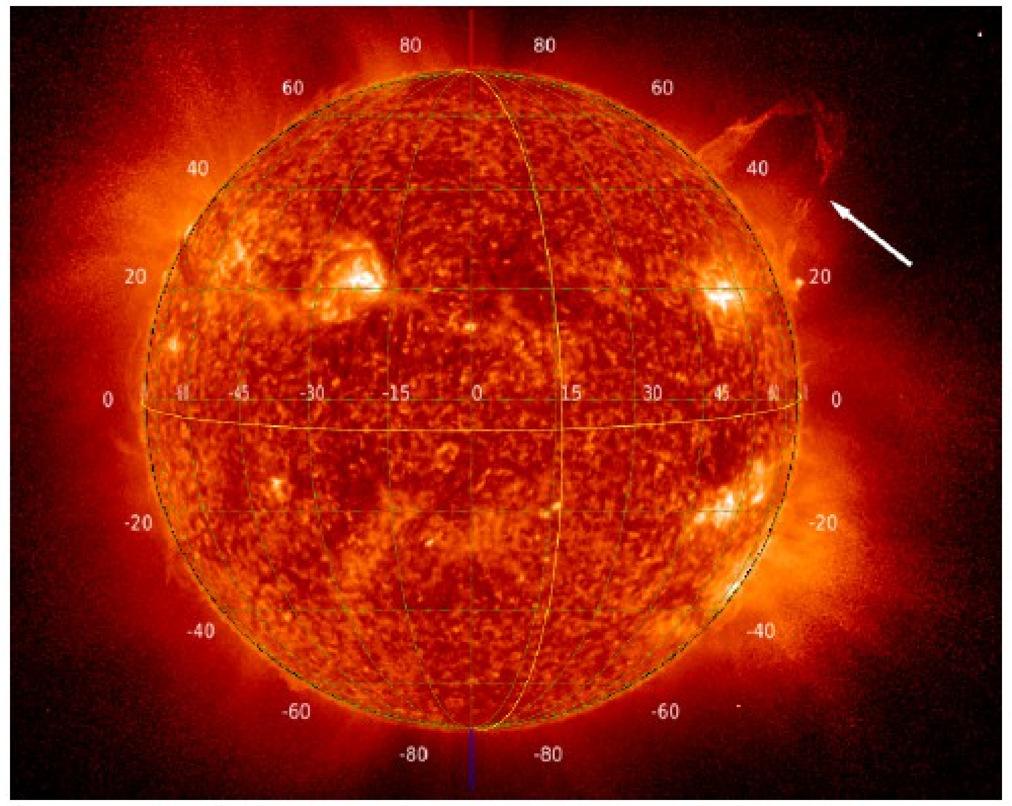
(c) 31-01-22 00:16:20 UTC



(d) 02-02-22 02:30:20 UTC



(e) 13-02-22 03:06:20 UTC

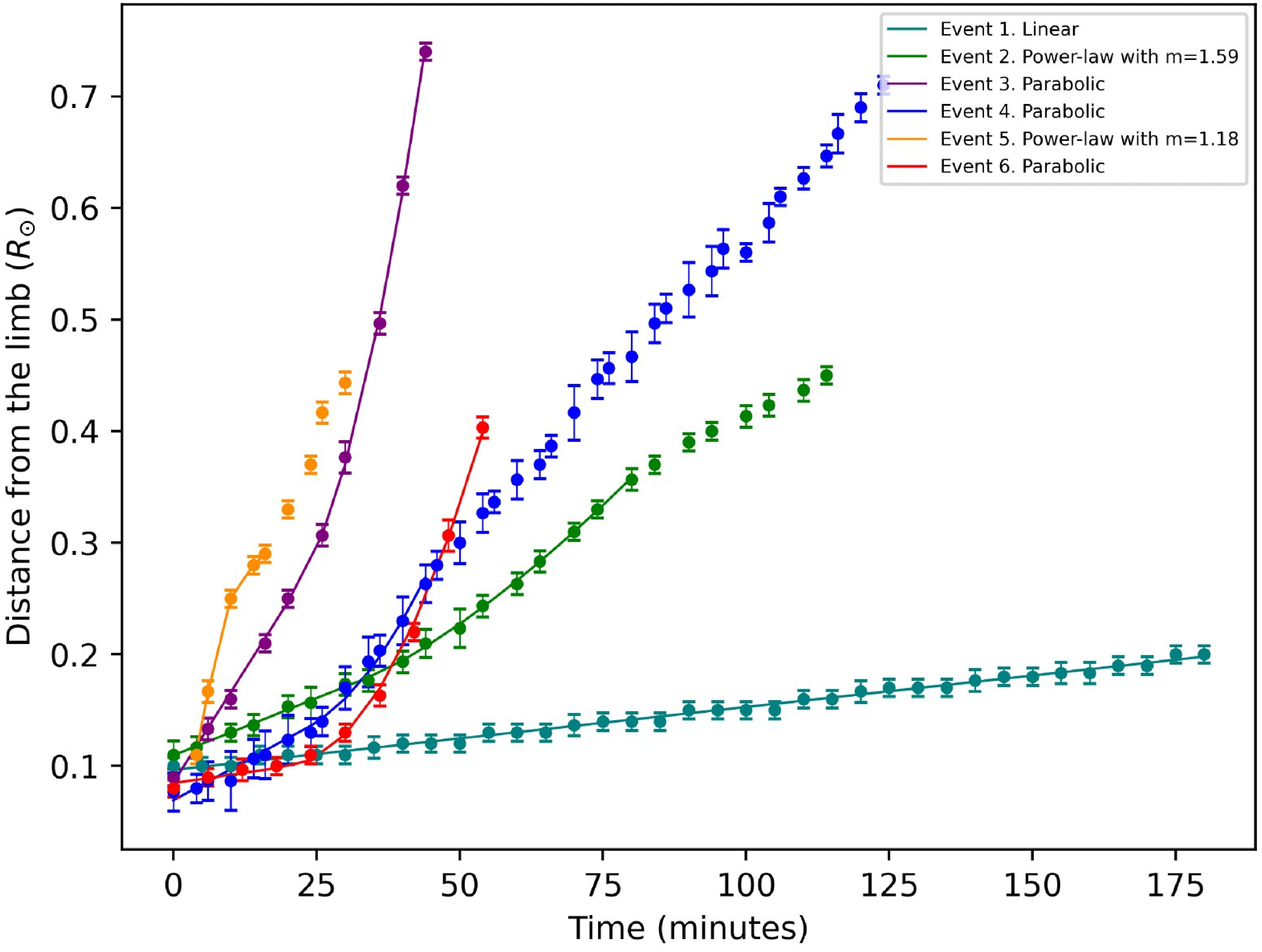


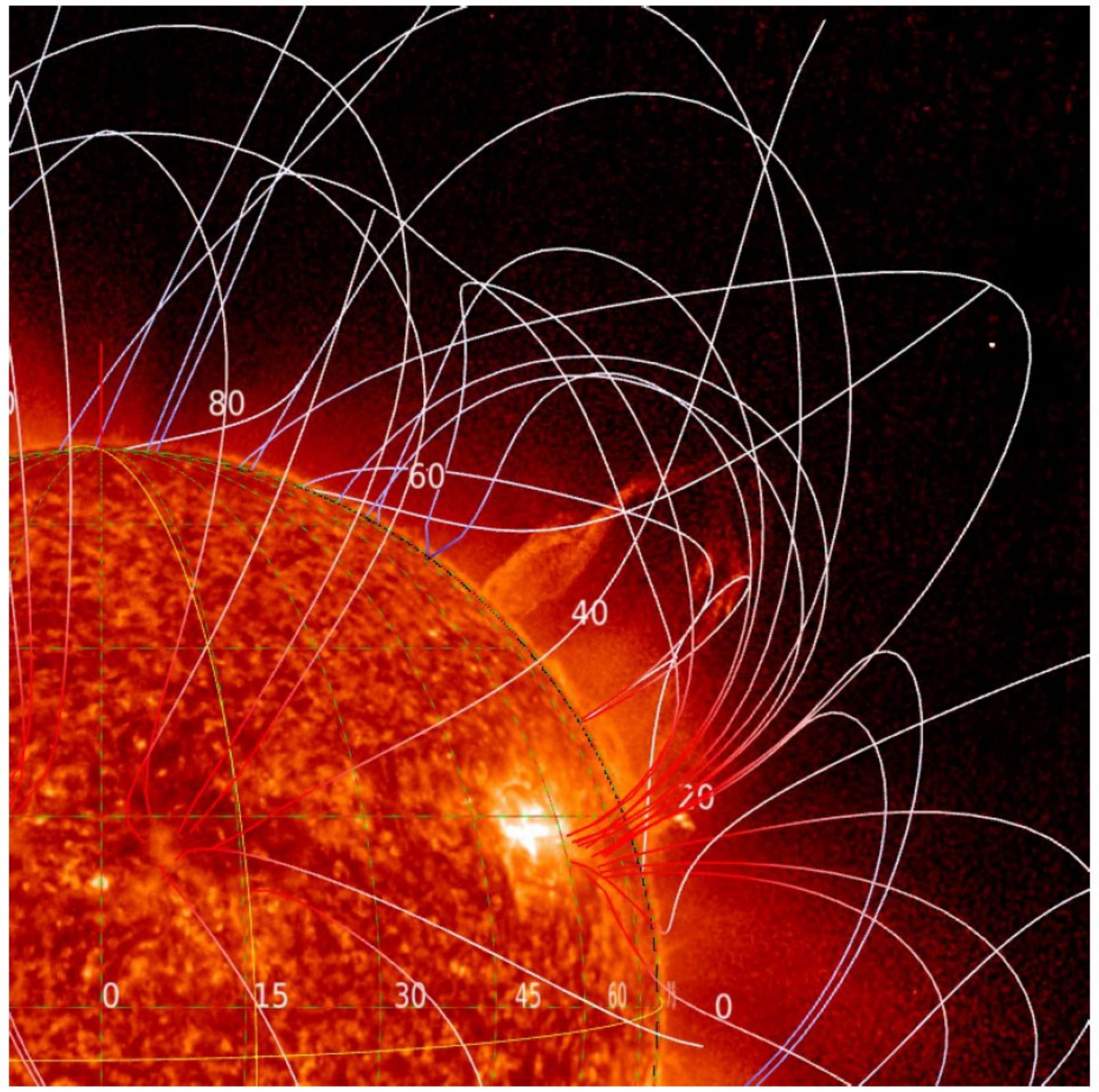
(f) 25-11-22 22:00:25 UTC

Casara, Master thesis, 2023

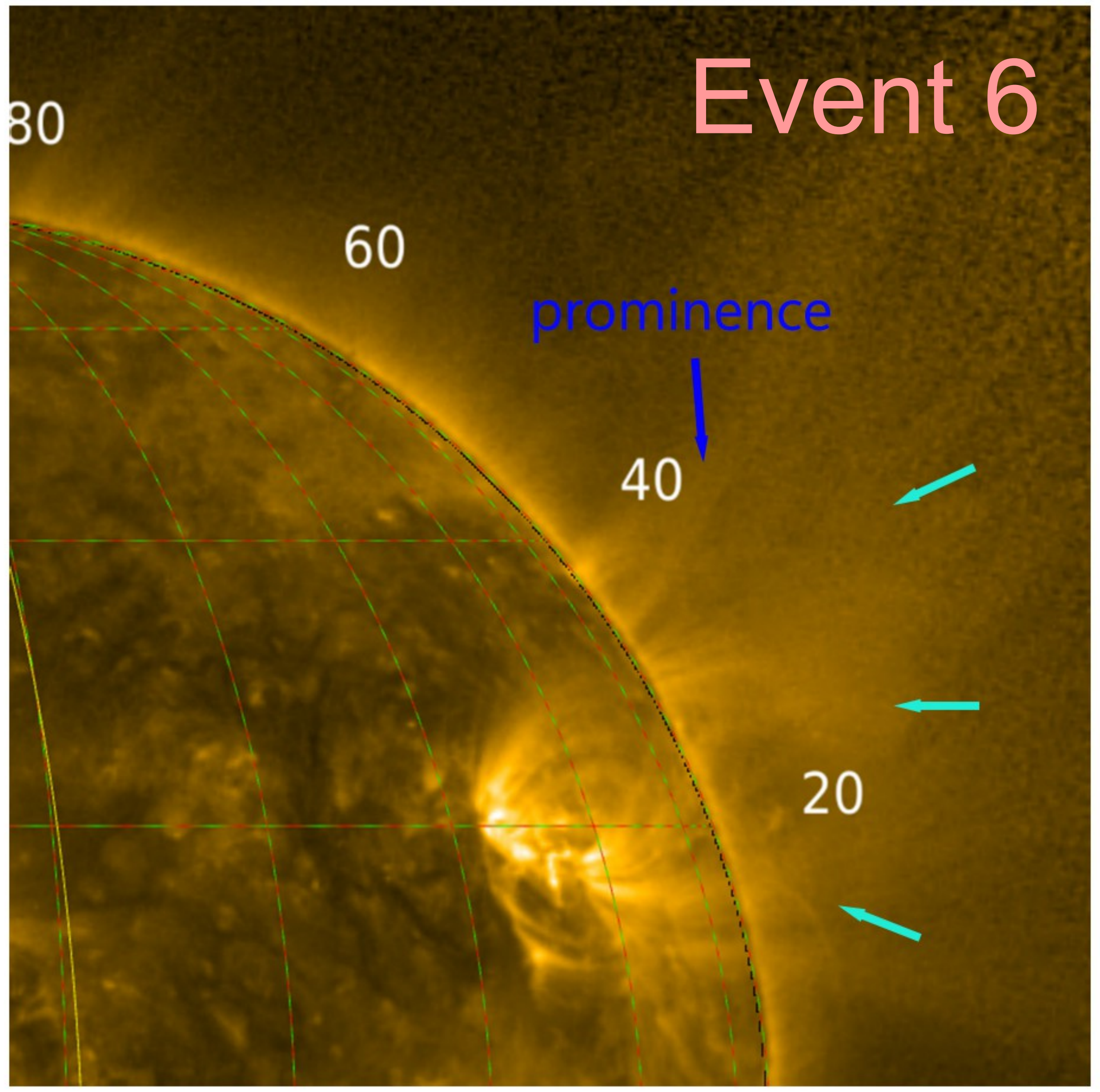
Eruption mechanisms – SolO/EUI/FSI observations

Out of the 6 prominence eruptions, half of the events exhibited a parabolic growth pattern in the acceleration phase, which may be indicative of a breakout model.





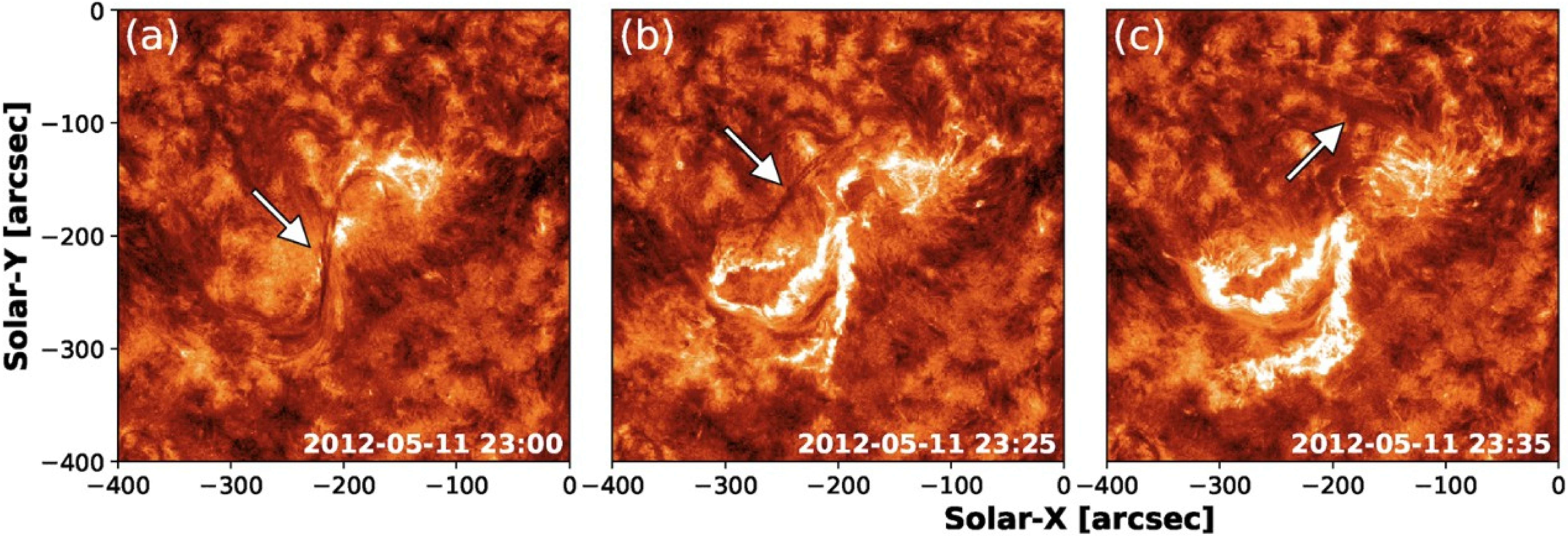
(a) FSI 304 Å.



(b) FSI 174 Å.

Casara, Master thesis, 2023

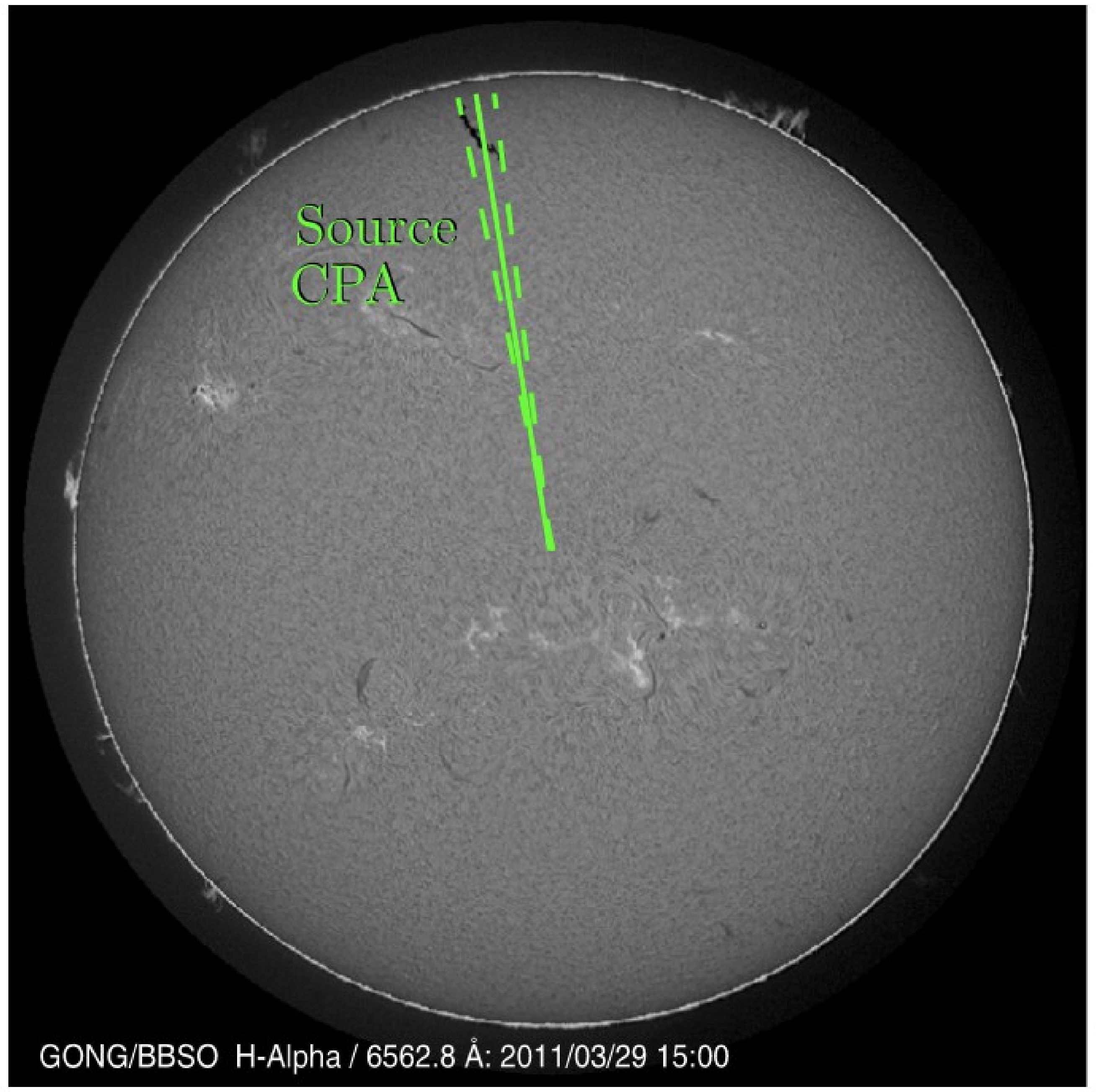
Rotation in the low corona

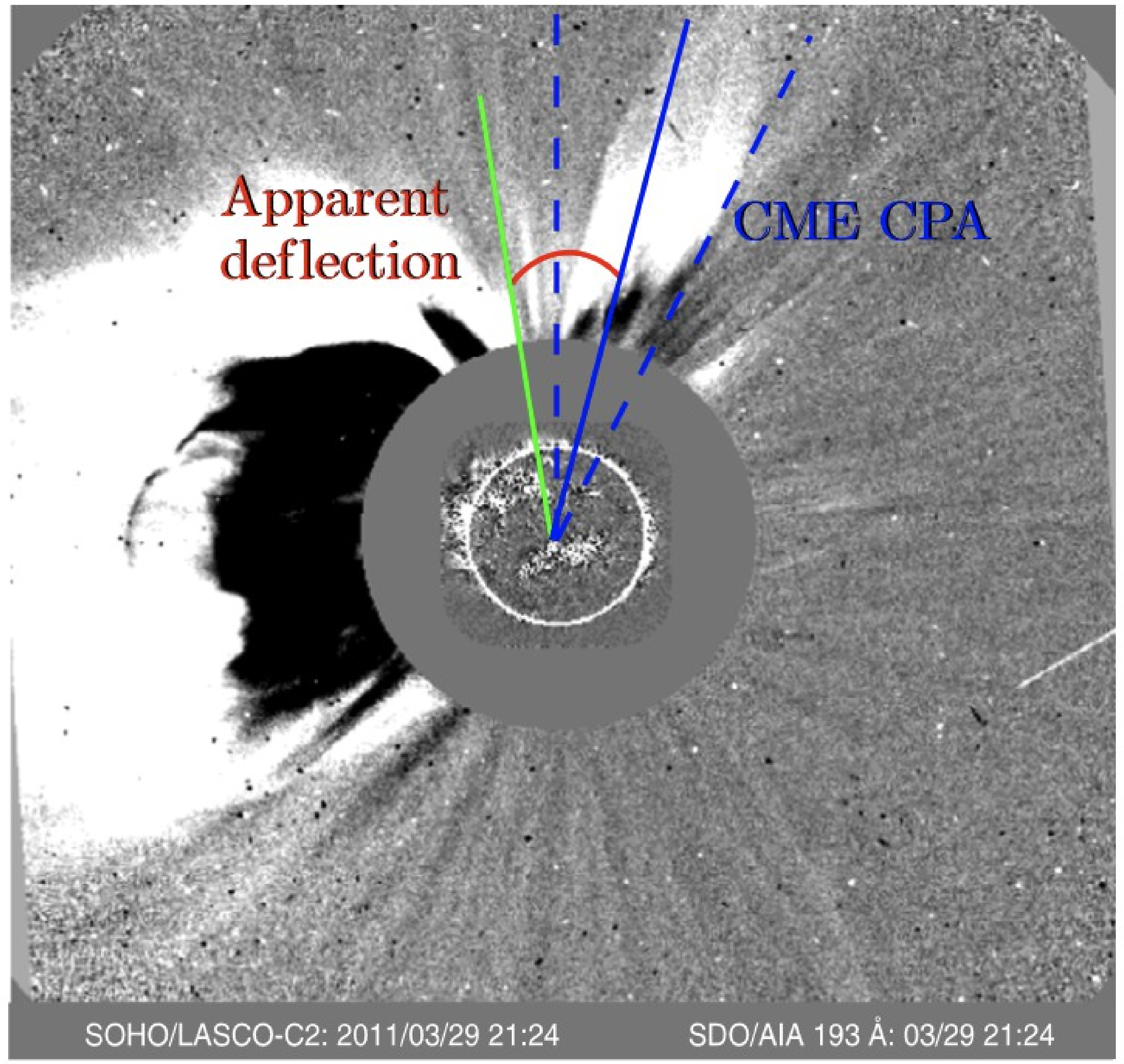


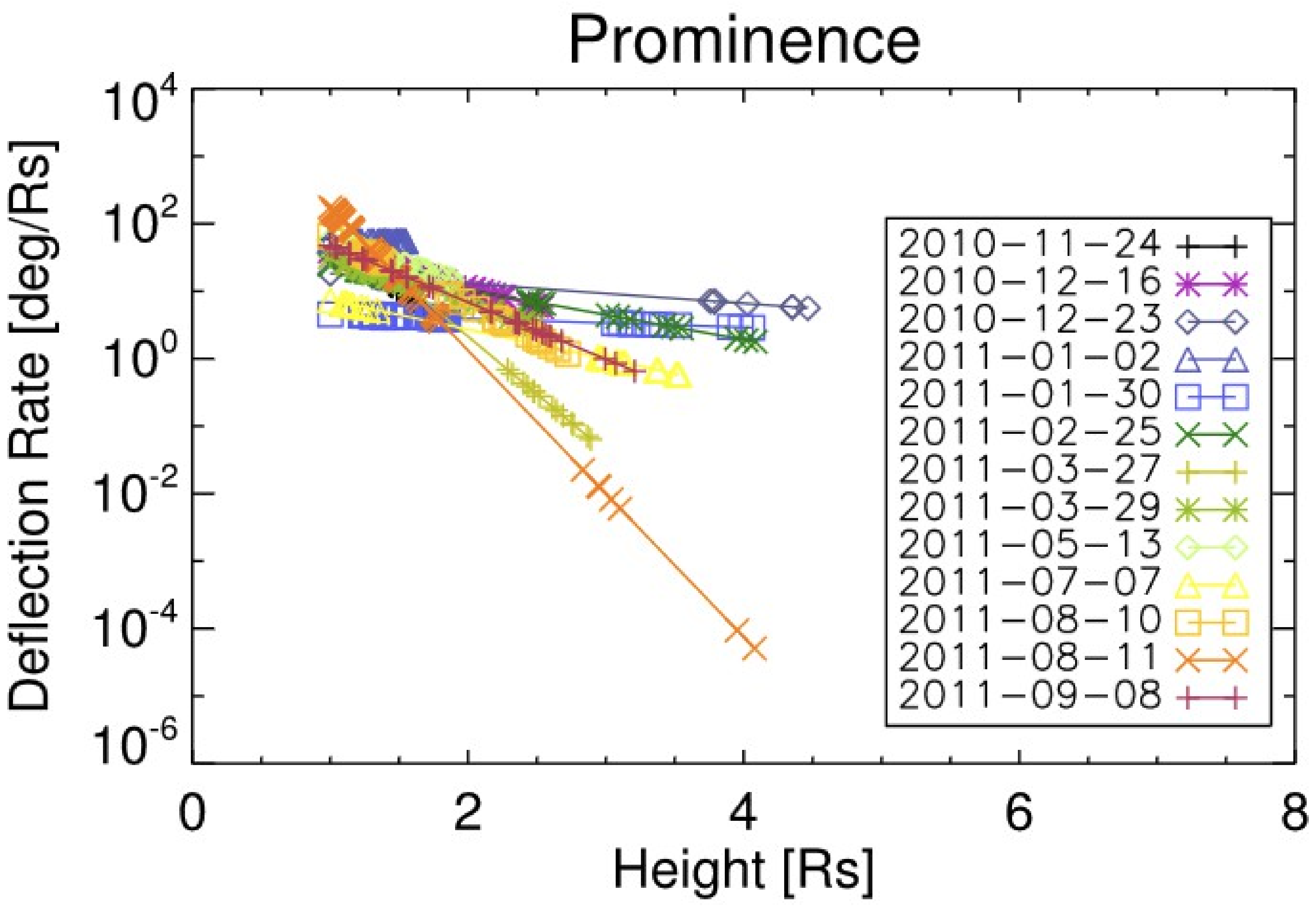
Palmerio et al. 2021

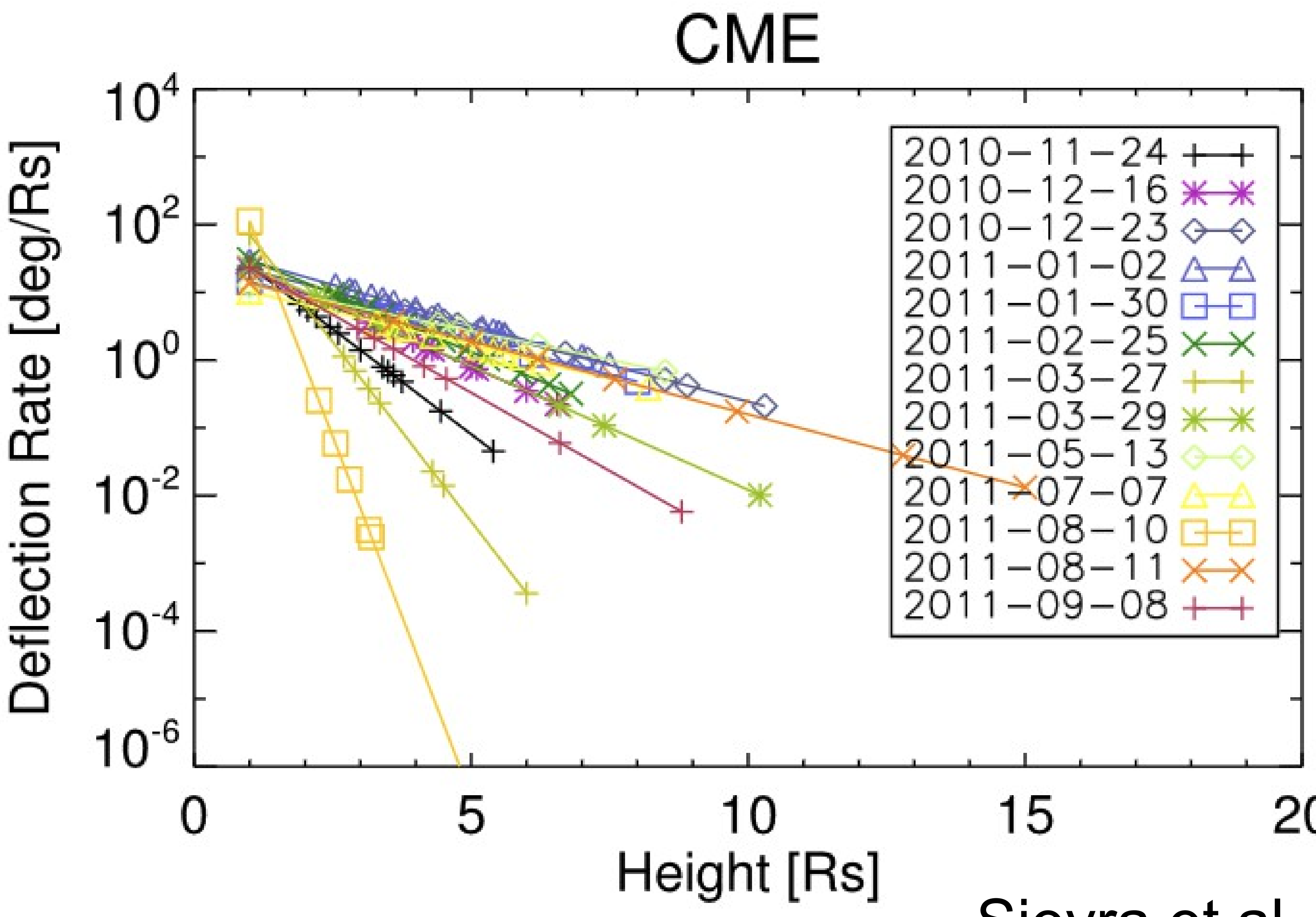
Deflection in the low corona

- Most of the deflection with respect to the source region occurs below 2.4Rs.
- The deflection rate of prominences is proportionally related with the magnetic gradient strength (the higher the gradient, the larger the deflection rate).





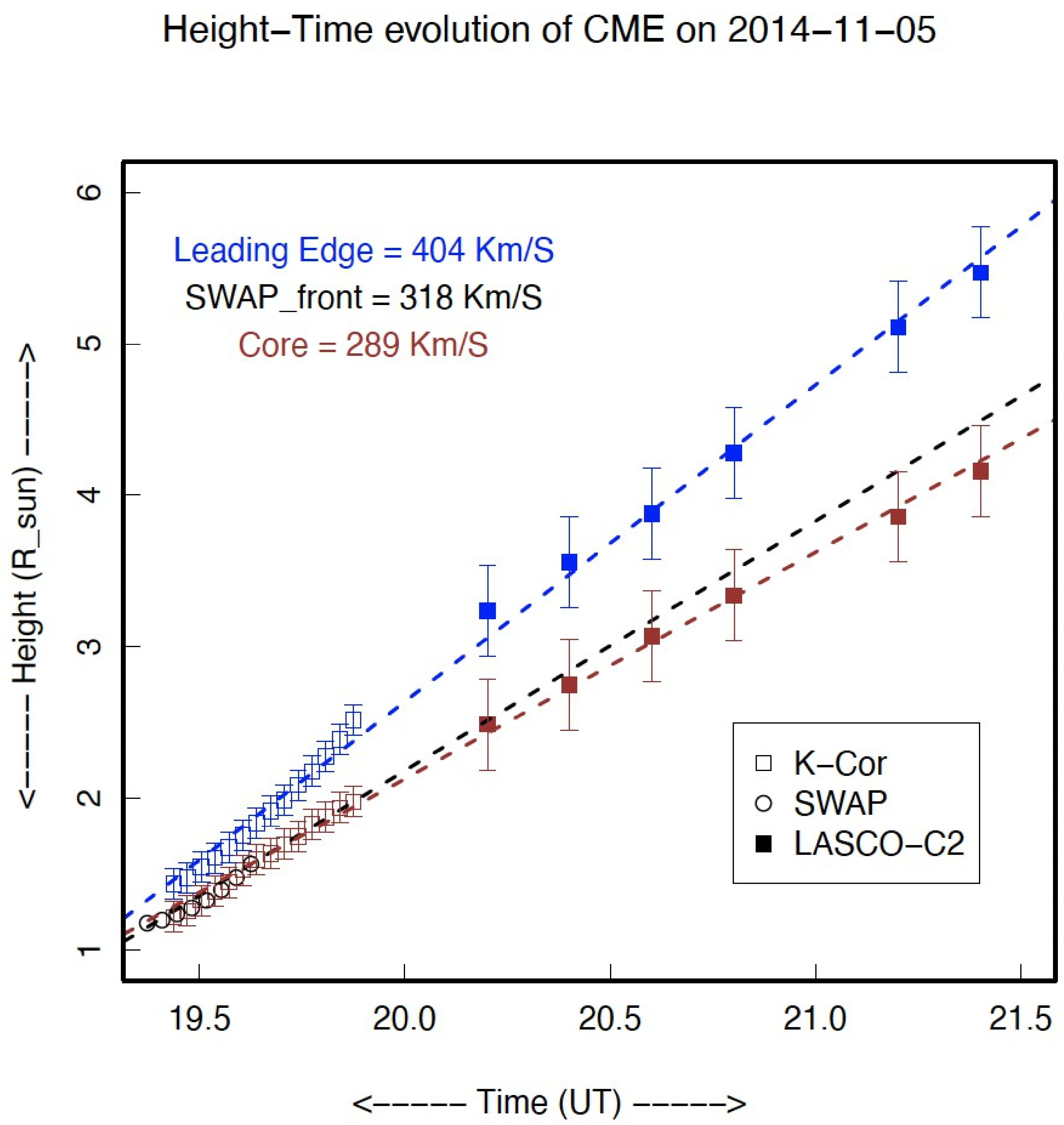


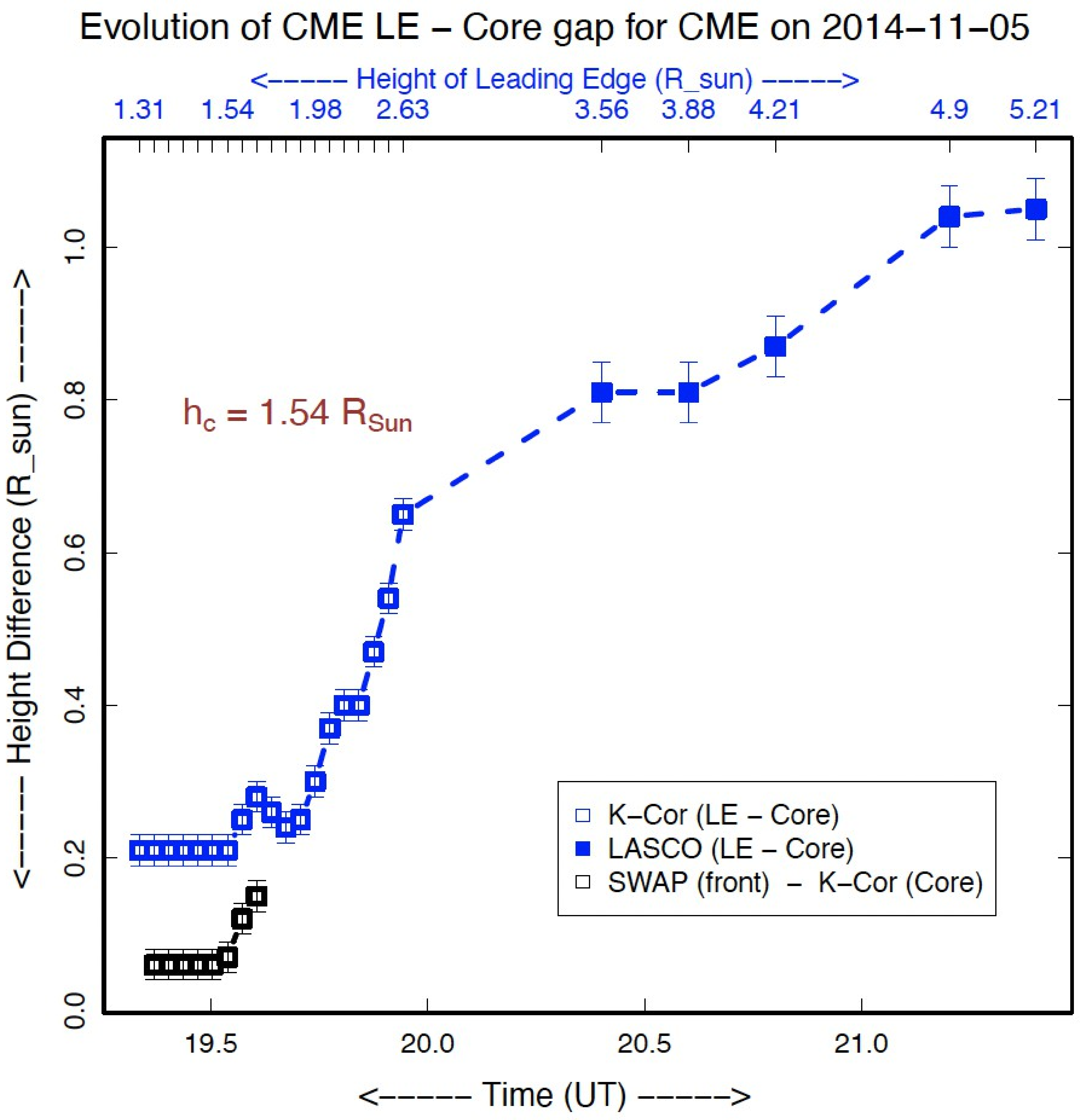


Sieyra et al. 2020, Cecere et al. 2020

Velocity dispersion in the low corona

The LE moves differently compared with the core of the CME.

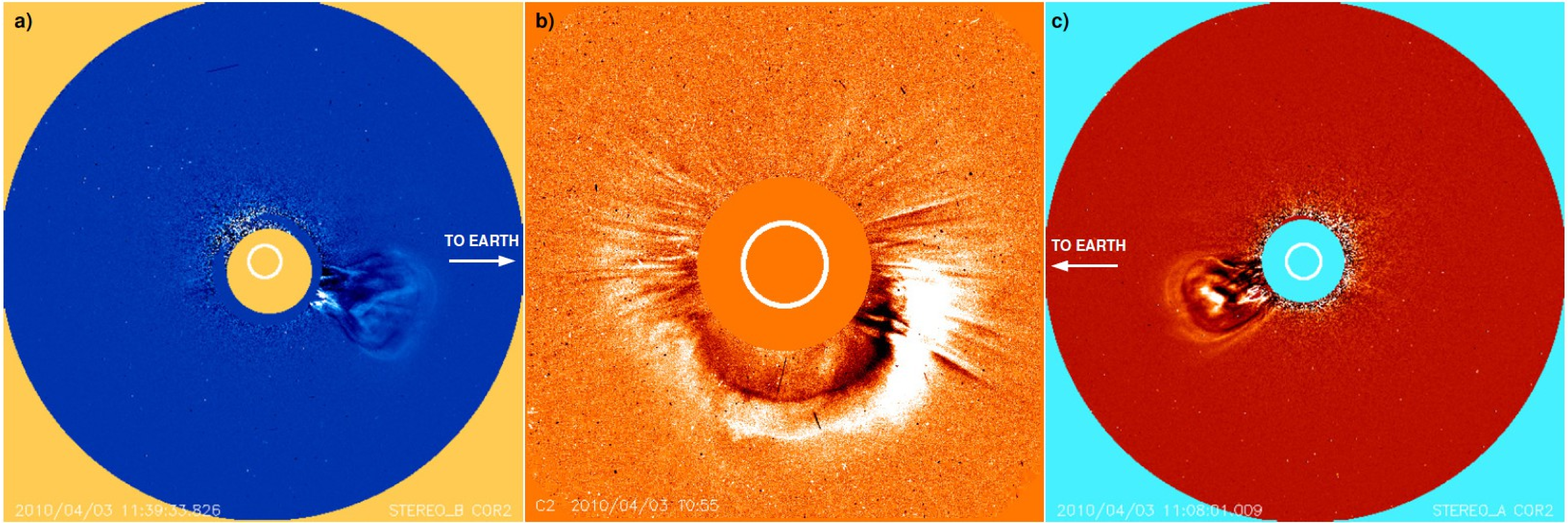




Majumdar et al. 2024

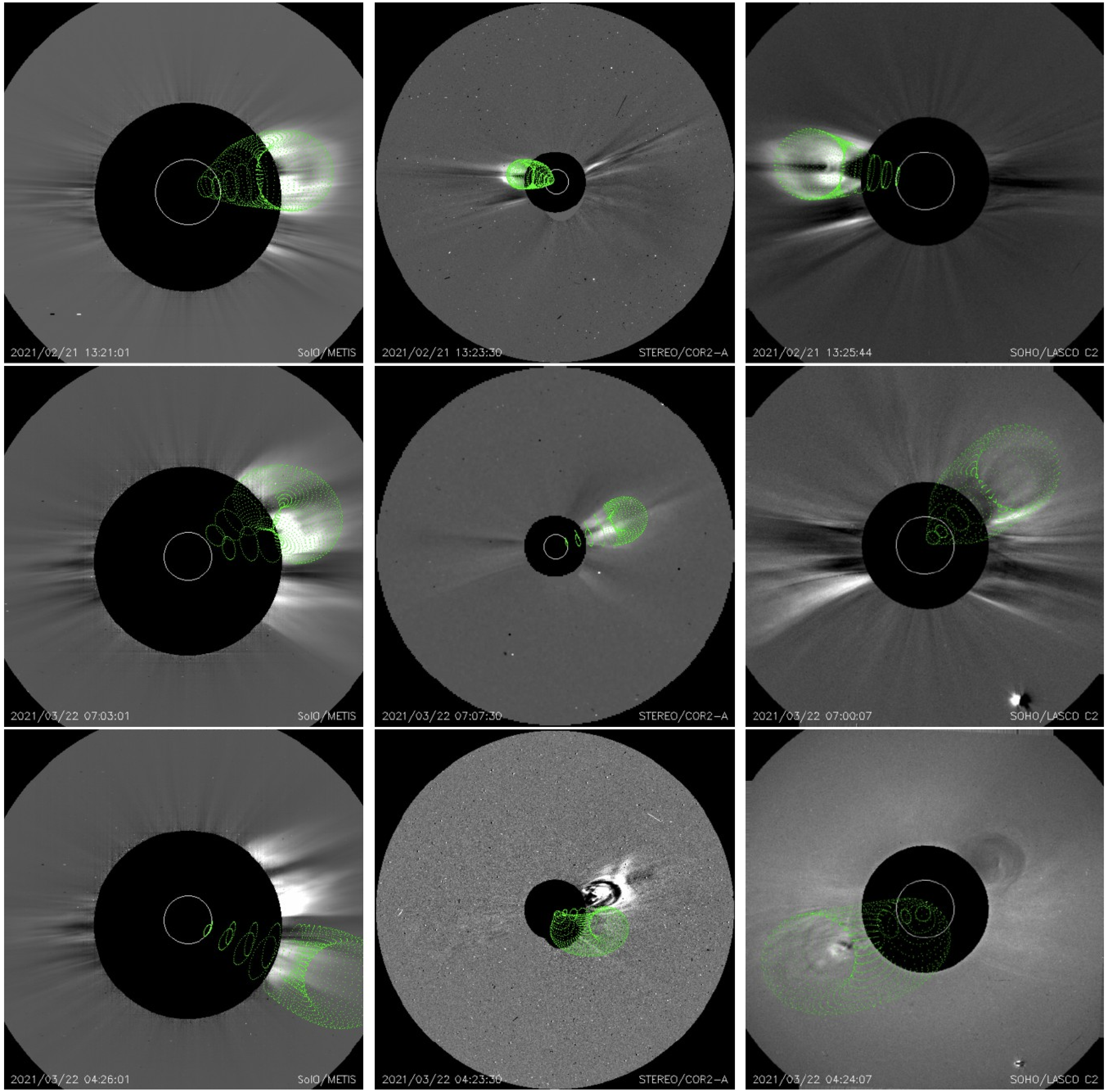
More CME Complexities

They appear different from different perspectives.



Webb and Howard 2012

3D Position - GCS

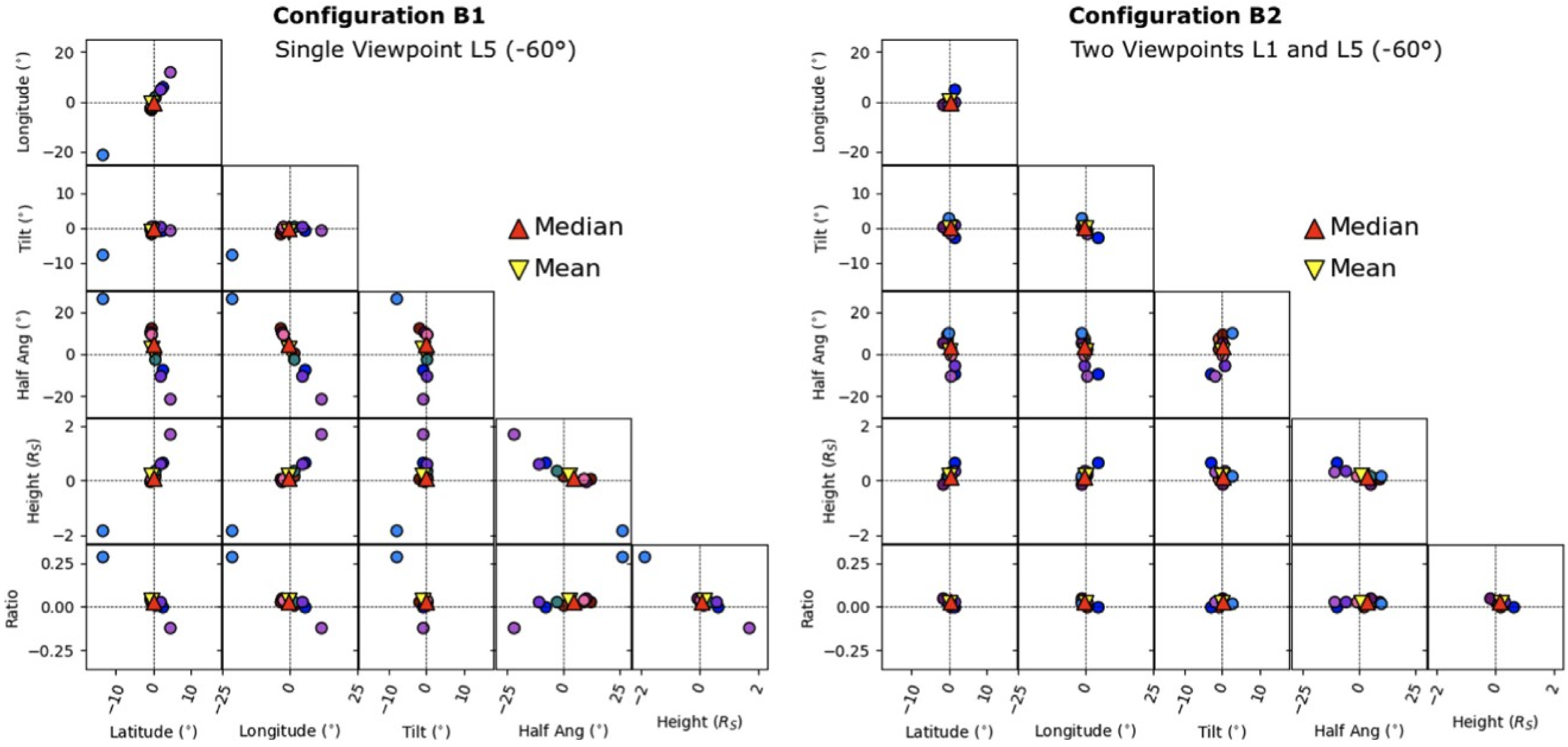


Three CMEs observed by:

- SolO/METIS
- STEREO/COR2A
- SOHO/LASCO-C2

Thernisien 2011, Mierla et al. 2023

Limitation in Number of Simultaneous Views



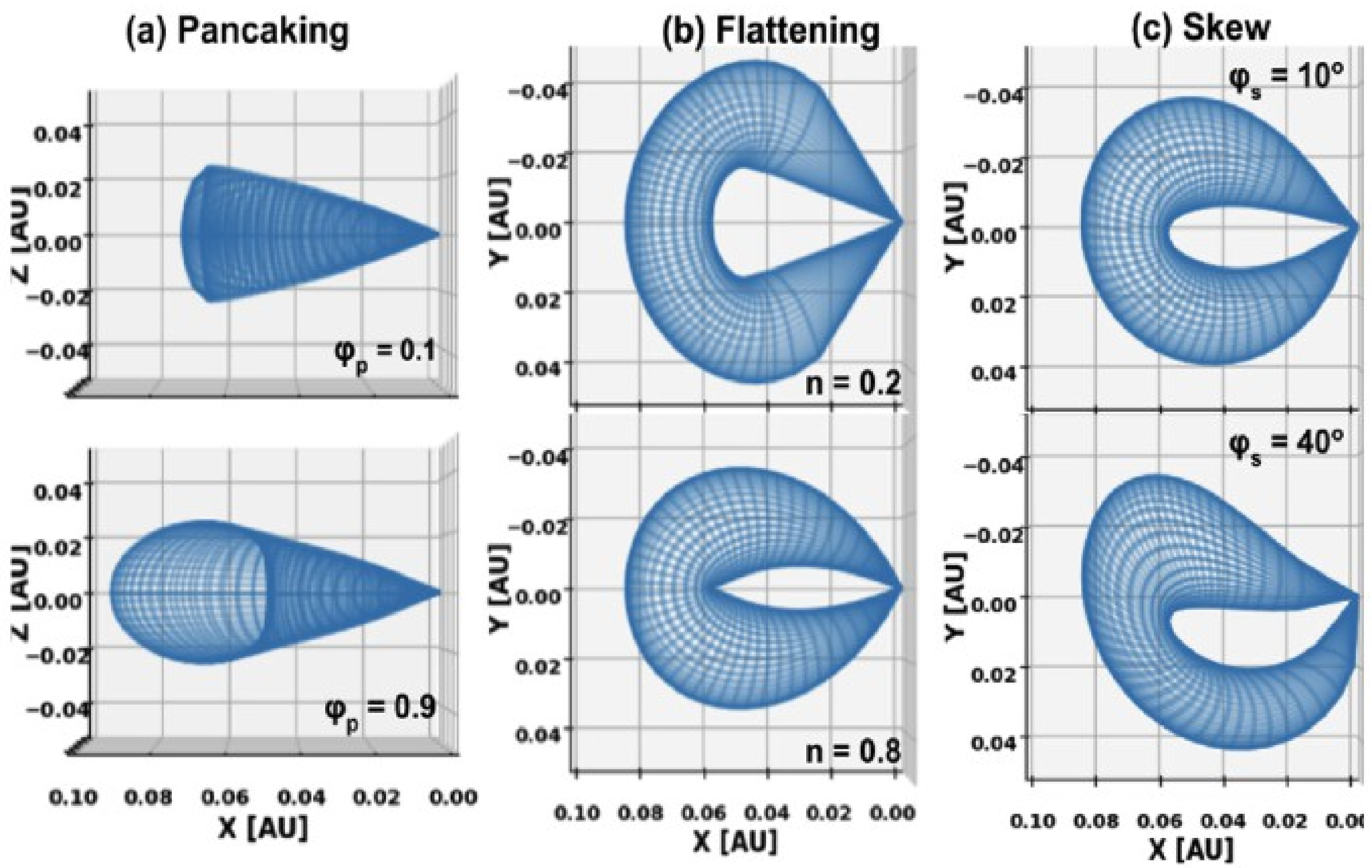
ISSI project, on *Understanding Our Capabilities In Observing And Modeling Coronal Mass Ejections* https://www.issibern.ch/teams/understandcormasseject/

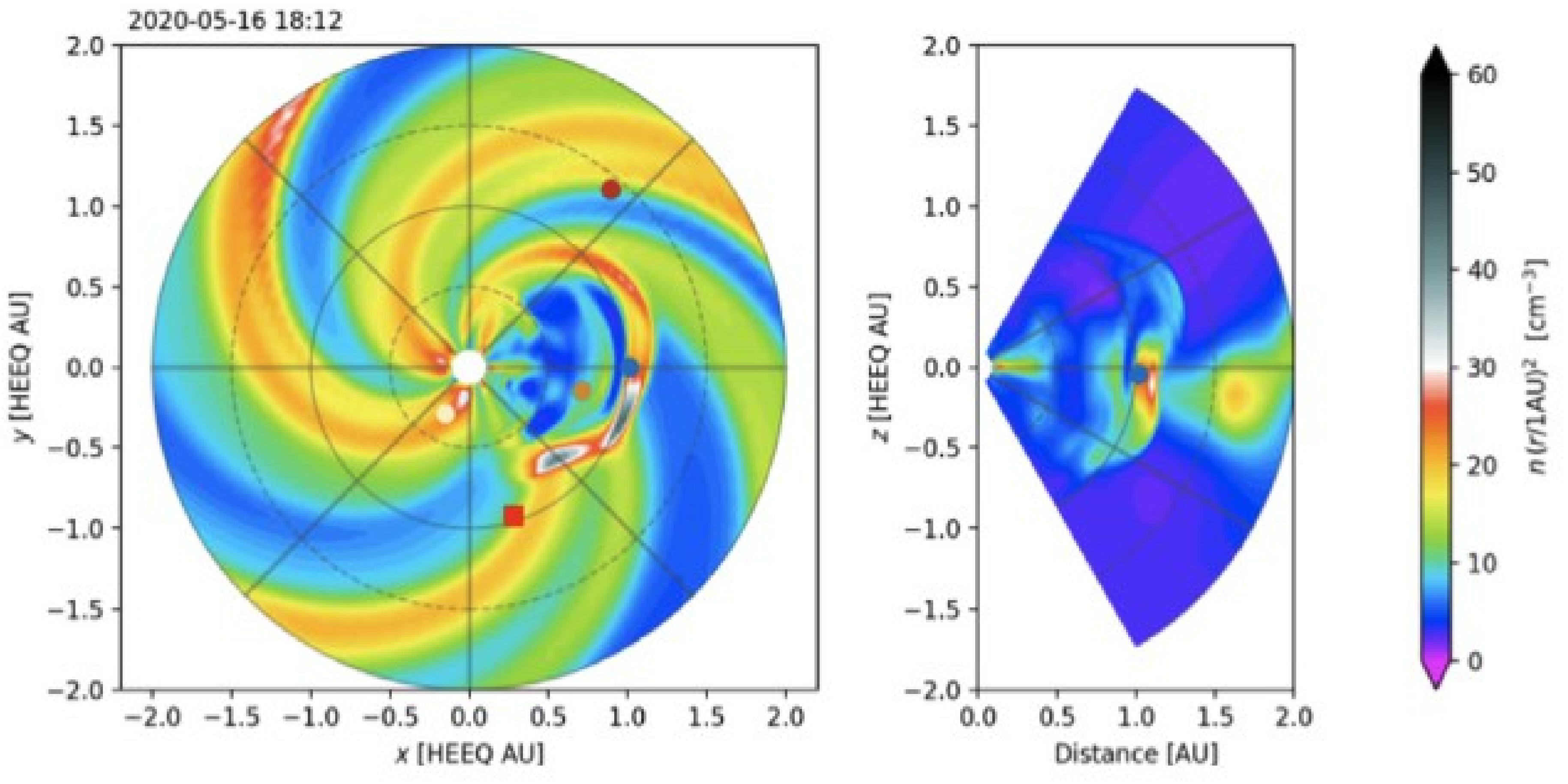
Verbeke et al. 2023

CME Modeling for EUHFORIA

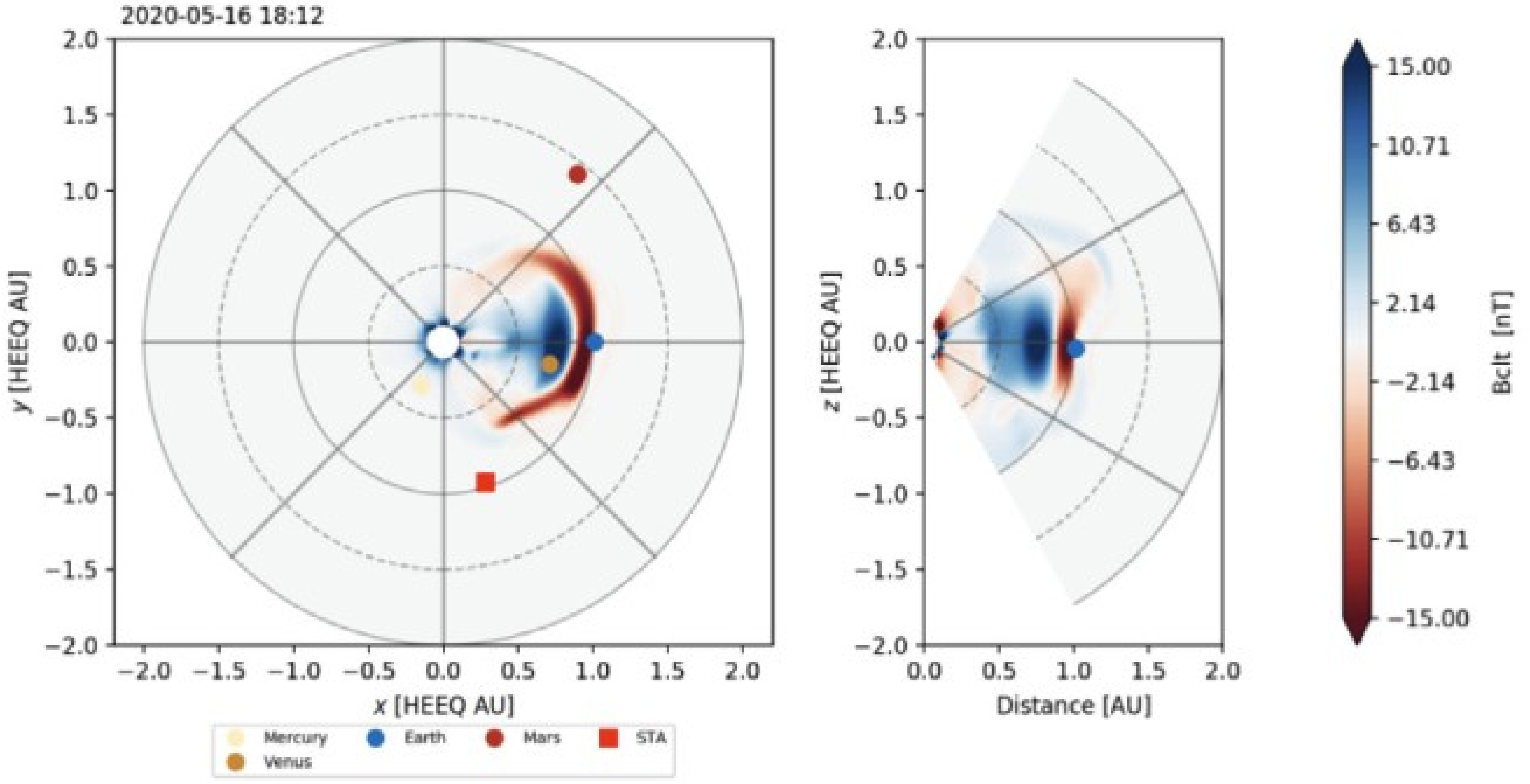
- The cone model - hydrodynamic cloud of plasma without any intrinsic magnetic field (see, e.g. Xue, Wang, and Dou, 2005; Gopalswamy et al., 2009; Na, Moon, and Lee, 2017, Scolini et al. 2019).
- The Graduated Cylindrical Shell model - GCS (Thernisien et al. 2006, 2009, Thernisien 2011)
- The Flux Rope in 3D (FRi3D) model - a global flux rope model that enables non-circular cross-section (Isavnin, 2016, Maharana et al. 2022) (https://pypi.org/project/ai.fri3d/)
- The spheromak model - magnetised linear force-free flux rope in spherical geometry (Chandrasekhar and Kendall, 1957; Verbeke, Pomoell, and Poedts, 2019; Scolini et al. 2019.)
- Toroidal model - non-circular cross-sections (Vandas and Romashets, 2017; Nieves-Chinchilla et al., 2022, 2023).
- Spheroid CME model (Scolini and Palmerio 2024)

CME Modeling for EUHFORIA - Fri3D





(c) FRi3D: Scaled number density



(e) FRi3D: Co-latitudinal magnetic field component

FRi3D improves the modelling of the total magnetic field magnitude and Bz at Earth as well as the predictions of minimum Dst.

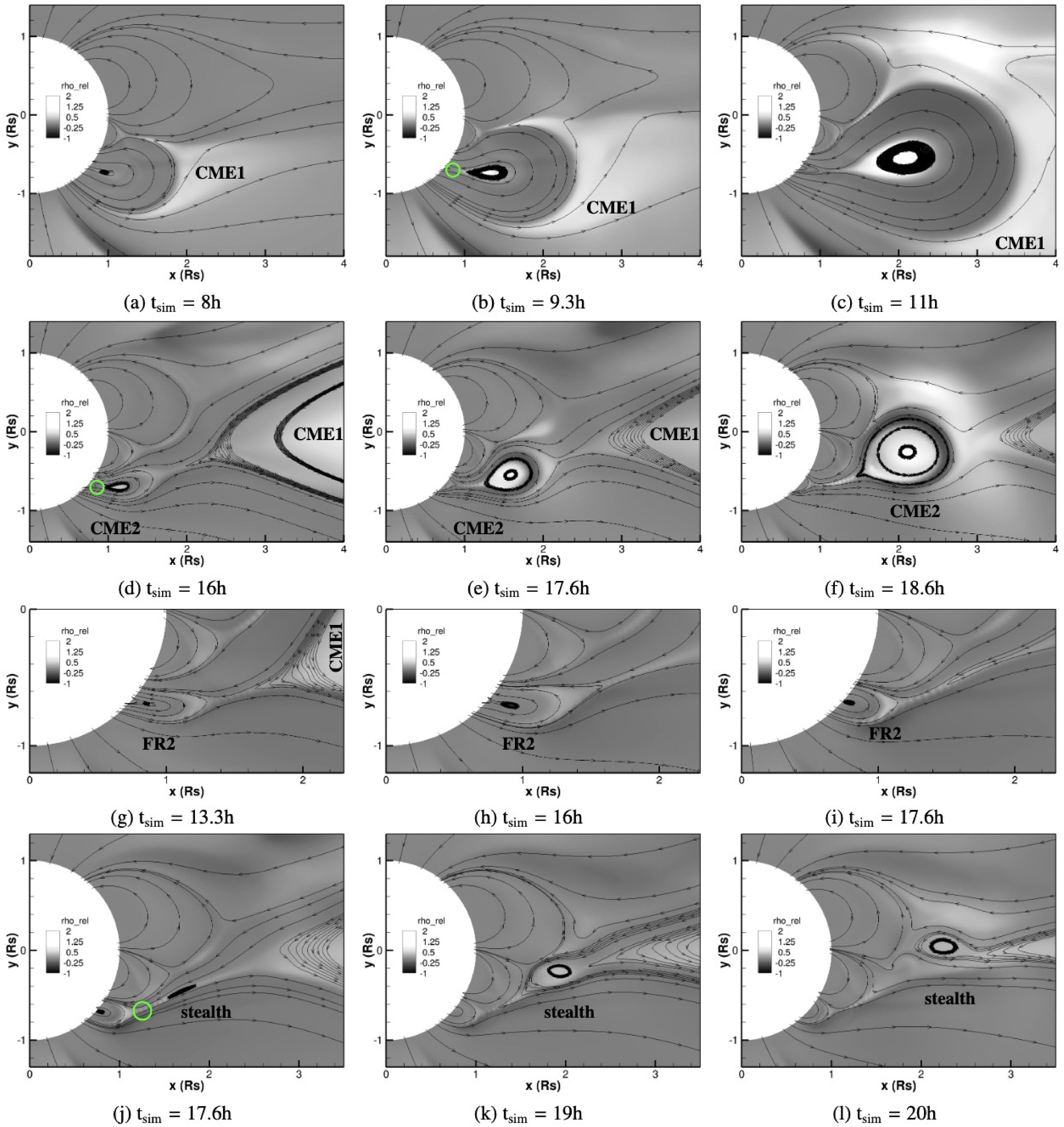
Maharana et al. 2022

MHD Simulations

MHD code: MPI AMRVAC (parallelized Adaptive Mesh Refinement Versatile Advection Code)

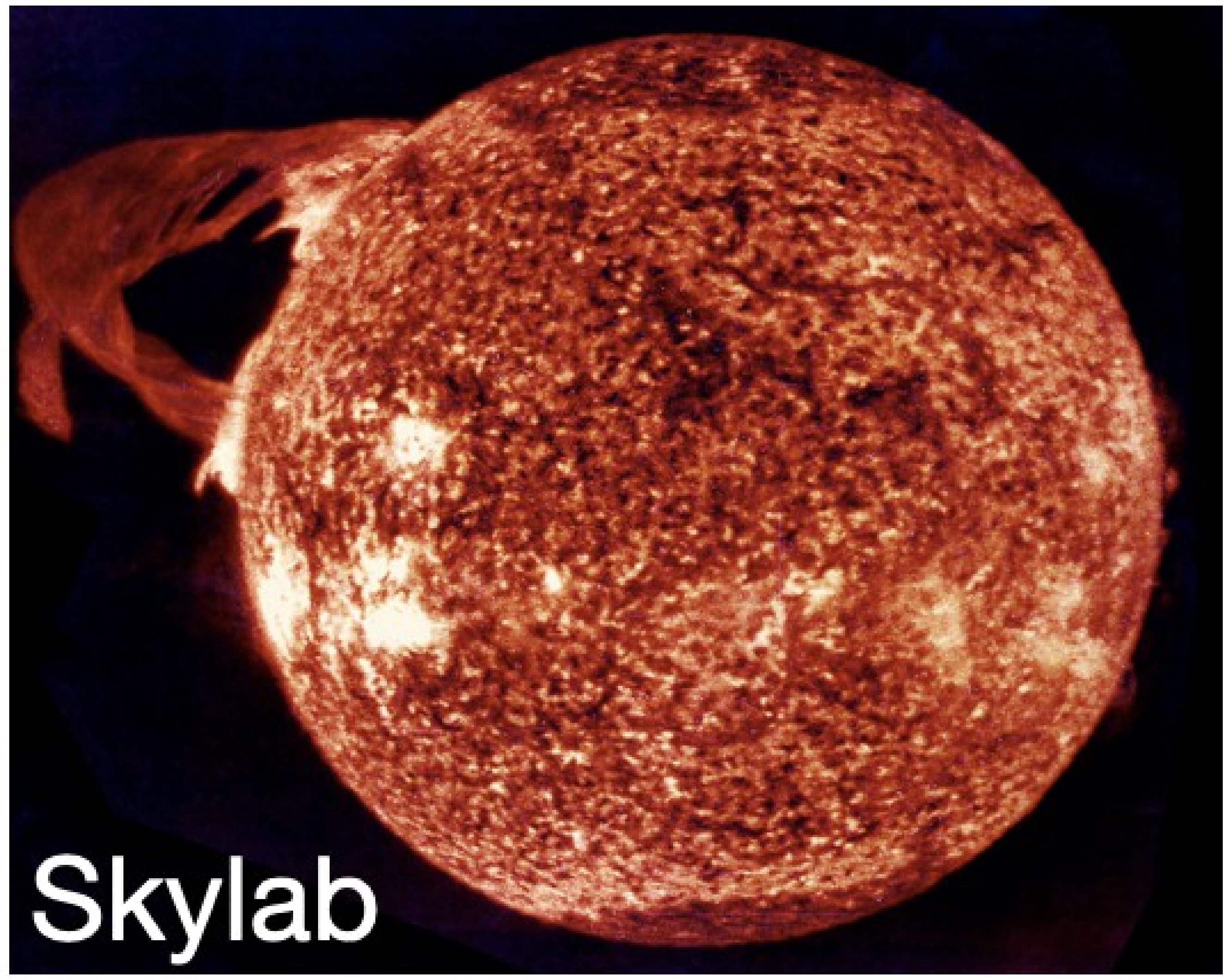
CME triggering: Symmetric shearing motions with respect to the southern most polarity inversion line

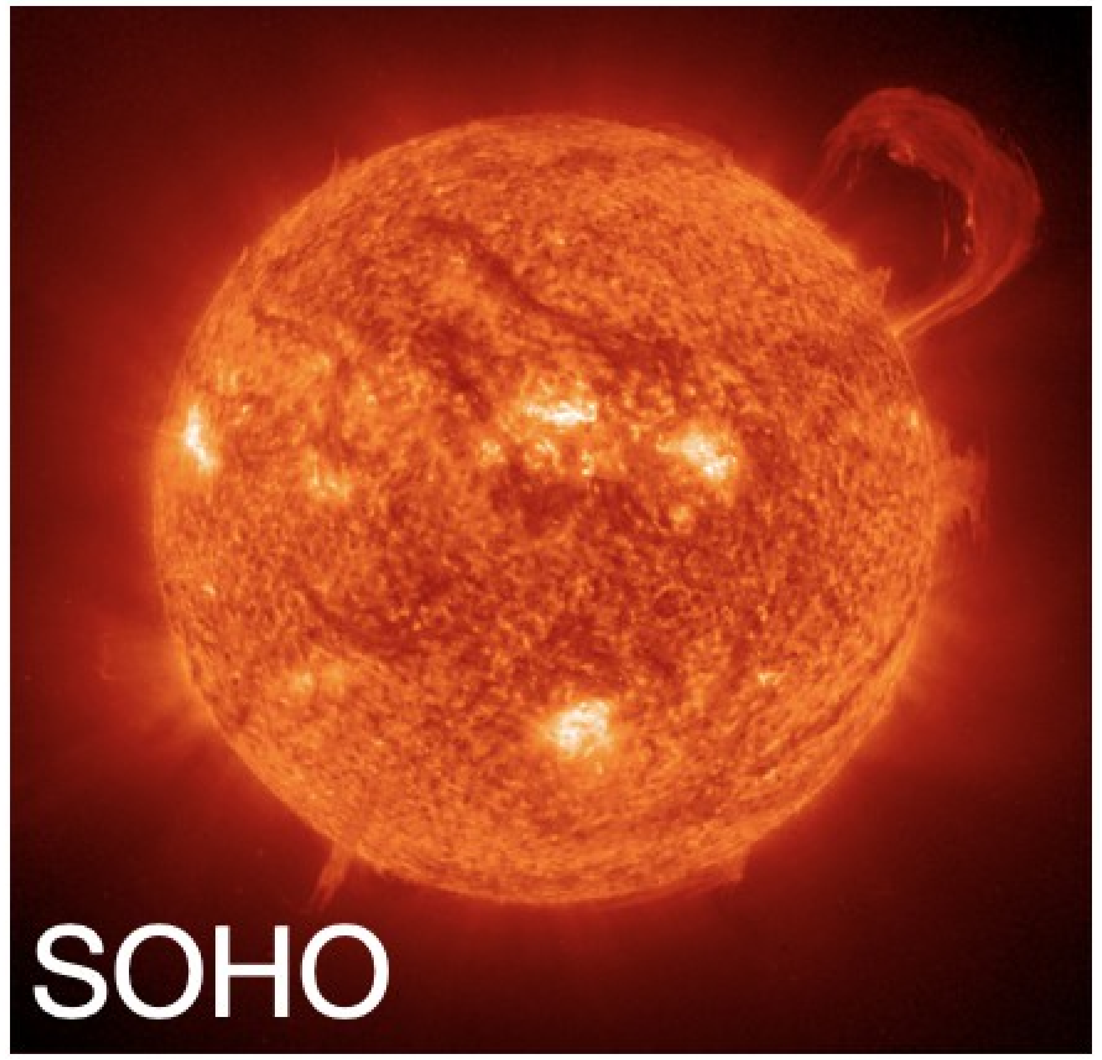
Stealth CME

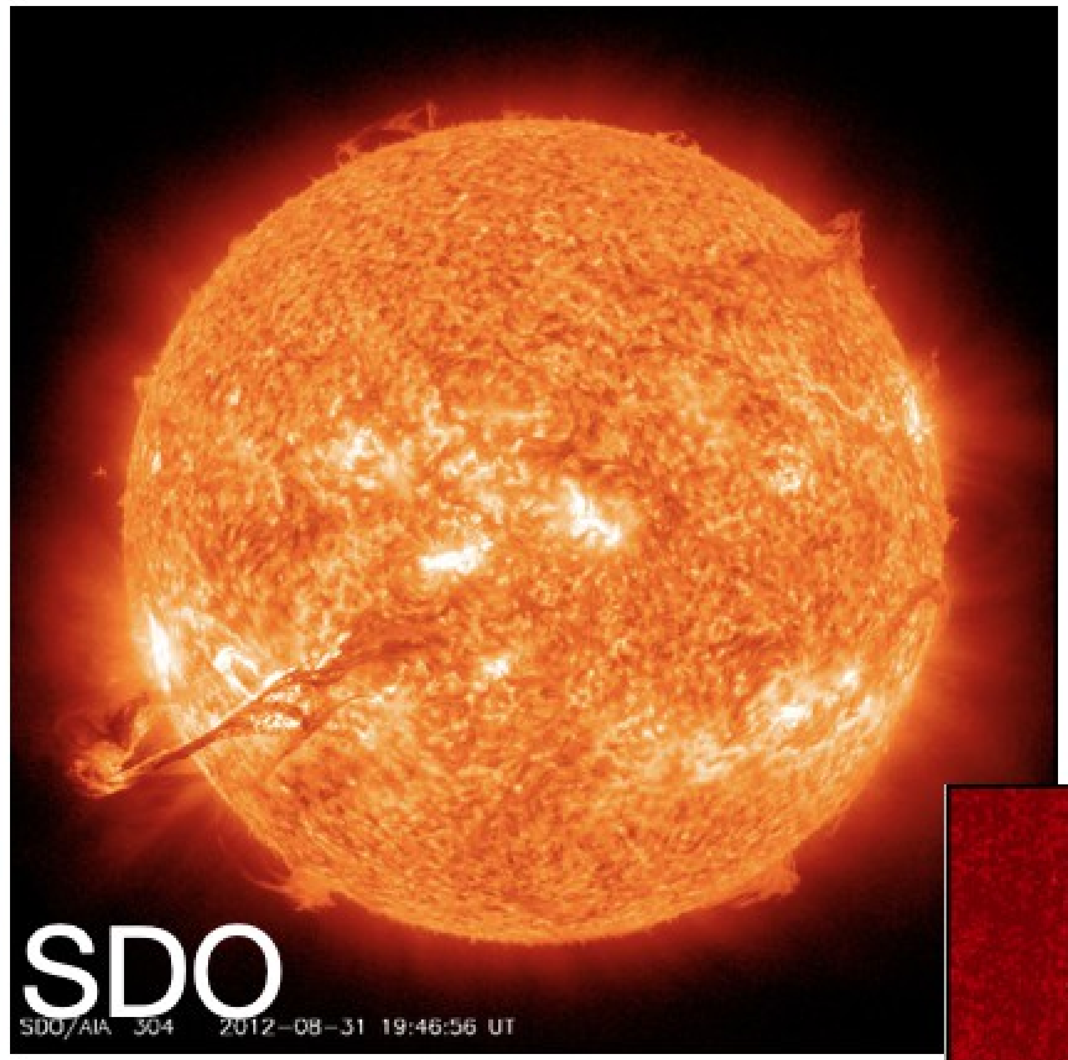


Talpeanu et al. 2020, 2021

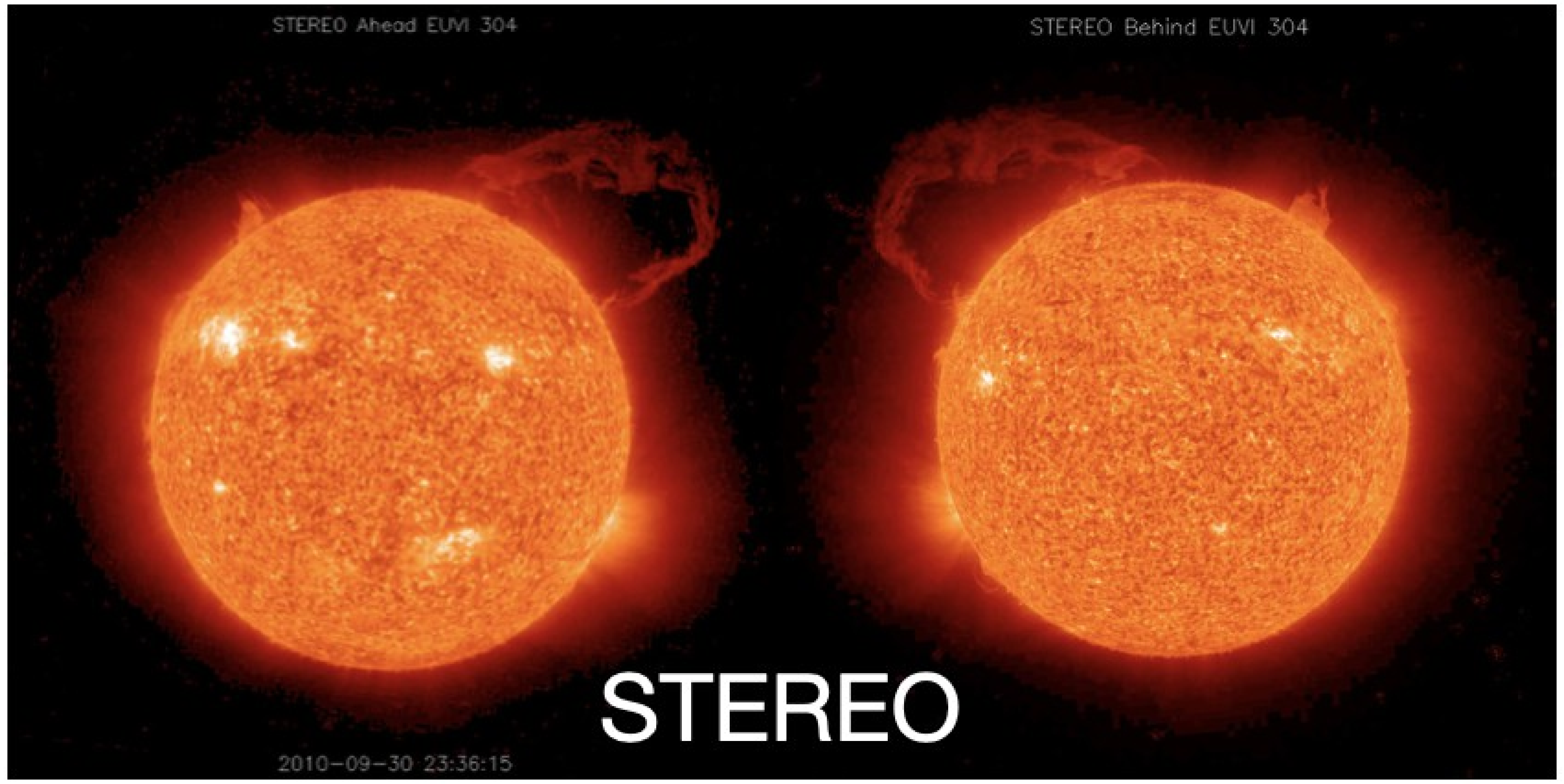
Prominence eruptions observed in He II 304 Å

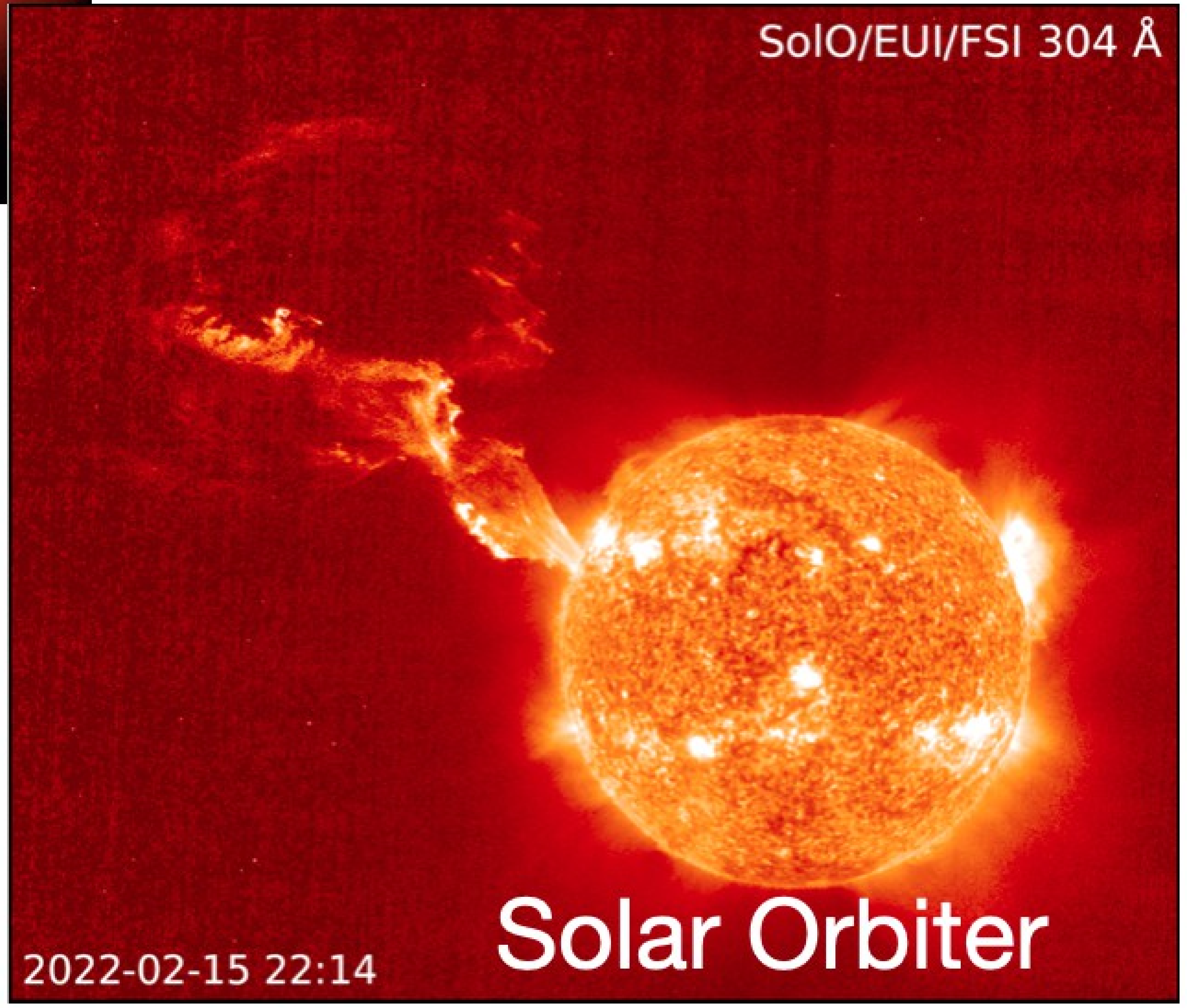




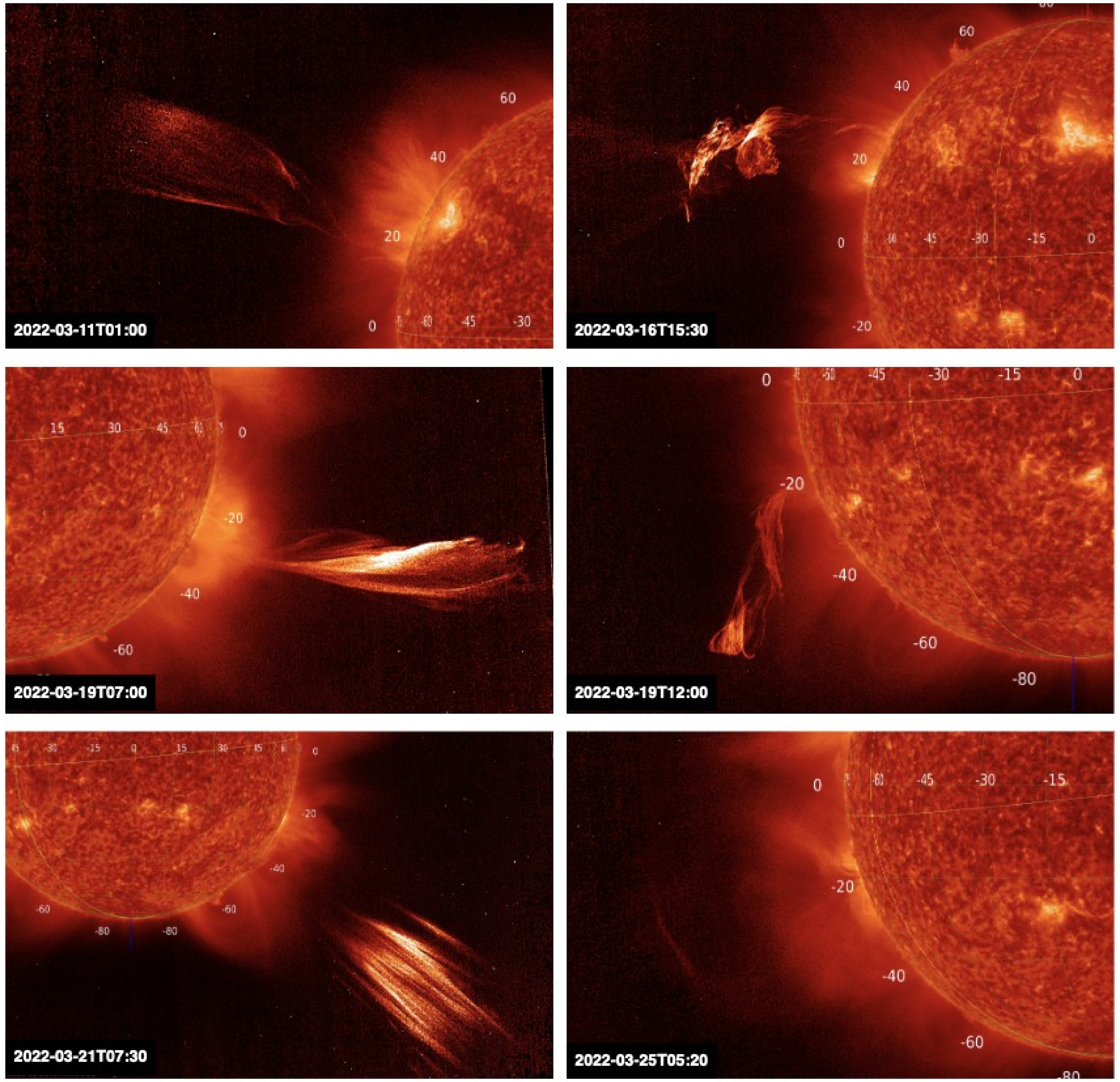


Each solar space mission has an iconic prominence eruption…



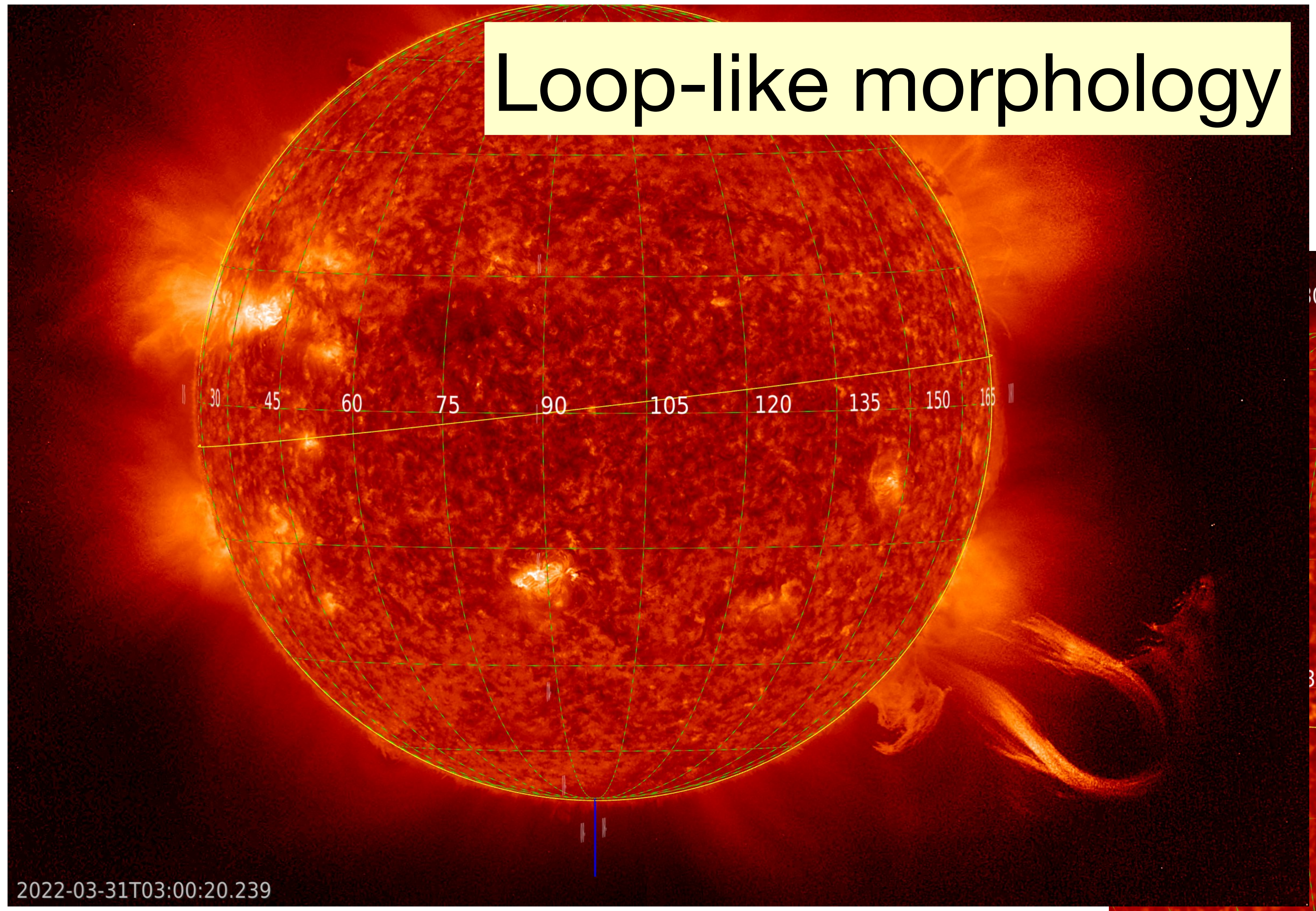


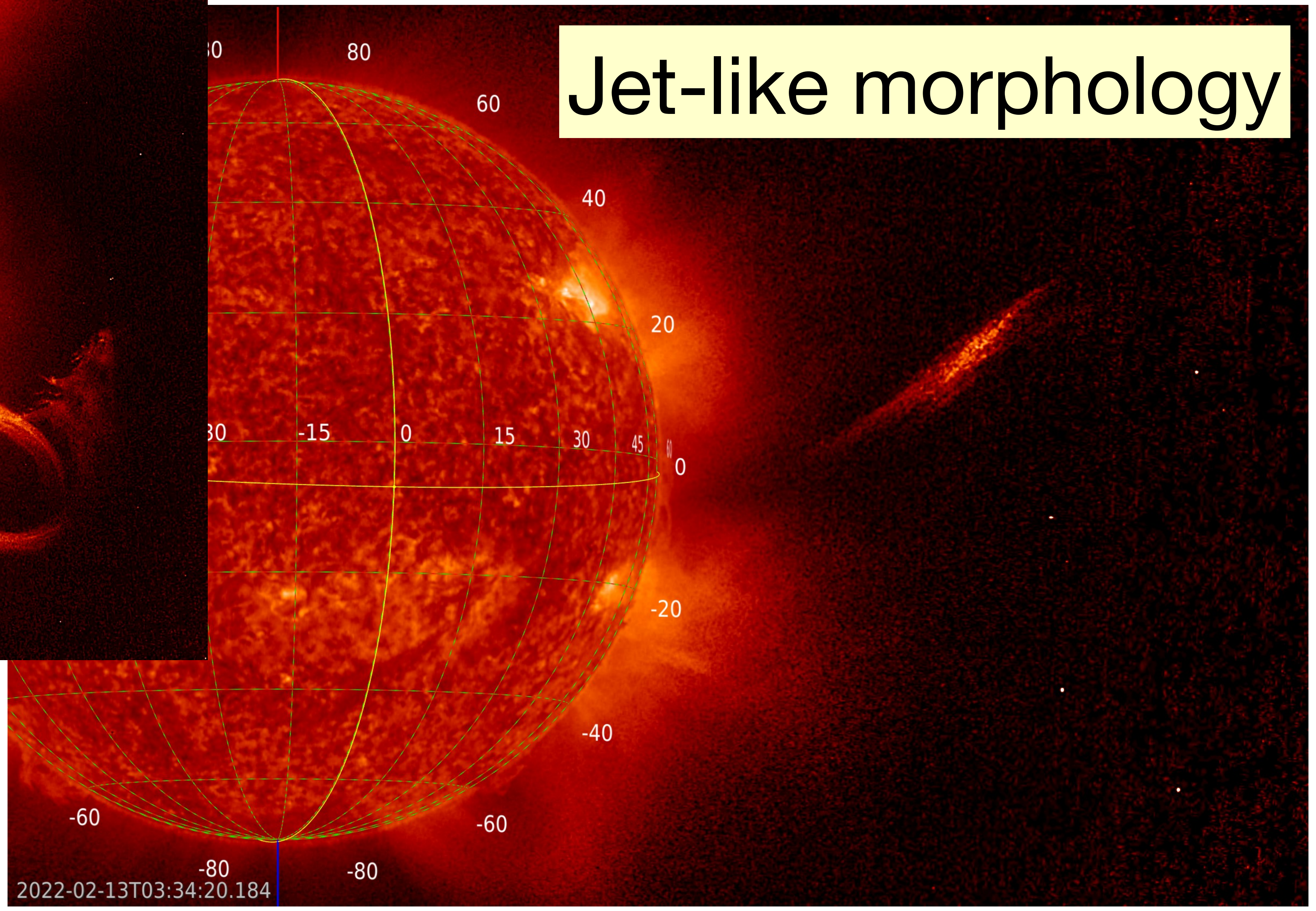
Prominence eruptions observed with SolO/EUI/FSI304

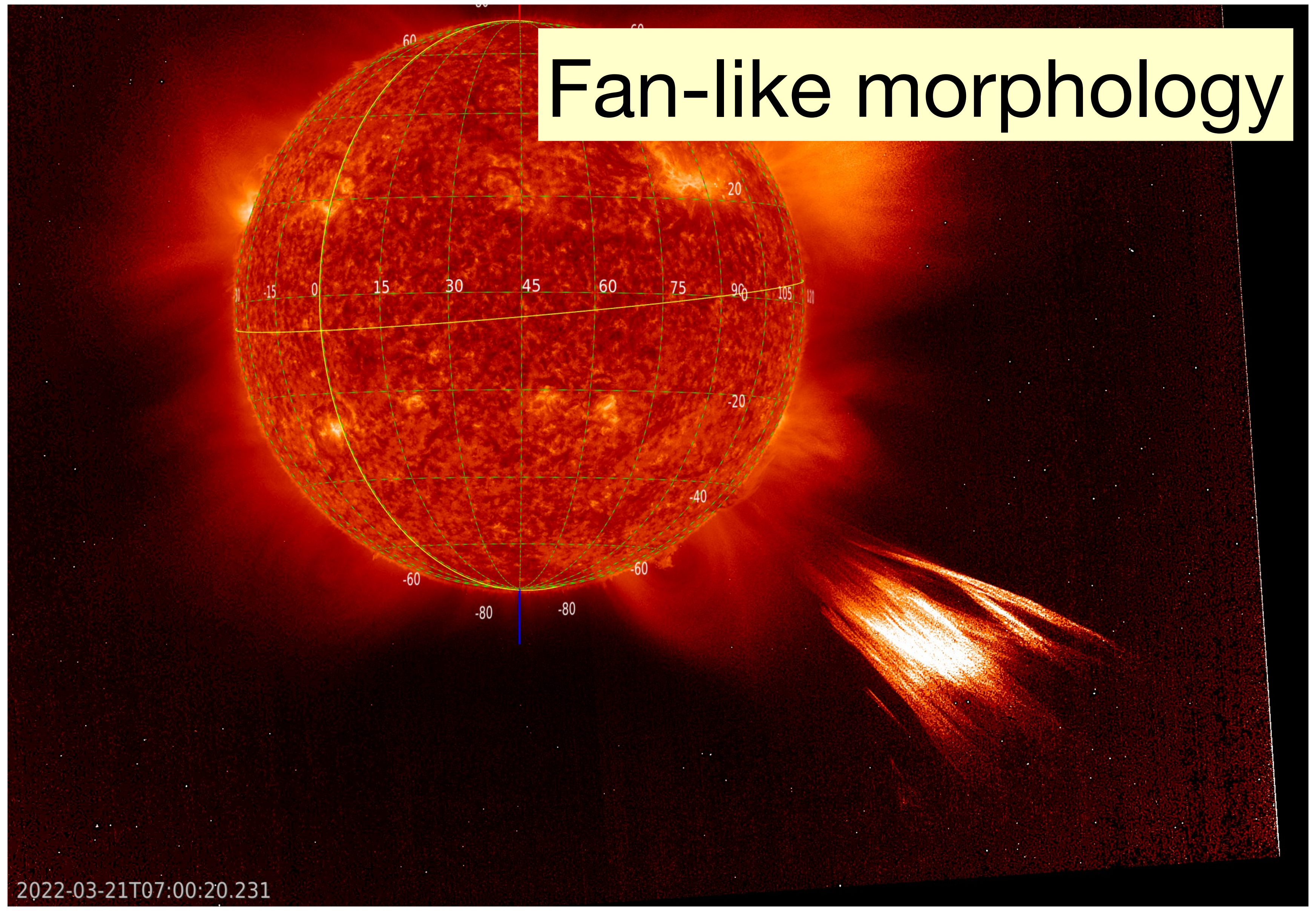


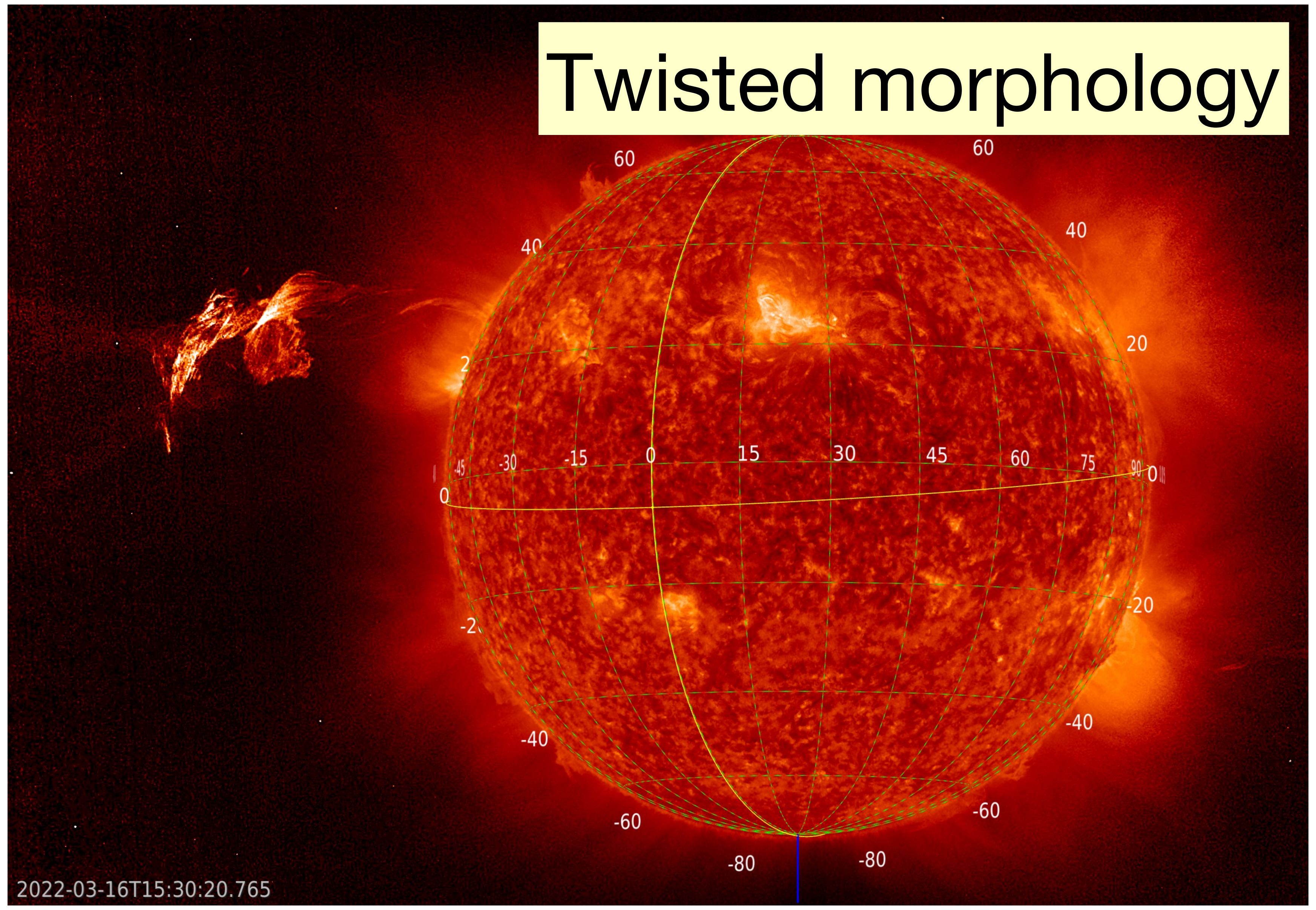
Berghmans et al. 2023

Prominence eruptions observed with SolO/EUI/FSI304



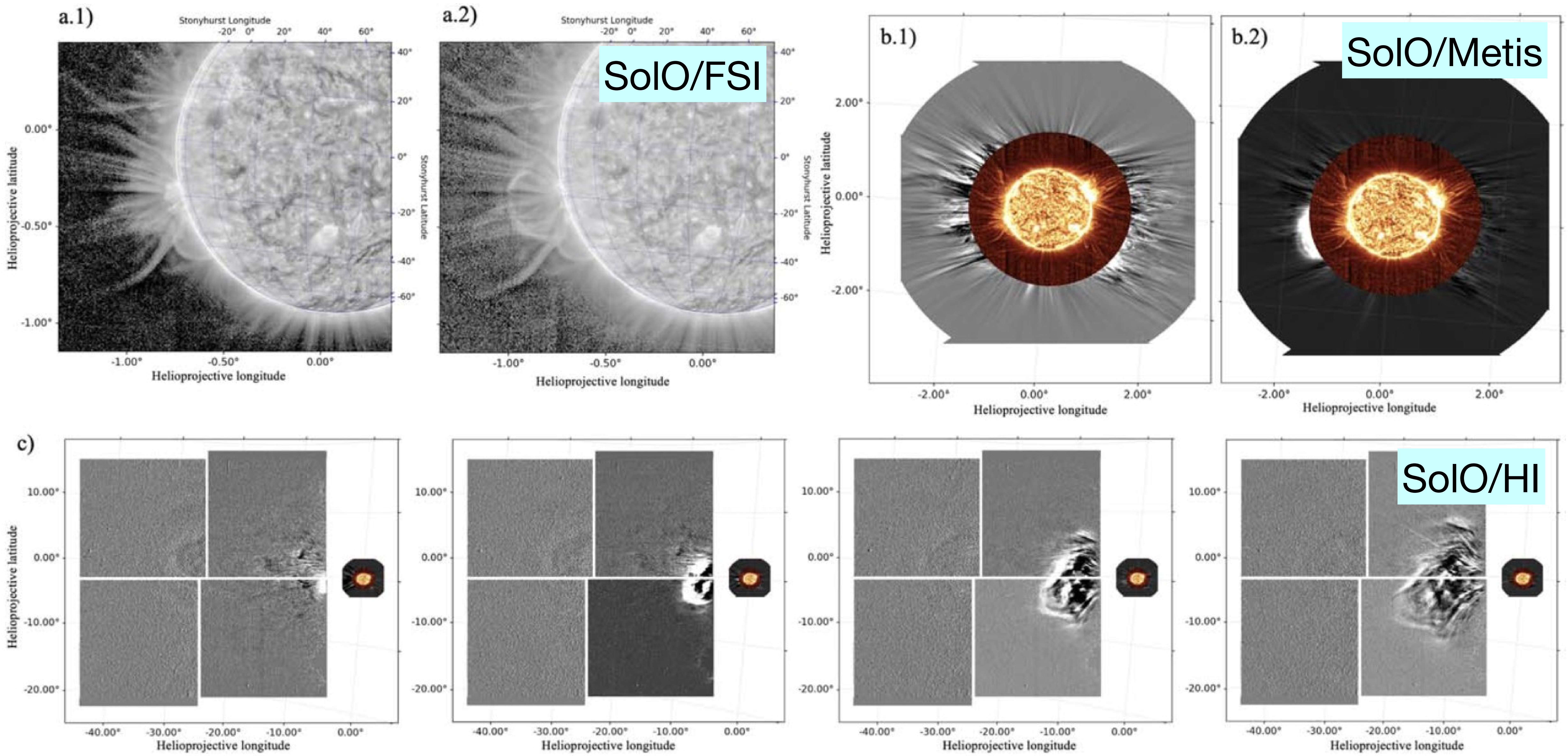






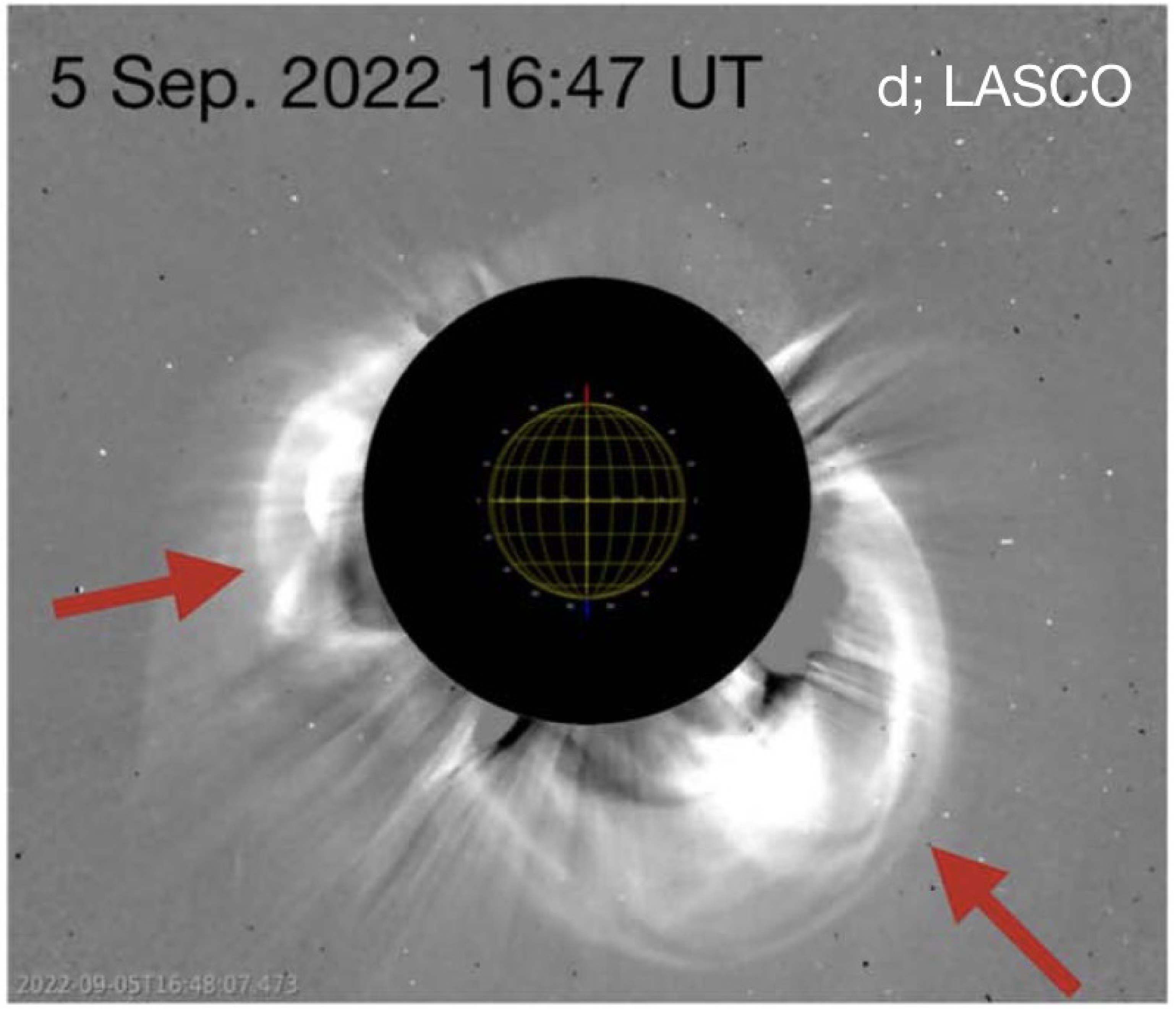
D'Huys et al., in preparation

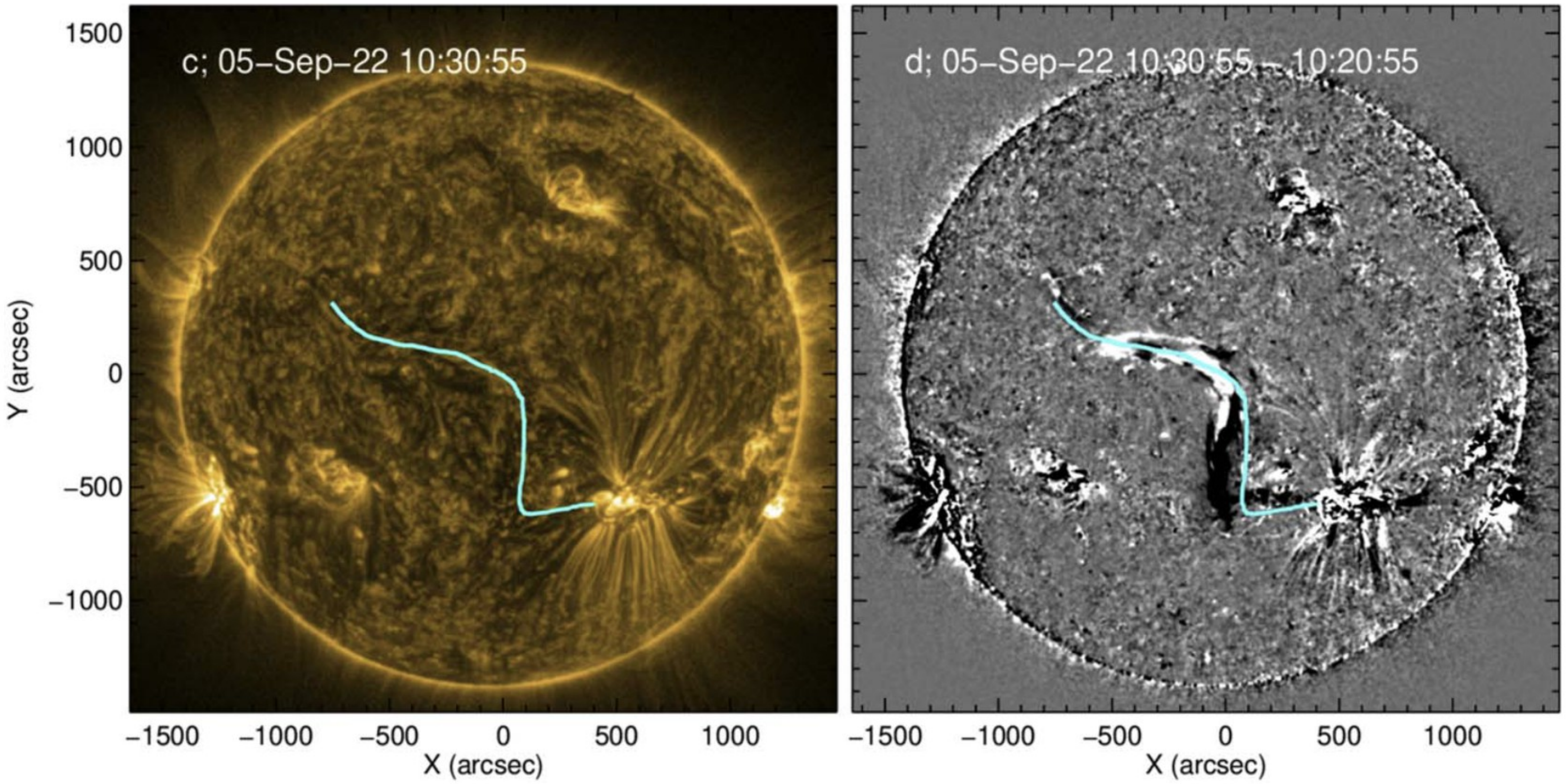
Multi-spacecraft Observations of the 2022 March 25 CME

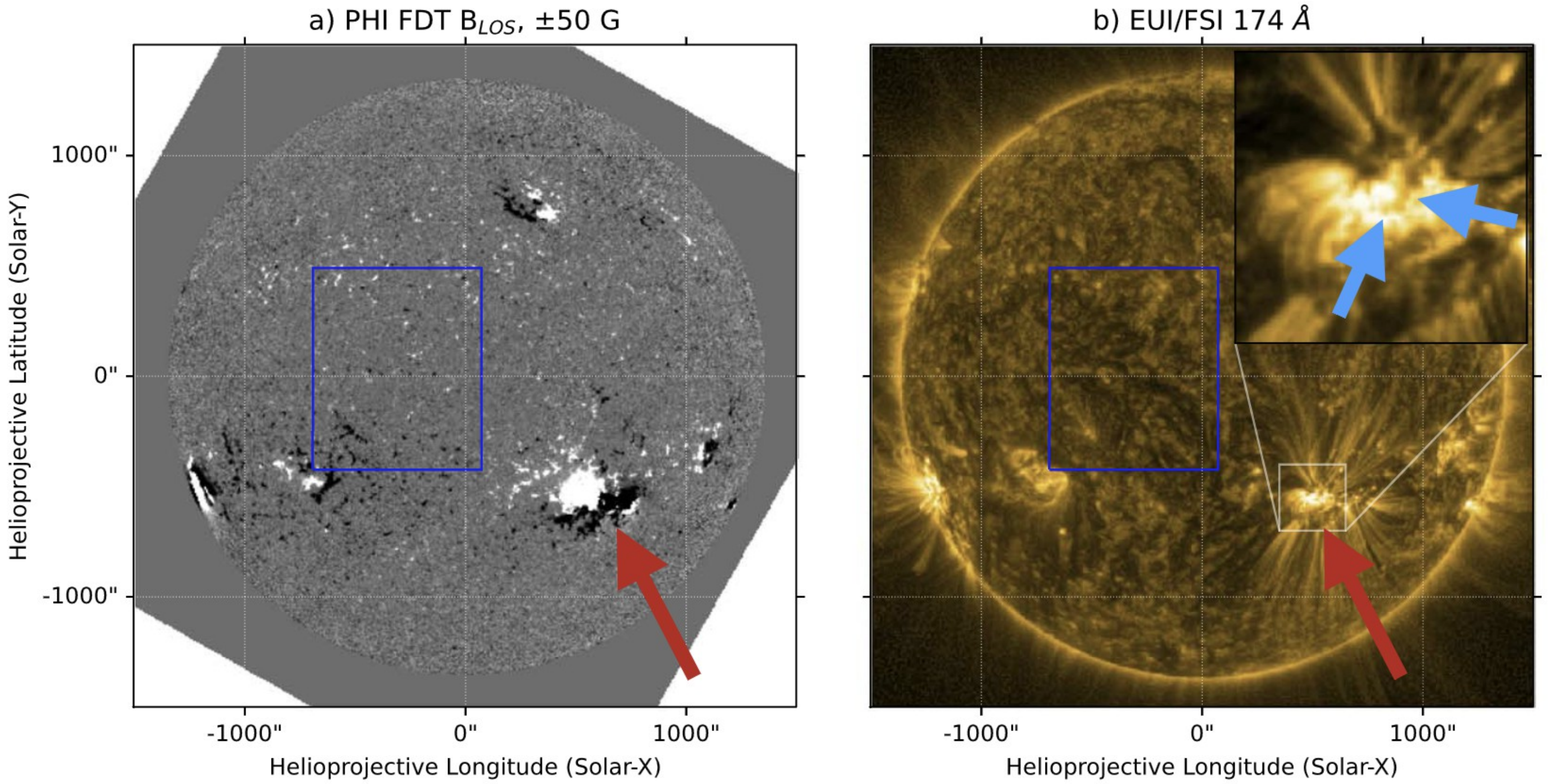


Liberatore et al. 2023

Eruption of a flux-rope observed by SolO and PSP

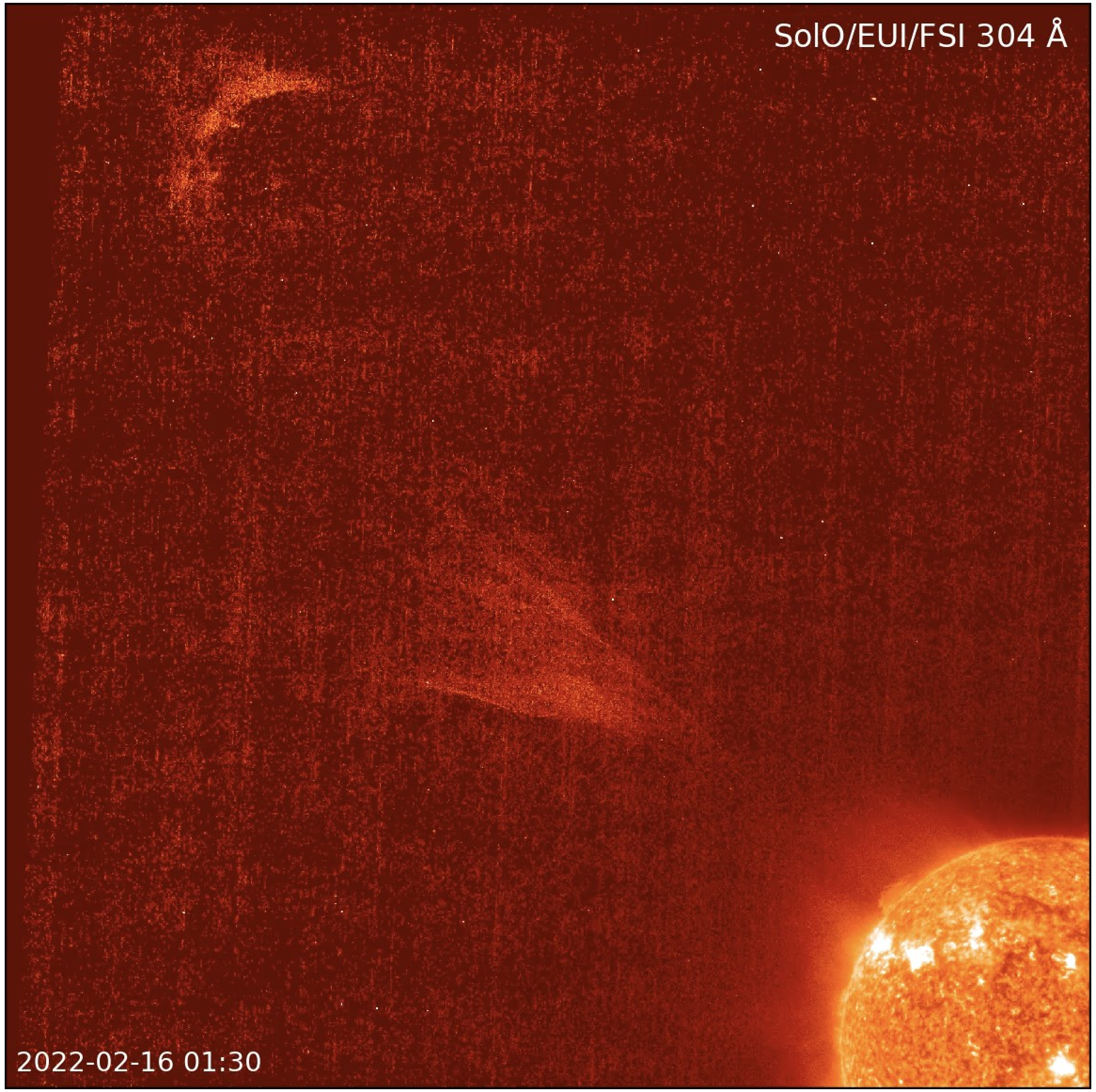






Long et al. 2023

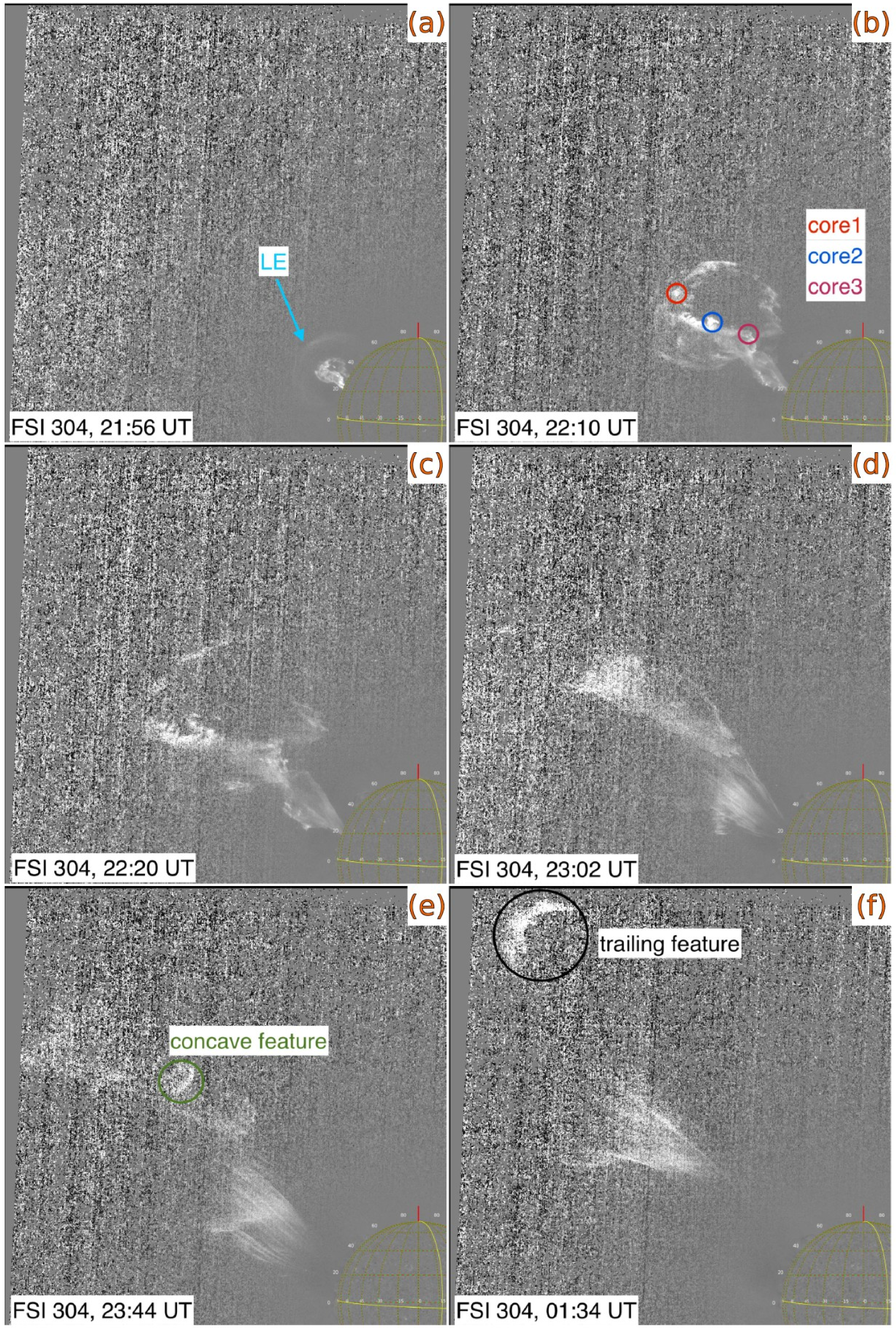
Prominence eruption on 15 February 2022

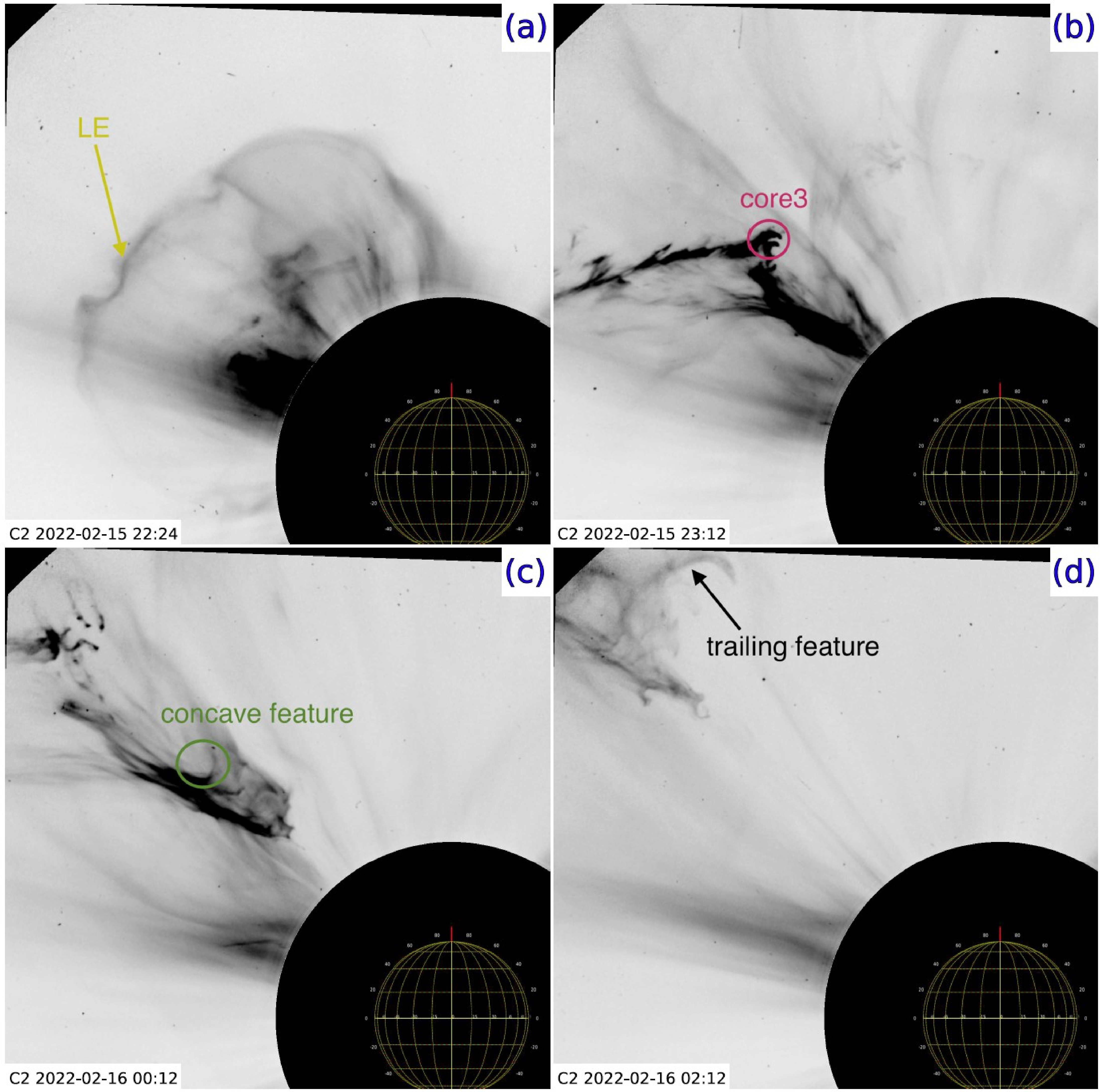


- The erupting prominence goes up to the corner of the EUI/FSI field of view.
- This was the first event in which the He II (304 Å) emission in a prominence could be tracked so far away from the Sun (plane-of-the-sky projected height of 6.64 Rs).

Mierla et al. 2022

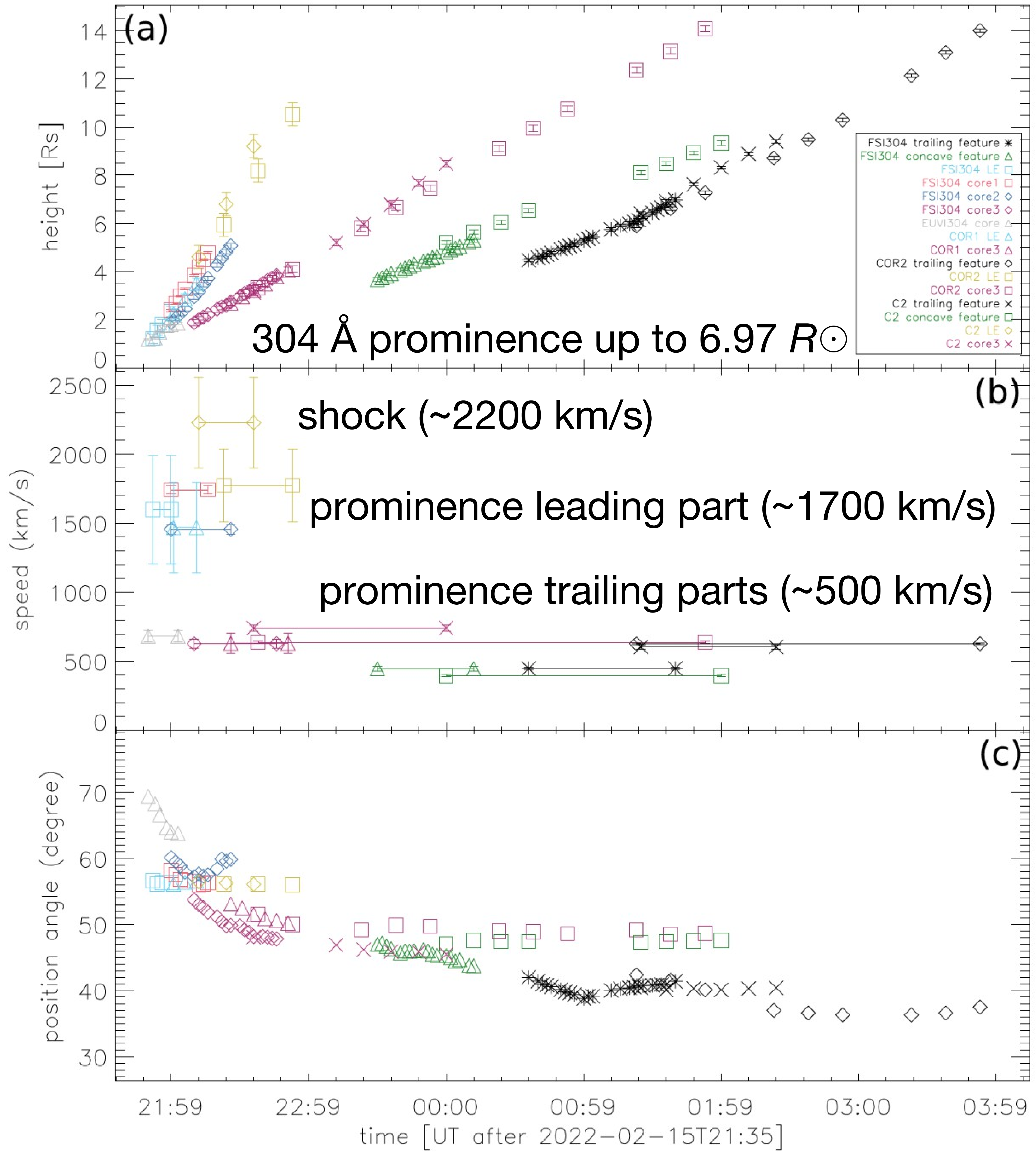
Solar Orbiter & SOHO views

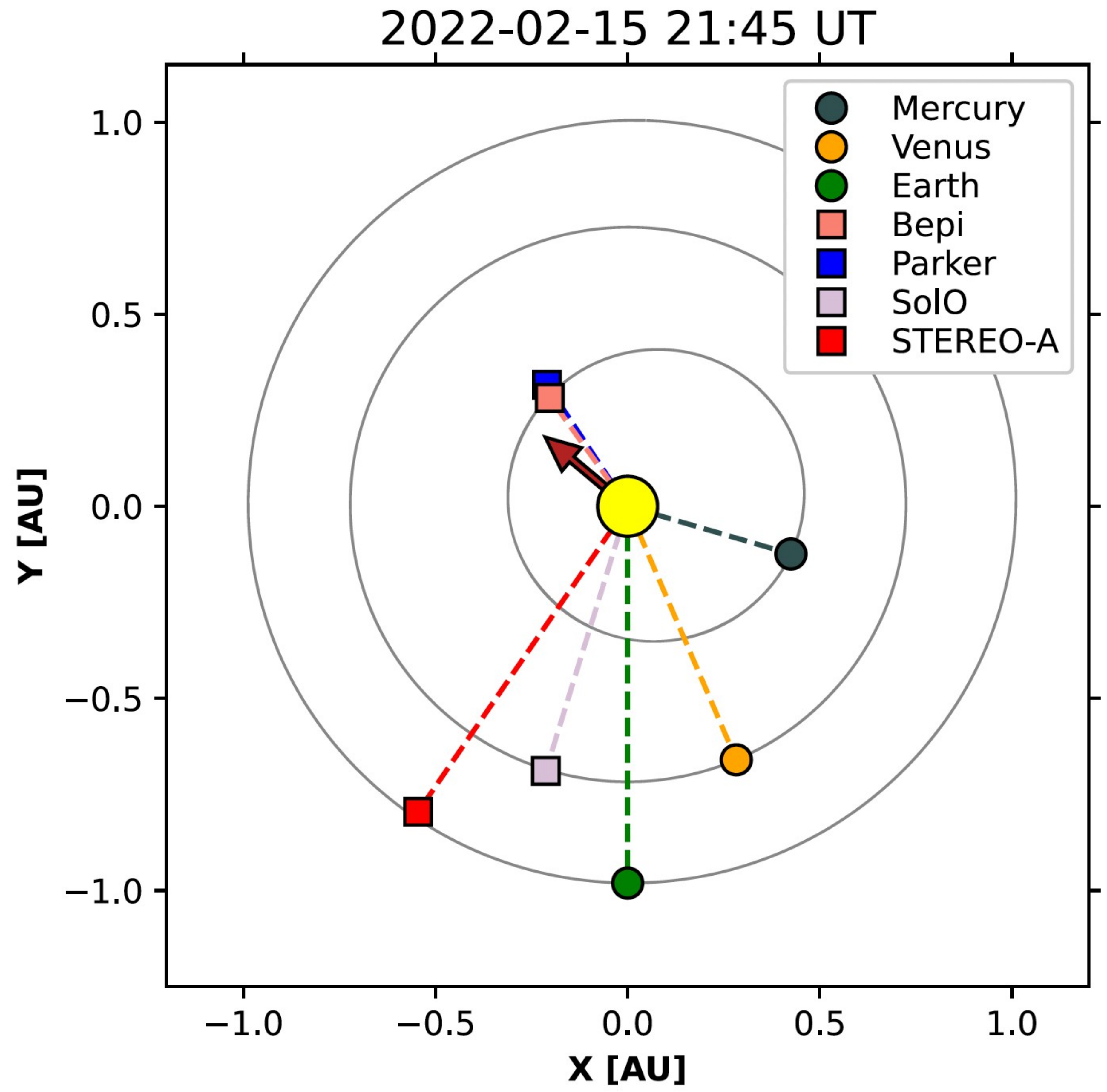




Mierla et al. 2022

De-projecting the kinematics

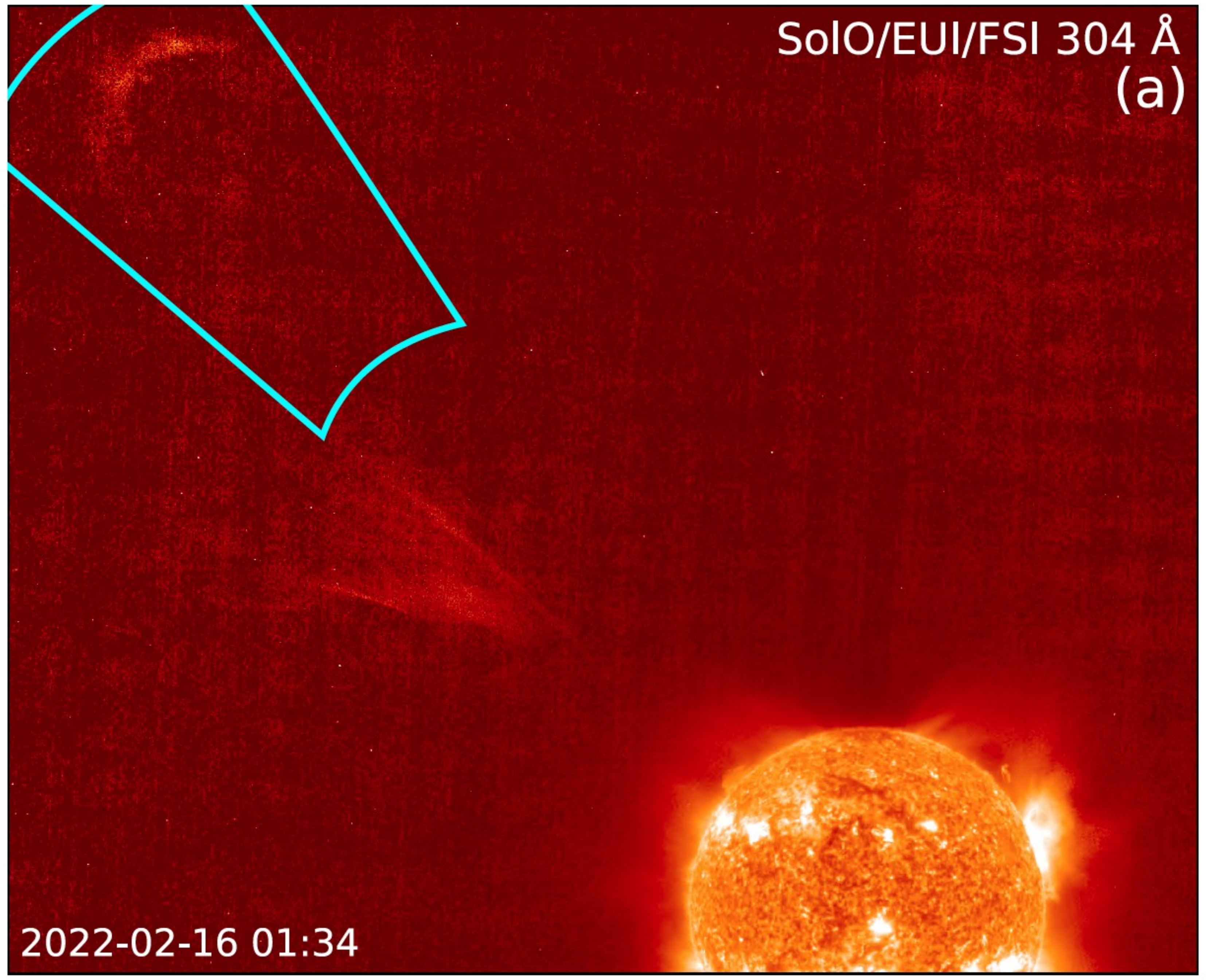


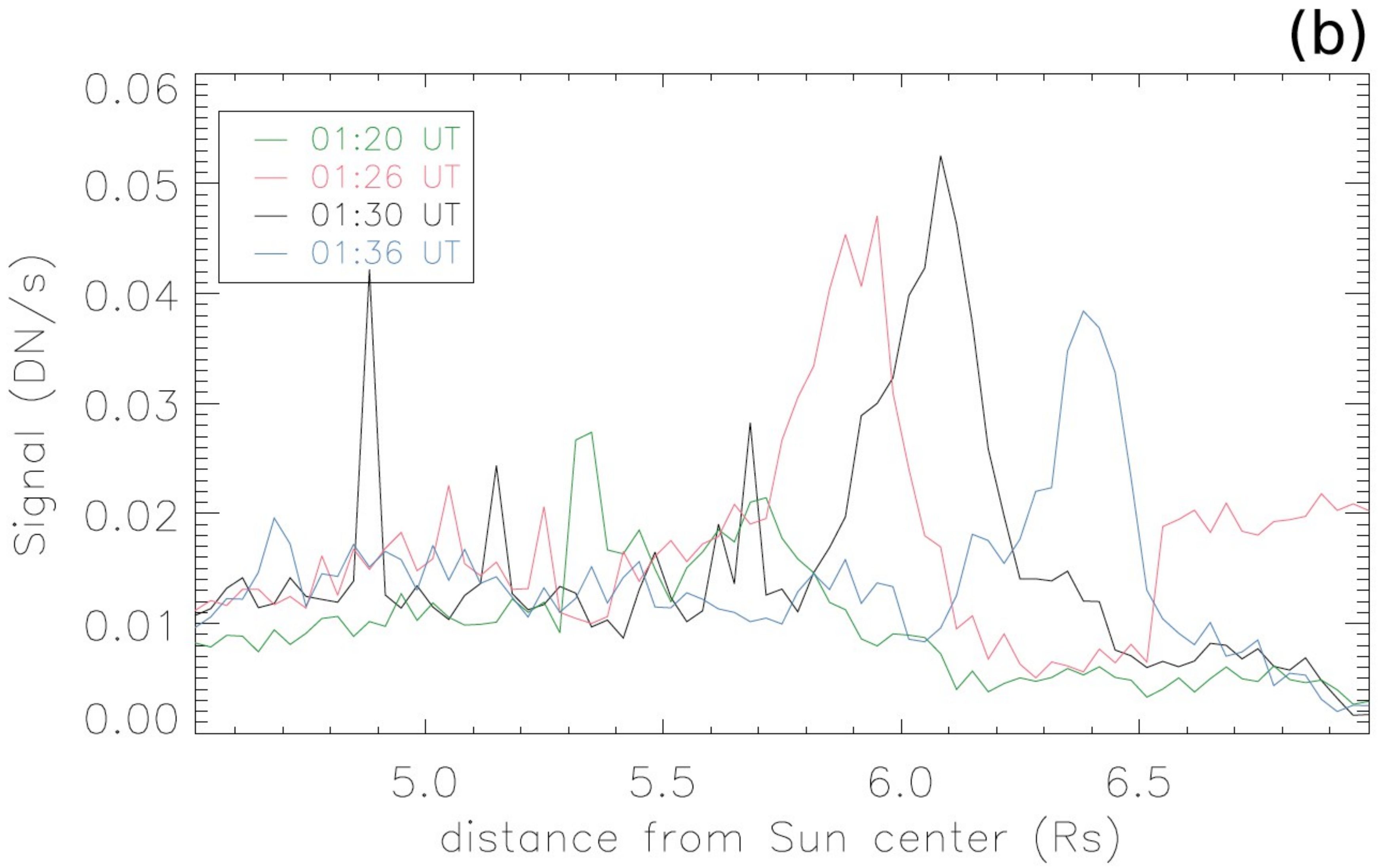


Mierla et al. 2022, Palmerio et al. 2024

Radiative properties of the prominence

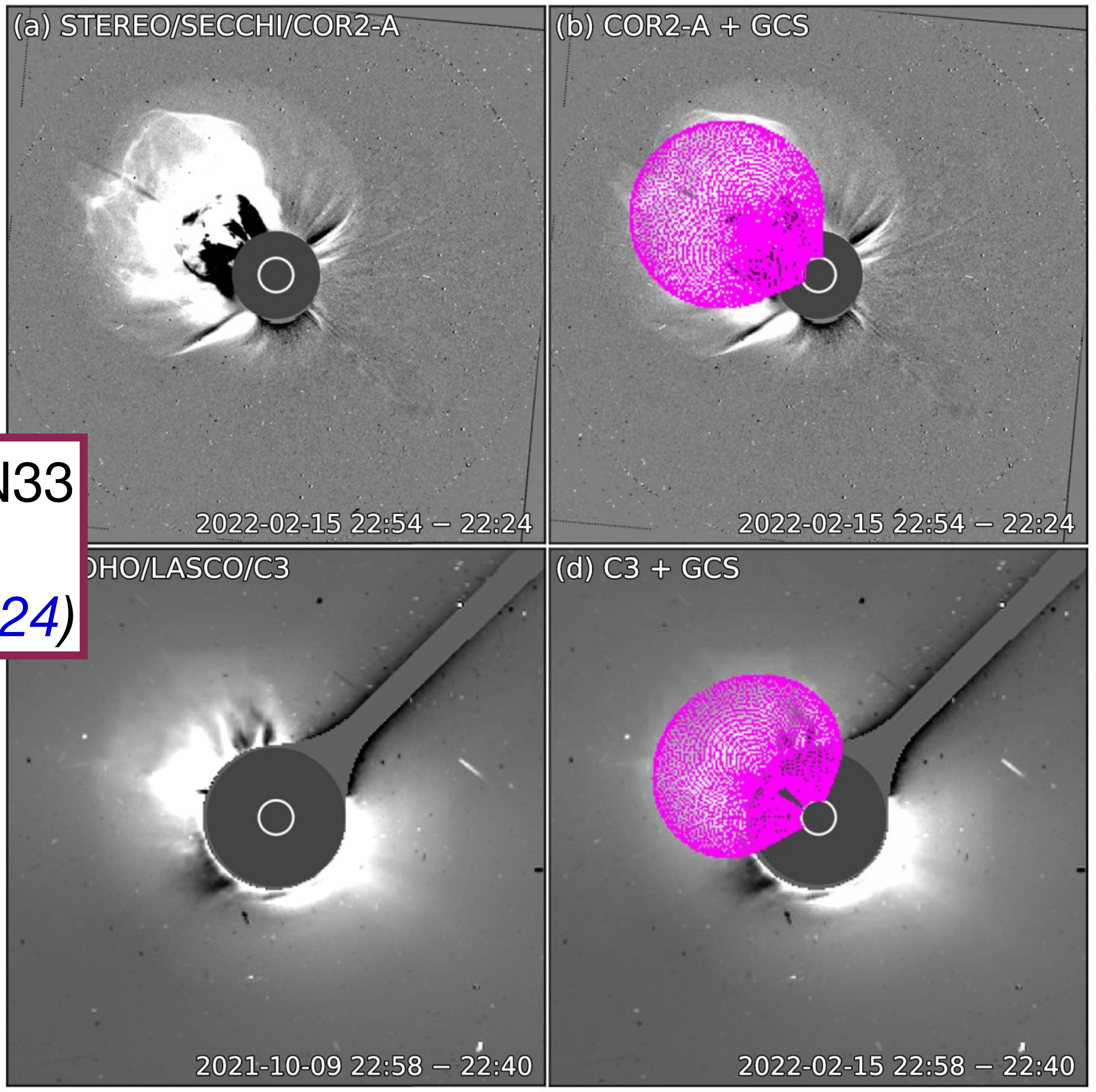
- ➢ The 304 Å passband of FSI is dominated by the He II emission line at 303.78 Å formed by the He+ ions (collisional excitation rather than resonance scattering of the disk radiation?).
- ➢ The presence of the He II 304 Å emission at heights above 6 *Rs* indicates that this part of the prominence was not heated to the fully ionised state during its propagation (the corresponding He+ ions are only very rarely detected in the solar wind).
- ➢ Something intriguing: a trailing feature becomes brighter as it propagates outward.



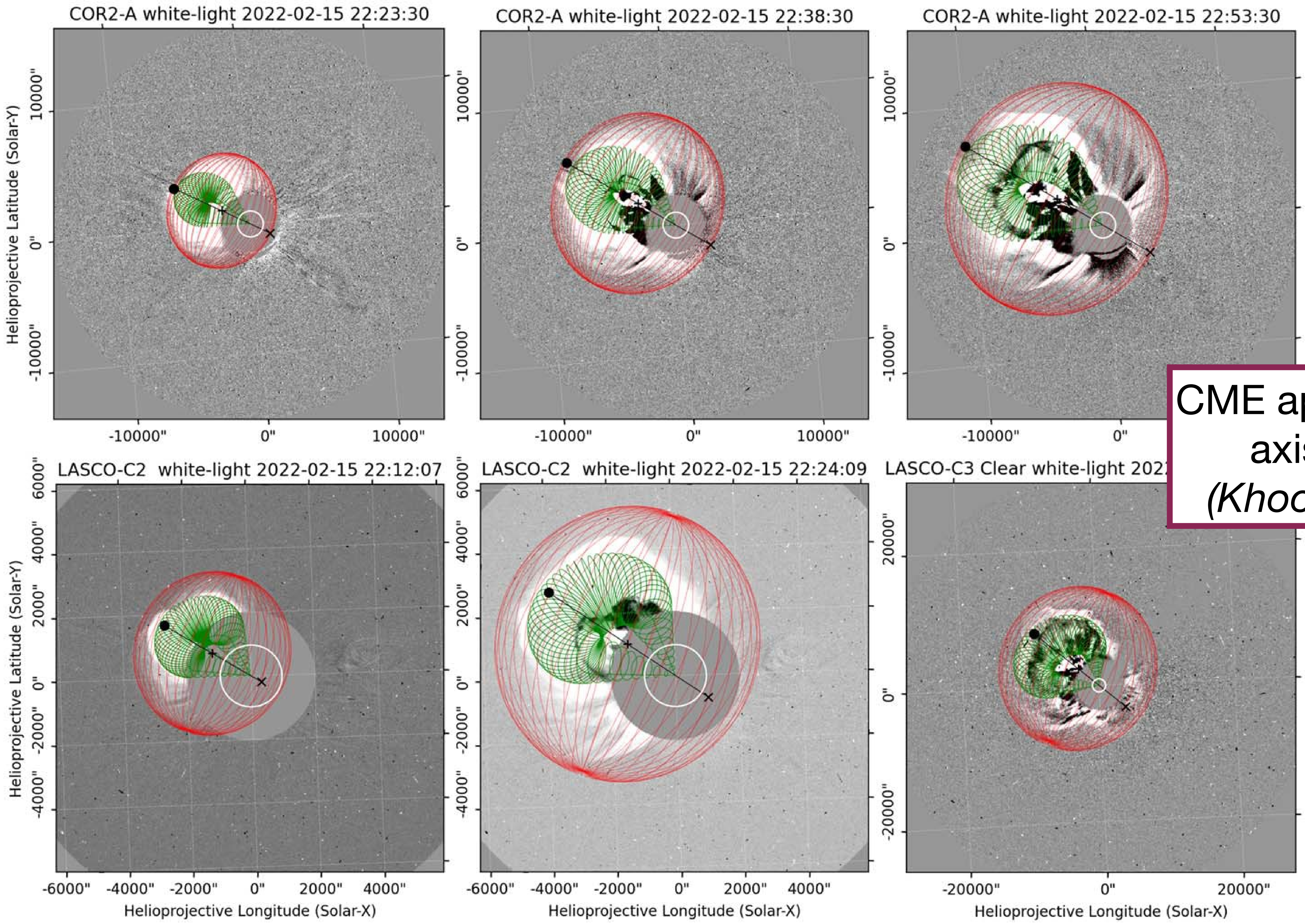


Mierla et al. 2022

3D reconstructions of the CME and the shock



CME apex: E130N33
axis tilt –60°
(Palmerio et al. 2024)

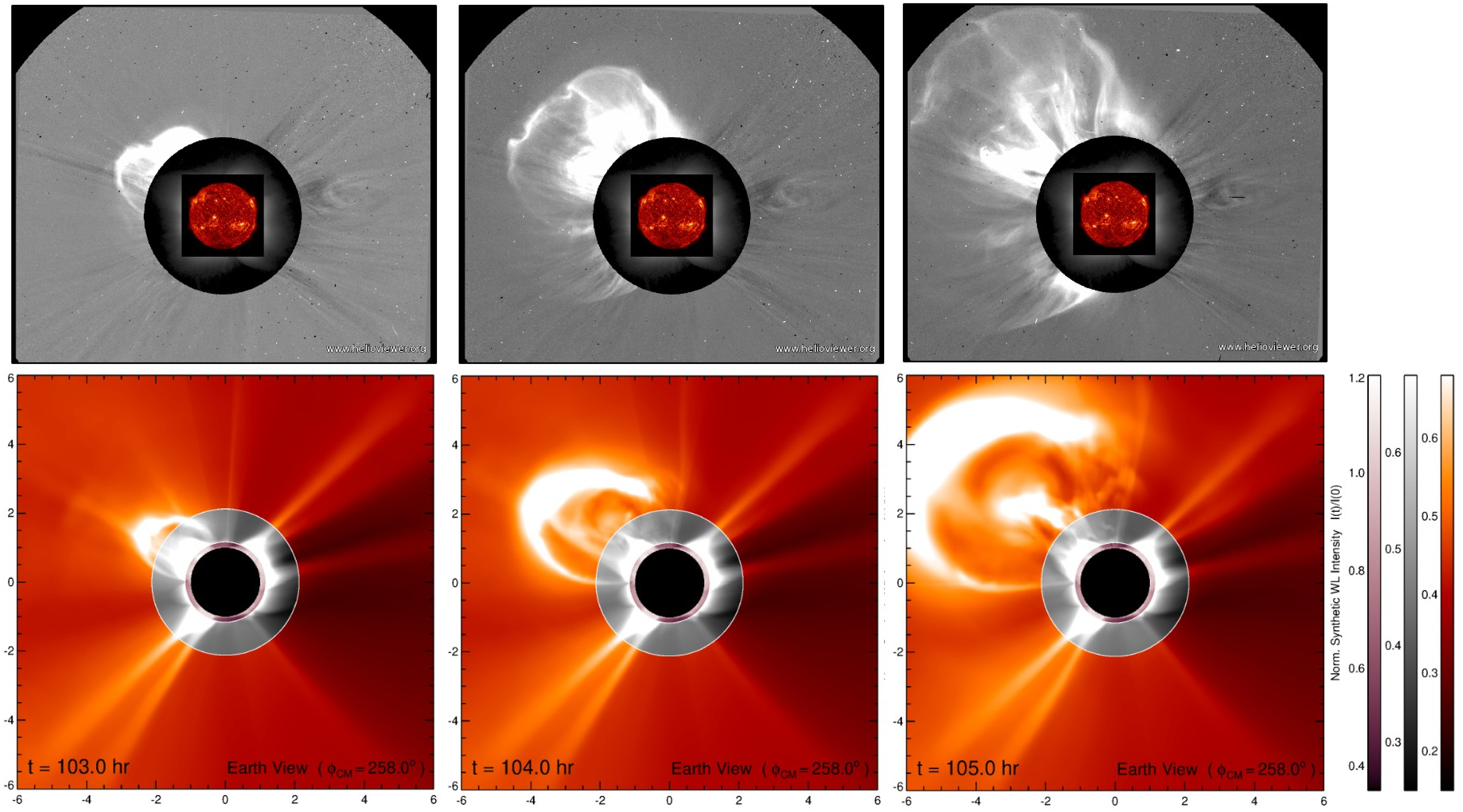


CME apex: E134N33
axis tilt: –50°
(Khoo et al. 2024)

- Two GCS reconstructions *(Thernisien et al. 2009)* of the CME *(Palmerio et al. 2024, Khoo et al. 2024)* give very similar results (consistent also with the prominence triangulation by *Mierla et al. 2022*).
- The reconstructions show a highly inclined CME flux rope propagating mostly north of the ecliptic and a wider CME-driven shock wave.

CME modeling

- The CME initiation was modeled with ARMS code starting with a PFSS extrapolation of the HMI synoptic magnetogram.
- Isothermal Parker wind to model the pre-eruption steady-state corona shows a good correspondence with streamers above the east limb.
- Active region was energized with STITCH procedure *(Dahlin et al. 2022)* to initiate the CME.
- CME shows up in synthetic white-light images in more-or-less the right place with more-or-less the right size!
- Some parameter fine-tuning remains to be done (timescales, total stored/released magnetic energy, etc.).



Lynch et al. 2024, in preparation

What next?

- Reconstructing the detailed CME structure ► many view directions are needed. Polar views will certainly improve the results. ► Observations from above the ecliptic (**Solar Orbiter**)

- Covering the gap in the inner corona ► Better temporal resolution for the observations close to the Sun, to see the acceleration profile (**SolO/EUI/FSI, Aditya-L1/VELC**, **PROBA-3/ASPIICS**)

- Better prediction of the geoeffective impact ► Possibility to measure magnetic field in CMEs (**ground observations?**)

- Better understanding of CMEs onset, propagation and interaction with the surrounding medium ► More realistic models

ESPM contributions on the topic - talks

- Petr Heinzel, invited, *Radiation Properties of Cool Coronal Condensations*, **9 Sept, 14:35**
- Clara Froment, invited, *Thermal non-equilibrium : its importance for the energy and mass cycles in the atmosphere and its possible solar wind implications*, **10 Sept, 11:25**
- Valeriia Liakh, invited, *Numerical Modeling of Prominence Dynamics, Eruption and Coronal Waves Propagation Using MPI-AMRVAC*, **10 Sept, 11:50**
- Lisa-Marie Zessner, *Simulation of a solar prominence with MURaM*, **10 Sept, 15:15**
- Sotiris Stamkos, *Refining Coronal Mass Ejection Dynamics: A Semi-Analytical Flux-Rope Model Incorporating Magnetic Erosion*, **10 Sept, 16:55**
- Astrid Veronig, *What can we learn about coronal mass ejections from their associated coronal dimmings?*, **10 Sept, 17:10**
- Tatiana Podladchikova, *Rare case of the three-part structure of coronal mass ejection observed in low coronal signatures*, **10 Sept, 17:25**
- Greta Cappello, *CME small-scale structures: new insights from white light observations taken between 0.06 -1AU*, **10 Sept, 17:40**
- Benjamin Lynch, *Synthetic Parker Solar Probe Observables of an Idealized Pseudostreamer CME Eruption*, **10 Sept, 17:55**
- Paolo Romano, *Helical Structures Captured by Metis During a Polar Crown Prominence Eruption*, **10 Sept, 18:10**
- Tibor Torok, *Solar Eruptions Triggered by Flux Emergence Below or Near a Coronal Flux Rope*, **11 Sept, 09:00**
- Andreas Wagner, *Identifying and Tracking CME Flux Ropes On The Example of AR12473*, **11 Sept, 09:30**
- Rui Liu, *The Role of Magnetic Reconnection in the Formation and Evolution of Eruptive Magnetic Flux Ropes*, **11 Sept, 09:15**
- Jaroslav Dudík, invited, *3D Magnetic reconnection and energy release in solar flares and eruptions*, **11 Sept, 11:30**
- Judith De Patoul, invited, *Why use real-time operational data in Solar Physics and Space Weather research?*, **13 Sept, 09:00**
- Michaela Brchnelova, invited, *Solar wind, space weather and solar-terrestrial connection*, **13 Sept, 09:25**
- Anwesha Maharana, *Predicting geo-effectiveness two days prior to CME impact with EUHFORIA*, **13 Sept, 09:50**
- Manuela Temmer, *Comparison of "homologous" solar eruptive events from two different solar rotations*, **13 Sept, 10:05**
- Stephanie Yardley, invited, *Exploring the connection between the Sun and the Heliosphere*, **13 Sept, 11:35**
- Emilia Kilpua, invited, *Challenges in forecasting space weather consequences of coronal mass ejections*, **13 Sept, 12:00**
- Federica Chiappetta, *Reconstruction of CME-driven shocks detected by multi-spacecraft observations*, **13 Sept, 12:25**

ESPM contributions on the topic - posters

- Alexis Blaise, Assessing the eruption scenario triggered by flux emergence in a non-zero beta environment, **session 1**
- Yidian Wu, Falling Filament Material During Solar Eruptions, **session 1**
- Martin Benko, Physical Properties of Sunspots during an Eruption, **session 1**
- Sonja Jejčič, Spectral diagnostics of a bright eruptive prominence detected with the Metis coronagraph, **session 1**
- Pavol Schwartz, Synthetic hydrogen Lyman-alpha images from 3D MHD simulation of an eruptive prominence: Towards analysis of Solar Orbiter/Metis observations, **session** 1
- Yara De Leo, Two Distinct Eruptive Events Observed by METIS on October 28, 2021, **session 1**
- Ruisheng Zheng, Why “solar tsunamis” rarely leave their imprints in the chromosphere, **session 1**
- Brenda Dorsch, *Modelling of Coronal Mass Ejections Through the Novel FRi3D Model and the Effect of Twist Parameter*, **session 2**
- Federica Frassati, 3D recostruction of a CME with polarimetric technique, **session 2**
- Ronish Mugatwala, A catalog of CME-ICME lineup events, **session 2**
- Clementina Sasso, Analysis of solar eruptive events captured by Solar Orbiter during the "Eruption Watch" coordination campaigns, **session 2**
- Jianchao Xue, Association between a Failed Prominence Eruption and the Drainage of Mass from Another Prominence, **session 2**
- Ketaki Deshpande, Complex interactions of the shock wave and ambient coronal structures, **session 2**
- Amaia Razquin Lizarraga, Coronal dimmings associated with the May 2024 flare/CME events from AR 13664, **session 2**
- Brigitte Schmieder, Deceleration of CMEs between Mercury and Earth tested by EUHFORIA/ICARUS MHD simulations, **session 2**
- Shantanu Jain, Dimming Inferred Estimation of CME Direction – DIRECD, **session 2**
- Philippe-A. Bourdin, Estimating the helicity and electromotive force with SolarOrbiter in-situ data of an iCME, **session 2**
- Zheng Sun, Fast Downflows Observed during a Polar Crown Filament Eruption, **session 2**
- Runbin Luo, Fast Magnetic Reconnection Excites a Global Blast Wave in the Solar Corona, **session 2**
- Alessandro Bemporad, First detection of small-scale helical flows in the void of a Coronal Mass Ejection with high-cadence coronagraphic images acquired by the Metis coronagraph on-board Solar Orbiter, **session 2**
- Luis Linan, Forecasting the propagation and evolution of CMEs using the space weather simulation chain: COCONUT + EUHFORIA, **session 2**

ESPM contributions on the topic - posters

- Anwesha Maharana, Horseshoe CME model in EUHFORIA for geo-effectiveness predictions, **session 2**
- Xiaomeng Zhang, Insights into the Rotation and Eruption of Magnetic Flux Ropes Influenced by External Toroidal Magnetic Fields, **session 2**
- Tomasz Mrozek, Kink-and-Disconnection Failed Eruption in 3D, **session 2**
- Mattia Sangalli, Magnetohydrodynamic drag simulations for a coronal mass ejection, **session 2**
- Clementina Sasso, Metis Observations of Geoeffective Solar Events, **session 2**
- Angelos Valentino, Modeling of non-radially propagating CMEs and forecasting their arrival time at Earth, **session 2**
- Andrea Lani, Modeling the Propagation of CMEs with COCONUT: Implementation and application of the RBSL Flux Rope Model, **session 2**
- Shuting Li, Mysterious heating source inside an erupting prominence as observed by Solar Orbiter/Metis and ASO-S/SDI instruments, **session 2**
- Alessandro Liberatore, Non-Radial and Multiple Interacting CMEs: A Multi-Spacecraft Perspective Combining Coronagraphs and Heliospheric Imagers, **session 2**
- Wensi Wang, Observations of photospheric signatures for pre-eruptive coronal structures, **session 2**
- Abril Sahade, Partial eruptions by breakout reconnection, **session 2**
- Oliver Rice, Potential Predictions of Magnetic Flux Rope Eruptions, **session 2**
- Can Wang, Radiative Magnetohydrodynamic Simulation of the Confined Eruption of a Magnetic Flux Rope: Unveiling the Driving and Constraining, **session 2**
- Jana Kasparova, Reconnection within the erupting flux rope during a solar flare, **session 2**
- Stefan Purkhart, The Rapid Filament Restructuring in AR 12975 on 28 March 2022 and its Connection to the Subsequent Eruption, **session 2**
- Gaetano Zimbardo, The September 5, 2022, coronal mass ejection characterized by remote observations, numerical simulations, and in situ measurements, **session 2**
- Chen Xing, Understanding Precursors of Coronal Mass Ejections and Flares, **session 2**
- Shifana Koya, Understanding the magnetic field evolution of the 10 March 2022 Coronal Mass Ejection, **session 2**
- Farhad Daei, Using Data-driven time-dependent Magnetofrictional modeling to initiate Magnetohydrodynamic simulations of coronal active regions, **session 2**
- Sivakumara Tadikonda, Wide-Field EUV Image Campaigns with GOES Solar UltraViolet Imager, **session 2**

Thank you!

Extra Slides

Review Papers

- **Forbes 2000,** JGR, *A review on the genesis of coronal mass ejections*
- **Schwenn 2006**, Living Reviews in Solar Physics, Space weather: the solar perspective
- **Chen 2011**, Living Reviews in Solar Physics, *Coronal Mass Ejections: Models and Their Observational Basis*
- **Zhukov 2011**, JASTP, *EIT wave observations and modeling in the STEREO era*
- **Rouillard 2011**, JASTP, *Relating white light and in situ observations of coronal mass ejections: A review*
- **Webb and Howard 2012**, Living Reviews in Solar Physics, *Coronal Mass Ejections: Observations*
- **Parenti 2014**, Living Reviews in Solar Physics*, Solar Prominences: Observations*
- **Manchester et al. 2017**, Space Science Reviews, *The Physical Processes of CME/ICME Evolution*
- **Green et al. 2018**, Space Science Reviews, *The Origin, Early Evolution and Predictability of Solar Eruptions*
- **Patsourakos et al. 2020**, Space Science Reviews, *Decoding the Pre-Eruptive Magnetic Field Configurations of Coronal Mass Ejections*
- **Nitta et al. 2021**, Space Science Reviews, *Understanding the Origins of Problem Geomagnetic Storms Associated with "Stealth" Coronal Mass Ejections*
- **Temmer 2021**, Living Reviews in Solar Physics, Space weather: the solar perspective

SolO/EUI/FSI Papers on Eruptions

- **Palmerio et al. 2024**, ApJ, *On the Mesoscale Structure of Coronal Mass Ejections at Mercury's Orbit: BepiColombo and Parker Solar Probe Observations*
- **Auchere et al. 2023**, A&A, *Beyond the disk: EUV coronagraphic observations of the Extreme Ultraviolet Imager on board Solar Orbiter*
- **Bergmans et al. 2023**, A&A*, First perihelion of EUI on the Solar Orbiter mission*
- **Janvier et al. 2023**, A&A*, A multiple spacecraft detection of the 2 April 2022 M-class flare and filament eruption during the first close Solar Orbiter perihelion*
- **Li et al. 2023**, A&A, *Evidence of external reconnection between an erupting mini-filament and ambient loops observed by Solar Orbiter/EUI*
- **Liberatore et al. 2023**, ApJ, *Multi-spacecraft Observations of the 2022 March 25 CME and EUV Wave: An Analysis of Their Propagation and Interrelation*

SolO/EUI/FSI Papers on Eruptions

- **Long et al. 2023**, ApJ, *The Eruption of a Magnetic Flux Rope Observed by Solar Orbiter and Parker Solar Probe*
- **Mierla et al. 2023**, SolPhys, *Three Eruptions Observed by Remote Sensing Instruments Onboard Solar Orbiter*
- **Patel et al. 2023**, ApJL, *The Closest View of a Fast Coronal Mass Ejection: How Faulty Assumptions Near Perihelion Lead to Unrealistic Interpretations of PSP/WISPR Observations*
- **Rodriguez et al. 2023**, SolPhys, *The Eruption of 22 April 2021 as Observed by Solar Orbiter: Continuous Magnetic Reconnection and Heating After the Impulsive Phase*
- **Zimbardo et al. 2023**, A&A, *A high-latitude coronal mass ejection observed by a constellation of coronagraphs: Solar Orbiter/Metis, STEREO-A/COR2, and SOHO/LASCO*
- **Mierla et al. 2022**, A&A Letters, *Prominence eruption observed in He II 304 Å up to >6 R℗ by EUI/FSI aboard Solar Orbiter*
- **Andretta et al. 2021**, A&A, *The first coronal mass ejection observed in both visible-light and UV H I Ly-α channels of the Metis coronagraph on board Solar Orbiter*

Green et al. 2018,
SpSciRev

Table 1 Compilation of suggested physical mechanisms of the "storage-and-release" type for the triggering and driving of solar eruptions. "FE" stands for flux emergence. Note that (i) we do not distinguish here between 2D and 3D simulations; (ii) we do not include simulations that model CMEs by starting with an "out-of-equilibrium" flux-rope configuration (e.g., Roussev et al. 2003; Manchester et al. 2004b; Tóth et al. 2007; Cohen et al. 2009; Lugaz et al. 2011; Pagano et al. 2013), even though they are compatible with the storage-and-release paradigm; and that (iii) each article is referenced only once, even if the model or scenario it describes involves more than one mechanism. The *bottom row* contains related review articles

Mechanism	References
TRIGGER:	
Sunspot rotation	Amari et al. (1996), Tokman and Bellan (2002), Török and Kliem (2003), Aulanier et al. (2005), Rachmeler et al. (2009)
Twisting overlying field	Török et al. (2013)
Shearing of arcade	Mikic et al. (1988), Biskamp and Welter (1989), Mikic and Linker (1994), Choe and Lee (1996a,b), Amari et al. (1996a), Jacobs et al. (2006, 2009), Roussev et al. (2007), Shiota et al. (2008), Downs et al. (2011)
Reversed shear	Kusano et al. (2004)
Self-induced shear flows	Manchester (2003, 2007), Manchester et al. (2004a)
Magnetic breakout	Antiochos et al. (1999), MacNeice et al. (2004), Lynch et al. (2004, 2008), van der Holst et al. (2007, 2009), Masson et al. (2013)
Tether cutting	Moore and Roumeliotis (1992), Moore et al. (2001), Aulanier et al. (2010)
Converging flows / Flux cancellation	Inhester et al. (1992), Amari et al. (2003a), Roussev et al. (2004), Zuccarello et al. (2012), Mikić et al. (2013)
Flux decrease / dispersion	Lin et al. (1998), Linker et al. (2001, 2003), Amari et al. (2000, 2003b), Titov et al. (2008), Reeves et al. (2010)
FE close/below flux rope	Chen and Shibata (2000), Lin et al. (2001), Shiota et al. (2005), Dubey et al. (2006)
FE into potential arcade	Zuccarello et al. (2008), Jacobs and Poedts (2012), Roussev et al. (2012)
FE into sheared arcade	Notoya et al. (2007), Kusano et al. (2012)
Helical kink instability	Sakurai (1976), Hood and Priest (1979), Gerrard et al. (2001), Fan and Gibson (2003), Török et al. (2004), Török and Kliem (2005)
Flux transfer/feeding	Zhang et al. (2014), Kliem et al. (2014b)
Tilt instability	Keppens et al. (2014)
Double-arc instability	Ishiguro and Kusano (2017)
DRIVER:	
Torus instability / Flux-rope catastrophe / Loss of equilibrium	van Tend and Kuperus (1978), Priest and Forbes (1990), Forbes and Isenberg (1991), Lin et al. (1998), Kliem and Török (2006), Török and Kliem (2007), Fan and Gibson (2007), Olmedo and Zhang (2010), Démoulin and Aulanier (2010), Kliem et al. (2014a)
Flare-reconnection	Lin and Forbes (2000), Vršnak (2008), Temmer et al. (2010), Karpen et al. (2012)
Review articles:	Forbes (2000), Chen (2001), Klimchuk (2001), Low (2001), Priest and Forbes (2002), Lin et al. (2003), Linker et al. (2003), Zhang and Low (2005), Forbes et al. (2006), Moore and Sterling (2006), Mikić and Lee (2006), Roussev (2008), Vršnak (2008), Amari and Aly (2009), Linton and Moldwin (2009), Schrijver (2009), Aulanier et al. (2010), Chen (2011), Jacobs and Poedts (2011), Kleimann (2012), Schmieder et al. (2013, 2015), Aulanier (2014), Inoue (2016), Chen (2017)

Complexity of CMEs, Properties

Properties	Values	Average value	Publications
speed	• < 20 km s^{-1} to • > 3000 km s^{-1}	250 km s^{-1} (min SC) 500 km s^{-1} (max SC)	Gopalswamy 2006 Webb&Howard 2012
mass	• 10^{10} - 10^{13} kg	1.6×10^{12} kg	Vourlidas et al., 2002 Colaninno&Vourlidas, 2009 Bein et al., 2013
kinetic energy	• 10^{20} - 10^{26} J	5×10^{22} J	Gopalswamy 2006 Priest 2014
angular width	• < 20° to • > 120°	40° - 50°	Yashiro et al. 2004 Gopalswamy 2006 Chen 2011
occurrence rates	• 1/day at min SC • up to 8/day at max SC		St Cyr et al. 2000 Gopalswamy et al. 2005 Robbrecht et al. 2009
location	• around equator at min SC • spreading over all latitudes at max SC		Gopalswamy 2004 Gopalswamy et al. 2010 Yashiro 2011

CME Properties, Continuation

signatures of CME origins	1. prominence eruptions 2. coronal dimmings 3. coronal waves 4. post eruption arcade or post-flare loops 4.1 sigmoids to arcade restructuring 5. streamer blowout 6. no source (stealth)		1. Hundhausen, 1999; Jing et al. 2004; Majumdar et al., 2020, 2021; Duchlev et al. 2021; Mierla et al. 2022. 2. Sterling and Hudson, 1997; Thompson et al., 1999; Zhukov&Auchere 2004. 3. Thompson et al. 1998; Biesecker et al. 2002; Webb 2002; Zhukov 2011. 4. Sterling et al., 2000; Tripathi et al. 2004. 4.1 Canfield, Hudson, and McKenzie, 1999; Green et al. 2007. 5. Howard et al. 1985; Illing&Hundhausen 1986; Hundhausen 1993; Vourlidas&Webb 2018. 6. Robbrecht et al., 2009; Ma et al. 2010; D'Huys et al. 2014; Alzate&Morgan 2017; Nitta et al. 2021.

CME Properties, Continuation

types - initiation	• gradual • impulsive		Sheeley et al. 1999
types - kinematics	• slow (e.g. streamer blowout) • fast (e.g. source in ARs)		Gosling et al. 1976; Sheeley et al. 1999; St Cyr et al. 1999.
forms/ morphologies	• three-part structure • loop-CME • halos • narrow jets		Illing&Hundhausen 1985 Howard et al. 1982 Schwenn 2006 Vourlidas et al. 2013