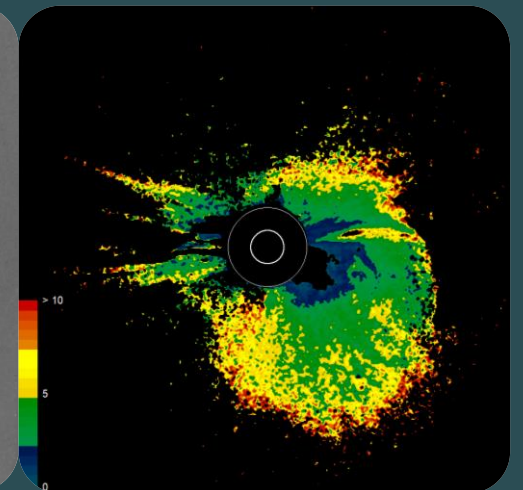
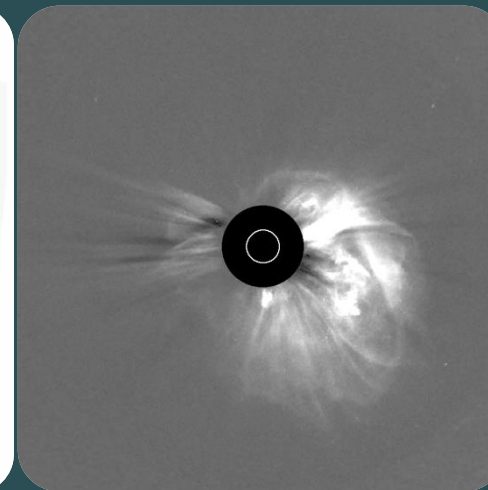
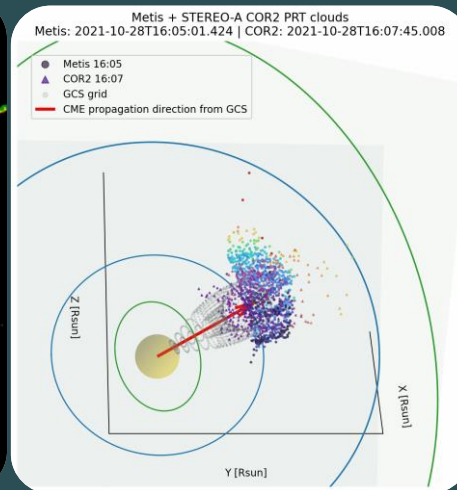
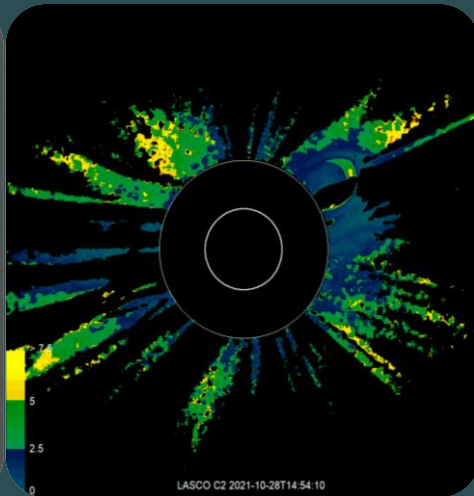
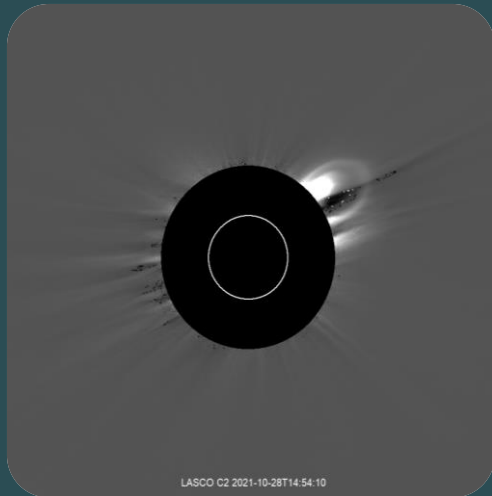


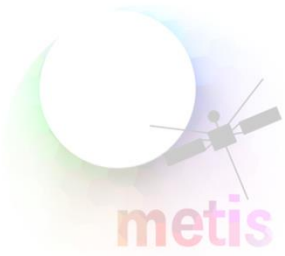


# Polarization and 3D Kinematic studies of CMEs from multi-mission observations: toward Metis–PUNCH synergies

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yara.deleo@gmail.com

Hebe Cremades, Manuela Temmer, Marco Romoli, Sarah Gibson, Roberto Susino  
and the Metis Team





- Brief recap about Metis
- A comprehensive study of the 2 eruptive events occurred on October 28, 2021
  - Outline of the methodology
  - The 3D reconstruction with the triangulation and the GCS model
  - Mass and density calculation
- **Polarization ratio technique and the 3D representation of the results**
- Toward the Metis-PUNCH synergy
  - considerations on the PRT
  - The case studies of 16 September 2025 and 21-22 September 2025
- Conclusions

# Metis, the coronagraph on board Solar Orbiter

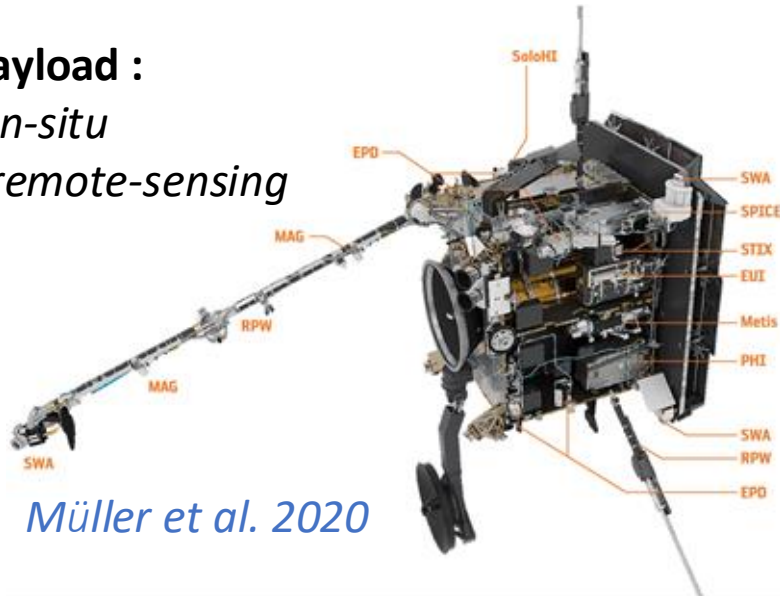
Solar Orbiter is an ESA/NASA mission with 2 characteristics of uniqueness:

- it approaches the Sun up to a perihelion of 0.28 au
- It observes the Sun and its atmosphere exiting the ecliptic plane (up to 30° of heliolatitude)

**Payload :**

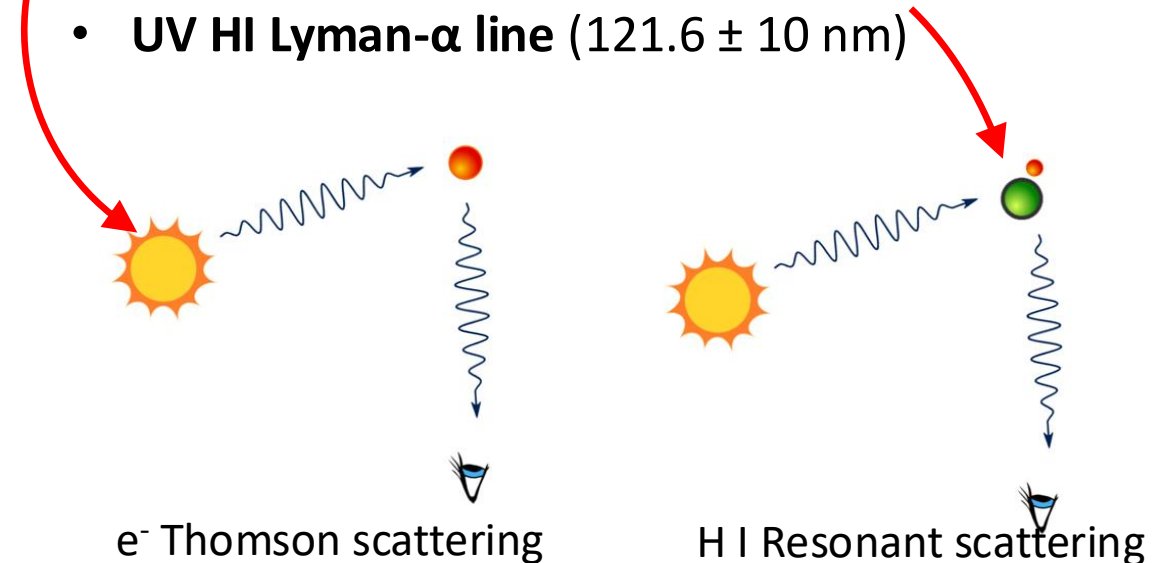
4 *in-situ*

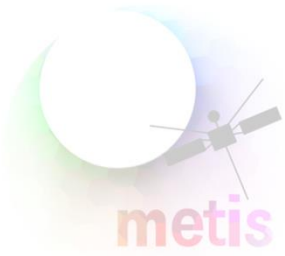
6 *remote-sensing*



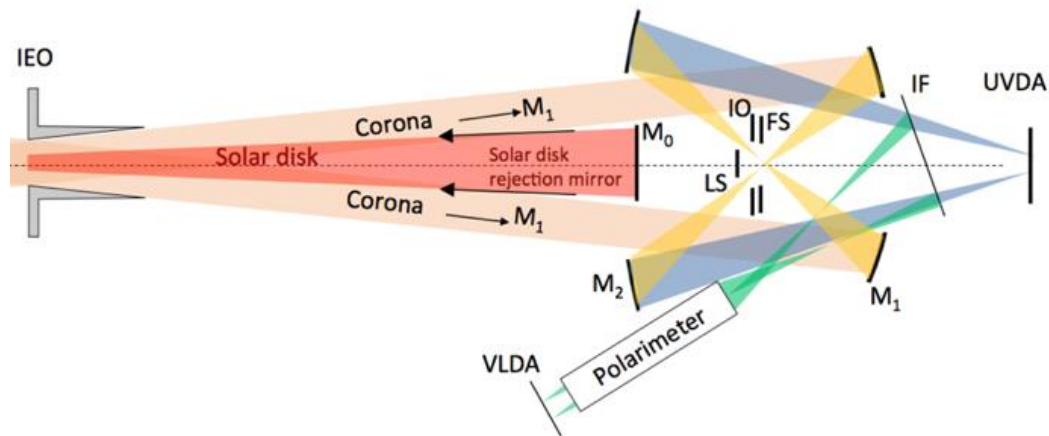
Metis is an externally-occulted coronagraph designed to provide full imaging of the extended corona ( $\sim 1.7-9 R_{\odot}$ ) in:

- **total and polarised visible-light brightness (580-640 nm) and**
- **UV HI Lyman- $\alpha$  line ( $121.6 \pm 10$  nm)**





# Metis, the coronagraph on board Solar Orbiter



Metis is an externally-occulted coronagraph designed to provide full imaging of the extended corona ( $\sim 1.7-9 R_{\odot}$ ) in:

- **total and polarised visible-light brightness** (580-640 nm) and
- **UV HI Lyman- $\alpha$  line** ( $121.6 \pm 10$  nm)



Metis observations allow the investigation of the:

- density distribution of coronal  $e^-$  and HI atoms (protons)
- 2D solar-wind outflow (HI/proton component)
- large-scale dynamics of  $e^-$  and HI in CMEs and other solar transients



# Two eruptive events observed by Metis on October 28, 2021

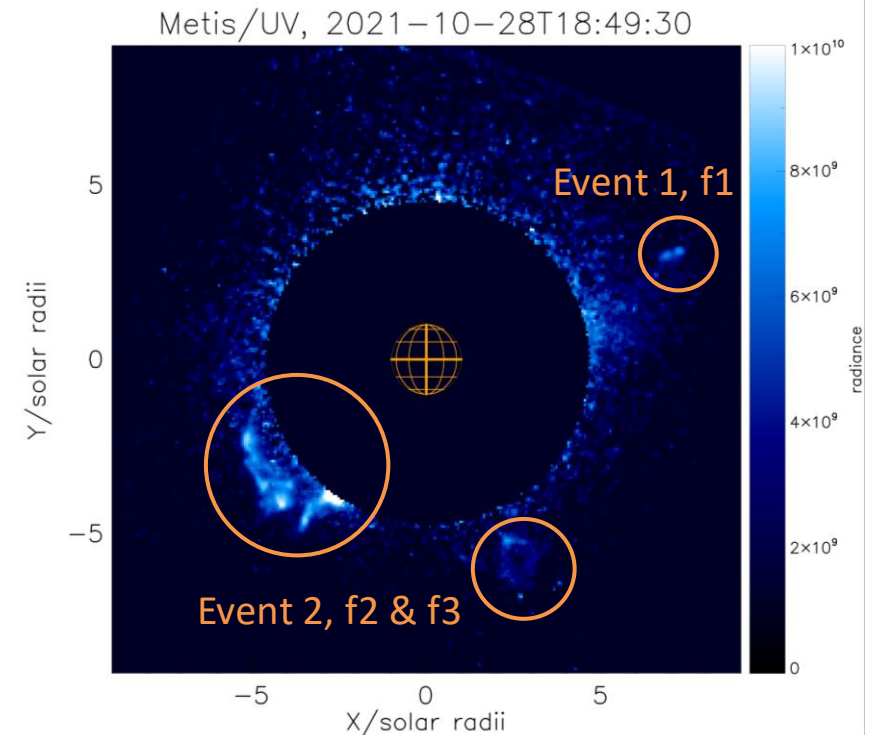
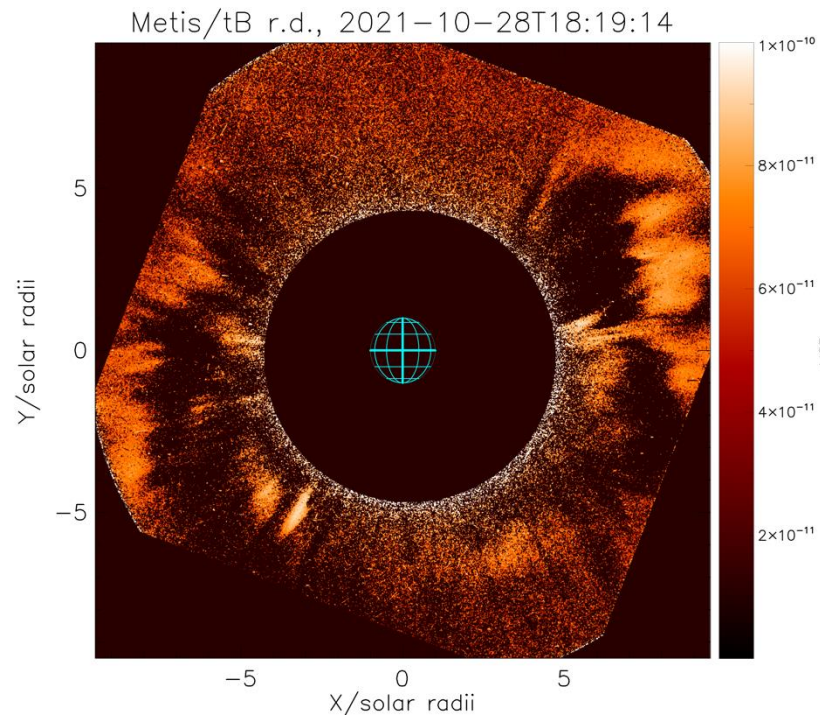
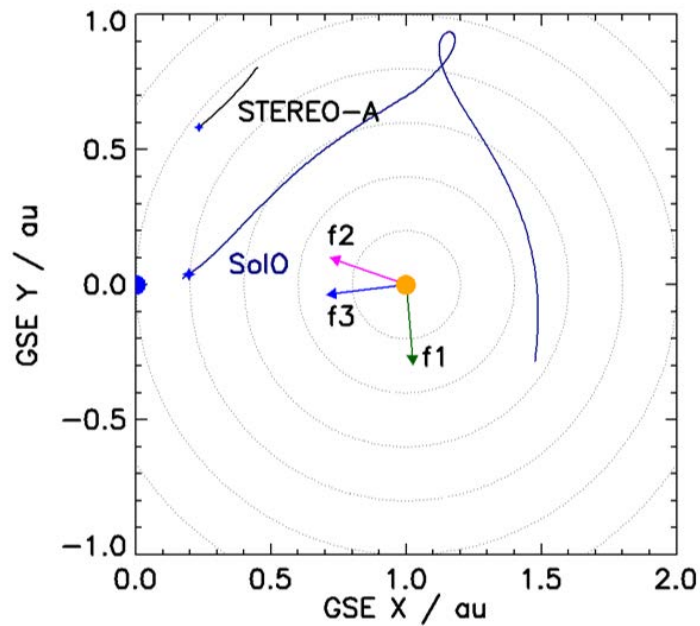
On October 28, 2021 the first X-class solar flare of Solar Cycle 25 occurred, along with a **fast halo CME** from Earth's perspective (f2 and f3). A few hours before, a **slower CME** had erupted from a quiet Sun region behind the NW solar limb (f1).

## Solar Orbiter facts:

- SoI almost aligned with Sun-Earth line ( $< \sim 4^\circ$ , Fig. 1)
- **Metis** detected the 2 CMEs in VL and UV channels (Fig. 2)
- $d_{S/C} = 0.8 \text{ au}$ ,
- $FoV_{Metis} = [4.8 - 10.3] R_\odot$

Follow-up study of [Russano et al. 2024](#). The events are characterized by a very high brightness in UV at those distances.

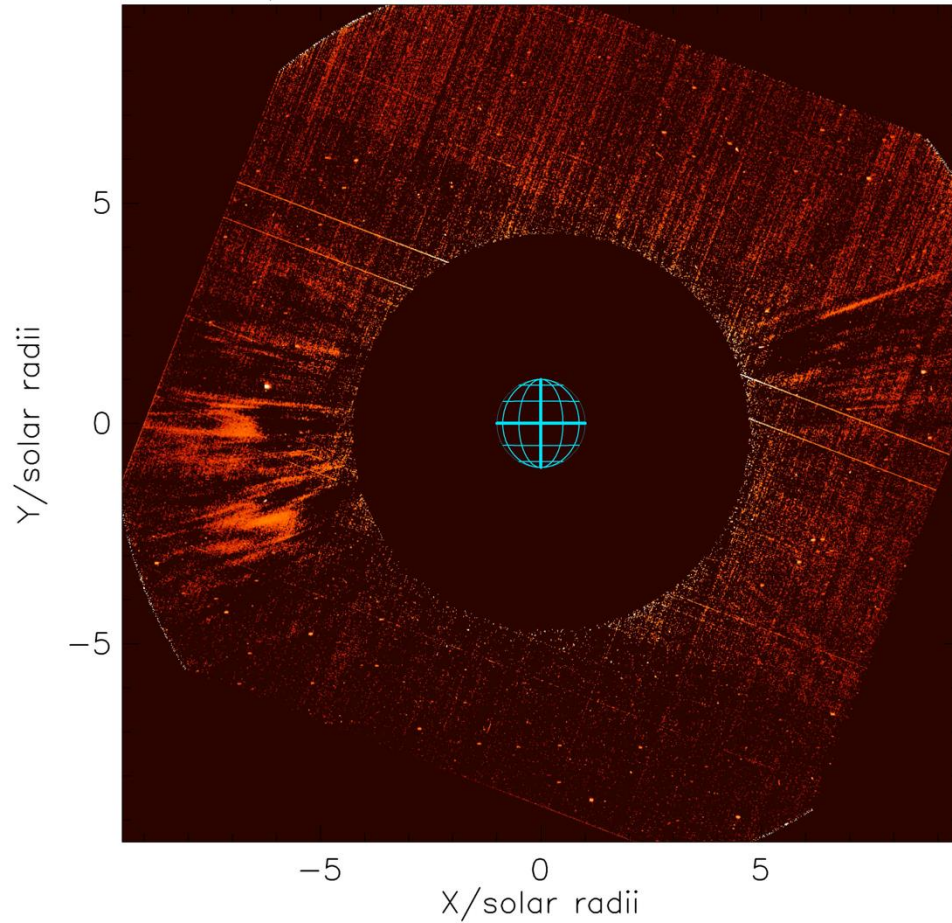
There are many CMEs without emission in UV. **Why do these two CMEs, so different in nature, show UV emission?**



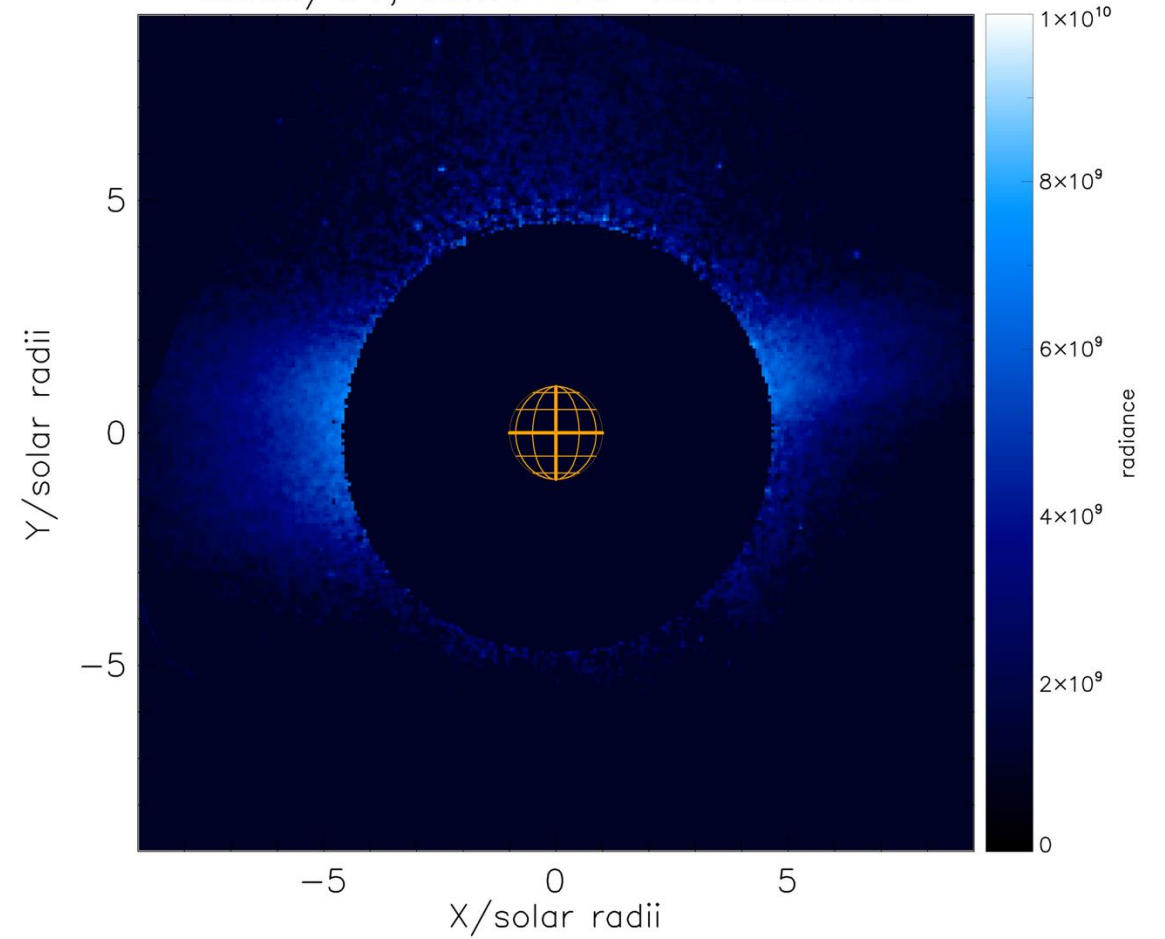


# Two eruptive events observed by Metis on October 28, 2021

Metis/tB r.d., 2021-10-28T09:19:15



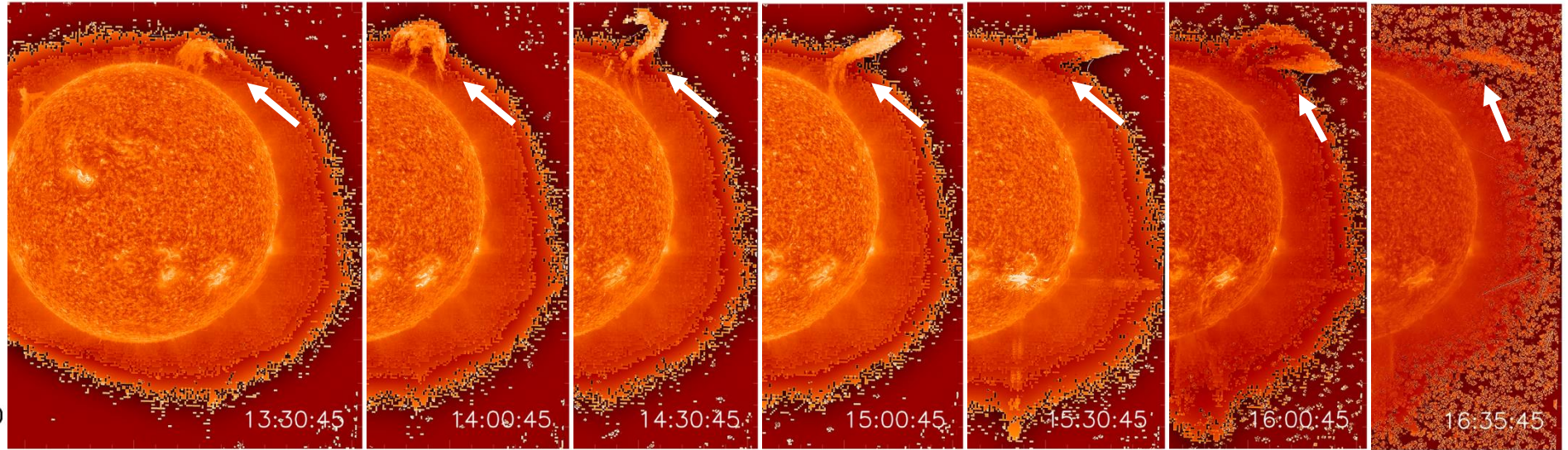
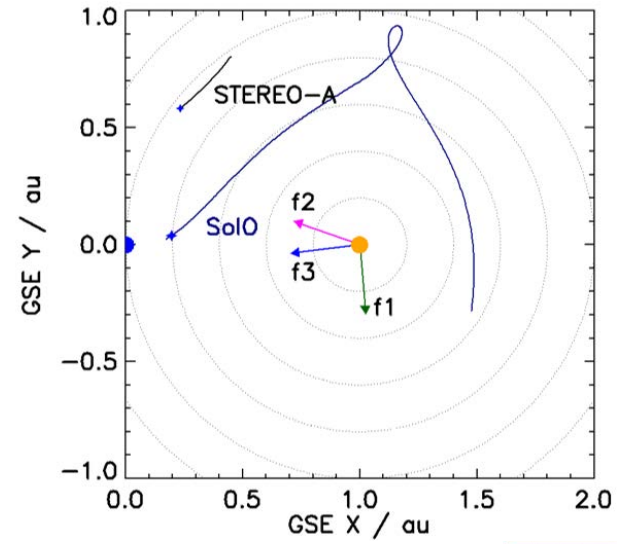
Metis/UV, 2021-10-28T15:39:30



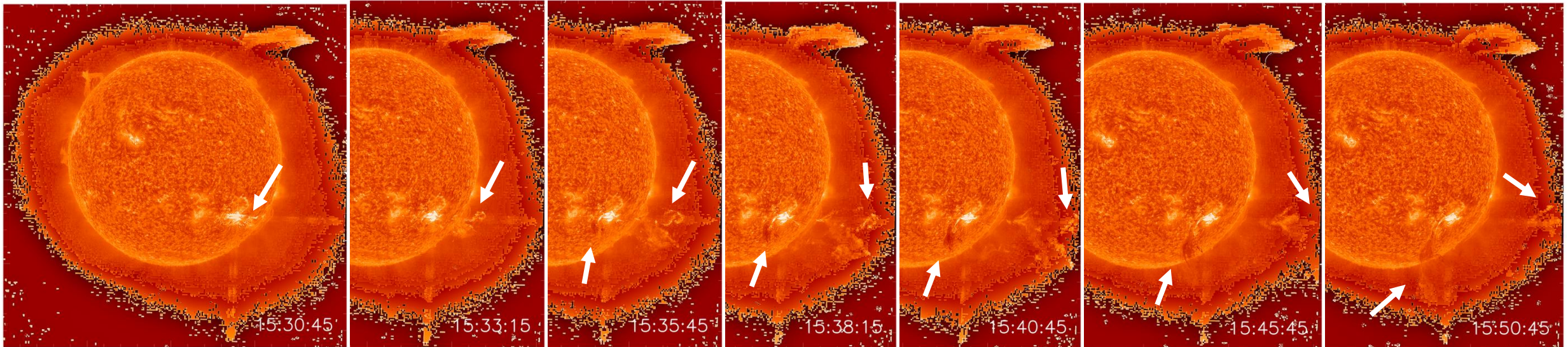


# The origin of the two events

## Event 1 - STEREO-A/EUVI 304

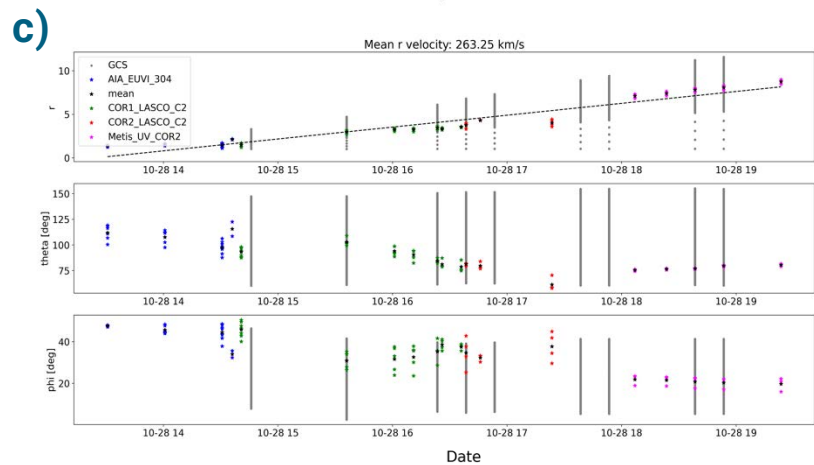
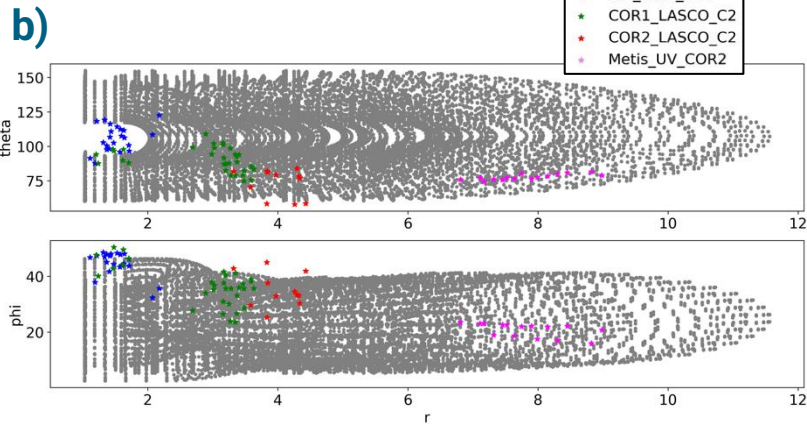
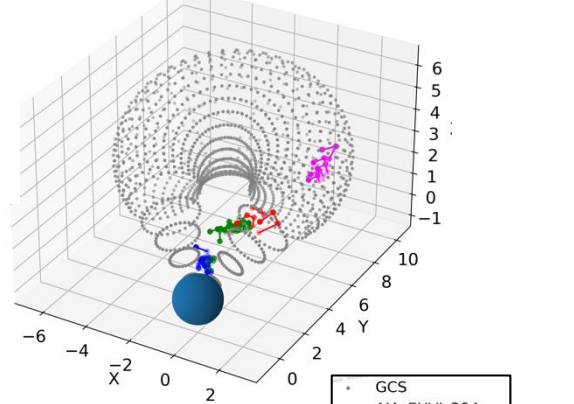


## Event 2 - STEREO-A/EUVI 304

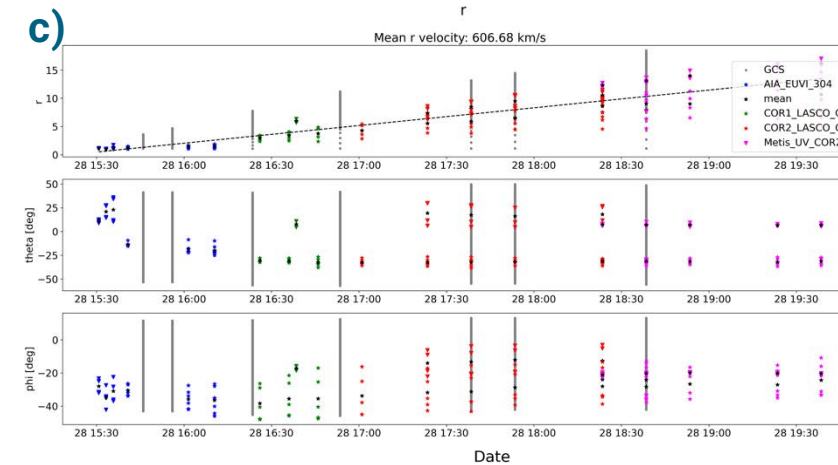
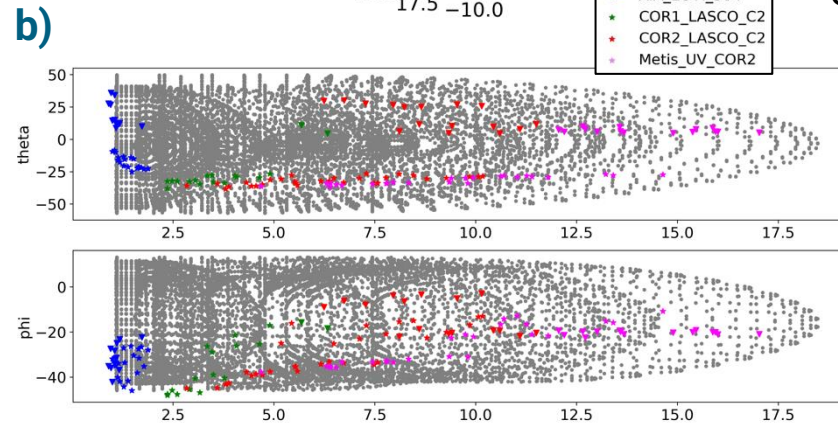
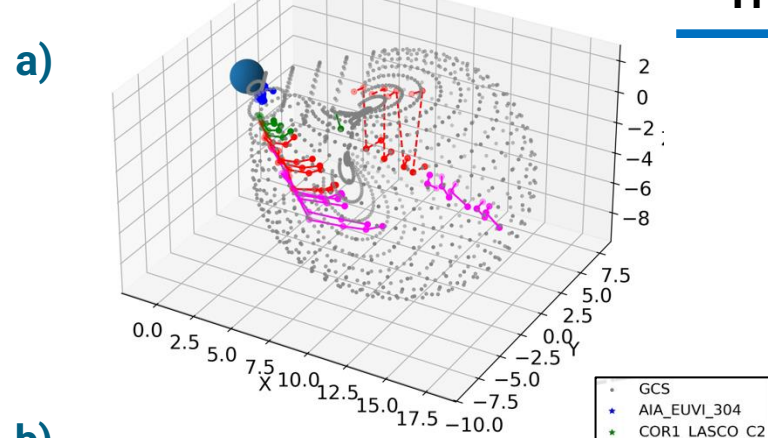




## Event 1



## Event 2



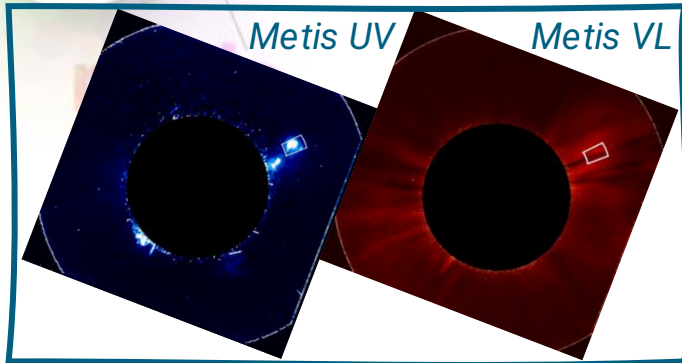
## Triangulation and GCS reconstruction results

- Characterization of the prominence evolution with the tie-point triangulation, adapted triangulation tool by Nisticò (2023).
- 3D reconstruction of CME's outer envelope (GCS reconstruction).

- a) 3D representation of the prominence and its outer shell;
- b) Polar coordinates  $(\vartheta, \varphi)$  of the triangulation points (colored) and the GCS reconstruction (grey) with respect to the radial distance  $r$ ;
- c) Evolution of the polar coordinates  $(r, \vartheta, \varphi)$  of the triangulation points (colored) and the GCS reconstruction (grey) with time; the plot contains the velocity best fit (dashed black line);  
for Event 1 (left) and Event 2 (right)

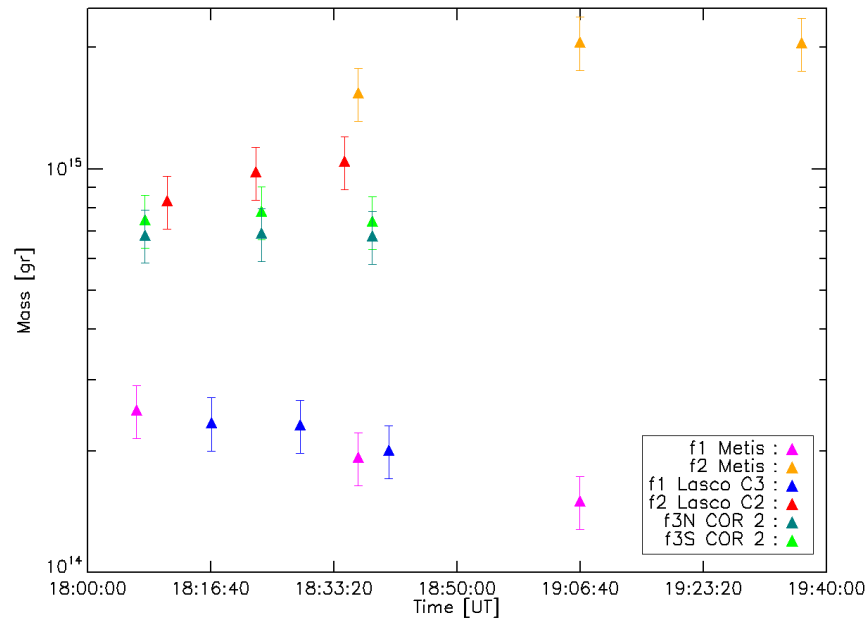
Plots from De Leo et al. 2026a, in preparation

# Mass and density calculation of the CME cores



Mass calculation was performed by applying the “excess brightness” method (e.g. Vourlidas et al. 2000, Colaninno & Howard 2009, Vourlidas et al. 2010) on sectors of total brightness images from various coronagraphs. The boundaries of the sectors were determined from Metis UV images.

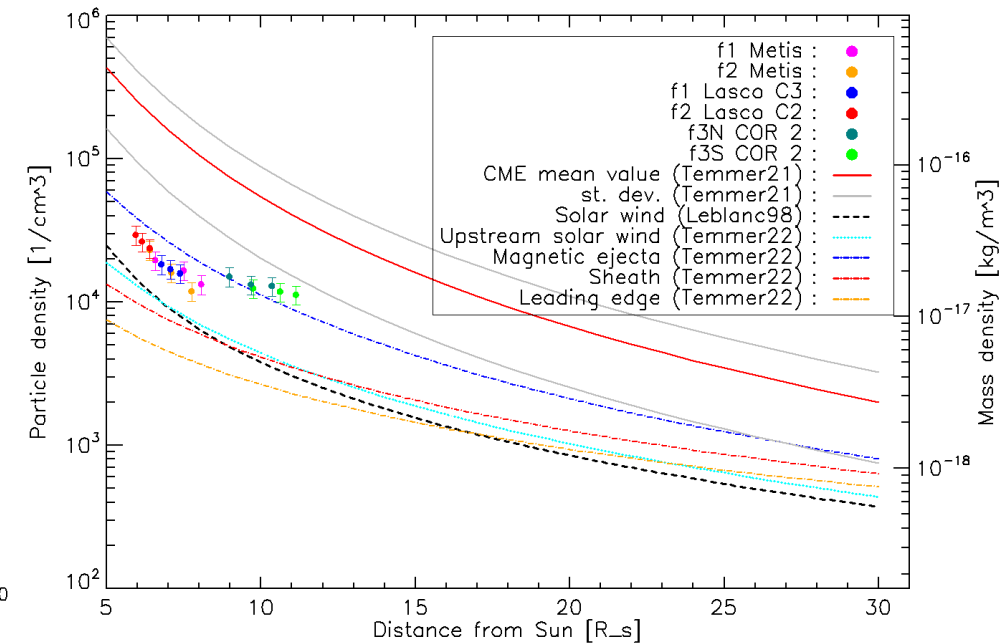
Mass of CME cores VS time.  
Errorbars: 15% (from Bein 2013)



- F1: LASCO C3 and Metis tB
- F2: LASCO C2 and Metis tB
- F3: ST-A COR 2

Plots from De Leo et al. 2026a, in preparation

Particle density VS distance and comparison with models in literature.





The following pipeline is developed to apply the PRT on Metis data and other space-based coronagraph (SOHO/LASCO, STEREO/COR1-A, COR2-A, PROBA 3/ASPIICS and PUNCH)

The technique is based on the the work of Moran&Davila 2004, and Moran et al. 2010, but insight from the work of many other authors are taken into account ([Dere+2005](#), [Vourlidas+2006](#), [Mierla+2009,2011,2022](#), [de Koning&Pizzo 2011](#), [De Forest+2013,2017](#), [Zuccarello+ 2013](#), [Bemporad and Pagano 2015...and Gibson+2026](#)).

## Bullet points:

- 1) **Preparation** of the pB, tB and uB ( $uB=tB-pB$ ) data set for the event in exam
- 2) **Pre-event subtraction:**  $pB \rightarrow pB(t) - pB(t_0)$ ;  $tB \rightarrow tB(t) - tB(t_0)$ ;  $uB \rightarrow uB(t) - uB(t_0)$ ;
- 3) **Measure** of the polarized-to-unpolarized ratio :  $R_m = pB/uB$
- 4) **Calculate** the theoretical values  $R_t: pB_t/uB_t$  and compare them with  $R_m$  to build the topographical maps
- 5) **Define** the region of interest (ROI)

## Step 4:

**Calculate** the theoretical values  $R_{theo}:pB_{theo}/uB_{theo}$  and compare them with  $R_m$ .

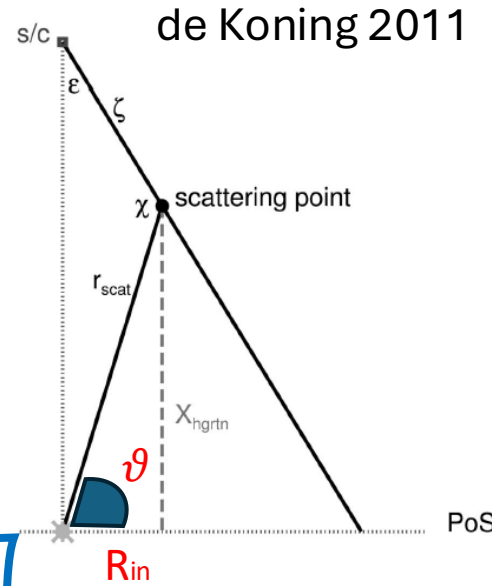
- For the analysis I performed up to now, I adopted the geometry displayed in figure, with the approximation that the Thomson Scattering is maximized on the POS (**FOV < 30 R<sub>sun</sub>**).
- I use SSW IDL eltheory.pro to retrieve the values of  $\vartheta$  for every pixel, given  $R_{in}$ .

pro ELTHEORY, Rin, T, R, B, Bt, Br, Pol with INPUTS:

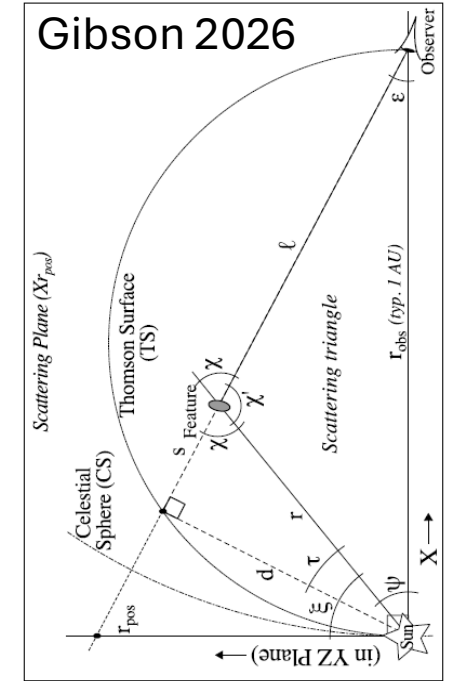
- Rin: Impact Distance (in solar radii)
- T: Angle from plane of sky (in degrees) ->  $\vartheta$

OUTPUTS:

- R: Distance of electron from sun center (in solar radii)
- B: Total Brightness for one electron at R,T
- Bt: Tangential Brightness for one electron at R,T
- Br: Radial Brightness for one electron at R,T
- Pol: Polarization for one electron at R,T  $Pol=(pB/B)$



For FOVs > 30 R<sub>sun</sub>



- I calculate  $R_{theo}$  as follows:

$$pB = Bt - Br \quad \longrightarrow \quad R_{theo}: pB_{theo}/uB_{theo}$$

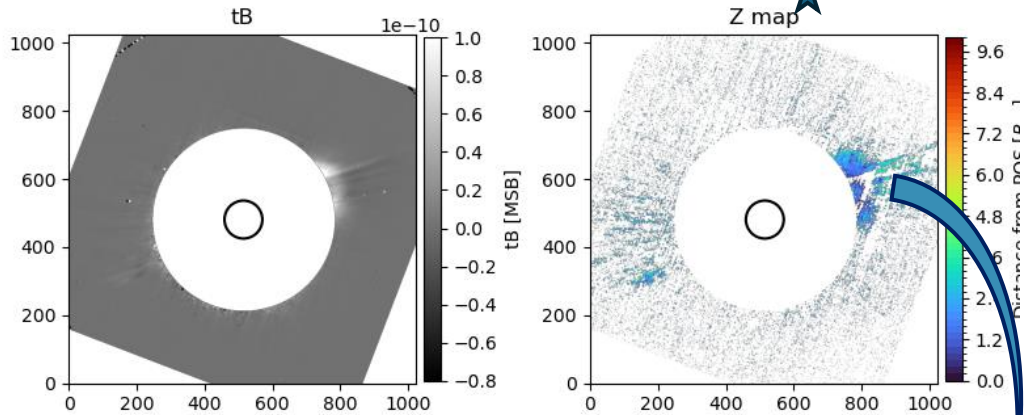
$$uB = B - pB$$

- I find the value of  $\vartheta$  which minimizes  $|R_m - R_{theo}|$
- Then I build the  $|Z|$  maps (same size as  $R$ ), where every pixel represents the distance of the CME plasma in solar radii from the POS:  $|Z| = R * \sin(\vartheta)$

Element	eltheory.pro (SSW/IDL)	Gibson et al. (2026)	Notation
<b>Observed quantities</b>	$B = B_t + B_r$ $pB = B_t - B_r$	$tB = B_T + B_R$ $pB = B_T - B_R$	Same definition
<b>Scattering kernel</b>	$pB \propto \text{sinchi}^2 * (a_{el} + u * (b_{el} - a_{el}))$	$G_1 \propto [(1 - u)A + uB] \sin \chi^2$	Equivalent
	$B_t \propto (c_{el} + u * (d_{el} - c_{el}))$	$G_2 \propto [(1 - u)C + uD]$	Equivalent
<b>Coefficients</b>	$a_{el}, b_{el}, c_{el}, d_{el}$	$A, B, C, D$ (Van de Hulst)	Notation difference, in Gibson+ 2026 functions of $r$
<b>Geometry</b>	$R_{in}, T, R$	$r_{POS}, \xi$ ( $\tau$ in POS approx), $r$	Equivalent
<b>Polarization ratio</b>	$Pol = pB / B$	$p = \frac{pB}{tB}$	Identical
<b>Limb darkening</b>	$u = 0.63$ (default)	coefficient $u$	Included
<b>Formulation</b>	Local (single point)	LOS-integrated (Delta function and distributed)	Second approach more general
<b>Physical object</b>	Single electron	$n_e(s)$	One of the main differences
<b>Physical output</b>	3D position	3D position or density slope	Equivalent

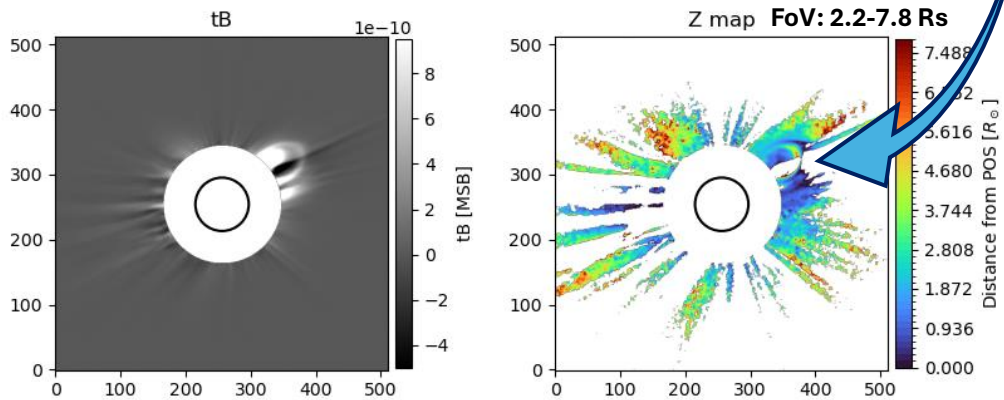
## Event 1 Earth/SolO perspective

METIS | 2021-10-28T15:35:01.421 | CROTA=-20.98 deg **FoV: 4.8-10.3 Rs**



Comparison

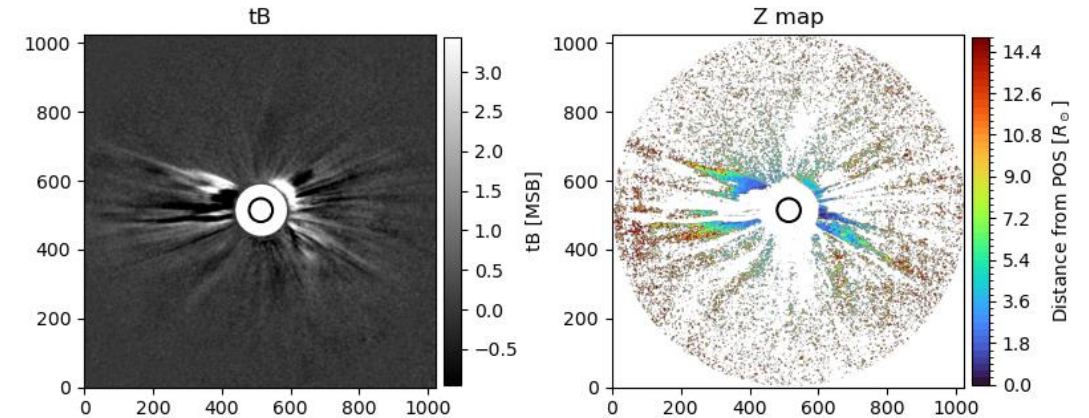
LASCO | 2021-10-28T14:54:10.983 | CROTA=0.00 deg



★|z|: distance from the POS in solar radii

## Event 1 STEREO-A perspective

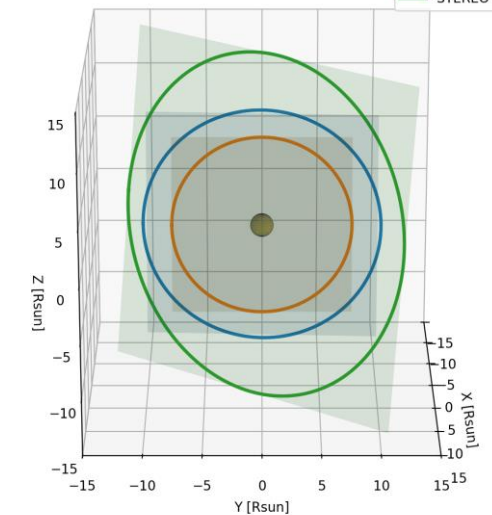
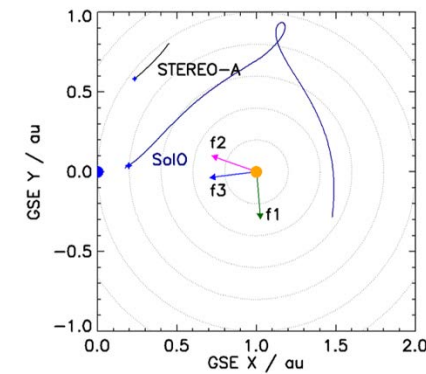
COR2 | 2021-10-28T15:07:45.006 | CROTA=0.00 deg **FoV: 2.5-15 Rs**



Metis, LASCO and STEREO-A Planes of Sky on 28/10/2021

— Metis POS  
— LASCO POS  
— STEREO-A POS

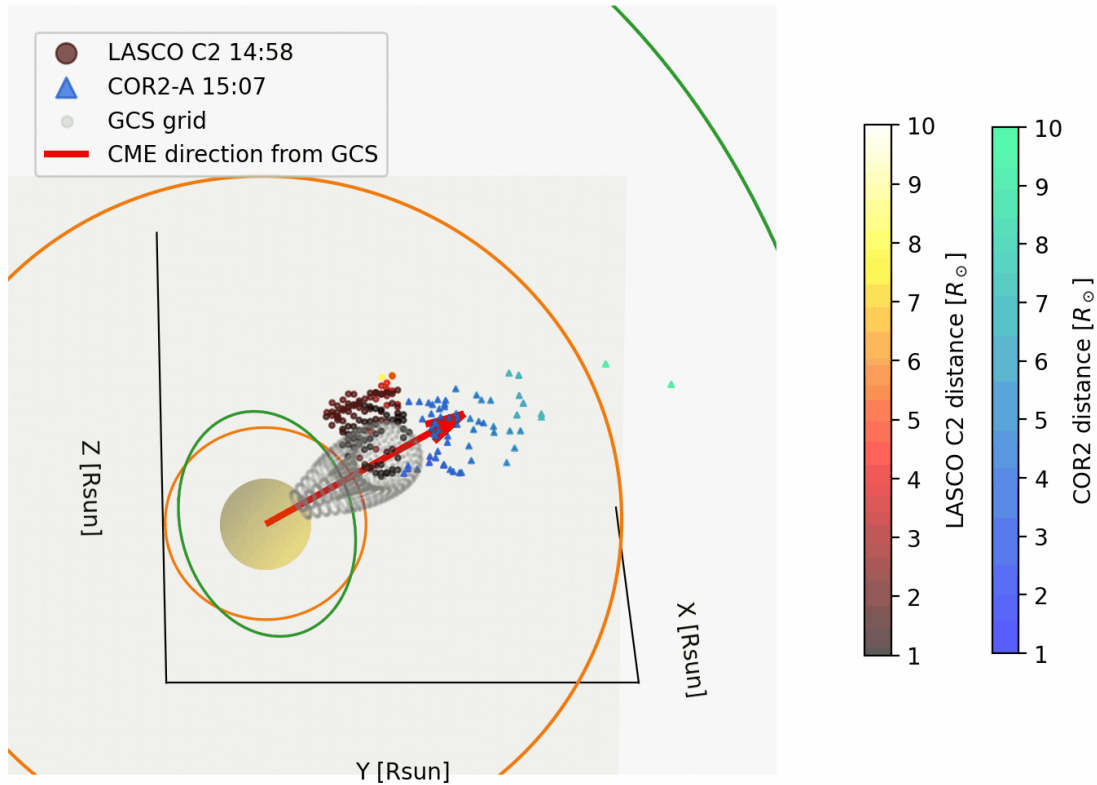
spacecraft constellation on 28-10-2021 (limb CME=f1)



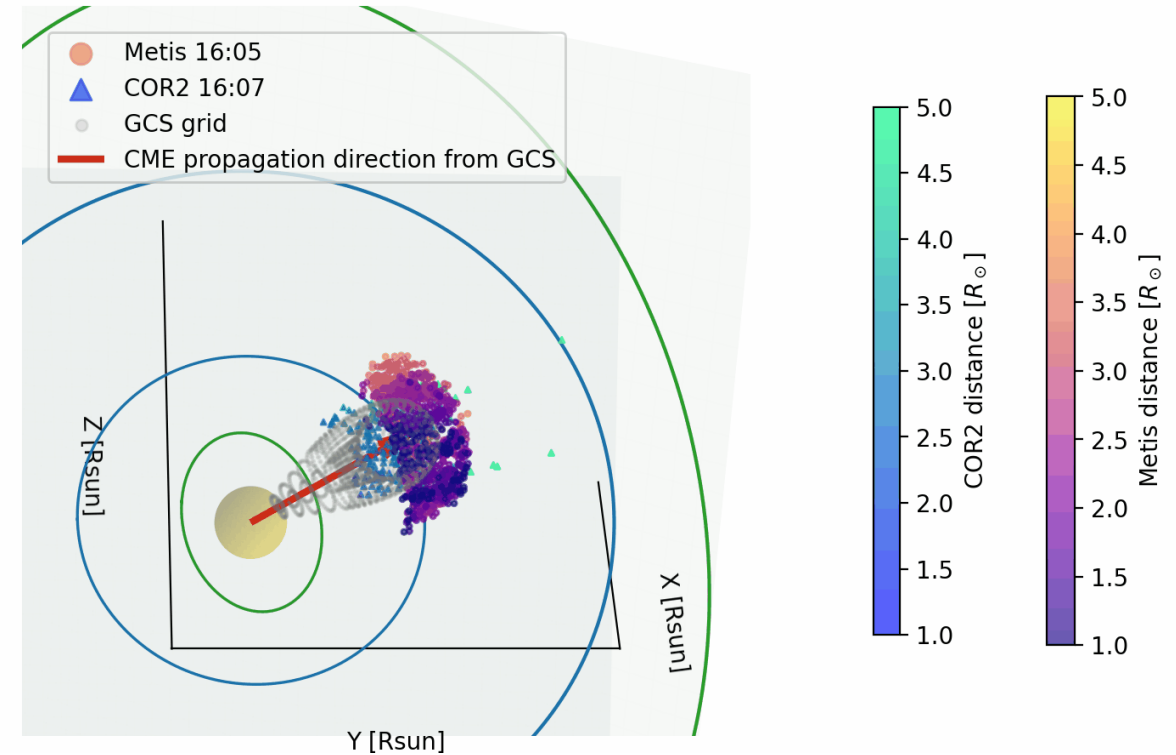


# Application of the PRT on the 20211028 limb CME

LASCO C2 + STEREO-A COR2 PRT clouds  
LASCO C2: 2021-10-28T14:54:10.983 | COR2: 2021-10-28T15:07:45.006



Metis + STEREO-A COR2 PRT clouds  
Metis: 2021-10-28T16:05:01.424 | COR2: 2021-10-28T16:07:45.008





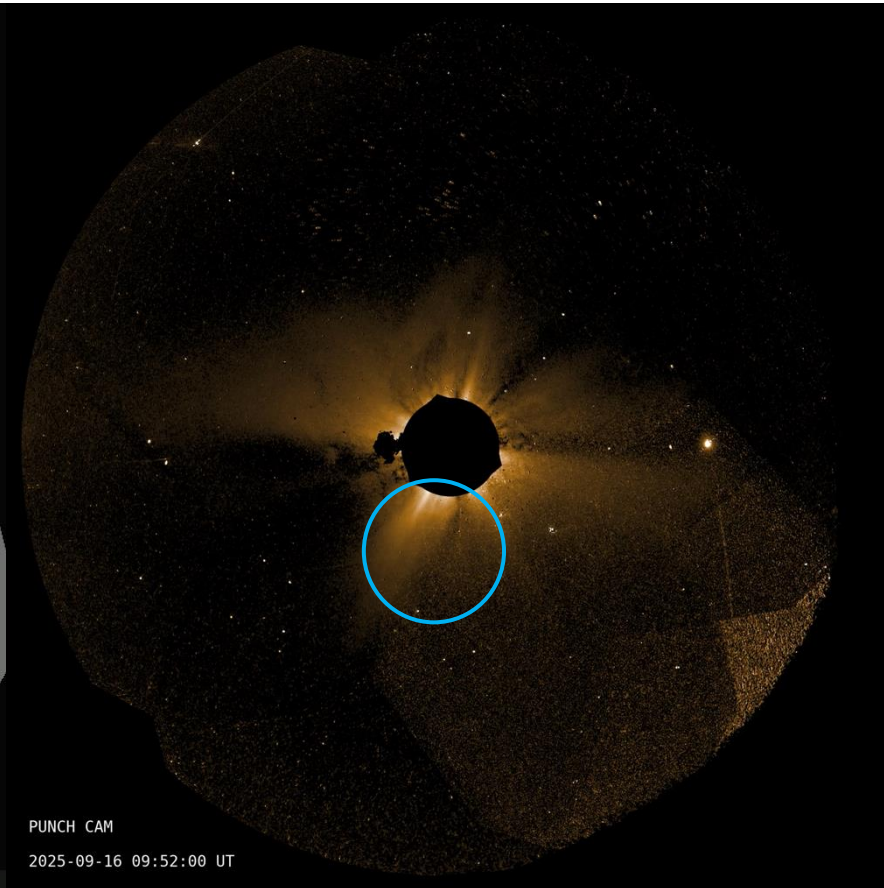
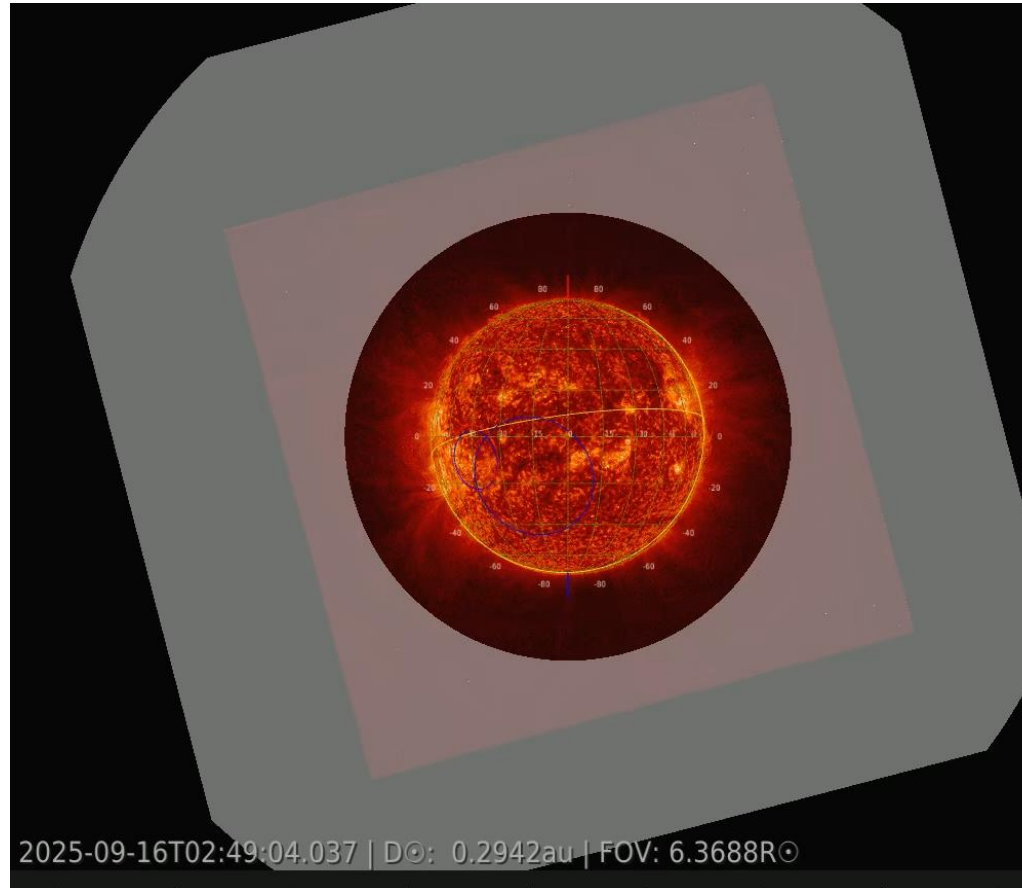
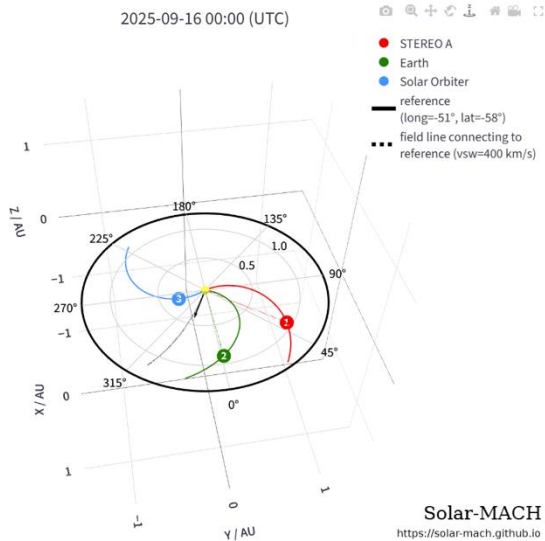
**Solar Orbiter facts:**

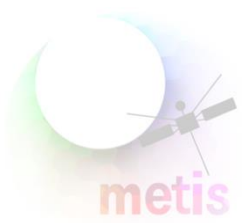
$d_{S/C} = 0.29 \text{ au}$ ,  
 $FOV_{Metis} = [1.7 - 3.2] R_{\odot}$

The event is visible in Metis FOV starting from 4:00UT

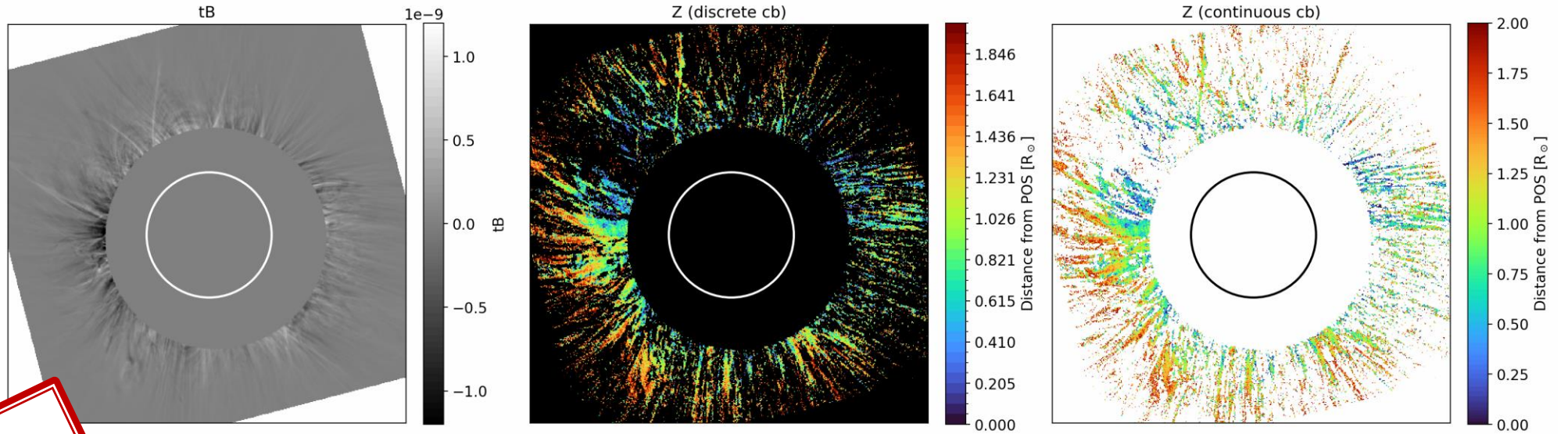
Source regions of the E and SE CMEs in the blue circles on the solar disk.

3d view



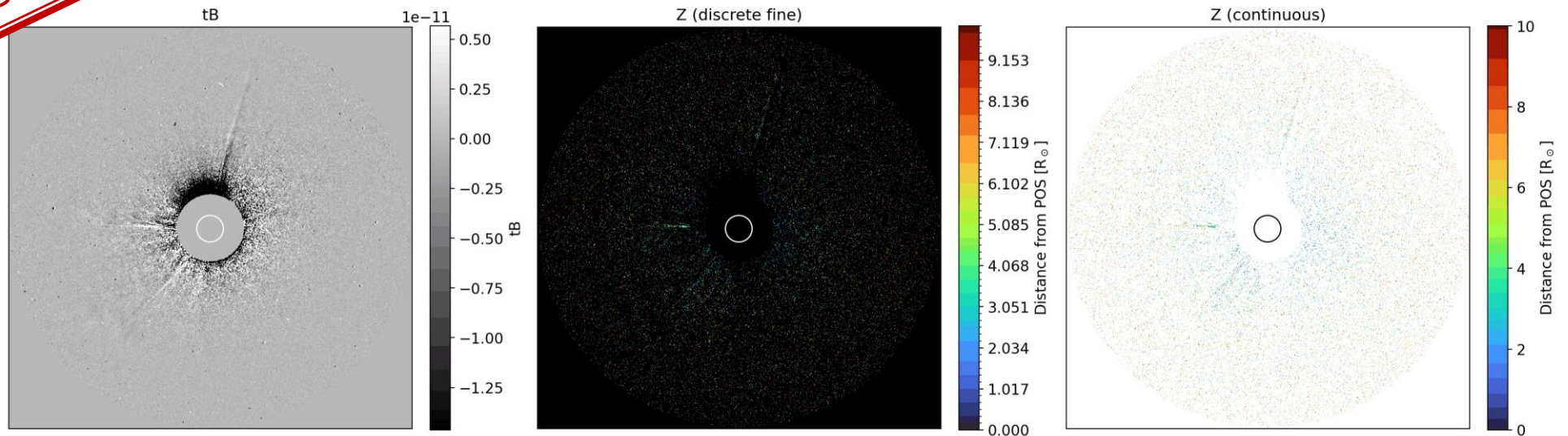


Metis PR 2025-09-16T03:36:01.369 [CROTA=14.63°]



Work in progress!

COR2 PR 2025-09-16T01:22:45.004





### Solar Orbiter facts:

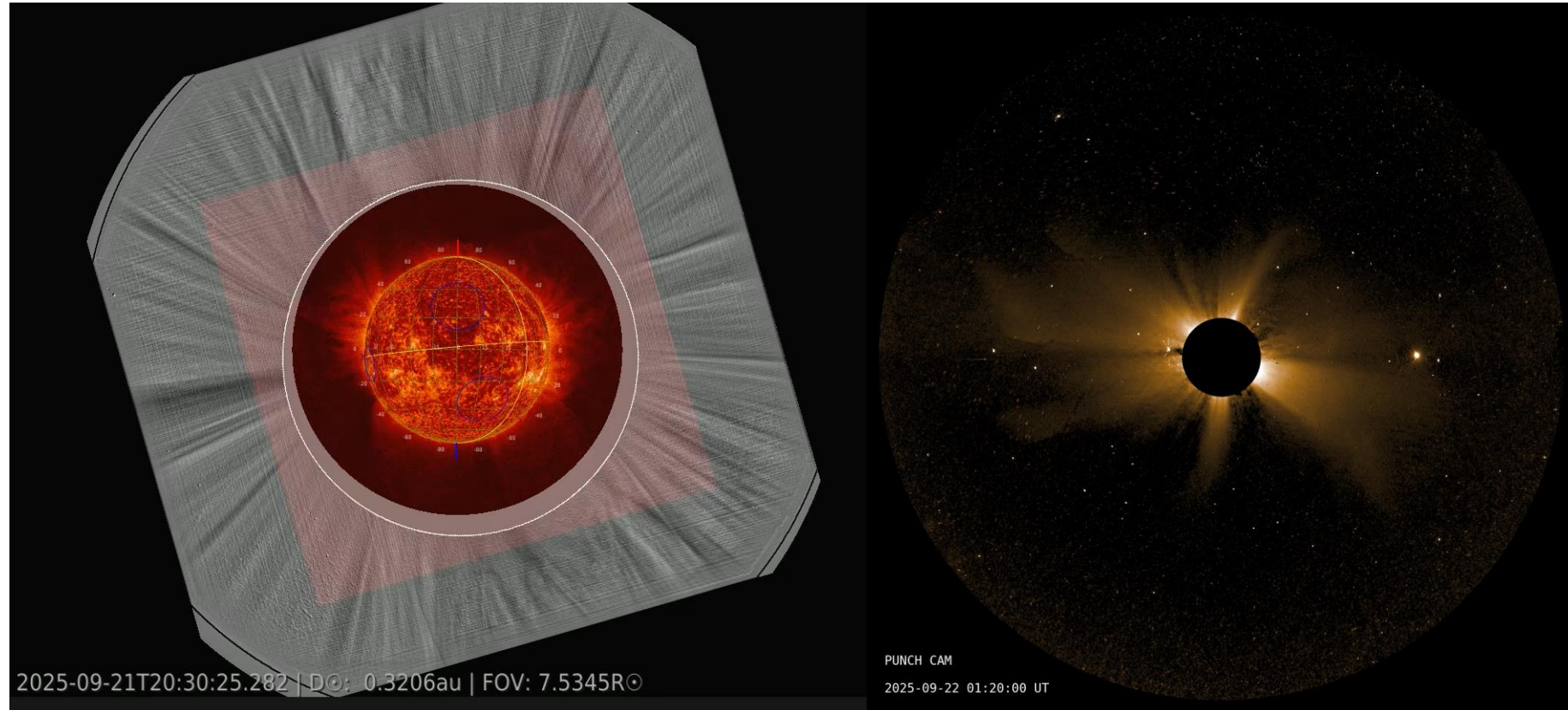
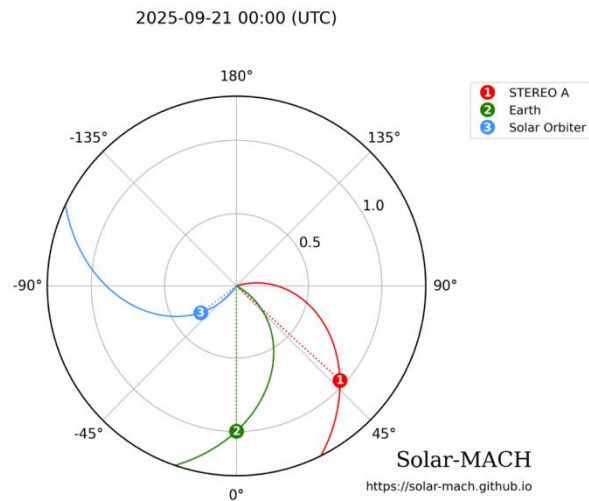
$$d_{S/C} = 0.36 \text{ au},$$

$$FoV_{Metis} = [2.2 - 4.0] R_{\odot}$$

The event is visible in Metis FOV from 22:50 UT.

### Source regions

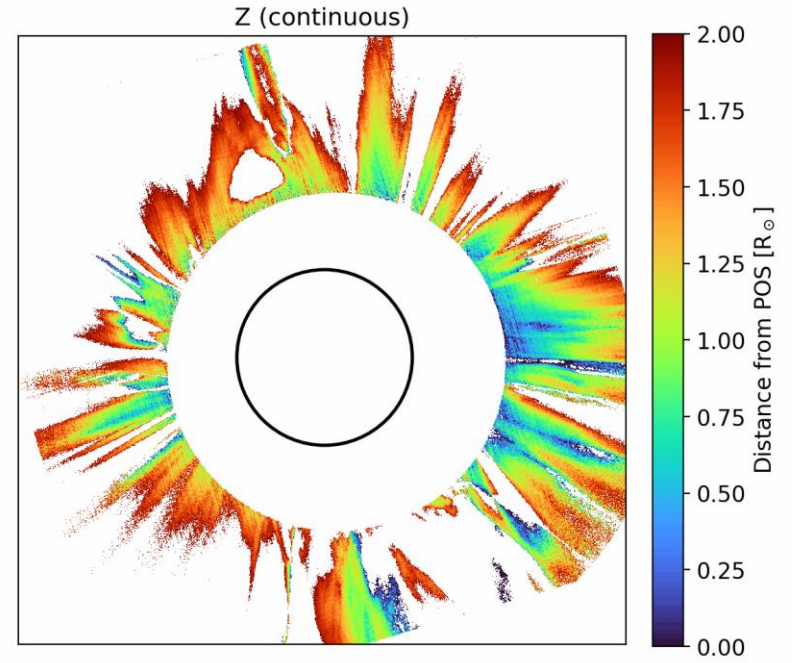
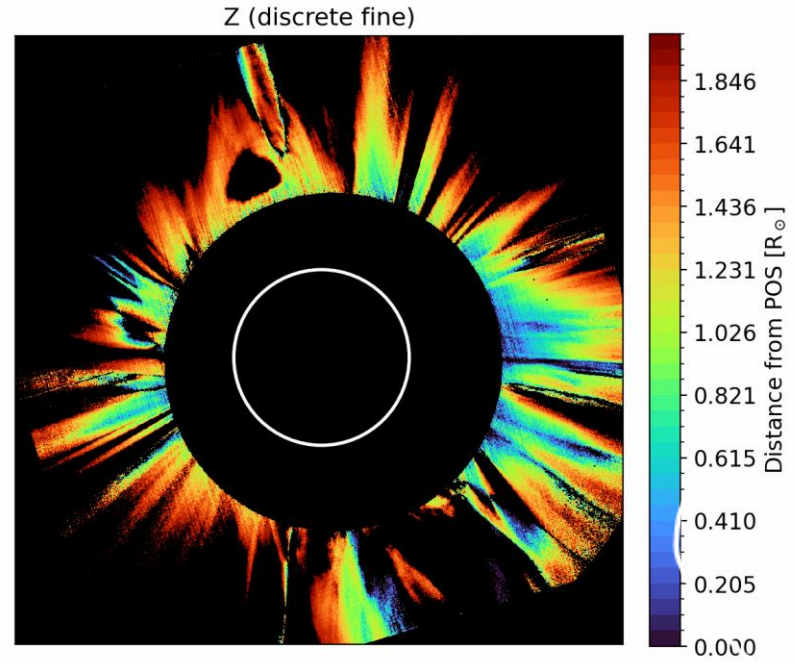
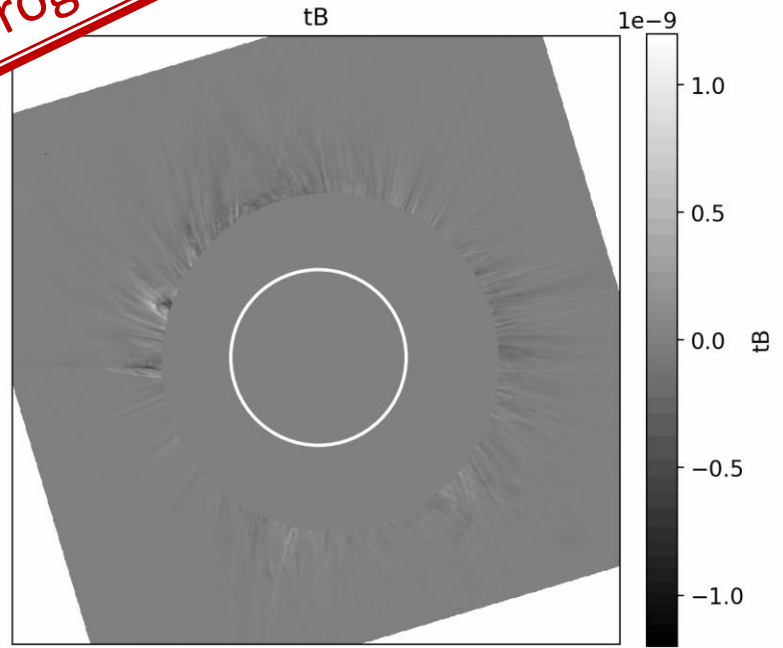
- 1) E-> narrow CME
- 2) On the meridian area, Northern hemisphere, big filament er.
- 3) Big filament er., SW

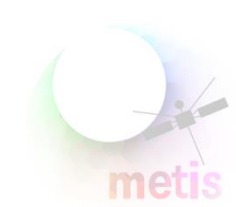




Work in progress!

Metis PR 2025-09-21T19:05:01.376 [CROTA=16.50°]





We performed a comprehensive multi-mission analysis of two co-temporal CMEs observed on 28 October 2021 using Metis, SOHO/LASCO, and STEREO-A observations.

Triangulation and GCS reconstruction were applied :

- Good agreement in the evolution among all imagers triangulation
- Reconstructed prominences lie within the GCS shells
- Metis enabled tracking of the features at farther distances with higher spatial resolution, also when using the UV channel

Mass measurements from Metis and Lasco C2 are consistent for **Event 1**. Mass density of the core of **Event 1** and **Event 2** are similar, this can explain why the **slower CME** is as bright as the **fast halo CME**.

**The comparison between PRT results and multi-viewpoint reconstructions highlights the potential of polarization diagnostics for CME 3D studies.**

We developed a PRT pipeline applicable to several coronagraphs, paving the way for future Metis–PUNCH synergistic investigations of CME evolution from the corona to the heliosphere.

Thanks for your attention!



Robert Gonsalves  
*Flower Eclipse, 2014*

Gonsalves  
© 2014

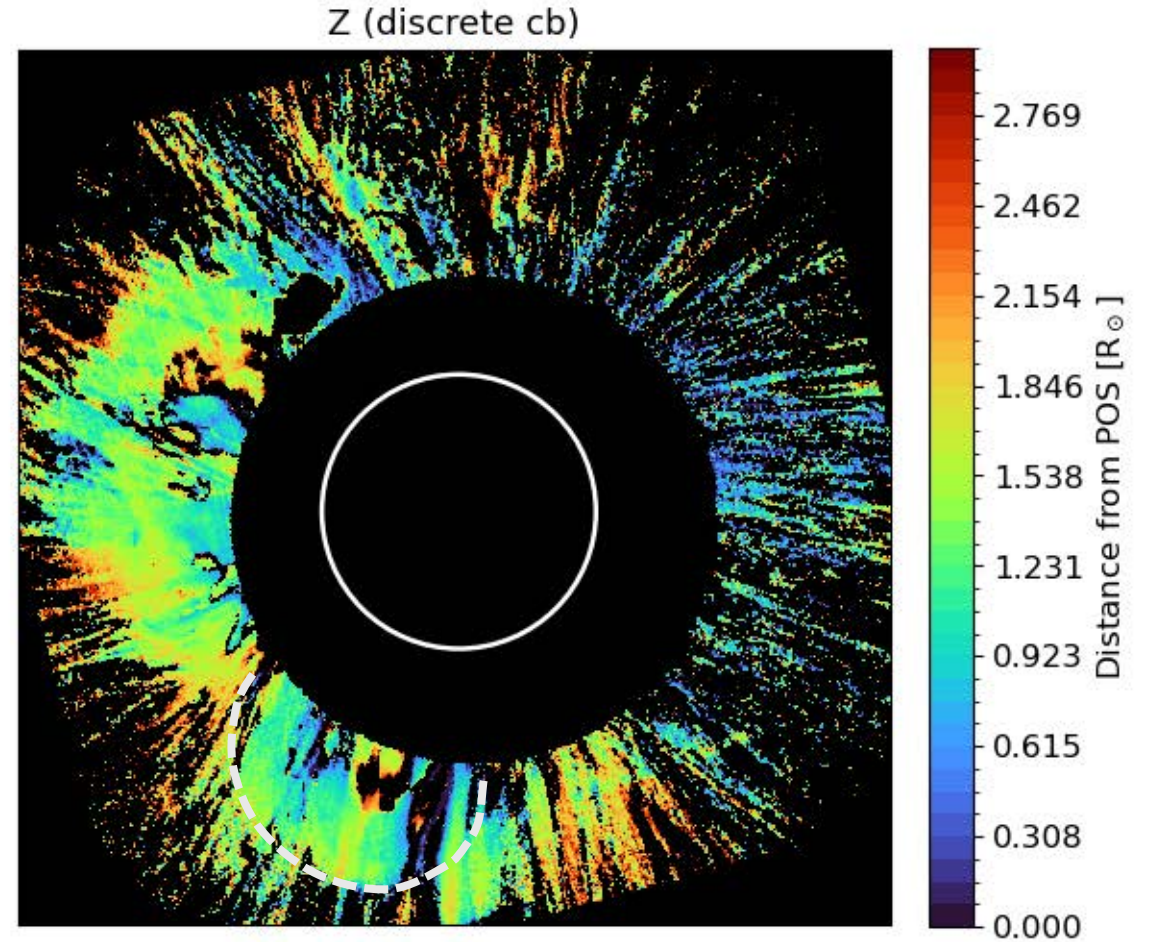
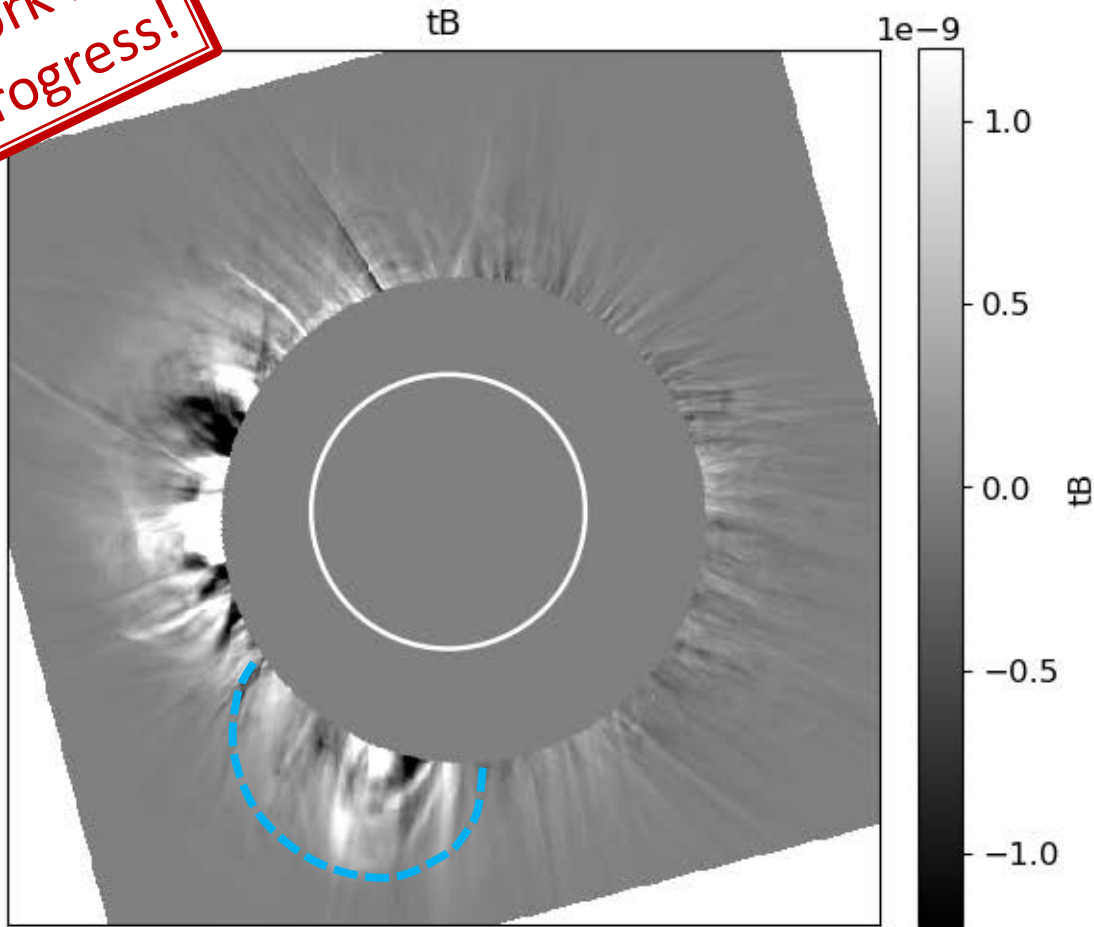
# Back-up slides

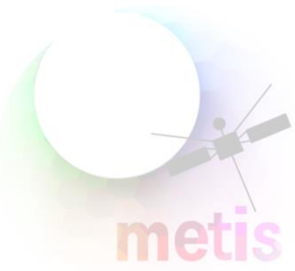
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Metis PR 2025-09-16T04:36:01.445 [CROTA=14.67°]

Work in progress!





# Metis science

Understanding **coronal mass ejections (CMEs)**: propagation and evolution, physical parameters inside all features of the eruption (CME front, flux rope, shock front, eruptive prominence, current sheet and/or blobs)

*Andretta+2021, Bemporad+2022, Heinzel+2023, Niembro+2023, Mierla+2023, Zimbardo+2023, Rodriguez+2023, Bemporad+2024, Frassati+2024, Russano+2024, Bemporad+2025, Amato+2026, Russano+2026, Jejčić+2026, De Leo+2026a in prep., De Leo+2026b in prep.*

**Solar wind velocity** on the plane of the sky by means of the **Doppler dimming technique** in several coronal structures (streamers, coronal holes, full corona)

*Romoli+2021, Capuano+2021, Antonucci+2023, Telloni+2023, Ngampoopun+2025, Giordano+2025, Rivera+2026 in preparation*

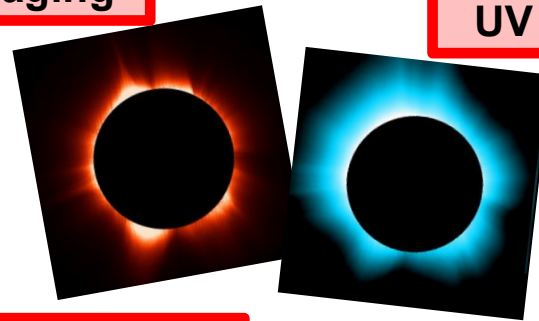
VL cosmic ray matrices to **monitor the galactic and solar proton flux** during the solar cycle

*Grimani+2021, 2023, 2024, 2026*

VL imaging

UV imaging

F corona



UV stars

Solar system objects: **comets, asteroids**

*Bemporad+2023, Corso+2026 in preparation*

Unprecedented **temporal cadence** ( $> 1\text{ s}$ ) and **spatial resolution** ( $> 5000\text{ km}$ )

Synergy with **space and ground based assets** (PSP, SOHO, STEREO, DKIST, and more)

**Structure and dynamics of the full corona**: magnetic field morphology, steady coronal features

*Vasquez+2023, 2024, Abbo+2025*

Electron **density fluctuations** observed in the VL, propagating **blobs**, and **wave structures** at different frequencies

*Ventura+2023, Andretta+2025, Romano+2025, Ventura+2026 submitted, Andretta+2026 in preparation*

**Switchbacks** in the solar magnetic field

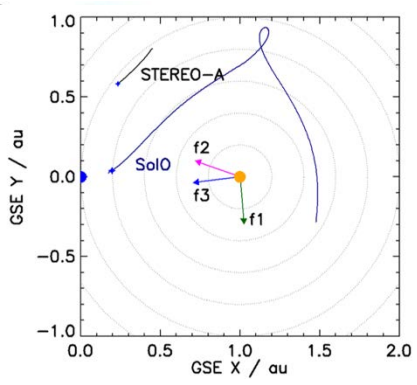
*Telloni+2023*

Evolution of the coronal dynamic and thermal state **into the heliosphere** (PSP quadrature)

*Telloni+2021, 2022, 2023*

# Application of the polarization ratio technique

Reminder of the spacecraft constellation for the events...

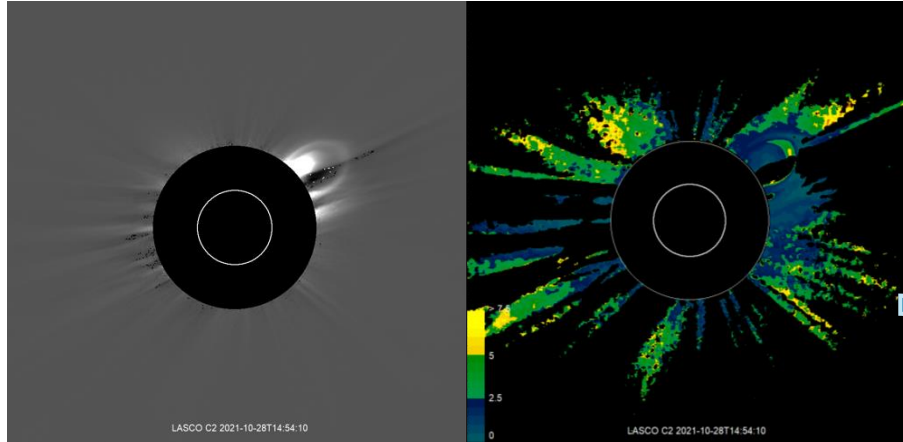


## Event 1

## Earth/SolO perspective

## Event 1 STEREO-A perspective

Lasco C2  
14:54 UT  
FoV: 2.2-7.8  $R_s$

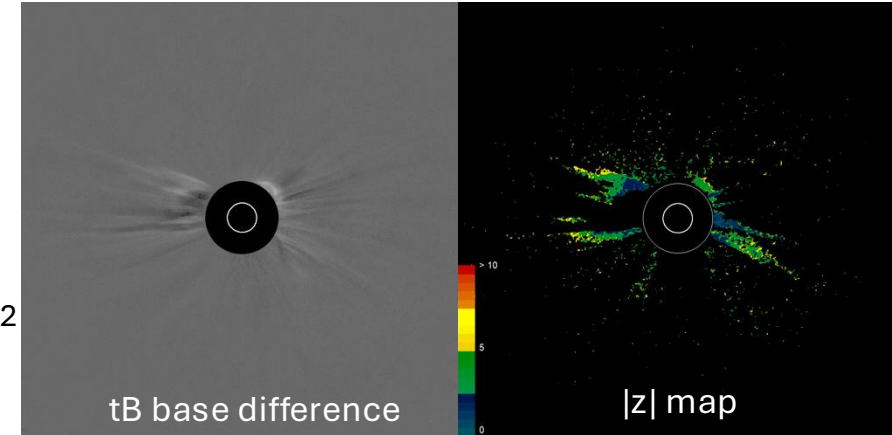


tB base difference

★  
|z| map

Comparison

STEREO-A COR2  
15:07 UT  
FoV: 2.5-15  $R_s$

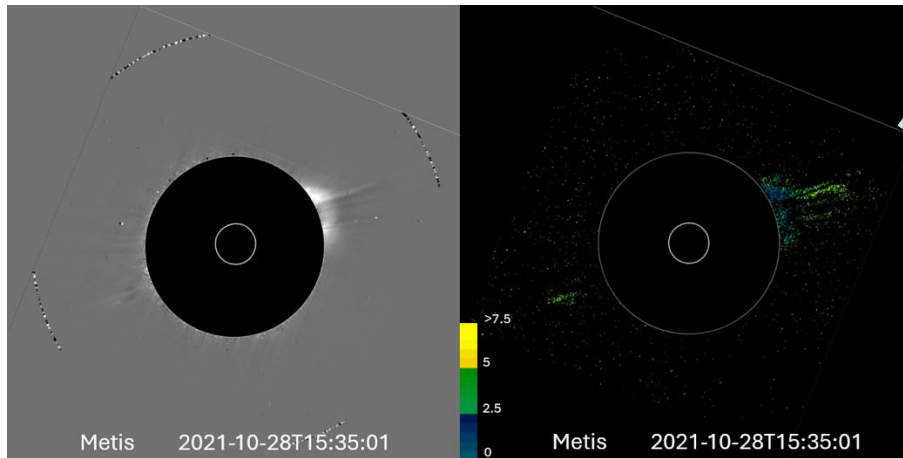


tB base difference

|z| map

## Event 2 STEREO-A perspective

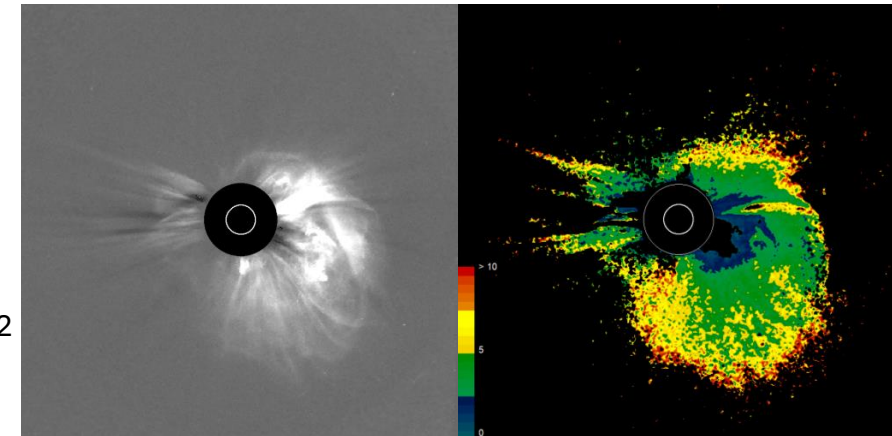
Metis  
15:35 UT  
FoV: 4.8-10.3  $R_s$



tB base difference

|z| map

STEREO-A COR2  
15:07 UT  
FoV: 2.5-15  $R_s$



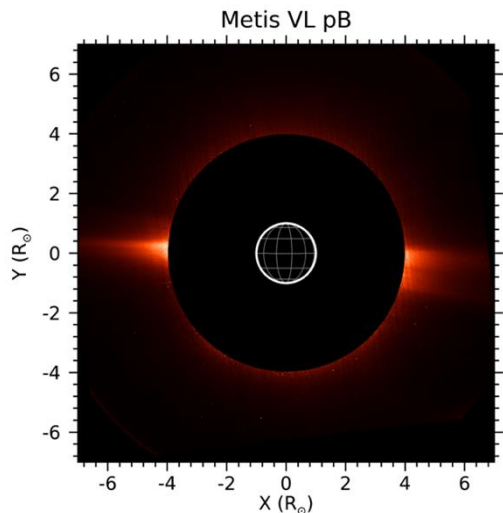
tB base difference

|z| map

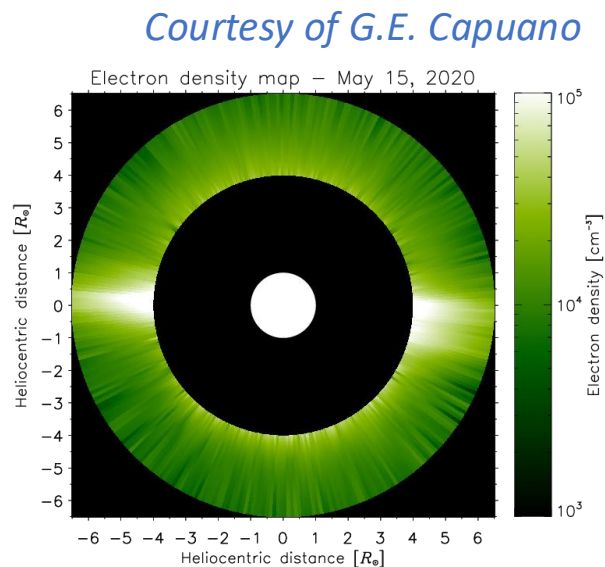
★  
|z|: distance from the POS in solar radii



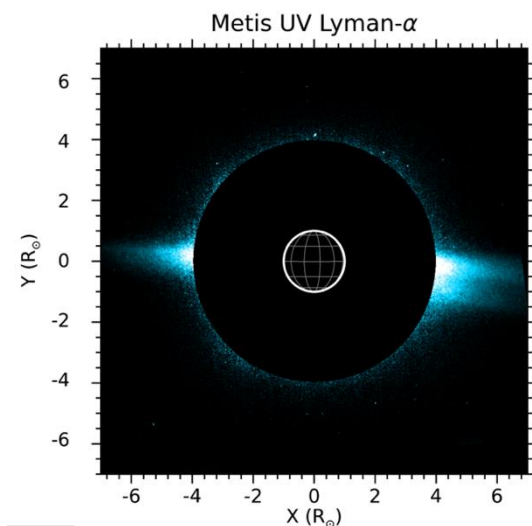
# Metis diagnostic techniques



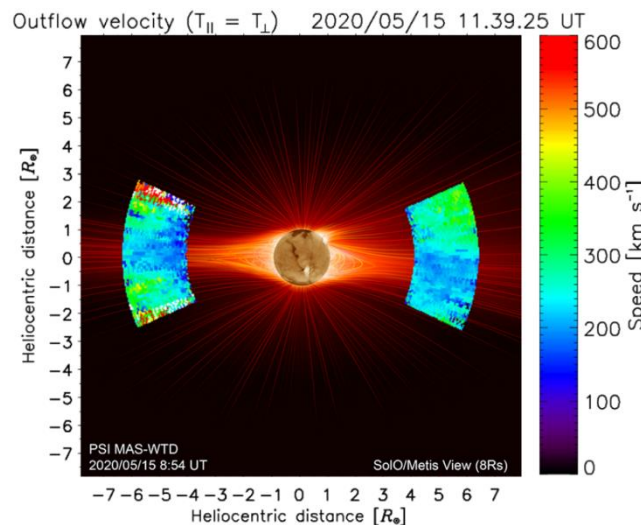
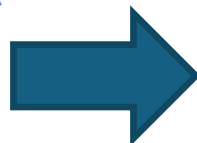
Van de Hulst inversion (1950)



It is possible to obtain the **electron density (LOS averaged)  $\langle N_e \rangle$**  from the derived pB frame that is corrected for the instrumental contribution and for the F-corona contribution.



Doppler Dimming inversion (Noci 1987)



Ly- $\alpha$  line (HI  $121.6 \pm 10 \text{ nm}$ ) is due to the resonant scattering of the chromospheric light by hydrogen atoms.

With Doppler Dimming inversion techniques is possible to obtain the **solar wind outflow velocity**.

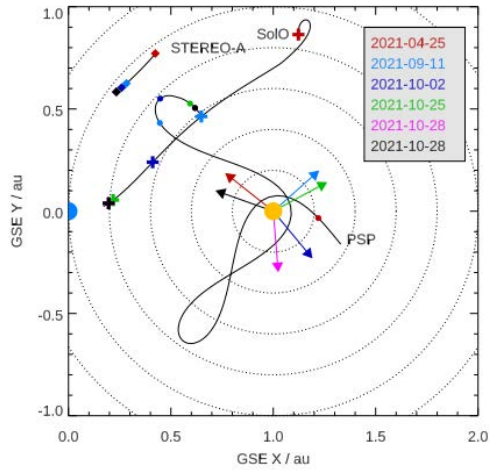


# Bright UV events in Metis

## Metis observations

Event date	Distance [au]	Annular FoV range [ $R_{\odot}$ ]	Binning		DIT [s]		NDIT		$T_{exp}$ [min]		Cadence [min]		Spatial scale [ $10^3$ km/px]	
			VL	UV	VL	UV	VL	UV	VL	UV	VL	UV	VL	UV
25 Apr. 2021	0.87	5.3 - 11.2	4x4	4x4	30	60	15	15	7.5	15	30.5	16	29	59
11 Sep. 2021	0.59	3.5 - 7.6	2x2	4x4	30	60	10	1	5	1	24	3	8.6	34
2 Oct. 2021	0.64	3.8 - 8.2	2x2	4x4	30	60	14	1	5	1	30	2	9.4	37.7
25 Oct. 2021	0.78	4.7 - 10.0	2x2	4x4	30	60	14	1	7	1	30	2	11	46
28 Oct. 2021	0.8	4.8 - 10.3	2x2	4x4	30	60	14	1	7	1	30	2	11.7	47.1

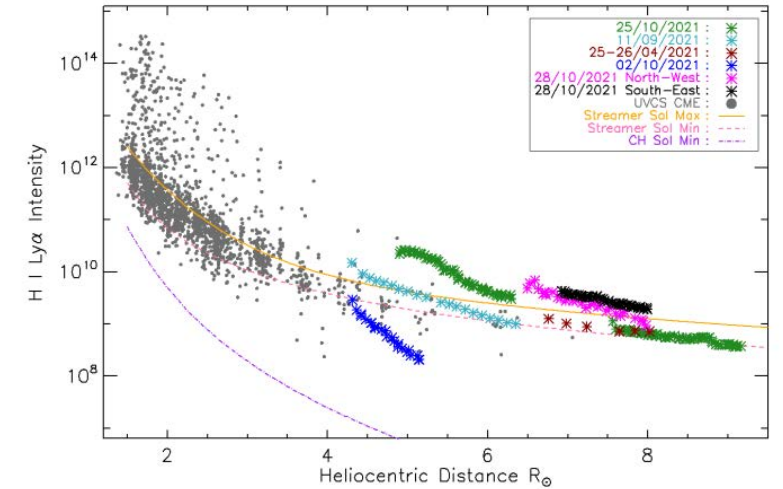
H I Lyman- $\alpha$  intensity radial profiles: comparison with Giordano et al. 2013



Data and plots from Russano, Andretta, De Leo et al. 2024

## Kinematics

Event date	Event range [UT]		PoS velocity [km/s]	De-projected radial velocity [km/s] (Doppler dimming coefficients)	Residual acceleration [ $m/s^2$ ]	Direction Carr. coord. [deg]	
	pB	UV				Lon.	Lat.
25 - 26 Apr. 2021	from 15:20 on 25/04 to 04:20 on 26/04	from 22:44 on 25/04 to 4:44 on 26/04	$152 \pm 6$	$177 \pm 7$ (0.17-0.29)	$1.7 \pm 0.4$	$179.5 \pm 0.3$	$-6 \pm 1$
11 Sep. 2021	07:03 - 11:07	10:05 - 11:17	$375 \pm 5$	$377 \pm 5$ (0.001-0.006)	$7 \pm 1$	$44.1 \pm 0.6$	$-34 \pm 1$
2 Oct. 2021	14:19 - 15:19 17:33 - 19:49	17:05 - 19:49	$228 \pm 13$	$367 \pm 22$ (0.001-0.004)	compatible with zero	$30 \pm 1$	$-28 \pm 1$
25 Oct. 2021	11:49 - 16:19 18:19 - 20:49	14:13 - 16:33 18:05 - 20:13	$150 \pm 1$	$265 \pm 3$ (0.009-0.04)	$0.7 \pm 0.1$	$169.6 \pm 0.5$	$-11 \pm 1$
28 Oct. 2021 North-West	15:49 - 16:19 18:19 - 20:49	18:07 - 19:11	$244 \pm 10$	$246 \pm 10$ (0.02-0.08)	$15 \pm 3$	$15.6 \pm 0.5$	$22.9 \pm 0.8$
28 Oct. 2021 South-East	18:19 - 20:49	18:05 - 22:57	$152 \pm 1$	$437 \pm 4$ (2.7-5.2) $\cdot 10^{-4}$	$-8.5 \pm 0.1$	$258.5 \pm 0.4$	$-2.8 \pm 0.6$

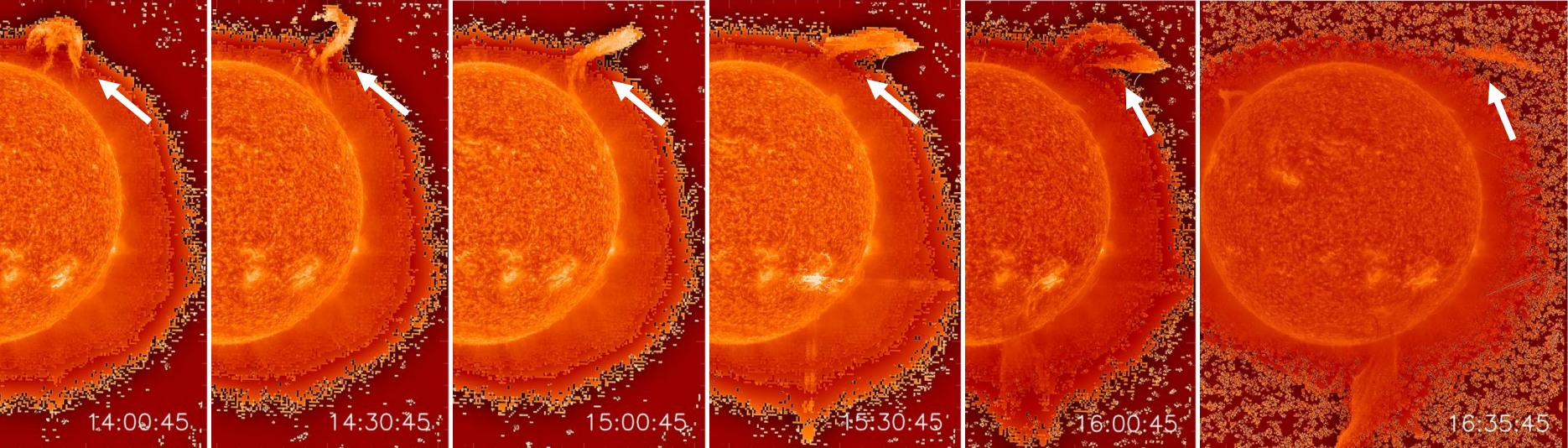
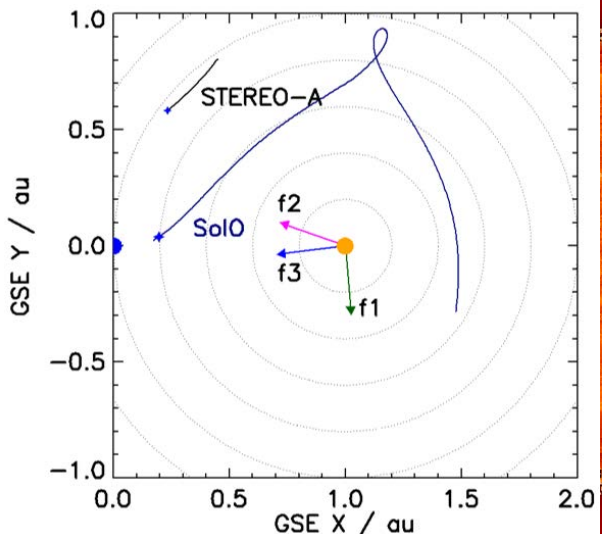


★ Results from the triangulation method (Metis, LASCO C2, COR2)

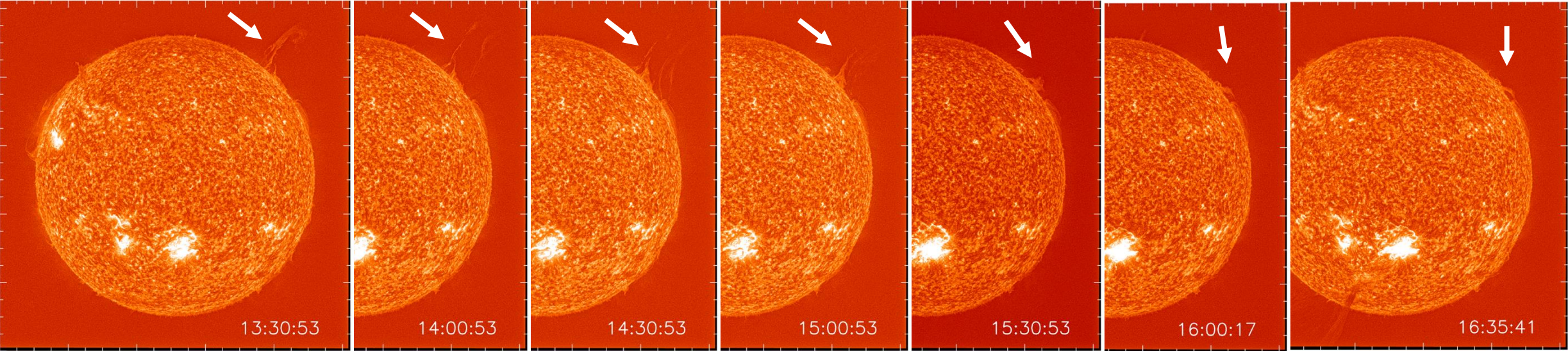
# The origin of event 1



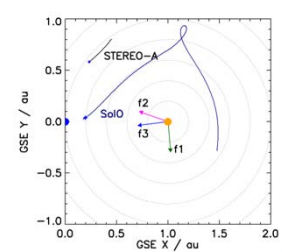
STEREO-A/EUVI 304



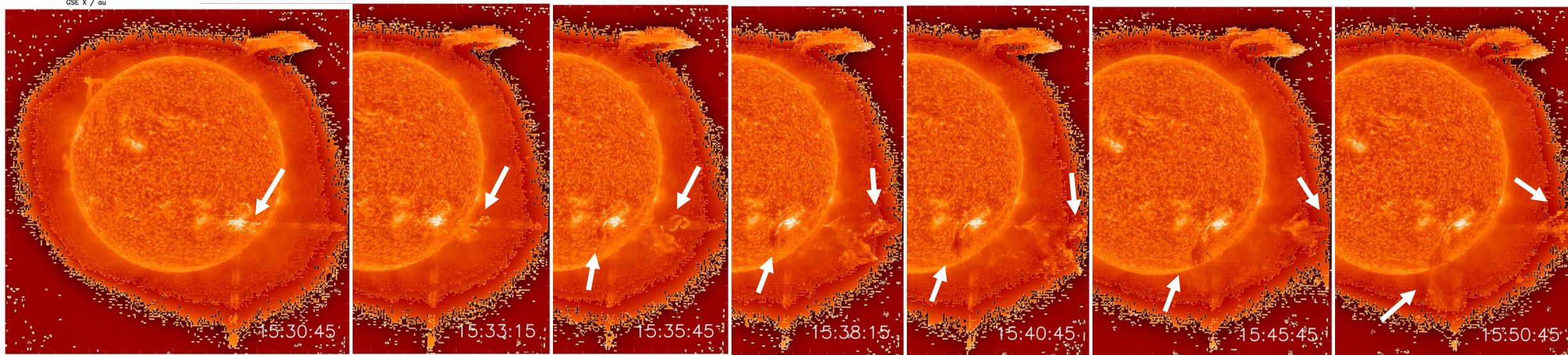
SDO/AIA 304



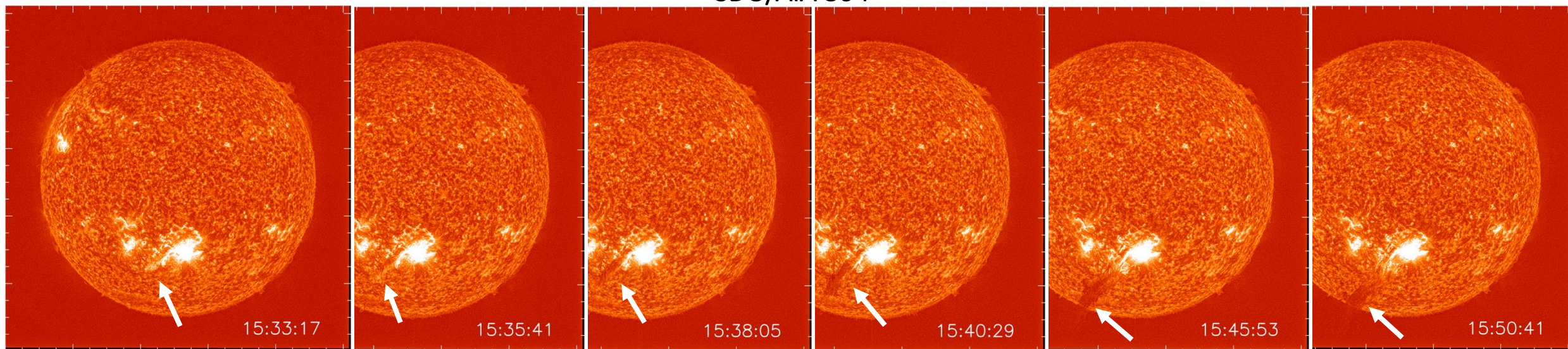
# The origin of event 2



STEREO-A/EUVI 304



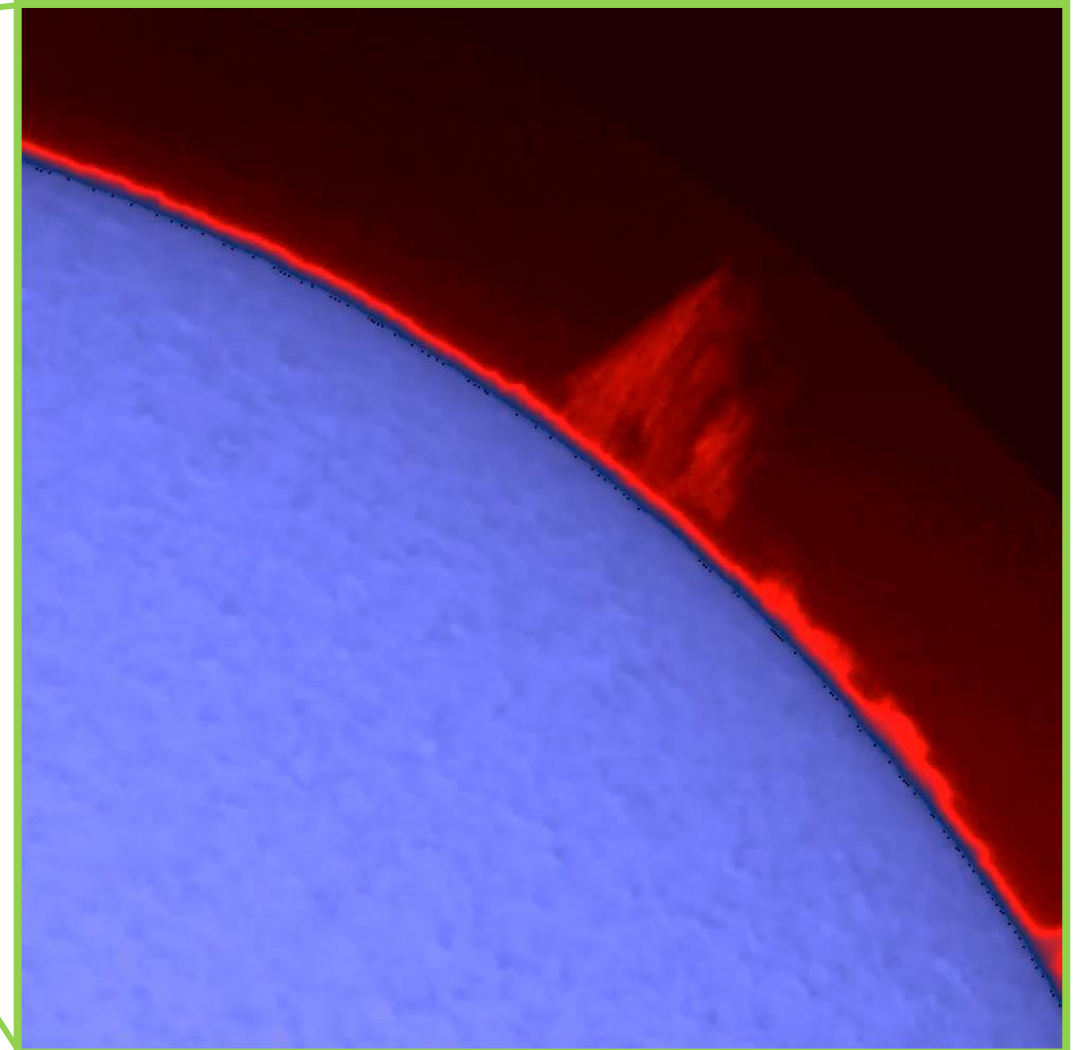
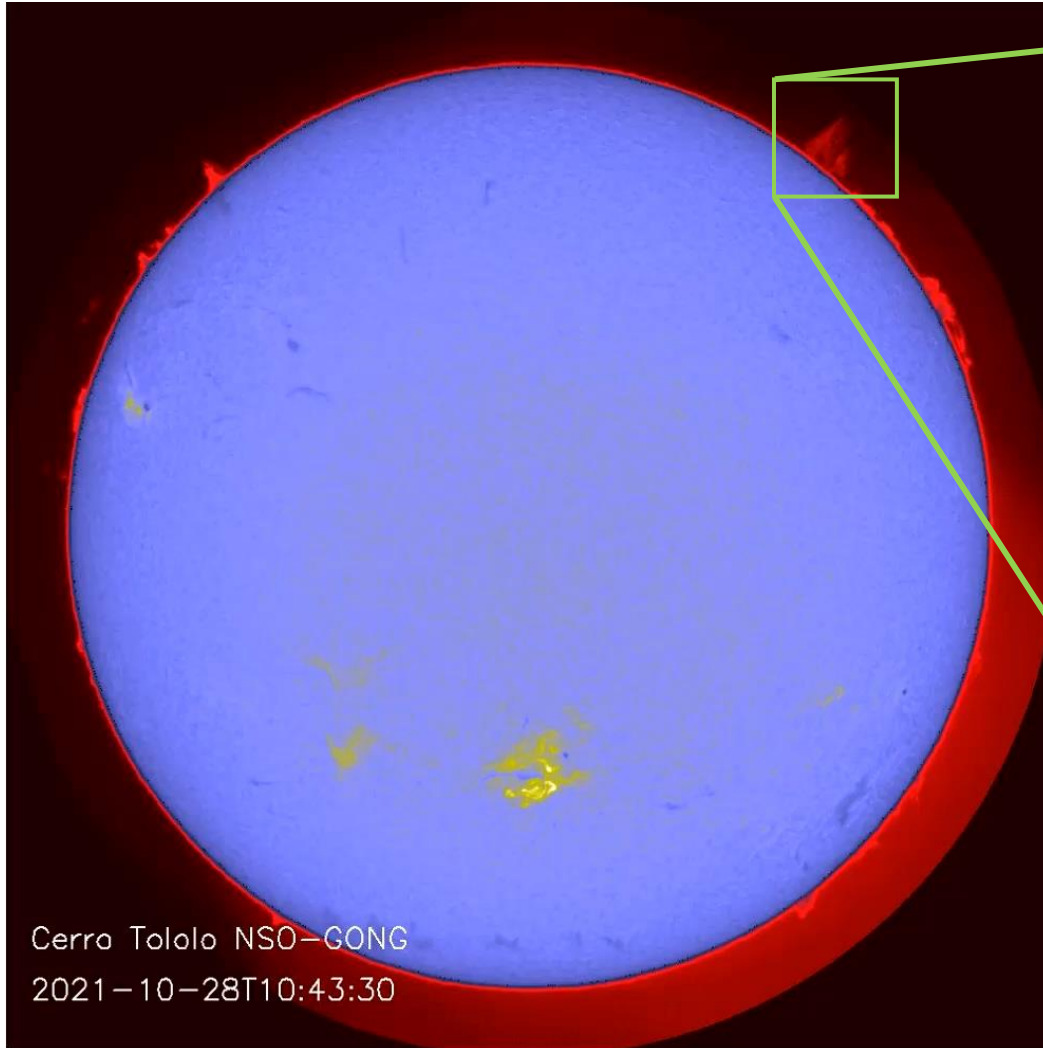
SDO/AIA 304

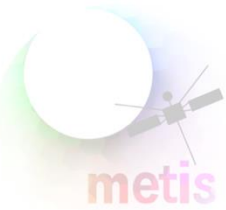


# Inspection of the data set



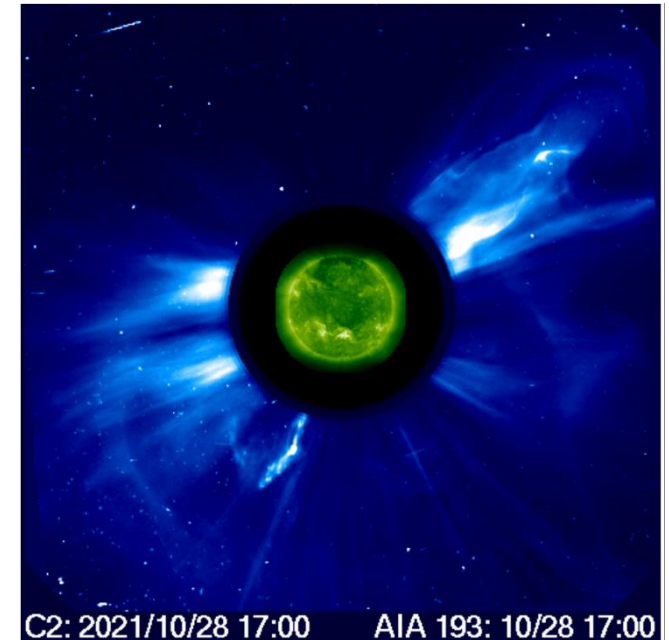
**H-alpha network:** El Teide/Cerro Tololo images confirmed that both legs of feature 1 are behind the NW limb



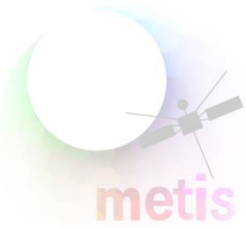


# Outline of the methodology

- Inspection of many data sets and use of several techniques of enhancement:
  - **STEREO-A/EUVI 171, 195, 284, 304** (wavelet-enhanced images at JHUAPL)
  - **SDO/AIA 171, 193, 211, 304** (`r_filter`, `stack of images`, `wavelets decomp.`, `mgn`)
  - **PROBA 2/SWAP** (`stack of images`, `mgn`)
  - **STEREO-A/COR1, COR2** (`cosmic rays removal`, `histogram equalization`)
  - **SOHO/LASCO-C2, C3**
  - **Solo/Metis VL, UV**
  - **H-alpha**: El Teide/Cerro Tololo images confirmed that both legs of feature 1 are behind the NW limb
- Characterization of the prominence evolution with the tie-point triangulation
- 3D reconstruction of CME's outer envelope (GCS reconstruction)
- Application of the polarization ratio (PR) technique on all the available images of space-based coronagraphs
- Mass and density calculation of the CME cores

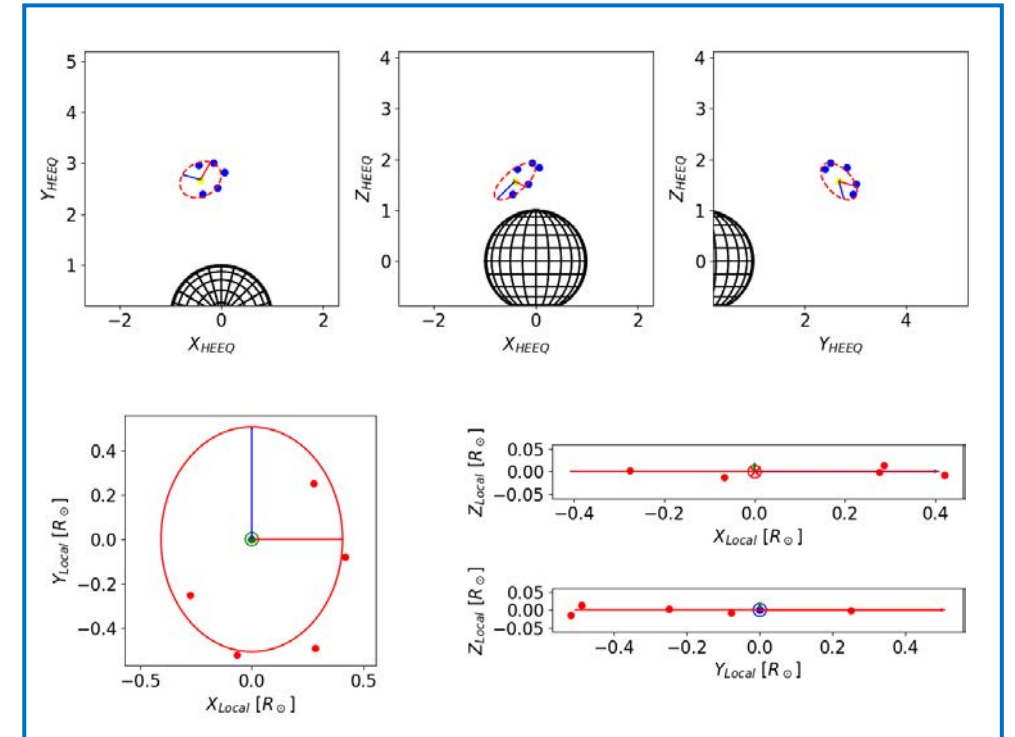
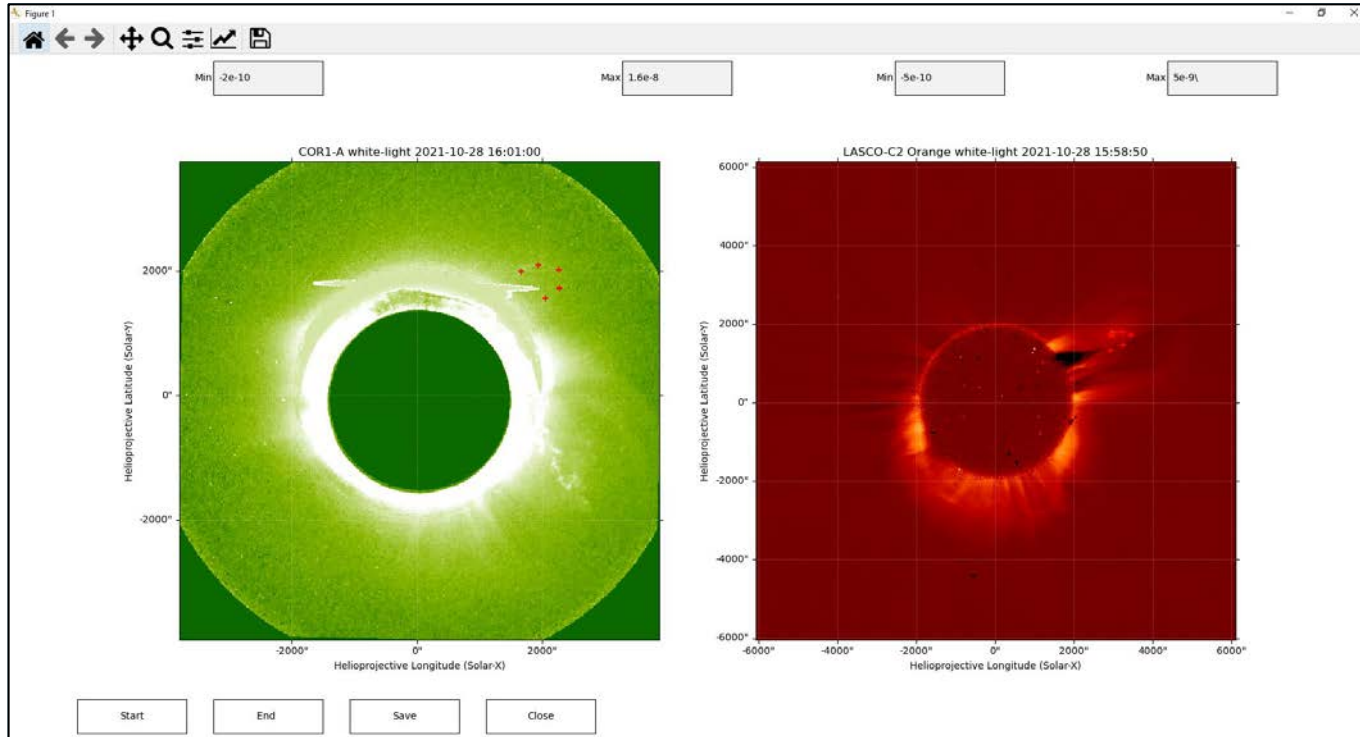


From <https://cdaw.gsfc.nasa.gov>



# Triangulation

We made use of a Python tool for Geometric Triangulation developed by Nisticò (Nisticò 2023, publicly available), with some changes to adapt the tool to our purposes.

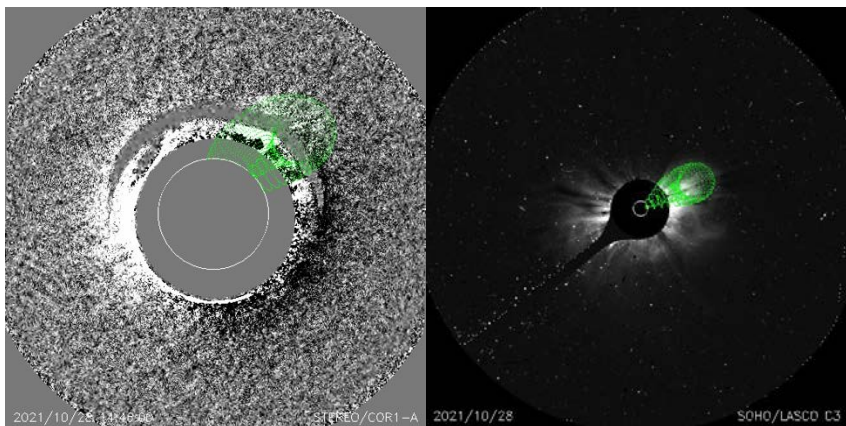


We triangulated the chosen features for several time stamps using the following pairs of instruments:

- STEREO-A/EUVI 304 and SDO/AIA 304 (FoV: until  $1.3 R_{\odot}$ )
- STEREO-A/SECCHI-COR1 and SOHO/LASCO-C2 (FoV:  $2.0-4.0 R_{\odot}$ )
- STEREO-A/SECCHI-COR2 and SOHO/LASCO-C2 (FoV:  $2.5-6.0 R_{\odot}$ )
- SoLO/Metis-UV and STEREO-A/SECCHI-COR2 (FoV:  $4.8-10.3 R_{\odot}$ )

f1

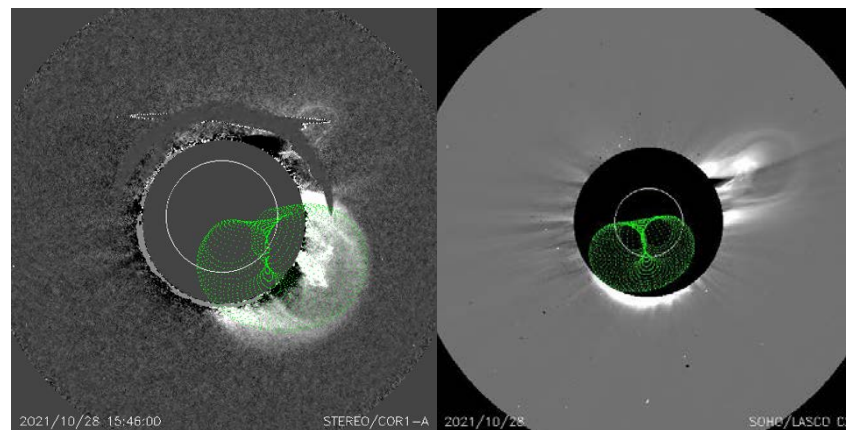
14:46



Long.[°]	106
Lat [°]	30
Tilt [°]	-13
Height ( $R_{\odot}$ )	3.3
Ratio	0.24
$\alpha$ [°]	25

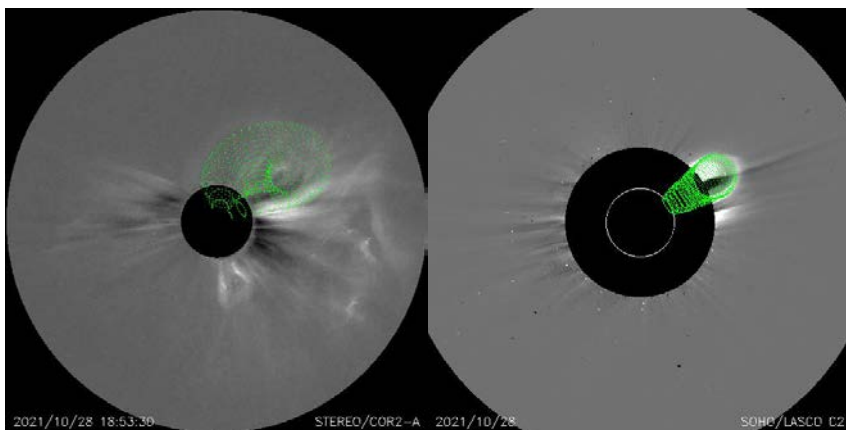
f2&f3

15:46



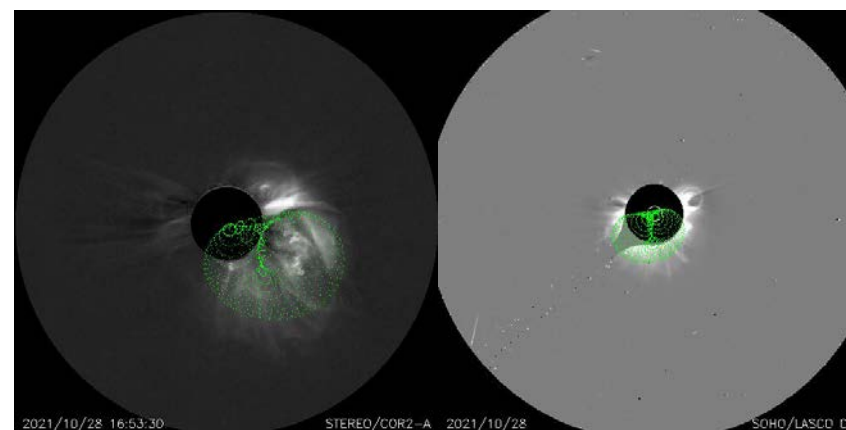
Long.[°]	355
Lat. [°]	-17
Tilt [°]	10
Height ( $R_{\odot}$ )	3.6
Ratio	0.4
$\alpha$ [°]	22

18:53

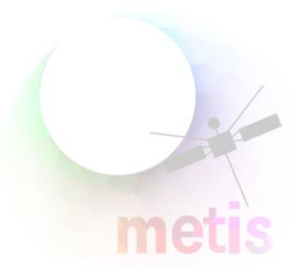


Long[°]	107
Lat [°]	25
Tilt [°]	1.1
Height ( $R_{\odot}$ )	11.6
Ratio	0.28
$\alpha$ [°]	27

16:53

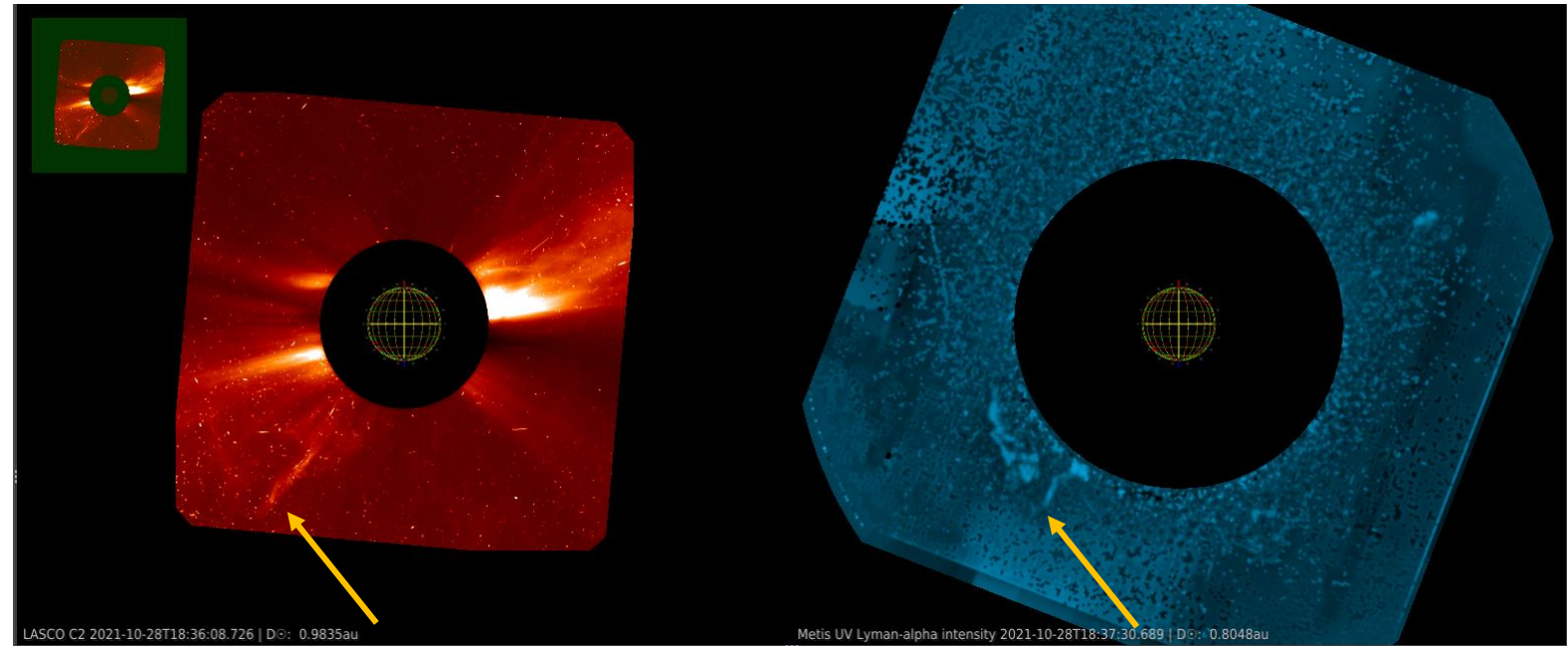


Long.[°]	353
Lat [°]	-18
Tilt [°]	10
Height ( $R_{\odot}$ )	11.2
Ratio	0.43
$\alpha$ [°]	22



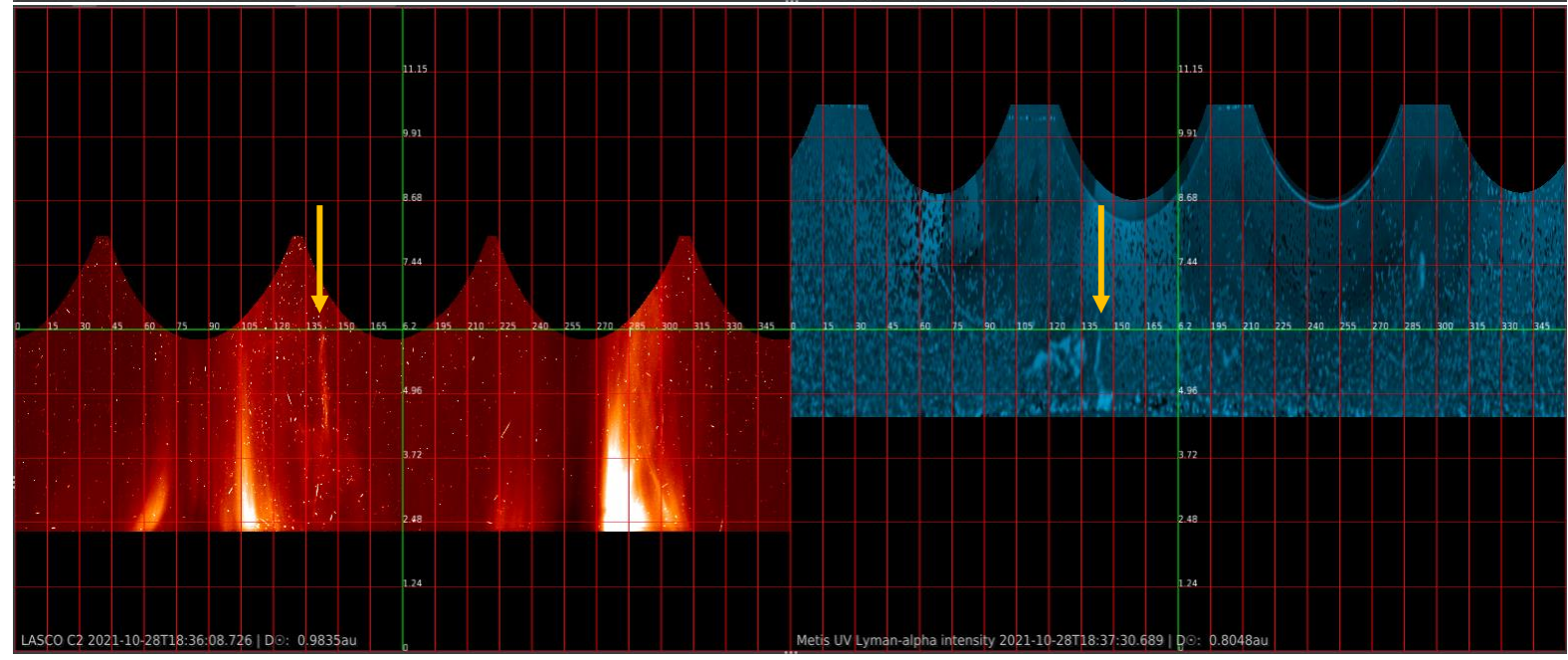
Metis UV 2021-10-28T18:35:30 &  
LASCO C2 2021-10-28T18:36:08

Cartesian coordinates

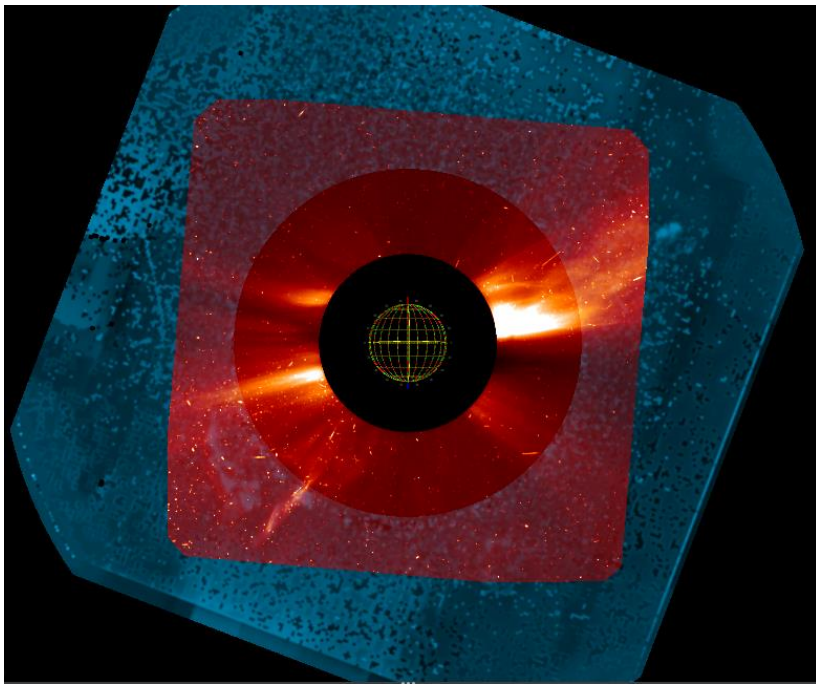


Made with  
JHelioviewer

Polar coordinates

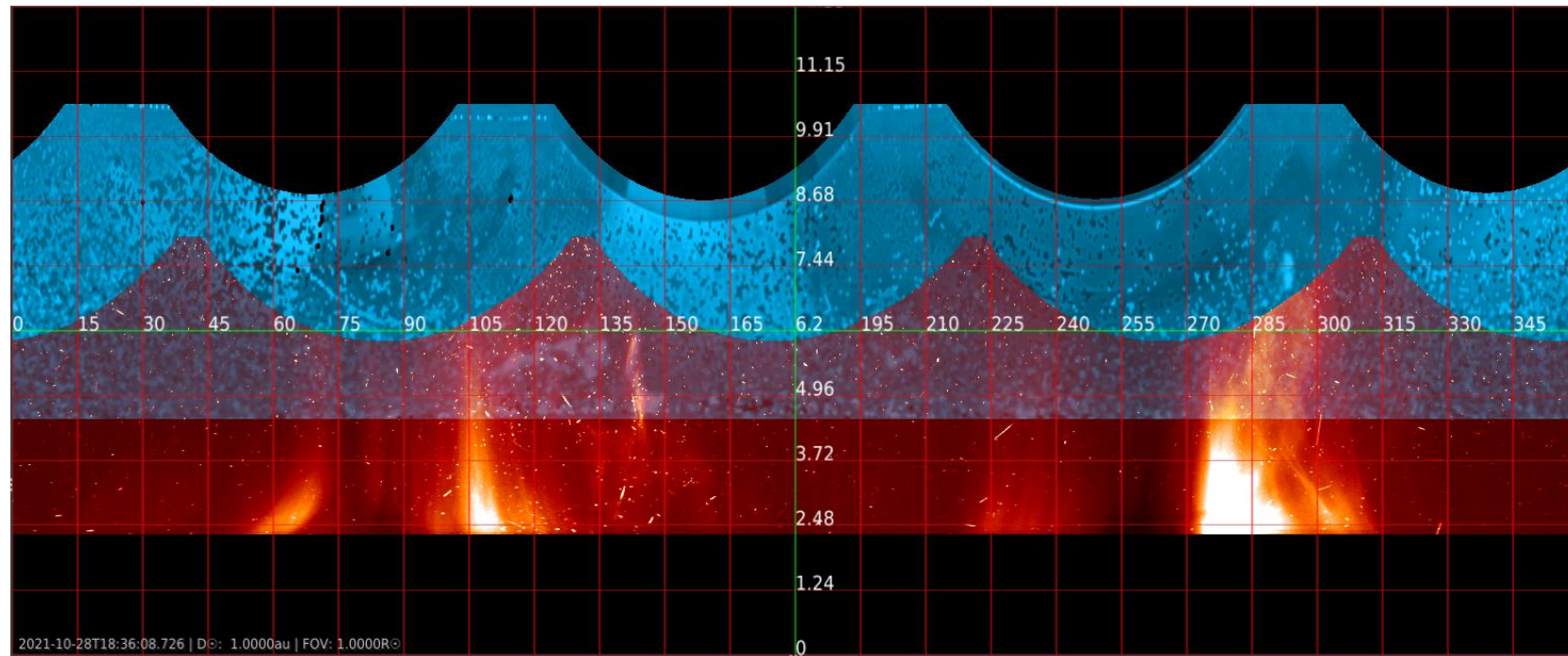


Cartesian coordinates



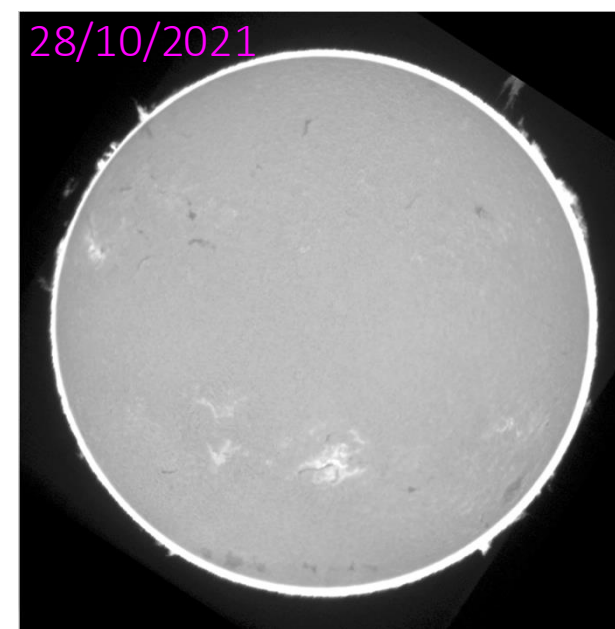
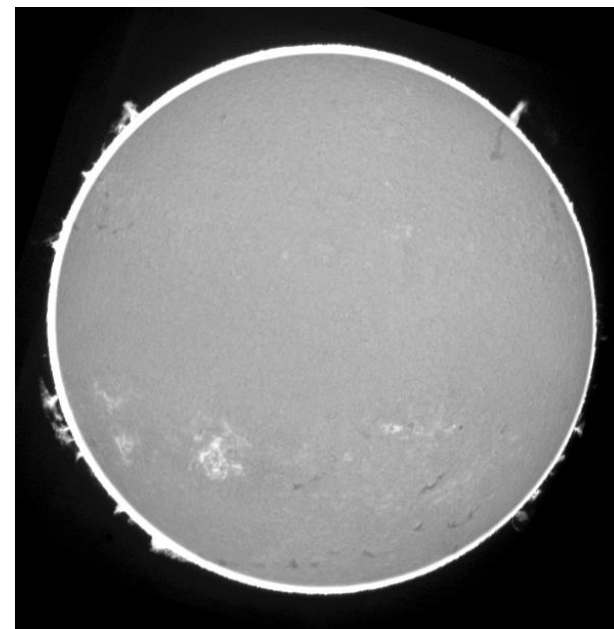
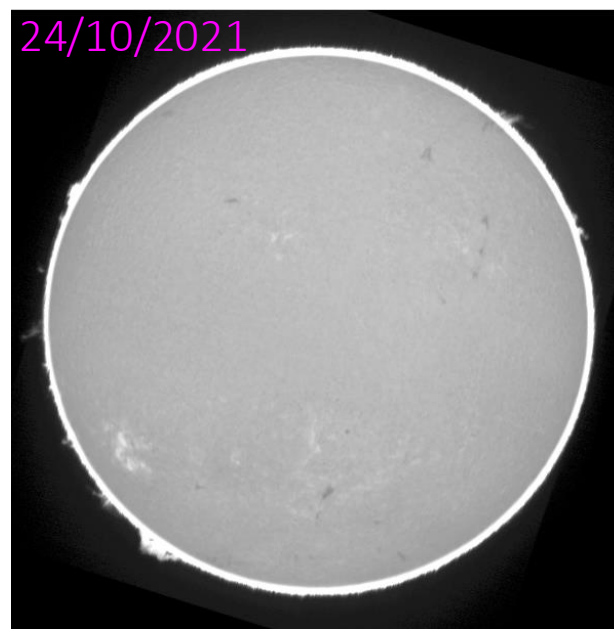
Metis UV 2021-10-28T18:35:30 &  
LASCO C2 2021-10-28T18:36:08

Polar coordinates

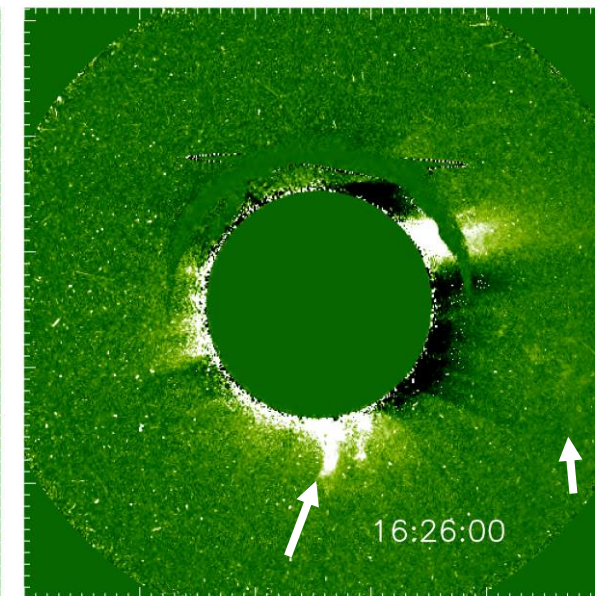
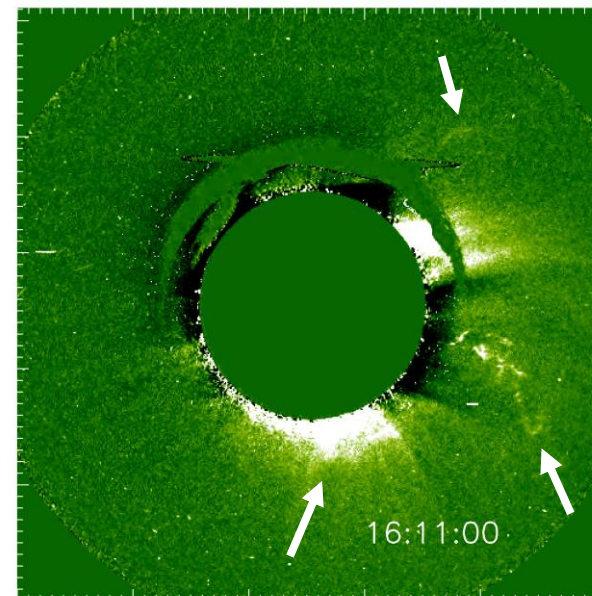
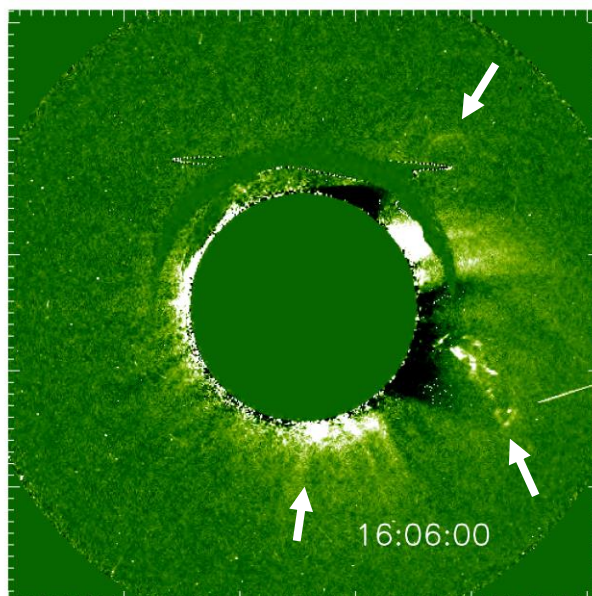
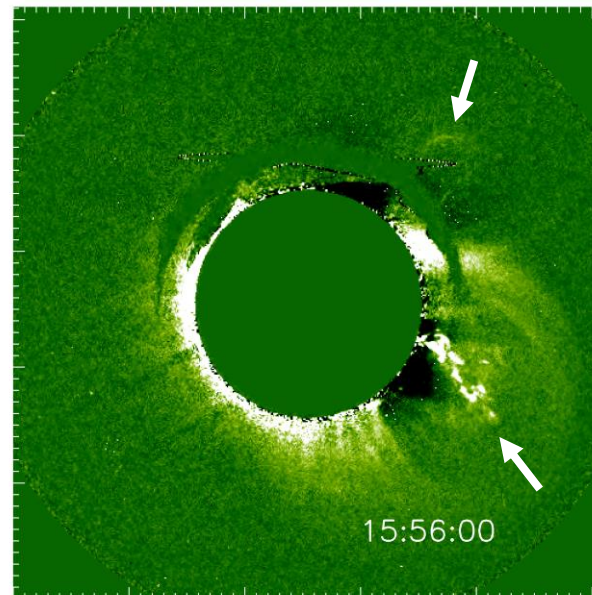
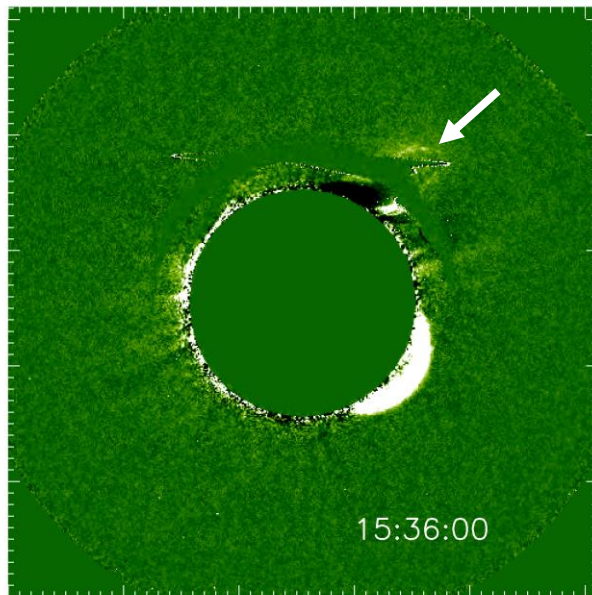
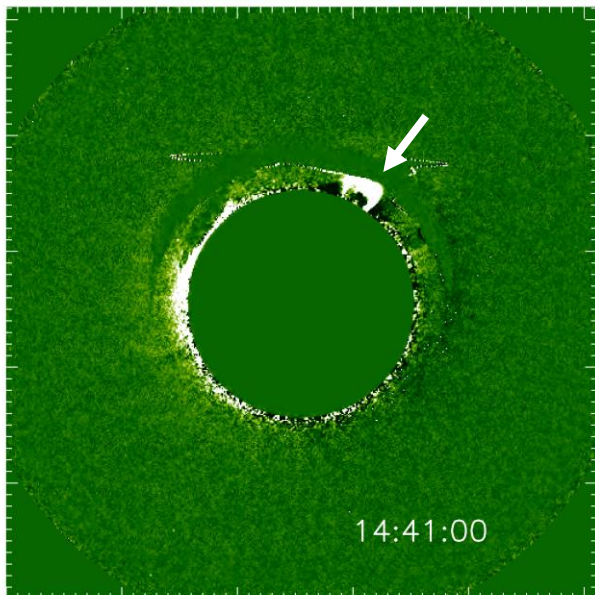


Made with JHelioviewer

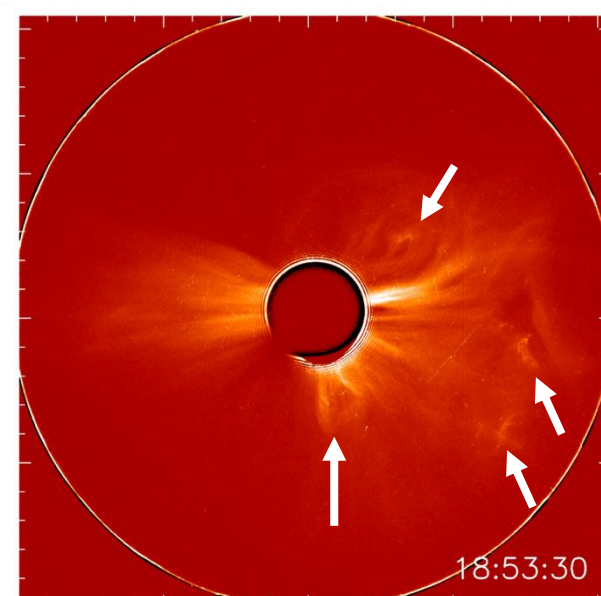
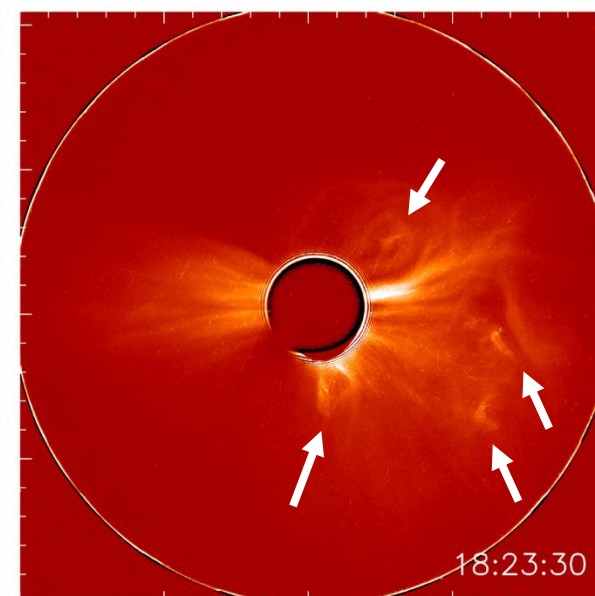
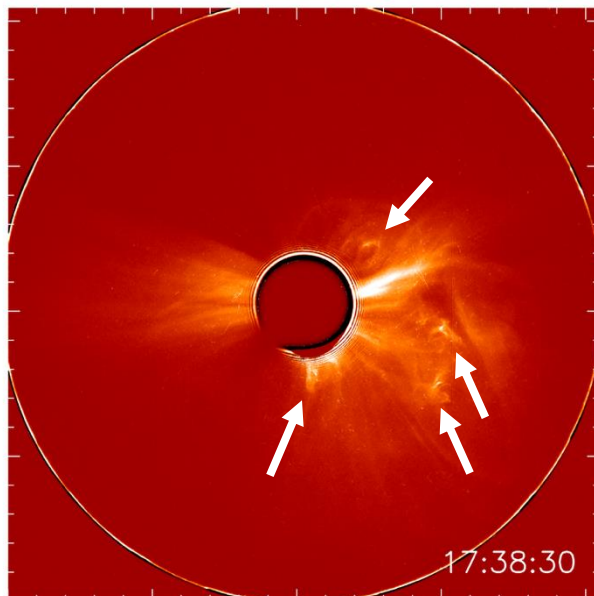
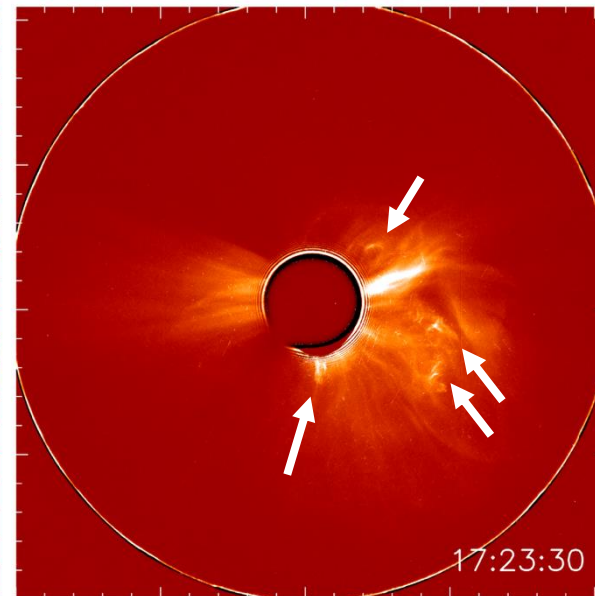
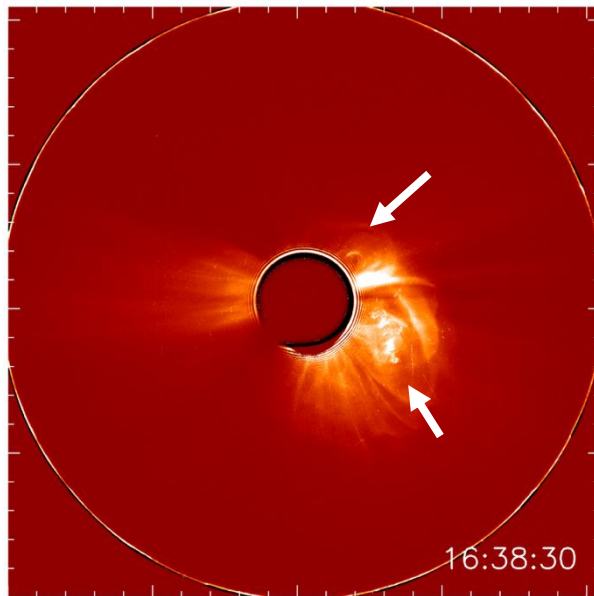
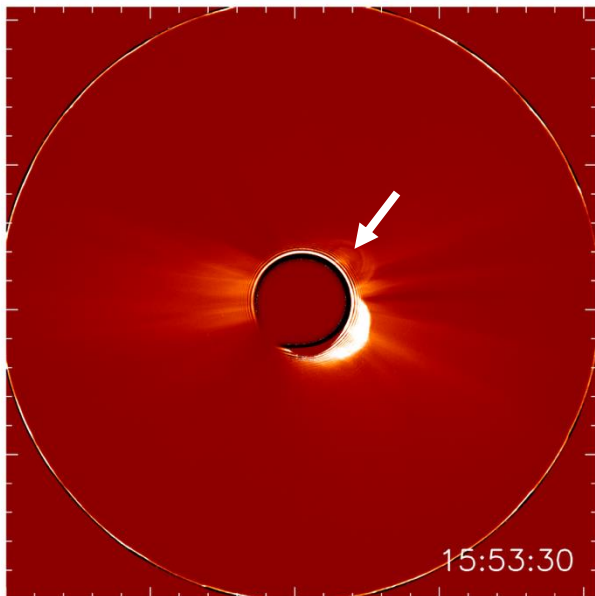
## H-alpha pre-event 1 (Meudon)



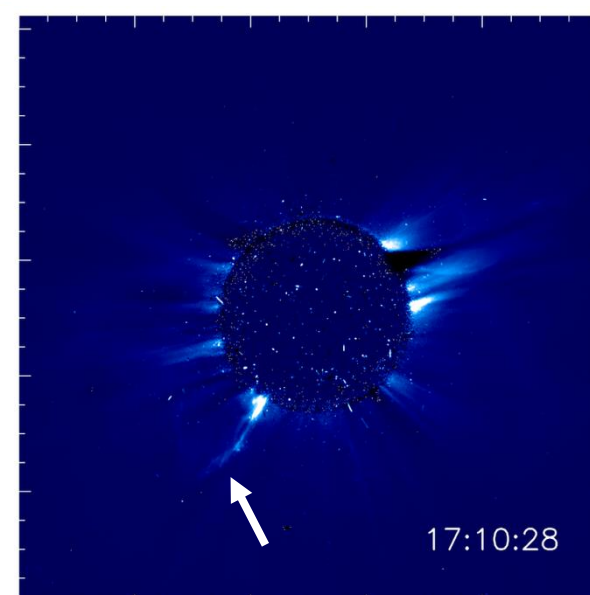
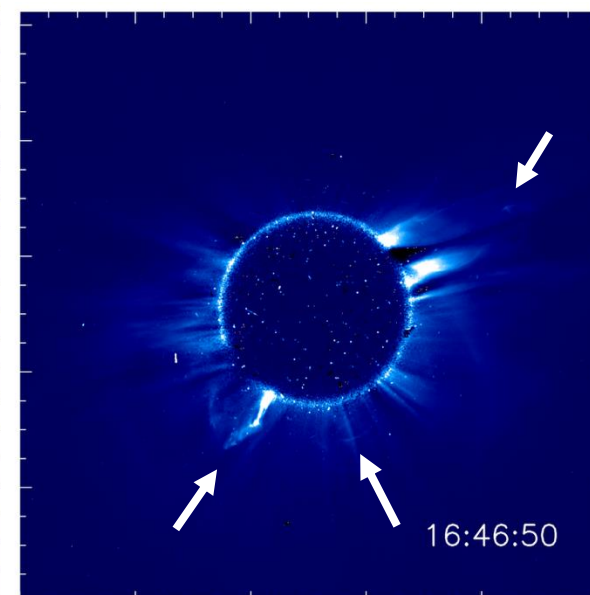
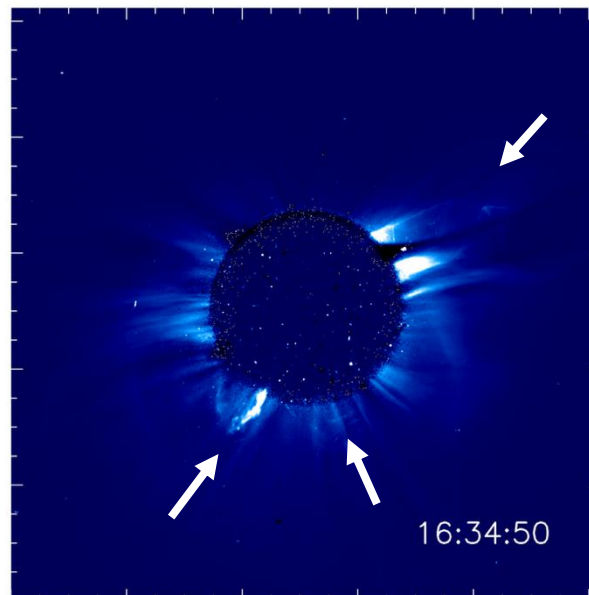
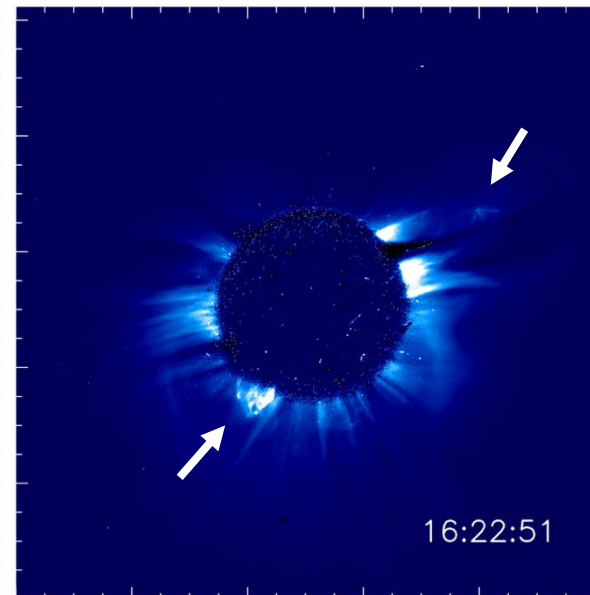
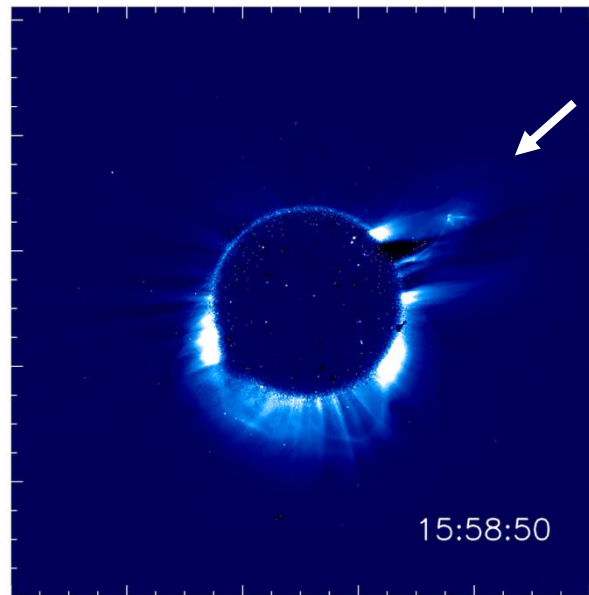
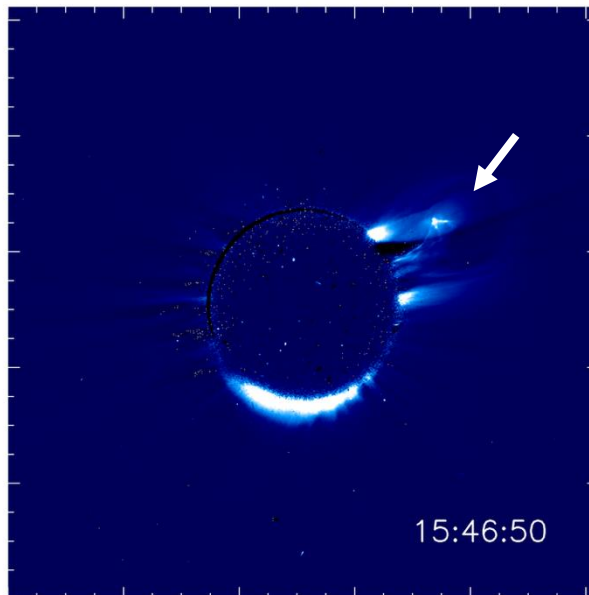
**STEREO-A/COR1**



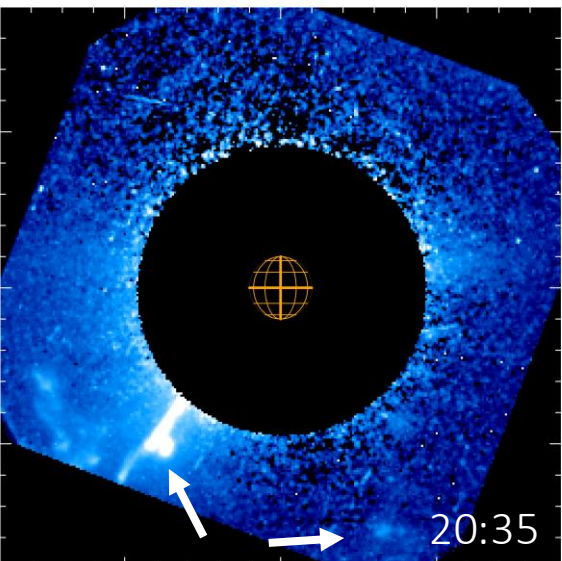
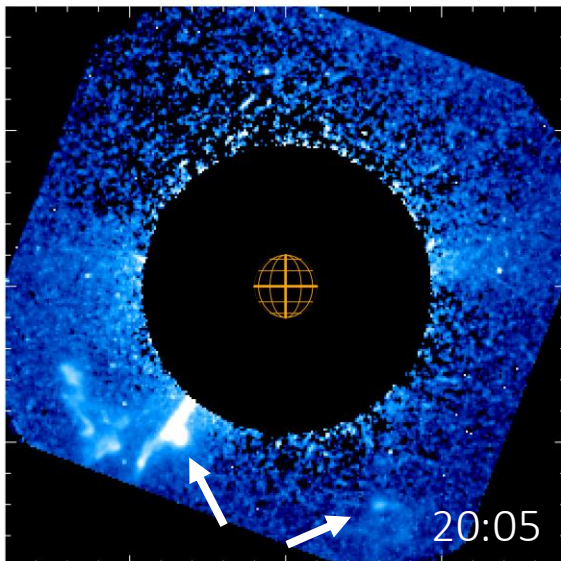
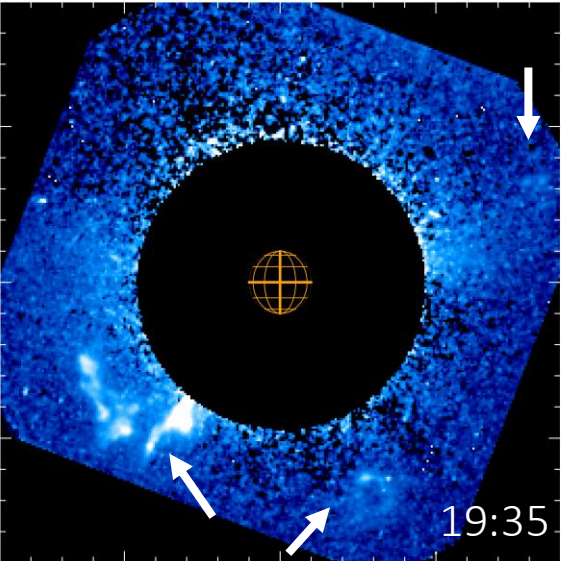
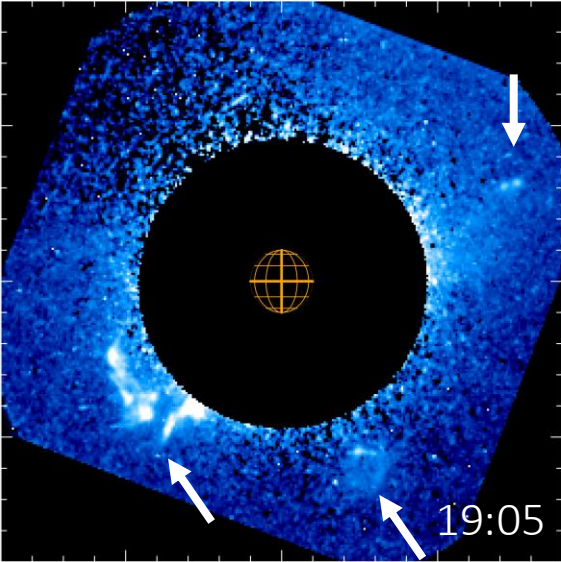
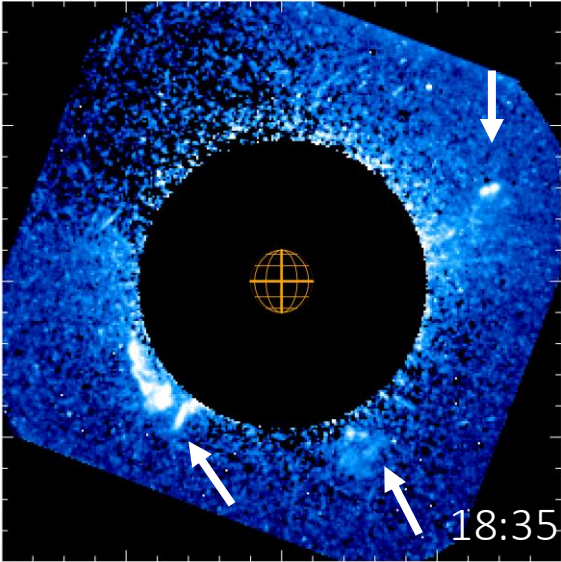
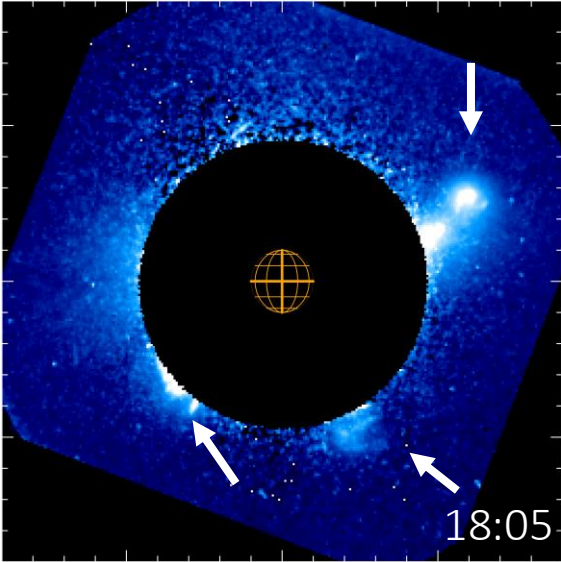
**STEREO-A/COR2**



SOHO/LASCO C2



**METIS UV**





metis

```
pro ELTHEORY,Rin,T,R,B,Bt,Br,Pol,LIMB=limb,CENTER=center
```

```
; NAME:
```

```
; ELTHEORY
```

```
; PURPOSE:
```

```
; This procedure computes various properties of the Thomson  
scattered
```

```
; light by an electron in the solar corona.
```

```
; CATEGORY:
```

```
; CME
```

```
; CALLING SEQUENCE:
```

```
; ELTHEORY, Rin, T, R, B, Bt, Br, Pol
```

```
; INPUTS:
```

```
; Rin: Impact Distance (in solar radii)
```

```
; T: Angle from plane of sky (in degrees)
```

```
; OUTPUTS:
```

```
; R: Distance of electron from sun center (in solar radii)
```

```
; B: Total Brightness for one electron at R,T
```

```
; Bt: Tangential Brightness for one electron at R,T
```

```
; Br: Radial Brightness for one electron at R,T
```

```
; Pol: Polarization for one electron at R,T
```

```
; KEYWORDS:
```

```
; LIMB: The limb darkening coefficient. If not set then use
```

```
; 0.63 (550 nm).
```

```
; CENTER: If set, then the output is returned as the central solar  
disk brightness. The default is mean solar brightness.
```

```
; PROCEDURE:
```

```
; This procedure uses the Thomson electron scattering equations
```

```
; to compute the total brightness, the radial and tangential
```

```
; components and the polarization associated with one electron.
```

```
; Limb darkening of 0.63 is included.
```

```
; The results are returned in units of mean solar brightness.
```

```
; MODIFICATION HISTORY:
```

```
; Created IDL version 16 May 1996, RA Howard, NRL
```

```
; $Log: eltheory.pro,v $
```

```
; Revision 1.1 2008/02/07 22:22:57 nathan
```

```
COMMON COM_ELTHEORY,ael,bel,cel,del
```

```
; const = sigma * pi / 2
```

```
; where sigma is the scattering cross section (7.95e-26 per steradian)
```

```
const = 1.24878D-25
```

```
IF KEYWORD_SET(limb) THEN u=limb ELSE u = 0.63 ; Limb darkening
```

```
u = DOUBLE(u)
```

```
IF NOT KEYWORD_SET(center) THEN const = const/(1-u/3) ; convert to mean solar brightness
```

```
Theta = double(t)<89.99d00 ; ensure less than 90 degrees from POS
```

```
R = Rin/COS(Theta/!radeg)
```

```
sinchi2 = (double(Rin)/R)^2 ; angle between sun center, electron, observer
```

```
s = (1.d00/R)<0.9999999d00 ; sin(omega)
```

```
s2 = s*s
```

```
c2 = (1.-s2)>0
```

```
c = SQRT(c2) ; cos(omega)
```

```
g = c2*(ALOG((1.+s)/c))/s
```

```
; Compute Van de Hulst Coefficients
```

```
; Expressions are given in Billings (1968) after Minnaert (1930)
```

```
;
```

```
ael = c*s2
```

```
cel = (4.-c*(3.+c2))/3.
```

```
bel = -(1.-3.*s2-G*(1.+3.*s2))/8.
```

```
del = (5.+s2-G*(5.-s2))/8.
```

```
;
```

```
; Compute electron brightness
```

```
; pB is polarized brightness (Bt-Br)
```

```
;
```

```
Bt = const*( cel + u*(del-cel) )
```

```
pB = const* sinchi2 *( (ael + u*(bel-ael) ) )
```

```
Br = Bt-pB
```

```
B = Bt+Br
```

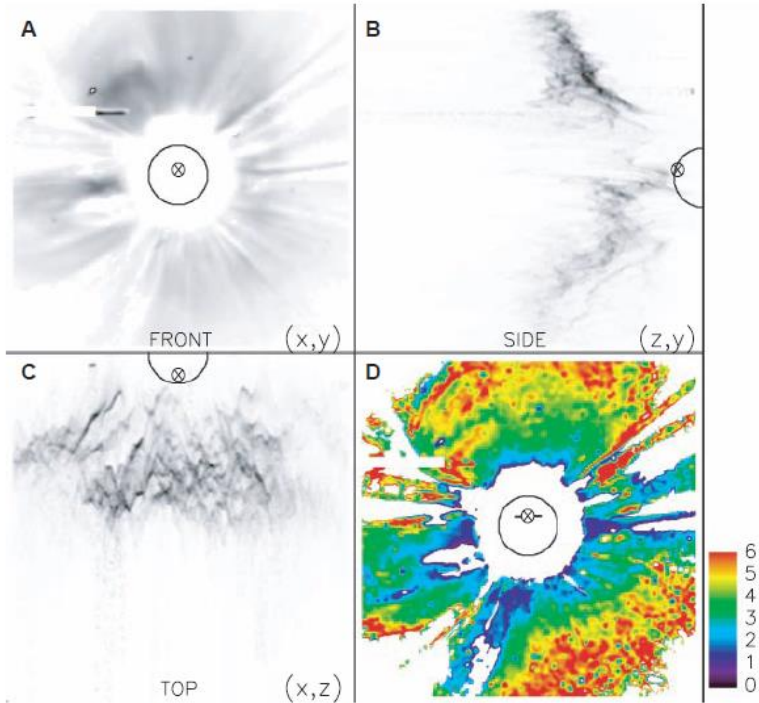
```
Pol = pB/B
```

```
RETURN
```

```
END
```

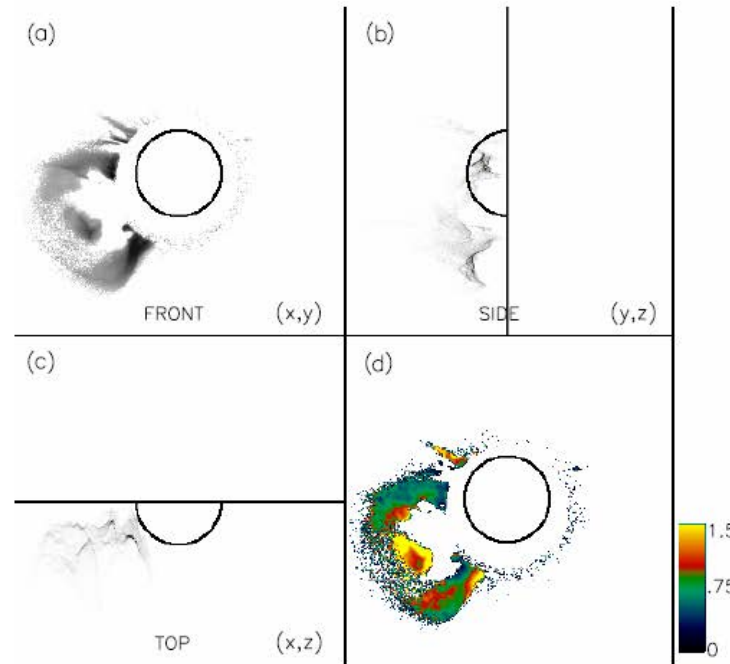
# An attempt to unify the Polarization Ratio Technique procedures and terminology

Paper	Scattering Thomson formulas	Name and formula of the ratio used	Coordinates (Dist. from the POS)	Notes	Geometrical scheme (Thom.Scatt.)
Moran&Davila 2004	Billing, Mineart, VDH	<b>Meas. ratio pol.-to-unpol.</b> $R_m = pB/uB$	z (or  z ) POS	For/Back Ambiguity ->EUV images	Described, but not present
Moran+2010	No TS formulas, Mineart 1930 cited	Meas. ratio pol.-to-unp.	z (or  z ) POS	For/Back Ambiguity ->EUV images	Described, but not present
Dere+2005	No TS formulas, cited Poland&Murnro,Moran&Davila	<b>Polarization fraction</b> $p = pl/l$	Z POS	It's a brief letter. <b>Dere mentions eltehory.pro</b>	Not present
Vourlidas+2006	No TS formulas, but Minnaert, VDH, Billings cited	Not used in this work	Not mentioned, <b>TS</b>	<b>For/back ambiguity resolved with TS geometry!</b>	<b>Described, present in TS representation for first time</b>
De Koning 2011	Billings, Hundhausen 1993, Howard and Tappin 2009	<b>Polarization fraction</b> $P_{frac} = pB/tB$	z-> x by rotation POS	--	Geometry present
Mierla+2009	No TS formulas, cited Davila and Dere	$R_m = pB/uB$	X toward Earth (HEEQ) POS	For/Back Ambiguity ->EUV images	Described, but not present
Mierla+2010	No TS formulas, cited Billings, Davila, Dere	<b>ratio of Pol. to unpol. bright</b>	N.A.	--	--
Mierla+2011	No TS formulas, cited Billings, Davila,Dere, Mierla 2009 etc	<b>Pol2unpol ratio</b> and <b>polarization ratio</b>	-- POS	For/Back Ambiguity ->2 vantage points (ST-A and B)	Not present
Mierla+2022	No TS formulas, all the citations present	<b>Polarization fraction</b> $P_{frac} = pB/tB$	-- POS	--	Not present
Zuccarello+2013	No TS formulas, Moran cited	<b>Meas. ratio pol.-to-unpol.</b> $R_m = pB/uB$	z (or  z ) POS	For/Back Ambiguity ->EUV images	Not present
De Forest+2013	Formulas present, adapted to TS geometry	Pol2unpol ratio and polarization ratio	Not mentioned, <b>TS</b>	TBC	<b>Described, present in TS representation</b>
Dai +2014	Formulas present, both the approx (POS and TS)	<b>Polarization fraction</b> $P_{frac} = pB/tB$	Z POS, TS	Classification of ambiguity and several possible solutions	Very well described and represented
De Forest+2017	No TS formulas present, citation of all the previous literature	<b>Degree of polarization (inversion)</b> $P_{frac} = pB/tB$	X TS	For/Back Ambiguity ->single NF images or WF reconstructions	Described, not present
Bemporad 2015	No formulas, previous	<b>Polarization fraction</b> , but	Z POS	--	Described, not present



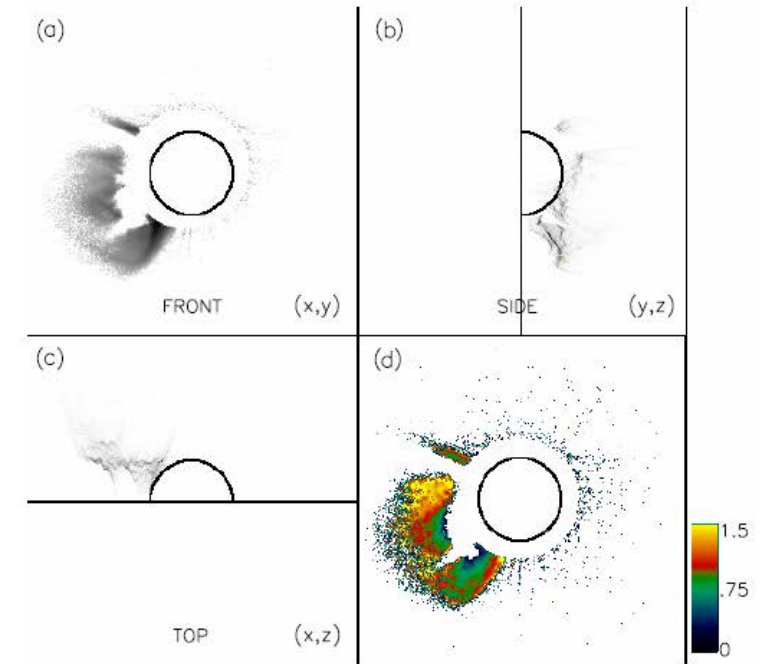
**Fig. 4.** (A) Total brightness of the halo CME occurring on 4 November 1998 (front view), (B) a reconstructed side view of the CME in the  $(z, y)$  plane, (C) a reconstructed top view of the CME in the  $(x, z)$  plane, and (D) a topographical map of the CME displaying distance from the  $(x, y)$  plane. The color bar indicates distance from the sky plane in  $R_{\odot}$ . The solar disk is outlined, and the CME source region within the disk is indicated by a  $\otimes$  symbol. An interrupted line segment through the  $\otimes$  symbol indicates the orientation of the magnetic neutral line.

Halo CME  
Moran & Davila 2004



**Figure 5.** (a) Total brightness of the loop-like CME occurring on 2007 December 31 at 01:30 UT recorded with *STEREO/SECCHI/COR1-B* (front view), (b) a reconstructed side view of the CME in the  $(z, y)$  plane, (c) a reconstructed top view of the CME in the  $(x, z)$  plane, and (d) a topographical map of the CME displaying distance from the  $(x, y)$  plane. The color bar indicates distance from the sky plane in  $R_{\odot}$ . The solar disk is outlined.

Loop-like CME  
Moran, Davila, Thompson 2010



**Figure 6.** (a) Total brightness of the loop-like CME occurring on 2007 December 31 at 01:30 UT (front view) recorded by *STEREO/SECCHI/COR1-A*, (b) a reconstructed side view of the CME in the  $(z, y)$  plane, (c) a reconstructed top view of the CME in the  $(x, z)$  plane, and (d) a topographical map of the CME displaying distance from the  $(x, y)$  plane. The color bar indicates distance from the sky plane in  $R_{\odot}$ . The solar disk is outlined.

## Some background about the theory of PRT...

The PRT was introduced by Moran & Davila in 2004.

It's a technique of 3D reconstruction of a CME by using only one vantage point.

Brief Summary:

- 1) Preparation of pB,tB and uB(=tB-pB) images. Pre-event subtraction has to be performed.
- 2) Calculation of  $R_m = \frac{pB}{uB}$
- 3) Comparison of  $R_m$  and  $R_t(\rho, |z|)$ : ELTHEORY, Rin, T, R, B, Bt, Br, Pol
- 4) Build the |z| image and select the ROI

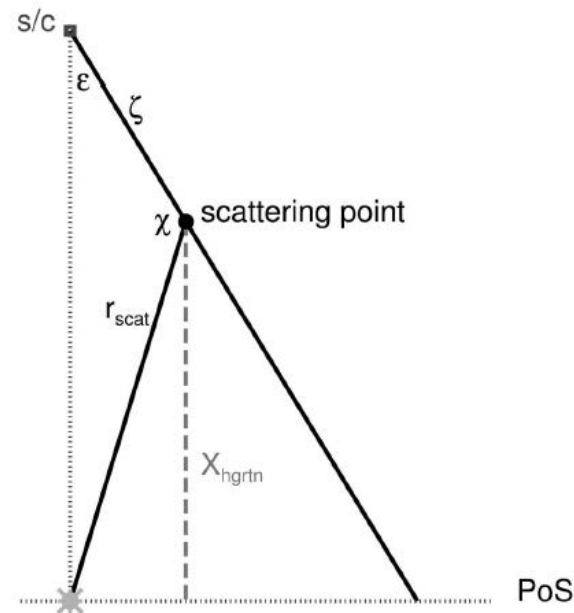


Figure 2. A schematic diagram defining some of the angles and distances used in equations (1)-(6). The diagram depicts the spacecraft (s/c) and its plane of sky (PoS), the Sun, and a scattering point. See text for additional details.

Polarization fraction

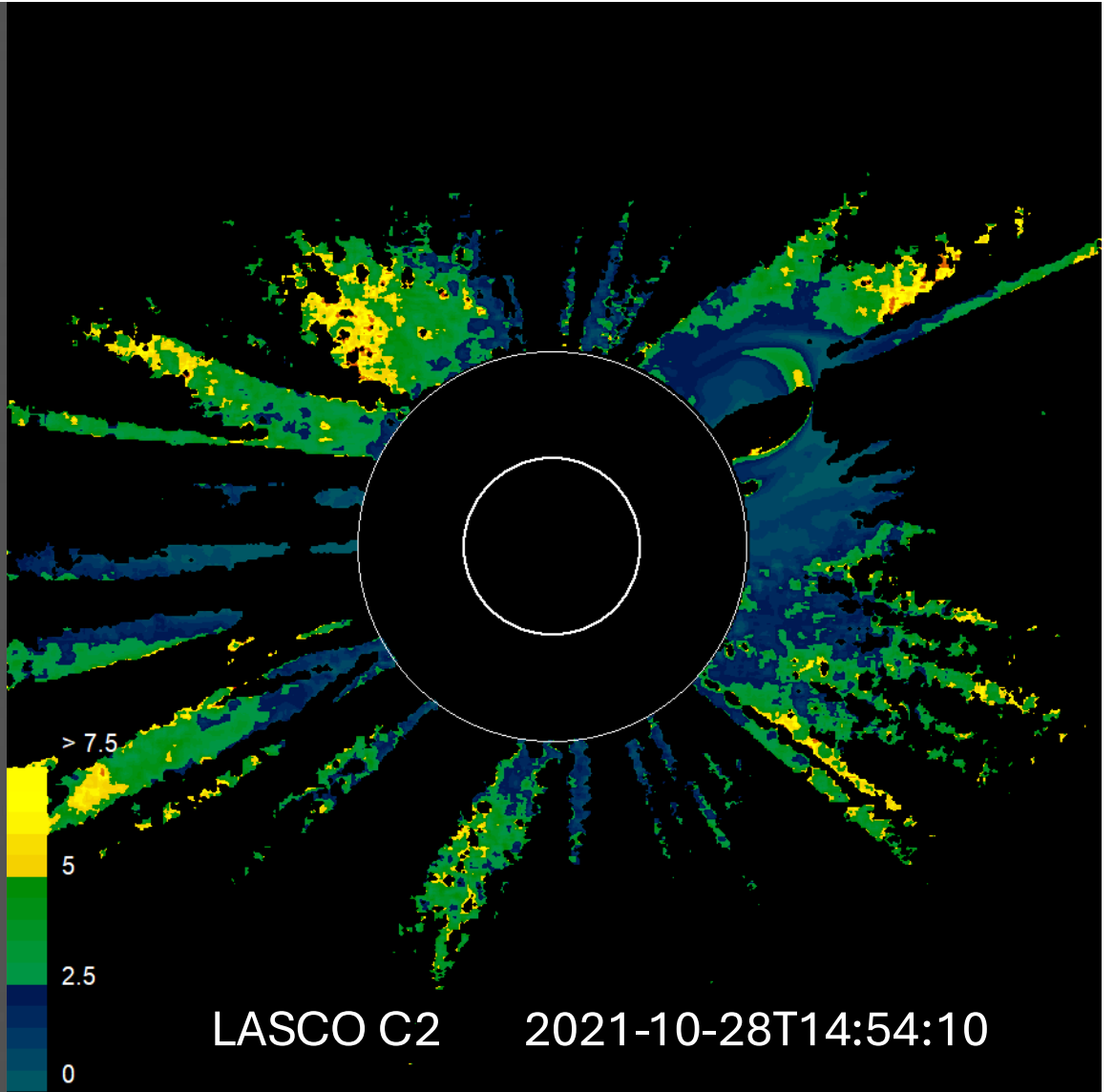
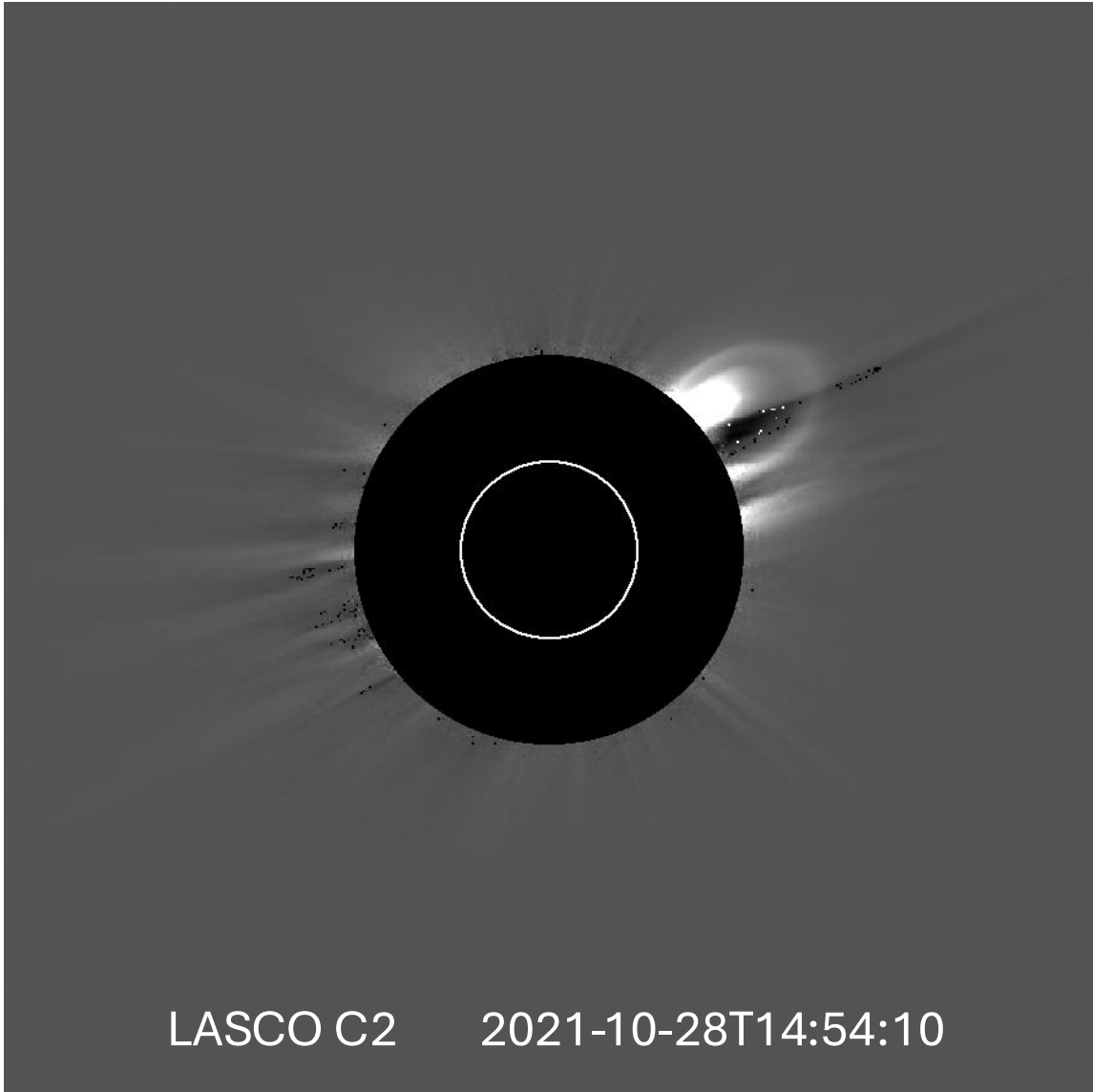
$$P_{frac} = \frac{I_t - I_r}{I_t + I_r} = \frac{P_B}{P_{total}}$$

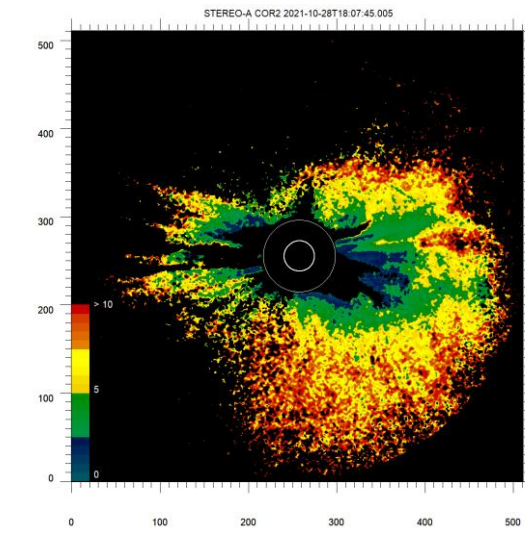
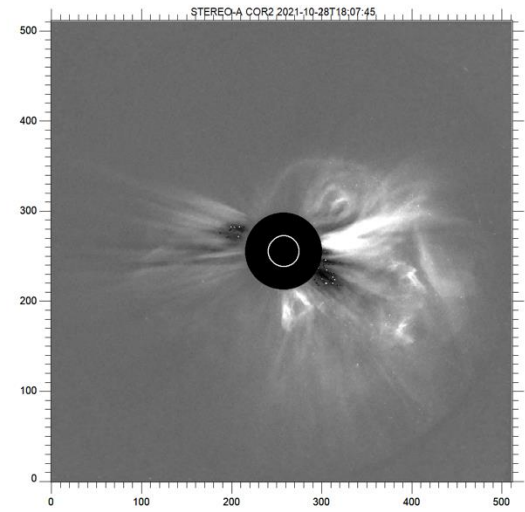
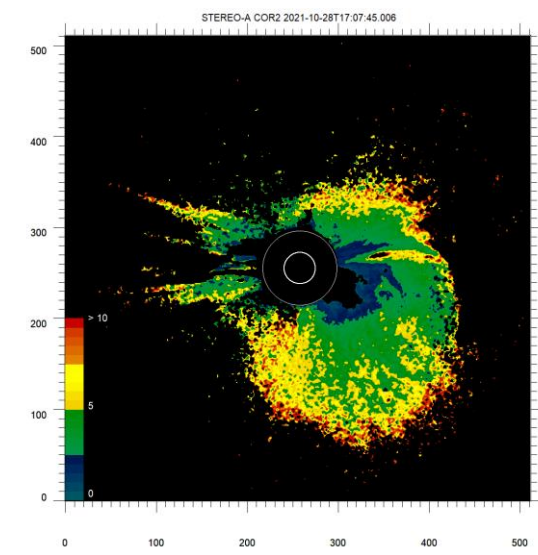
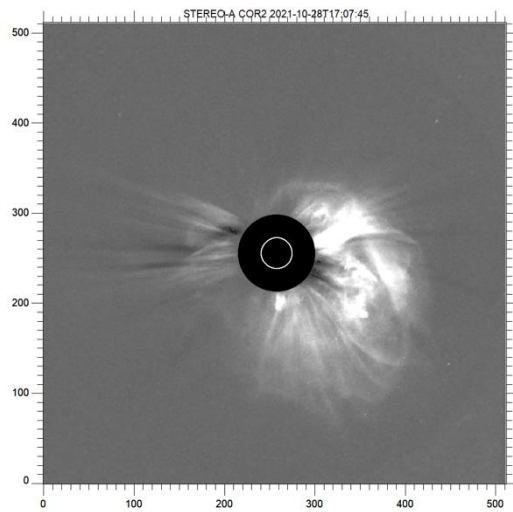
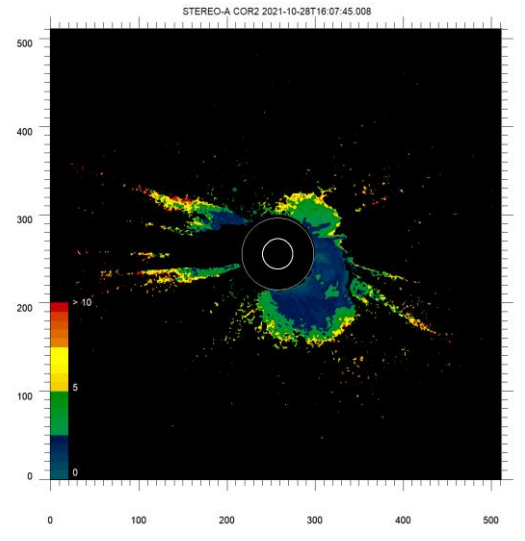
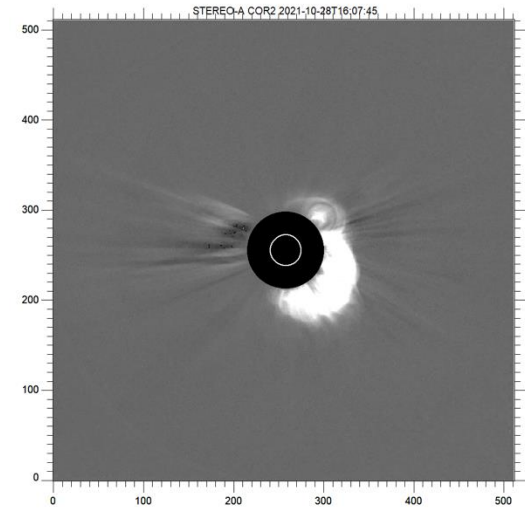
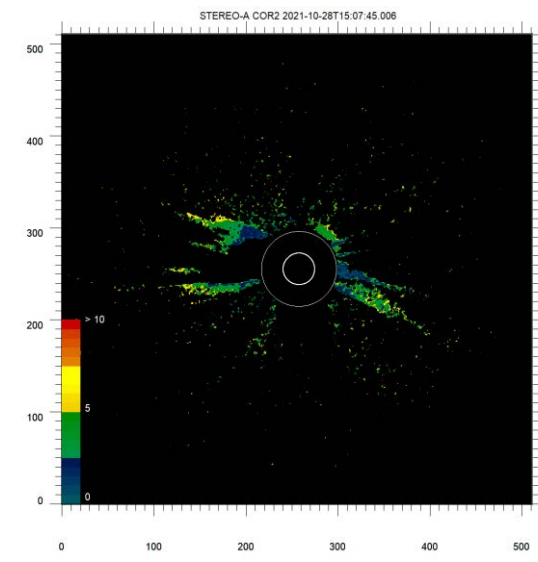
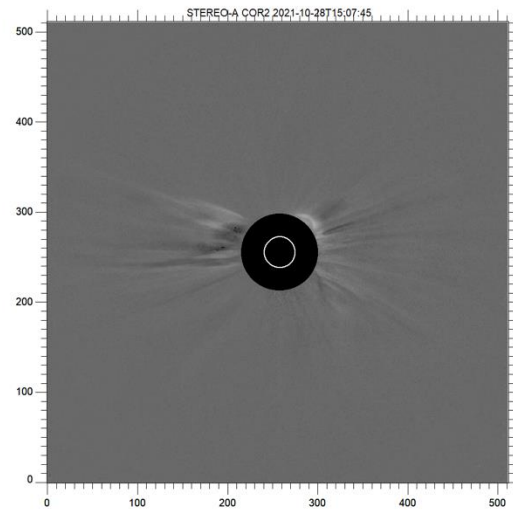
with

$$I_t = I_o \frac{N_c \pi \sigma}{2} [(1 - u)C + uD]$$

$$I_t - I_r = I_o \frac{N_c \pi \sigma}{2} \sin^2 \chi [(1 - u)A + uB]$$

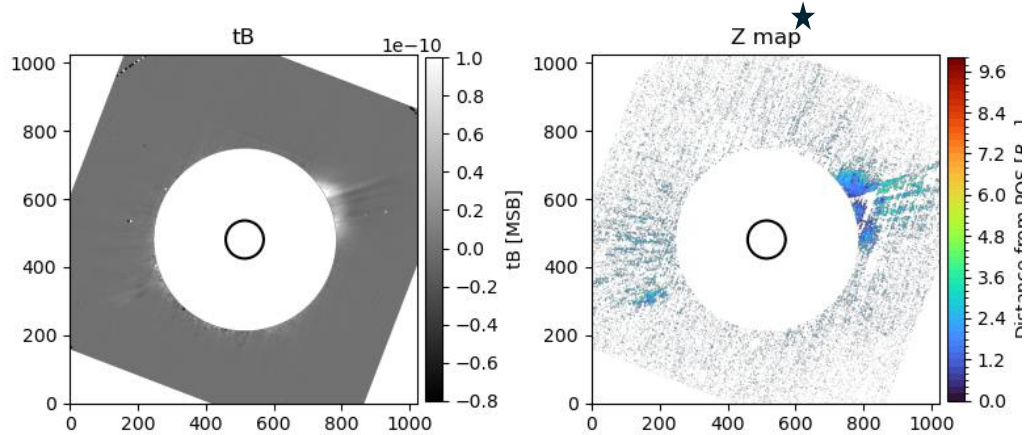
where  $N_e$  is the local coronal density;  
 $\sigma$  is the Thomson-scattering cross section;  
 and the constants  $A, B, C$ , are geometrical factors



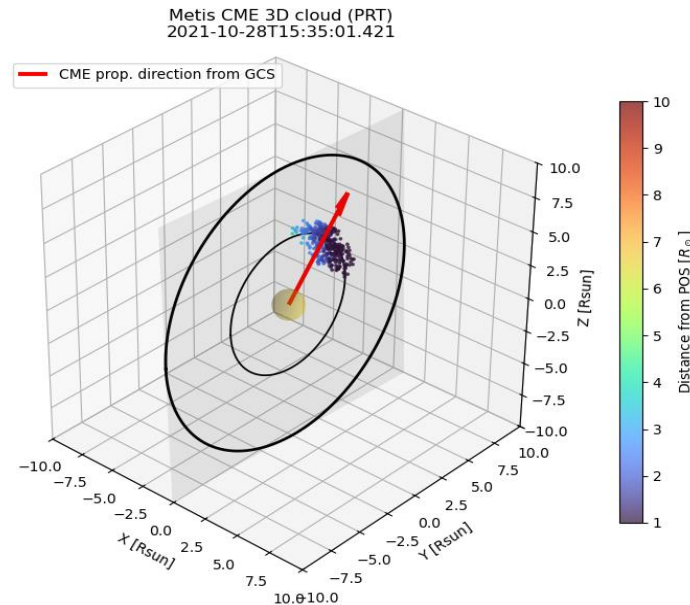
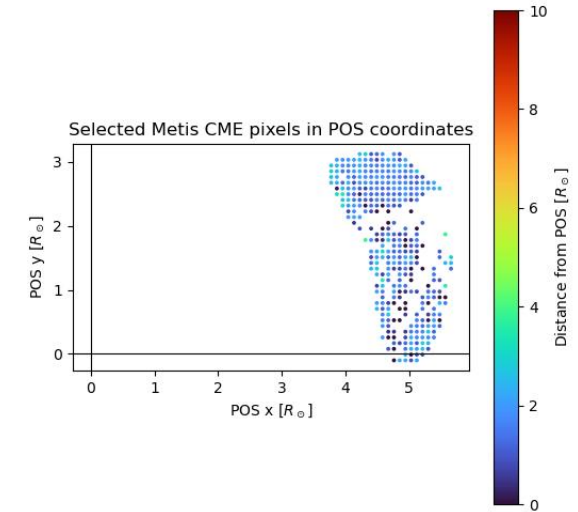


## Event 1 SolO perspective

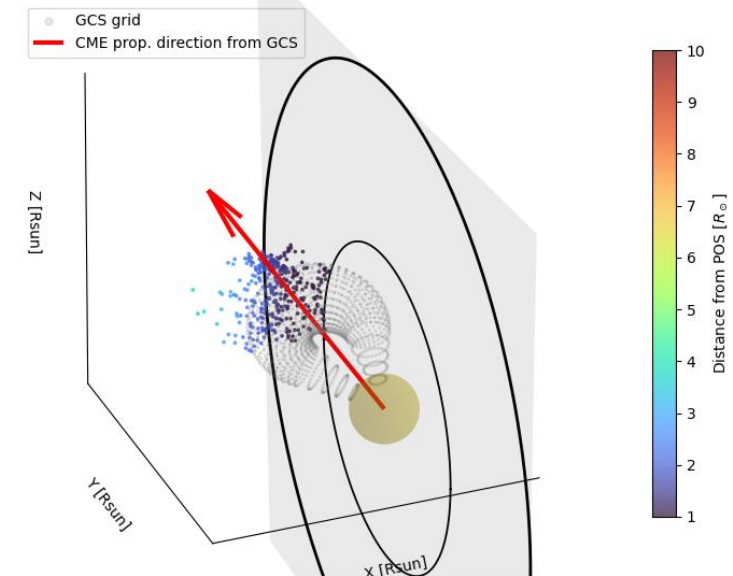
METIS | 2021-10-28T15:35:01.421 | CROTA=-20.98 deg **FoV: 4.8-10.3 Rs**



Plots from De Leo et al. 2026, in preparation



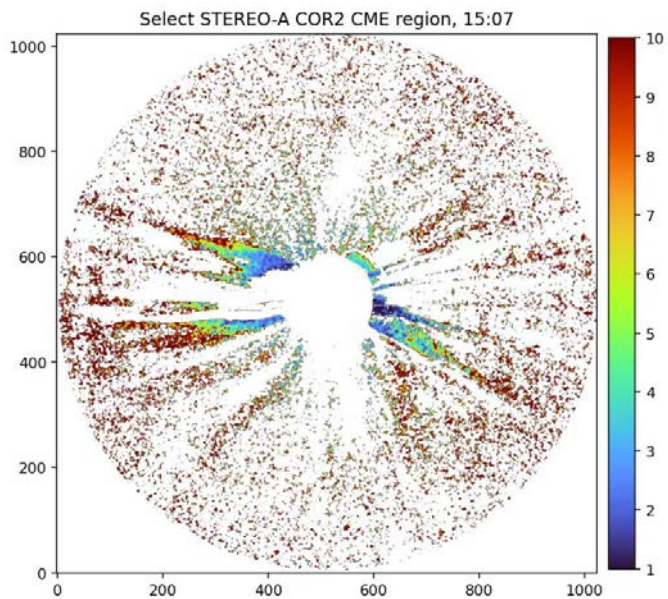
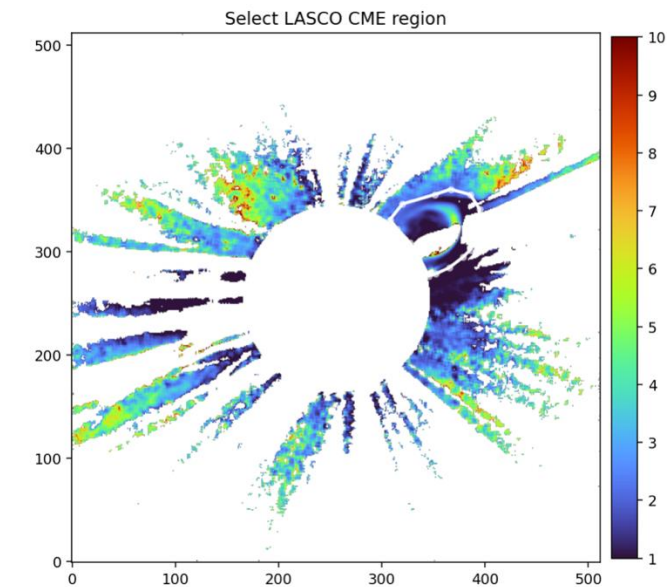
Metis CME 3D cloud (PRT)  
2021-10-28T15:35:01.421



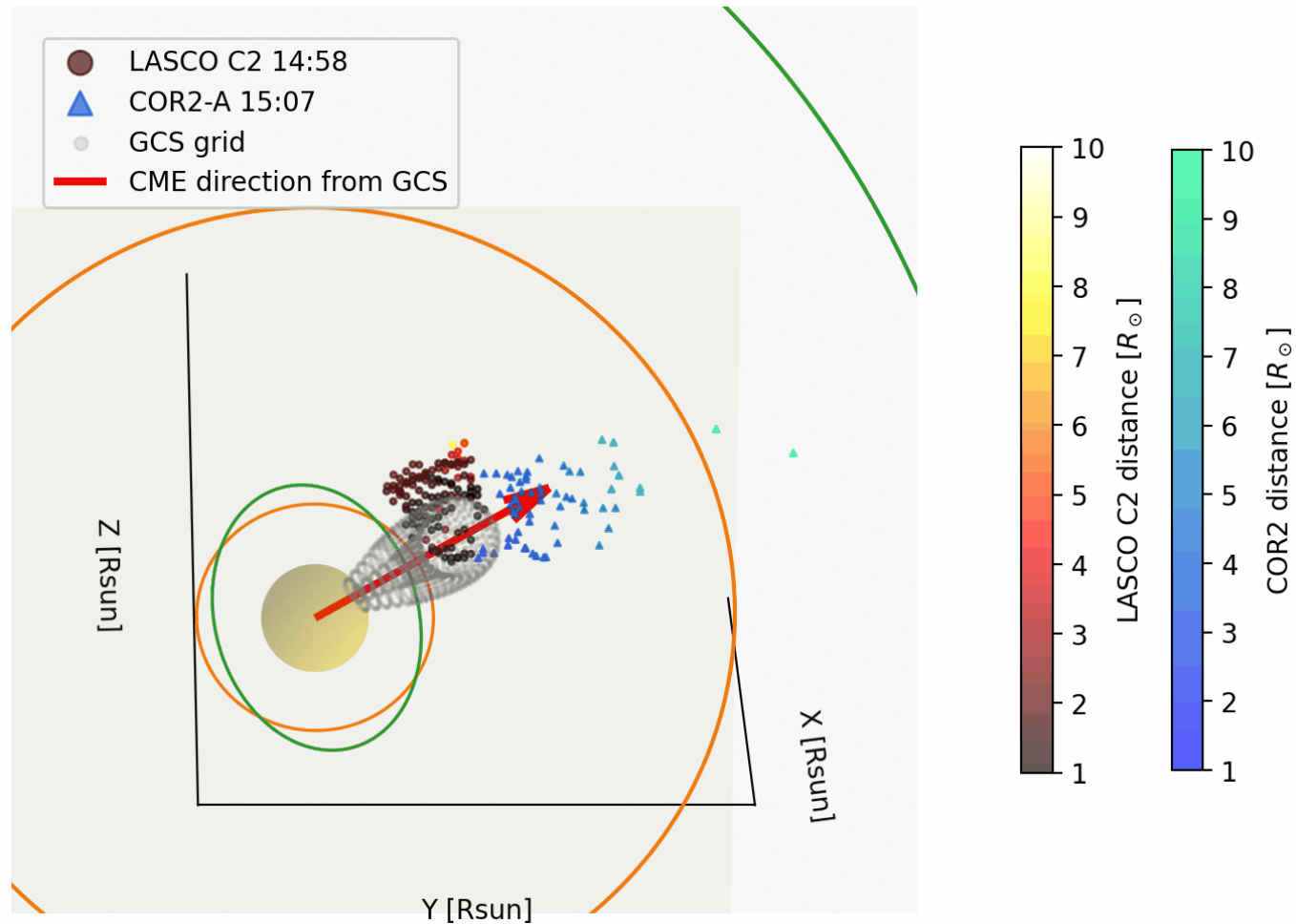
[z]: distance from the POS in solar radii



# Application of the PRT on the 20211028 limb CME



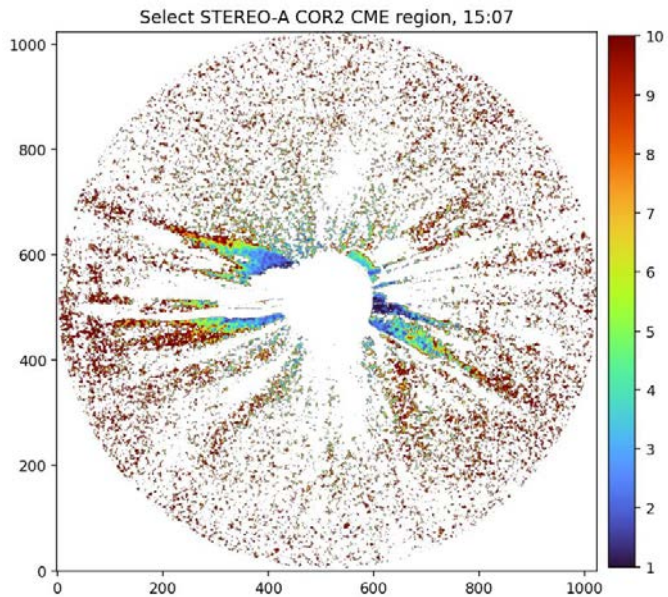
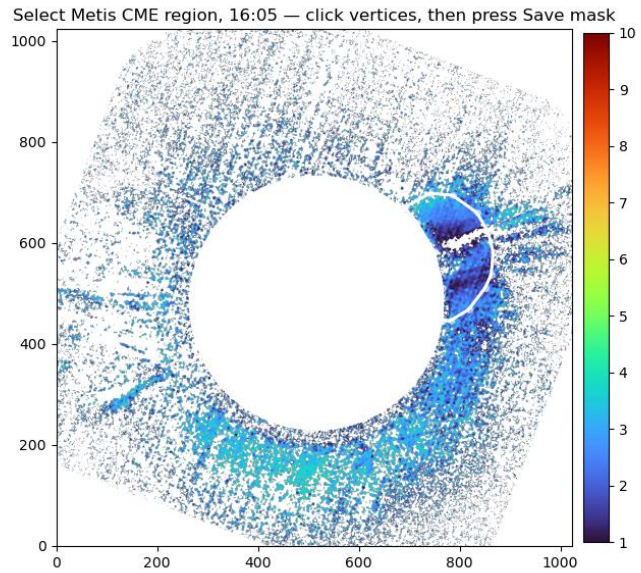
LASCO C2 + STEREO-A COR2 PRT clouds  
LASCO C2: 2021-10-28T14:54:10.983 | COR2: 2021-10-28T15:07:45.006



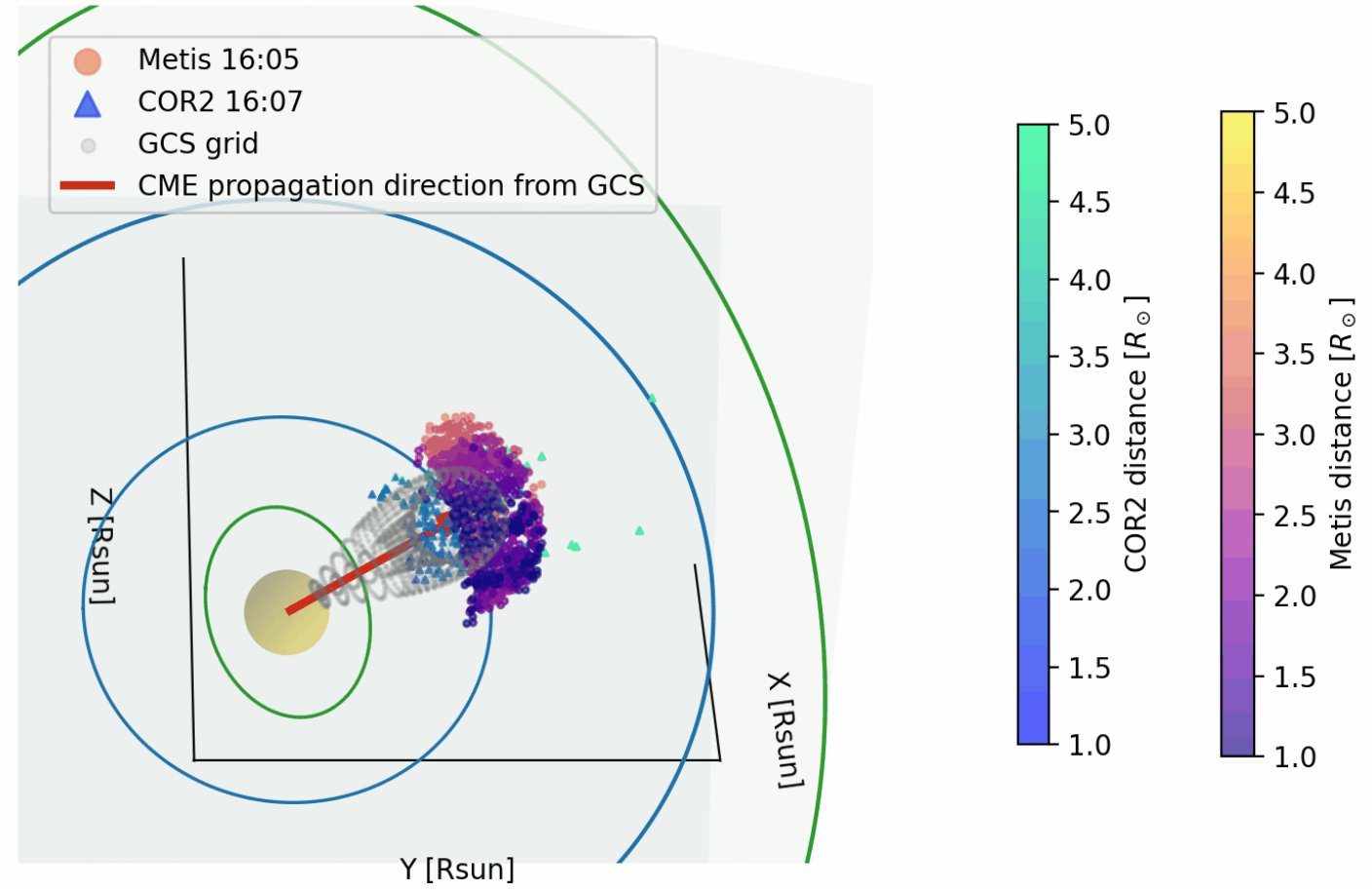
|z|: distance from the POS in solar radii



# Application of the PRT on the 20211028 limb CME



Metis + STEREO-A COR2 PRT clouds  
Metis: 2021-10-28T16:05:01.424 | COR2: 2021-10-28T16:07:45.008



|z|: distance from the POS in solar radii



Metis PR 2025-09-16T04:36:01.445 [CROTA=14.67°]

Work in progress!

