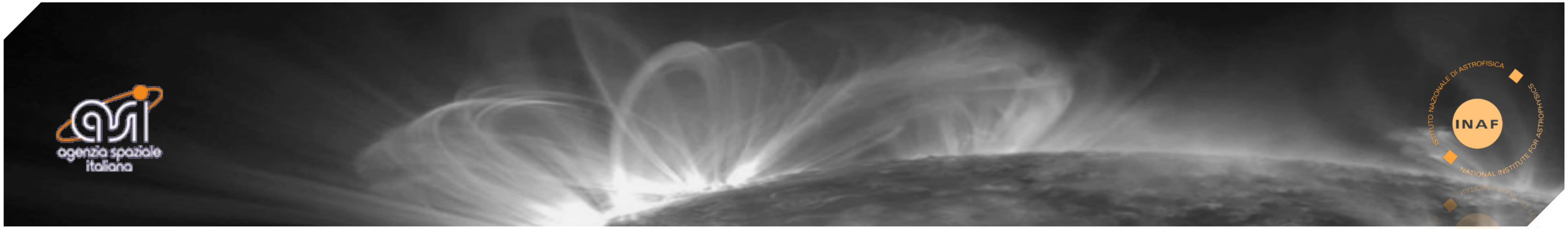


Metis Coronagraph and its Implications for Space Weather Studies

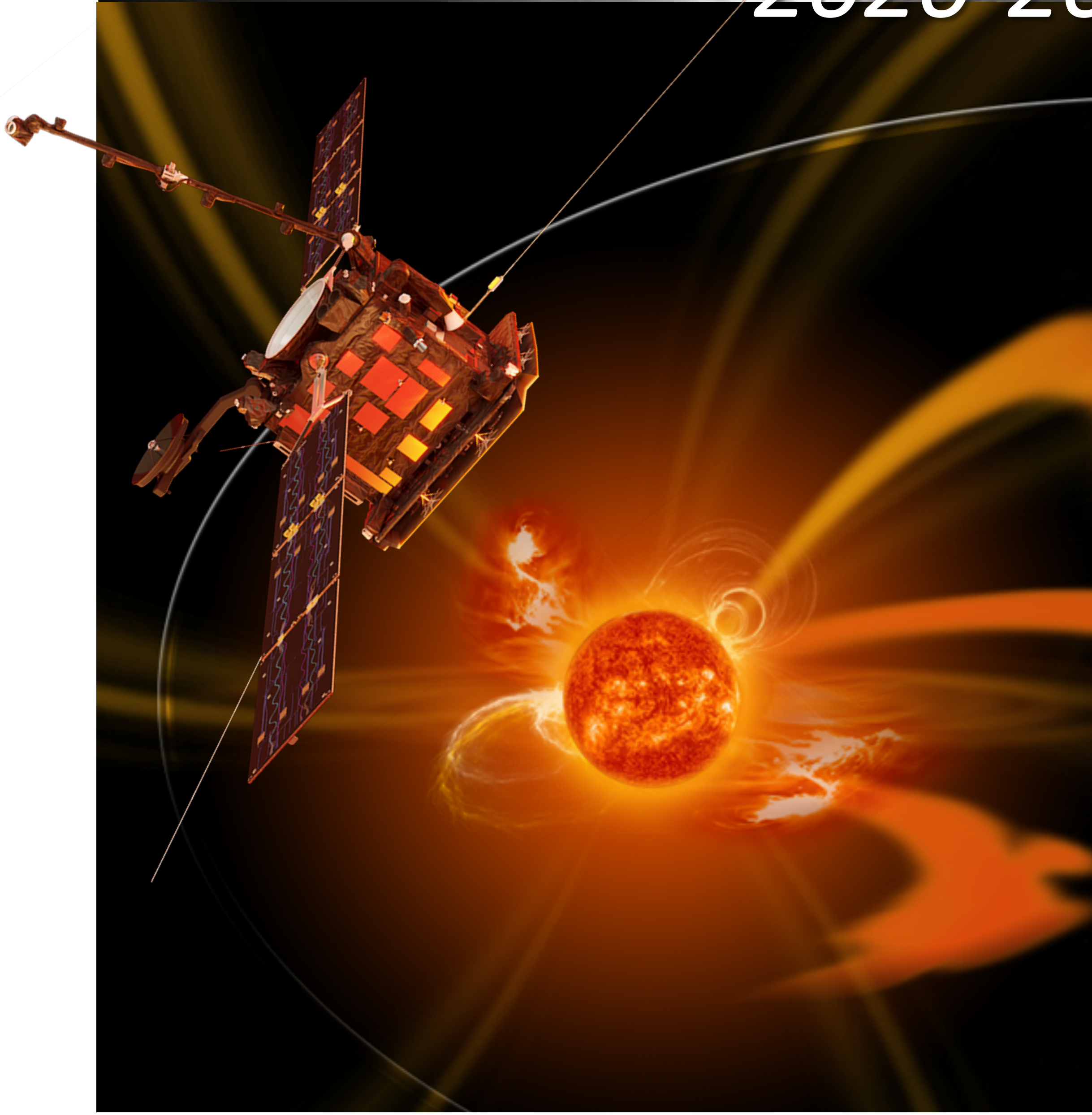
Ester Antonucci

Osservatorio Astrofisico di Torino – INAF

ISWI Workshop

Trieste 20-24 May 2019

Solar Orbiter Mission ESA-NASA 2020-2030

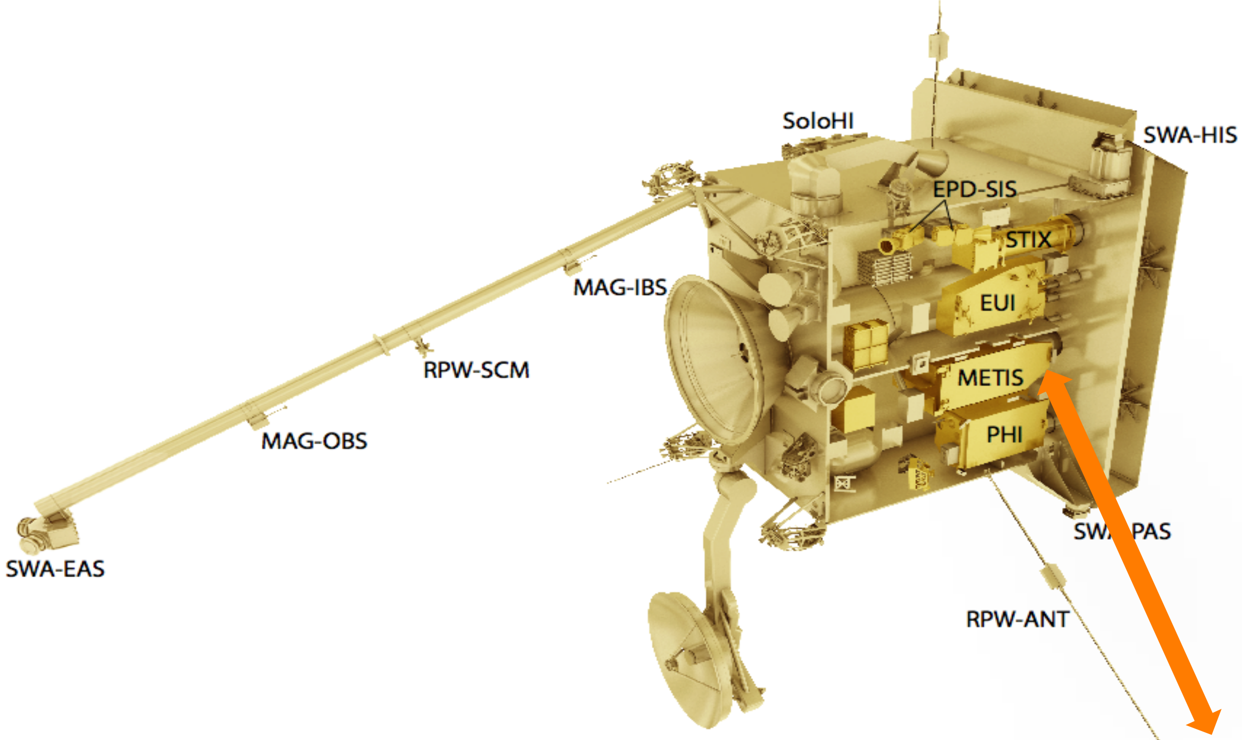


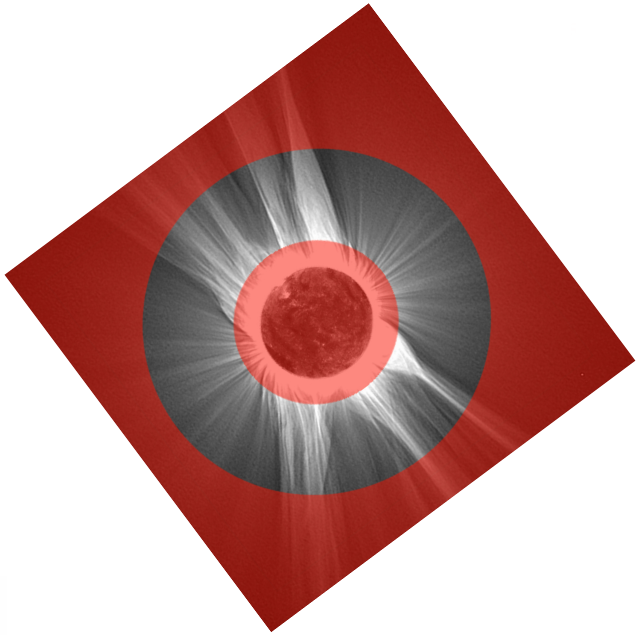
The Spacecraft

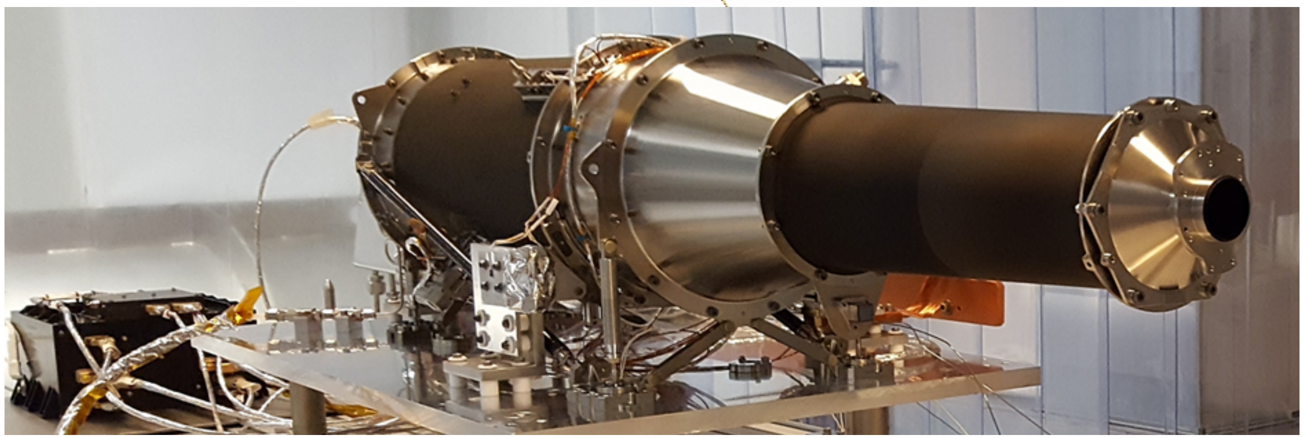
Three-axis stabilized spacecraft, Sun pointing

- Closest Sun encounter: 0.28 AU
- Heat shield to protect spacecraft and payload
- Overall mass: ~1800 kg
  Maximum power demand:~1100W
- Re-use of BepiColombo unit designs and technology
- NASA-provided launch vehicle
- Payload: 10 remote sensing instruments, 4 *in situ* instruments

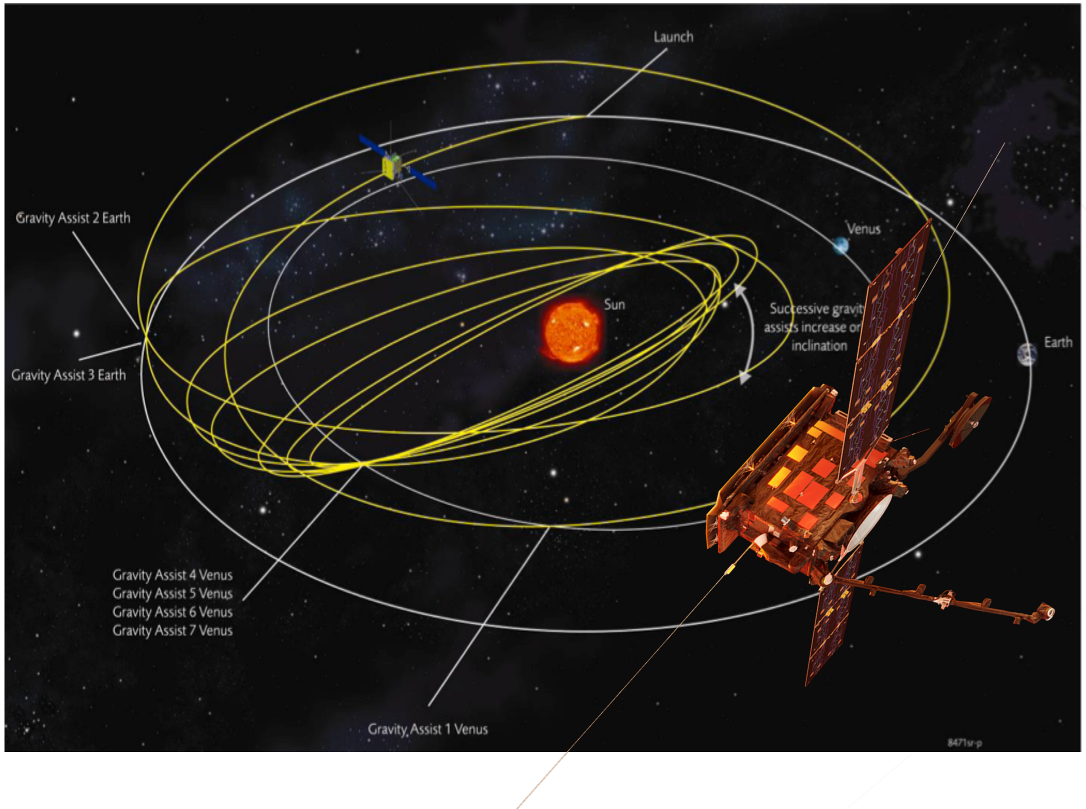
Metis Coronagraph of Solar Orbiter







Solar Orbiter Mission Profile



first visit to the Sun

- out of ecliptic 33° (extended mission)
- at 0.28 AU (60 $R_{\odot}$) (minimum perihelion)

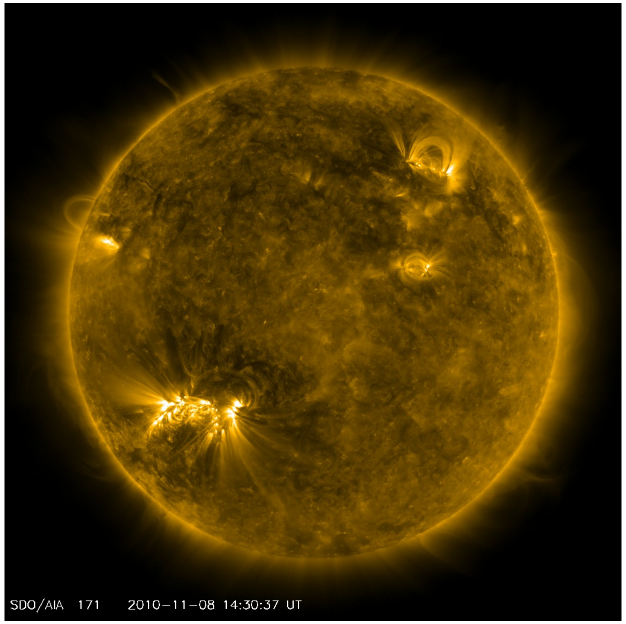
first remote sensing instruments pointing

- to the Sun at 0.28 AU

reduced relative motion

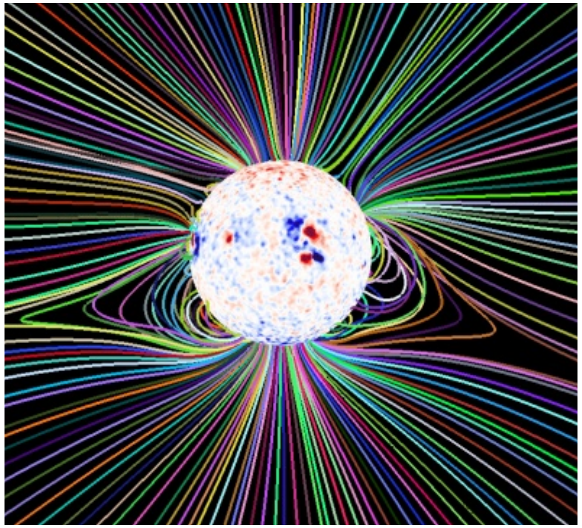
- at perihelion

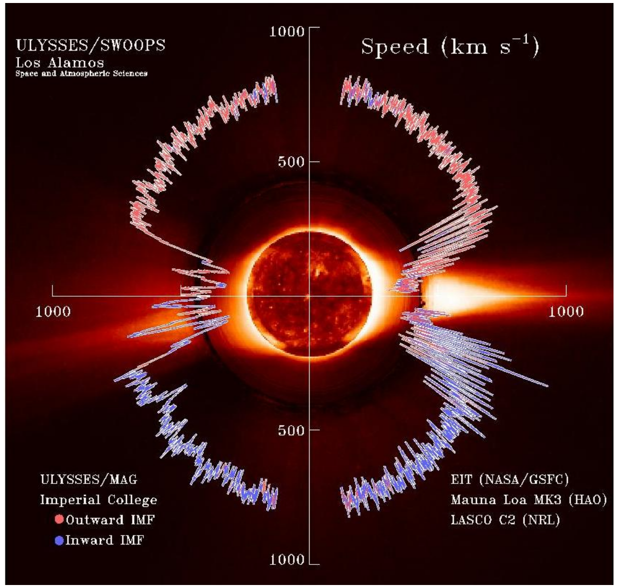
Solar Atmosphere Heliosphere System



The Sun's magnetic field

Eclipse August 21, 2017
(Predictive Science Inc. ,
San Diego)





Ulysses (1992-2008)

- creates and shapes the hot corona
- guides the solar wind, due to the expansion of the hot corona, into the heliosphere along the open field lines
- its activity induces the heliospheric variability

Solar Orbiter Mission Objective

Solar Orbiter mission - understanding how our nearby star

- forms the heliosphere – the magnetic shield of the solar system - with the expansion of its hot atmosphere, the $\geq 10^6$ K corona
- perturbs the heliosphere with its moderate, cyclic magnetic activity of variable star and, in turn, the solar system planetary magnetospheres/atmospheres

Metis coronagraph - understanding the solar corona, source region of the main drivers of geomagnetic storms on Earth

- Solar wind (acceleration and pattern of slow and fast speed streams)
- Coronal mass ejections (mechanisms and initial propagation)

Metis Contribution to Solar Orbiter Science

Solar Orbiter Science Questions	METIS investigates the
How and where do the solar wind plasma and magnetic field originate in the corona	region where the solar wind is accelerated from about 100 km s^{-1} to approximately its asymptotic value
How do solar transients drive heliospheric variability	region where the first, crucial phase of the propagation of coronal mass ejections occurs
How do solar eruptions produce energetic particle radiation that fills the heliosphere	path of the shock front accelerating particles in the solar corona
How does the solar dynamo work and drive connections between the Sun and the heliosphere	overall magnetic configuration - closed and open magnetic field regions of the corona - inferred from solar wind outflow detection

Metis Investigation of the Solar Corona

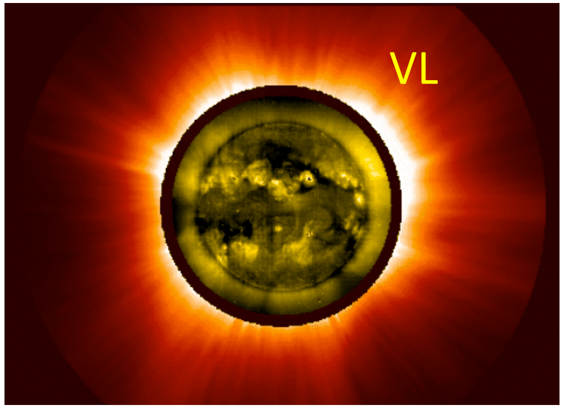
First multi-wavelength imaging of the outer corona in

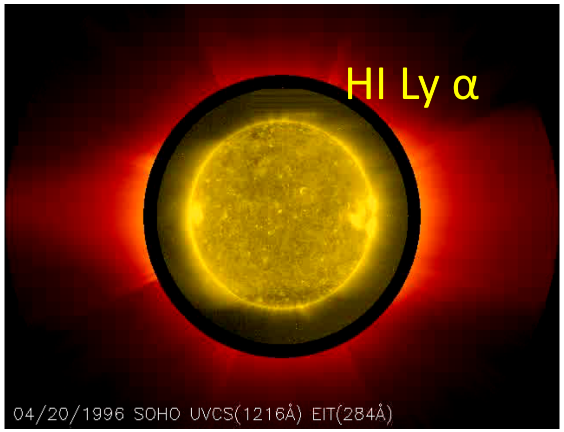
- *Visible Light band 580-640 nm (polarized VL)*

  Structure and evolution of electron component

- *UV (HI Ly α) 121.6 nm*

  Structure and evolution of neutral H and proton components





Global dynamics of the corona and coronal wind

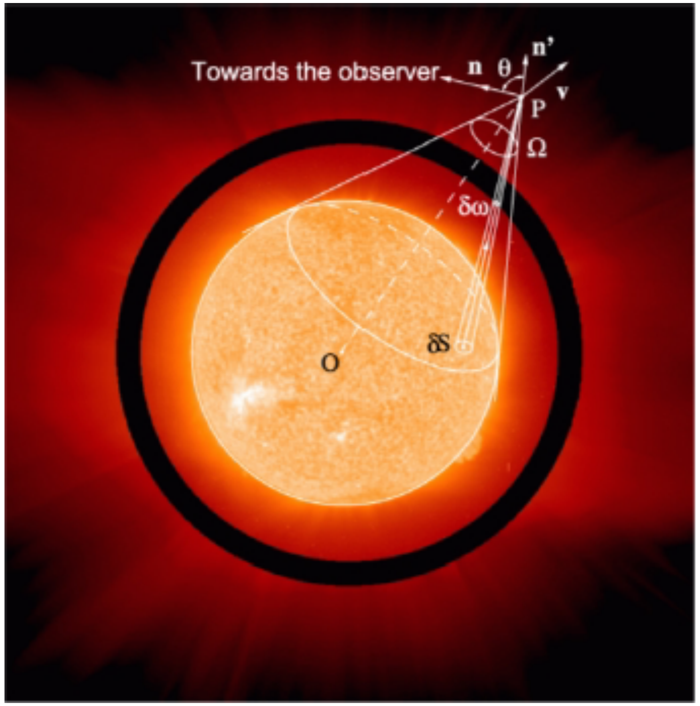
Observation of Solar Wind in the Outer Corona

- **Coronal HI Ly α,** observed during the 7 March, 1970 eclipse, due to resonant scattering by neutral hydrogen of the chromospheric HI Ly α (Gabriel, 1971). Few residual H atoms (a few 10^{-7}) in a hot corona (10^6 K), but abundant hydrogen, and strong chromospheric HI Ly α emission

- **Doppler dimming** of resonantly scattered emission in a moving system of reference (Beckers and Chipman, 1974): the **diagnostic technique to measure coronal expansion**, i.e. to detect solar wind outflows in the outer corona
(G. Noci, proposal to SAO for the development of UV coronagraphs, early 70s)

- First application of UV spectrometry-coronagraphy to observe the extended corona with **UVCS/SOHO** during **activity cycle 23** (1996- 2013)
(Kohl et al. 1997, 1998, etc.)

Doppler Dimming

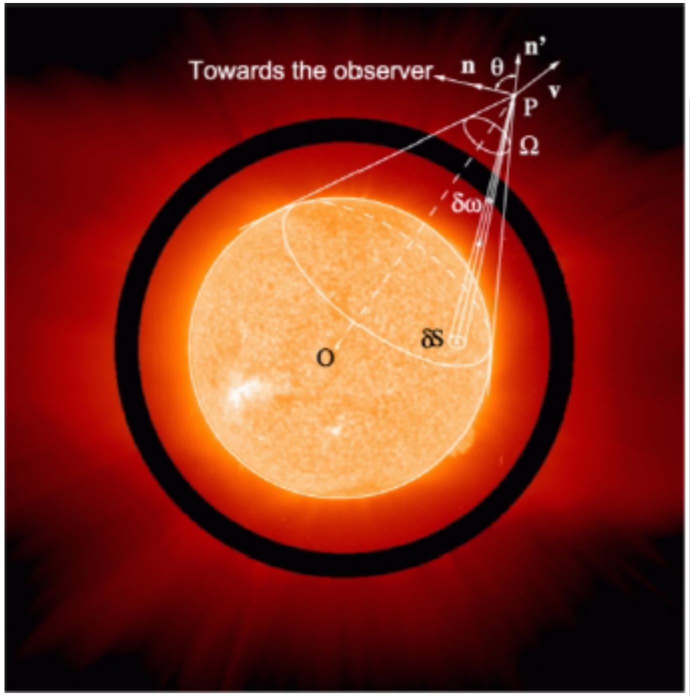


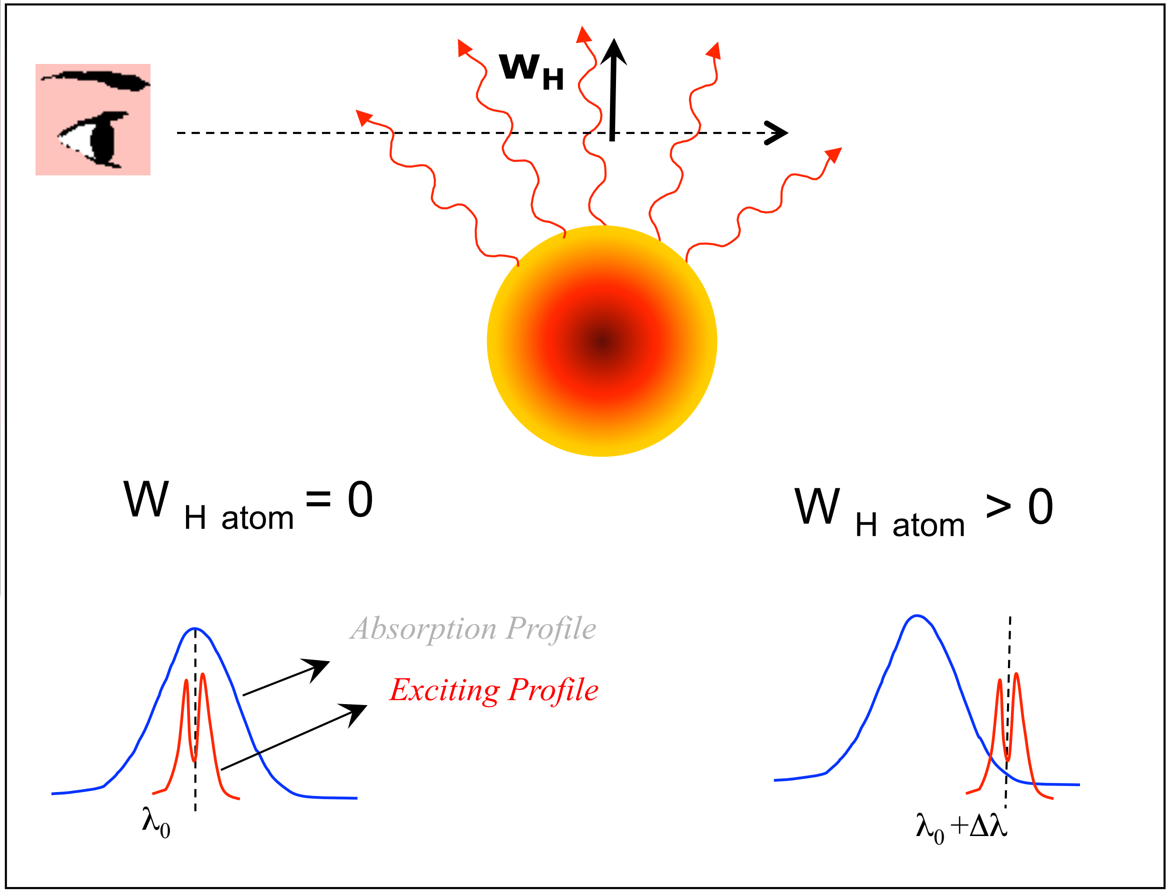
$$I_{rad} = \frac{0.83}{4\pi} \, b \, h\lambda_0 B_{12} \int_{\Omega} p(\phi) d\omega \int_{l.o.s.} \Phi(\delta\lambda) A_{el} R_{ion}(T_e) n_e dl$$

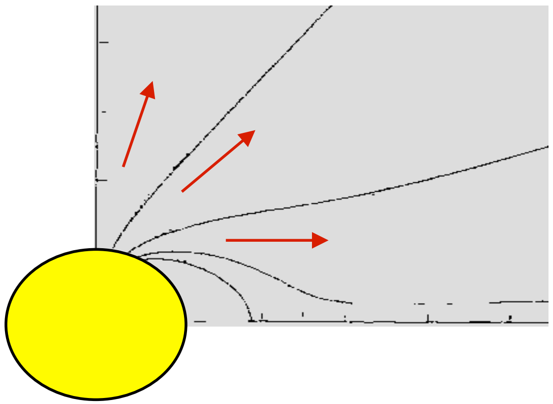
$$\delta\lambda = \frac{\lambda_0}{c} w \cdot n'$$

Doppler dimming due to a reduction of the intensity of the resonantly scattered component of the spectral line which depends on the ***outflow velocity w*** of the coronal plasma.

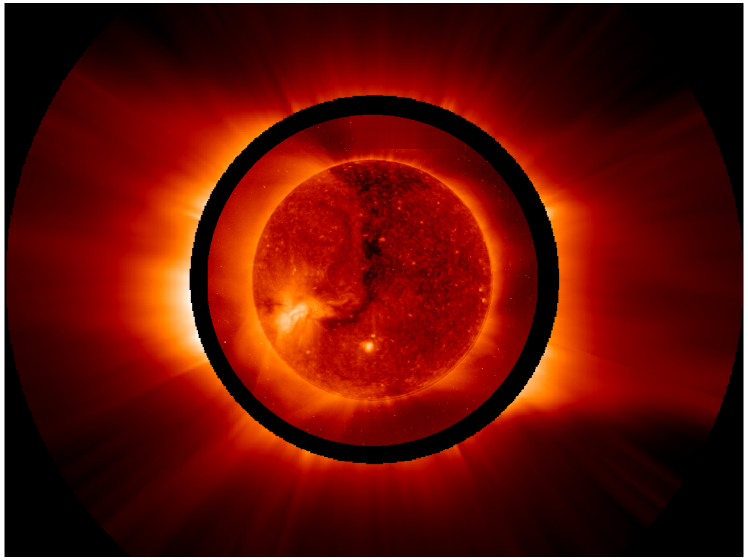
Doppler Dimming of the Resonantly Scattered HI Lyα







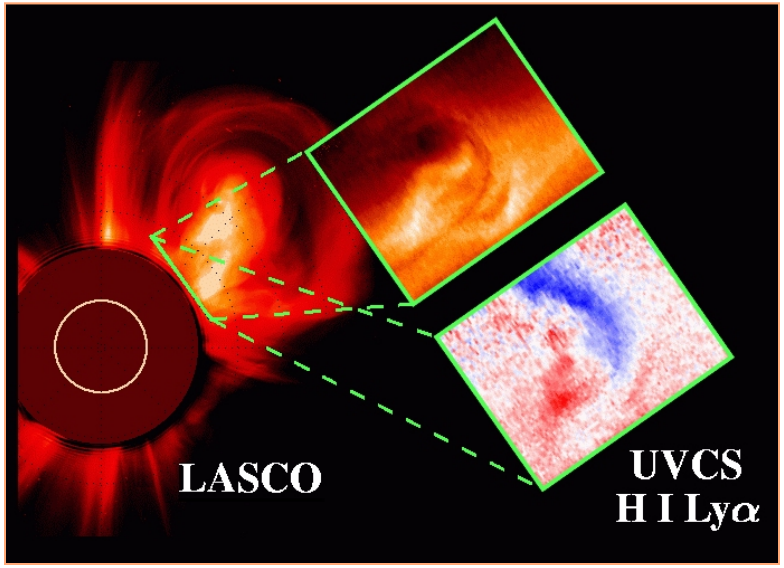
Coronal Spectroscopy with UVCS/SOHO



Detection of solar wind in the corona with UVCS SOHO (Kohl et al. 1997, 1998)

Coronal signatures of the solar wind

- outflow velocity and acceleration
- kinetic temperatures (T_k perpendicular to B)
- ion velocity distribution anisotropy



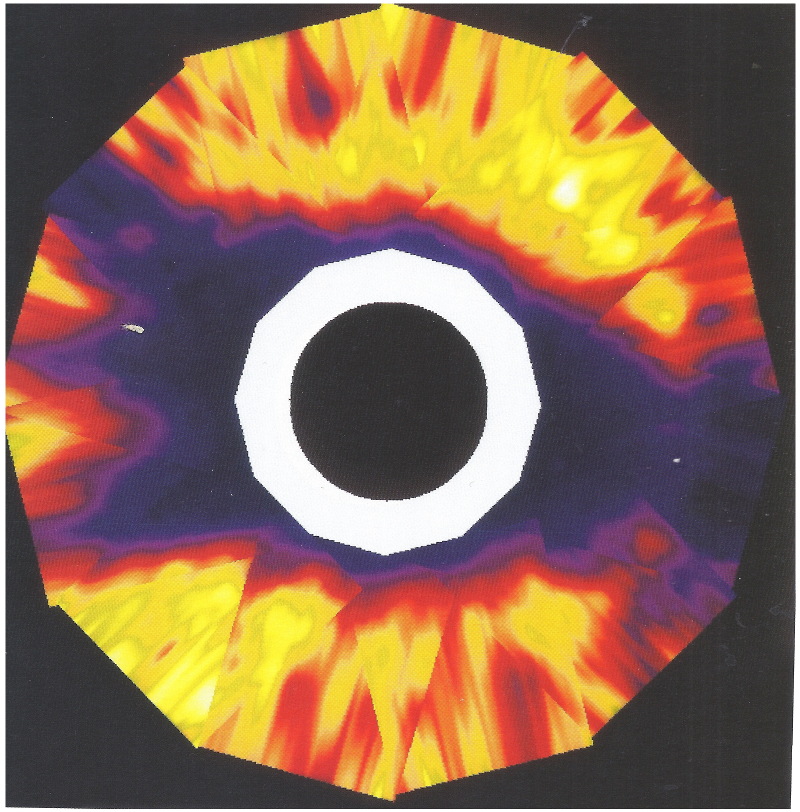
Spectroscopy of the coronal mass ejections

- Thermal structure of coronal mass ejections
- Plasma parameters at the shock front
- Plasma parameters at the reconnection region

First Outflow Velocity and Kinetic Temperature with UVCS

Solar minimum cycle 22
Super- synoptic 19 Aug-1 Sep 1996
UV outer corona : 1.5 – 3.8 $R_\odot$

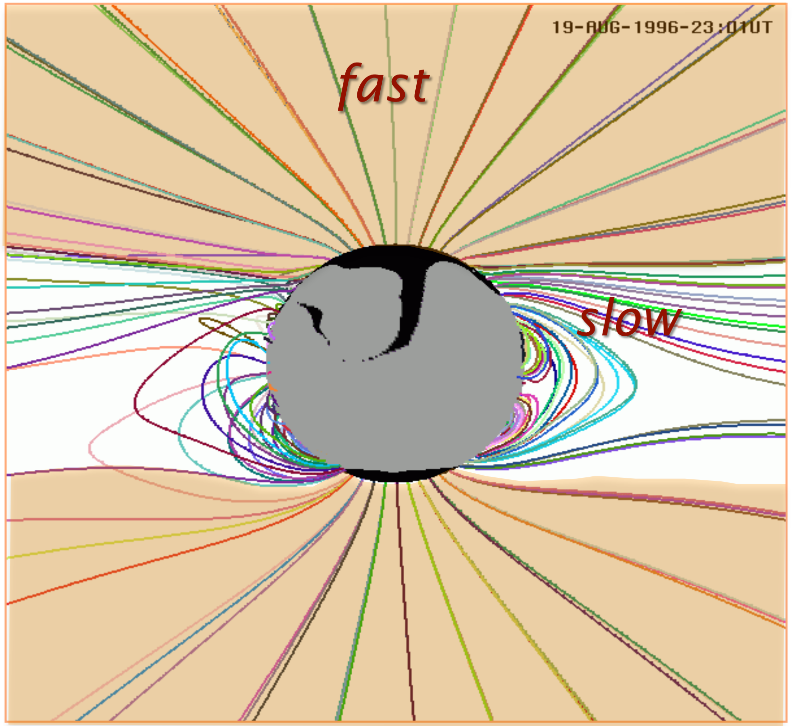
100 km s^{-1} countour (OVI doublet ratio)



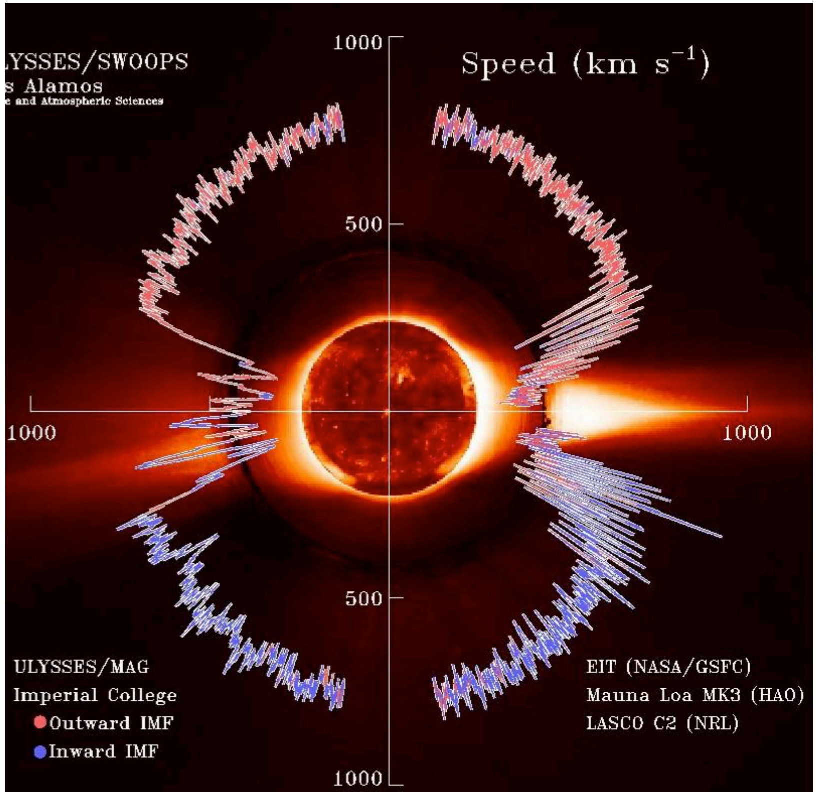
Kinetic temperature of the Oxygen ions (up to 10^8 K)

Coronal and Heliospheric wind

(McComas et al. 1998)



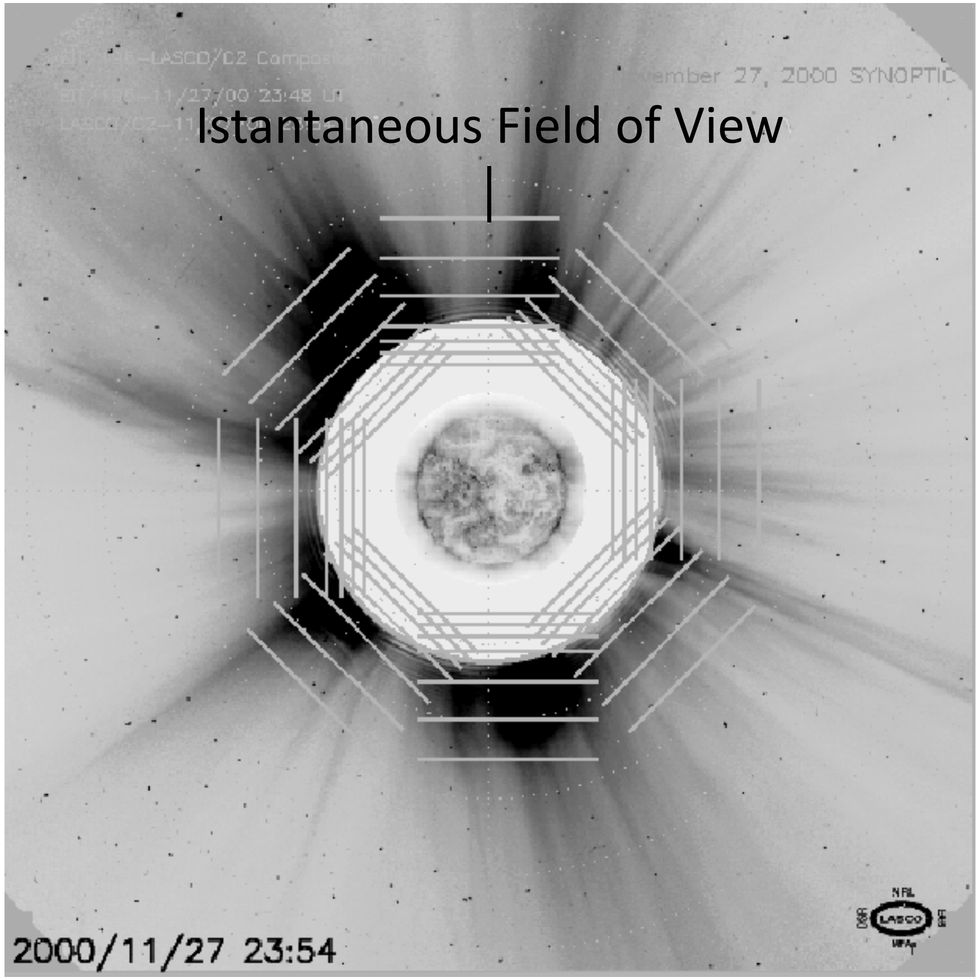
Coronal wind (UVCS/SOHO)

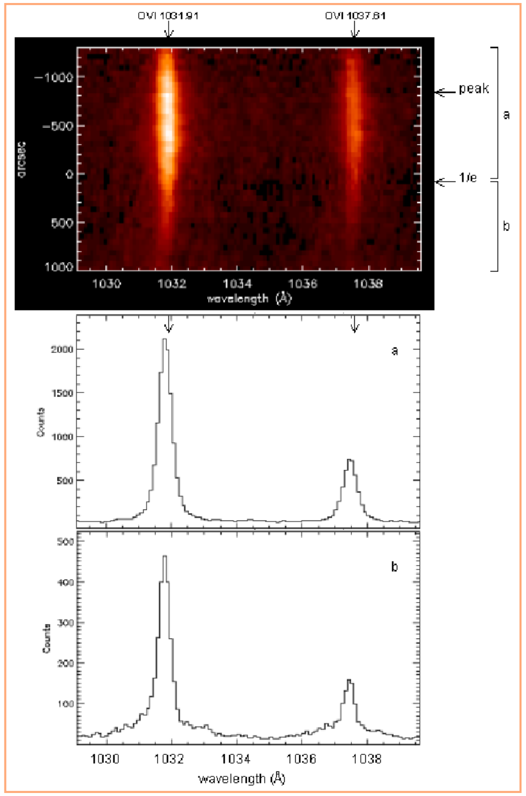


Heliospheric wind (Ulysses)

Open field lines channel toward the heliosphere the <u>fast</u> and <u>slow</u> wind streams structuring the heliospheric wind patterns

UVCS-SOHO Coronal 'Images'

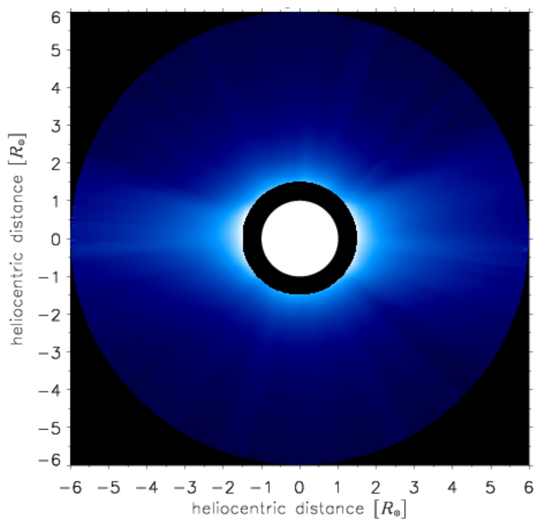




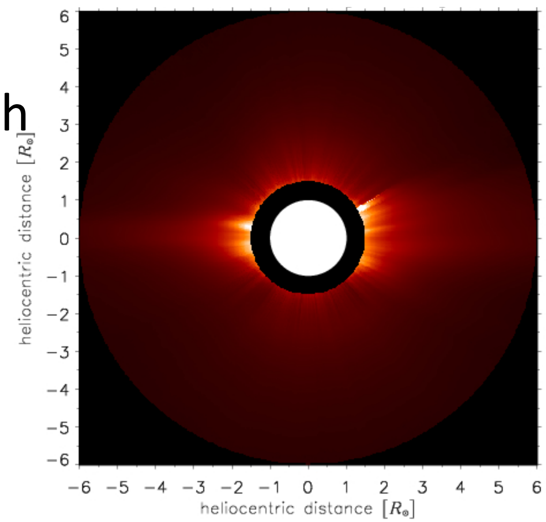
UVCS images derived from spectroscopic observations performed in IFoVs (synoptic data acquired over ≈ 10 h)

Proton Component Outflow Detection

UV HI Lyα image, e.g. derived from UVCS – SOHO observations



UV HI Lyα, e.g. synthesized image of a *static corona* using Pb data obtained with LASCO-SOHO images

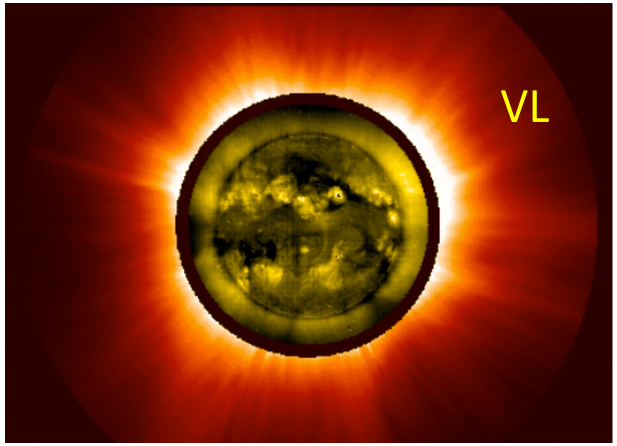


To derive 2D map on the plane of the sky of the speed of coronal plasma outflows

Metis VL&UV Coronal Imager

Metis multi-wavelength imaging of the extended corona (1.7 – 9 $R_\odot$)

Simultaneous imaging in



- *Visible Light band 580-640 nm (polarized VL)*

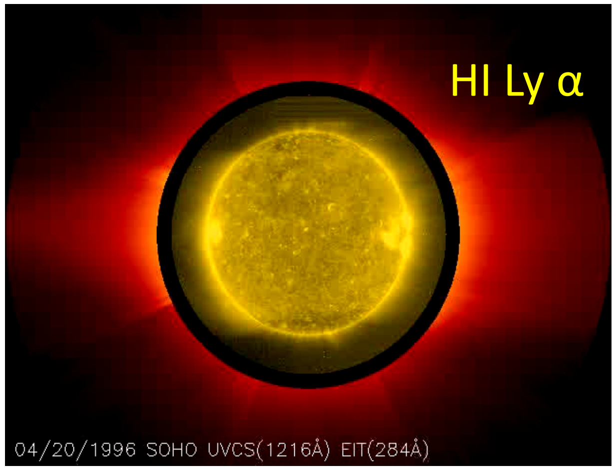
- *UV (HI Ly α) 121.6 nm*

  high temporal resolution ≥ 1 sec (≥ 1 min)

  high space resolution ≥ 2000 km VL

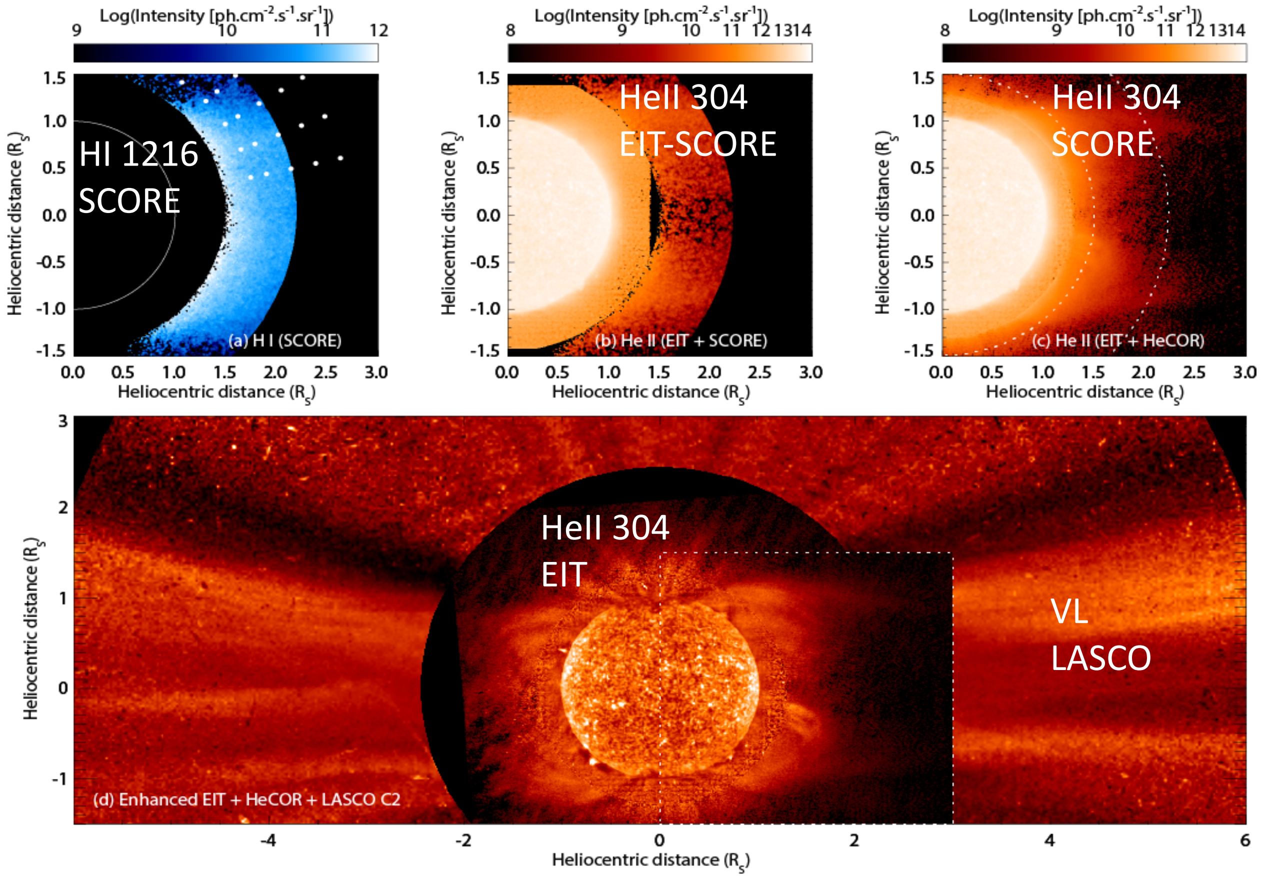
  ≥ 15000 km UV

to study coronal dynamics



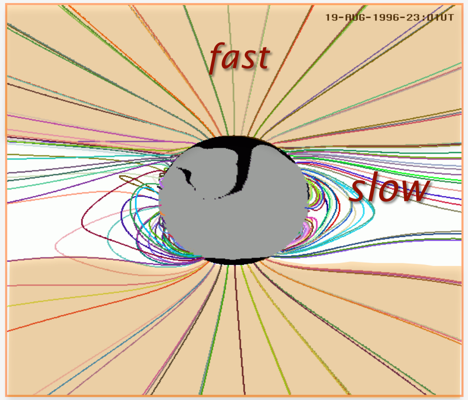
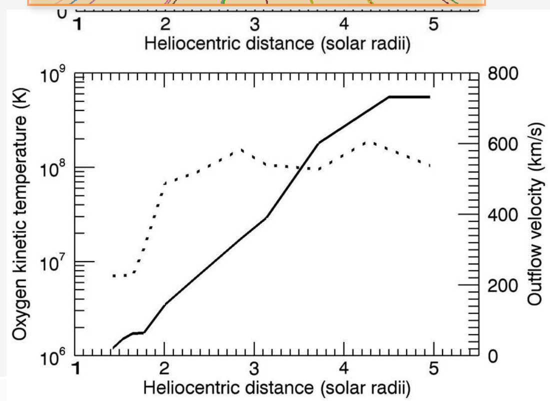
SCORE Multi-wavelength Coronagraph Prototype

Simultaneous VL and UV images acquired only during HERSCHEL rocket flight (Sep 2009)

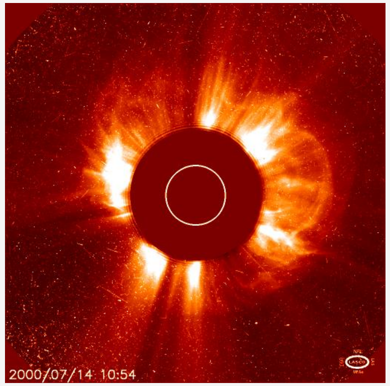
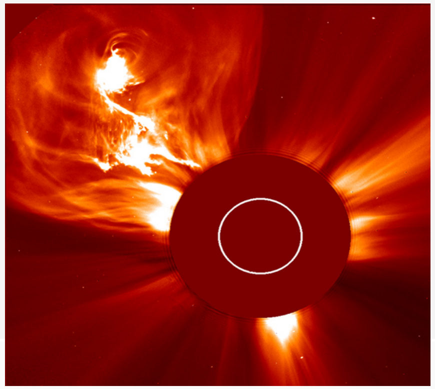


- UV Herschel observations with EIT and SCORE (NRL, IAS, INAF)
- VL data with ground–based instrumentation (Mark IV HAO, LASCO)

Metis Scientific Performance

METIS	Achievable Scientific Performance	Solar Orbiter Core Science
UV&VL imaging	*Present Visible Light imaging coronagraphy* Measure the electron density in the solar corona and its longitudinal distribution ***Solar wind*** Identify the coronal wind and measure its parameters: • velocity to discriminate fast and slow wind • acceleration to locate energy deposition in corona • mass and energy flux • longitudinal distribution fast and slow streams Observe the coronal density fluctuations, and assess their role in the acceleration of the solar wind Trace, through the flows, the open coronal magnetic field and the overall magnetic topology	***Solar wind origin and acceleration***  

Metis Scientific Performance

METIS	Achievable Scientific Performance	Solar Orbiter Core Science
UV&VL channel	***Coronal mass ejections*** Measure the • temporal evolution • mass content • overall dynamics • directionality to infer its geo-effectiveness • longitudinal distribution of the plasma erupted from the Sun. Identify the shock front where particles can be accelerated	***Solar Coronal Mass Ejections origin and propagation***  ***Acceleration of energetic particles*** ***Prominence activity*** 

Metis & Mission Profile

Close to the Sun 0.28 AU (minimum perihelion)

Coronal fine structure at all latitudes & longitudes (0˚-33º inclination)

Out of the ecliptic ≥ 33˚

Third dimension of solar wind (magnetic topology) coronal structure and CME's

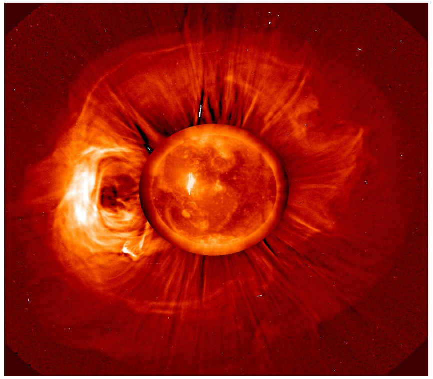
Quasi-Corotation

intrinsic evolution of the corona cancelling rotation effects

e.g. coronal fluctuations, slow wind origin, streamer physics, evolution of configuration prior and post CMEs

Out of the geocorona

Best UV coronal seeing conditions



Metis Instrument

ASI – INAF

MPS

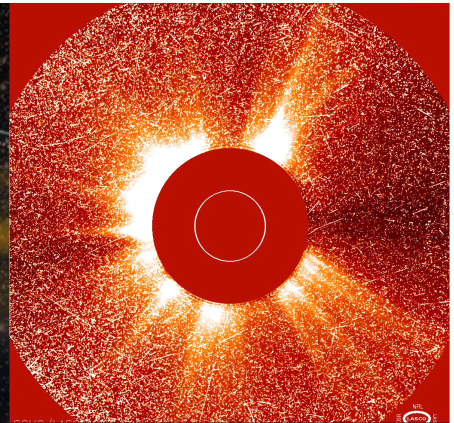
AIAS

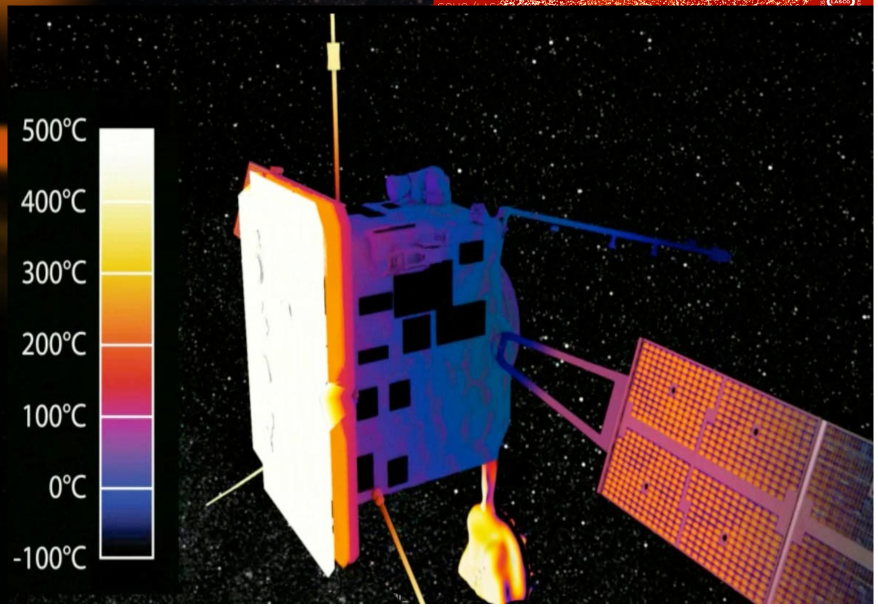
Metis flight model

Challenging enviromental conditions

Requirements

- •low mass
- •low power
- •thermally robust
- •radiation proof





Metis Instrument

Externally occulted coronagraph

- Annular FOV: 1.6°-2.9° (1.7-3.1 $R_\odot$ @ 0.28 AU)

Simultaneous imaging in 2 channels

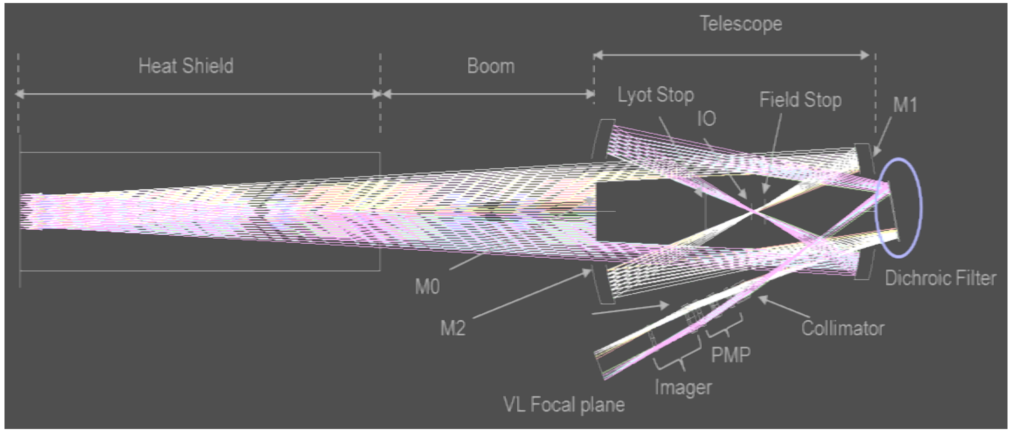
- broad-band polarized visible light (580-640 nm)
- narrow-band UV @ Lyman α (121.6±10 nm)

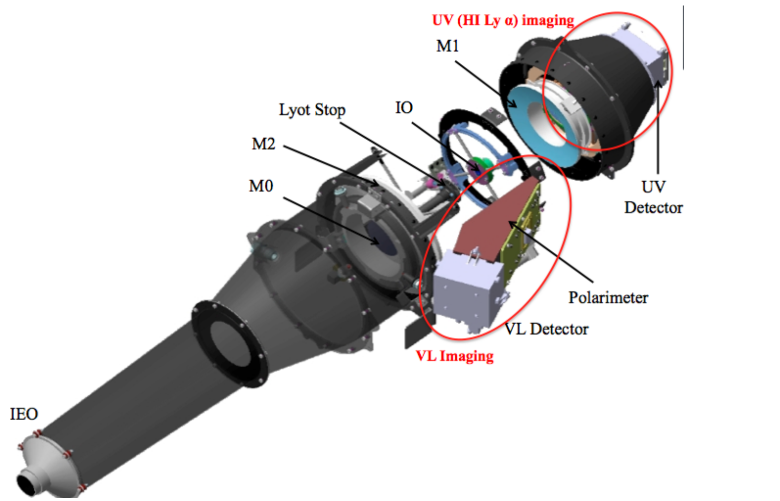
Spatial resolution

- ≤20" (VL & UV phot. count.) → 2000 km @ 0.28 AU
- ≥80" (UV analog mode) → 15000 km @ 0.28 AU

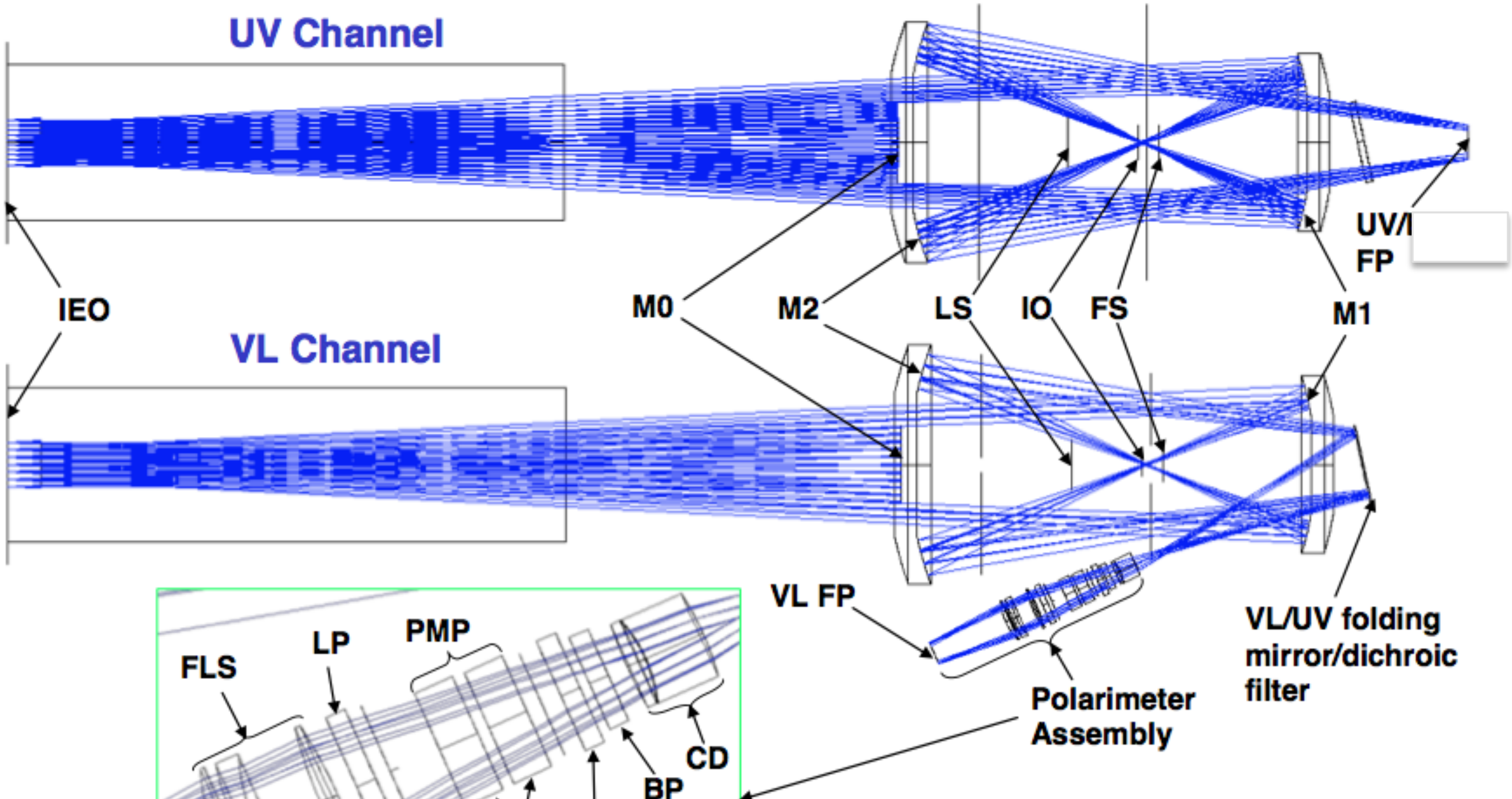
Temporal resolution

- ≥1 min typically
- 1 s (VL only, coronal fluctuations)
- Possibility of CME-triggered obs.





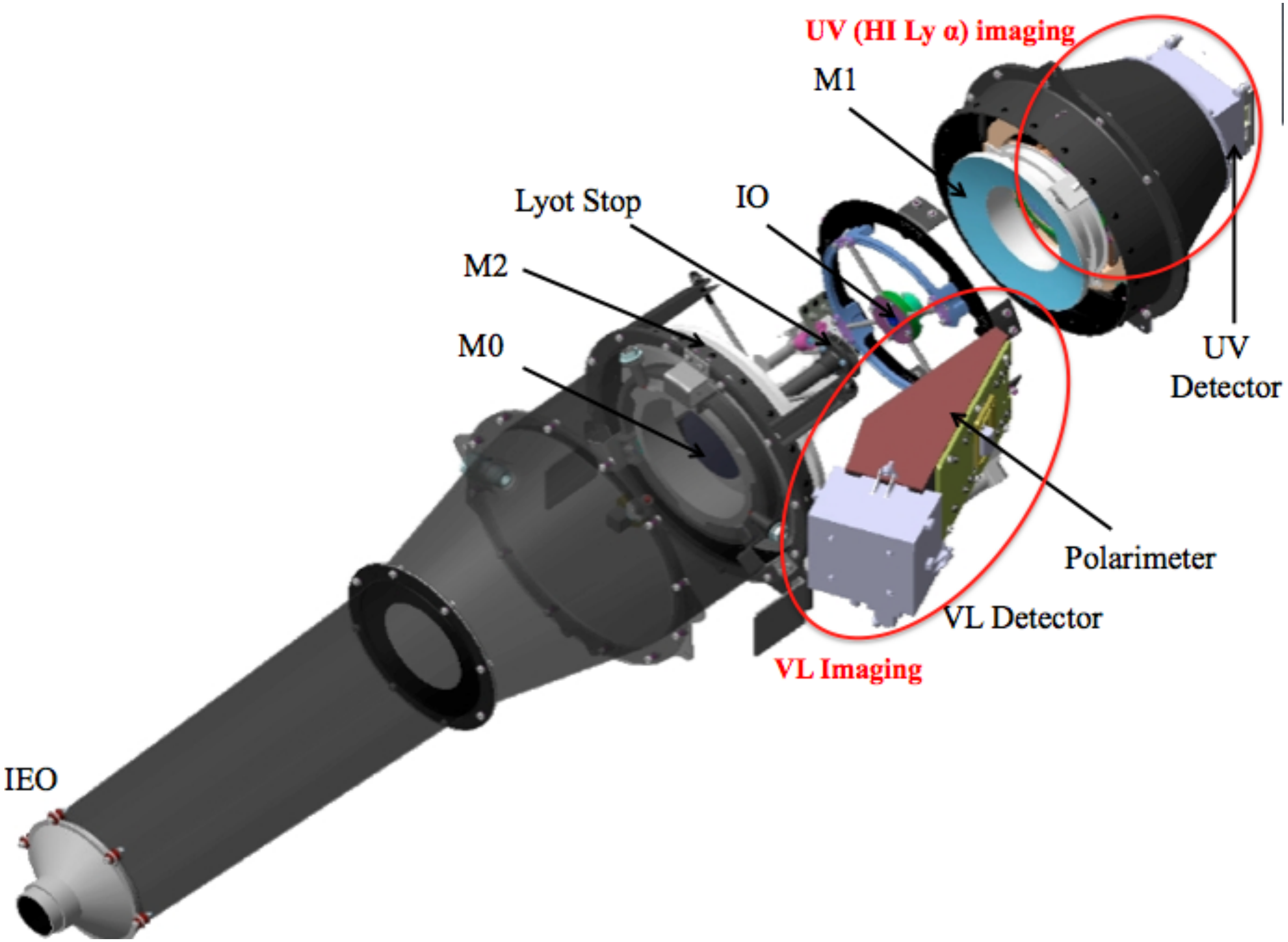
METIS Optical Design



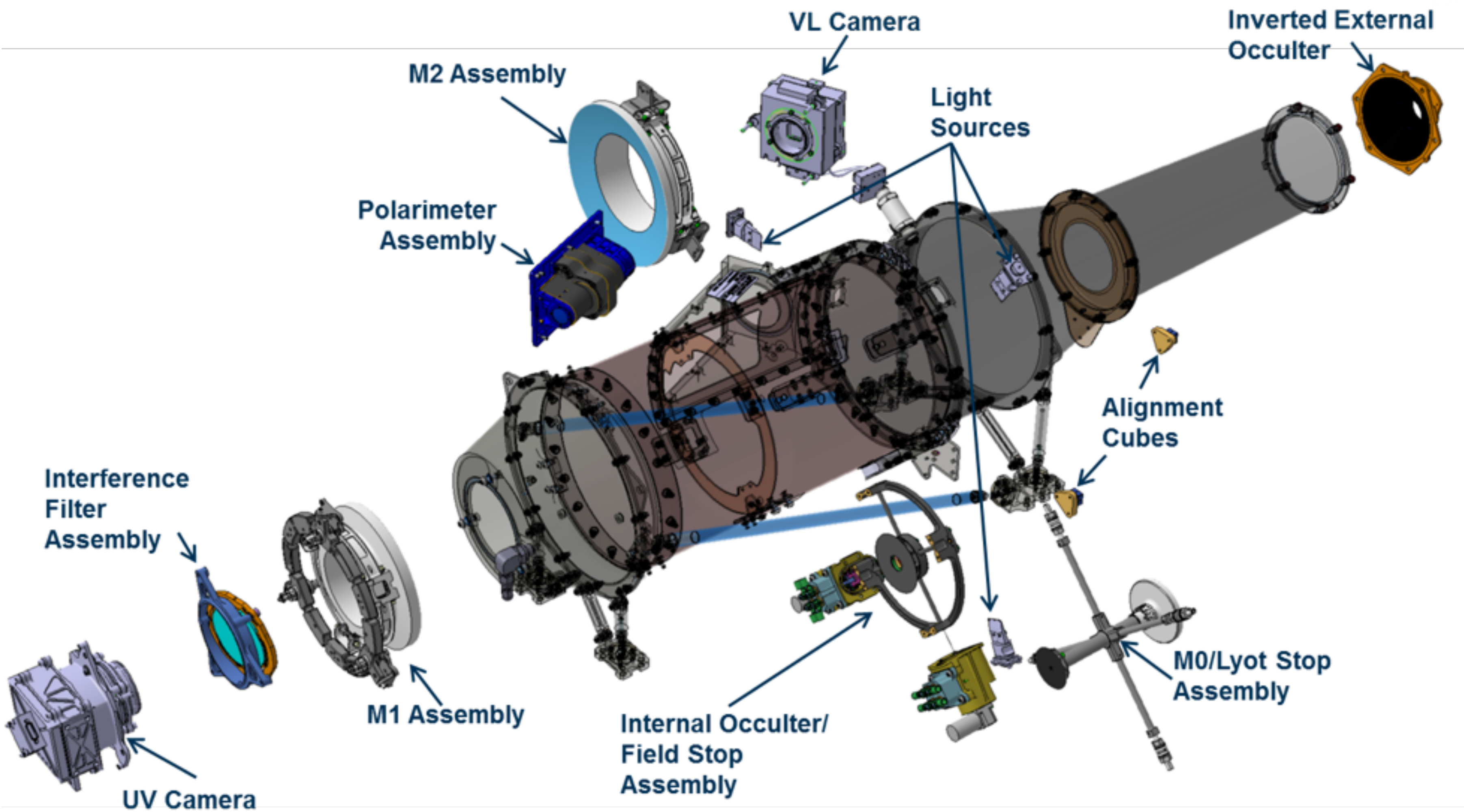
METIS instrument is an externally occulted coronagraph on-axis Gregorian with imaging capabilities.

Polarimetry performed with liquid crystal retarders

Metis Opto-Mechanical Layout

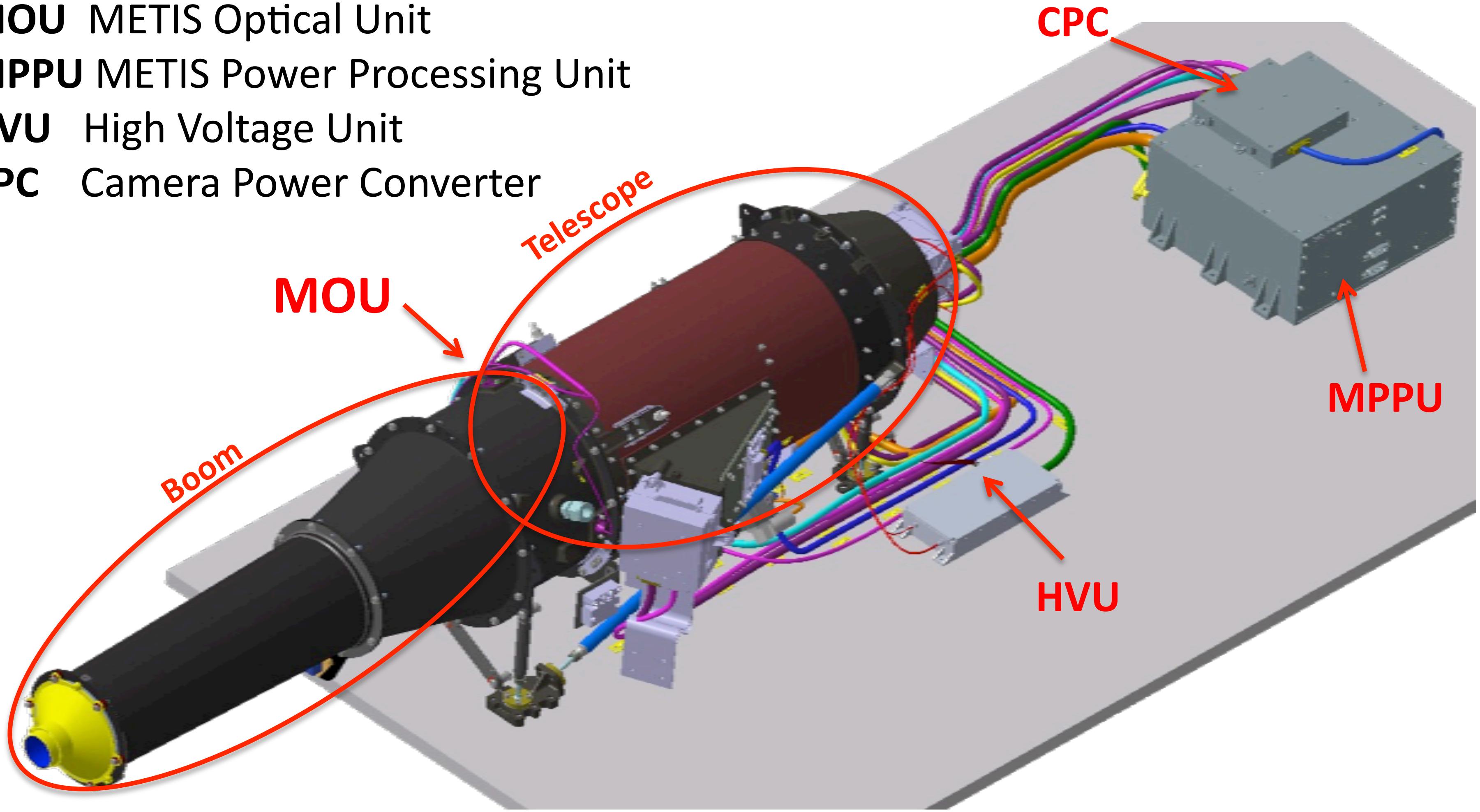


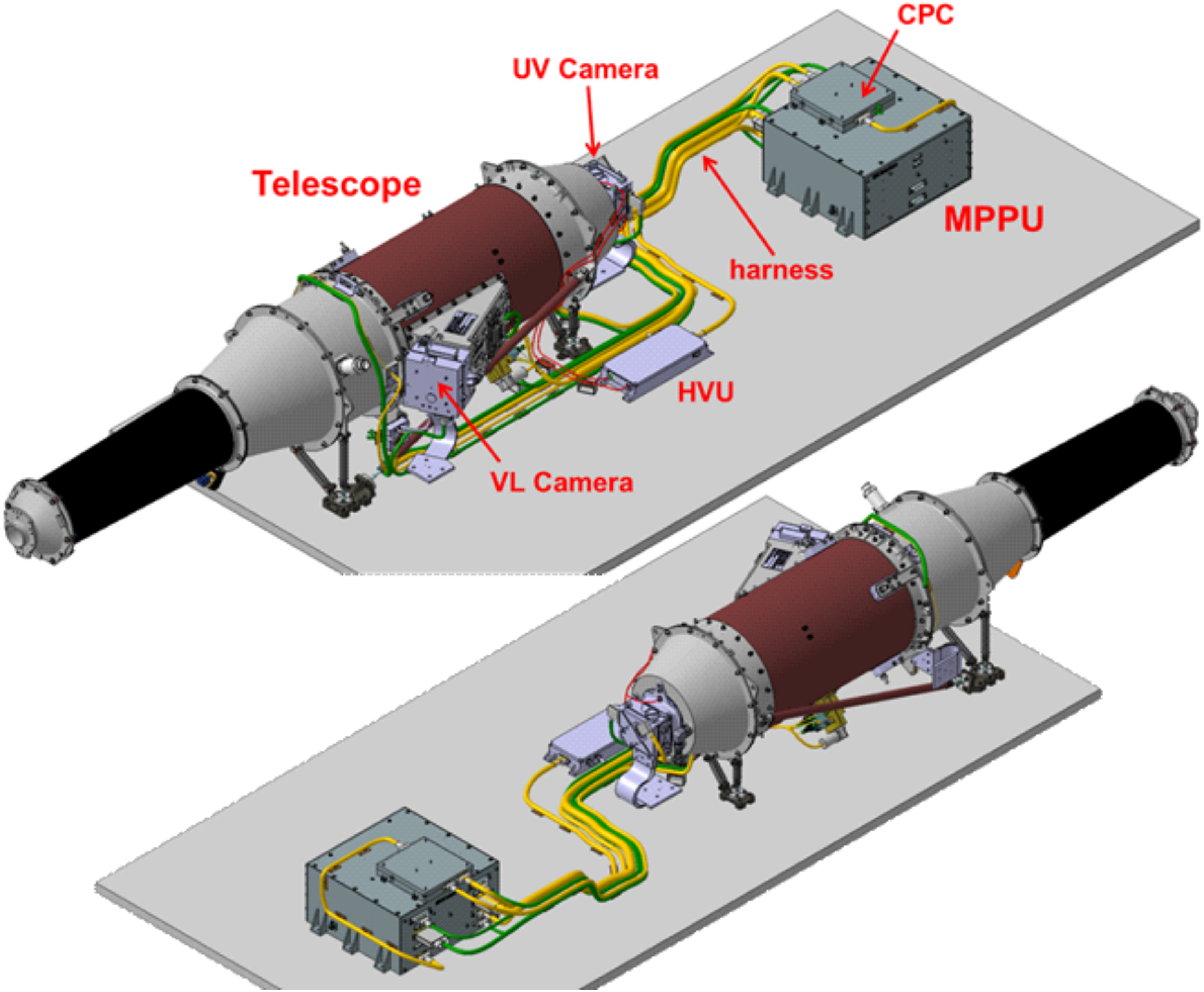
Metis Subsystems



METIS Units

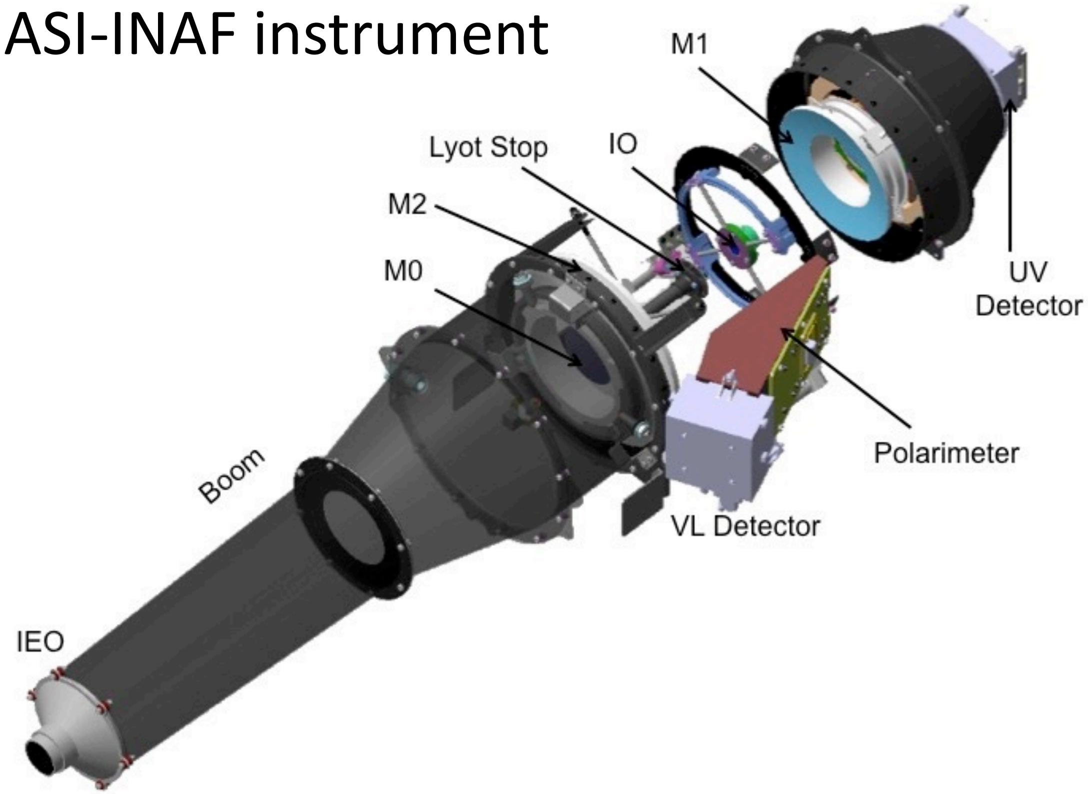
MOU METIS Optical Unit
MPPU METIS Power Processing Unit
HVU High Voltage Unit
CPC Camera Power Converter



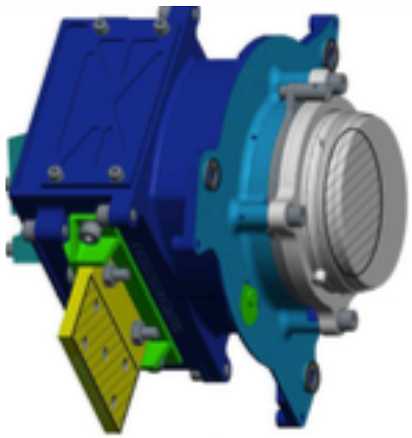

CPC
UV Camera
Telescope
MPPU
harness
HVU
VL Camera

METIS Subsystem Contributions

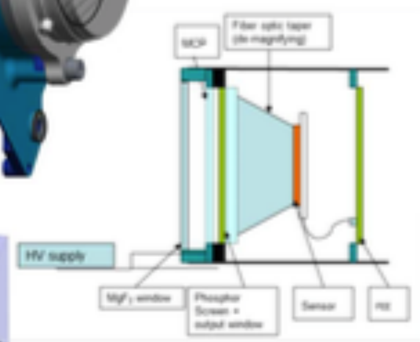
ASI-INAF instrument

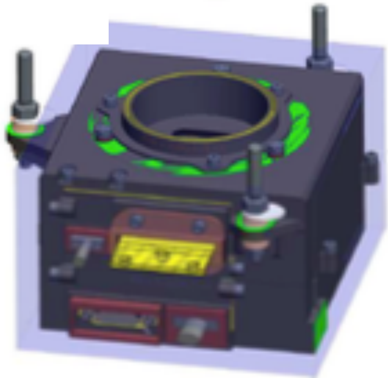


Metis Detection Subsystem contributed/implemented by Max Planck Institut für Sonnensystemforschung (MPS)



UVDA equipped with CMOS Active Pixel Sensor (1024 x 1024 pixels, 15x15 μm² size).





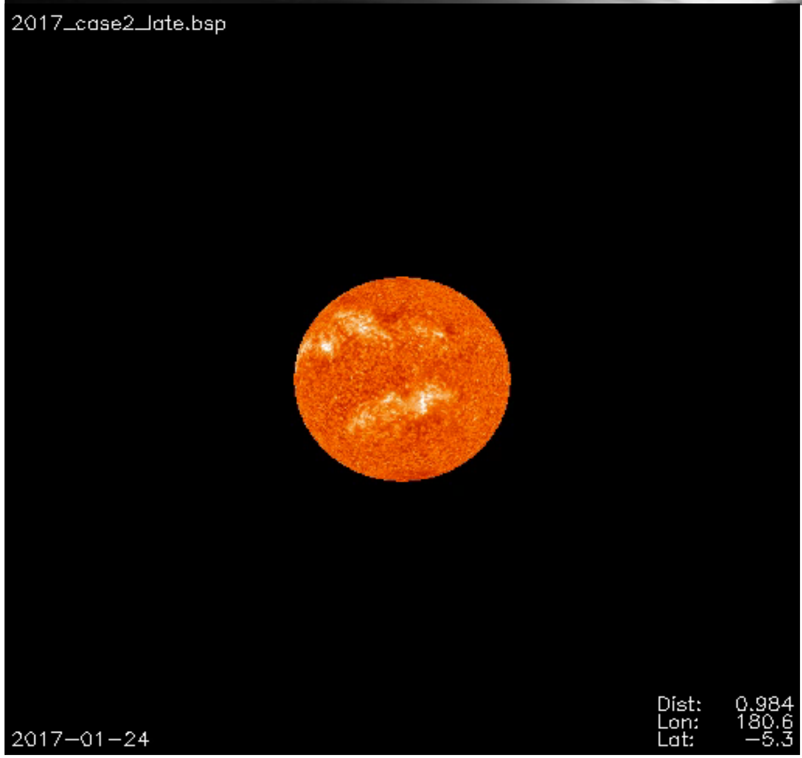
VLDA equipped with CMOS Active Pixel Sensor (2048 x 2048 pixels, 10 x10 μm² size).

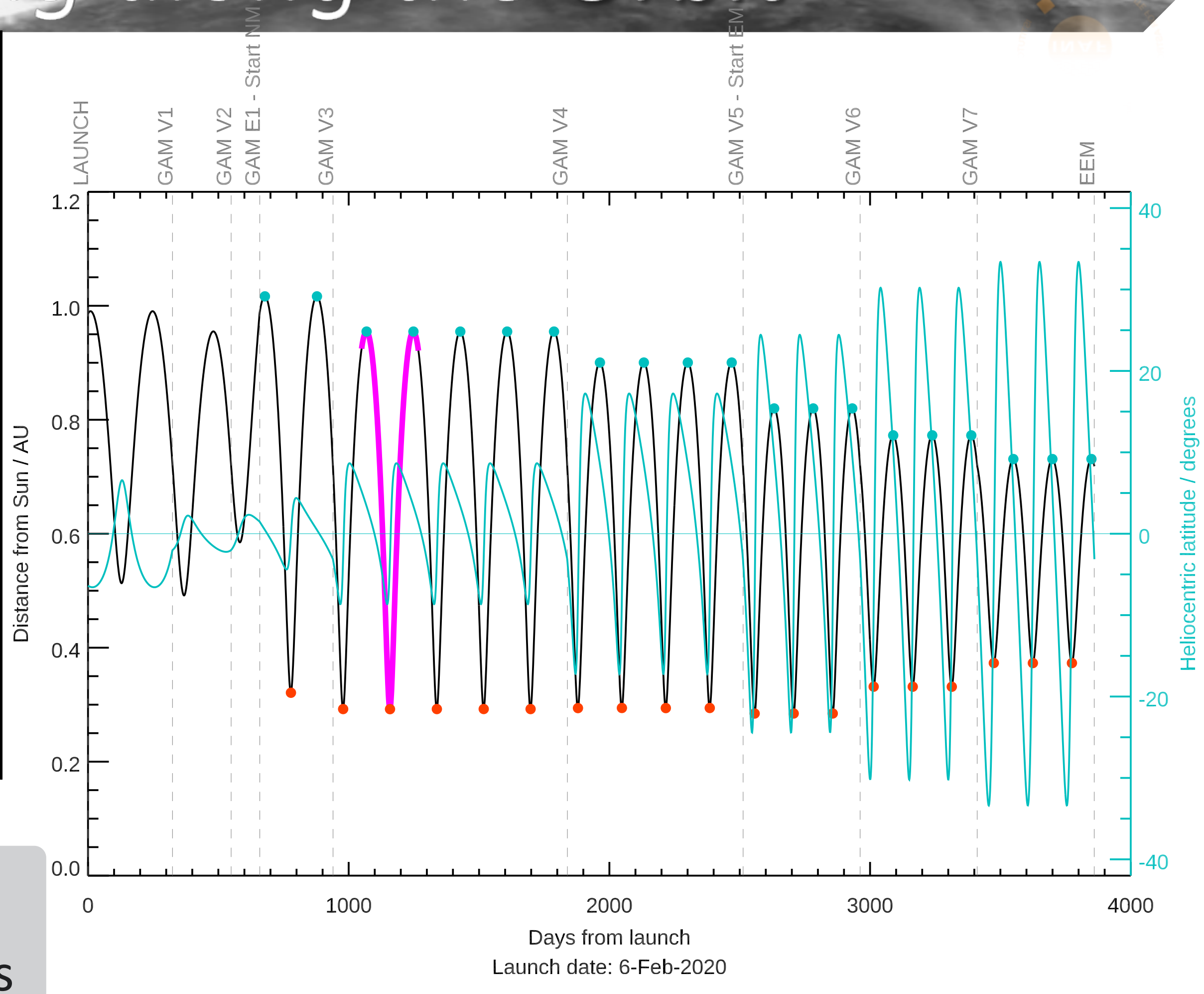
Mirrors M1, M2 contribution of the Institute of Astronomy, Czech Academy of Science

Metis Instrument Integration

Metis Integration on the Spacecraft

Mission Profile
Zooming along the Orbit



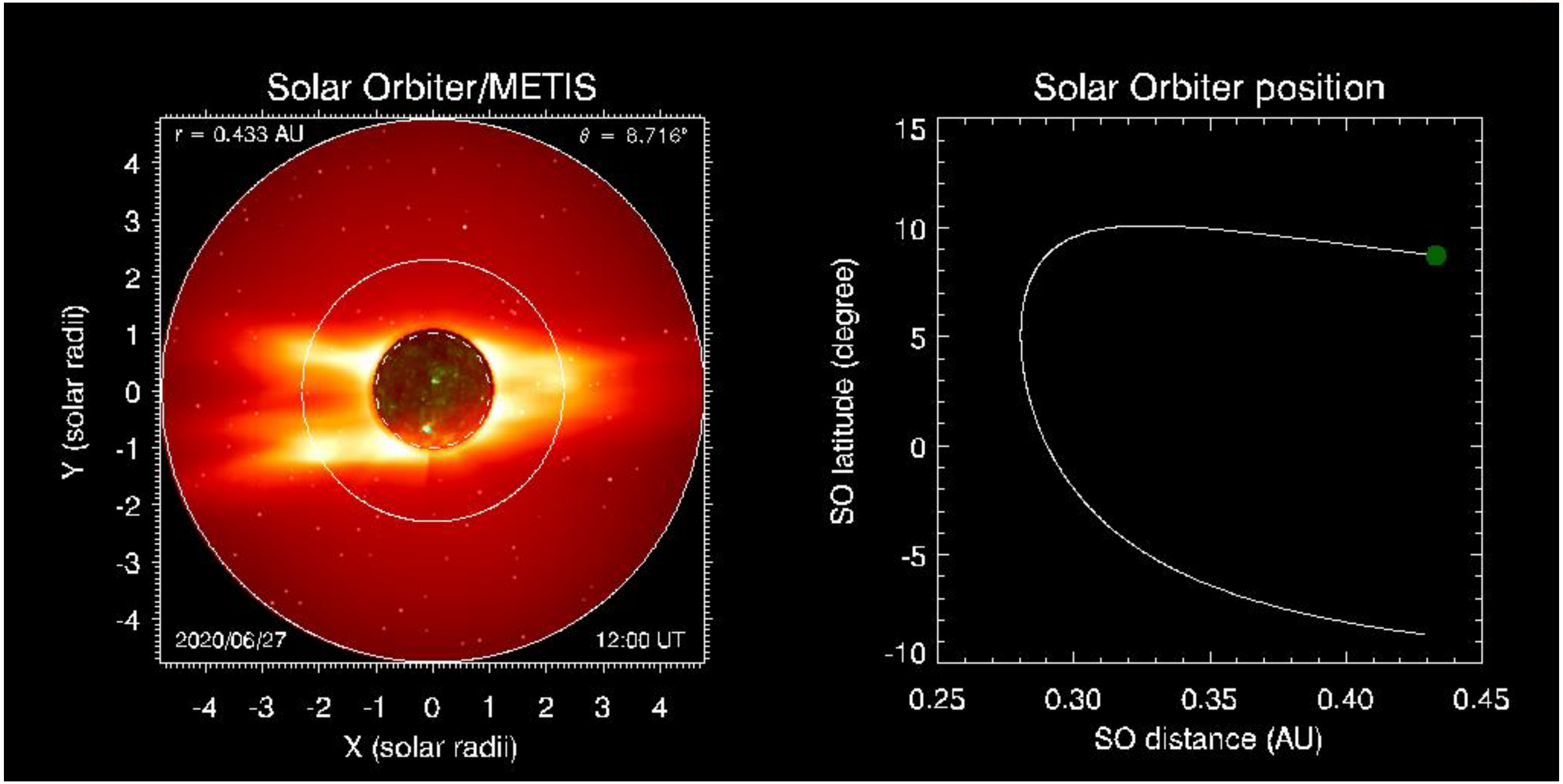


Launch 7 Feb 2020

Cruise phase	1.8 years
Nominal mission phase	5 years
Extended phase	3.7 years

Minimum perihelion	0.28 AU
Maximum solar inclination	33.4°
Maximum angular rate	7.7 °/day
Orbital period	200-150 days

Corona as viewed along the Orbit
Low Latitudes

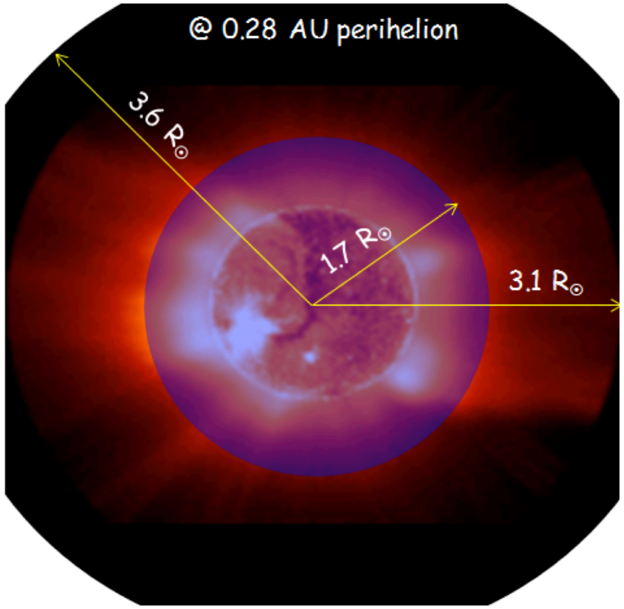


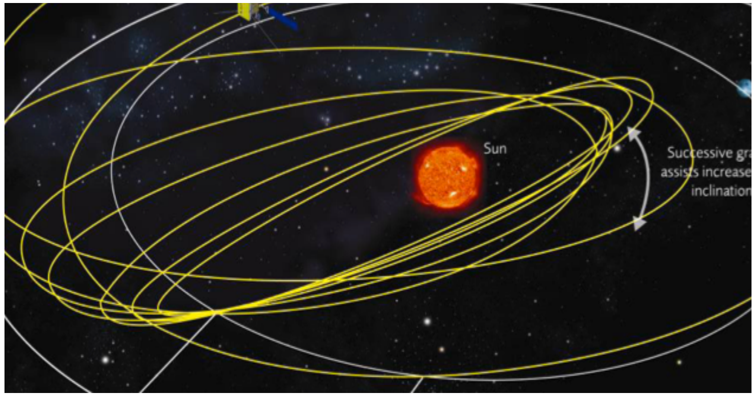
- LASCO/C2 and Mauna Loa/Mark IV coronal images during Carrington Rotation CR1931 (1997)
  → construction of a 3D cube integrated step-by-step along the LOS depending on the spacecraft position
- EIT 195 A coronal images on disk
- Actual stars in the METIS field-of-view from Hipparcos star catalog

(Credit: A. Bemporad)

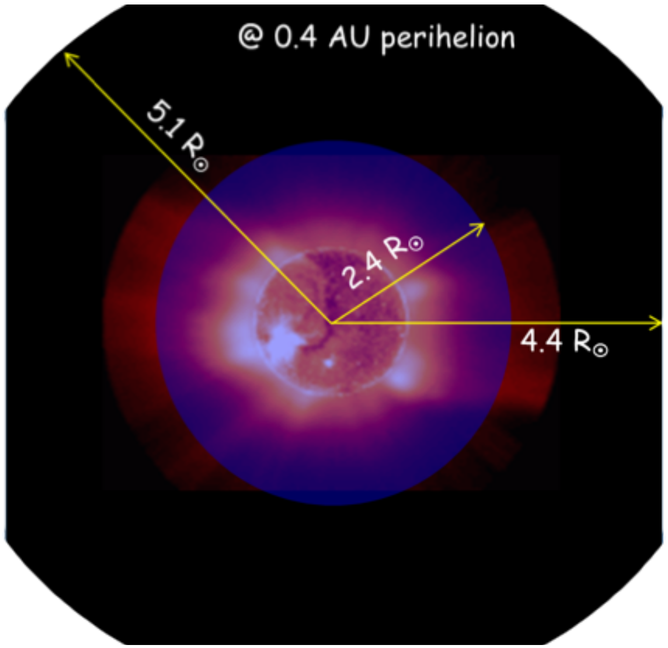
Metis Variable Field of View within 1.7 – 9 $R_\odot$

Variable FoV due to the orbit eccentricity



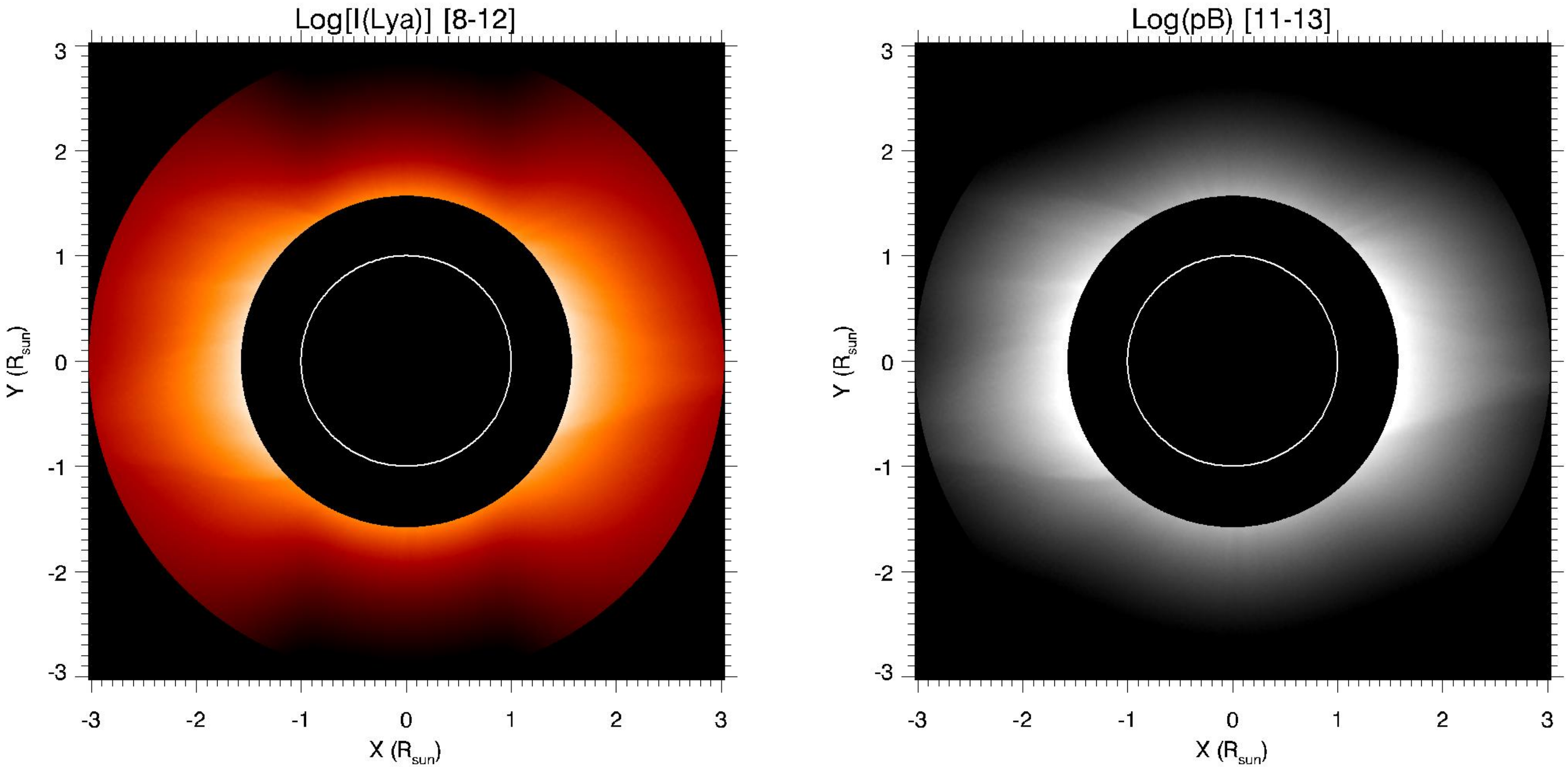


Perihelion at 0.28 AU
FoV 1.7-3.6 $R_\odot$



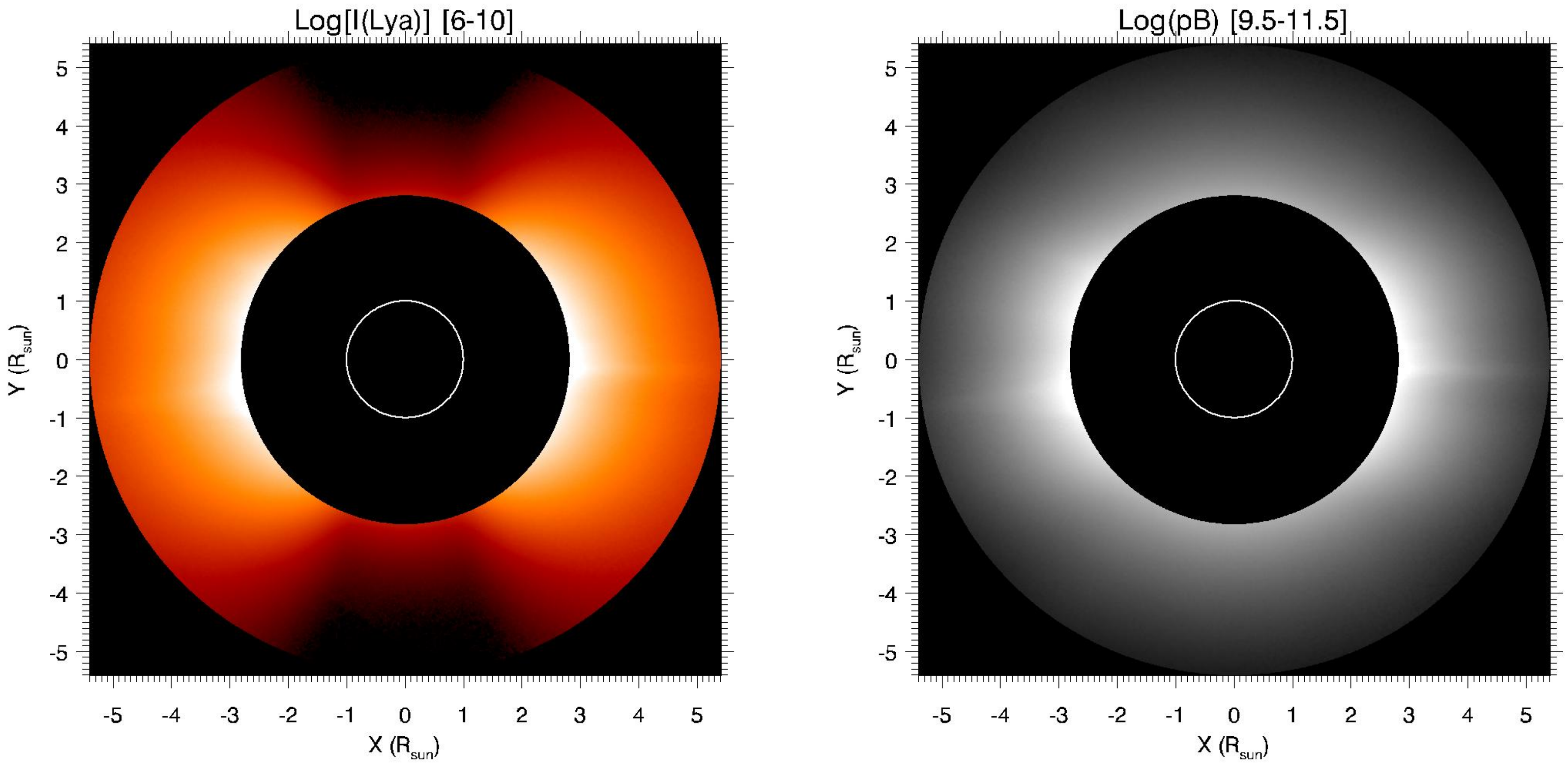
Perihelion at 0.4 AU
2.4-5.1 $R_\odot$

FoV at 0.28 AU
Metis Synthetic Images



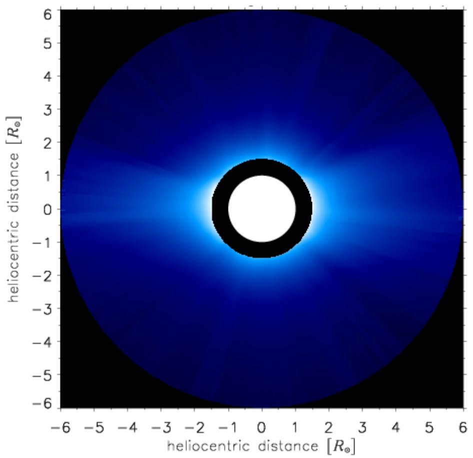
Expected Metis HI Lyα and polarized brightness images at 0.28 AU heliodistance, obtained on the basis of typical coronal parameters (static corona assumption)

FoV at 0.50 AU
Metis Synthetic Images

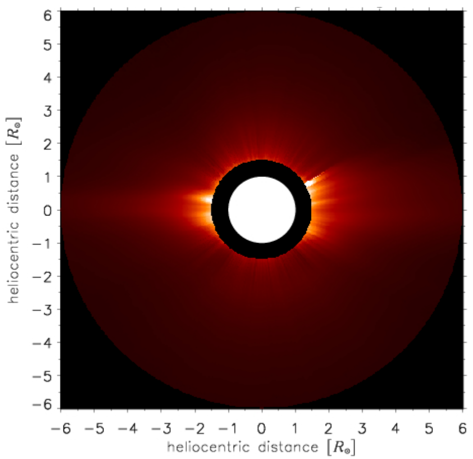


Expected Coronal Outflow Maps

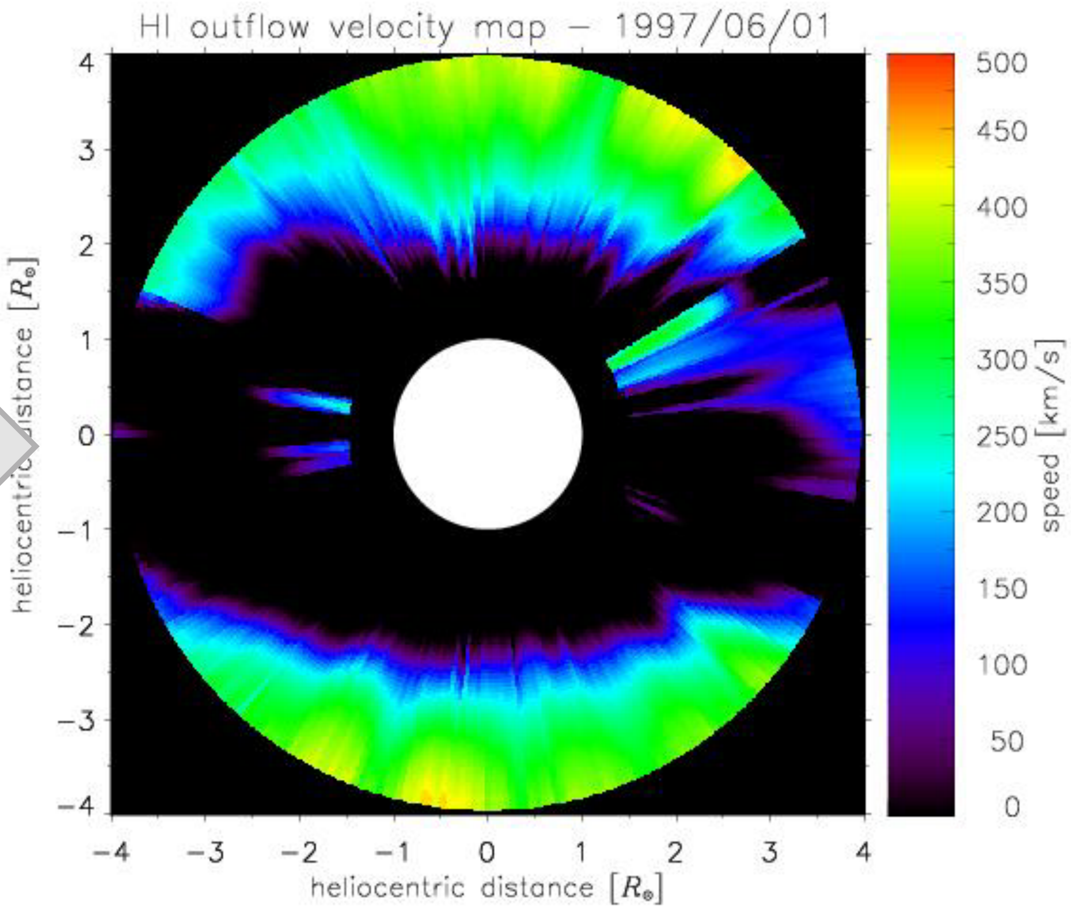
UV HI Lyα image derived from UVCS –SOHO observations



UV HI Lyα synthesized image of a *static corona* using Pb data obtained with LASCO-SOHO images

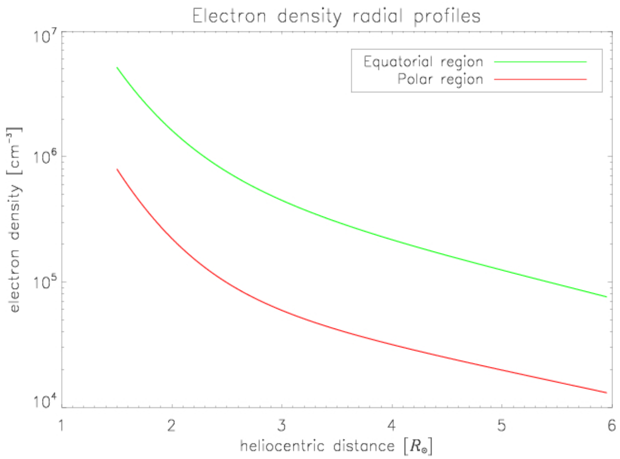


Derived 2D map on the plane of the sky of the speed of coronal plasma outflows

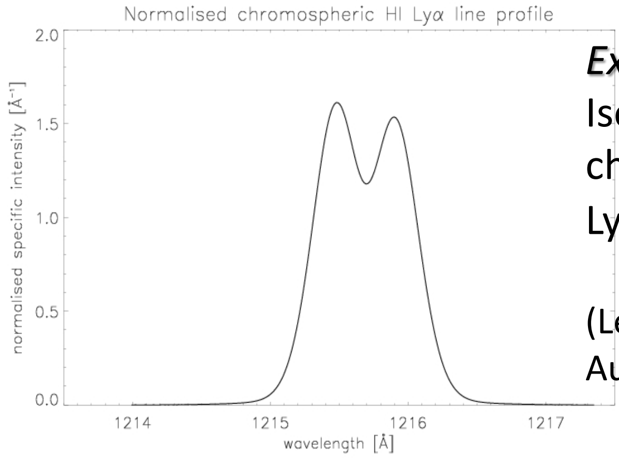


(Dolei et al. 2017)

UV HI Lyα Synthesized Images Parameters

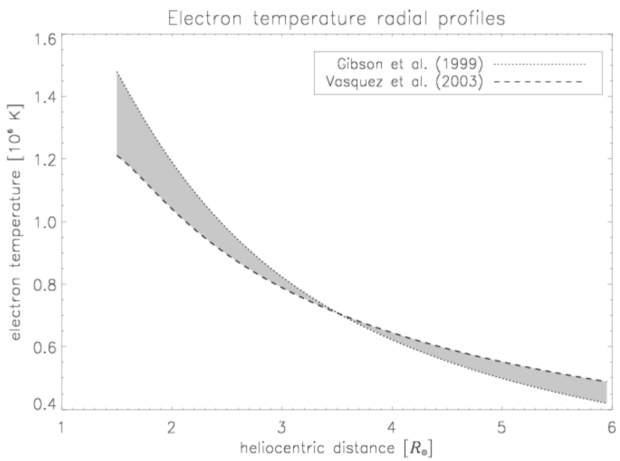


Coronal n_e from Van De Hulst inversion of the polarized VL images (PB images)

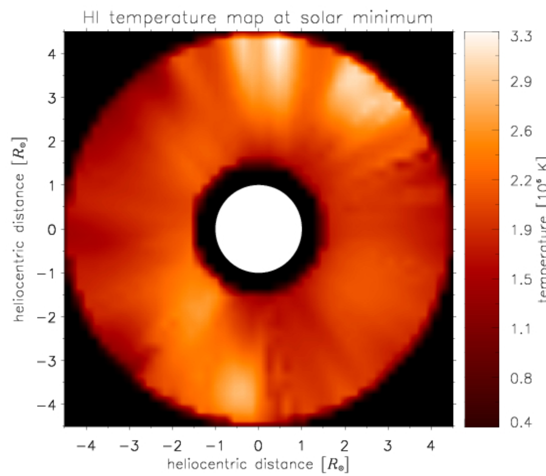


Exciting photons
Isotropic chromospheric HI Lyα line profile

(Lemaire et al. 2002; Auchère 2005)



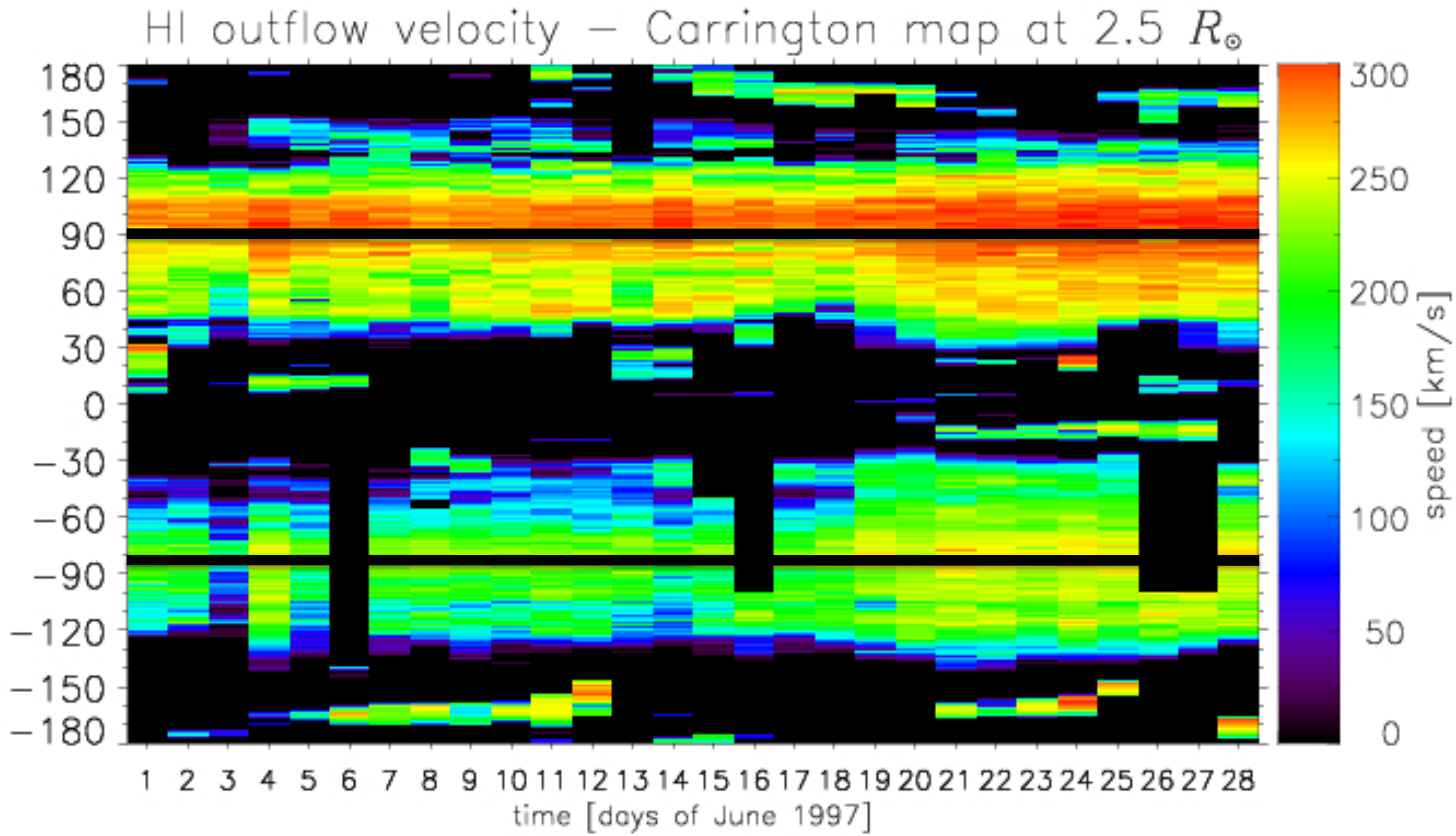
Coronal T_e radial profiles from interpolation of known profiles for equatorial streamers and polar coronal holes



Kinetic temperature map of coronal HI atoms from UVCS Lyα observations at solar minimum

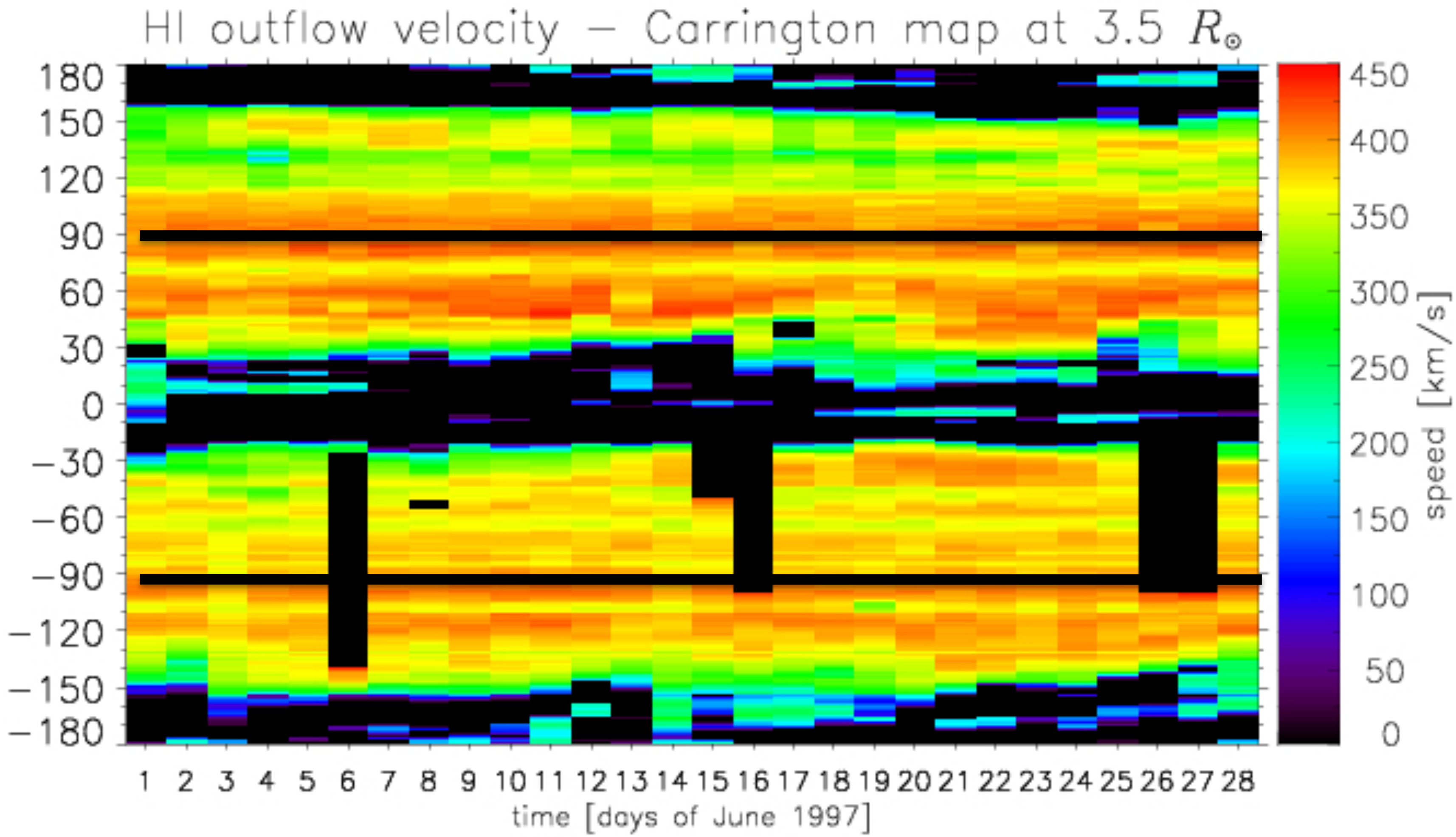
(Dolei et al. 2017)

Solar Wind Outflows @2.5 $R_\odot$
Neutral Hydrogen/Proton Component



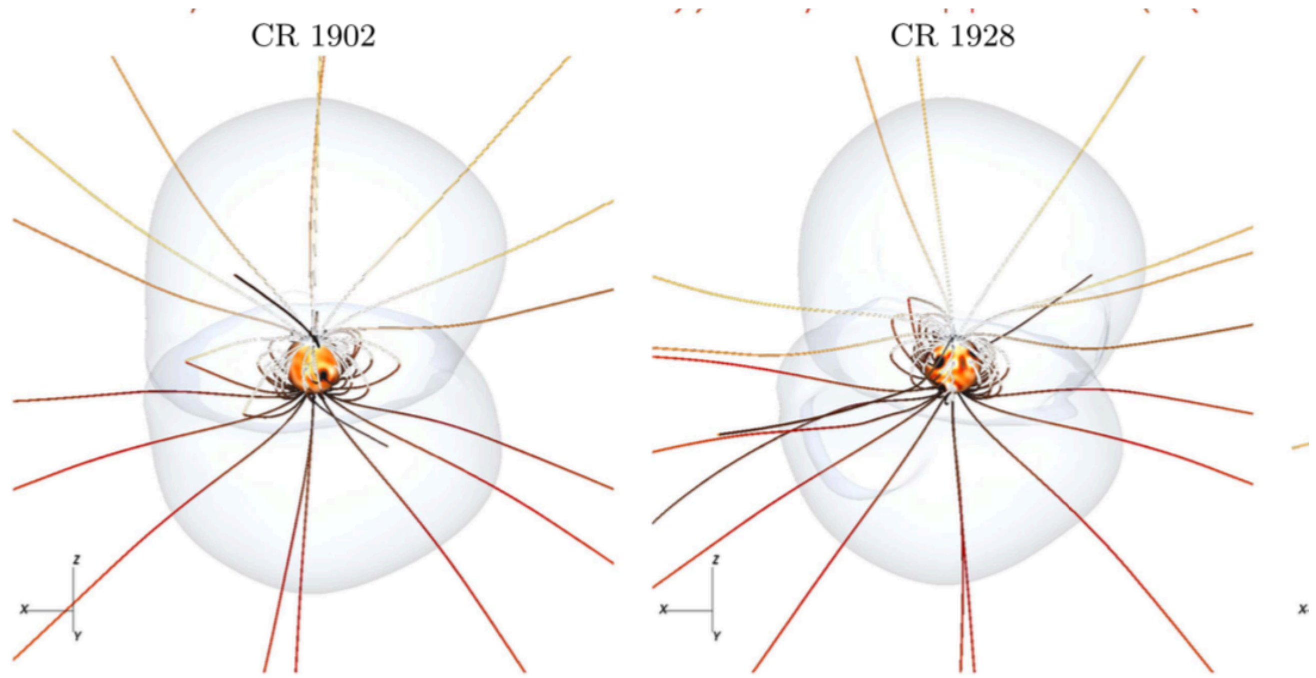
(Dolei et al, 2017)

Solar Wind Outflows @3.5 $R_\odot$
Neutral Hydrogen/Proton Component



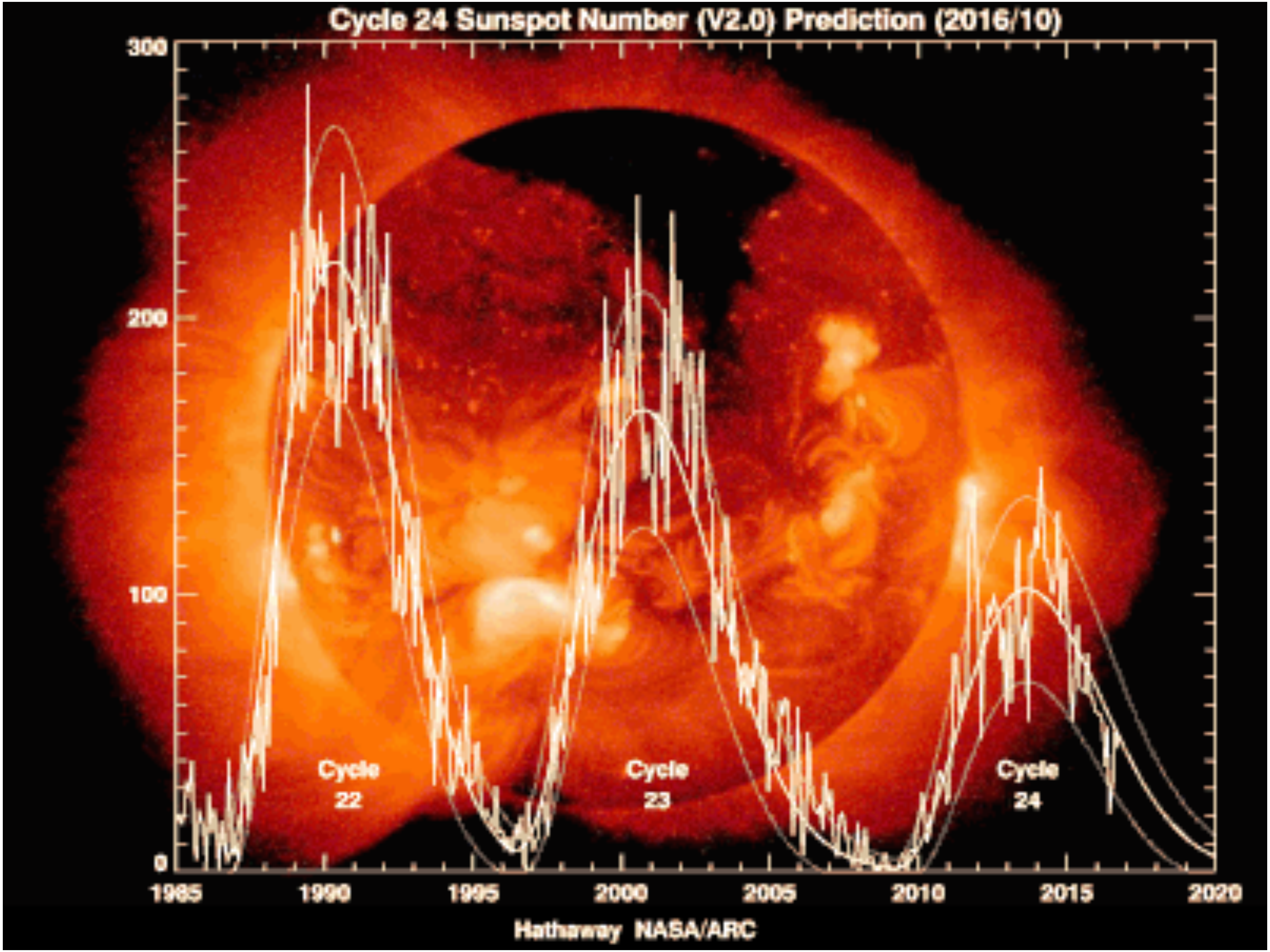
(Dolei et al, 2017)

Solar Wind Propagation Outward

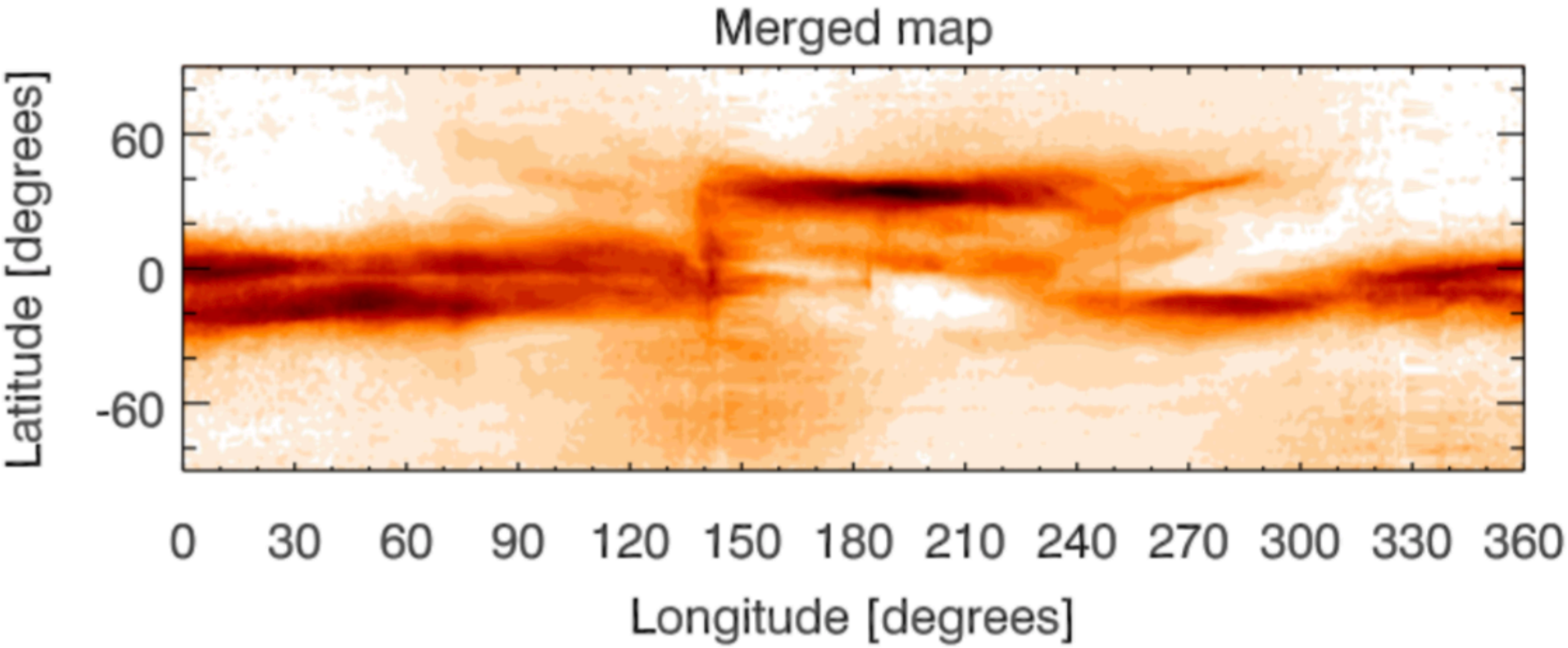


MHD solutions of the solar wind using WSO maps
identification of the Alfven surface
CR 1902/1928 - Carrington rotations initiating on 27 Oct 1995 and 5 Oct 1997, respectively, minimum phase cycle 22

(Reville and Brun, 2017)


Cycle 24 Sunspot Number (V2.0) Prediction (2016/10)
300
200
100
0
1985
1990
1995
2000
2005
2010
2015
2020
Cycle 22
Cycle 23
Cycle 24
Hathaway NASA/ARC

Corona @ 2.5 $R_\odot$

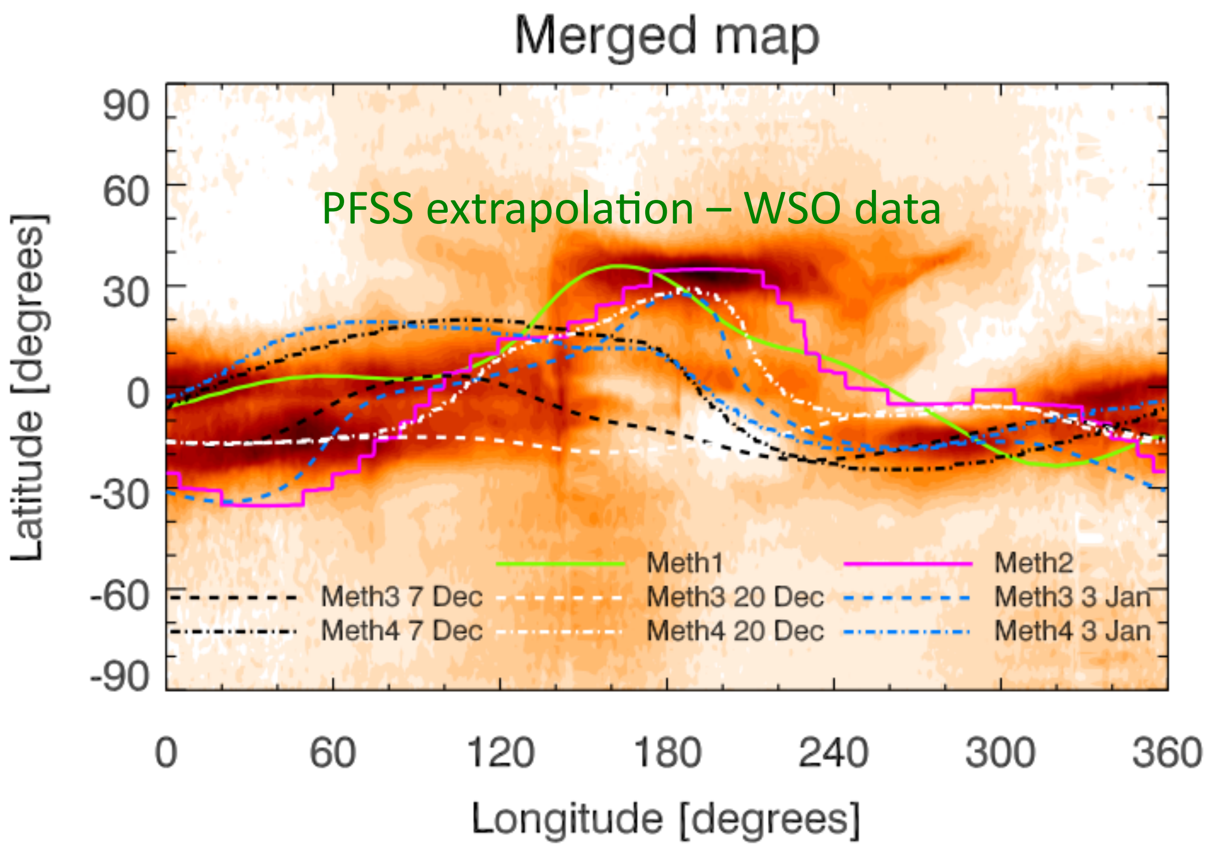


Carrington map CR 2091 - Dec 07, 2009 - Jan 03 2010, minimum cycle 23 - rising phase solar cycle 24

STEREO-B + SOHO + STEREO-A combined data
minimum temporal evolution of the corona (4.5 days) in the observation from the different spacecraft

(C. Sasso et al., 2019)

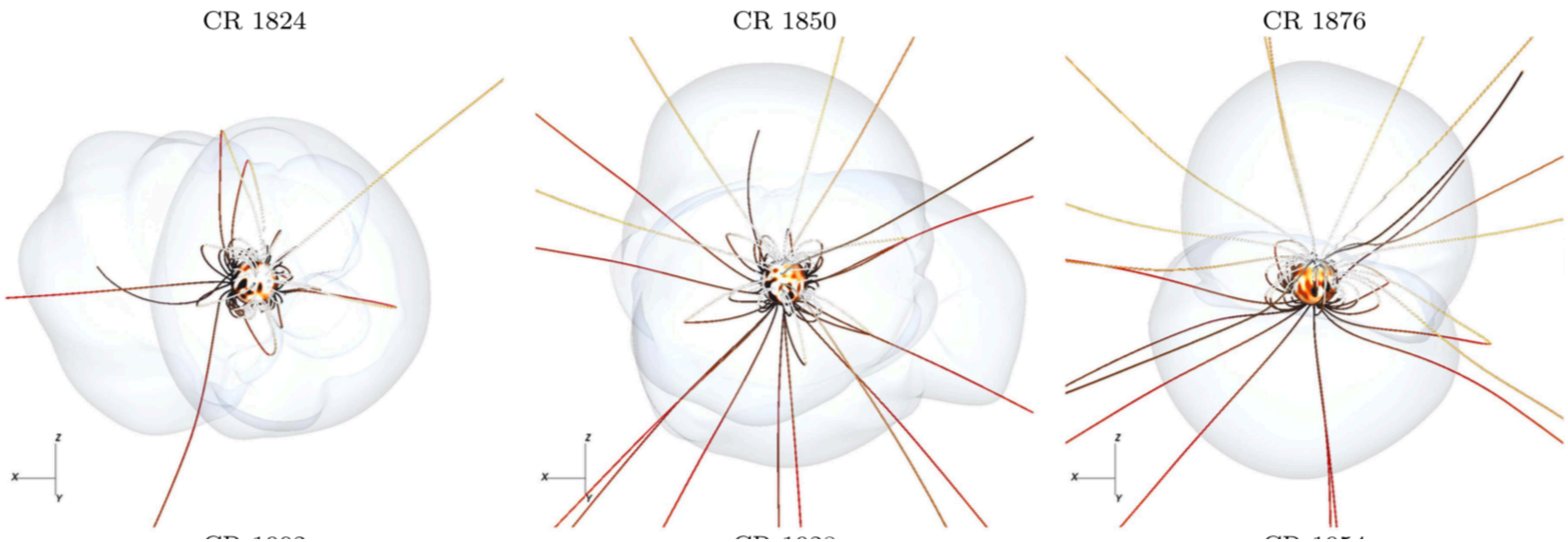
Corona @ 2.5 $R_\odot$



Visible light coronal map (STEREO-B + SOHO + STEREO-A) and superposed magnetic field neutral line obtained with different extrapolation methods: 1) – PFSS extrapolation WSO data; 2) - PFSS extrapolation WSO data with polar field correction

(PFSS Potential Field Source Surface)

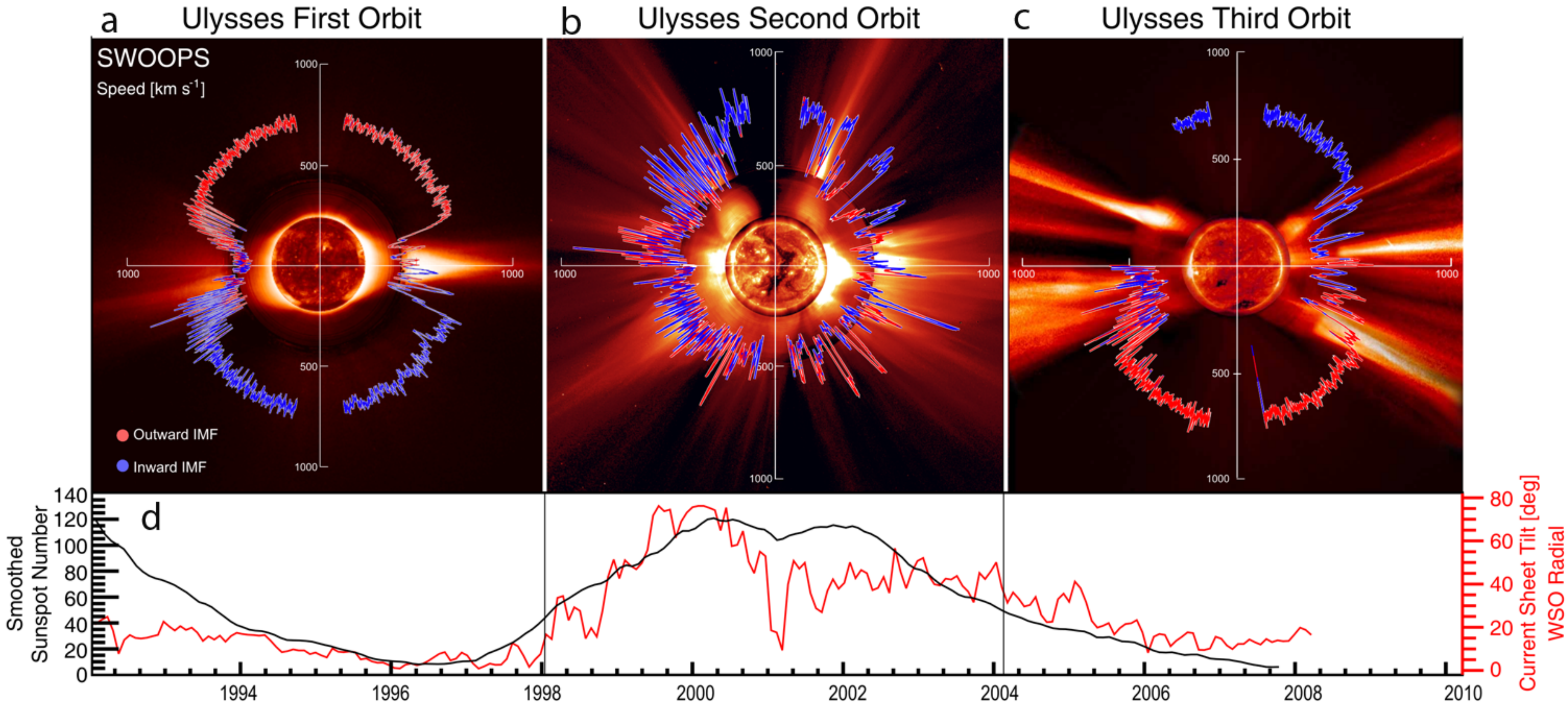
(C. Sasso et al., 2019)



MHD solutions of the solar wind using WSO maps
identification of the Alfven surface
CR 1824/1850/1876 - Carrington rotations initiating on 28 Dec 1991, 8 Dec 1991 and 17 Nov 1993, respectively, maximum and descending phases of cycle 22

(Reville and Brun, 2017)

Solar Wind in the 3D Heliosphere
2 Solar Cycles



McComas et al. 2008

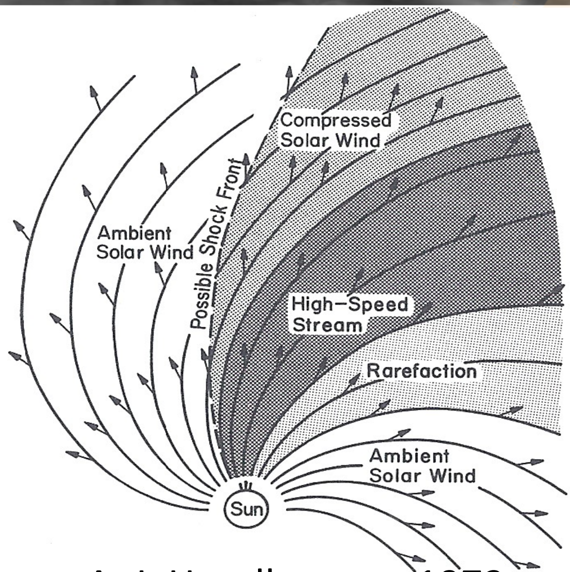
Mass Ejections Propagation

CME in Ly α emission

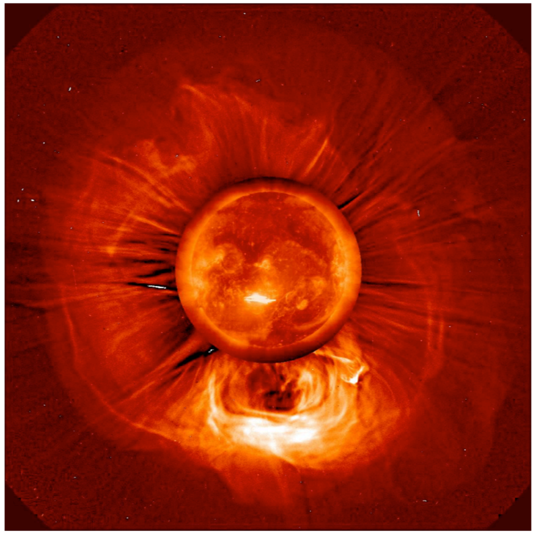
- dynamics of the ambient corona (coronal wind) affecting CME propagation in corona
- determining the heliospheric wind pattern affecting CME propagation in heliosphere

CME in polarized VL light

- direction of propagation with different methods
- identification of the source on disk (extrapolated)
- information on dynamics & energetics of the ejected plasma



A. J. Hundhausen, 1972

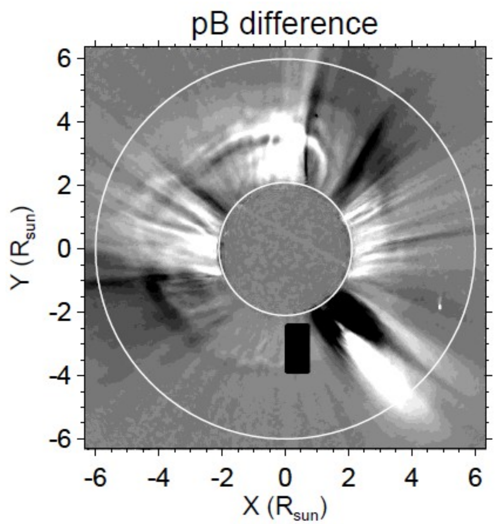


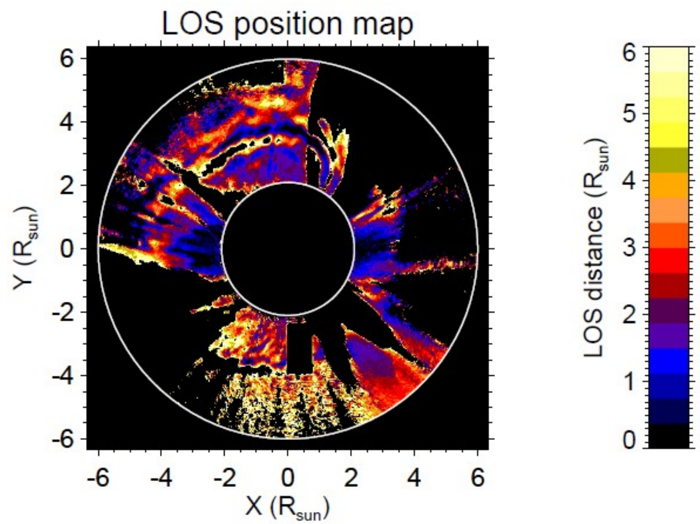
CME Propagation Direction

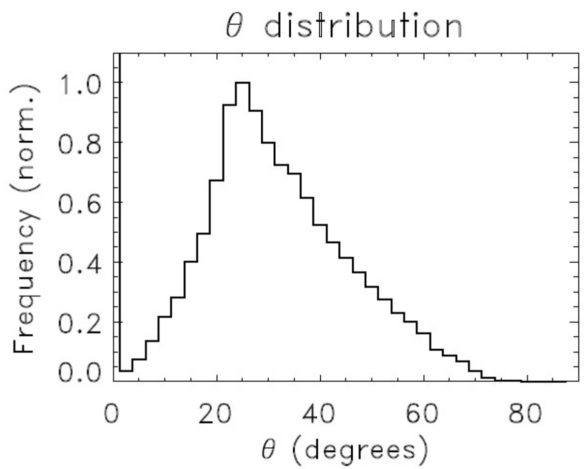
CME propagation direction inferred from polarization ratio

degree of polarization of Thomson-scattering of photospheric light by coronal electrons depends on scattering angle (Billings 1966)

pB-tB images contain information on CME 3-D structure (e.g. Crifo et al. 1983, Moran & Davila 2004, Moran 2010)



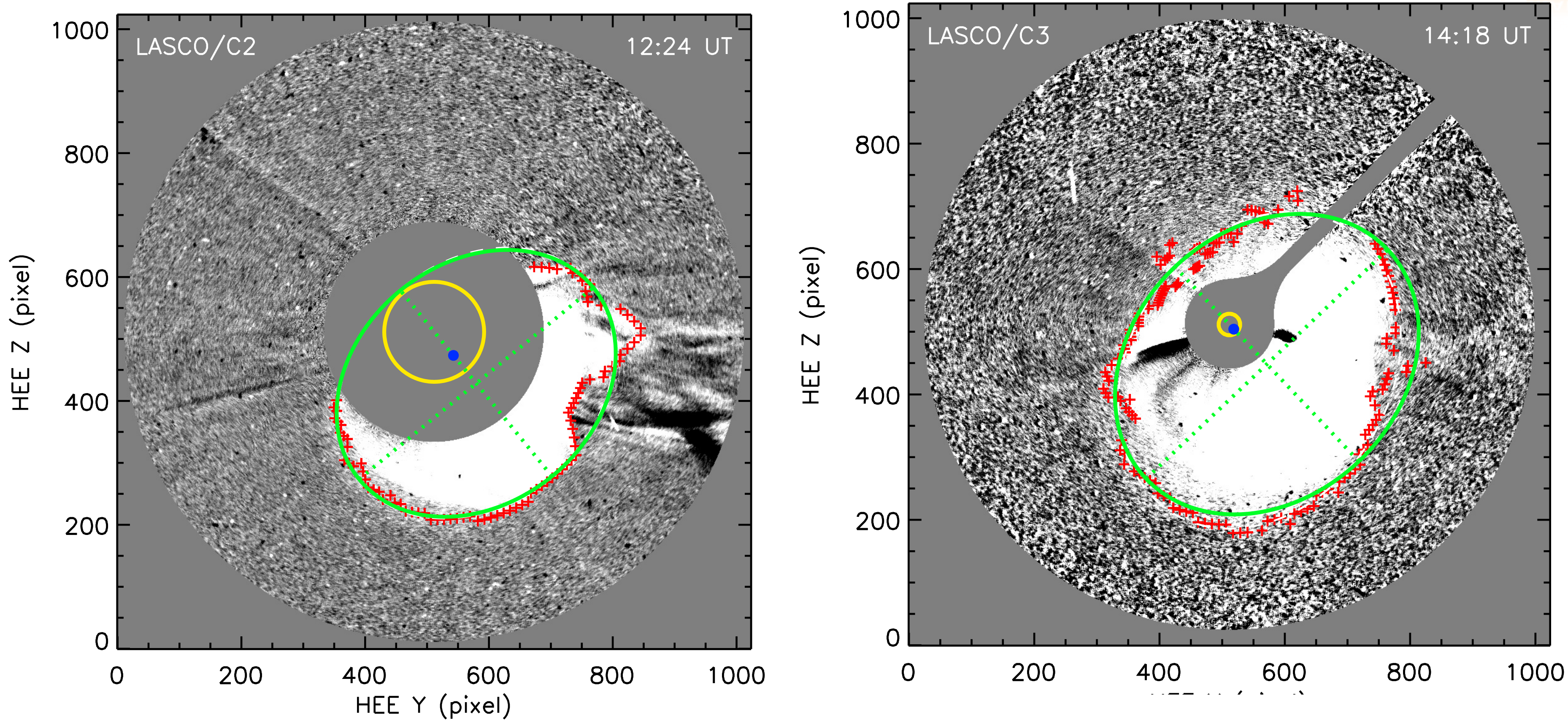




Example of inferred angle of propagation (25°) relative to the plane of the sky during the June 21, 2015 CME

(Piersanti et al. 2017)

CME Propagation Direction and Extent



CME propagation direction and CME on disk

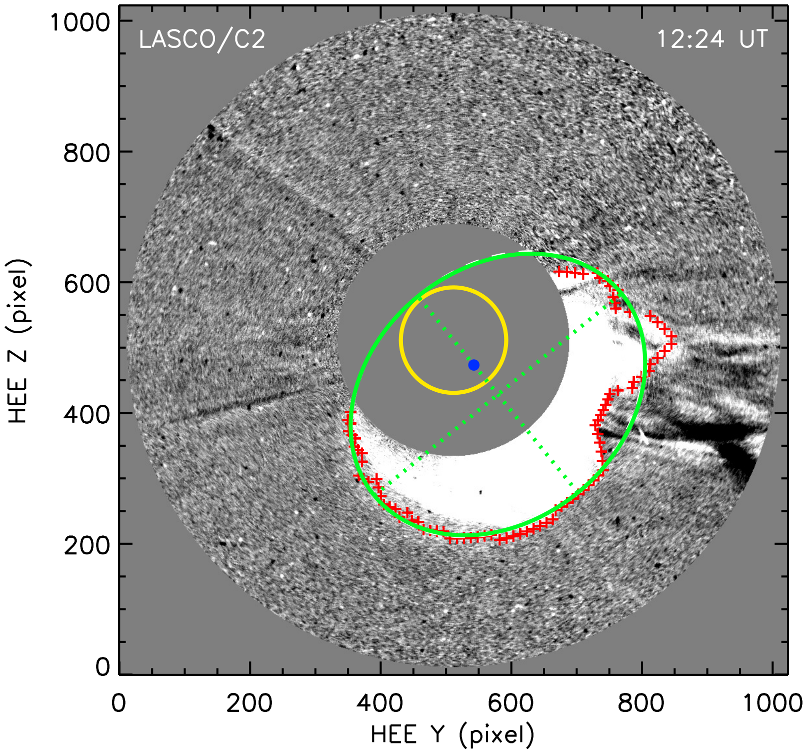
edge of the CME front is identified in the map along each radial direction

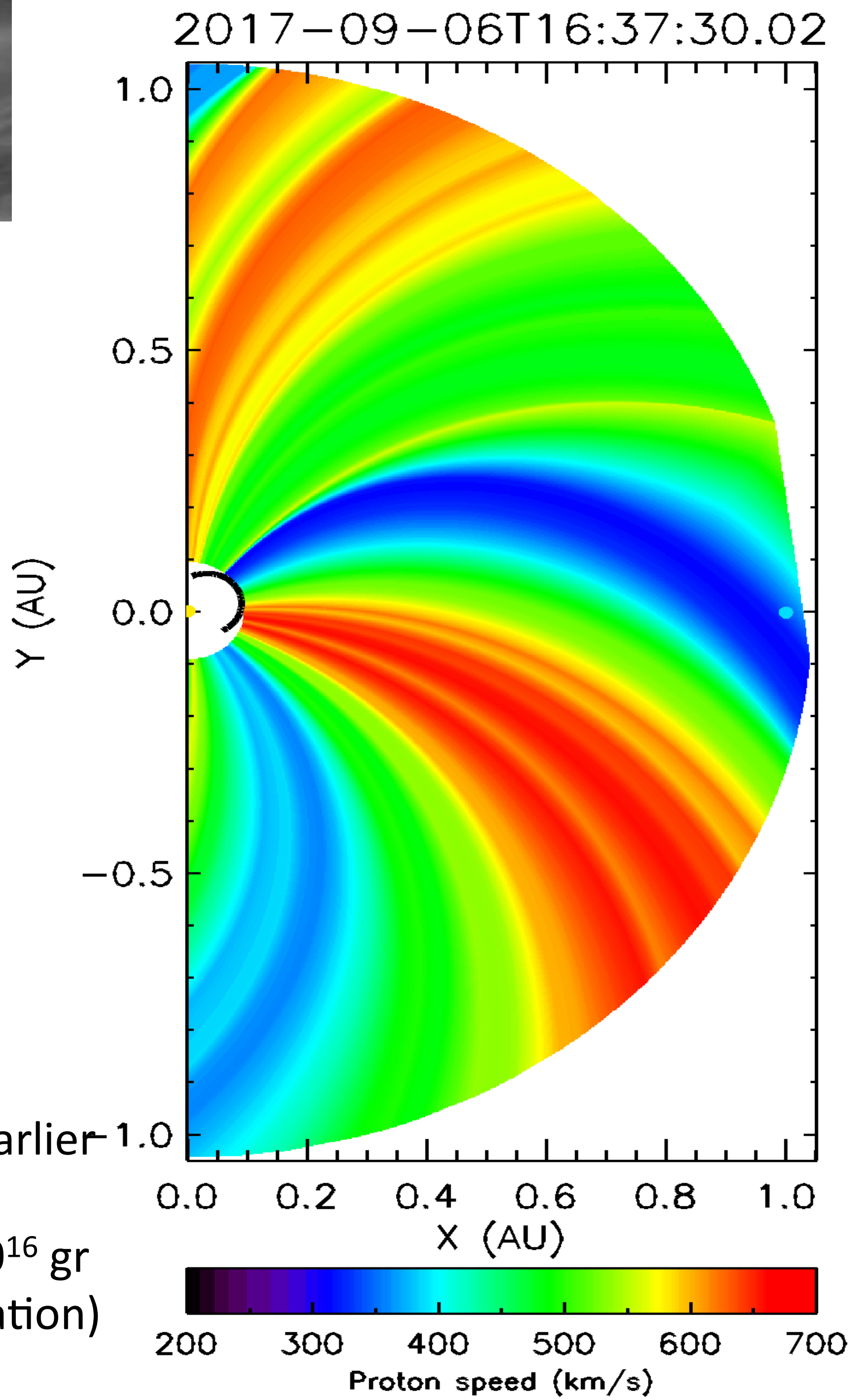
points enveloping the CME front are fitted with an ellipsis

derived cone axis is projected back to the Sun's disk

(Susino et al. 2019)

CME Sep 6, 2017





CME propagation in the solar wind

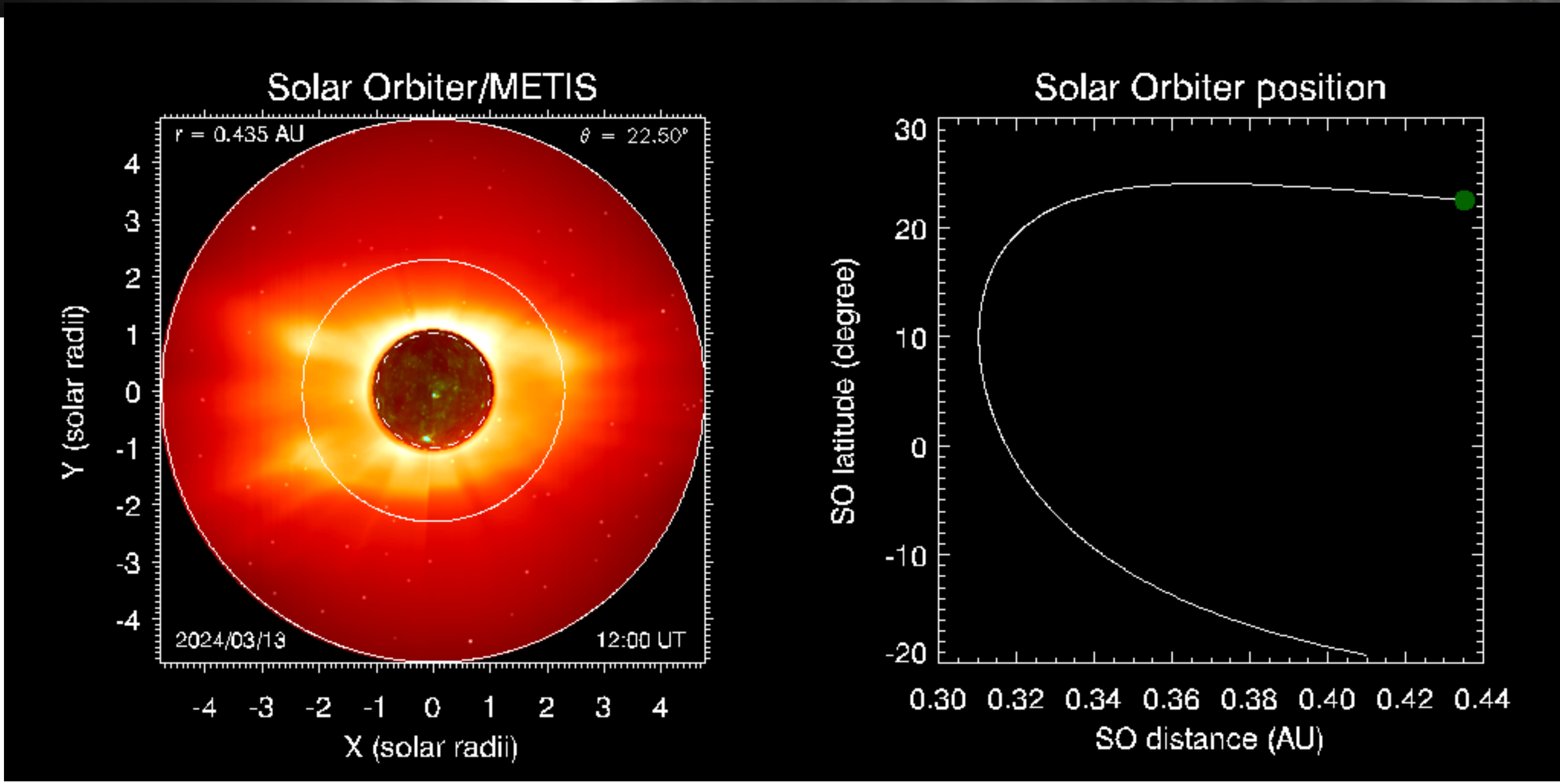
Wind model using DSCVR & STEREO-A data 10 d earlier

Parker model

CME initial speed 1300 km s^{-1}, 120° long. ext., 5 10^{16} gr

(see R. Susino presentation)

Solar Corona out of Ecliptic View

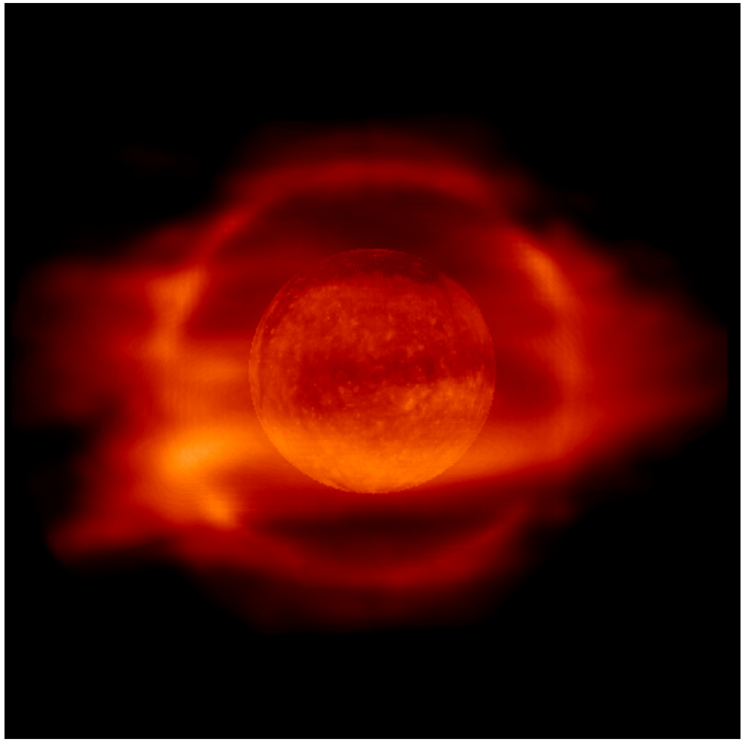


Movie of METIS FOV evolution during 30 days period centered on the perihelium passage:

- METIS «zooming» effect as SO approaches the Sun
- 3D rotation of the solar disk (*from EIT Carrington map*)
- 3D rotation of solar corona seen from different latitudes (*from LASCO+MaunaLoa MK IV images*)
- Decrease in the solar rotation speed as SO approaches the Sun
- Increase in the apparent speed of the stellar field as SO approaches the Sun (*Hipparcos catalog*)

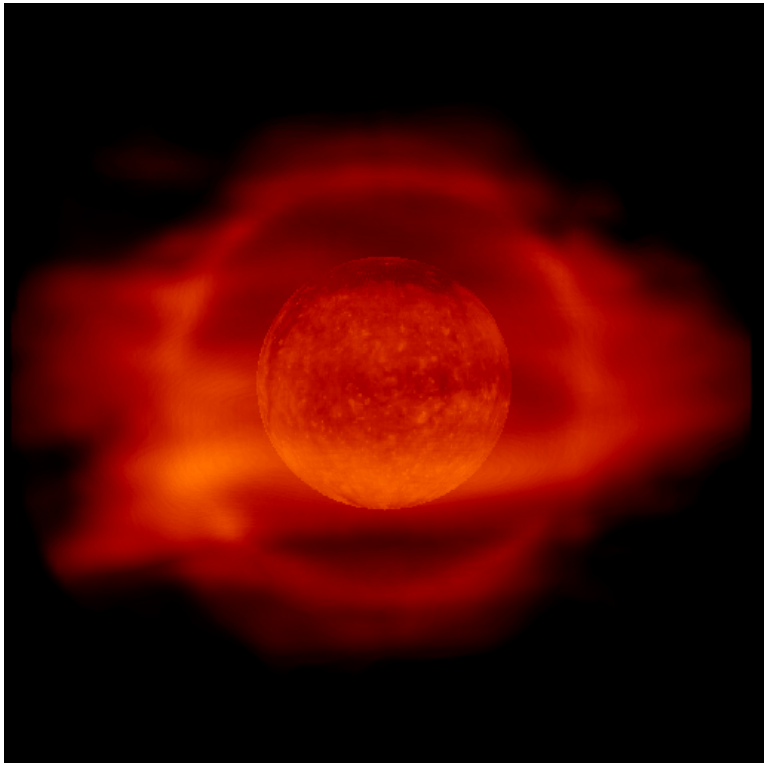
(Credit: A. Bemporad)

Out of the Ecliptic Observations

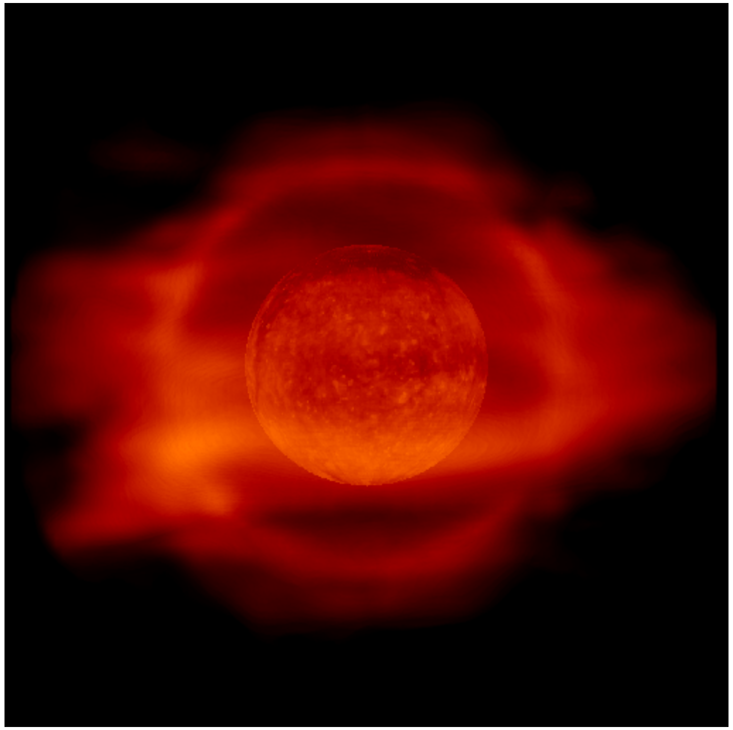


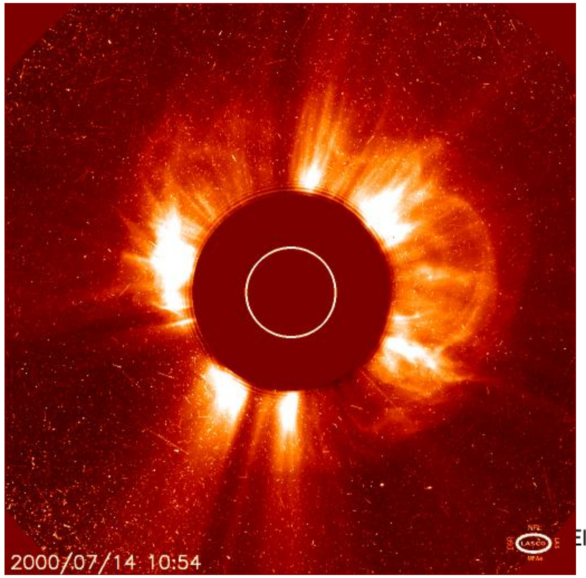
View of the equatorial corona

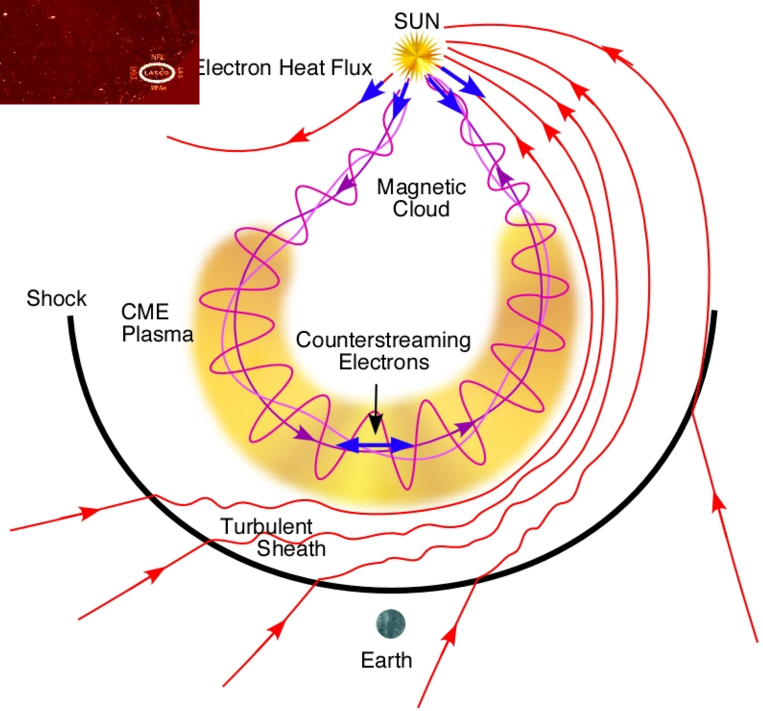
Access to the longitudinal structure of the corona and longitudinal extent of coronal mass ejections.



Out of the Ecliptic View

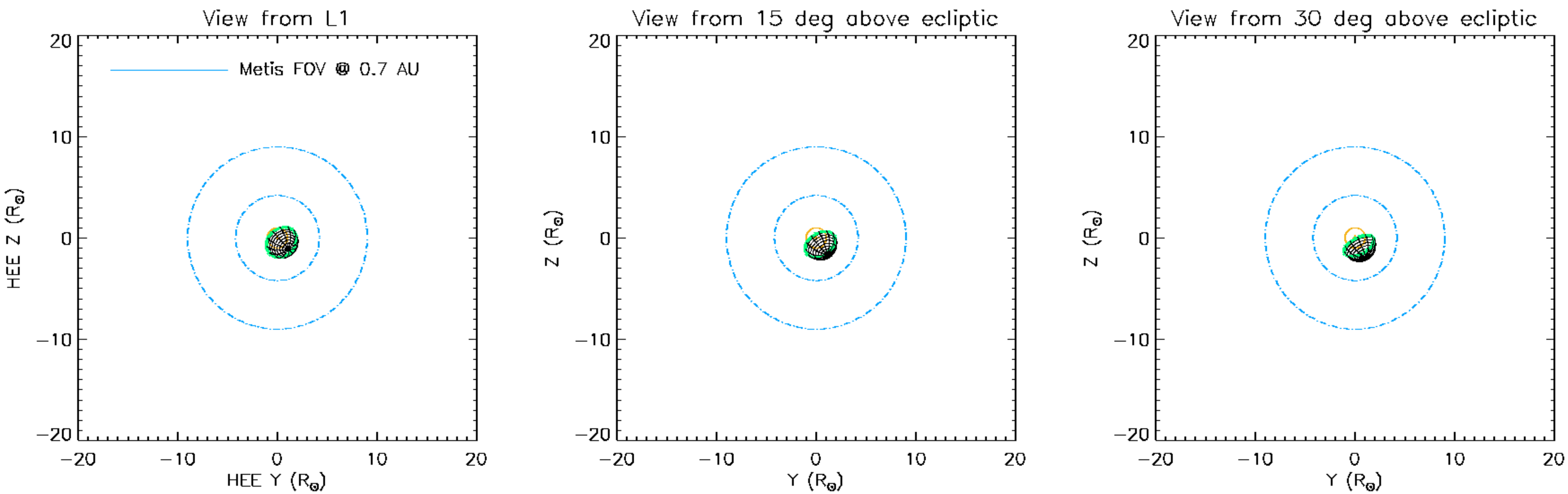






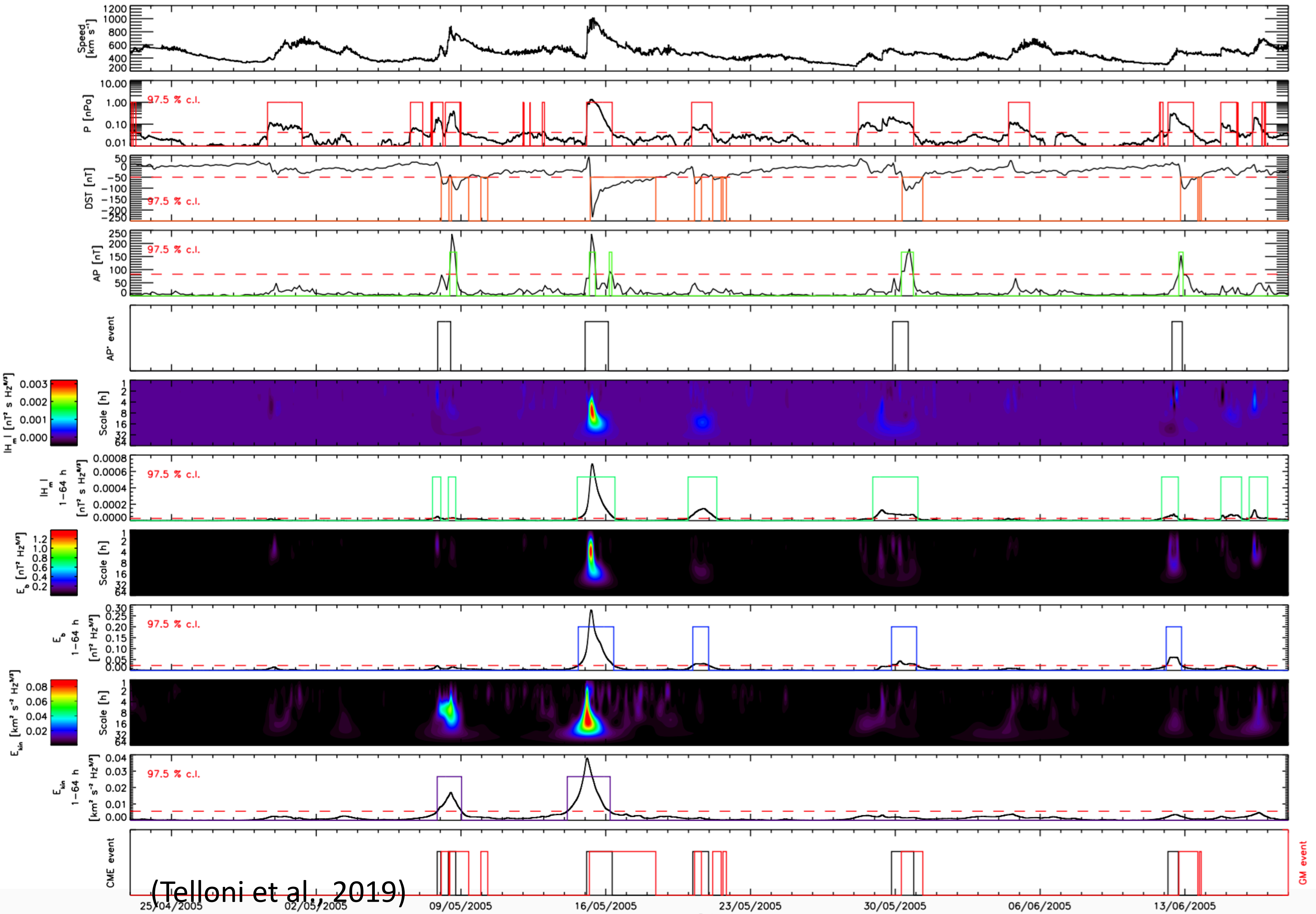
Out of ecliptic (33°) observation of halo coronal mass ejections, impacting the Earth magnetosphere (geo-effective events)

L1 *15°* *30°*



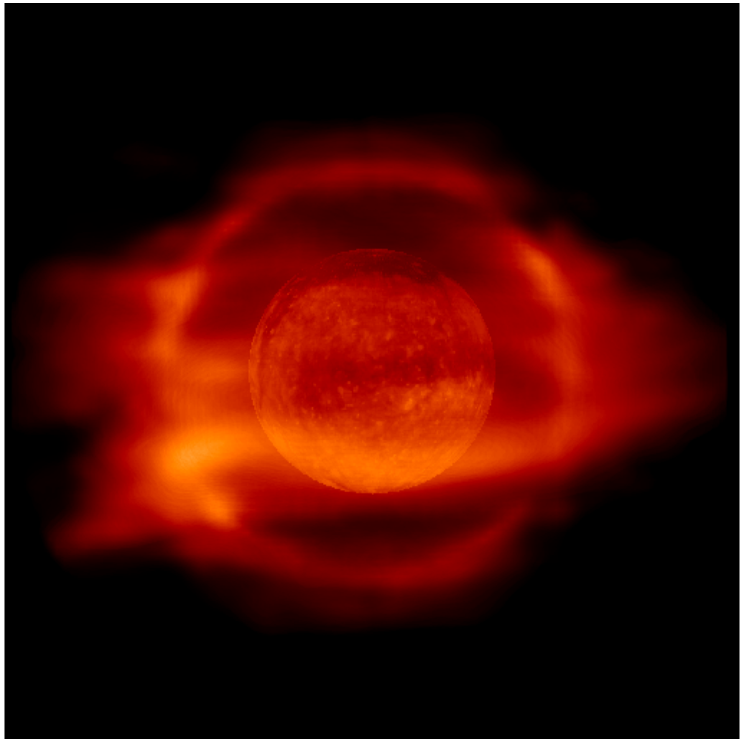
Sep 6, 2017 CME
cone expansion viewed from L1, 15°, 30°

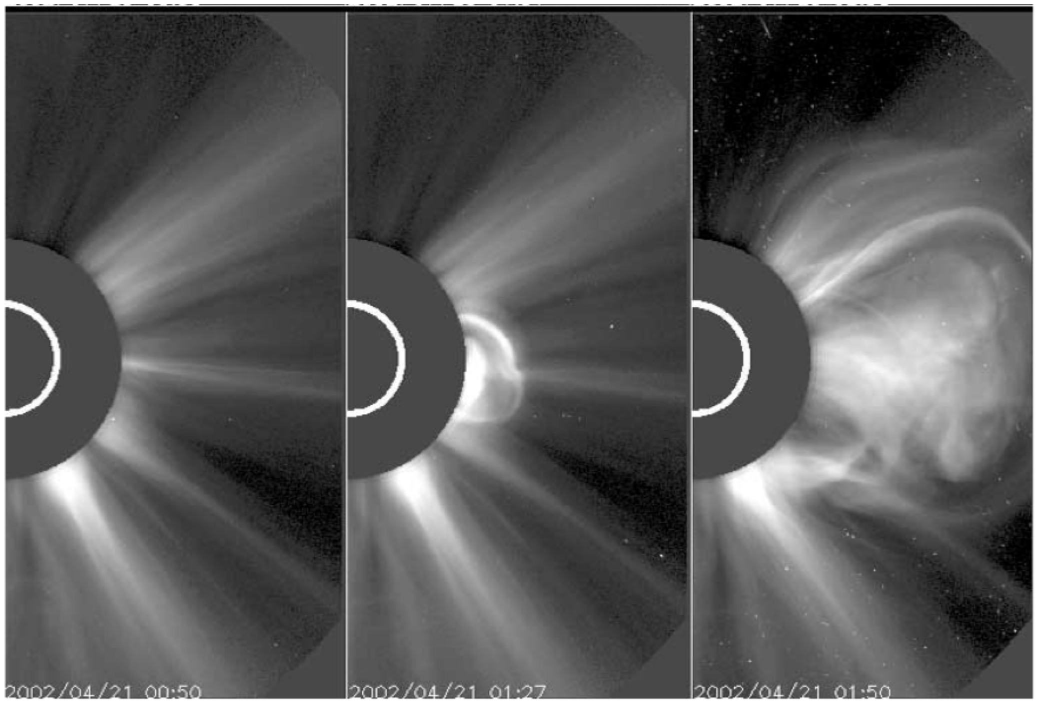
Credit: R. Susino



(Telloni et al., 2019)

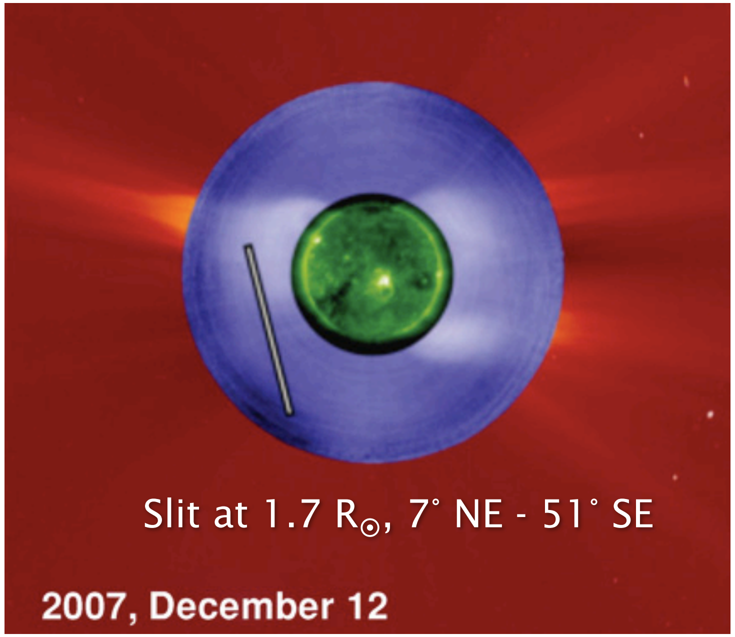
Quasi Co-rotation with the Sun

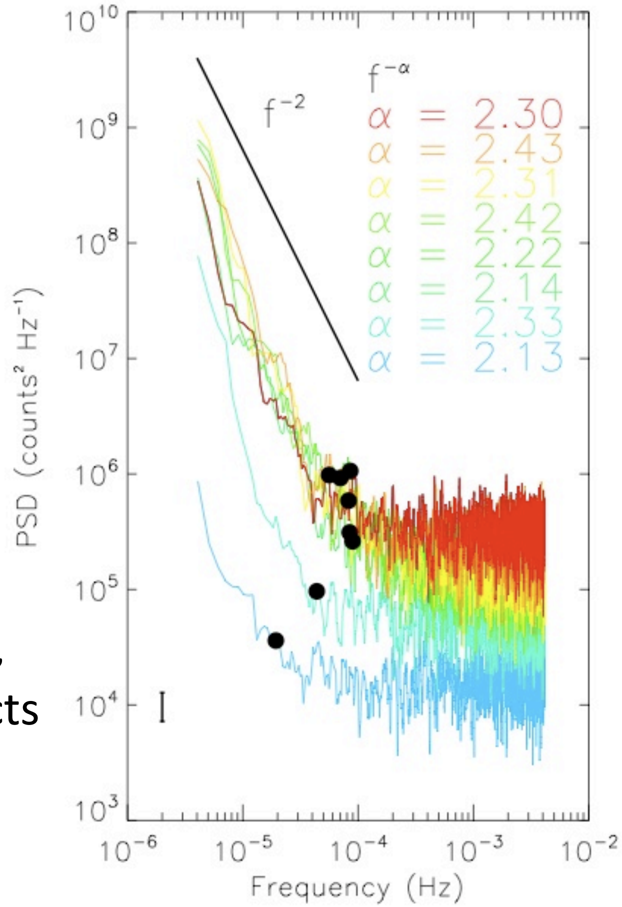




'Freezing' the corona at the limb in quasi-corotation allows the observation of the magnetic field evolution prior to coronal mass ejections and thus possibly the identification of the physical process originating them.

Coronal density fluctuations



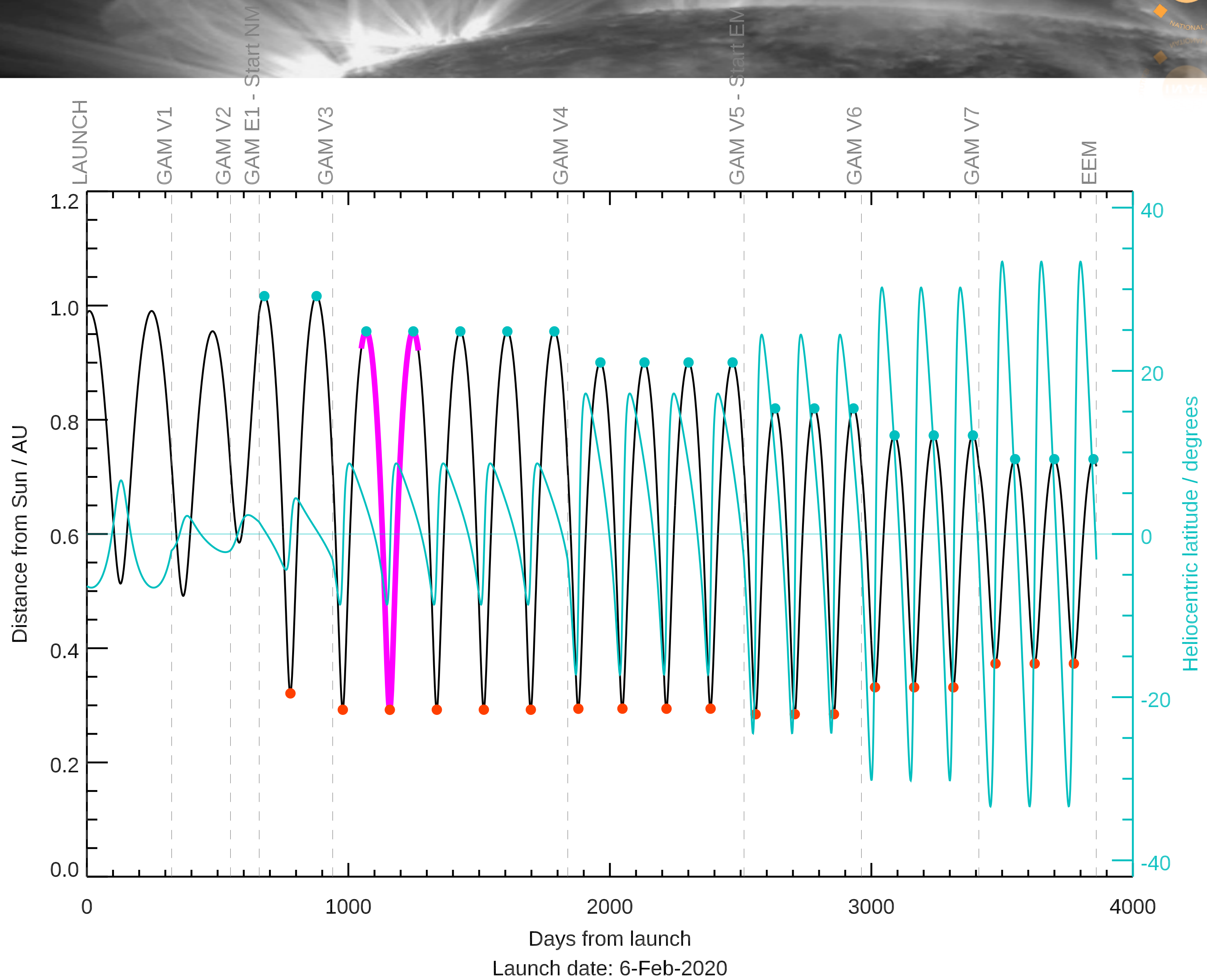


Power spectra of HI Lyα
51° SE (blue) to 7° NE (red)
(Telloni et al., 2009)

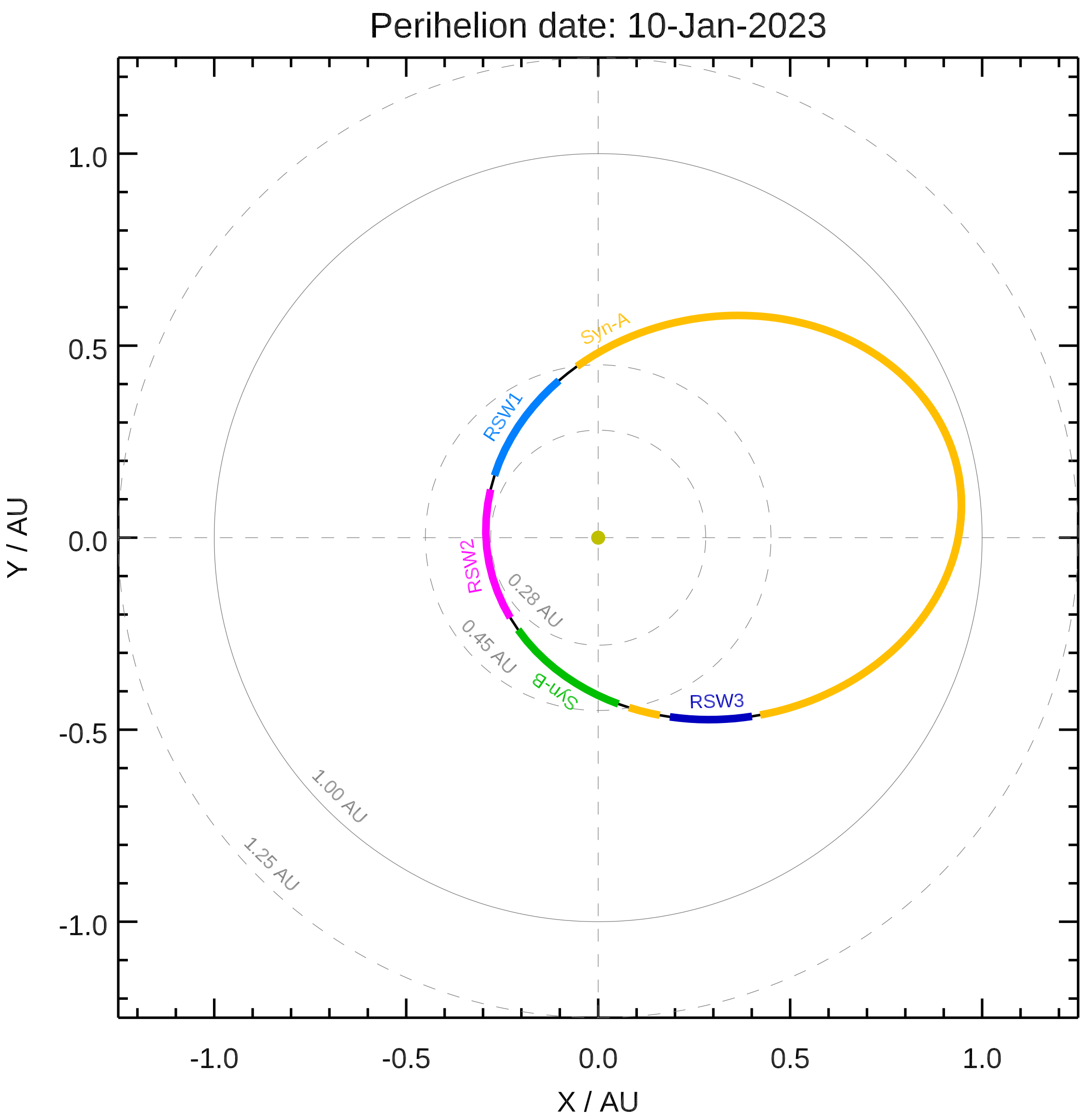
Maintain magnetic link of the heliospheric plasma to the source, disentangle the plasma intrinsic evolution and solar rotation effects link the plasma parameters to the evolution of the solar source.

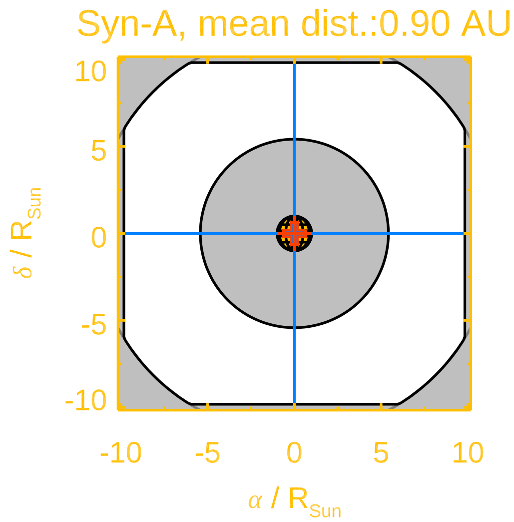
Example of corotation vs. propagation
Persistent, $\langle\alpha\rangle$=2.36, coronal density fluctuations (few hours to a few days period); if corotating structures, spatial scale ≥ 3 x 10^4 km, photospheric supergranulation scale

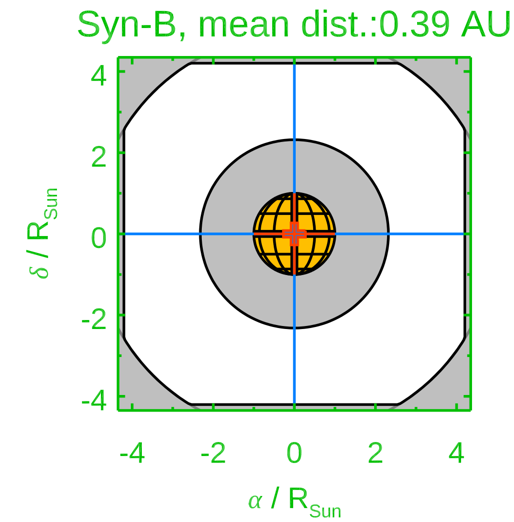
Solar Orbiter mission profile



Remote Sensing Windows and Synoptic Observations







METIS Instrumental Performance

Wavelength range:	580 – 640 nm (polarized VL) HI 121.6 ± 10 nm (UV)
Field-of-view (square)	1.6º - 2.9°/3.4º
Spatial Plate Scale	10 arcsec (VL) 20 arcsec (UV)
Angular resolution	≤20 arcsec (VL) *≥80 arcsec (UV analog)*
Instrumental Stray Light	VL < 10^{-9} UV < 10^{-7}
Cadence	≥ 1 sec fluctuation detection ≥ 1 min CME ≥ 5-10 min streamers/solar wind
Mass	24.55 kg
Total data volume	**27.2 Gb per orbit**

Metis-Solar Orbiter and ASPIICS-PROBA3 Synergy

ASPIICS coronagraph (PROBA-3, ESA, formation flying technology demonstrator mission) includes:

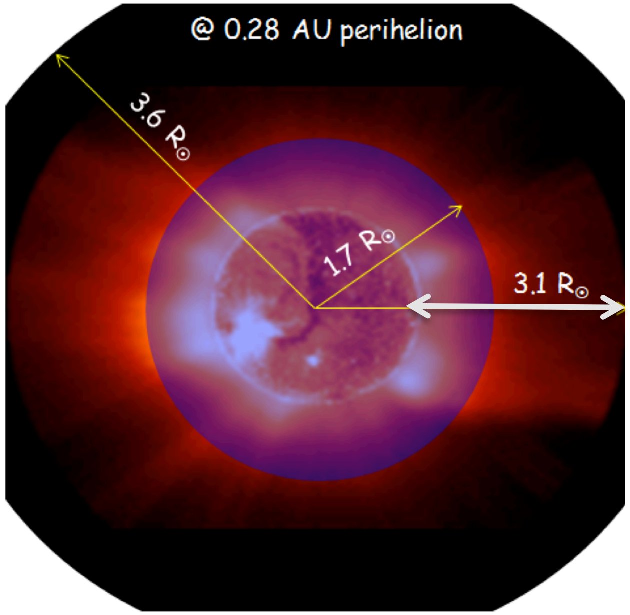
1. telescope on the main spacecraft
2. occulting disk on the smaller spacecraft, 150 m apart (separation between the two spacecraft to mm and arc second precision).

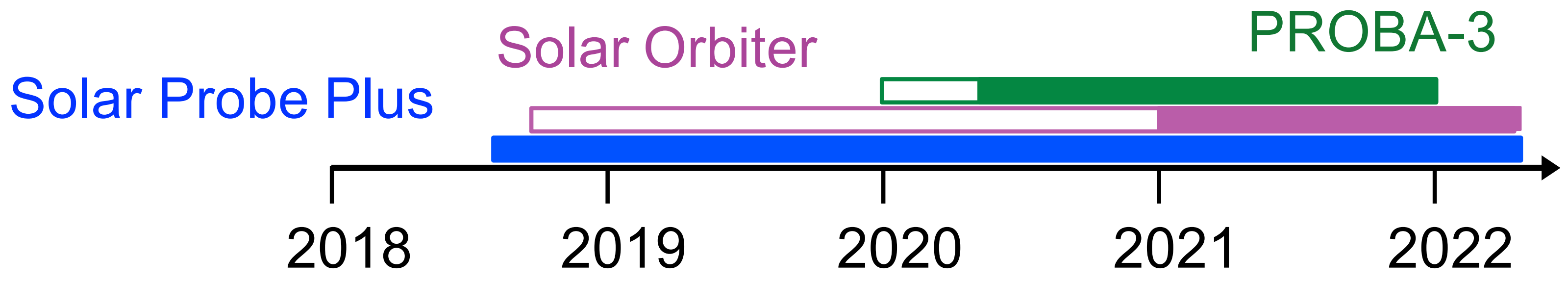
•Orbit duration (highly elliptical Earth orbit) 19h38min

•Formation flying phase 6 h (coronal observations)

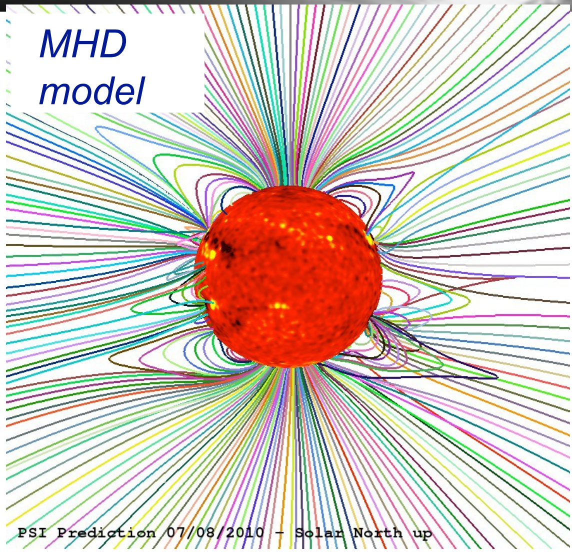
•*FoV 1.08-3.0 $R_{\odot}$*

• 1 year of overlap for coordinated observations with Solar Orbiter and Solar Probe Plus.





Coronal structuring and dynamics from the solar surface

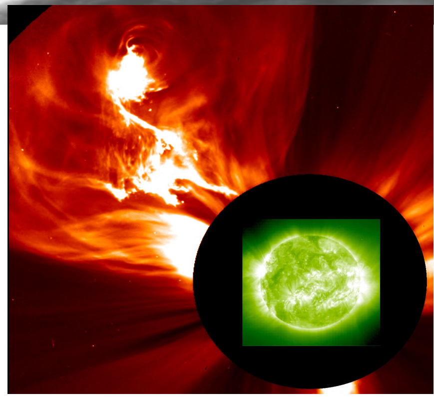


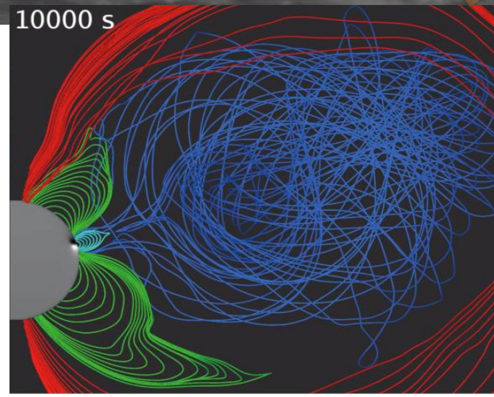
Transition between closed-field regions (magnetic field dominated) and open-field regions (solar wind dominated)

Connectivity of coronal structures back to the solar surface, in combination with state-of-the-art MHD models)

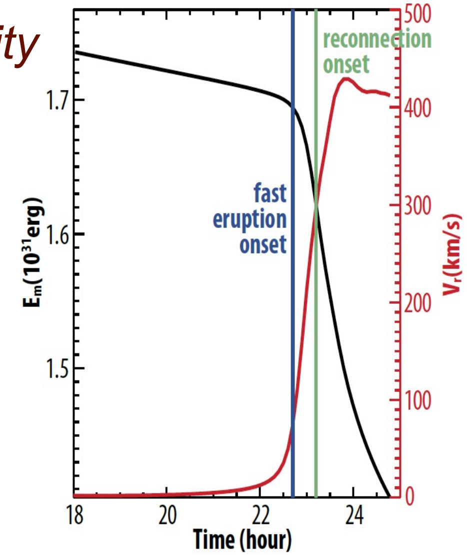
Constrain the models of the coronal and interplanetary magnetic field, i. e. to determine the connectivity of field lines sampled by Solar Orbiter in situ instruments (Sun-heliosphere connection)

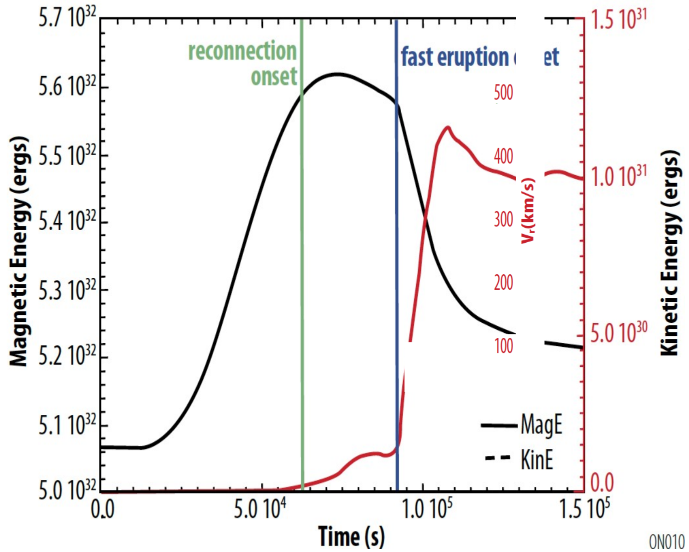
CME onset and acceleration





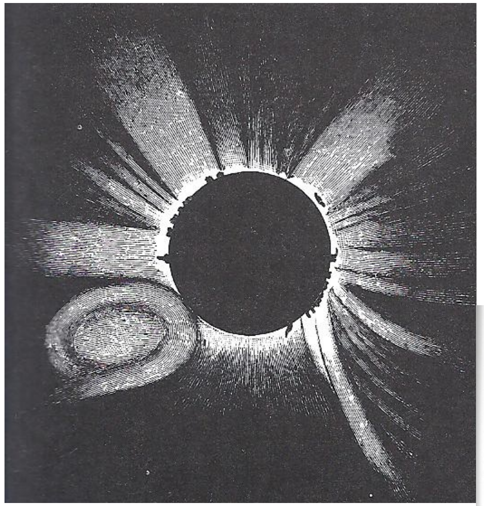
torus instability



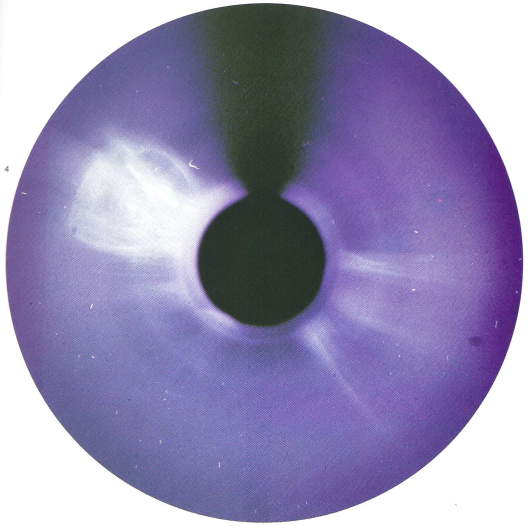


magnetic breakout

Observe dynamics of both the CME and the shock in the inner corona, providing us with conclusive evidence for the origin of coronal ejections and shock waves.

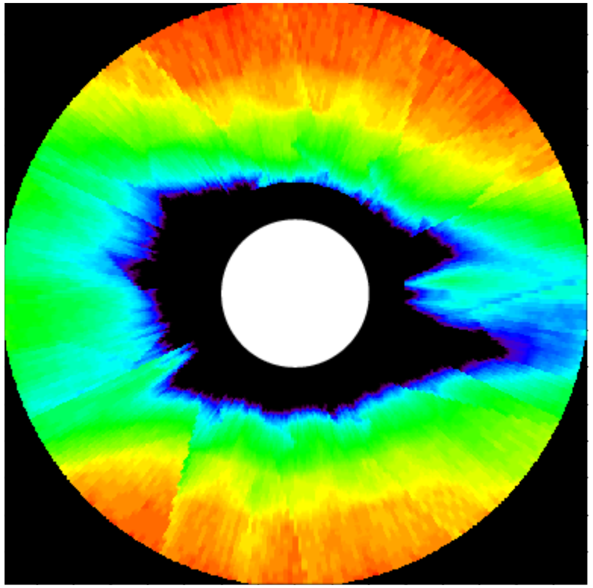


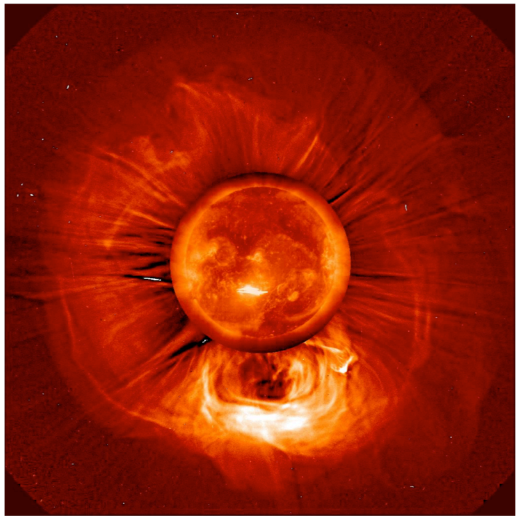
1860 E.W.L. Temple



Skylab 1973

Solar Orbiter
2020-2030





SOHO
Cycle 23-24

Metis Team

Metis Team funded by the Italian Space Agency (ASI &INAF))
Max Planck Institut für Sonnensystemforschung (detectors)
Institute of Atsronomy, Czech Academy of Science and Toptec (mirrors)

Industrial Team (Italy)

- OHB Italia, Milan
- Thales Alenia Space – Turin

HW Team (Italy)

- University of Florence
- INAF – Turin Astrophysical Observatory
- University of Padua
- CNR-IFN Padua
- INAF – Capodimonte Astrophysical Observatory, Naples
- INAF – Catania Astrophysical Observatory
- INAF –IASF Milan
- University of Urbino