Solar coronagraphy from space: recent results from Solar Orbiter

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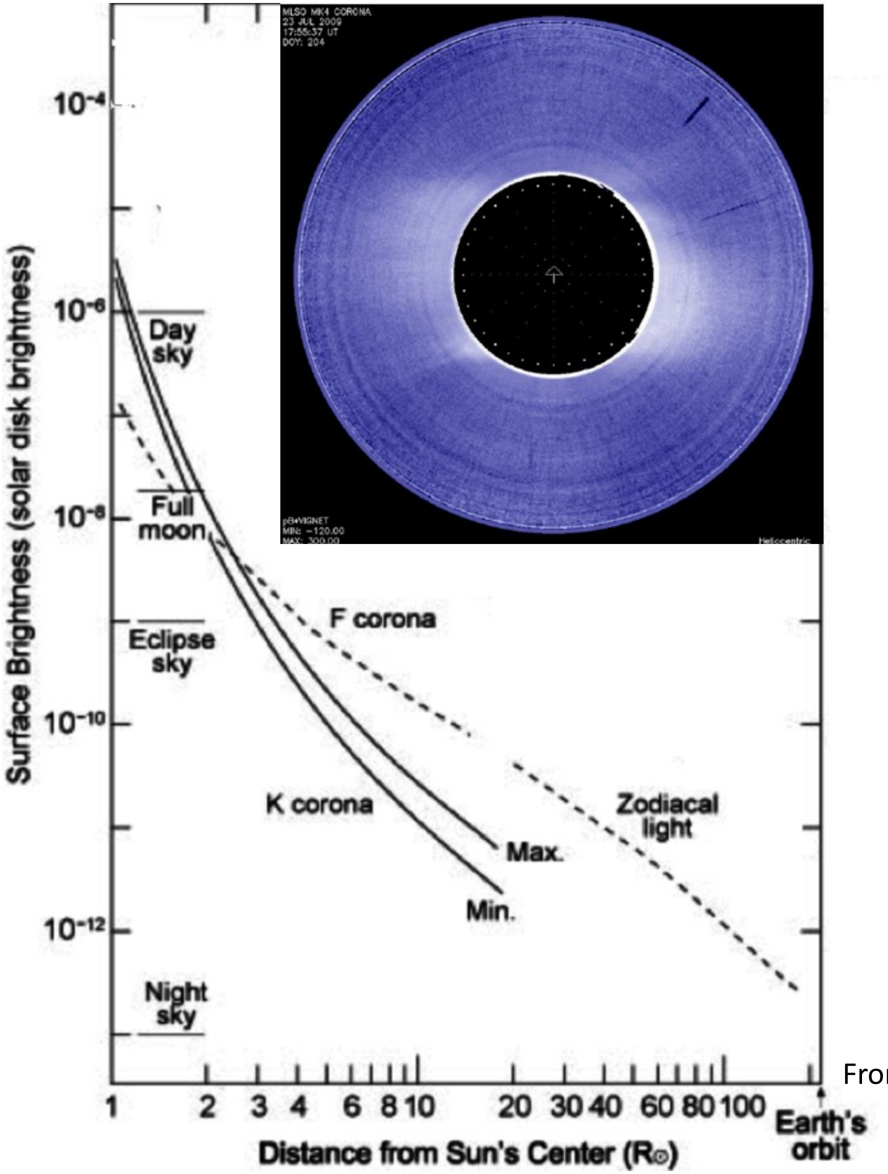
Solarnet-S3 Science in society, 11-15 September 2023

Need for space coronagraphs

Credit: Boyang Liu, 21/4/23 Western Australia

The essential problem to observe the corona outside of **solar eclipse** is the low contrast of the corona above the **background sky** and instrumental **scattered light** (stray light).

- **Stray light** is removed with technical improvements in the coronagraph optical design.
- **Day sky is too bright**. Corona is visible for a few tenth of solar radii. The solar wind acceleration region for example extends above 2 R_s
- The hot corona emits **UV and soft-X** lines, that can be observed only from space



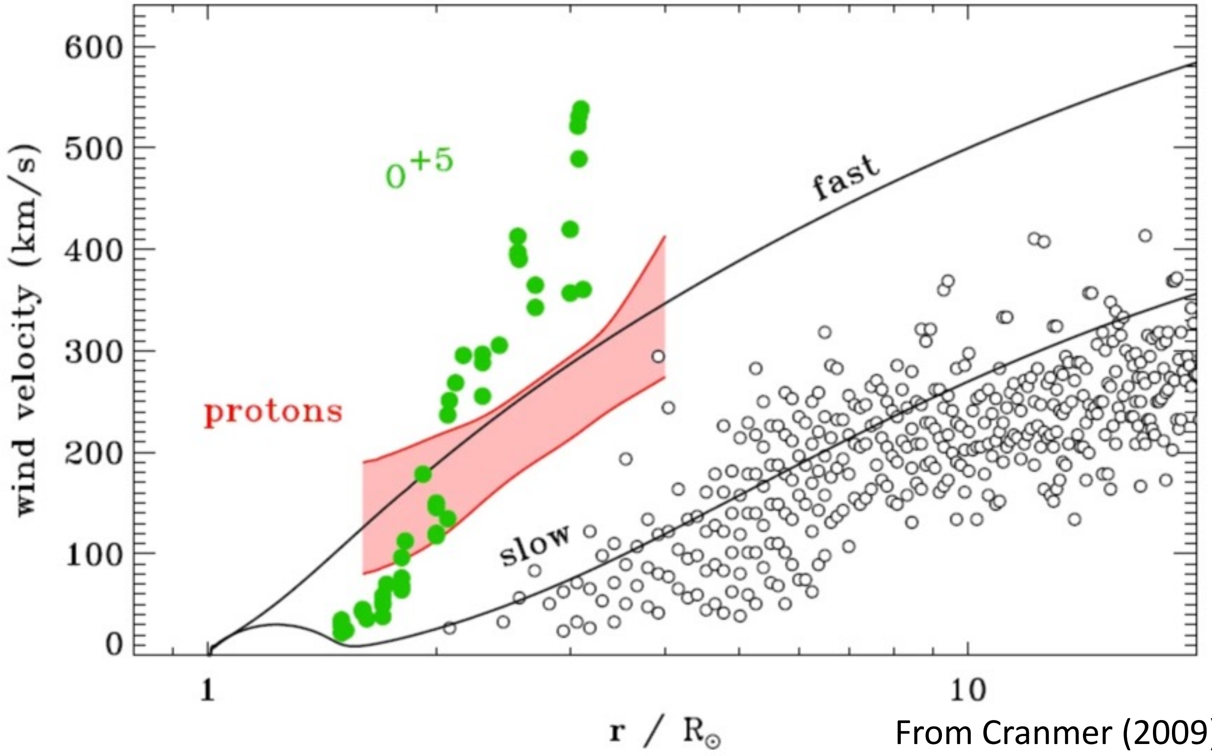
From Lang (2010)

Coronagraphs Over-arching Science Objectives

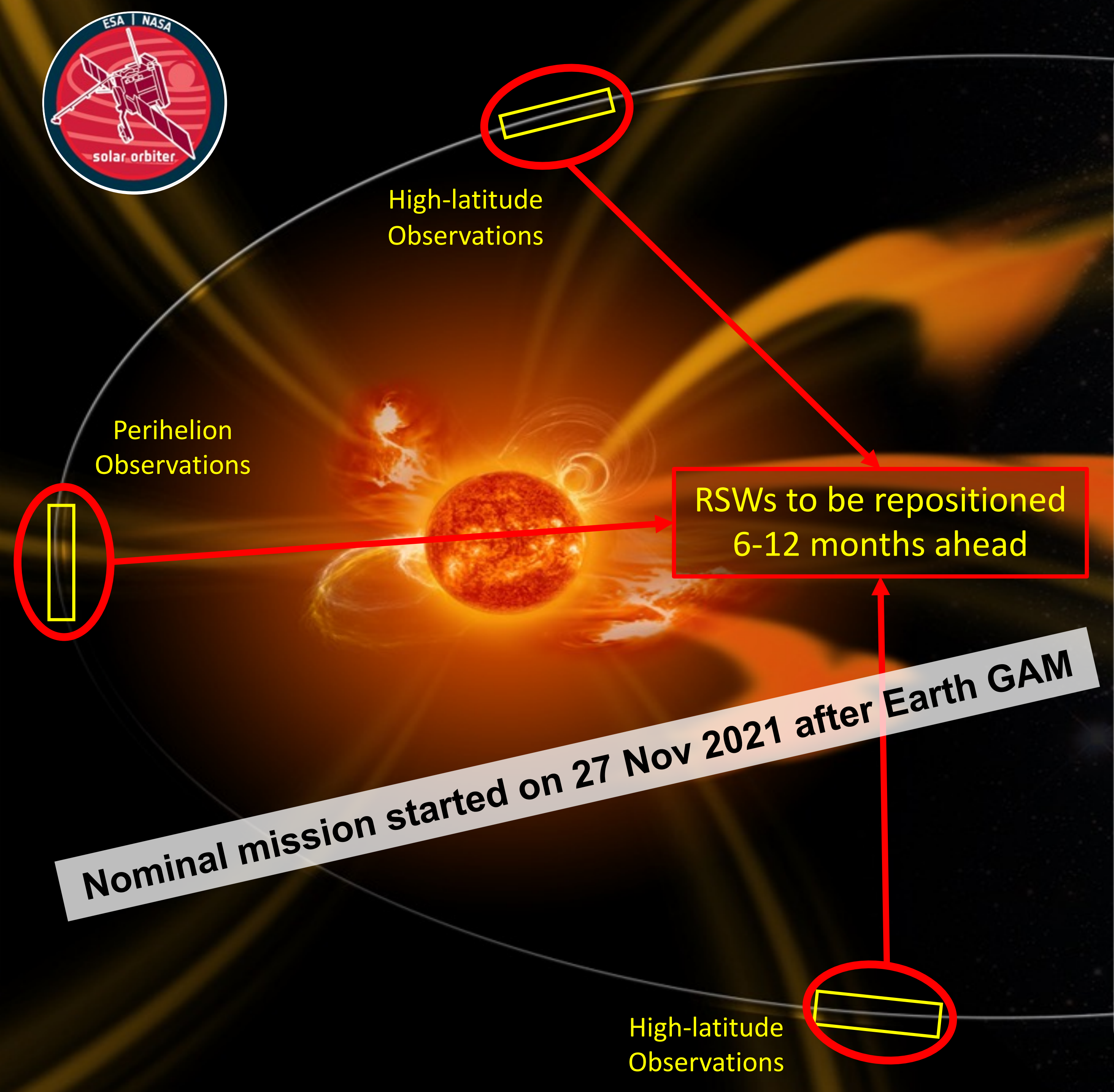
To determine the structure and dynamics of the Sun's coronal magnetic field, Understand how the solar corona and wind are heated and accelerated, and determine what mechanisms accelerate and transport energetic particles

Observations inside 20 Rs:

- Coronal magnetic structure still channels the flow
- Wave, turbulence are strongest
- Temperature maximum
- Collisional-collisionless transition



From Cranmer (2009)



Solar Orbiter Mission
M1 of Cosmic Vision 2015-2025

Launch date: 10 February 2020
Commissioning + Cruise Phase: ~1.9 years
Nominal Mission Phase (NMP): 5 years
Extended mission: 3 years

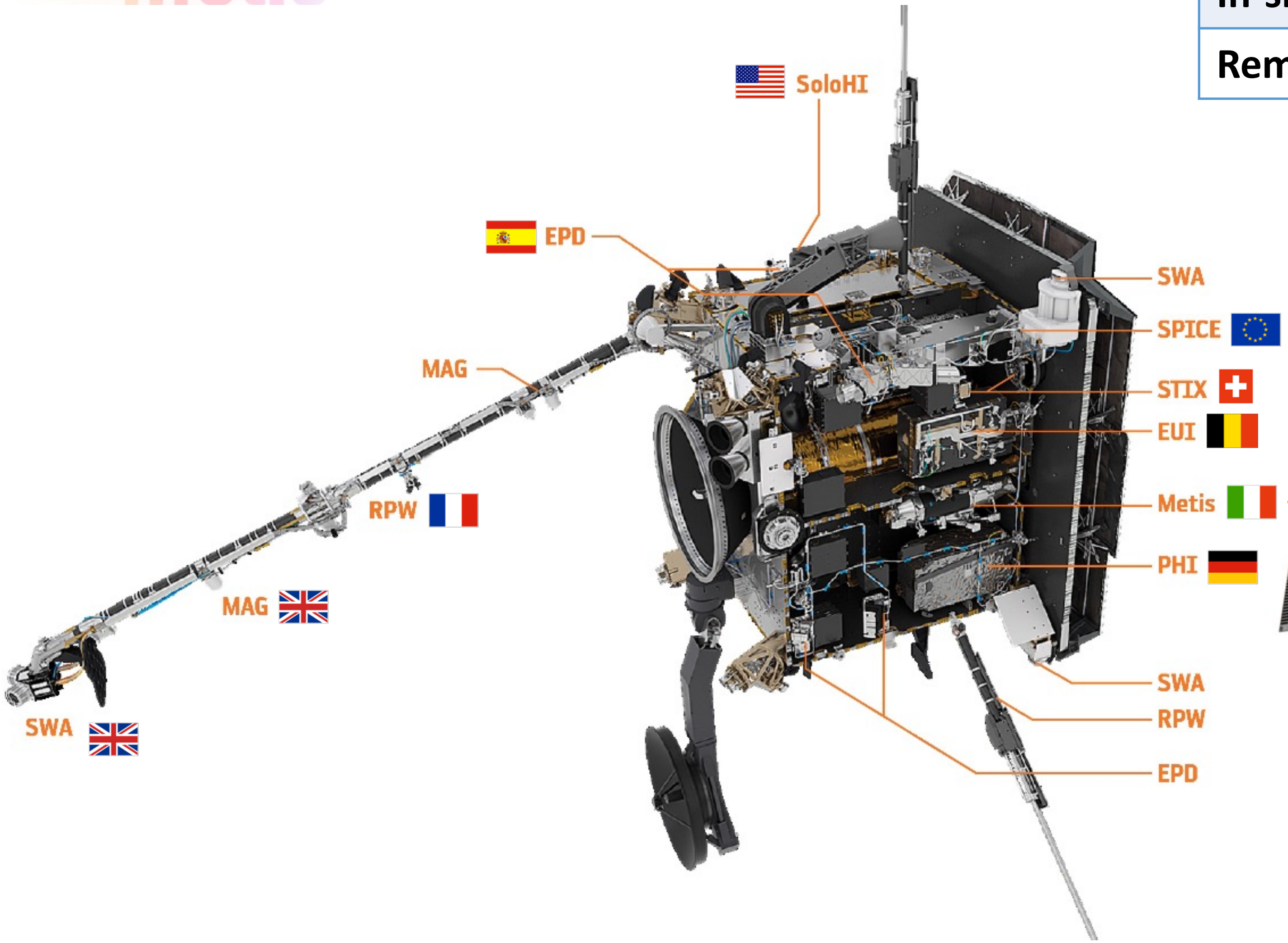
Orbit:
- 0.28-0.32 au (perihelion)
- 0.74-0.91 au (aphelion)

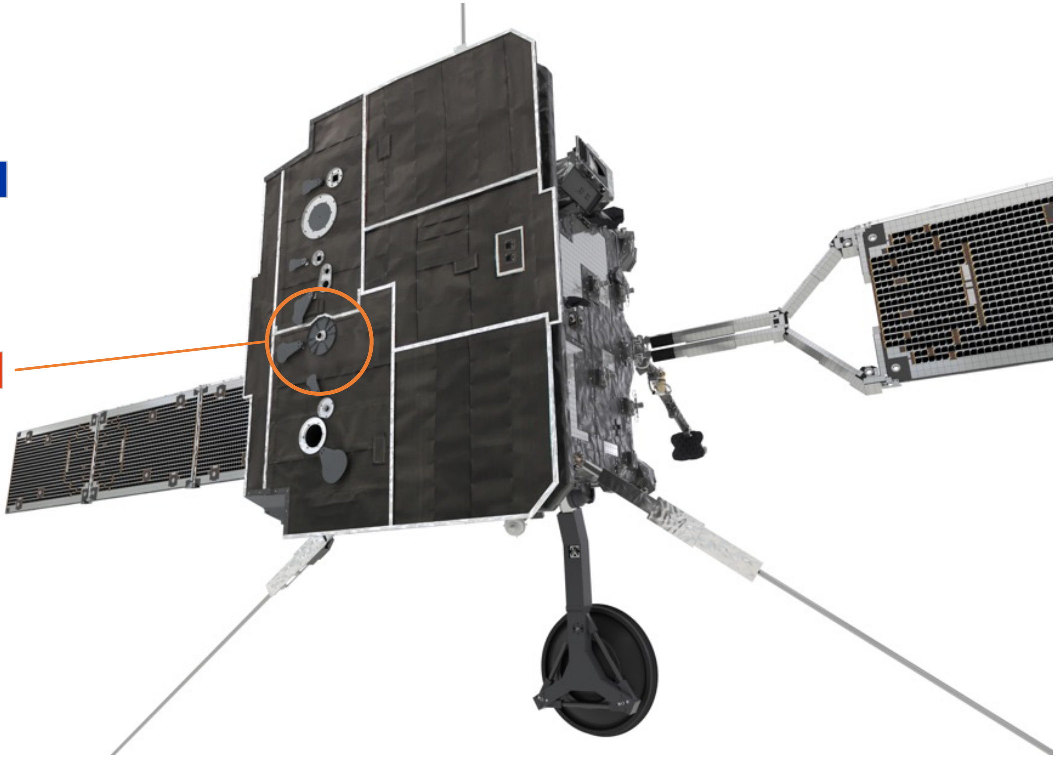
Out-of-ecliptic view:
Multiple gravity assists with Venus to increase inclination out of the ecliptic to ~24° (nominal mission), 30°-34° (extended mission)

Reduced relative rotation:
Continuous observation of evolving structures on the solar surface and heliosphere for almost a complete solar rotation

Solar Orbiter payload

In-situ	*SWA*, MAG, RPW, EPD
Remote-sensing	*Metis*, *STIX*, EUI, PHI, SPICE, SoloHI

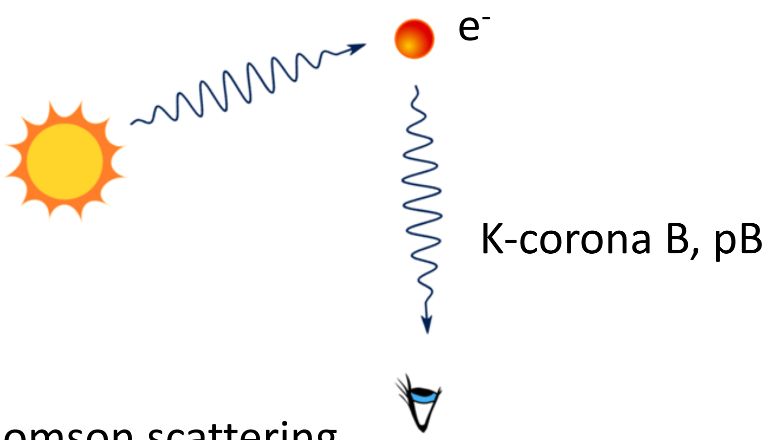




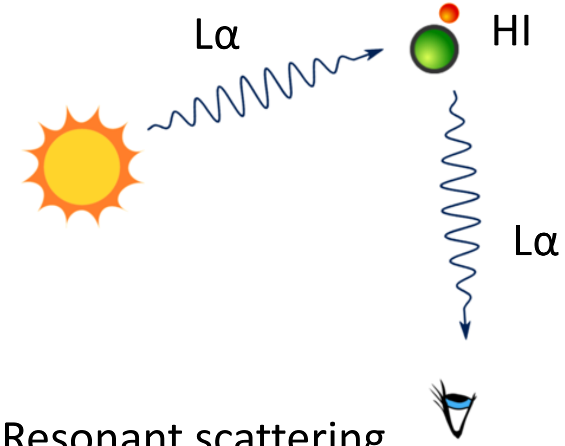
Metis: the Solar Orbiter coronagraph

Metis is an externally-occulted coronagraph designed to provide full imaging of the extended corona in:

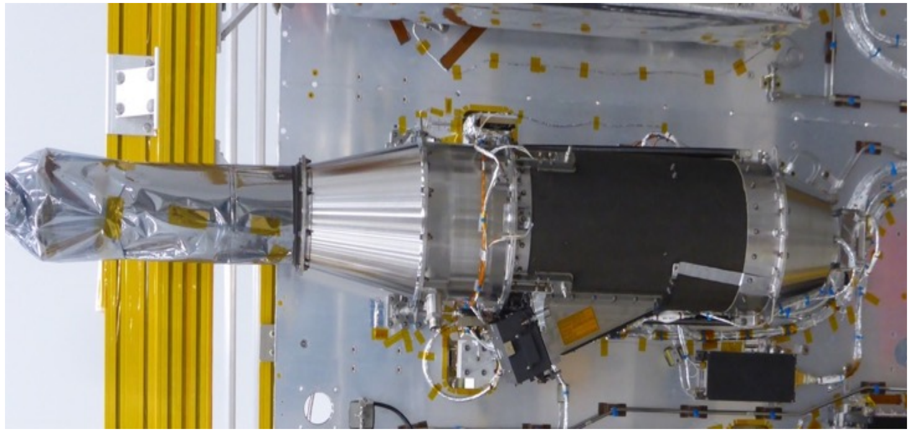
- **total and polarised visible-light brightness** (580-640 nm)
- **UV HI Lyman-α line** (121.6 ± 10 nm)

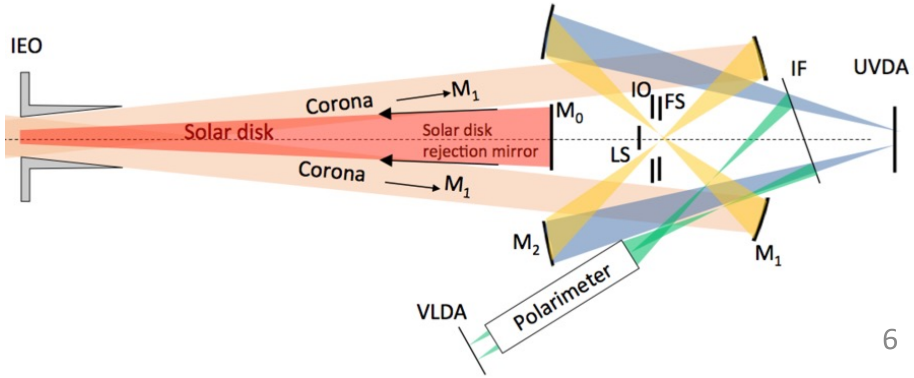


Thomson scattering



Resonant scattering





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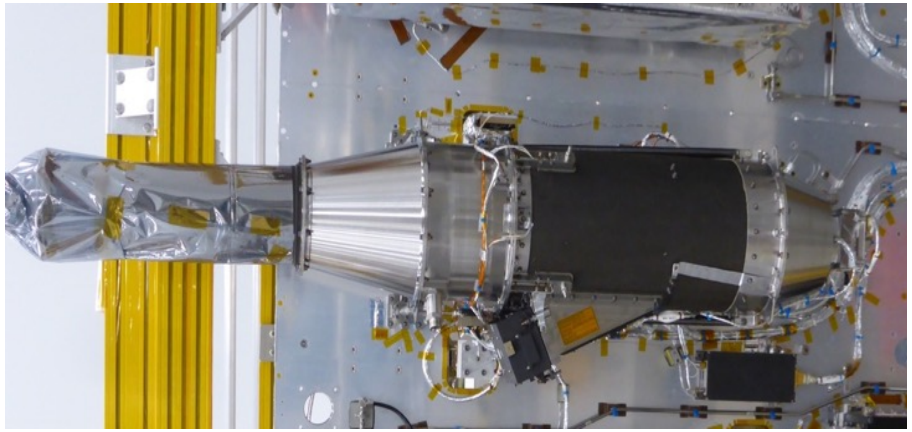
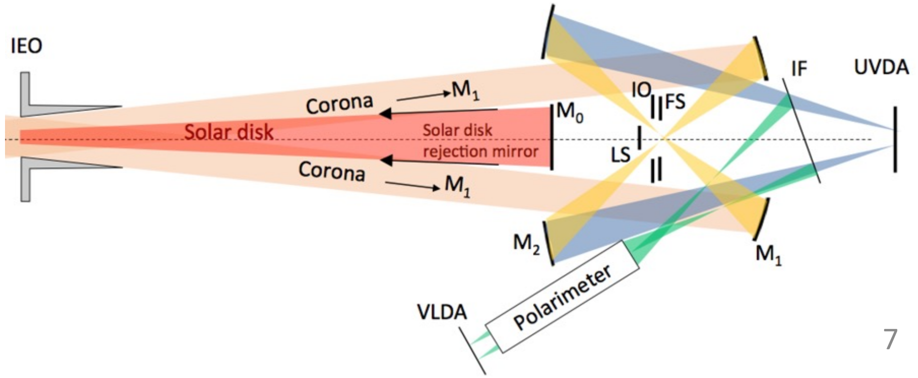
Metis observations allow the investigation of the:

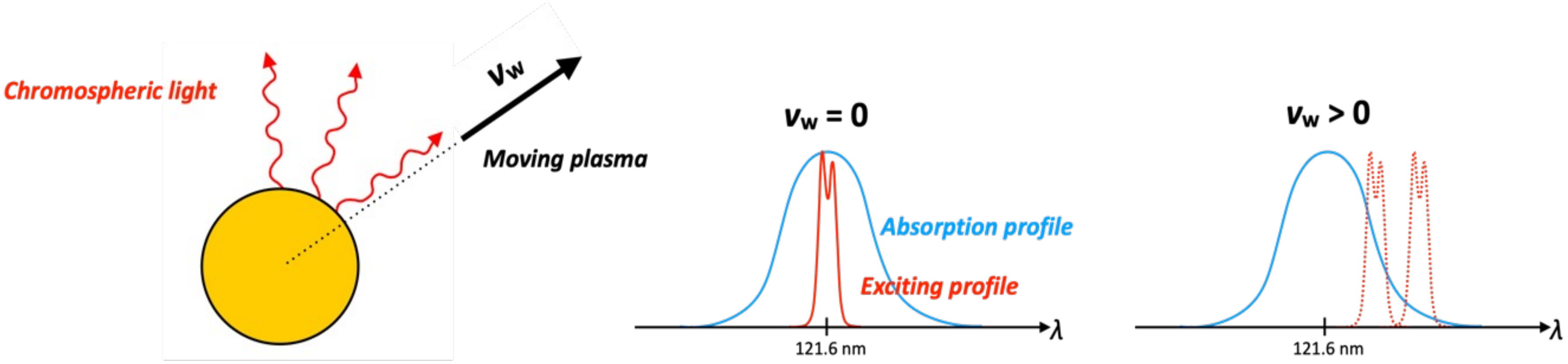
- **density distribution of coronal e$^-$ and HI atoms** (protons)
- **2D solar-wind outflow** (HI/proton component)
- **large-scale dynamics of e$^-$ and HI in CMEs** and other solar transients





Solar wind

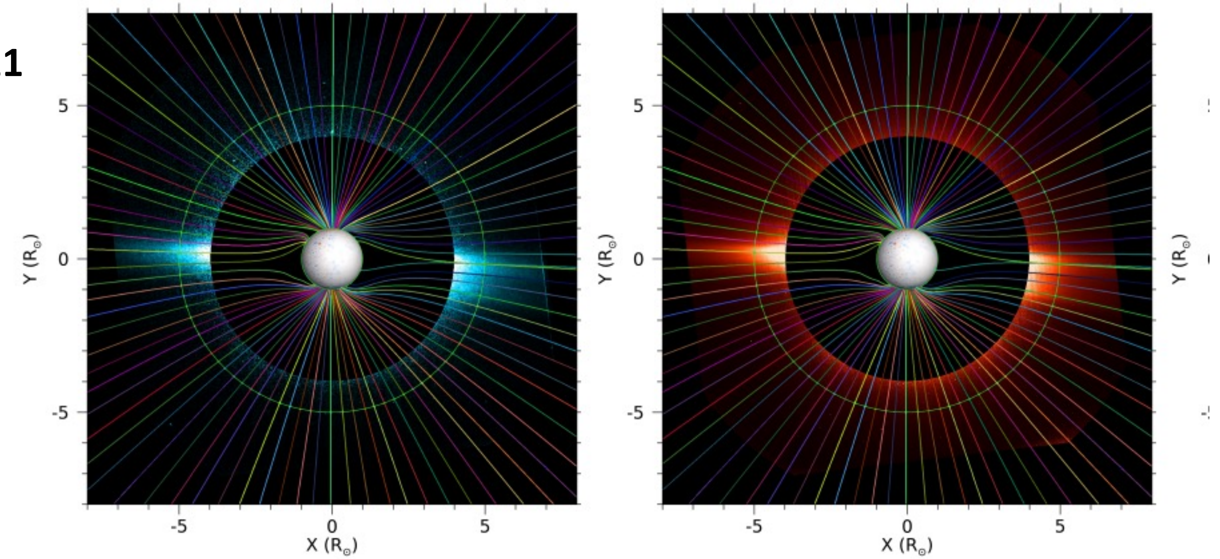
- Metis maps the regions where **the solar wind undergoes acceleration** from ∼ 100 km/s to near its asymptotic value
- **Doppler dimming analysis** (Withbroe+ 1982; Noci+ 1987):
  - outflow speed can be derived from the comparison of coronal UV HI Lα emission (dimmed due to coronal expansion) with Lα emission for a static corona (no dimming) expected based on the electron density from pB maps of the coronal plasma (Dolei+ 2018; Dolei+ 2019)



Solar wind

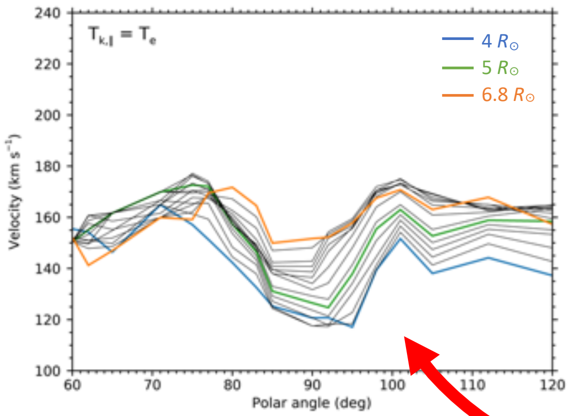
Romoli+ 2021

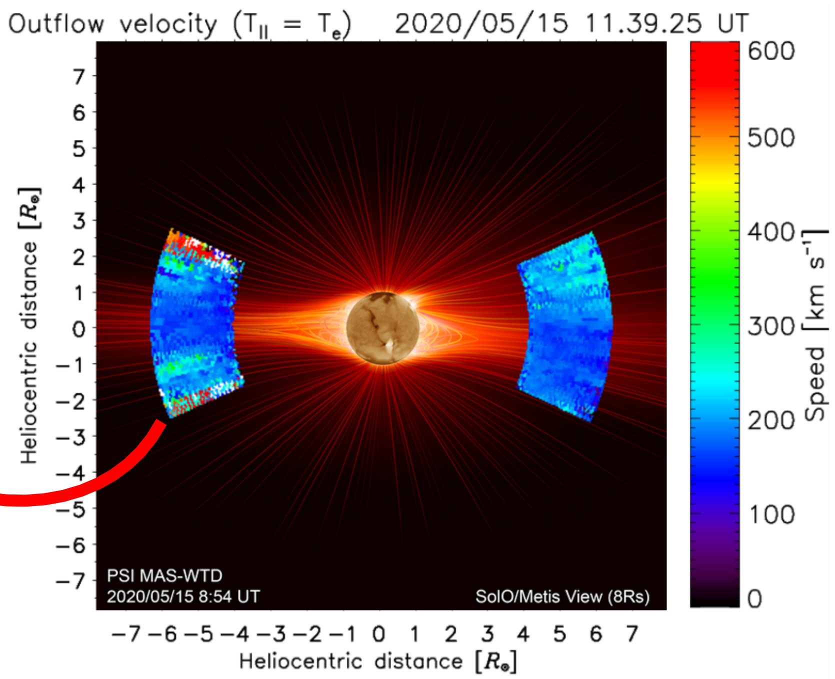
0.64 AU heliodistance
FOV ~ 4-7 R⊙

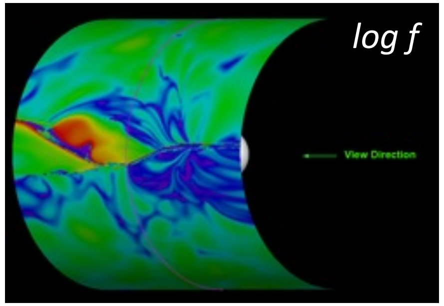


Analysis of the first images acquired by Metis in May 2020

- *Identification of a high-density layer centred on the extension of a quiet equatorial streamer - the coronal origin of the heliospheric current sheet*
- *The slow wind is found to flow along the axis of the equatorial streamer at ~160 km/s from 4 R⊙ to ~7 R⊙*
- *The wind velocity rapidly increases beyond this layer, marking the transition between slow and fast wind in the corona*







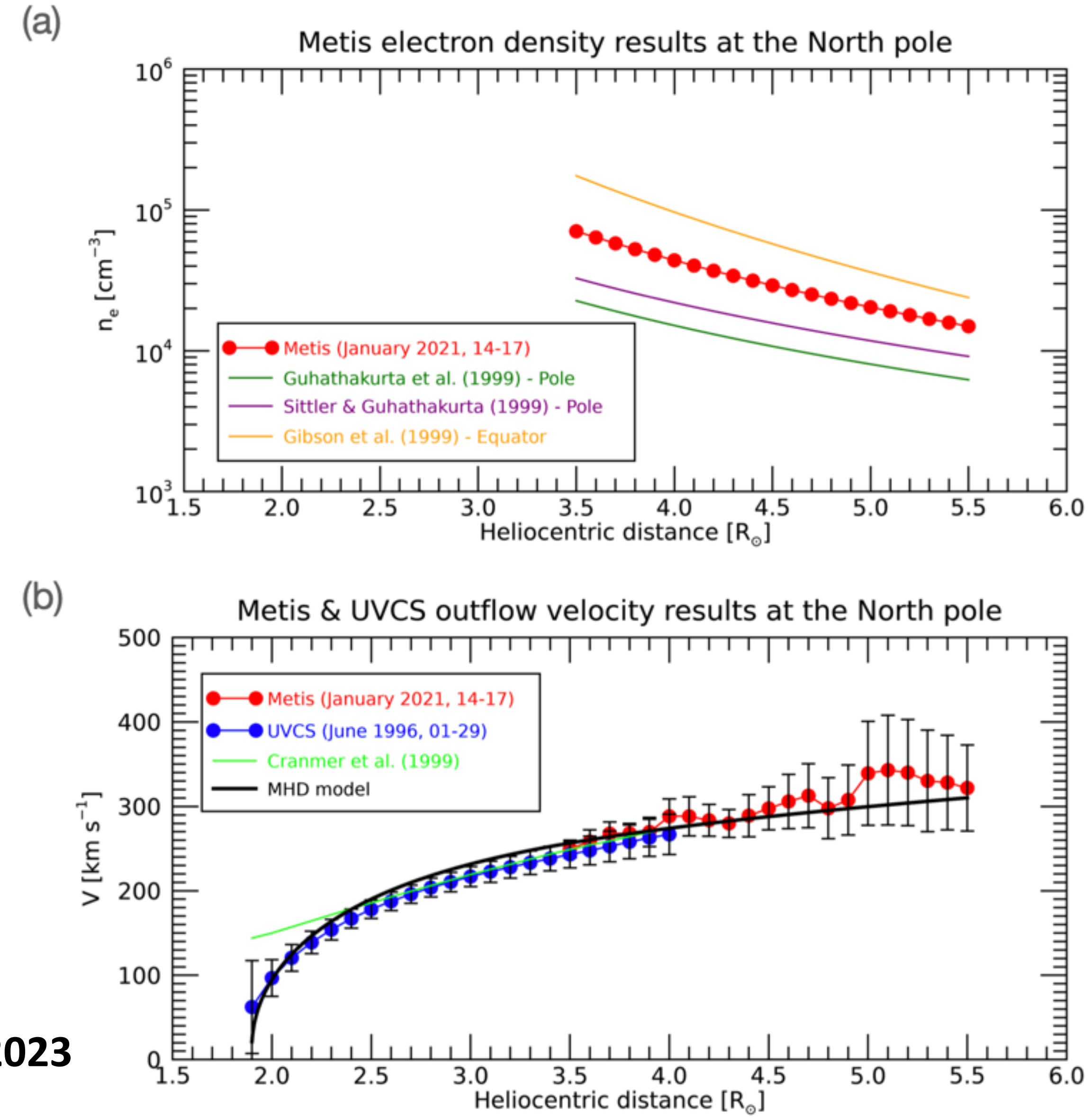
Antonucci+ 2023

Solar wind

First estimate of the expansion rate of polar coronal flows

- *Simultaneous measurements in pB and UV intensity of the Lα line allow observations of the outflow velocity of the main component of the solar wind from polar coronal holes to be extended out to 5.5 $R_\odot$ - the limit of diagnostic applicability and observational capabilities*
- *Outflow velocities are satisfactorily reproduced by a 2D MHD turbulence model (Zank+ 2017, Adhikari+ 2020, Telloni+ 2022): dissipation of turbulence energy is a viable mechanism for coronal plasma heating and the subsequent acceleration of the fast solar wind*

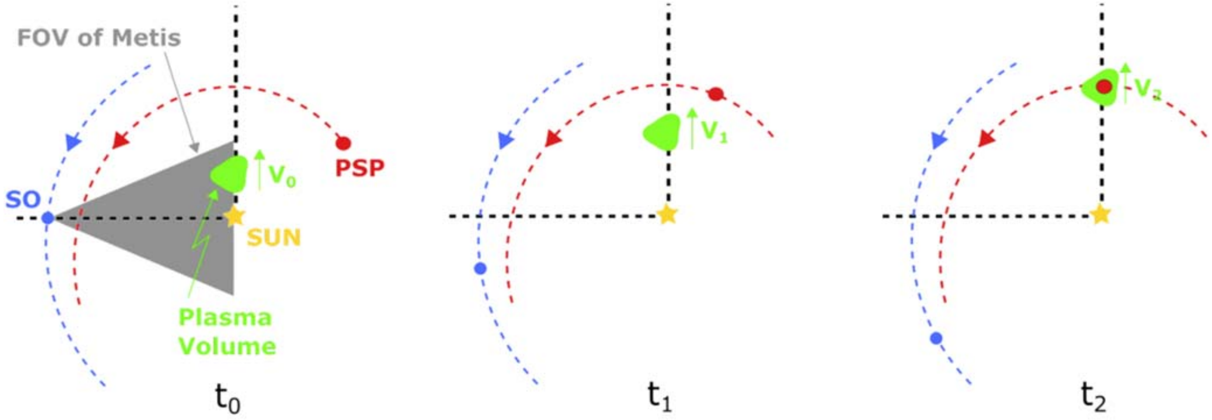
Telloni+ 2023



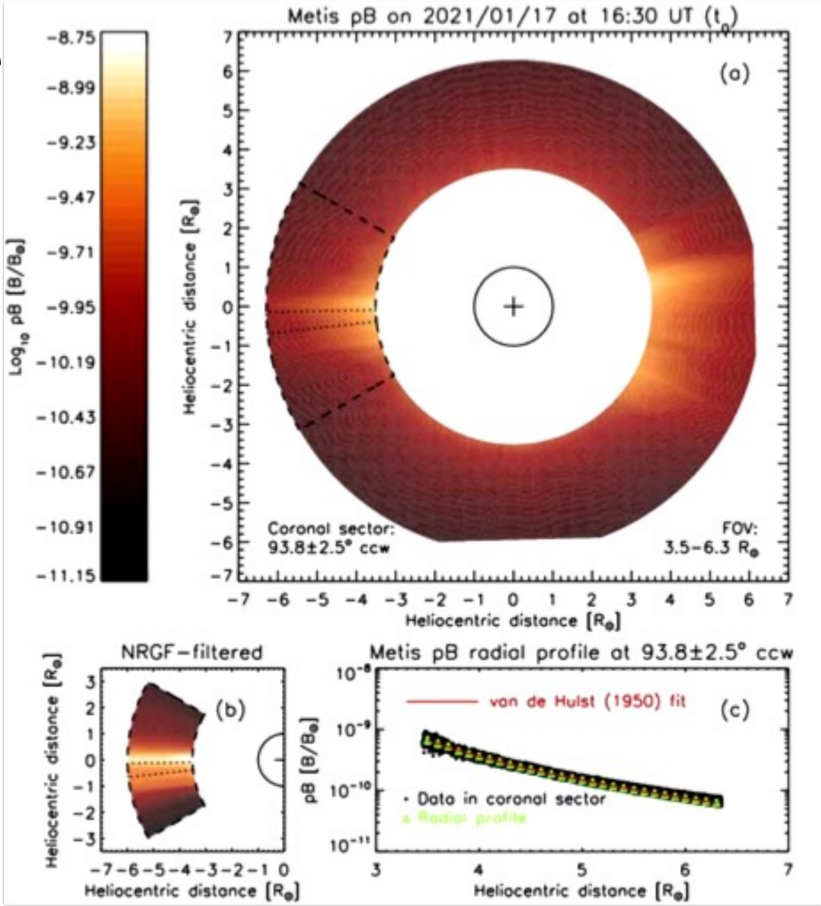
Solar-wind diagnostics with in-situ & coronal data

Exploring the solar wind from its source on the corona into the inner heliosphere

Remote sensing and in-situ coordinated measurements, like during **quadratures between Solar Orbiter and PSP**, but not only, provide a valuable tool to probe the physical parameters of the solar wind throughout the solar corona and the heliosphere



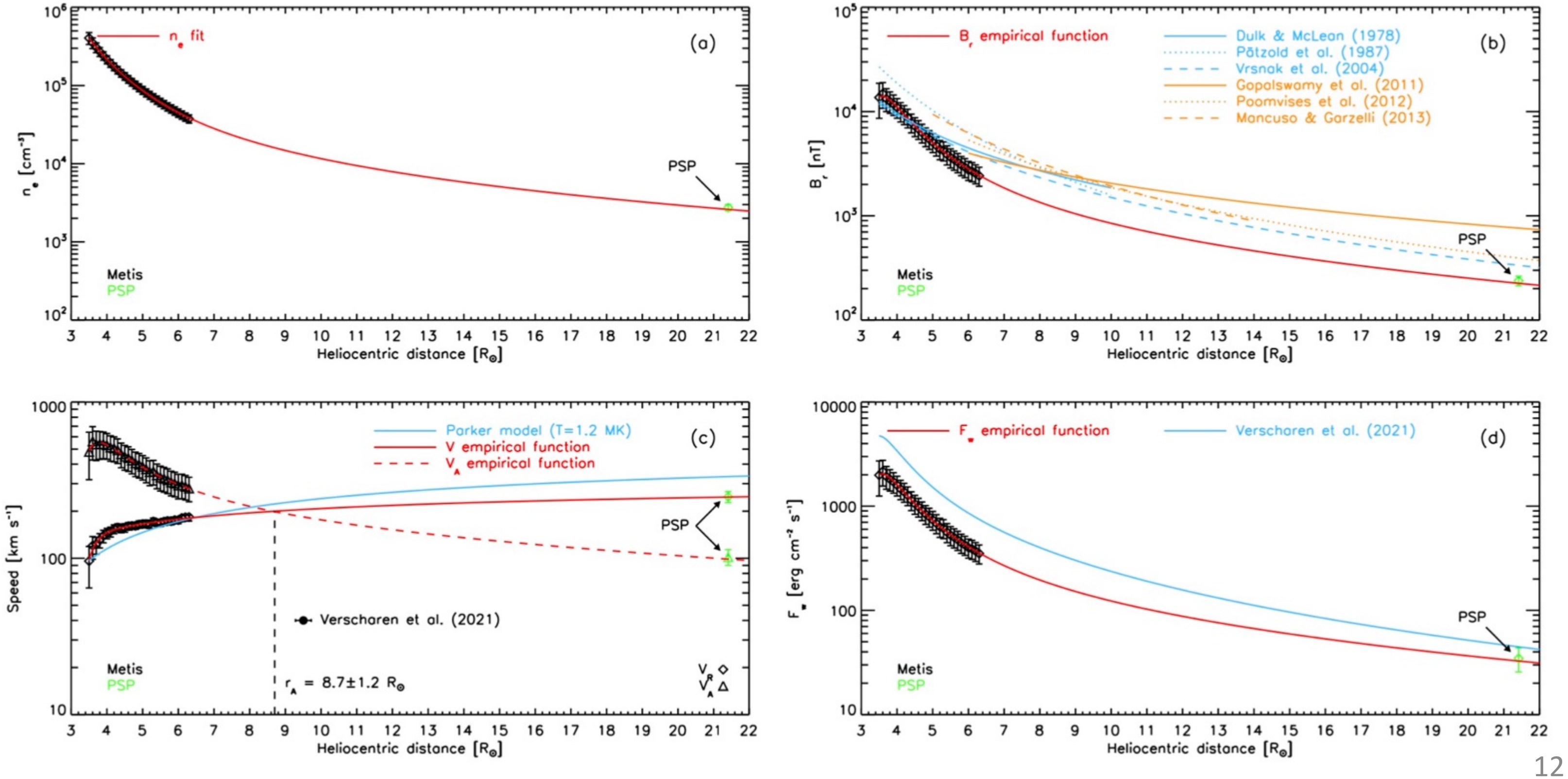
Telloni+ 2021



Solar-wind diagnostics with in-situ & coronal data

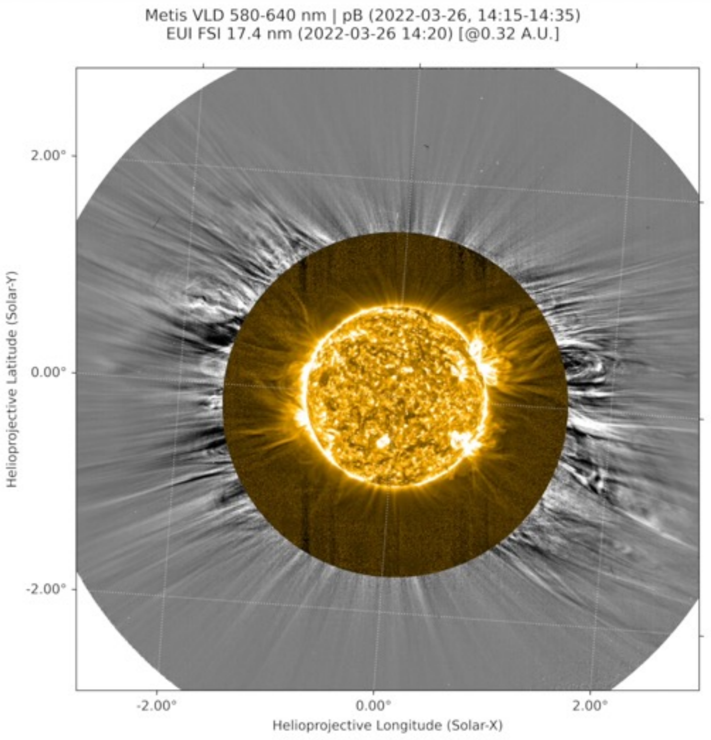
Exploring the solar wind from its source on the corona into the inner heliosphere

- *Estimate of the magnetic field through conservation of mass and magnetic flux (assuming flux-freezing) and PSP constraints*
- *Estimate of the bulk kinetic energy flux density through conservation of total energy along the stream line*
- *Estimate of the Alfvén speed and Alfvén radius = 8.7 $R_\odot$*
- *Comparison with the Parker outflow solution for an isothermal solar corona with $T = 1.2 \times 10^6$ K*

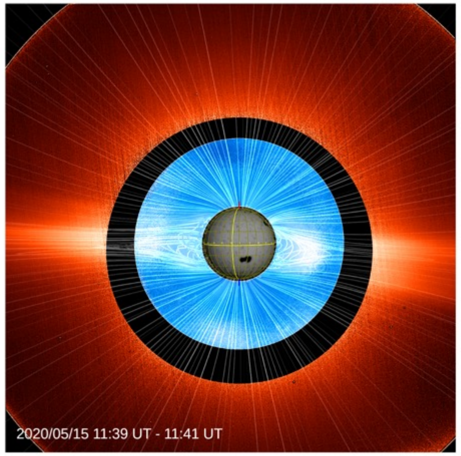


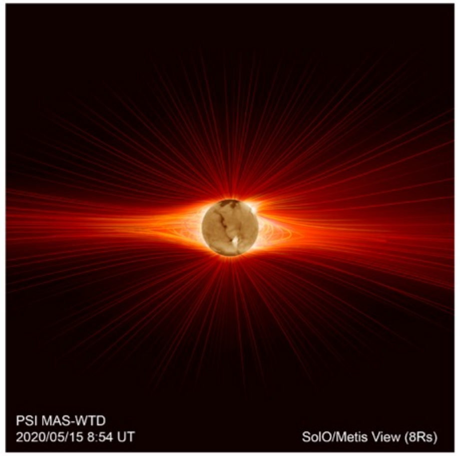
Telloni+ 2021

Magnetic-field morphology

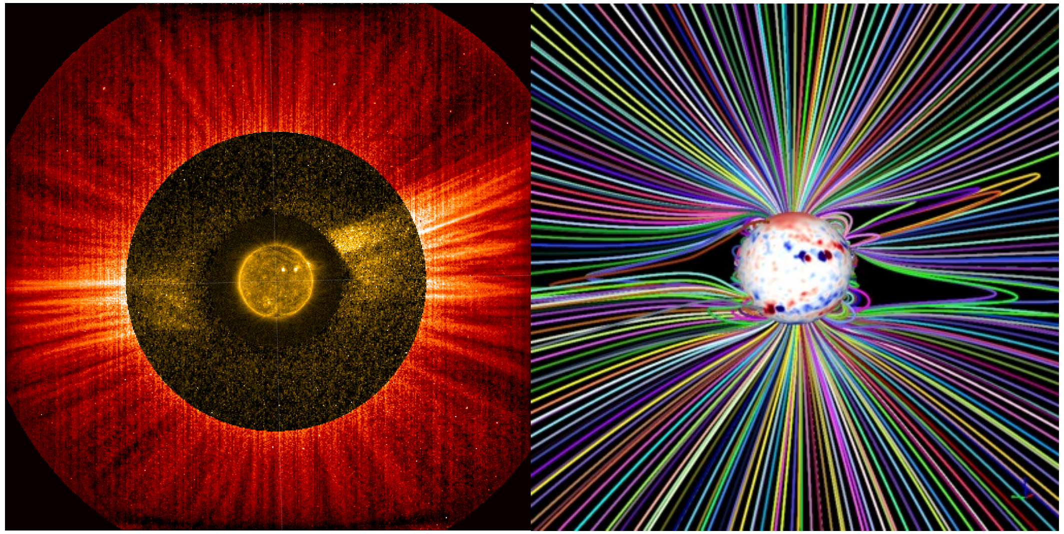


- Metis produces synoptic maps that combined with images of other space and ground-based instruments and magnetic-field extrapolations (WSO + PSI) can provide from the ecliptic and out-of-the ecliptic plane:
  - **the overall magnetic configuration**
  - **tomographic reconstructions of electron density** (Vasquez+ 2019,2022)
- The highest spatial resolution achieved during perihelia (~2000 km in the VL) is comparable or better than that of total solar eclipse images
- Highly detailed view of the very dynamical corona





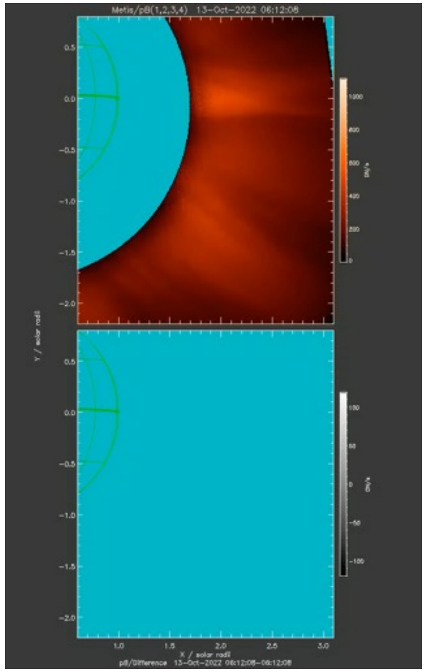
Romoli+ 2021
Antonucci+ 2023



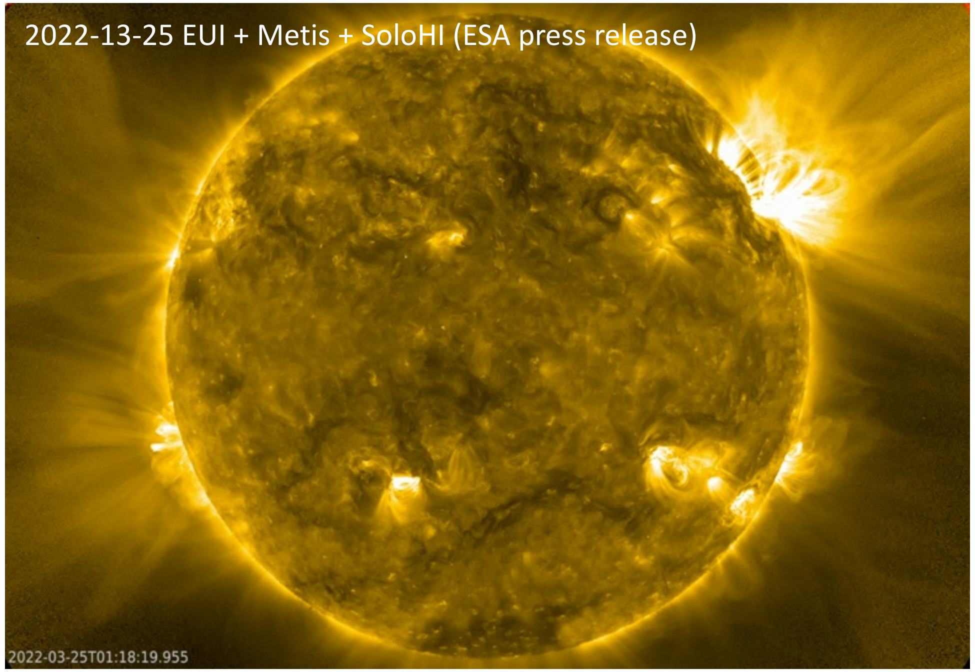
Abbo+ in preparation

Solar transients

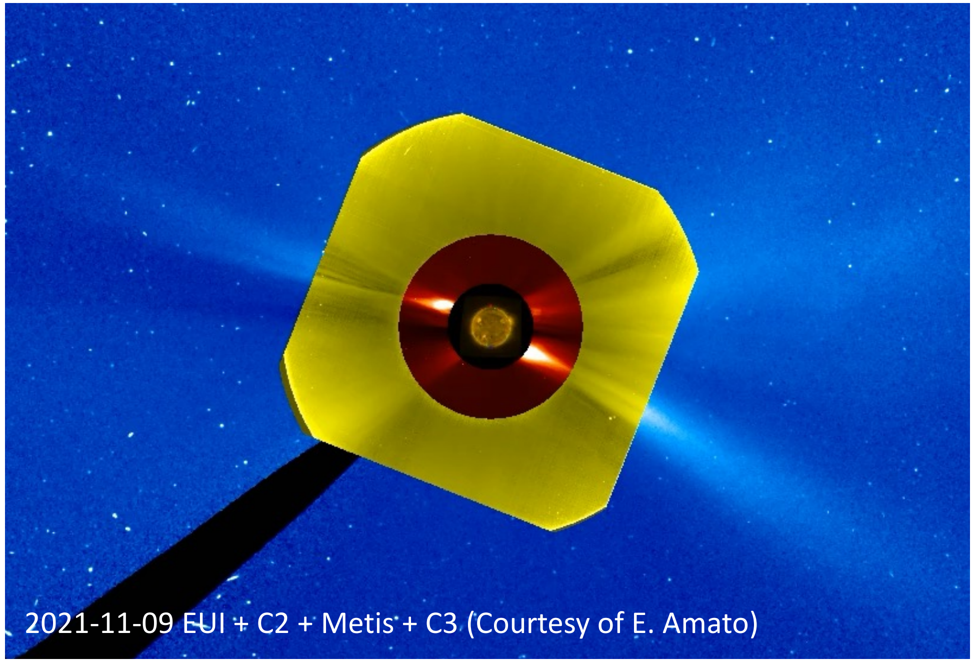
- Metis observations of CMEs and related phenomena are crucial to
  - **identify of the mechanism/s driving the eruptions**
  - ascertain whether **the main source of the flux injection** into the heliosphere **resides in the corona**
  - study **the restructuring of the global solar atmosphere** following a CME
- The unique combination of VL and UV images allows for the first time the investigation of the thermodynamic evolution of CME plasma
  - UV Lα and VL have different behaviour during the CME transient allowing for the **derivation the physical parameters** of the event
- **Synergies** with EUI/FSI (coronagraphic mode), SoloHI, STEREO, and LASCO



2022-10-13 Metis
Courtesy of V. Andretta



2022-13-25 EUI + Metis + SoloHI (ESA press release)



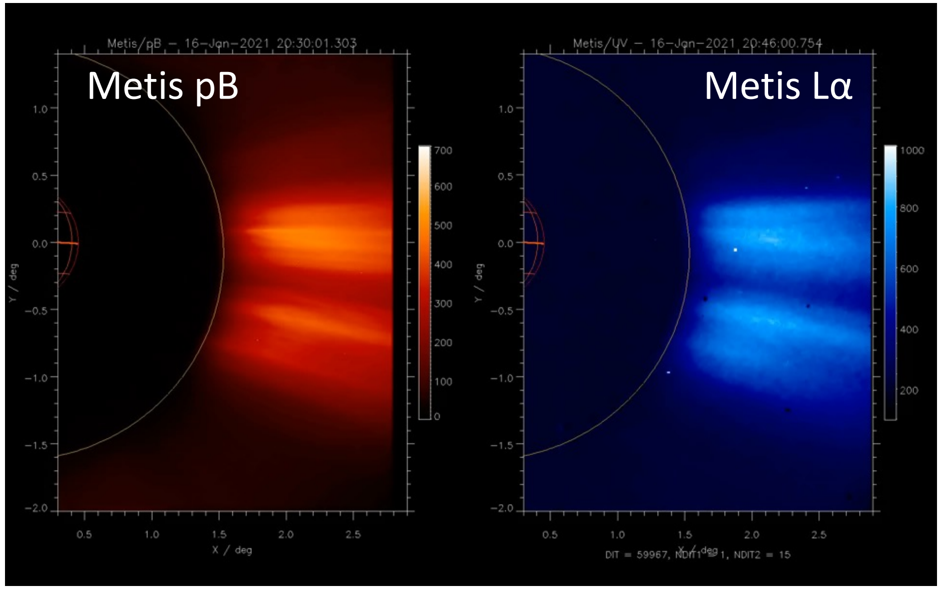
2021-11-09 EUI + C2 + Metis + C3 (Courtesy of E. Amato)

Metis observations of CMEs

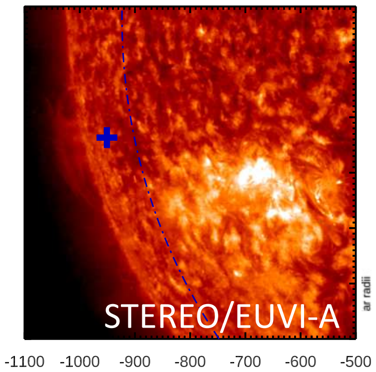
First Metis observations of a CME on 2021 January 16-17

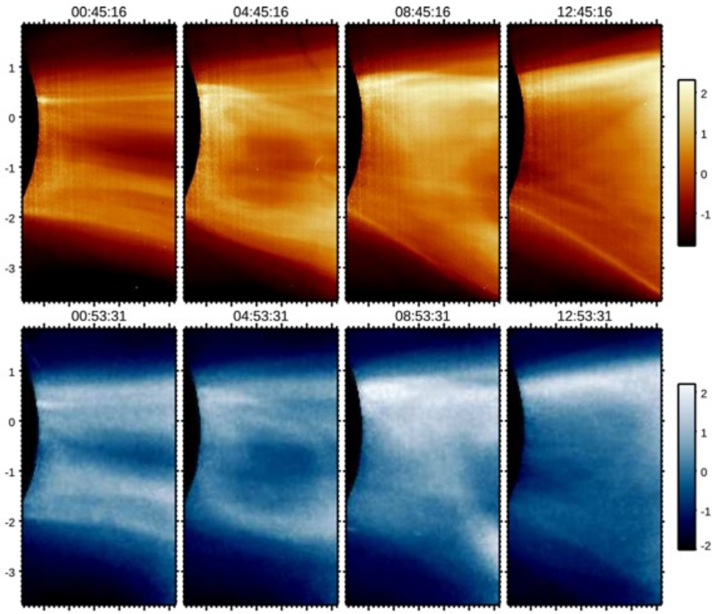
- *Most probable source region identified in a filament channel*
- *Expansion velocity of the CME front of the order of ~140 km/s*
- *Evidence of motions compatible with some untwisting features*
- *Both Metis channels show essentially the same features, although some appear more structured in Lα than their pB counterparts*

More on CMEs with Metis data (Bemporad+ 2022, Mierla+ 2022; Rodriguez+ 2022, Sasso+ in preparation)



0.6 AU heliodistance
FOV ~ 3.5-6.5 $R_\odot$



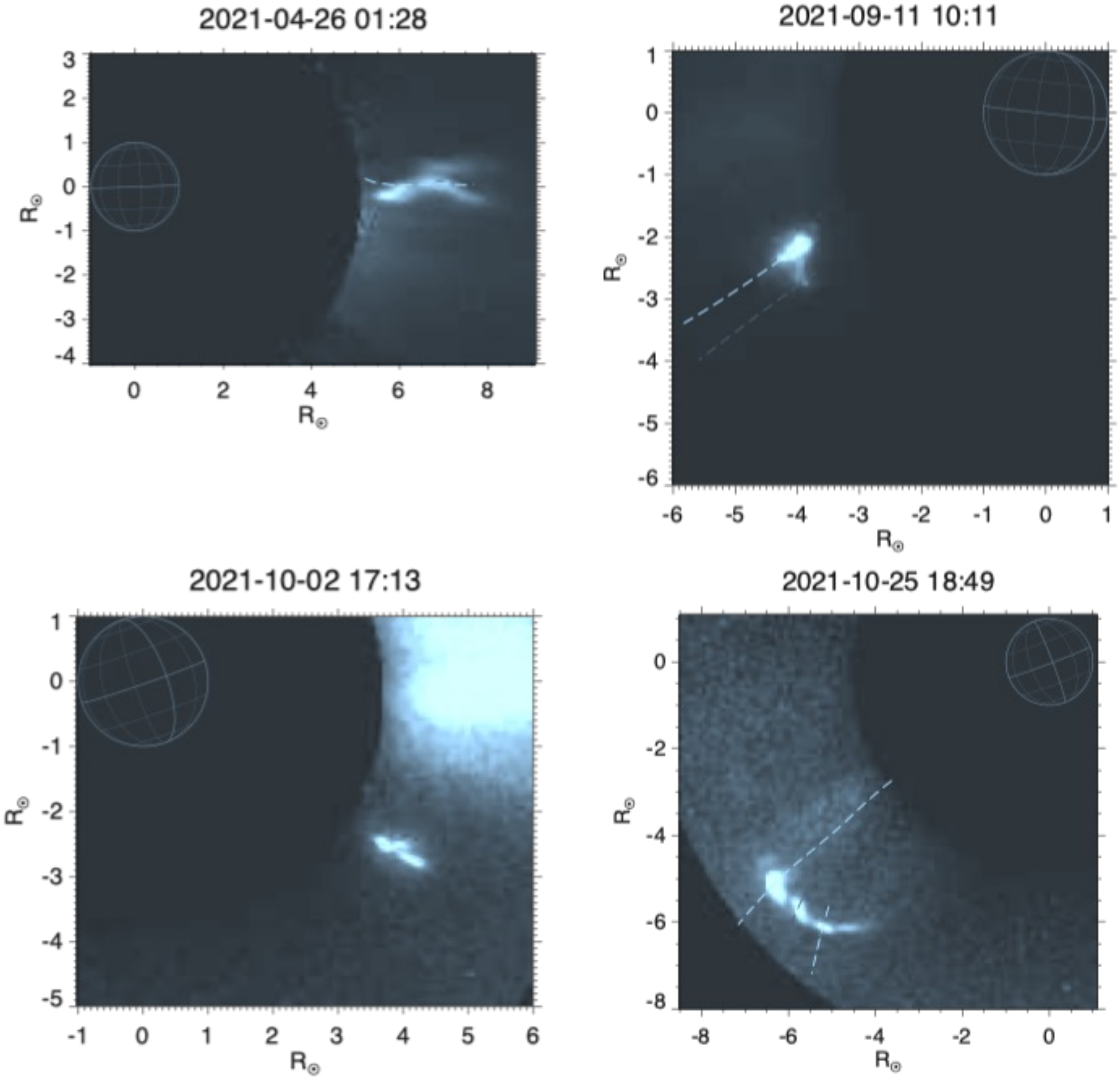


Andretta+ 2021

Metis observations of prominences

- Metis allows study of the **overall dynamics of prominences**, mass content, outflow propagation velocity in the expanding corona
- UV Lα emission can provide information on the **temporal evolution of plasma temperature, and elemental composition**
- Plasma diagnostic techniques and numerical modelling can be further employed to determine the plasma physical parameters
    - Diagnostics of cool plasmas through the analysis of the **He D3 line** (587.7 nm) polarization signature in Metis VL passband

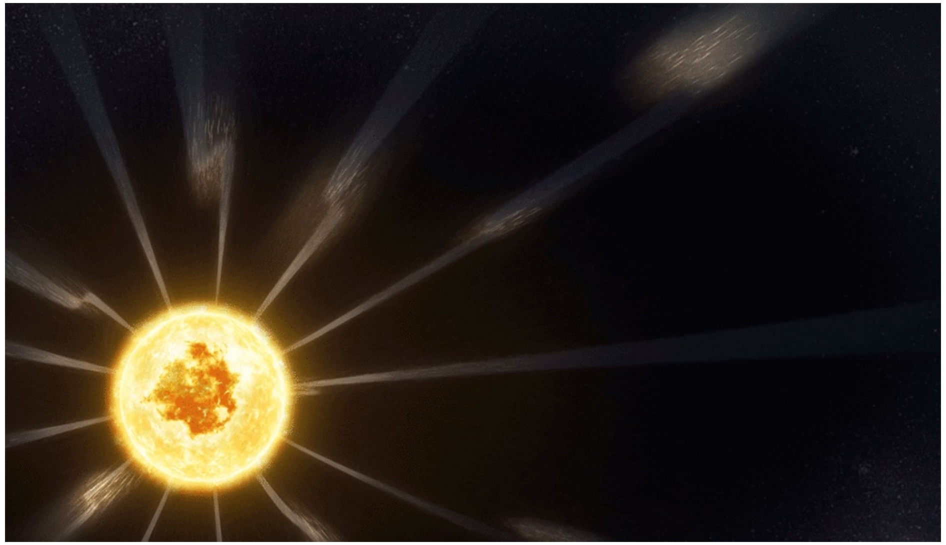
Russano+ submitted
Heinzel+ in press



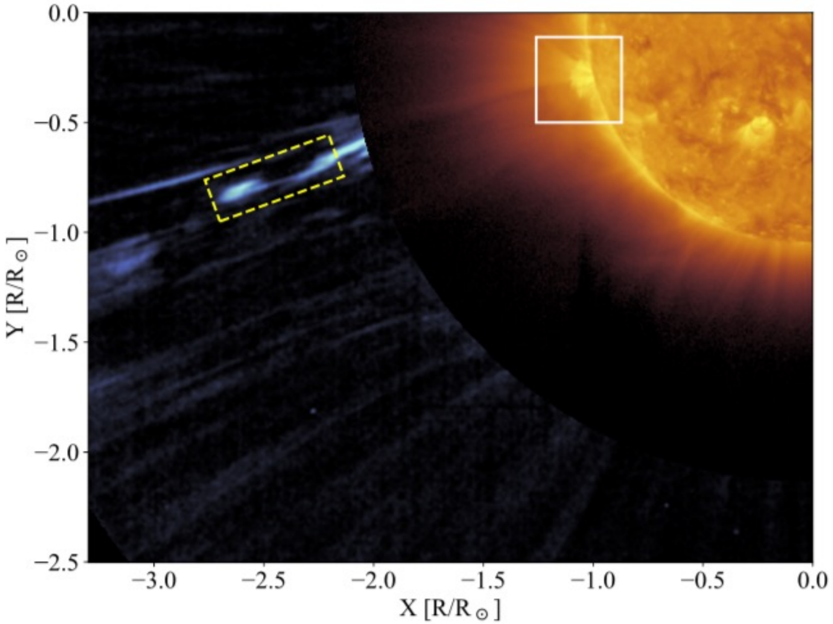
Metis observation of a magnetic switchback

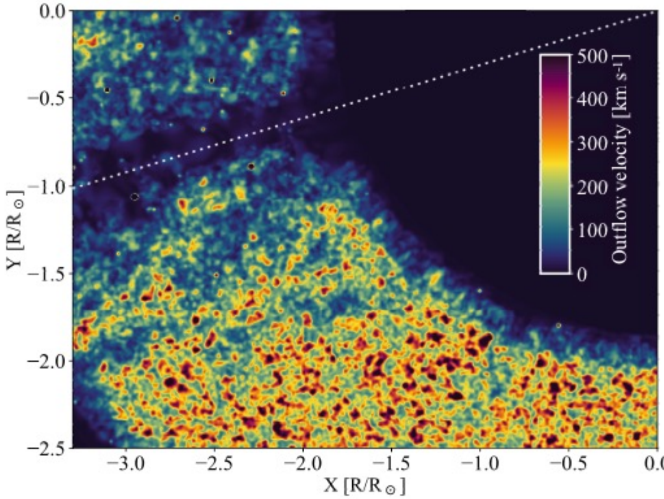
One of the major topics debated widely in the Solar and heliospheric community is the **switchback phenomenon,** which PSP has put in the spotlight.
The main question concerning switchback is: do the they have a solar origin, or they form locally in the solar wind, as it expands into the interplanetary space?

During the first perihelion passage, the Metis coronagraph on board Solar Orbiter **observed for the first time a magnetic switchback** in the solar corona, thus solving the puzzle on the switchback formation mechanism and sources.



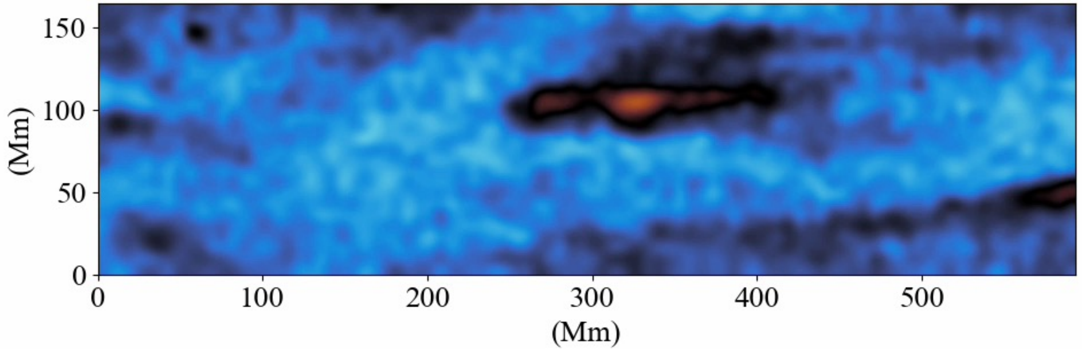
Credits: NASA's Goddard Space Flight Center Conceptual Image



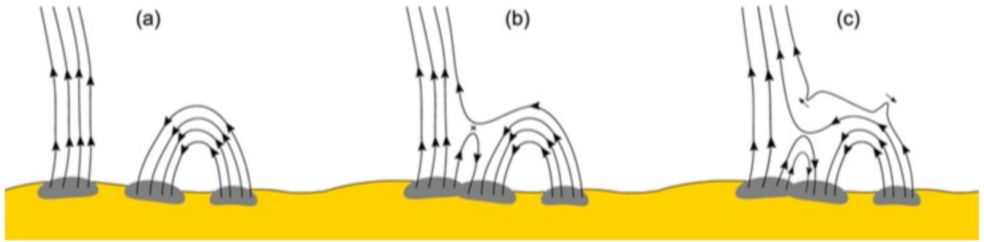


Telloni+ 2022

Generation of switchbacks interpreted as the result of the **interchange reconnection** occurring between closed magnetic loops developing above active regions of the Sun and the open magnetic field lines emerging from neighbor of coronal holes, which suggests a common genesis for the magnetic switchbacks and the slow solar wind streams.



Zank+ 2020



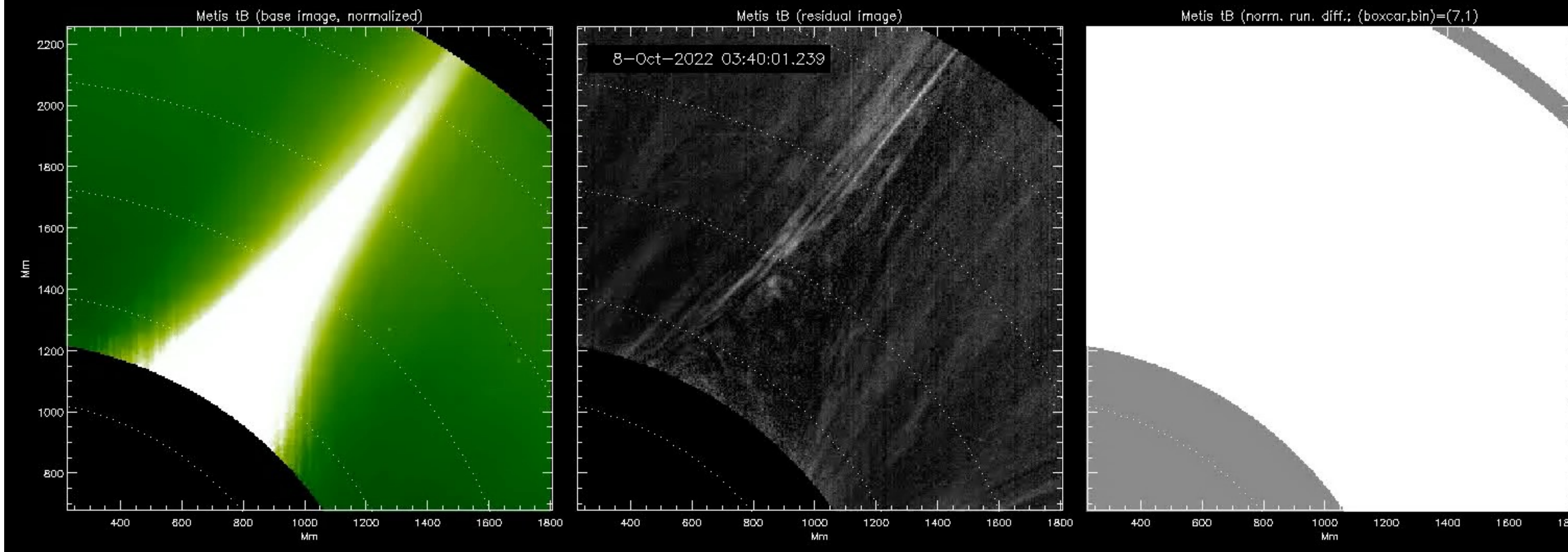
Density fluctuations

Metis design permits unprecedented observations at high temporal cadence:

- down to 1 s per frame, in single polarization mode (FP)
- down to 20 s per frame in total brightness HW mode (tB)
- and down to 1 polarized brightness (pB) image per minute

One example
8/10/2022, before perihelion.
Density enhancements in the streamer at north-west: magnetic reconnection events, caused by Alfvén waves?

Metis high cadence observations provide a new window on the dynamics of the solar corona in a range of physical parameters never explored before

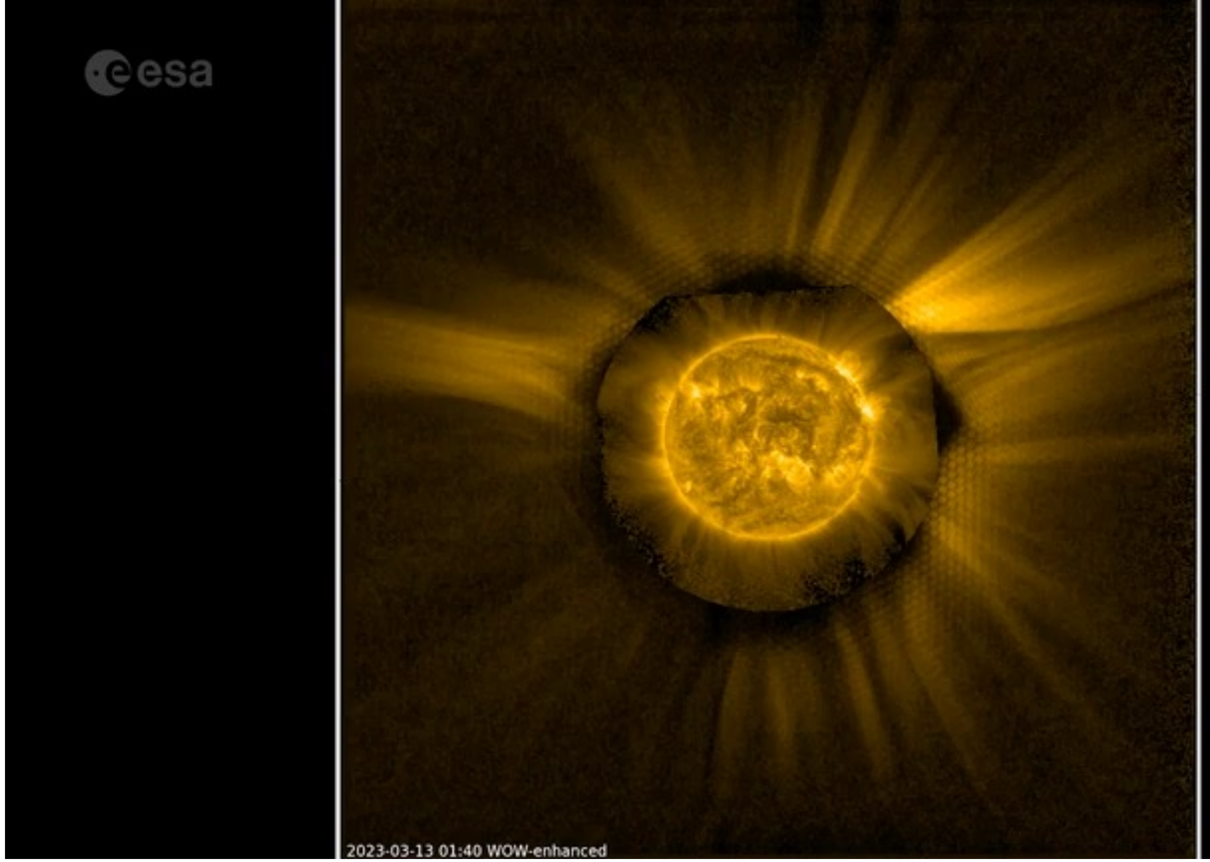


Courtesy V. Andretta

Synergies

This decade will provide for the first time multi-point of view observations of the Sun

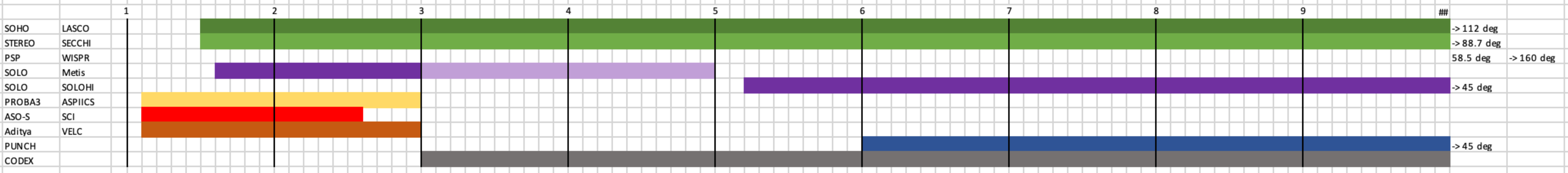
- **SOHO:** Lasco [NRL] (1995)
- **STEREO-A:** Secchi [NRL] (2008)
- **Solar Orbiter**: Metis [INAF] and SOLOHI [NRL] (2020)
- **ASO-S**: Lyman-alpha Solar Telescope (LST) [CAS] (2022)
- **Aditya**: Visible Emission Line Coronagraph (VELC) [IIA] (2023)
- **Proba3**: ASPIICS [ESA] (2024)
- **CODEX** Coronal Diagnostics Experiment [NASA-GSFC] ISS coronagraph (2024)
- **PUNCH**: Polarimeter to Unify the Corona and the Heliosphere [SWRI] (2025)



Solar Orbiter EUI coronagraphic mode

FeIX/FeX 17.4nm

'Wavelets Optimized Whitening' algorithm enhances the visual appearance of the movie.



Thank you

Metis website

www.metis.oato.inaf.it