Metis status

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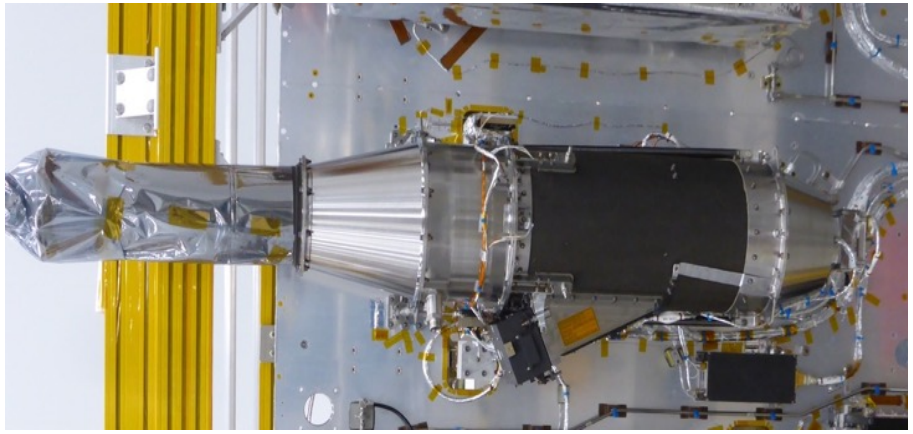
9th Metis Workshop, Catania, January 24-26, 2024

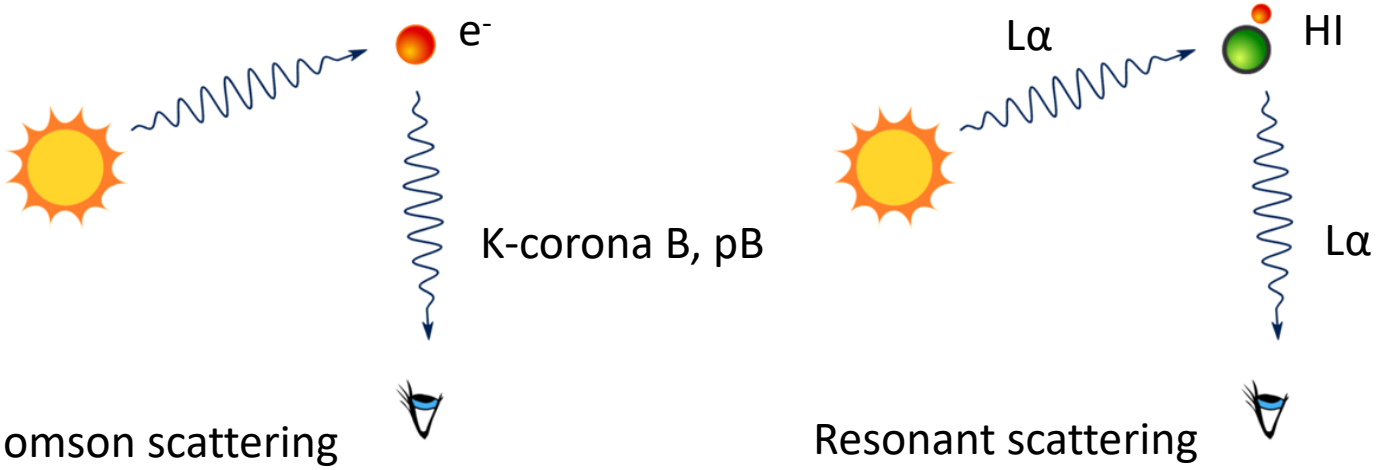
Metis: the Solar Orbiter coronagraph

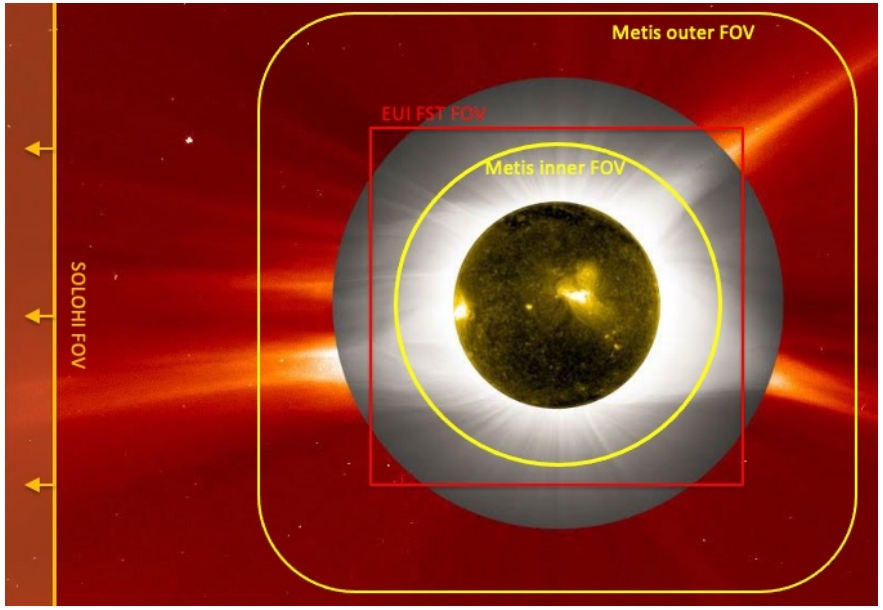
Metis is an externally-occulted coronagraph designed to provide full imaging of the extended corona in:

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



(1.6° · 2.9° annular, 1.7 – 3.0 $R_\odot$ @ 0.28 AU)

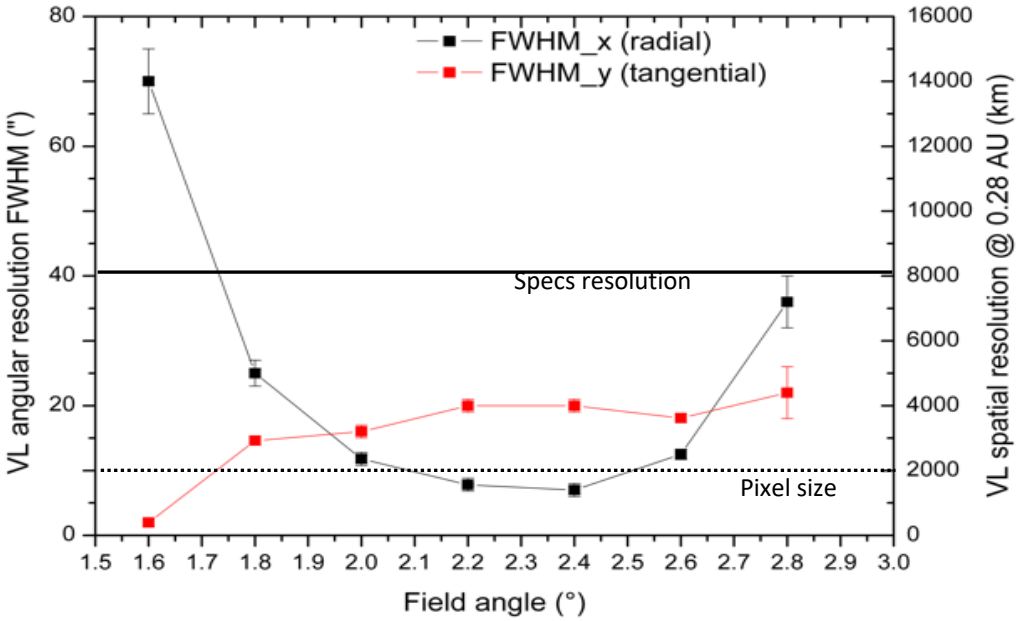




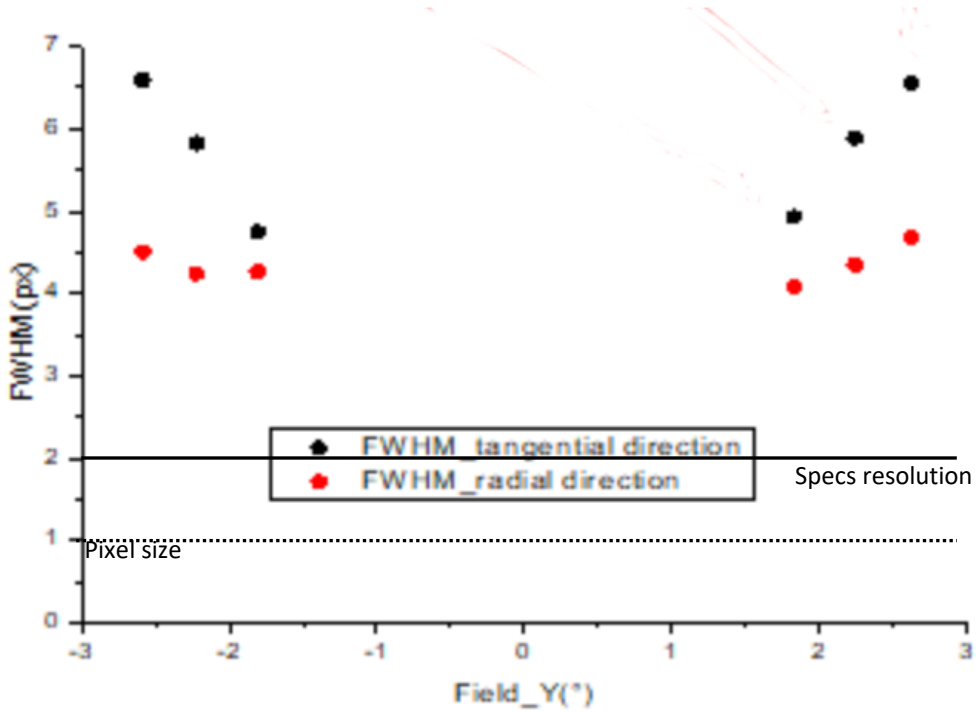
Metis performance: Spatial and temporal resolution

- **Spatial resolution:** checked in-flight with Star observations

VL



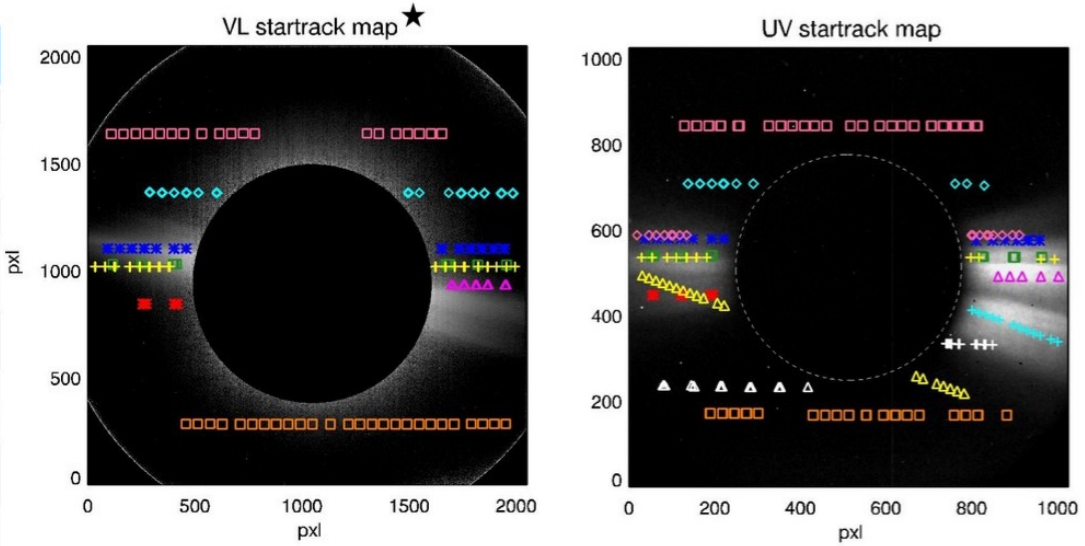
UV



- **Temporal resolution:**
  UV: > 1s limited by countrate
  VL: 60s in pB, 20s in tB, >1s in fixed polarization

Metis performance: Radiometric calibration

Star ID and symbol	Observation date
α Leonis	15 June 2020
ϱ Leonis	17 June 2020
ν Scorpii	15 March 2021
β01 Scorpii	15 March 2021
ω Scorpii	15 March 2021
λ Librae	15 March 2021
Θ Ophiuchi	25 March 2021 23 December 2021
δ Scorpii	15 March 2021
σ Sagittarii	09 April 2021
121 Tauri	16 January 2021 28 August 2021
τ Tauri	24 August 2021



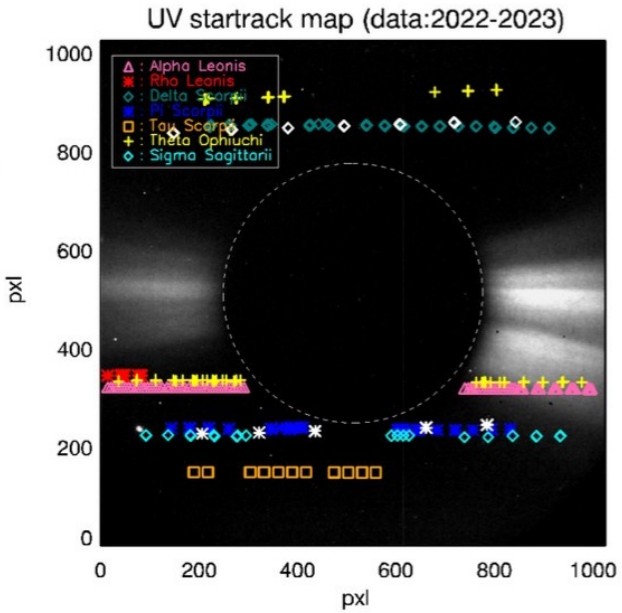
★ **limiting factors**: not all the VL stars are visible in the UV channel, stellar variability, technical issue (corrupted frames, loss of data), not optimized observations, etc.

Cruise Phase

VL and UV radiometric calibration performed on ground is checked periodically using bright UV stars, with dedicated observations.

1. Theta Ophiuchi (3t), 5-14 July 2022, STP 211
2. Sigma Sagittarii (2t), 4-10 August 2022, STP 215
3. ~~HD 210424 (Eps Aqr), 15-18 September 2022, STP 222~~ (only 5 frames!)
4. ~~Alpha Vir, 9-11 November 2022, STP 230,~~ (only 4 frames!)
5. Pi Scorpii, 10-15 December 2022, STP 234-235
6. Delta Scorpii (2t), 10-15 December 2022, STP 234-235
7. Tau Scorpii, 20-25 December 2022, STP 236
8. Alpha Leo (2t), 20-21 April 2023, STP 254
9. Rho Leo (2t), 20-21 April 2023, STP 254
10. Pi Scorpii, 7-12 June 2023, STP 261
11. Delta Scorpii, 7-12 June 2023, STP 261
12. Theta Ophiuchi, 1-6 July 2023, STP 264

All the ToO available from 2022 up to now (Metis data status)

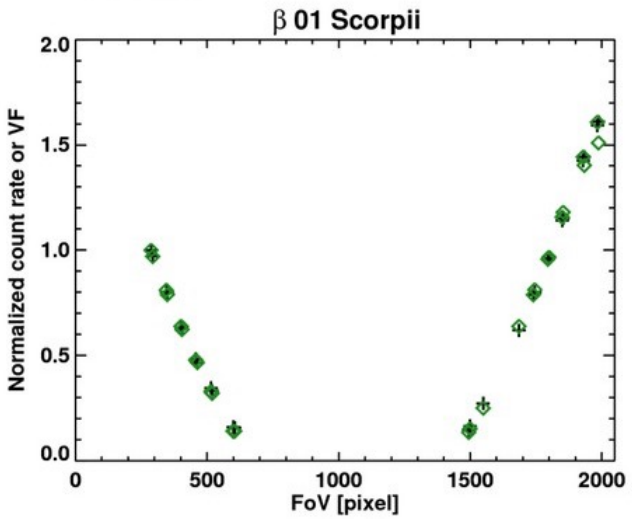


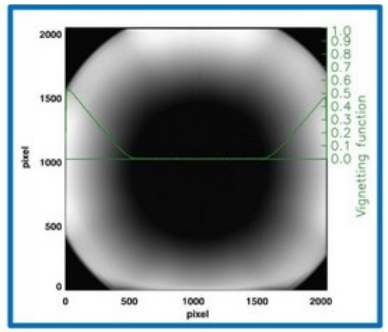
NMP

Courtesy of Y. De Leo

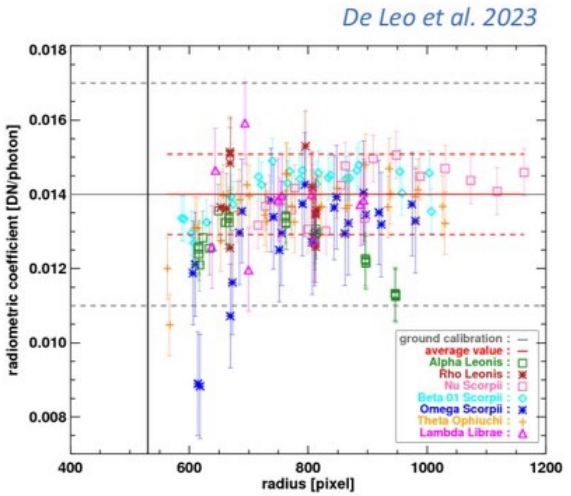
Metis performance: Radiometric calibration

VL channel





$$\varepsilon_{VL} = \frac{N_{VL}(FoV)}{\bar{f}_{Metis} \cdot A_{pup} \, VF(FoV)}$$



$$\varepsilon_{VL} = 0.014 \pm 0.001 \text{ DN/photon}$$

Aperture photometry → Inversion → Calibration across the FoV

Results:

In-flight radiometric calibration

ε_{VL} =0.014+/- 0.001 [DN/Photon]

on-ground measurement

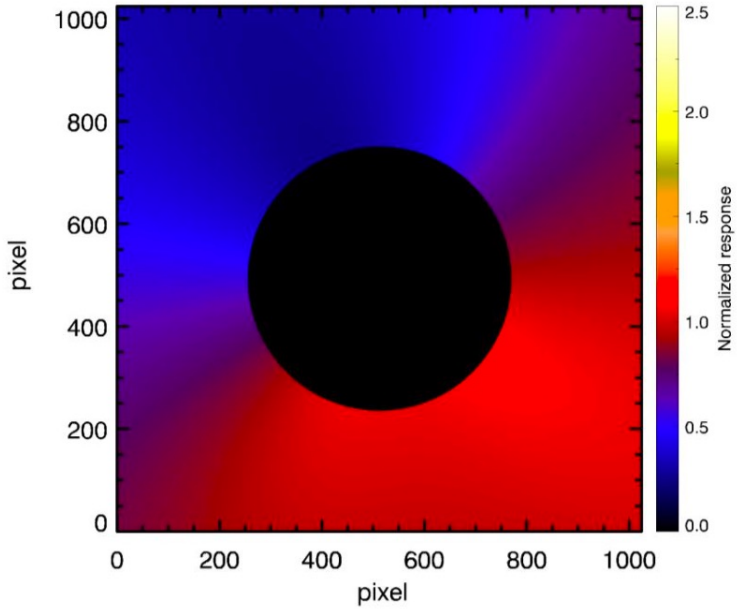
ε_{VL} =0.014+/- 0.003 [DN/Photon]

De Leo et al., A&A 676, A45 (2023)

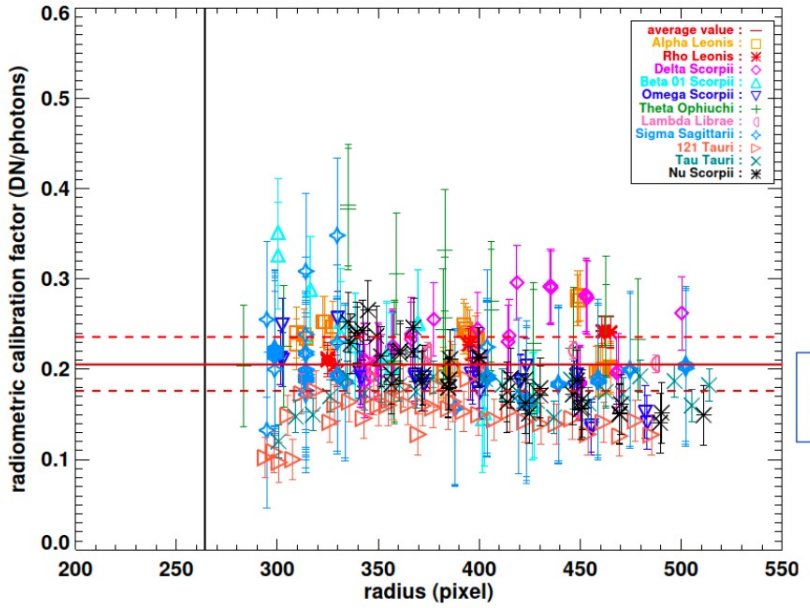
Metis performance: Radiometric calibration

UV channel: Cruise phase

$$VF_{flight} = VF \cdot (M_{UV2VL}(FoV)/z)$$



Radiometric calibration factor ε_{UV}



$$\varepsilon_{UV} = \frac{N_{UV}(FoV)}{f_* \cdot A_{pup} \cdot VF(FoV)}$$

$$\varepsilon_{UV} = \frac{N_{UV}(FoV)}{f_* \cdot A_{pup} \cdot VF(FoV) \cdot (M_{UV2VL}(FoV)/z)}$$

$$\varepsilon_{UV} = 0.21 \pm 0.03 \text{ DN/photon}$$

De Leo et al., A&A in preparation

Metis performance: Radiometric calibration

UV channel: NMP (in progress)

From the image headers

UVRC 1 : hv_s = 2787 815 V
hv_m= 3273 4500 V

real gain screen : 0.52
real gain mcp : 1.94

1.00*rcf

From the image headers

UVRC 2 : hv_s = 2742 860V
hv_m= 3448 3500 V

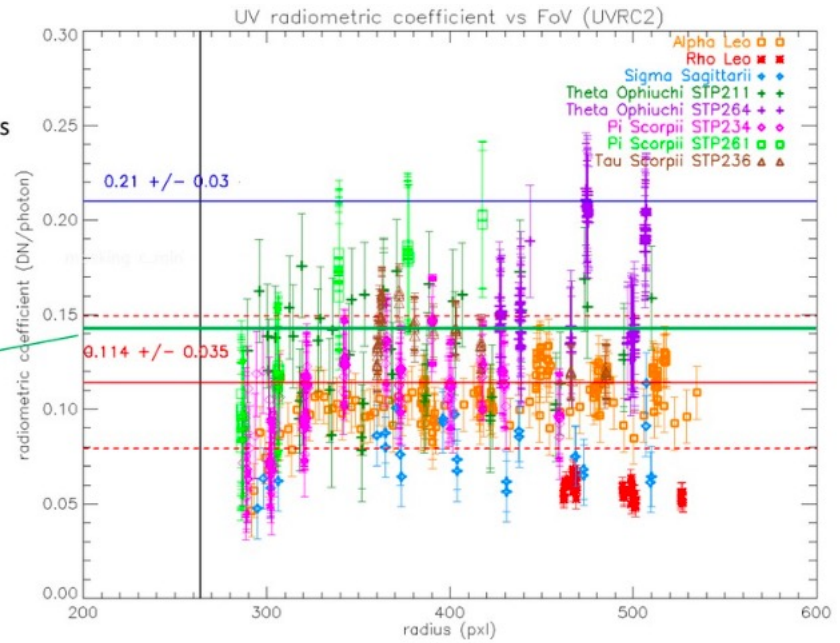
real gain screen: 0.20
real gain mcp: 3.39

0.68*rcf

Scaling factor
from radiometric calibration factors
0.54 +/- 0.24 (45% err prop)

0.68*rcf 1

Scaling factor
From count-rate/VF (east_det)
0.66 +/- 0.12 (20%)



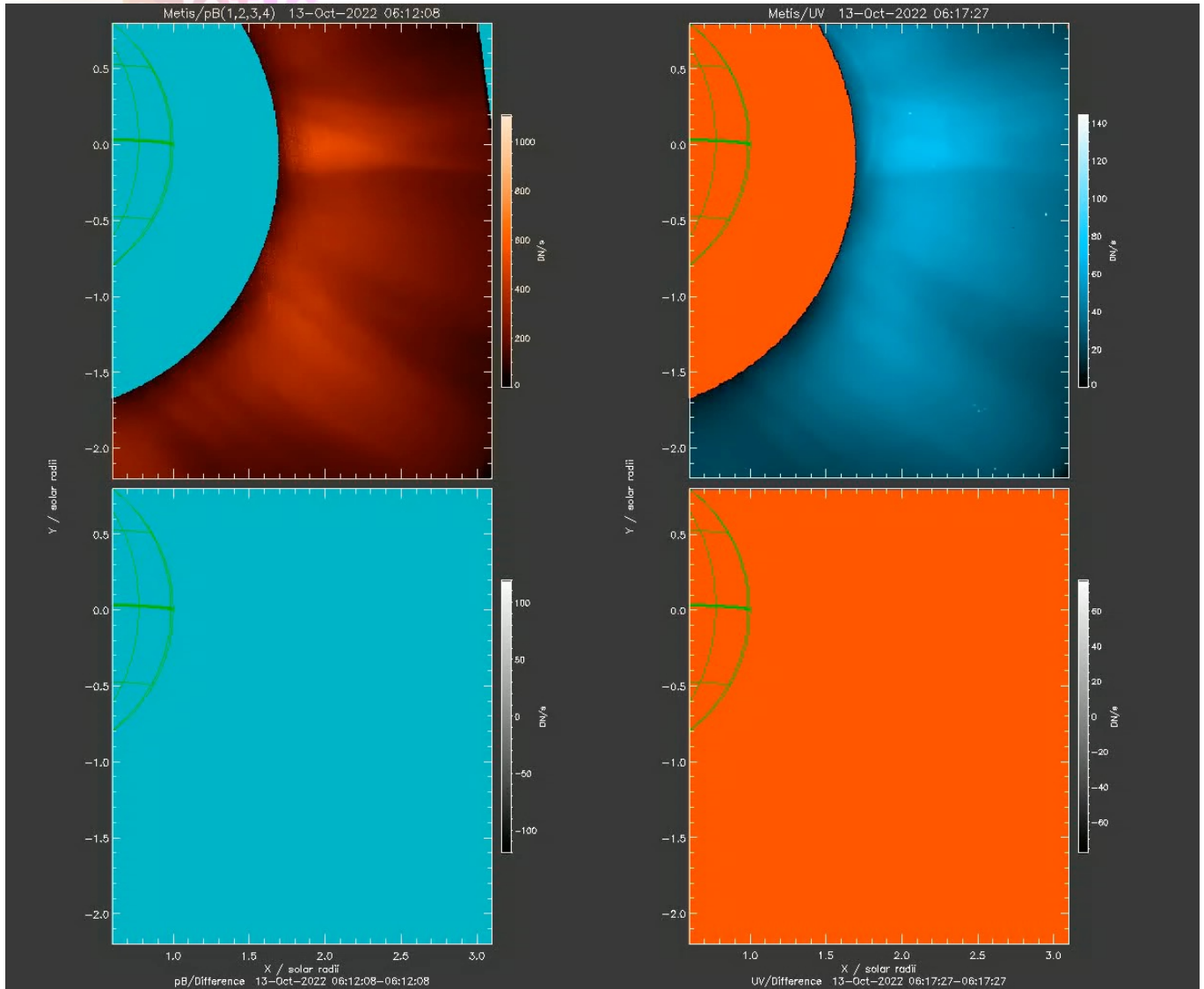
This calibration has been implemented in the UV NMP data

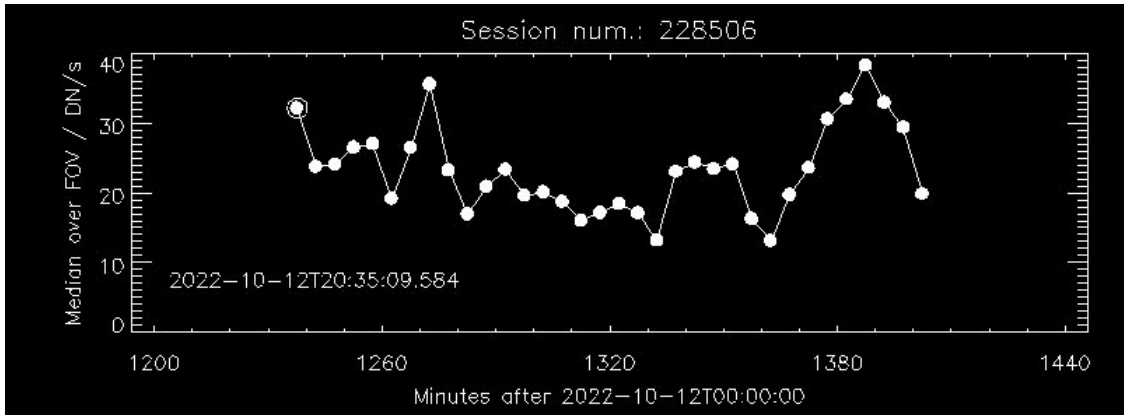
Courtesy of Y. De Leo

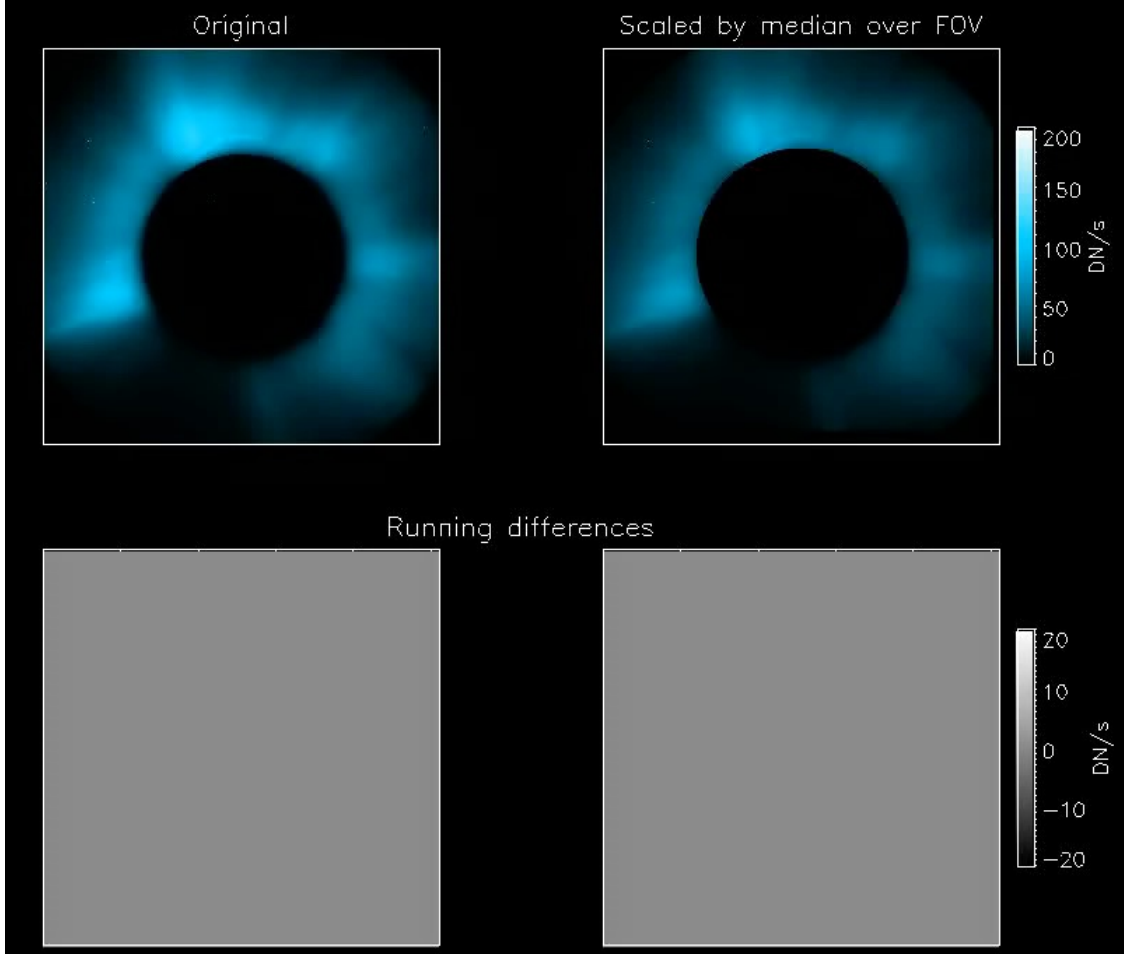
UVD Anomaly

The UV detector displays a variable radiometric behaviour with periodic fluctuations in intensity

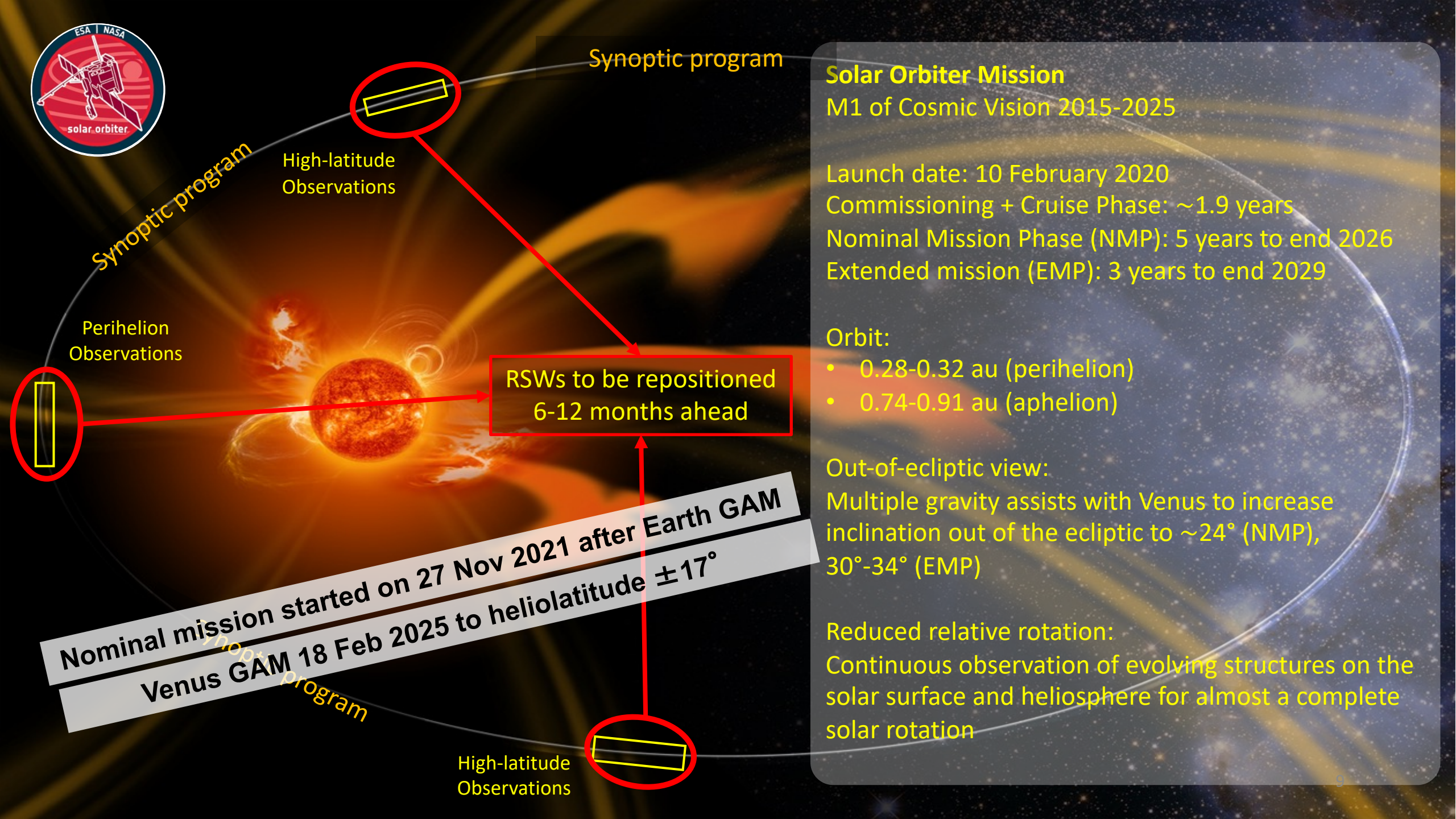
The work to understand a eventually correct the issue is in progress.







Courtesy of V. Andretta



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 to end 2026
Extended mission (EMP): 3 years to end 2029

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° (NMP), 30°-34° (EMP)

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

Metis observation

Solar Orbiter is on the ecliptic plane until February 2025.

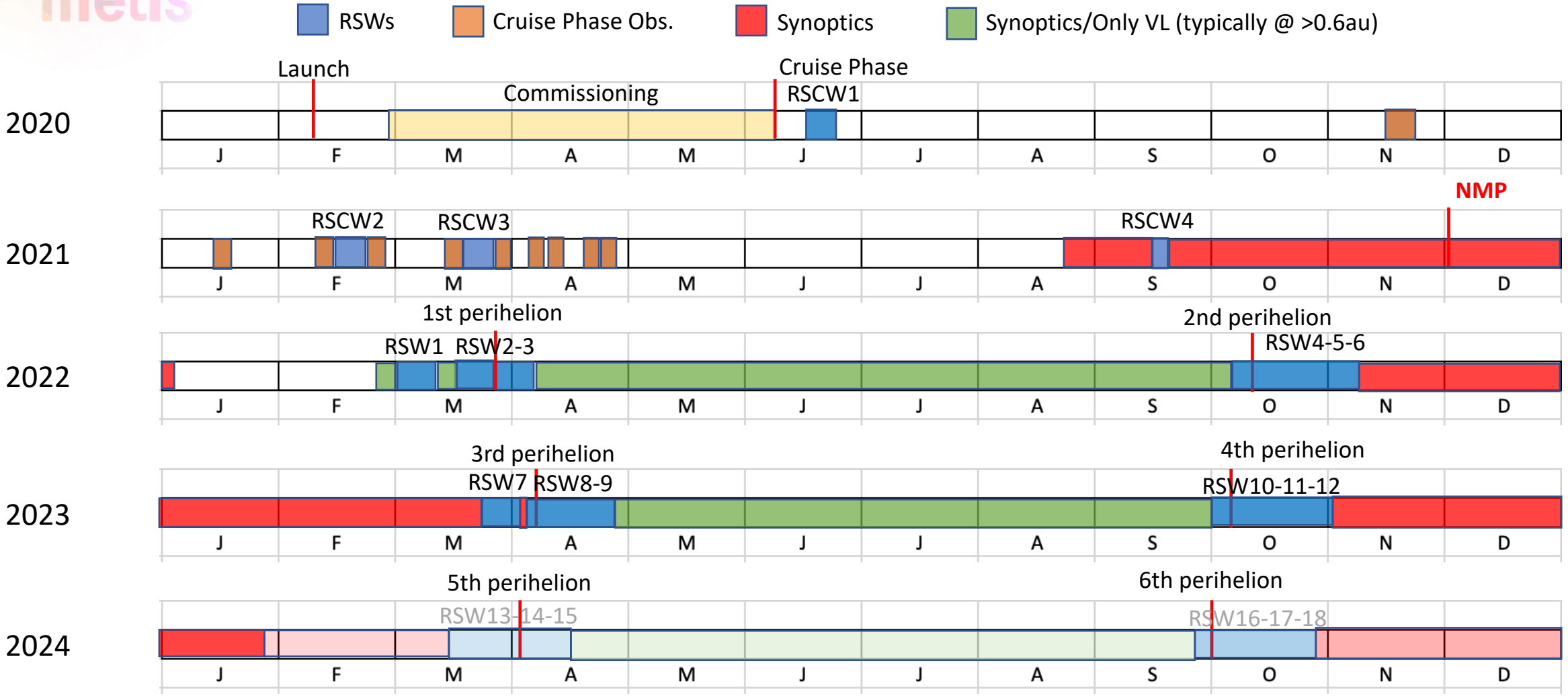
Observations strongly limited by telemetry

Metis observations performed:

- during **Remote Sensing Windows (RSWs)** within the framework of the **Solar Orbiter Observing Plans (SOOPs)** with payload shared objectives (30 days/orbit)
- along the rest of orbit as **synoptics**
- During **Target of Opportunities** (UV star observations and joint observations with other assets)

Metis activity in the Cruise Phase and the first orbit of the Nominal Mission Phase (NMP)

Metis observations are listed in the Metis webpage: http://metis.oato.inaf.it/obs_summary_new.html#



Interruptions in the flow of observations due to: **unexpected Metis and/or S/C switch off – S/C off-pointing**

Summary of proposed SOOPs

Below the proposed SOOPS for LTP15 perihelion in the second trimester of 2024

Last year with SOLO on the ecliptic

- **L_BOTH_HRES_LCAD_CH-Boundary-Expansion** Cadence 10 min VL pB 2x2, 1 UV 2x2
  MAGTOP high resolution,
  (Coord. R. Susino)

- **R_FULL_LRES_MCAD-Probe-Quadrature C**adence 30s VL tB 2x2, UV 2x2
  (Coord. D. Telloni)

- **R_FULL_HRES_HCAD_Density-Fluctuations** VL FP 1x1 + UV 2x2 high temporal cadence (1-20 s, 2 min, 5 min)
  (Coord. V. Andretta)

- **L_FULL_HRES_HCAD_Eruption-Watch** 10 min cadence binning 4x4 VL pB + UV
  (Coord. C. Sasso)

- **COORD_CALIBRATION** Intercomparison with LASCO and STEREO in opposition
  15 min cadence binning VL pB 1x1 UV 2x2
  (Coord. A. Burtovoi)

R_SMALL_HRES_LCAD_Composition_vs_Height (SPICE led)

Science Activity Plan (SAP)

Synoptics

- **Standard synoptic:** **R_FULL_LRES_LCAD_RS-Synoptics** VL pB + UV Cadence 1h
  binning VL 2x2 UV 4x4

- **High cadence synoptic:** **R_FULL_LRES_LCAD_RS-Synoptics-High** VL pB + UV Cadence 1h
  binning VL 2x2 UV 4x4

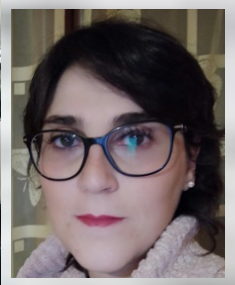
- **High cadence synoptic:** **R_FULL_LRES_LCAD_RS-Synoptics-Low** VL pB + UV Cadence 2-3h
  binning VL 2x2 UV 4x4

(Coord. R. Susino)

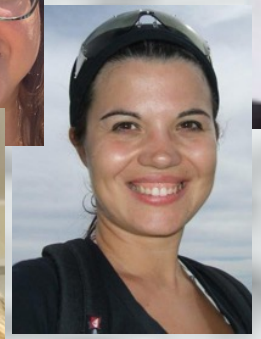
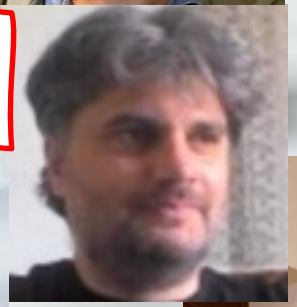
SOLAR ORBITER REMOTE-SENSING SYNOPTIC PROGRAMMES

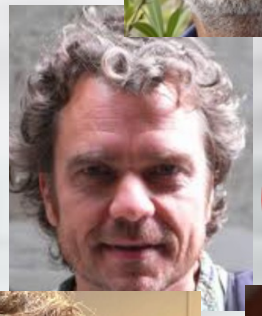
No UV images when sun distance >0.6au

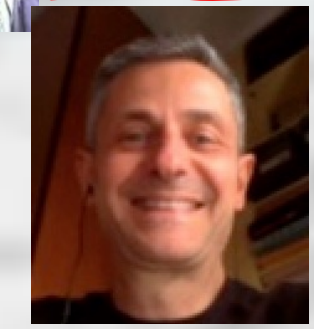
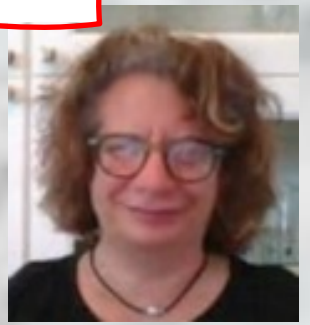
Metis operations



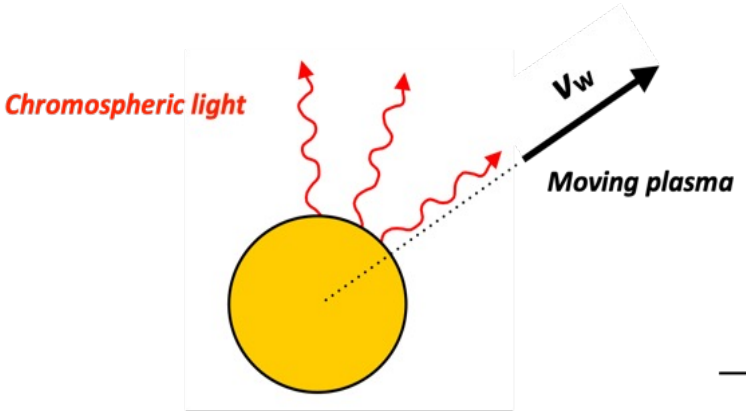

Weekly planning

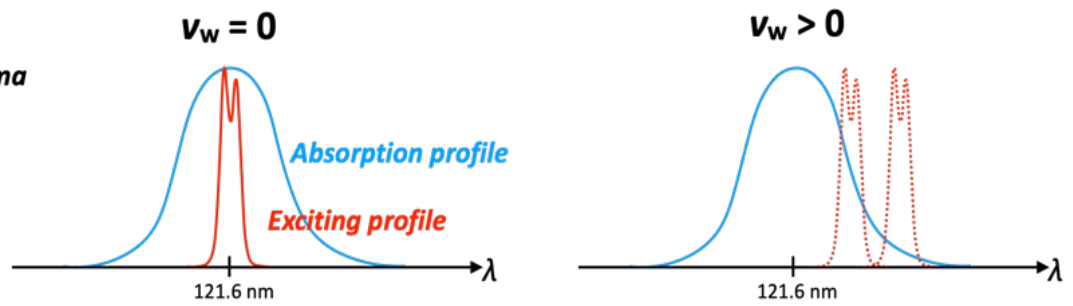
Ground segment + Pipelines + data validation

ALTEC Archive and data processing pipeline

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)



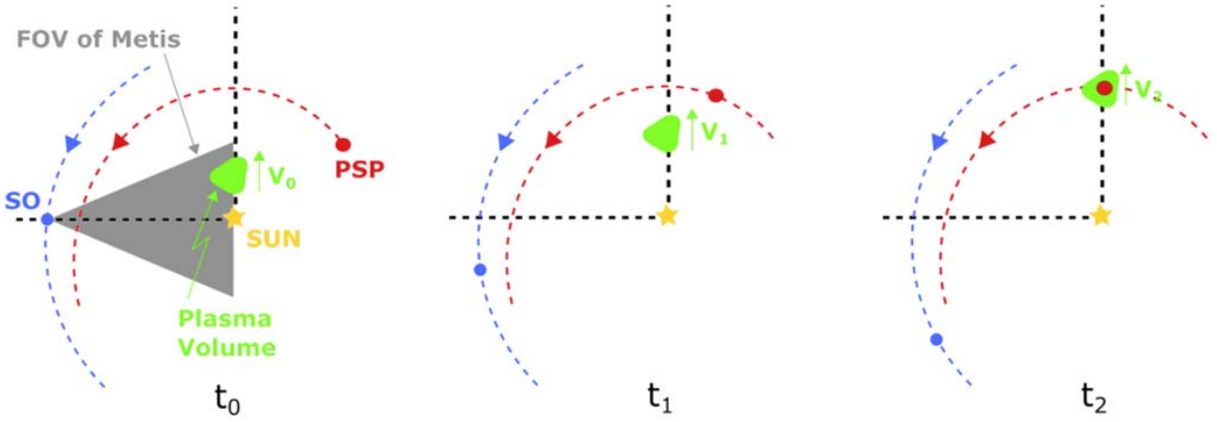


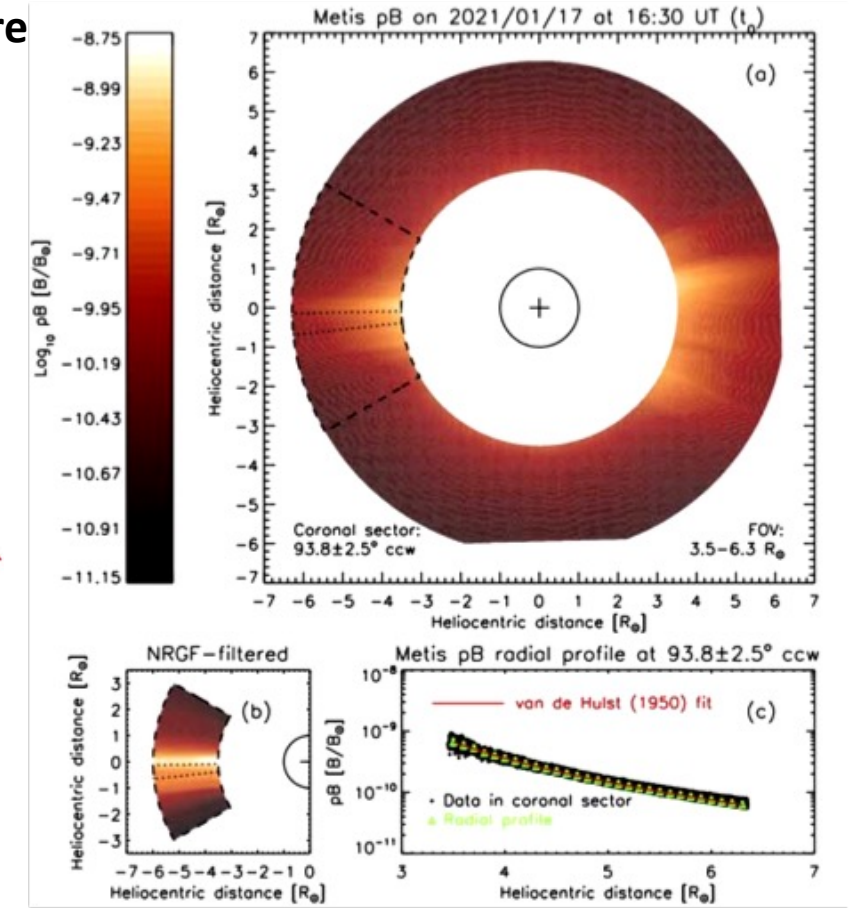
Antonucci+2023
Telloni+ 2023
Romoli+ 2021
Capuano+ 2021

Solar-wind diagnostics with in-situ & coronal data

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

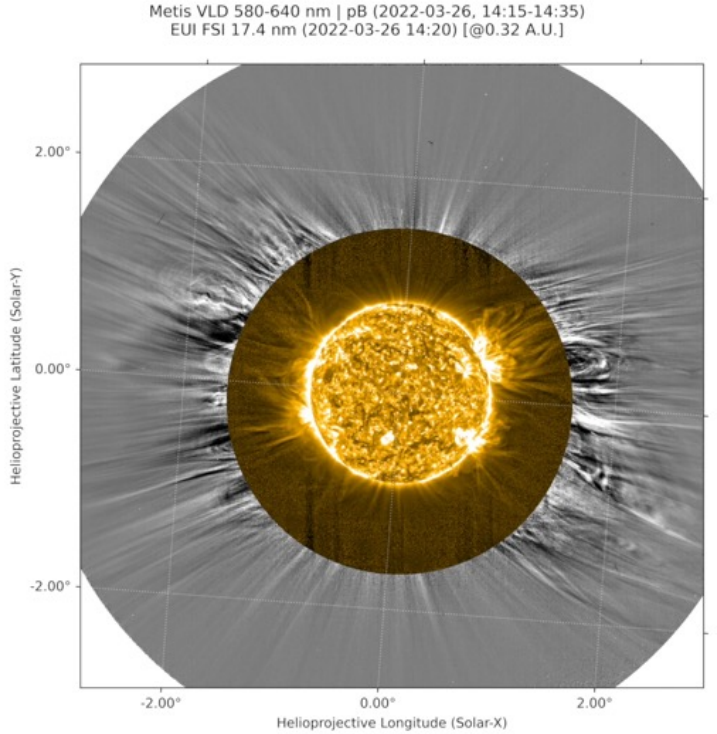
Remote sensing and in-situ coordinated measurements, like during **quadratures between Solar Orbiter and PSP**, but not only, provide a valuable tool to probe the physical parameters of the solar wind throughout the solar corona and the heliosphere



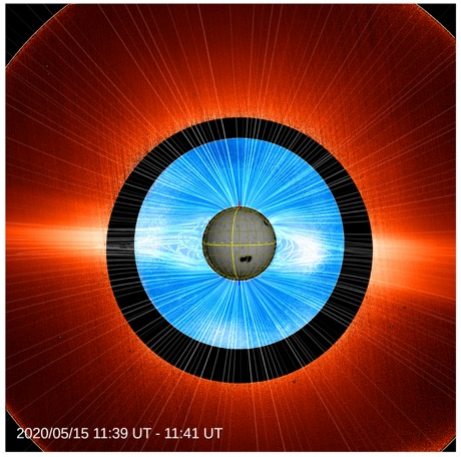


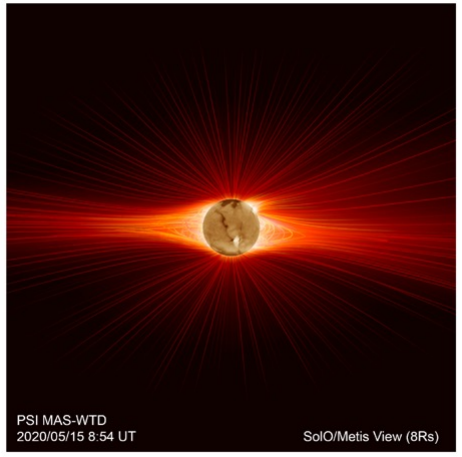
Telloni+ 2021
Biondo+ 2022
Telloni+ 2022
Niembro+ 2023
Telloni+ 2023
Telloni+ 2023

Magnetic-field morphology

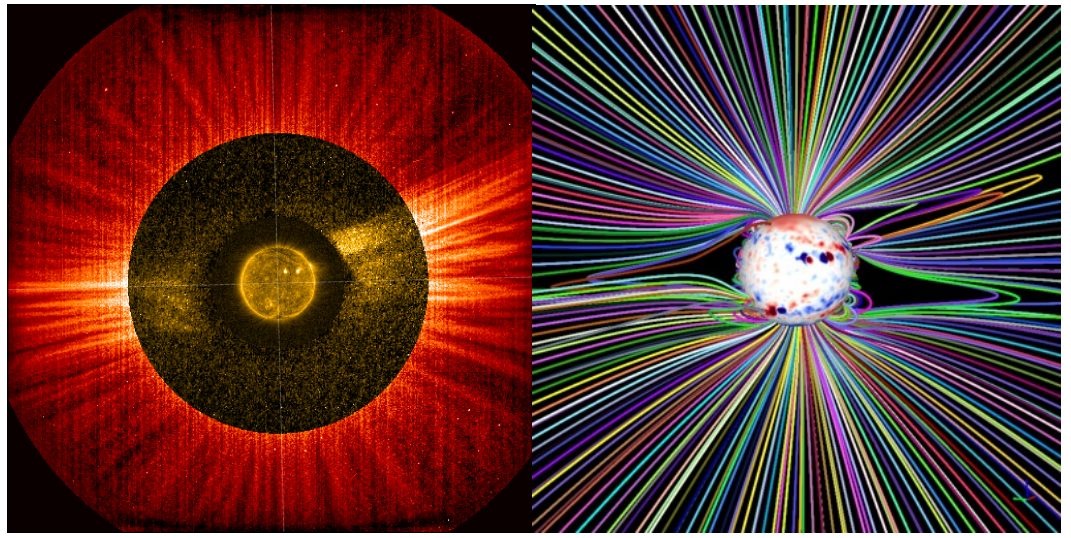


- Metis produces synoptic maps that combined with images of other space and ground-based instruments and magnetic-field extrapolations (WSO + PSI) can provide from the ecliptic and out-of-the ecliptic plane:
  - **the overall magnetic configuration**
  - **tomographic reconstructions of electron density** (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





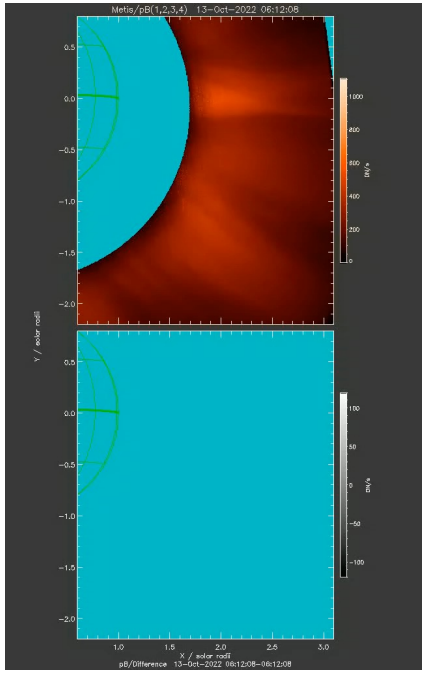
Romoli+ 2021
Antonucci+ 2023



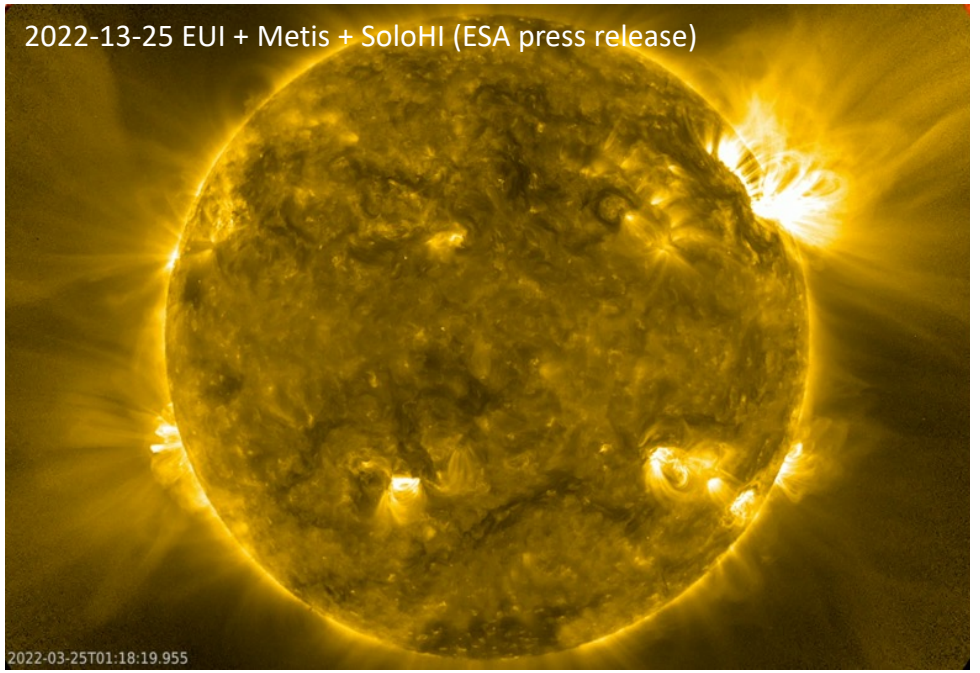
Abbo+ submitted
Vasquez+ in preparation

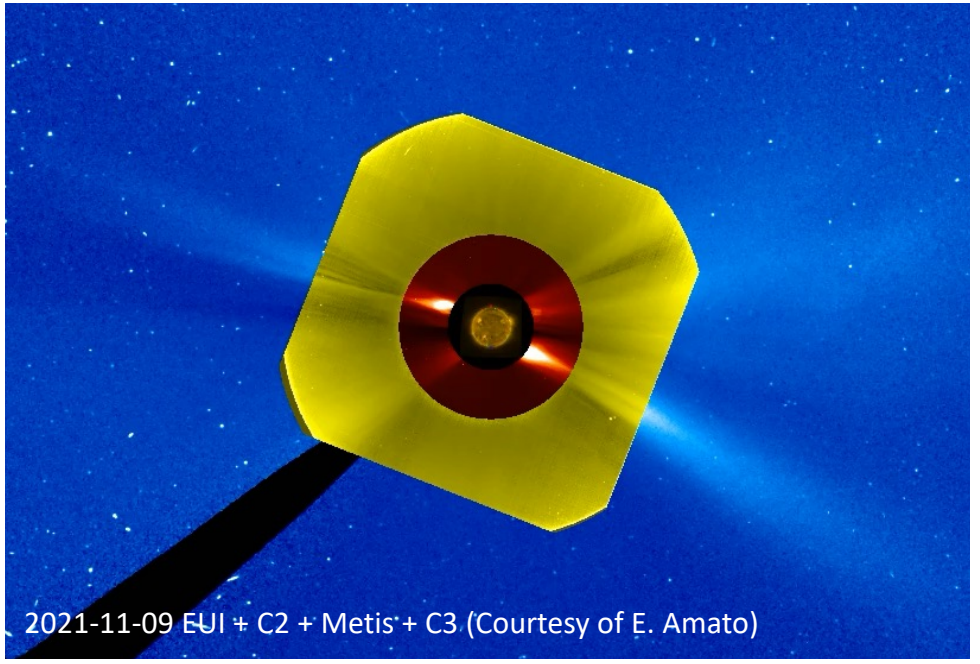
Solar transients

- 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



2022-10-13 Metis
Courtesy of V. Andretta





- 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 of the the physical parameters** of the event
- **Synergies** with EUI/FSI (coronagraphic mode), SoloHI, STEREO, and LASCO

Frassati+ 2023
Heinzel+ 2023
Zimbardo+ 2023
Rodriguez+ 2023
Andretta+ 2021
Russano+ 2023
Niembro+ 2023
Mierla+ 2023
Bemporad+ 2022

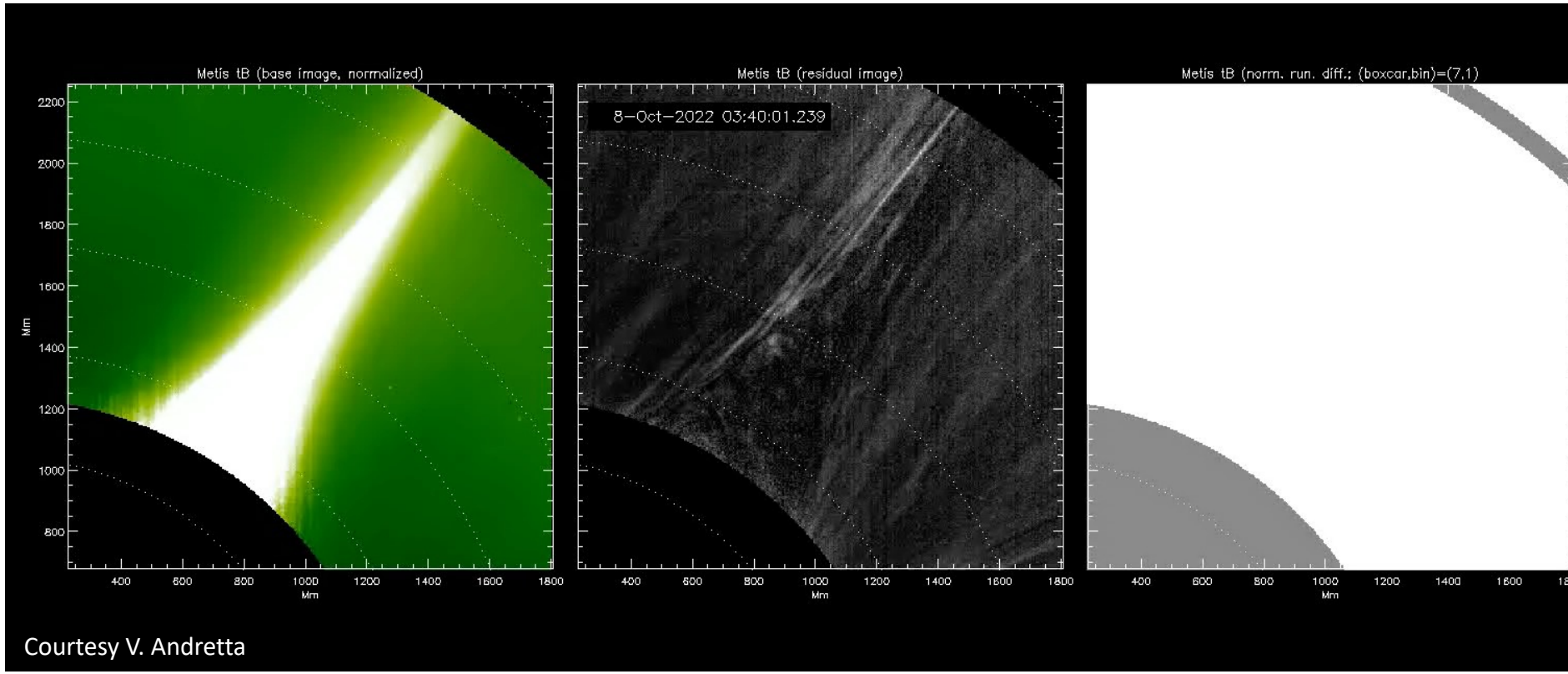
Density fluctuations

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 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



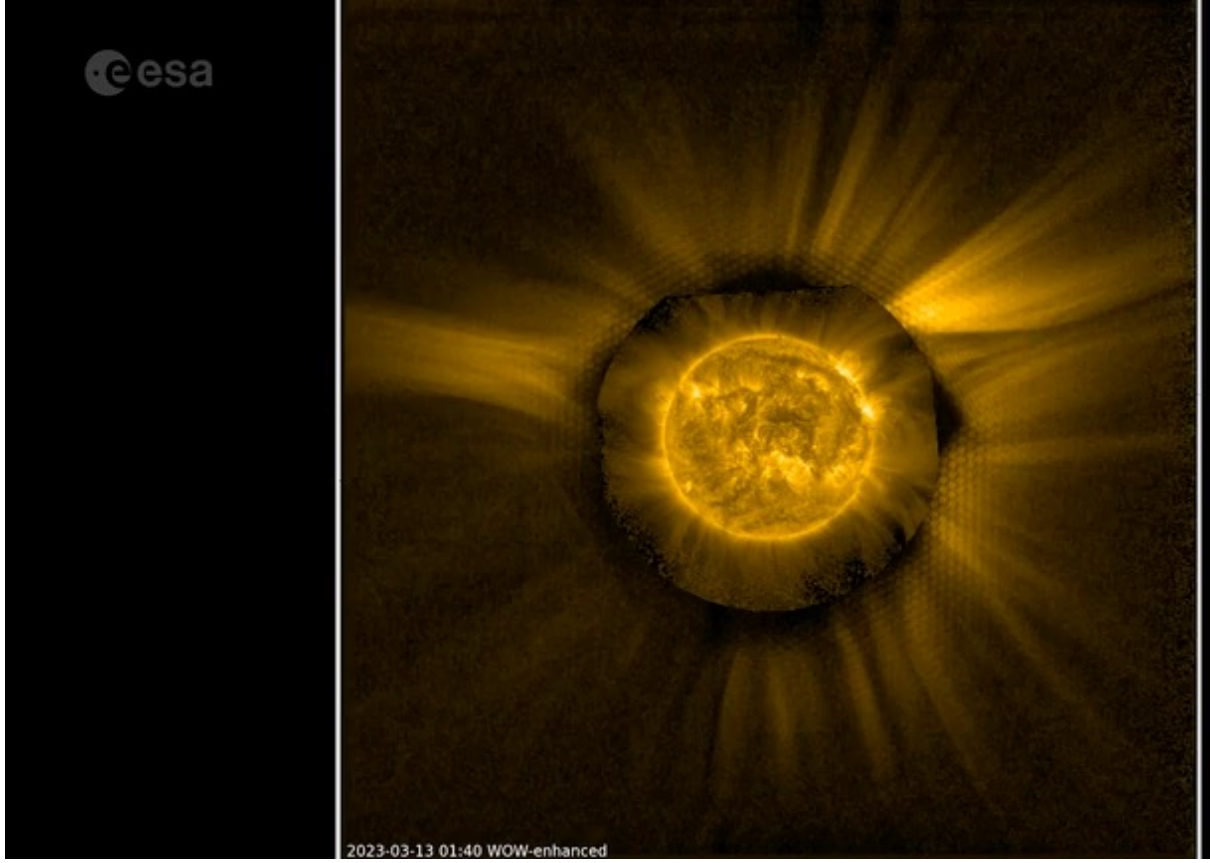
Courtesy V. Andretta

Andretta+ 2023, in preparation

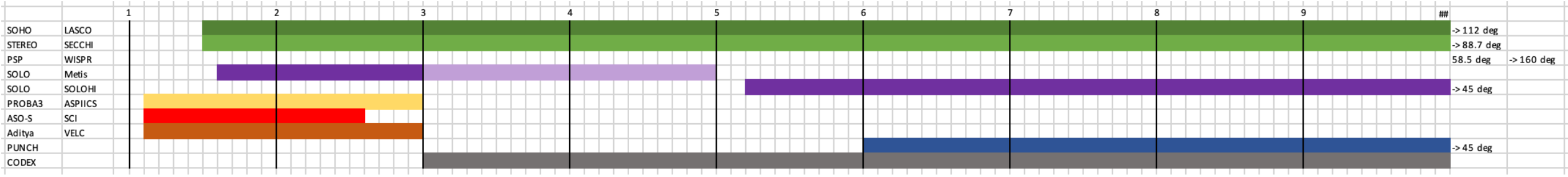
Synergies

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 L1**: 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

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Metis science topics working groups

TT1 - Wind diagnostics (R. Susino)
a. **Electron density (and electron temperature)** (S. Fineschi)
b. **Hydrogen density** (J.C. Vial)
c. **Wind velocity with Doppler dimming** (R. Susino)
EUI, SPICE

TT2 - F-corona (F. Landini)
SOLOHI

TT3 - Combined synoptics (L. Teriaca)
EUI, SOLOHI,PHI

TT4 - Helium Diagnostics (V. Andretta)
EUI, SPICE

TT5 - Image enhancements (F. Frassetto)
SOLOHI

TT13 - Cosmic Rays (C. Grimani)

TT14 - Sun grazing comets and other solar system bodies (V. Da Deppo)

TT6 - Solar Wind (D. Telloni) SW sources

TT7 - Large scale magnetic configuration and evolution, Streamers and pseudo-streamers (L. Strachan) PHI, EUI, STEREO, LASCO, SOLOHI, 3D

Stationary corona
O1 Wind
O4 MagField

TT8 - CMEs, prominence eruptions and blobs (P. Heinzel) PHI, EUI, SPICE, SOLOHI

TT12 - Modelling of CME propagation/evolution in corona and solar wind in connection with space weather (A. Bemporad) IN SITU

O2 Transient
O3 HEP

TT9 - Coronal shocks, particle acceleration (G. Zimbardo) IN SITU

Transient Corona

TT10 - Plasma density fluctuations and waves (G. Nisticò) IN SITU

O1 Wind

TT11 - Flux emergence, magnetic field reconnection, coronal heating, flares (F. Reale) STIX, PHI, EUI, SPICE

Plasma heating and acceleration

Synergies with several space missions:
SOHO, STEREO, SDO, *PSP, Proba3, ASO-S, Aditya, UVSC, PUNCH, CODEX, Solar C,* and Ground based telescopes

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