Solar Orbiter

Science Highlights and Mission Status

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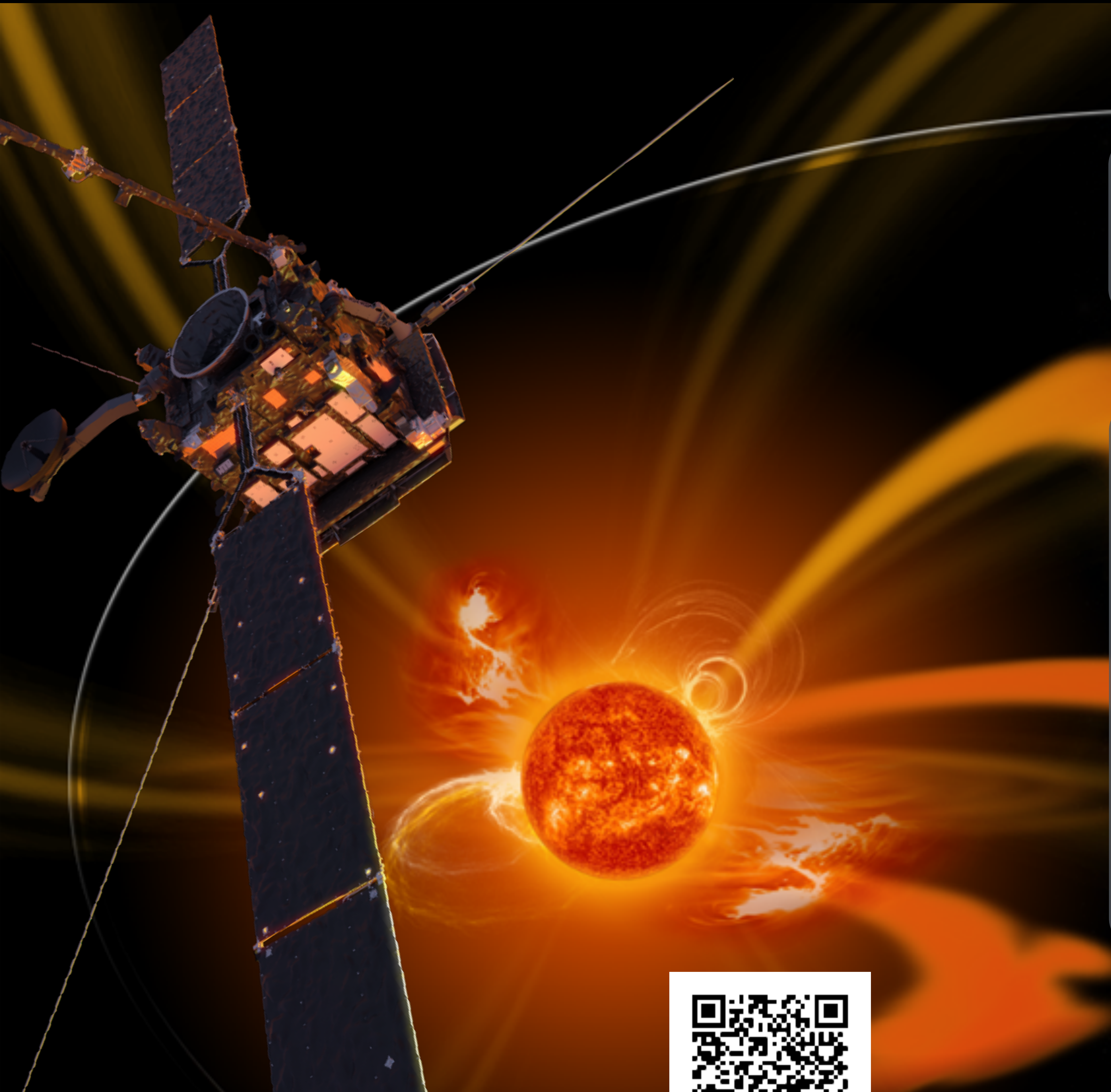
Solar Orbiter: Exploring the Sun and heliosphere



How does the Sun create and control the heliosphere – and why does solar activity change with time?

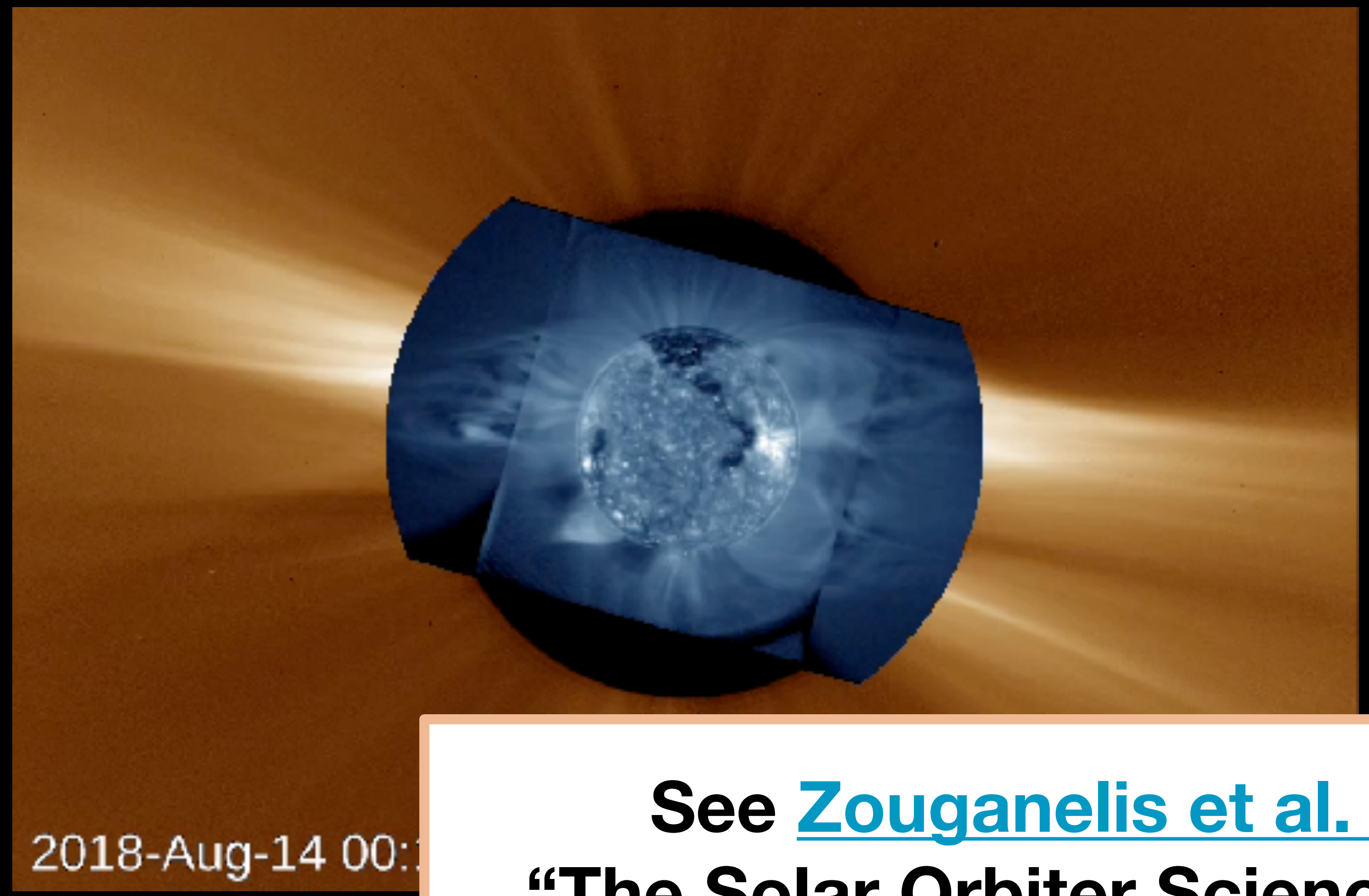
Observations

- In situ: Measurements of the solar wind plasma, fields, waves, and energetic particles as close as 0.28 au
- Remote-sensing:
  - Observe the entire Sun in visible light, UV, X-rays, including its uncharted polar regions
  - Simultaneous high-resolution imaging and spectroscopy
  - Vector magnetic field of solar photosphere
  - Image the corona and heliosphere

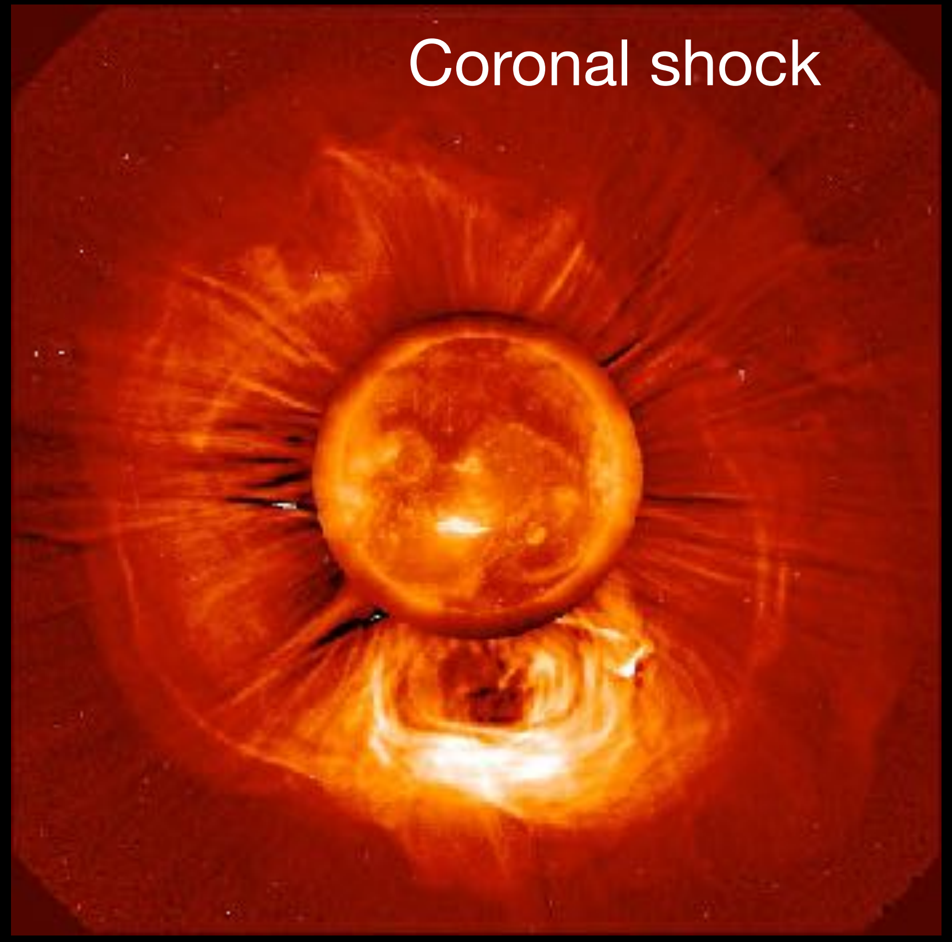
Mission overview:
Müller et al., A&A Special Issue, 2020

Top-level science objectives

#1: How and where do the solar wind plasma and magnetic field originate?

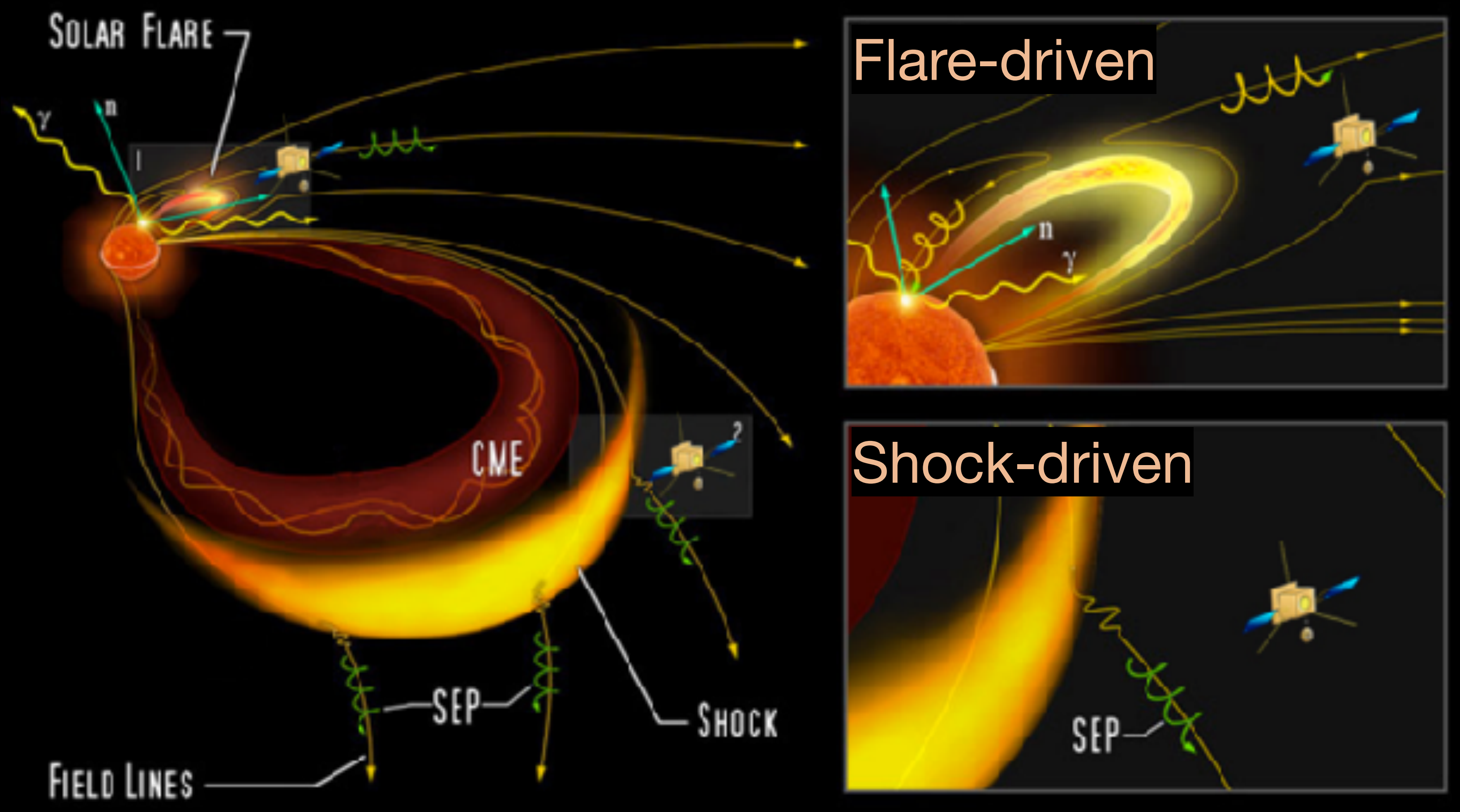


#2: How do solar transients drive heliospheric variability?

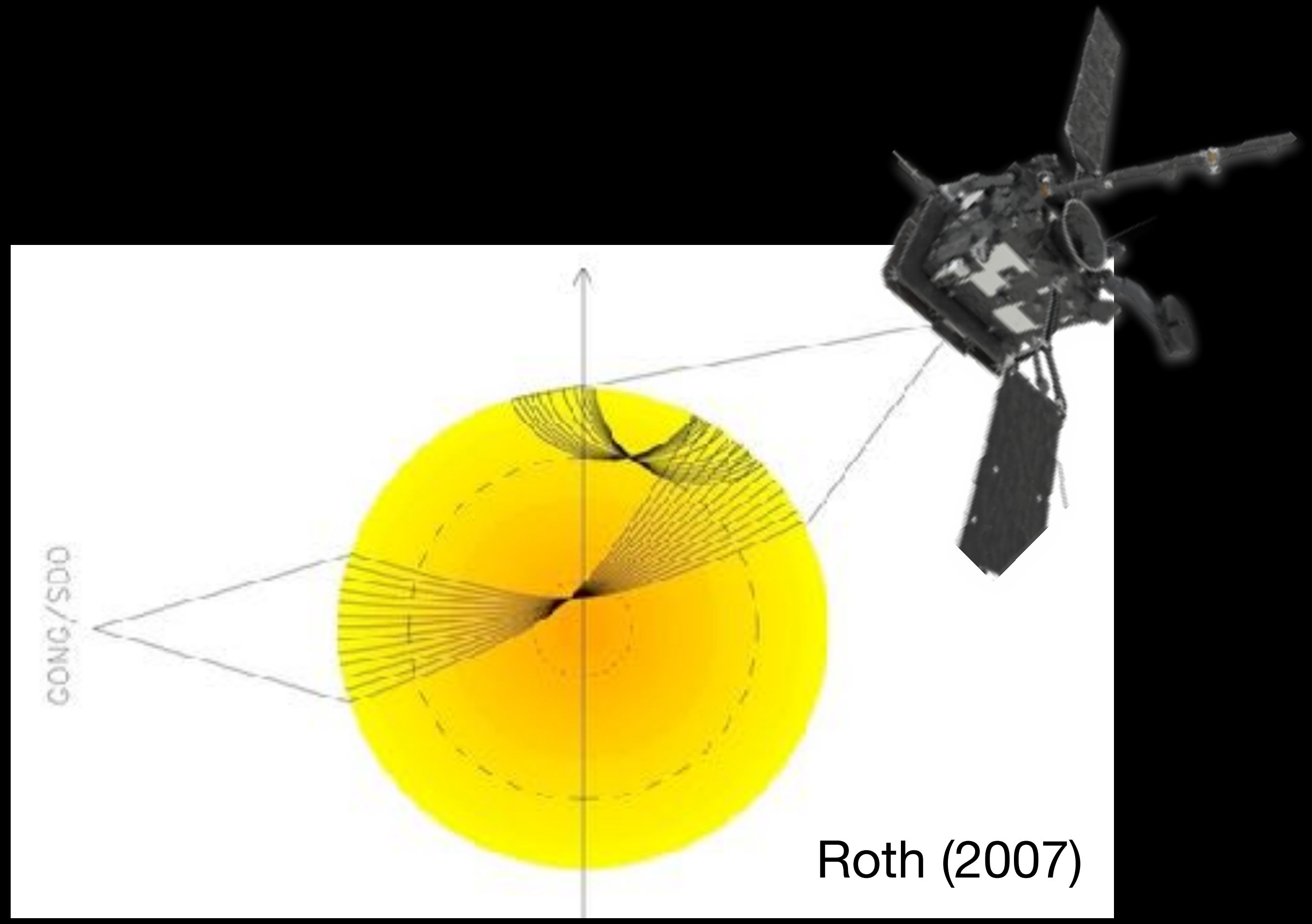


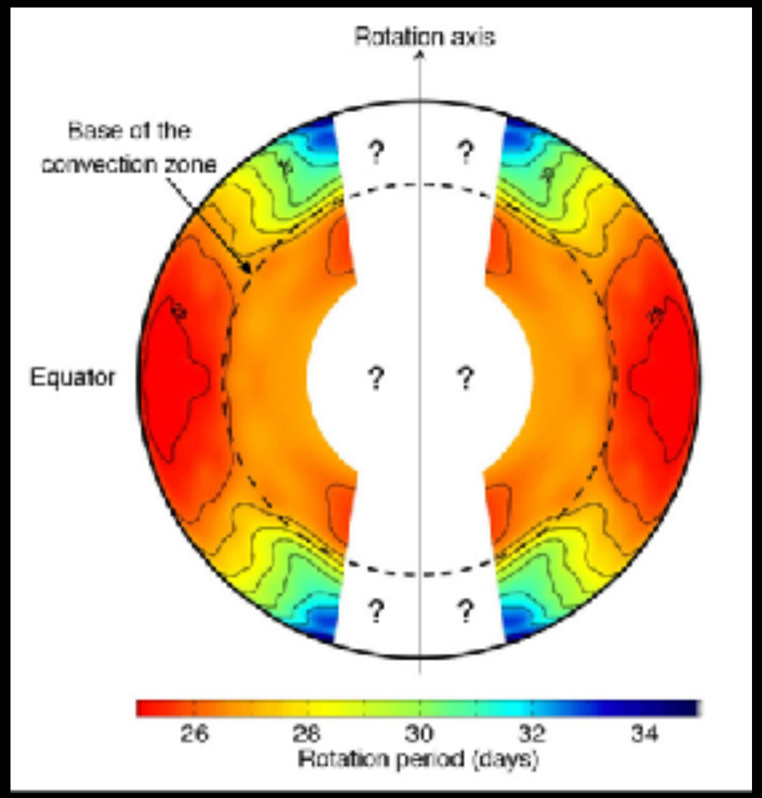
See [Zouganelis et al. (A&A 2020)](): "The Solar Orbiter Science Activity Plan. Translating solar and heliospheric physics questions into action"

#3: How do solar eruptions produce energ… that fills the heliosphere?



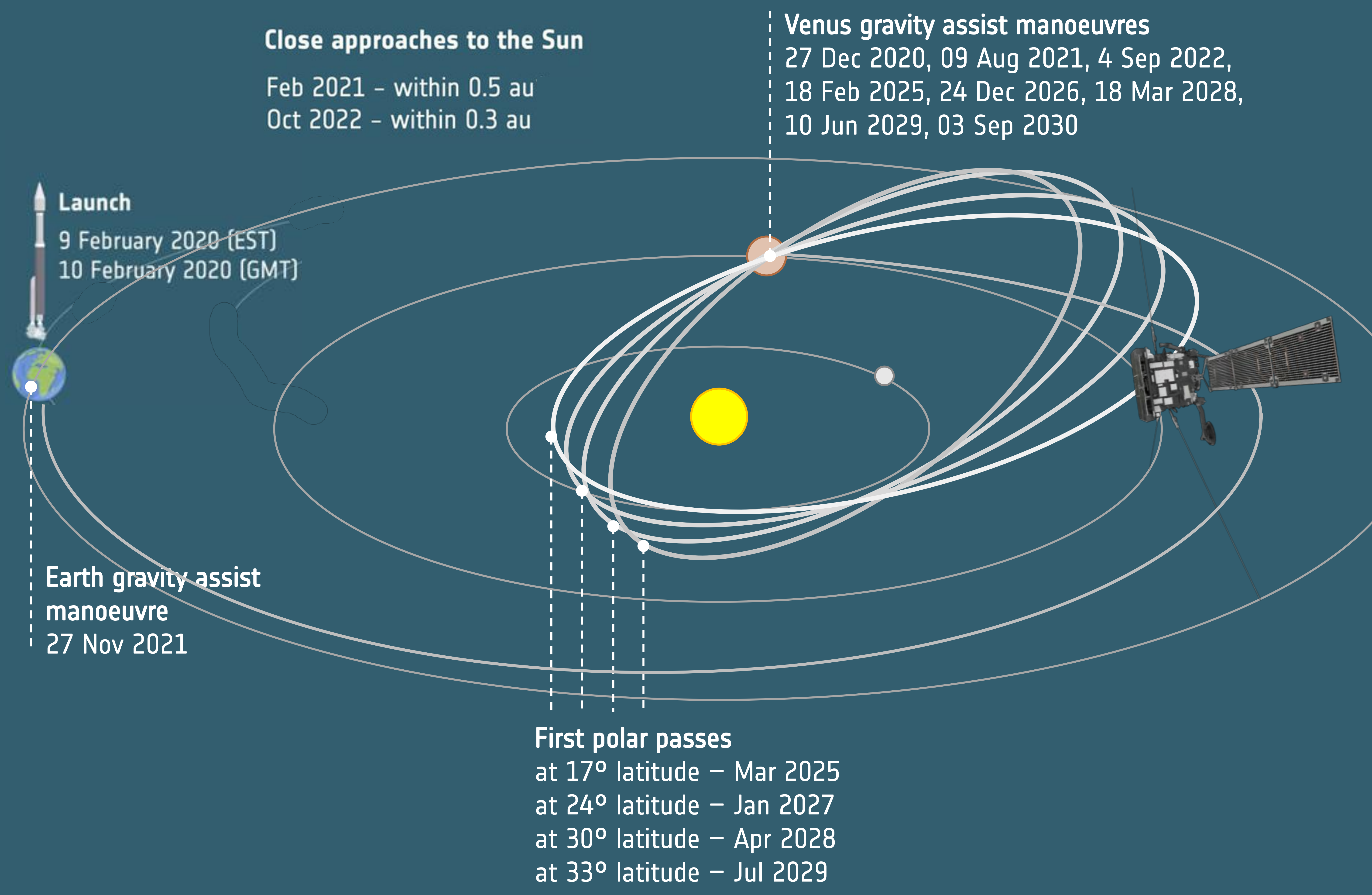
…ynamo work and drive connections … heliosphere?





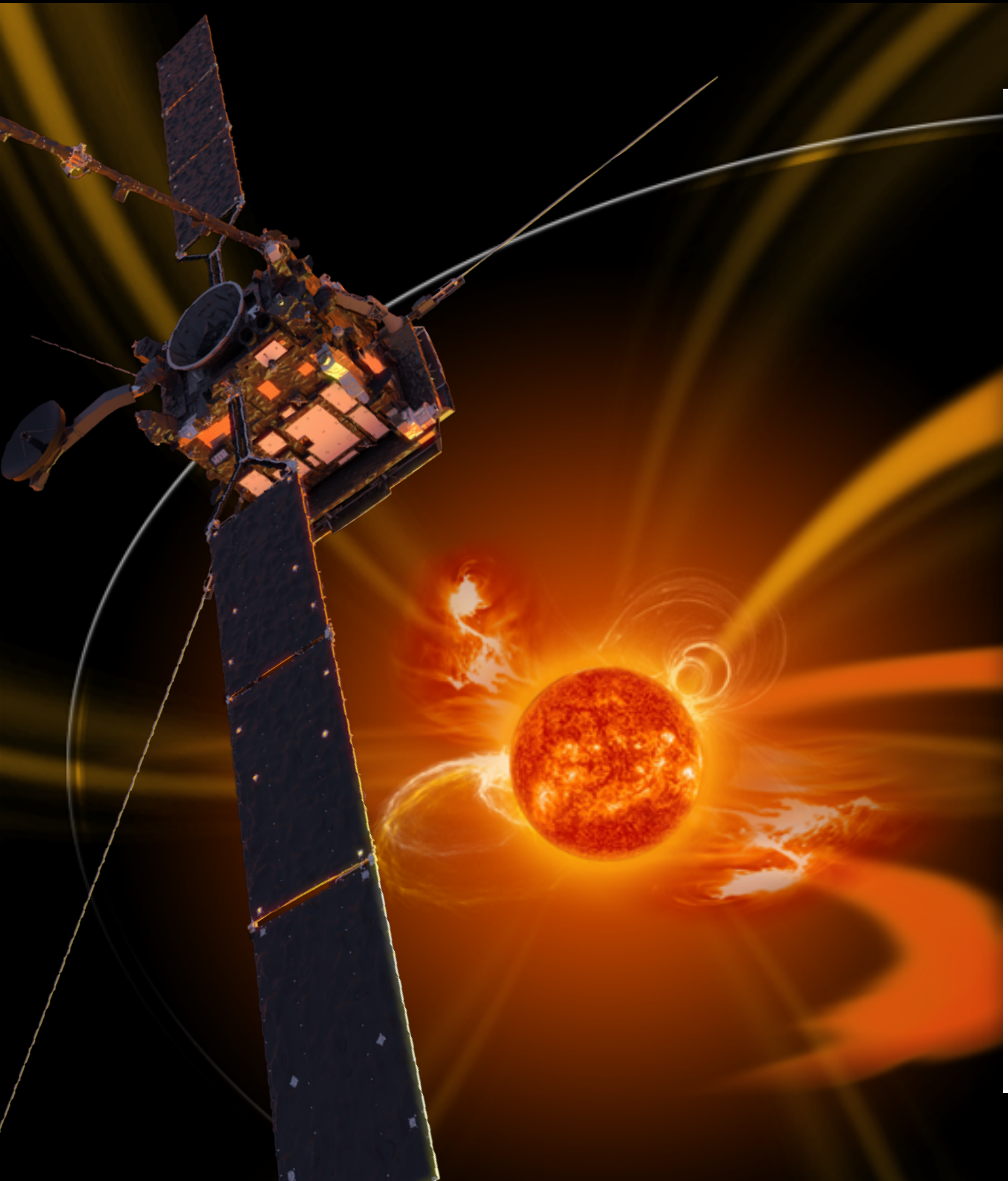
Mission Summary

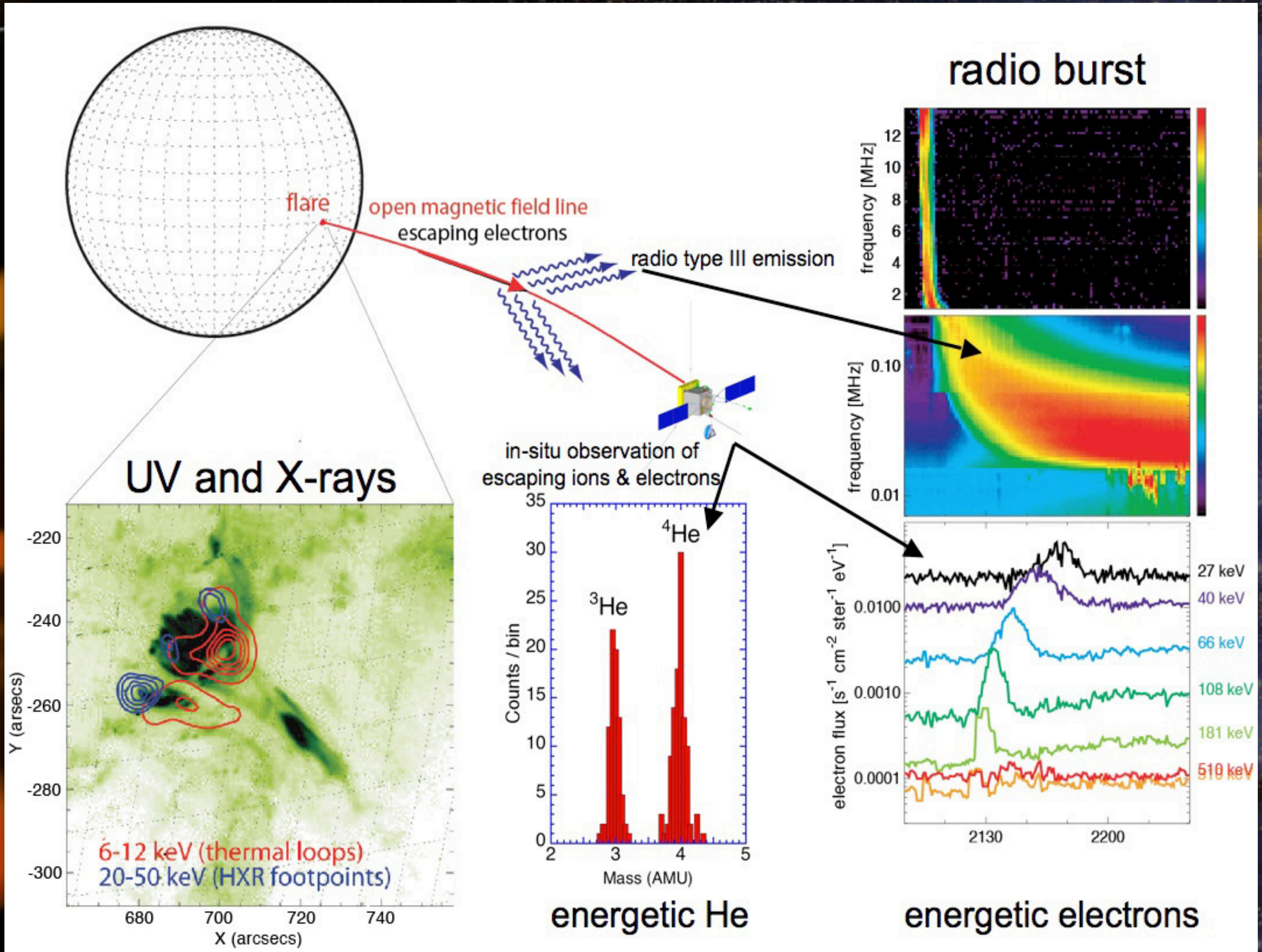
- Launch: 10 Feb 2020
- Nominal Mission Phase: Dec 2021-Dec 2026
- Orbit: 0.28-0.91 au (period: 150-180 days)
- 7 close perihelia so far
- Polar views: Venus gravity assists will increase inclination w.r.t. solar equator:
  17° in March 2025 ✔
  24° in Jan 2027 (start of extended mission)
  33° in July 2029



Solar Orbiter: Mission Timeline

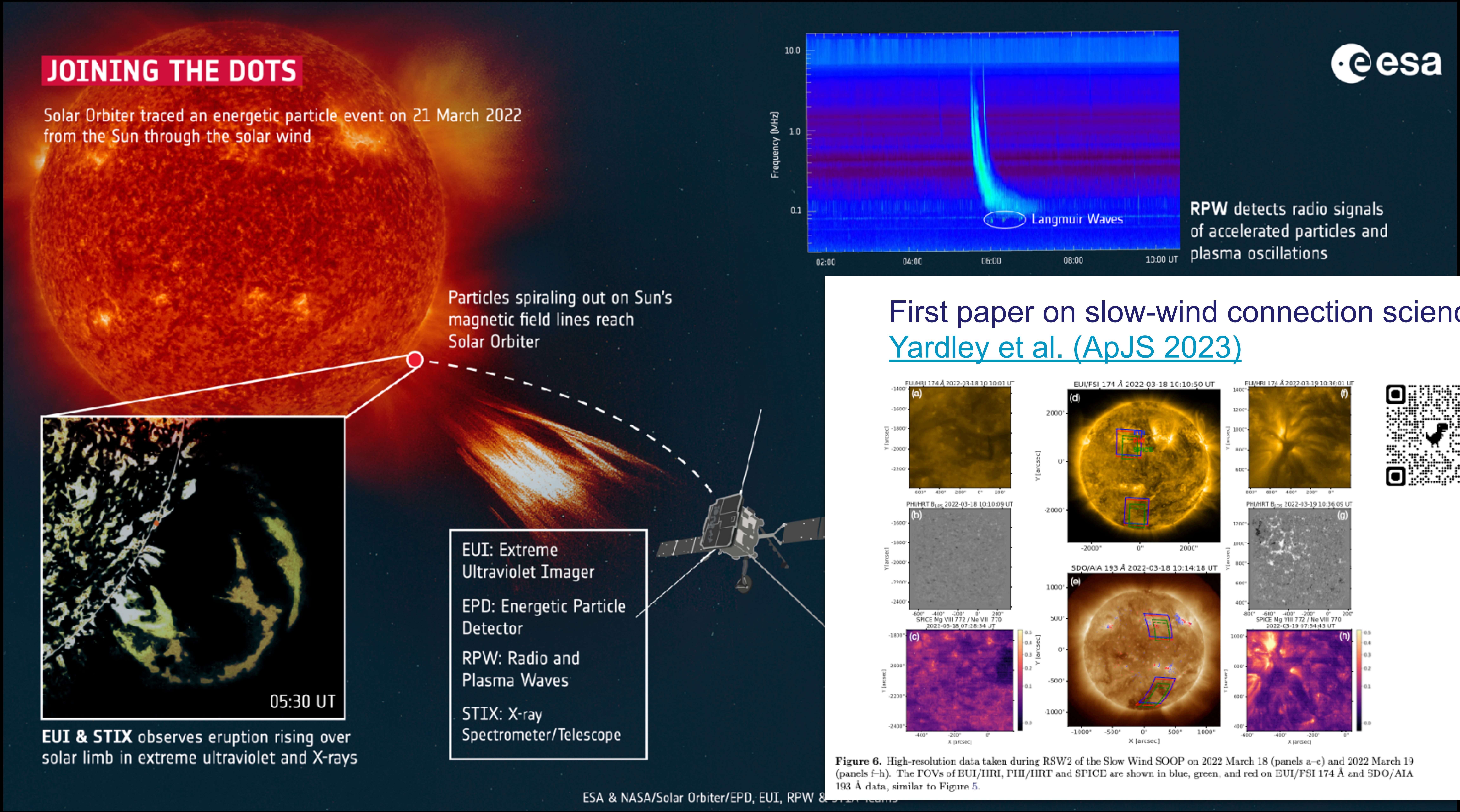
Goal: Linking the Sun to the heliosphere





[Solar Orbiter Assessment Study Report (2009)]

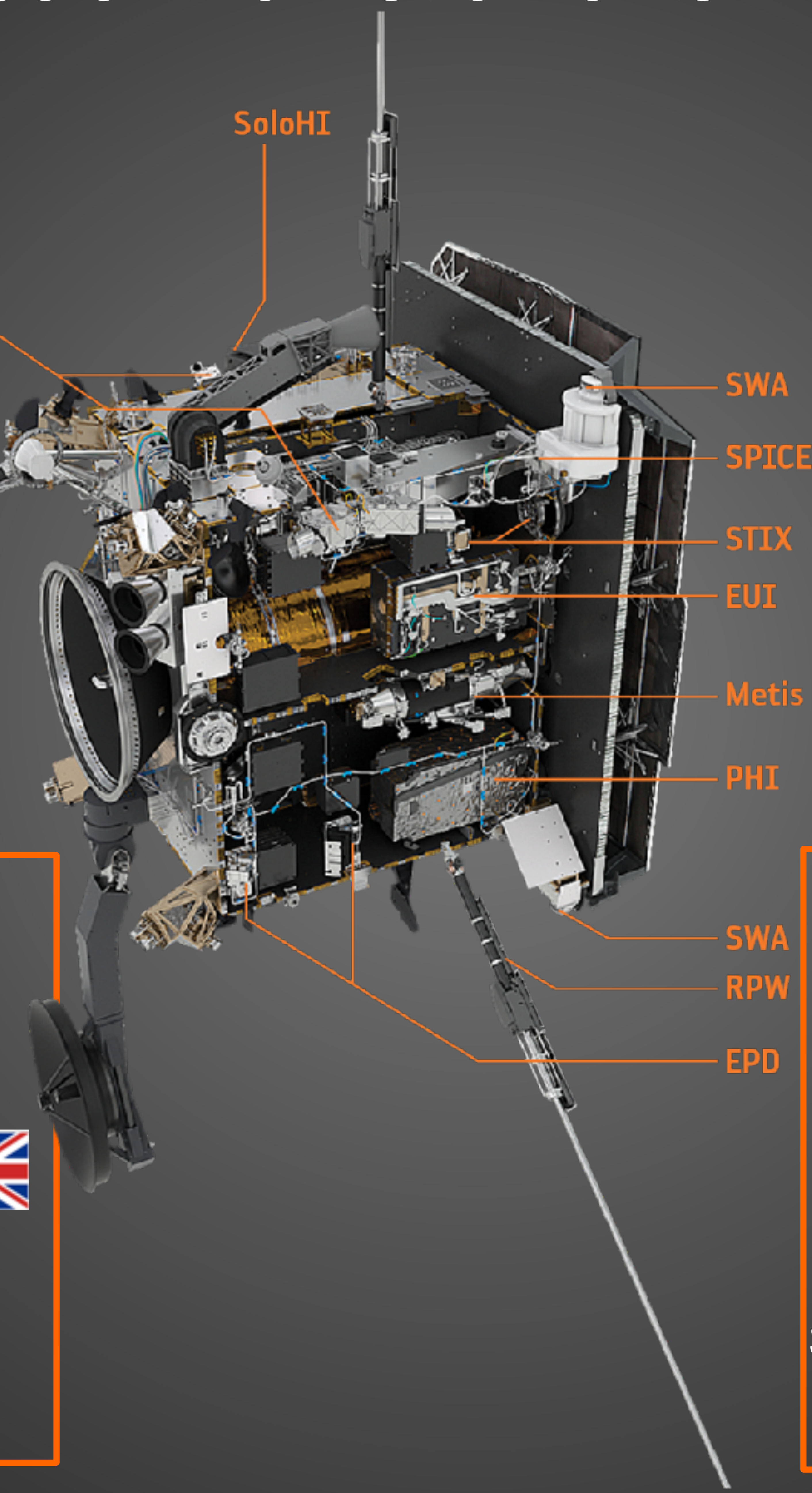
Goal: Linking the Sun to the heliosphere ✔



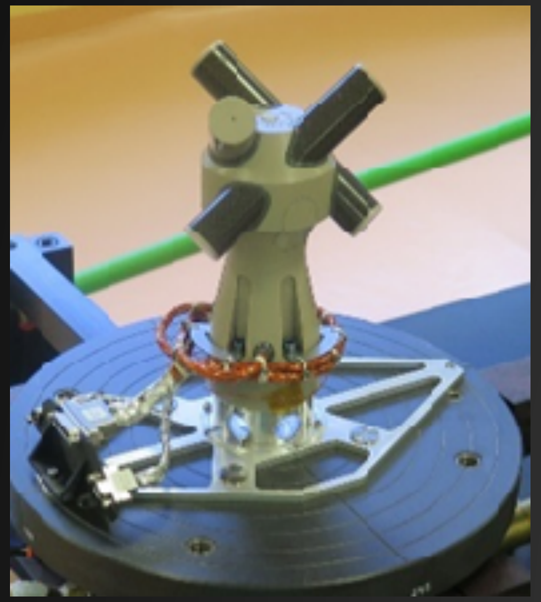
First paper on slow-wind connection science: [Yardley et al. (ApJS 2023)]

Figure 6. High-resolution data taken during RSW2 of the Slow Wind SOOP on 2022 March 18 (panels a–e) and 2022 March 19 (panels f–h). The FOVs of EUI/HRI, PHI/HRT and SPICE are shown in blue, green, and red on EUI/FSI 174 Å and SDO/AIA 193 Å data, similar to Figure 5.

Scientific instruments: in situ

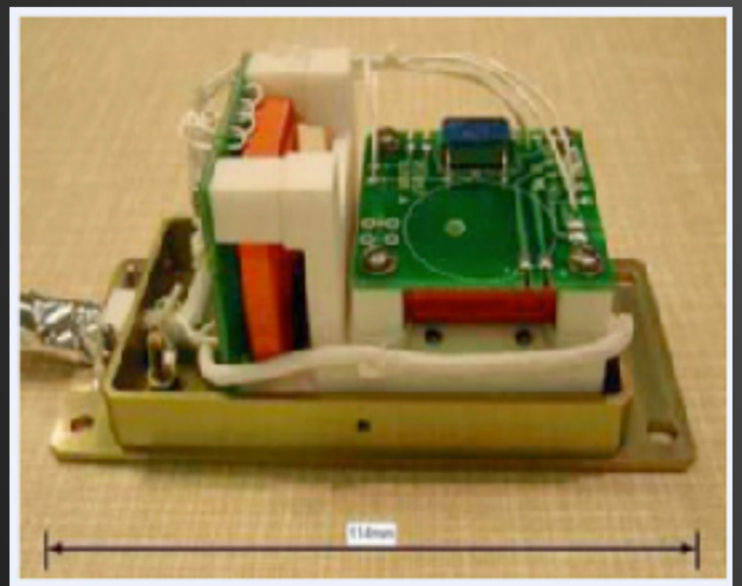


RPW: Radio & Plasma Waves



Search Coil Magnetometer

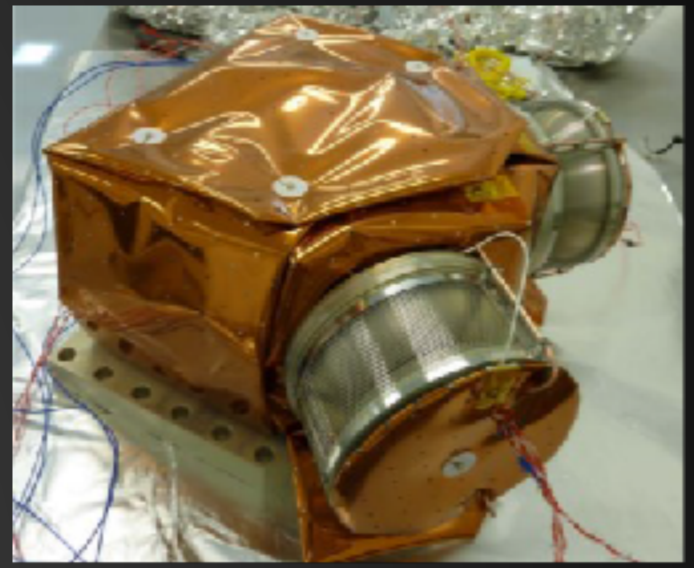
MAG: Magnetometer



Fluxgate Sensor
(cover removed)

SWA: Solar Wind Analyser

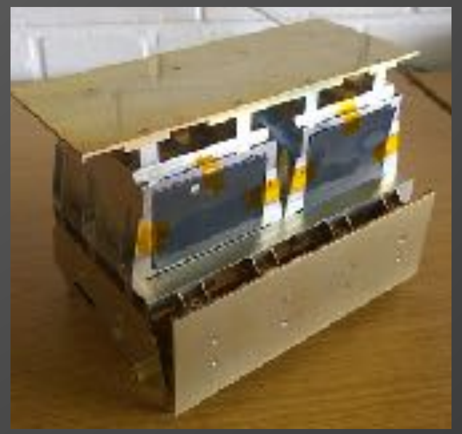
Heavy Ion Sensor



Electron Analyser System

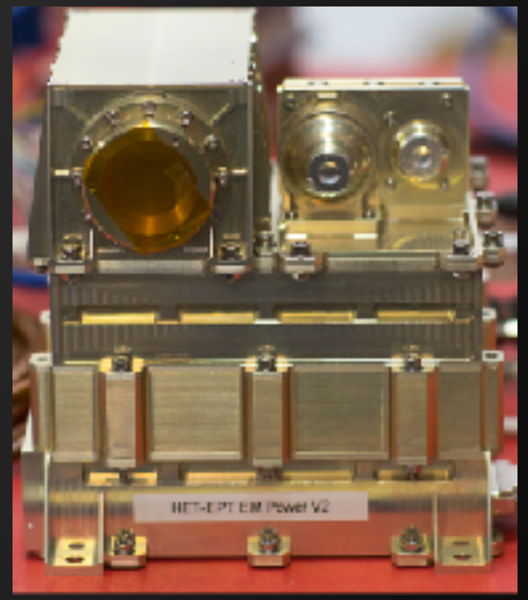
Proton Alpha Sensor

EPD: Energetic Particle Detector



Suprathermal e^- and p^+

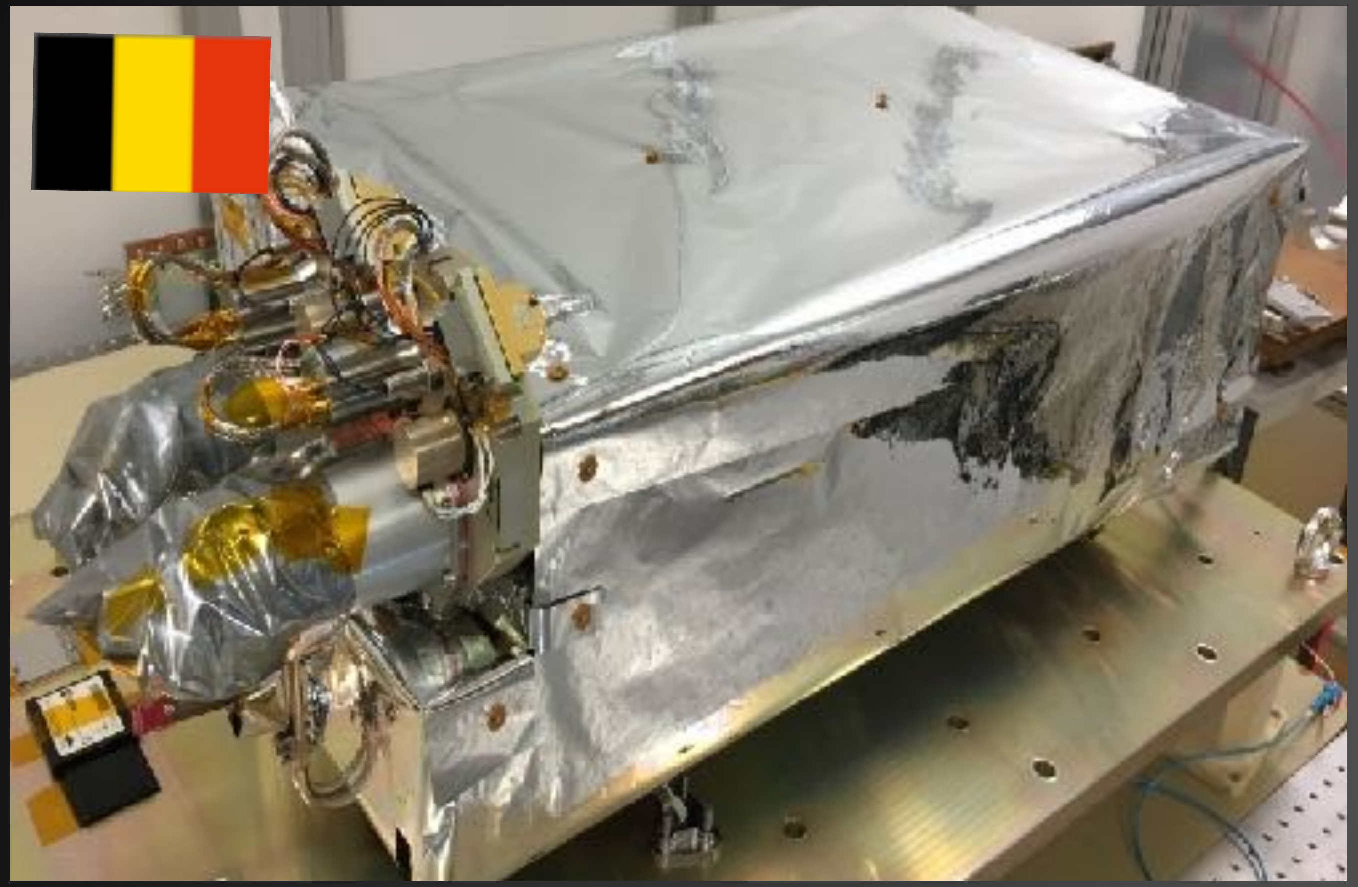
Suprathermal Ion Spectrograph



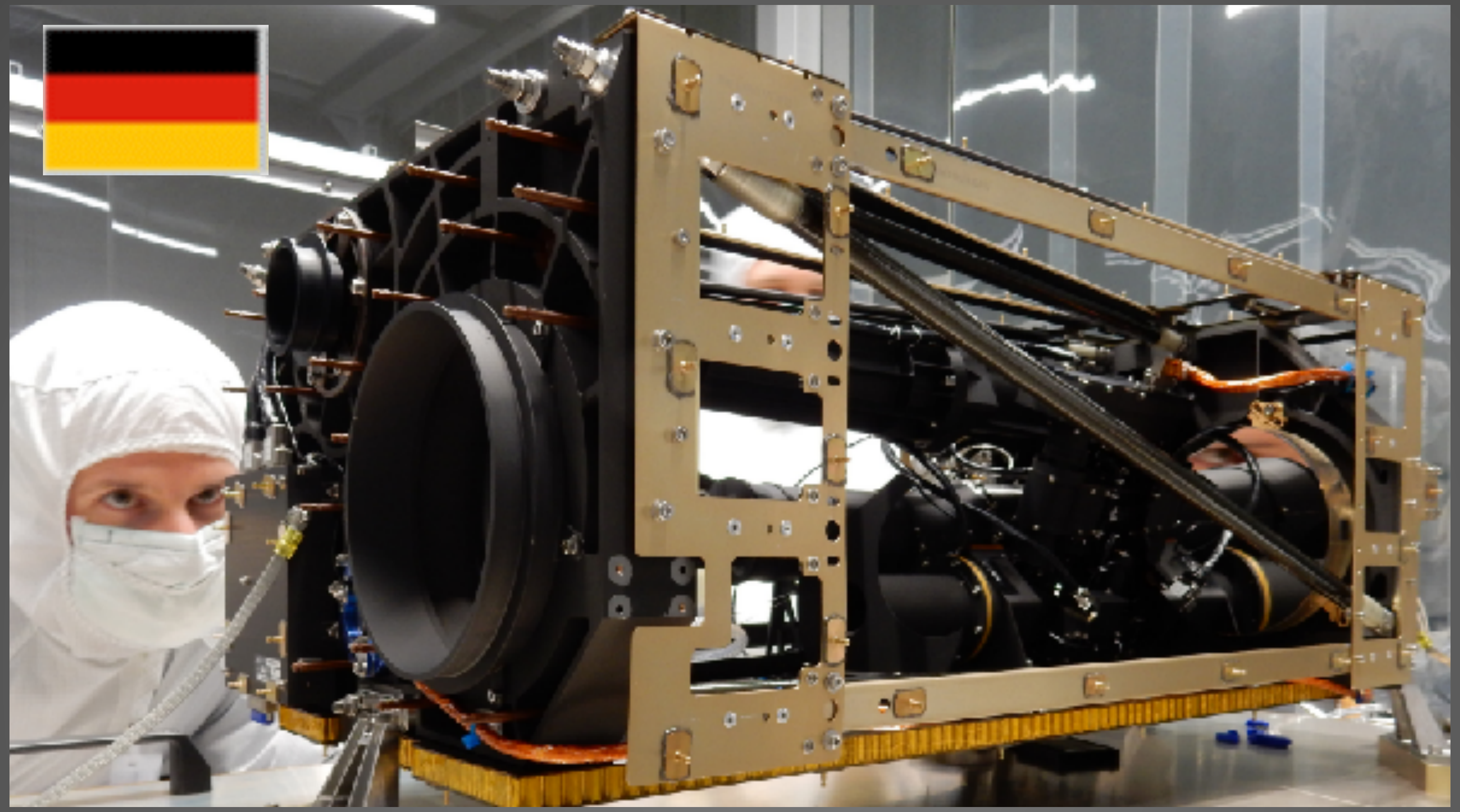
High Energy/ e^- p^+ Telescope

Scientific instruments: remote sensing

EUI: Full disk and high resolution images in EUV

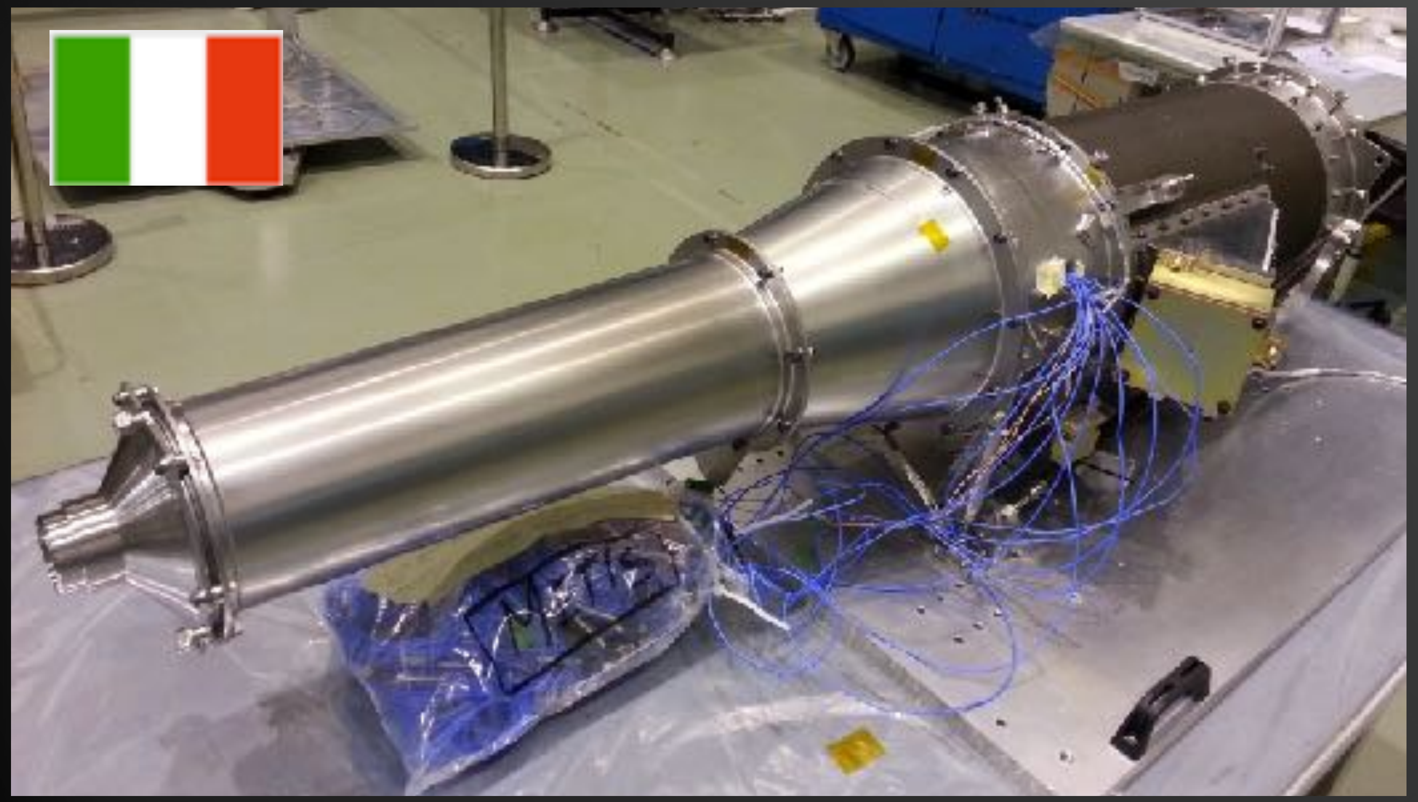


PHI: Full disk & high res vector magnetograms & velocity maps

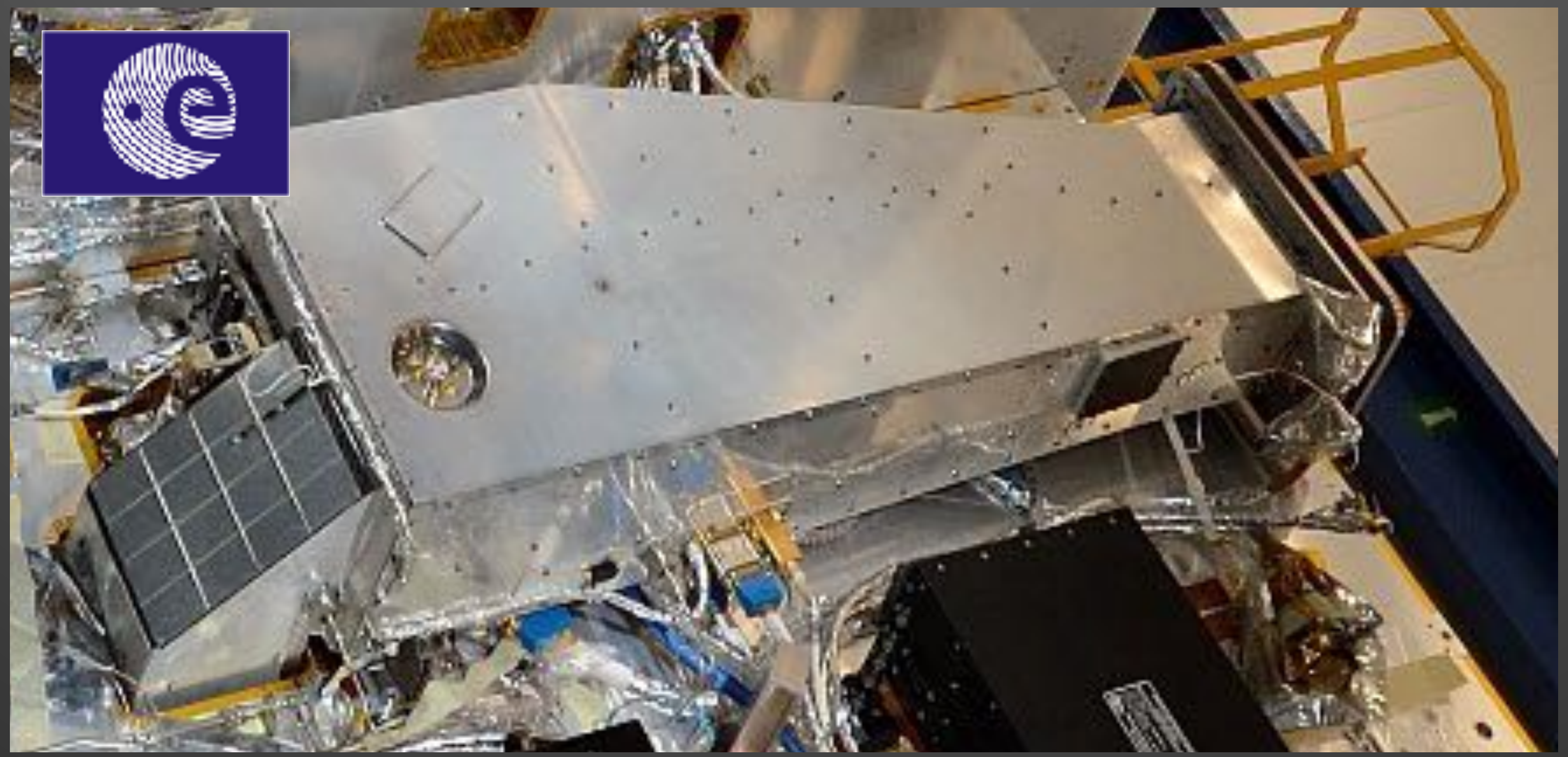


STIX: Localise flares, record X-ray spectra

Metis: Coronagraphy in UV & visible



SPICE: EUV on-disk & off-limb spectroscopy



SoloHI: Heliospheric imager

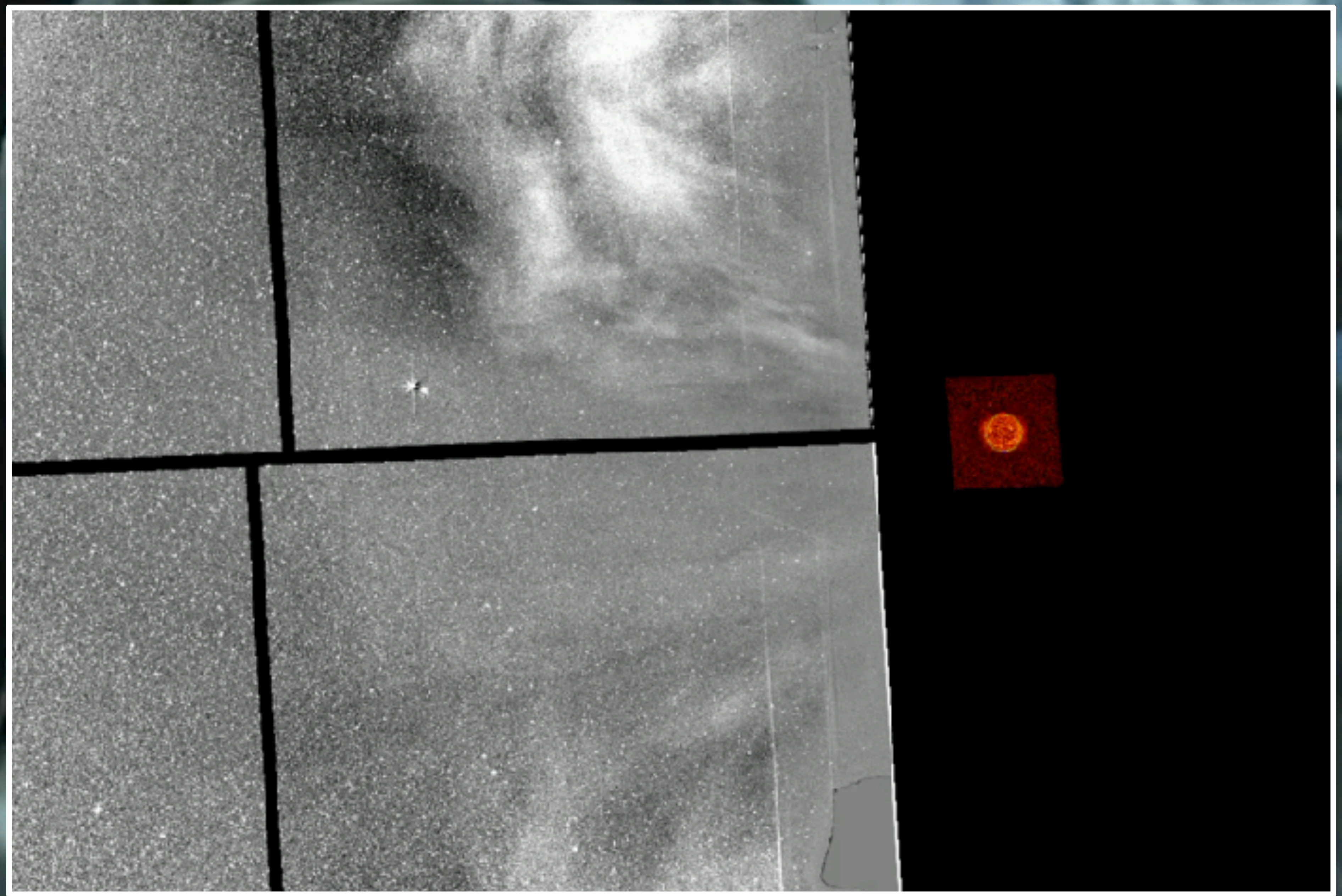
Solar Orbiter science planning: drivers

- Solar Orbiter is an encounter mission

  Telemetry varies strongly due to changing spacecraft–Earth distance
  Onboard-storage is limited
  Science opportunities vary along orbit
  Most remote-sensing during 3x10 days per orbit
  → Need to plan ahead

- 10 instruments on-board: in-situ + remote-sensing (co-pointed)

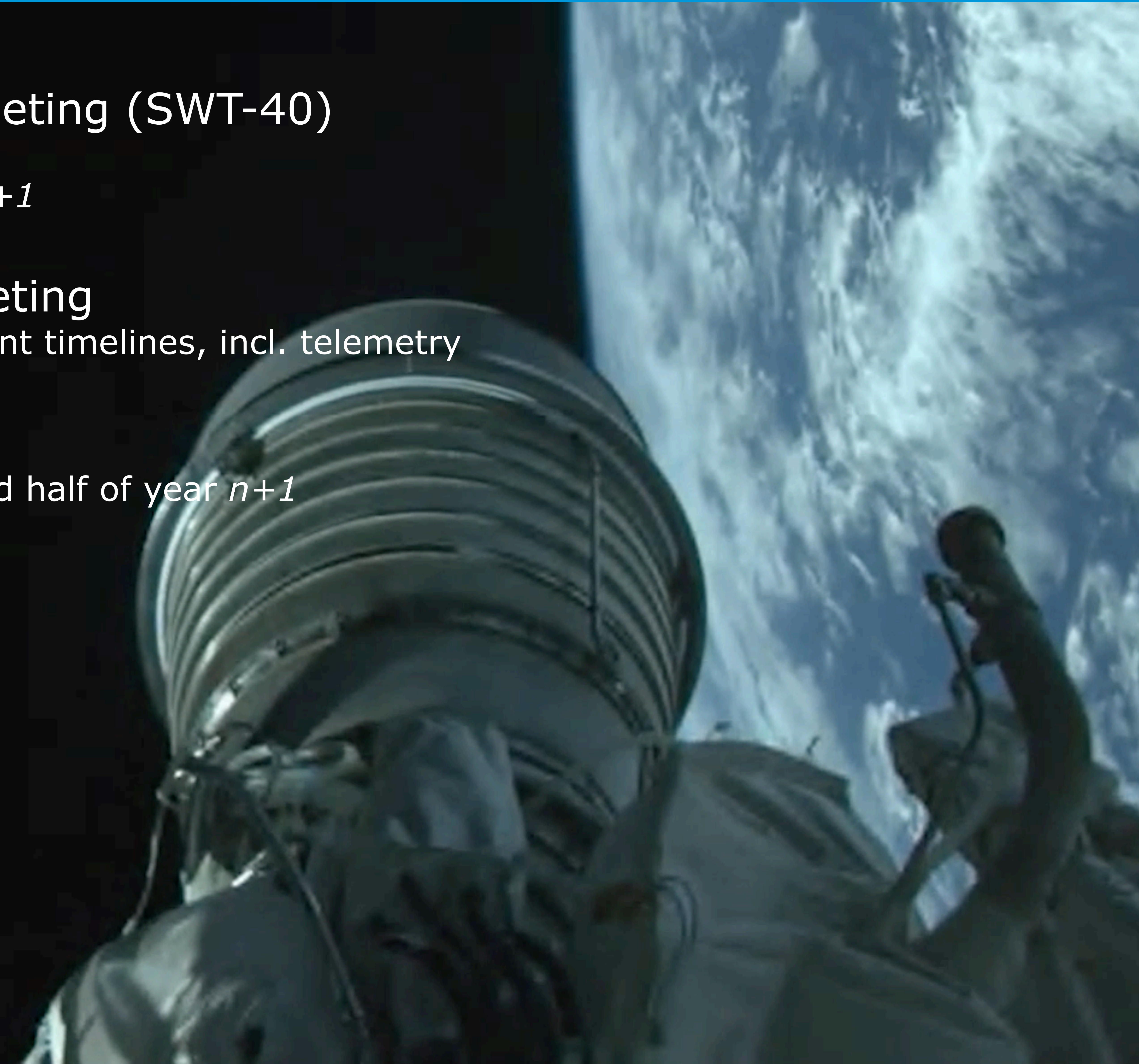
  → Define science priorities in mission-level Science Activity Plan
  → Implement via Solar Orbiter Observing Plans (SOOPs)



Top-level science planning timeline

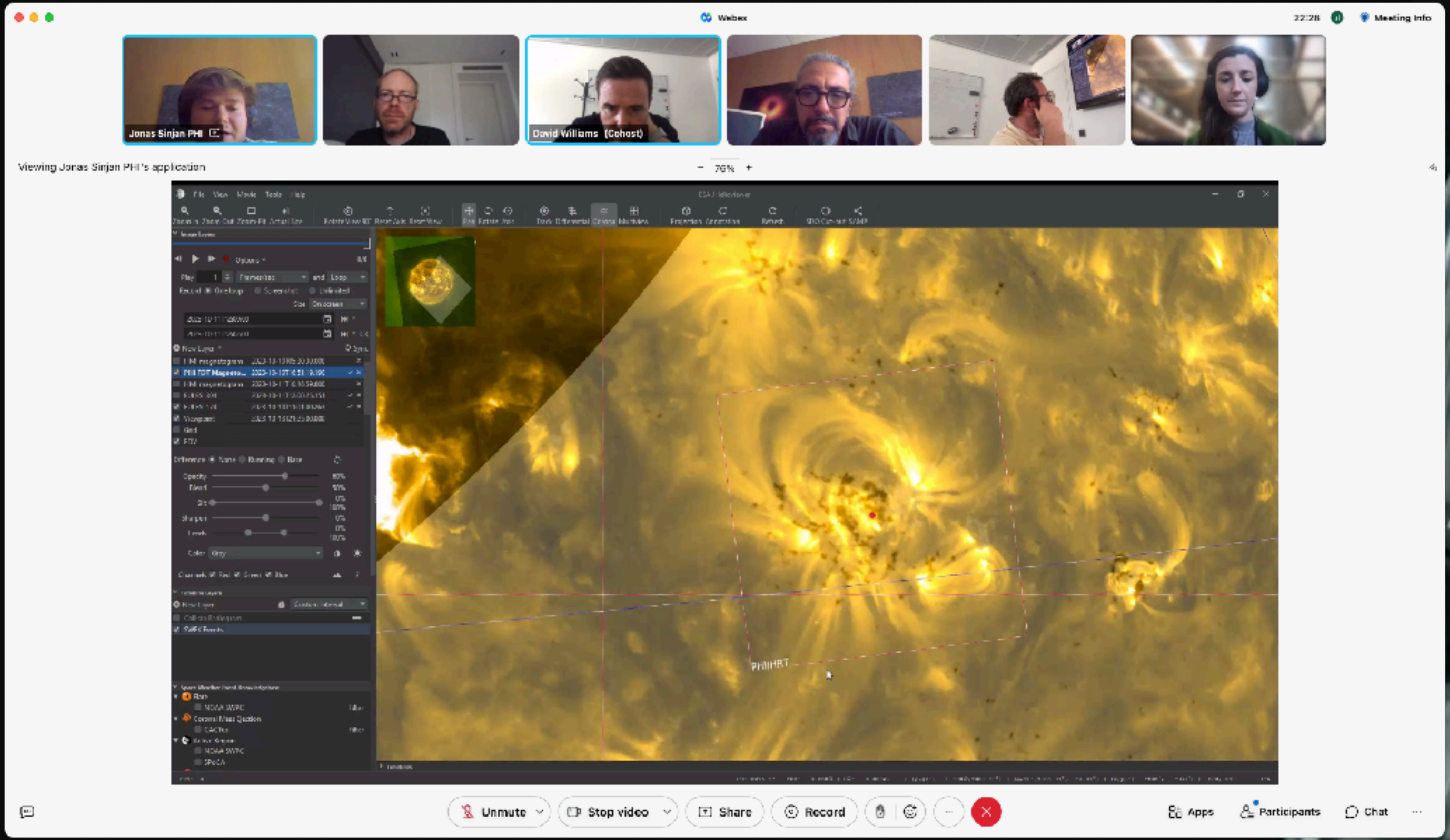
- April 2025 (‘year *n*’): Science Working Team meeting (SWT-40)
  Decide on science priorities for year *n+1*
  Place remote-sensing windows, SOOPs for first half of year *n+1*
- July 2025: Science Operations WG (SOWG) meeting
  Plan science ops. for second half of year *n:* Detailed instrument timelines, incl. telemetry
- September 2025: SWT-41 meeting
  Place or confirm remote-sensing windows + SOOPs for second half of year *n+1*
- January 2026: SOWG meeting
  Plan science ops. for first half of year *n+1*

Detailed roadmap online:



But… you don’t know where to point months in advance!

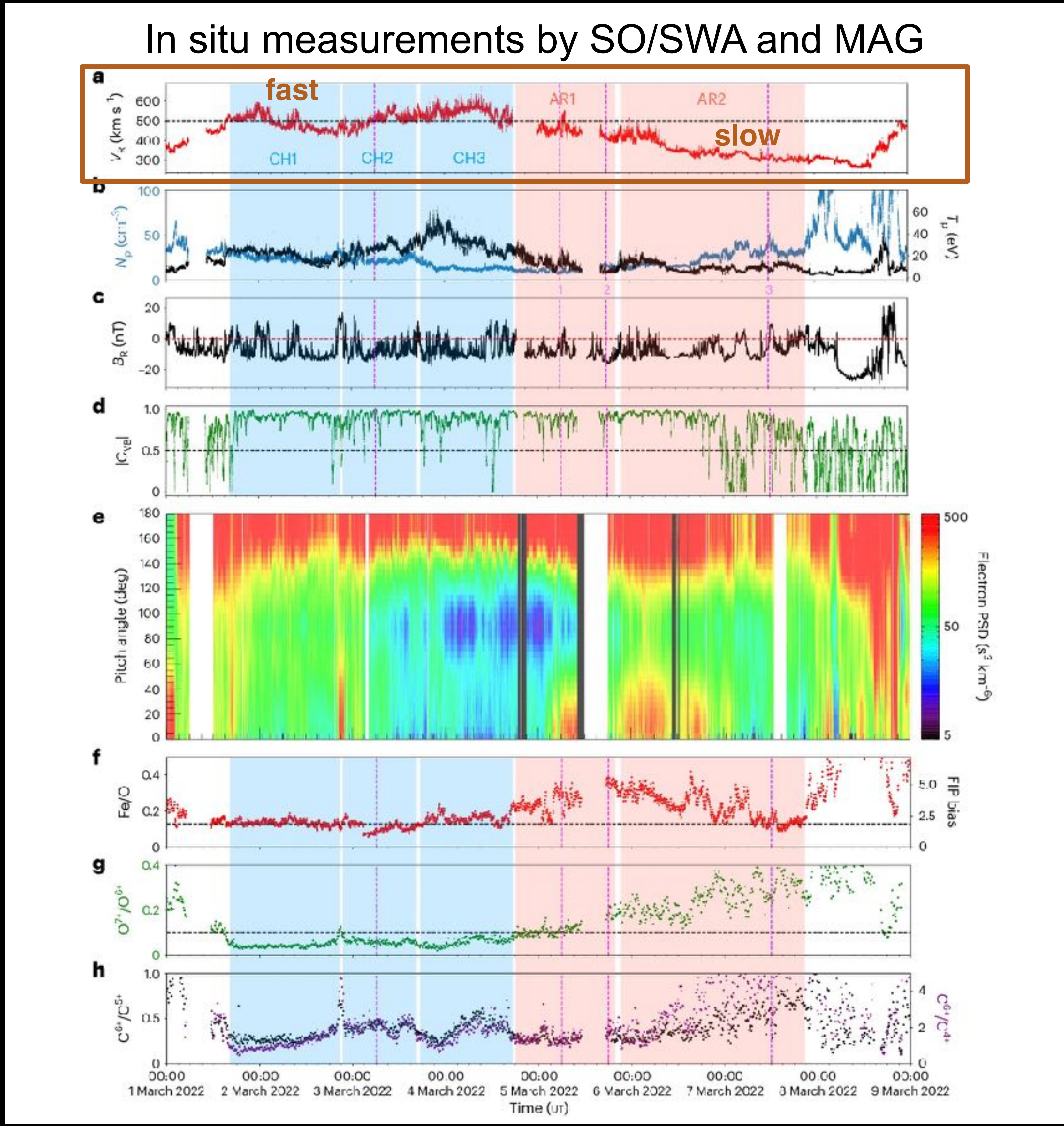
- The challenge: Need to fix many details about observations months in advance, but need to decide where to point as late as possible
- The solution:’Very-short-term planning’ for spacecraft pointing (pVSTP)



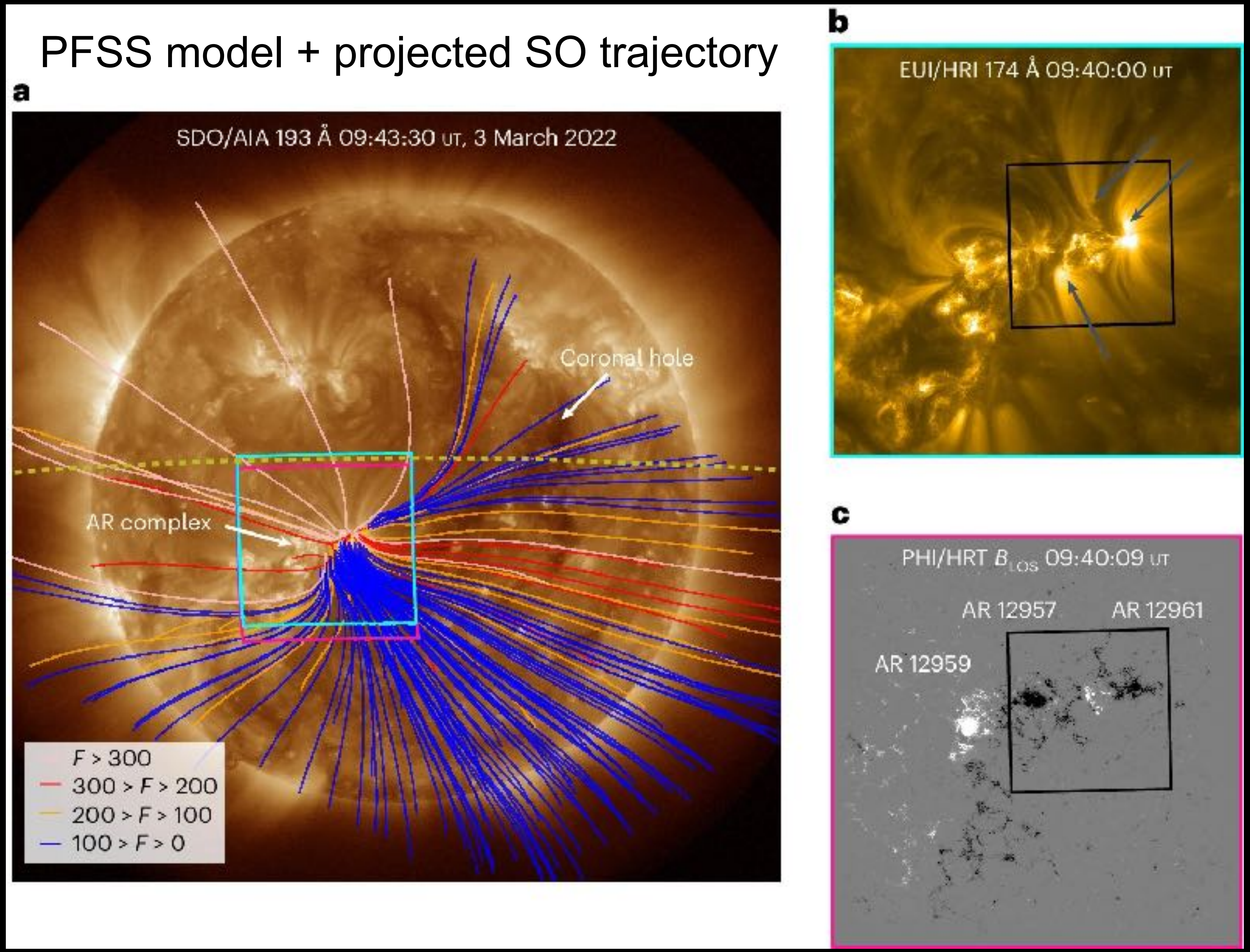
[Planning web page for coordinated observations:]()

Multi-source connectivity as the driver of solar wind variability in the heliosphere

(Yardley et al., Nature Astronomy 2024)

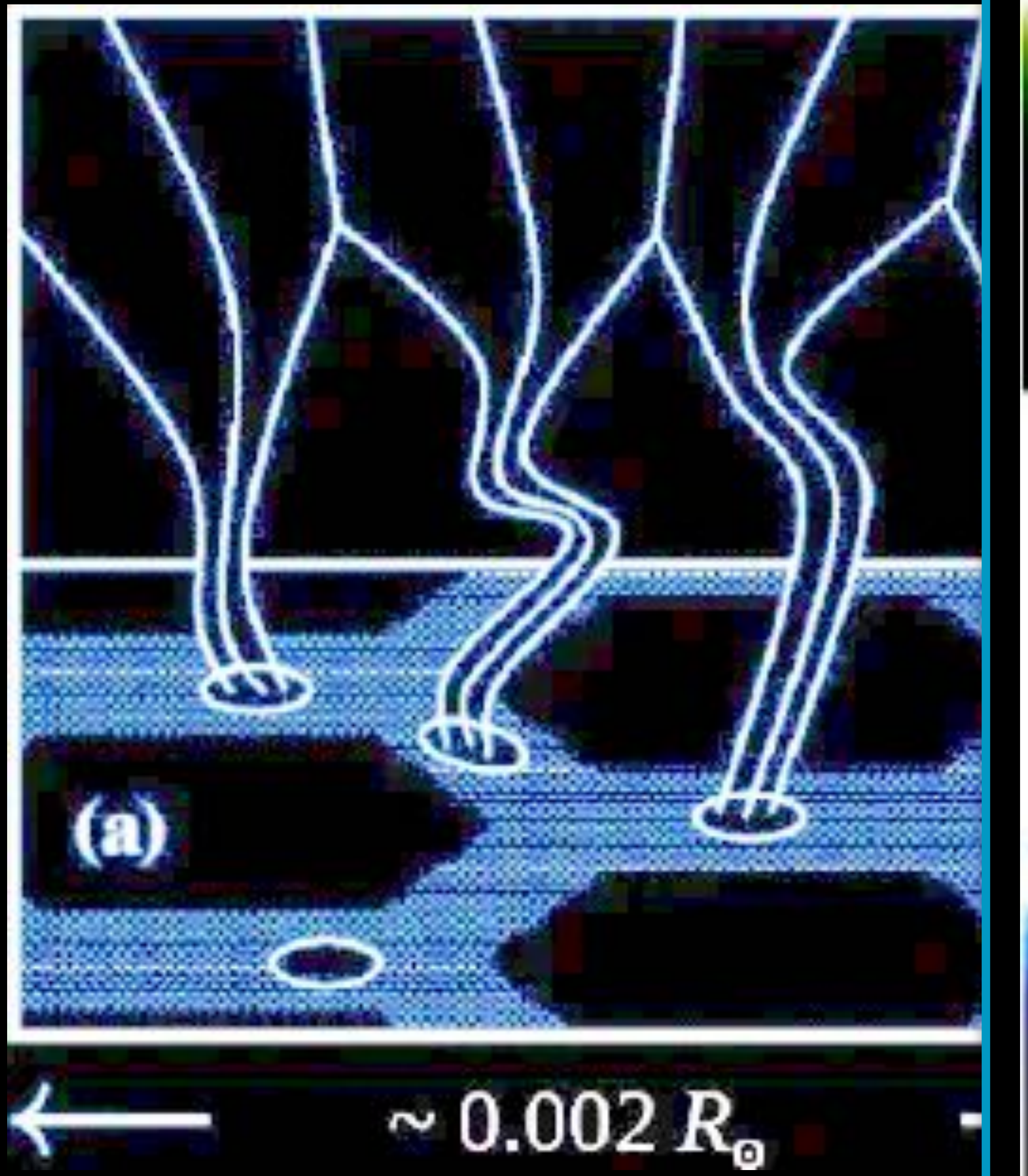


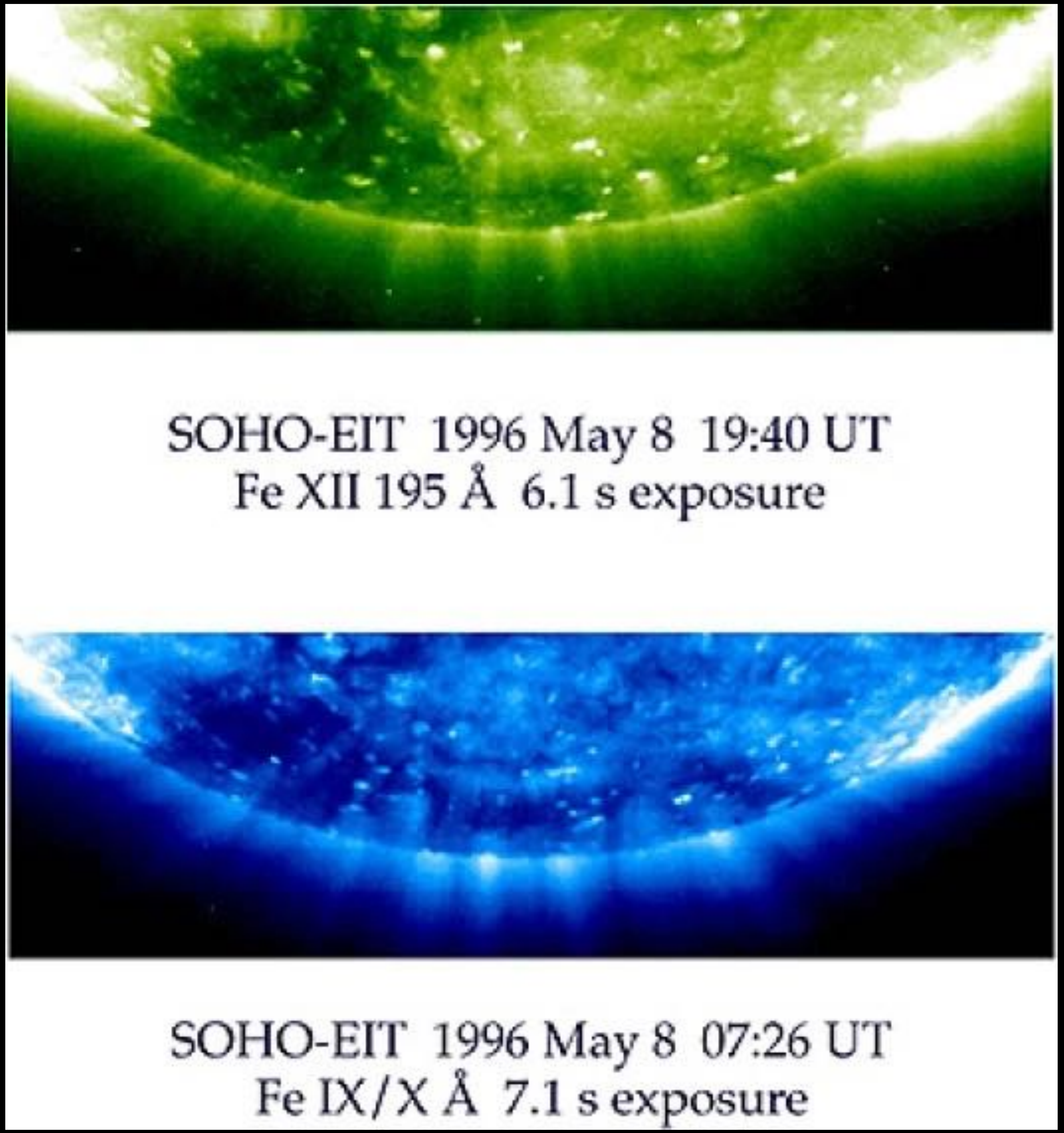
- Evidence that solar wind variability is driven by the connectivity changing across a coronal hole–active region complex.
- Plasma composition measured *in situ* indicates that material from the closed-field active region cores is released into the solar wind by interchange reconnection. (See review by Laming, LRSP 2015)



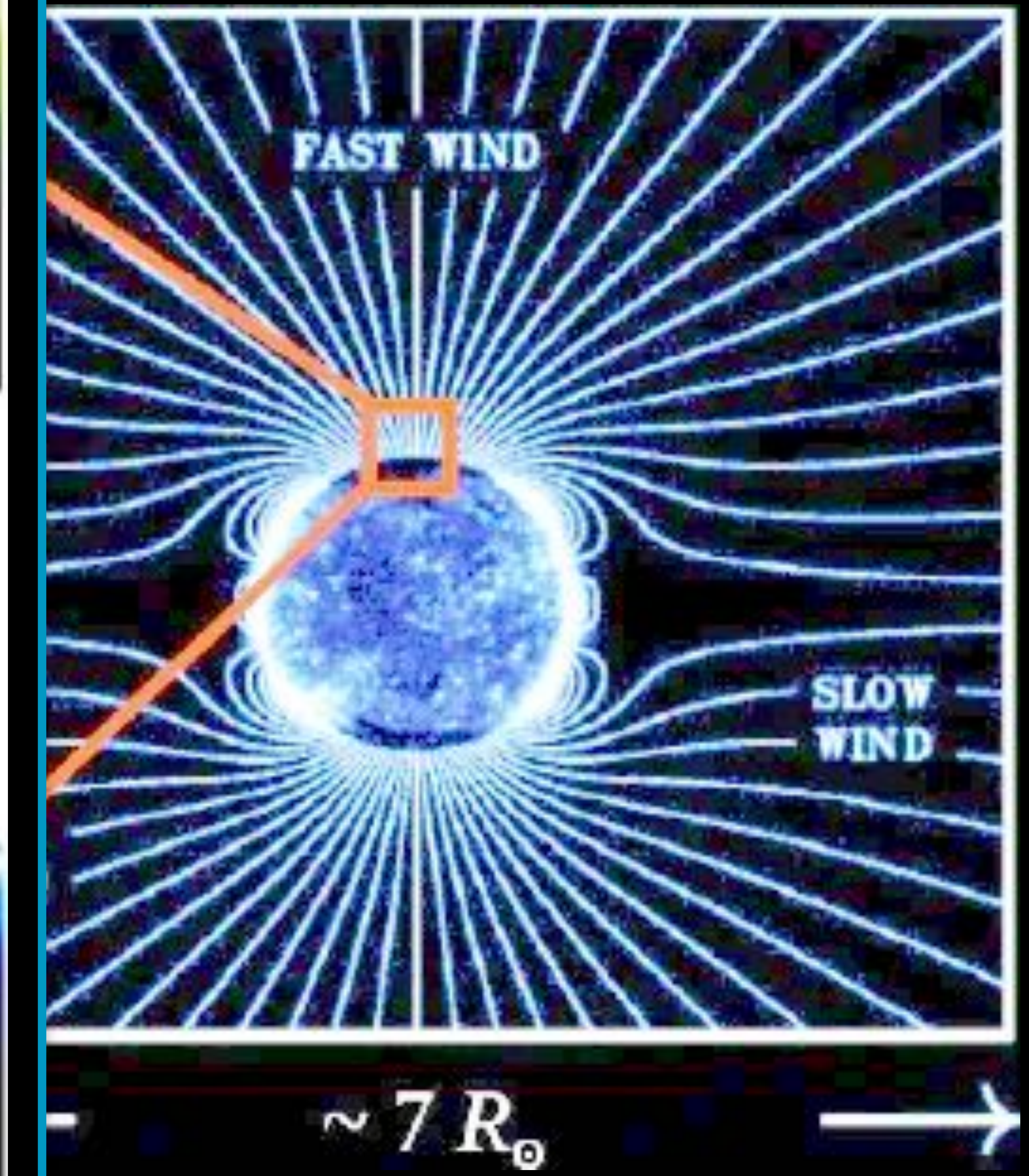

Picoflare jets power the solar wind emerging from a polar coronal hole
(Chitta et al., *Science* 2023)
2022–03–30 UT 04:30:30
0.33 au | Spatial resolution: ~ 240 km | Cadence: 3 s
Earth to scale

“Coronal holes are the darkest and least active regions of the Sun, as observed both on the solar disk and above the solar limb”





Poletto, G., Solar Coronal Plumes. Living Rev. Sol. Phys. 12, 7 (2015)



Cranmer, S. R. & van Ballegooijen, A. A. ApJS, 156, 265 (2005)

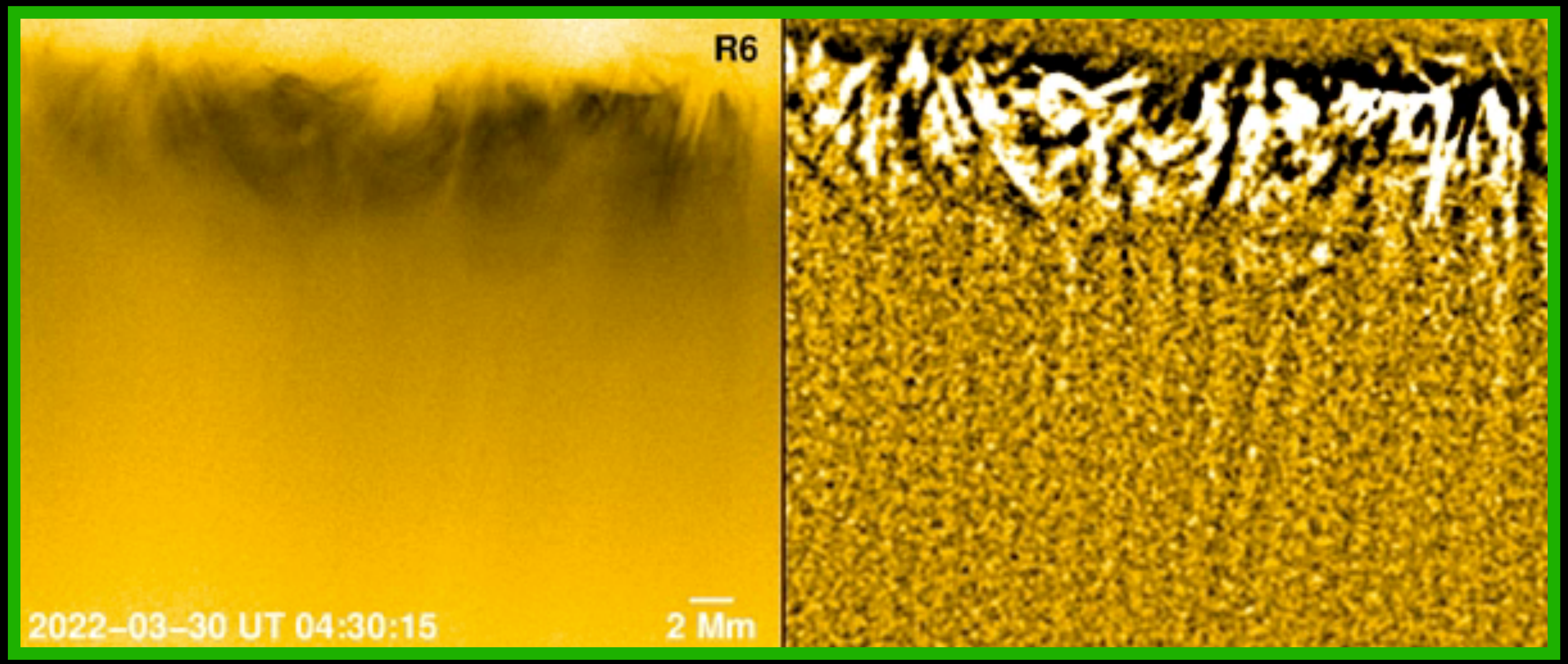
“The extend … ronal holes
t … ,

Courtesy P. Chitta

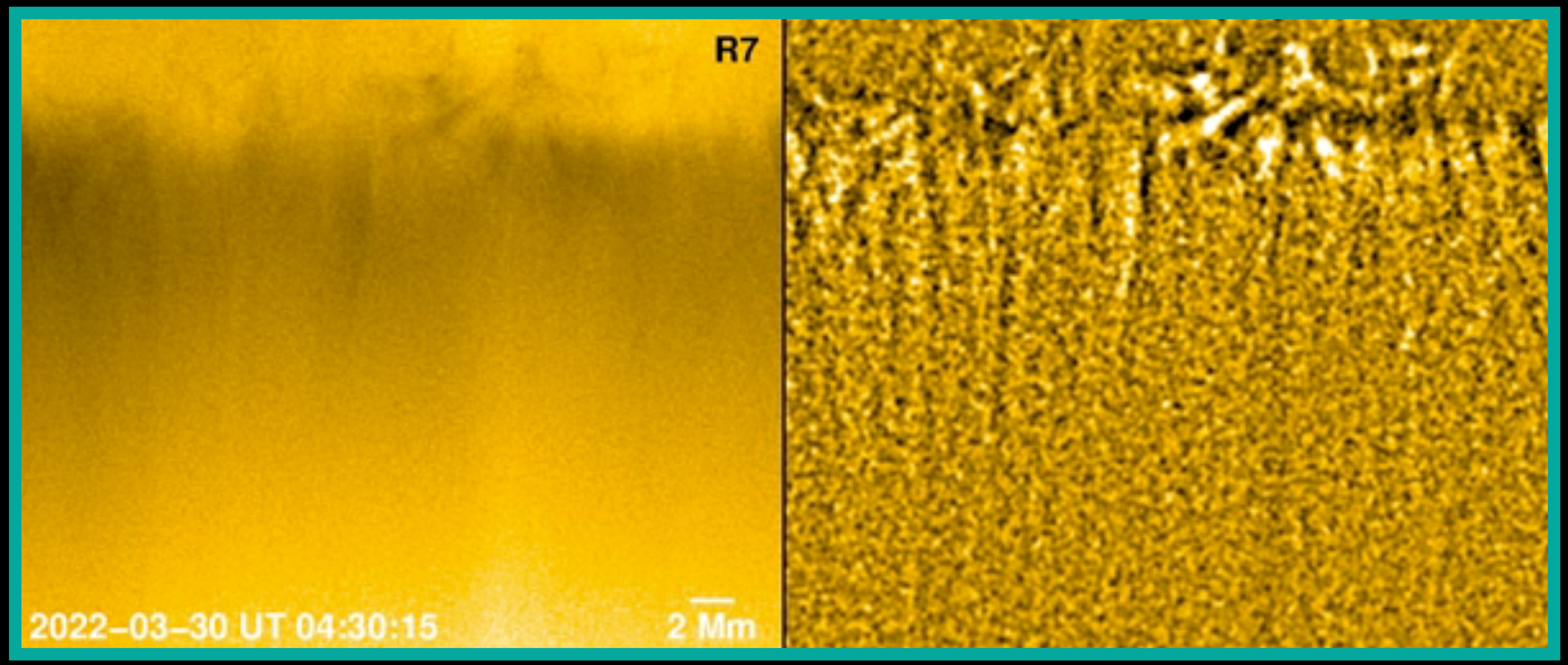
Picoflare jets power the solar wind emerging from a polar coronal hole

(Chitta et al., Science 2023)

- EUI observed (sub-)granular-scale intermittent jets emerging from a coronal hole
- Y-shaped jet morphology indicates magnetic reconnection as the likely driver



Plume Y-shaped outflows



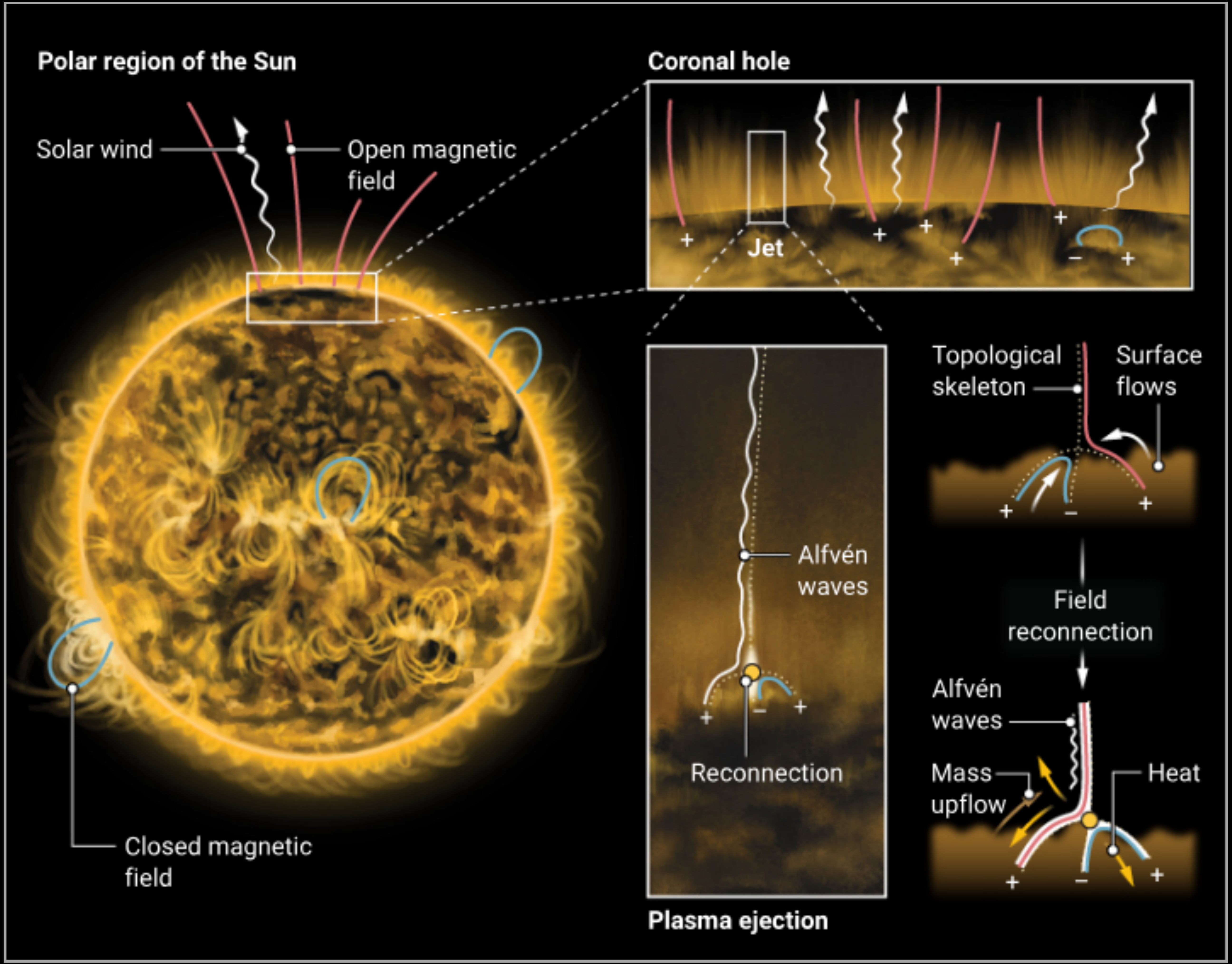
Interplume Y-shaped outflows

Courtesy P. Chitta

Picoflare jets power the solar wind emerging from a polar coronal hole

(Chitta et al., Science 2023)

- EUI observed (sub-)granular-scale intermittent jets emerging from a coronal hole
- Y-shaped jet morphology indicates magnetic reconnection as the likely driver
- Kinetic energy content in the picoflare range (10^{21} erg)
- Observed jets
  - Form a substantial source of the solar wind
  - Could play a role in the formation of structures in the solar wind, such as switchbacks



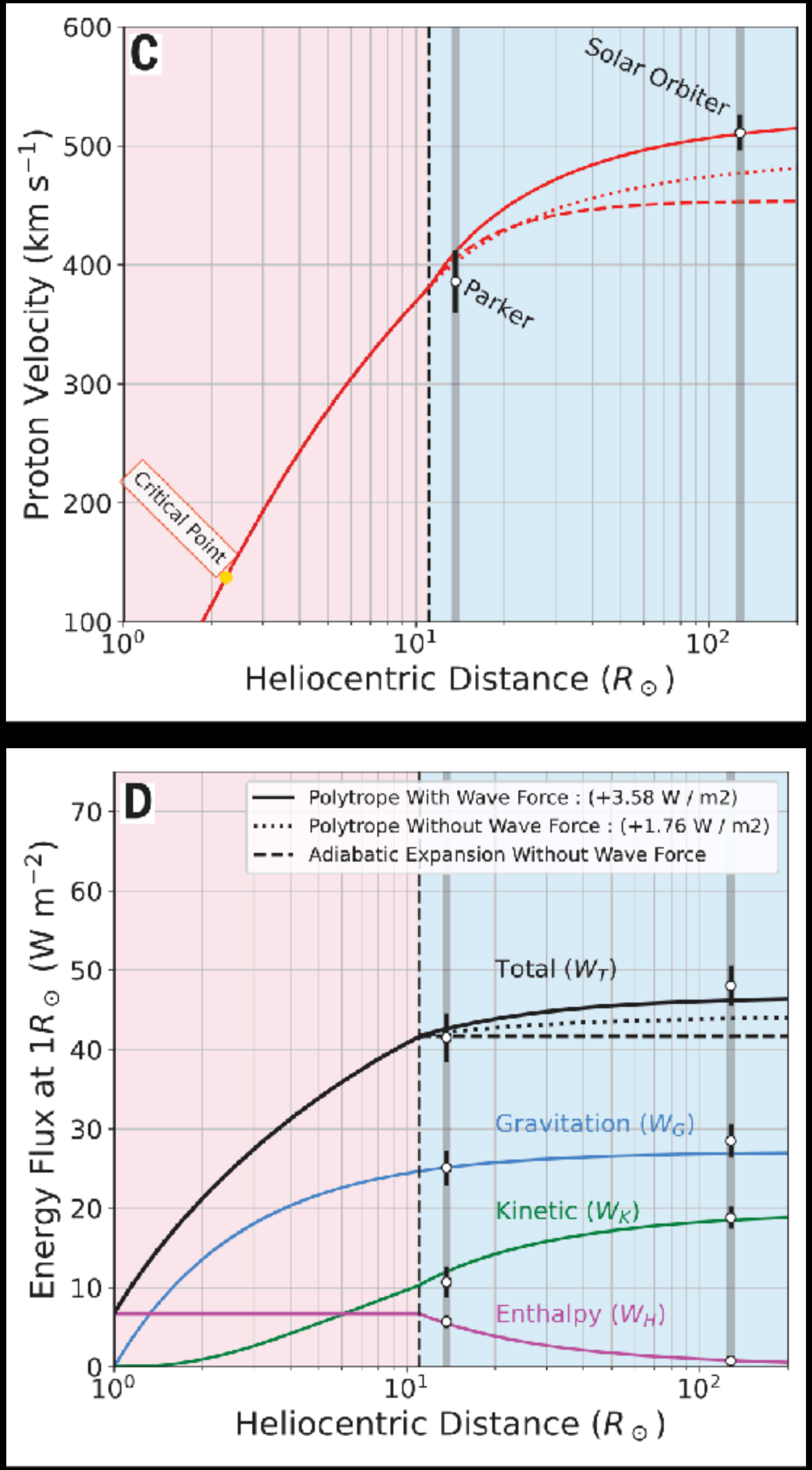
Thin jets underlie the solar wind
(Ugarte-Urra & Wang, *Science* Perspective, Sep 2023)


MAGNETIC WAVES POWER HIGH-SPEED SOLAR WIND
Rivera, Badman et al., Science 2024
esa
On 25 February 2022
Parker Solar Probe
detected protons with
390 km/s
1 400 000 °C
...two days later
Solar Orbiter
detected protons with
510 km/s
200 000 °C
9.3 million km
solar wind
88.8 million km
Solar wind streams out from a coronal hole
Magnetic switchbacks accelerate the wind
Further out, solar wind reaches high speeds
ESA | NASA
solar orbiter

Alfvén waves power the fast solar wind

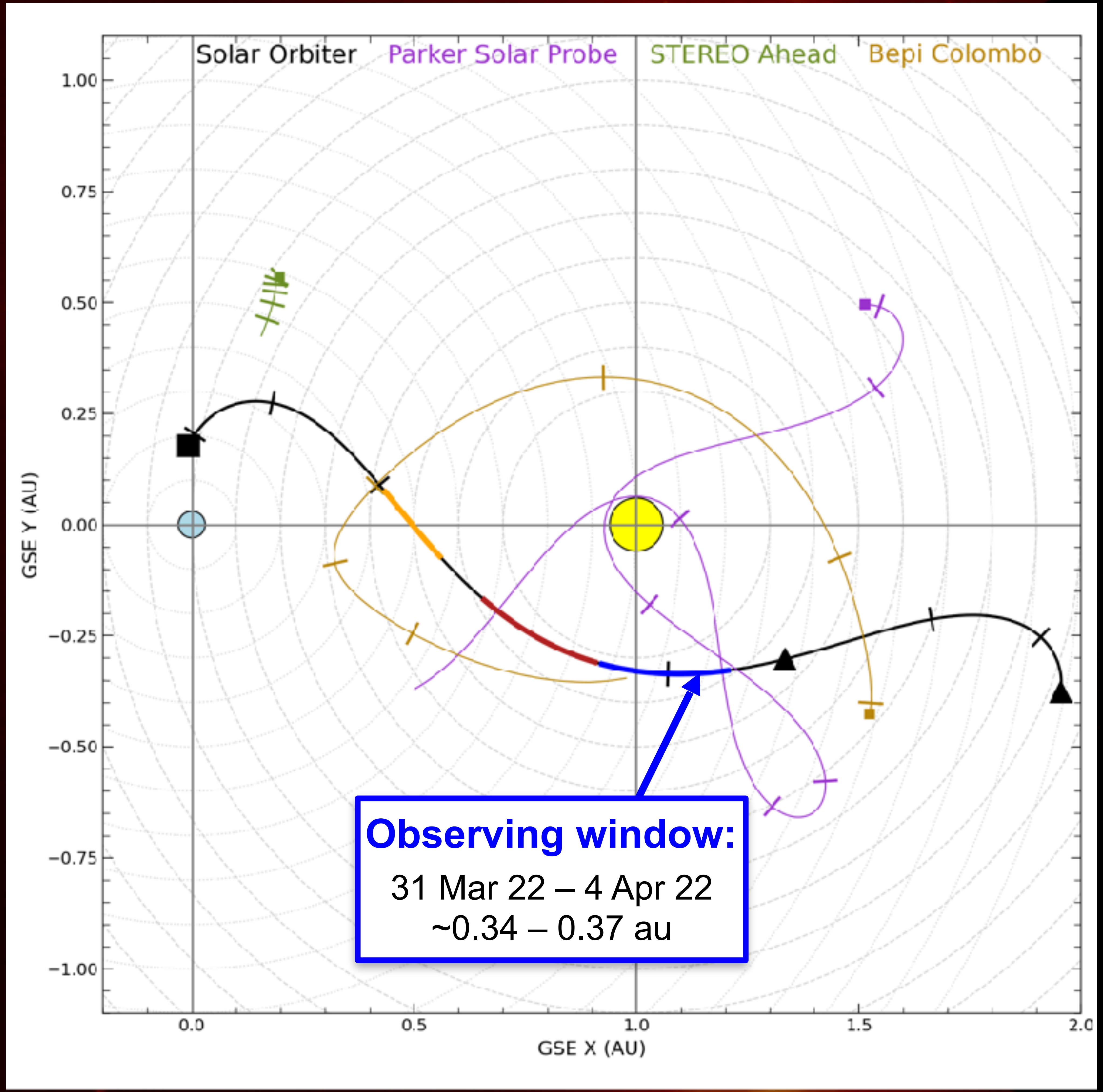
(Rivera, Badman et al., Science 2024)

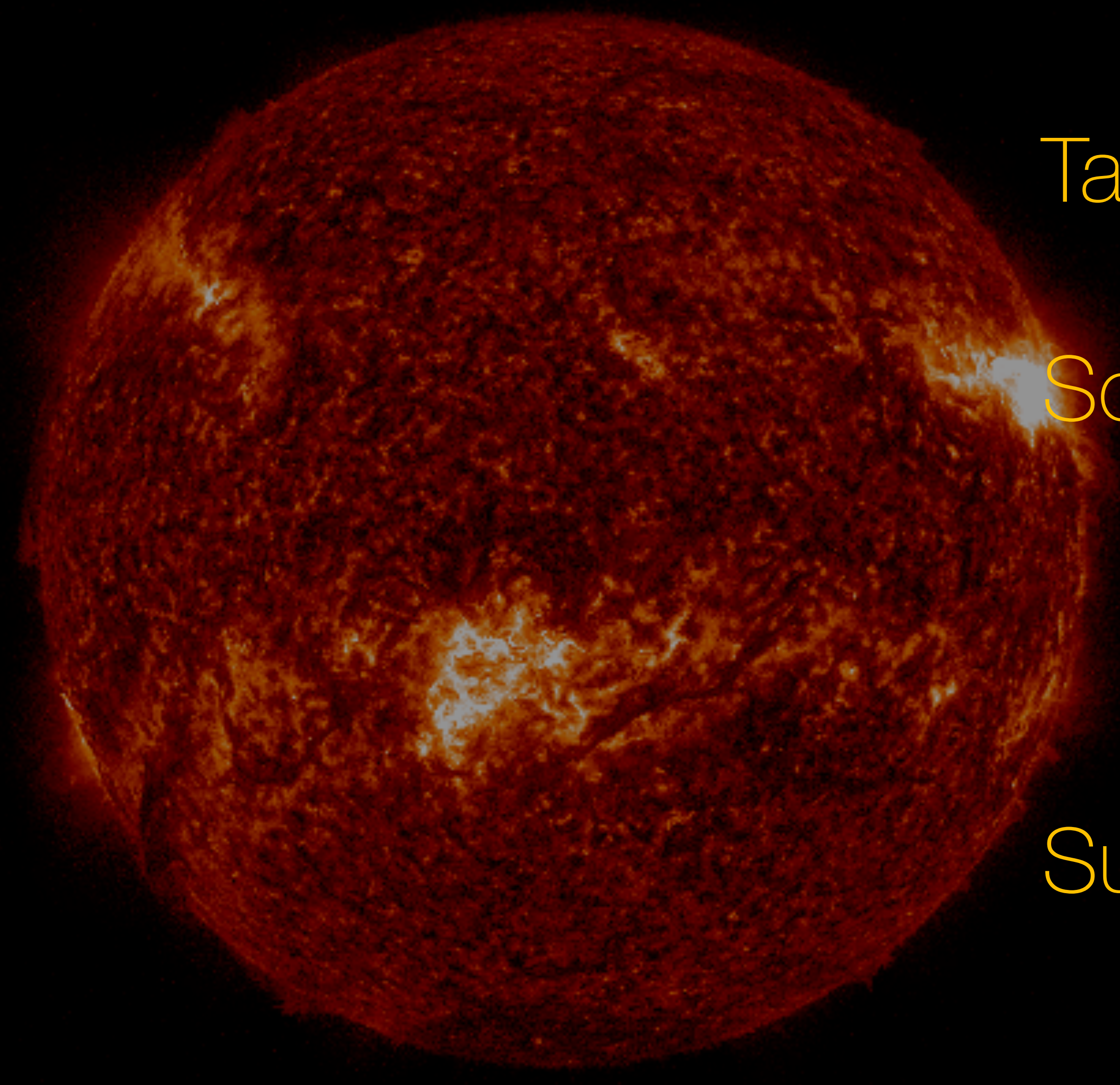
- In February 2022, Parker Solar Probe and Solar Orbiter crossed the same solar wind streamline within 2 days of each other.
- Close to the Sun ~10% of the total energy was found in the magnetic field. At Solar Orbiter, this number had dropped to just 1% but the plasma had accelerated and had cooled more slowly than expected.
- From this, the authors concluded that the switchback wave energy at Parker Solar Probe is required to maintain overall energy conservation.
- The magnetic energy lost on the way to Solar Orbiter was powering the solar wind's acceleration and slowing down the cooling of the plasma.



A SOOP with many ingredients: Long-term active region tracking

SOOP Coordinators: L. Bellot-Rubio, M. Janvier





Objective: Long-term monitoring of an AR

Target: Decaying ARs 12975, 12976

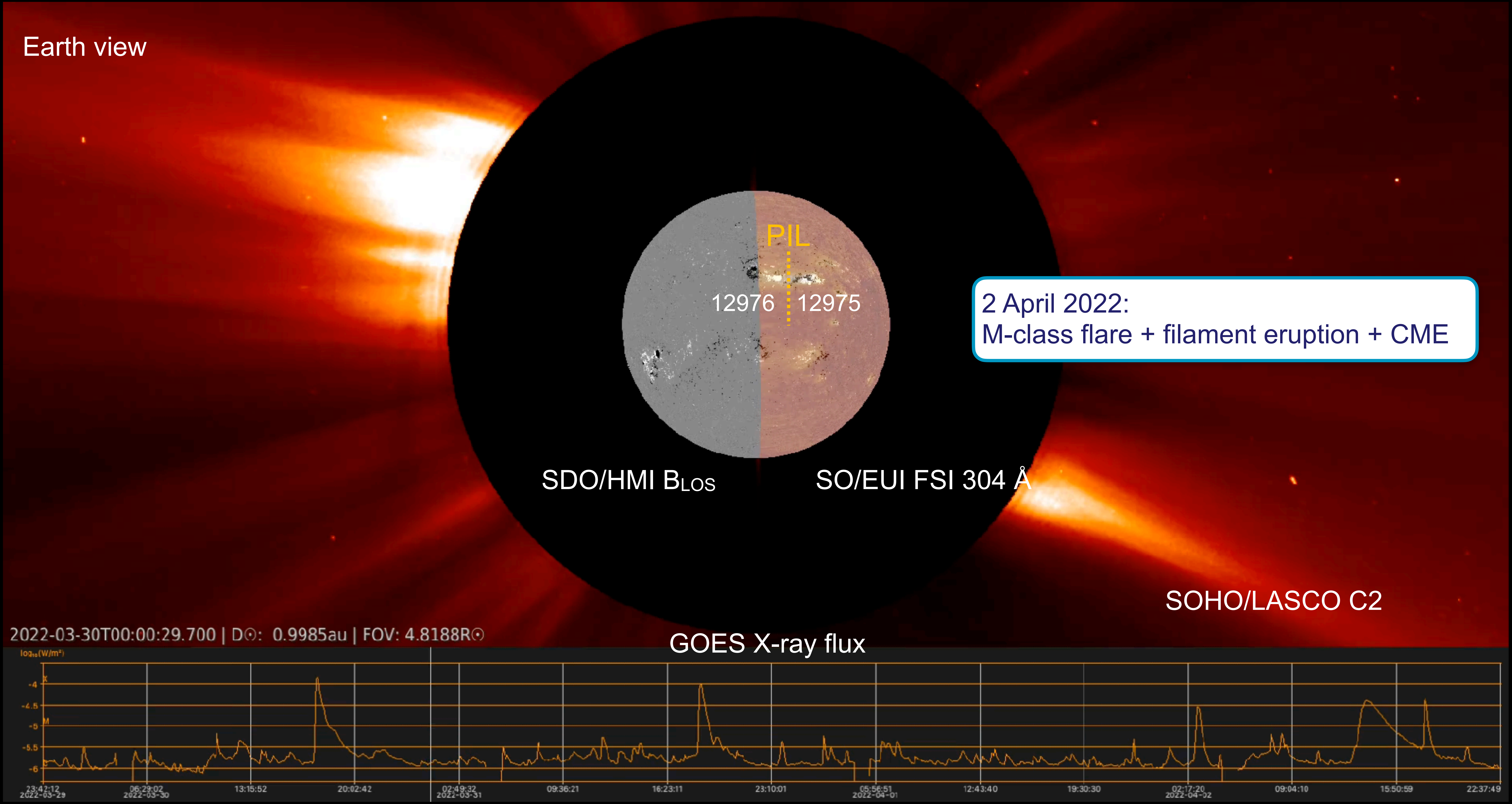
Solar Orbiter observations:

- EUI/HRI bursts (75min/day @10s), FSI throughout
- PHI/HRT throughout @30min cadence
- SPICE modes: composition, dynamics, spectral atlas

Supporting observations include:

- Hinode
- IRIS
- DKIST

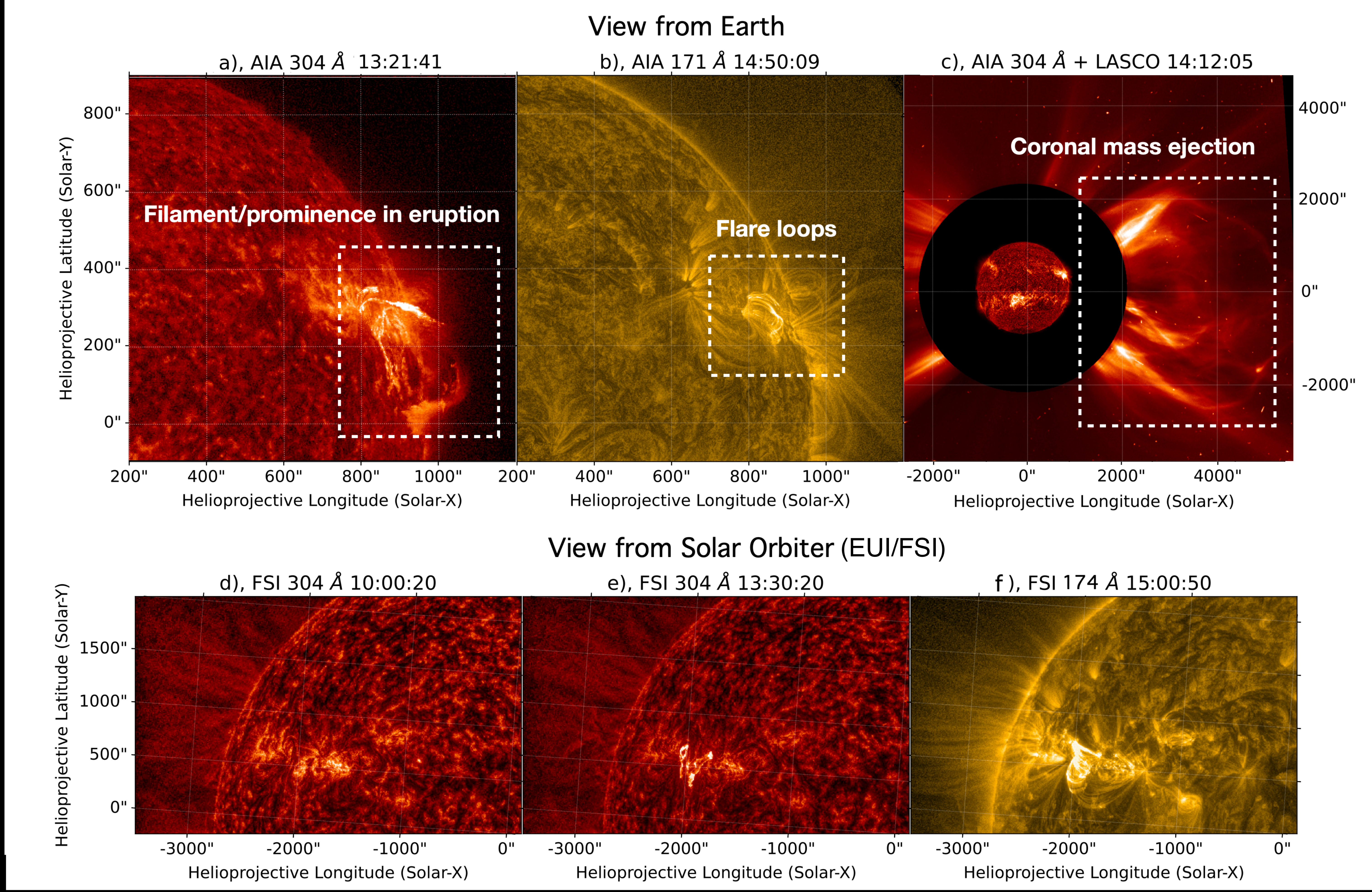
Long-Term Active Region SOOP

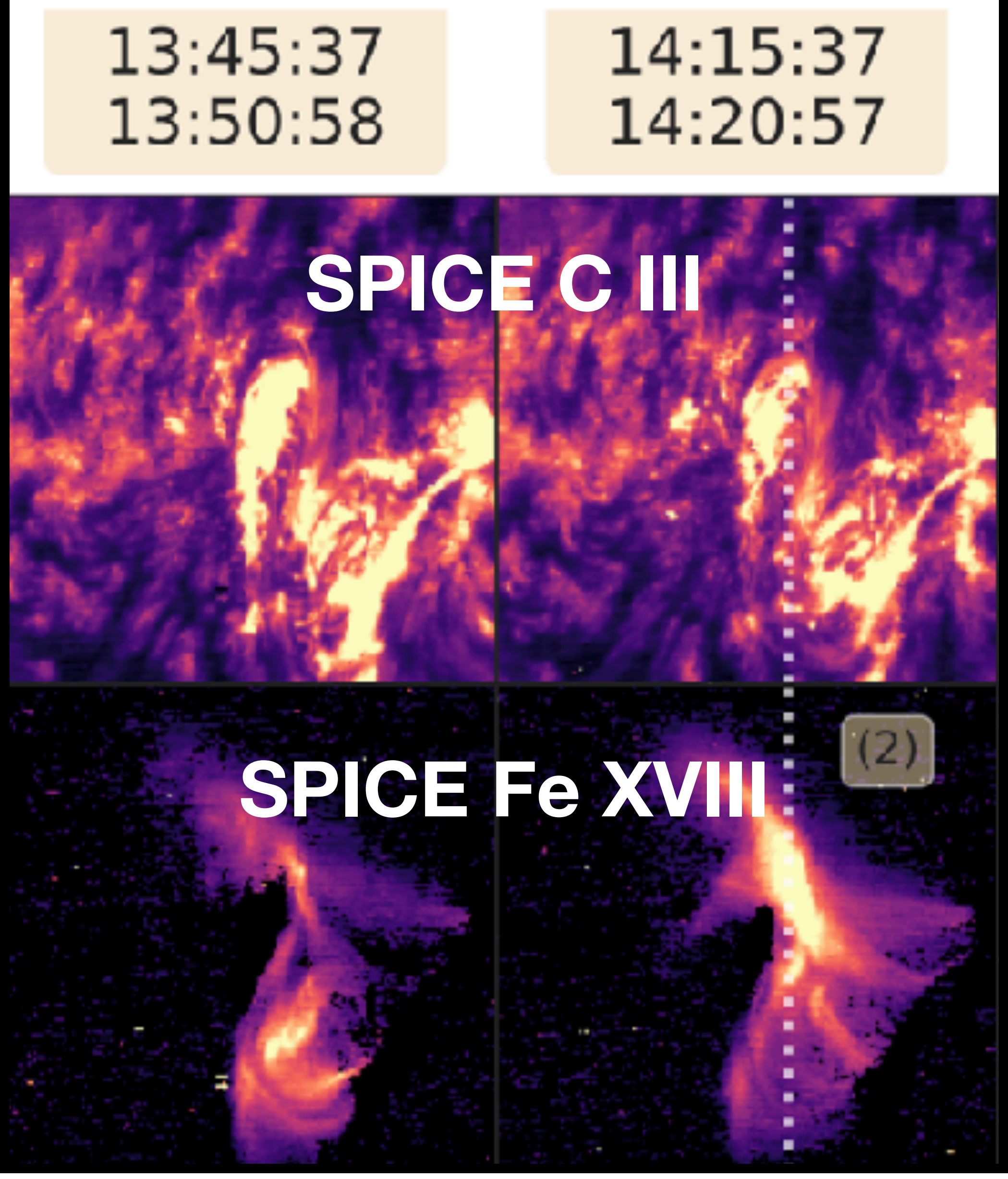


Multiple views of the 2 April 2022 M-class flare

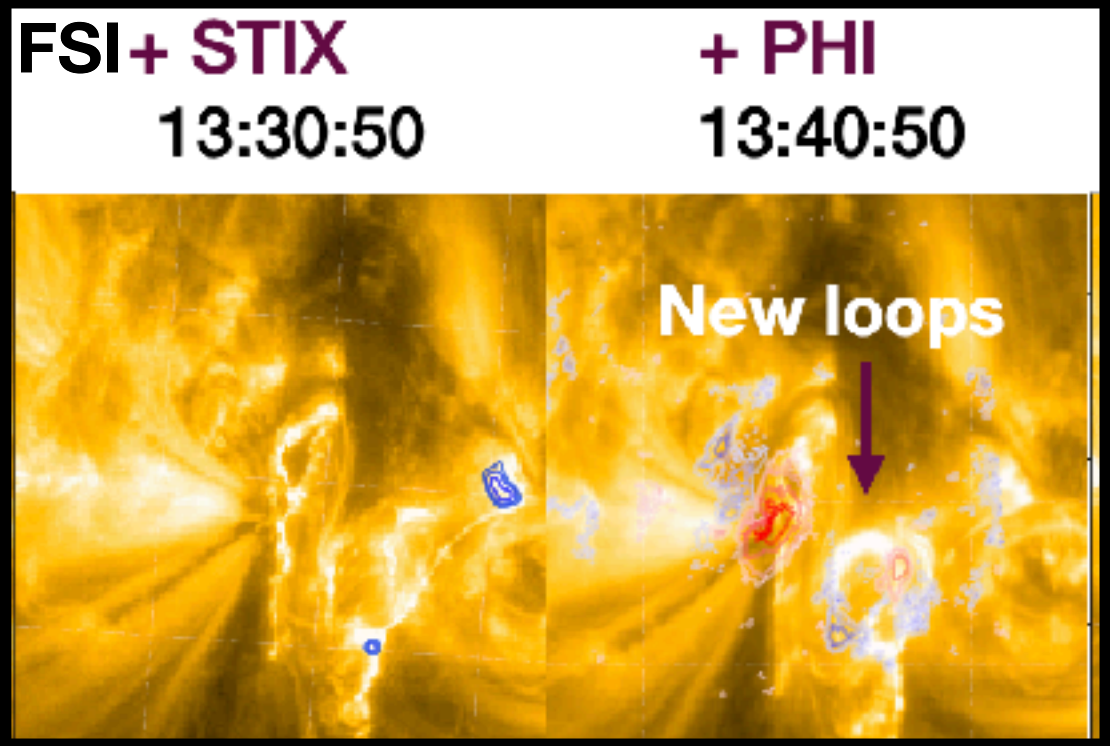
(Janvier et al., A&A 2023)

- Captured by all Solar Orbiter remote-sensing instruments except Metis
- Comprehensive data → Detailed investigation of all flaring aspects, from magnetic field evolution to reconnection consequences
- Great event to test 3D flare models: confirms model predictions*, but added complexity due to parasitic polarity
  *starting from the CSHKP model: Carmichael 1964; Sturrock & Coppi 1966; Hirayama 1974; Kopp & Pneuman 1976





Flare ribbon and flare loops diagnostics with spectroscopy



Parasitic polarity confirmed with PHI data +HXR sources from STIX

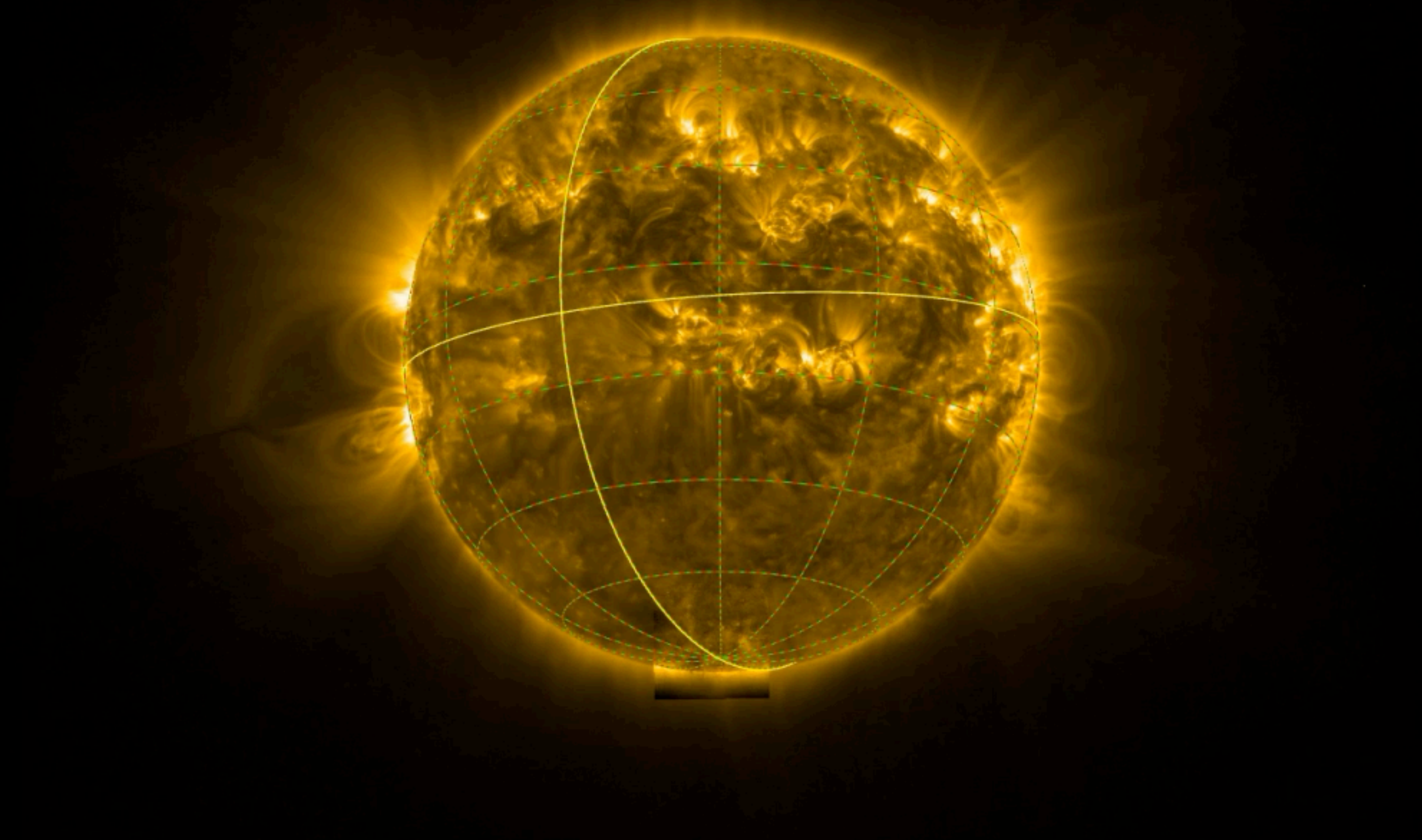
The active Sun: Approaching solar max with STIX

- Solar Orbiter/STIX has been observing continuously since January 2021
- > 60 000 flares so far – many not visible from Earth

Graphics: L. Hayes, ESA

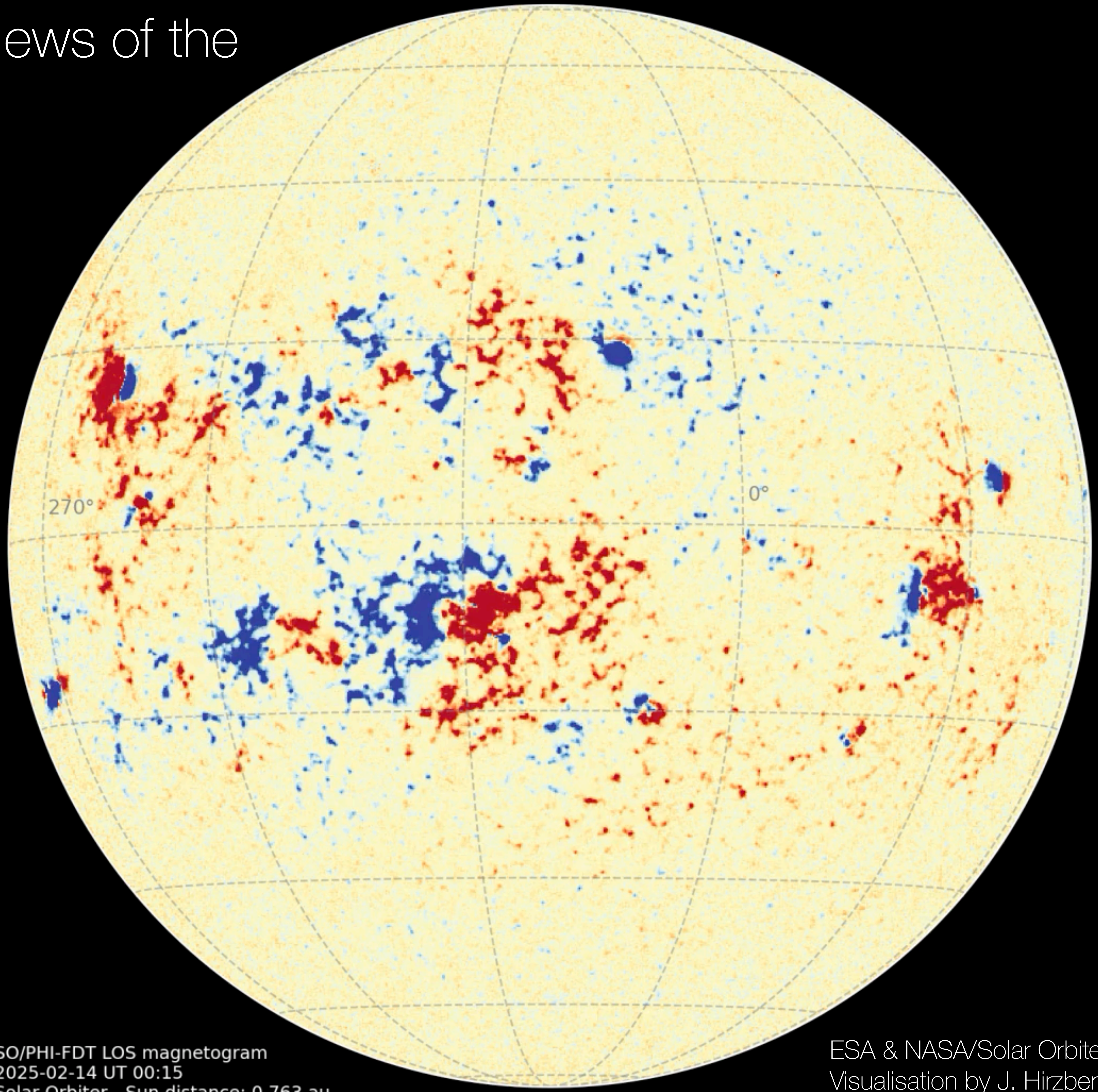
Teamwork in the heliosphere
Solar Orbiter
Parker Solar Probe
SDO
SOHO
Solar Orbiter PHI
PHI HRT
DKIST VBI
DKIST VBI
2022-08-30T00:06:08.453

March 2025: First views of the Sun’s polar regions

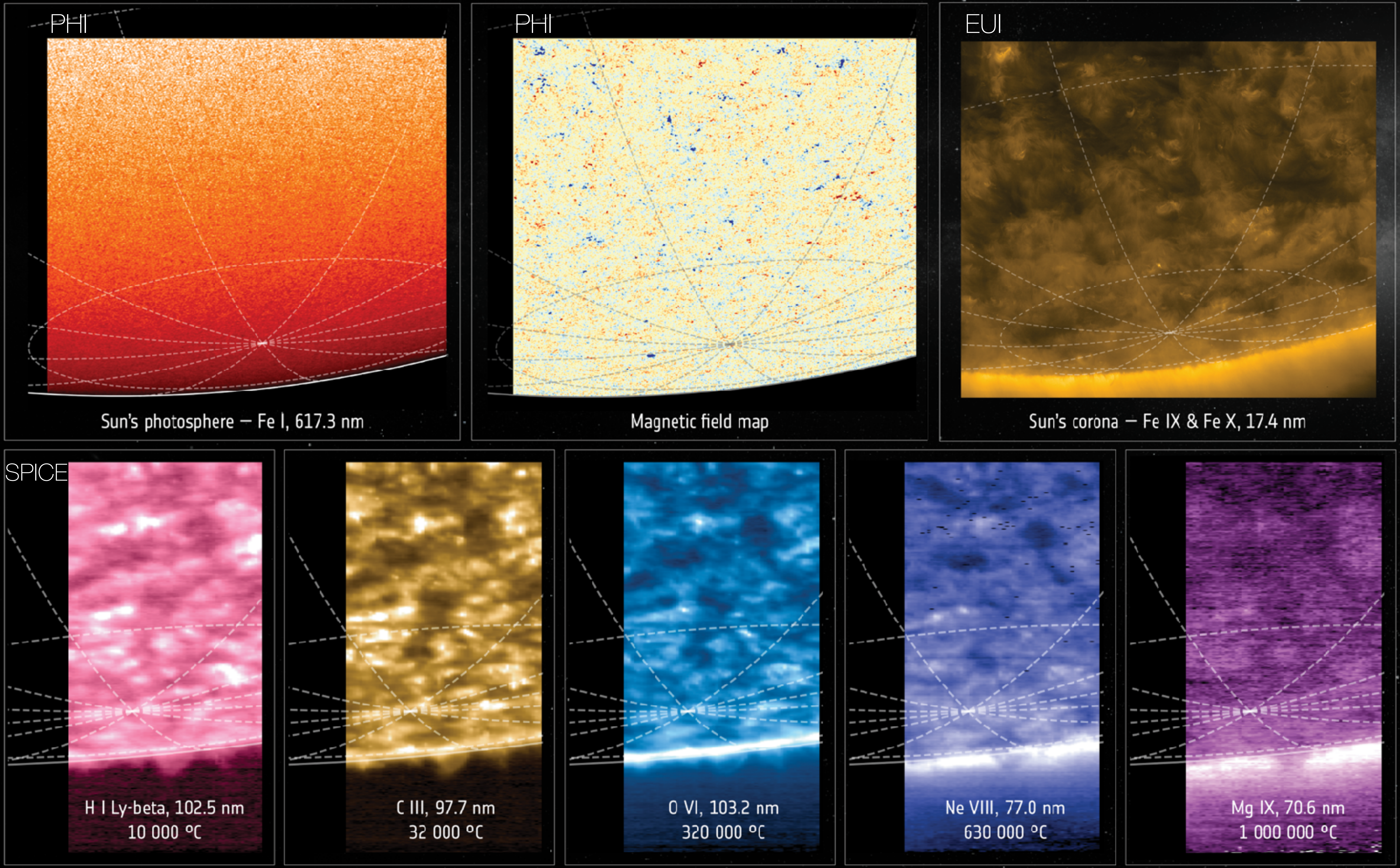


ESA & NASA/Solar Orbiter EUI Team
EUI Full Sun Imager + High Resolution Imager, Fe IX/X 174Å (10^6 K)
Visualisation by D. Berghmans (ROB) using JHelioviewer

March 2025: First views of the Sun's polar regions



ESA & NASA/Solar Orbiter PHI Team
Visualisation by J. Hirzberger (MPS)

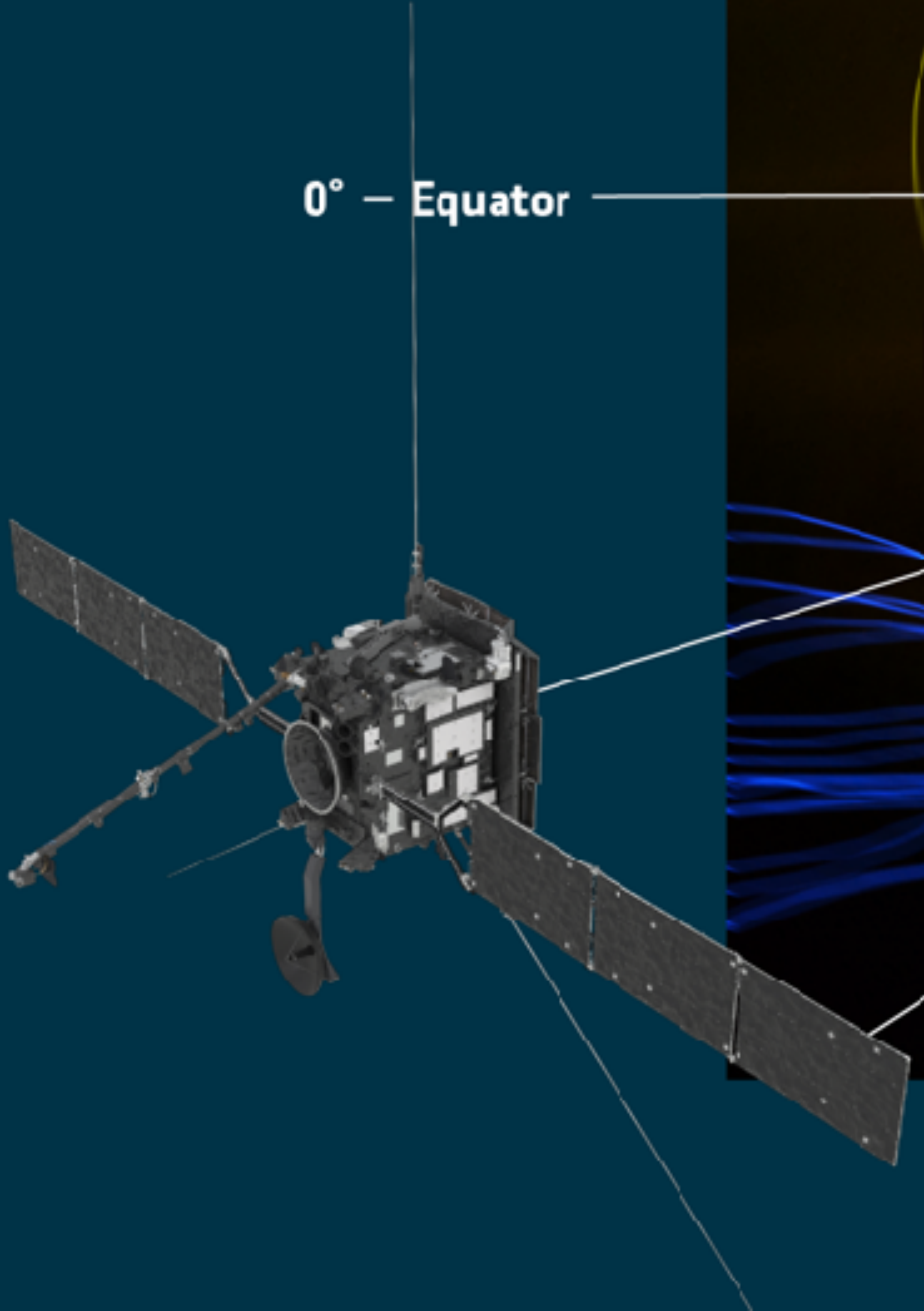

PHI
Sun's photosphere – Fe I, 617.3 nm
PHI
Magnetic field map
EUI
Sun's corona – Fe IX & Fe X, 17.4 nm
SPICE
H I Ly-beta, 102.5 nm
10 000 °C
C III, 97.7 nm
32 000 °C
O VI, 103.2 nm
320 000 °C
Ne VIII, 77.0 nm
630 000 °C
Mg IX, 70.6 nm
1 000 000 °C

WHY SOLAR ORBITER IS ANGLING TOWARDS THE SUN'S POLES

The planets and almost all spacecraft to date orbit around the Sun's equator. Since February 2025, the ESA-led Solar Orbiter spacecraft's orbit is tilted out of this plane, giving us the first-ever clear views of the Sun's polar regions. Over the next few years, it will watch the Sun from ever-higher angles.

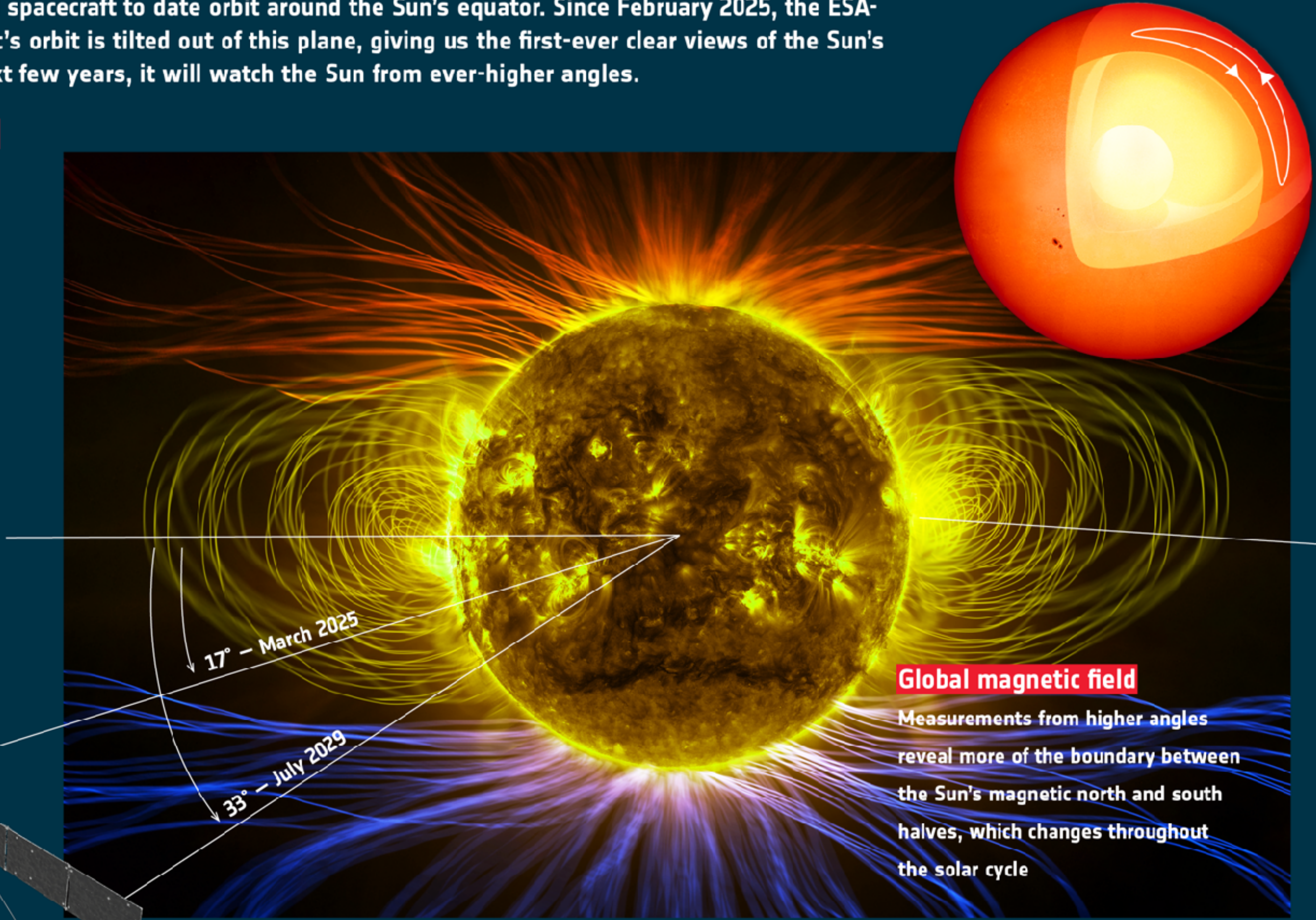
First polar views

Getting the first ever views of the Sun's poles may reveal polar vortices (swirling gas) or other unexpected patterns, and the impact of the Sun's magnetic field opening up to space in these regions



The solar dynamo

Tracking movement at and below the surface near the poles will improve models of how the Sun's magnetic field is generated and changes over time, crucial for predicting the solar cycle



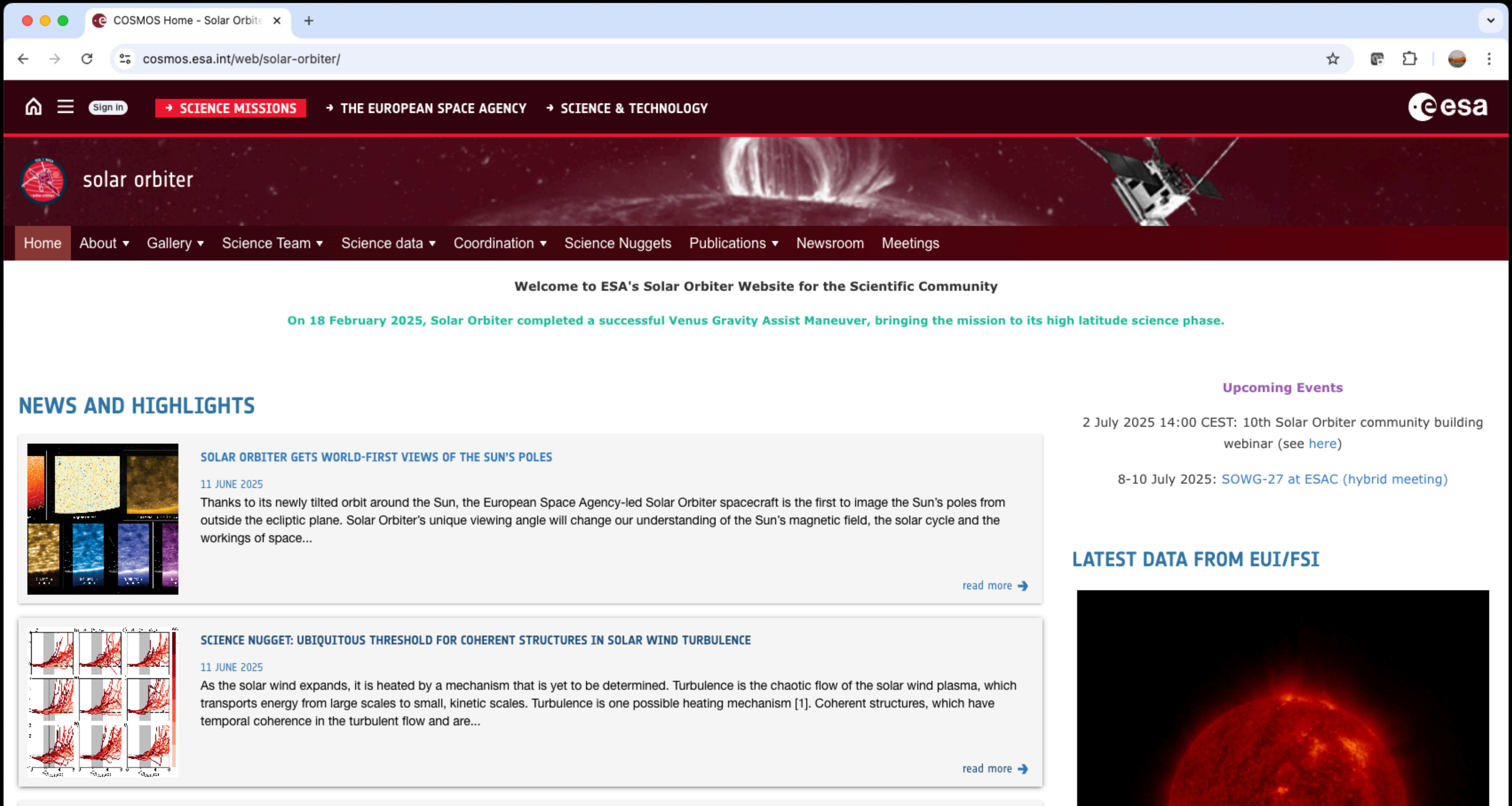
Global magnetic field

Measurements from higher angles reveal more of the boundary between the Sun's magnetic north and south halves, which changes throughout the solar cycle

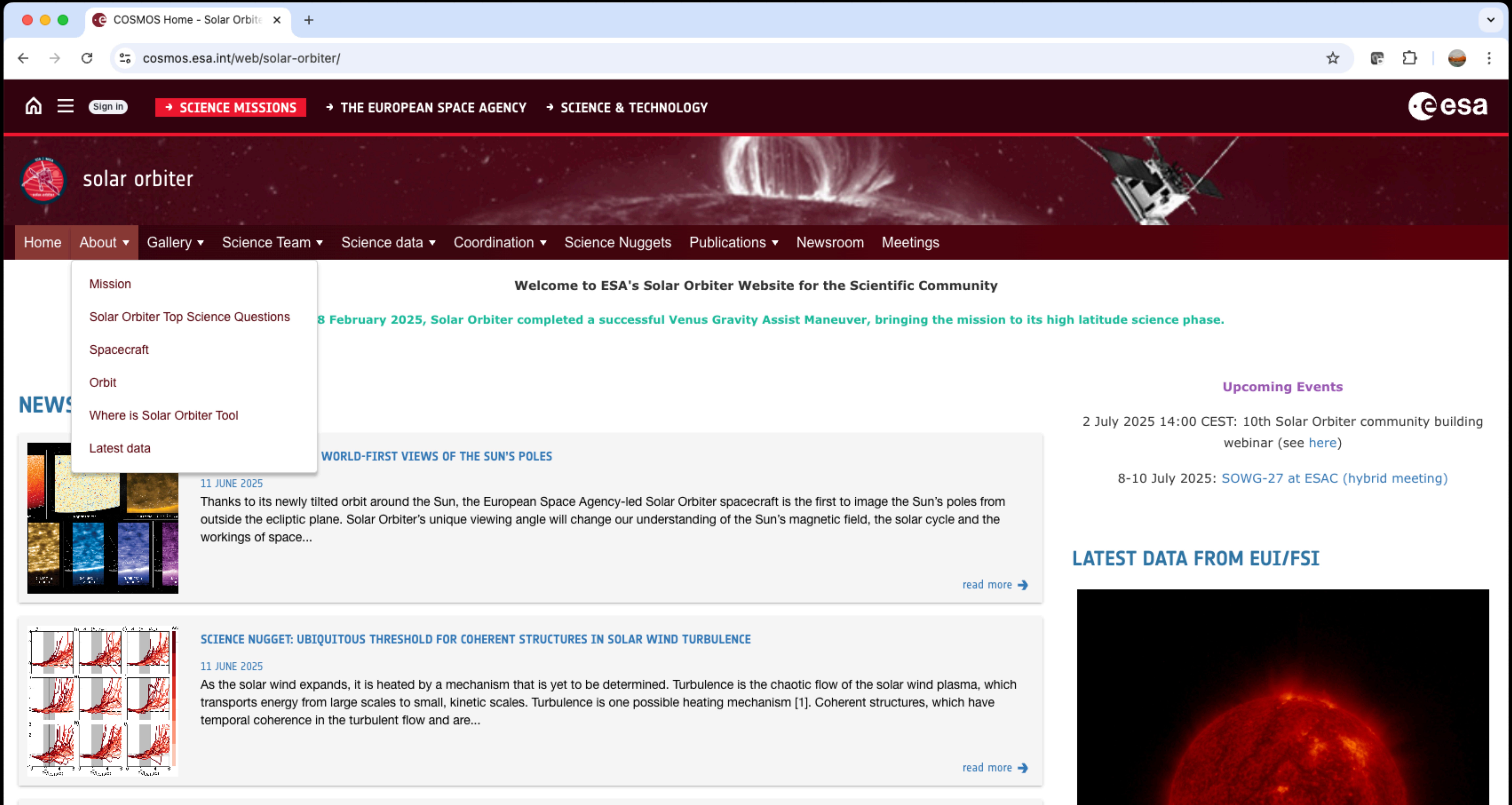
Space weather

Tracking the movement and makeup of solar wind and solar storms away from the Sun's equator will improve space weather forecasts

Resources: Cosmos website



Resources: Cosmos website



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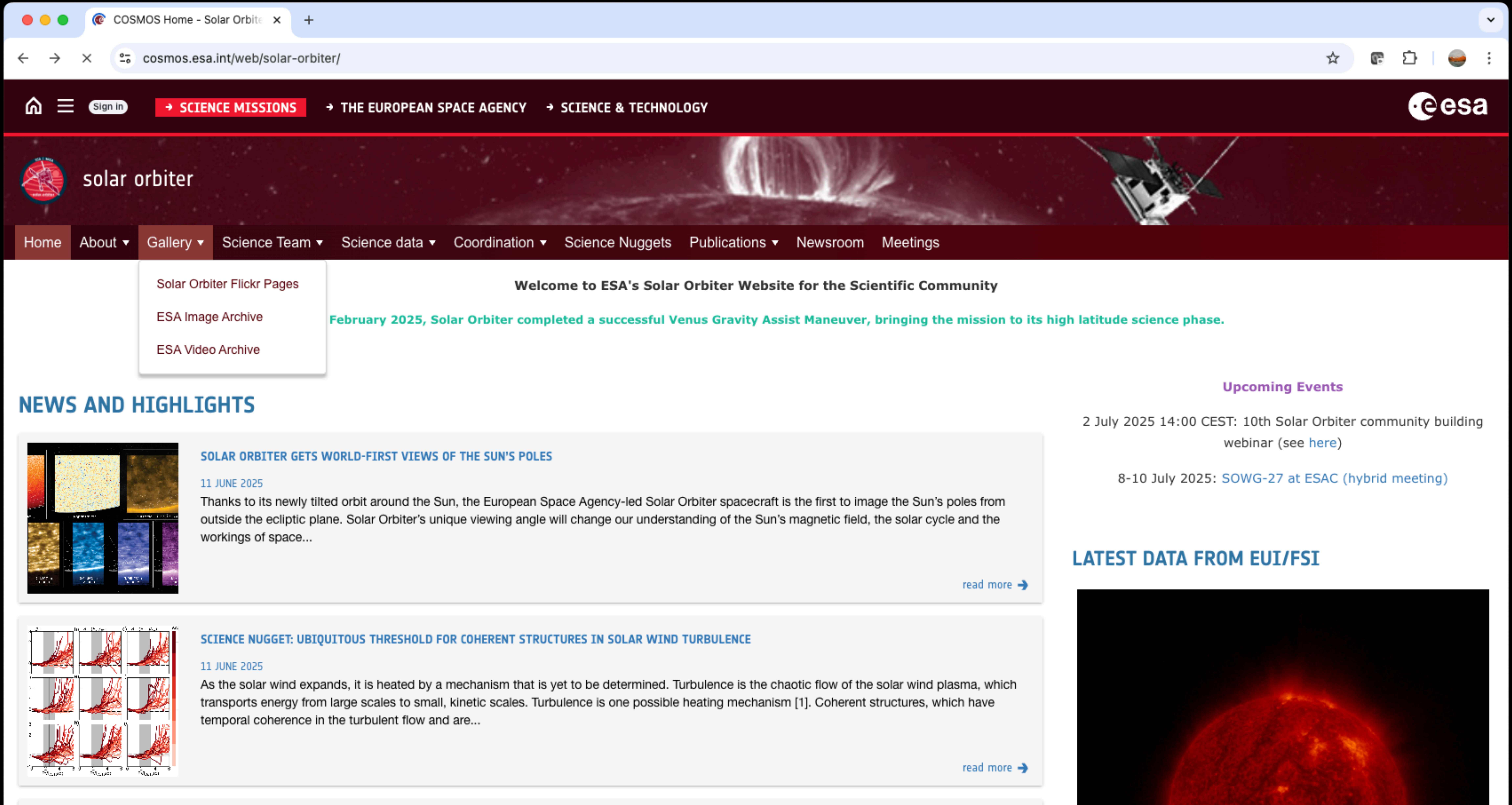

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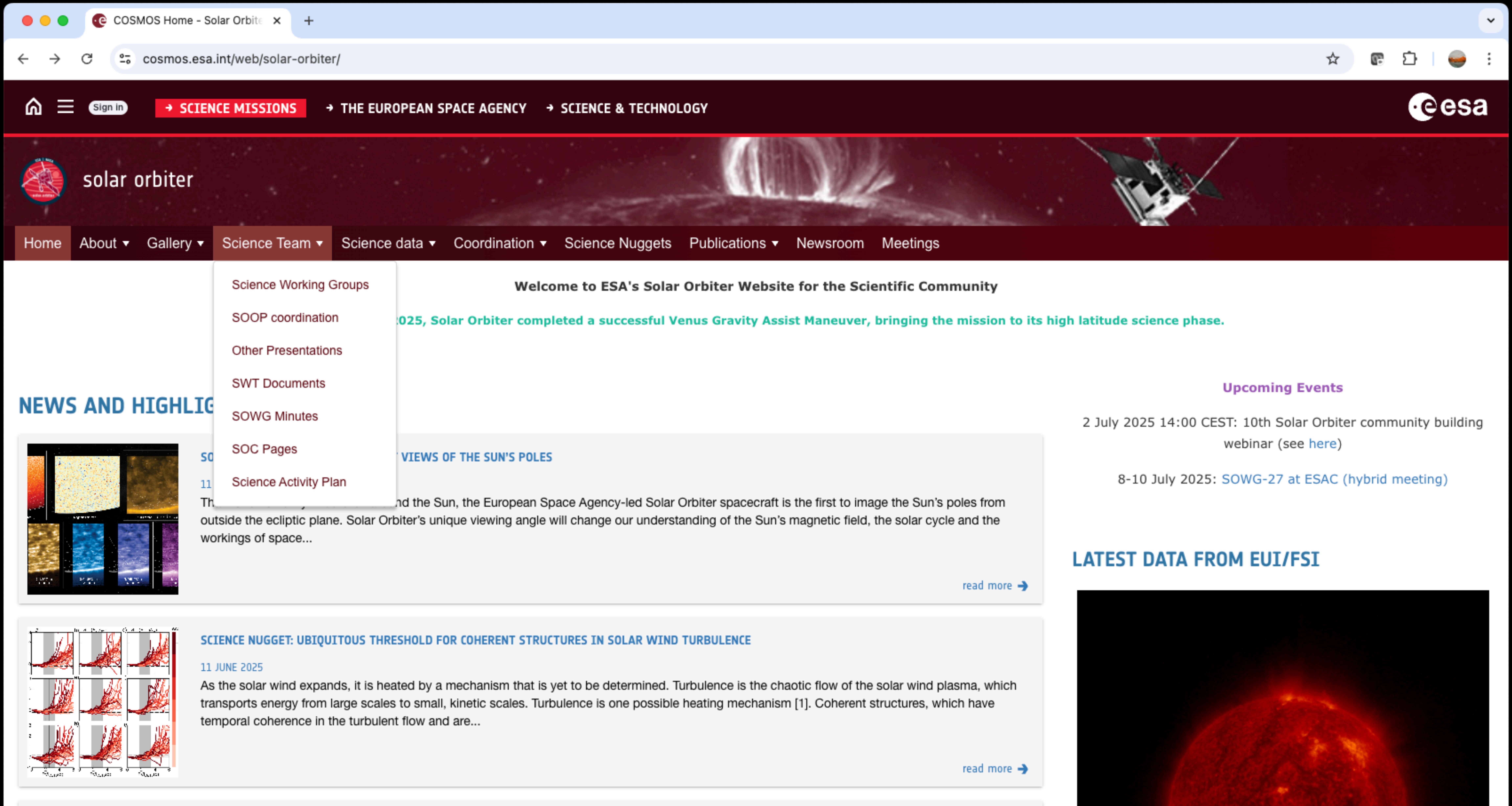

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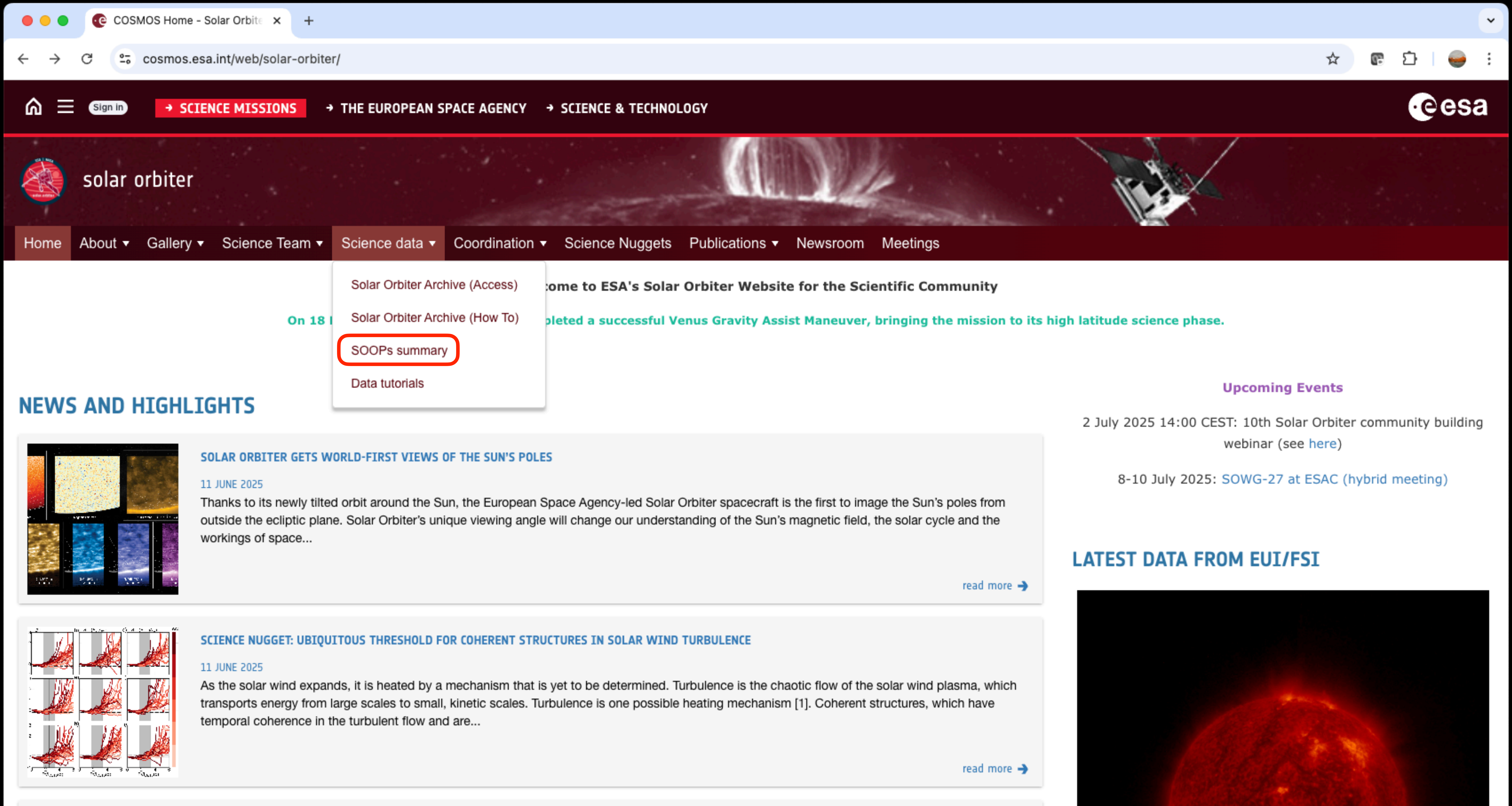

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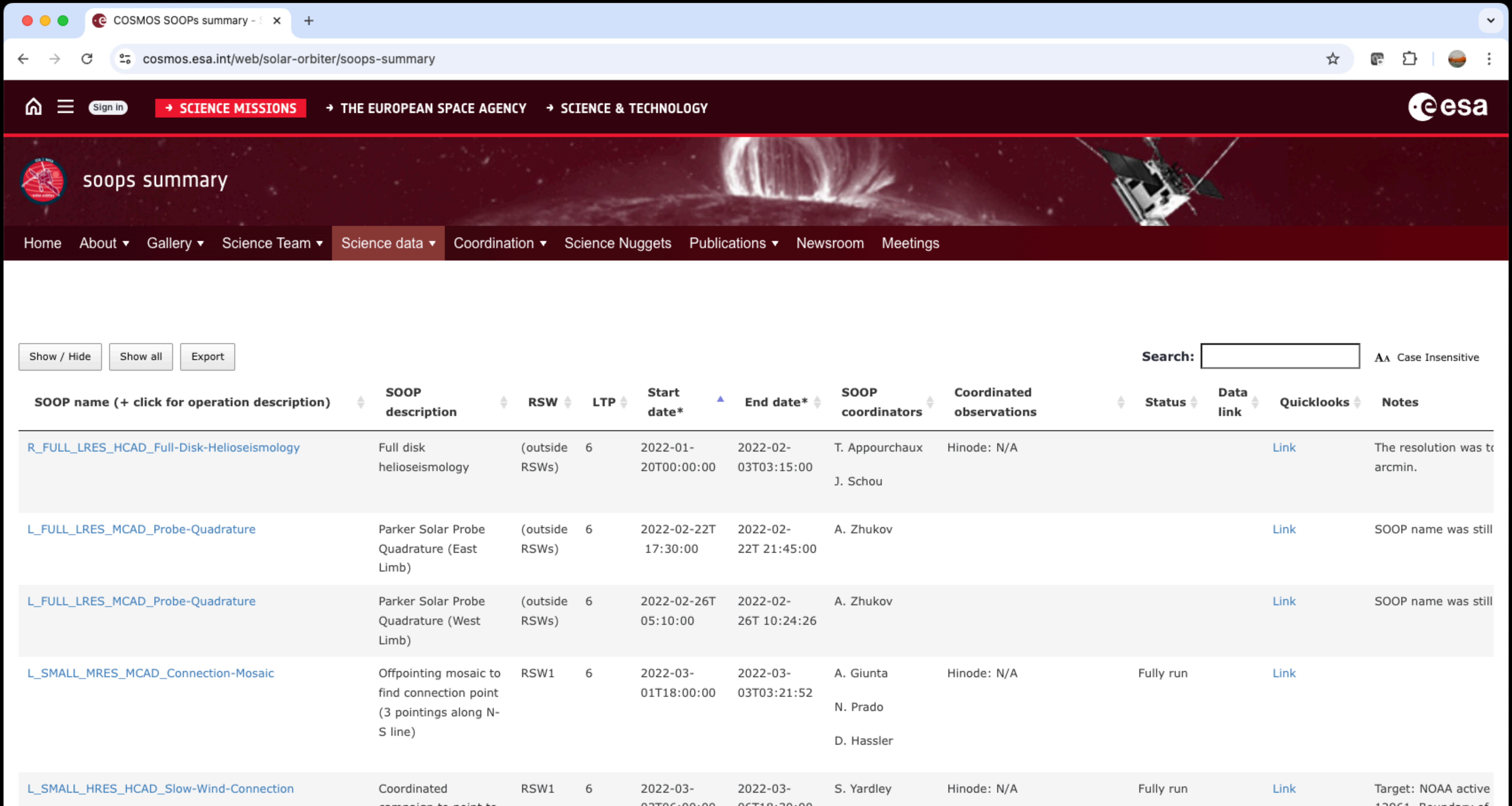

COSMOS SOOPs summary

cosmos.esa.int/web/solar-orbiter/soops-summary

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soops summary

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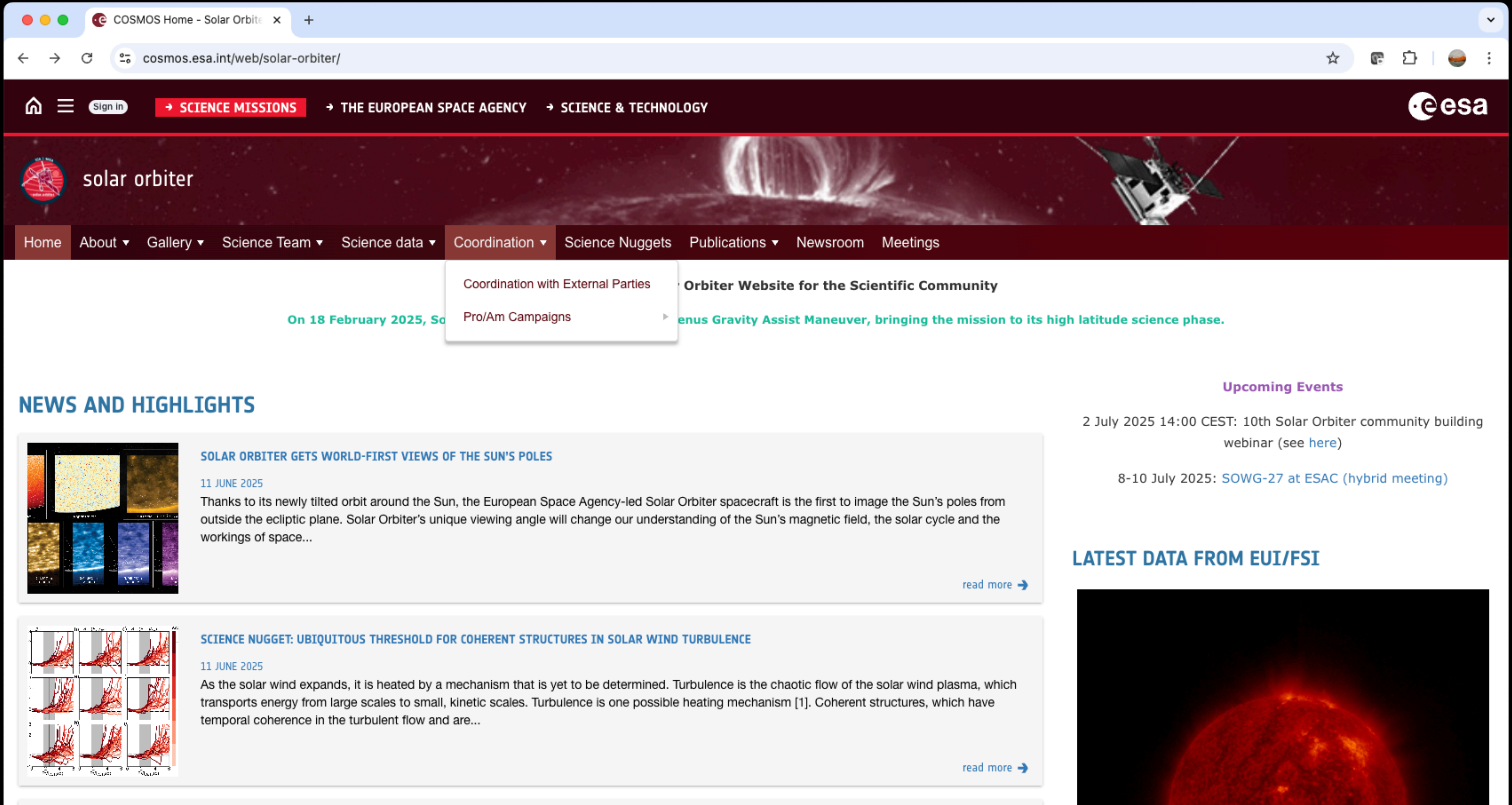
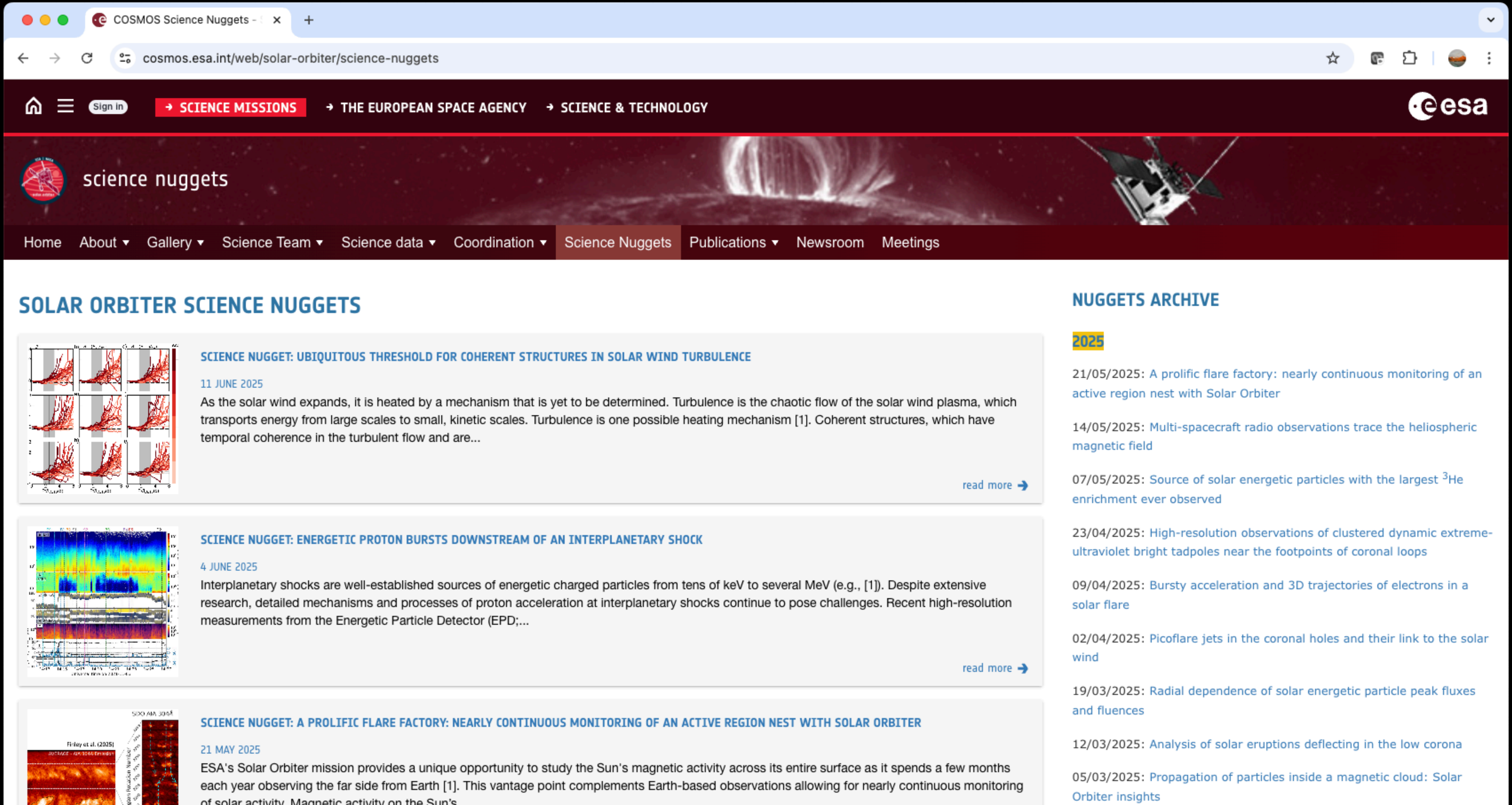
SOOP name (+ click for operation description)	SOOP description	RSW	LTP	Start date*	End date*	SOOP coordinators	Coordinated observations	Status	Data link	Quicklooks	Notes
R_FULL_LRES_HCAD_Full-Disk-Helioseismology	Full disk helioseismology	(outside RSWs)	6	2022-01-20T00:00:00	2022-02-03T03:15:00	T. Appourchaux J. Schou	Hinode: N/A			Link	The resolution was t arcmin.
L_FULL_LRES_MCAD_Probe-Quadrature	Parker Solar Probe Quadrature (East Limb)	(outside RSWs)	6	2022-02-22T 17:30:00	2022-02-22T 21:45:00	A. Zhukov				Link	SOOP name was still
L_FULL_LRES_MCAD_Probe-Quadrature	Parker Solar Probe Quadrature (West Limb)	(outside RSWs)	6	2022-02-26T 05:10:00	2022-02-26T 10:24:26	A. Zhukov				Link	SOOP name was still
L_SMALL_MRES_MCAD_Connection-Mosaic	Offpointing mosaic to find connection point (3 pointings along N-S line)	RSW1	6	2022-03-01T18:00:00	2022-03-03T03:21:52	A. Giunta N. Prado D. Hassler	Hinode: N/A	Fully run		Link	
L_SMALL_HRES_HCAD_Slow-Wind-Connection	Coordinated	RSW1	6	2022-03-	2022-03-	S. Yardley	Hinode: N/A	Fully run		Link	Target: NOAA active

Resources: Cosmos website



Resources: Cosmos website



COSMOS Science Nuggets -

cosmos.esa.int/web/solar-orbiter/science-nuggets

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SOLAR ORBITER SCIENCE NUGGETS

SCIENCE NUGGET: UBIQUITOUS THRESHOLD FOR COHERENT STRUCTURES IN SOLAR WIND TURBULENCE

11 JUNE 2025

As the solar wind expands, it is heated by a mechanism that is yet to be determined. Turbulence is the chaotic flow of the solar wind plasma, which transports energy from large scales to small, kinetic scales. Turbulence is one possible heating mechanism [1]. Coherent structures, which have temporal coherence in the turbulent flow and are...

read more

SCIENCE NUGGET: ENERGETIC PROTON BURSTS DOWNSTREAM OF AN INTERPLANETARY SHOCK

4 JUNE 2025

Interplanetary shocks are well-established sources of energetic charged particles from tens of keV to several MeV (e.g., [1]). Despite extensive research, detailed mechanisms and processes of proton acceleration at interplanetary shocks continue to pose challenges. Recent high-resolution measurements from the Energetic Particle Detector (EPD;...

read more

SCIENCE NUGGET: A PROLIFIC FLARE FACTORY: NEARLY CONTINUOUS MONITORING OF AN ACTIVE REGION NEST WITH SOLAR ORBITER

21 MAY 2025

ESA's Solar Orbiter mission provides a unique opportunity to study the Sun's magnetic activity across its entire surface as it spends a few months each year observing the far side from Earth [1]. This vantage point complements Earth-based observations allowing for nearly continuous monitoring of solar activity. Magnetic activity on the Sun's

NUGGETS ARCHIVE

2025

21/05/2025: A prolific flare factory: nearly continuous monitoring of an active region nest with Solar Orbiter

14/05/2025: Multi-spacecraft radio observations trace the heliospheric magnetic field

07/05/2025: Source of solar energetic particles with the largest ^3He enrichment ever observed

23/04/2025: High-resolution observations of clustered dynamic extreme-ultraviolet bright tadpoles near the footpoints of coronal loops

09/04/2025: Bursty acceleration and 3D trajectories of electrons in a solar flare

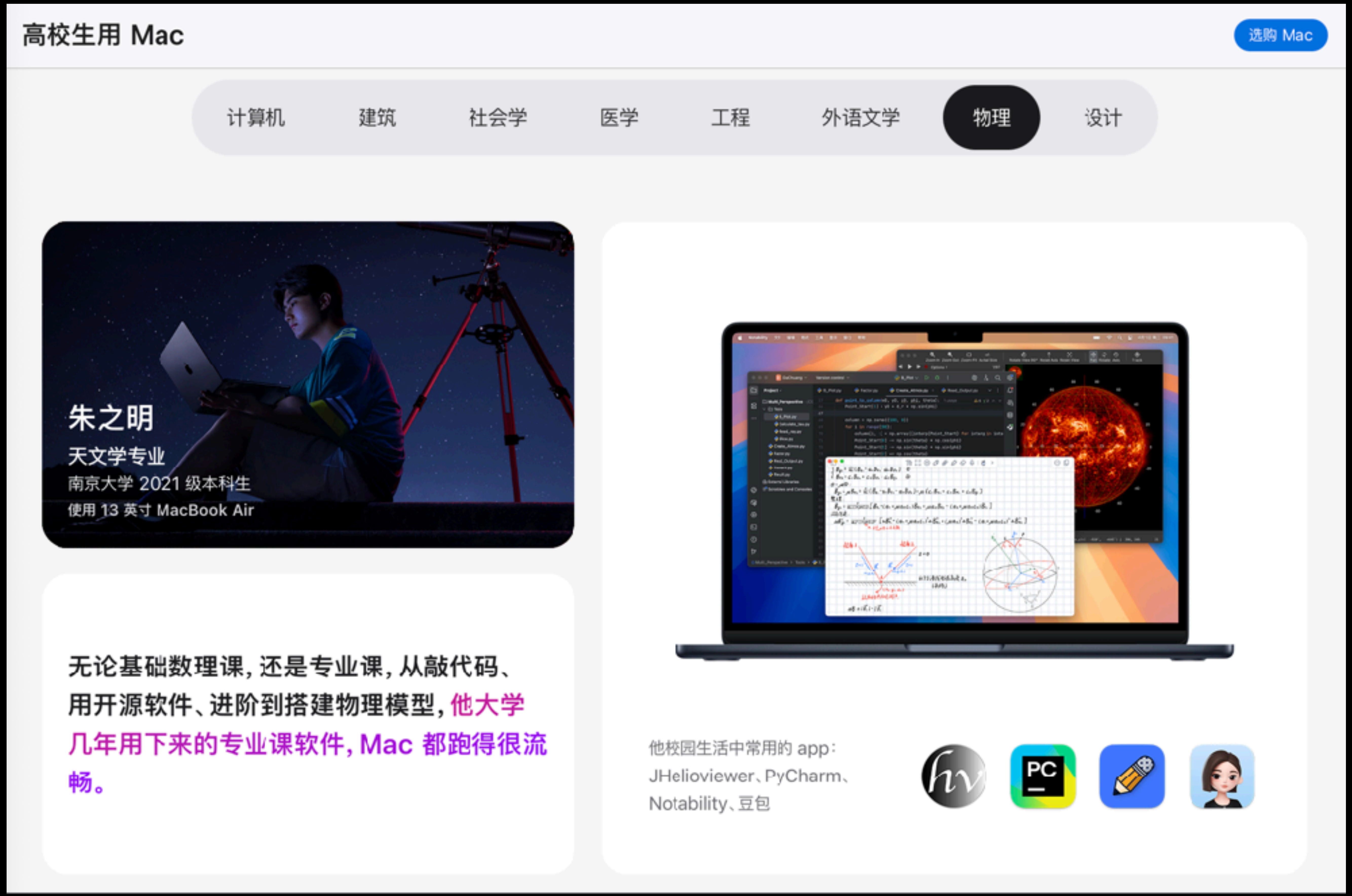
02/04/2025: Picoflare jets in the coronal holes and their link to the solar wind

19/03/2025: Radial dependence of solar energetic particle peak fluxes and fluences

12/03/2025: Analysis of solar eruptions deflecting in the low corona

05/03/2025: Propagation of particles inside a magnetic cloud: Solar Orbiter insights

Resources: JHelioviewer

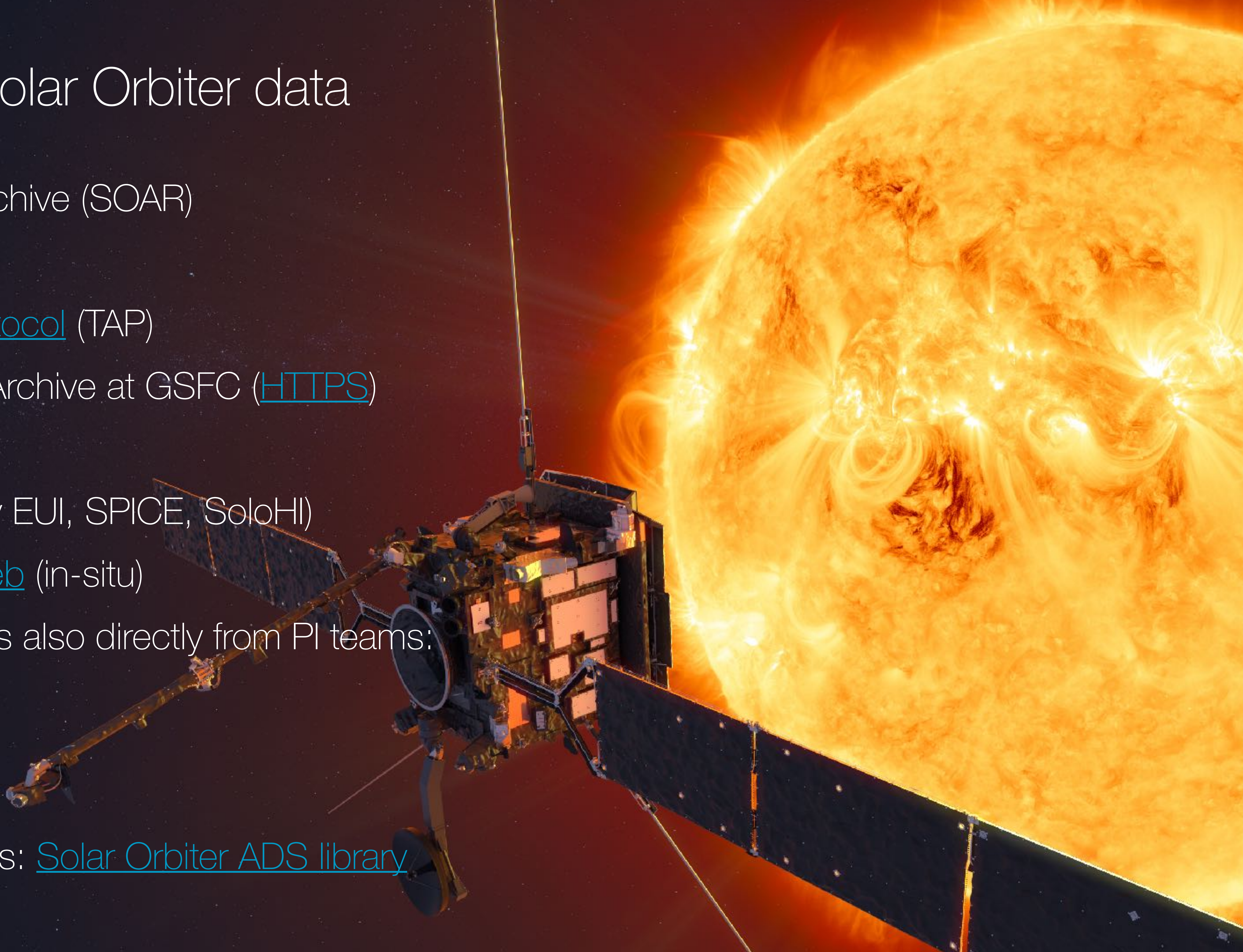


[Müller et al., A&A 2017]

How to access Solar Orbiter data

- ESA Solar Orbiter Archive (SOAR)
  - Web interface
  - Table-Access Protocol (TAP)
- NASA Solar Orbiter Archive at GSFC (HTTPS)
- SunPy
- NASA VSO (currently EUI, SPICE, SoloHI)
- NASA SPDF CDAWeb (in-situ)
- For some instruments also directly from PI teams: Data tutorials

Refereed publications: Solar Orbiter ADS library



Solar Orbiter: Here comes the Sun

Summary

- First seven close perihelia successfully completed
- Exciting science results
- Successful multi-mission coordination
- Out-of-ecliptic phase has just started!

A vibrant science community:

- Solar Orbiter's topical science WGs: Open to everyone

Open data policy:

- Upon receipt of data, instrument teams have 3 months for data calibration & validation
- After submission to ESA, all data is publicly accessible from the Solar Orbiter Archive