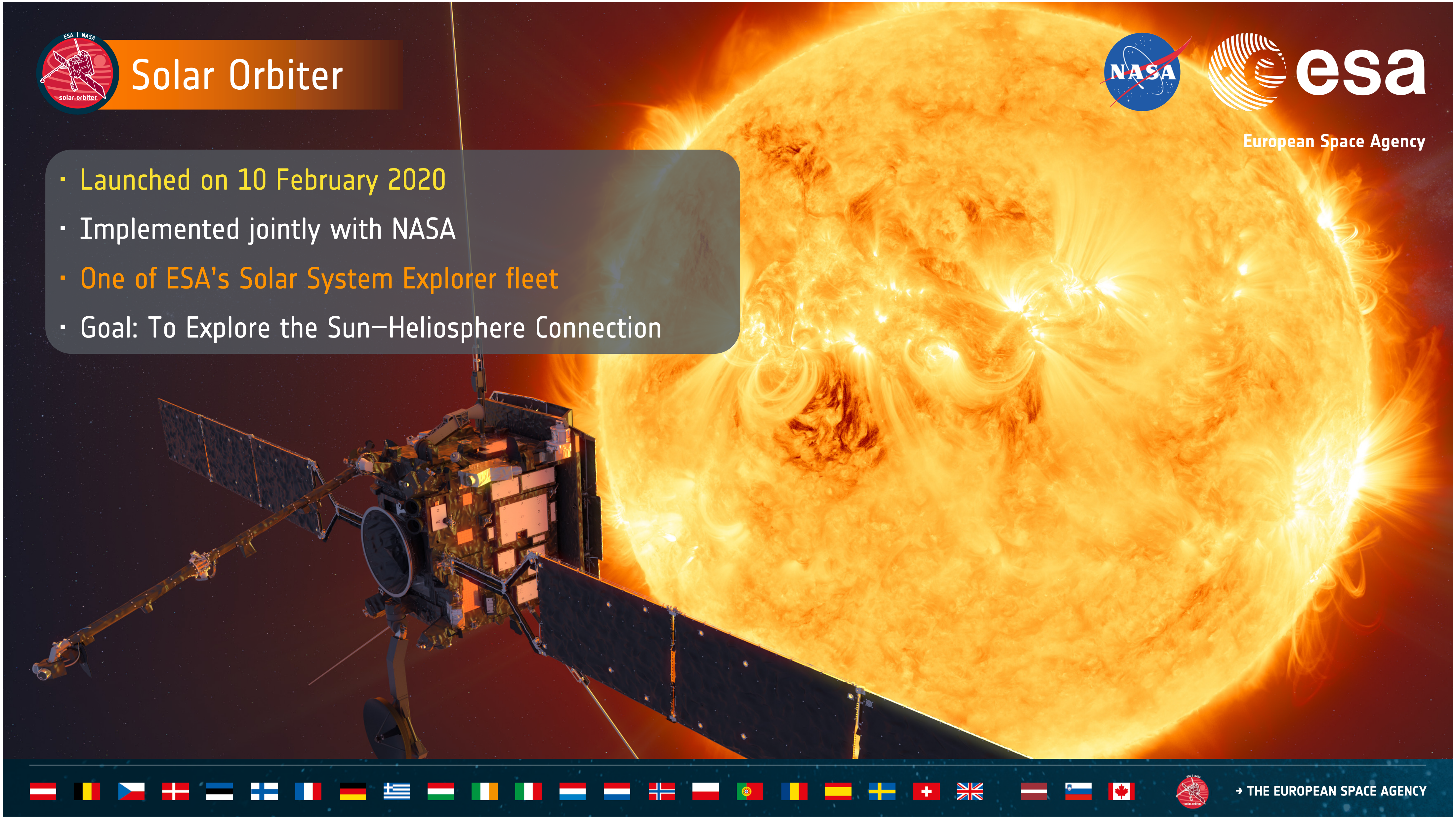
Solar Orbiter:
The mission and what we've learned so far

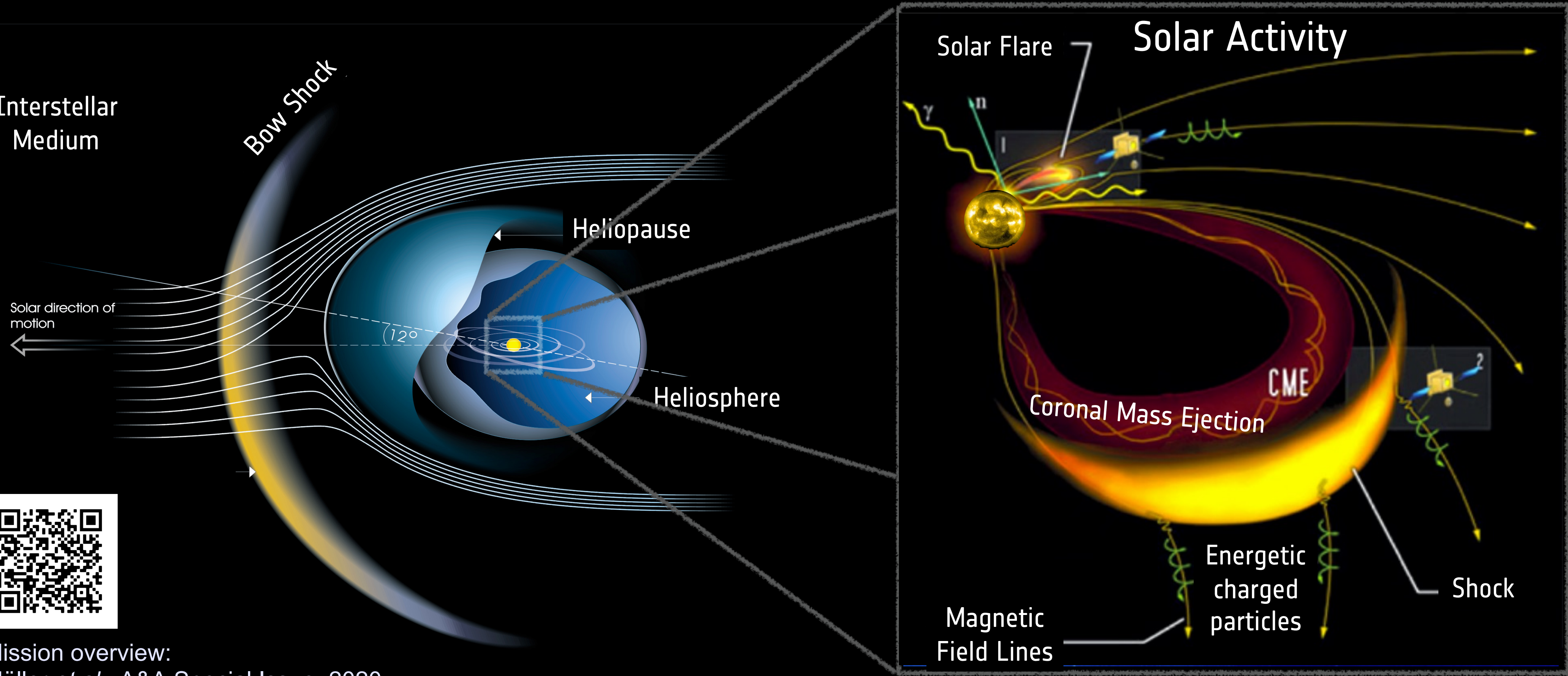
David Williams

Science Operations Scientist,
Solar Orbiter Science Operations Centre
European Space Agency, ESAC, Madrid.

Space For All
ESAC, 2022 Oct 20


Solar Orbiter
ESA | NASA
solar orbiter
NASA
esa
European Space Agency
Launched on 10 February 2020
Implemented jointly with NASA
One of ESA's Solar System Explorer fleet
Goal: To Explore the Sun–Heliosphere Connection
→ THE EUROPEAN SPACE AGENCY

Solar Orbiter's motivation: Exploring the Sun & Heliosphere

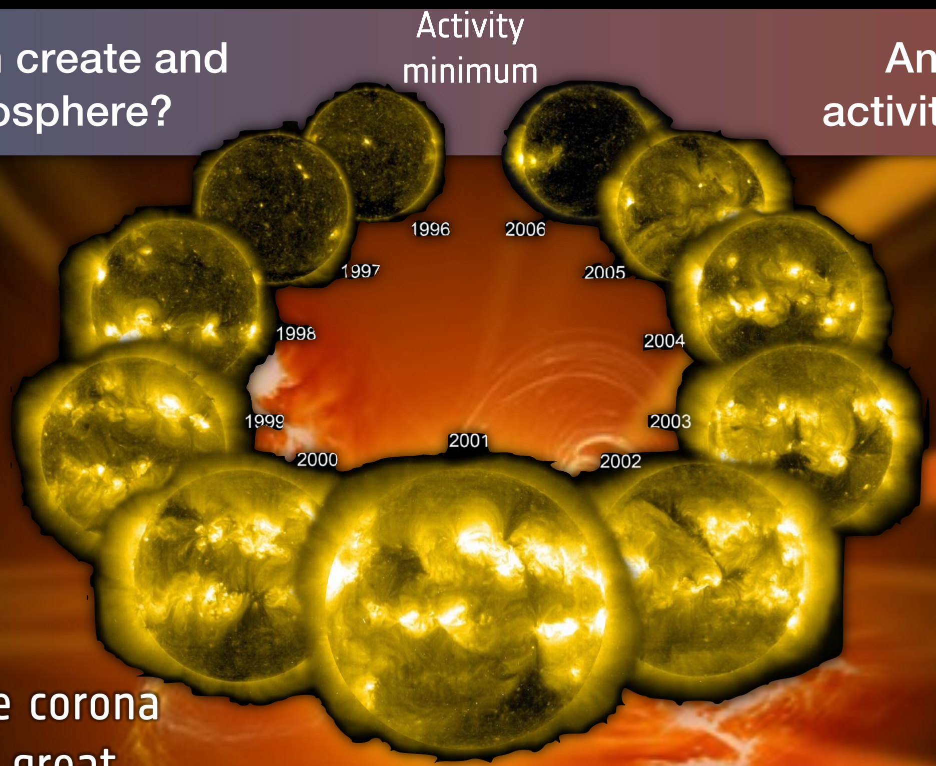


Mission overview:
Müller *et al.*, A&A Special Issue, 2020

The big questions for Solar Orbiter

How does the Sun create and control the heliosphere?

And why does solar activity change with time?



We see it much dimmer at activity minimum (no sunspots)...

...and much brighter at activity maximum (many sunspots).

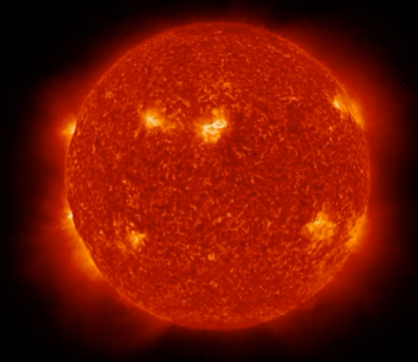
It is over 1 million degrees celsius in temperature!

We can see the corona of the sun in great detail in ultraviolet (UV) light.

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

→ THE EUROPEAN SPACE AGENCY

Zooming into the Sun: First close perihelion, March 2022



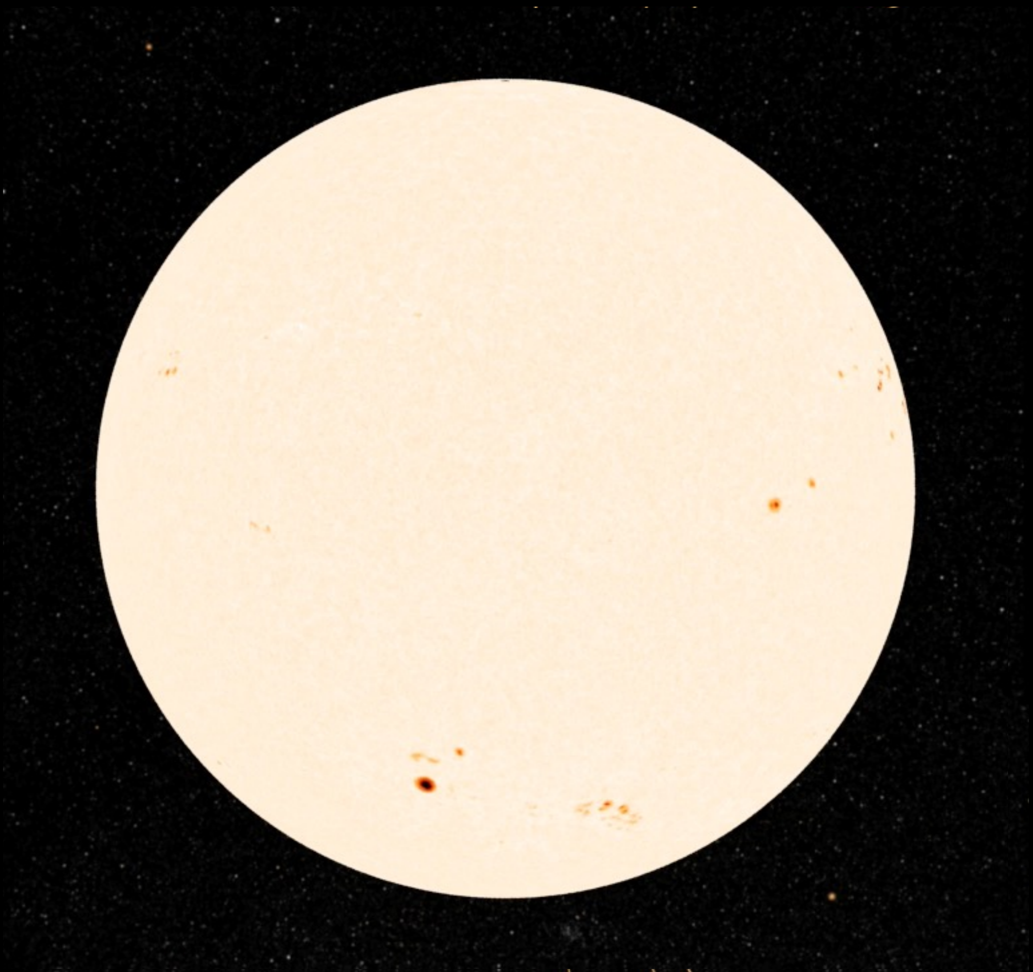
Movies from Solar Orbiter’s *Extreme Ultraviolet Imager*, taken in 2 specific wavelengths (colours) of UV light.

Notice all the loops, especially in the left image. These are caused by superheated gas being stuck to the Sun’s magnetic field!

EUI FSI 174 2022-01-29T00:00:50.185

EUI FSI 304 2022-01-29T00:00:20.184

The origin of solar activity: its twisted magnetic field



Animation: NASA/Goddard Space Flight Center Scientific Visualization Studio

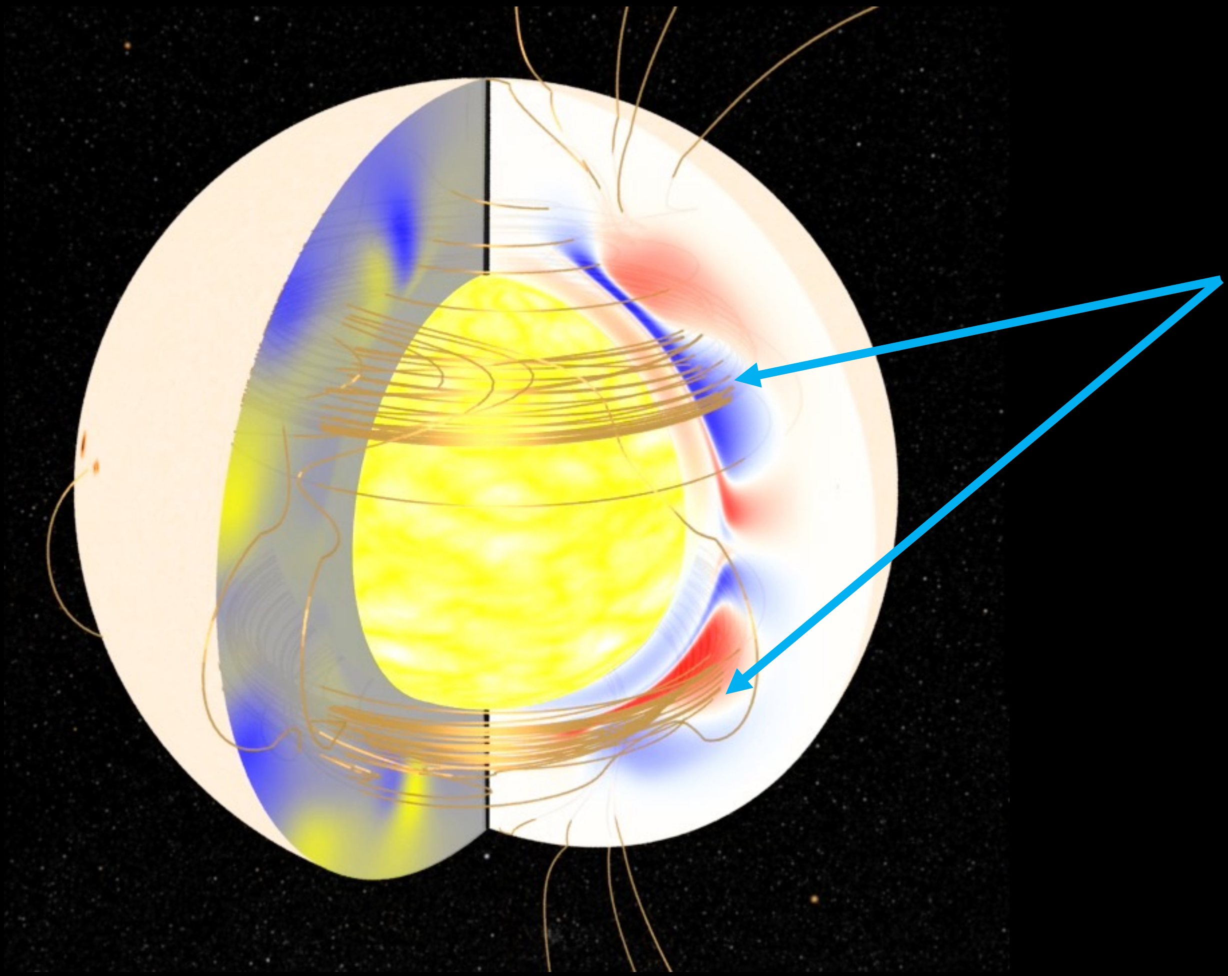
Where do these magnetic loops come from?

The Sun's magnetic field gets twisted up inside it. The equator makes a full revolution in less time than the parts nearer the poles.

Twisted magnetic fields are strong, and buoyant, and burst through the surface as sunspots (in visible light) and magnetic loops (in UV).

Circular flow patterns inside the Sun drag magnetic field to the poles.

The origin of solar activity is still hidden from our view



Animation: NASA/Goddard Space Flight Center Scientific Visualization Studio

We know the Sun's activity is all caused and shaped by its magnetic field.

We think it comes from this depth inside the Sun, but we need more data to understand how it's created.

Even worse, we have incomplete measurements of the magnetic field because we've never directly seen the solar poles!

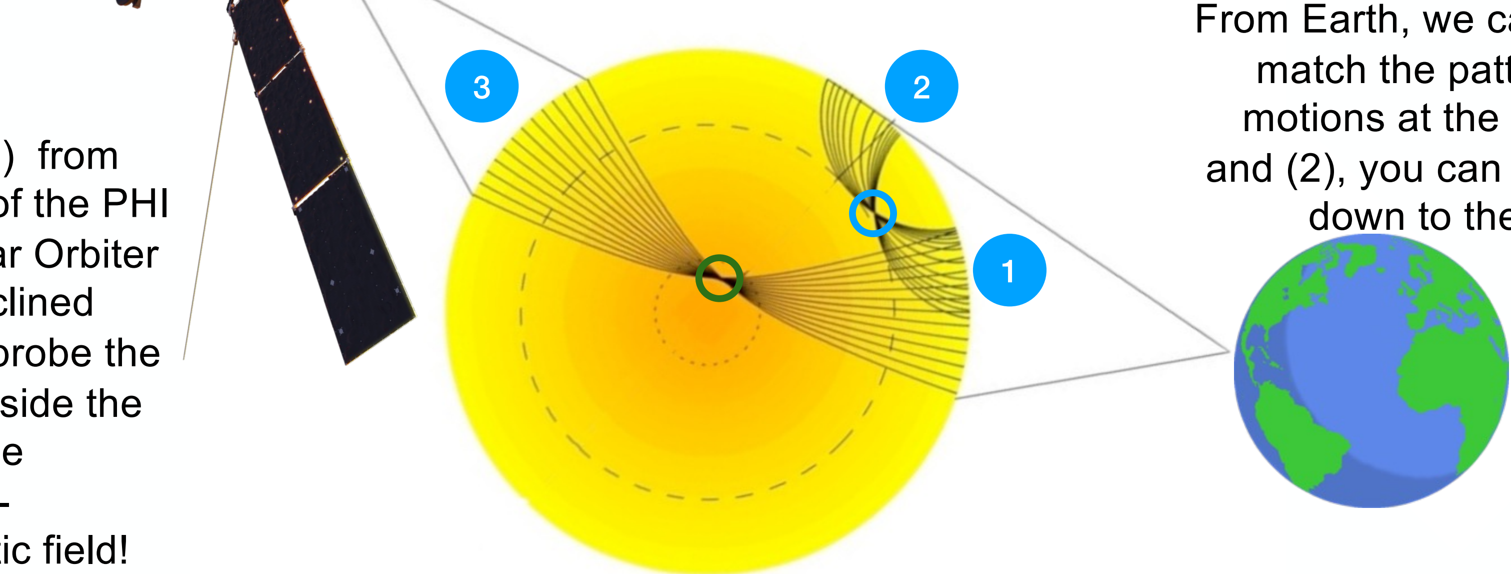
It isn't easy to sense what's happening inside the Sun because we only see the light from far above, at the surface.

So we use a trick learned from earthquake science and from mining and oil exploration: **seismology!**

Seismology: probing the depths of the Sun

Sound waves follow a curved path inside the Sun

When they bounce at the surface, they cause it to move up and down



From Earth, we can sense and match the patterns of these motions at the surface at (1) and (2), you can probe depths down to the dashed line.

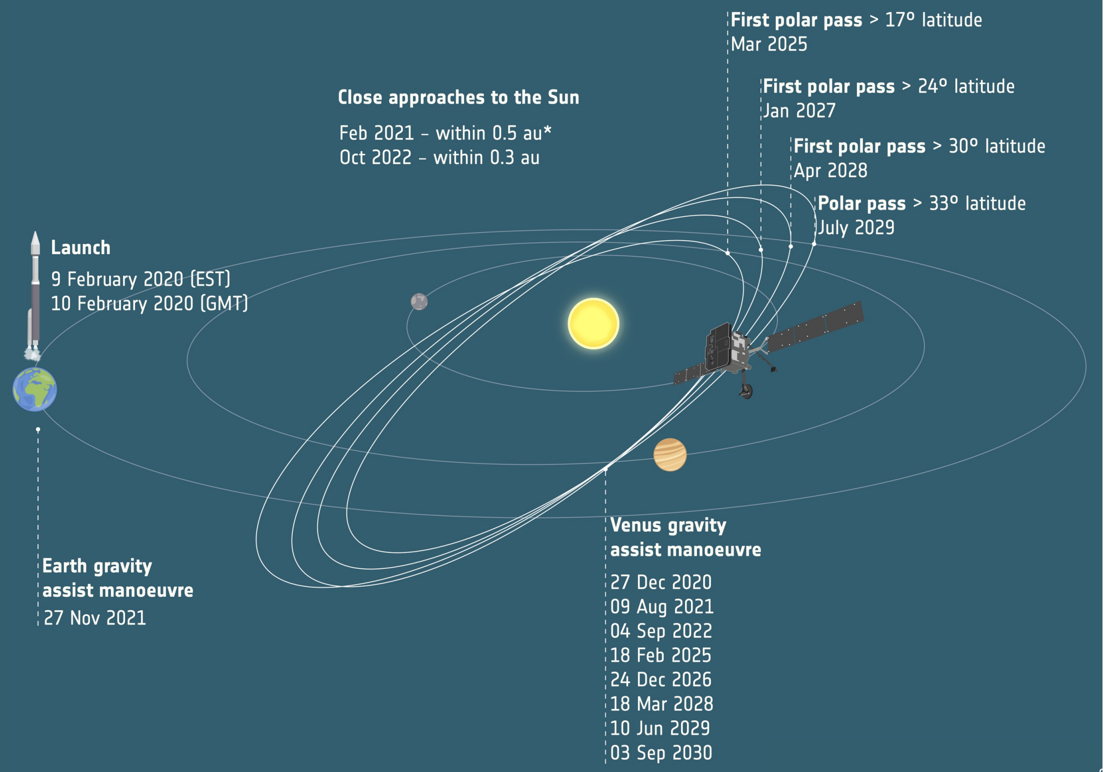
Combining the measurements (1) from Earth with those of the PHI telescope on Solar Orbiter when it's at an inclined orbit (3), we can probe the gas flows deep inside the Sun that should be generating the all-important magnetic field!

With the inclined orbit of Solar Orbiter, we can map the solar poles for the first time!

Solar Orbiter is a mission into the Solar Wind

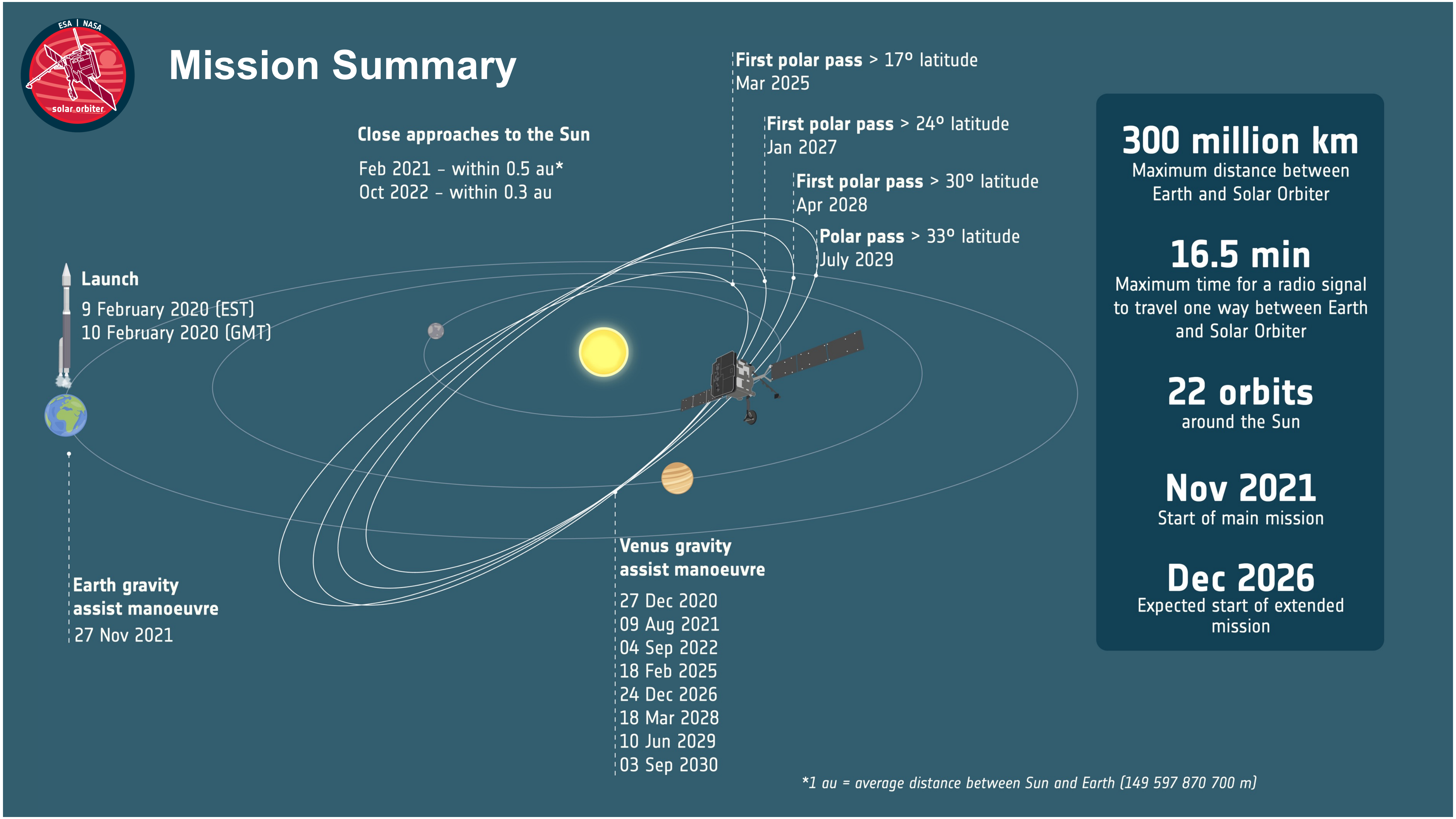
To achieve its missions, Solar Orbiter has to…

- fly into the Solar Wind, getting much closer to the Sun
- Measure the solar wind around the spacecraft
- observe the parts of the Sun most likely to affect the space around it
- Look at the Sun to see where the effects in the solar wind might come from *on the Sun*

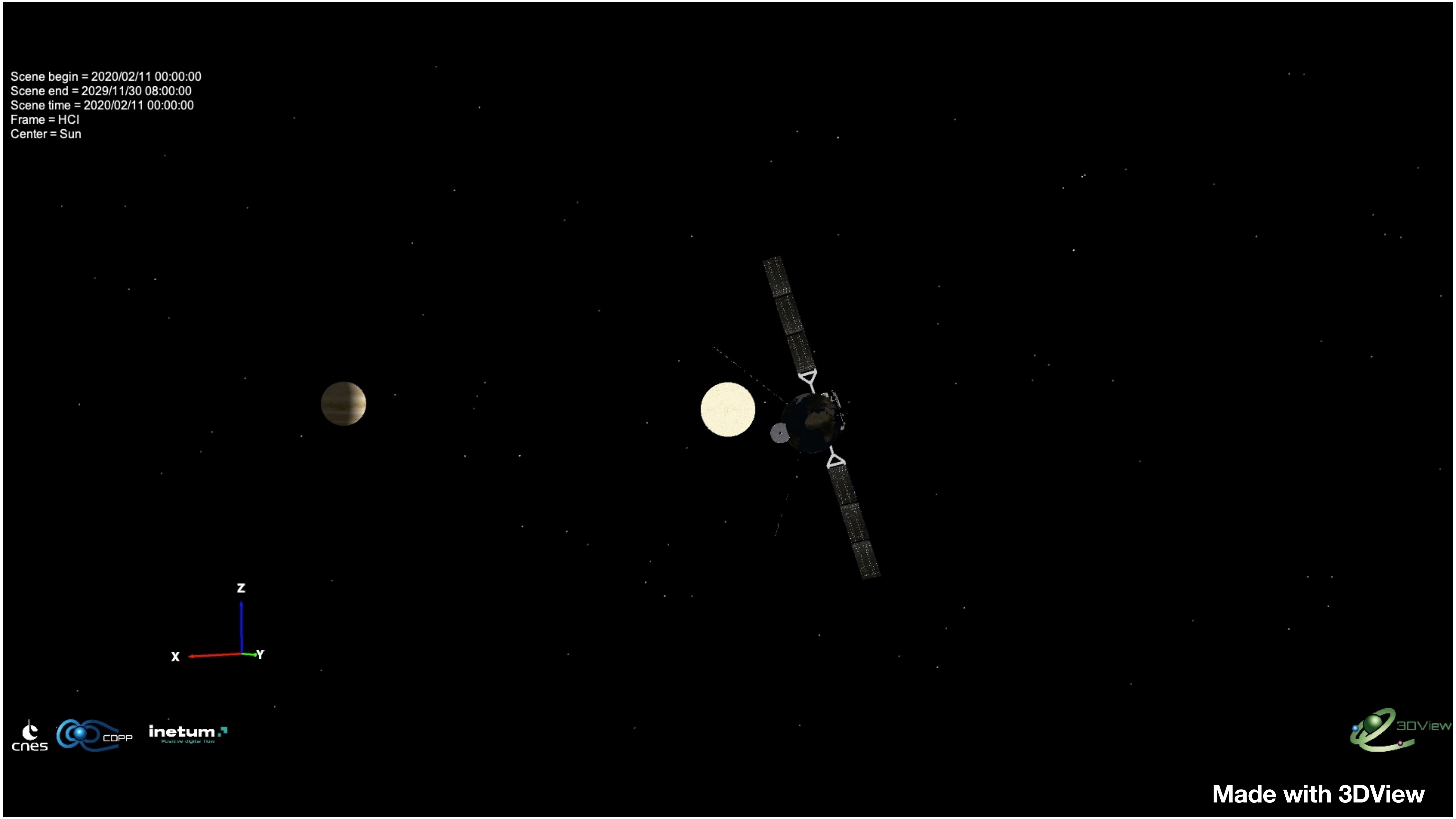


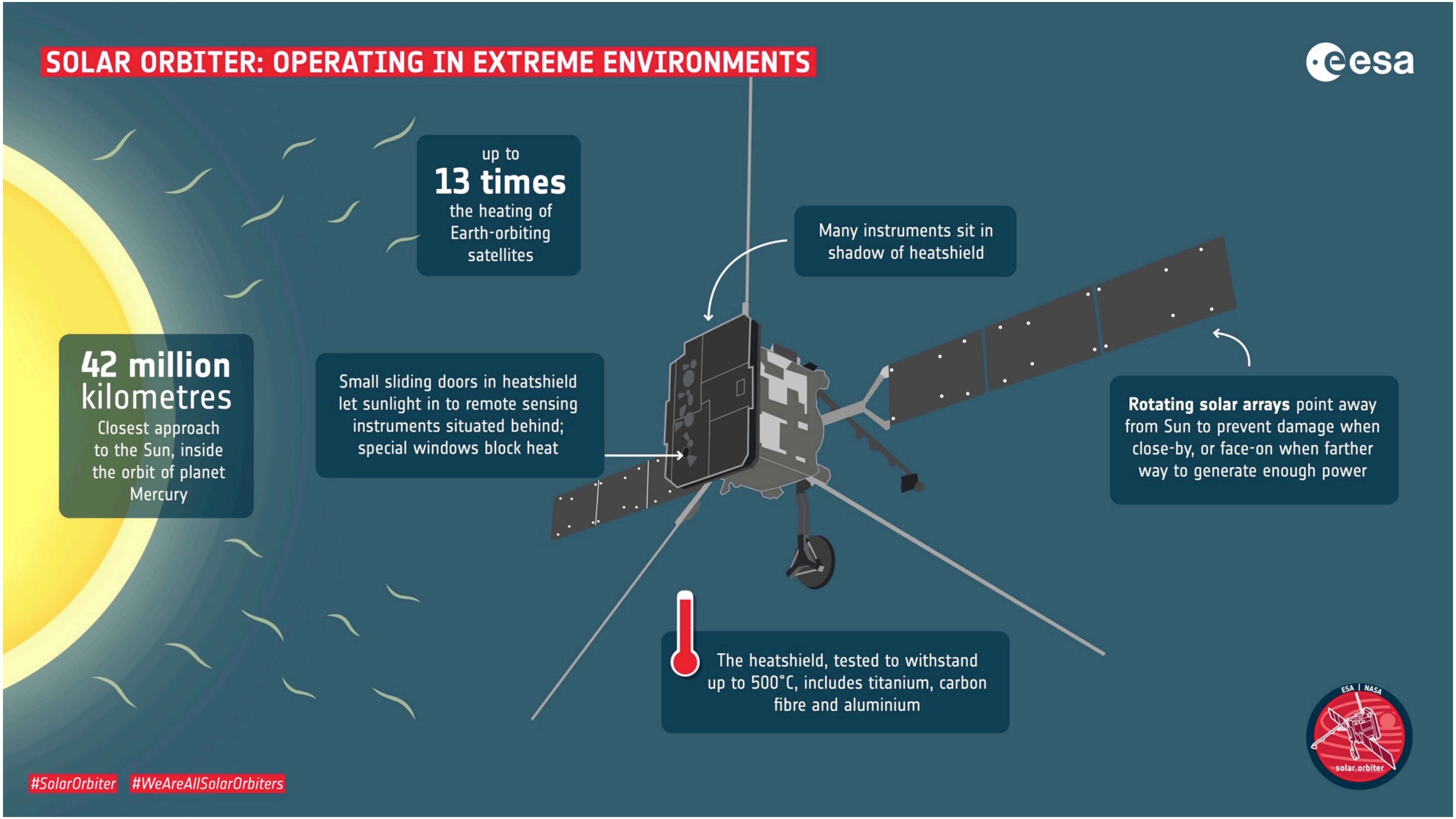
To be able to get close to the Sun, the spacecraft uses an elliptical orbit.

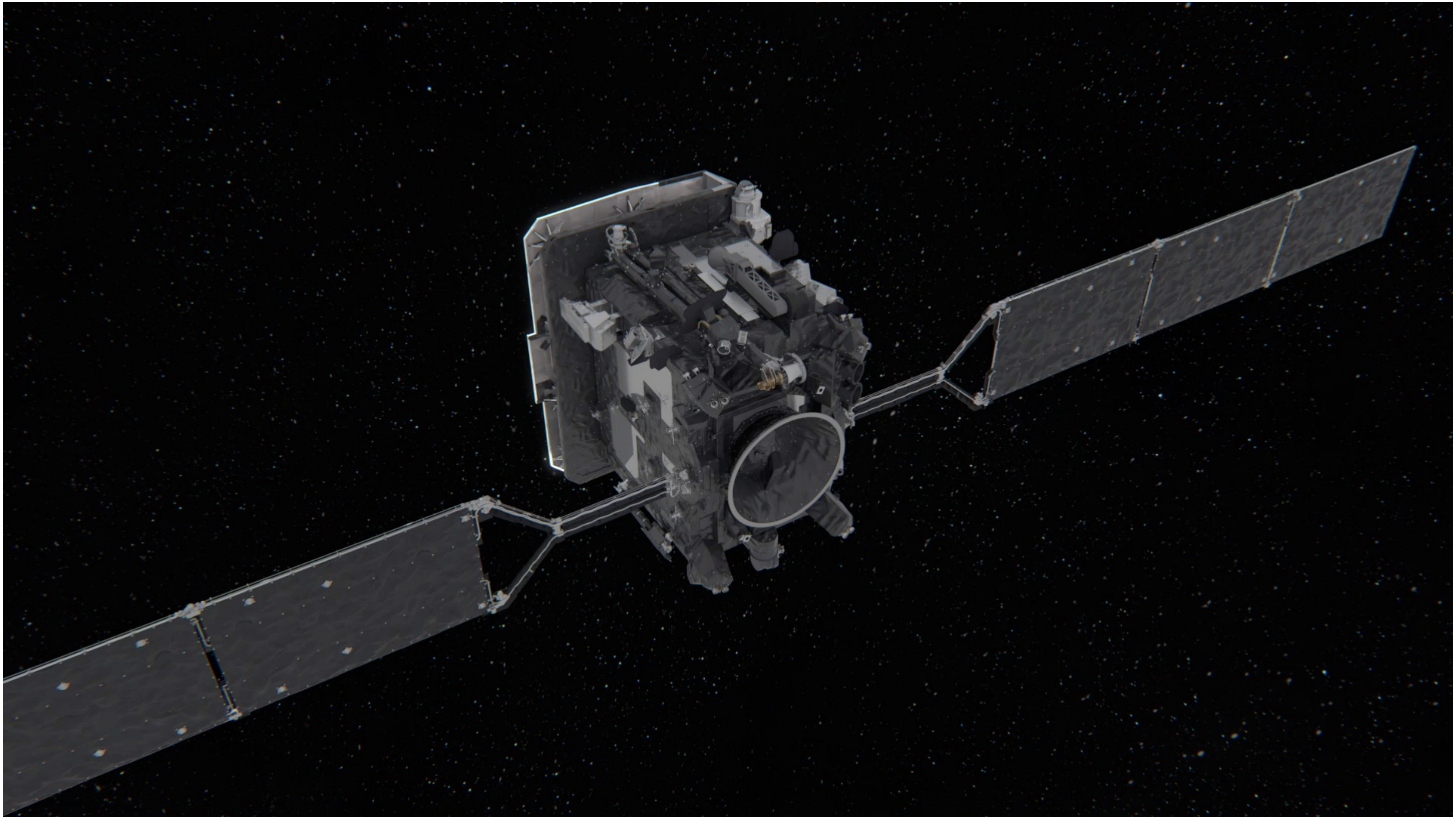
To see the north and south pole of the Sun, it has to tilt its orbit away from the Earth's orbit, using gravitational slingshots past Venus



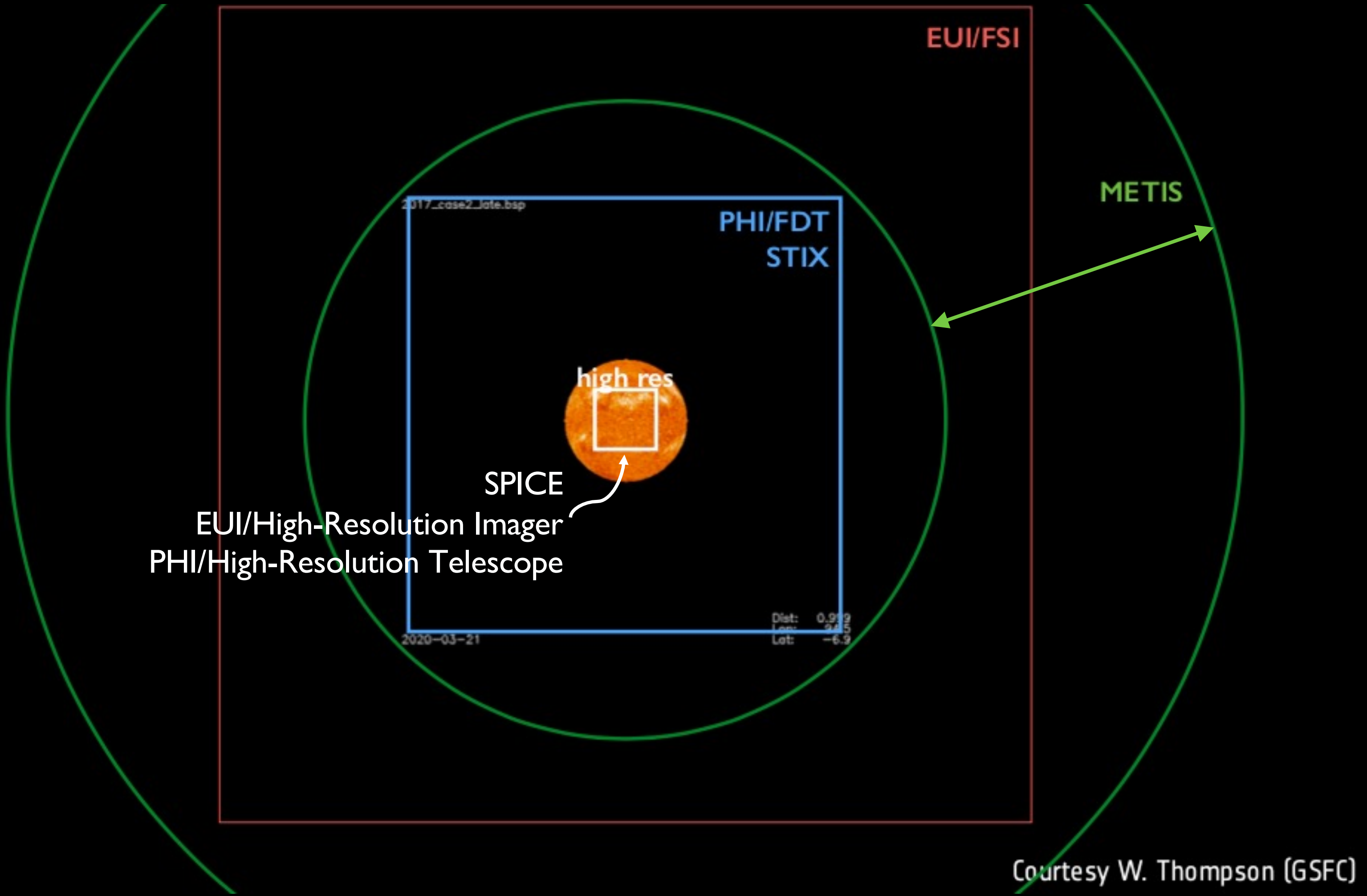
Mission Summary
Close approaches to the Sun
Feb 2021 – within 0.5 au*
Oct 2022 – within 0.3 au
First polar pass > 17° latitude
Mar 2025
First polar pass > 24° latitude
Jan 2027
First polar pass > 30° latitude
Apr 2028
Polar pass > 33° latitude
July 2029
Launch
9 February 2020 (EST)
10 February 2020 (GMT)
Earth gravity
assist manoeuvre
27 Nov 2021
Venus gravity
assist manoeuvre
27 Dec 2020
09 Aug 2021
04 Sep 2022
18 Feb 2025
24 Dec 2026
18 Mar 2028
10 Jun 2029
03 Sep 2030
300 million km
Maximum distance between Earth and Solar Orbiter
16.5 min
Maximum time for a radio signal to travel one way between Earth and Solar Orbiter
22 orbits
around the Sun
Nov 2021
Start of main mission
Dec 2026
Expected start of extended mission
*1 au = average distance between Sun and Earth (149 597 870 700 m)


Scene begin = 2020/02/11 00:00:00
Scene end = 2029/11/30 08:00:00
Scene time = 2020/02/11 00:00:00
Frame = HCI
Center = Sun
Z
X
Y
cnes
COPP
inetum.
3DView
Made with 3DView

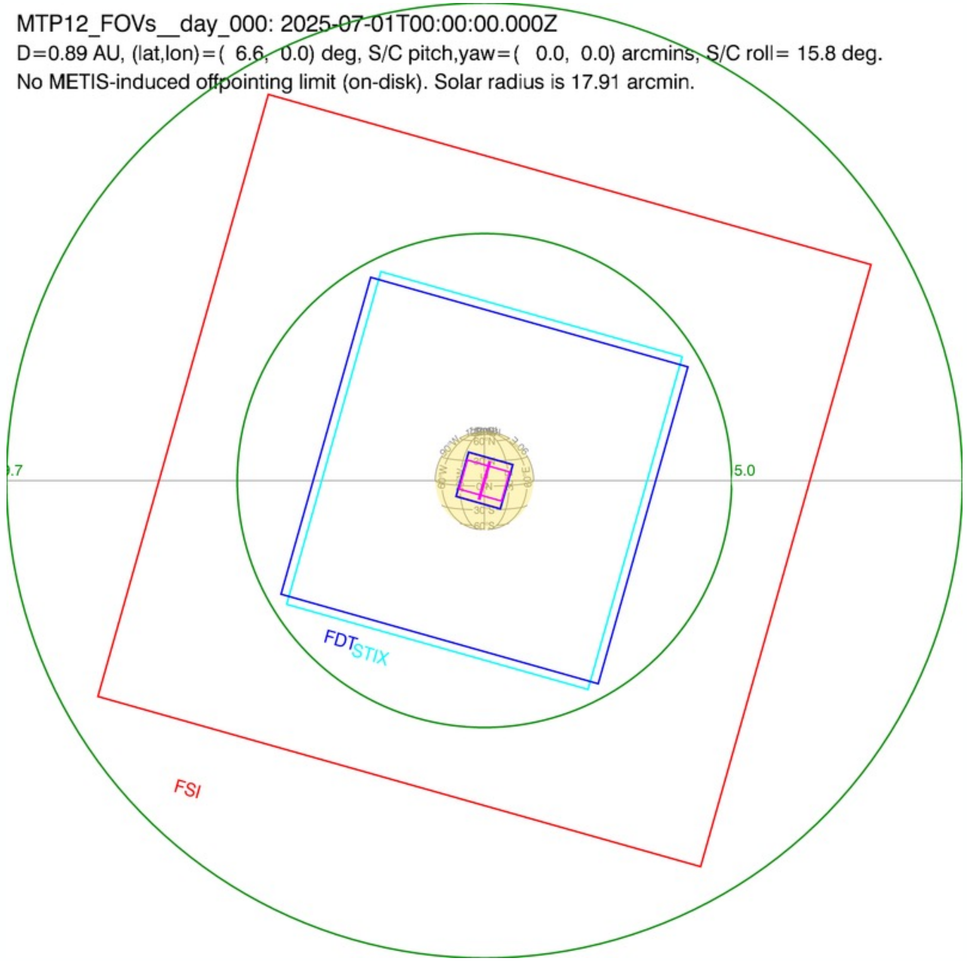

SOLAR ORBITER: OPERATING IN EXTREME ENVIRONMENTS
esa
up to
13 times
the heating of Earth-orbiting satellites
Many instruments sit in shadow of heatshield
42 million kilometres
Closest approach to the Sun, inside the orbit of planet Mercury
Small sliding doors in heatshield let sunlight in to remote sensing instruments situated behind; special windows block heat
Rotating solar arrays point away from Sun to prevent damage when close-by, or face-on when farther way to generate enough power
The heatshield, tested to withstand up to 500°C, includes titanium, carbon fibre and aluminium
ESA | NASA
solar orbiter
#SolarOrbiter
#WeAreAllSolarOrbiters

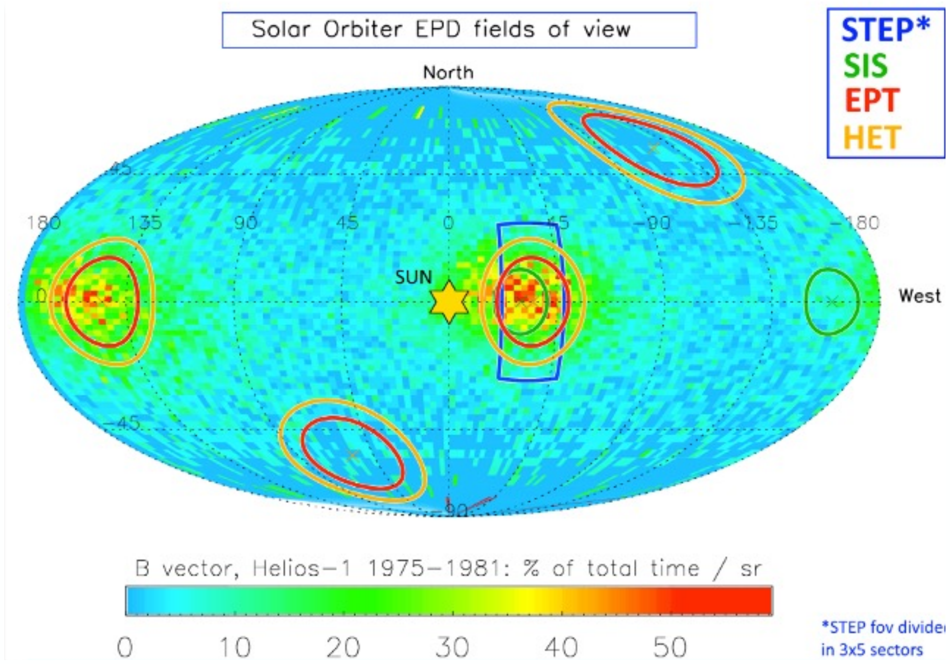


Telescope Fields of View

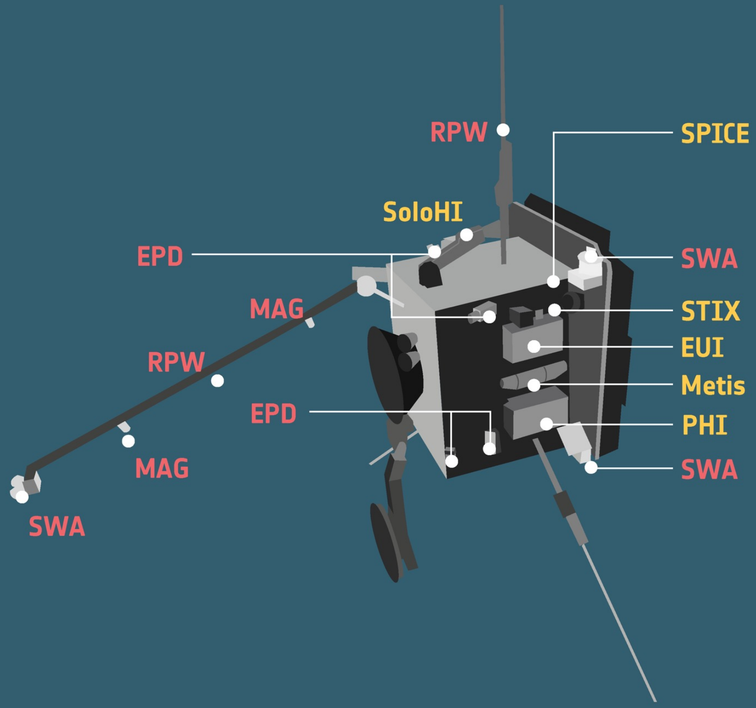


How Solar Orbiter's perspective changes



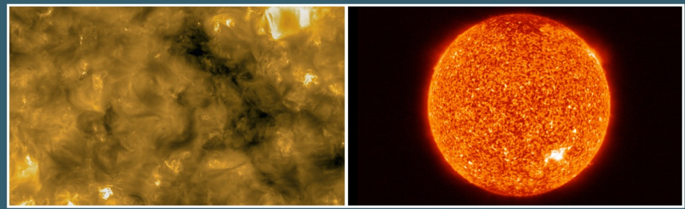


All the instruments on board

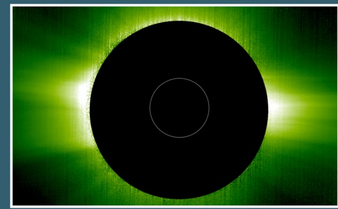


The *in situ* instruments

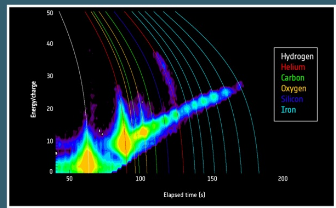
The remote-sensing instruments



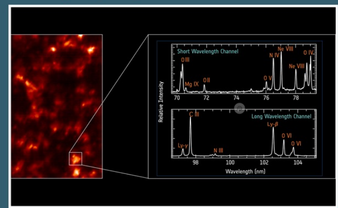
Extreme Ultraviolet Imager **(EUI)**



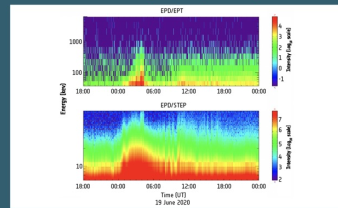
Coronagraph **(Metis)**



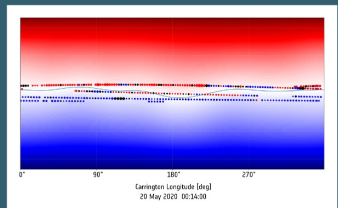
Solar Wind Analyser **(SWA)**



Spectral Imaging of the Coronal Environment **(SPICE)**

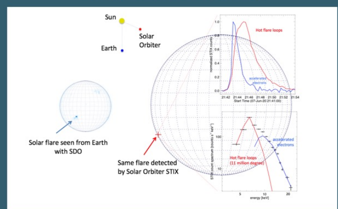


Energetic Particle Detector **(EPD)**

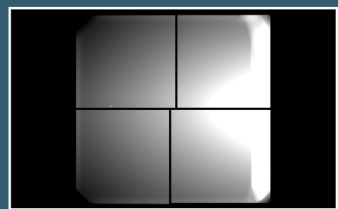


Magnetometer **(MAG)**

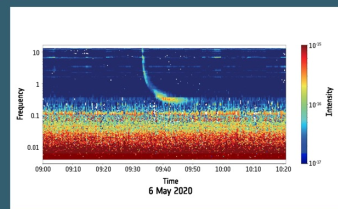
Polarimetric and Helioseismic Imager **(PHI)**



X-ray Spectrometer/Telescope **(STIX)**



Heliospheric Imager **(SoloHI)**



Radio and Plasma Waves **(RPW)**

All images show real data from the first year of the mission

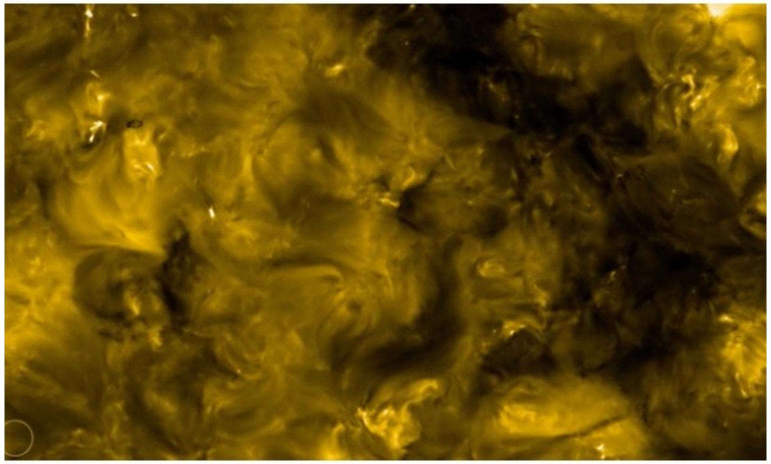
#TheSunUpClose

First-Light Press Event

The New York Times

Closest Pictures Ever Taken of Sun Show Tiny Campfire Flares

Images of the new phenomenon were captured by Solar Orbiter, a joint European-NASA mission to study the sun.



Images captured by the European Space Agency's solar orbiter show many tiny solar flares that scientists are calling "campfires." The small circle at left represents the Earth to scale.

Selected Headlines

Solar probe reveals sun's tiny 'campfires' in closest-ever photos

Reuters, 16.07.2020

ESA-SONDE SCHICKT ERSTE BILDER

So nah haben wir die Sonne noch nie gesehen!

bild.de, 16.07.2020

BBC World News, 16.07.2020

Las imágenes más cercanas del Sol muestran minierupciones nunca vistas antes

EFE, 16.07.2020

THE SUN'S ON FIRE!

Incredible close-up photo by British spacecraft shows miniature solar flares dubbed 'campfires'

Daily Mail, 17.07.2020

Esa-Raumsonde Solar Orbiter macht spektakuläre Sonnenbilder

spiegel.de, 16.07.2020

Una nave europea toma la imagen más cercana del Sol

elpais.com, 16.07.2020

Spazio Le immagini da una sonda con tecnologia italiana a bordo

Il Sole tra fuochi e caos calmo
Mai fotografato così da vicino

Corriere della Sera, 16.07.2020

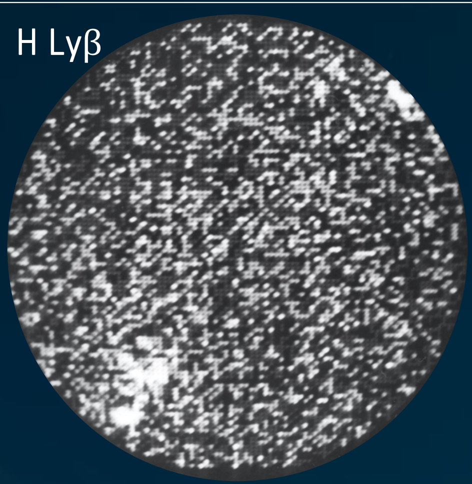
Le vaisseau spatial Solar Orbiter zoome sur le soleil et dévoile ses tourments

Les Echos, 17.07.2020

Sånn har du aldri sett sola

dagbladet.no, 16.07.2020

Making maps of the chemical balances on the Sun

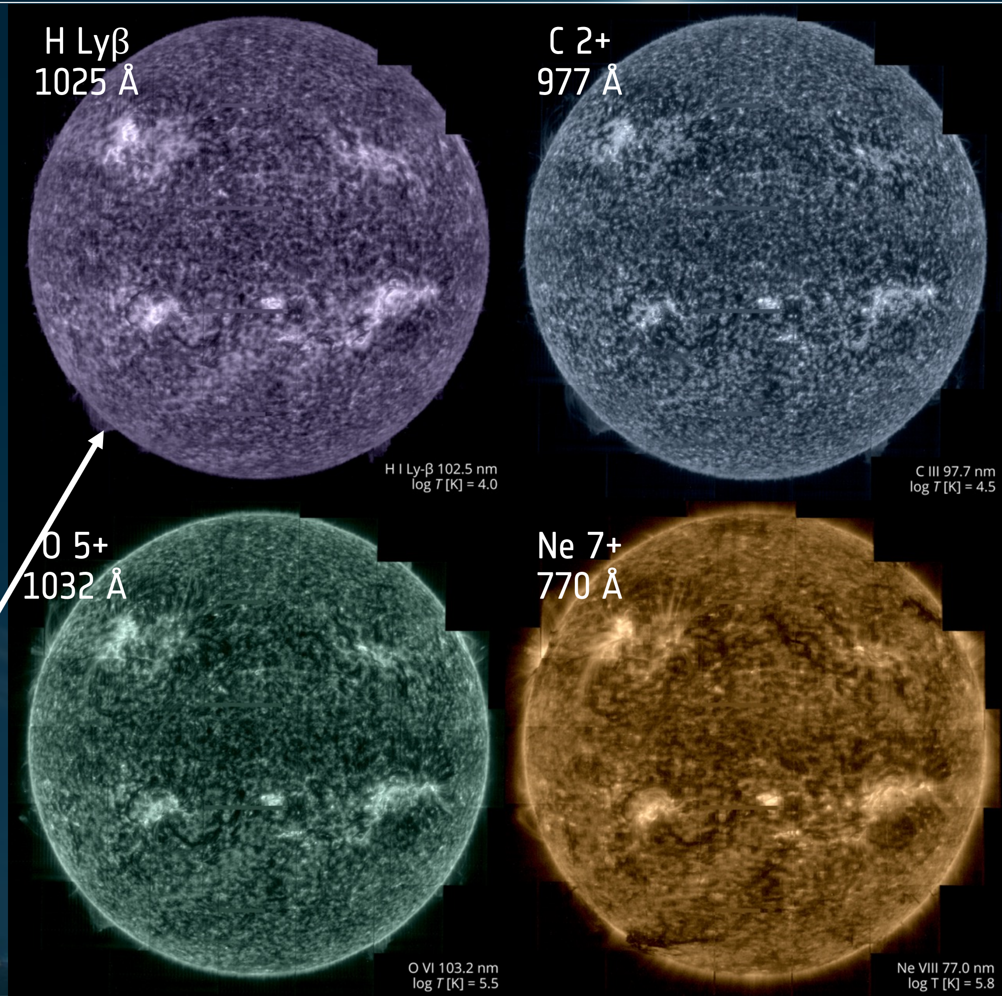


The previous best image of the full Sun in Lyman-β

From OSO-8

Courtesy: Philippe Lemaire

Best map of the full Sun in Lyman-β since 1970s



These are images of the whole sun, made as a mosaic, in light emitted by different chemical elements.

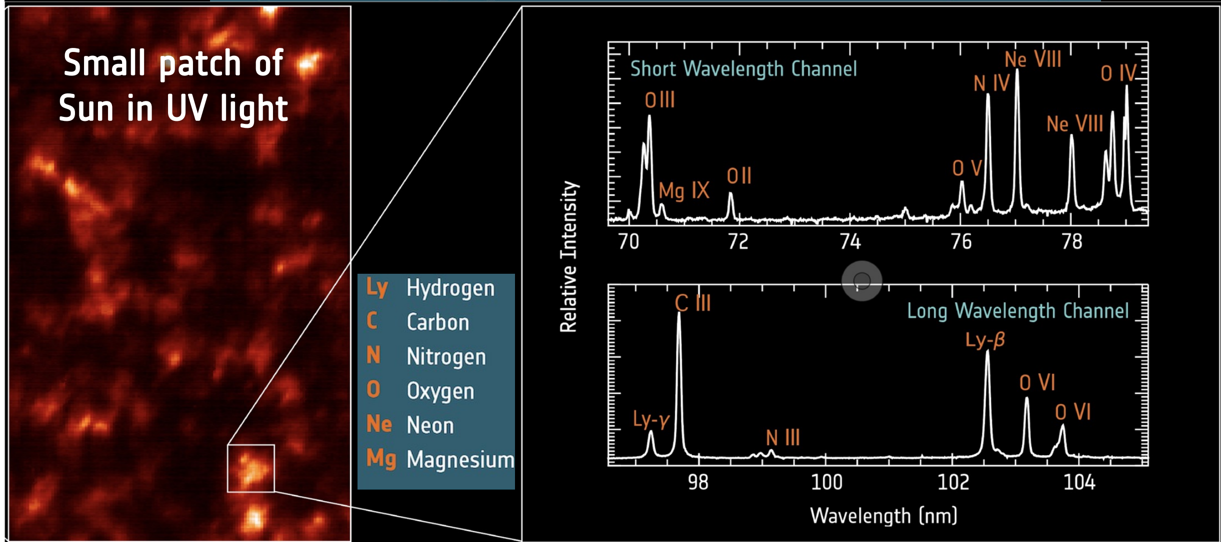
The balance of their brightness at any location can tell us relatively how much there is of each element.

This lets us chemically fingerprint each possible source of the solar wind so we can check against the balance of elements that we measure later when the solar wind arrives at our spacecraft

Courtesy Gabriel Pelouze / SPICE Consortium / ESA / NASA

Chemical fingerprinting the sources of solar wind

Spectral Imaging of the Coronal Environment (SPICE)

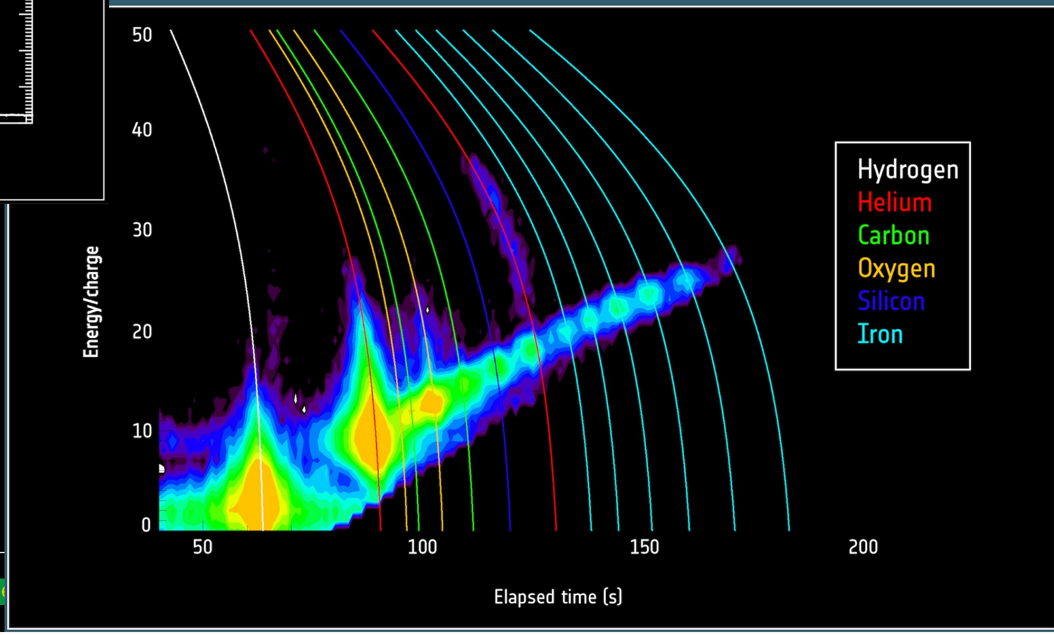


Separate solar wind flows from different sources.

We can use the Doppler effect in UV light to see the outflowing material on the Sun, and UV spectra can give us the concentrations of different chemical elements.

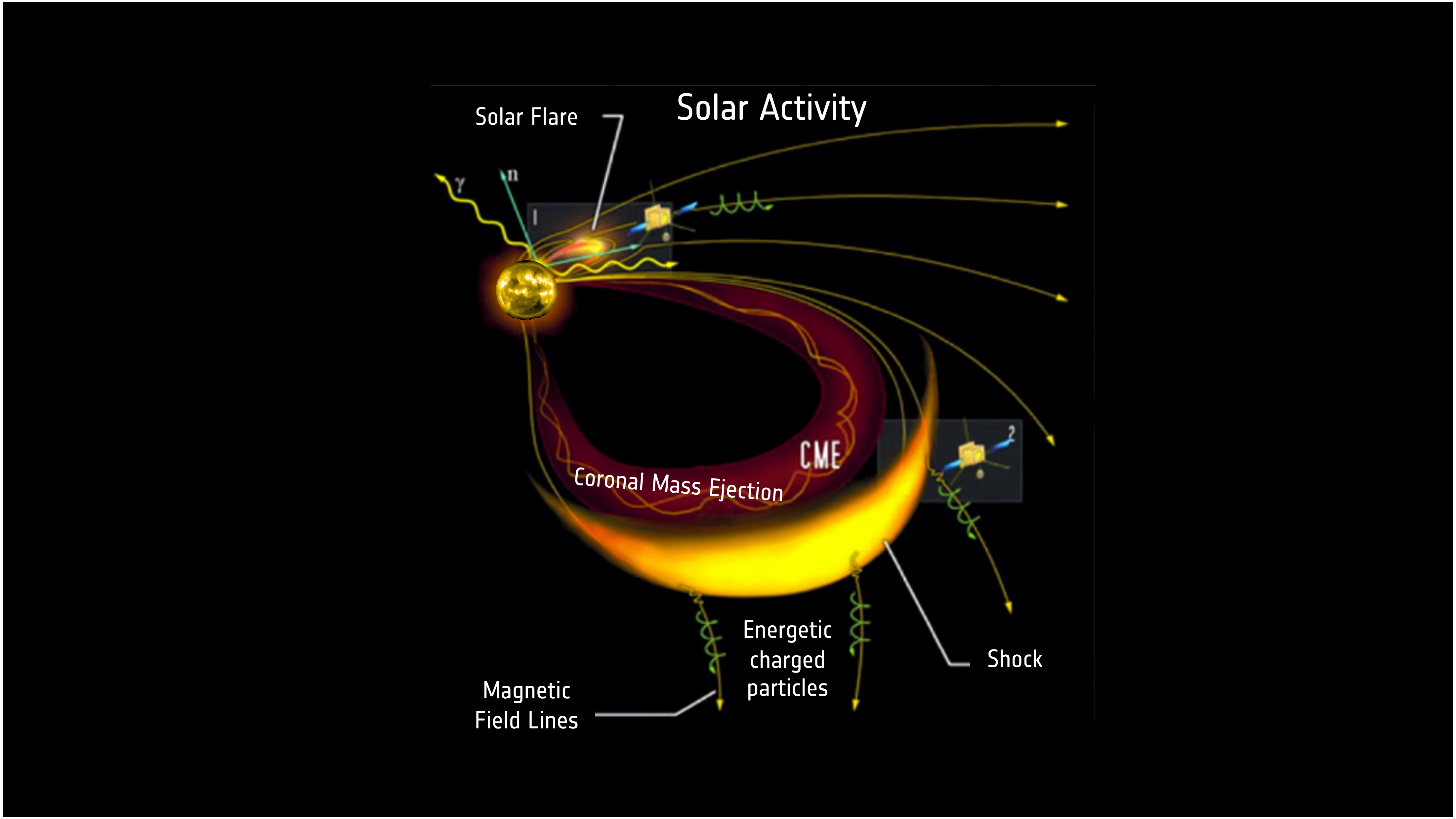
Enhancement of easily-ionised elements usually means the plasma has been trapped for a while in the corona, and the wind will more likely be slow.

Solar Wind Analyser (SWA)

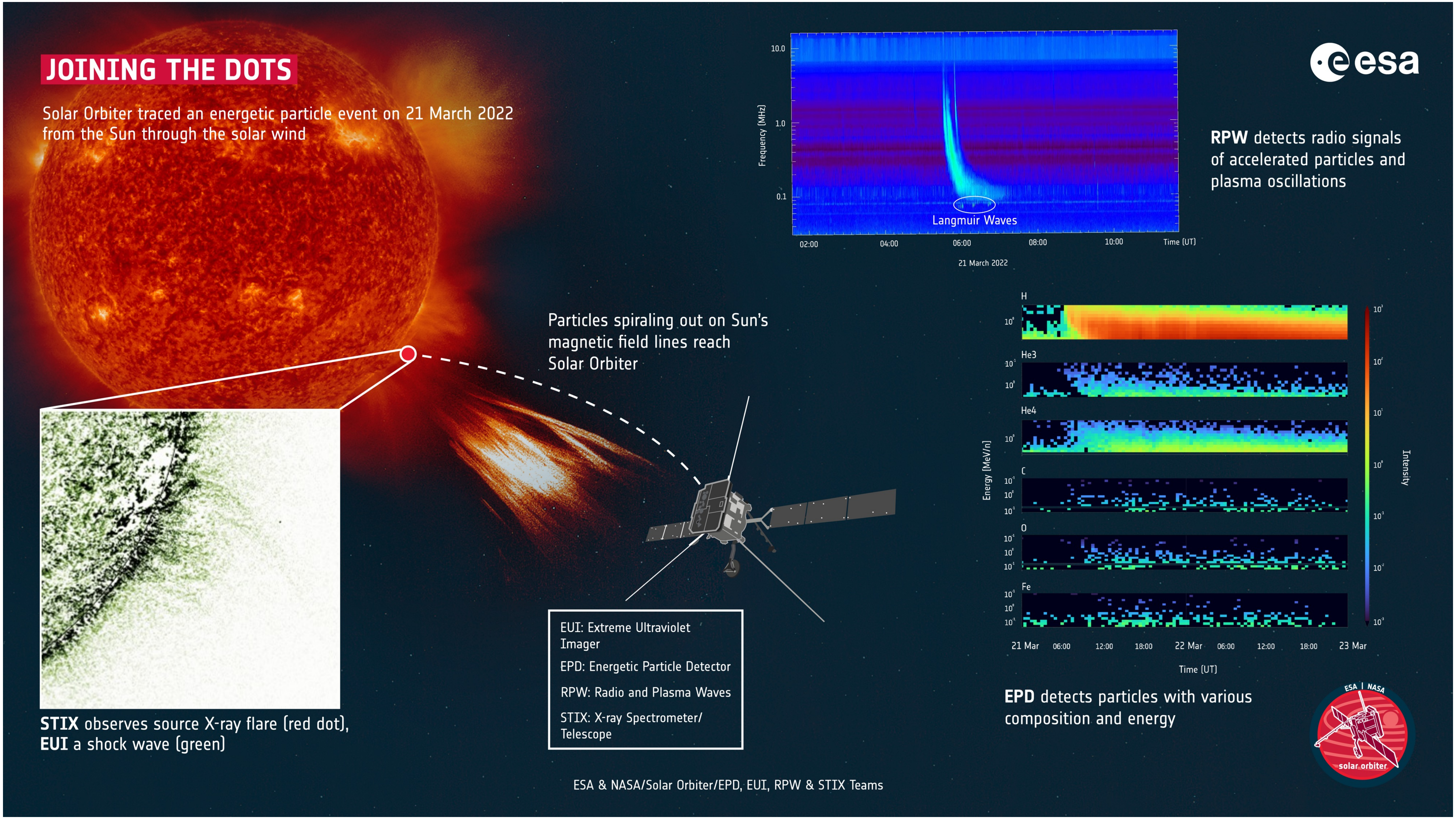


Then we compare that combined wind-speed and chemical fingerprint with the concentrations of chemicals and solar wind speed at Solar Orbiter.

This is a big part of trying to make the connection between sources on the Sun and effects in the solar wind.



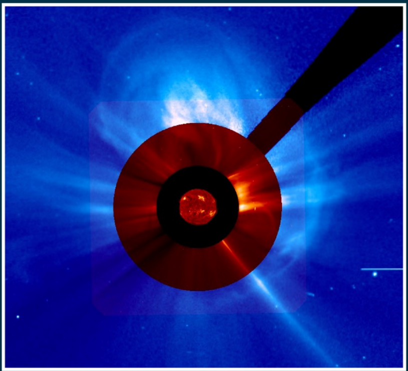
Solar Activity
Solar Flare
γ
n
1
2
CME
Coronal Mass Ejection
Energetic charged particles
Shock
Magnetic Field Lines



JOINING THE DOTS
Solar Orbiter traced an energetic particle event on 21 March 2022 from the Sun through the solar wind
esa
10.0
1.0
0.1
Frequency (MHz)
Langmuir Waves
02:00
04:00
06:00
08:00
10:00
Time (UT)
21 March 2022
RPW detects radio signals of accelerated particles and plasma oscillations
Particles spiraling out on Sun's magnetic field lines reach Solar Orbiter
H
He3
He4
C
O
Fe
Energy (MeV/n)
Intensity
21 Mar
06:00
12:00
18:00
22 Mar
06:00
12:00
18:00
23 Mar
Time (UT)
EUI: Extreme Ultraviolet Imager
EPD: Energetic Particle Detector
RPW: Radio and Plasma Waves
STIX: X-ray Spectrometer/ Telescope
STIX observes source X-ray flare (red dot), EUI a shock wave (green)
EPD detects particles with various composition and energy
ESA & NASA/Solar Orbiter/EPD, EUI, RPW & STIX Teams
ESA | NASA
solar orbiter

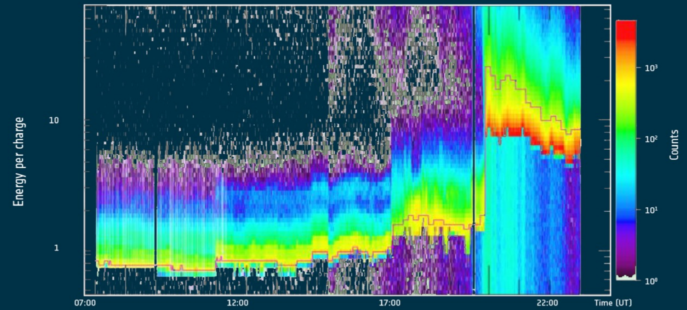
TRACKING SPACE WEATHER

Solar Orbiter felt a coronal mass ejection (CME) wash over it on 11 March 2022, predicting when it would hit Earth and allowing astronomers to capture its impact as aurora



10 March: CME observed on Sun by Solar Orbiter and Soho

11 March: Solar Orbiter SWA detects CME as a change in properties of the solar wind



11 March: Solar Orbiter MAG detects CME in magnetic field

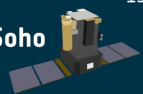
Solar Orbiter
67 million km from Sun

EUI: Extreme Ultraviolet Imager
MAG: Magnetometer
SWA: Solar Wind Analyser

13 March: CME reaches Earth; Wind detects CME in magnetic field

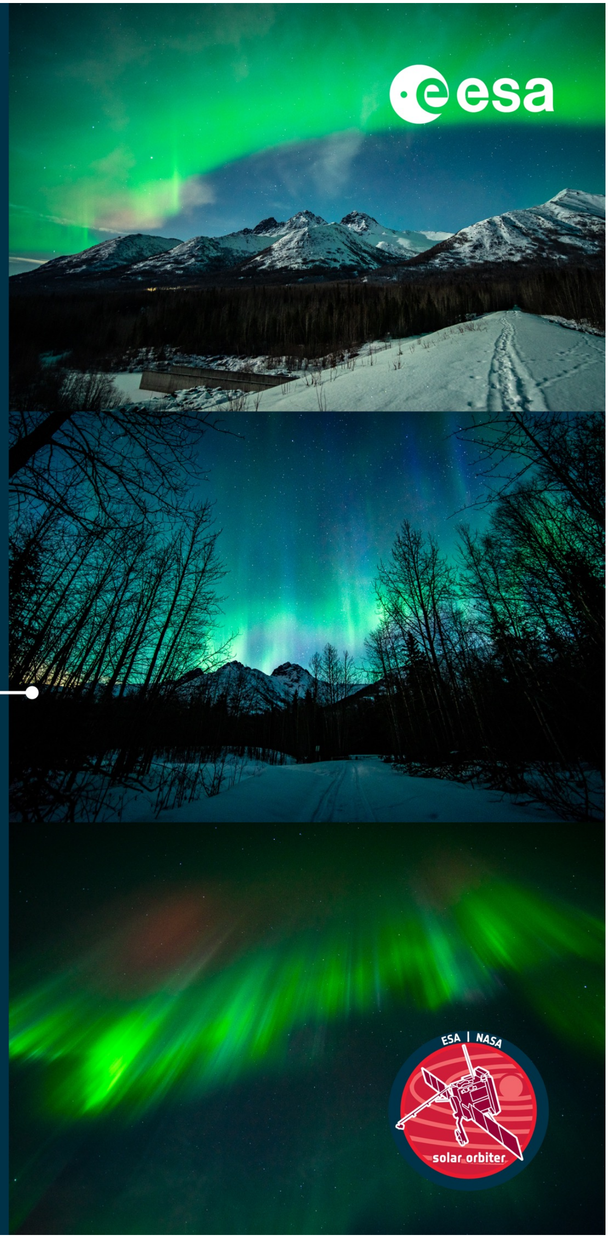
Wind

- 1.5 million km from Earth
150 million km from Sun



Soho

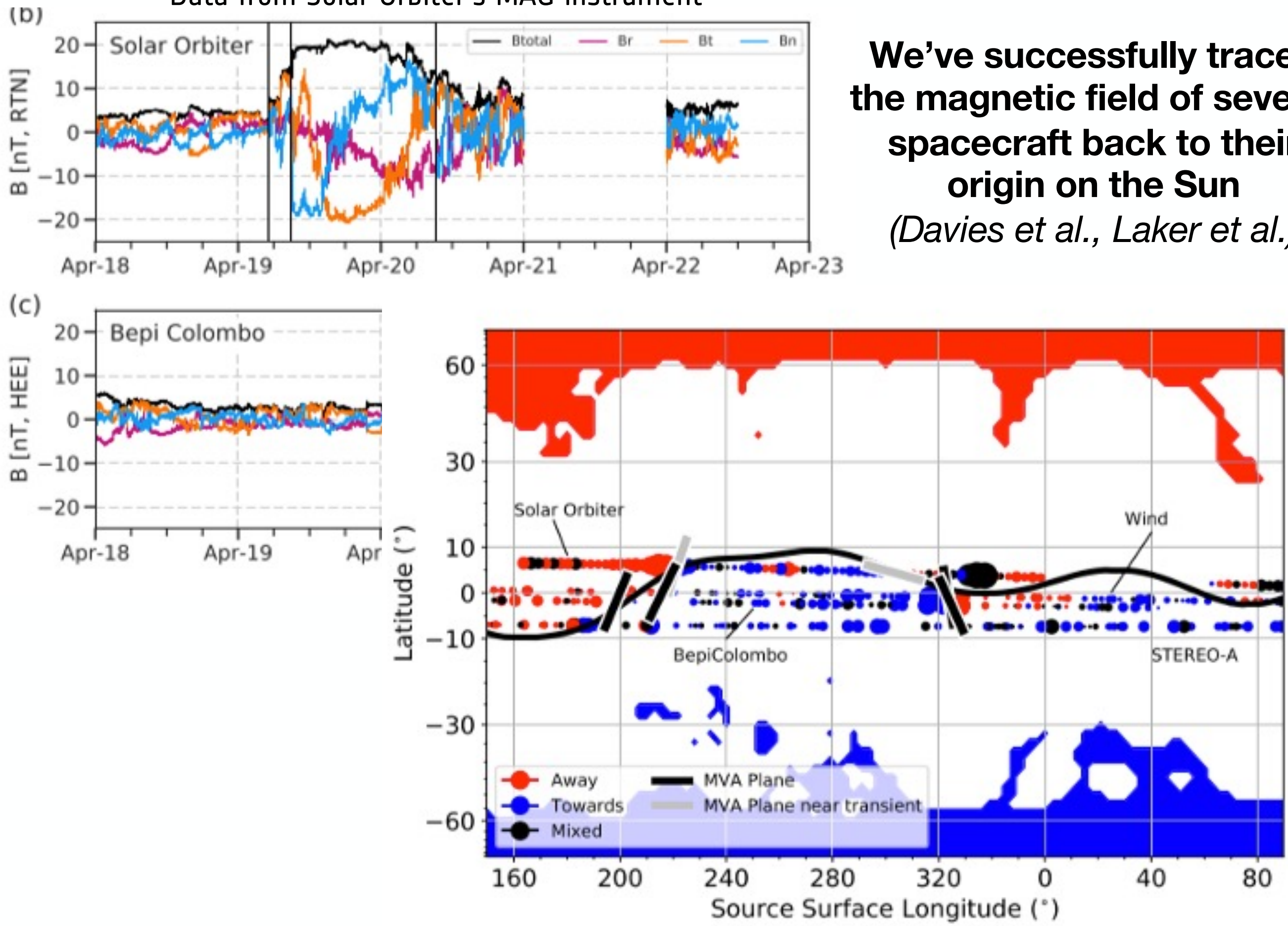
13 March:
Aurora triggered in Earth's atmosphere



Central Sun image: ESA & NASA/Solar Orbiter/EUI team; corona imagery: SOHO (ESA & NASA); Solar Orbiter data: ESA & NASA/Solar Orbiter/MAG & SWA Teams; Wind data: NASA/GSFC/Wind; Aurora: J Bant Sexson IV

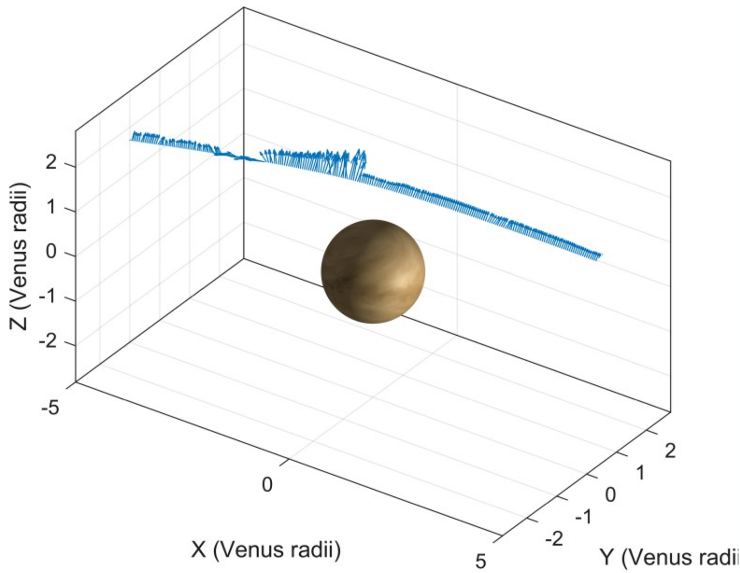
Measuring the magnetic field around Solar Orbiter

Data from Solar Orbiter's MAG instrument

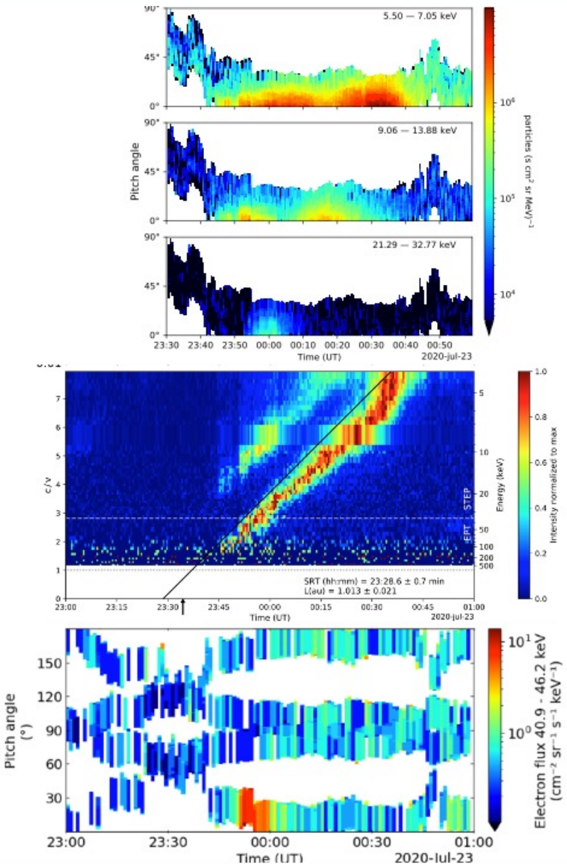


We've successfully traced the magnetic field of several spacecraft back to their origin on the Sun
(Davies et al., Laker et al.)

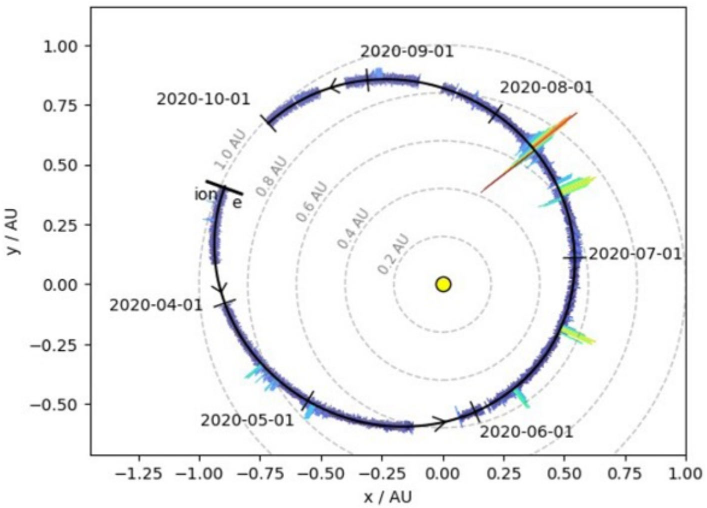
We've also been able to measure the magnetic field around Venus, as we passed by on a slingshot
(Volwerk et al.)

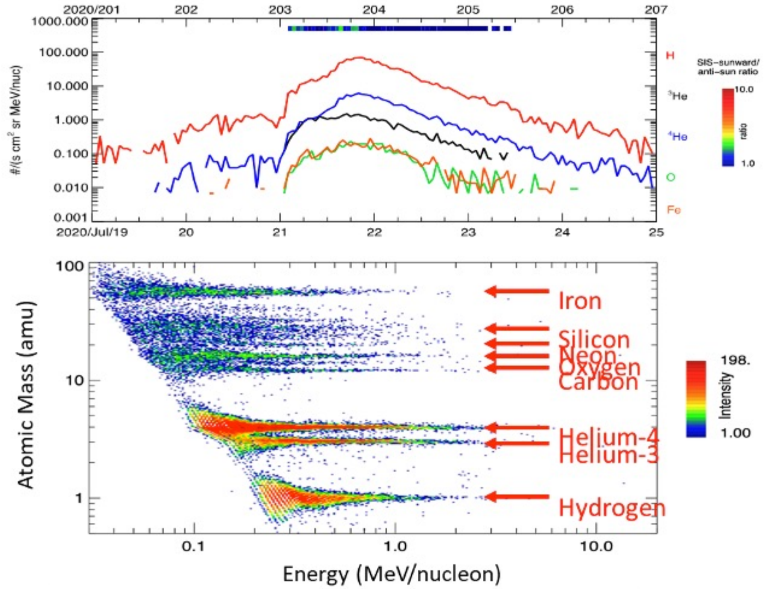


Bursts of energetic particles detected throughout the solar wind

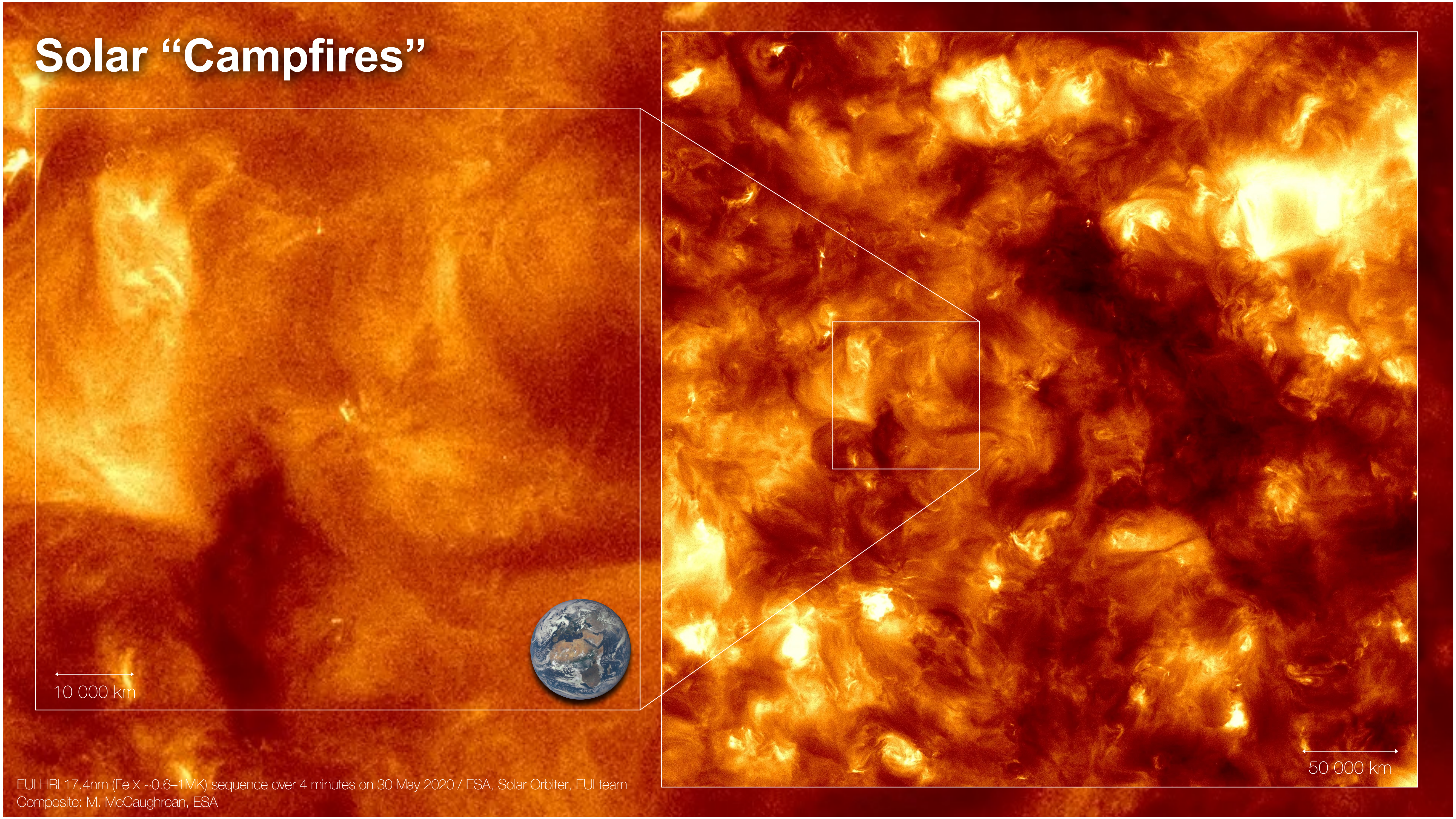


Adapted from Gómez-Herrero R. et al.,
https://doi.org/10.1051/0004-6361/202039883





From Mason G.. et al.
https://doi.org/10.1051/0004-6361/202039752


Solar “Campfires”
10 000 km
50 000 km
EUI HRI 17.4nm (Fe X ~0.6–1MK) sequence over 4 minutes on 30 May 2020 / ESA, Solar Orbiter, EUI team
Composite: M. McCaughrean, ESA

ANATOMY OF A SOLAR CAMPFIRE

Solar Orbiter has discovered thousands of mini solar flares – 'campfires' – in its first year since launch.

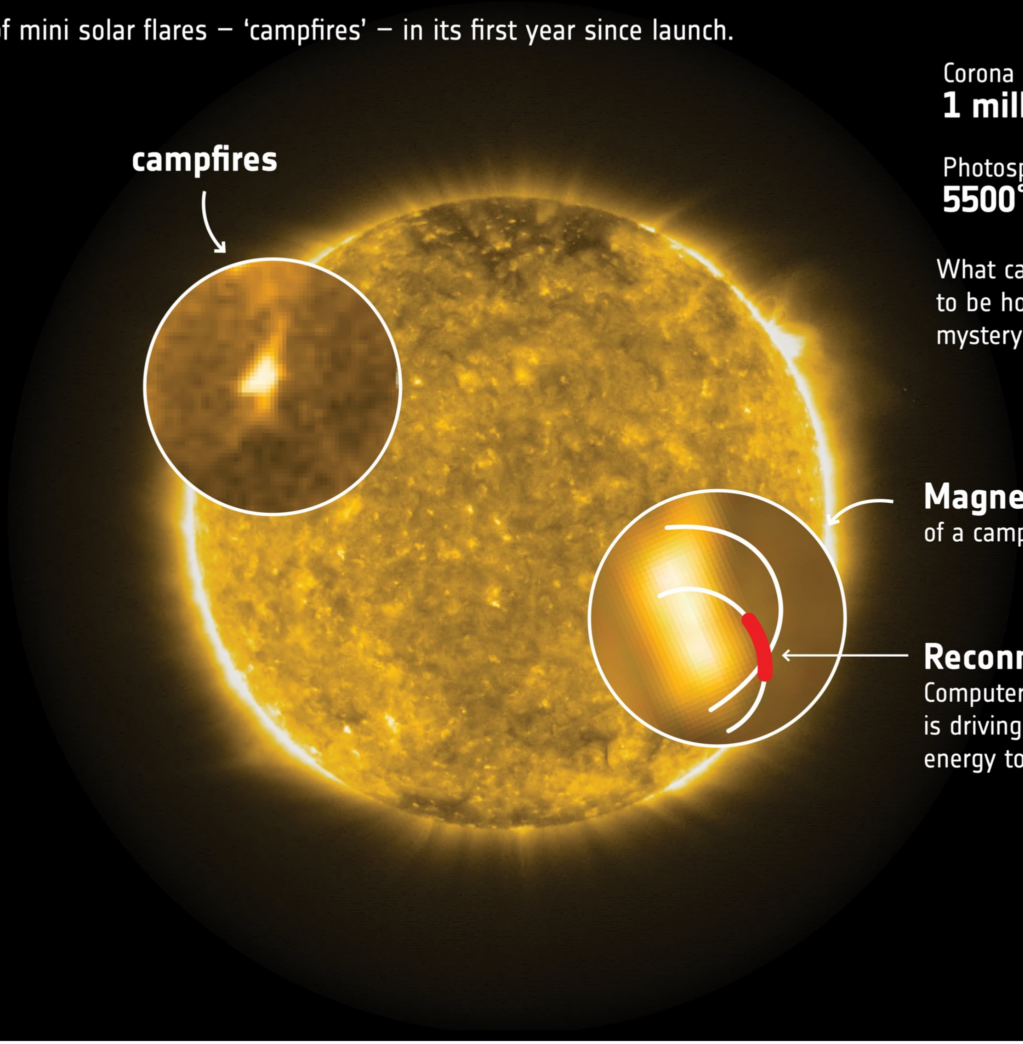
Duration
10-200 seconds

Temperature
1 million-1.6 million°C

Length
400-4000 km

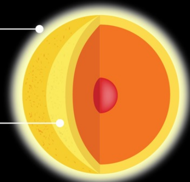
Height (above the photosphere)
1000-5000 km

campfires



Corona
1 million°C

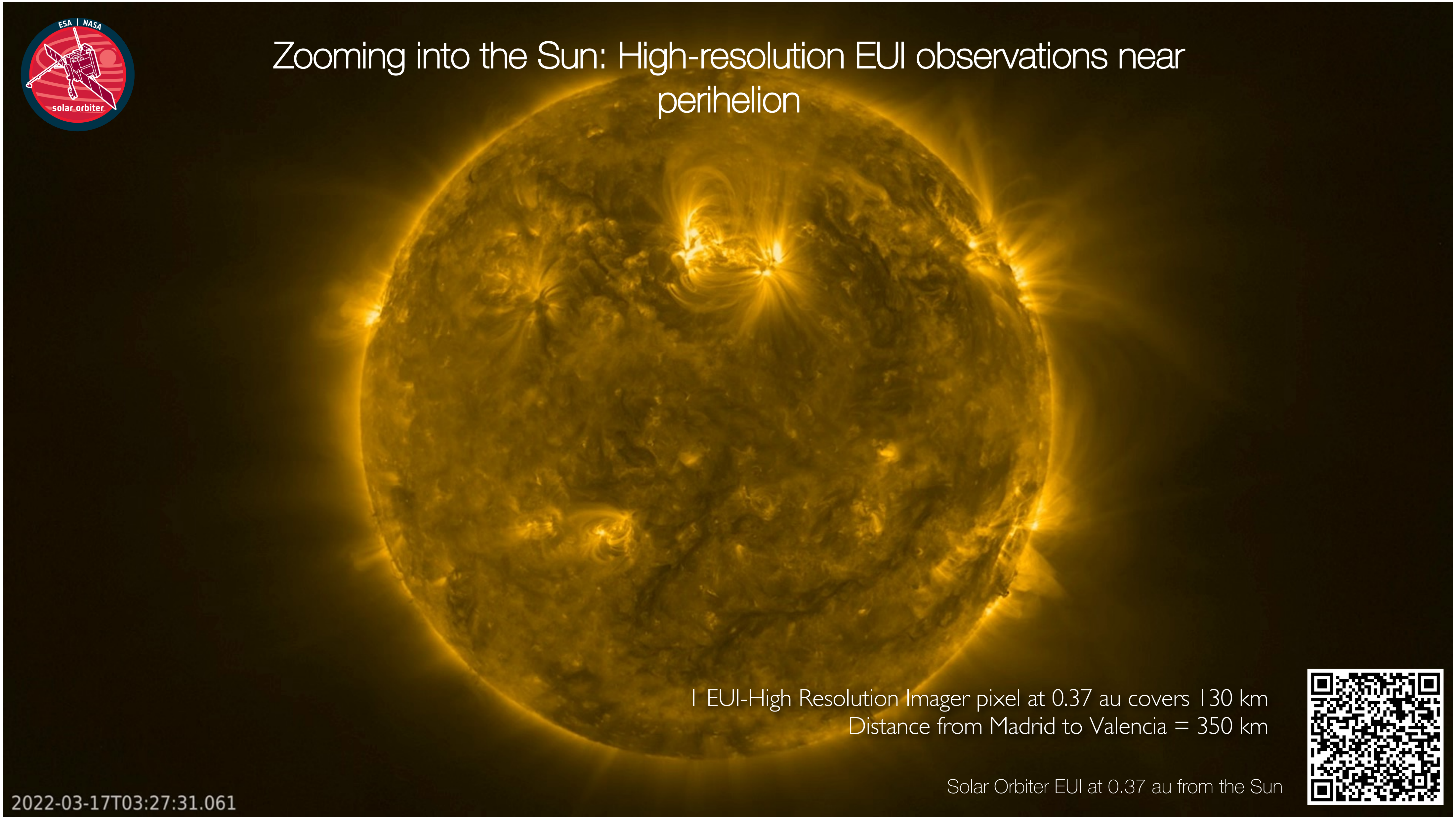
Photosphere
5500°C

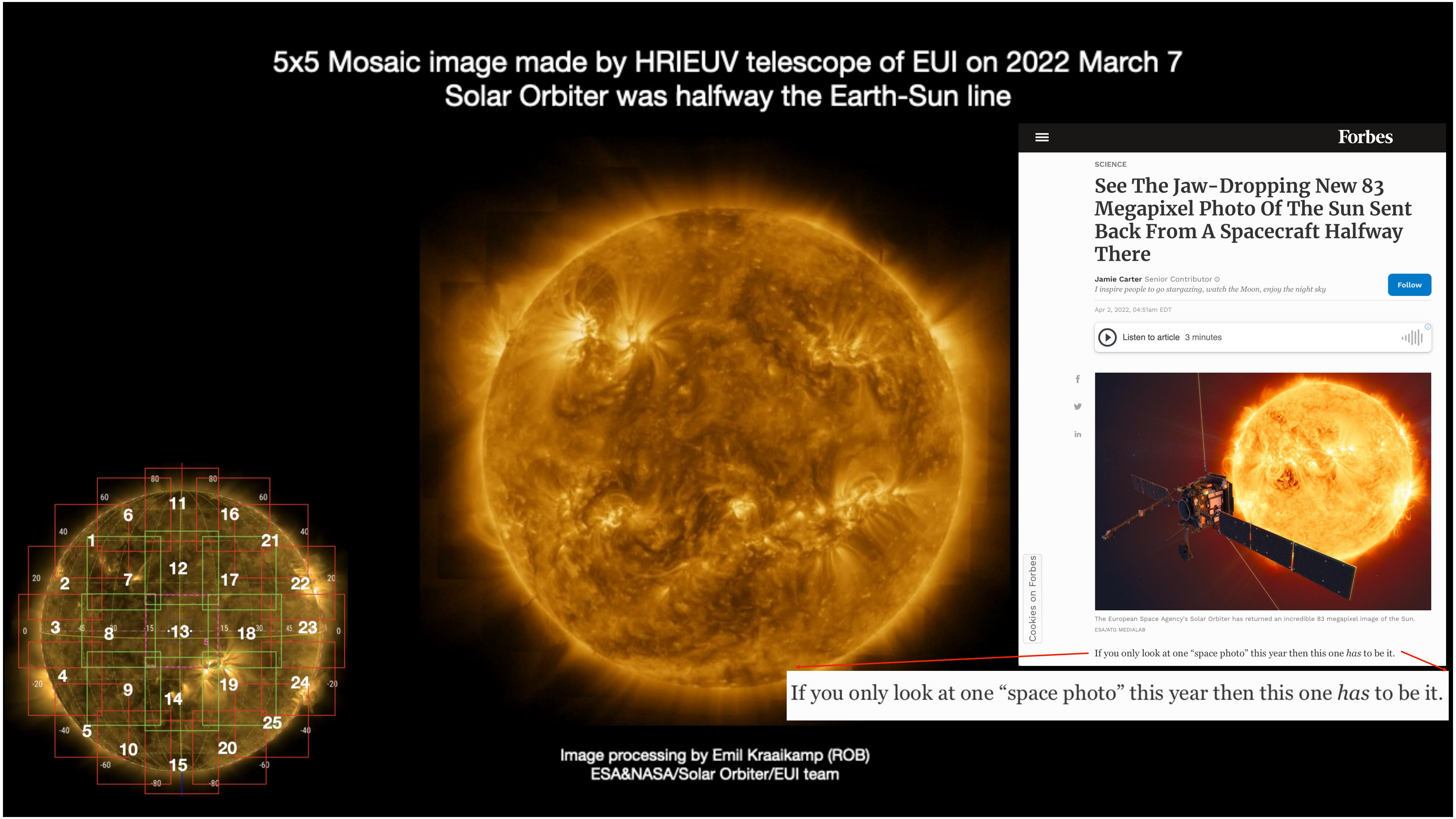


What causes the Sun's outer atmosphere to be hotter than the surface is a big mystery in solar physics

Magnetic structure
of a campfire

Reconnection
Computer simulations indicate that reconnection is driving the campfires, and may generate enough energy to maintain the temperature of the corona


solar orbiter
ESA | NASA
Zooming into the Sun: High-resolution EUI observations near perihelion
1 EUI-High Resolution Imager pixel at 0.37 au covers 130 km
Distance from Madrid to Valencia = 350 km
Solar Orbiter EUI at 0.37 au from the Sun
2022-03-17T03:27:31.061


5x5 Mosaic image made by HRIEUV telescope of EUI on 2022 March 7
Solar Orbiter was halfway the Earth-Sun line
Forbes
SCIENCE
See The Jaw-Dropping New 83 Megapixel Photo Of The Sun Sent Back From A Spacecraft Halfway There
Jamie Carter Senior Contributor
I inspire people to go stargazing, watch the Moon, enjoy the night sky
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Apr 2, 2022, 04:51am EDT
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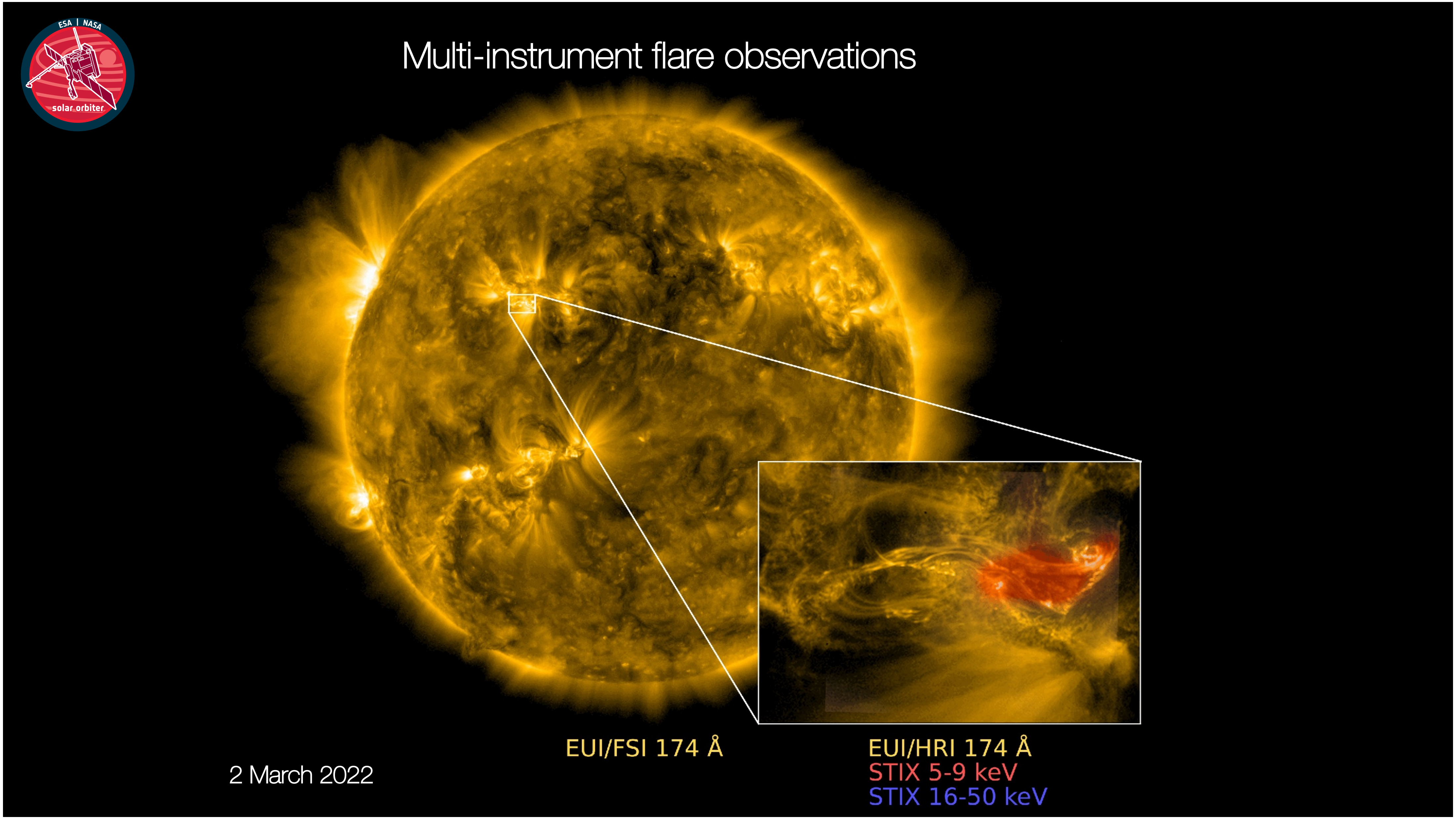
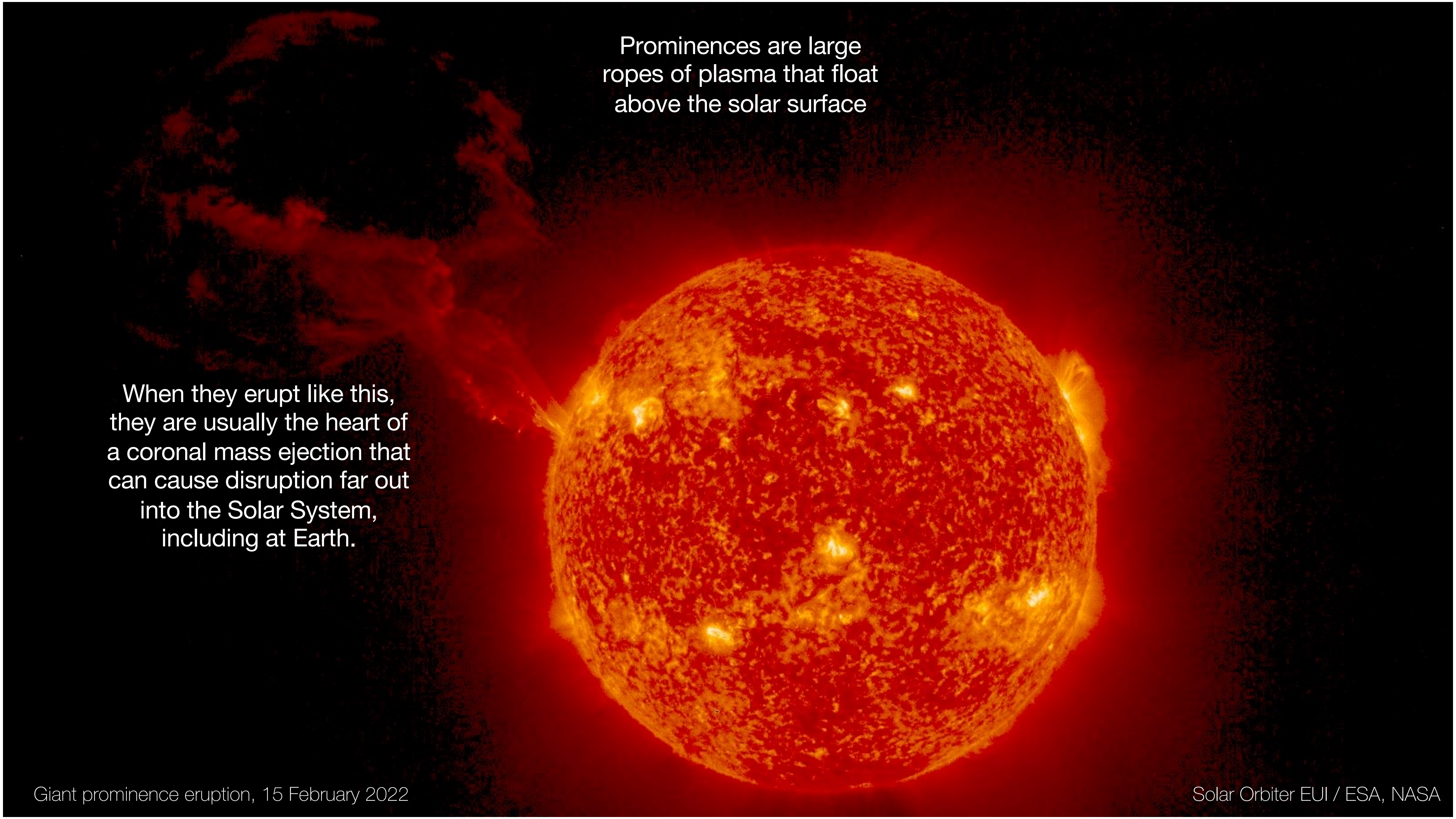
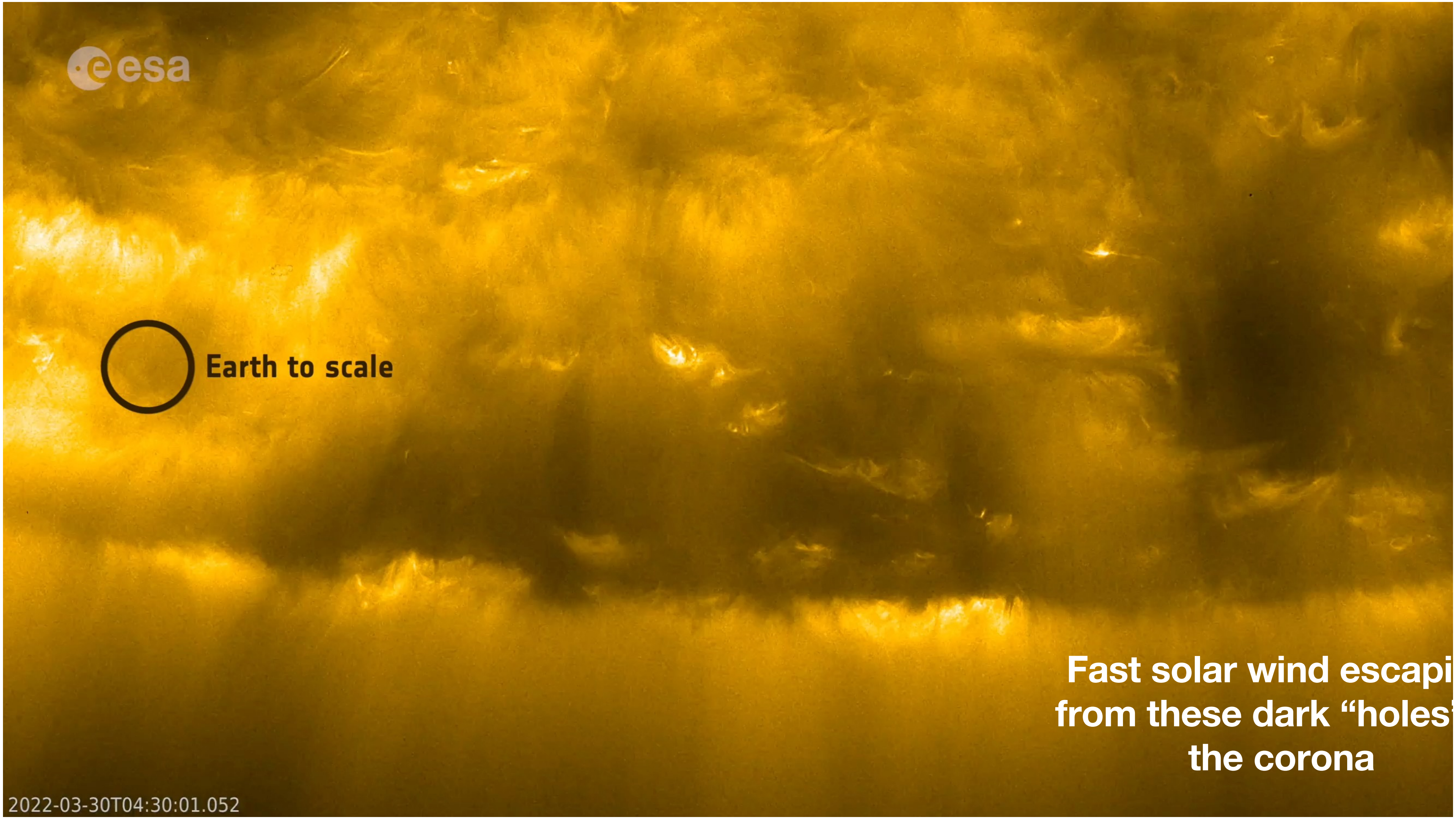
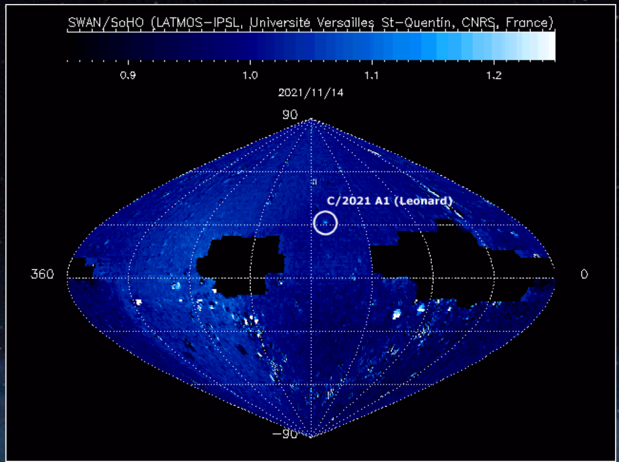
The European Space Agency's Solar Orbiter has returned an incredible 83 megapixel image of the Sun.
ESA/ATG MEDIALAB
If you only look at one "space photo" this year then this one *has* to be it.
Cookies on Forbes
If you only look at one "space photo" this year then this one *has* to be it.
Image processing by Emil Kraaikamp (ROB)
ESA&NASA/Solar Orbiter/EUI team


ESA | NASA
solar orbiter
Multi-instrument flare observations
EUI/FSI 174 Å
EUI/HRI 174 Å
STIX 5-9 keV
STIX 16-50 keV
2 March 2022

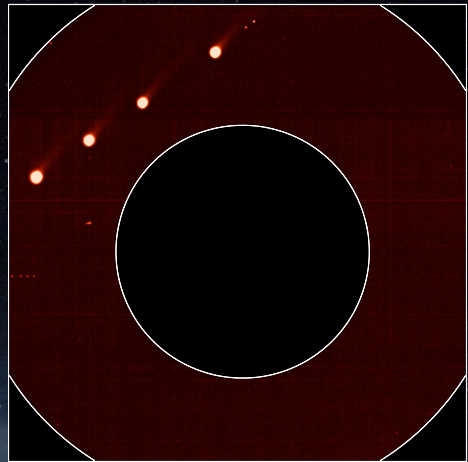

Prominences are large ropes of plasma that float above the solar surface
When they erupt like this, they are usually the heart of a coronal mass ejection that can cause disruption far out into the Solar System, including at Earth.
Giant prominence eruption, 15 February 2022
Solar Orbiter EUI / ESA, NASA


esa
Earth to scale
Fast solar wind escapi
from these dark "holes
the corona
2022-03-30T04:30:01.052

Catching a comet by the tail (Comet Leonard)

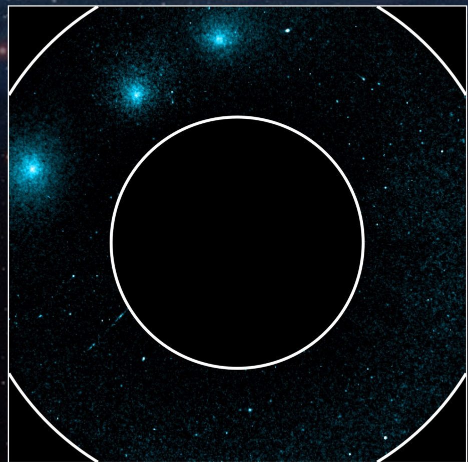


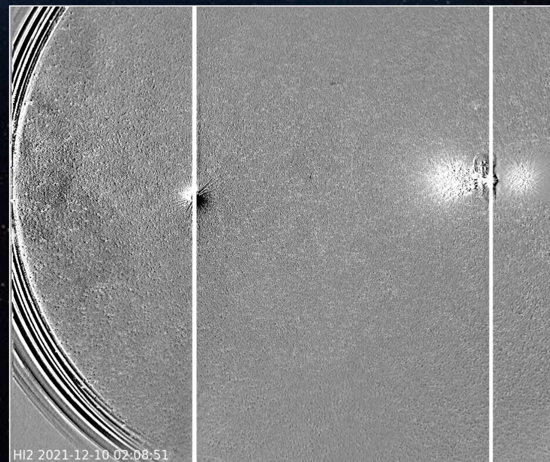
SOHO SWAN, 14 Nov 2021 – 11 Jan 2022


Solar Orbiter METIS visible, 15–16 Dec


Solar Orbiter SoloHI, 17–19 Dec

Parker Solar Probe WISPR, 7 Dec


Solar Orbiter METIS UV, 15–16 Dec



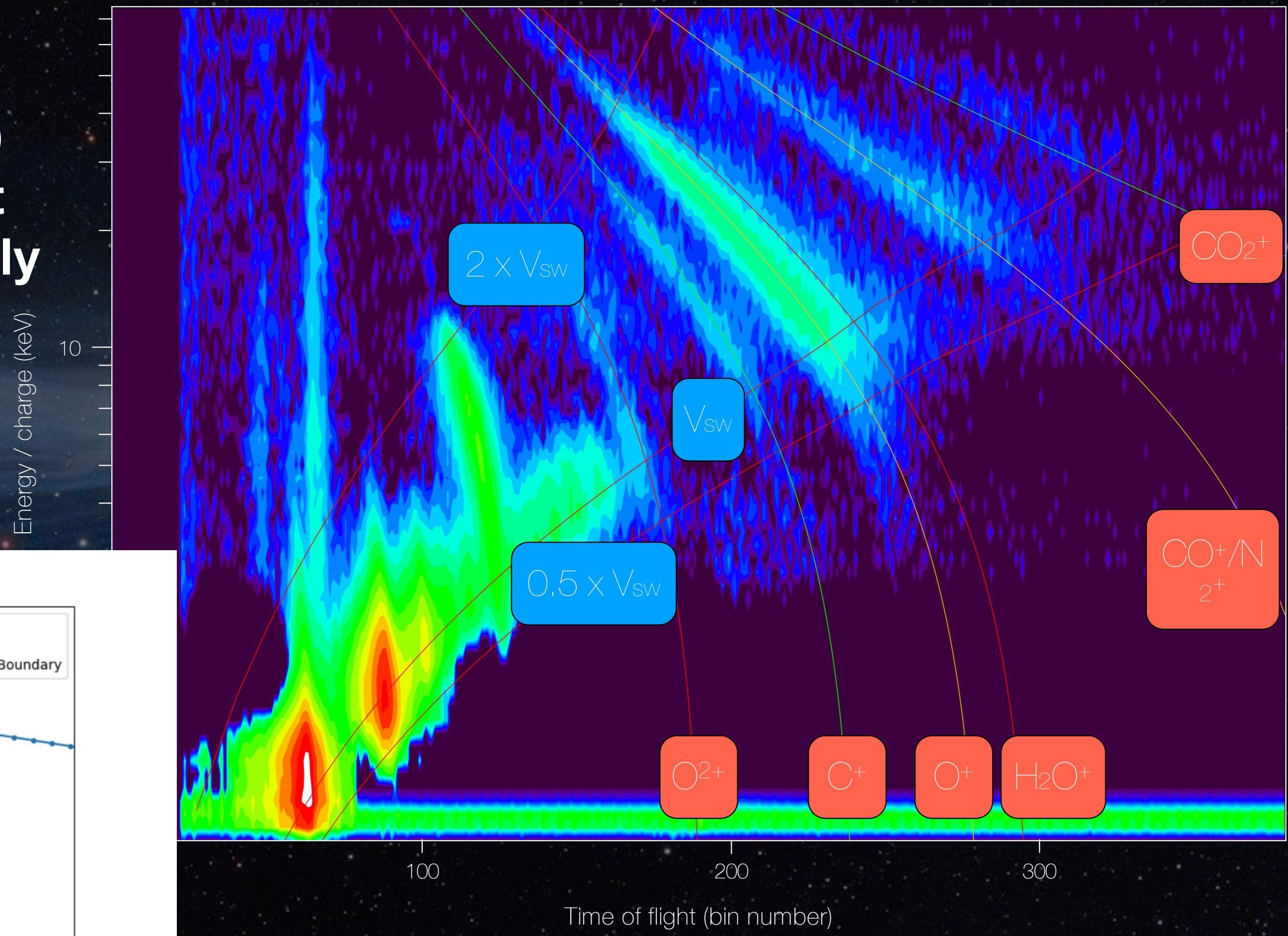
STEREO-A HI, 10–23 December

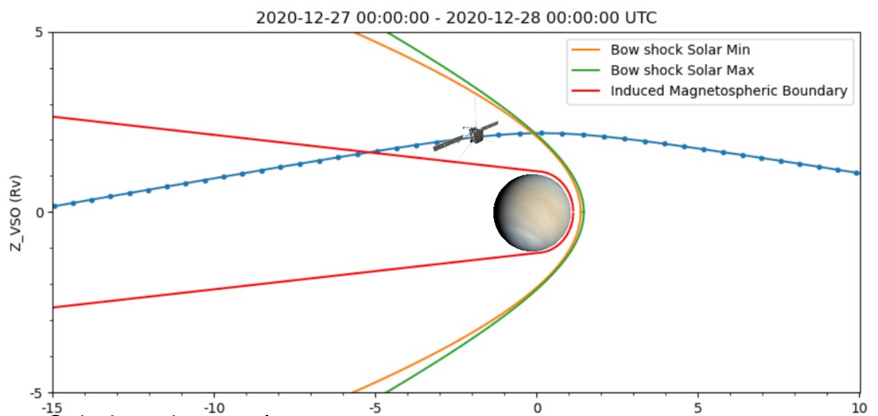
C/2021 A1 (Leonard) from Namibia on Christmas Day 2021

Michael Jäger & Lukas Demetz

17 December 2021 – during comet tail passage

Solar Orbiter detected (ionised) water from Comet Leonard as it passed through its tail, completely by chance!





Wimmer-Scheingruber et al.

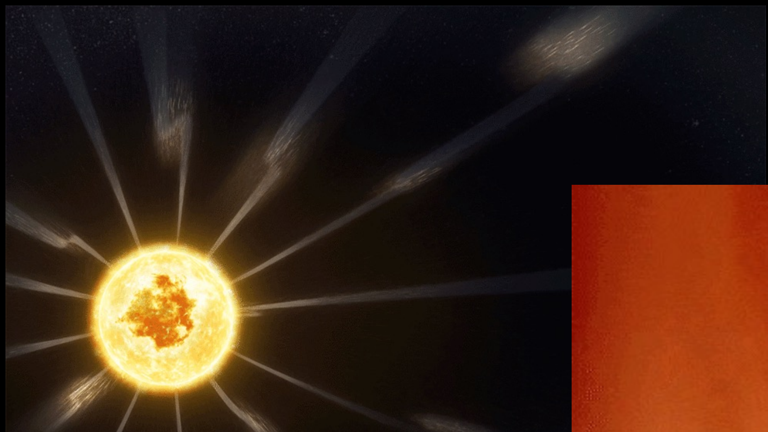
Solar Orbiter Solar Wind Analyser suite, PI Chris Owen, MSSL

Comet Leonard: Michael Jäger & Lukas Demetz

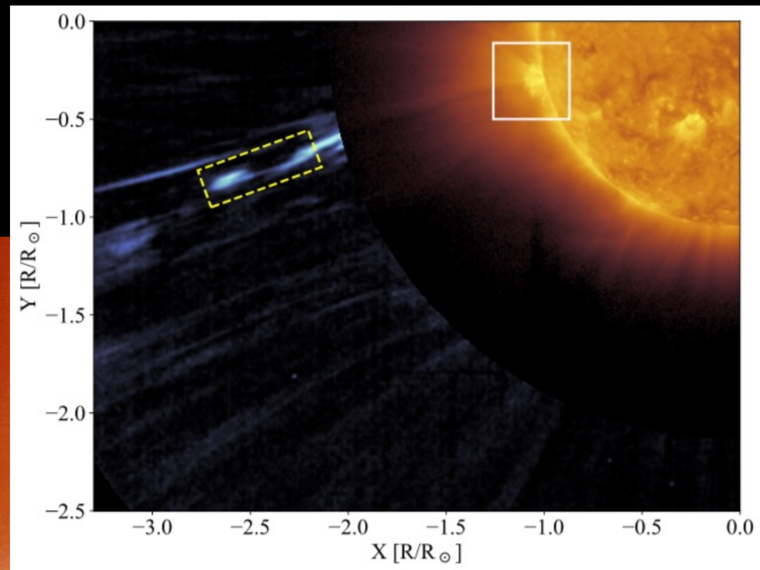
Formation of magnetic switchbacks in the solar corona

- Parker Solar Probe observations have revived the interest in magnetic "switchbacks"
- These are kinks in the magnetic field that might cause dangerous particle radiation bursts in space
- Do switchbacks begin at the Sun, or do they form in the solar wind itself??

- During the March 2022 close approach to the Sun, Metis imaged for the first time a magnetic switchback in the solar corona (Telloni et al. 2022, ApJL)

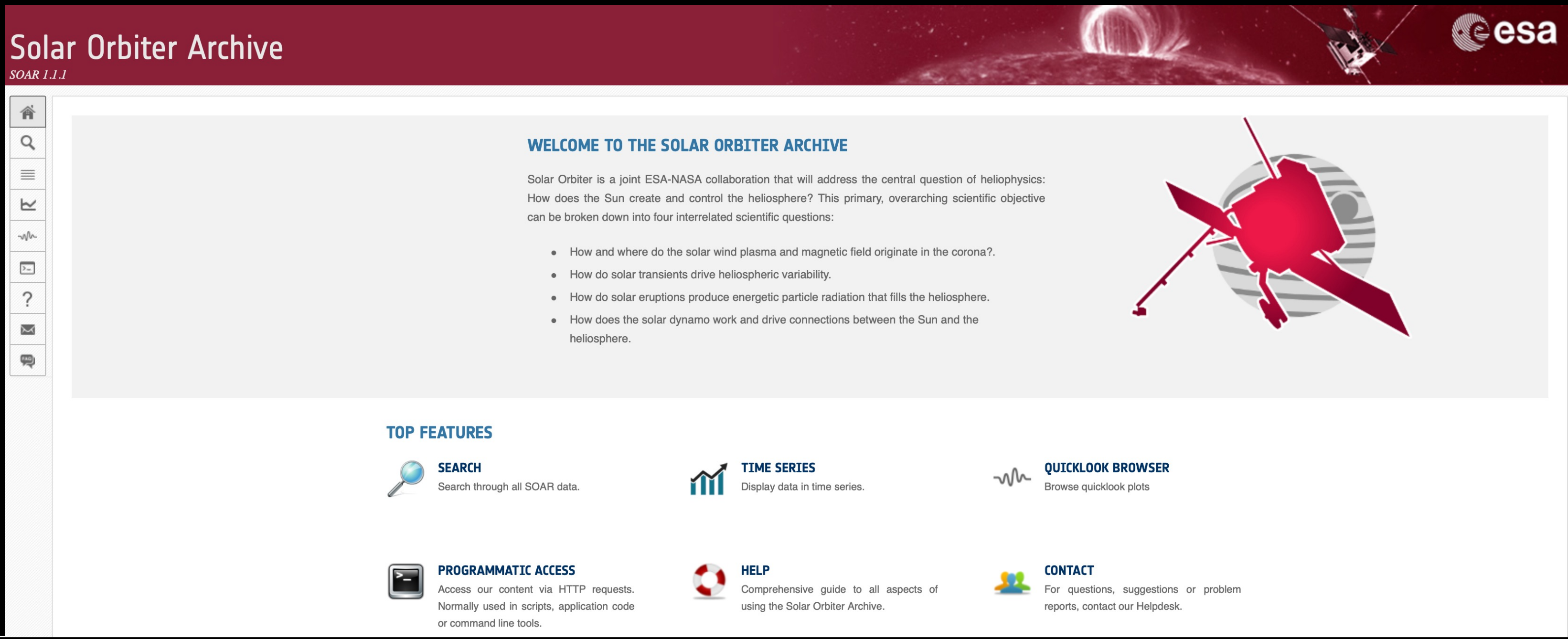


Credits: NASA GSFC/Conceptual Image Lab/Adriana M. Gutierrez

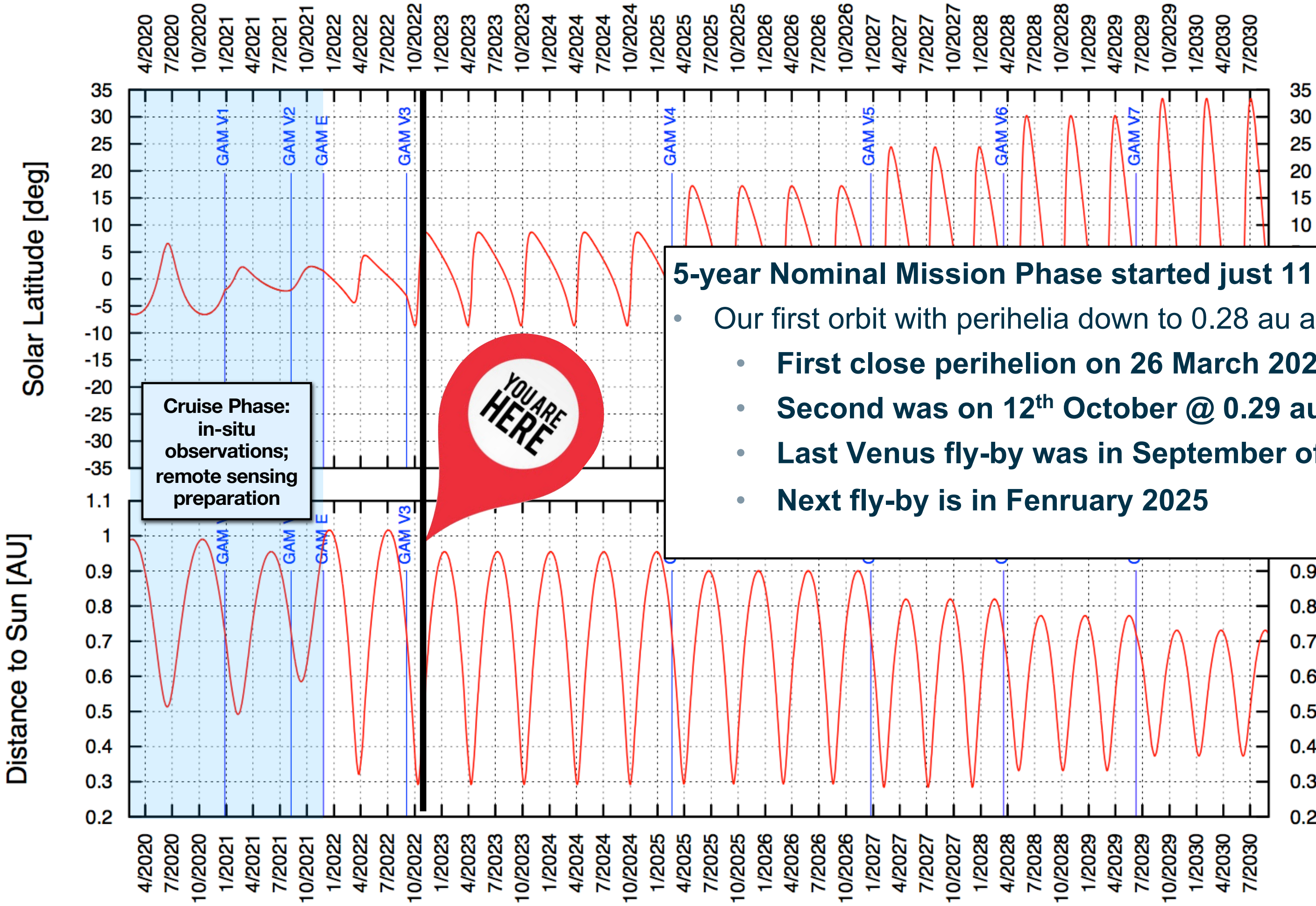


Our data are open!

- Open data policy for science data: Upon receipt of data, each instrument team has 3 months for data calibration & validation
- Because of the distance to the spacecraft, it can sometimes take ≤6 months for data to come down
- After submission to ESA, all data is publicly accessible from the SOAR (Solar Orbiter ARchive)



Solar Orbiter: where are we now?



5-year Nominal Mission Phase started just 11 months ago

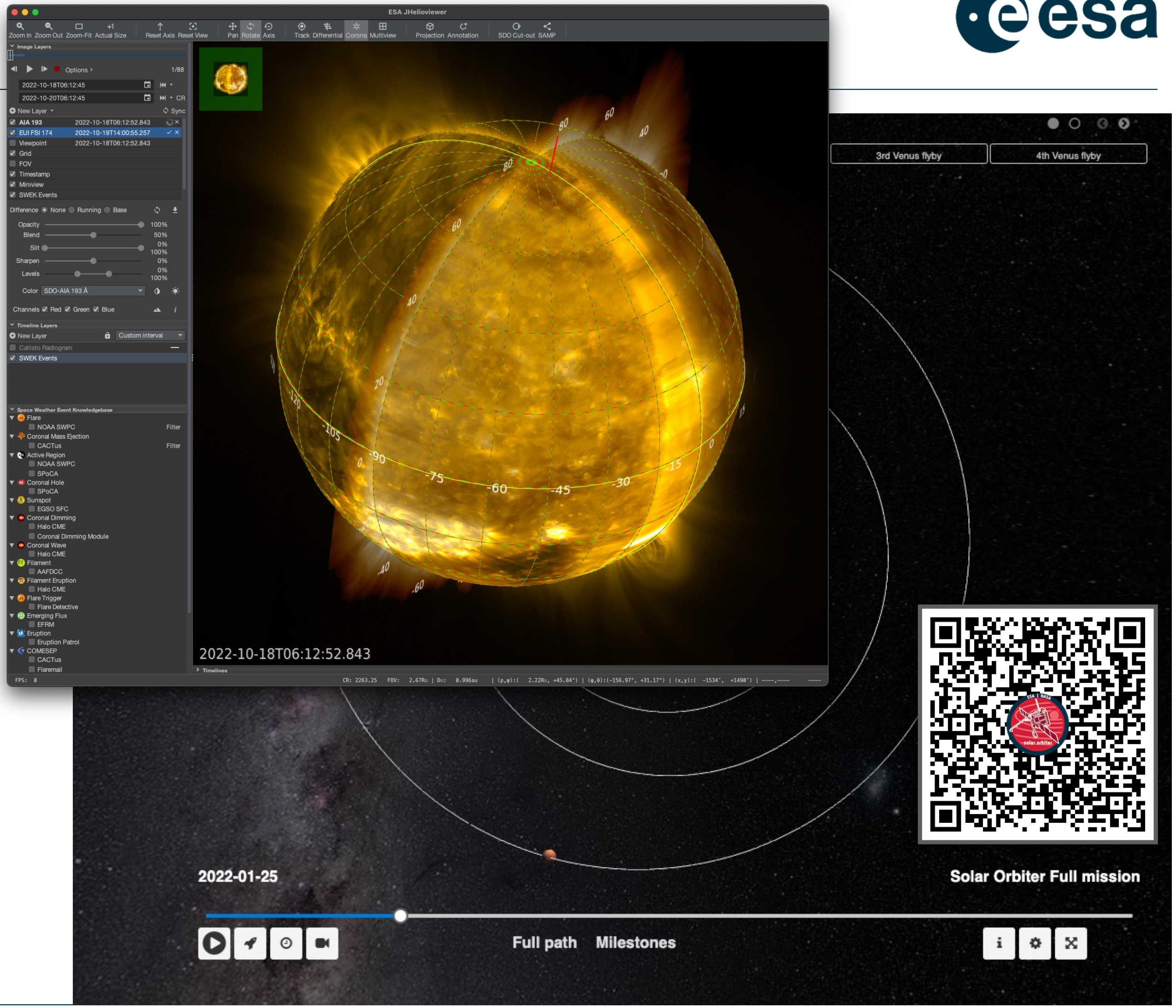
- Our first orbit with perihelia down to 0.28 au and aphelia beyond 1 AU
  - **First close perihelion on 26 March 2022 @ 0.32 au**
  - **Second was on 12th October @ 0.29 au**
  - **Last Venus fly-by was in September of this year**
  - **Next fly-by is in Fenruary 2025**

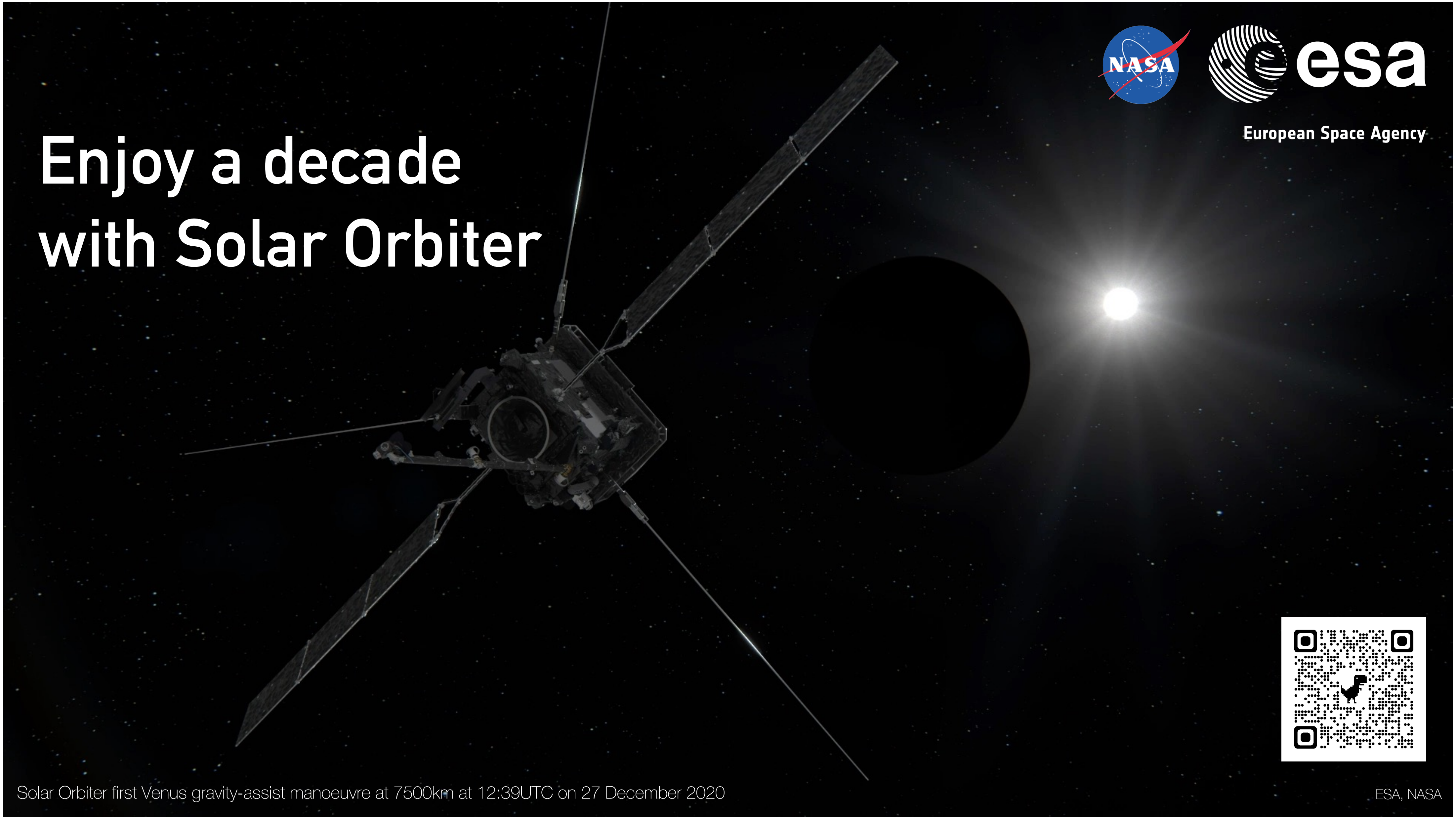
Interactive
"Where is Solar Orbiter?" GUI

Outlook

Solar Orbiter is …orbiting the Sun!

- **Next Venus fly-by is in February 2025**
- **We will start to get a good view of the solar poles after that.**
- **Until then, we continue to gather data constantly on the connection between the Sun and the Solar Wind**
- We have open data!
- We have open *software* in Python (SunPy)
- We have tools for you to explore Solar Orbiter and other data easily (JHelioViewer)
- You can find out where Solar Orbiter is at any time by going to the QR link opposite
- You can make your own orbit movies with the Java application at 3dview.irap.omp.eu
- And there's a coming VR project…!





Solar Orbiter first Venus gravity-assist manoeuvre at 7500km at 12:39UTC on 27 December 2020

ESA, NASA