Solar Orbiter

Exploring the Sun-Heliosphere Connection

A Mission Overview

19 July 2018

Daniel Müller
Solar Orbiter Project Scientist

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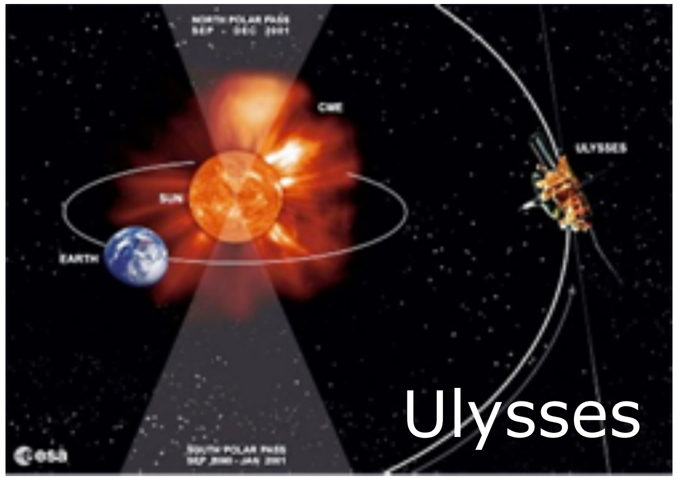
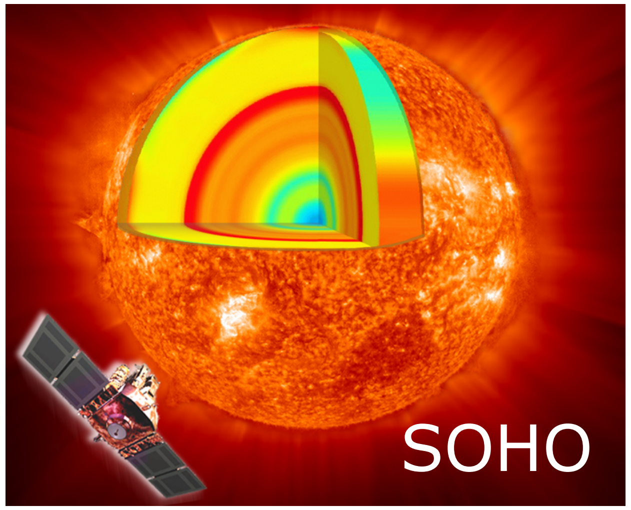
Solar Orbiter

- First medium-class mission of ESA's Cosmic Vision 2015-2025 programme, implemented jointly with NASA
- Dedicated payload of 10 remote-sensing and in-situ instruments measuring from the photosphere into the solar wind

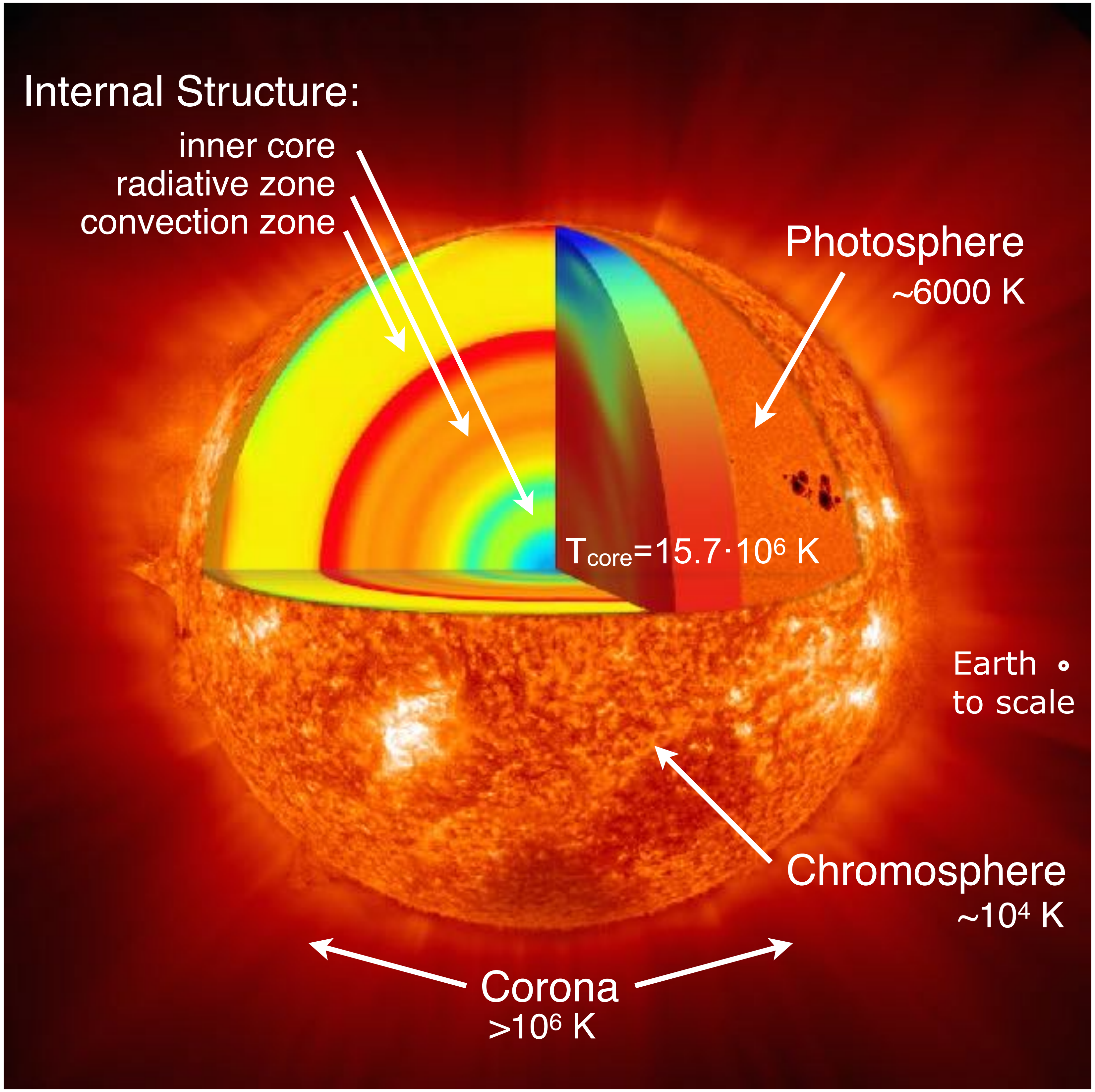




Overarching Science Question

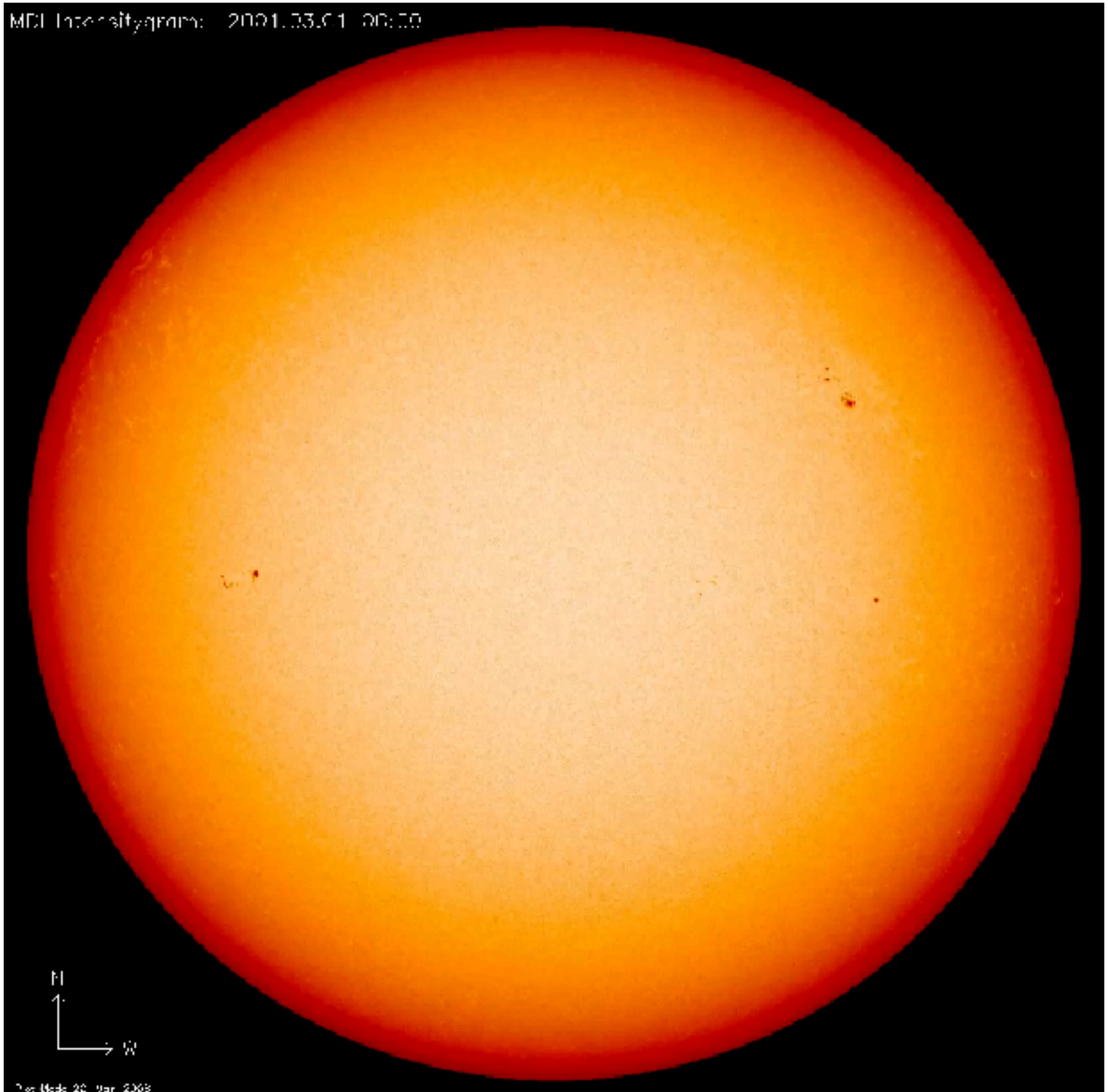
- How does the Sun create and control the Heliosphere – and why does solar activity change with time?

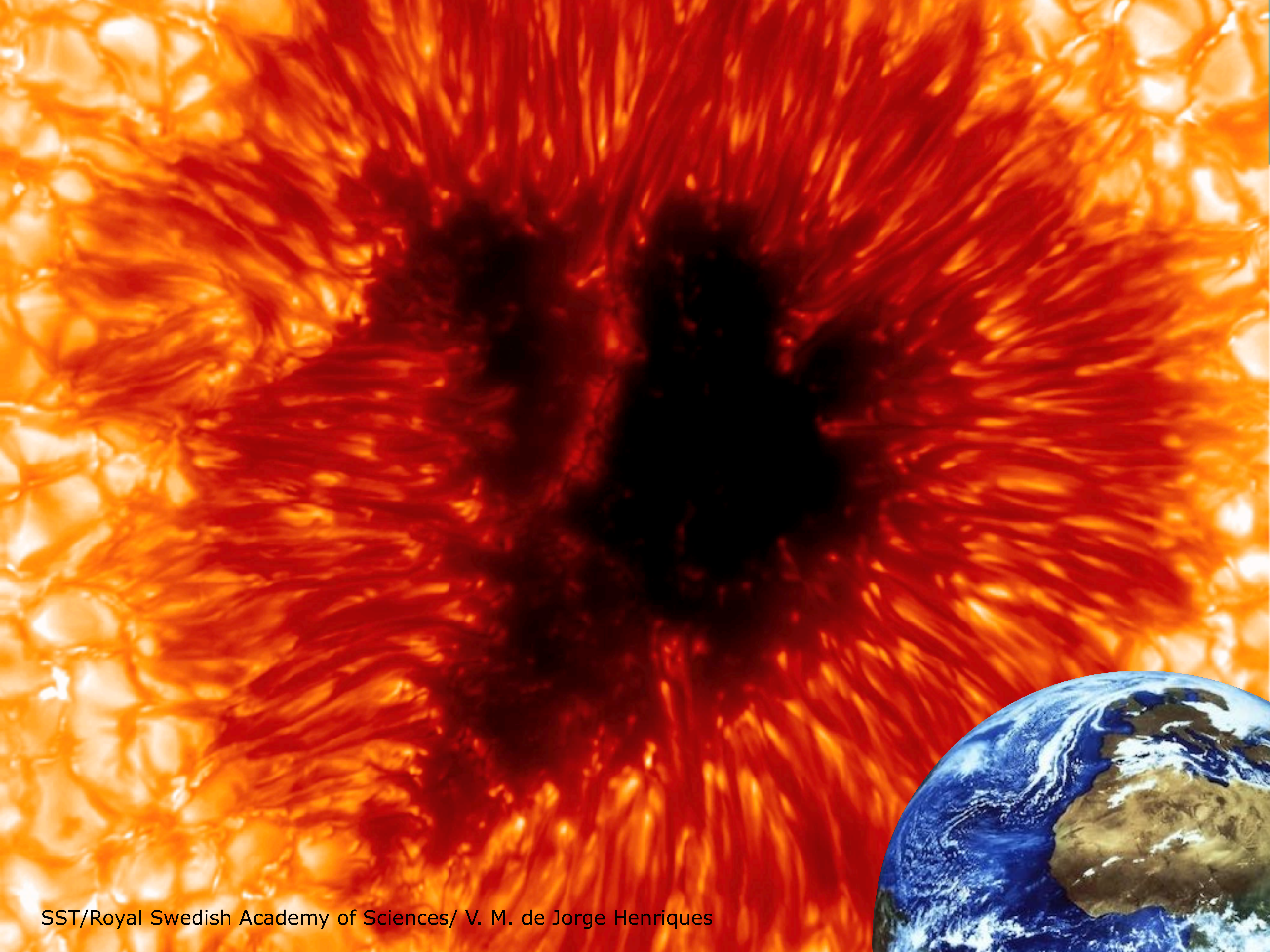
Here comes the Sun and I say… it's all right [G. Harrison, 1969]



European Space Agency

Sunspots

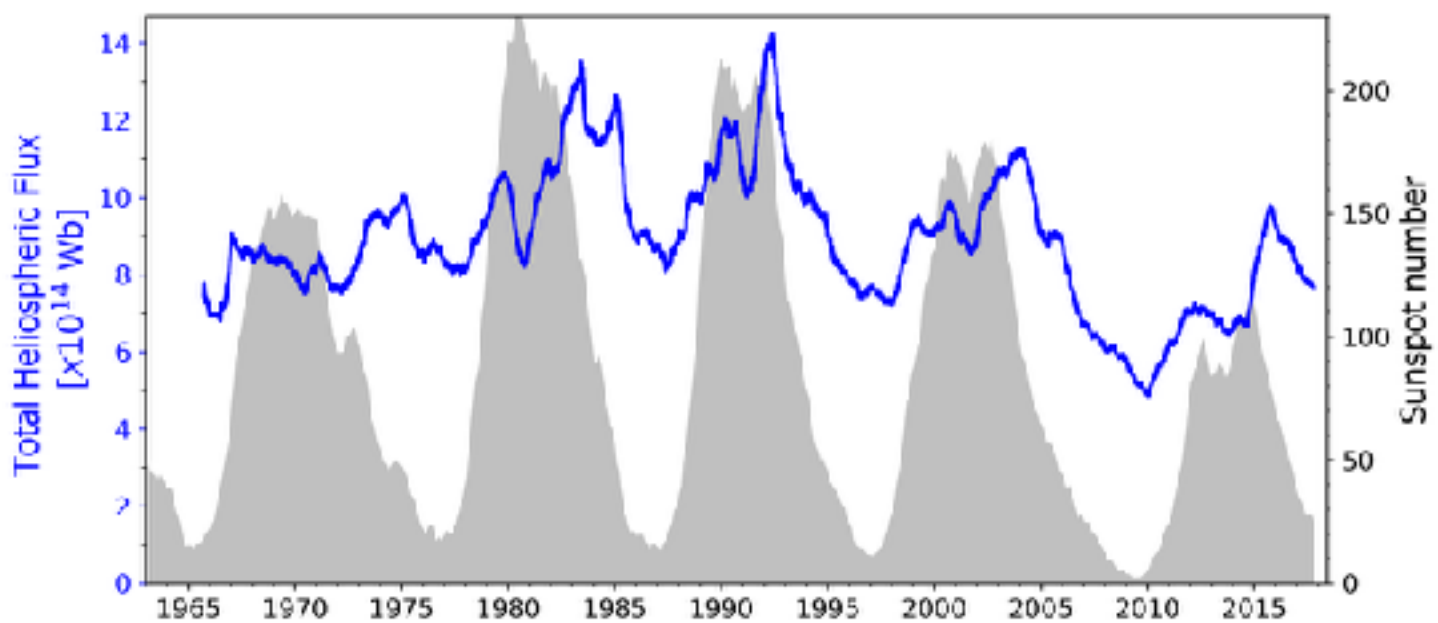




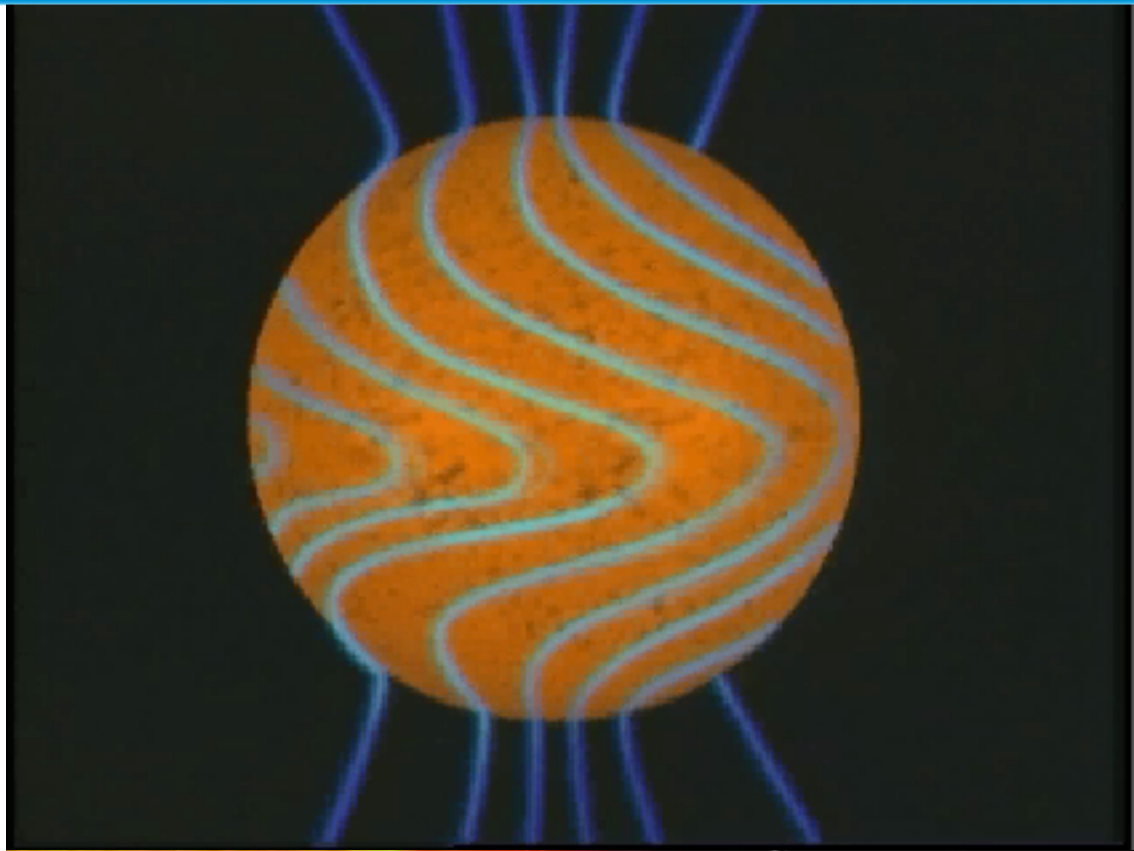
SST/Royal Swedish Academy of Sciences/ V. M. de Jorge Henriques

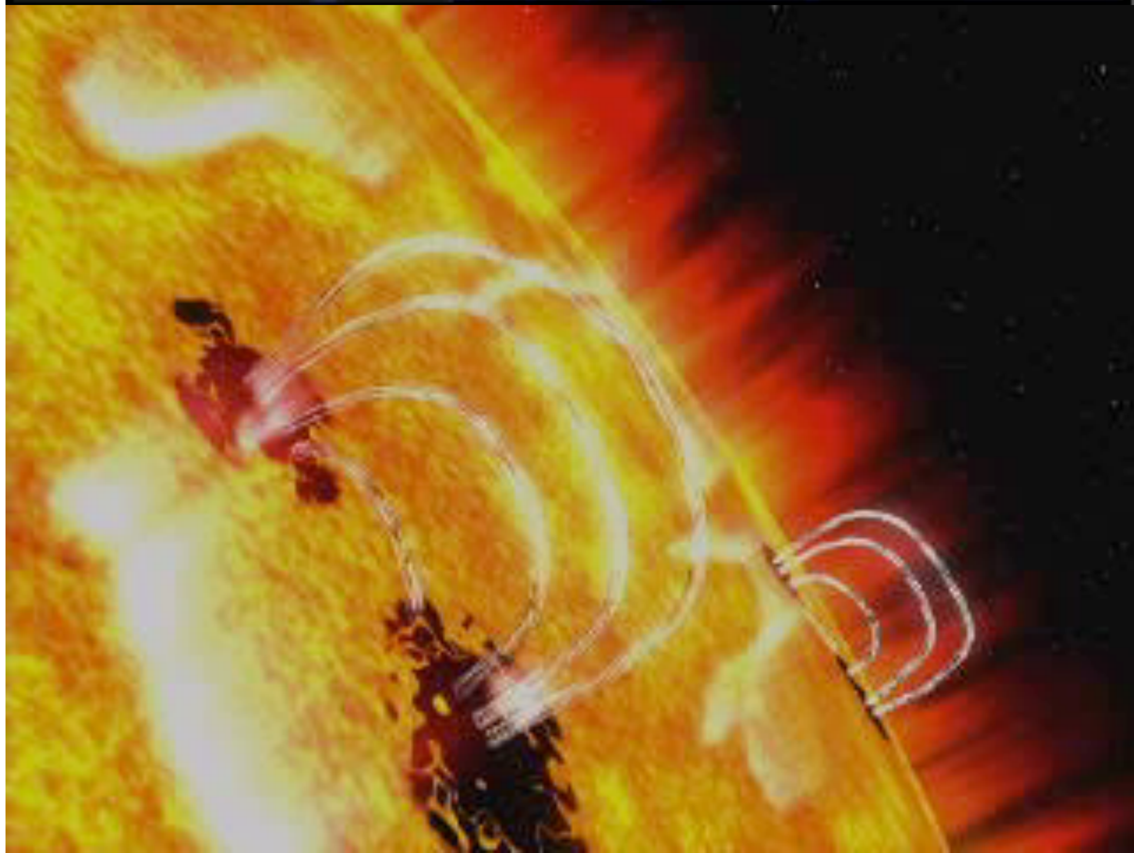
Solar activity changes with time - but what drives the solar cycle?

- Inside the Sun, moving charges generate magnetic field
- Solar Dynamo:Field amplification at the base of the convection zone
- Bundles of intense magnetic field rise to the Sun's surface due to magnetic buoyancy → Sunspots
- Sunspot Cycle: Period of ~11 years - but why?

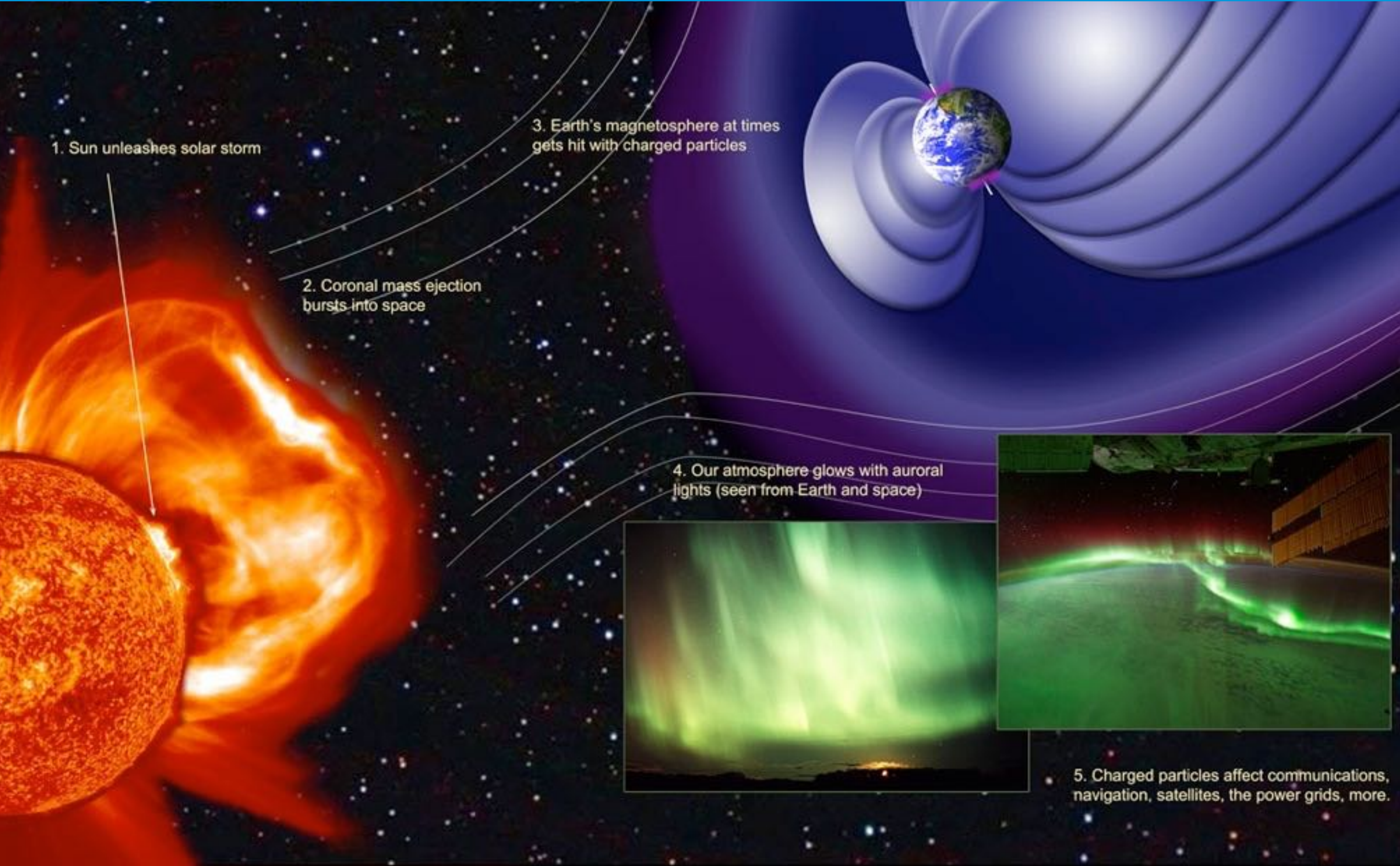


M. Owens, University of Reading

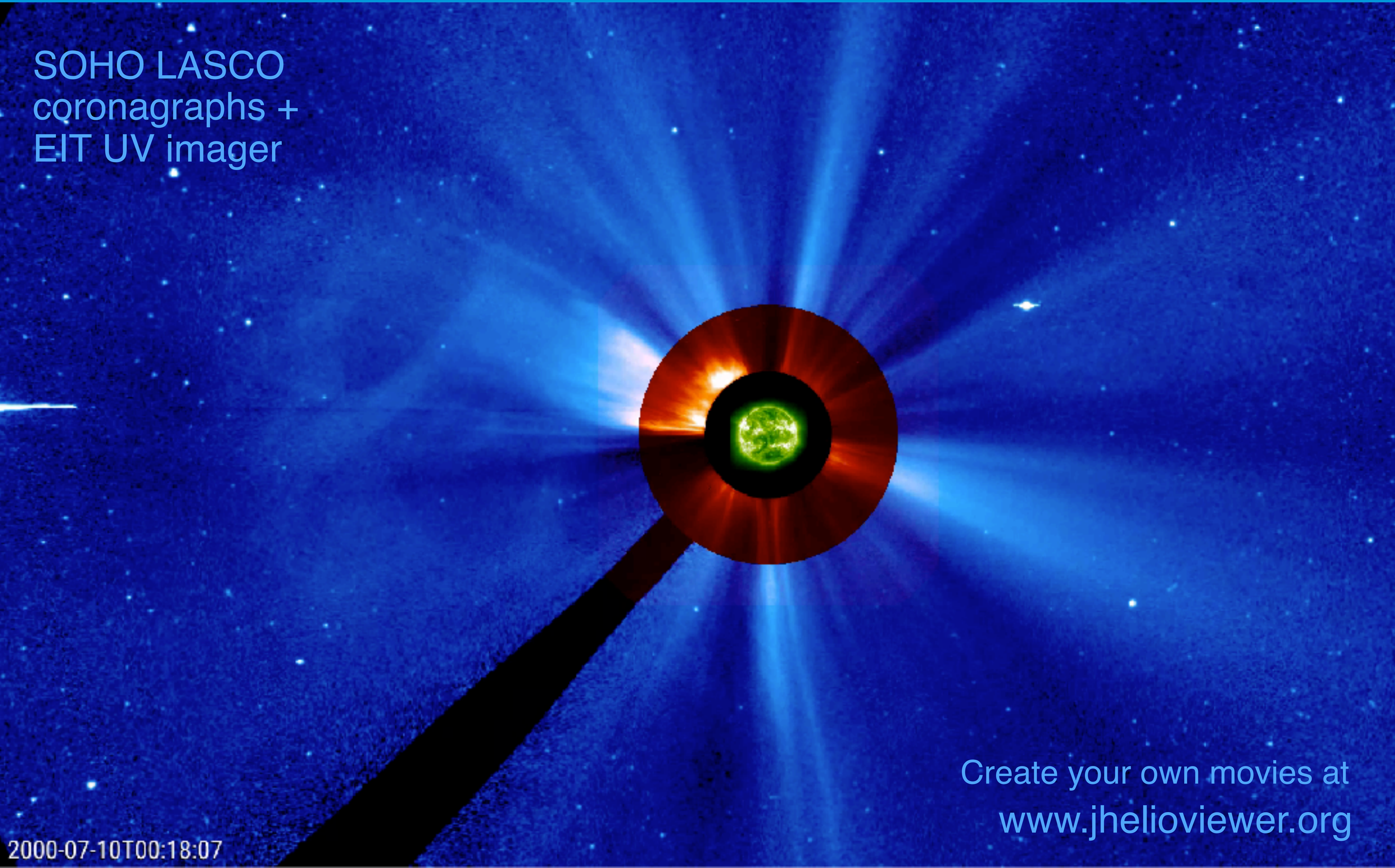




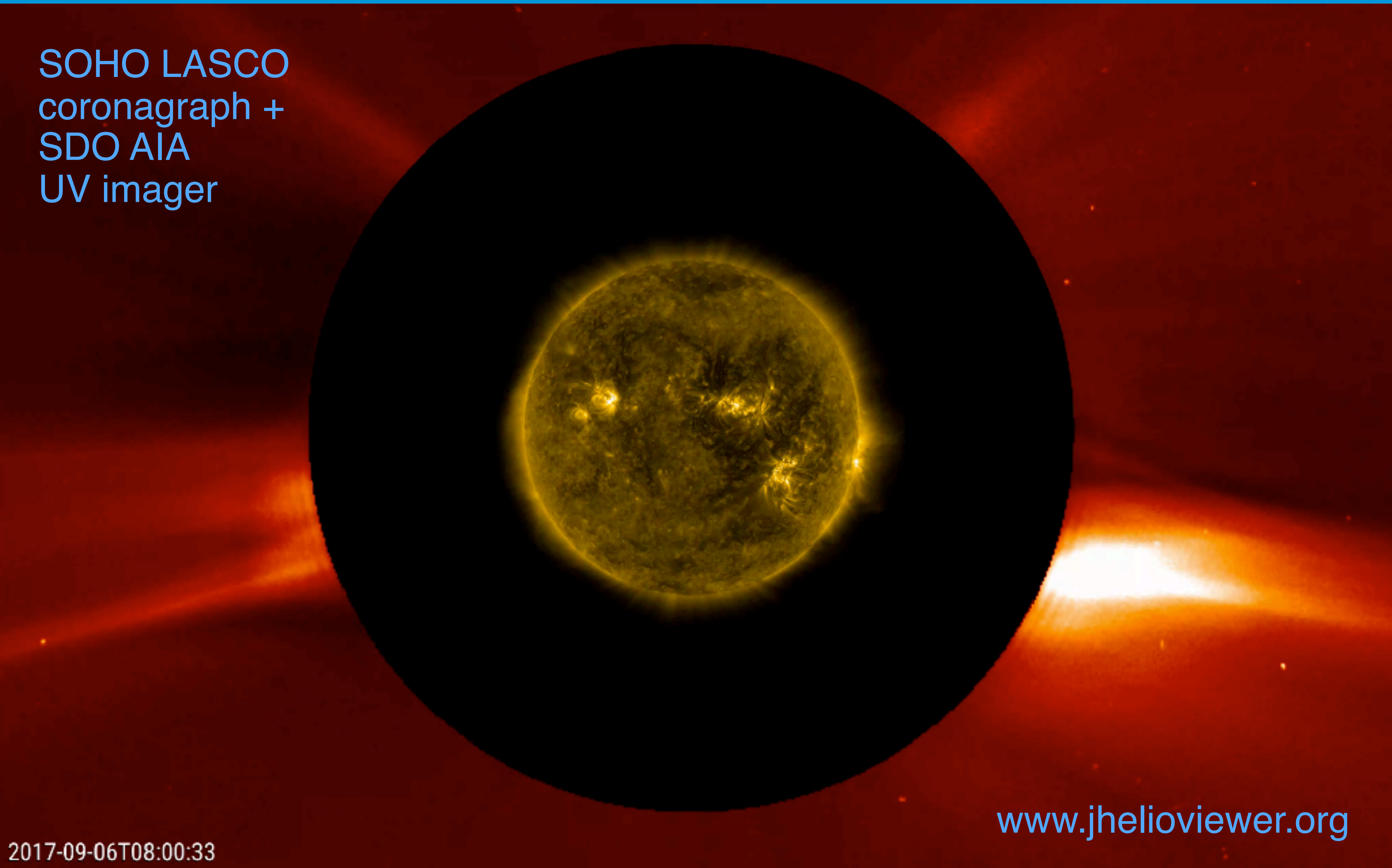
The Sun’s Magnetic Field: Main Driver of Space Weather



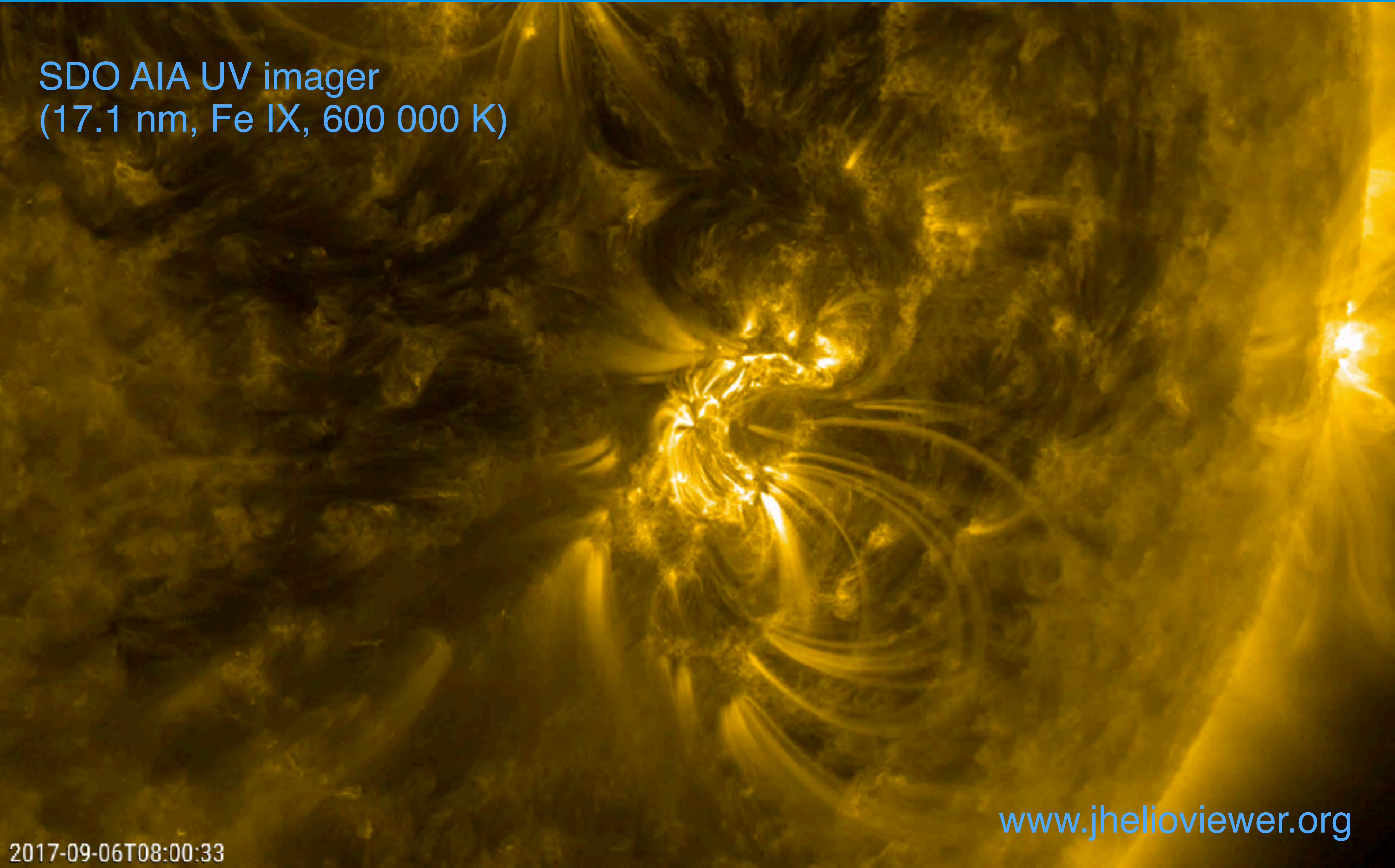
The Sun’s Dynamic Heliosphere: “Bastille Day Event”, 14 July 2000



X-Class Solar Flare, 6 September 2017

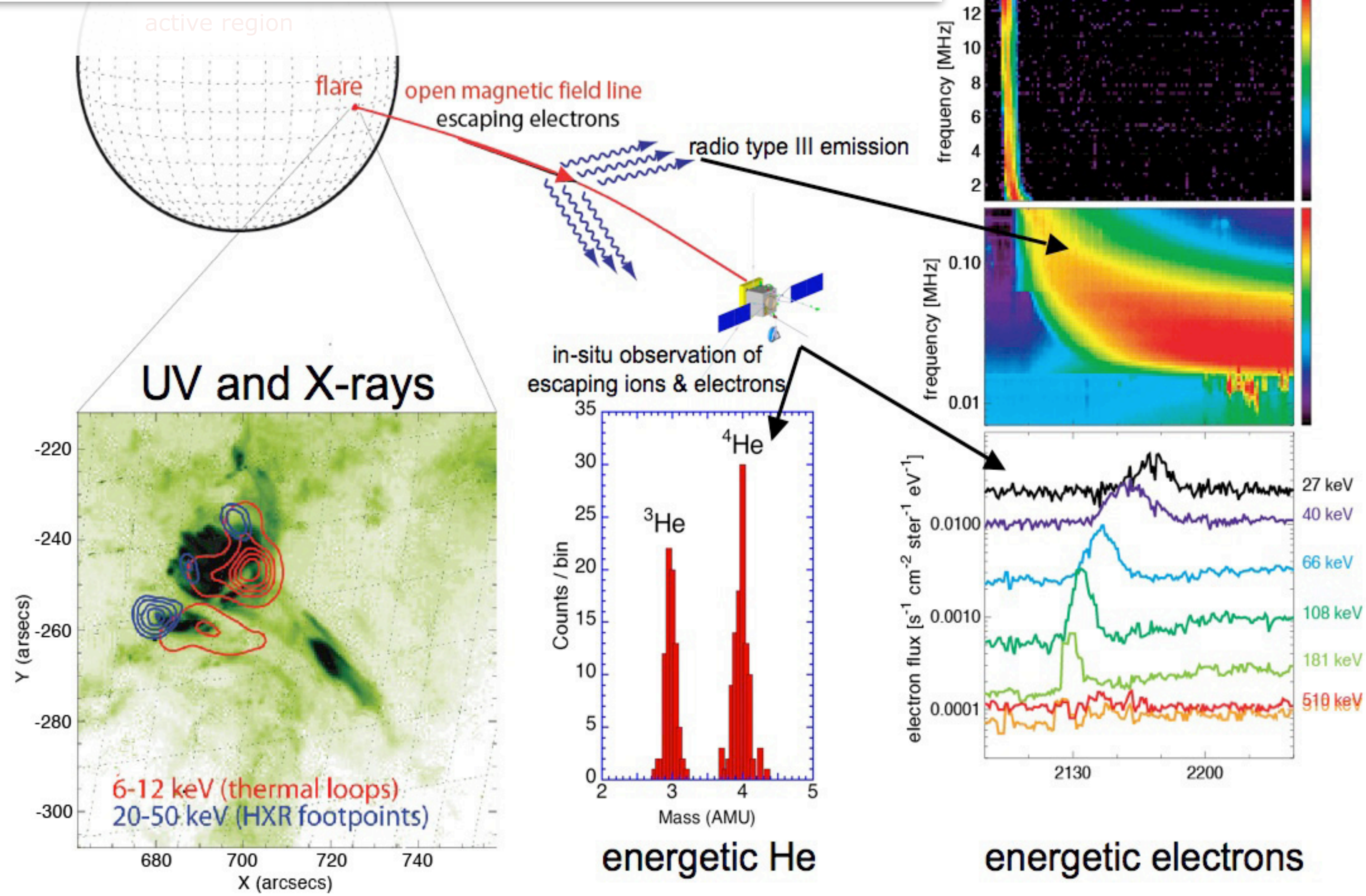


X-Class Solar Flare, 6 September 2017



Solar Orbiter
Exploring the Sun-Heliosphere Connection

Solar Orbiter is a mission designed to observe the Sun and the heliosphere, and link heliospheric phenomena back to their sources on the Sun.



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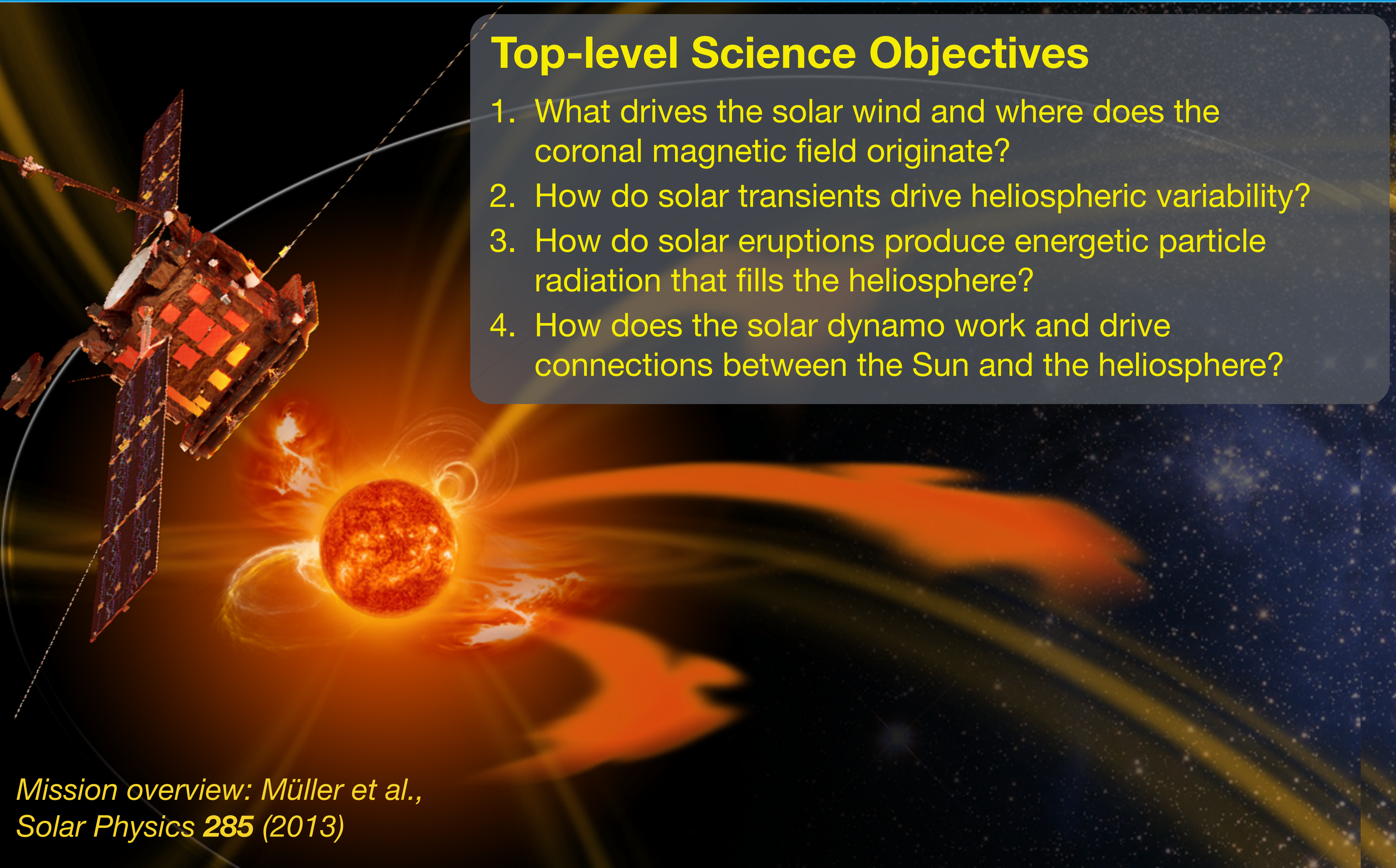

Top-level Science Objectives

1. What drives the solar wind and where does the coronal magnetic field originate?
2. How do solar transients drive heliospheric variability?
3. How do solar eruptions produce energetic particle radiation that fills the heliosphere?
4. How does the solar dynamo work and drive connections between the Sun and the heliosphere?

Mission overview: Müller et al., Solar Physics ***285*** *(2013)*

Solar Orbiter
Exploring the Sun-Heliosphere Connection

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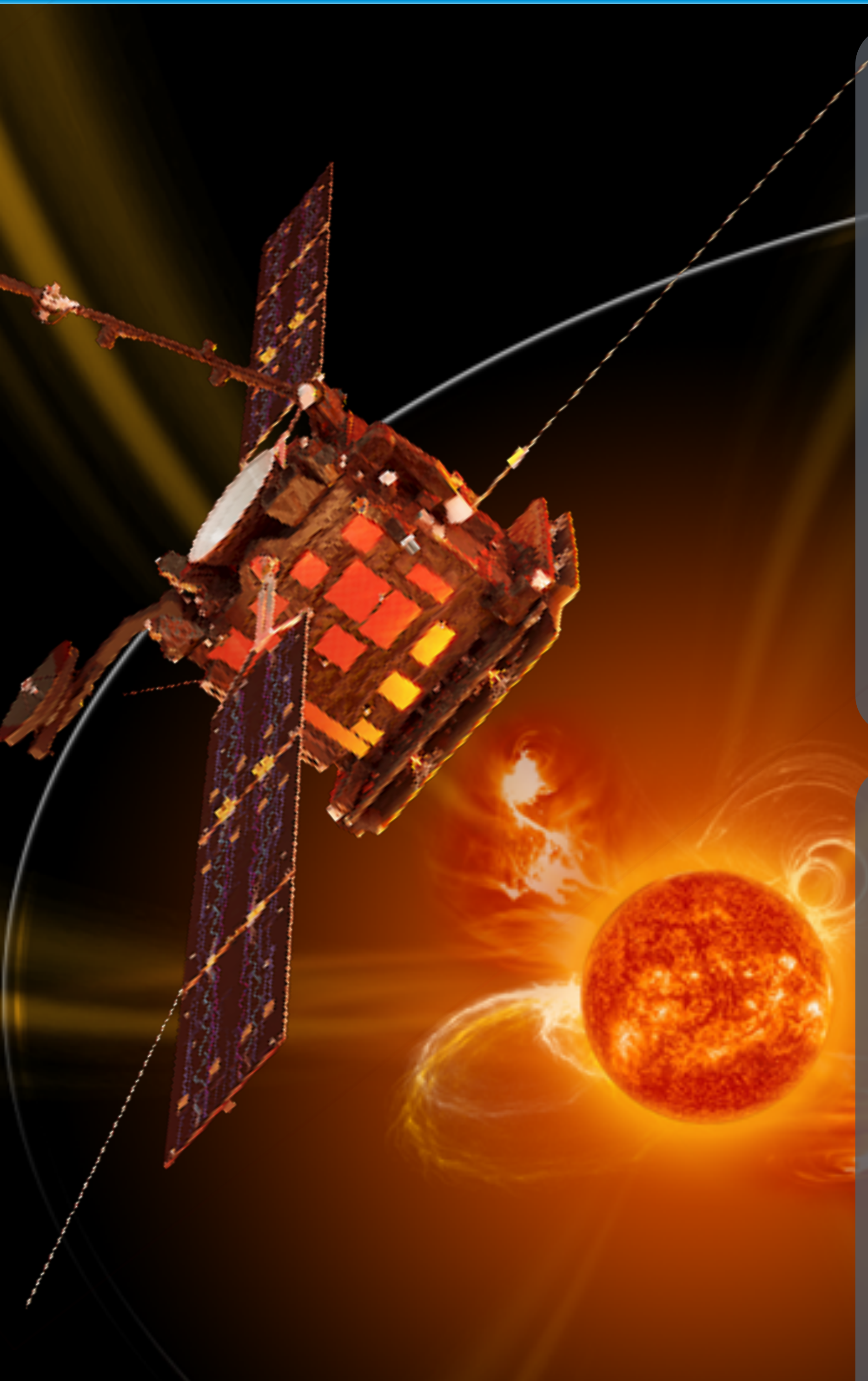

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Observations

- *In-situ*: Measurements of the solar wind plasma, fields, waves and energetic particles as close as 0.28 AU
- *Remote-sensing*:
  - Simultaneous high-resolution imaging and spectroscopic observations of the Sun in and out of the ecliptic plane.
  - Vector magnetic field of solar photosphere
  - Full-disk imaging in visible, UV, X-rays
  - Coronal imaging

Mission overview: Müller et al., Solar Physics ***285*** *(2013)*

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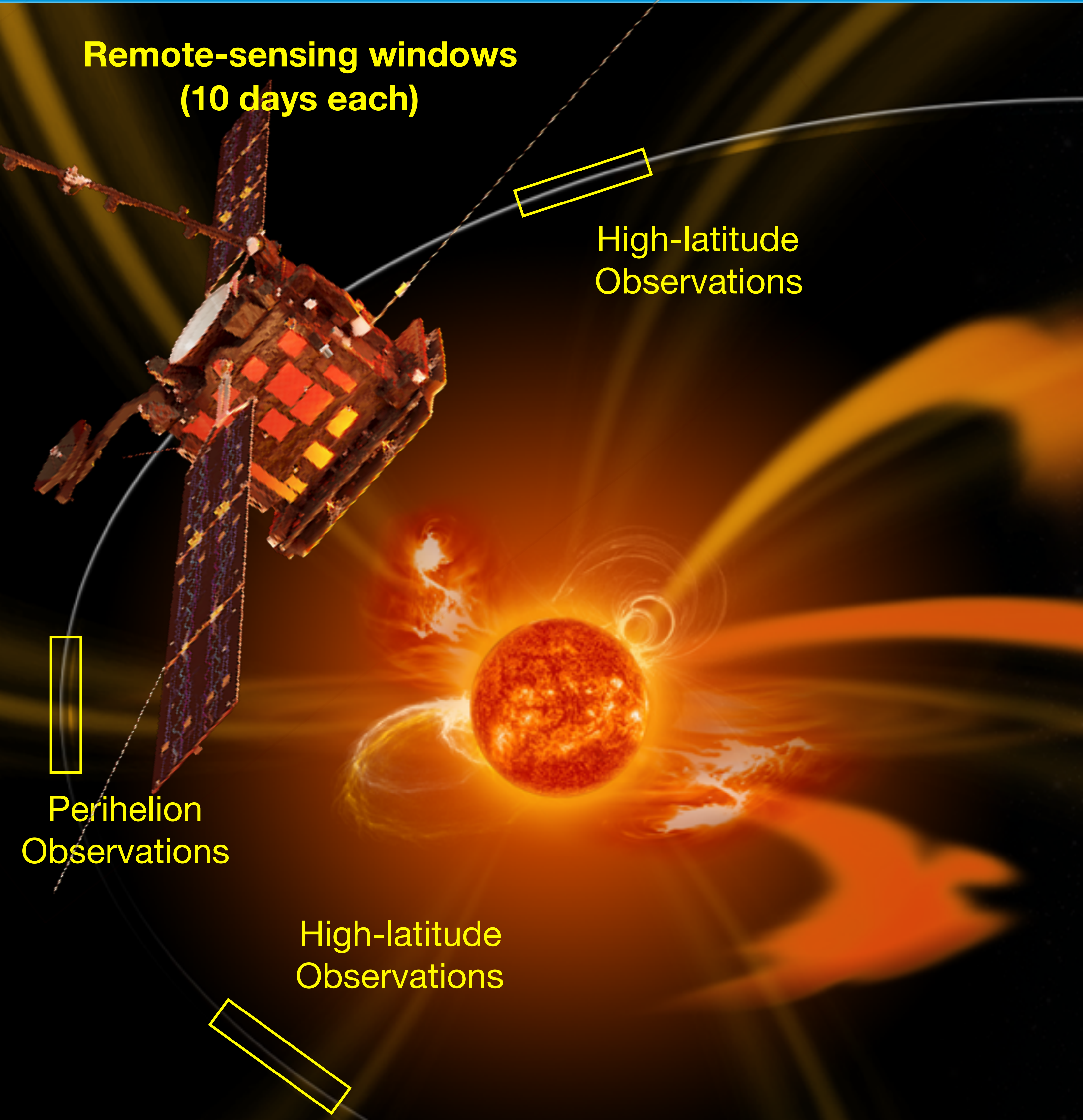


Mission Summary

Planned Launch: Feb 2020

Cruise Phase: 1.8 years (for Feb 2020)

Nominal Mission: 4 years

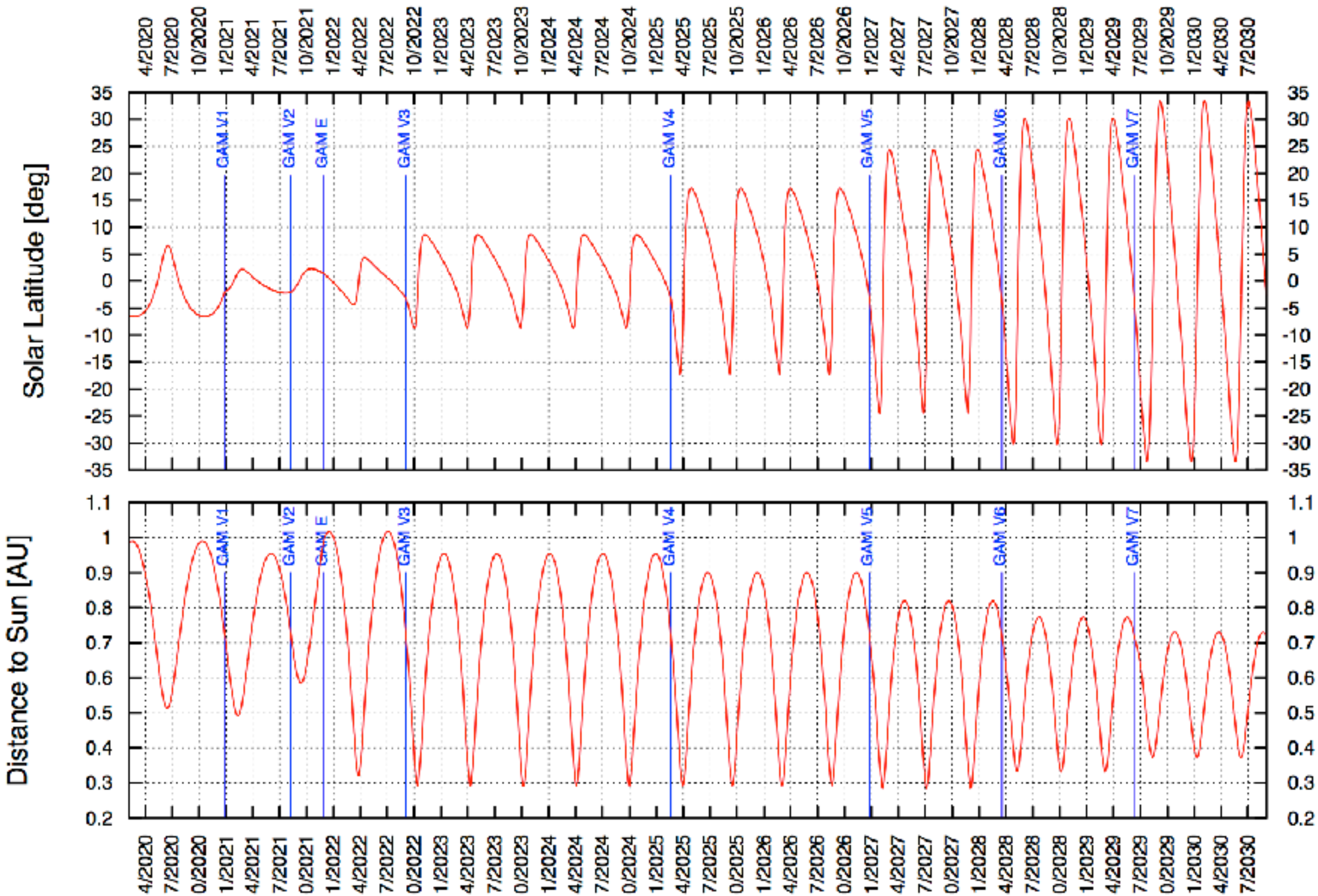
Extended Mission: 3.5 years

Orbit: 0.28–0.91 AU (P=150-180 days)

Out-of-Ecliptic View:
Multiple gravity assists with Venus to increase inclination out of the ecliptic to >24° (nominal mission), >33° (extended mission)

Reduced relative rotation:
Observations of evolving structures on solar surface & in heliosphere for almost a complete solar rotation

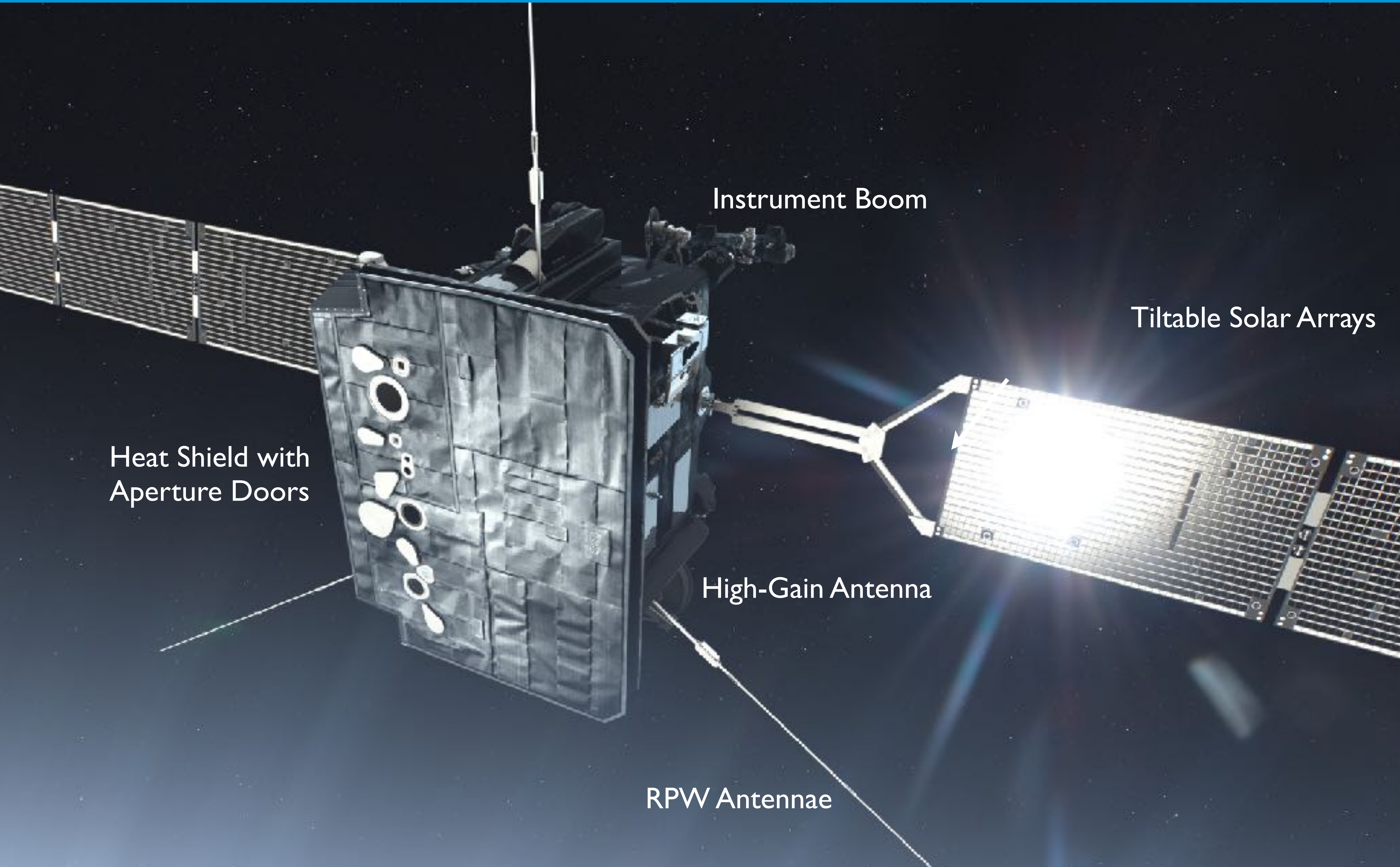
Solar Latitude & Distance (for launch in Feb 2020)



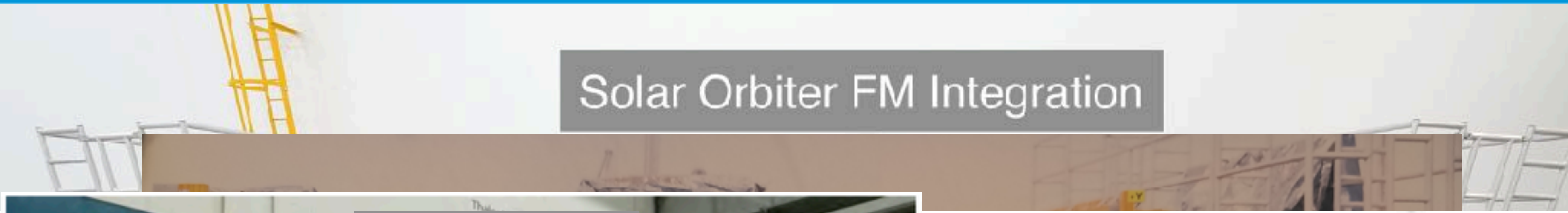
Solar Orbiter Payload

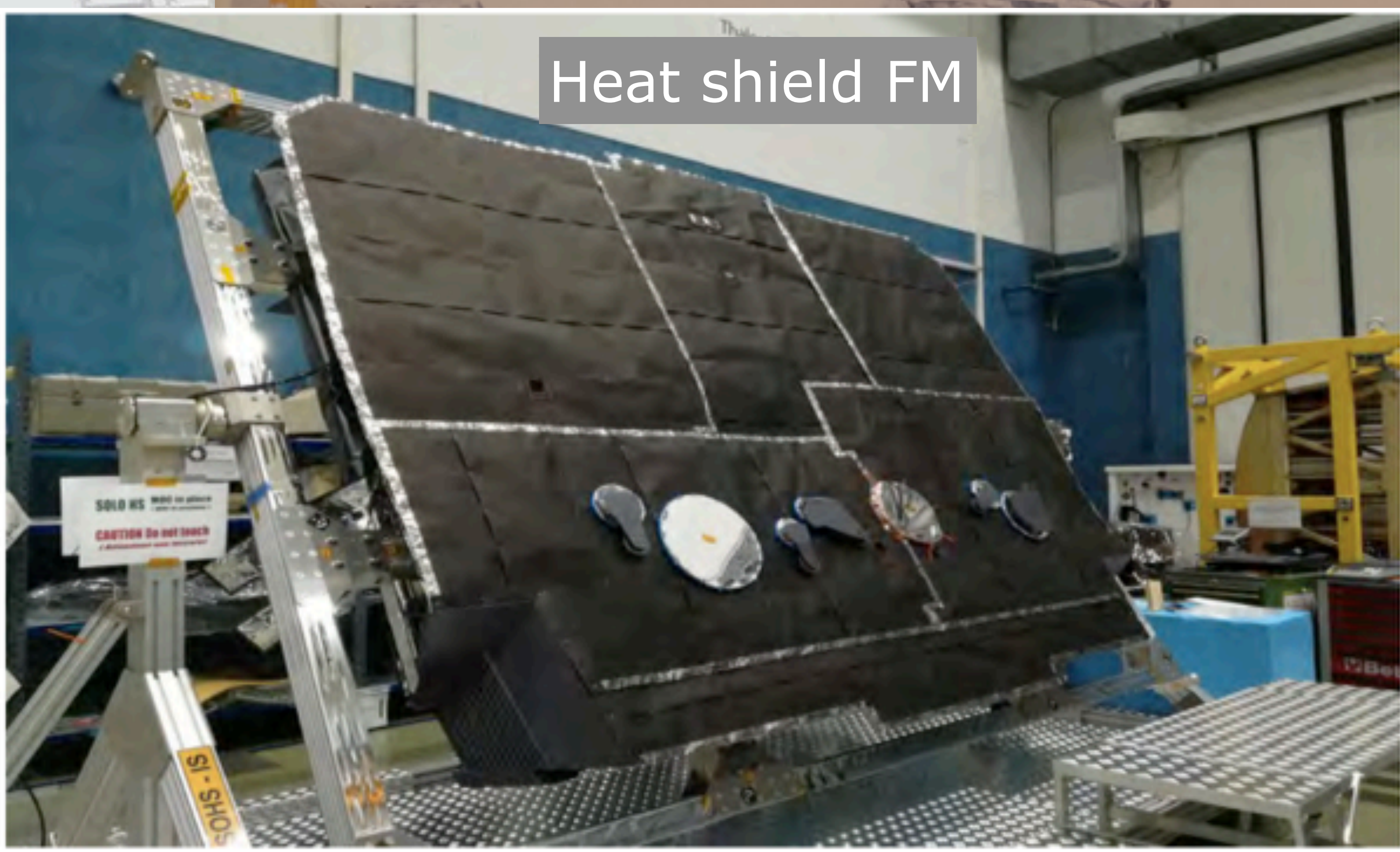
In-Situ Instruments			
EPD	Energetic Particle Detector	J. Rodríguez-Pacheco	Composition, timing and distribution functions of energetic particles
MAG	Magnetometer	T. Horbury	High-precision measurements of the heliospheric magnetic field
RPW	Radio & Plasma Waves	M. Maksimovic	Electromagnetic and electrostatic waves, magnetic and electric fields at high time resolution
SWA	Solar Wind Analyser	C. Owen	Sampling protons, electrons and heavy ions in the solar wind
Remote-Sensing Instruments			
EUI	Extreme Ultraviolet Imager	P. Rochus	High-resolution and full-disk (E)UV imaging of the on-disk corona
METIS	Coronagraph	M. Romoli	Visible and UV Imaging of the off-disk corona
PHI	Polarimetric & Helioseismic Imager	S. Solanki	High-resolution vector magnetic field, line-of-sight velocity in photosphere, visible imaging
SoloHI	Heliospheric Imager	R. Howard	Wide-field visible imaging of the solar off-disk corona
SPICE	Spectral Imaging of the Coronal Environment	ESA facility instrument	EUV imaging spectroscopy of the solar disk and near-Sun corona
STIX	Spectrometer/Telescope for Imaging X-rays	S. Krucker	Imaging spectroscopy of solar X-ray emission

The Spacecraft



Solar Orbiter Flight Model Integration





-Y wing – Rear-side conductive foil

Solar Orbiter Flight Model Integration

Instrument Panel (-Y)

Solar Orbiter
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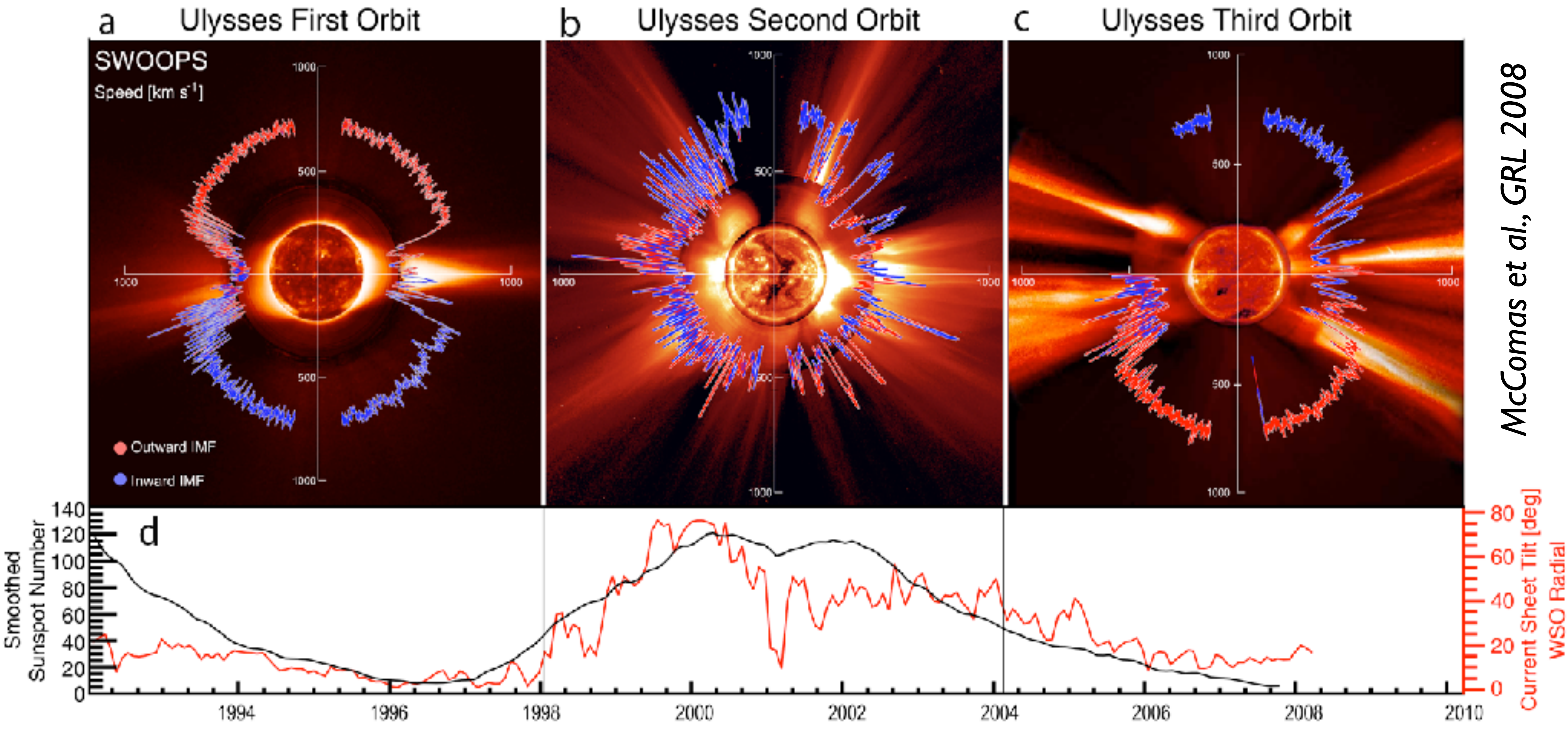
How does the Sun create and control the Heliosphere – and why does solar activity change with time ?

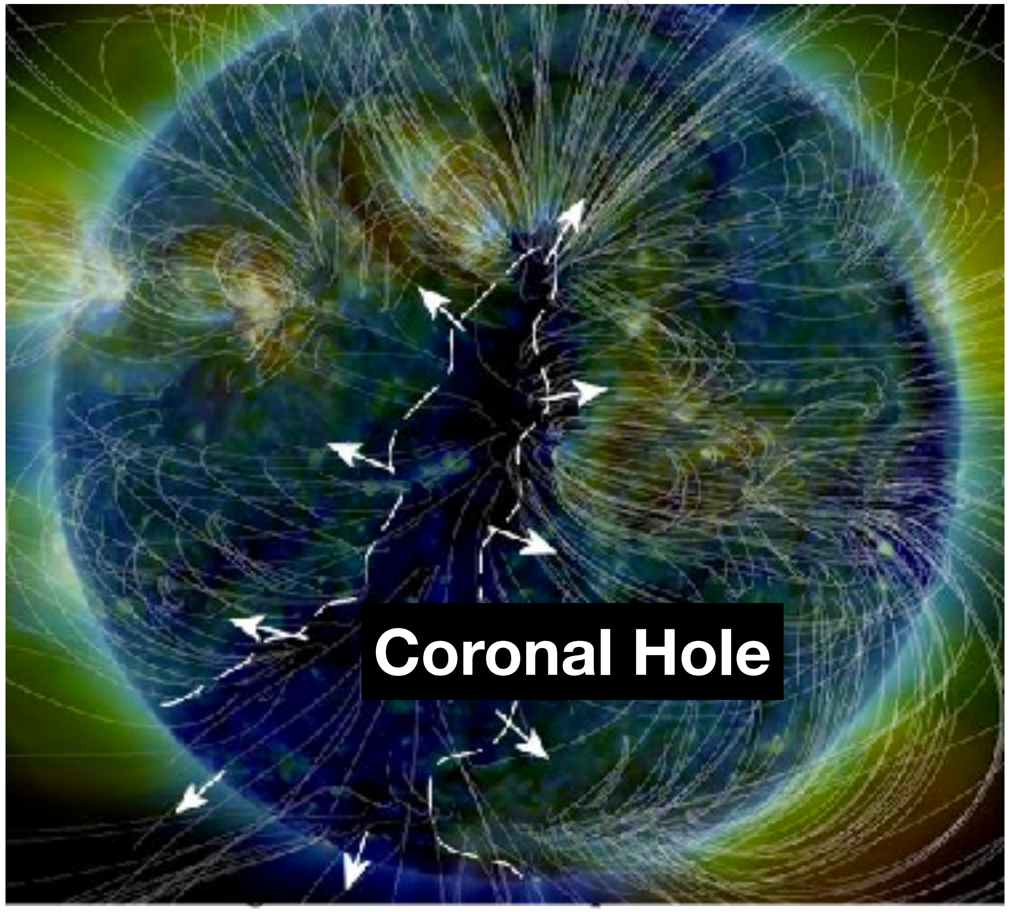


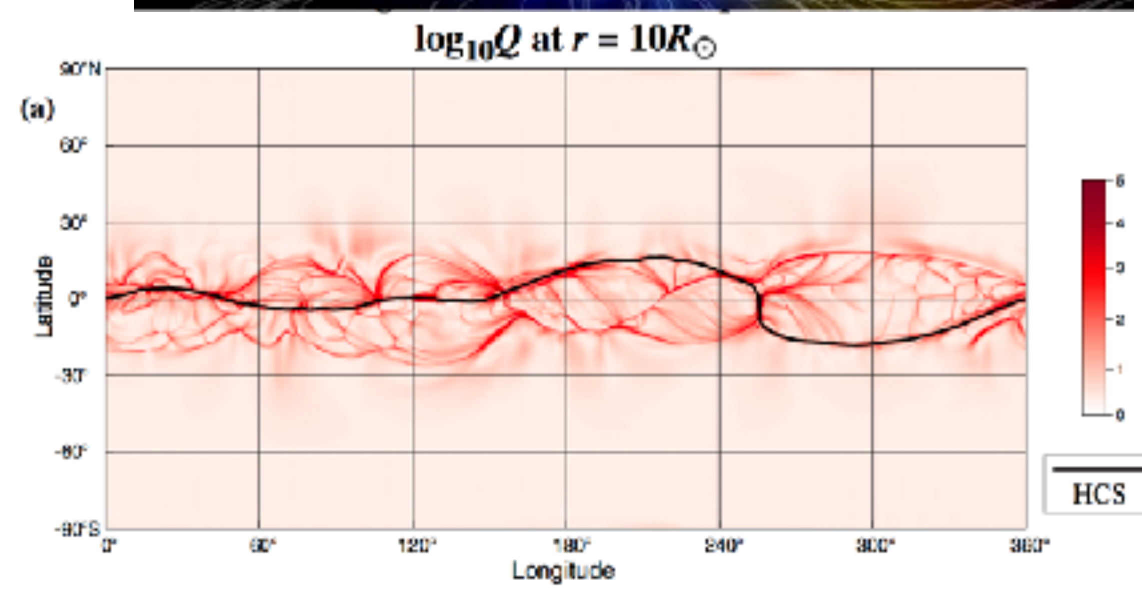
McComas et al., GRL 2008

1. What drives the solar wind and where does the coronal magnetic field originate?

- Fast solar wind originates from open field regions
- Slow wind originates from ???
- Ulysses and SOHO posed the problem - Solar Orbiter will try to solve it

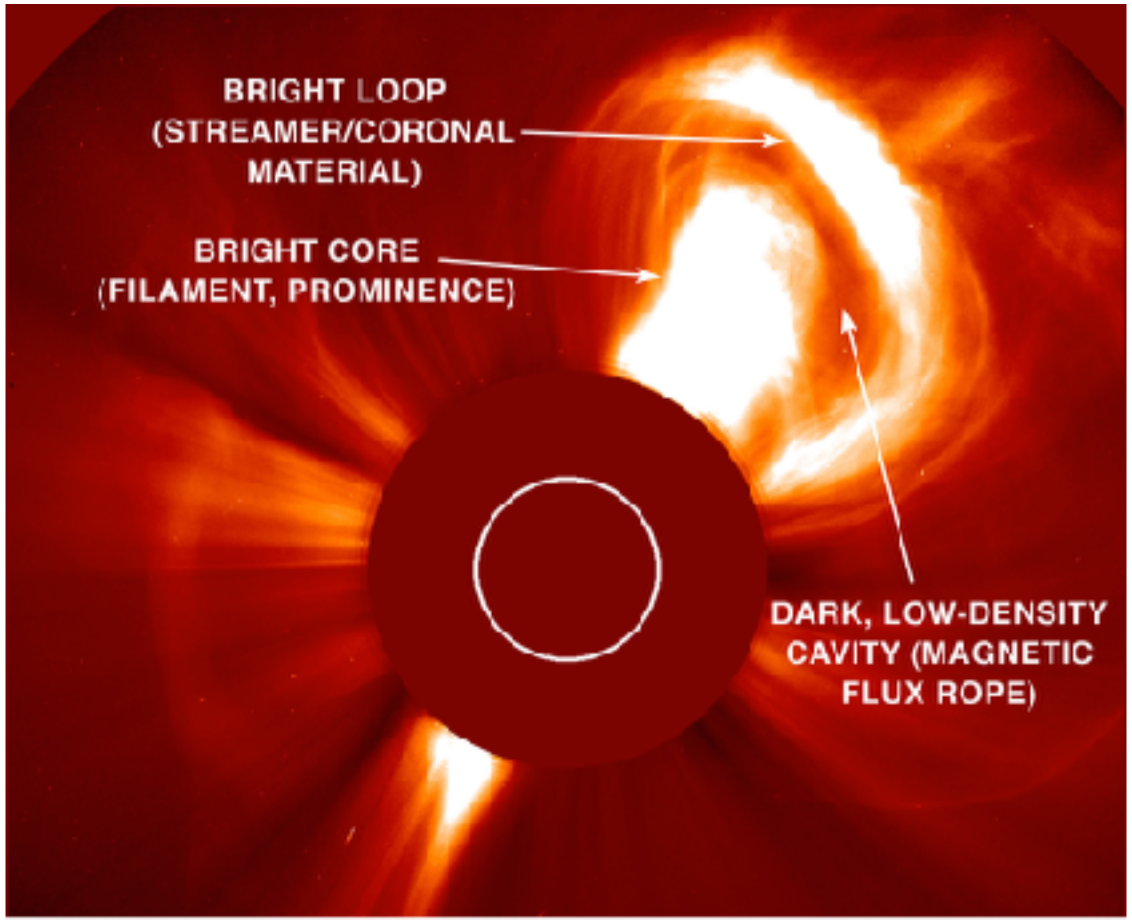
- **Magnetic structure/topology of corona:**
  - Determined primarily by photospheric sources
  - Driven by photospheric motions and magnetic flux evolution and reconnection in the corona
  - Stress builds up primarily in closed field
- Energy is released impulsively at open-closed field boundaries, both via small bursts and major explosions
- Assumed to be a basic process underlying slow wind/ streamer blobs/coronal jets (Antiochos, Wyper, Higginson et al.)





S-Web model: Mapping of field from photosphere to heliosphere (Antiochos et al. 2011)

2. How do solar transients drive heliospheric variability?



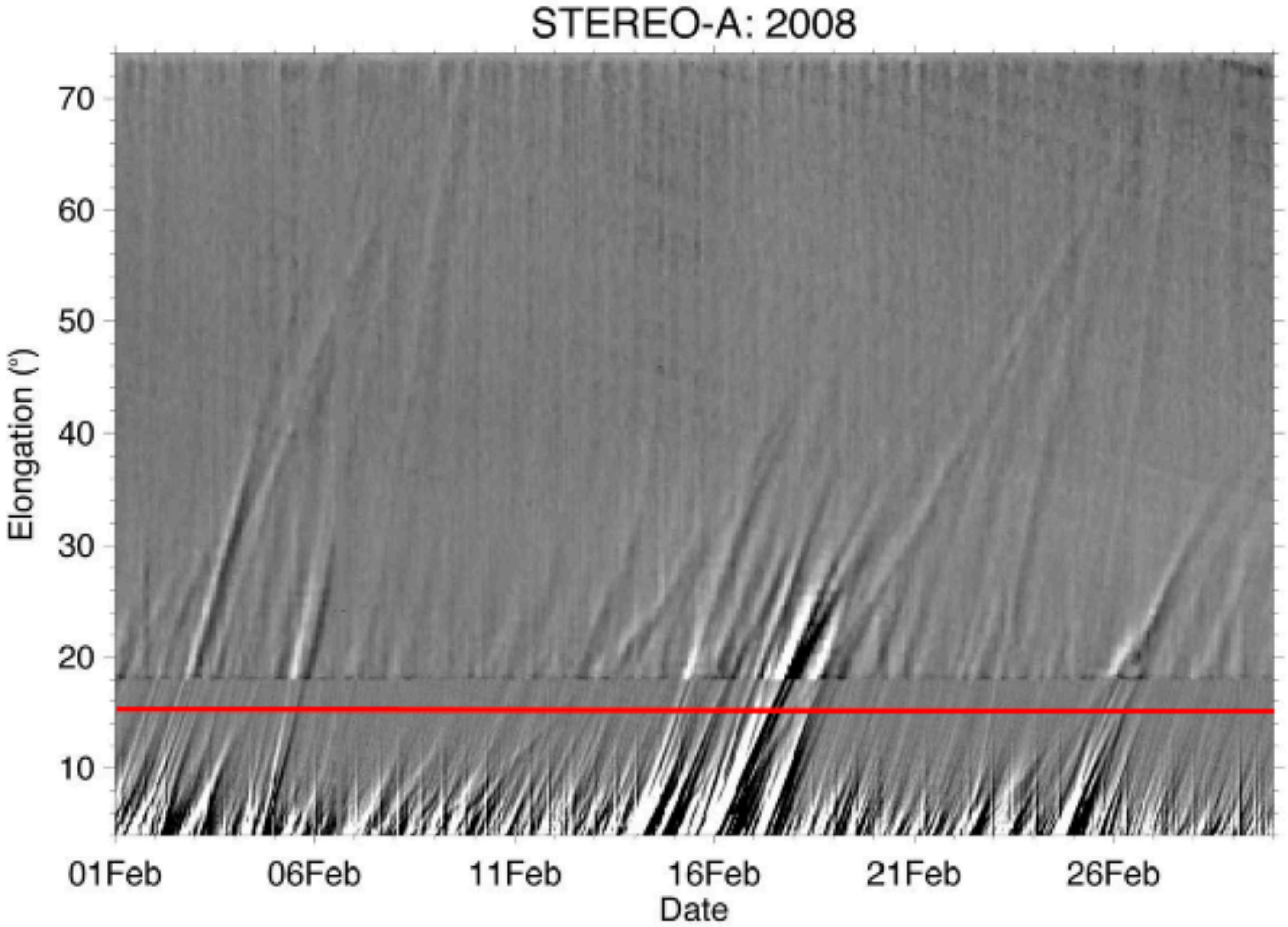
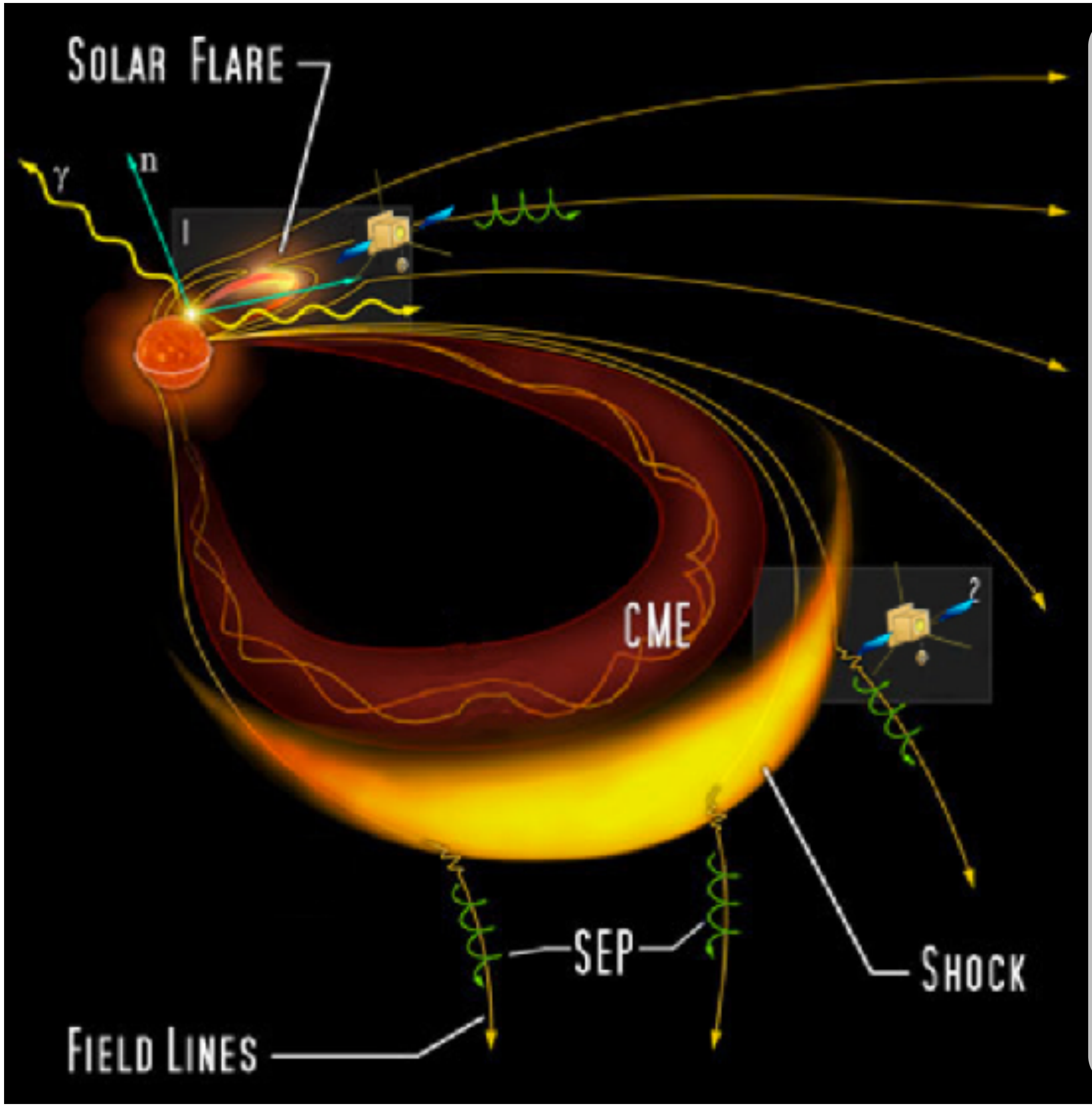


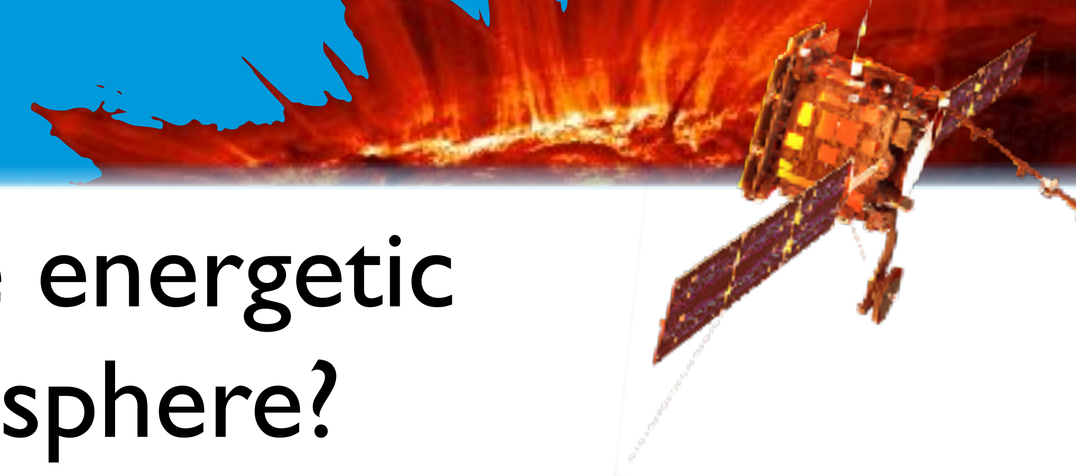
Figure courtesy J. Davies, RAL

3. How do solar eruptions produce energetic particle radiation that fills the heliosphere?



- Main mechanisms of SEP acceleration (Wild et al. 1963, Reames 2013):
  - Flares
  - CME driven shocks
- Relative importance of these cannot be determined at 1 AU due to particles mixing
  → Solar Orbiter will measure energetic particles *in situ* as shocks pass the spacecraft

esa SOLAR ORBITER



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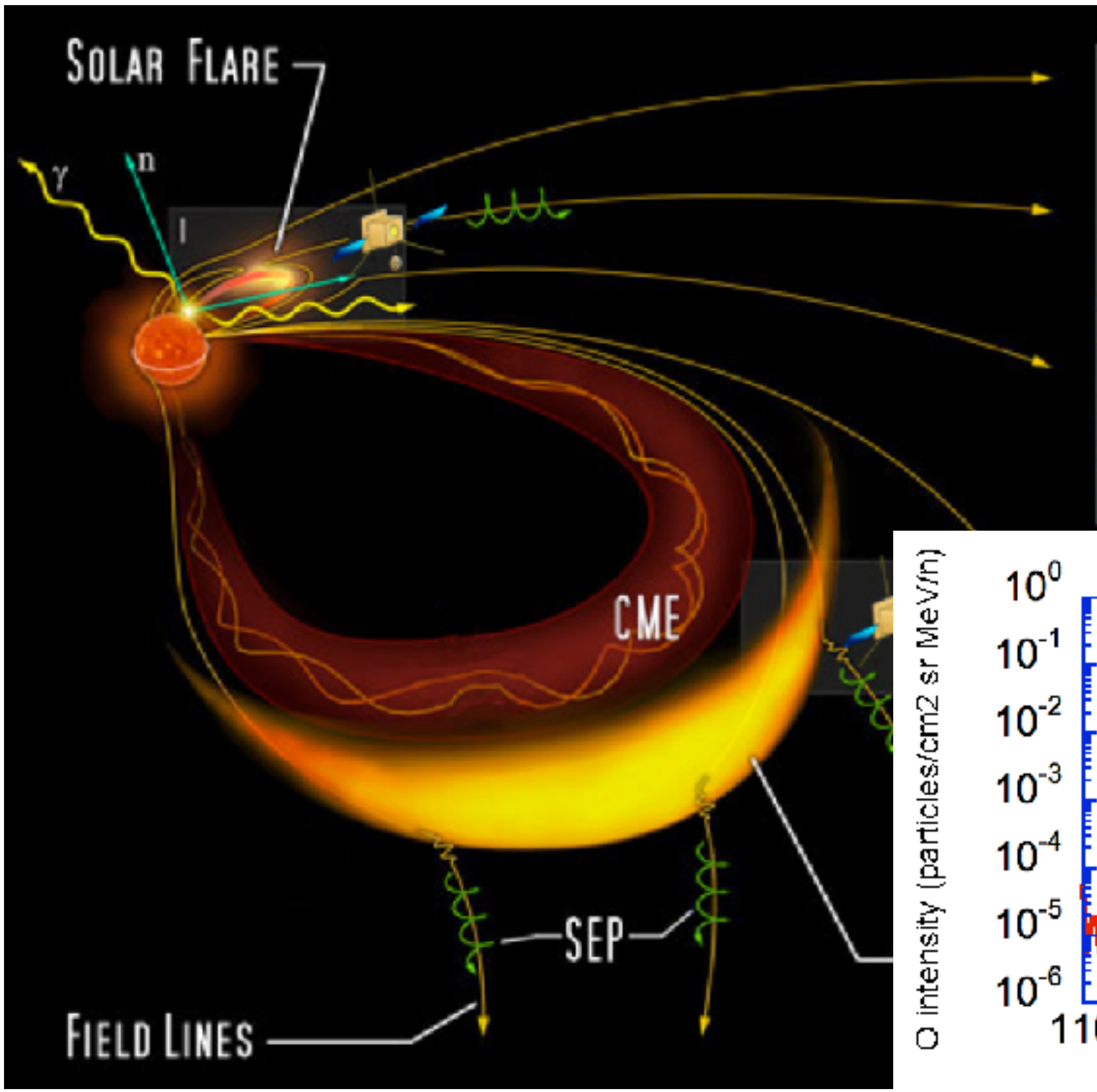
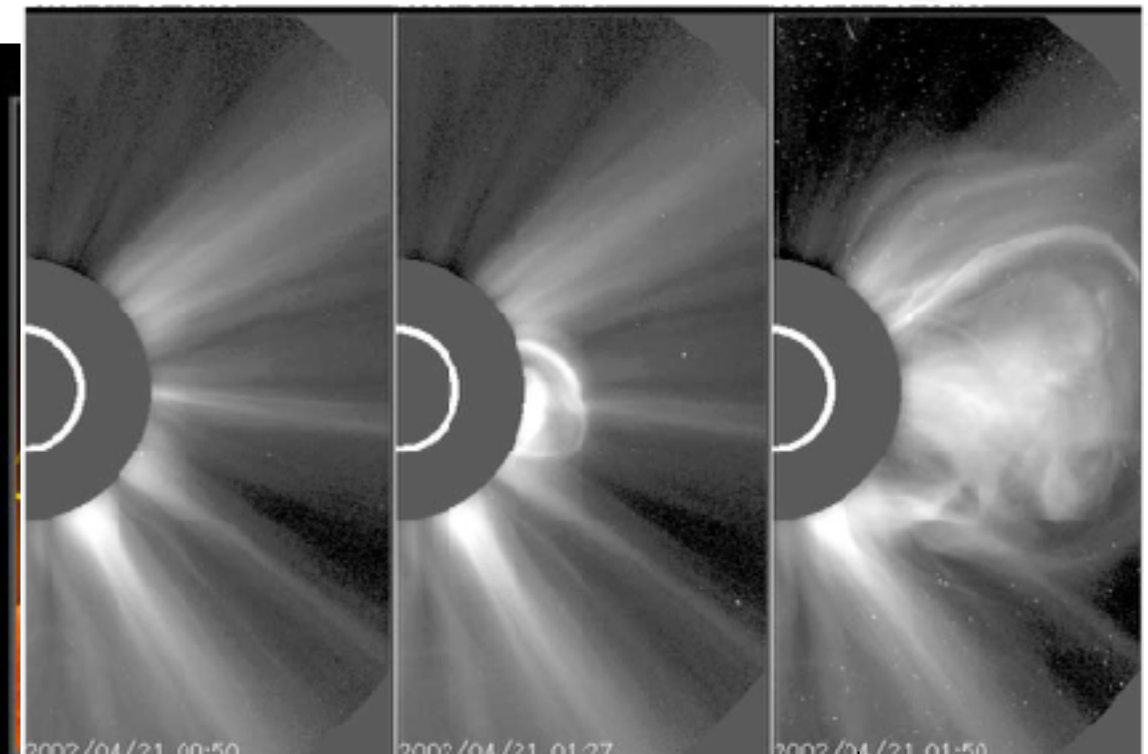
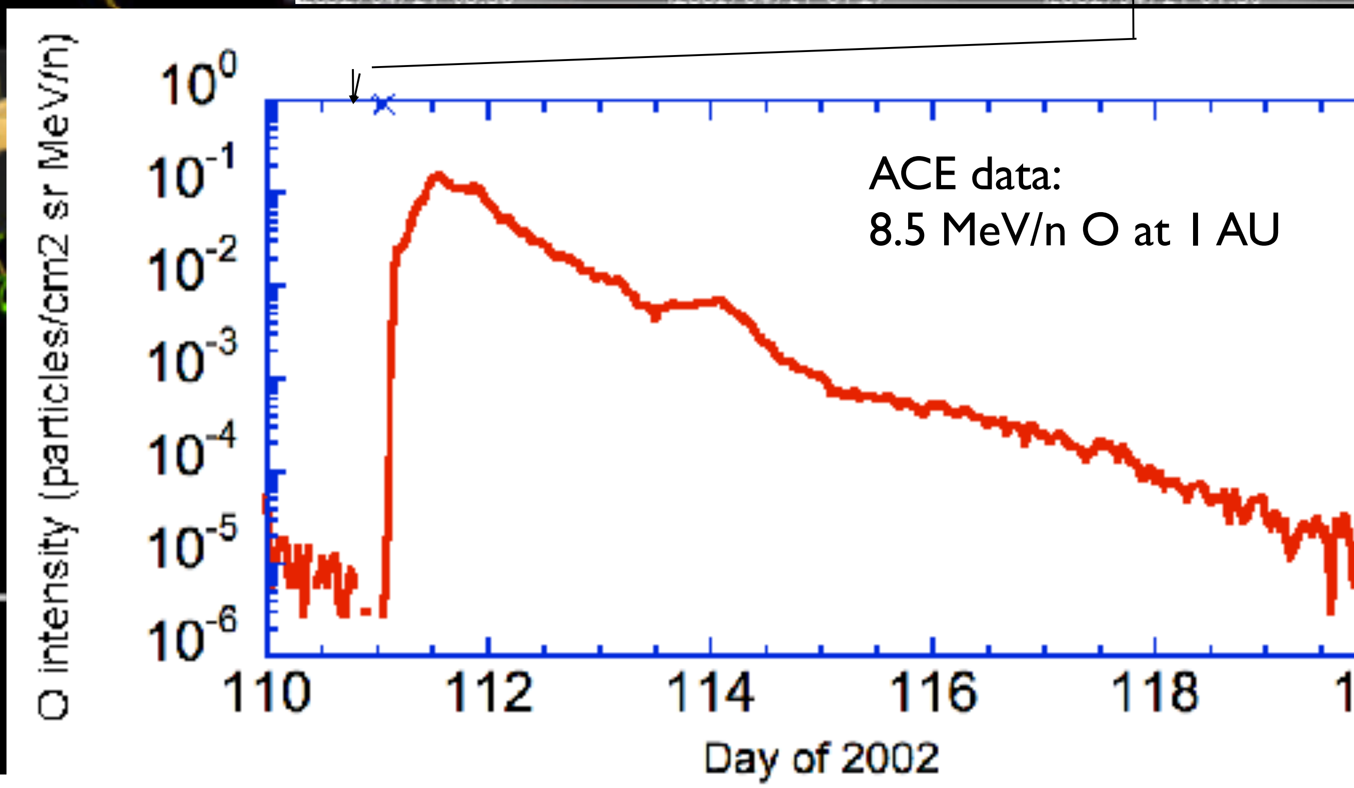


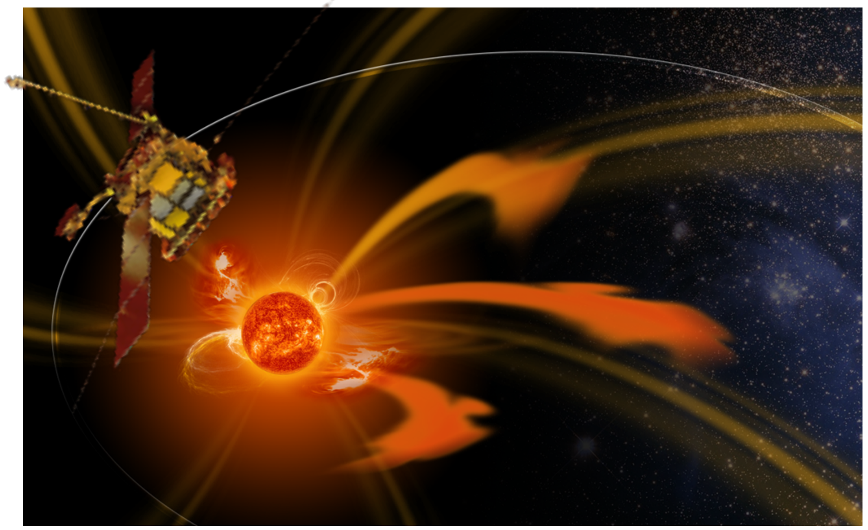




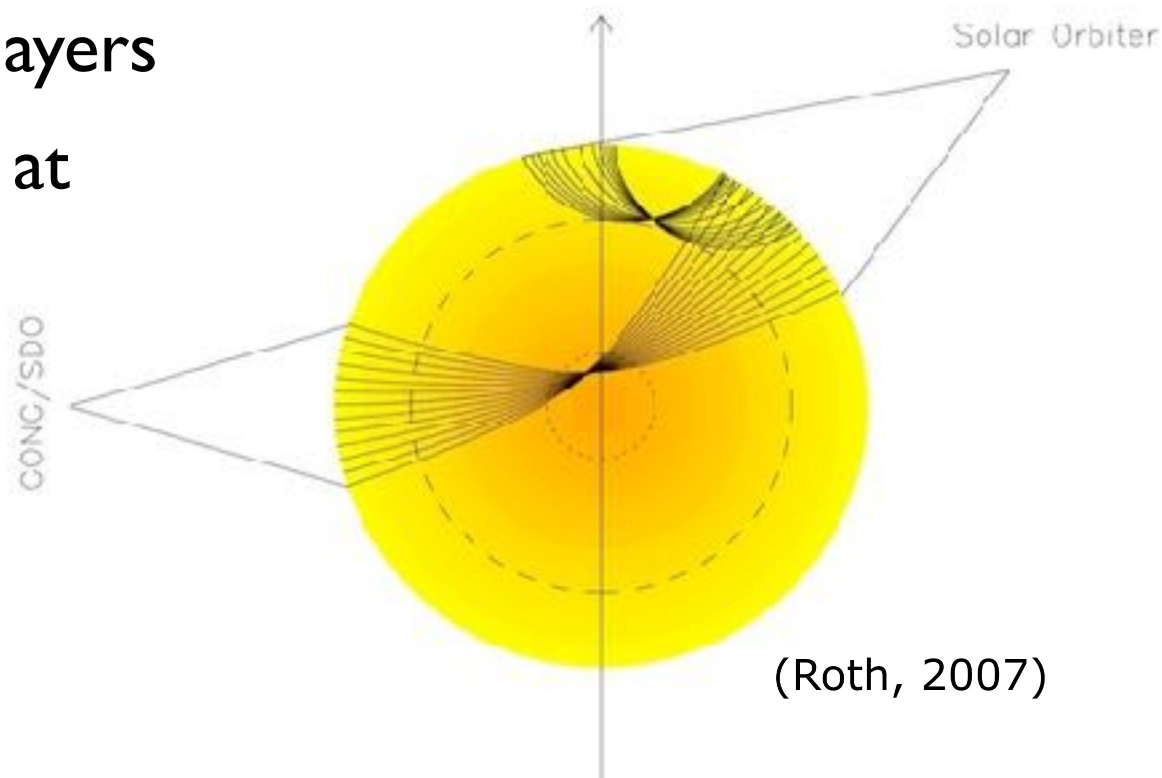
Emslie et al., JGR 2004

4. How does the solar dynamo work and drive connections between the Sun and the heliosphere?

- **Solar Orbiter will see the Sun's far side and**
  higher latitudes
  - Improved combined helioseismic data (near + far sides)
    - ➡ Global helioseismology: reduces leakage effects
    - ➡ Local helioseismology: can probe deeper layers
  - Observe large- and small-scale flow patterns at solar poles



- **Probing of the deep solar interior**
  - Seismic estimates for the deep meridional return flow



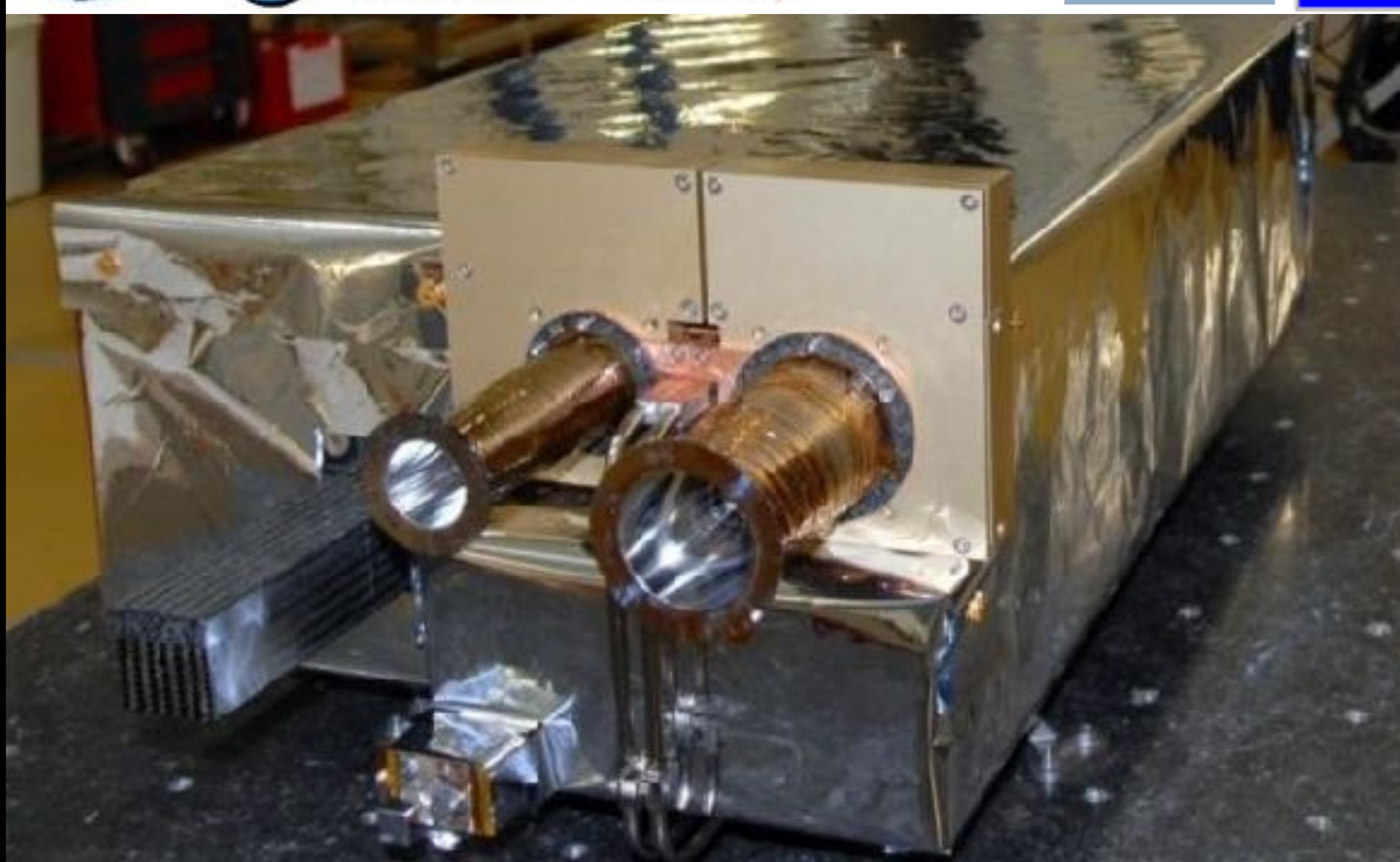
(Roth, 2007)

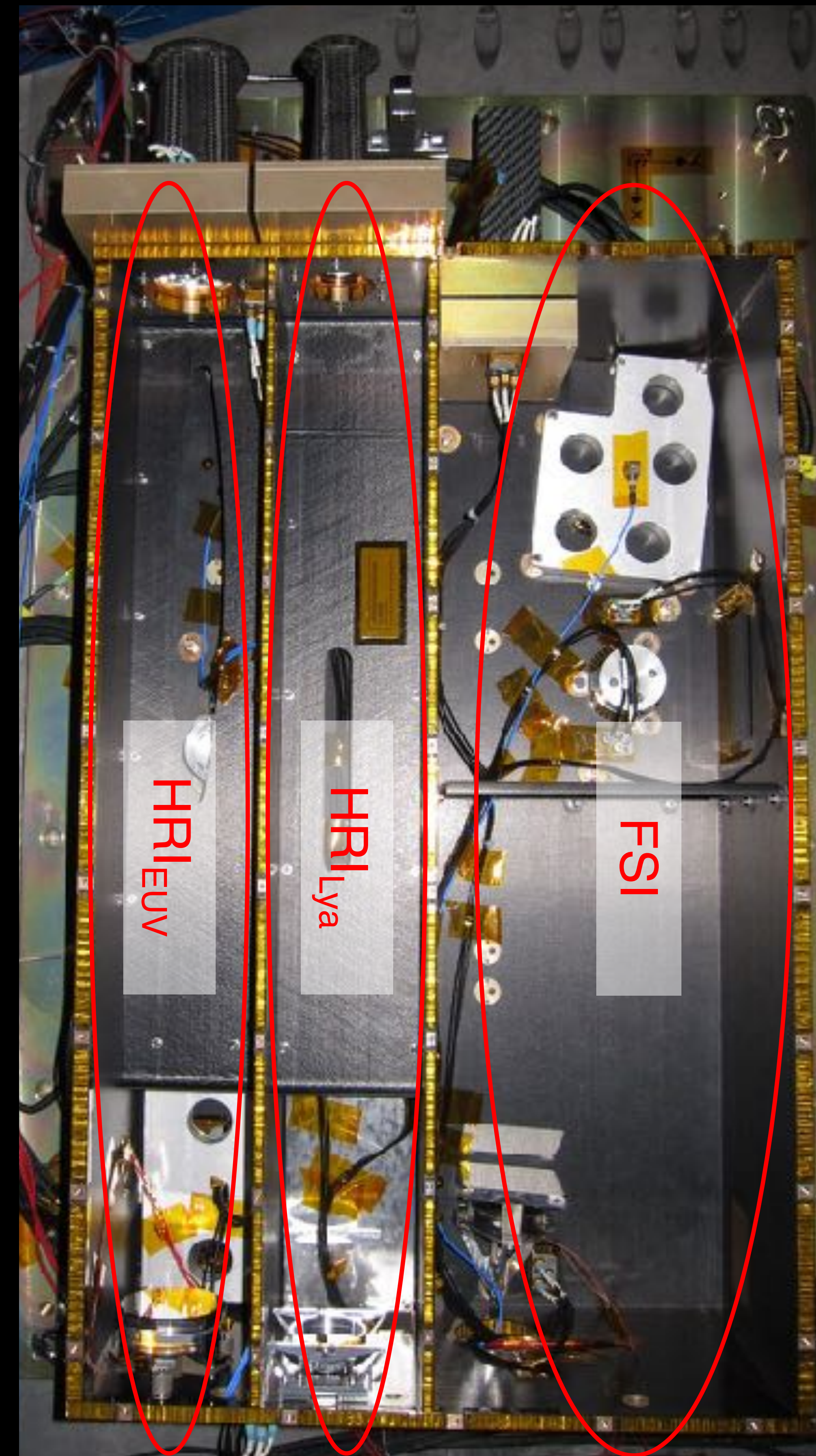
Remote-Sensing Instruments

EUI	Extreme Ultraviolet Imager	P. Rochus		High-resolution and full-disk EUV imaging of the on-disk corona
METIS	Coronagraph	M. Romoli		Visible and UV Imaging of the off-disk corona
PHI	Polarimetric & Helioseismic Imager	S. Solanki		High-resolution vector magnetic field, line-of-sight velocity in photosphere, visible imaging
SoloHI	Heliospheric Imager	R. Howard		Wide-field visible imaging of the solar off-disk corona
SPICE	Spectral Imaging of the Coronal Environment	European-led facility instrument		EUV spectroscopy of the solar disk and near-Sun corona
STIX	Spectrometer/Telescope for Imaging X-rays	S. Krucker		Imaging spectroscopy of solar X-ray emission

Extreme Ultraviolet Imager (PI: Pierre Rochus, CSL)

FSI dual EUV	Passband centre	174 Å and 304 Å alternatively
	Field of View	3.8 arcdeg × 3.8 arcdeg
	Angular resolution (2 px)	9 arcsec
	Typical cadence	600 s
HRI EUV	Passband centre	174 Å
	Field of View	$(1000\ \text{arcsec})^2$
	Angular resolution (2 px)	1 arcsec
	Typical high cadence	2 s
HRI Lyman-α	Passband centre	1216 Å
	Field of View	$(1000\ \text{arcsec})^2$
	Angular resolution (2 px)	1 arcsec
	Typical high cadence	Sub-second

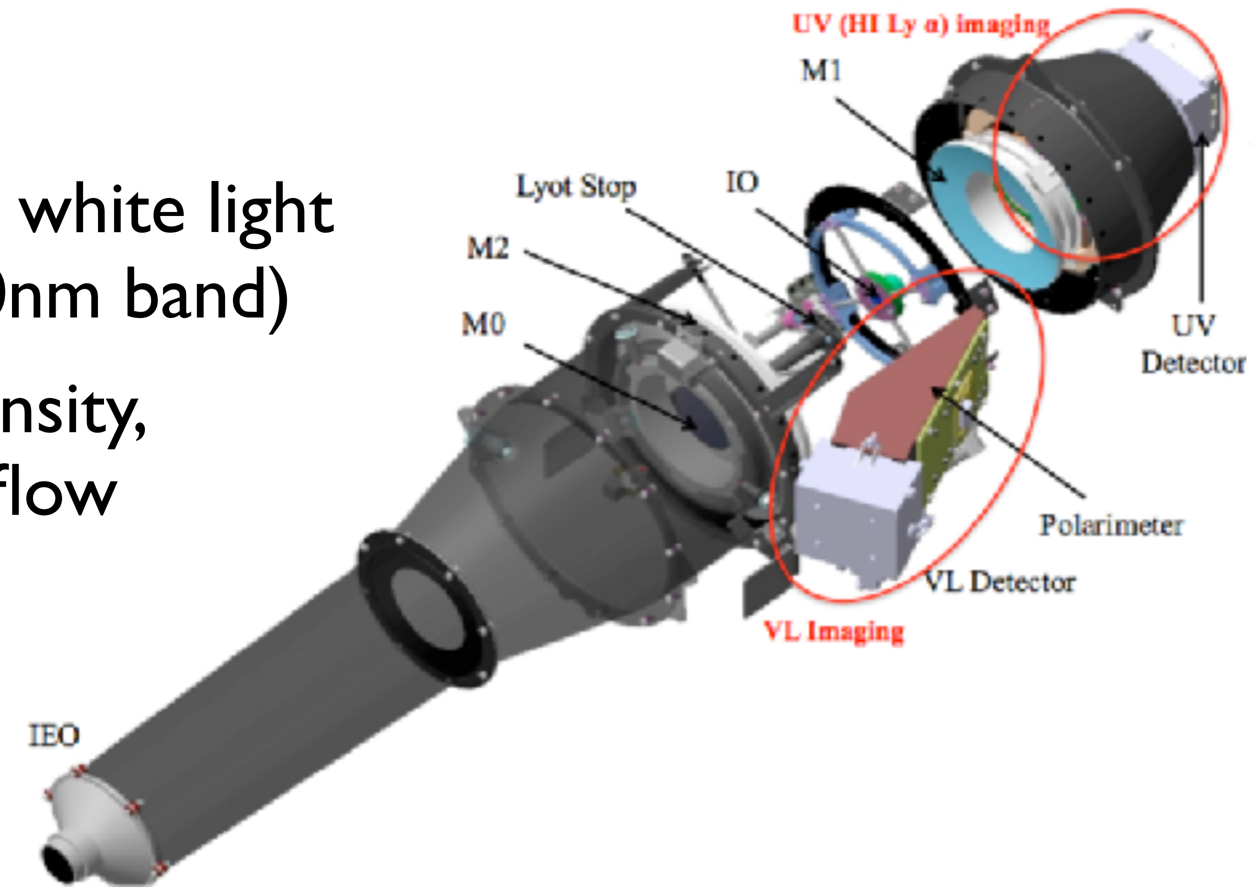


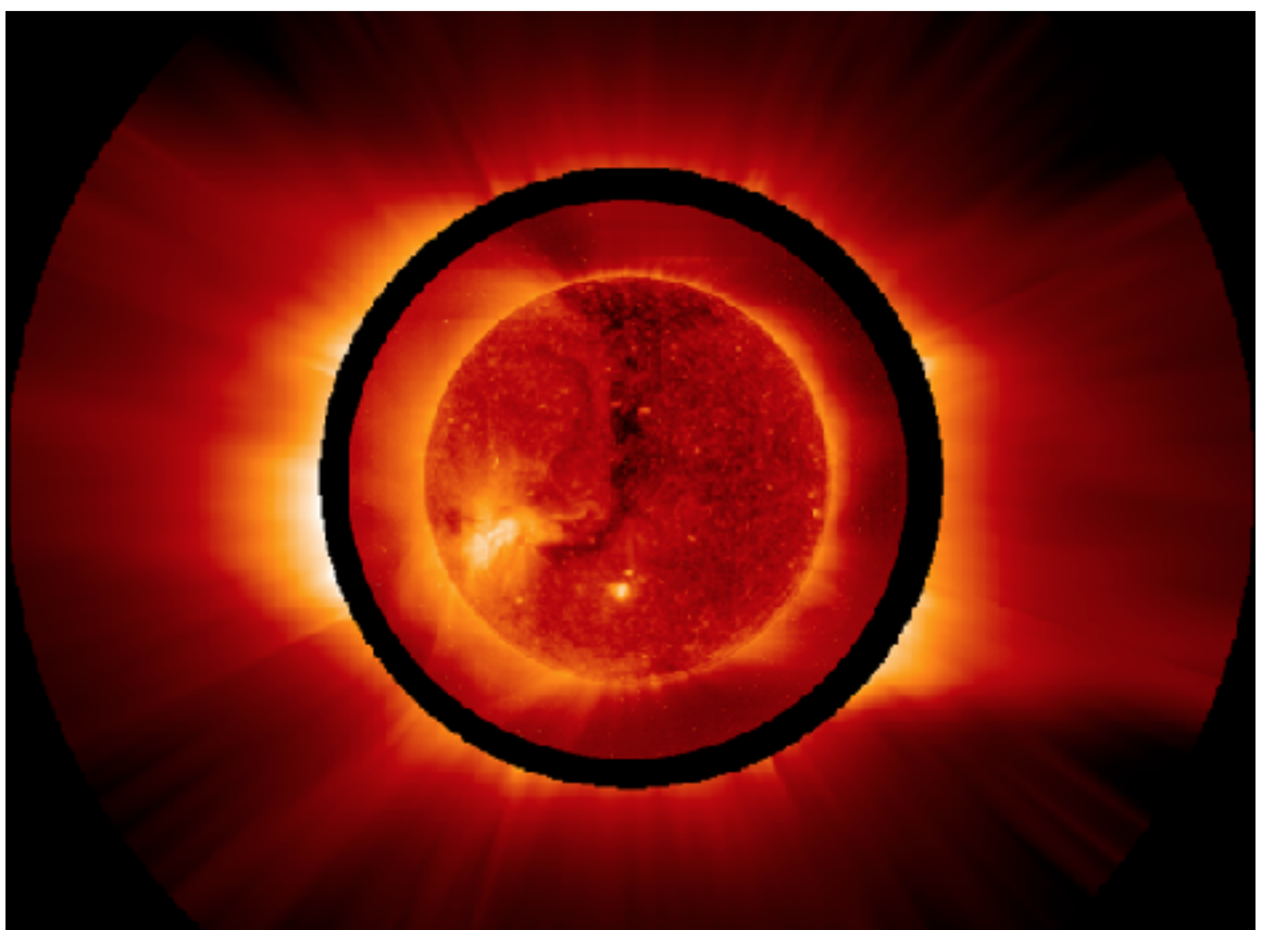


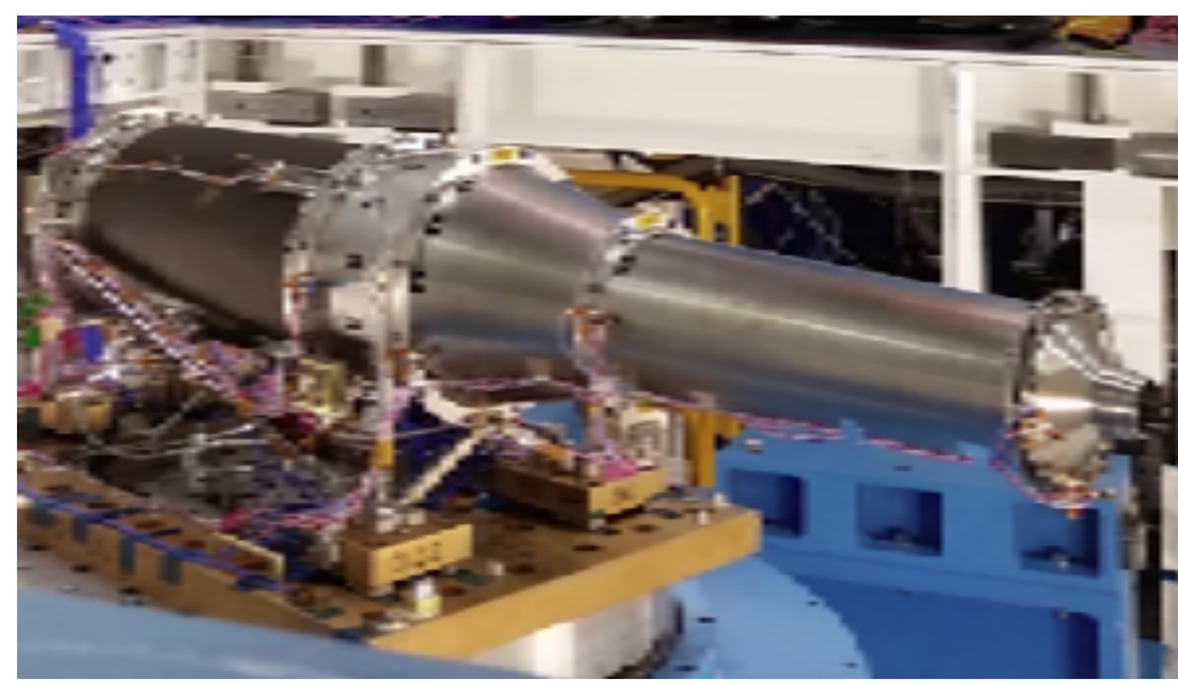
METIS Coronagraph

(PI: Marco Romoli, Univ. Florence)

- Imaging of the near-Sun corona in polarized white light (580-640 nm) and UV (H I Ly α121.6nm, 10nm band)
  - Can derive coronal maps of electron density, neutral H density, neutral H/proton outflow velocity







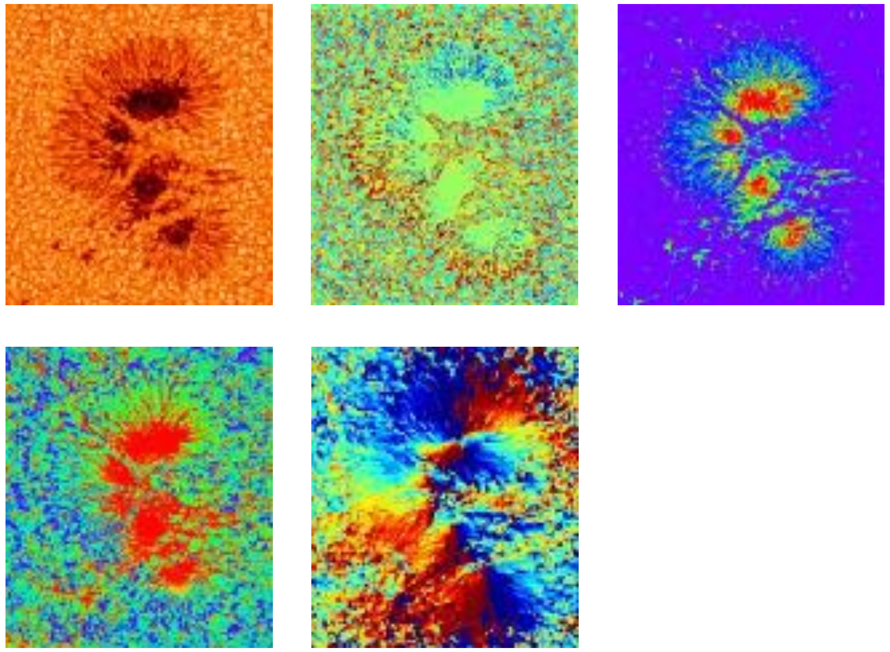
The SO/PHI Instrument *(PI: Sami Solanki, MPS)*

Optics Unit

- HRT: off-axis Ritchey-Chrétien telescope
- FDT: off-axis refractor
- Polarization Packages: Liquid-Crystals *(first ever in space)*
- Filtergraph: $LiNbO_3$ solid state etalon *(first ever in space)*
- Image stabilization: 30 Hz CT
- Focal Plane: 2k / >10fps APS detector
- AlBeMet Structure + CFRP struts

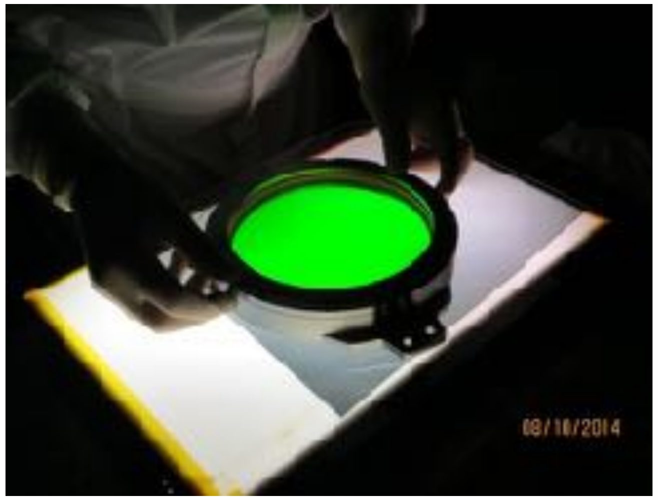
Data Products (high resolution + full disk):

- *continuum intensity, I_c*
- *LOS velocity, v_{LOS}*
- *magnetic field strength, B_{LOS}*
- *magnetic field inclination, γ*
- *magnetic field azimuth, ϕ*

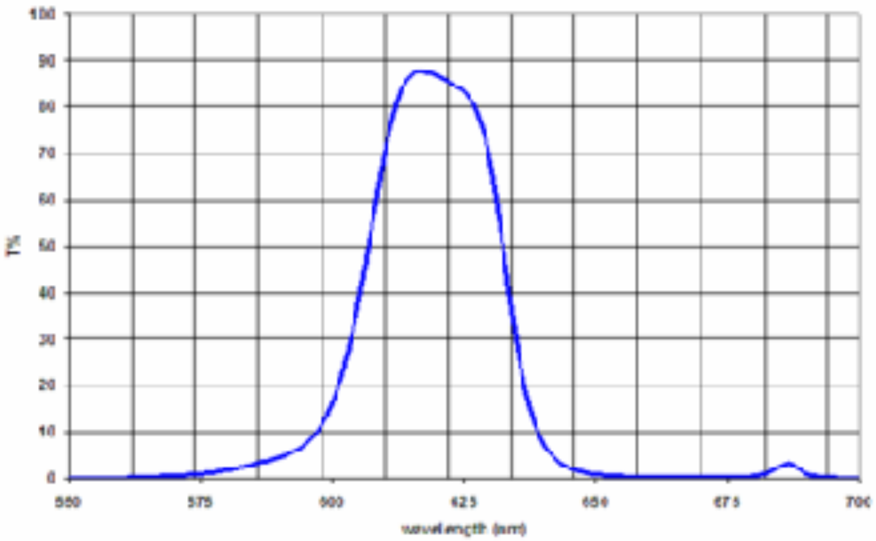


Onboard Processing:

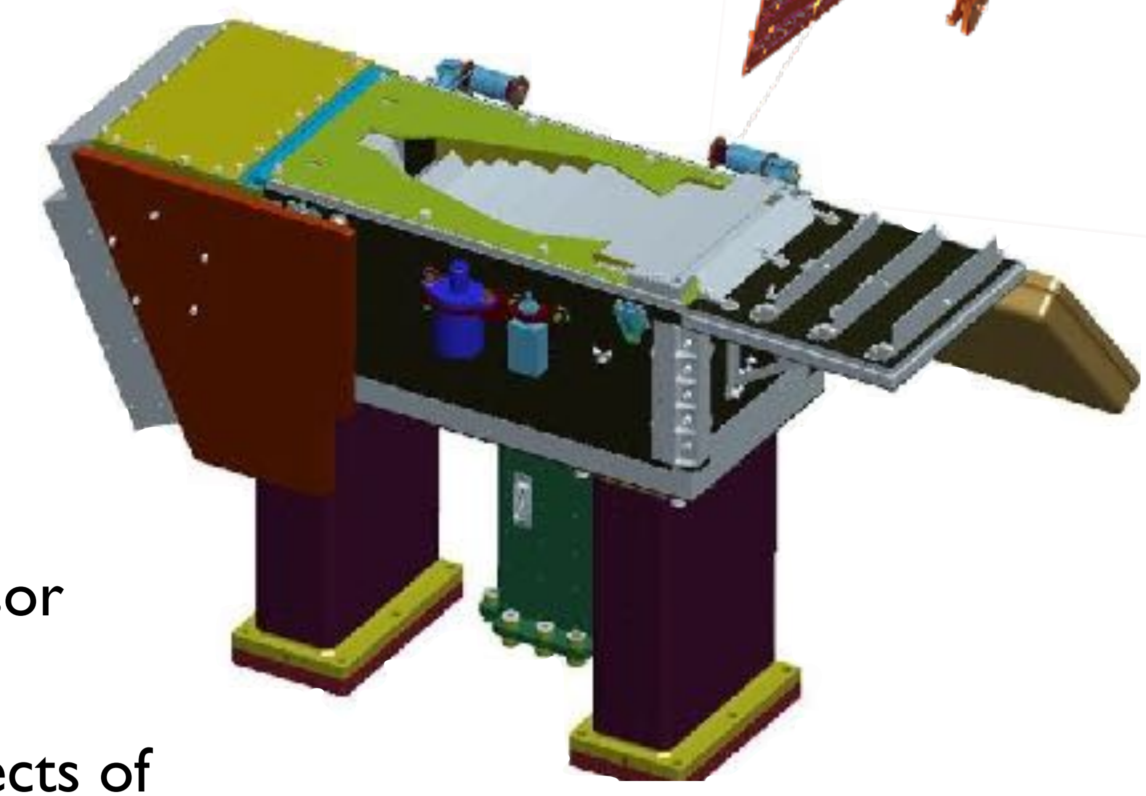
- *First ever* autonomous data calibration and scientific analysis (including inversion of the Radiative Transfer Equation) in order to comply with TM allocation
- Based on powerful reconfigurable FPGAs



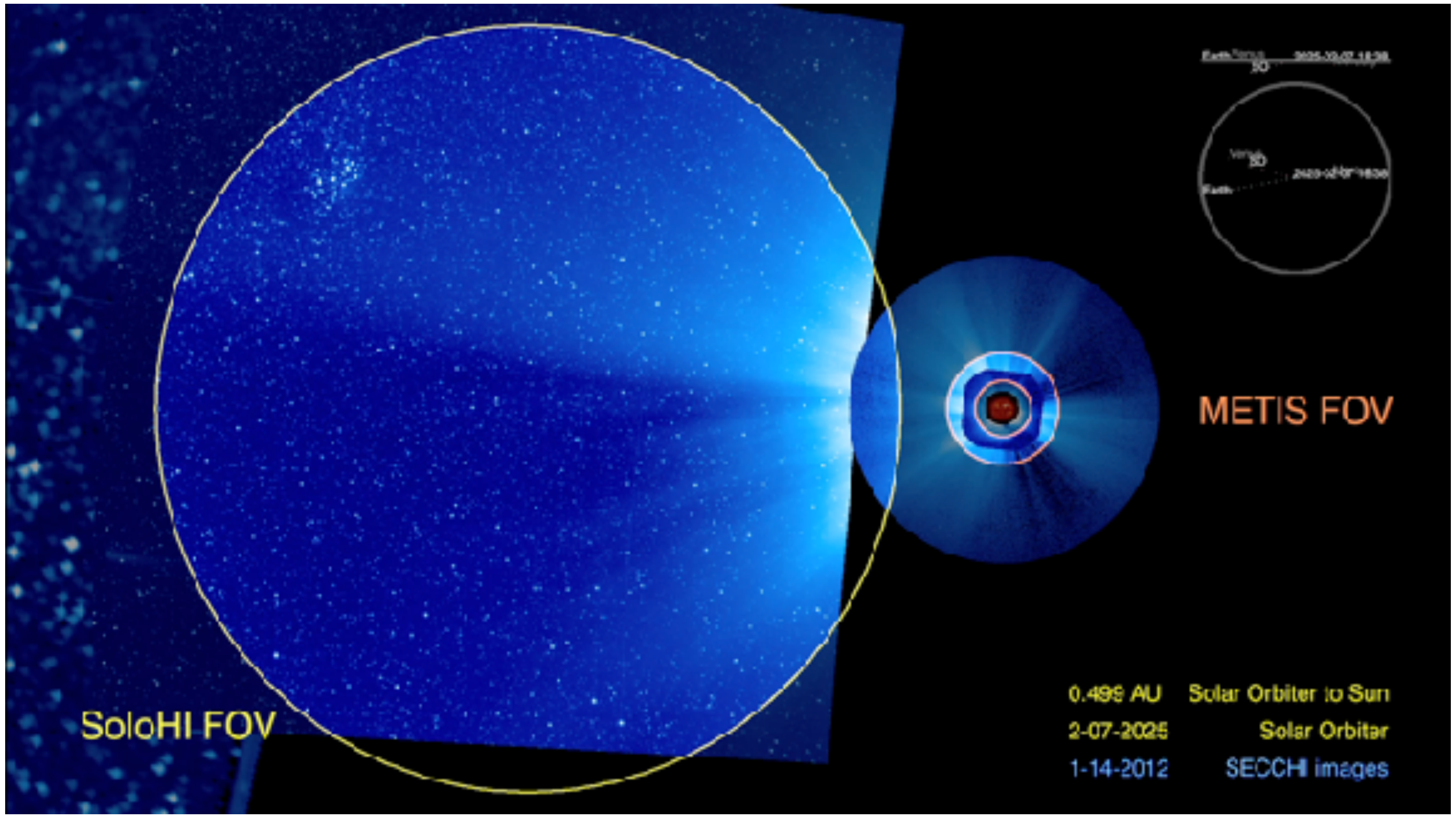
Entrance Windows



SoloHI *(PI: Russ Howard, NRL)*



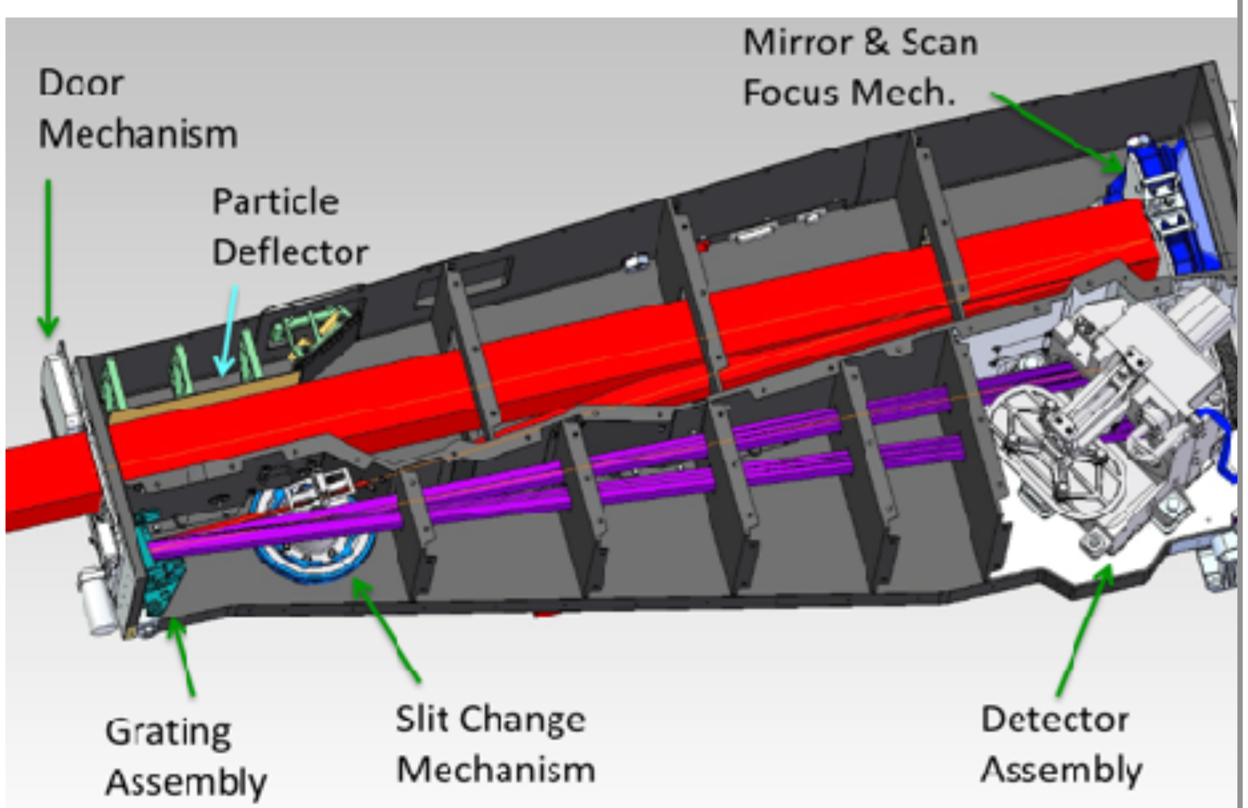
- Images the solar corona from 4 to 44° in visible light
- Uses the S/C Heat Shield Edge and instrument baffles to reduce the diffracted light from the Sun
- Reduces stray light reflected from S/C components from reaching the detector by specialized coatings and baffles
- Uses an array of 4 two-side buttable Advanced Pixel Sensor (APS) visible light detectors each of 2048 x 1920 pixels
- Cool the APS to -65°C to minimize dark current and effects of radiation damage

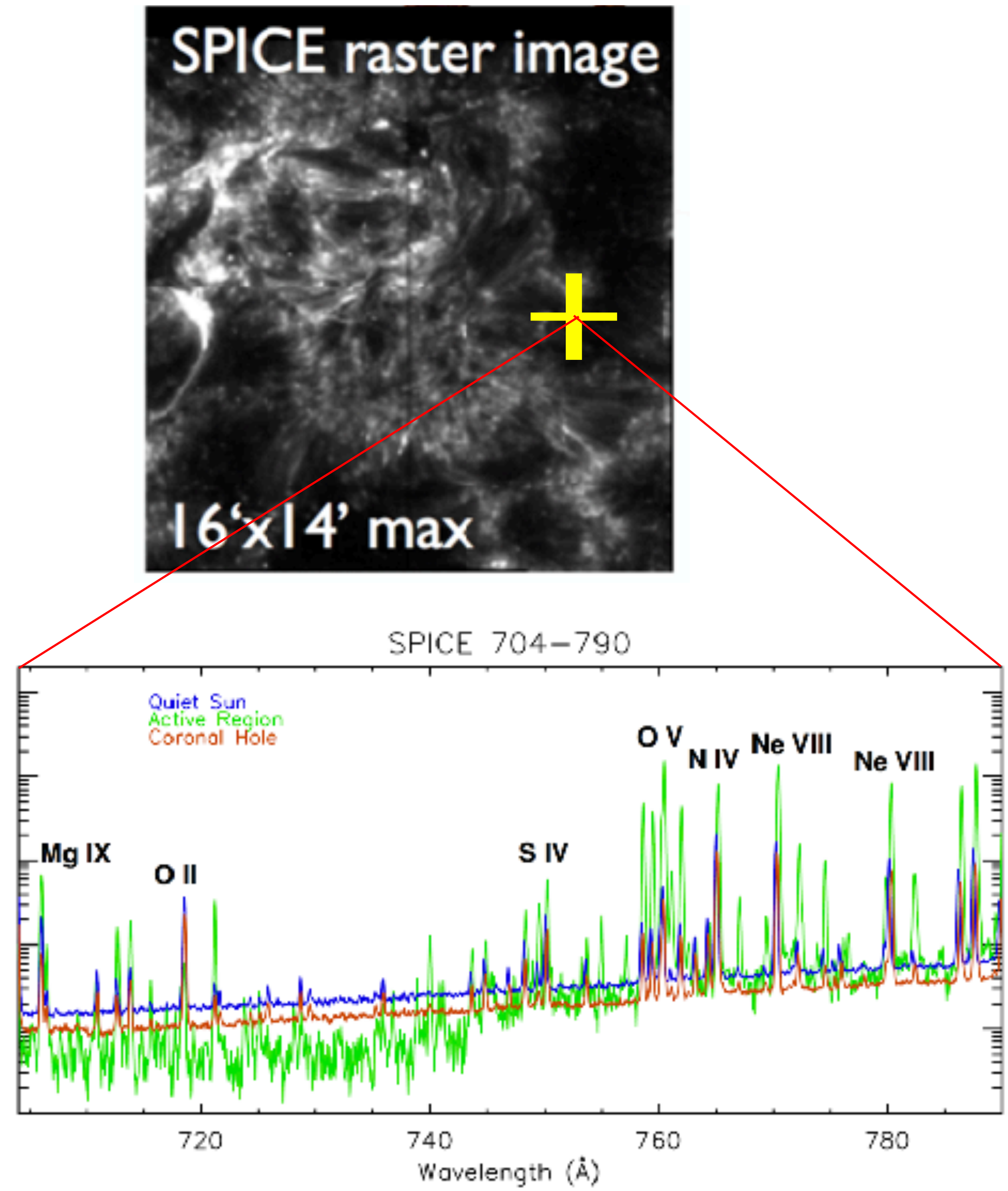


SPICE: EUV Spectrometer

ESA Facility Instrument, Consortium Lead: Andrzej Fludra (RAL Space), Operations PI: Frédéric Auchère (IAS)

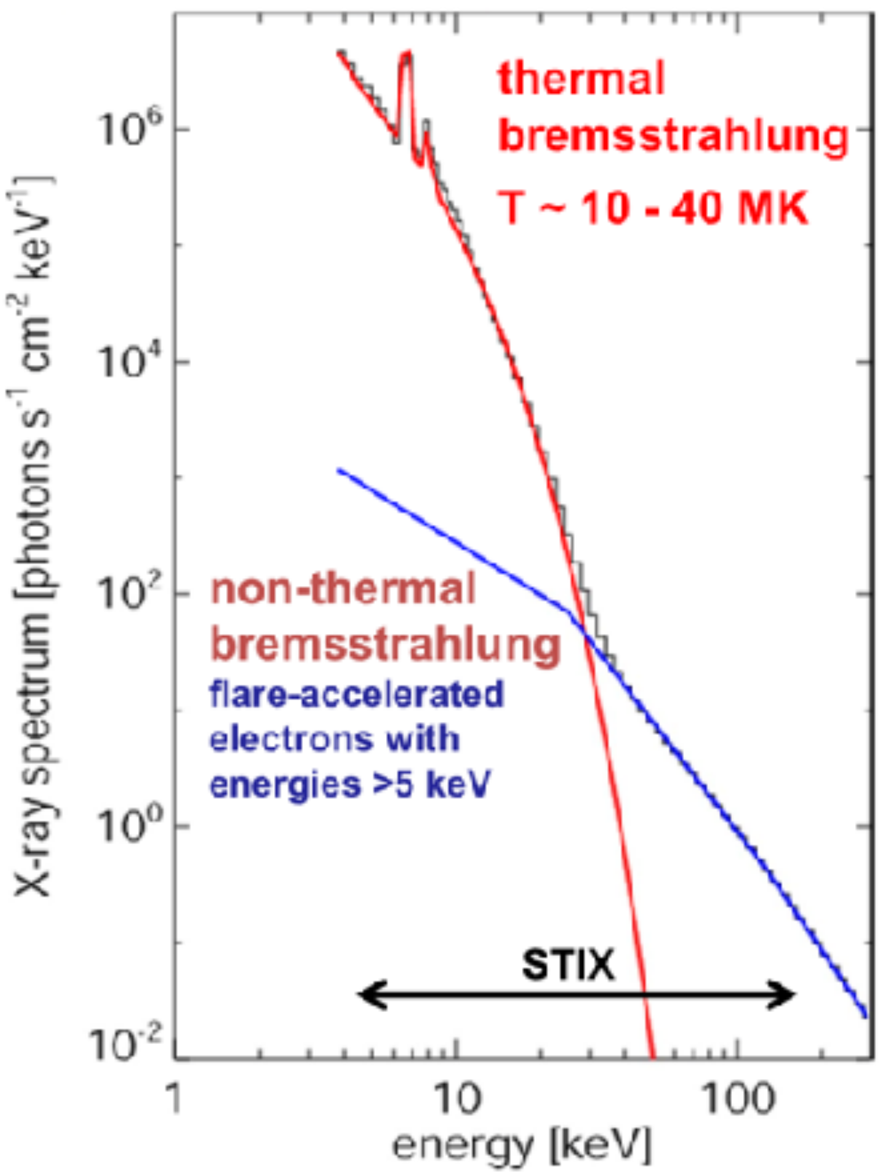
- SPICE is a high-resolution imaging sp
- It will record EUV spectra and spect EUV bands: 70−79 nm and 97−105 n
  - 50 spectral lines, excellent plasma
  - Selection of lines covering temper corona ($2\times10^4 - 10^7$ K)



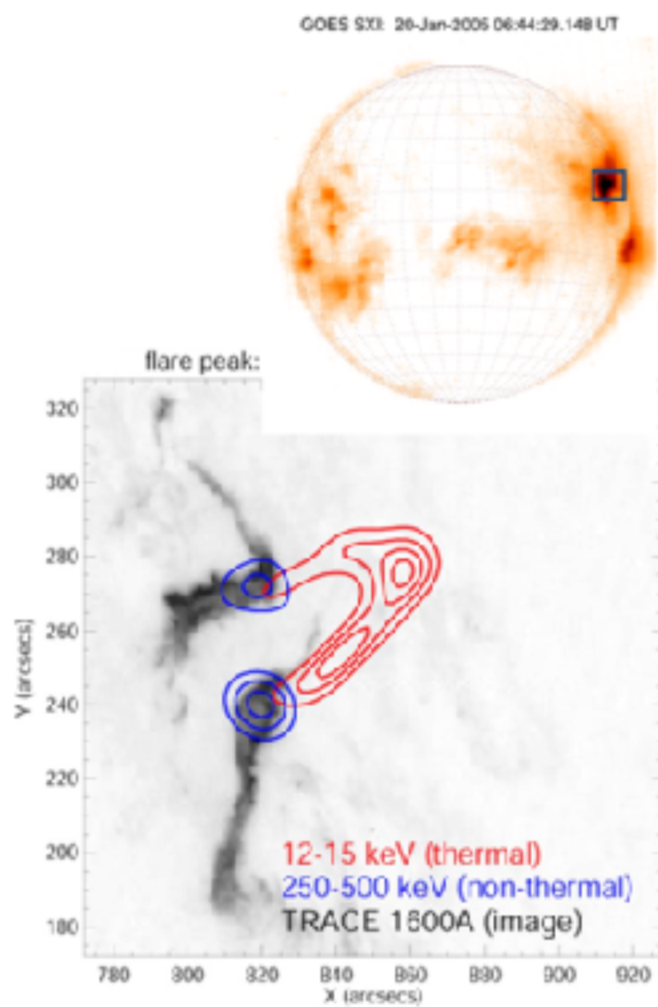


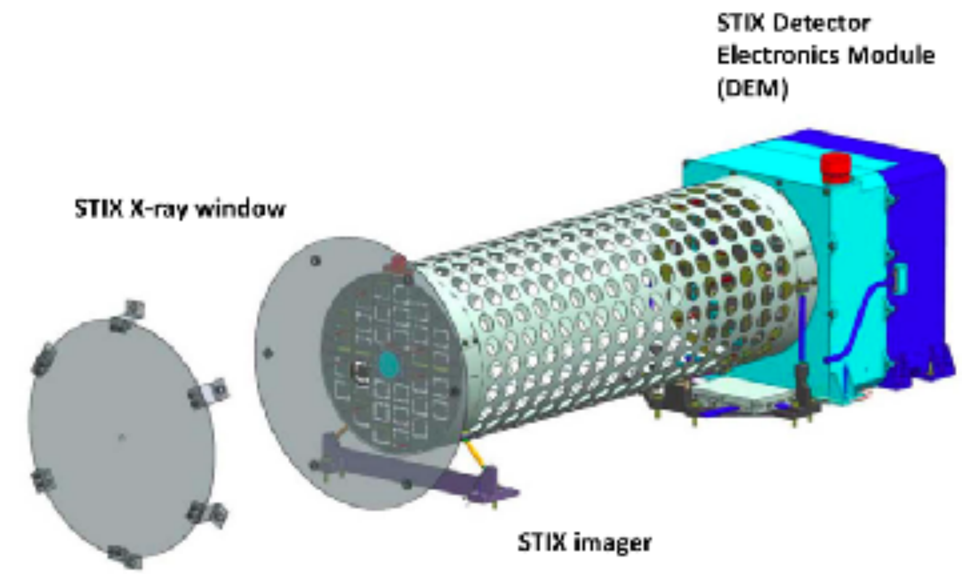
STIX: Spectrometer/Telescope for Imaging X-rays

(PI: Säm Krucker, FHNW & SSL Berkeley)



Imaging & Spectroscopy
Typical observations of a solar eruption





Instrument performance

Energy range: 4−150 keV
Energy resolution: 1 keV at 5 keV
15 keV at 150 keV
Finest angular resolution: 7 arcsec
Field of view: 2°
Image placement accuracy: 4 arcsec
Time resolution (statistics limited): ≥0.1 s

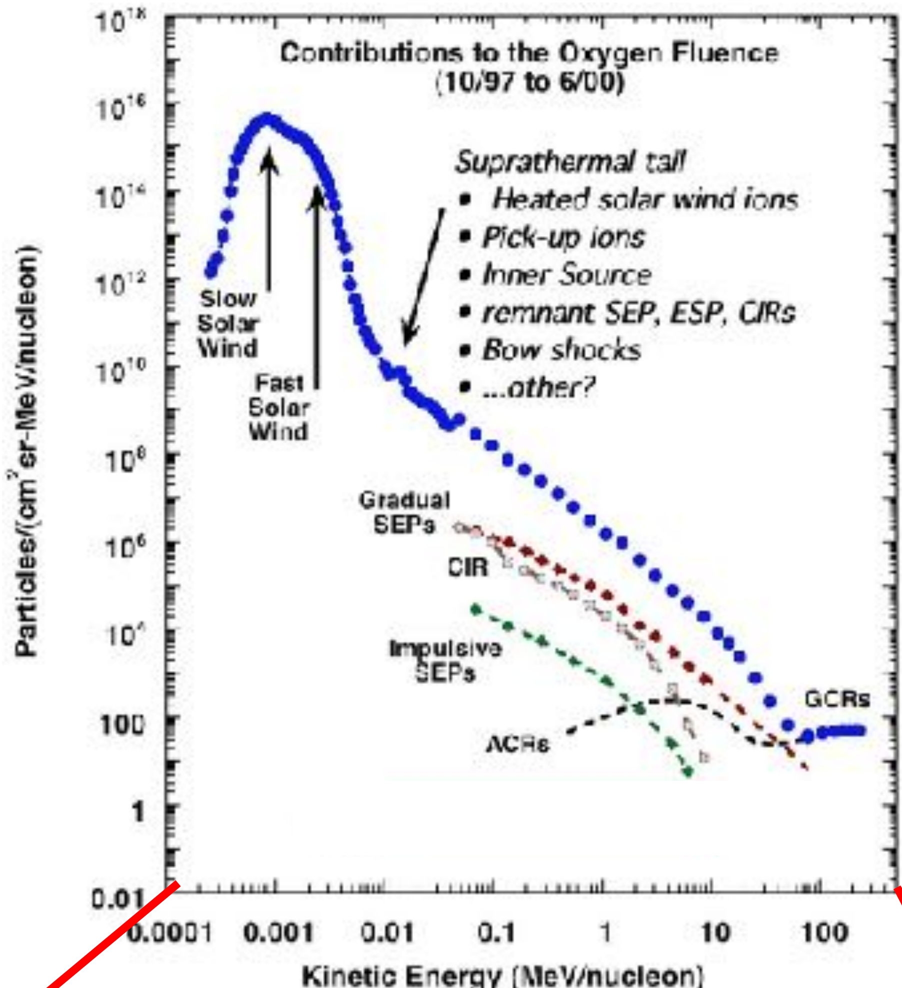
In-Situ Instruments

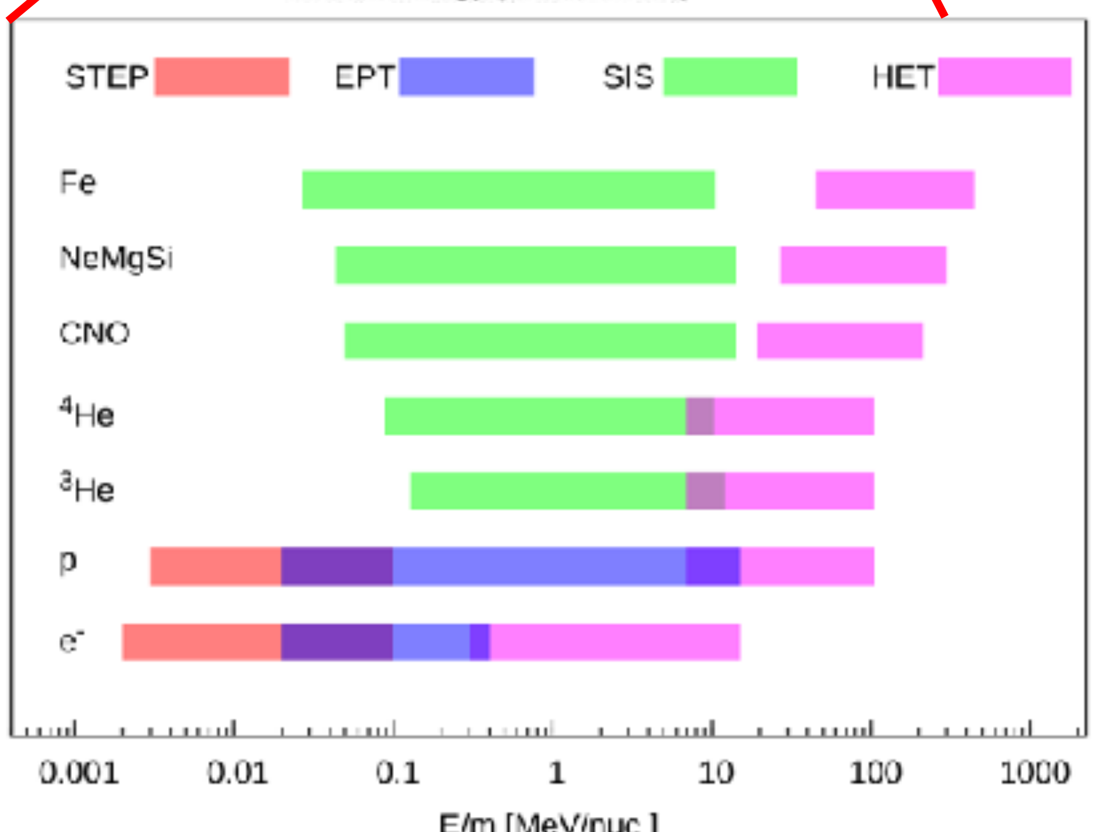
EPD	Energetic Particle Detector	J. Rodríguez-Pacheco	Composition, timing and distribution functions of energetic particles
MAG	Magnetometer	T. Horbury	High-precision measurements of the heliospheric magnetic field
RPW	Radio & Plasma Waves	M. Maksimovic	Electromagnetic and electrostatic waves, magnetic and electric fields at high time resolution
SWA	Solar Wind Analyser	C. Owen	Sampling protons, electrons and heavy ions in the solar wind

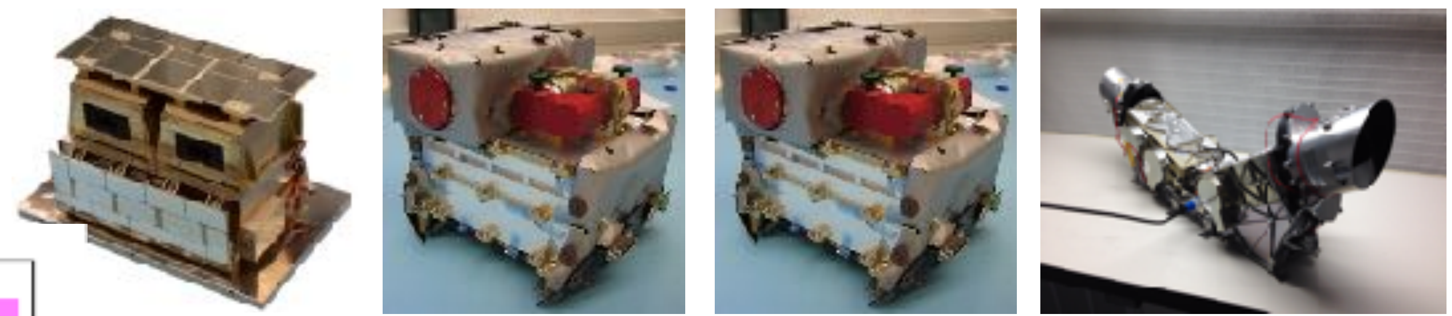
EPD: Energetic Particles Detector

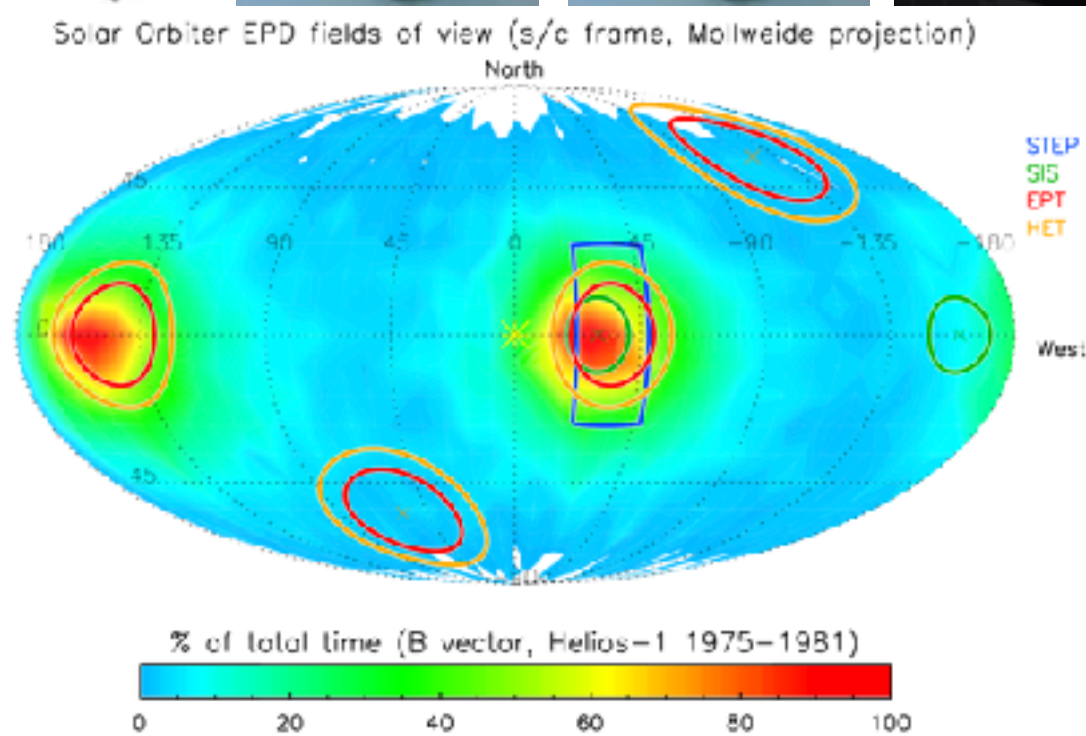
PI: Javier Pacheco (U. Alcalá), Co-PI: Robert Wimmer-Schweingruber (U. Kiel)

EPD measures charged particles in a wide energy range using a combination of four sensors: STEP, EPT, SIS, HET



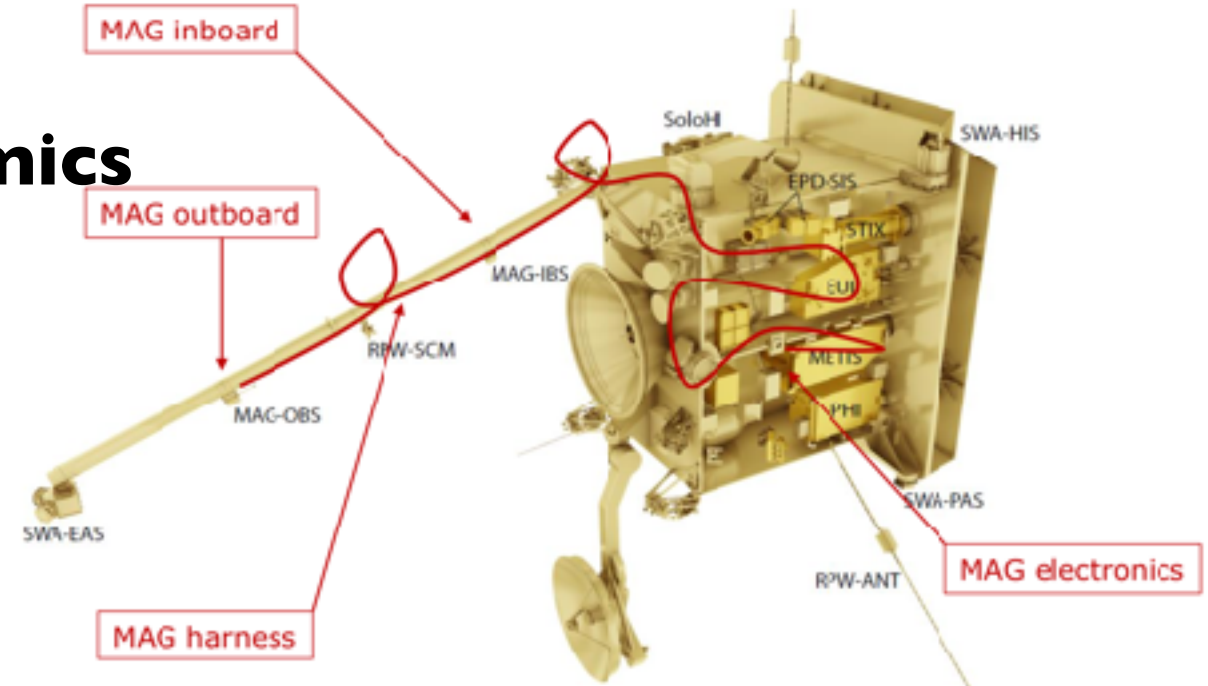




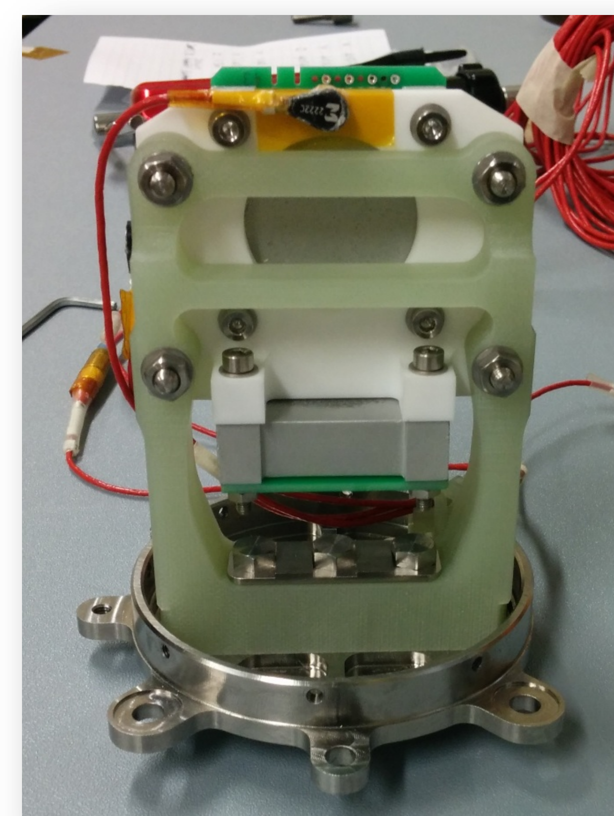


MAG: Measuring the heliospheric magnetic field

PI: Tim Horbury (Imperial College)



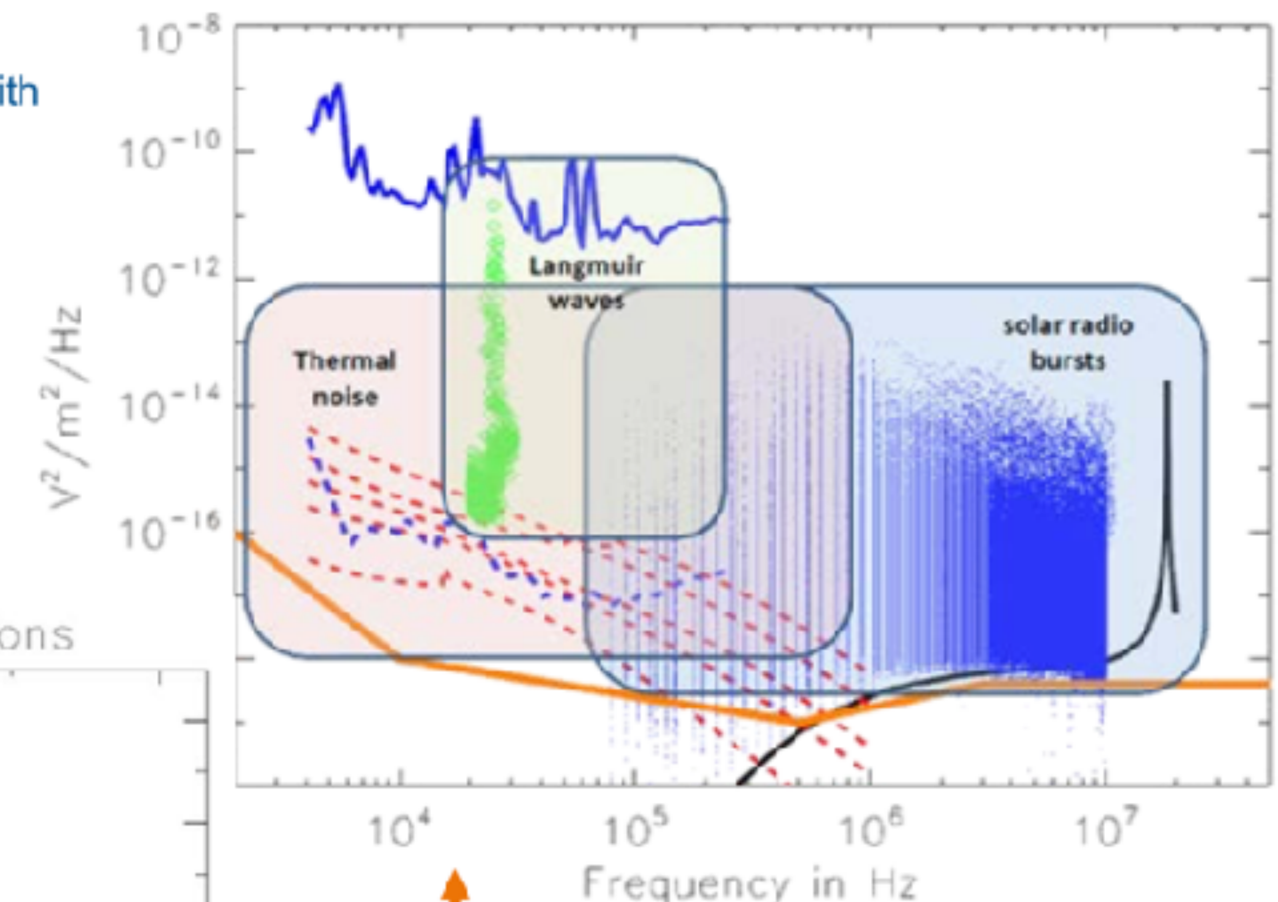
- **Magnetic field is key to plasma dynamics**
  - Orders all particle motion
  - Field-particle interactions heat the plasma
- **Magnetic connectivity**
  - Connecting remote and local observations
- **MAG will provide:**
  - High-precision measurements to study waves, turbulence, shocks
  - Local field direction to particle instruments
  - Derived products, e.g. moments
  - Science modes:
    - 16 vectors/s most of the time
    - Burst mode: 128 vectors/s, ~ 1 hour/day
    - Internal and inter-instrument triggering



RPW: Radio and Plasma Waves

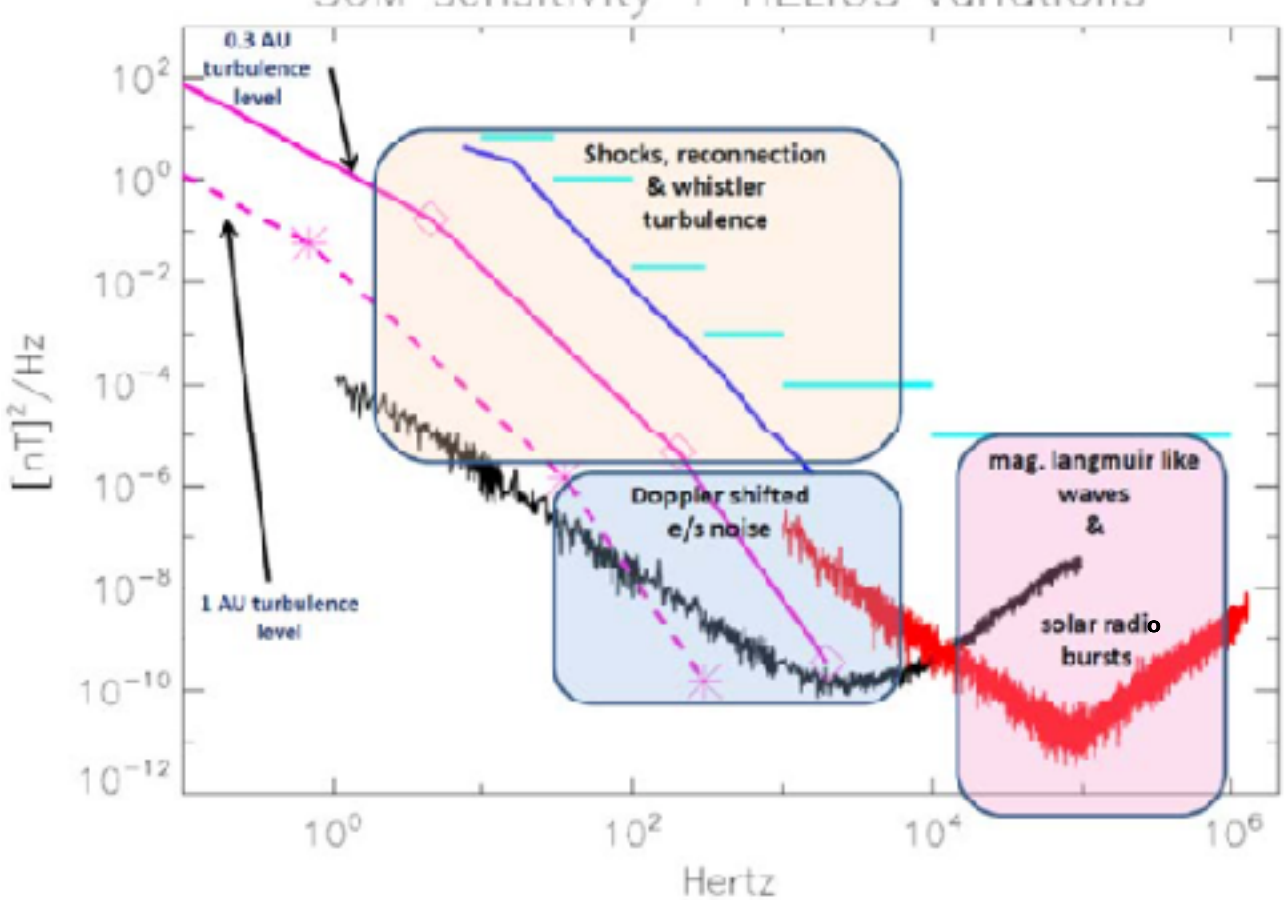
PI: Milan Maksimovic (Observatoire de Paris - Meudon)

- Solar & Interplanetary Radio Burst
- Electron density & temperature measurements with the Quasi-Thermal Noise spectroscopy
- Radio emission processes from electron beams: Langmuir waves and electromagnetic mode conversion
- Solar wind microphysics and turbulence
- Shocks, Reconnection, Current Sheets, and Magnetic Holes
- Interplanetary Dust



Electric Sensitivity of the RPW Sensors

SCM sensitivity + HELIOS variations

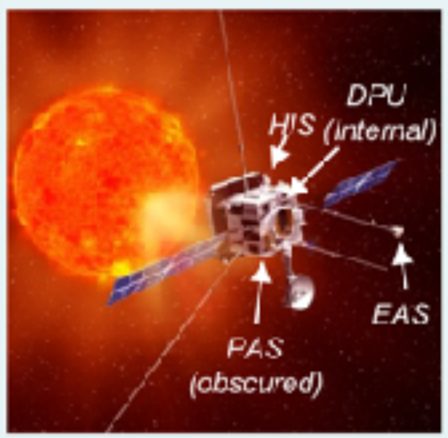
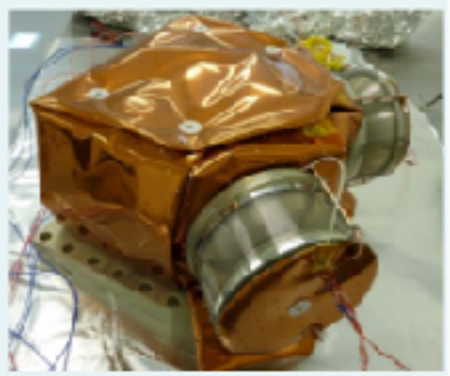
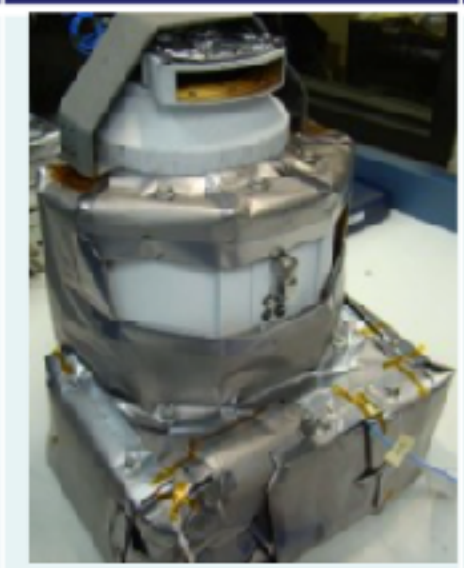


Magnetic Sensitivity of the RPW Sensors

RPW cnes

SWA: Solar Wind Analyser

PI: Christopher Owen (MSSL)

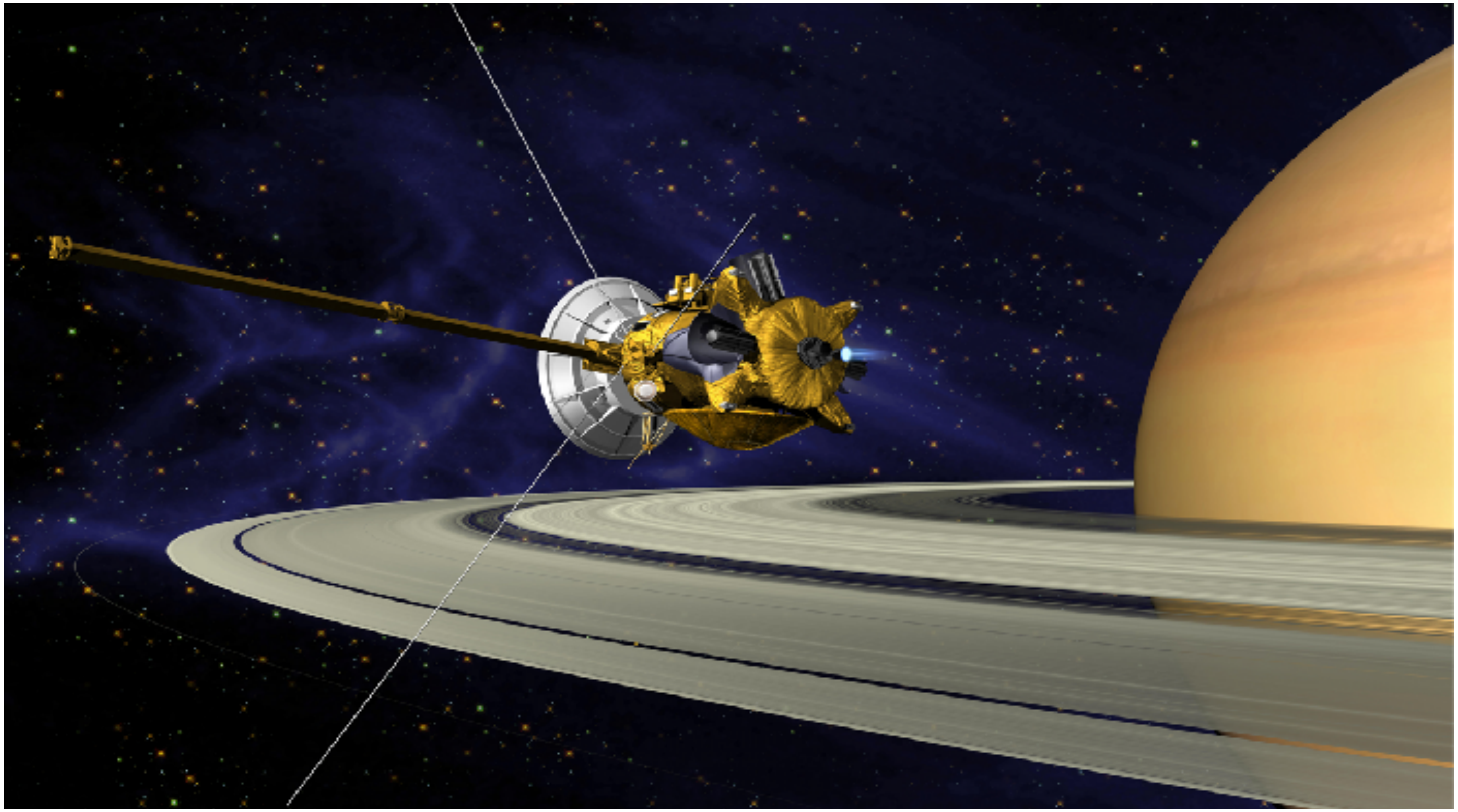
Subsystem	Electron Analyser system (EAS)	Heavy Ion sensor (HIS)	Proton and Alpha sensor (PAS)	Data Processing Unit (DPU)
				
Species	Electrons	Heavy Ions	Protons and Alpha Particles	-
Measurement	High temporal resolution determination of the core, halo and strahl **electron** velocity distributions (1 eV < E < 5 keV) and their moments	Major charge states of C, O and Fe; 3-D velocity distributions of prominent heavy solar wind ions, suprathermal ions, and pick-up ions of various origins, such as weakly-ionized species (He^+, O^+)	The velocity distribution of **protons and alpha particles** (0.2 < E < 20 keV/q) at high time resolution equivalent to the ambient proton cyclotron period.	Provide SWA suite control, commanding and data handling functions.

What Solar Orbiter isn't

- SDO at 0.3 AU
- SoHO at 0.3 AU
- Hinode at 0.3 AU
- STEREO at 0.3 AU
- ACE at 0.3 AU
- Cluster at 0.3 AU

(sorry)

What Solar Orbiter (almost) is



Less like past solar missions, more like a planetary one!

- **Limited observation time**
  - RS instruments nominally operate for 3x10 days per orbit of 150-180 days.
- **Constrained & variable downlink**
  - Data downlink depends on S/C distance to Earth, i.e. varies by > factor 20.
  - Periods of best downlink often not close to periods of most exciting observations
  - On-board storage is limited.
- **Offline Commanding**
  - Limited opportunities to respond to a changing target (like the Sun…)
- **Lots of scientific objectives that need coordinated observations, at specific opportunities**

And we need models!

- Solar Orbiter relies on *remotely* measuring the source region of the solar wind that is then measured *in situ*.
- This is difficult and requires good models of magnetic field configuration that can be run quickly to inform our pointing.
  - **Robust, stable** operational models – not necessarily the most complex/sophisticated scientific models.
- Modelling and Data Analysis Working Group (MADAWG), chaired by Alexis Rouillard (IRAP, Toulouse), looks into what is needed and is coordinating some developments.

Synergy between Solar Orbiter and other Observatories

Solar Orbiter:

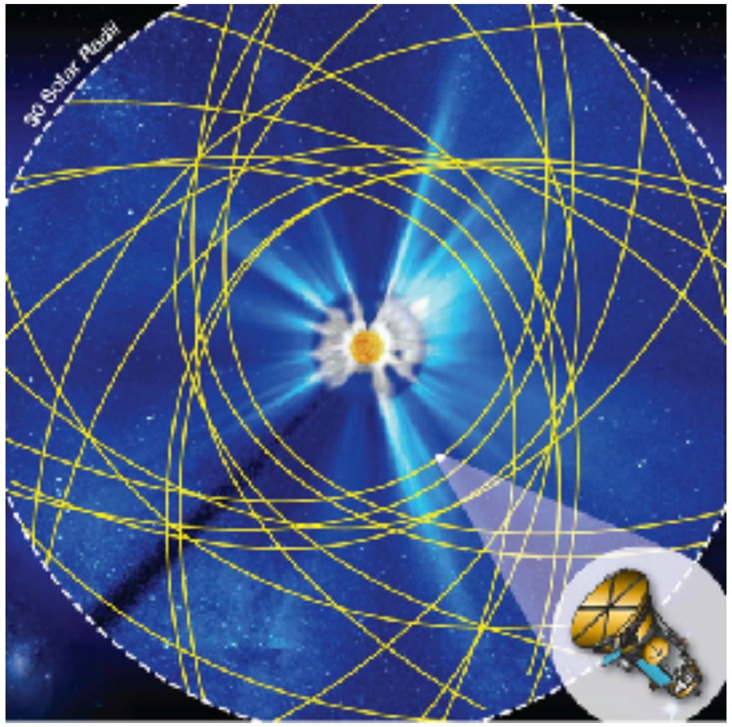
+ unique orbit (close-in and out of the ecliptic)
+ comprehensive payload suite
− limited telemetry (deep space mission!)

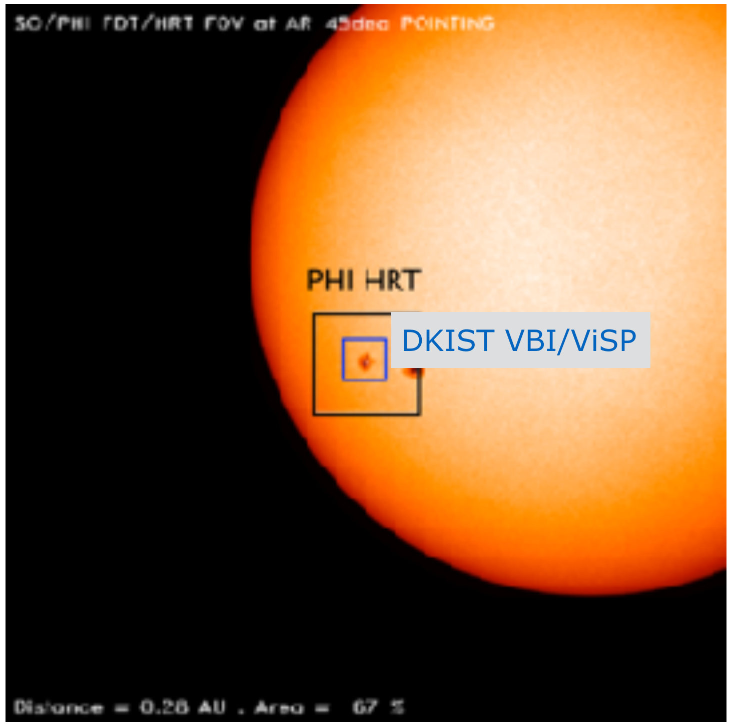
Parker Solar Probe:

+ unique orbit (closest perihelion ≲10 R_{Sun} !)
− limited telemetry and payload mass, mostly in-situ instrumentation

Near-Earth assets (SDO, DKIST, PROBA-3):

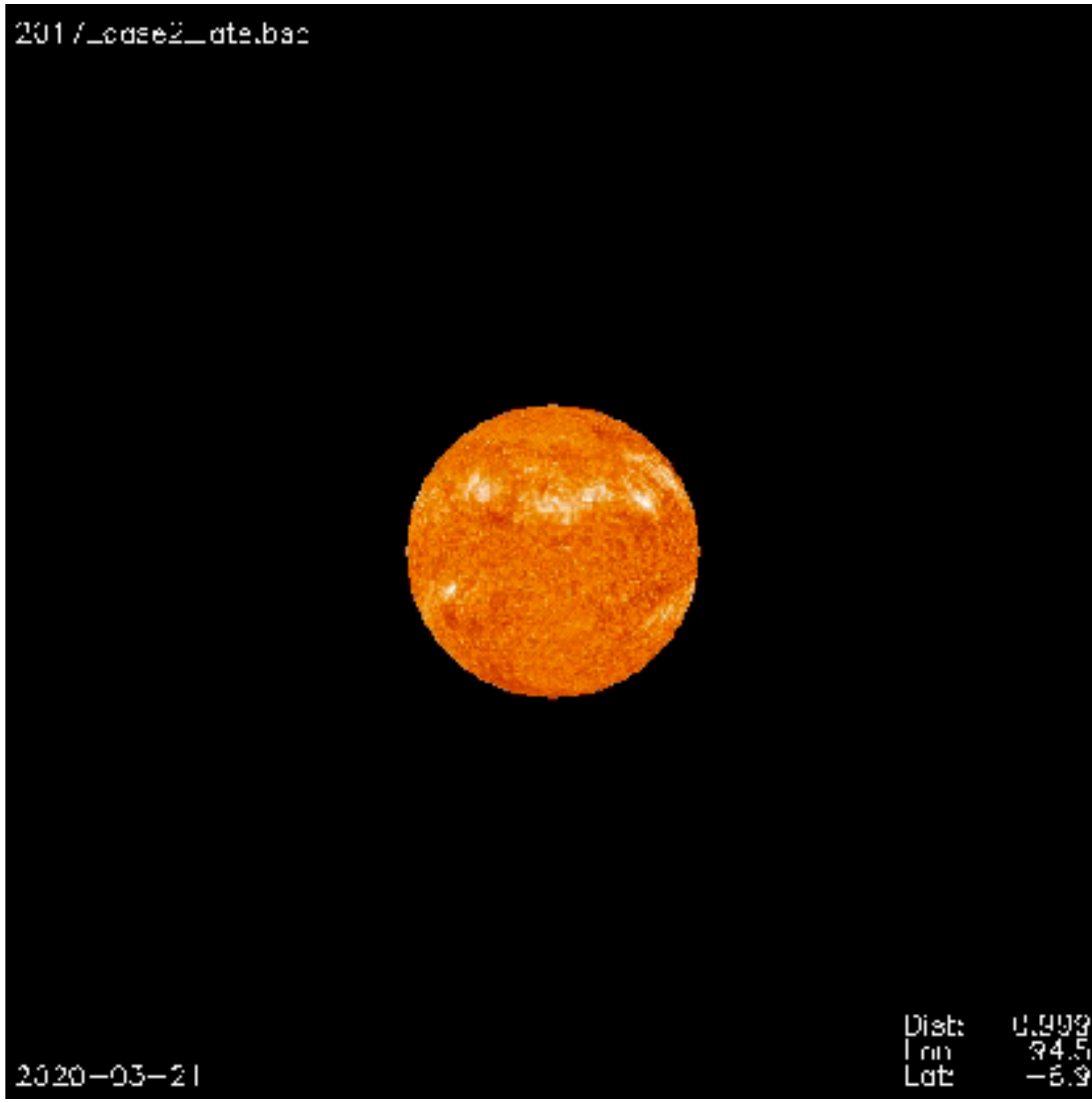
+ much higher data return
− limited to Sun-Earth line





Summary

- Solar Orbiter will provide unique up-close and out-of-ecliptic views of the Sun.
- Solar Orbiter will perform
  - In-situ measurements of the solar wind plasma, fields, waves and energetic particles as close as 0.28 AU from the Sun
  - Simultaneous high-resolution imaging and spectroscopic observations of the Sun in and out of the ecliptic plane (up to ~33°).
- The combination of in-situ and remote-sensing instruments, together with the new, inner-heliospheric perspective, distinguishes Solar Orbiter from all previous and current missions, enabling new science which can be achieved in no other way.
- Solar Orbiter has unique synergies with NASA's Parker Solar Probe, DKIST and other new observatories.



Courtesy W. Thompson (GSFC)

esa

→ ESA SPACE-SCIENCE FELLOWSHIP PROGRAMME

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Applications due: 1 October 2018

https://www.cosmos.esa.int/web/science-faculty/research-fellowship

The ESA Postdoctoral Research Fellowship Programme is aimed at providing scientists in the early stages of their career, holding a PhD or the equivalent degree, with the means to perform research in space science. The programme is open to suitably qualified applicants from ESA member states who have completed their PhD (or equivalent) or will have completed it by the start of the fellowship (Autumn 2019). Preference will be given to applications submitted by candidates within five years of receiving their PhD and nationals from under-represented states at ESA.

About 8 positions shall be offered in this call, shared between two ESA centres: ESAC (Spain) and ESTEC (Netherlands). Appointments are for two years, with a possible third year extension.