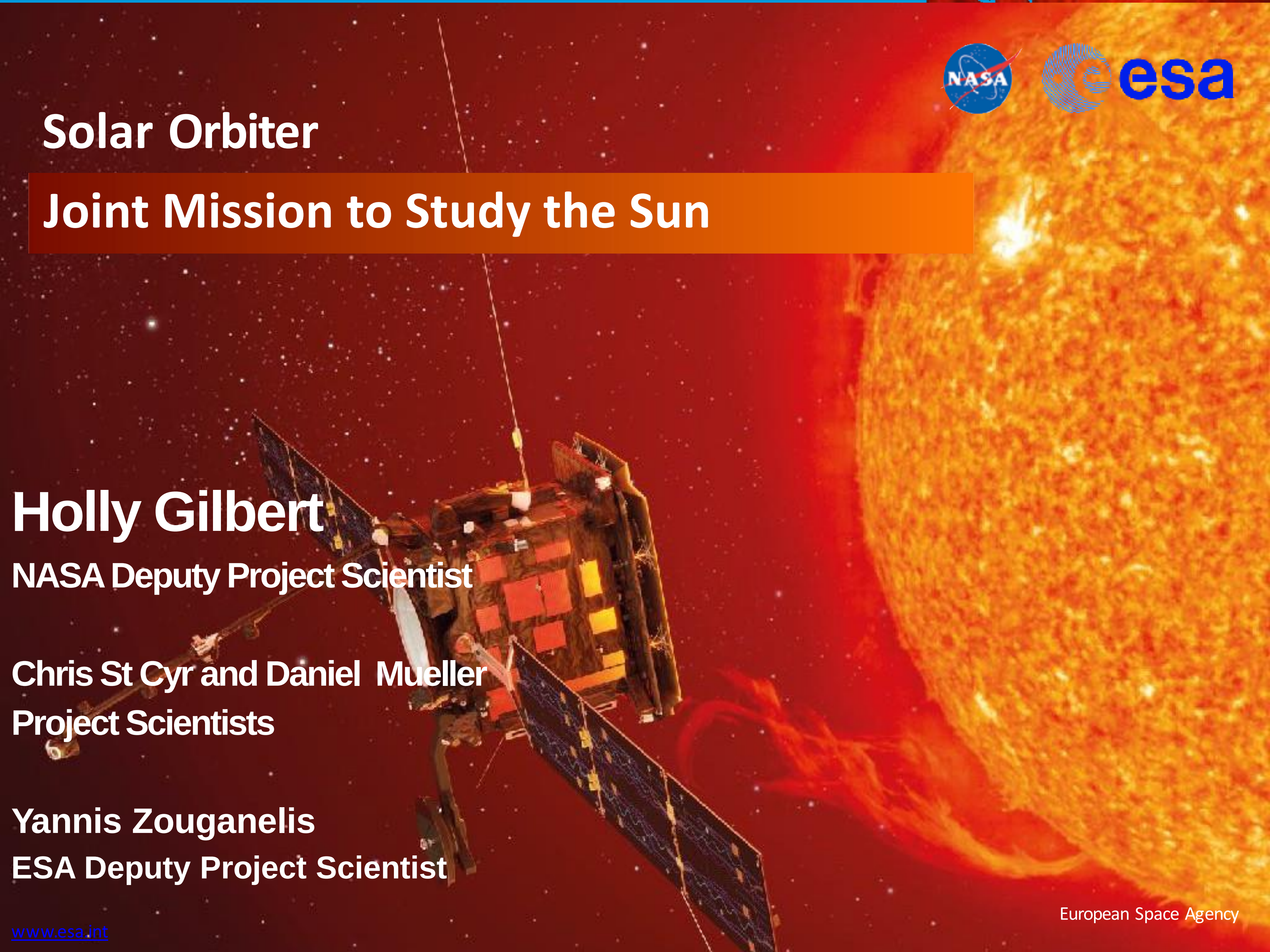


Solar Orbiter

Joint Mission to Study the Sun

Holly Gilbert
NASA Deputy Project Scientist

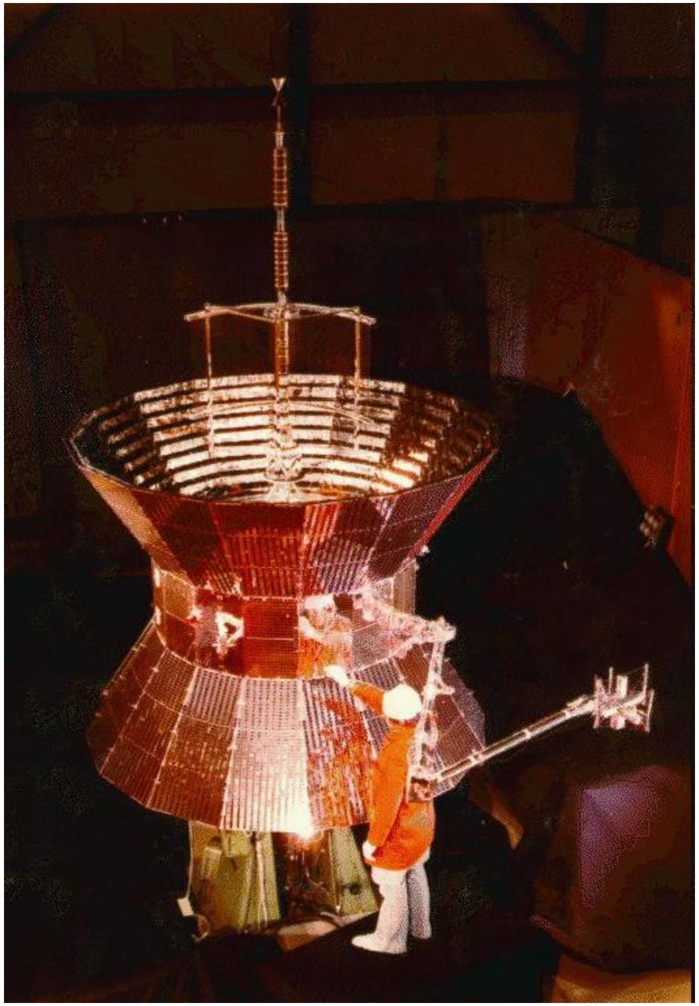
Chris St Cyr and Daniel Mueller
Project Scientists

Yannis Zouganelis
ESA Deputy Project Scientist

Helios

The *Only* Space Physics Mission to the Inner Solar System

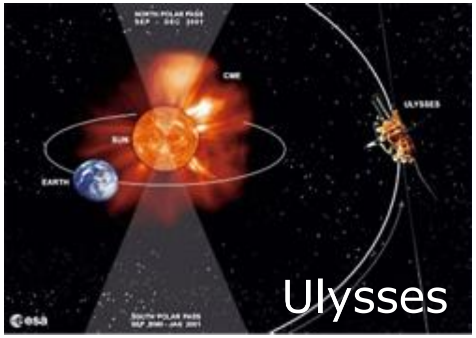
- Helios 1 and Helios 2 were a pair of deep space probes developed by the Federal Republic of Germany (FRG) in a cooperative program with NASA.
- PURPOSE: make pioneering measurements of the interplanetary medium from the vicinity of the earth's orbit to 0.3 AU.
- Experiments were provided by scientists from both FRG and the U.S. NASA supplied the Titan/Centaur launch vehicle.
- Payload: fluxgate magnetometer; electric and magnetic wave experiments (frequency range 6 Hz to 3 MHz); charged-particle experiments, which covered various energy ranges starting with solar wind thermal energies and extending to 1 GeV; a zodiacal-light experiment; and a micrometeoroid experiment.

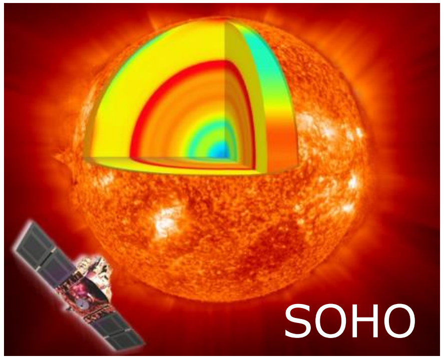


Solar Orbiter
Exploring the Sun-Heliosphere Connection

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?

Solar Orbiter
Exploring the Sun-Heliosphere Connection

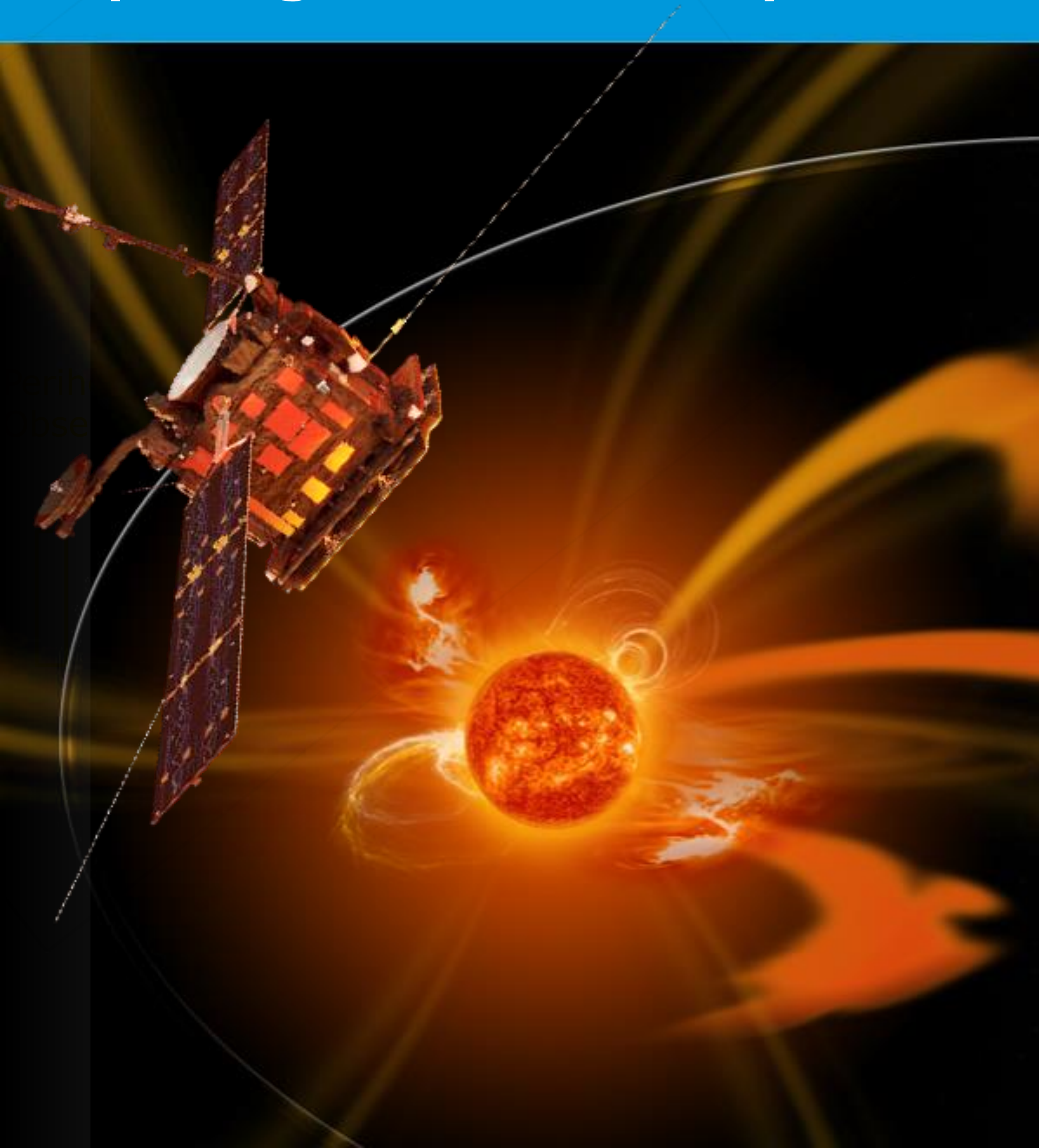
Science Objectives

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

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



Mission Summary

Launch: February 2019 (back-up Feb ’20)

Cruise Phase: 2-3 years

Nominal Mission: 4-5 years

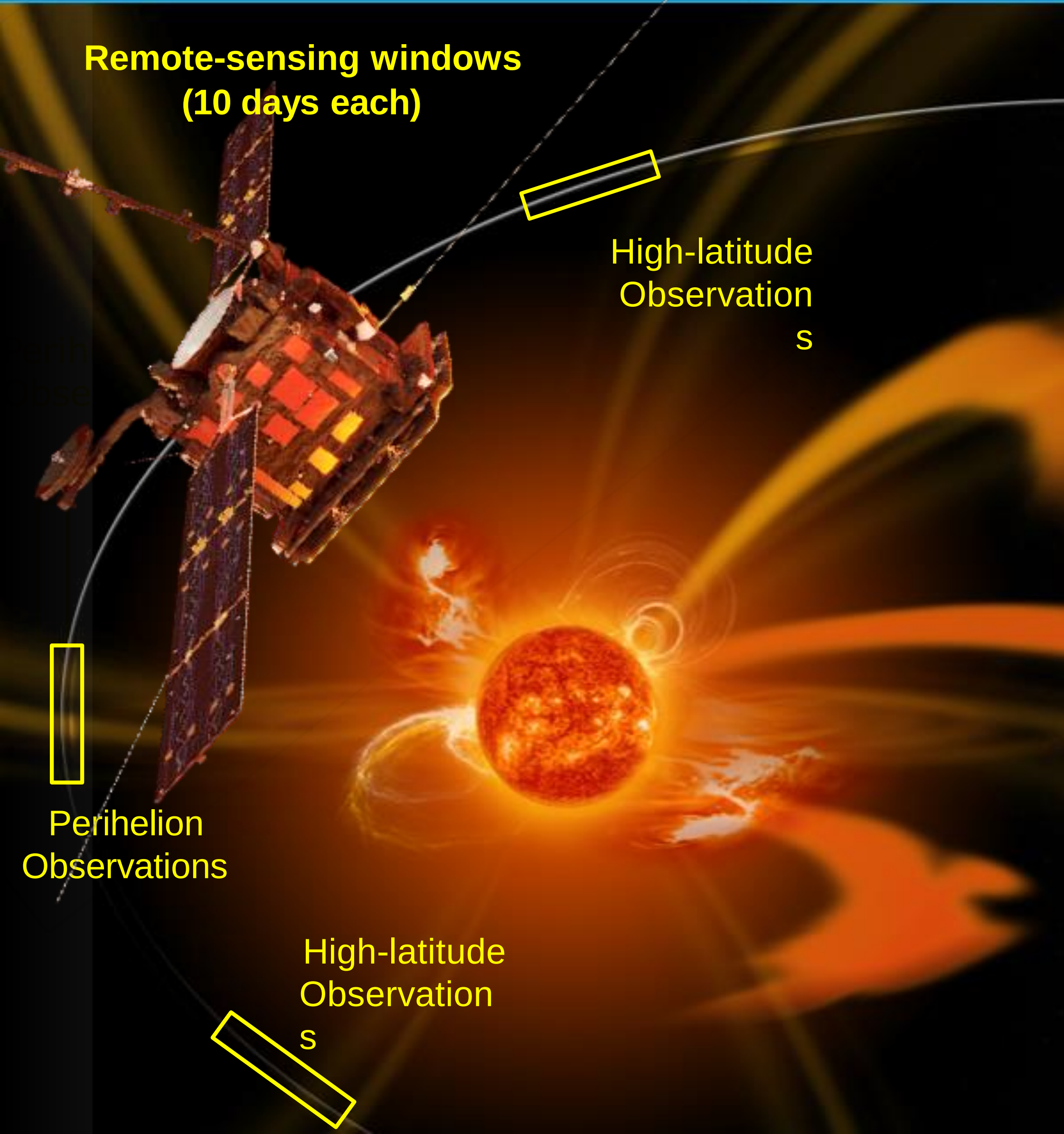
Extended Mission: 2.5-3.5 years

Orbit: 0.28–0.95 (1.2) AU (P=150-200 days)

Out-of-Ecliptic View:
Multiple gravity assists with Venus to increase inclination out of the ecliptic to >12° (24°) (nominal mission),
>29° (32°) (extended mission)

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

Solar Orbiter
Exploring the Sun-Heliosphere Connection



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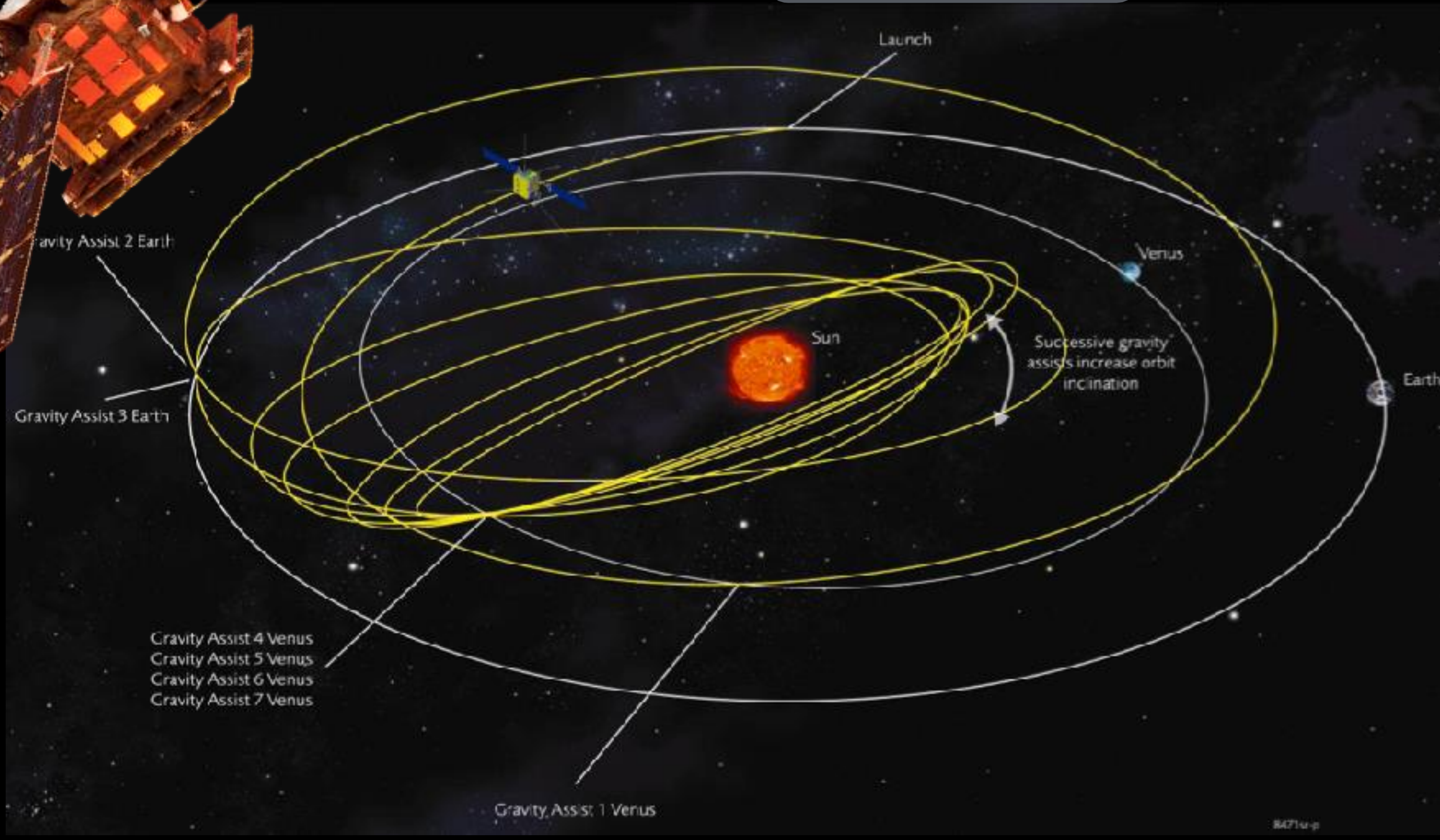
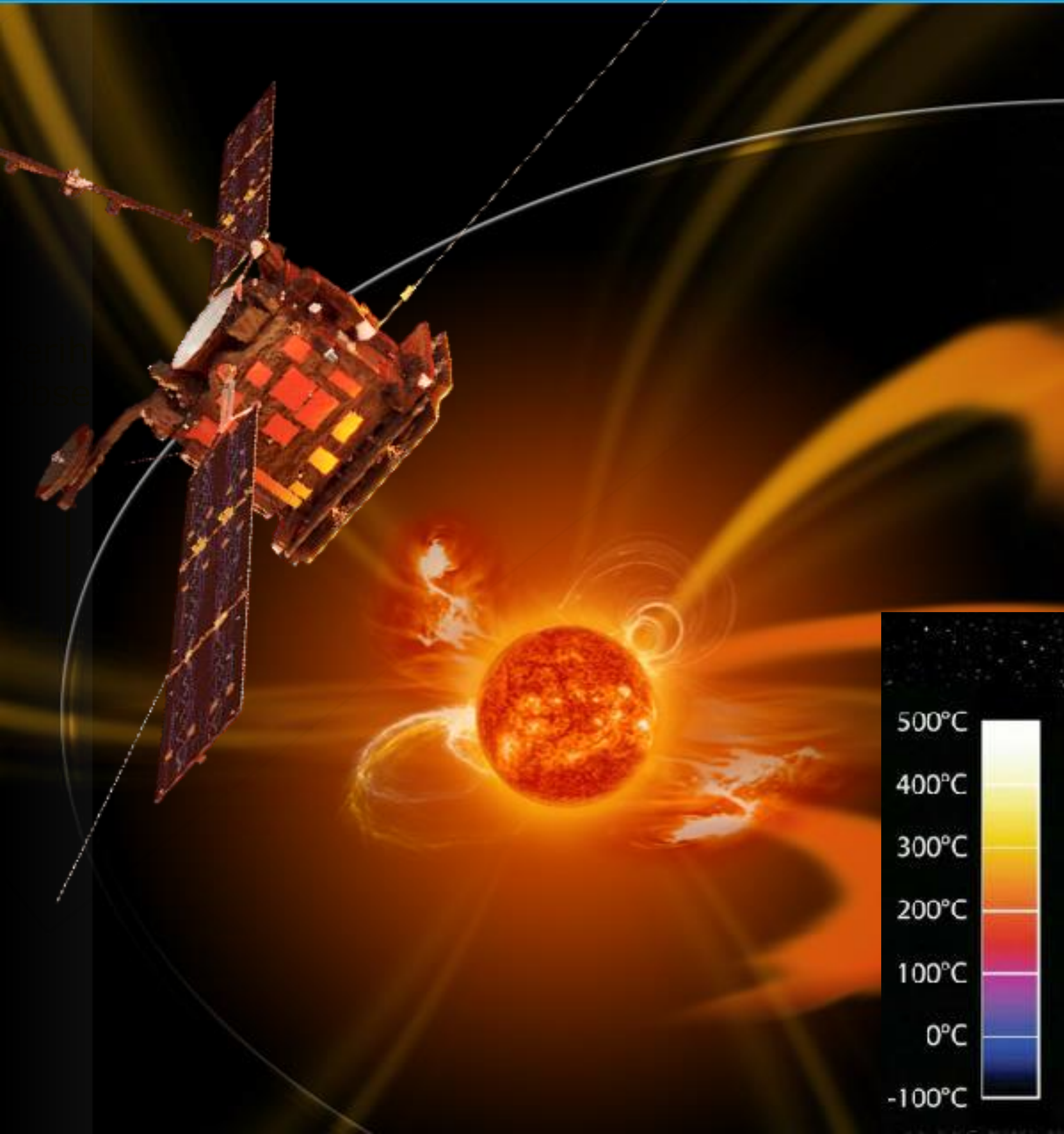
Solar Orbiter
Exploring the Sun-Heliosphere Connection

Mission Profile



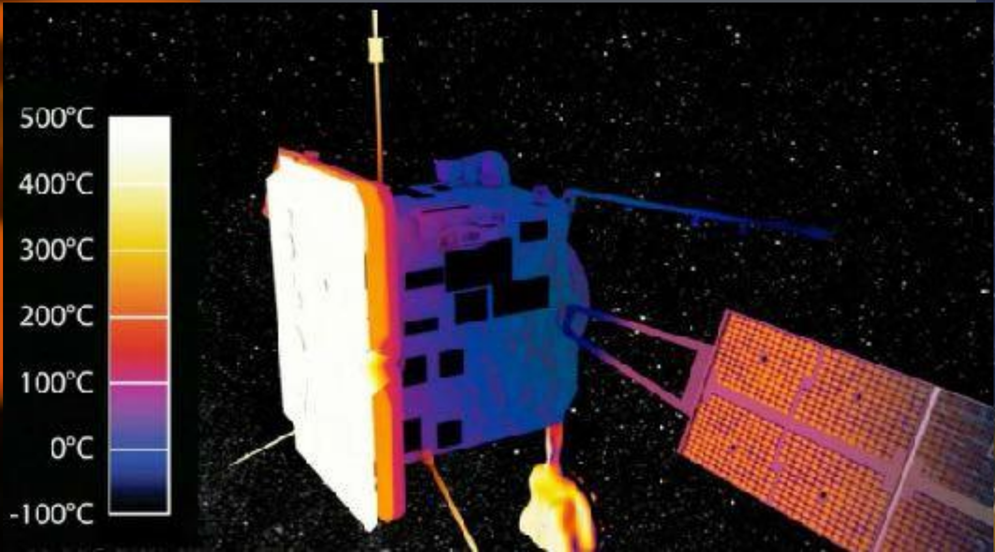
Solar Orbiter
Exploring the Sun-Heliosphere Connection



The Spacecraft

Three-axis stabilised spacecraft, Sun pointing

- Closest Sun encounter: 0.28 AU
- Heat shield to protect spacecraft and payload



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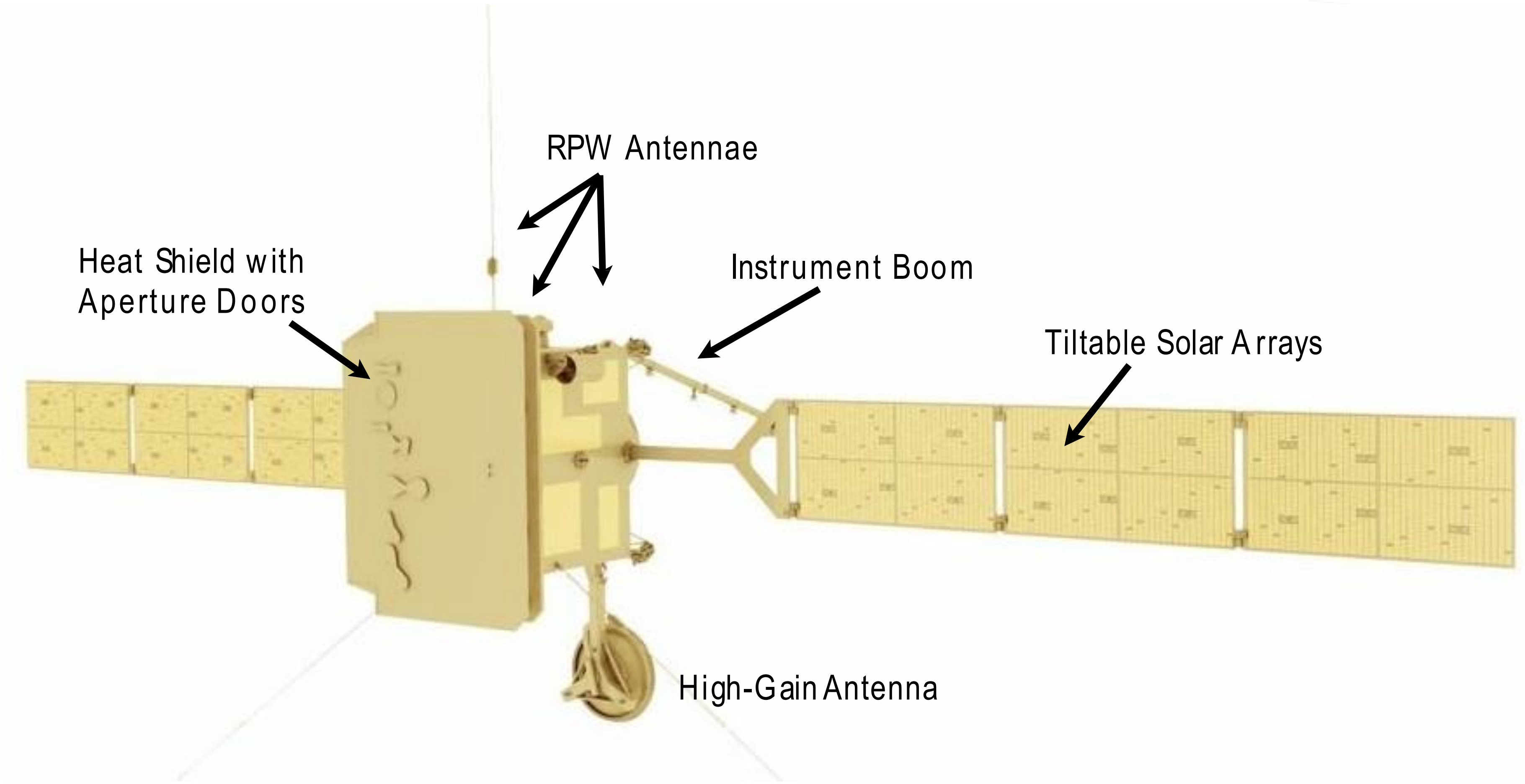
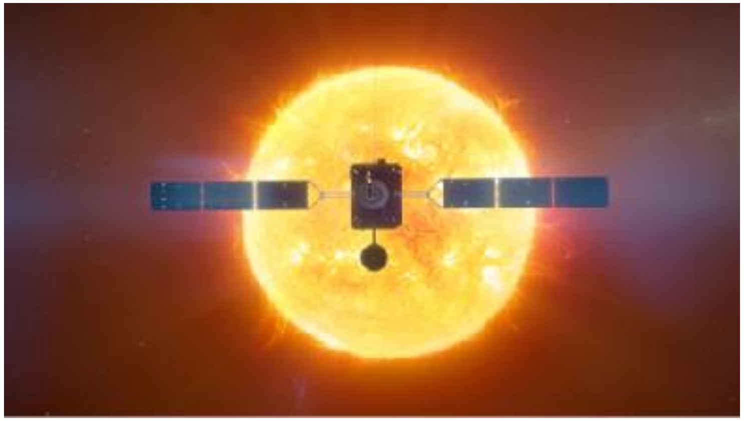
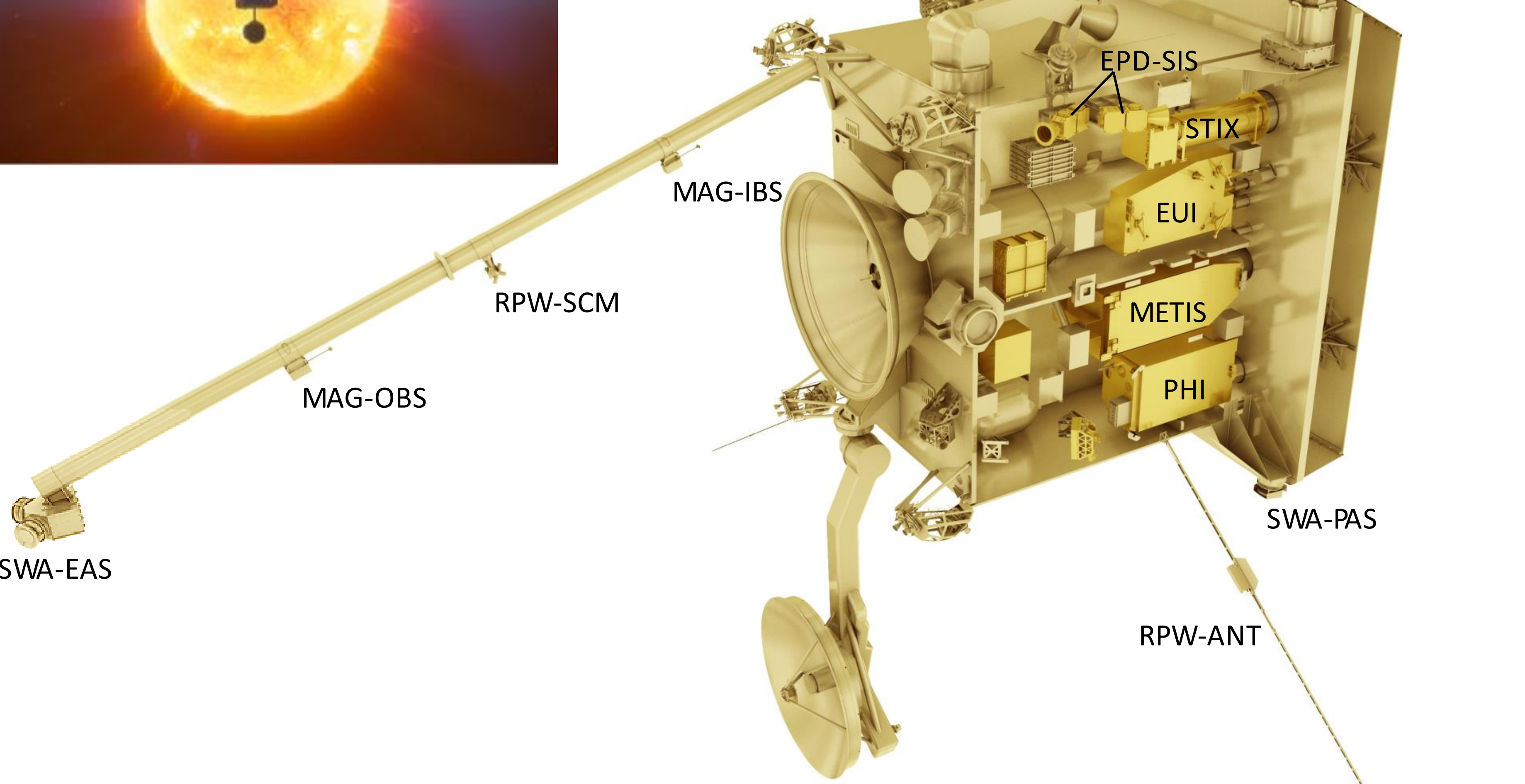


Payload

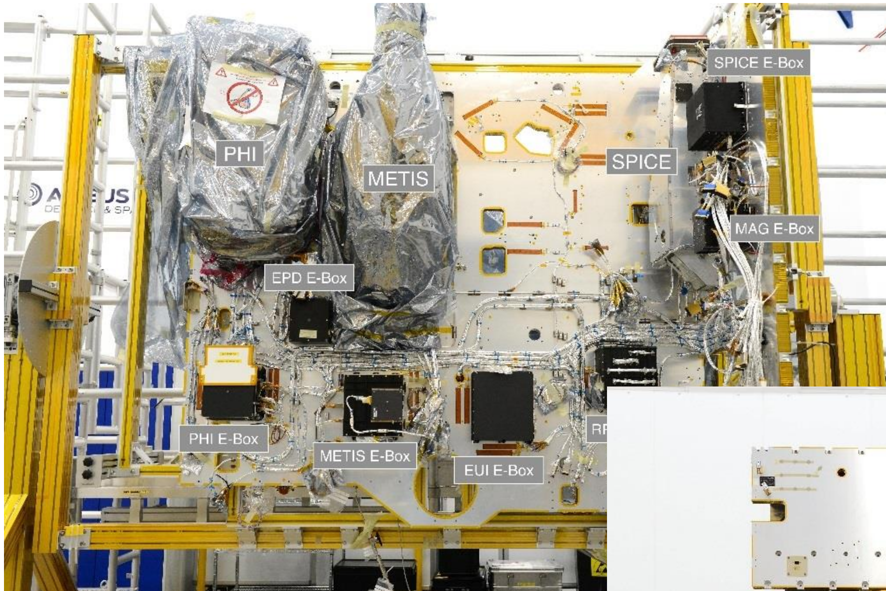
In-Situ Instruments			
EPD	Energetic Particle Detector	J. Rodríguez-Pacheco	Composition, timing and distribution functions of energetic particles
MAG	Magnetometer	T. Horbury	High-precision measurements of the heliospheric magnetic field
RPW	Radio & Plasma Waves	M. Maksimovic	Electromagnetic and electrostatic 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 EUV imaging of the on-disk corona
METIS	Coronagraph	~~E. Antonucci~~ Marco 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

Payload Accommodation



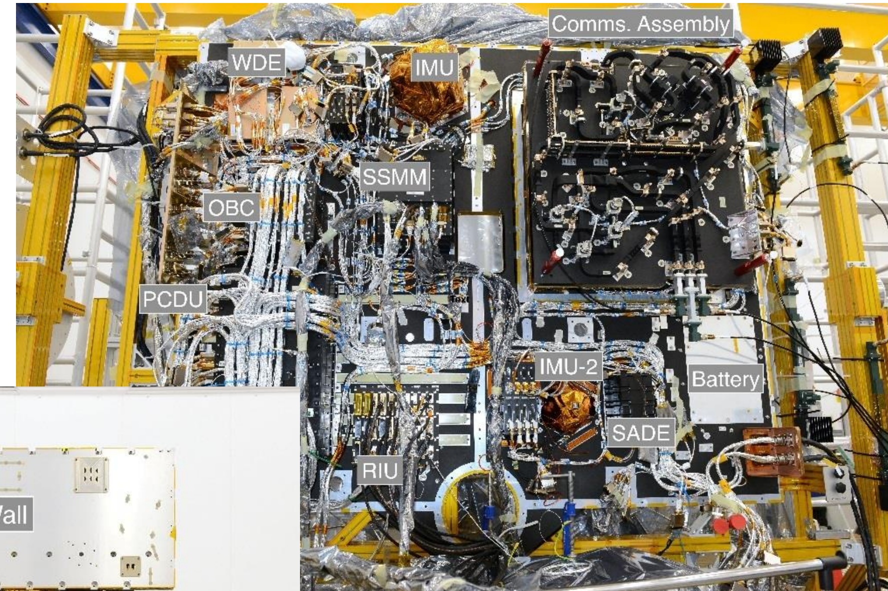


August 2017 Photos



Panel with RS instruments

S/C Core



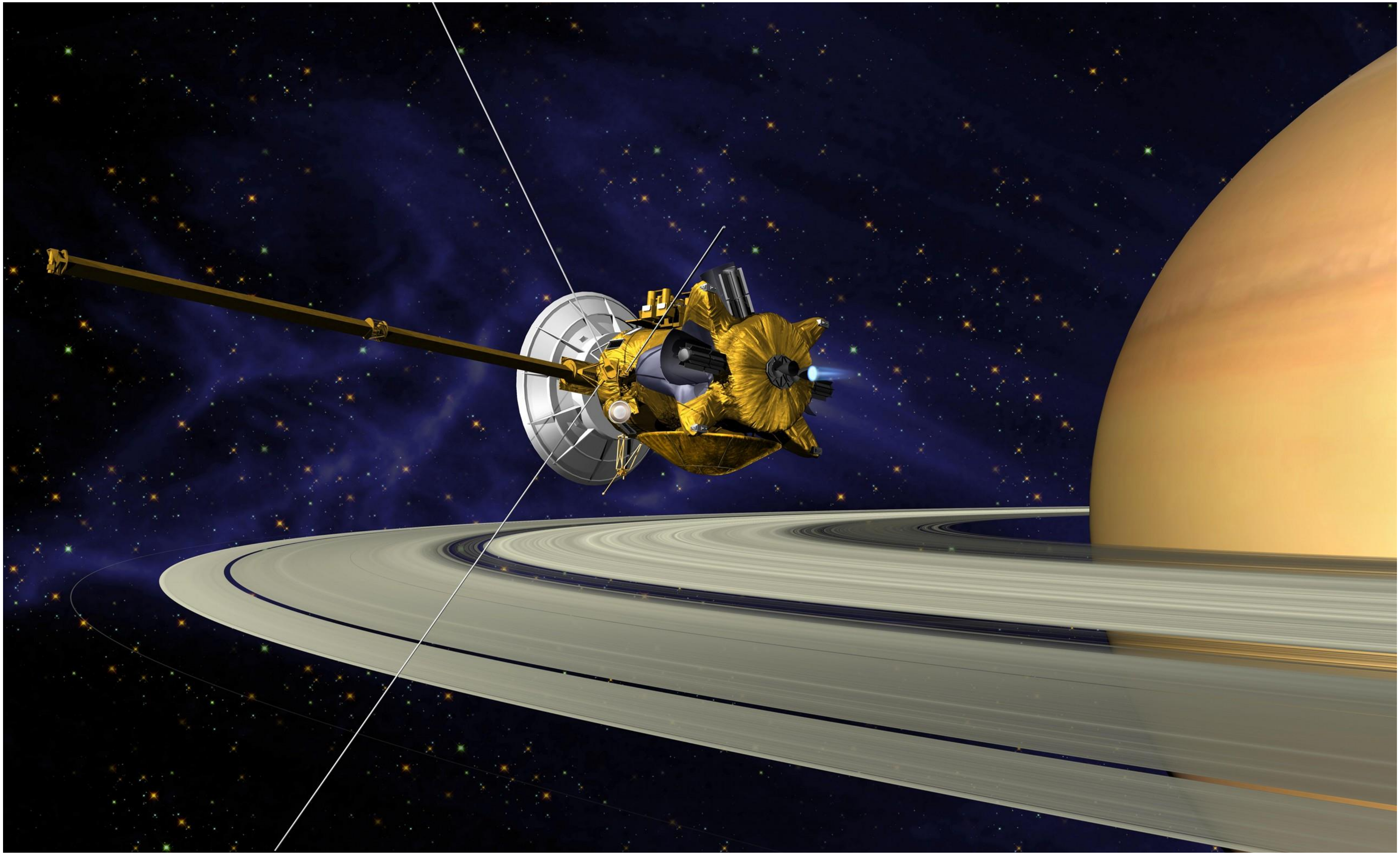
Panel with S/C Avionics

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

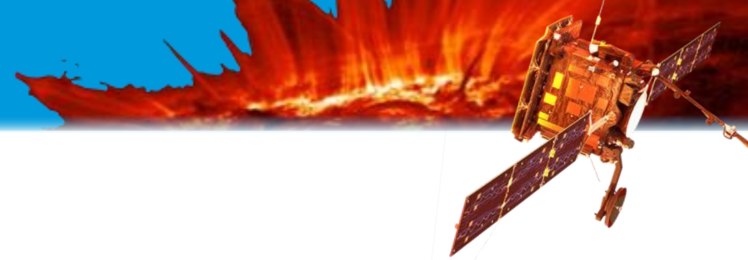
(sorry)

What Solar Orbiter (Almost) Is



Similarities to Planetary Missions

- Limited Observation Time (RS Instruments operate for ~600 days out of ~3000).
- Constrained & variable downlink. Limited on board storage.
    - Sometimes you can generate loads of data, sometimes not.
    - You can’t store data on board indefinitely. You can’t always downlink it immediately.
- Offline Commanding
    - We upload commands to the spacecraft and wait for them to execute.
    - Limited opportunities to respond to a changing target (like the Sun…)
- Lots of scientific objectives that need coordinated observations.

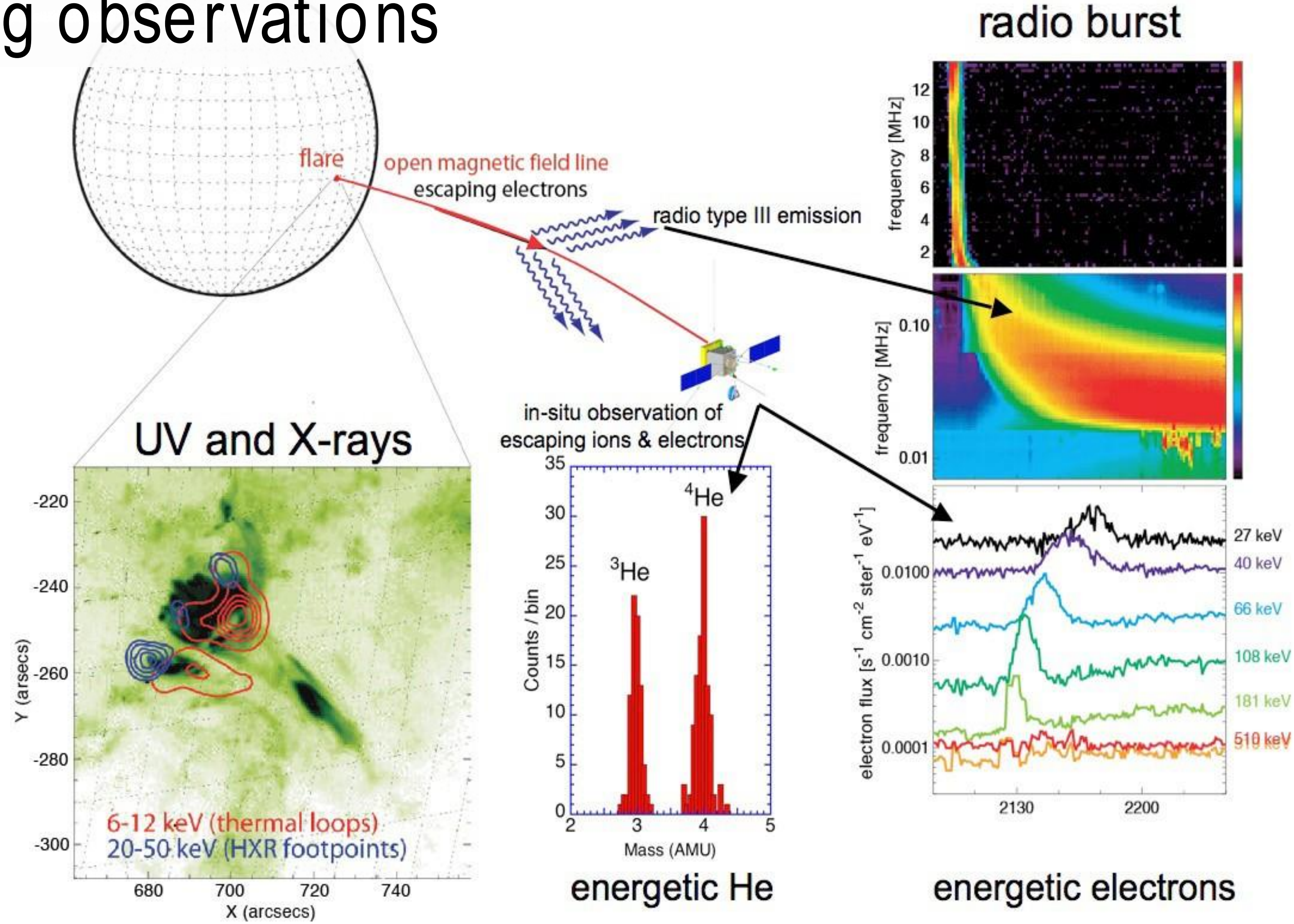


In 85 minutes, SDO [at 130 Mb/s] has downlinked all data Solar Orbiter will be able to send down in one orbit!

- **Low latency (<24h) quick-look products will be available for short-term science planning**
- **Project Scientists are working with the PI's to release those to the SWx forecasting community**

Measurements

Solar Orbiter = Linking in-situ and remote-sensing observations



What Will Solar Orbiter Measure?

When you're in the solar wind, your environment consists of…

Fields:

Electric

Magnetic

Photons & **Waves**

Particles:

Electron
s

Protons & α-**particles**

Other ions
(Z≥3)

(Dust)

~~Neutrons~~

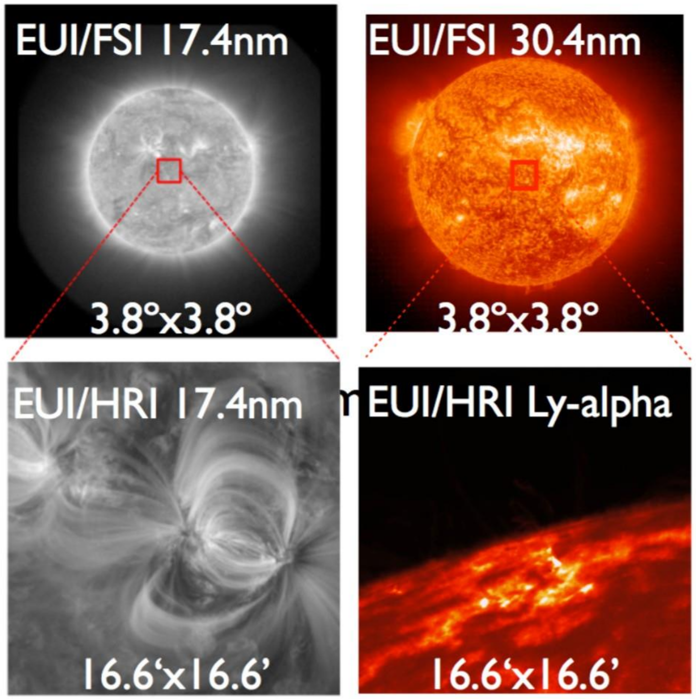
~~Neutrinos~~ Dark

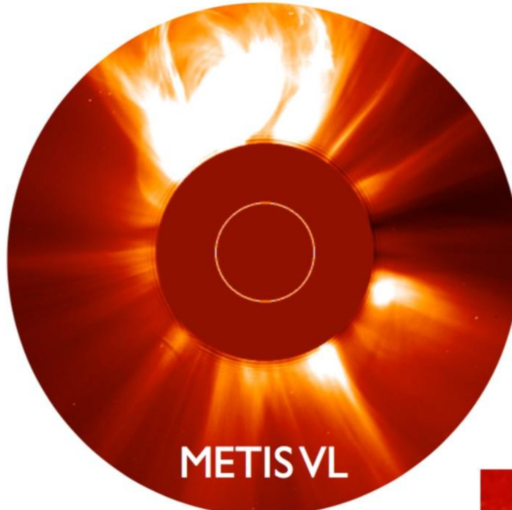
~~Matter Dark~~

~~Energy~~

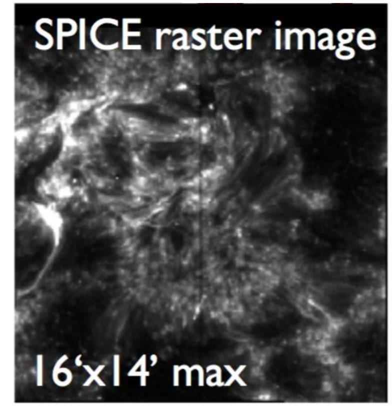
Photons

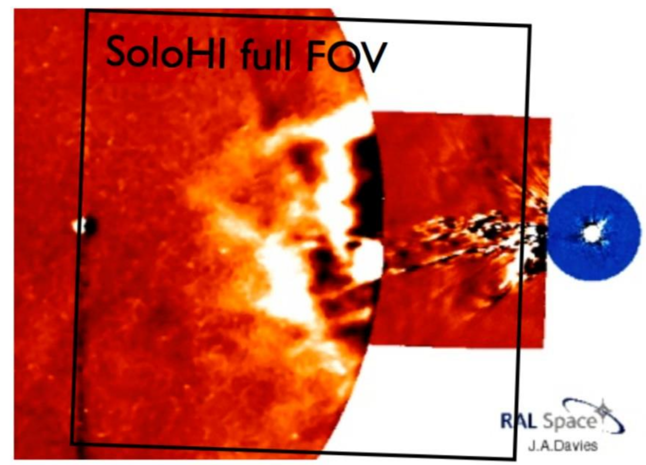
- **Surface** maps of:
  - **Magnetic field** strength & direction
  - Doppler **velocity**
  - Visible-light **intensity**
- **Mid- and upper atmosphere**:
  - **Images of structures** in…
    - Chromosphere/transition region (H^0 Lyα)
    - Transition region (He^+)
    - Corona (Fe^{+9})
  - **Slit spectra**:
    - Spatially scanning ("rastering") and fixed-slit (temporal variations)
    - **Large *T* range**: (chromosphere) $4.0 < \log_{10} T < 6.5$ (corona)
    - Plasma **composition** (balance of elements) & Doppler **velocity**
  - Impulsive events:
    - Spectrally and spatially resolved (Hard X-rays: e^- **bremsstrahlung**)
- **Outer corona**
  - Images of **large-scale structures** & **shocks**
    - visible light intensity and **polarisation** (electrons)
    - Lyα @ 121.6 nm (hydrogen)

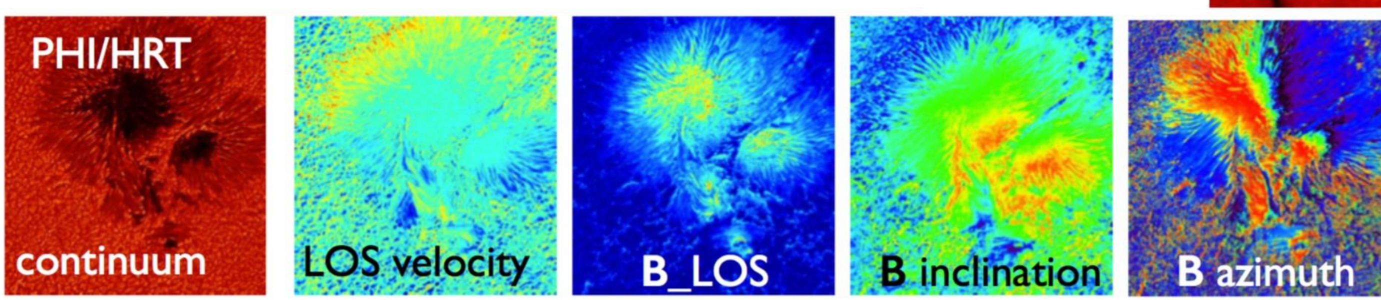




+ similar for Ly-alpha

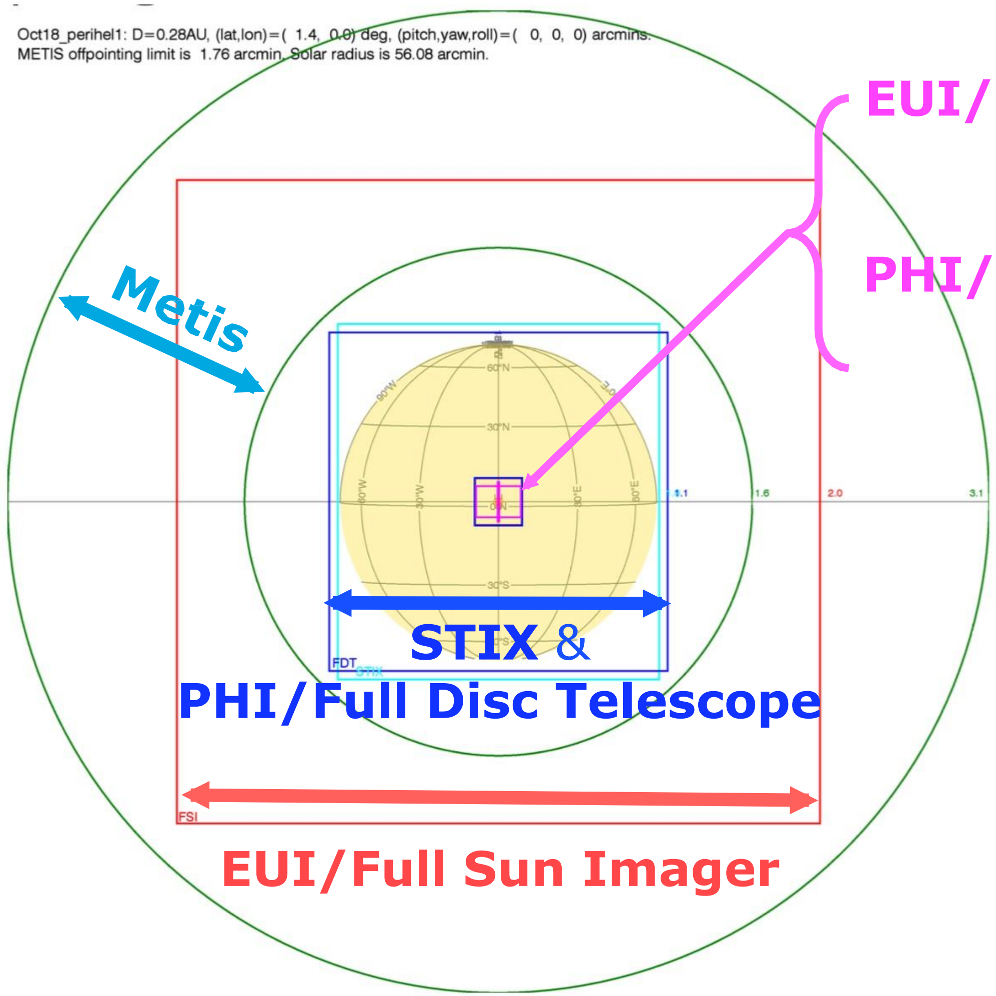






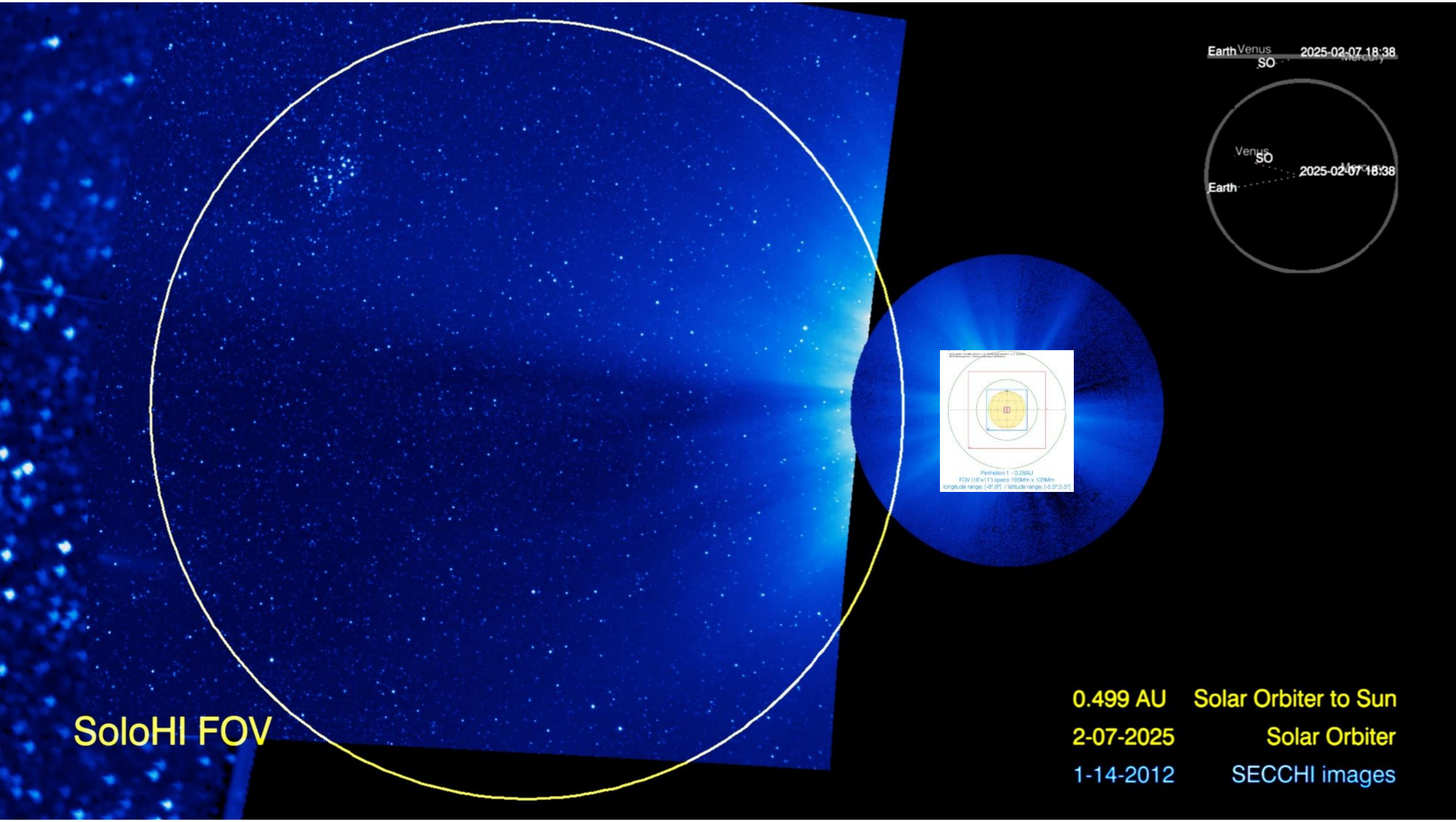
+ similar images for PHI/FDT

Remote Sensing Fields of View 1



Perihelion 1 - 0.28AU

Remote Sensing Fields of View 2



Particles

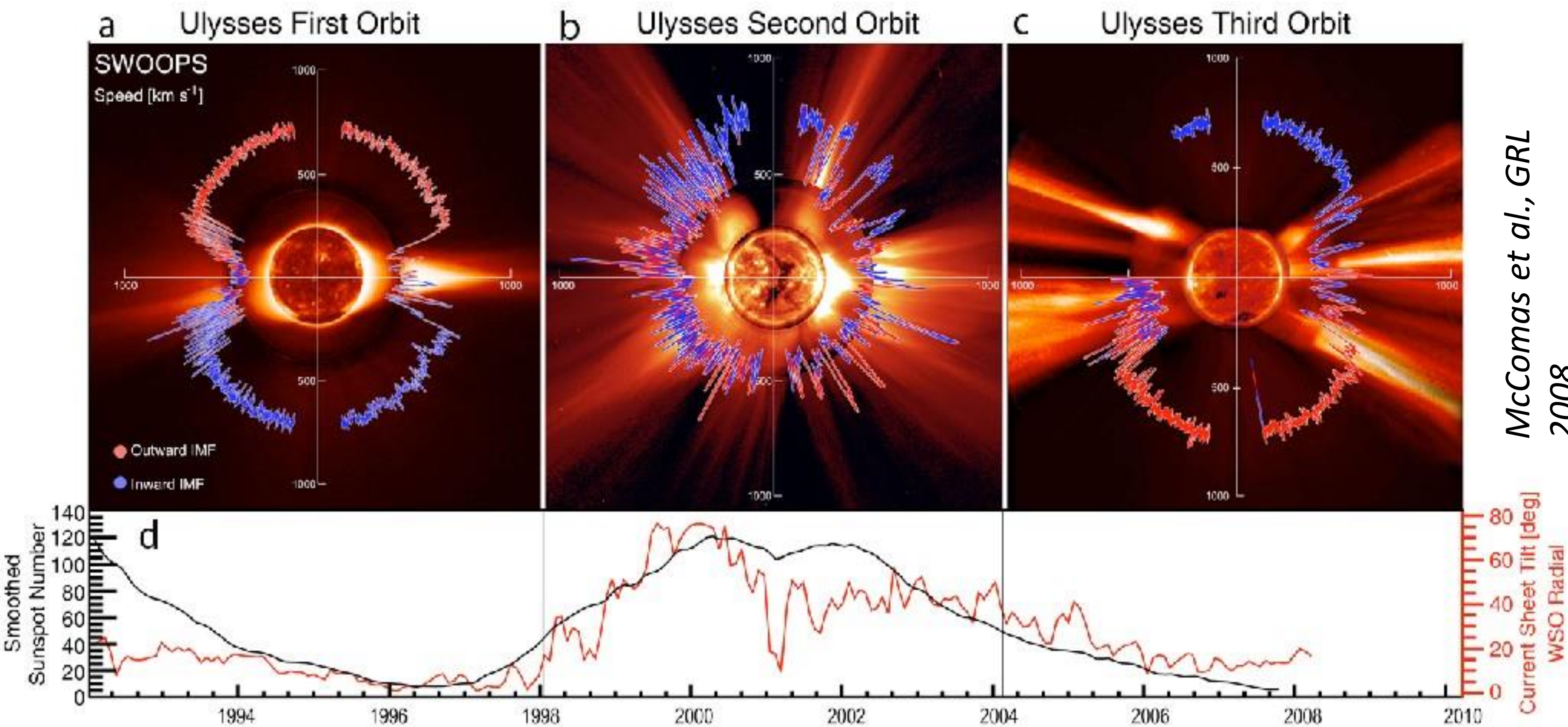
- **Electrons**
  - 1 eV – 5 KeV Energy Distributions & Moments
  - 2 keV – 15 MeV Fluxes & Anisotropies
- **Protons**
  - 200 eV – 20 KeV Energy Distributions & Moments
  - 3 keV – 105 MeV Fluxes and Anisotropies
- **Heavy Ions**
  - Fe, Ne, Mg, Si, C, N, O – **composition** of solar wind
  - ^{3}He, ^{4}He – isotope balance matters
  - 500 eV to 200 MeV/nucleon
  - 2 – 56 a.m.u./q

Fields & Waves

- **Magnetic fields**
  - Fluctuations of down to 5 pT
  - on timescales of < gyro-frequencies < *t* < days
- **Electrostatic fields**
  - DC (and low-*f*) electric fields
  - Density fluctuations in the solar wind
  - **E** due to Shocks, reconnection
  - Electron density & temperature
- **Electromagnetic waves**
  - High-sensitivity (low-background) at < 1 kHz
  - Radio emission from electron beams
  - Waves associated with turbulence (temperature anisotropies)
  - Solar and interplanetary radio bursts
  - Dust particles' spatial distribution, mass & dynamics

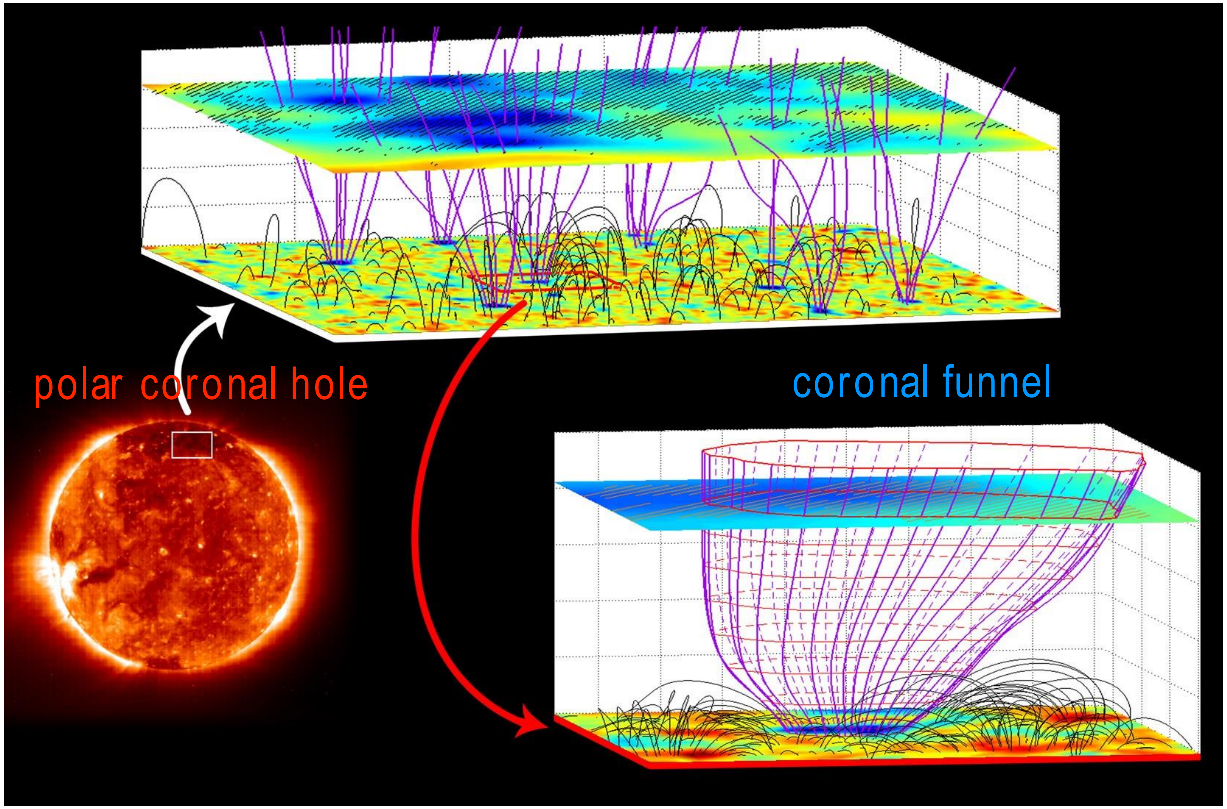
Solar Orbiter Science Focus:

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



McComas et al., GRL 2008

How and where do the solar wind plasma and magnetic field originate in the corona?

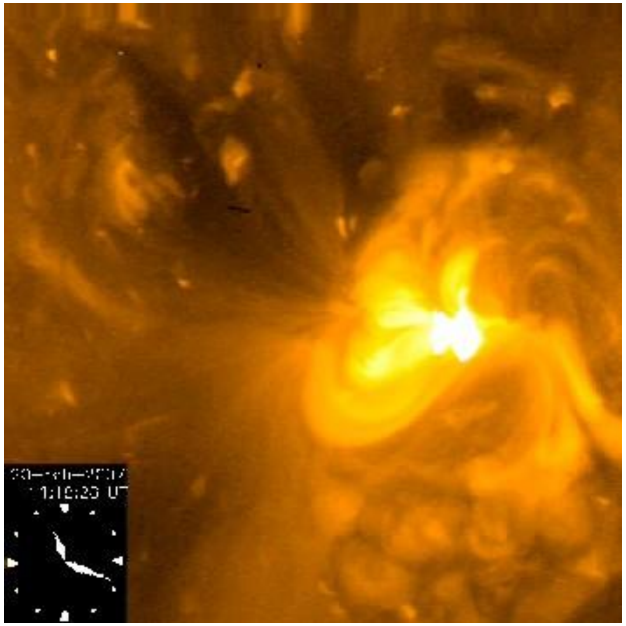


Tu, Zhou, Marsch et al., Science 2005

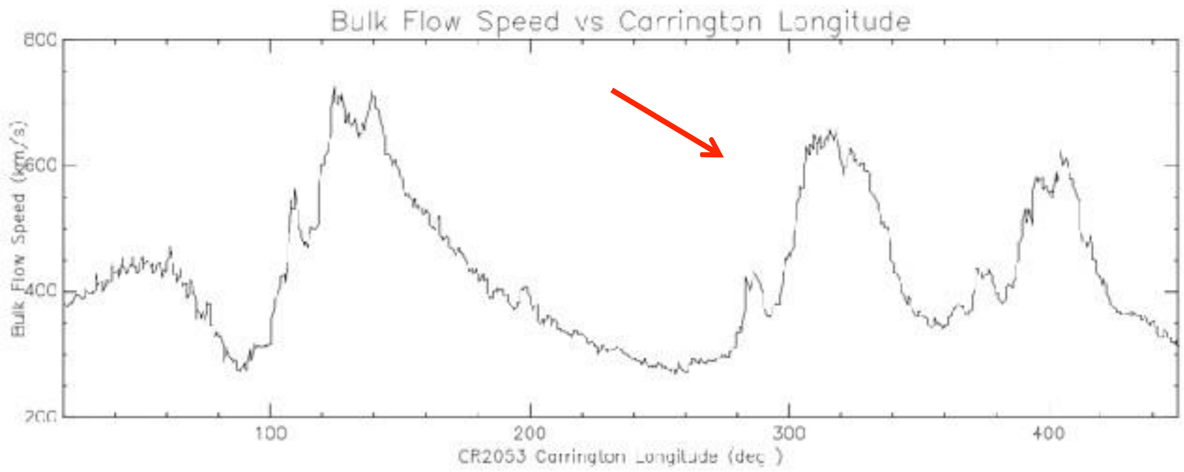
- Complex connections between solar surface and corona
- Source region of the wind at chromospheric and TR heights is structured and dynamic

How and where do the solar wind plasma and magnetic field originate in the corona?

The Slow Solar Wind



Harra et al., ApJL 2008



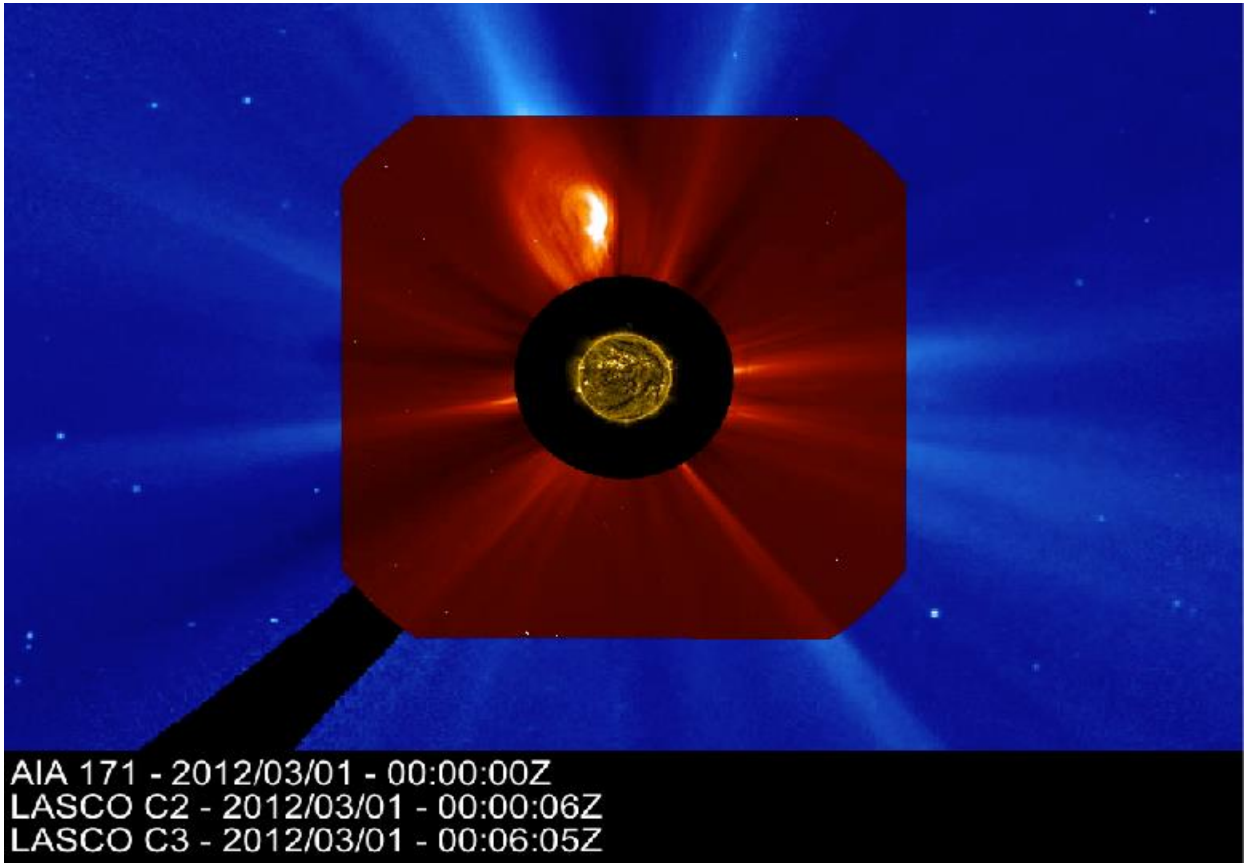
There are multiple sources of slow solar wind – active regions are one source. Identifying the source directly in the wind by the time it gets to 1 AU is extremely challenging and can only be carried out on a statistical basis.

Understanding the detailed physical processes can only be achieved by getting closer.

How and where do the solar wind plasma and magnetic field originate in the corona?

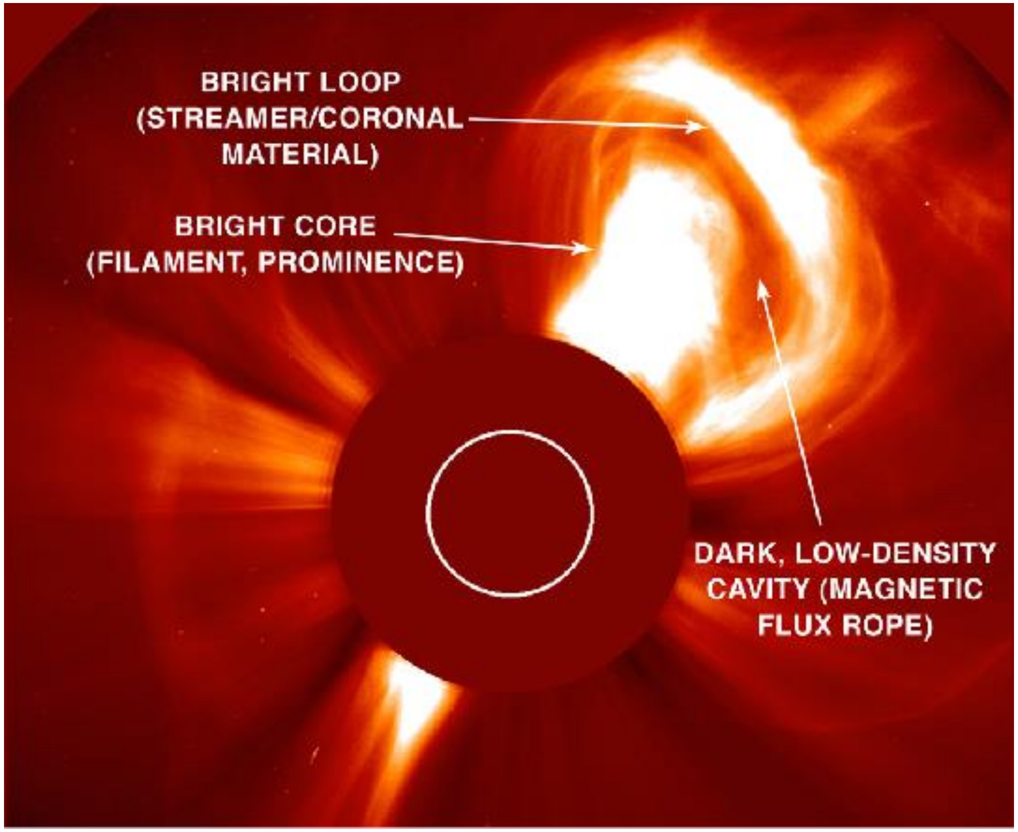
- Solar Orbiter will measure solar wind plasma and magnetic field in situ + remote sensing of photosphere and corona
- Correlating SW properties measured in situ with observed structures in the source region at the Sun

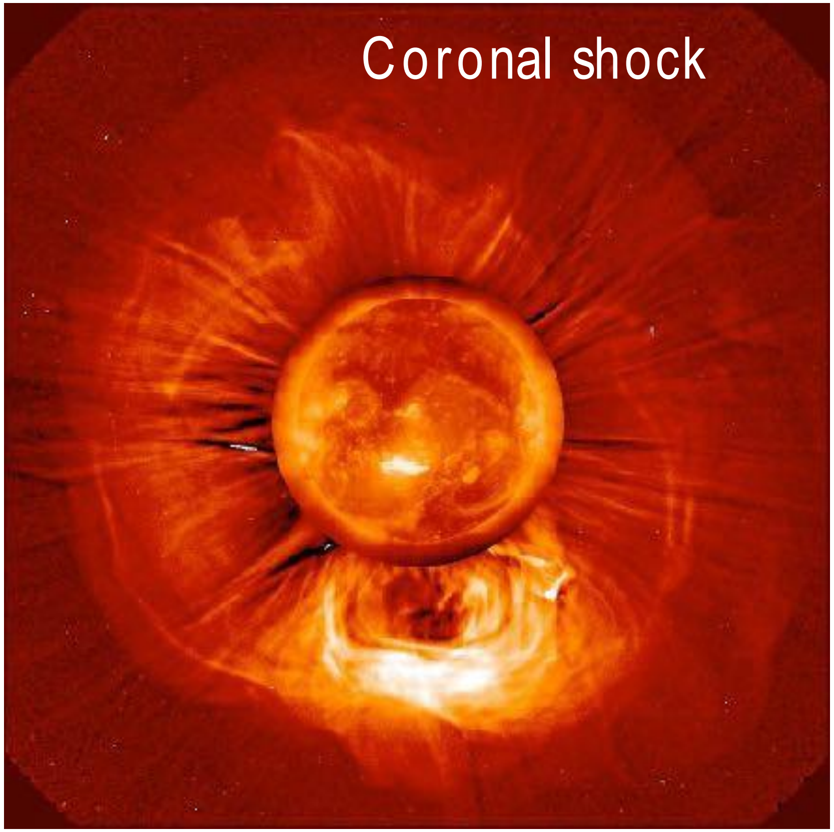
Solar corona, wind and magnetic activity → dynamic heliosphere



Heliospheric consequences of eruptive events

How do solar transients drive heliospheric variability?



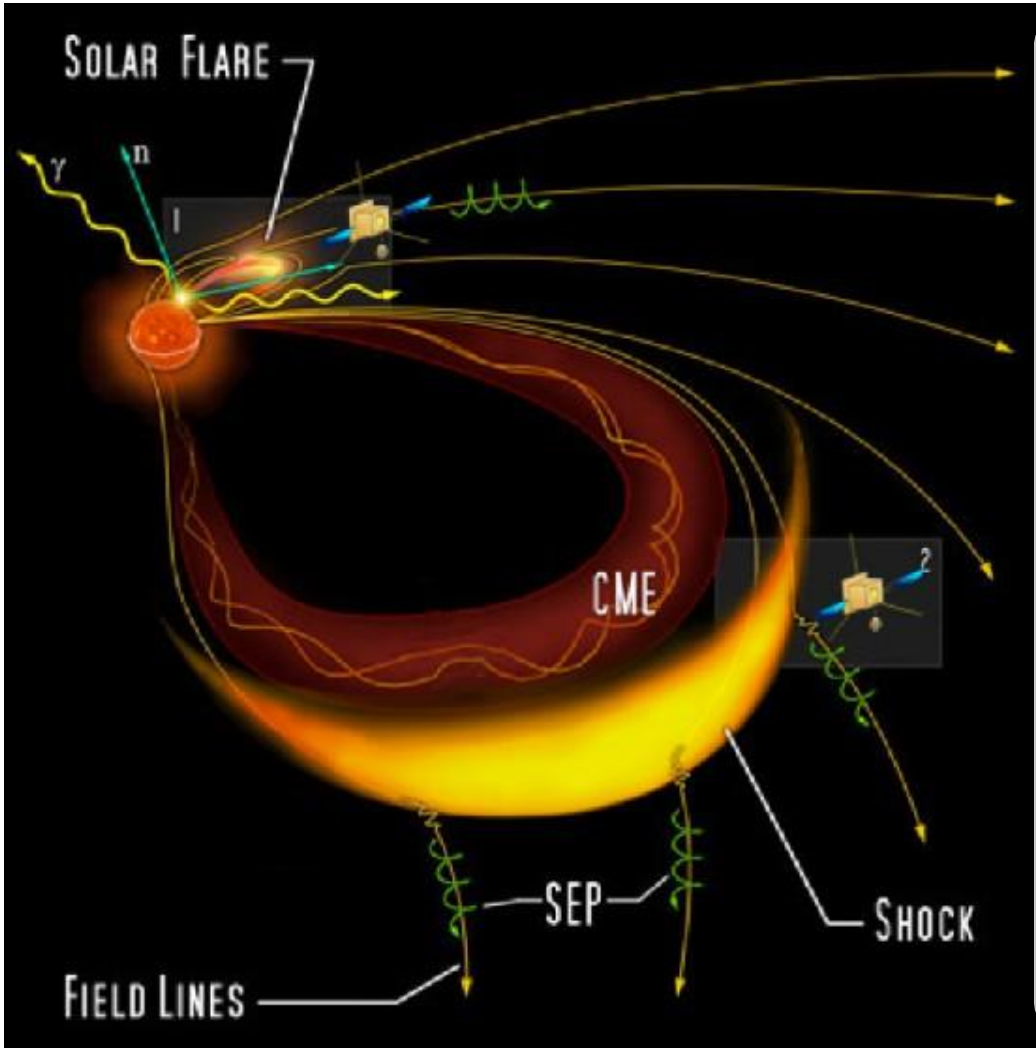


How do solar transients drive heliospheric variability?

- Solar Orbiter will determine inputs to heliosphere and measure directly the heliospheric consequences of eruptive events at distances close enough to sample the fields and plasmas in the pristine state

- Will advance our understanding of ICMEs structure and its relation to CMEs at the Sun (requires remote sensing + in situ measurements at close perihelion and in near-corotation with the Sun)

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



- Relative importance of SEP acceleration due to flares and CME driven shocks cannot be determined at 1 AU due to particles mixing

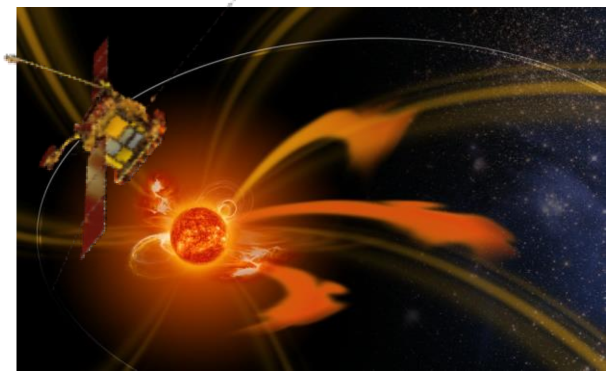
- Solar Orbiter will allow tests of the relative importance of these two acceleration mechanisms

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

- Solar Orbiter will advance understanding of SEP acceleration (CME driven shocks) by probing the inner heliospheric sites where particle acceleration and release take place

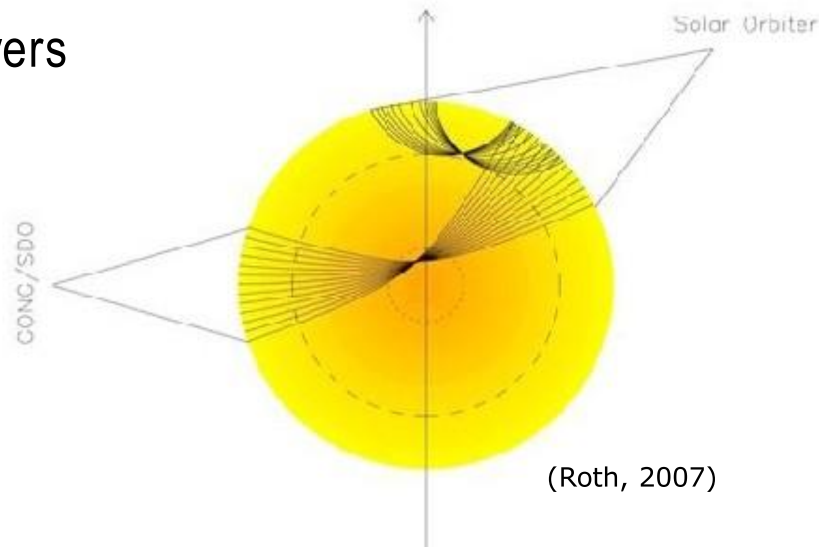
- Will observe how shocks evolve and whether they are still accelerating particles as they pass by the S/C

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



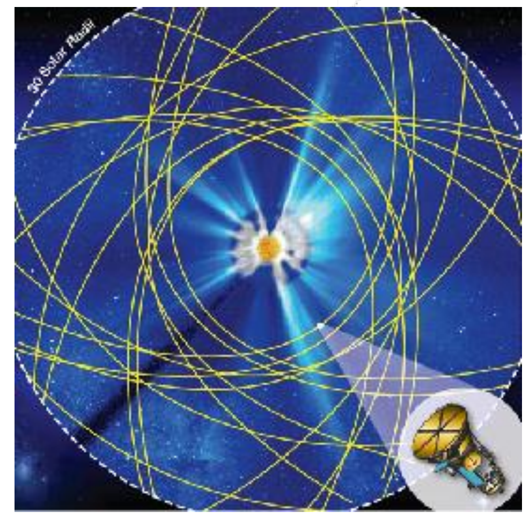
- **Solar Orbiter will see the Sun's far side and higher latitudes**
  - Improved combined helioseismic data (near + far sides)
    - Global helioseismology: reduced leakage effect
    - Local helioseismology: probing deeper layers
  - Large- and small-scale flow patterns at poles

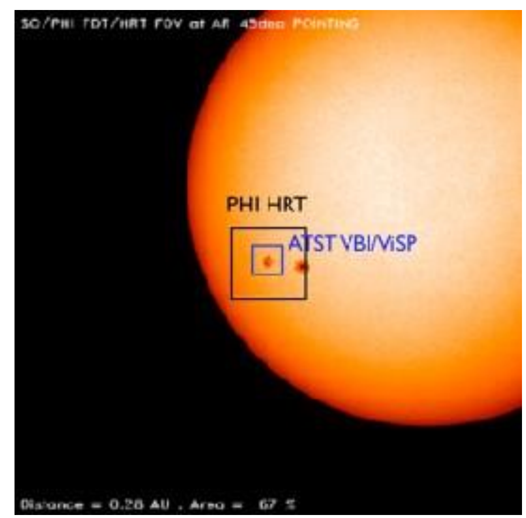
- **Probing of the deep solar interior**
  - Seismic estimates for the deep meridional return flow



(Roth, 2007)

Synergy between Solar Orbiter and other Observatories





<u>Solar Orbiter:</u>

+ unique orbit (solar distance, inclination, longitude)
+ comprehensive payload suite
- limited telemetry due to orbital characteristics

<u>Parker Solar Probe:</u>

+ unique orbit (min. perihelion ⪅10 R_{Sun})
- payload mass constrained by orbital characteristics, mostly in-situ instrumentation

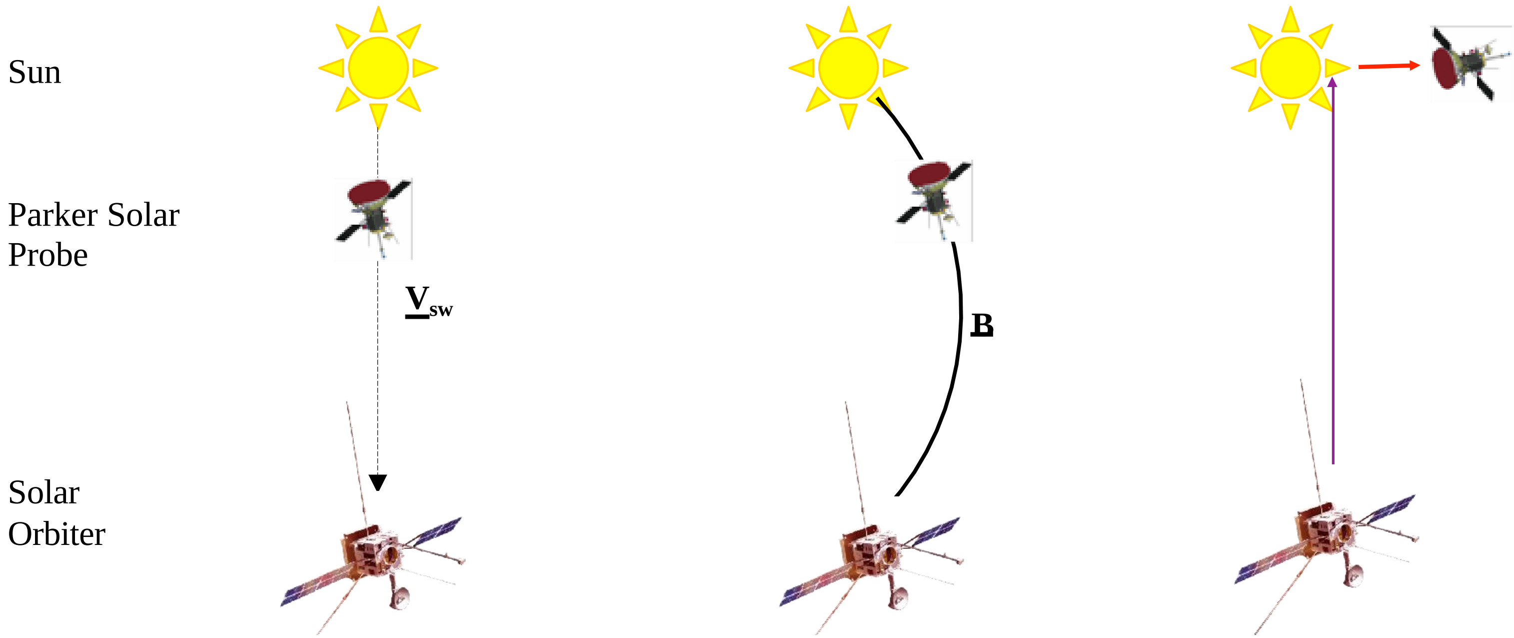
<u>Near-Earth assets:</u>

+ much higher data return (SDO, DKIST)
- limited to Sun-Earth line

→ Depending on orbit, Solar Orbiter remote-sensing data can be complemented either by high-res/high-cadence **co-spatial** data from other observatories or data with **additional spatial coverage** (e.g. for helioseismology)

Joint Observations Solar Orbiter - Parker Solar Probe

Example of alignments/quadratures:



Radial alignments:

SO and PSP observe the same SW plasma

IMF alignments:

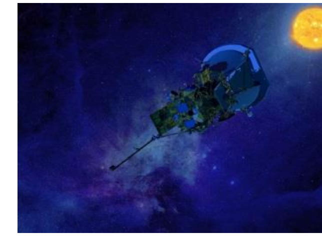
SO and PSP connect to the same IMF footpoint

Quadratures:

SO remote-sensing and PSP in- situ @ ≥9.5 Rs

Questions?

PAYLOAD Comparison



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STIX	Spectrometer/Telescope for Imaging X-rays	S. Krucker

ISIS D. McComas [SwRI]

FIELDS S. Bale [UCB]

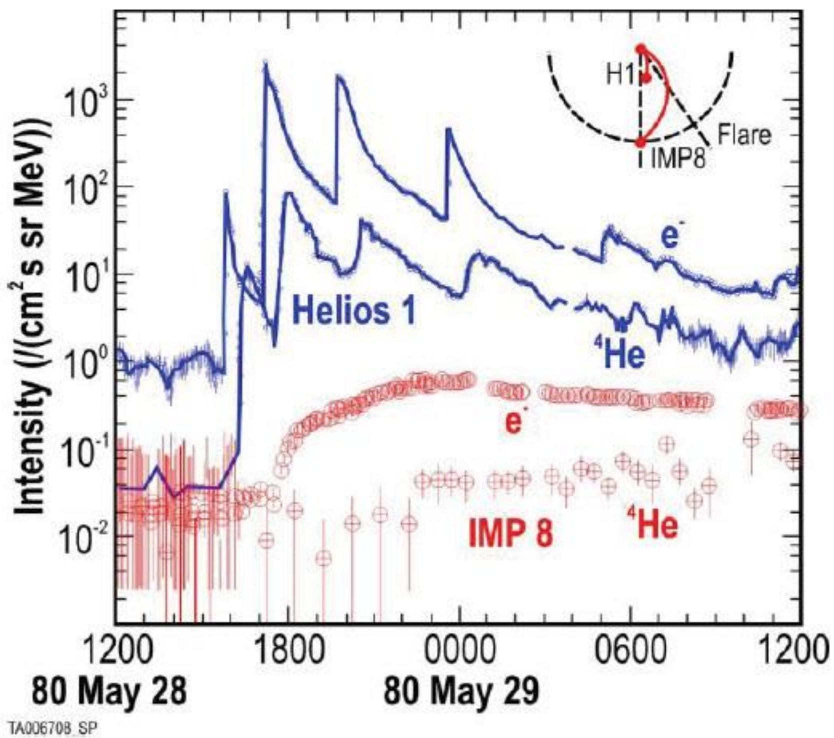
SWEAP J. Kasper [Umich]

WISPR R. Howard [NRL]

Explore the mechanisms that accelerate and transport energetic particles

Solar Probe Plus
A NASA Mission to Touch the Sun

- Understanding solar energetic particle (SEP) acceleration at 1 AU is difficult
  - distance from sources
  - mixing during transport
- Helios showed advantages of near-Sun observations of SEP processes near origin
- SP+ will observe 50-100 ISEP and ≳50 large SEP events inside 0.25 AU
- Enabling detailed studies of
  - flare and CME-shock acceleration
  - seed particle identities
  - the effects of particle transport in the interplanetary medium.



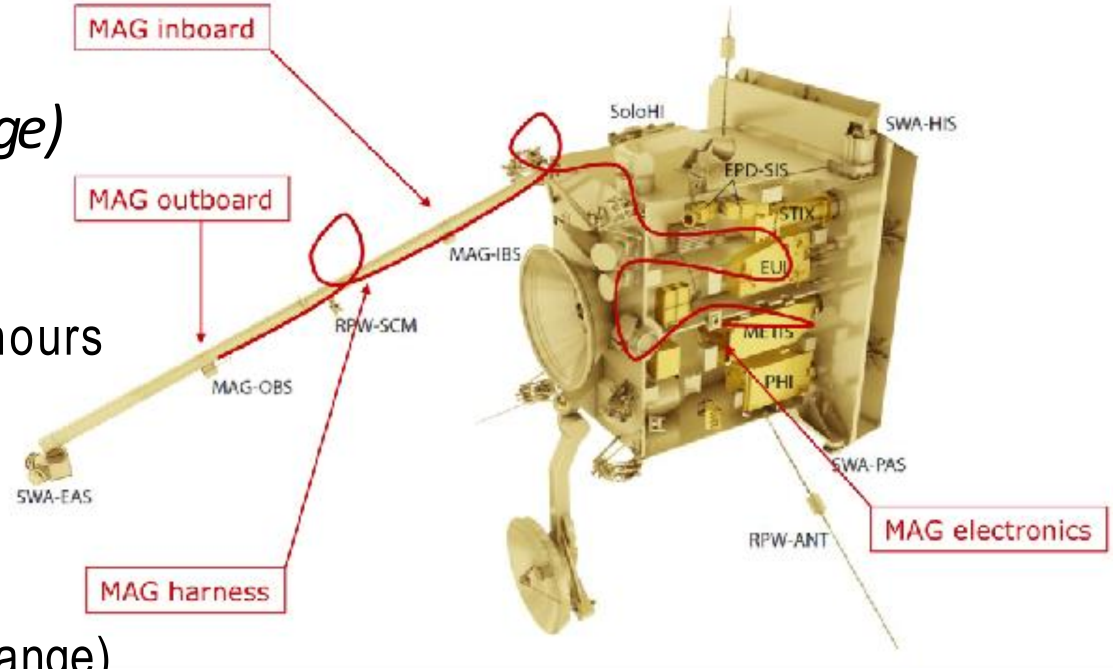
(Wibberenz and Cane 2006)

2-4 MeV He

Payload overview & performance

MAG: Measuring the heliospheric magnetic field

PI: Tim Horbury (Imperial College)



- **Instrument performance:**
  - Noise < 10 pT/√Hz (at 1 Hz)
  - Offset stability: < 0.5 nT / 100 hours
  - Measurement ranges: ±32 nT, ±128 nT, ±512 nT, ±2048 nT
  - Auto-ranging
  - Resolution: 4 pT (in ± 128 nT range)

- **Science modes:**
  - 16 vectors/s most of the time (MHD, proton gyroscope)
  - Burst mode: 128 vectors/s, ~ 1 hour per day (ion kinetic)
  - Internal and inter-instrument triggering

SWA: Solar Wind Analyser

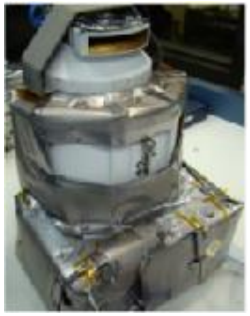
PI: Christopher Owen (MSSL)

EAS: Electron Analyser System

Energy range: 1 eV - 5 keV, Normal mode: 4 s (100 s full 3-D VDF), Burst mode: 0.125 s

PAS: Proton and Alpha Sensor

Energy range: 0.2 eV/q - 20 keV/q, Normal mode: 4 s (100 s full 3-D VDF), Burst mode: 0.125 s



HIS: Heavy Ion Sensor

^{3}He – ^{56}Fe

Energy range: 0.5 keV/q - 60 keV/q, Normal mode: 300 s (heavy ions), 30 s (alphas)

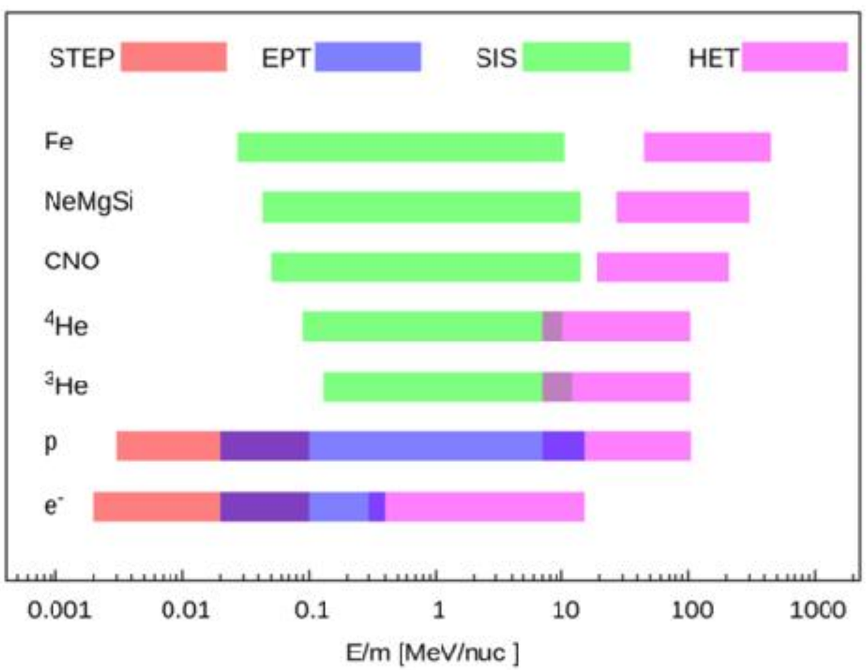
Burst mode: 30 s (heavy ions), 4 s (alphas)

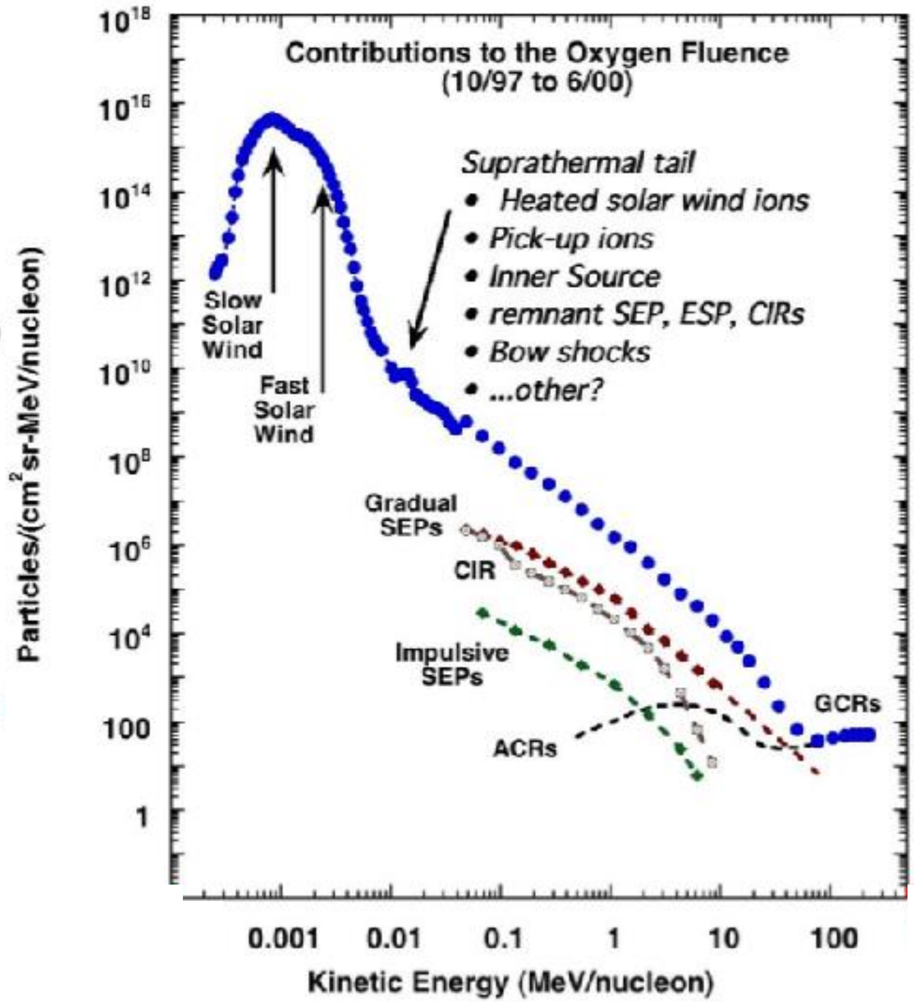
Mass resolution m/Δm: 4 (at 30 s), 3 (at 300 s)

EPD: Energetic Particles Detector

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

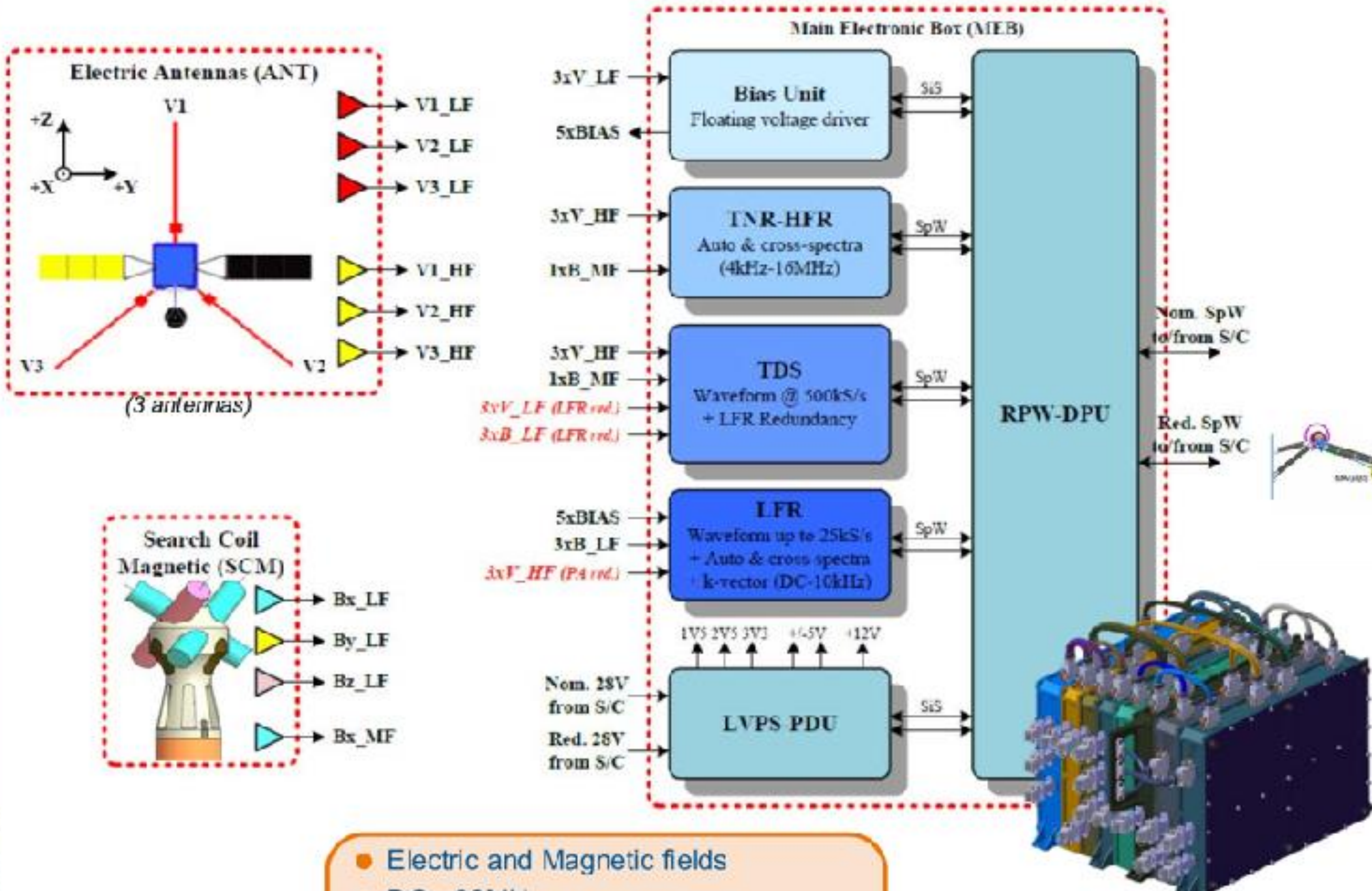
EPD will measure
electrons from 2keV – 20 MeV,
protons from 3keV – 100 MeV,
ions from 8 keV – 200 MeV/nuc
At high cadence (1 s, SIS: 3 s)
In up to 4 view directions (STEP: 15)

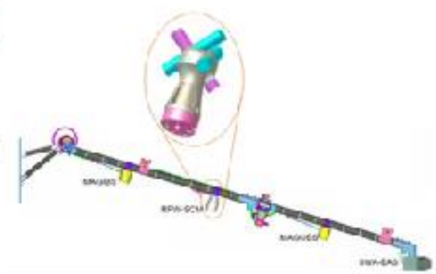




RPW: Radio and Plasma Waves

PI: Milan Maksimovic (Observatoire de Paris)



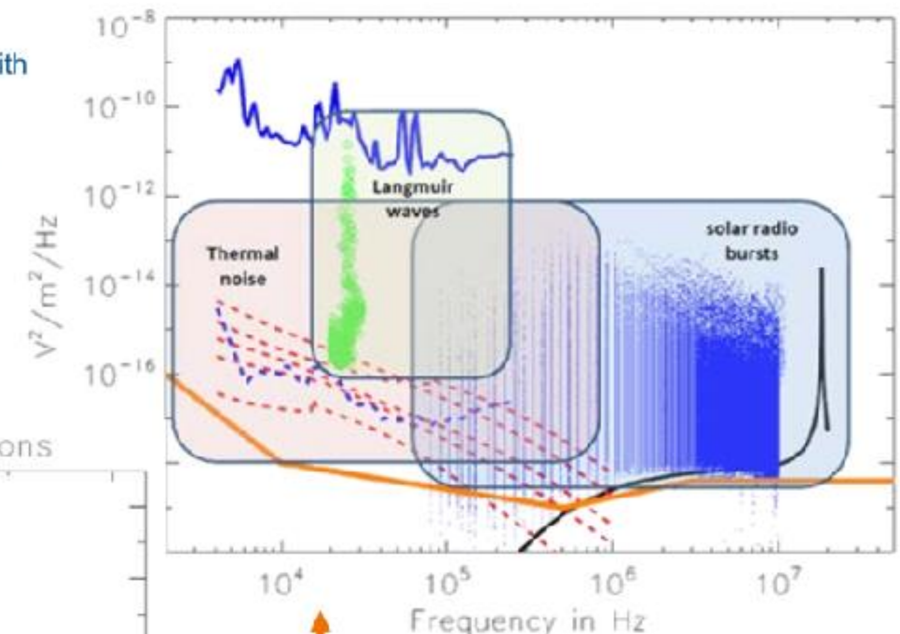


- Electric and Magnetic fields
- DC->20MHz
- Plasma current compensation
- Temporal analysis, waveforms (TDS)
- Frequential analysis (LFR, TNR-HFR)

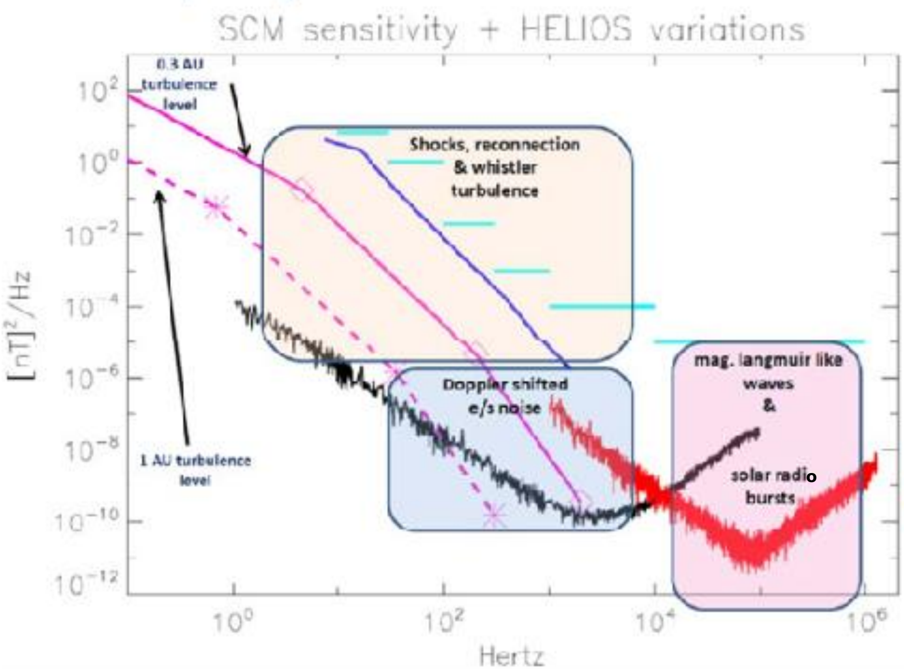
RPW: Radio and Plasma Waves

PI: Milan Maksimovic (Observatoire de Paris)

- 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

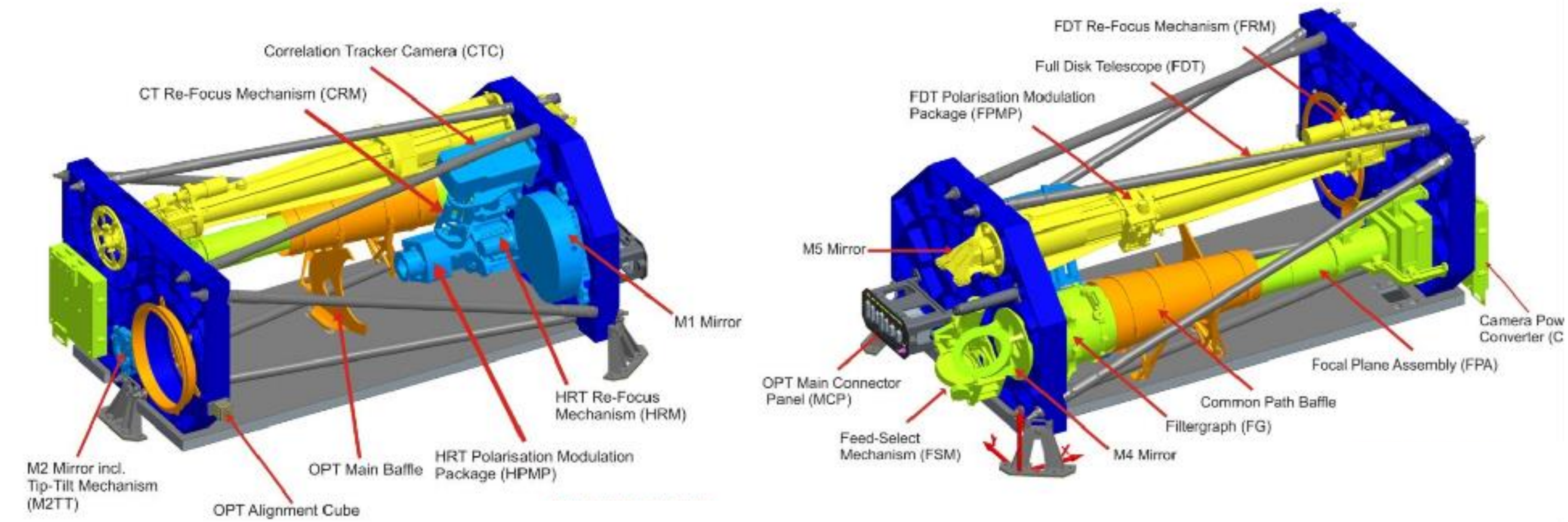


Magnetic Sensitivity of the RPW Sensors

RPW cnes

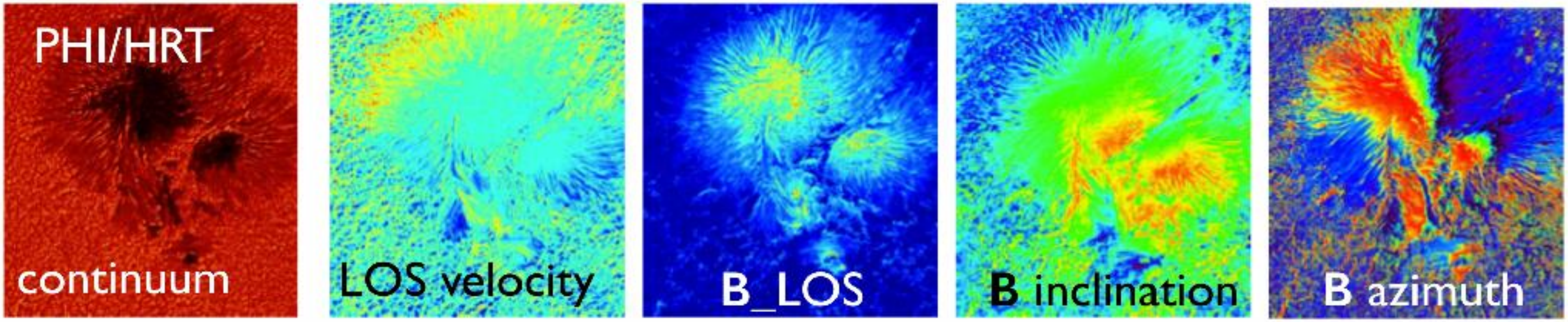
PHI: Polarimetric and Helioseismic Imager

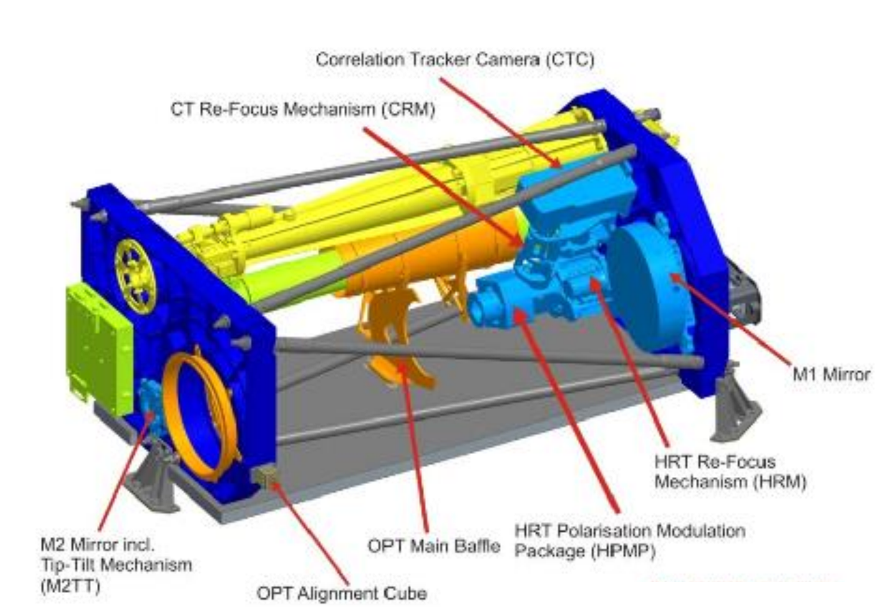
- Mapping the vector magnetic field and the LOS velocity of the solar plasma
  - Mapping → Imaging instrument → Two telescopes
  - Magnetography → Polarimetry → LCVR-based PMPs
  - Tachography → Spectroscopy → Fabry-Pérot etalon as a filtergraph

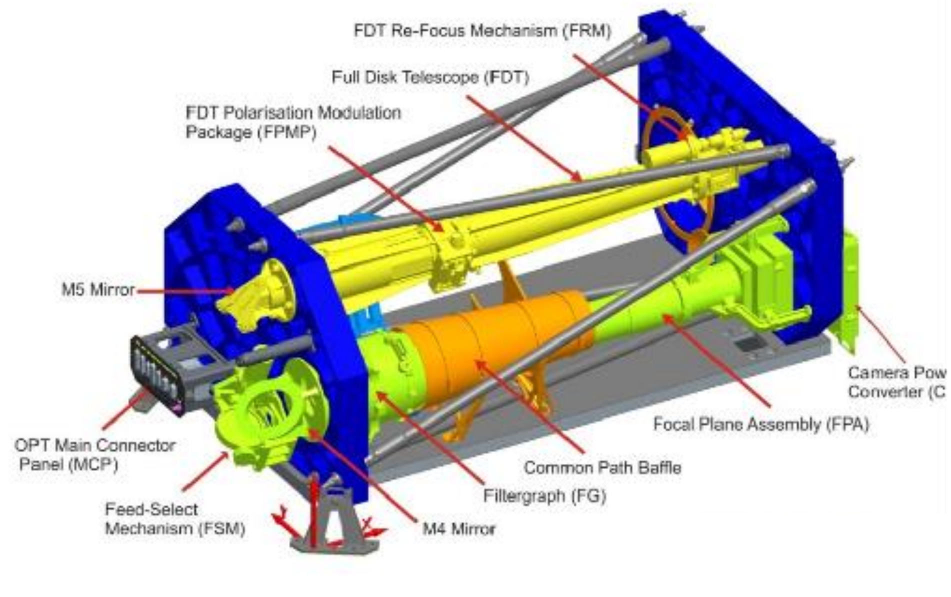


High spatial resolution: ~180 km at perihelion **Cadence possibility: 1 min**

PHI: Polarimetric and Helioseismic Imager







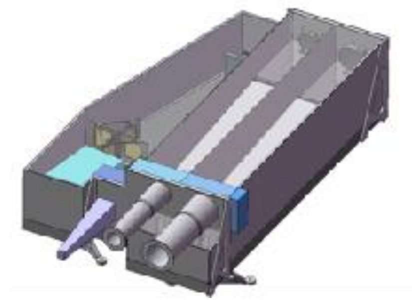
High spatial resolution: ~180 km at perihelion

Cadence possibility: 1 min

esa SOLAR ORBITER

EUI: Extreme Ultraviolet Imager

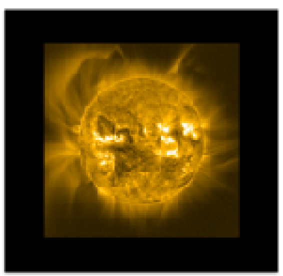
Dual FSI	FSI 304 Å: He II 0.08 MK FSI 174 Å: Fe IX-X 1MK	FSI-304 FSI-174
EUV HRI	HRI 174 Å: Fe IX-X 1MK	HRI-174
Ly α HRI	HRI 1216 Å: H Ly α, 10-80 kK upper chromosphere	HRI-Ly α

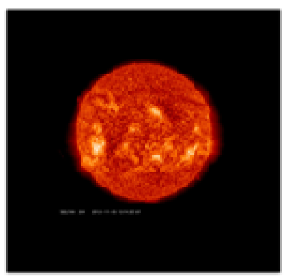


FSI: Full Sun Imager

FOV: 3.8°x3.8°, @ 0.28 AU: 4 Rsun x 4 Rsun

17nm

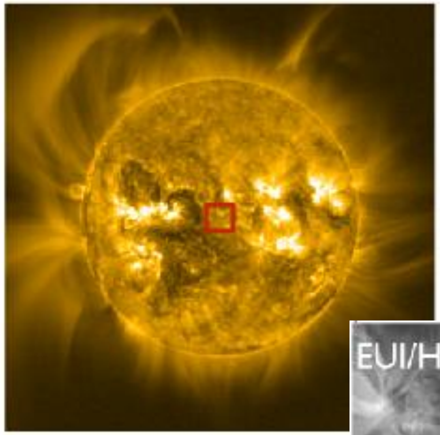




30.4nm

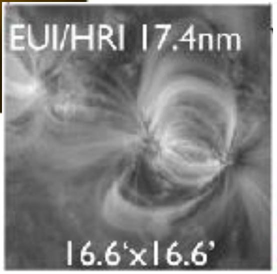
resolution: 9 arcsec on 2 pixels
@ 0.28 AU =1830 km on 2 pixels

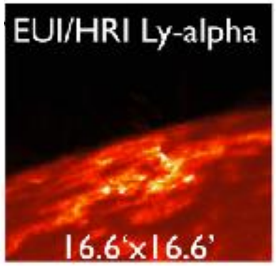
HRI:High Resolution Imagers



FOV:
17'x17'
@ 0.28 AU = (0.16 R)^2

resolution:
1 arcsec on 2 pixels
@ 0.28 AU = 200km

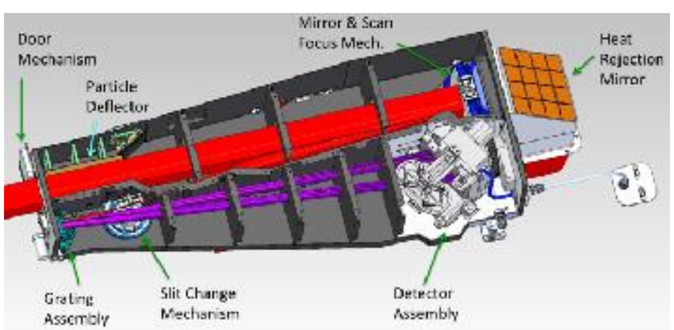


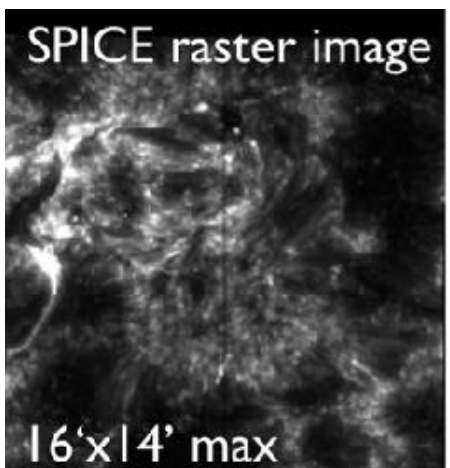


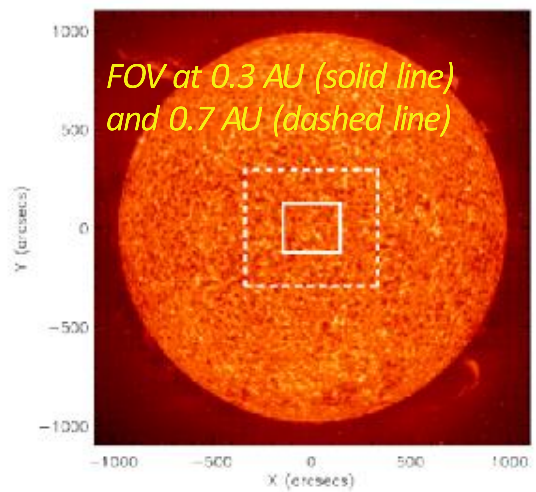
SPICE: EUV Imaging Spectrometer

ESA Instrument, Consortium Lead: Andrzej Fludra (RAL Space)

- SPICE is a high-resolution imaging spectrometer
- It will record EUV spectra & spectral images from the Sun's atmosphere in two EUV bands: 70.39 – 79.02 nm and 97.25 - 104.92 nm
  - 50 spectral lines, excellent plasma diagnostic
  - Selection of lines covering temperatures from chromosphere to flaring corona (2x10^4 – 10^7 K)
  - High resolution chromospheric and coronal images revealing the structure of the atmosphere at different temperatures







16' x 14' area

14' = slit length incl. windows

11' = narrow slit length

Target stays inside the FOV for 2.85 day

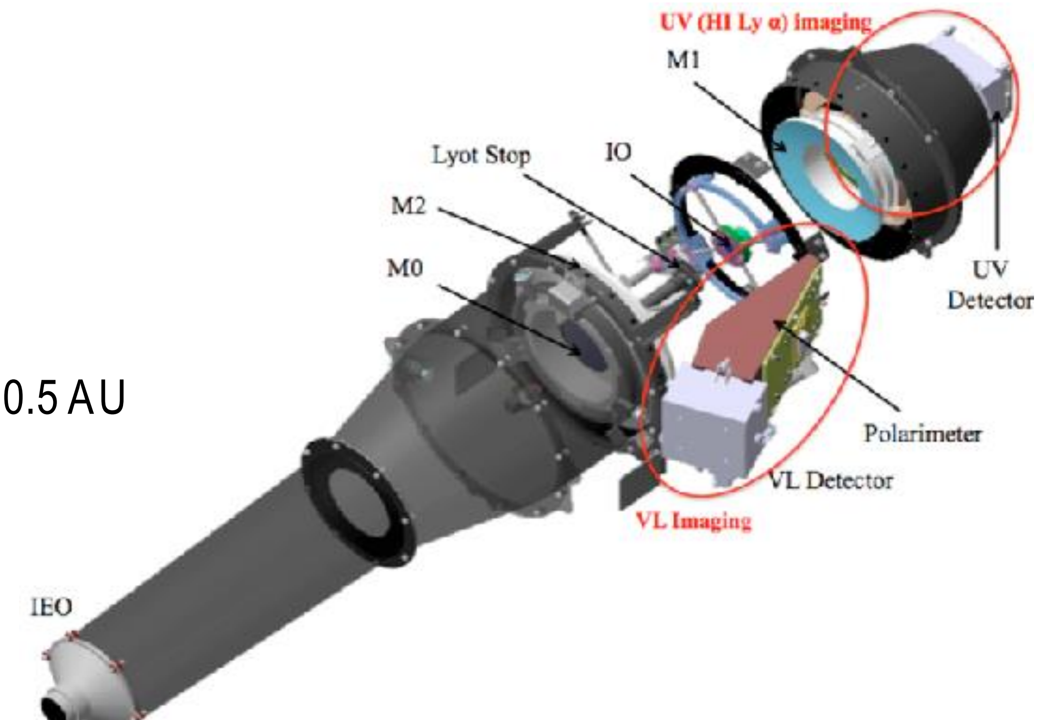
s/c repointing needed

METIS: Multi Element Telescope for Imaging

PI: Ester Antonucci (INAF)

Imaging

- VL (580 - 640 nm polarized light)
- UV (HI Ly α 121,6 nm, 10 nm band)

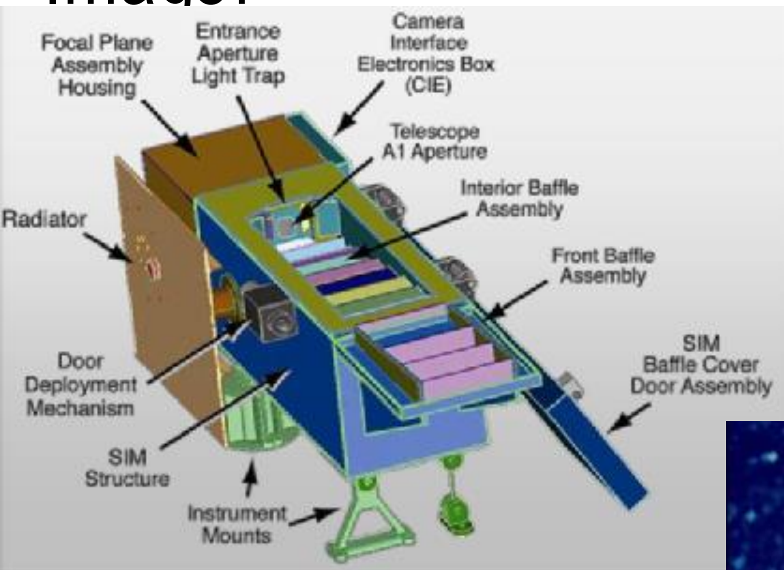


Annular Field of View: 2.6 - 5.5 R⊙ at 0.5 AU
1.6 - 3.1 R⊙ at 0.28 AU

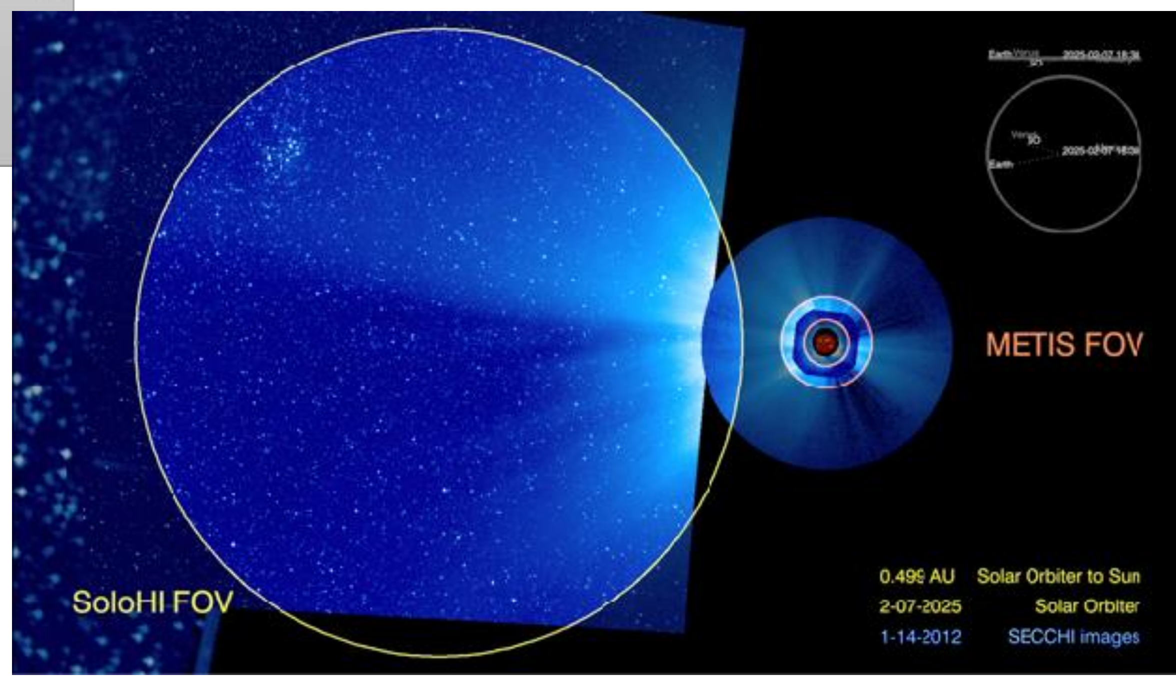
Time resolution: >1 min

Spatial resolution at 0.28 AU:
VL: 4000 km UV: 8000 km

SoloHI: Heliospheric Imager

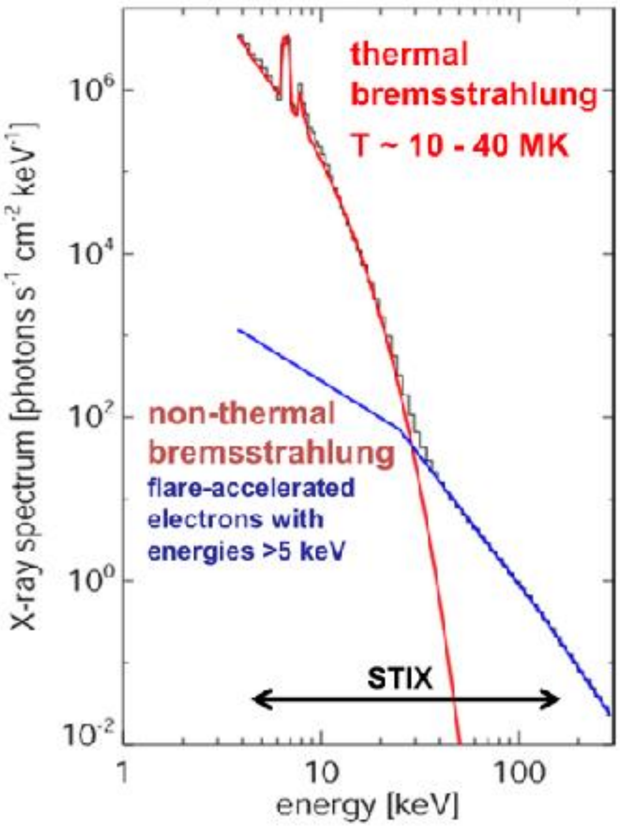


- Wide-field imager from 5 to 45 deg from the Sun
- Visible light observations
- STEREO/SECCHI Heritage

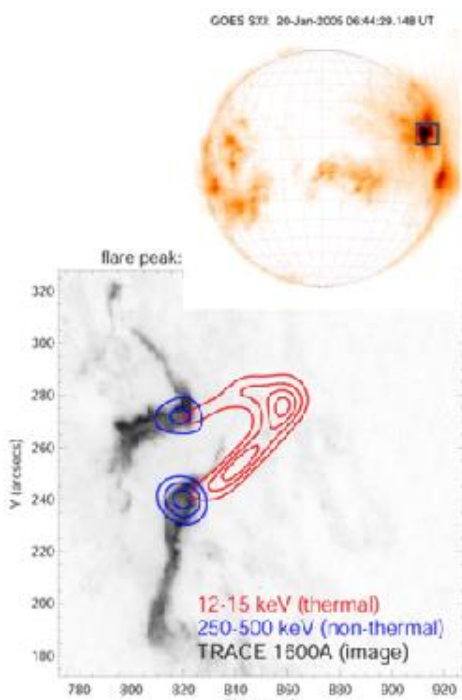


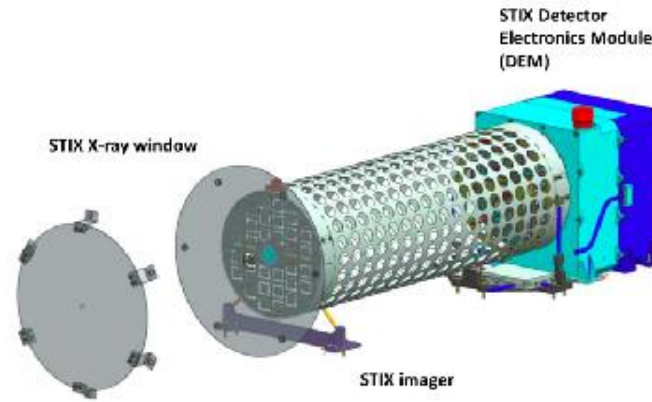
STIX: Spectrometer/Telescope for Imaging X-rays

PI: Säm Krucker (FHNW)



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