Solar Orbiter: Mission, Payload and Operations concept

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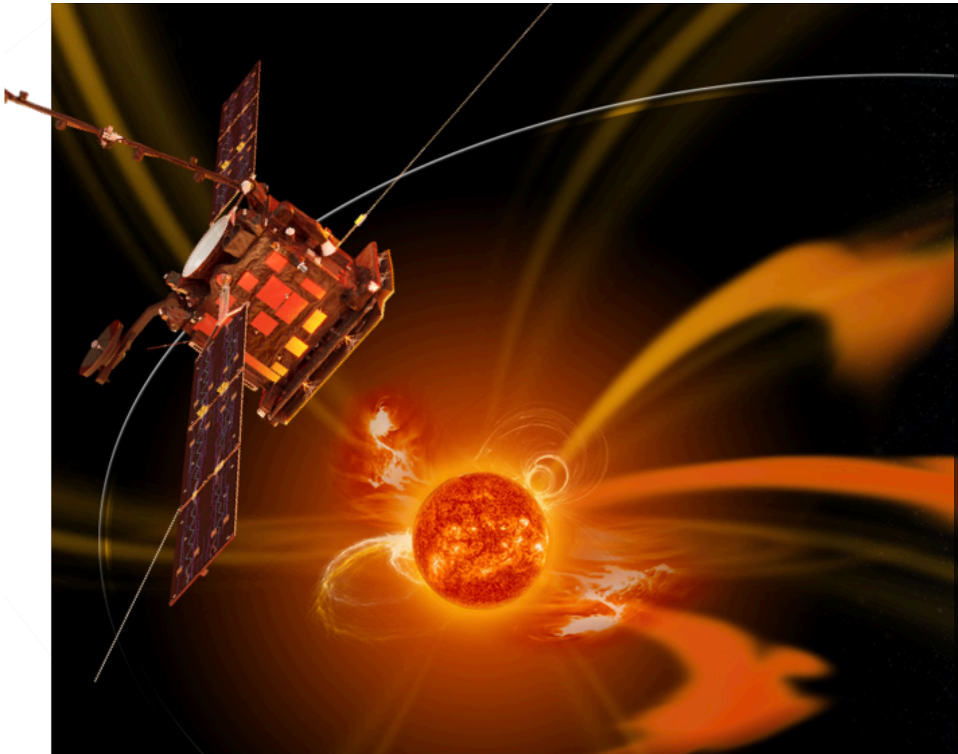
Outline

1. Solar Orbiter: Introduction to the mission's science goals and trajectory
2. Solar Orbiter's Payload
3. Main challenges regarding science operations
4. Planning science operations: Science Activity Plan to Very Short Term Planning
5. Value and opportunities for coordinated science with DKIST and PSP

Solar Orbiter:

MISSION & TRAJECTORY

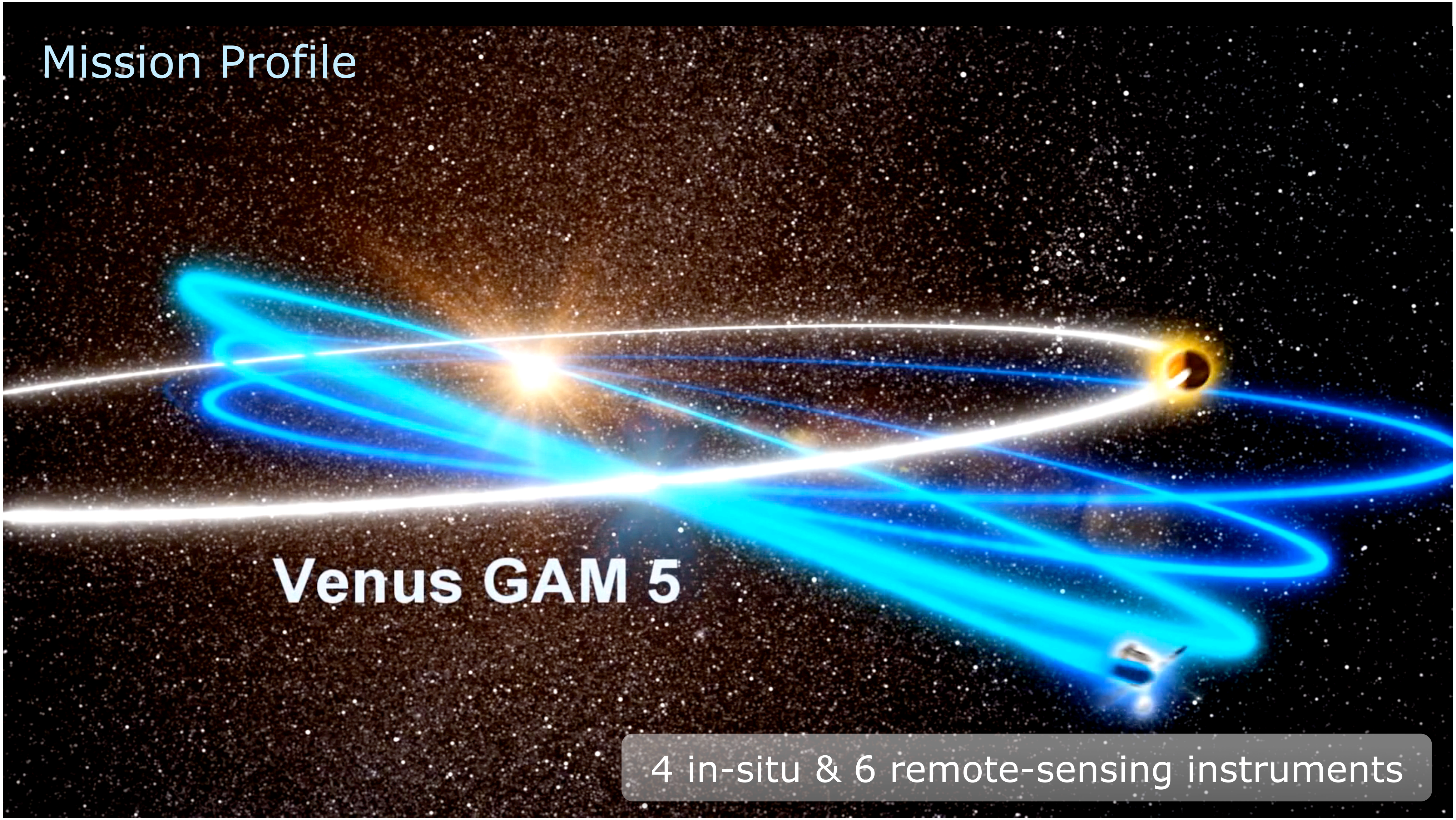
Solar Orbiter: Linking Sun & Heliosphere



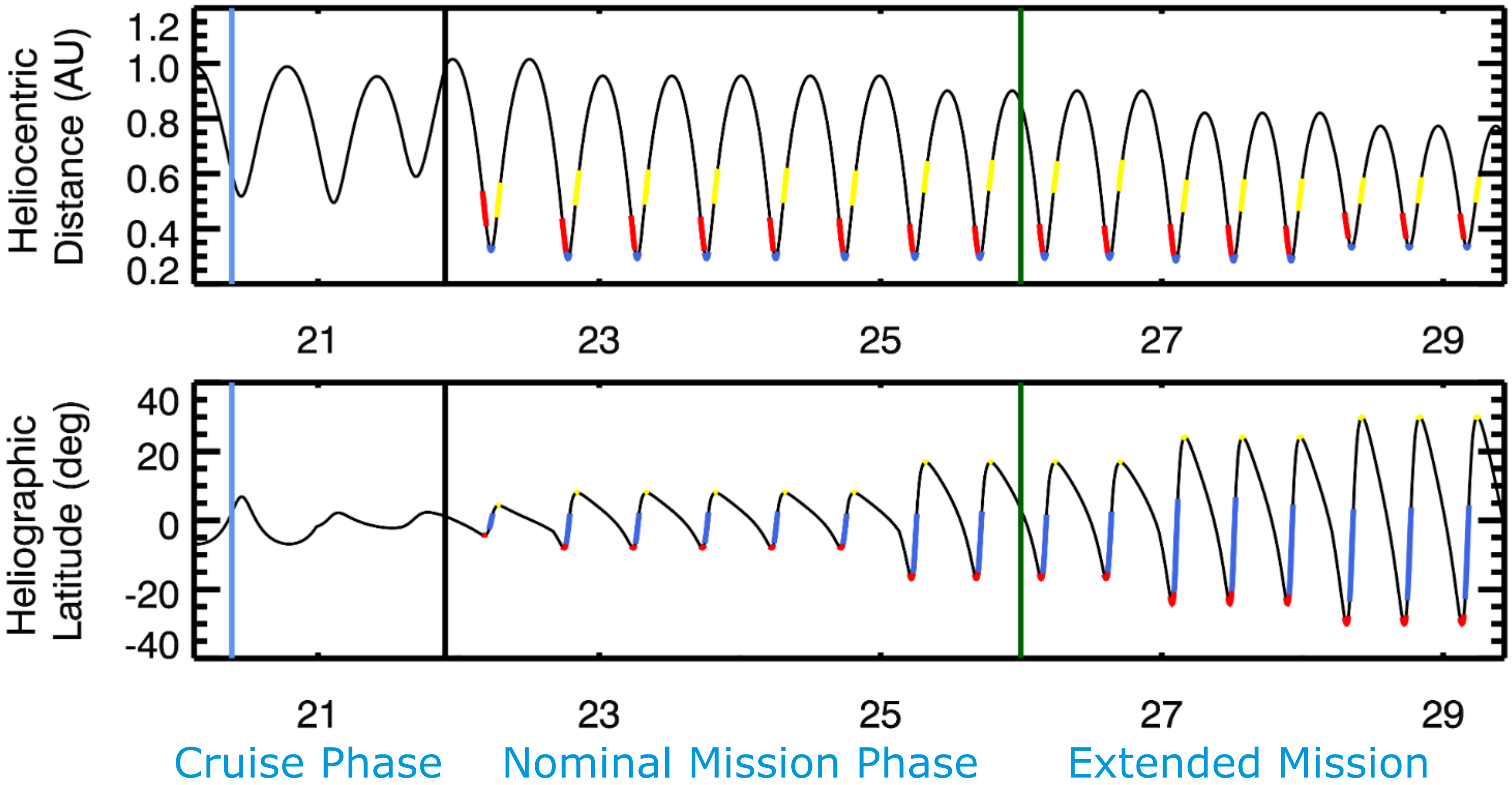
First M-class mission of ESA's Cosmic Vision 2015-2025 (collaboration NASA)

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

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


Mission Profile
Venus GAM 5
4 in-situ & 6 remote-sensing instruments

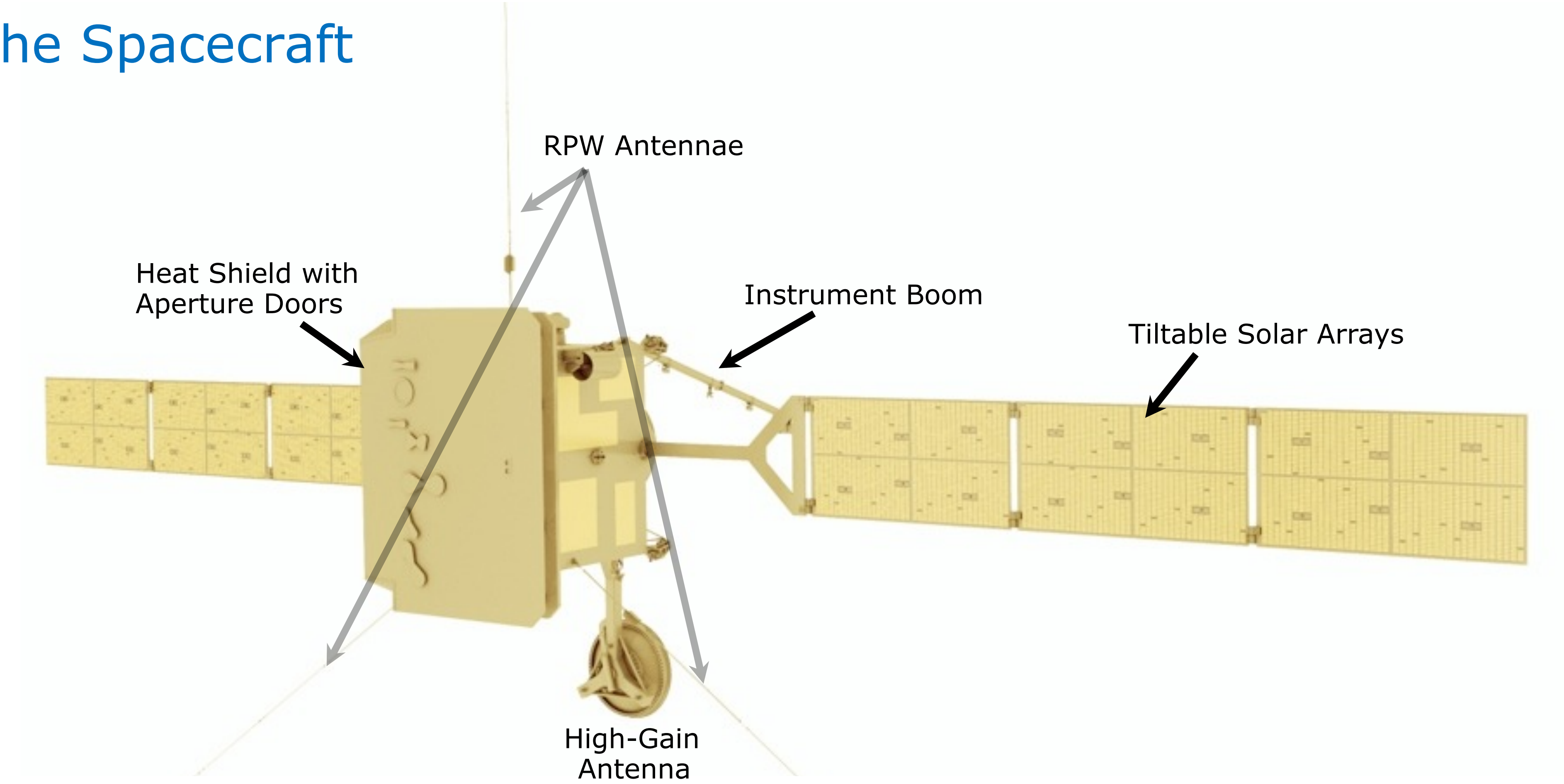
Mission phases (Feb 2020)



Solar Orbiter:

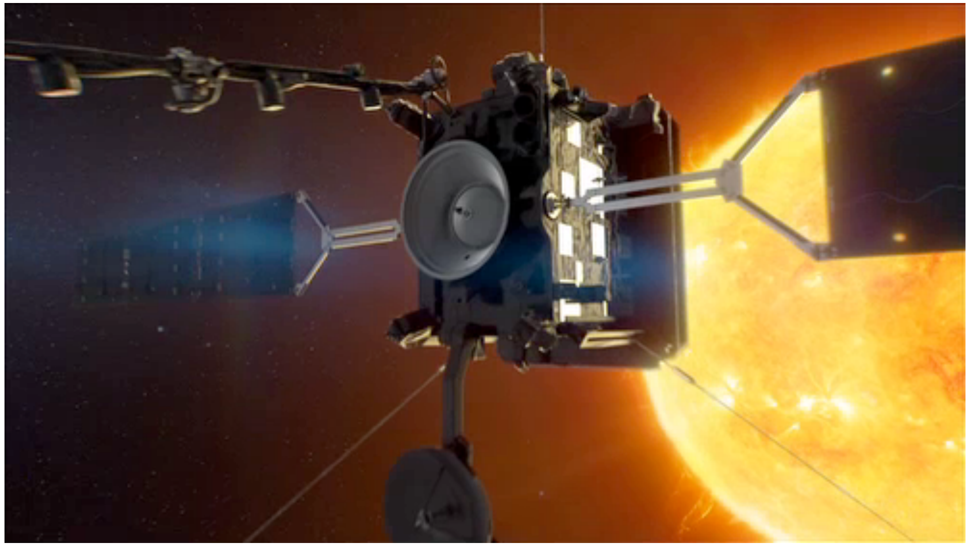
SPACECRAFT & PAYLOAD

The Spacecraft



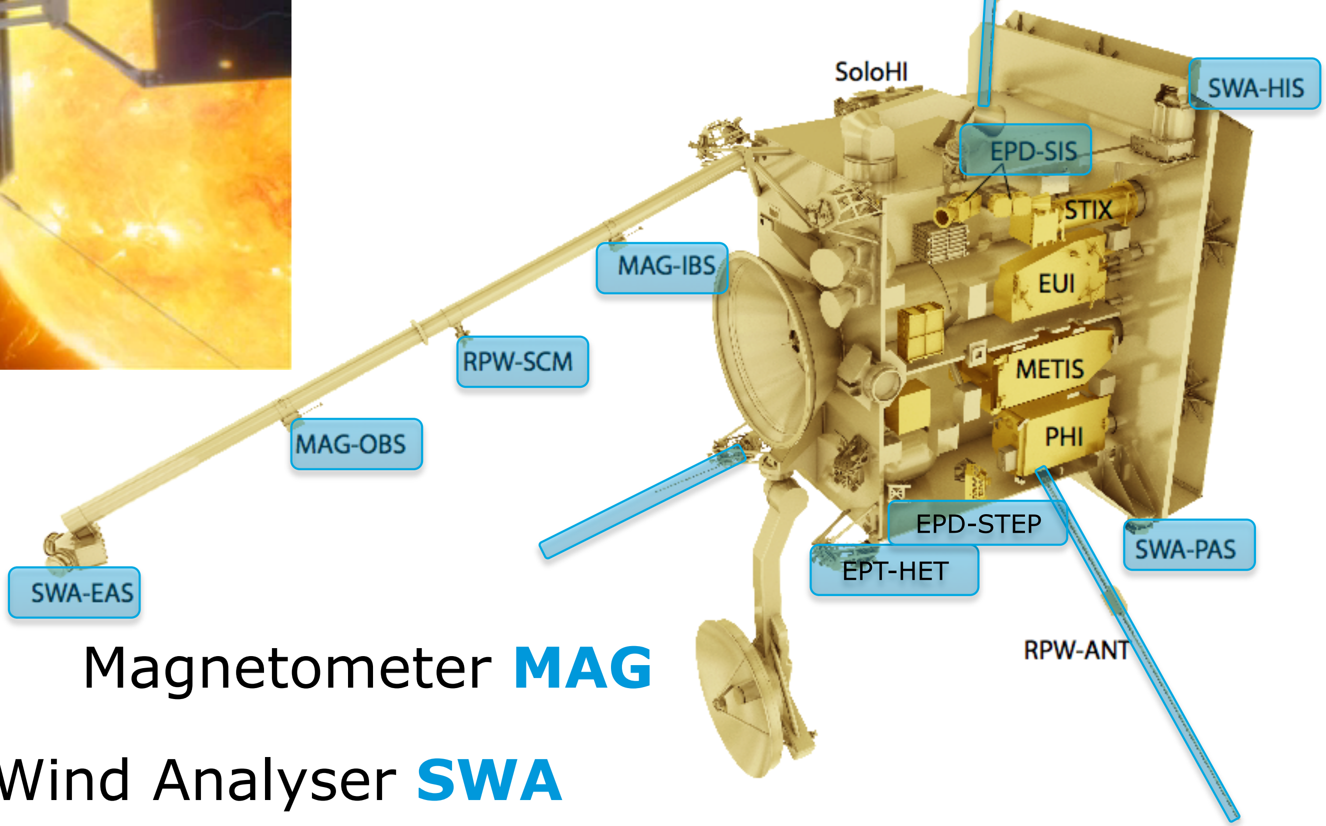
Payload

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	Visible and (E)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



Radio and Plasma Waves **RPW**

Energetic Particle Detector **EPD**



Magnetometer **MAG**

Solar Wind Analyser **SWA**

In-Situ Payload

What will Solar Orbiter measure In Situ?

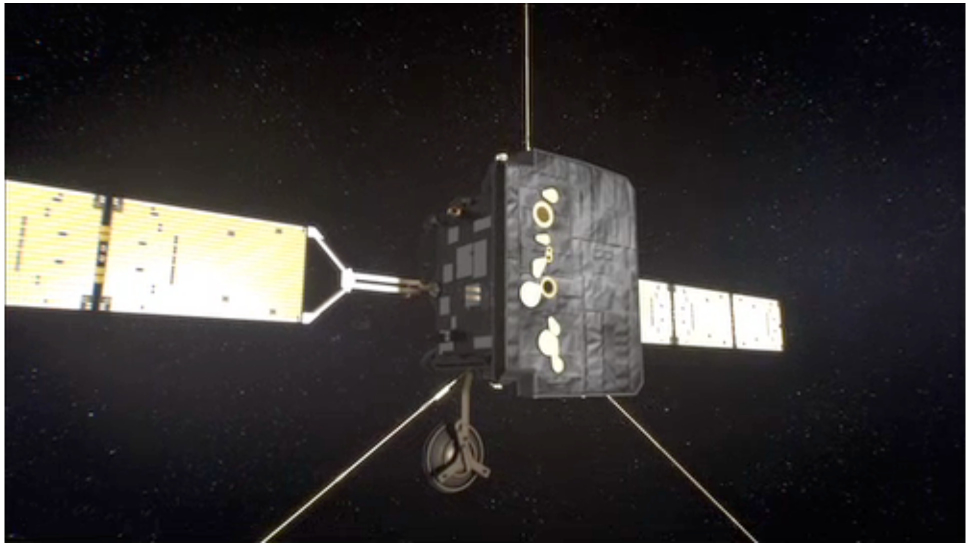
Particles:

- **Electrons**
    - 1 eV - 5 KeV Energy Distributions & Moments
    - 2 keV - 15 MeV Fluxes & Anisotropies
- **Protons**
    - 200 eV - 20KeV 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

What will Solar Orbiter measure In Situ?

Fields:

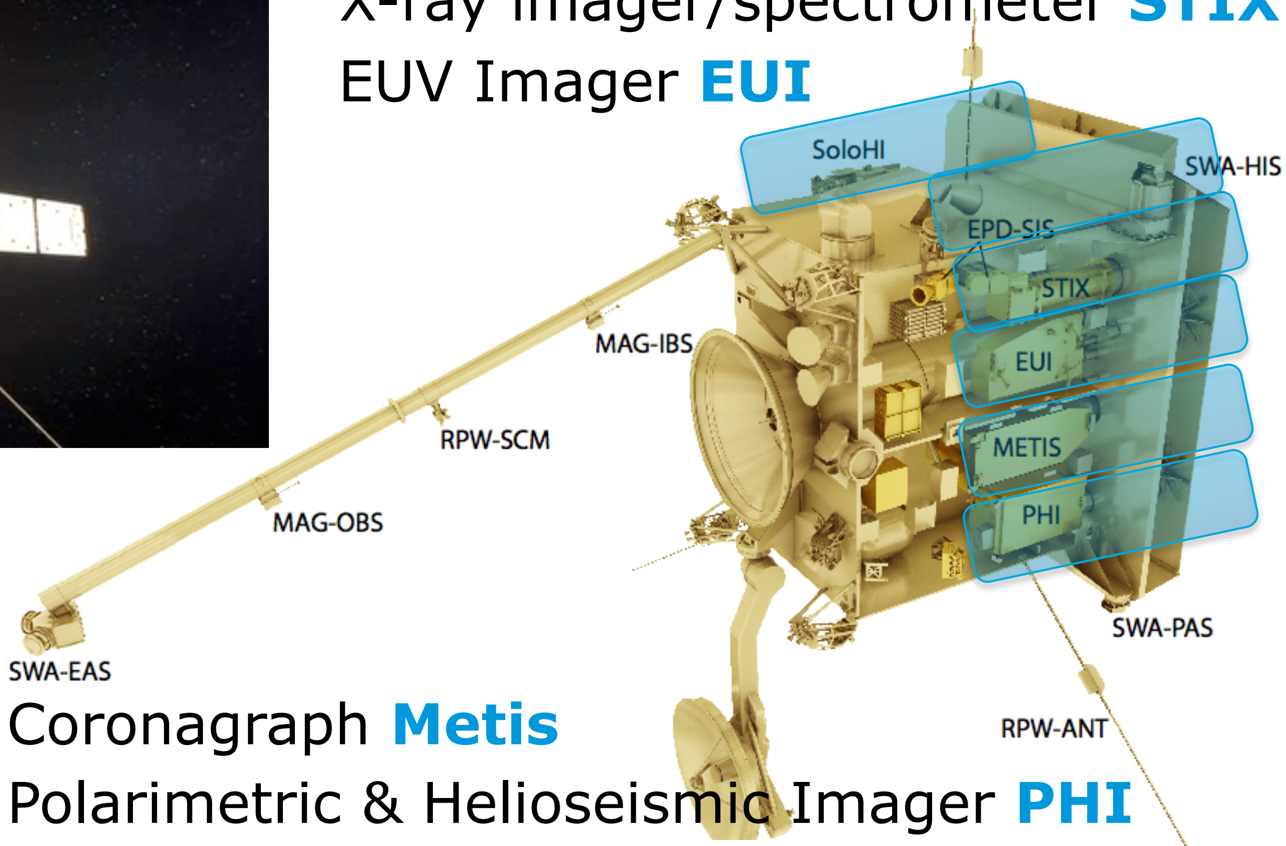
- **Magnetic fields:**
  - Fluctuations of down to 5 pT
  - on timescales of < gyro-frequencies < *t* < days
- **Electrostatic fields**
  - DC (and low-*f*) electric fields
  - Density fluctuations in the solar wind
  - **E** due to Shocks, reconnection
  - Electron density & temperature
- **Electromagnetic 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



Imaging Spectrometer **SPICE**

X-ray imager/spectrometer **STIX**

EUV Imager **EUI**



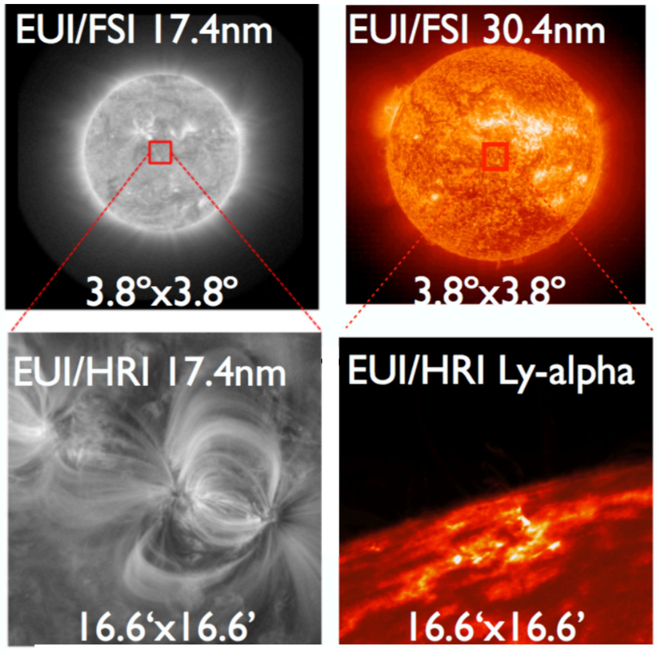
Remote-Sensing Payload

Coronagraph **Metis**

Polarimetric & Helioseismic Imager **PHI**

Heliospheric Imager **SoloHI**

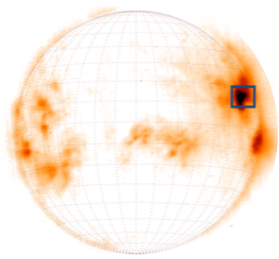
Photons 1



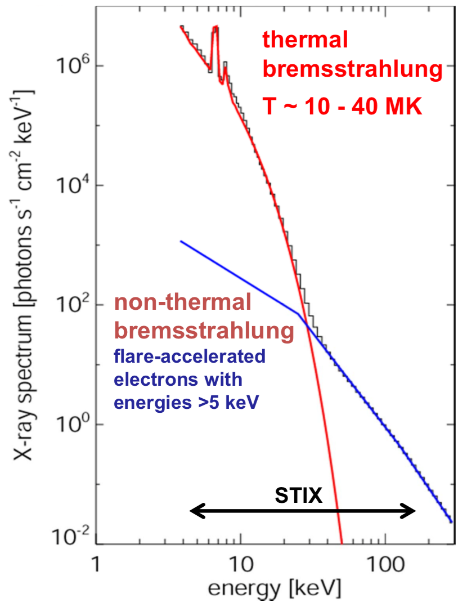
EUV Imager **EUI**

Full Sun Imager FSI

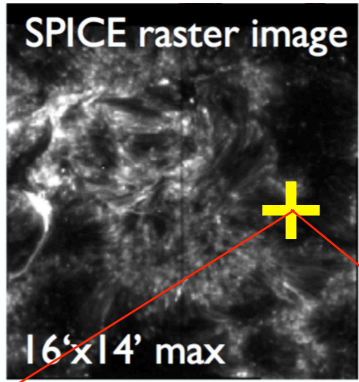
2 High Resolution Imagers HRI



STIX imaging

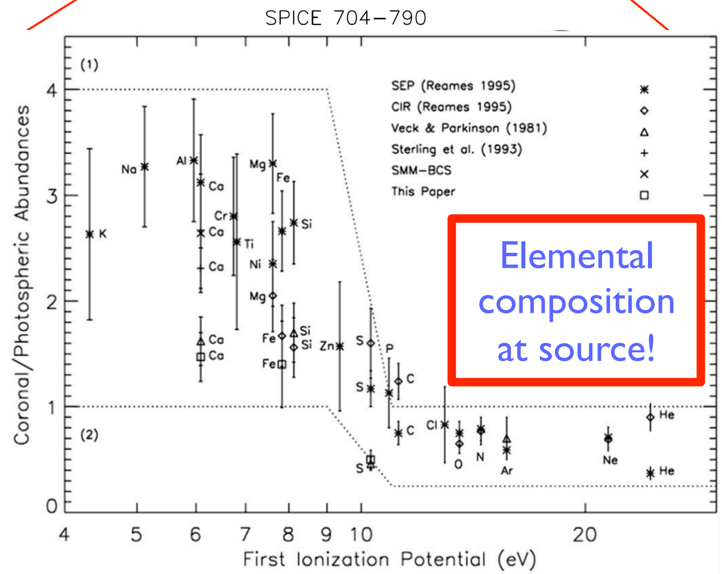


STIX spectra



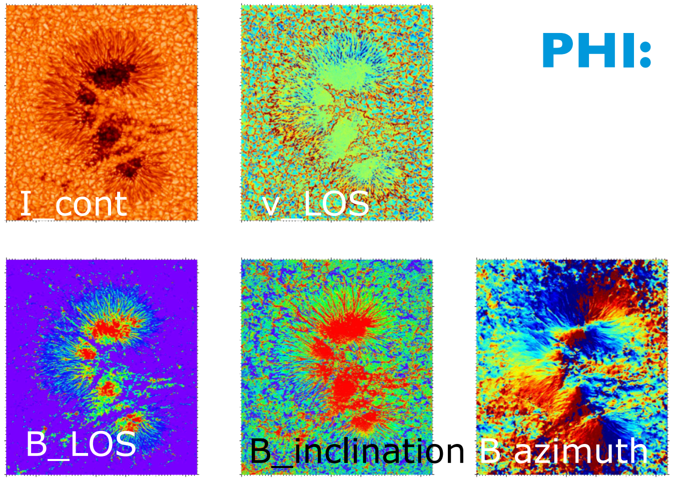
SPICE

sit-and-stare or rasters

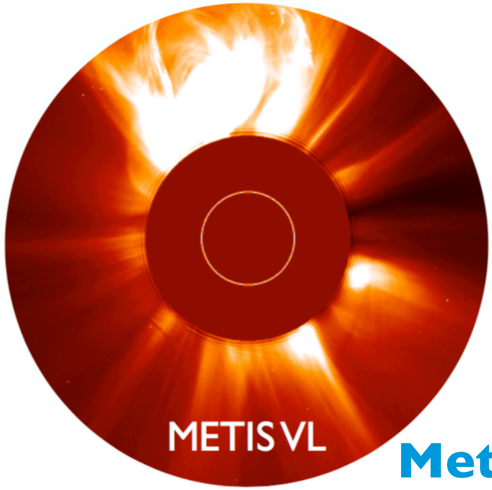


Photons 2

PHI: Full Disc Telescope FDT *or*
High Resolution Telescope HRT



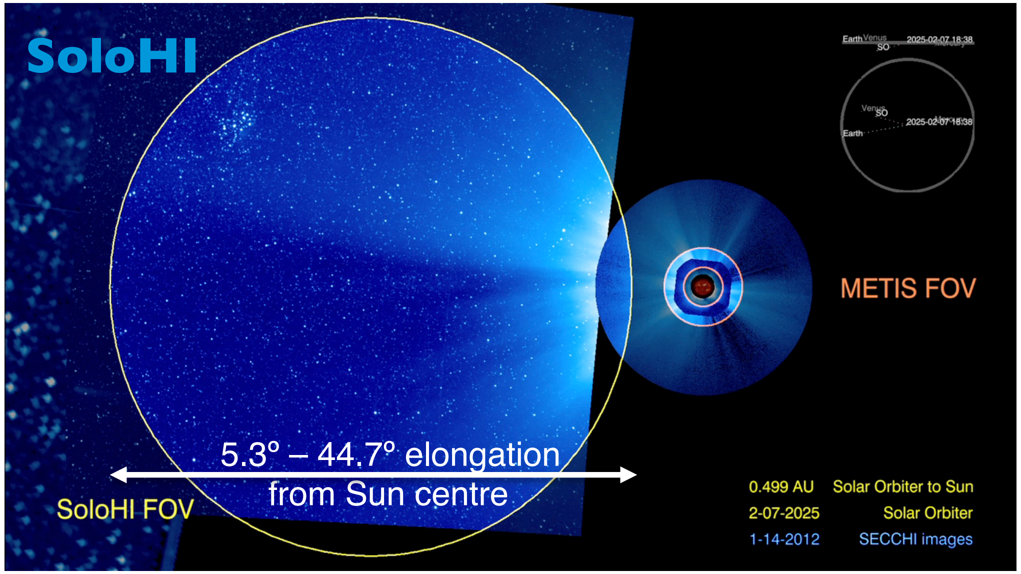
These 5 physical quantities are being produced onboard after processing raw filtergrams at 6 spectral positions (around FeI 617.3nm) and 4 polarisations.



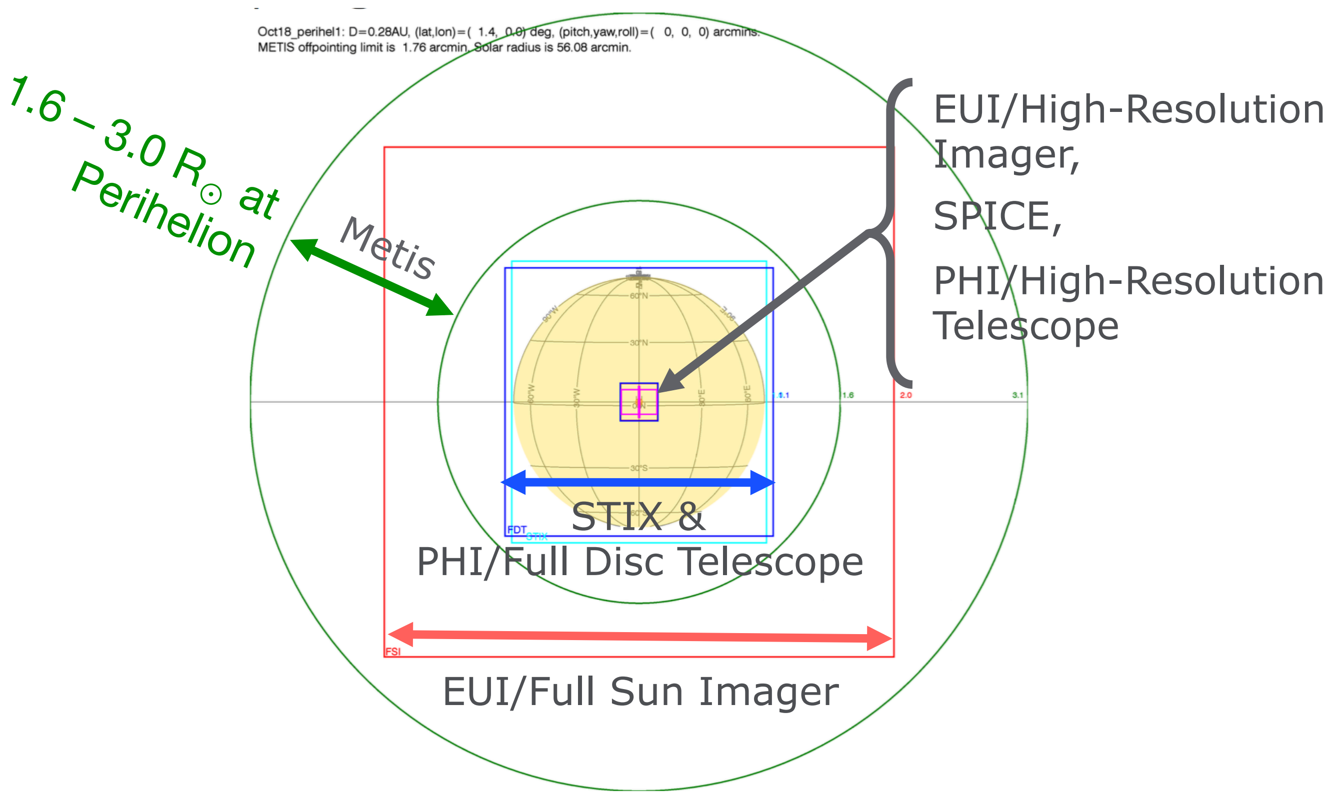
Metis

UV (HI 121.6 ± 5 nm
VL (580 – 640 nm)
polarised light

Combination also gives solar wind speed *via* Doppler dimming



Remote Sensing Fields of View



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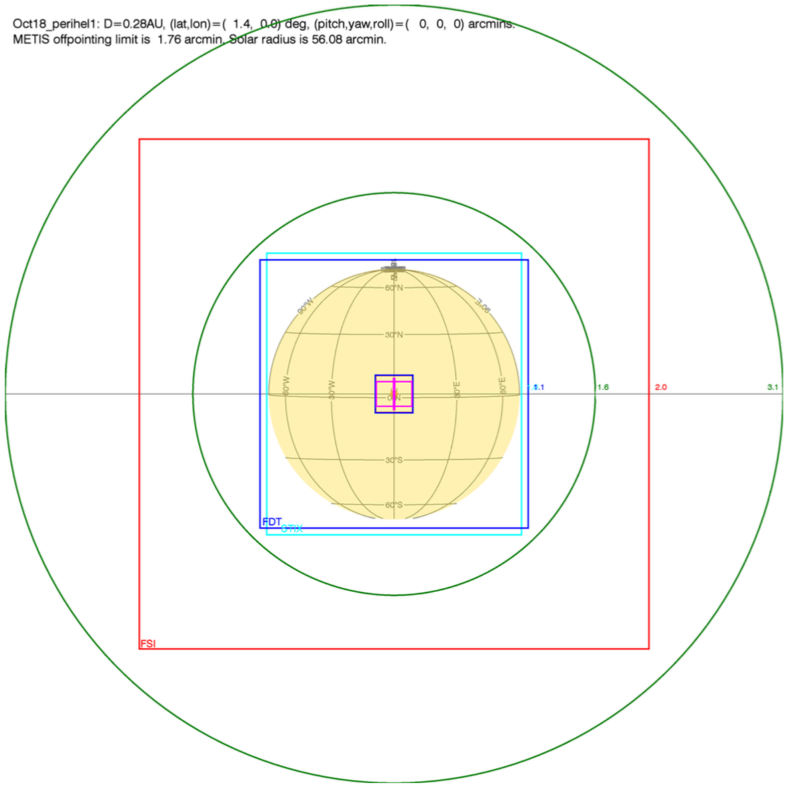
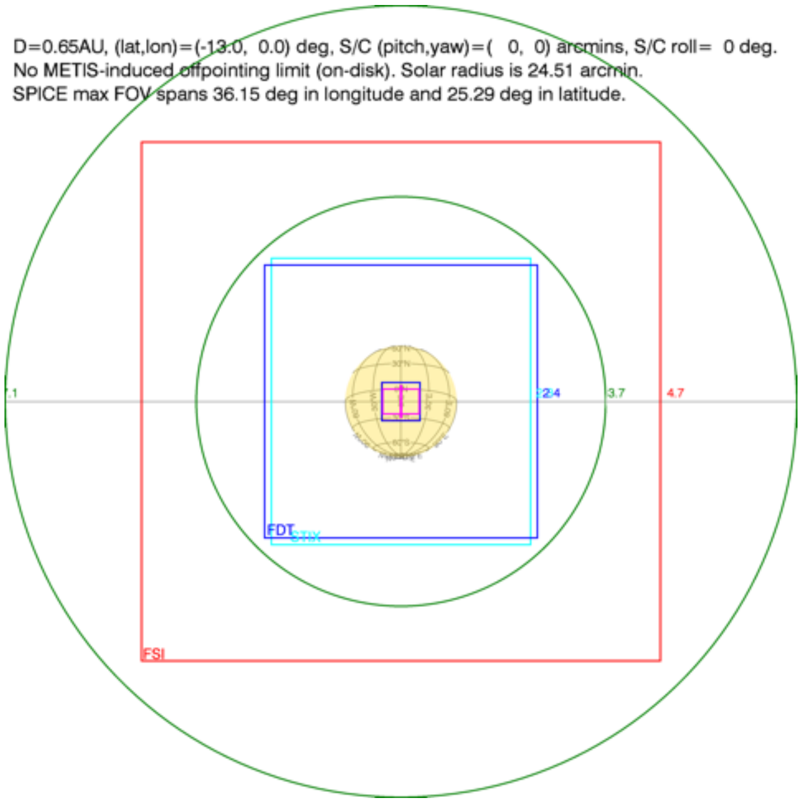


Perihelion 1 - 0.28AU



0.65AU

Remote Sensing Payload: details

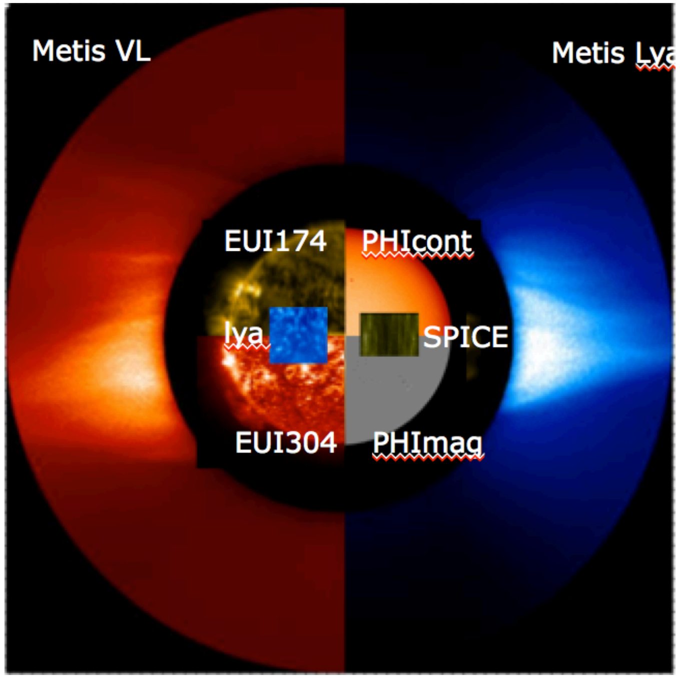
Instr	Telescope	WL	FOV	Resolution @ 0.28AU	Resolution @ 0.8AU	Cadence
EUI	FSI (full disk)	17.4 nm 30.4 nm	3.8°x3.8°	9″ (1800km)	9″ (5200km)	≥10s
	HRI_EUV HRI_Lya	17.4 nm 121.6nm Ly-a	16.6′x16.6′	1″ (200km)	1″ (580km)	≥1s ≥0.1s
PHI	FDT (full disk)	617.3 nm	2°x2°	7″ (1400km)	7″	≥1min
	HRT	617.3 nm	16.8′x16.8′	1″ (200km)	1″ (580km)	≥1min
SPICE		70.4-79nm 1st 97-105nm 2nd	Slits 2″ to 30″ Max 16′x11′	1″ along slit 2″ min step		≥few sec
Metis	Visible UV	580-640nm 121.6nm Ly-a	1.5°-2.9°	10″ (1.6–3.1 $R_{\odot}$)	10″	≥1s
STIX		1.9°x2.1°		7″ (1400km)		
SoloHI		475-755nm	40°x39°, 5° E	~2′	~2′	≥12s

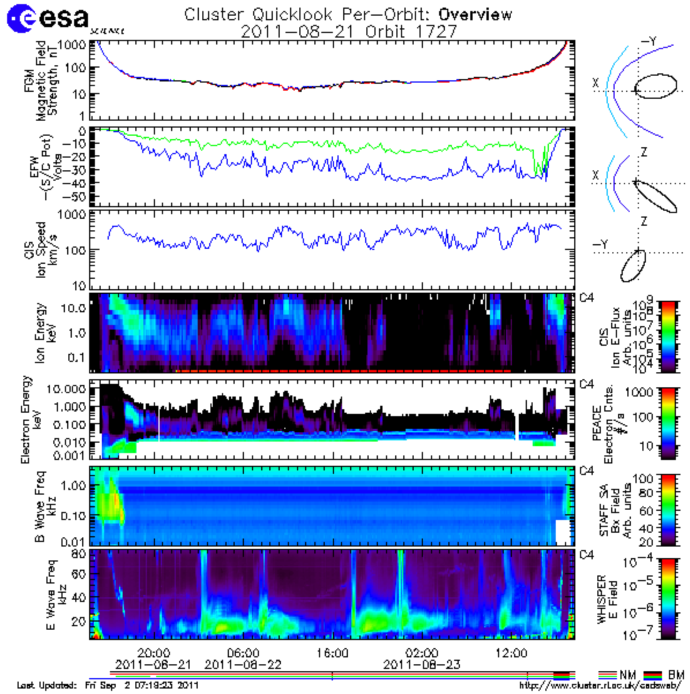
Solar Orbiter:

OPERATIONAL CHALLENGES

Solar Orbiter: Operational challenges

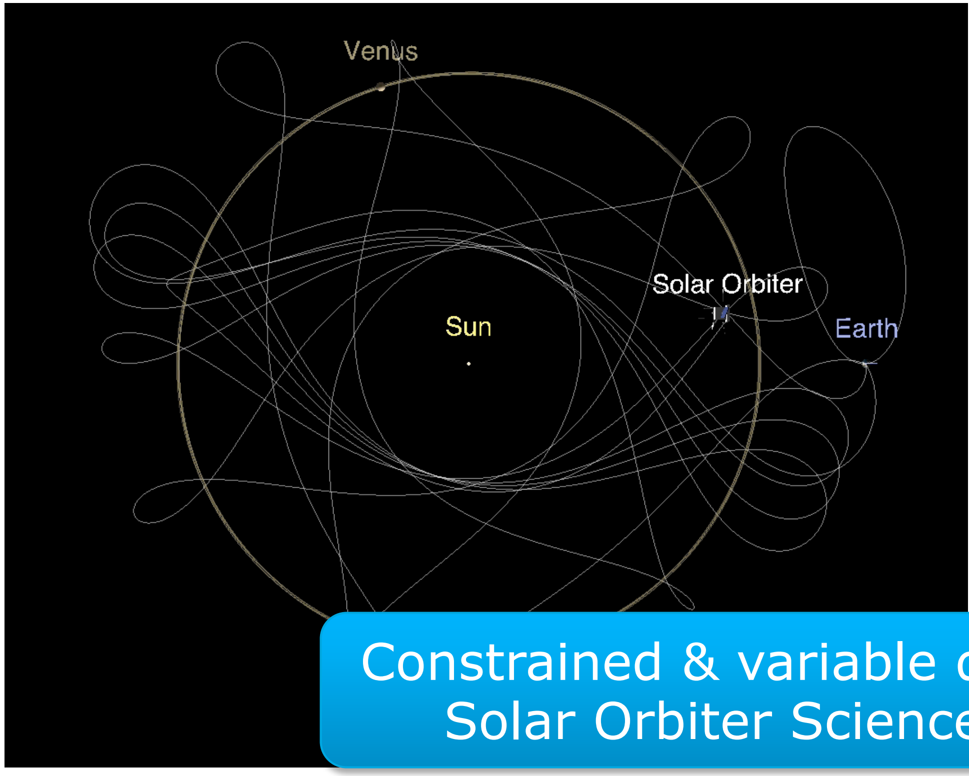
- Combines 2 worlds: **in-situ** + **remote-sensing** observations
  -> different requirements, EMC, linking!



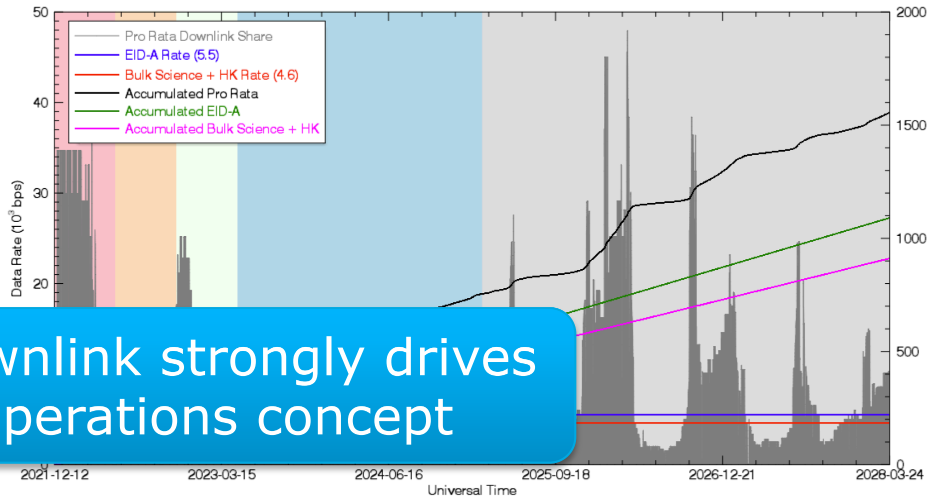


Solar Orbiter: Operational challenges

- **Variable** viewpoint, distance from Sun and from Earth:



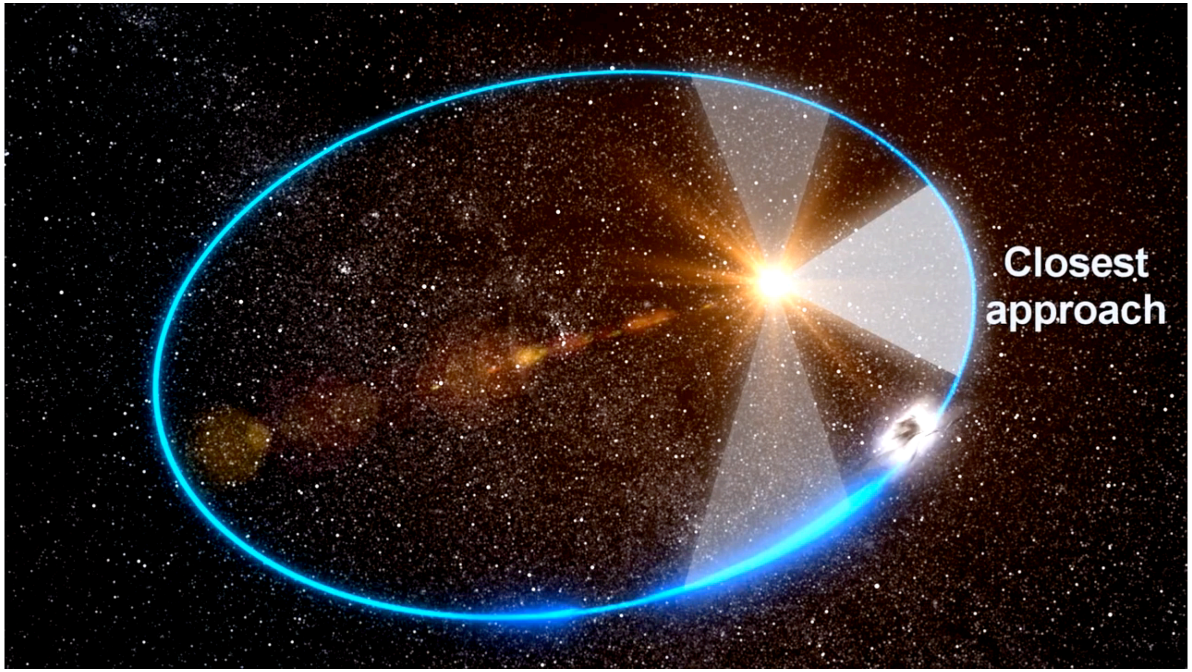
- Different observation opportunities (geometric alignments, quadrature, Parker-spiral alignments, … wrt Earth and PSP)
- Data **latency** up to 6 months, limited onboard storage



Constrained & variable downlink strongly drives Solar Orbiter Science Operations concept

Solar Orbiter: Operational challenges

- **Limited observation time** for remote-sensing (~1/5 of the time): three 10-day RS windows per orbit
- **Offline Commanding**: limited opportunity to respond to changing Sun
- **Shared pointing**



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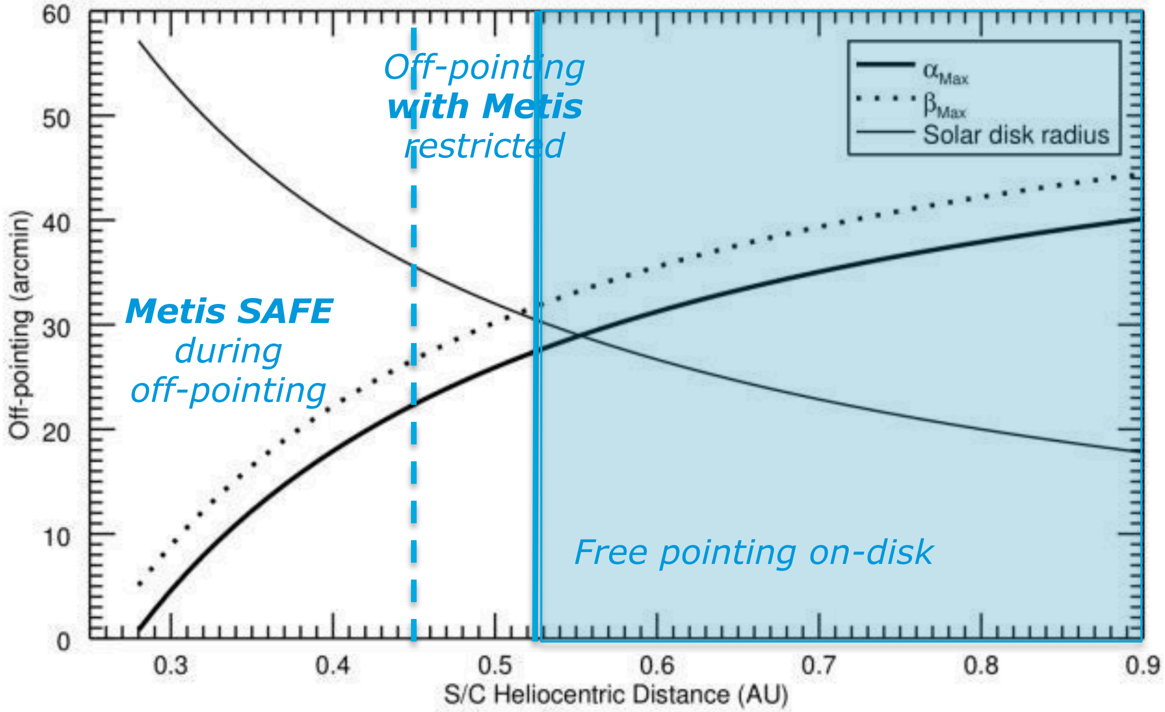
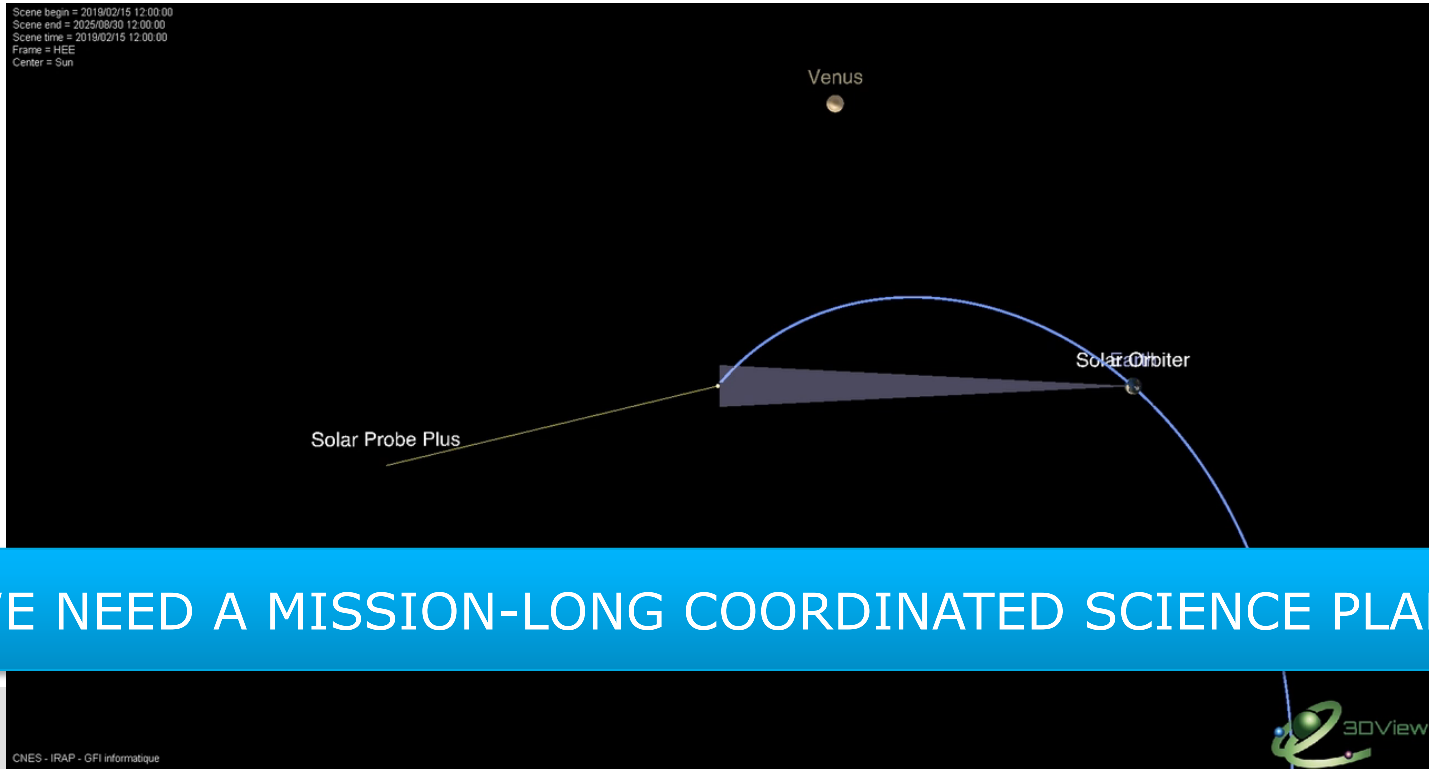


Metis' off-pointing constraint

Solar Orbiter: Operational challenges

Most scientific objectives need **coordinated observations** with **whole payload**, at specific opportunities.

+ coordination with other missions (Parker Solar Probe) and ground (DKIST, …)



WE NEED A MISSION-LONG COORDINATED SCIENCE PLAN!

Solar Orbiter:

PLANNING CYCLES

Solar Orbiter's Planning Cycles

- Mission-level Planning *(now) ->* **SAP**
- Long-Term Planning *(6-12m ahead)*

  Science Operations Working Group schedules Solar Orbiter Observing Plans (SOOPs). Covers 6 months.

→ Planning coordination & high-level constraint checking

- Medium-Term Planning *(1-7m ahead)*

  Detailed commanding per instrument over 6 months, validated against mission constraints.
- Short-Term Planning *(1-2w ahead)*

  Covers 1 week, last call for changes in instrument modes.

→ Instrument commanding (IORs) & detailed constraint checking

- Very-Short-Term Planning *(2-3 days)* → Adapting to the changing Sun
  - p-VSTP: adjust S/C pointing to solar activity
  - i-VSTP: limited instrument fine-tuning (resource-neutral)

Solar Orbiter's Science Activity Plan (SAP)

- Strategic plan covering the science we are going to do and when over the whole mission (Science Working Team + SOC).
- How?

trajectory independent:

Detailed science objectives

↓ *Group objectives that require similar, coordinated observations*

Set of SolO Observing Plans (SOOPs)

↓ *Find best opportunities for each SOOP in typical trajectories.*

SOOP scheduling strategy

↓ *Schedule all SOOPs in given trajectory*

Science Activity Plan for particular trajectory

L_SMALL_HRES_HCAD_SlowWindConnection

Instrument	Mode	Comments
EUI	EUI/HRI Coronal hole mode (C) EUI/FSI Synoptic mode (S) (FSI)	HRI (C) at 1 min cadence FSI (S) throughout
Metis	MAGTOP or GLOBAL for context & to link solar wind source regions to S/C	Only applicable if beyond ~0.5AU during target tracking
PHI	PHI_HRT_MODE_2	Regularly spaced HRT data at med- to hi-res. PHI LL magnetograms needed throughout
SoloHI	HI_SYN_NEAR	
SPICE	SPICE_WIND_CONNECT*	Dynamics & SPICE Composition Mapping. Raster area should be optimized to make sure open-closed field boundary is captured
STIX	STX_NORMAL	not strictly needed for SOOP although context is appreciated
EPD	Close mode + Scheduled/triggered burst	
MAG	Normal + Scheduled/triggered burst	
RPW	normal + scheduled/triggered burst	selective downlink useful
SWA	normal + scheduled/triggered burst	

Mapping Objectives to the SOOP

L_SMALL_HRES_HCAD_SlowWindConnection

SAP objective	Target	Duration	Opportunity (*e.g.*, orbital requirements, solar cycle phase, quadrature …)	Operational constraints
1.1.4.1.1 Interchange reconnection between open and closed field lines and its role in slow wind generation *(see Planning exercise Jan 2016 - SOOP2)*	Open-Closed field line boundaries (near ballistic connection point): • CH boundaries • AR edges close to low-latitude open field • Intermediate areas of quiet Sun **Target tracking**	~1 RSW (10 days)	• to be studied for CHs in different locations (high vs low latitudes) • different opportunities along the orbit: high-latitude windows + perihelion • to be studied in different solar cycle phases • Earth view before the observations would be asset to use modelling to define best target	• During RSW • pre-window synoptics needed for target choice • VSTP updates needed for target tracking • EMC quiet for connectivity
1.1.2.2 Does slow and intermediate solar wind originate from coronal loops outside of coronal holes?	coronal loops outside of coronal holes	few days	• near perihelion for resolution & better linkage conditions • different phases of solar cycle	• it may be worthwhile to map around the whole AR to have higher chance of being connected • EMC quiet for connectivity
1.2.2.6 Study fast plasma flows from the edges of solar active regions discovered with Hinode/EIS	edges of solar active regions - at most likely ballistic connection point	few hours/days		• fast flows require high cadence observations (mainly SPICE and HRI?)
1.1.2.10 Trace streamer blobs and other structures through the outer corona and the heliosphere.			• Near-quadrature, so that SoloHI can image Earth-directed blobs	
1.2.2.5 Magneti[c] … chromosphere, … corona				

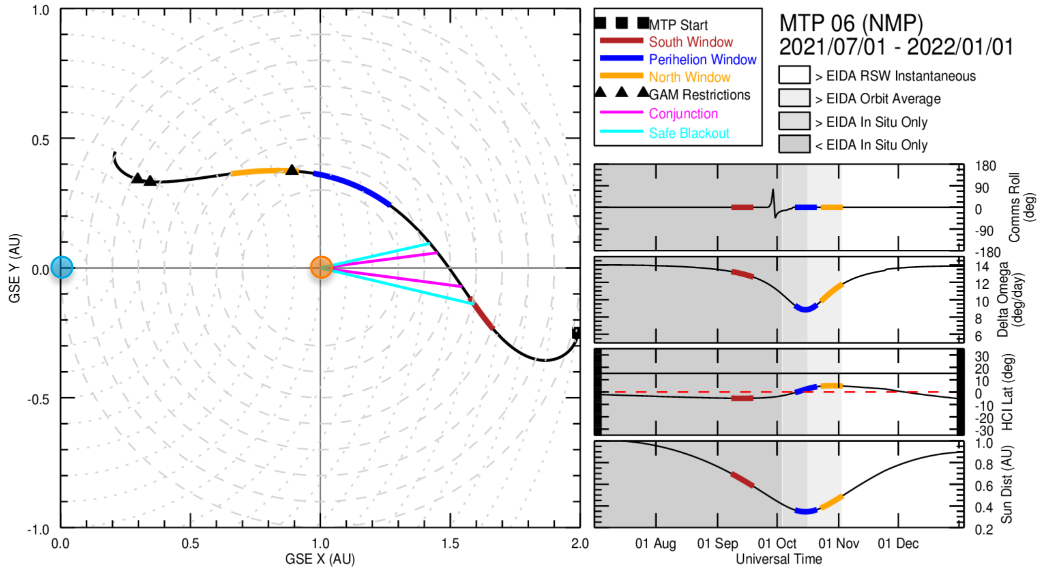
Each SOOP can have different objectives, targets, durations, etc., but operations are similar.

Solar Orbiter's Science Activity Plan - Status

- SAP v0 for NMP has been written, by SOC & Project Scientists. Under review by SWT.
  - First set of SOOPs defined
  - Preliminary SOOP scheduling strategy, based on typical opportunities along trajectory
  - First attempt to schedule SOOPs in one particular trajectory (default RSwindows still)
- Cruise Phase SAP has been drafted (SO only)

Available on wiki-pages 'SOC Public':

- Orbit Plots
- Instruments: observables, modes and operational constraints
- SAP-related work
  - Solar Orbiter detailed science objectives
  - SOOP pages
  - General Planning strategy for first version SAP v0
  - Planning periods Option E (LTP/MTP)



Solar Orbiter's Planning Cycles

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  Science Operations Working Group schedules SOOPs in more detail. Covers 6 months.

Planning coordination & high-level constraint checking

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- Short-Term Planning *(1-2w ahead)*

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Instrument commanding (IORs) & detailed constraint checking

- Very-Short-Term Planning *(2-3 days)*
  - p-VSTP: adjust S/C pointing to solar activity
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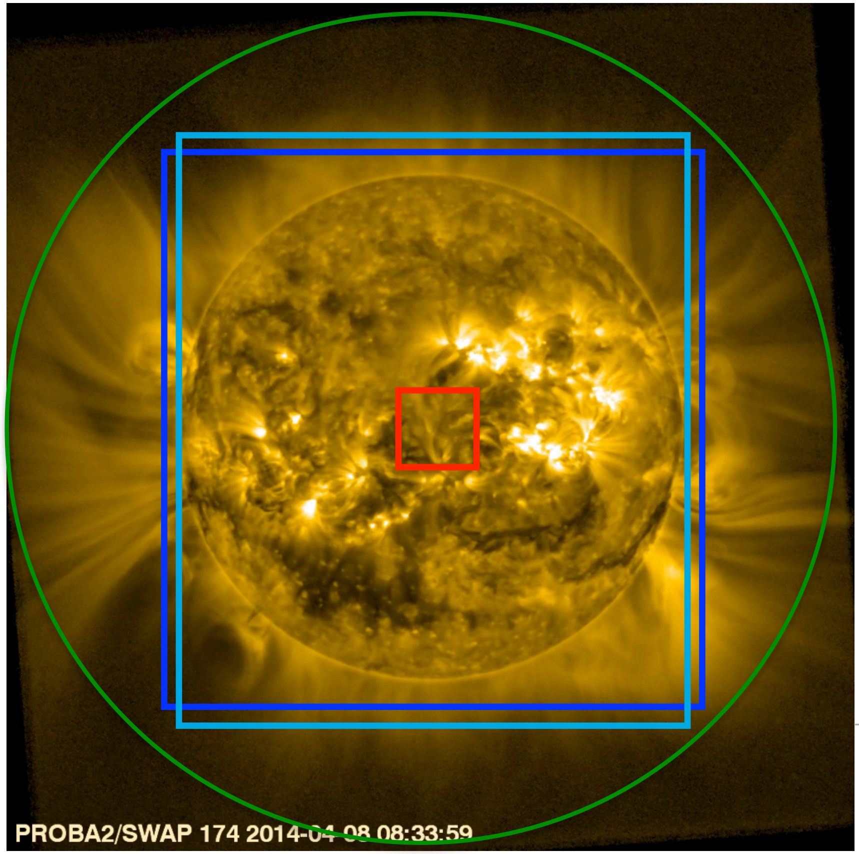
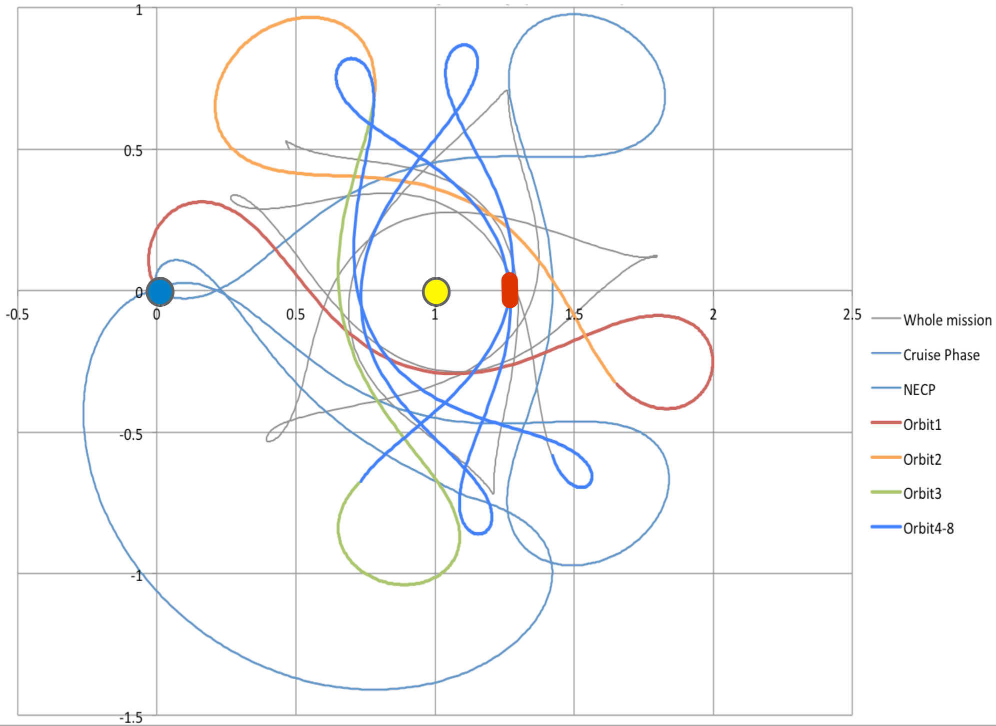
Adapting to the changing Sun

Very Short Term Plan: Reacting to variable Sun





High-res FOV are small and all share same pointing. You cannot always rely on Earth context for target picking!

Very Short Term Plan relies on Low-Latency data

Solar Orbiter needs minimal set of data to be downlinked at next pass, to allow target selection and tracking

= Low-Latency (LL) data

-> minimal set of science data (~1MB/instrument), downlinked daily

e.g.

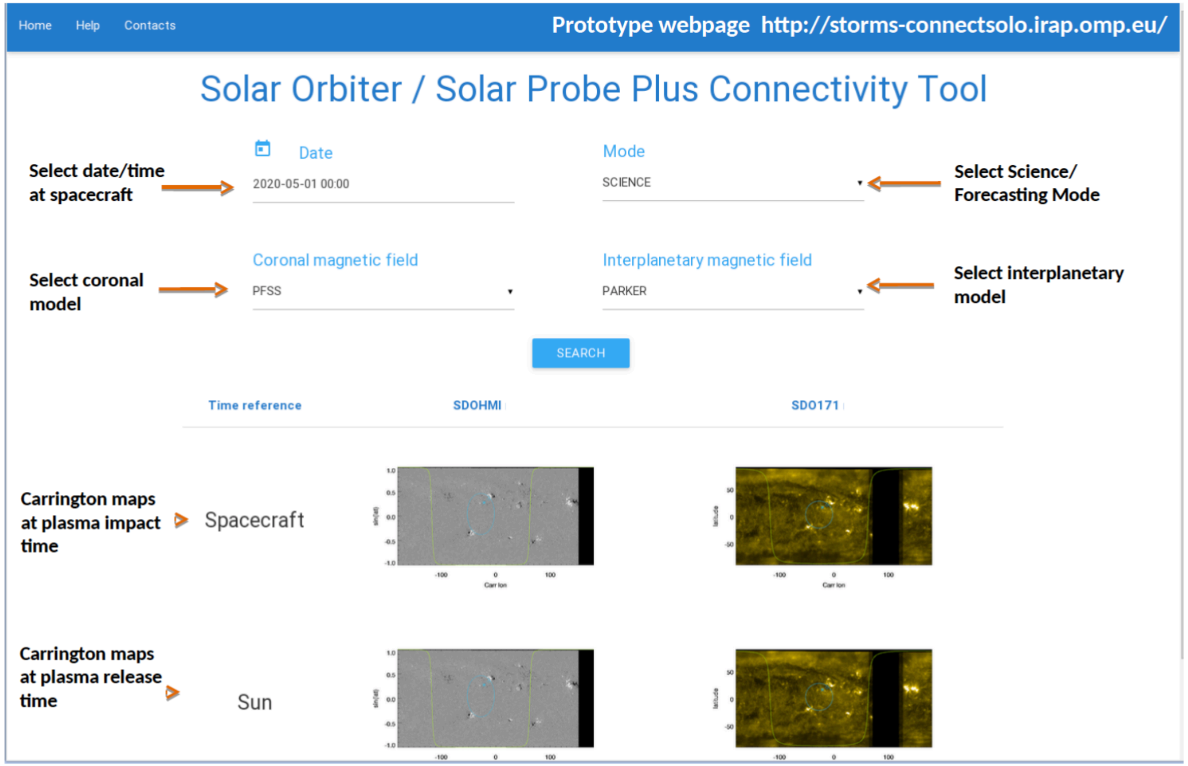
- EUI low-resolution, full-disk data (~STEREO beacon data)
- PHI full-disk magnetograms and intensity data
- STIX flare detections
- Metis lightcurves incl. CME detections
- Subsets of in-situ data (e.g. low-cadence)
- ...

Very Short Term Plan: Reacting to variable Sun

- During RS windows, **update S/C fine-pointing** to track features
  - Fine-pointing can be updated daily, but takes ~3 days to execute!

- Based upon
  - **Low-Latency data**
  - **Modelling** Sun-S/C connection (magnetic field)

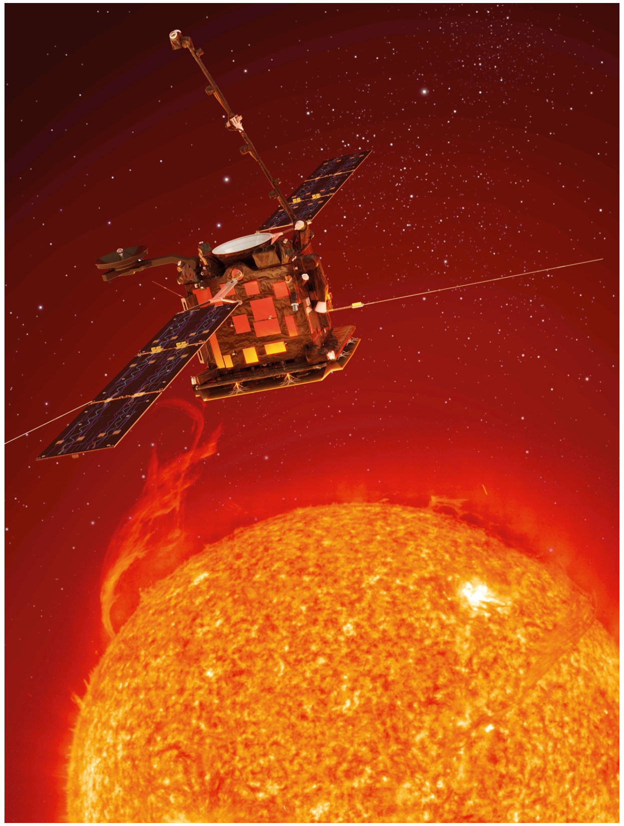
- Resource neutral instrument fine-tuning



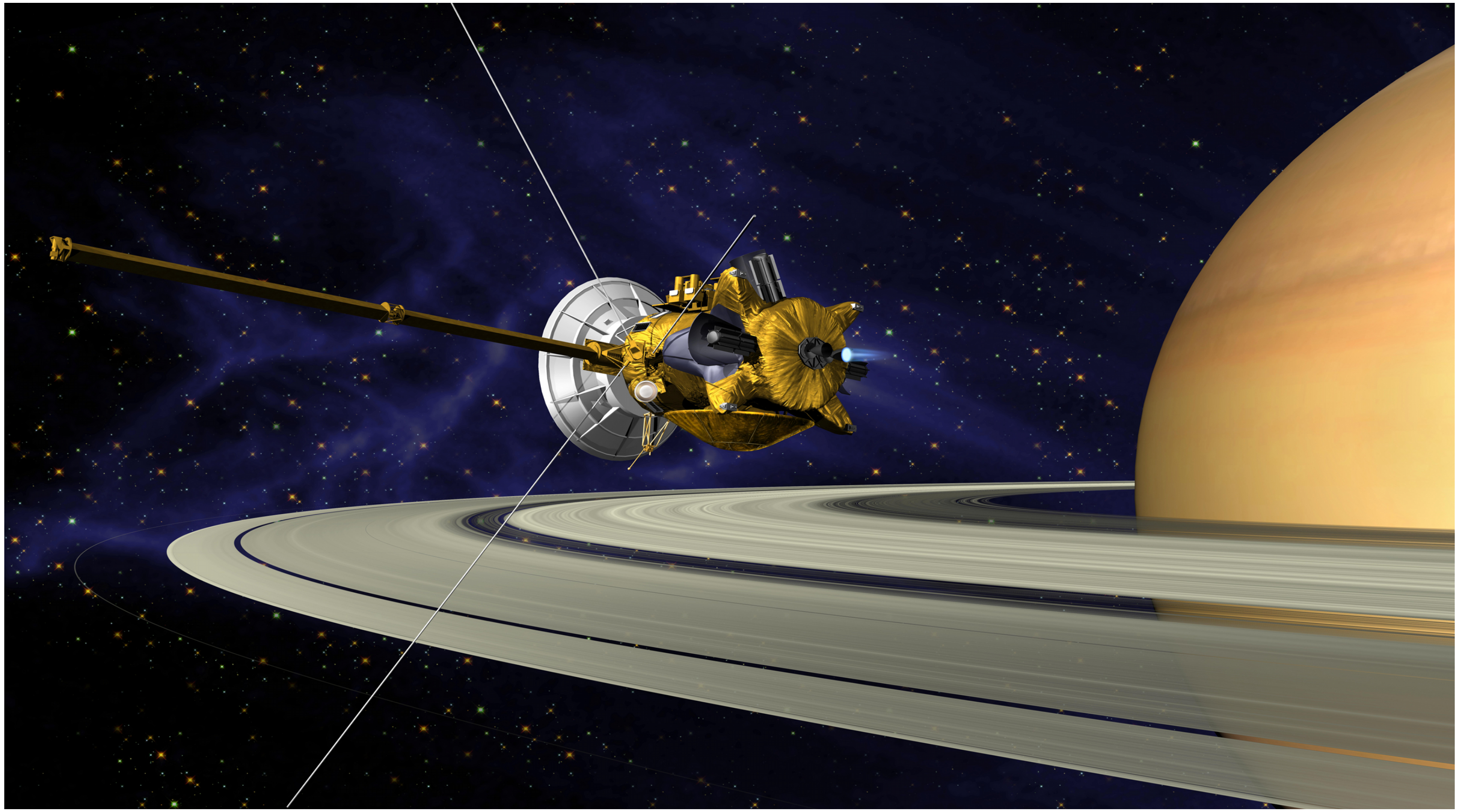
What Solar Orbiter Isn't

- 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



Summary: What Solar Orbiter is

Different from the solar community is used to. Difficult, but...

- A unique opportunity:
  - Coordinated IS and RS observations where they are important
  - Space-based Lyman Alpha imaging
  - True mass discrimination of heavy ions at high cadence
  - A search coil magnetometer in the inner heliosphere
- A source of open data:
  - Not necessarily immediately, and not necessarily predictably - it takes time to downlink everything
  - But 6 months after data hit the ground they will be public in our archive, which will interface with the VSO.
- A unique chance to coordinate observations with complementary solar telescopes

Solar Orbiter:

SYNERGIES WITH OTHER OBSERVATORIES

Synergy between Solar Orbiter and other Observatories

Solar Orbiter:

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

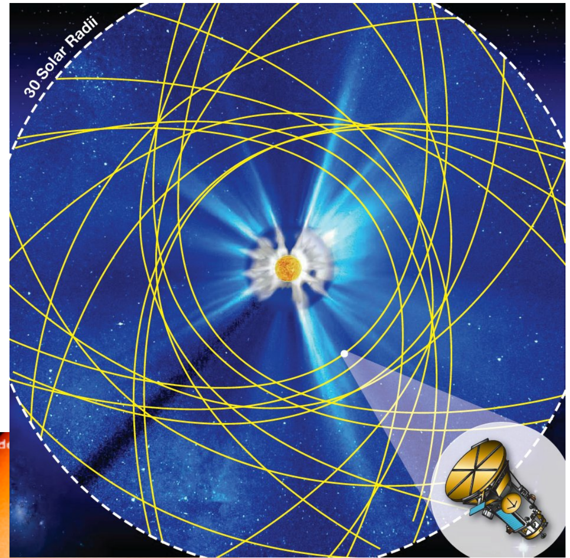
Parker Solar Probe:

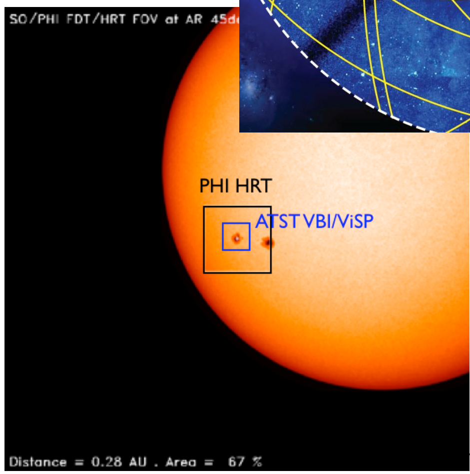
+ unique orbit (min. perihelion ≲10 R_{Sun})
- payload mass constrained by orbital characteristics, mostly in-situ instrumentation

Near-Earth assets:

+ 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





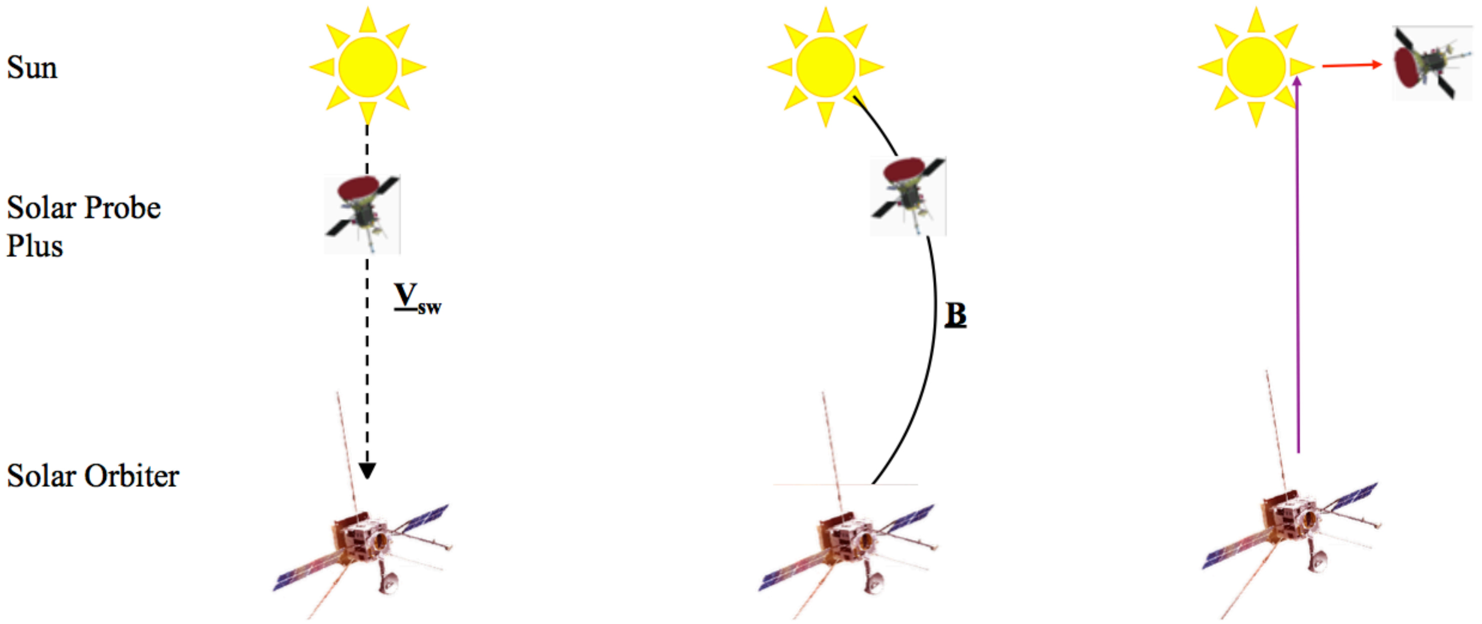
Joint Observations Solar Orbiter – DKIST

Examples of interesting opportunities:

- DKIST – SolO in conjunction:
    - high spatial resolution imaging of photospheric & chromospheric plasmas
    - coronal studies combining DKIST coronagraph, Metis and EUI/FSI
- Quadrature:
    - DKIST observing at limb & SolO observing same location on disk (or vv)
    - CME tracking from surface (DKIST) through inner (EUI) and outer corona (Metis, SoloHI) possibly to solar wind (PSP)
- Stereo observations of same structures:
    - 3D reconstruction of e.g. spicules, wave stereoscopy
    - removal of 180º ambiguity in magnetic field
- Oppositions: PHI far side magnetic field -> 3D magnetic field map

Joint Observations Solar Orbiter – Parker Solar Probe

Example of alignments/quadratures:



Radial alignments:

SO and SPP observe the same SW plasma

IMF alignments:

SO and SPP connect to the same IMF footpoint

Quadratures:

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

How to coordinate campaigns with Solar Orbiter?

- Science opportunities with DKIST that need special SO operations need discussing with SWT and need to flow in SAP: being written in upcoming year.
- Each science case needs linking to a SOOP, with details of the required observations & orbital opportunities, so that suitable time period(s) can be found