SOLI INVICTO

ASPIICS, a Giant Coronagraph Aboard the PROBA-3 mission

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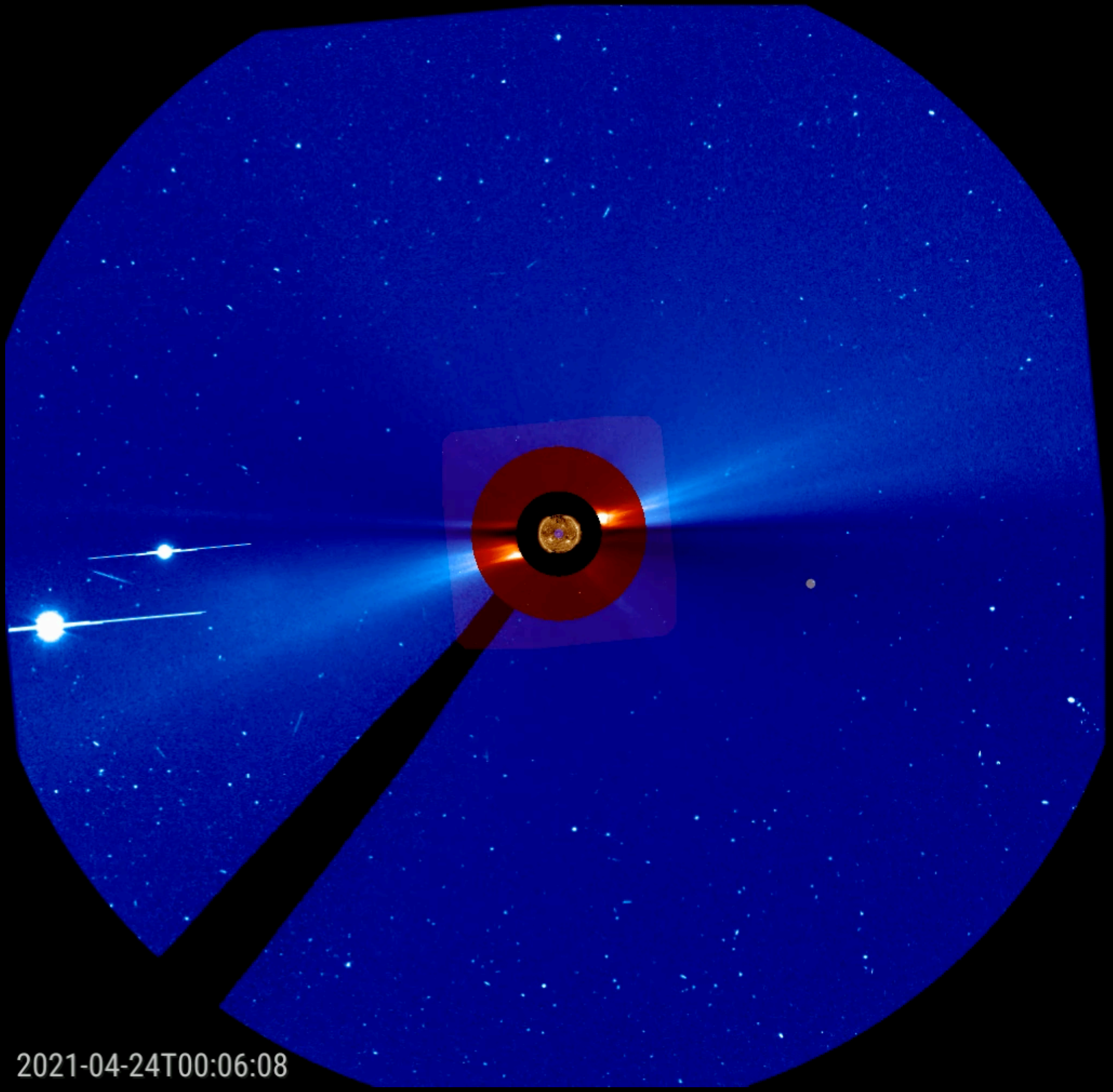
on behalf of the PROBA-3/ASPIICS Science Consortium

Heliophysics in a nutshell

- Heliophysics is the science that unites all of the linked phenomena in the region of the cosmos influenced by the Sun:
  - ✳ solar physics,
  - ✳ space physics
  - ✳ heliospheric physics,
  - ✳ physics of planetary magnetospheres, etc.
- Objects under study:
  - ✳ Sun and its corona,
  - ✳ solar wind,
  - ✳ solar cosmic rays,
  - ✳ plasma environment of planets.
- Measurements performed:
  - ✳ remote-sensing measurements,
  - ✳ in situ measurements.



(movie courtesy B. Nicula & the JHelioviewer team at ROB)

Remote-sensing observations of the corona

Between the low corona and the high corona, there is a region ("The Gap") where observations are difficult to make.

The *high corona* is typically observed by externally occulted coronagraphs.

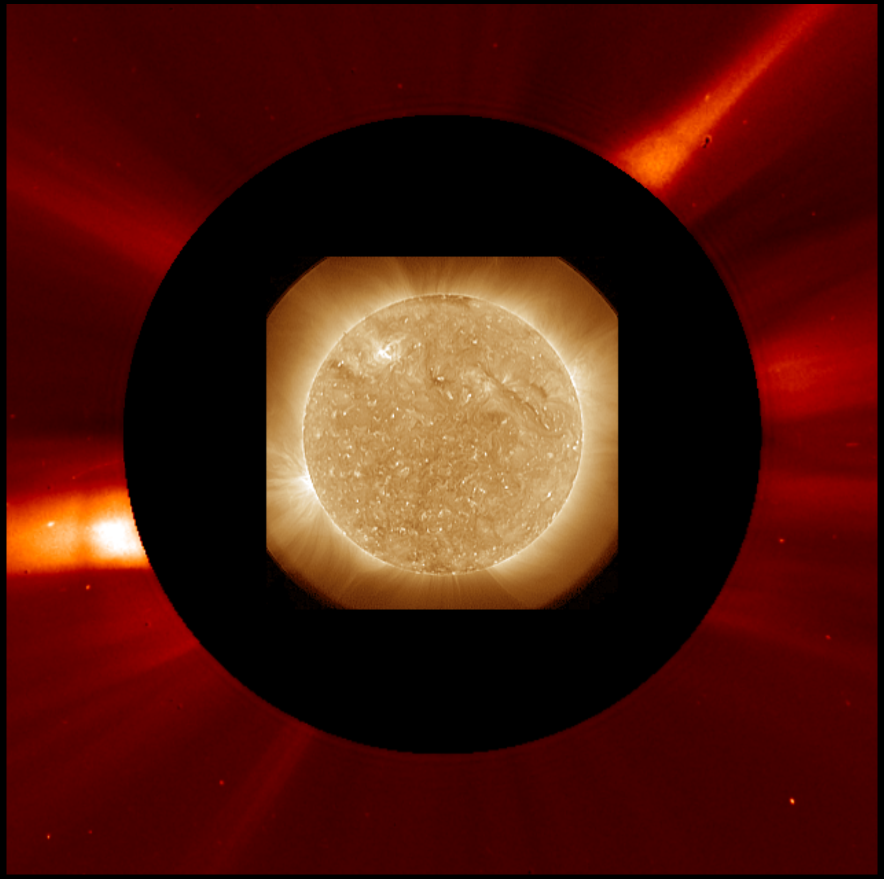
EUV imagers vs white-light coronagraphs

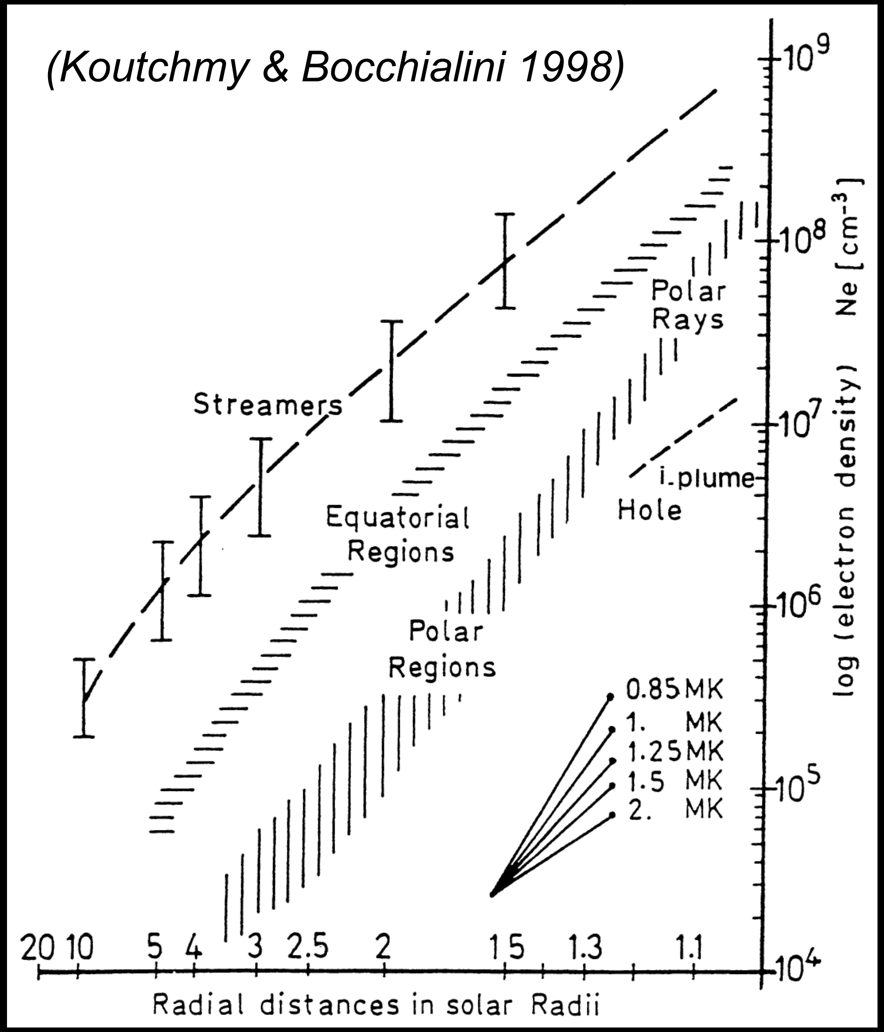
- White-light and EUV intensities are proportional to integrals along the line of sight (LOS):

$$I_{\mathrm{WL}} \sim \int_{\mathrm{LOS}} n_{\mathrm{e}} dl$$

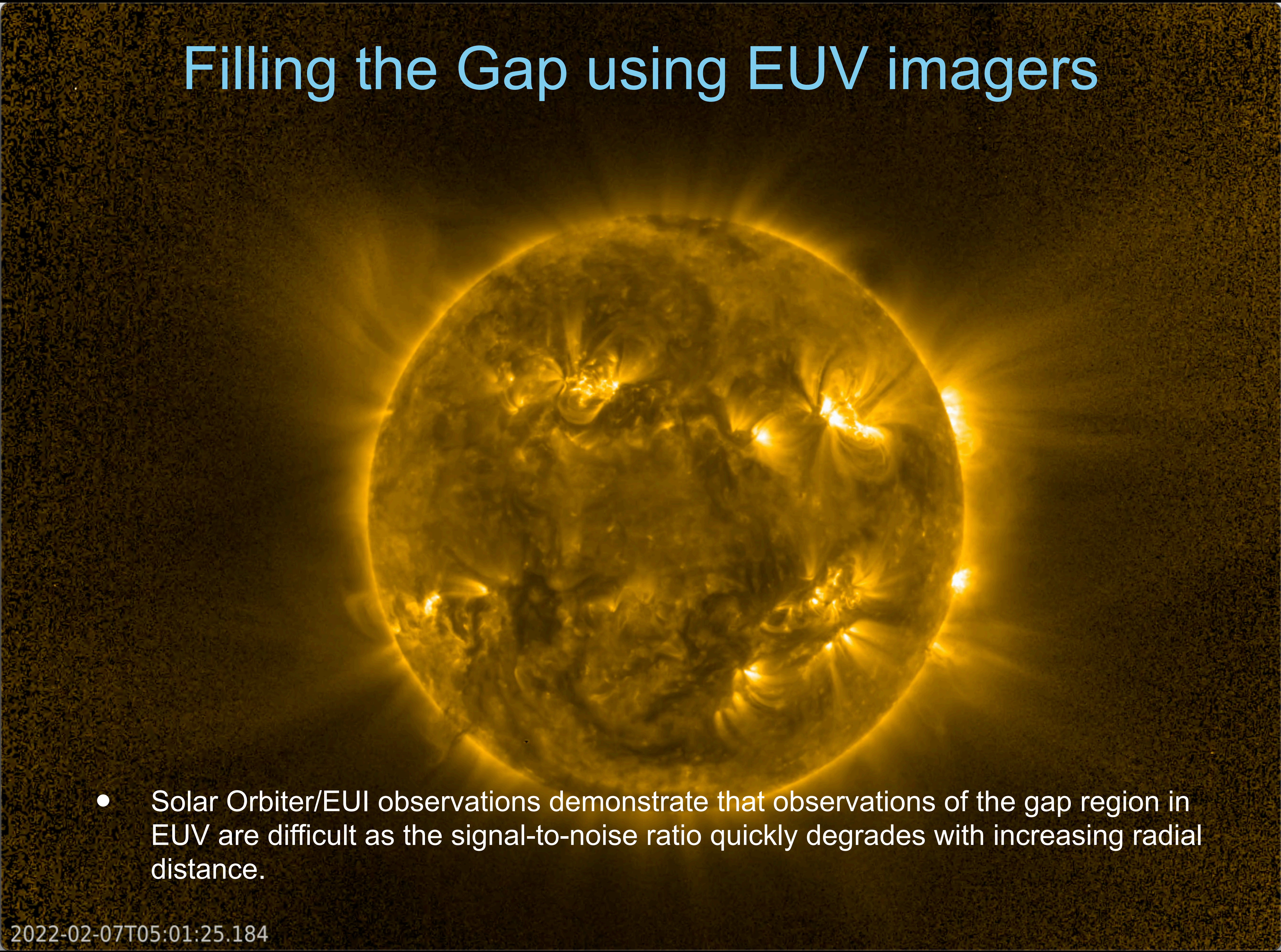
$$I_{\mathrm{EUV}} \sim \int_{\mathrm{LOS}} n_{\mathrm{e}}^2 dl$$

- Due to the coronal electron density n_{e} falling off rapidly with distance from the Sun, the white-light intensity falls off slower than does the EUV intensity.
- This makes the upper corona easier to observe in white light than in EUV.
- Wide field-of-view EUV imagers (PROBA2/SWAP, Solar Orbiter/EUI FSI) need long exposure times (minutes) to have acceptable signal-to-noise ratio in the upper corona.





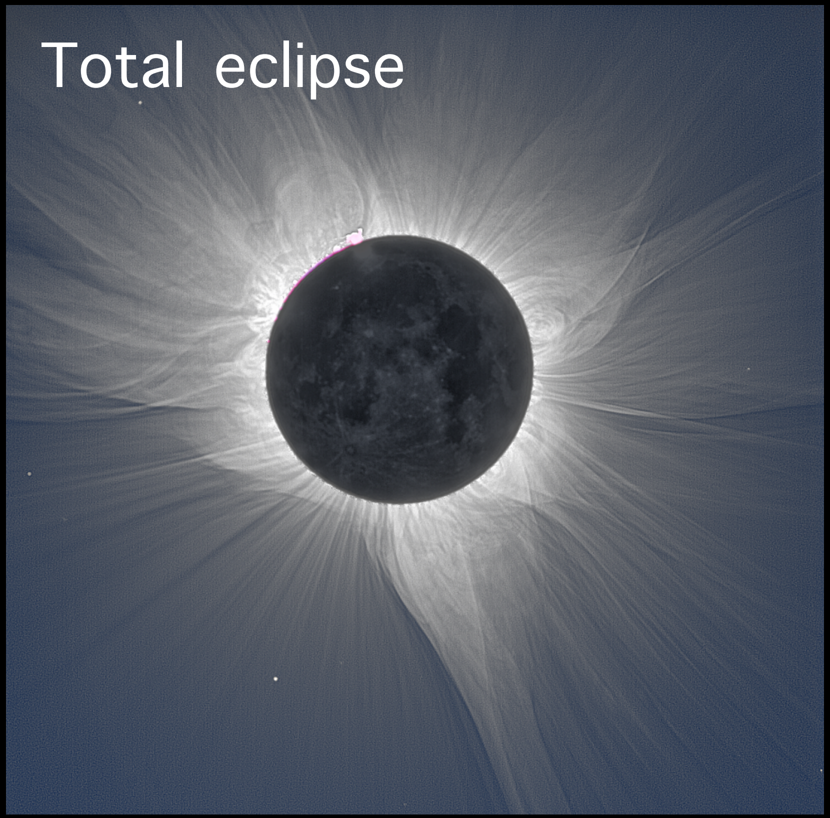
Filling the Gap using EUV imagers

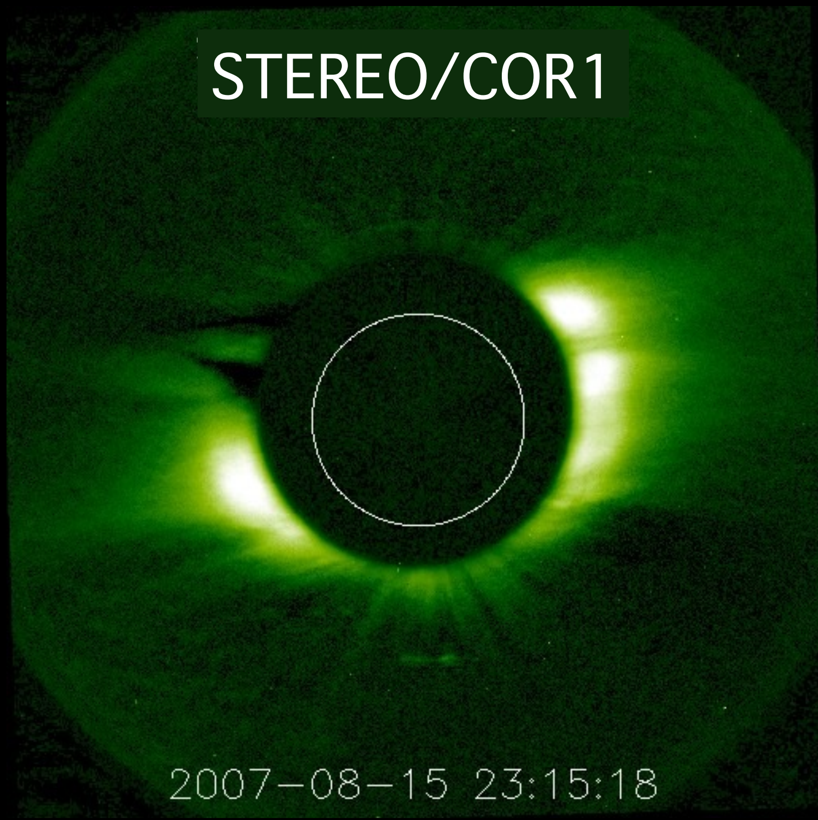


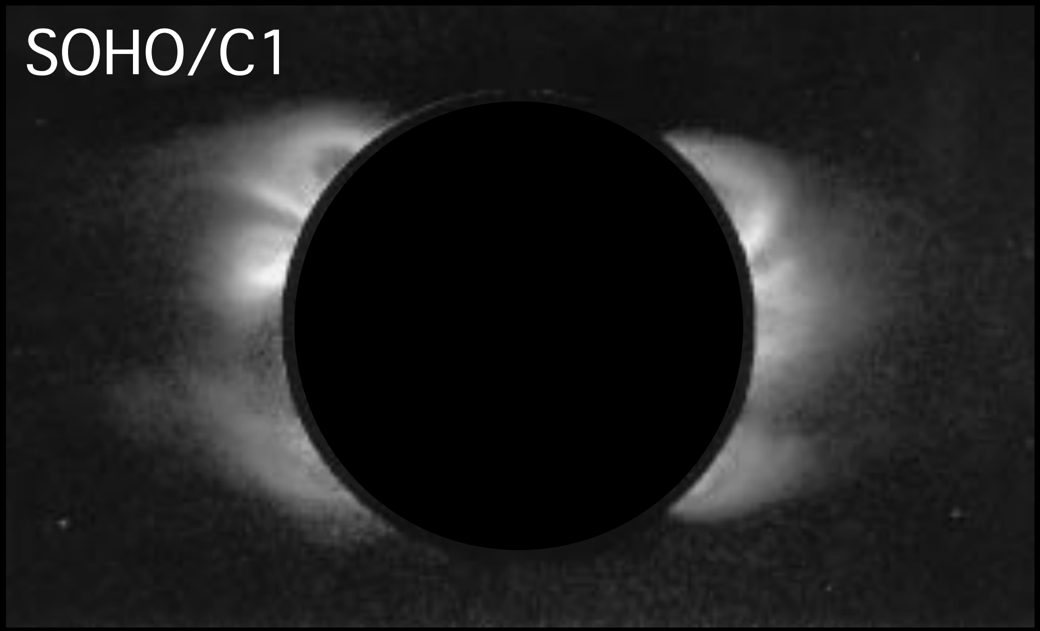
- Solar Orbiter/EUI observations demonstrate that observations of the gap region in EUV are difficult as the signal-to-noise ratio quickly degrades with increasing radial distance.

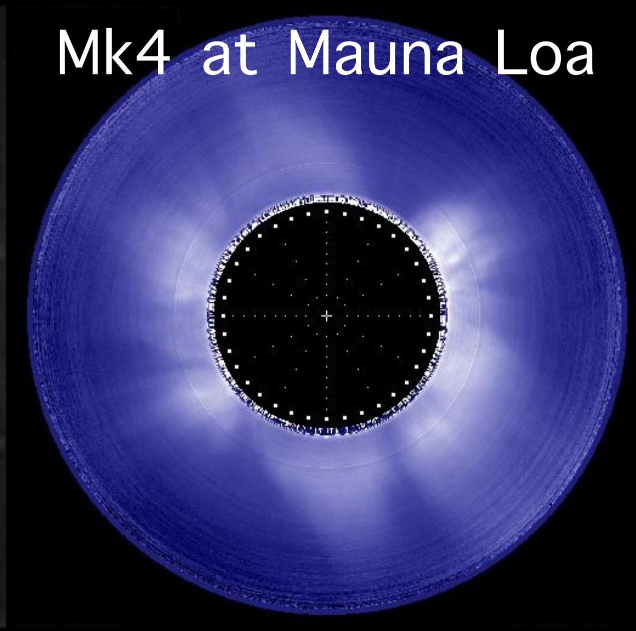
Why are we not happy with previous coronagraphic observations?

- A short answer: straylight
- Straylight in coronagraphs is very difficult to suppress when the corona below 2 $R_\odot$ is observed.
- High straylight means that signal-to-noise ratio, the contrast of small-scale features, and the effective spatial resolution become low.





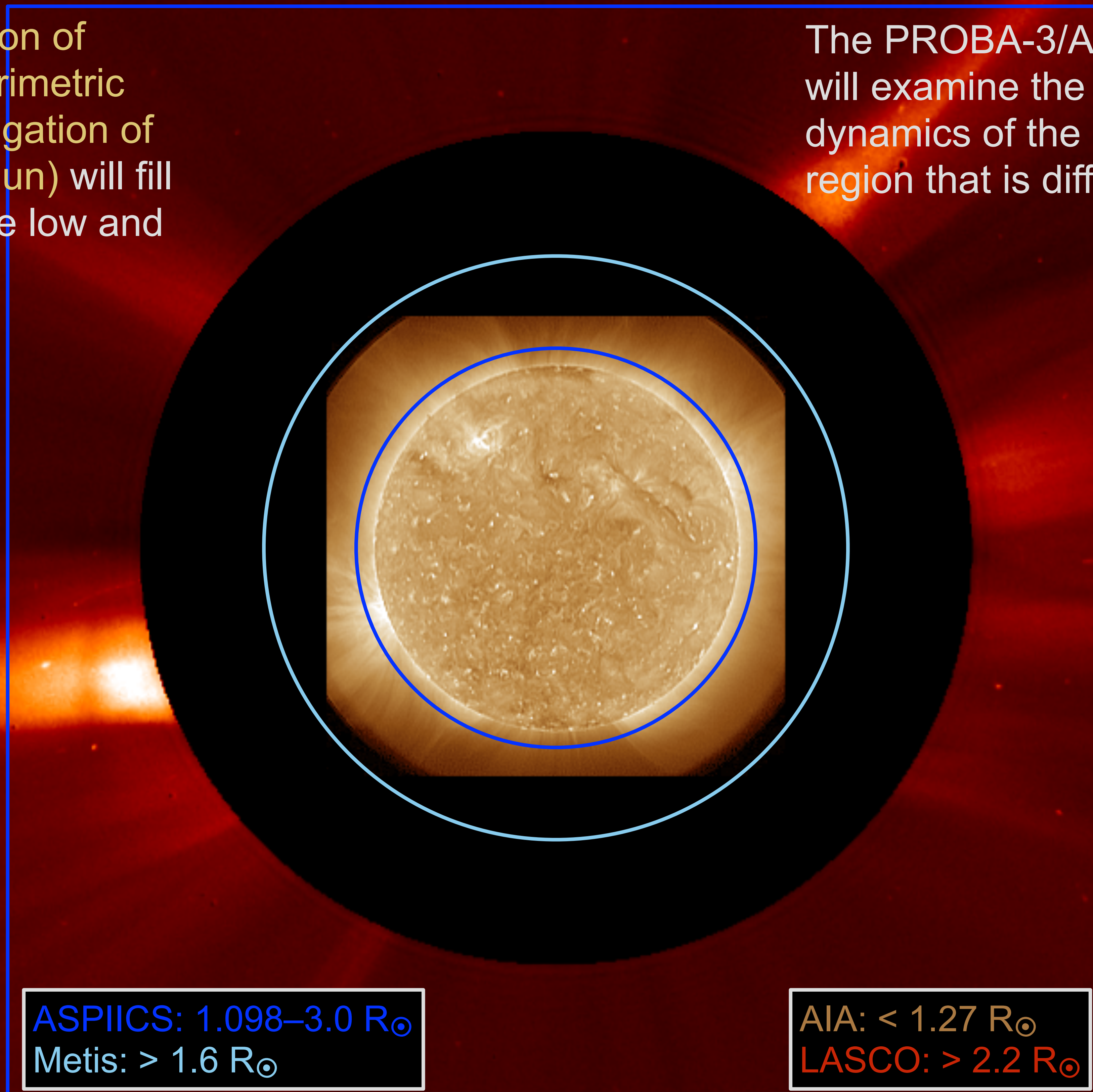




Filling the Gap using coronagraphs

ASPIICS (Association of Spacecraft for Polarimetric and Imaging Investigation of the Corona of the Sun) will fill the gap between the low and high corona.

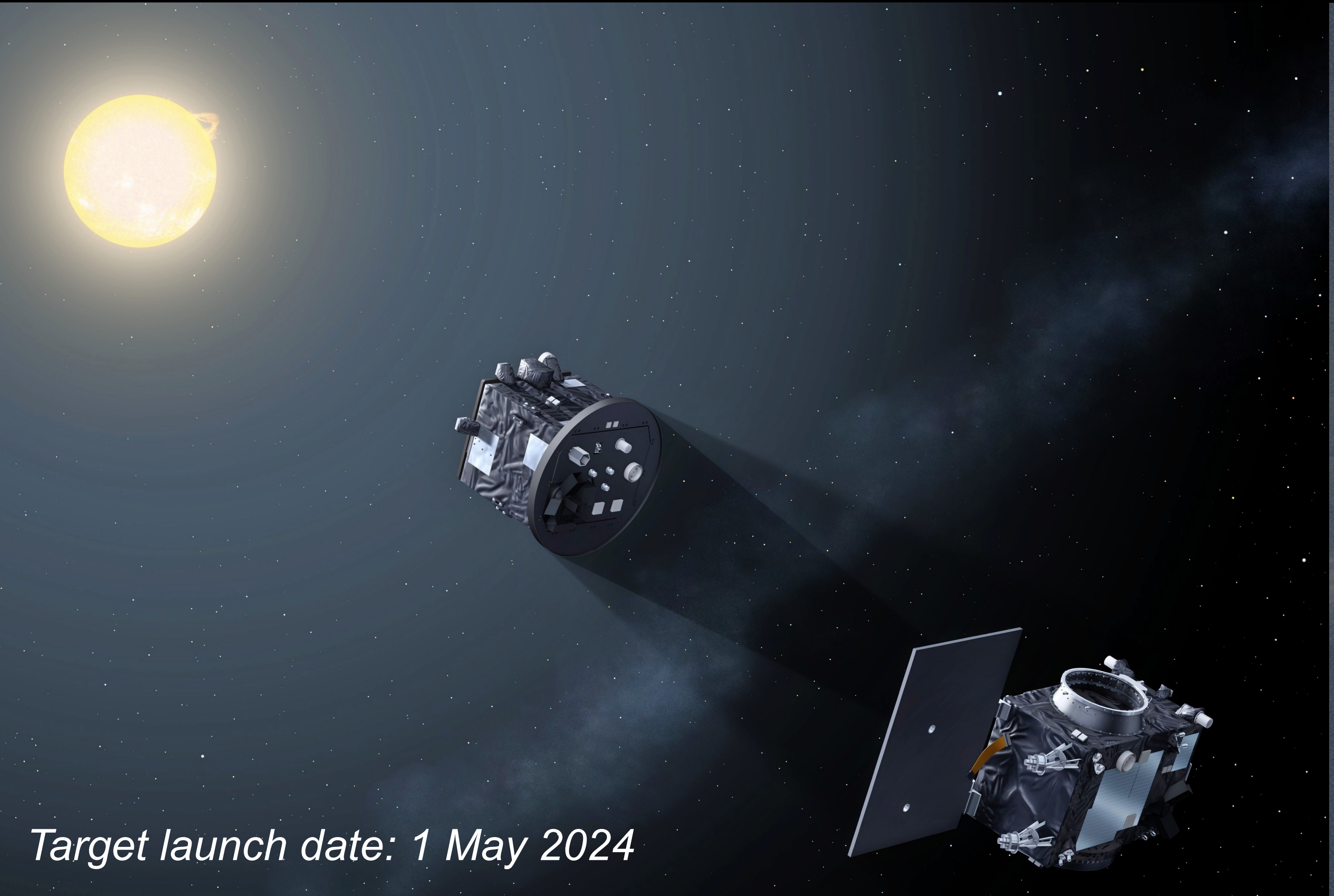
The PROBA-3/ASPIICS coronagraph will examine the structure and dynamics of the corona in the crucial region that is difficult to observe.

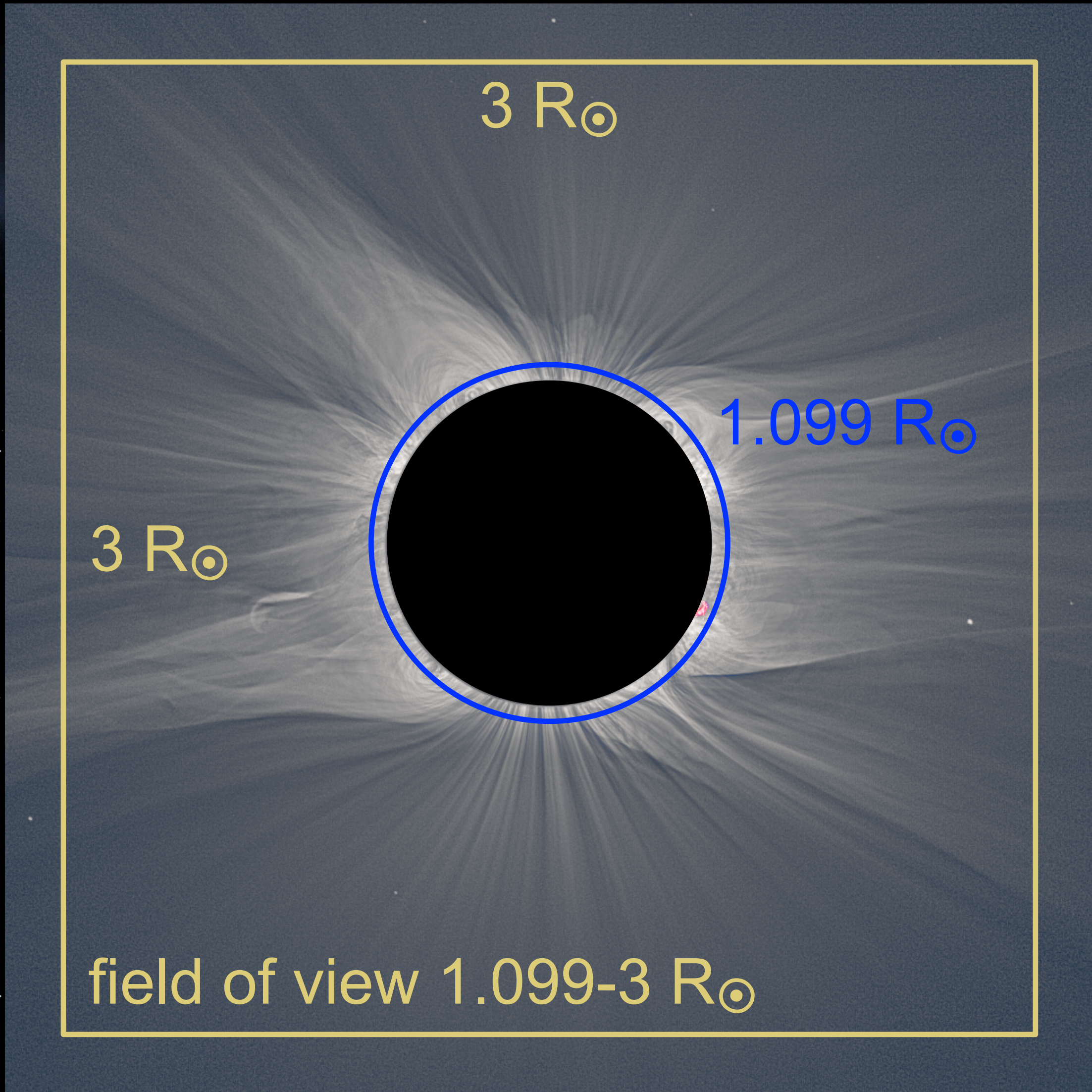


PROBA-3/ASPIICS: the ultimate coronagraph!

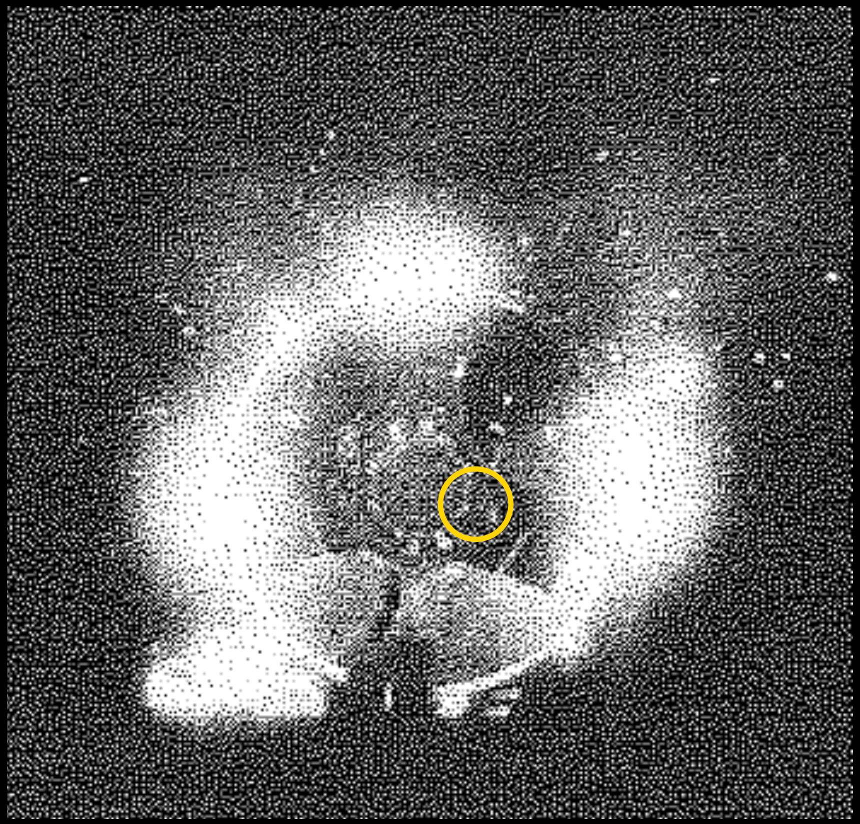
- The formation flying will be maintained over 6 hours in every 20-hour orbit: *around a factor 100 improvement* in the duration of uninterrupted observations in comparison with a total eclipse.
- PROBA-3 will observe the corona two orbits per week on average: *around a factor 50 improvement* in the occurrence rate in comparison with a total eclipse.

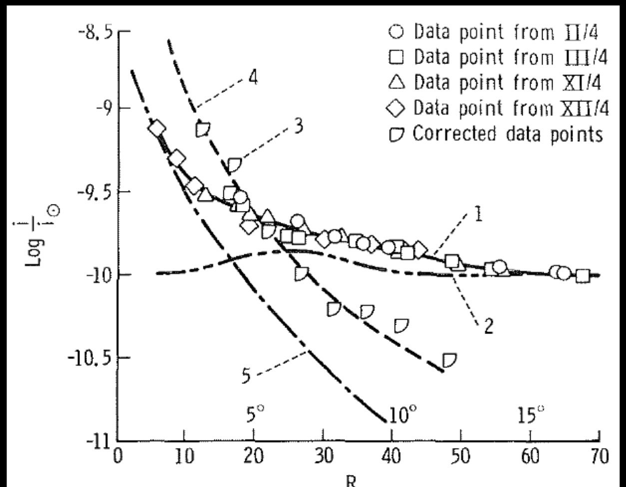
- 6 spectral channels:
  - white light (5350-5650 Å),
  - 3 polarized white light,
  - Fe XIV passband at 5304 Å.
  - He I D3 passband at 5877 Å.
- 2048x2048 pixels (2.817 arc sec per pixel)
- 60 s nominal synoptic cadence
  - 2 s using a quarter of the field of view.





Observing solar corona using formation flying: Apollo-Soyuz Test Project (1975)





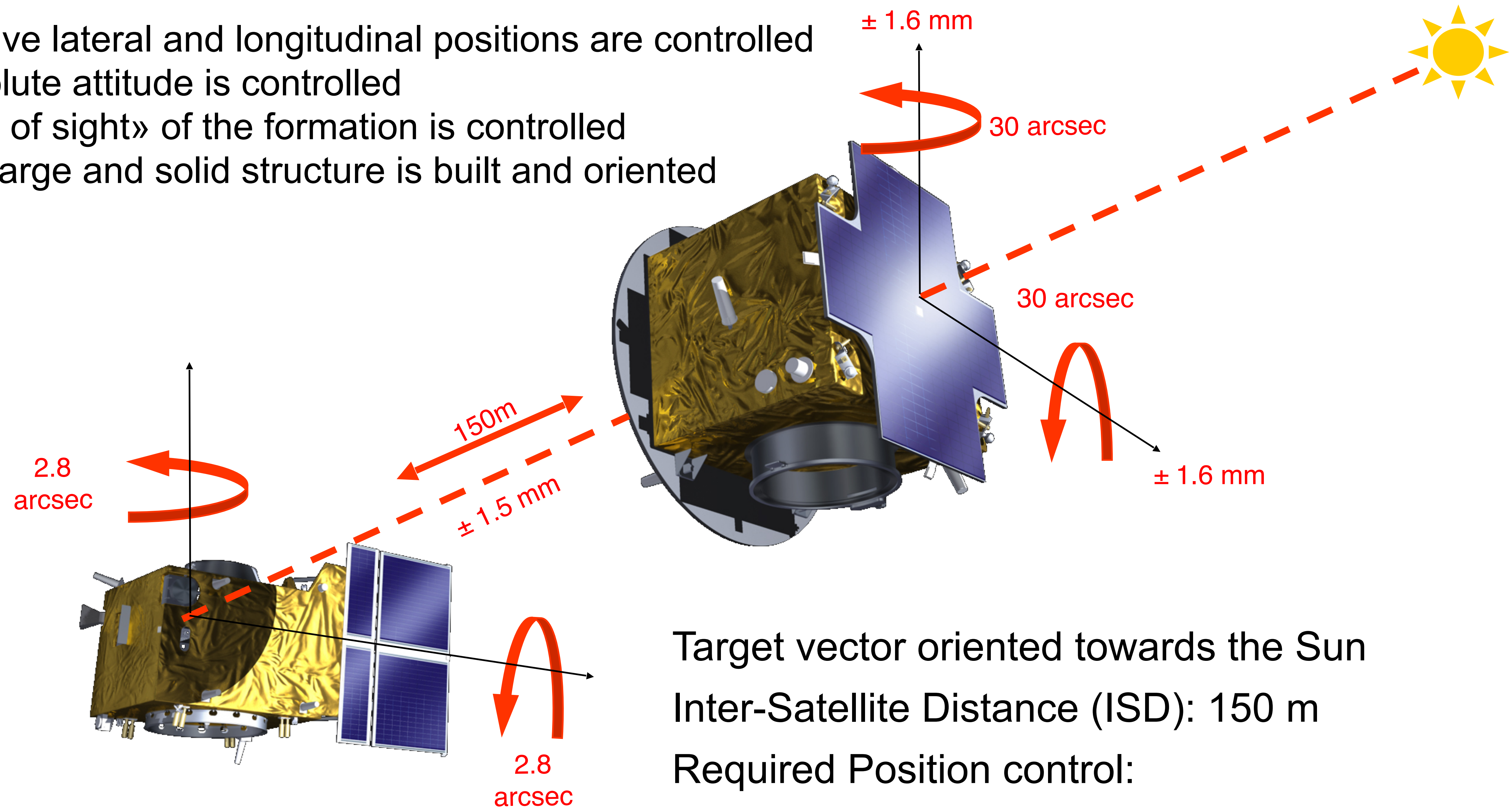
(Nikolskiy et al. 1977)

- First formation flying coronagraphic experiment: images taken by the crew of Soyuz with Apollo occulting the Sun.

Precise formation flying

PRECISE FORMATION FLYING

- The relative lateral and longitudinal positions are controlled
- The absolute attitude is controlled
- The «line of sight» of the formation is controlled
- A virtual large and solid structure is built and oriented



Target vector oriented towards the Sun

Inter-Satellite Distance (ISD): 150 m

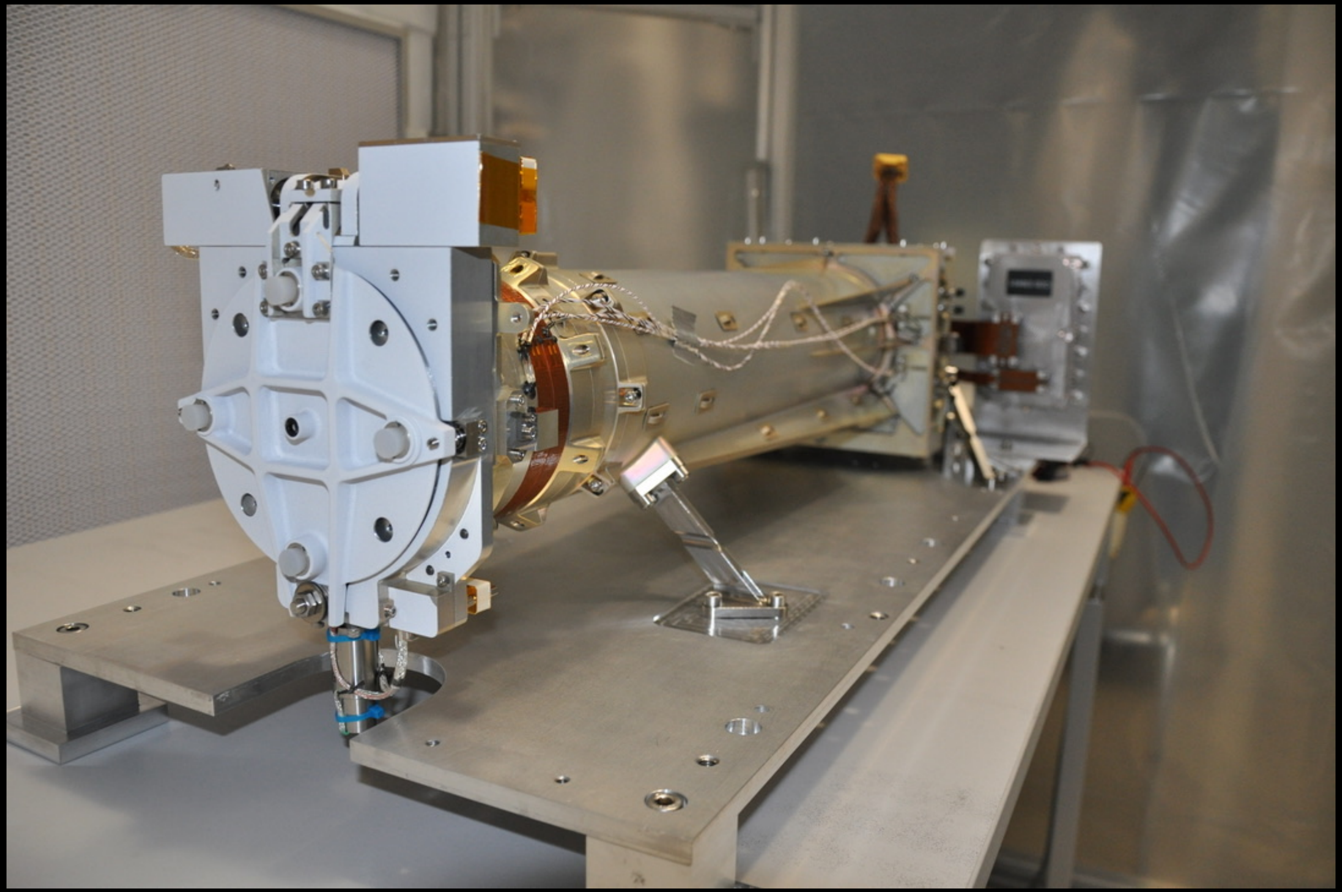
Required Position control:

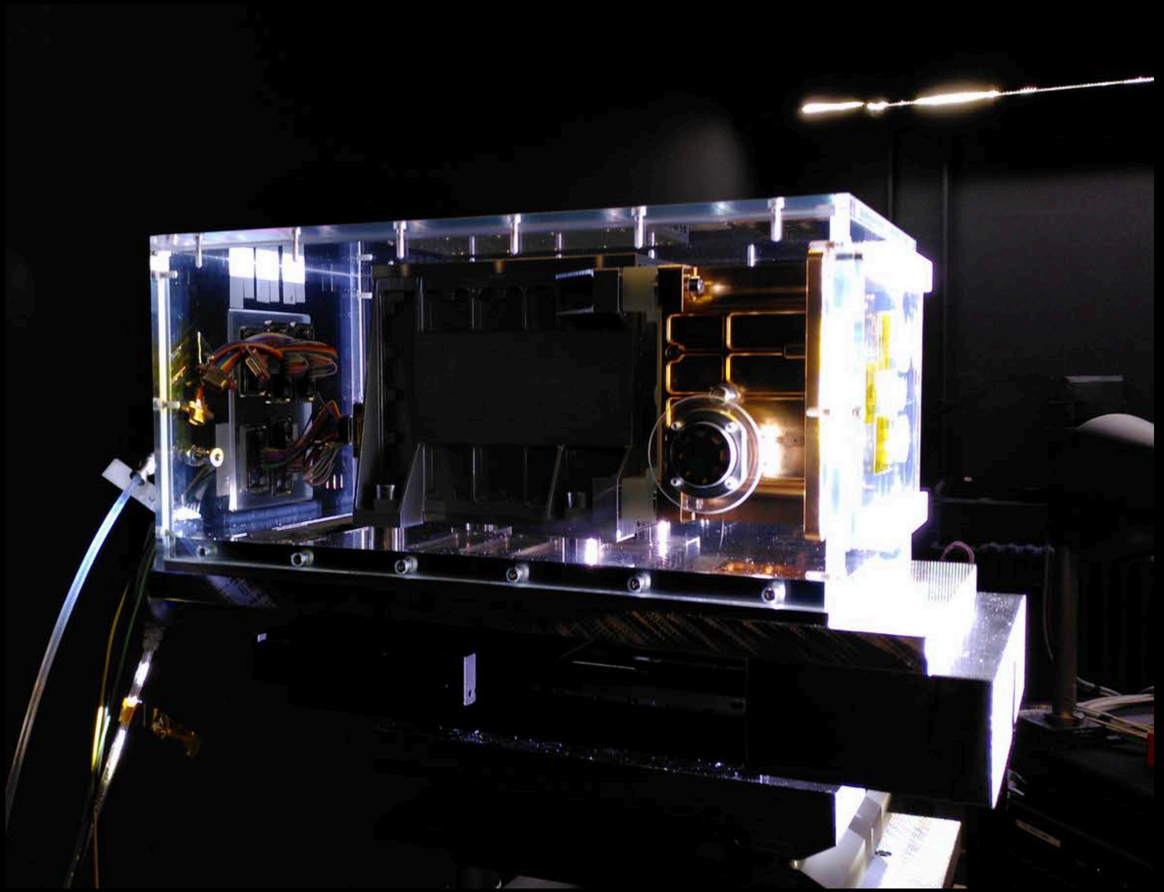
Lateral: 5 mm (1σ @ 150 m ISD)

Longitudinal: 1.5 mm (1σ @ 150 m ISD)

Courtesy D. Galano (ESA)

Scientific payload of PROBA-3





ASPIICS
(Association of Spacecraft for Polarimetric and Imaging Investigation of the Corona of the Sun)

PI: Andrei Zhukov (ROB, Belgium)

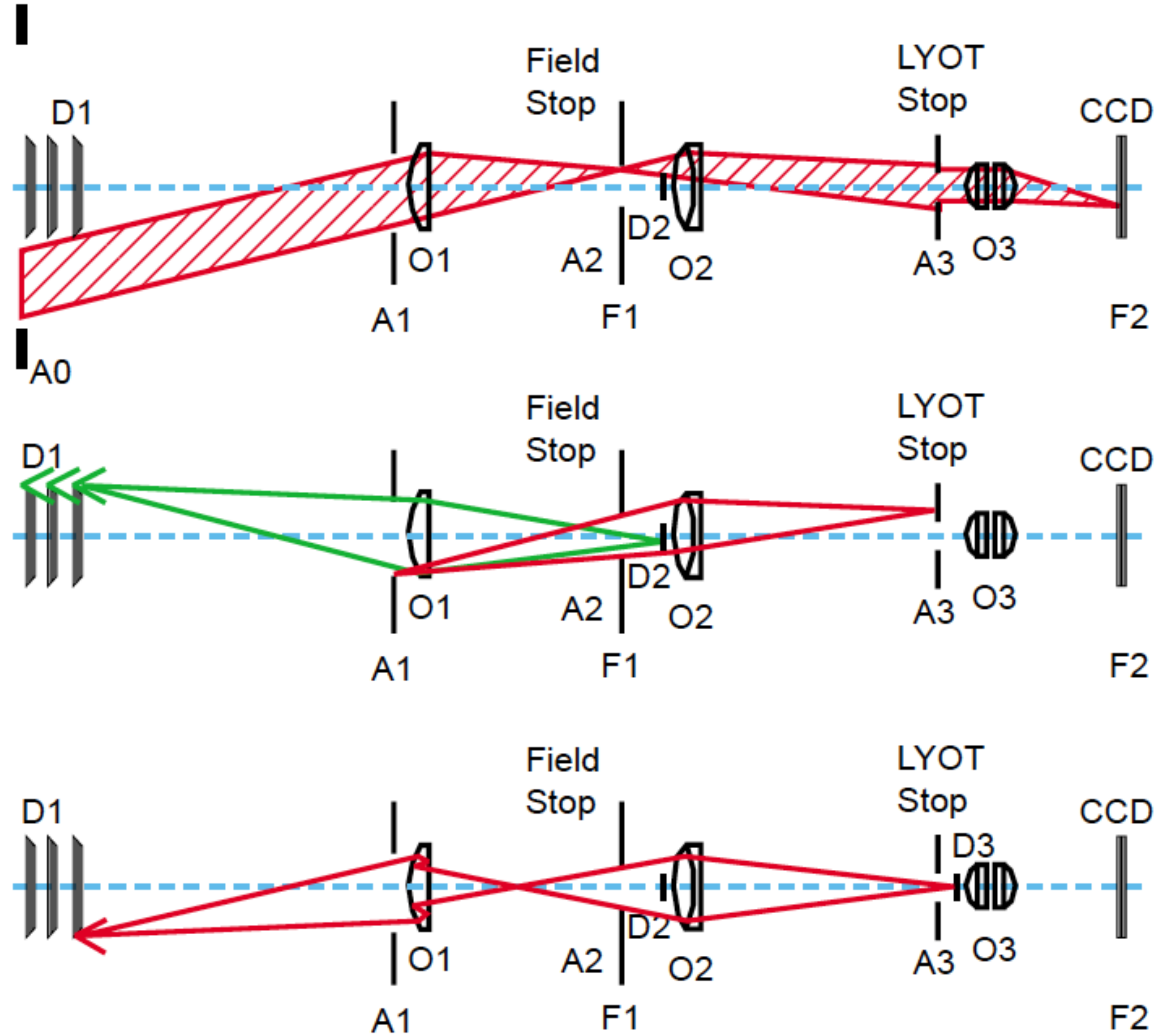
The telescope is placed on the main spacecraft, and the occulting disk is placed on the smaller spacecraft 144 m away. Together they form a giant coronagraph.

DARA
(Digital Absolute RAdiometer)

PI: Werner Schmutz (PMOD, Switzerland)

DARA is a total solar irradiance monitor placed on the occulter spacecraft.

The classic Lyot design of a solar coronagraph



A0, front aperture
A1, entrance aperture
A2, field stop
A3, Lyot stop
D1, external occulter
D2, internal occulter
D3, Lyot spot

F1, primary focal plane
F2, secondary focal plane
O1, objective lens
O2, field lens
O3, relay lens

(Howard et al. 2000)

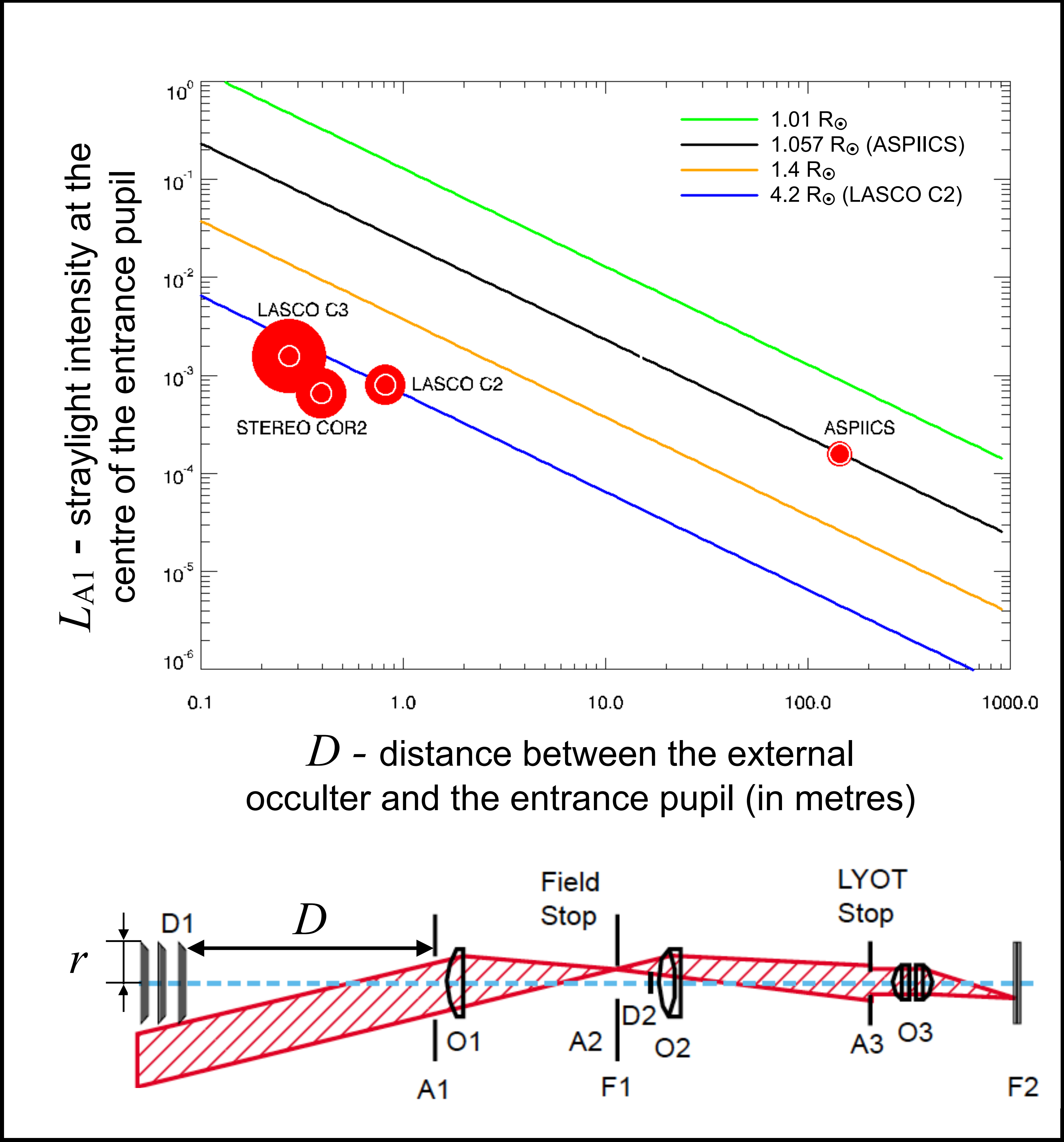
The main advantage of PROBA-3/ASPIICS

- The straylight critically depends on the distance between the external occulter and the entrance pupil *(Fort et al. 1978, Lenskii 1981)*:

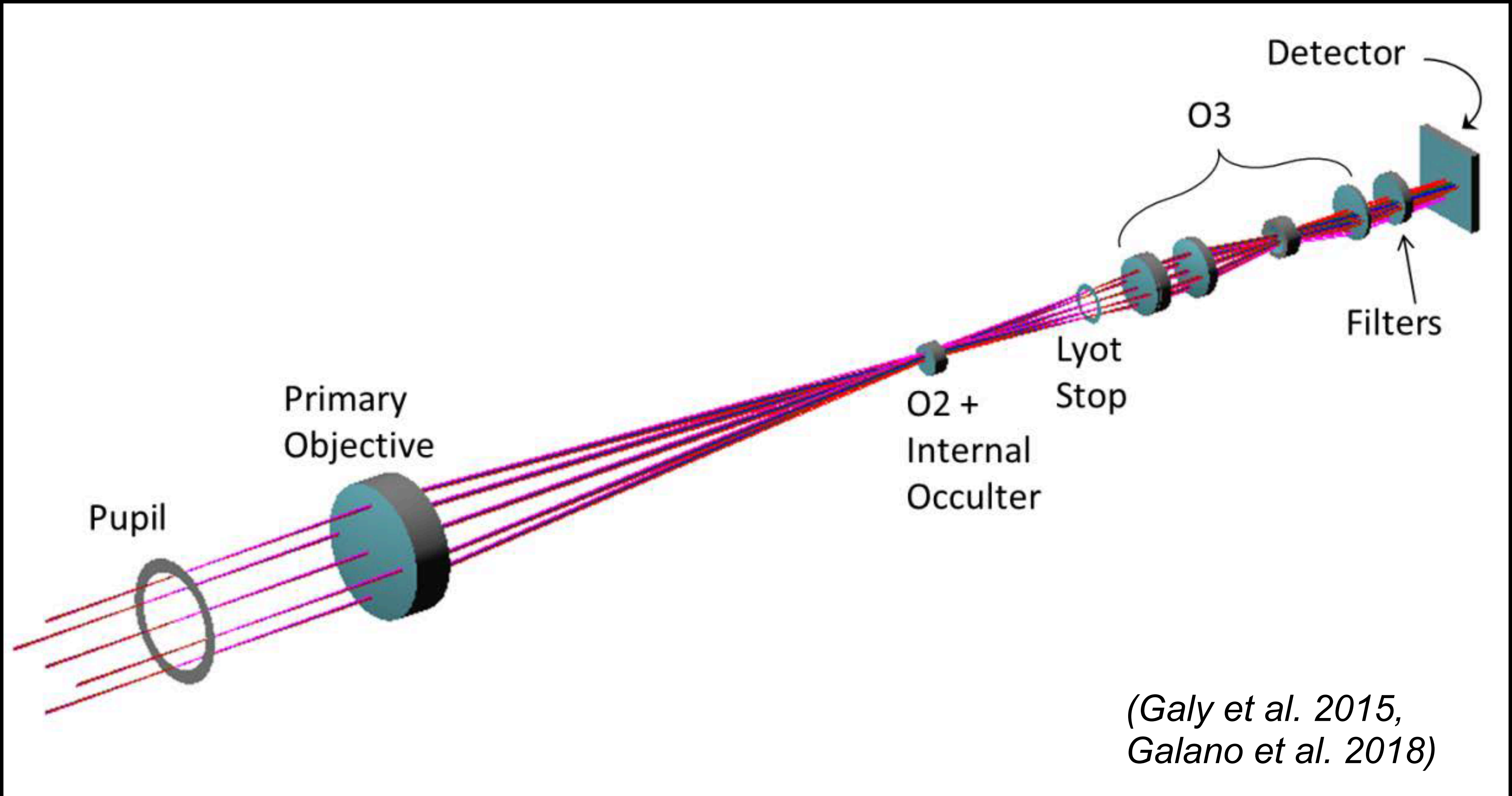
$$L_{A1} = \left\{ \pi^2 R_\odot \left[1 - \left(\frac{R_\odot D}{r} \right)^2 \right] \right\}^{-1} \frac{\lambda}{r}$$

- In ASPIICS, this distance is around two orders of magnitude larger than that in any other coronagraph built so far.

- This increase of distance allows in the same time:
  - to reduce the position of the inner edge of the field of view from 2.2 $R_\odot$ (LASCO C2) to 1.099 $R_\odot$ (ASPIICS),
  - to have the straylight around 5 times lower than that in other coronagraphs.



PROBA-3/ASPIICS optical design



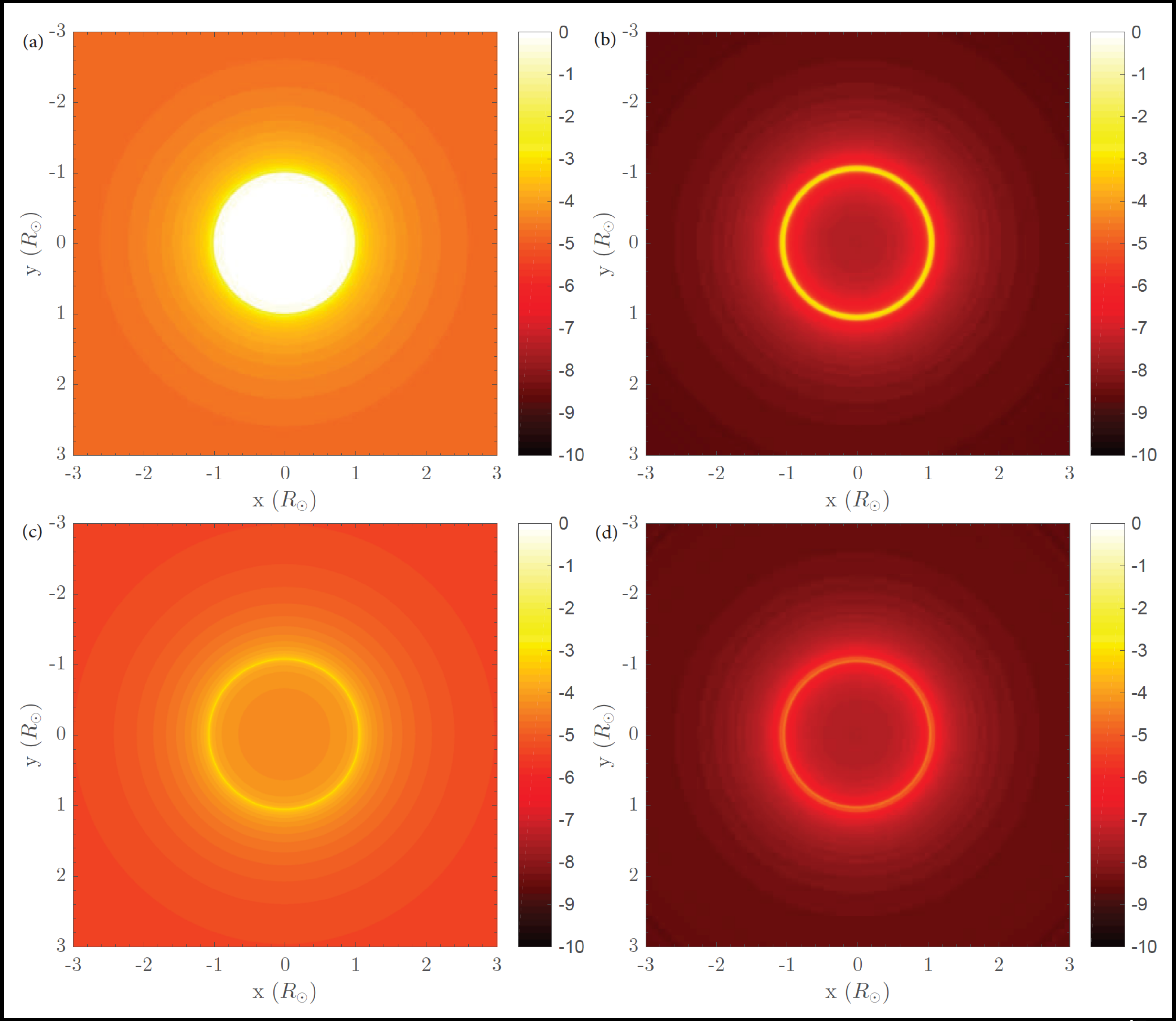
(Galy et al. 2015,
Galano et al. 2018)

- The optical design of ASPIICS follows the principles of the classic externally occulted Lyot coronagraph.
- The external occulter is placed about 144 m in front of the entrance pupil.

Importance of external and internal occulters

no occulters

external occulter only

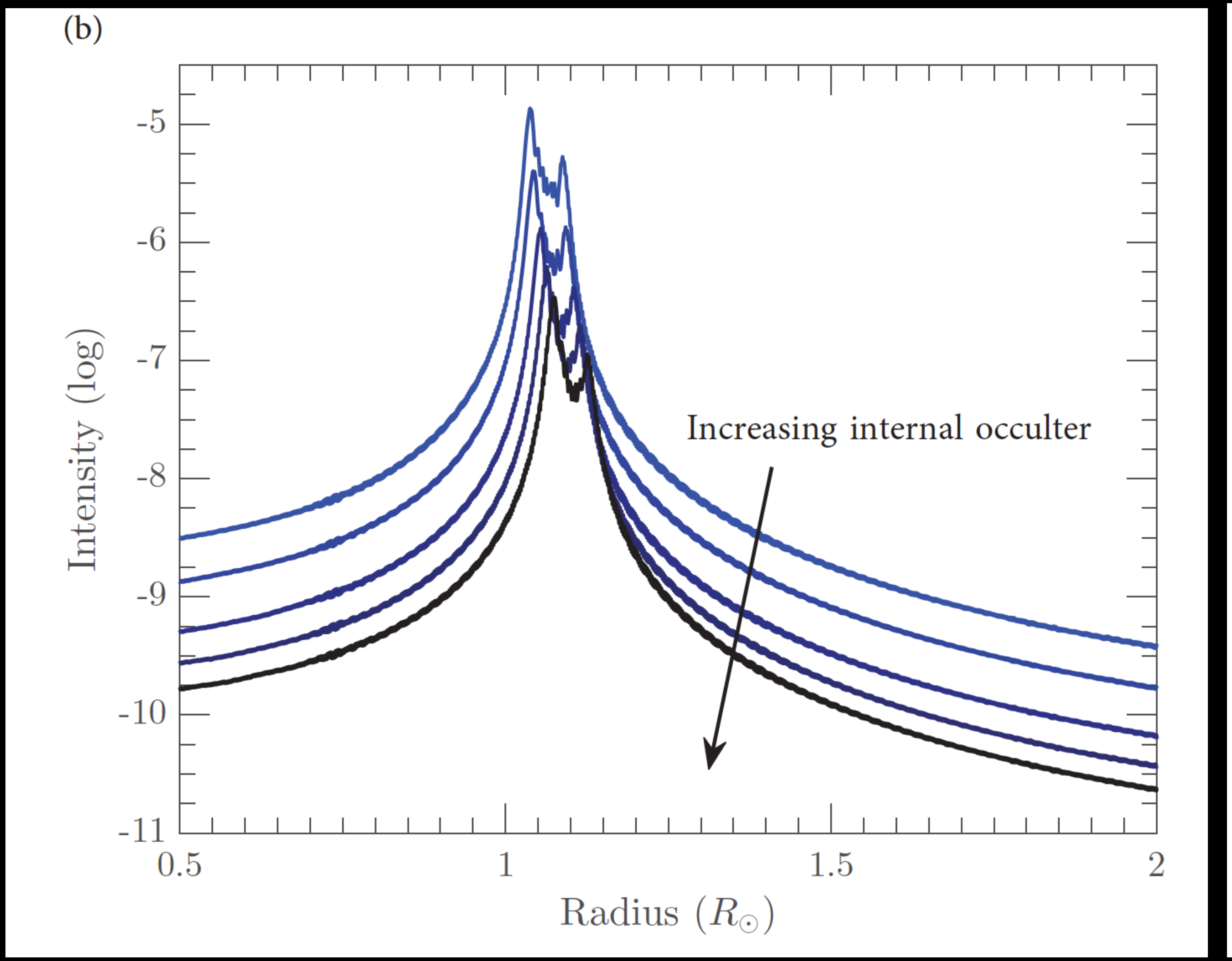


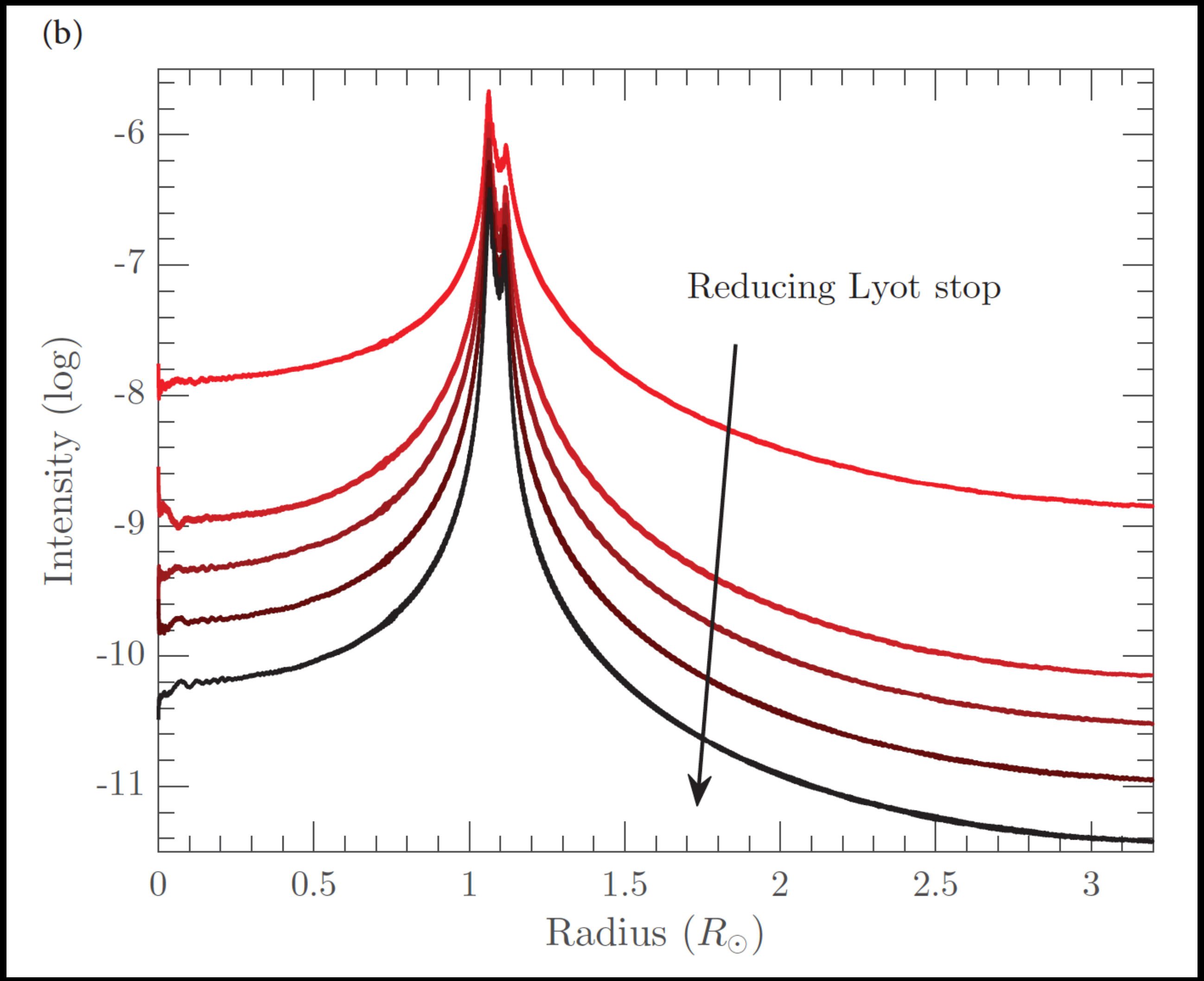
internal occulter only

external and internal occulters

(Rougeot et al. 2017)

Straylight in ASPIICS (1)



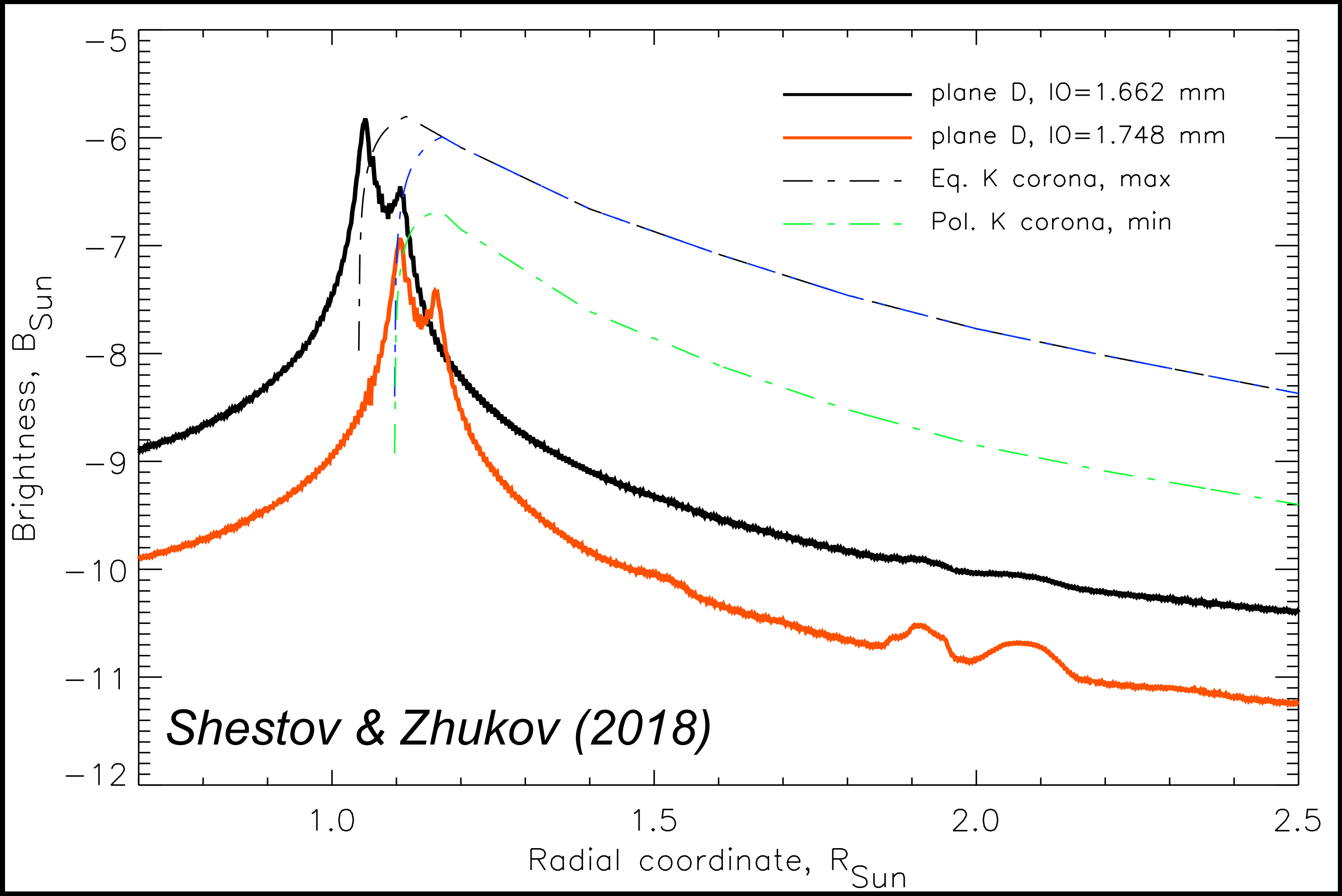


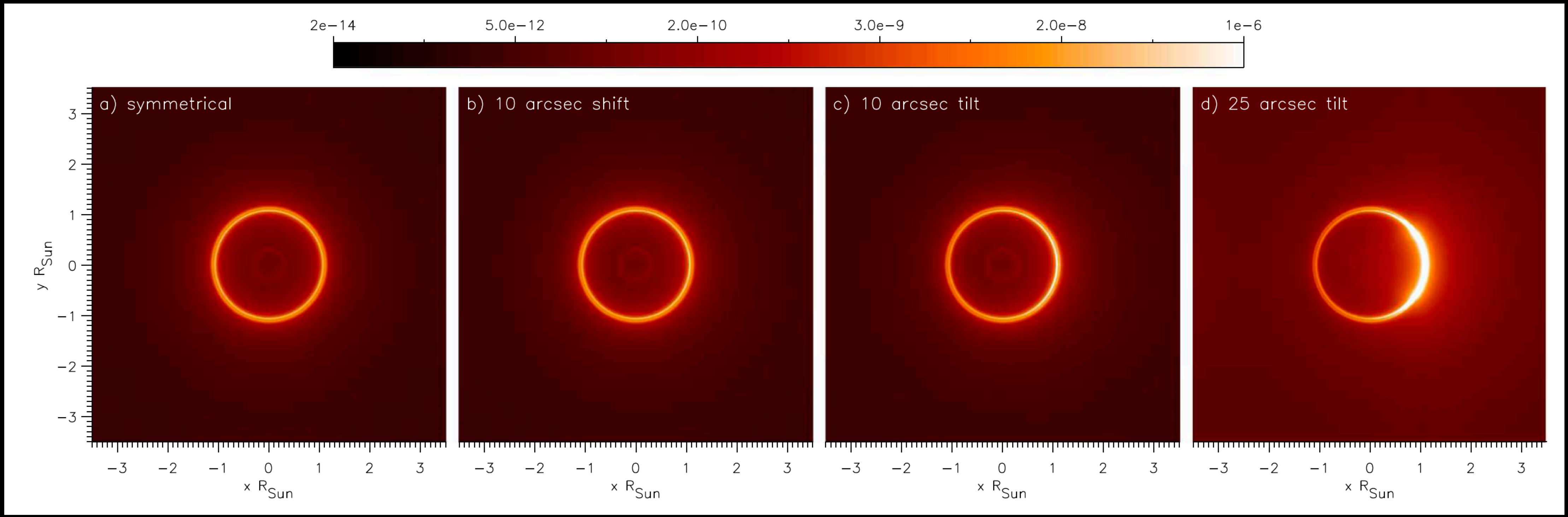
(Rougeot et al. 2017)

- We used state-of-the-art diffraction model *(Aime 2013, Rougeot et al. 2017, Shestov & Zhukov 2018)* to calculate the straylight in the detector plane.

Straylight in ASPIICS (2)

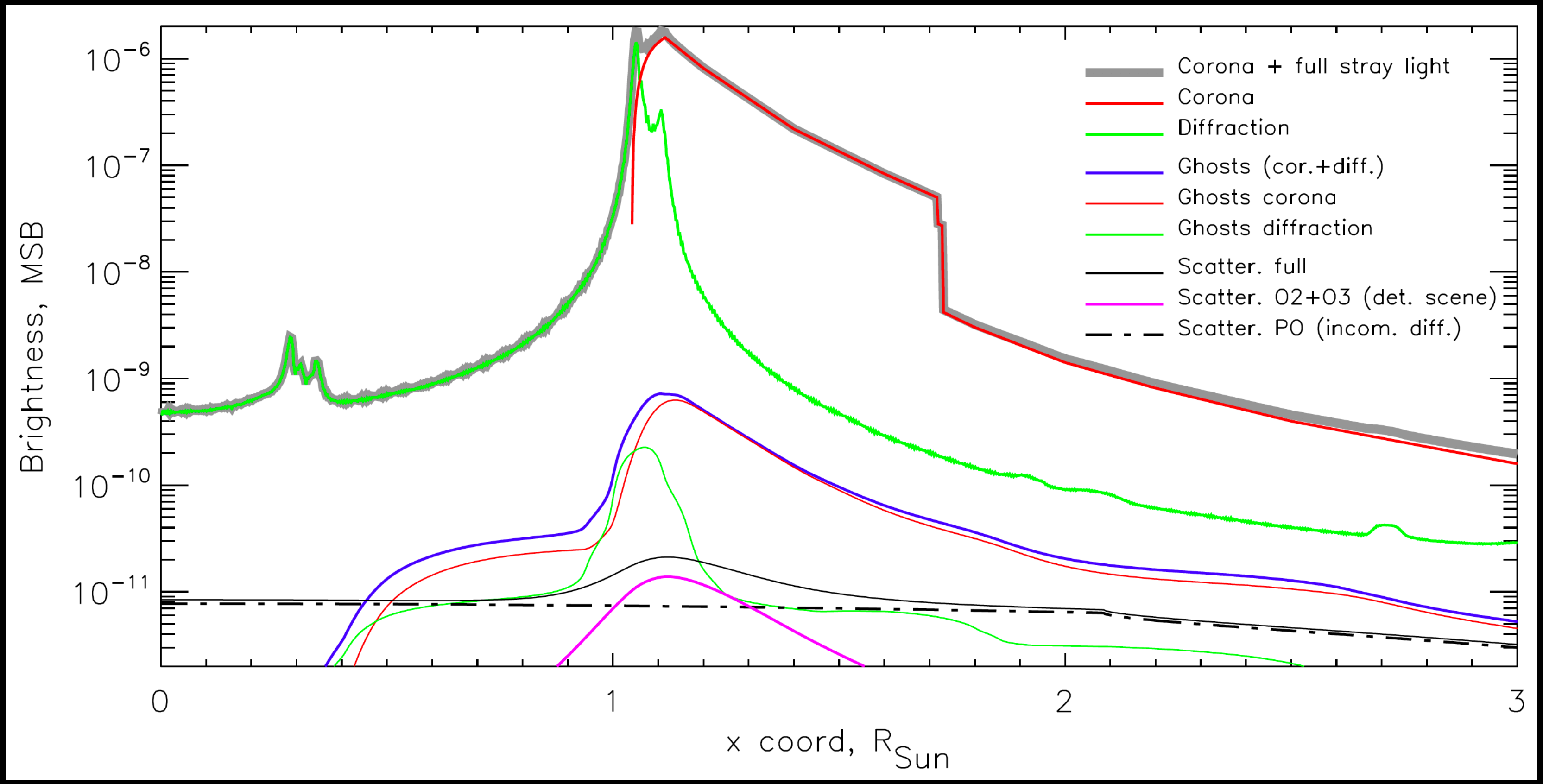
- In the inner part of the field of view, the straylight is dominated by the diffraction of the solar disk light on the external occulter.
- State-of-the-art diffraction calculations *(Aime 2013, Rougeot et al. 2017)* allow a reliable estimation of the straylight, even in a misaligned configuration (*Shestov & Zhukov 2018)*.





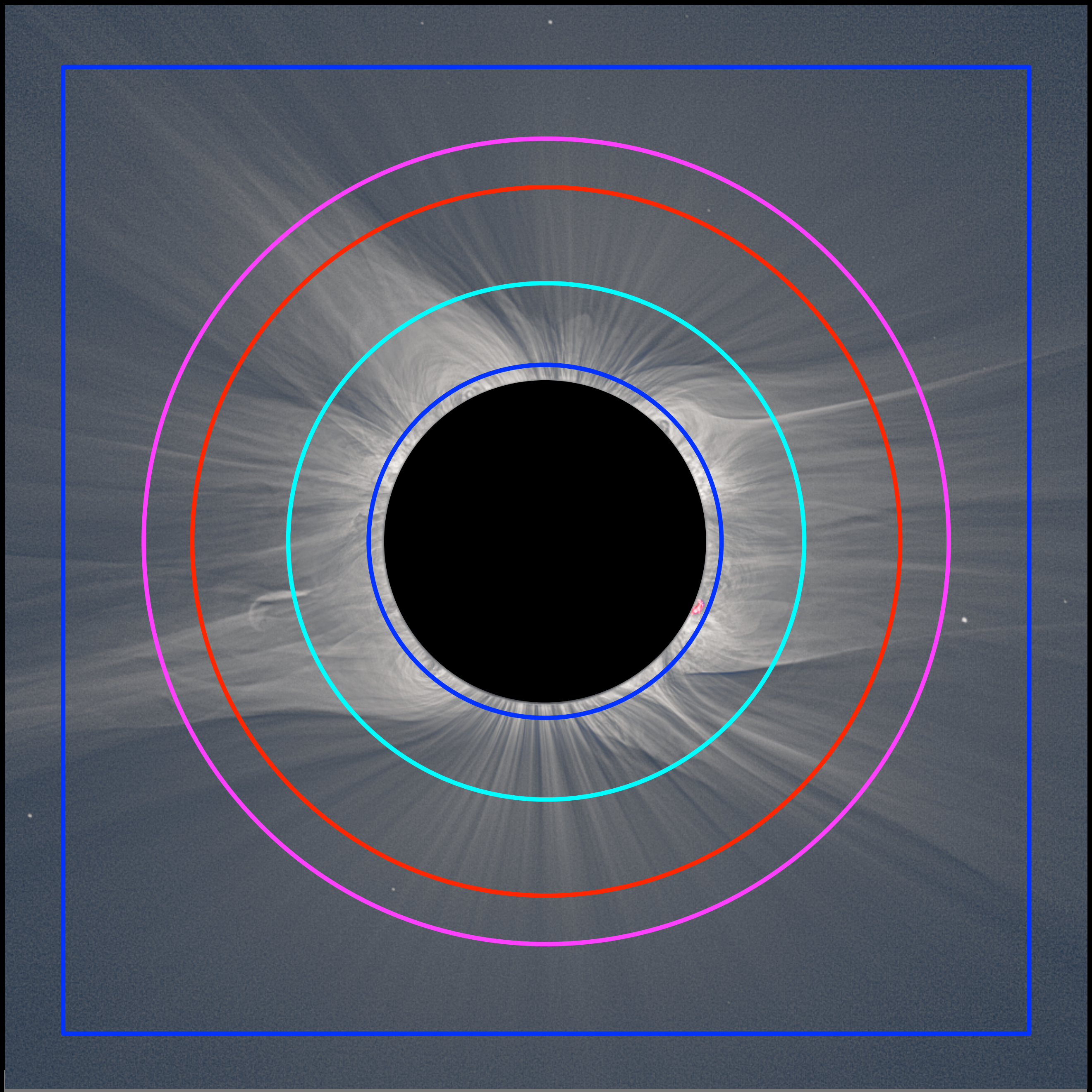
Straylight in ASPIICS (3)

Shestov, Zhukov & Seaton (2019)



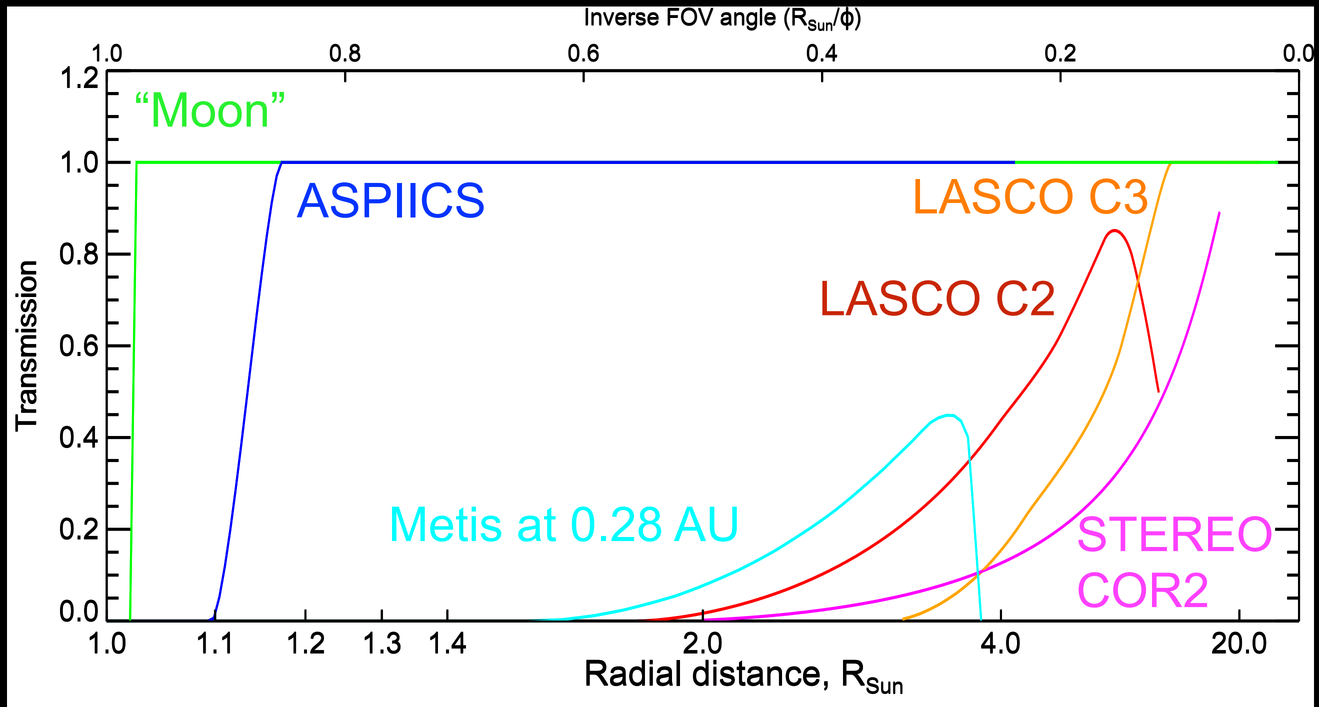
- Straylight modeling confirms that in the inner part of the field of view, the straylight is dominated by the diffraction of the solar disk light on the external occulter *(Shestov et al. 2019)*.
- Different contributions into the total straylight (diffraction, scattering, ghosts) have been calculated.

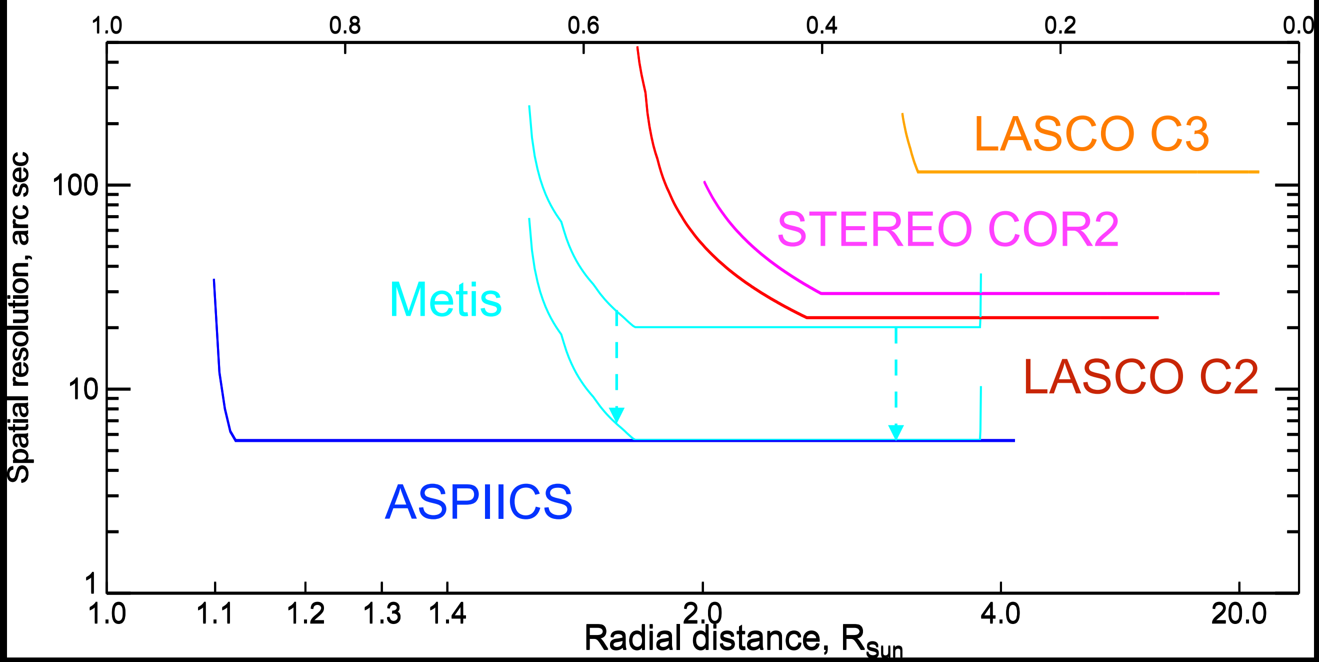
PROBA-3/ASPIICS in comparison with other coronagraphs



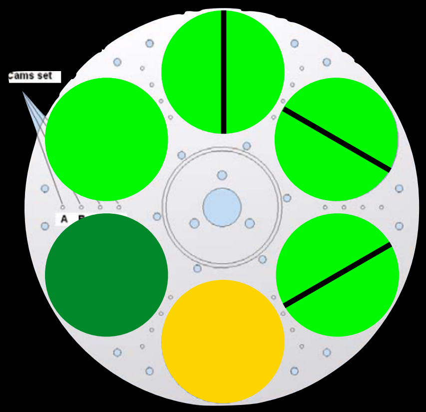
Inner edge of the field of view:
ASPIICS - 1.099 R☉
STEREO COR2 - 2.5 R☉
SOHO/LASCO C2 - 2.2 R☉
Solar Orbiter Metis at 0.28 au - 1.6 R☉

vignetting function





spatial resolution

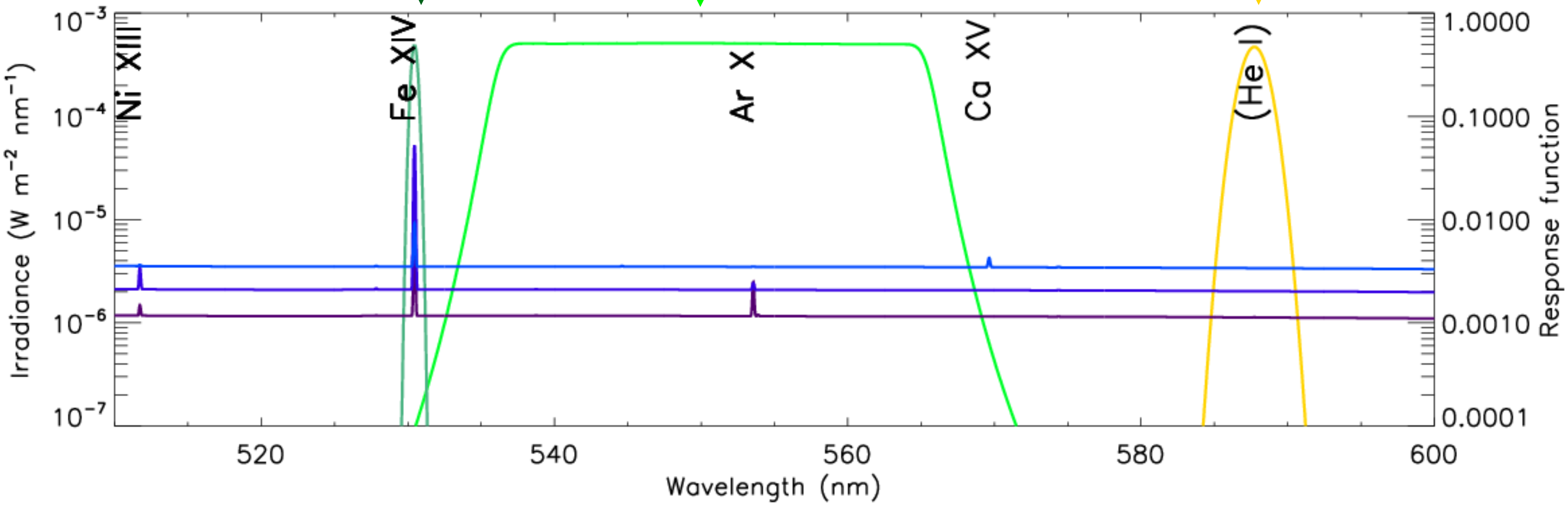


Six filters of ASPIICS

Fe XIV passband at 5304 Å

green continuum passband

He I D3 passband at 5877 Å



- wide (5350-5650 Å) white-light (green continuum) passband containing essentially the coronal continuum produced by the Thomson scattering,
- wide white-light passband combined with 3 polarizers oriented at angles of 0°, 60°, 120°,
- narrow (6 Å) passband centered at 5304 Å (coronal green line of Fe XIV + coronal continuum),
- narrow (20 Å) passband centered at 5877 Å (prominence line of He I D3 + coronal and prominence continuum).

PROBA-3/ASPIICS scientific objectives

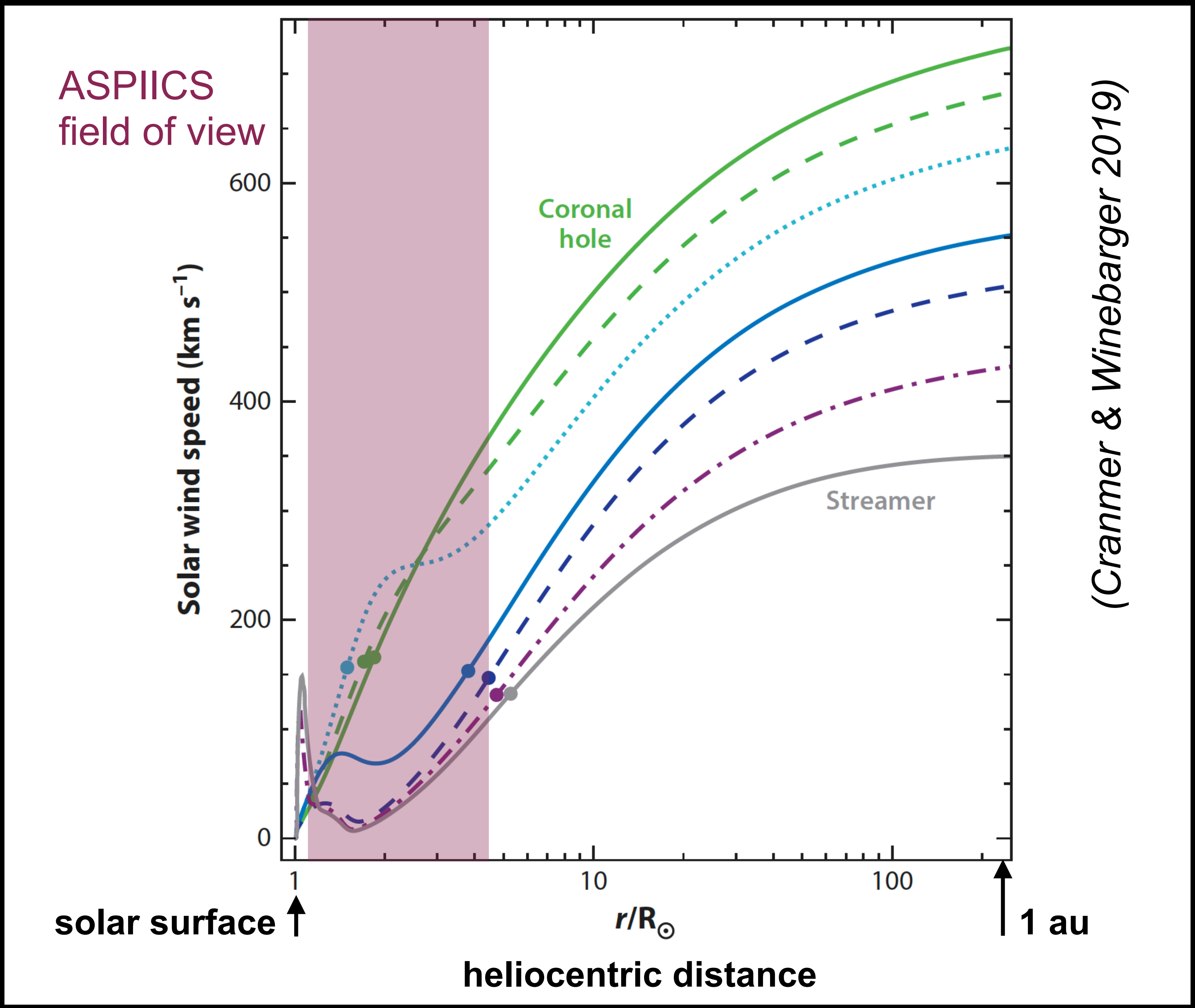
- PROBA-3 will address one of the main questions of the ESA Cosmic Vision plan *"How does the solar system work?"*

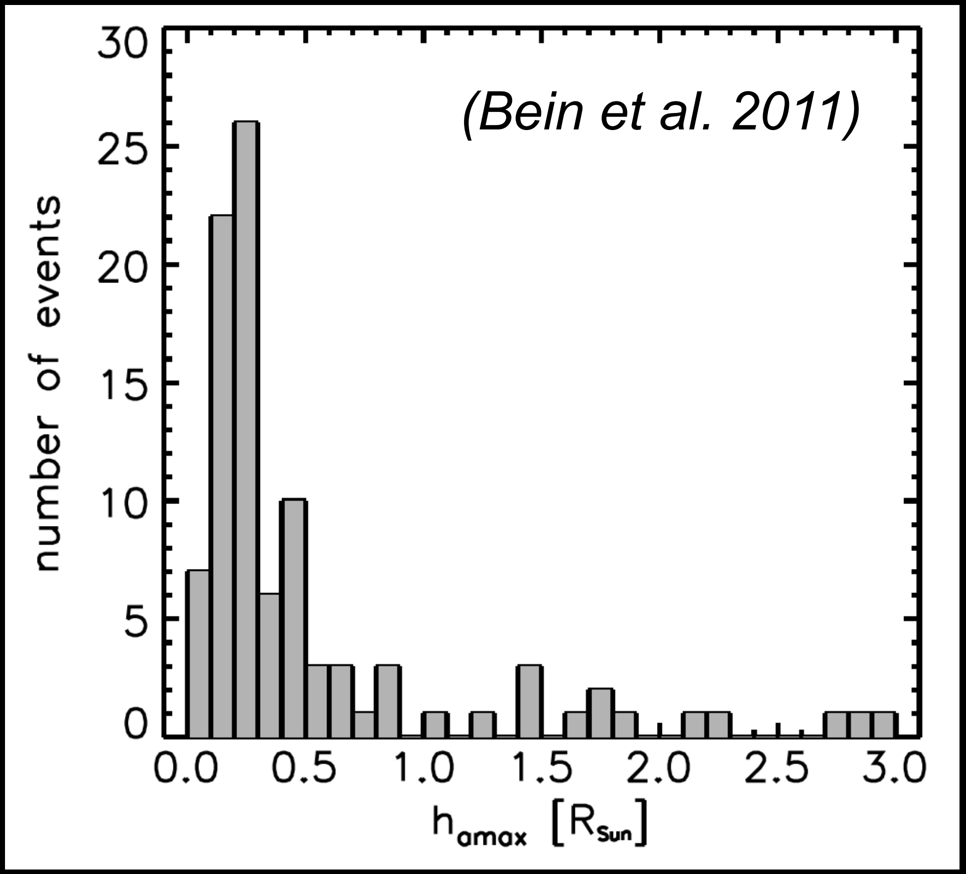
- The top-level scientific objectives of ASPIICS are:

1. Understanding the physical processes that govern the quiescent solar corona by answering the following questions:
   - What is the nature of the solar corona on different scales?
   - What processes contribute to the heating of the corona?
   - What processes contribute to the solar wind acceleration?

2. Understanding the physical processes that lead to CMEs and determine space weather by answering the following questions:
   - What is the nature of the structures that form the CME?
   - How do CMEs erupt and accelerate in the low corona?
   - What is the connection between CMEs and active processes close to the solar surface?
   - Where and how can a CME drive a shock in the low corona?

Why are observations of the inner solar corona so important?





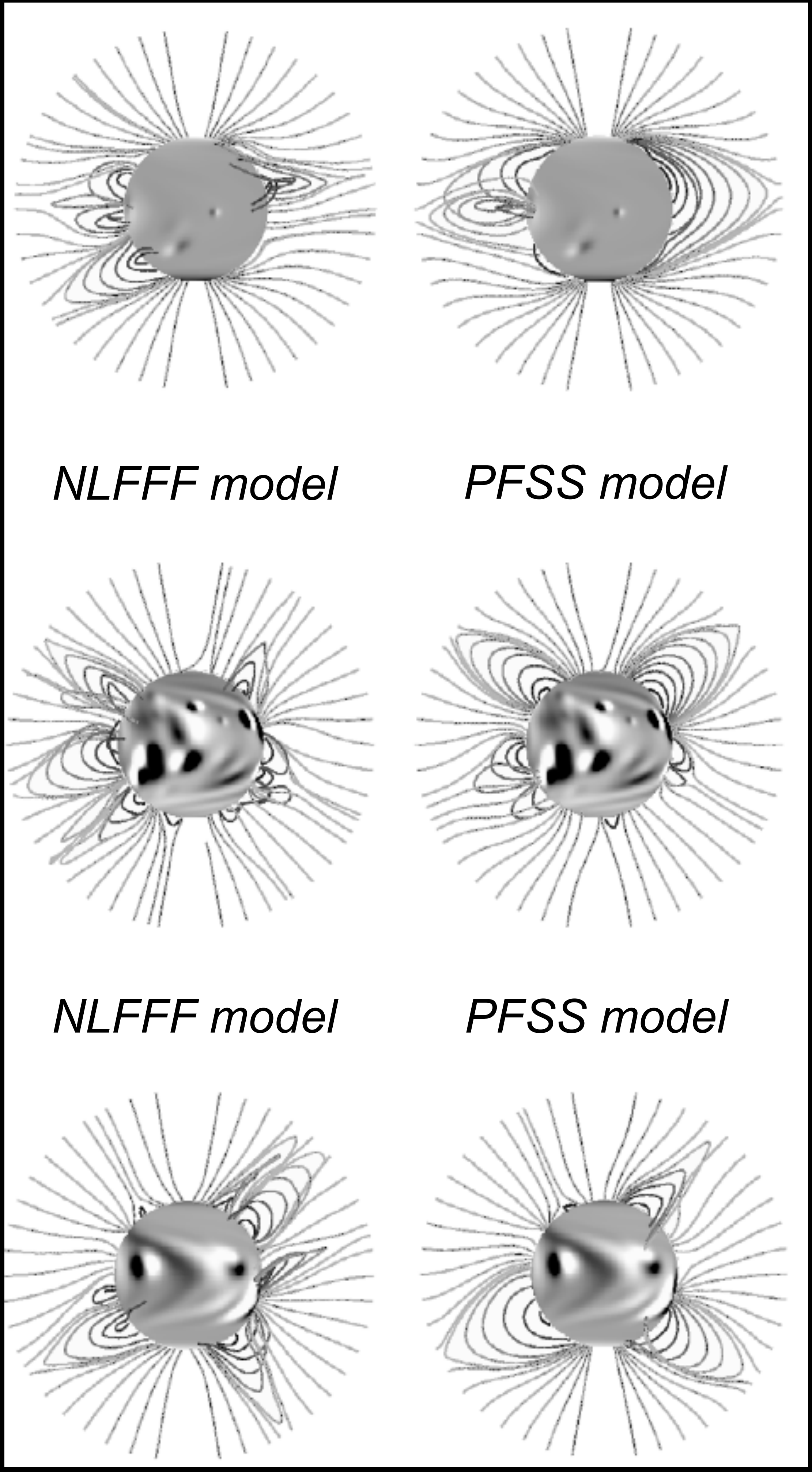
- The peak acceleration of coronal mass ejections (CMEs) also occurs in this region.

- Simulations show important acceleration of the solar wind (to supersonic velocities) around 2-3 $R_\odot$ from the center of the Sun.

Examples of science cases

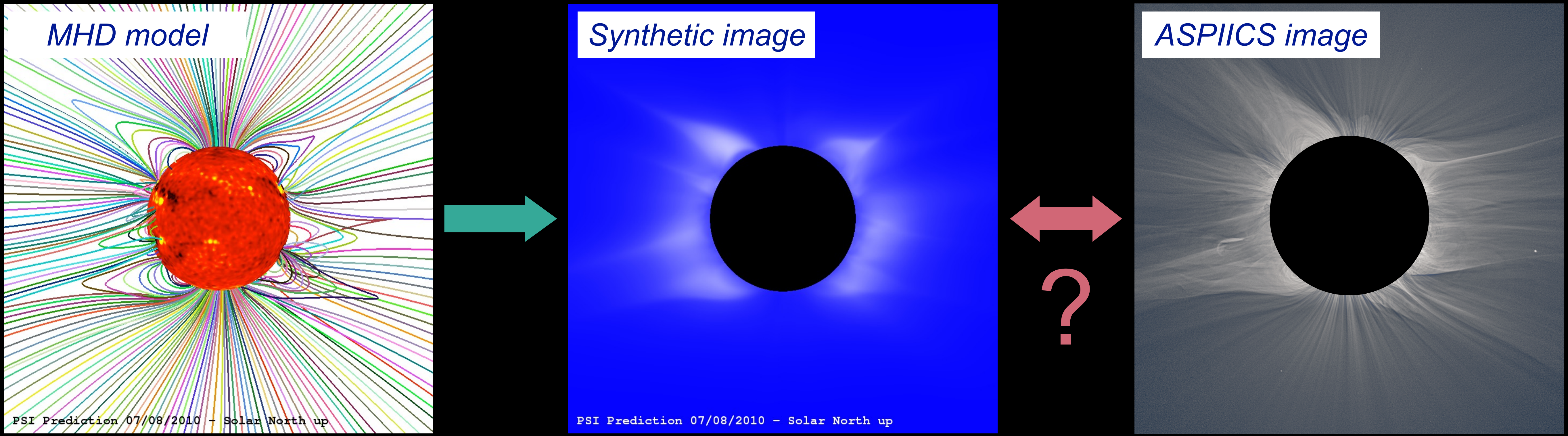
Problems of models to derive coronal magnetic fields

- The extrapolated field is strongly model-dependent.
- The extrapolated field is static.
- Realistic extrapolations also require difficult horizontal photospheric field measurements and strong assumptions about critical but unobserved quantities (e.g. magnetic field at the low-β coronal base is assumed to be the same as in the high-β photosphere).
- The extrapolated field cannot always reproduce accurately complex magnetic configuration of the solar corona.



(Yeates et al. 2010)

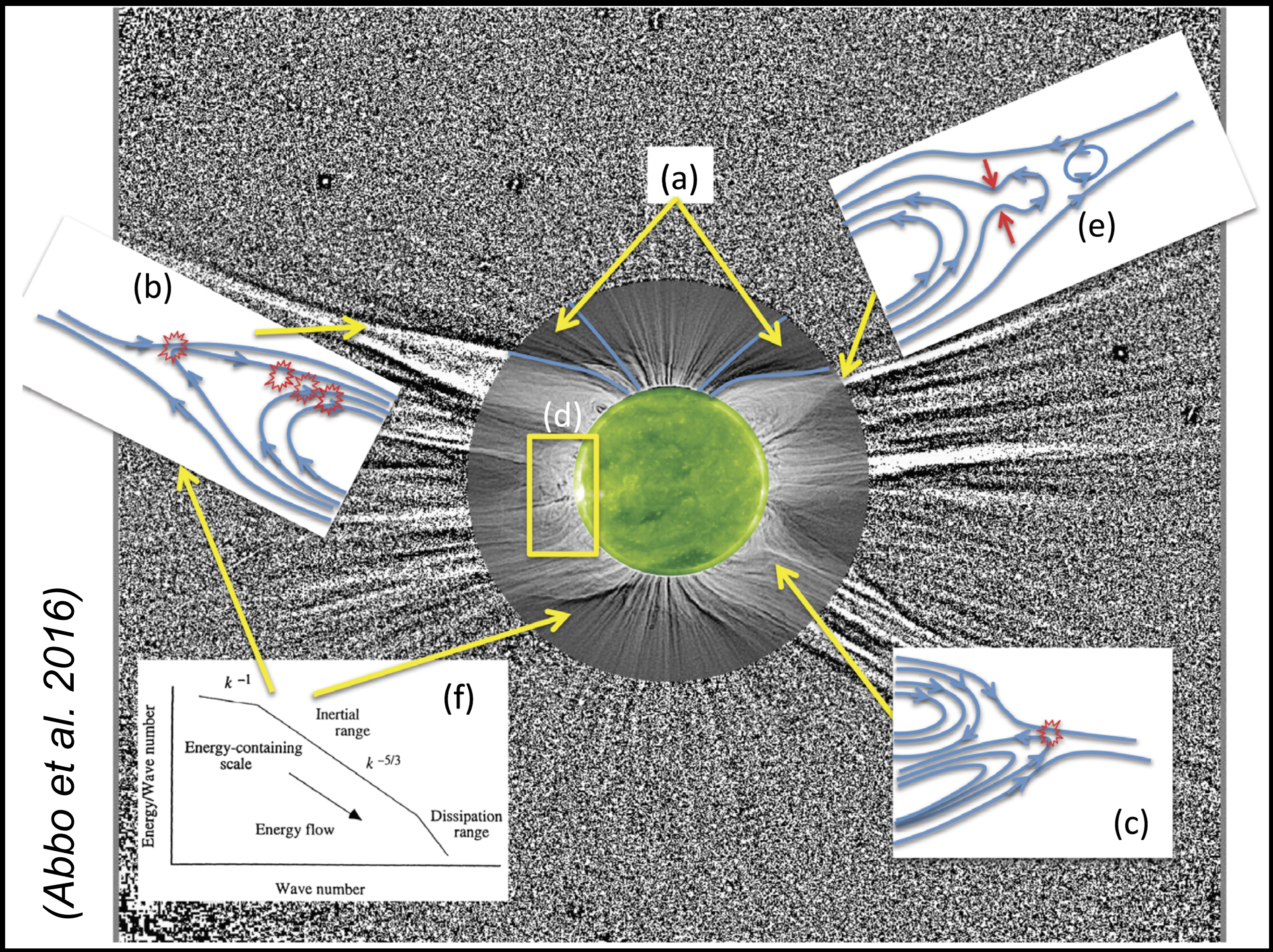
Coronal structuring and dynamics

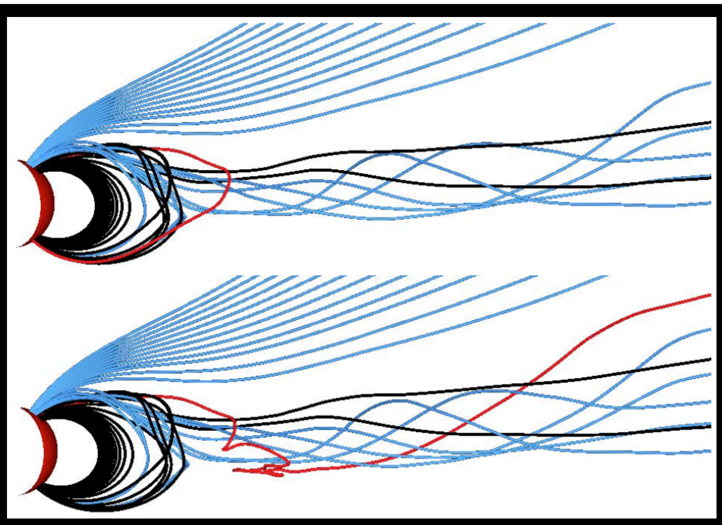


- The crucial transition between closed-field regions (magnetic field dominated) and open-field regions (solar wind dominated) is poorly observed by other missions (SOHO, SDO, PROBA2, Solar Orbiter).
- PROBA-3/ ASPIICS will track the connectivity of coronal structures to the solar surface and, in combination with state-of-the-art MHD models, allow us to determine reliably the large-scale coronal magnetic field configuration.
- The excellent spatio-temporal resolution of ASPIICS will allow us to investigate the fine structure and dynamics of the corona above the field of view of modern EUV imagers.

Origin of the slow solar wind

- Six processes may contribute to the slow solar wind.
- Only two of them (d, f) can be constrained by current observations due to insufficient field of view of modern instrumentation (Hinode, SDO, IRIS).
- Four other processes (a, b, c, e) involve dynamics at the (pseudo-)streamer cusps that can be observed for the first time in white light by PROBA-3/ASPIICS.



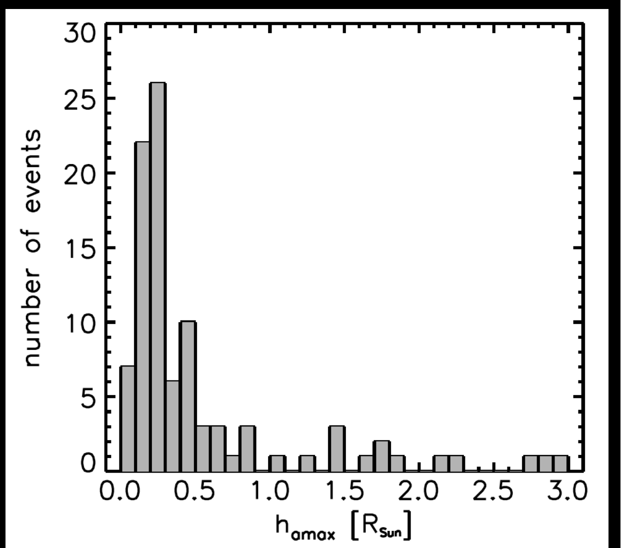


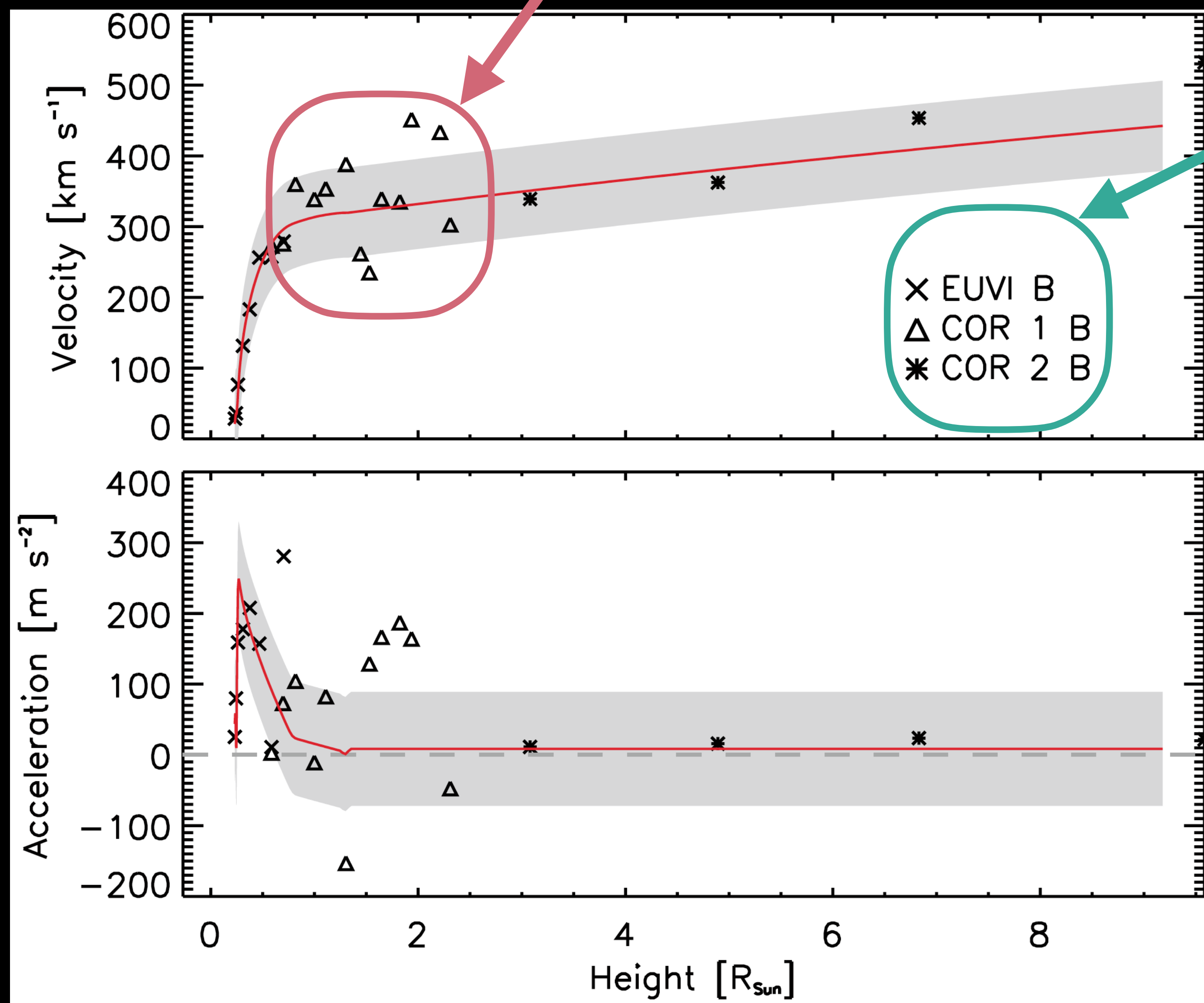
MHD model of interchange reconnection at the streamer cusp (b)
(Higginson et al. 2017)

The peak acceleration of 95% of CMEs is reached within 2 R$_\odot$ from the surface

strong scatter of points in the inner corona due to high straylight

measured by three different instruments

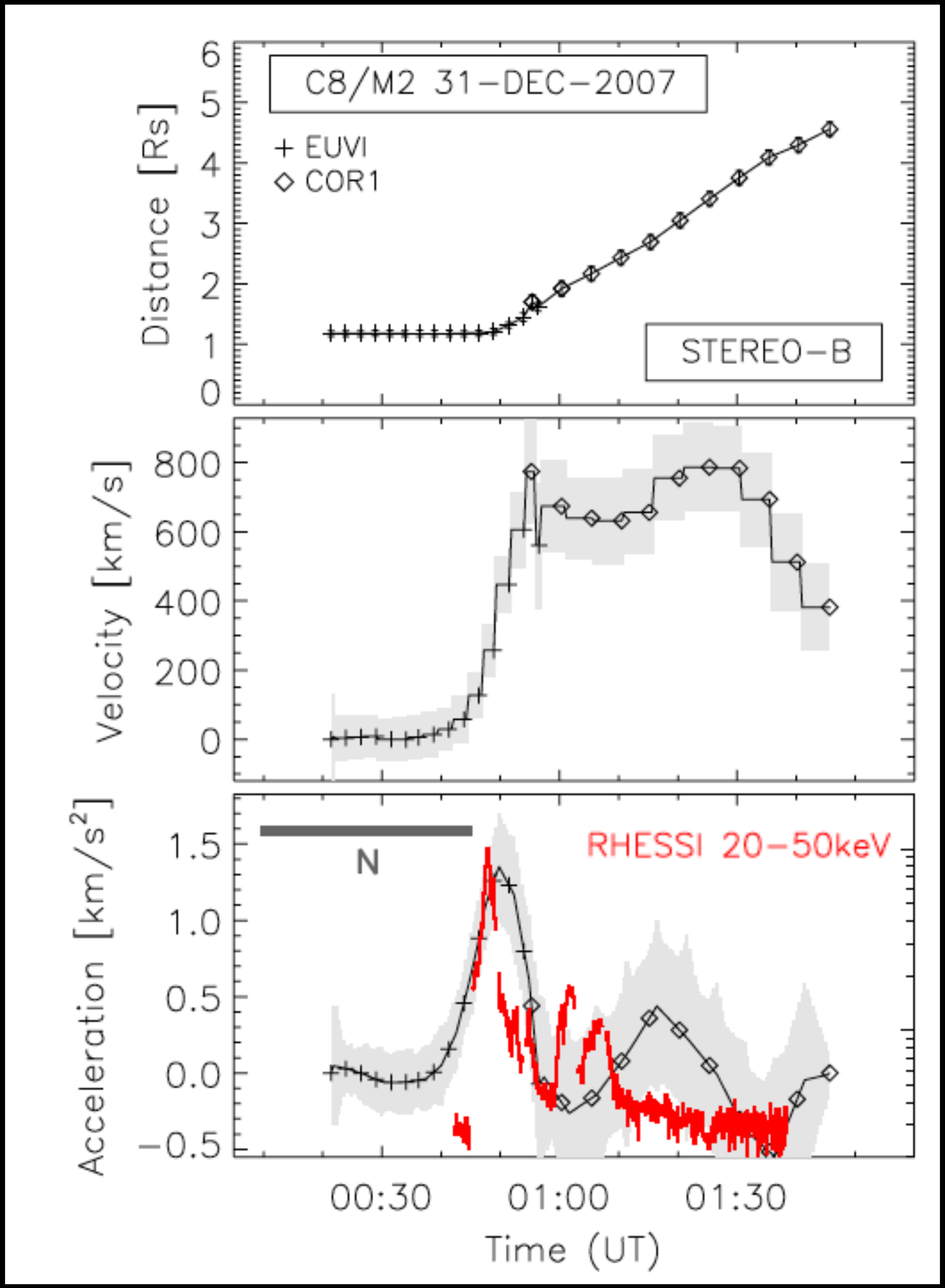




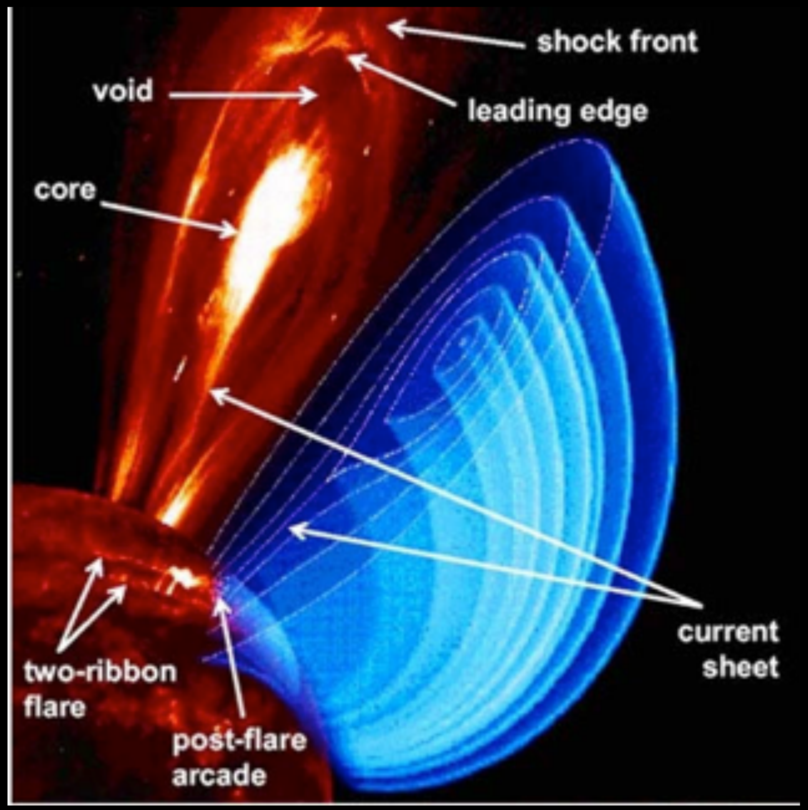
(Bein et al. 2011)

- The heterogeneous observations made with three different types of instruments (EUV imagers, internally and externally occulted white-light coronagraphs) do not allow distinguishing between different proposed mechanisms of the CME initiation.

CME-flare association

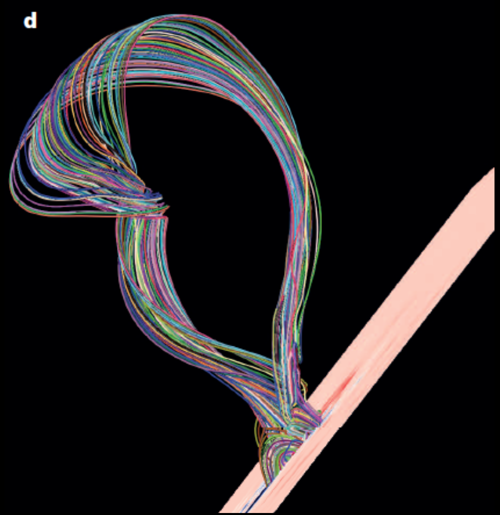


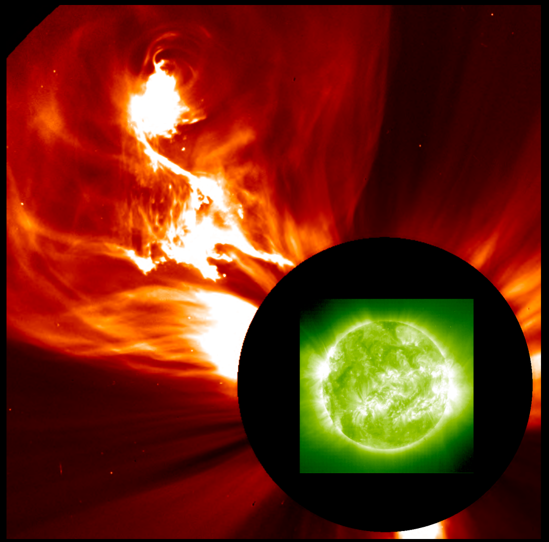
(Temmer et al. 2010)

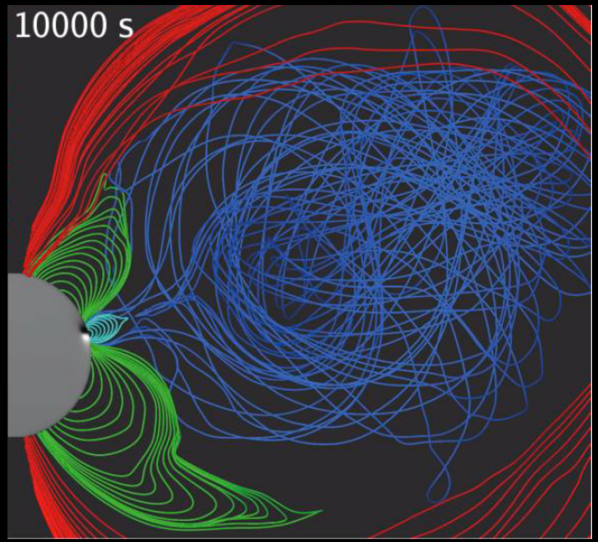


- The frequent temporal coincidence between the impulsive acceleration of a CME and the associated flare energy release can be interpreted as evidence of a common cause in many flares and CMEs – magnetic energy release.
- However, the coincidence does not occur in all CMEs.
- CMEs gain most of their acceleration below 3 $R_\odot$, i.e. in a region not very well observed by past and present coronagraphs onboard SoHO and STEREO.

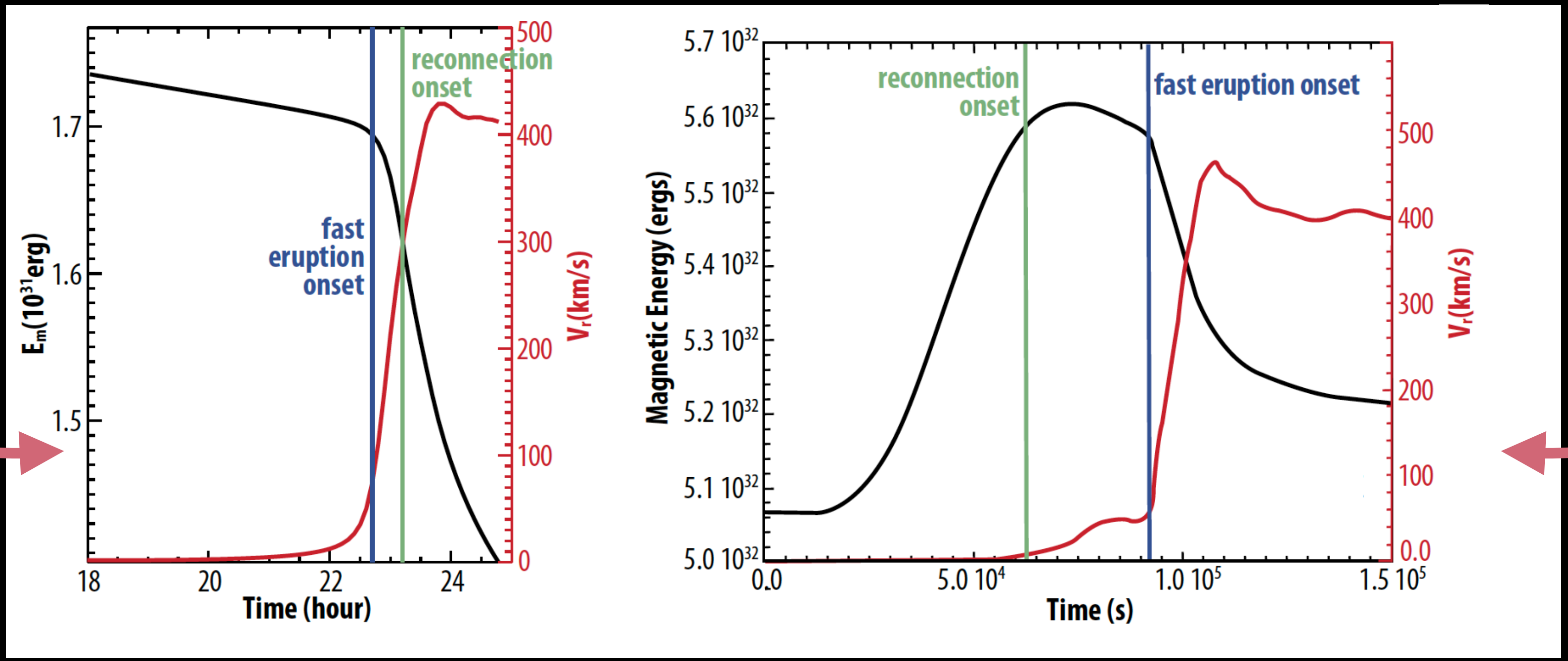
CME onset and acceleration







torus instability



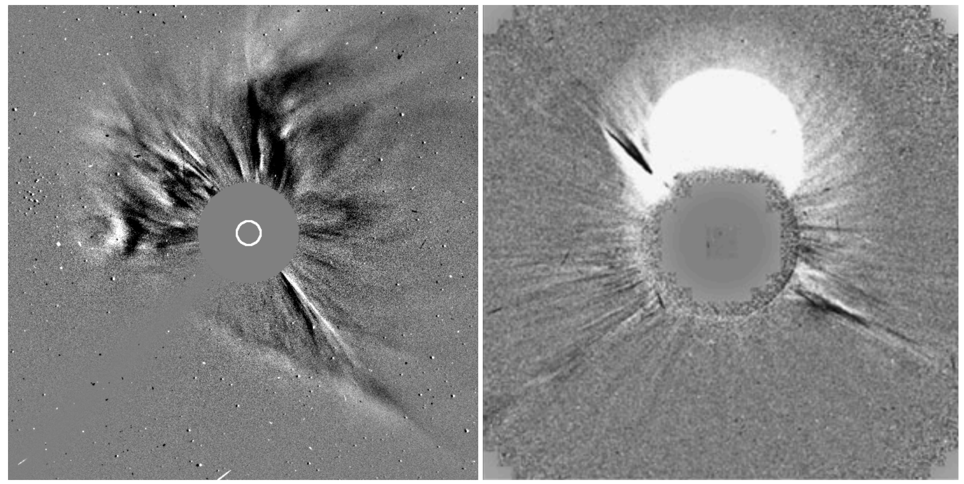
magnetic breakout

- PROBA-3/ASPIICS will:
  - measure the CME kinematics in the inner corona,
  - for the first time observe in detail the full coronal restructuring during CMEs.

Can be poorly done by the current instrumentation.

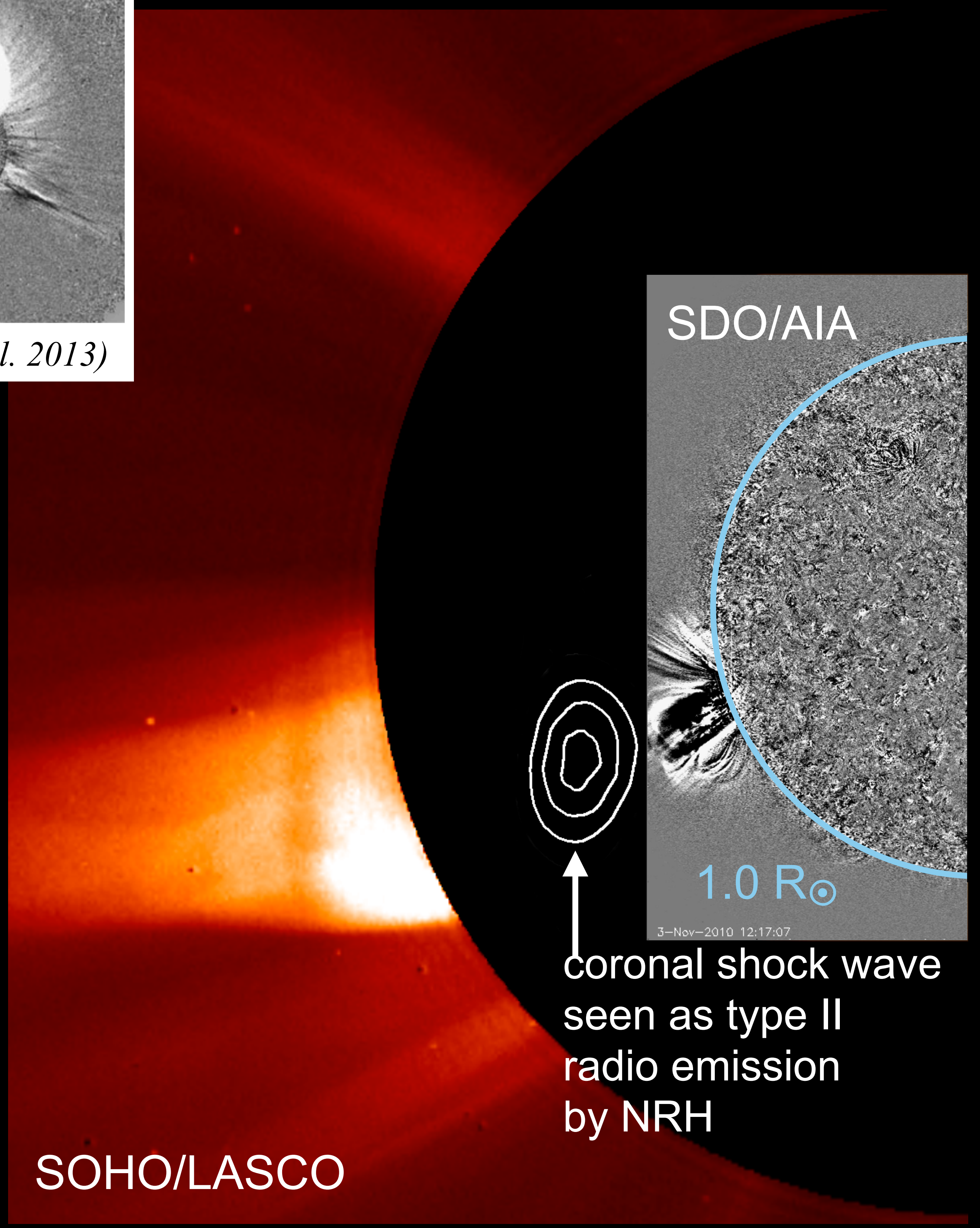
Cannot be fully done by the current instrumentation.

Origin of shock waves in the inner corona

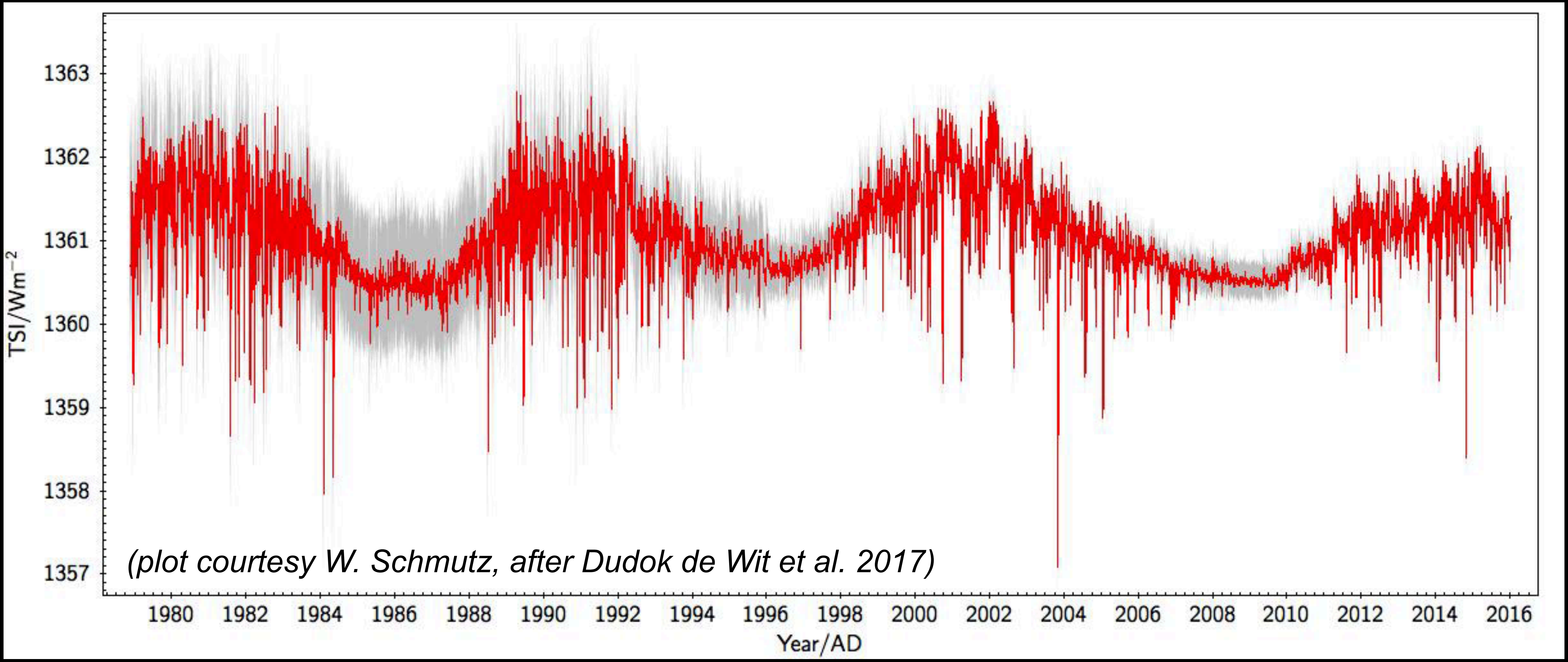


(Sheeley et al. 2000) *(Vourlidas et al. 2013)*

- Coronal shock waves can be observed by coronagraphs in white light.
- Ground-based radio telescopes with very low spatial resolution detect shock waves formed in the inner corona as type II radio bursts.
- High-resolution EUV imagers and conventional white-light coronagraphs can observe only parts of the region where the type II radio burst sources propagate.
- PROBA-3/ASPIICS will observe the dynamics of both the CME and the shock in the crucial region of the inner corona for the first time, providing us with conclusive evidence for the origin of coronal shock waves.

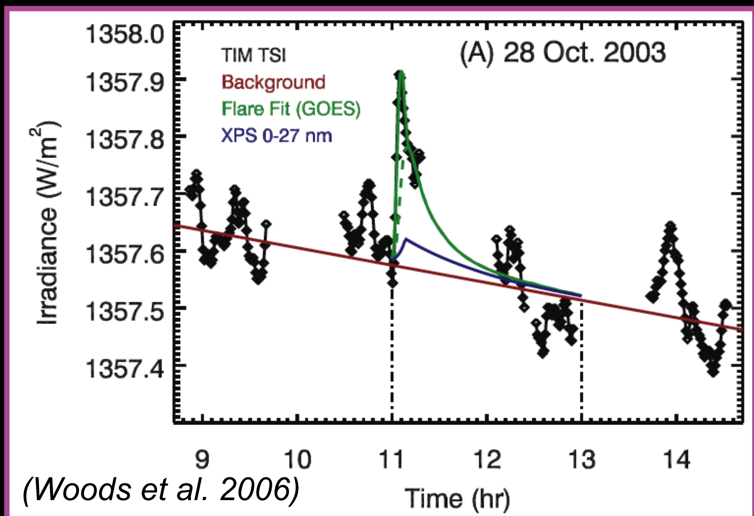


DARA - a novel instrument to measure the evolution of the "solar constant"

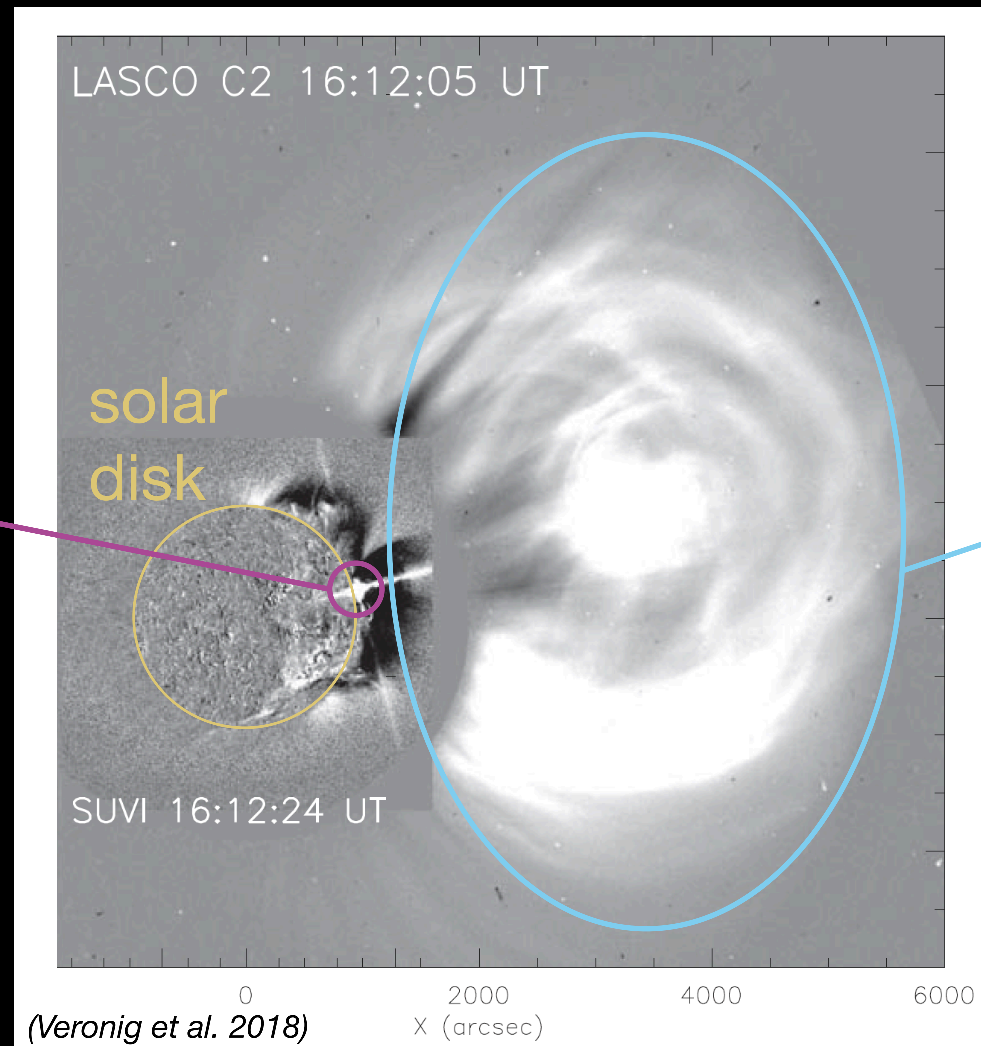


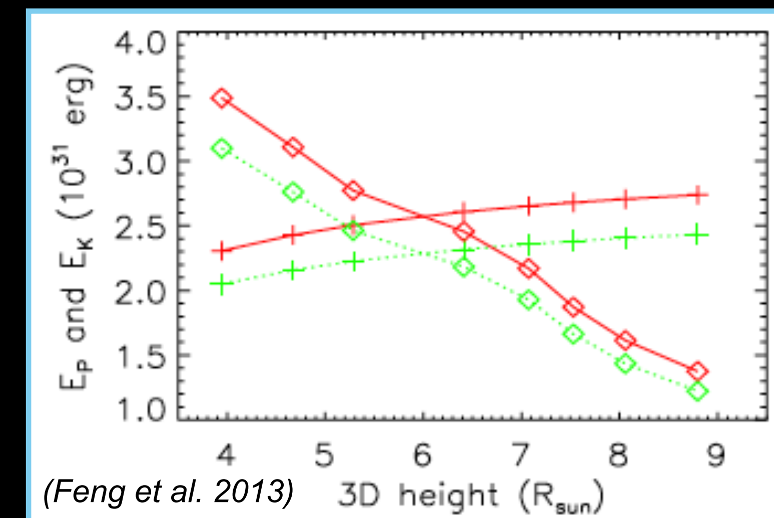
- The main scientific objective of DARA is to extend the measurements of the total solar irradiance ("solar constant").

Solar eruptions: common science of ASPIICS and DARA



Radiative energy of flares can be estimated from the DARA measurements.

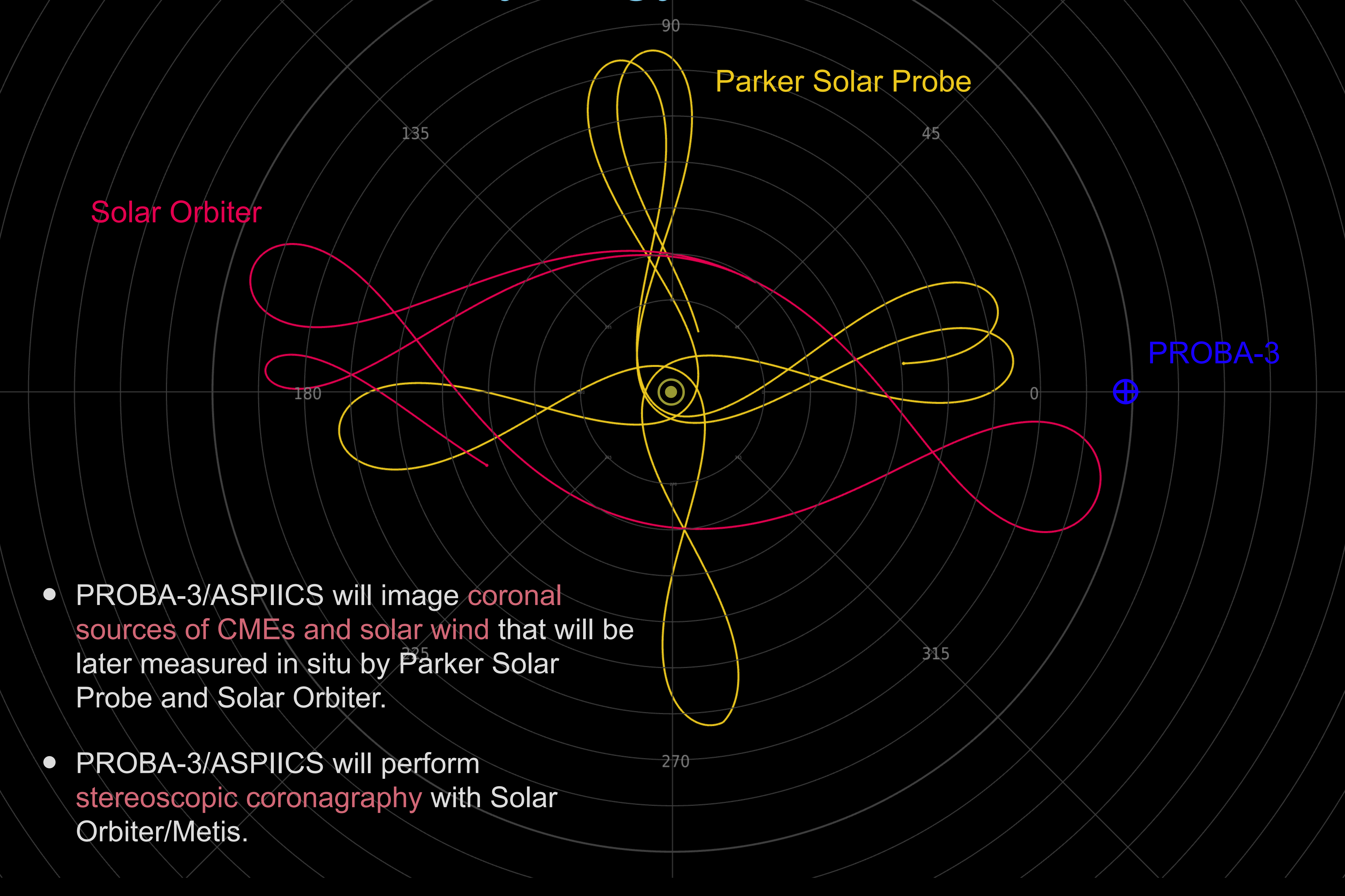




Kinetic energy of CMEs can be calculated from ASPIICS measurements.

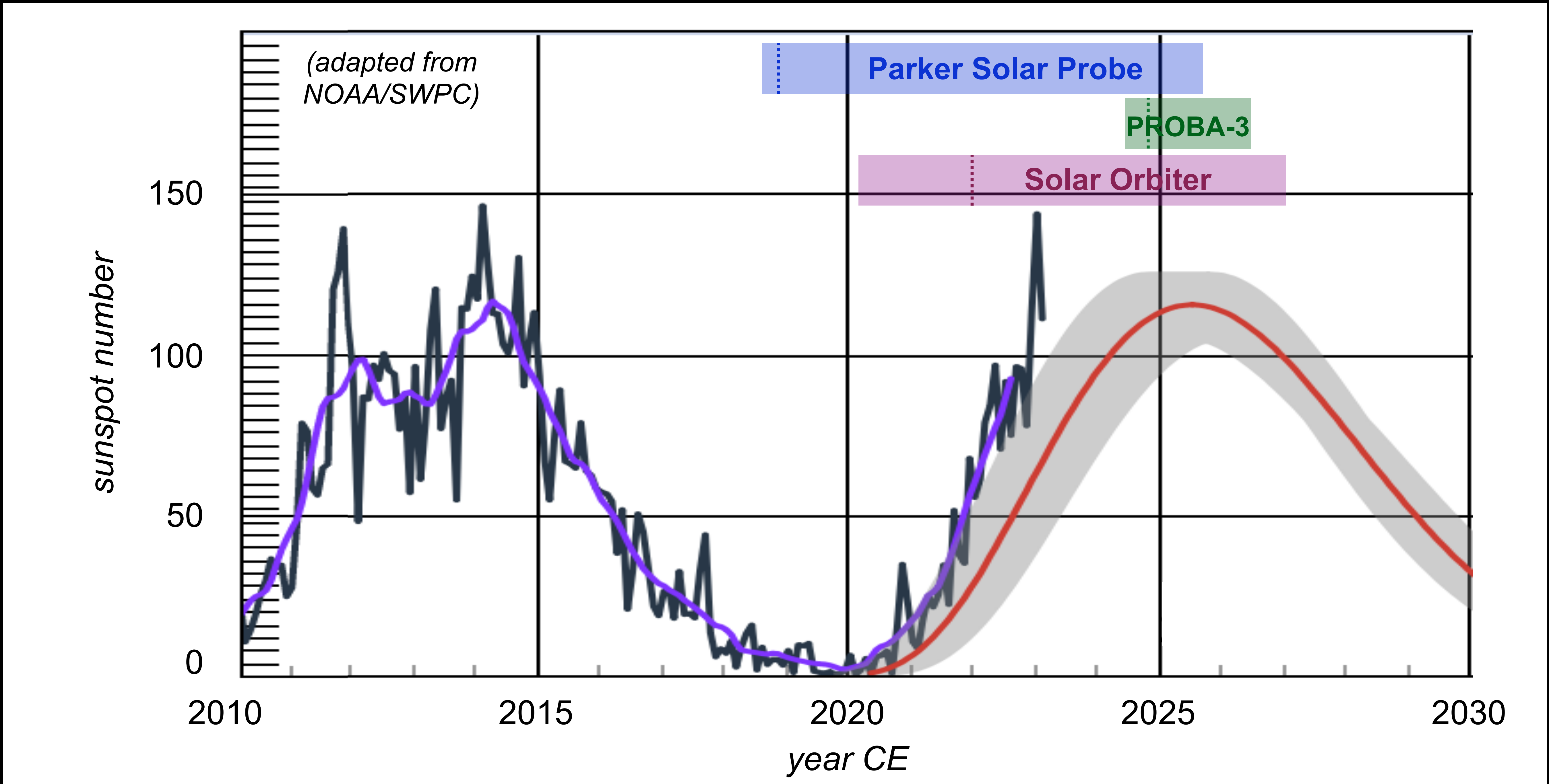
- During solar eruptive events, free magnetic energy in the corona is converted into radiative energy (flare) and kinetic energy of plasma motions (CME).
- The physics of the energy partition into radiative and kinetic energies is currently unclear.

PROBA-3 in synergy with other missions



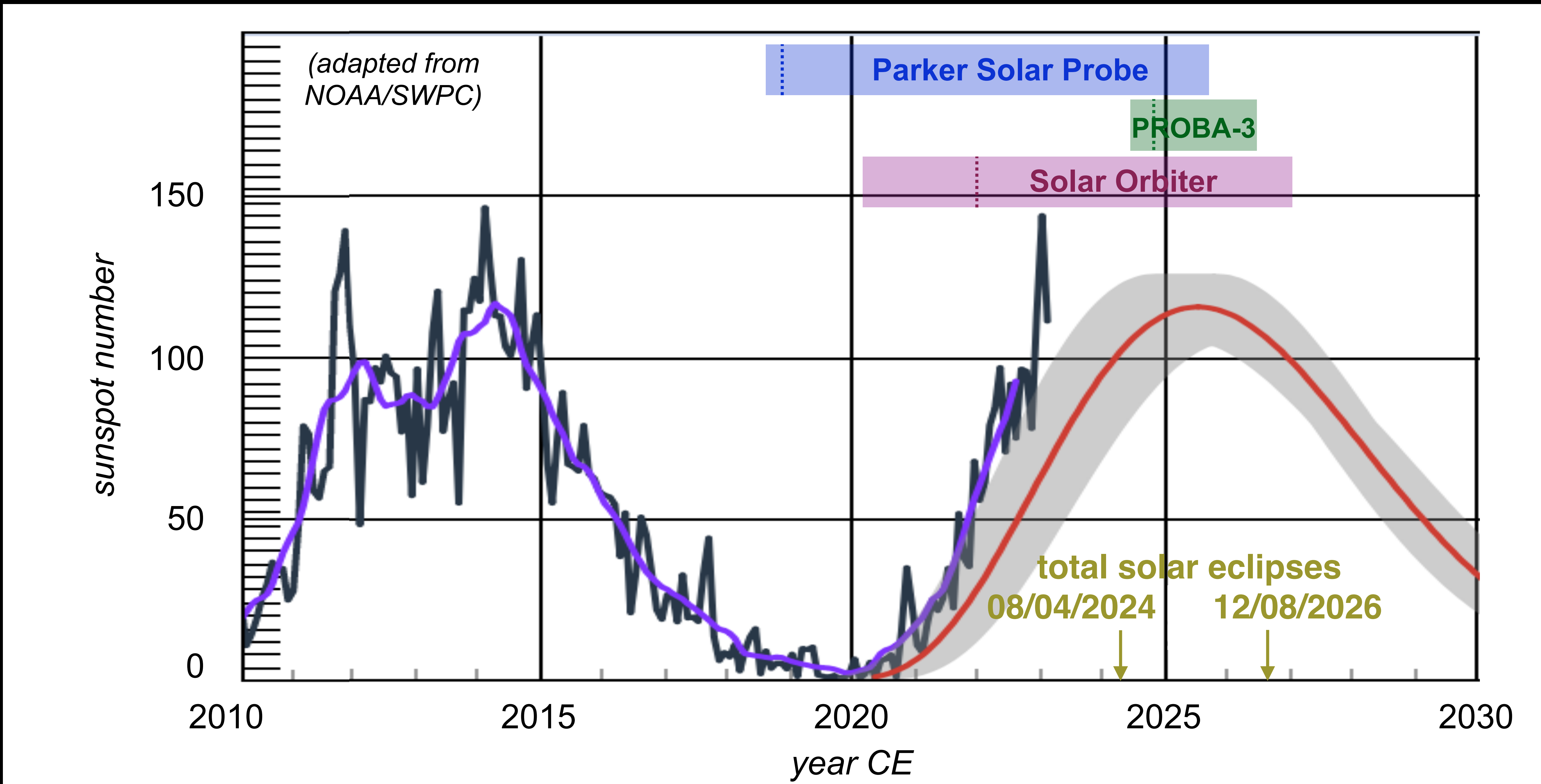
- PROBA-3/ASPIICS will image coronal sources of CMEs and solar wind that will be later measured in situ by Parker Solar Probe and Solar Orbiter.
- PROBA-3/ASPIICS will perform stereoscopic coronagraphy with Solar Orbiter/Metis.

PROBA-3 in synergy with other missions



- The PROBA-3 launch on 01 May 2024 would allow to make coordinated observations with other solar and heliospheric space missions, e.g., Solar Orbiter (ESA) and Parker Solar Probe (NASA) during more than a year of the nominal mission.
- During the science operations of PROBA-3 (2024-2026) the Sun is expected to go through the maximum of the solar cycle.

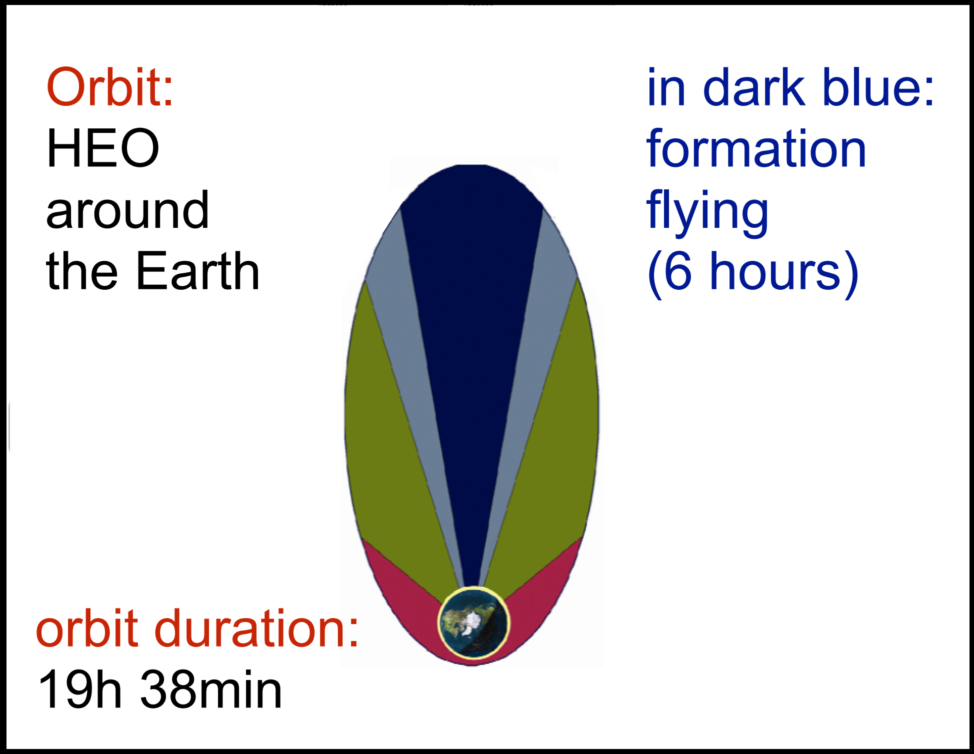
Total eclipse: a unique calibration opportunity!



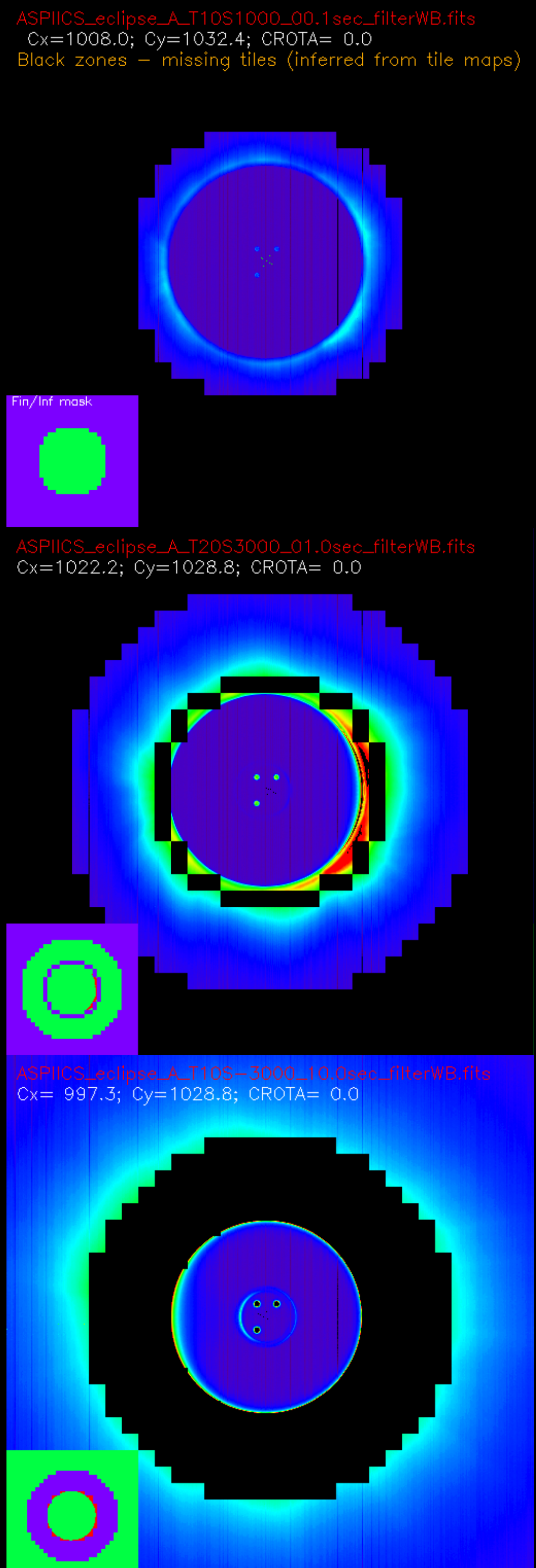
- The PROBA-3 launch in Q2 2024 would allow to use the ground-based observations of the total solar eclipse in August 2026 to calibrate the ASPIICS observations - in case the nominal mission is prolongated by a few months.
- The following total eclipse will be only in August 2027.

PROBA-3 science operation concept

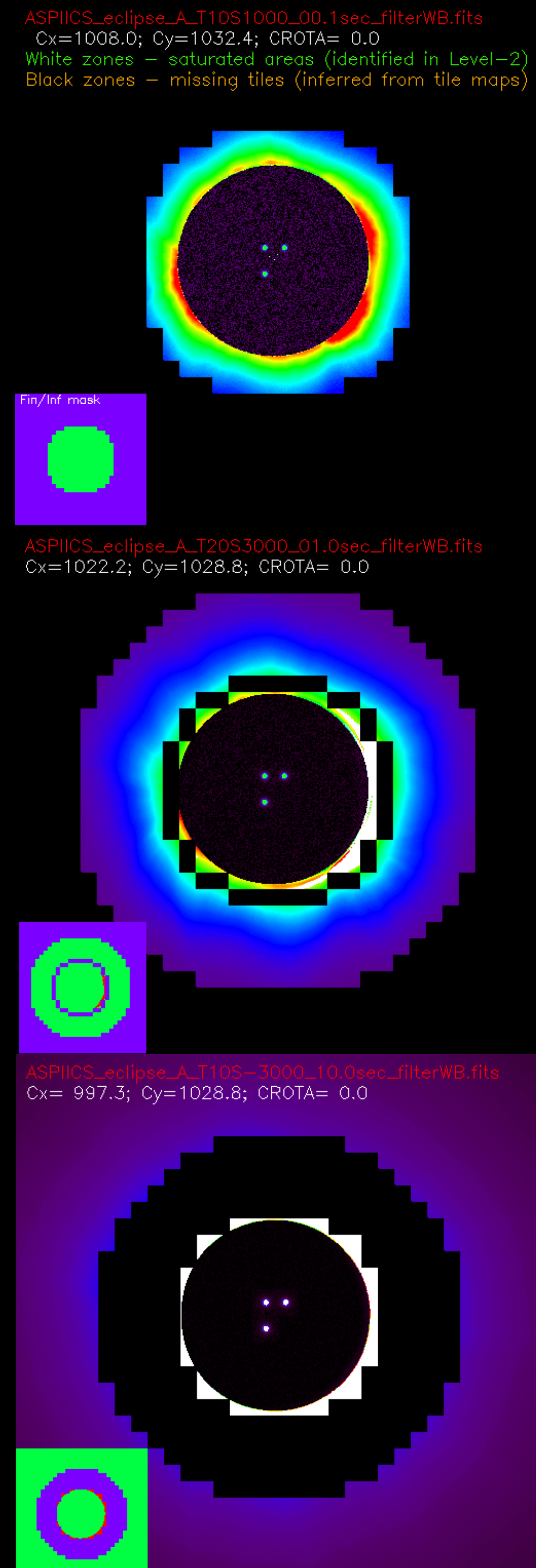
- The duty cycle of PROBA-3 will allow observing the corona only during limited periods of time - 6 hours out of 19 h 38 min of the orbit duration, and on average 2 orbits per week.
- This implies complex real-time planning of science operations by the SOC.
- The PROBA-3 Project at ESA D/TEC, MOC, and SOC will choose the periods of observations, which need to be optimised to collect the data on as many CMEs (rare events) as possible.
- SOC will choose the observational programme for the next formation flying orbit, depending on the science objective - e.g., “Synoptic programme”, “Waves programme”, “CME-Watch programme”.
- Solar activity is a major driver of the planning. The observations of solar activity will be provided by other space missions and ground-based observatories.
- Another driver of the planning is to maximise the synergies with other missions, e.g. with Solar Orbiter and Parker Solar Probe.



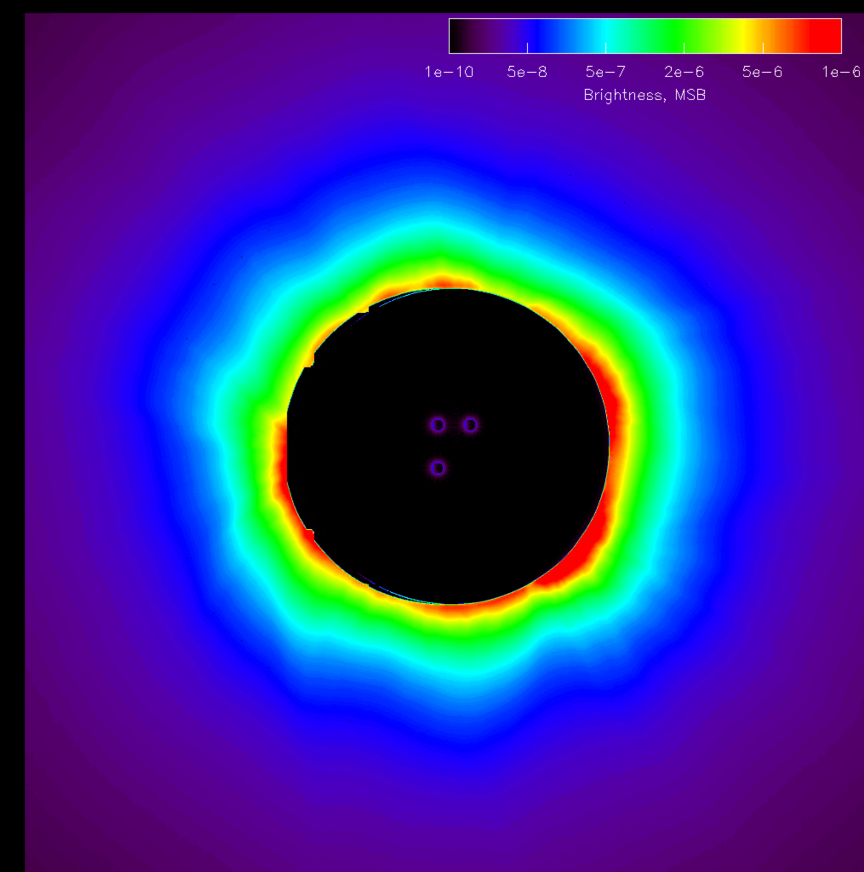
ASPIICS data pipeline



Level 1 (raw)



Level 2 (calibrated)



Level 3 (calibrated, full field of view)

Summary

- ✳ PROBA-3 is a perfect example of a mission driven by both science and technology.
  - Technology demonstration mission: PROBA-3 will test precise formation flying technologies that can be used by future missions.
  - Mission of Opportunity in the ESA Science Programme: PROBA-3/ASPIICS will be a significant advance from previous, current, and planned solar coronagraphs.
- ✳ Due to the unique telescope to occulter separation (around 144 m), ASPIICS will be able to observe the inner corona as close to the solar centre as 1.099 $R_\odot$ in low straylight conditions.
- ✳ PROBA-3/ASPIICS will fill the gap between the low corona (typically observed by EUV imagers) and the high corona (typically observed by externally occulted coronagraphs).
- ✳ ASPIICS observations will be crucial for solving several outstanding problems in solar physics:
  - structure of the magnetised solar corona,
  - sources of the slow solar wind,
  - onset and early acceleration of CMEs.


Thank you for your attention!

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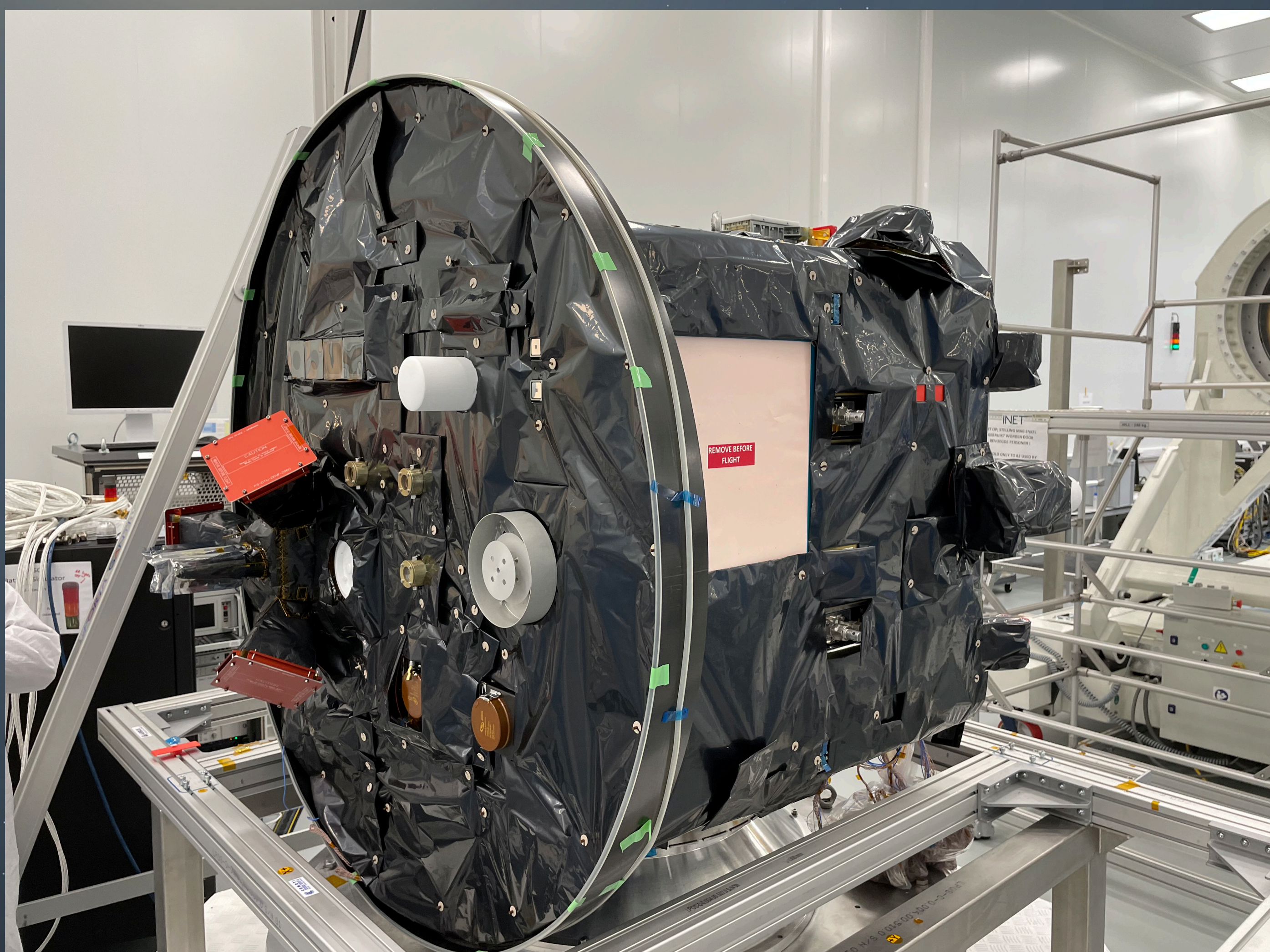

Target launch date: 1 May 2024