SOLI INVICTO

The PROBA-3 Mission
and Its Contribution to Space Weather Studies

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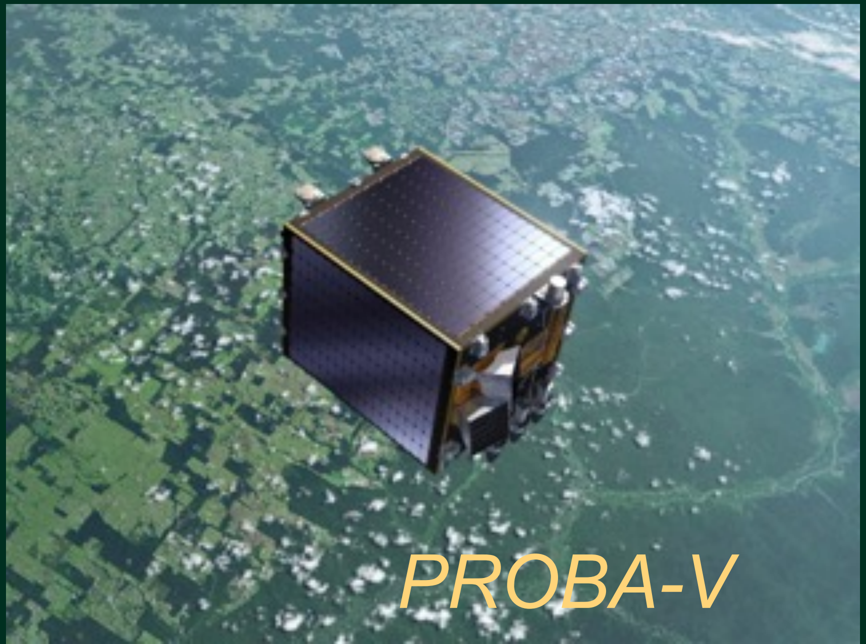
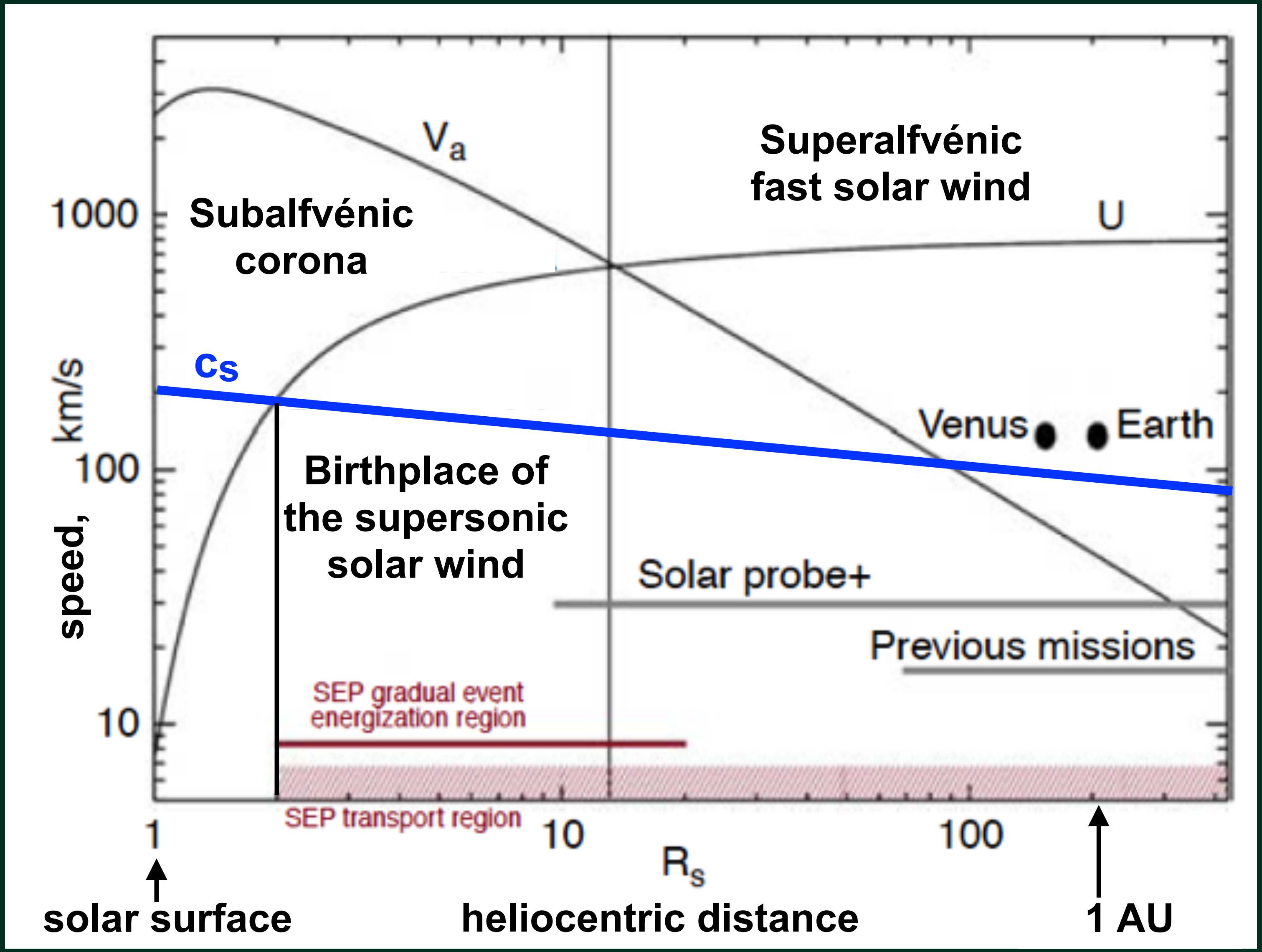
PROBA-3: the next in line

Spacecraft in the PROBA (PRoject for On-Board Autonomy) series of the European Space Agency are small technology demonstration missions that also have scientific goals.

- PROBA-1 (2001 - to date): Earth observations
- PROBA2 (2009 - to date): solar corona observations and space weather
- PROBA-V (2013 - to date): monitoring of the worldwide vegetation
- PROBA-3 (to be launched in 2018): a giant solar coronagraph to study the inner corona.



Why do we need observations of the inner solar corona?

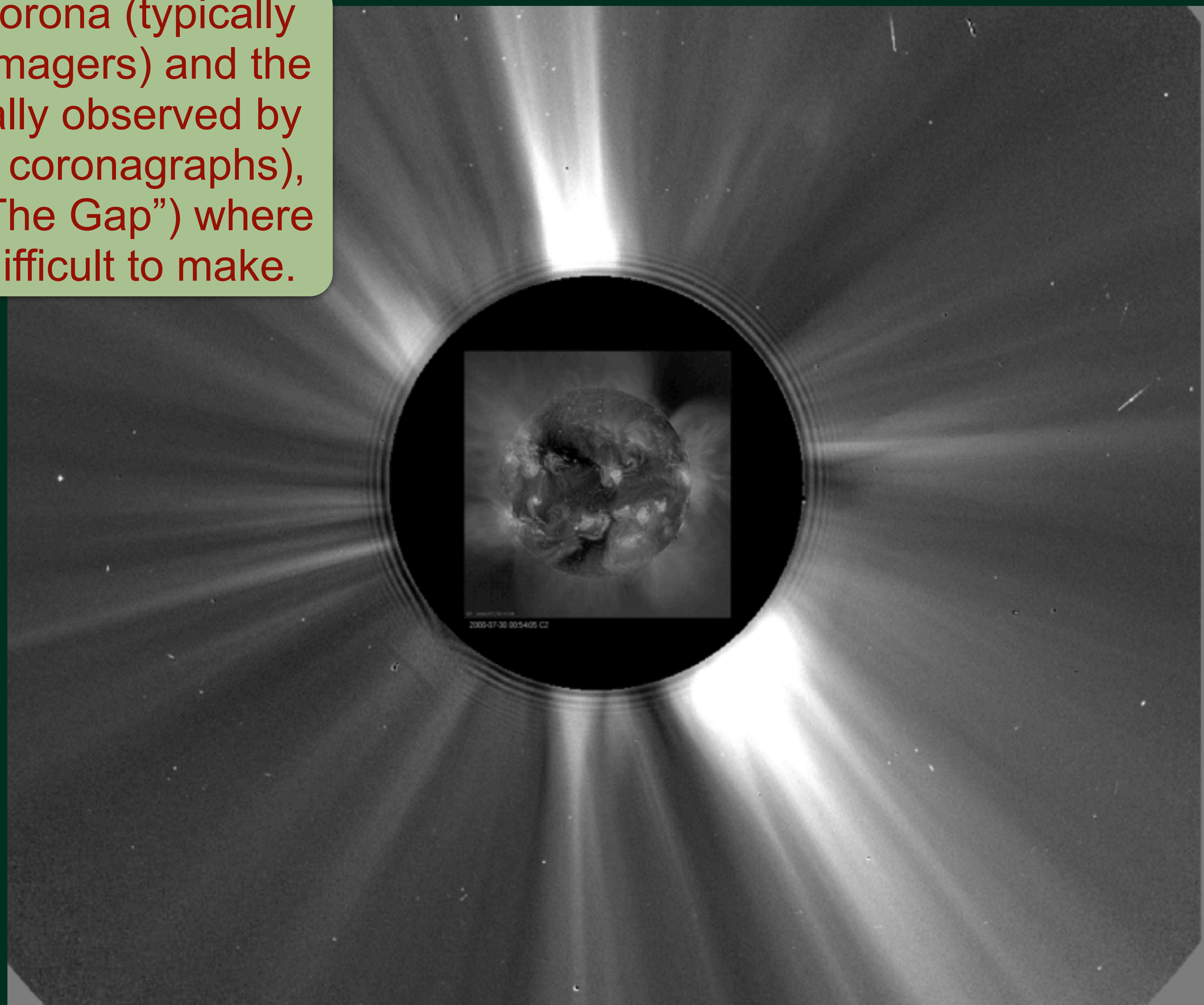


(After the report of the Science and Technology Definition Team of Solar Probe Plus)

- A typical simulated solar wind acceleration profile shows that the solar wind becomes supersonic around 2-3 $R_\odot$ from the center of the Sun.
- Coronal mass ejections (CMEs) are also accelerated in this region.

Imaging observations of the solar corona

Between the low corona (typically observed by EUV imagers) and the high corona (typically observed by externally occulted coronagraphs), there is a region ("The Gap") where observations are difficult to make.



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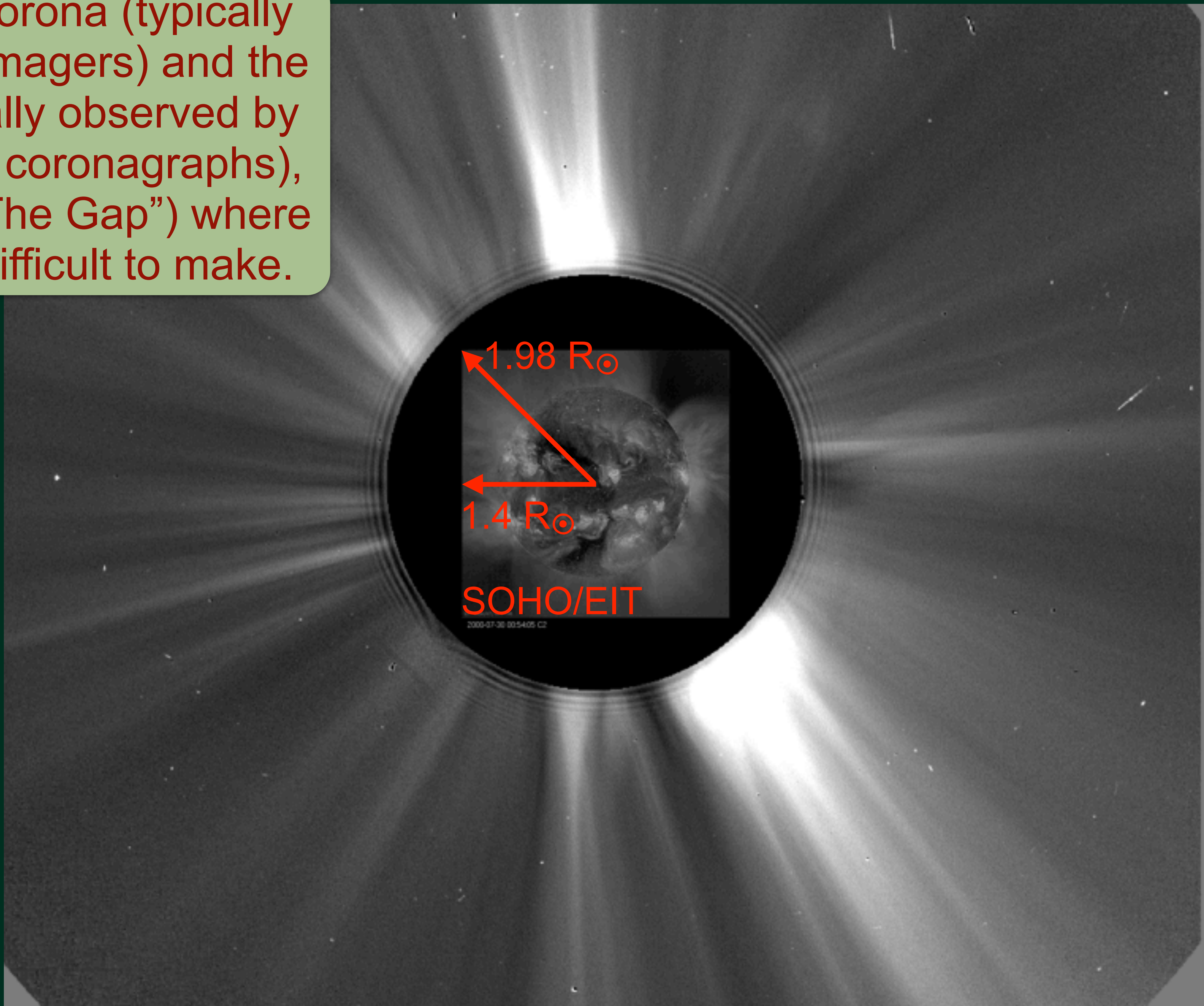

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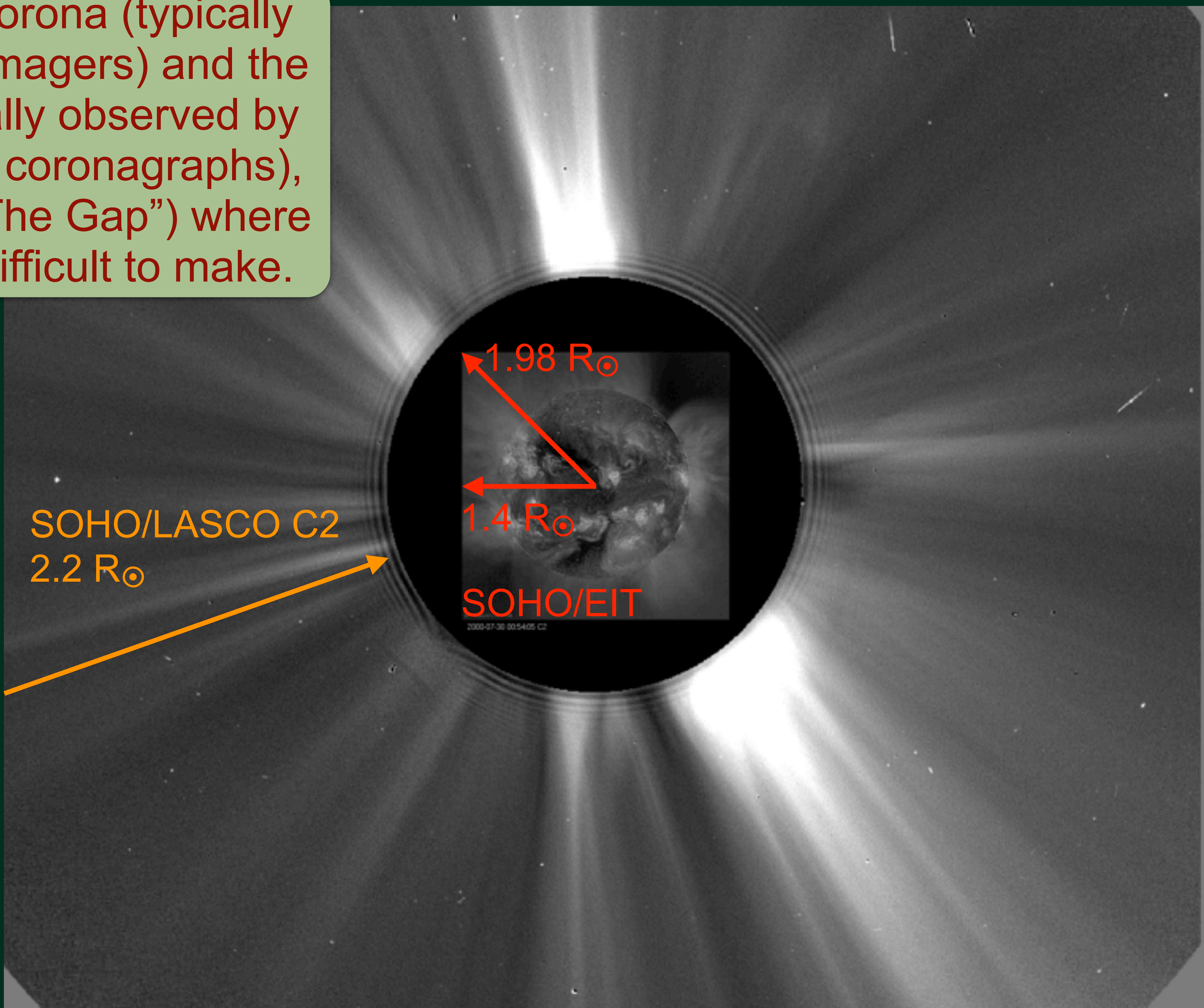

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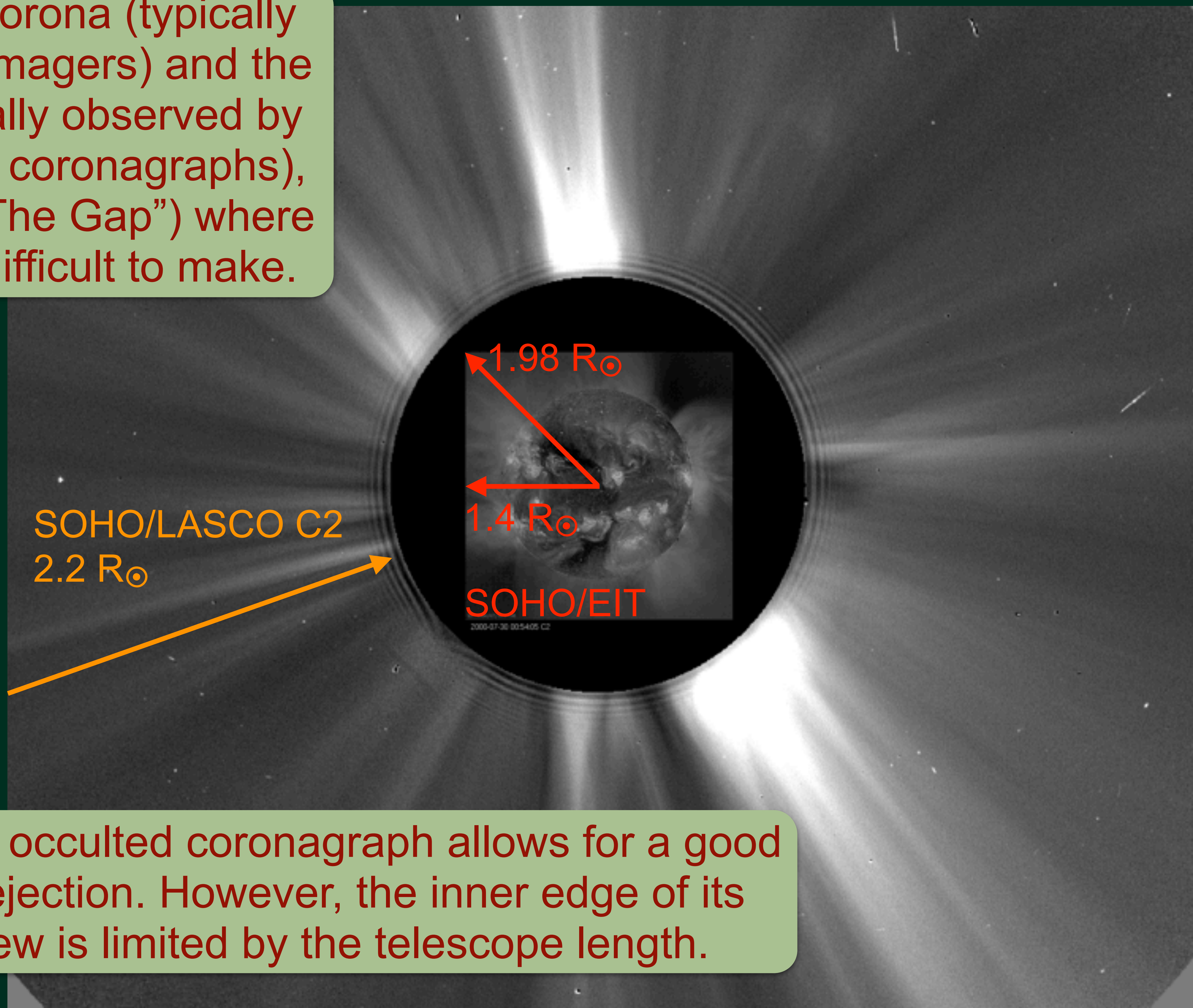
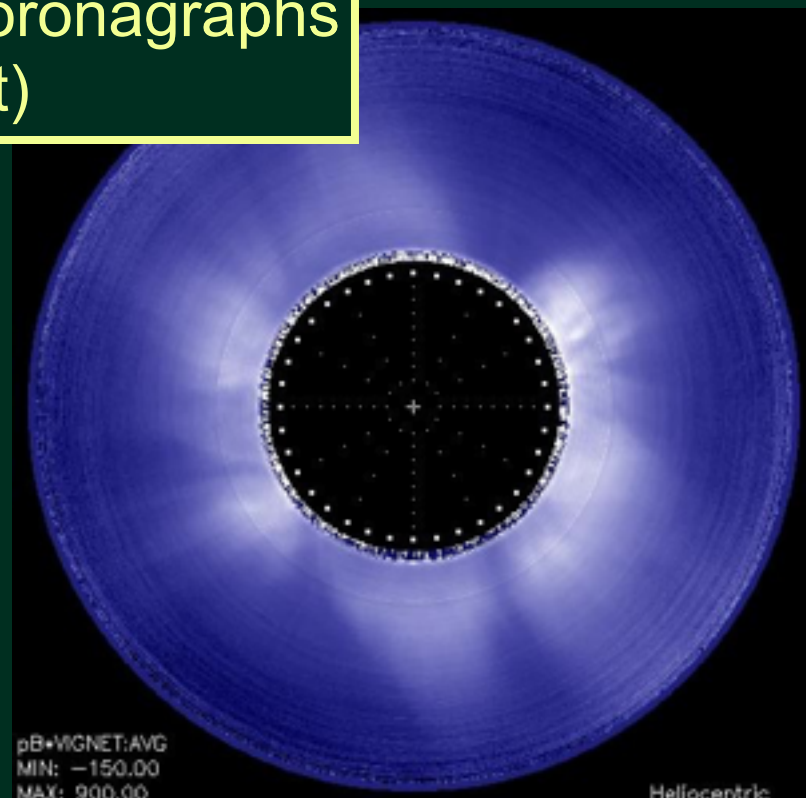


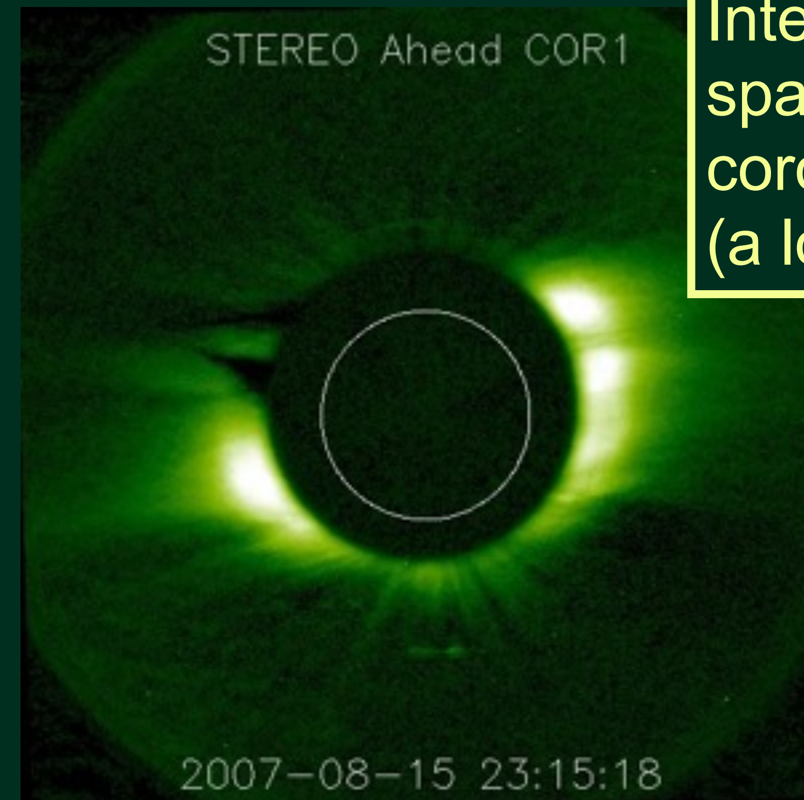
An externally occulted coronagraph allows for a good straylight rejection. However, the inner edge of its field of view is limited by the telescope length.

How to close *The Gap*?

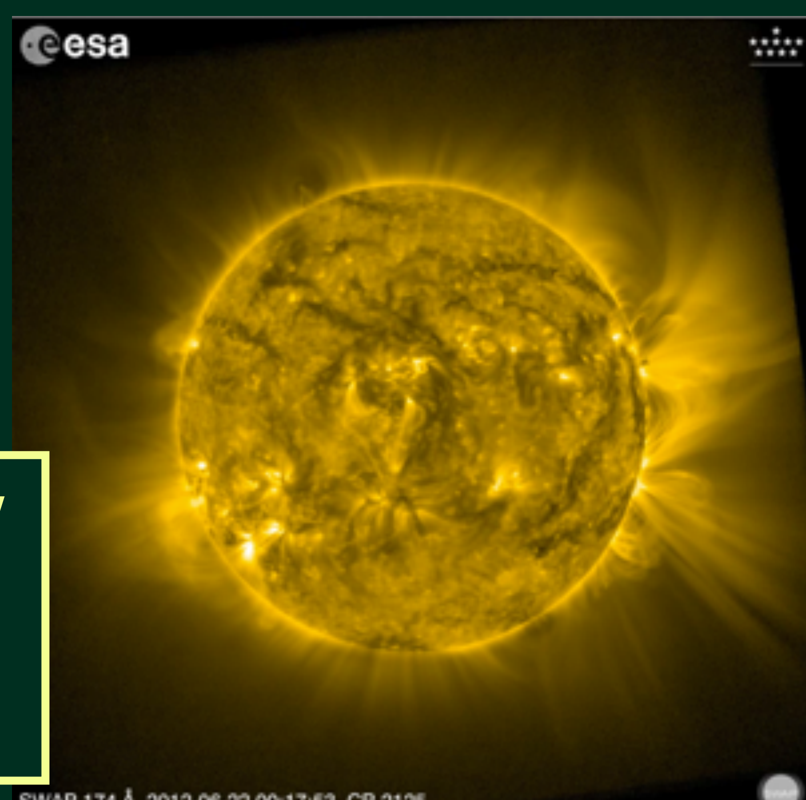
Ground-based coronagraphs
(a lot of straylight)



Internally occulted
space-borne
coronagraphs
(a lot of straylight)

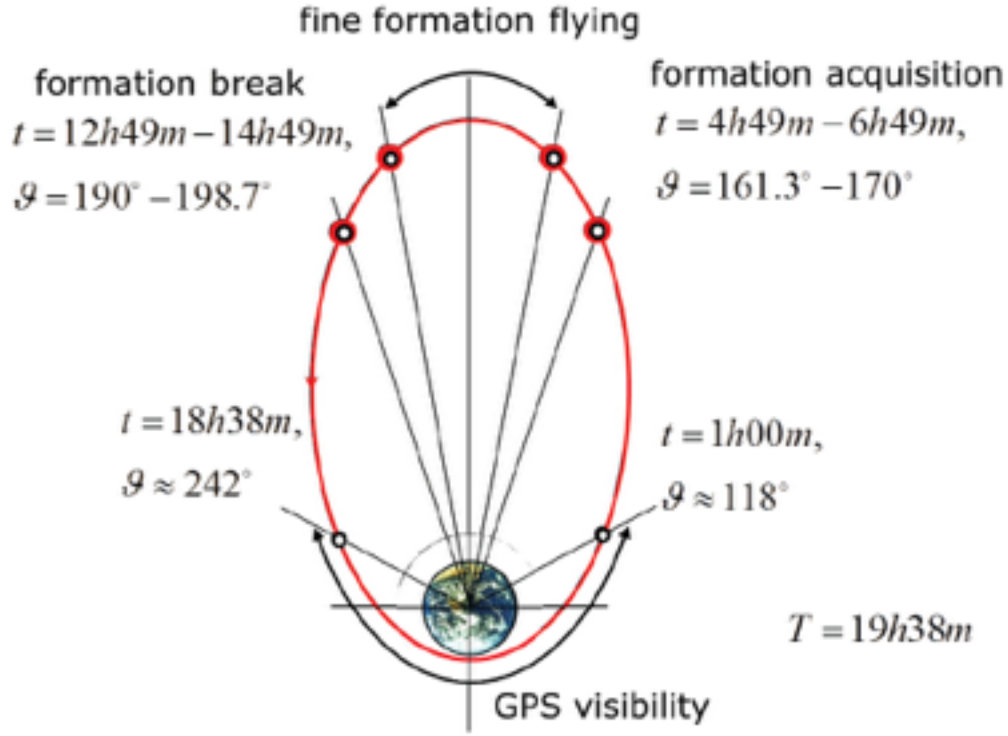


Wide field-of-view
EUV imagers
(very long
exposure times)



Total solar eclipses
(are rare and last only
several minutes)

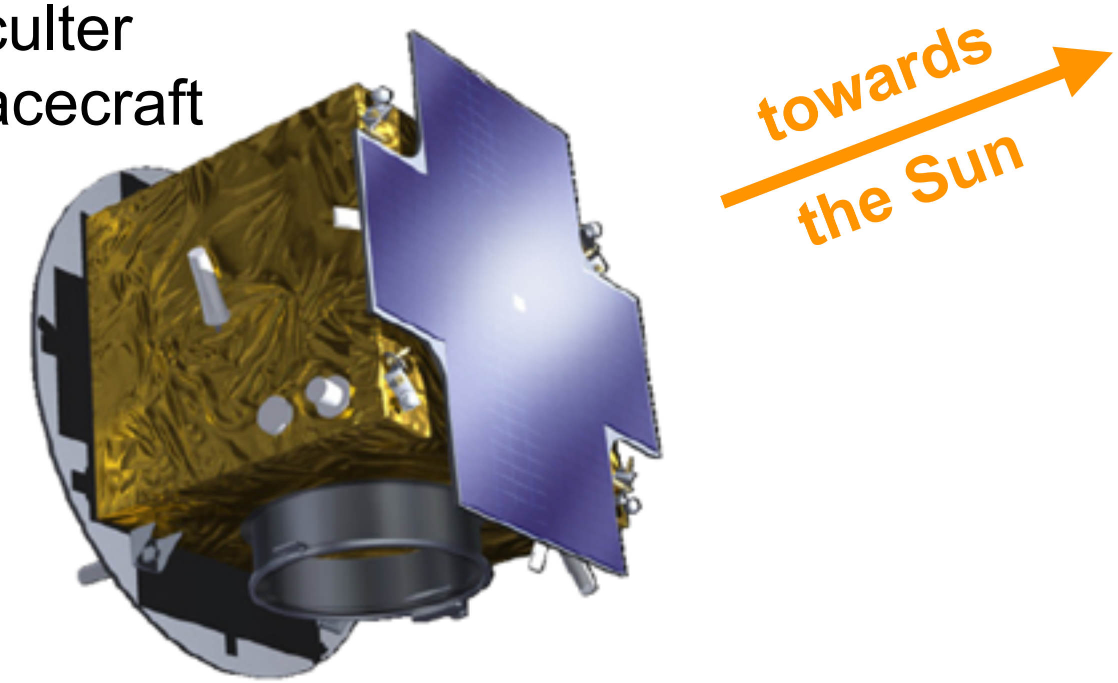
The PROBA-3 mission

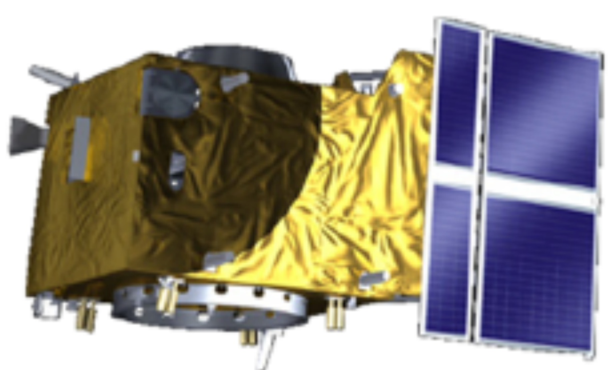


PROBA-3 orbit

The ultimate coronagraph: artificial total eclipse created using two spacecraft in flight formation.

occulter spacecraft





main spacecraft

- The formation flying is 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.
- A technological challenge: the distance between the spacecraft is about 150 m, and the accuracy of their positioning should be around a few mm!

Tentative launch date: end 2018

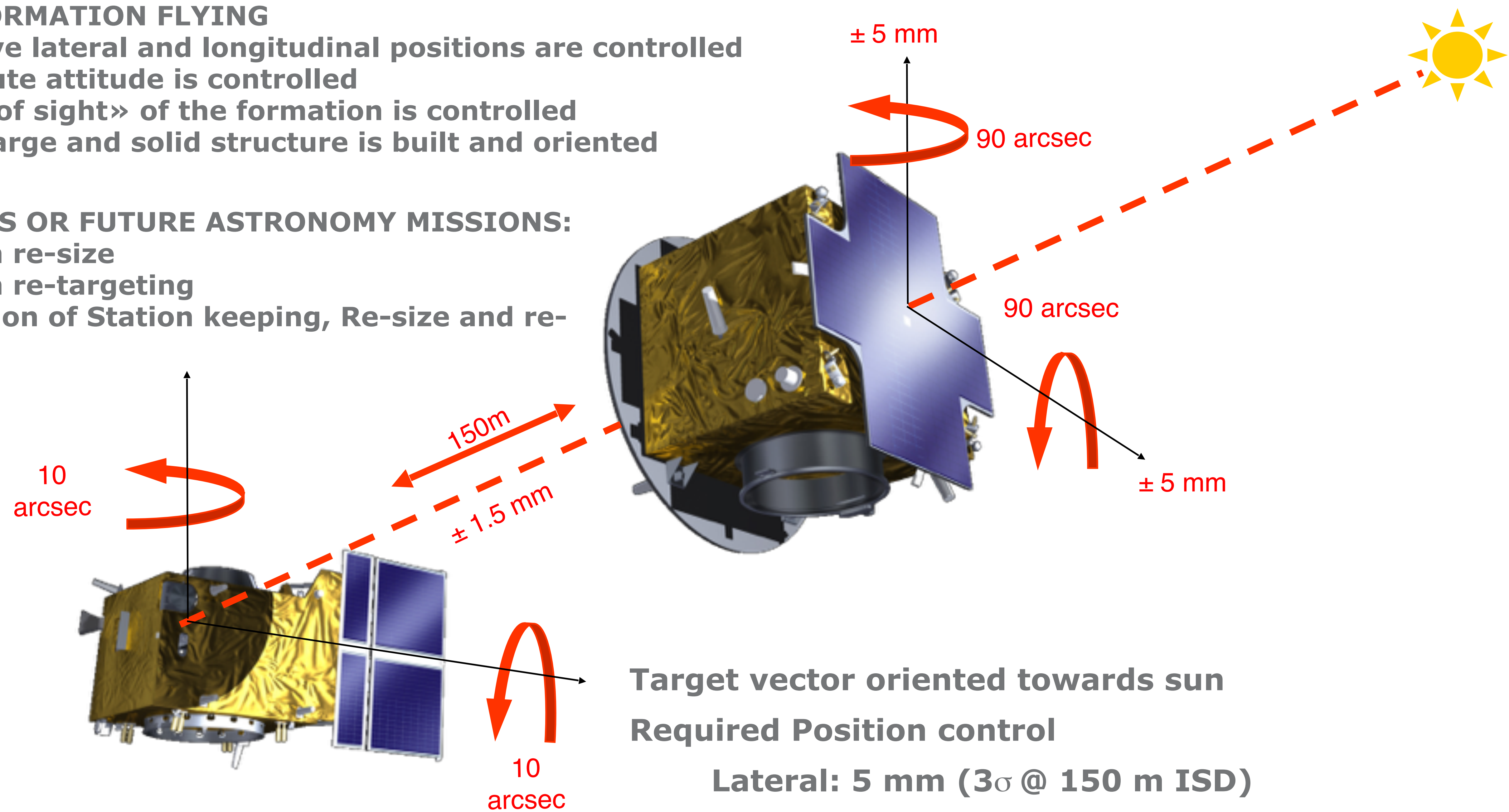
Precise formation flying

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**

MANEUVERS OR FUTURE ASTRONOMY MISSIONS:

- **Formation re-size**
- **Formation re-targeting**
- **Combination of Station keeping, Re-size and re-targeting**



Target vector oriented towards sun

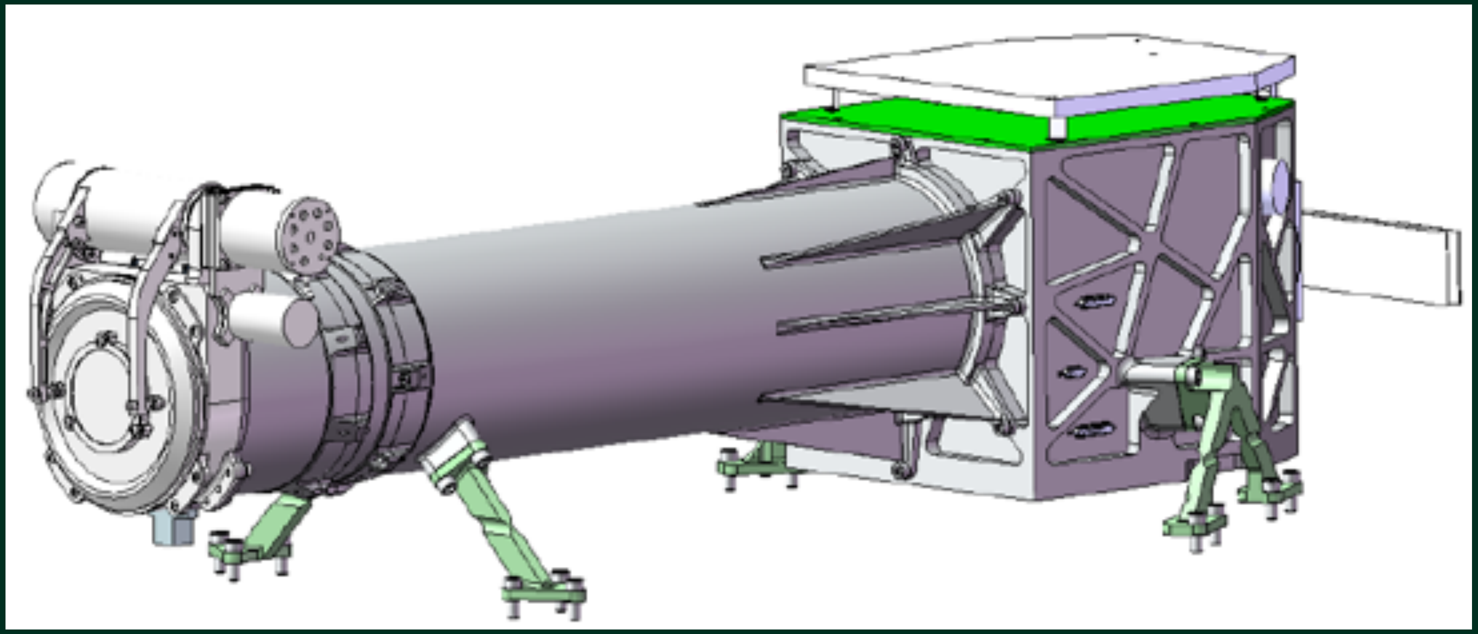
Required Position control

Lateral: 5 mm (3σ @ 150 m ISD)

Longitudinal: 1.5 mm (3σ @ 150 m ISD)

(courtesy D. Galano, ESA D/TEC)

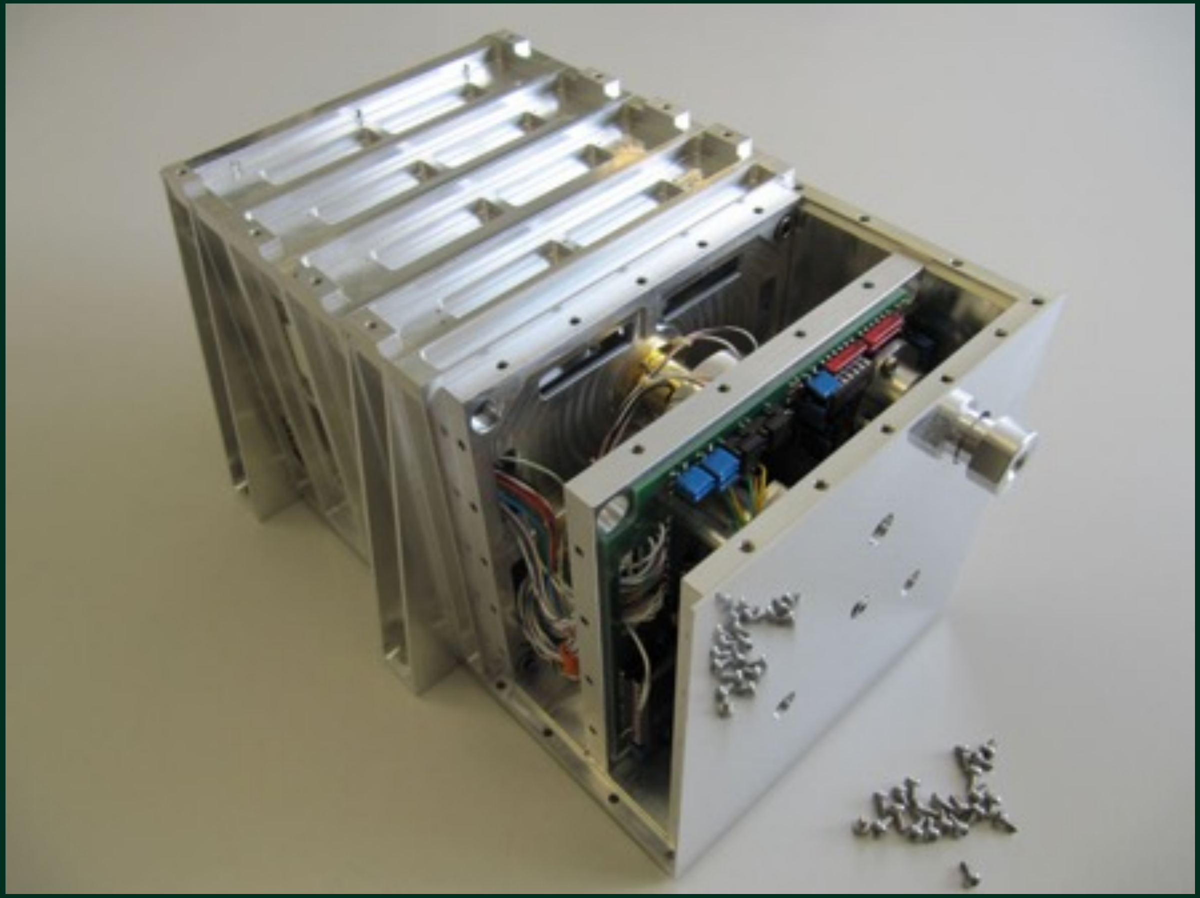
Scientific payload of PROBA-3



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 occulter spacecraft.
Together they form a giant coronagraph.

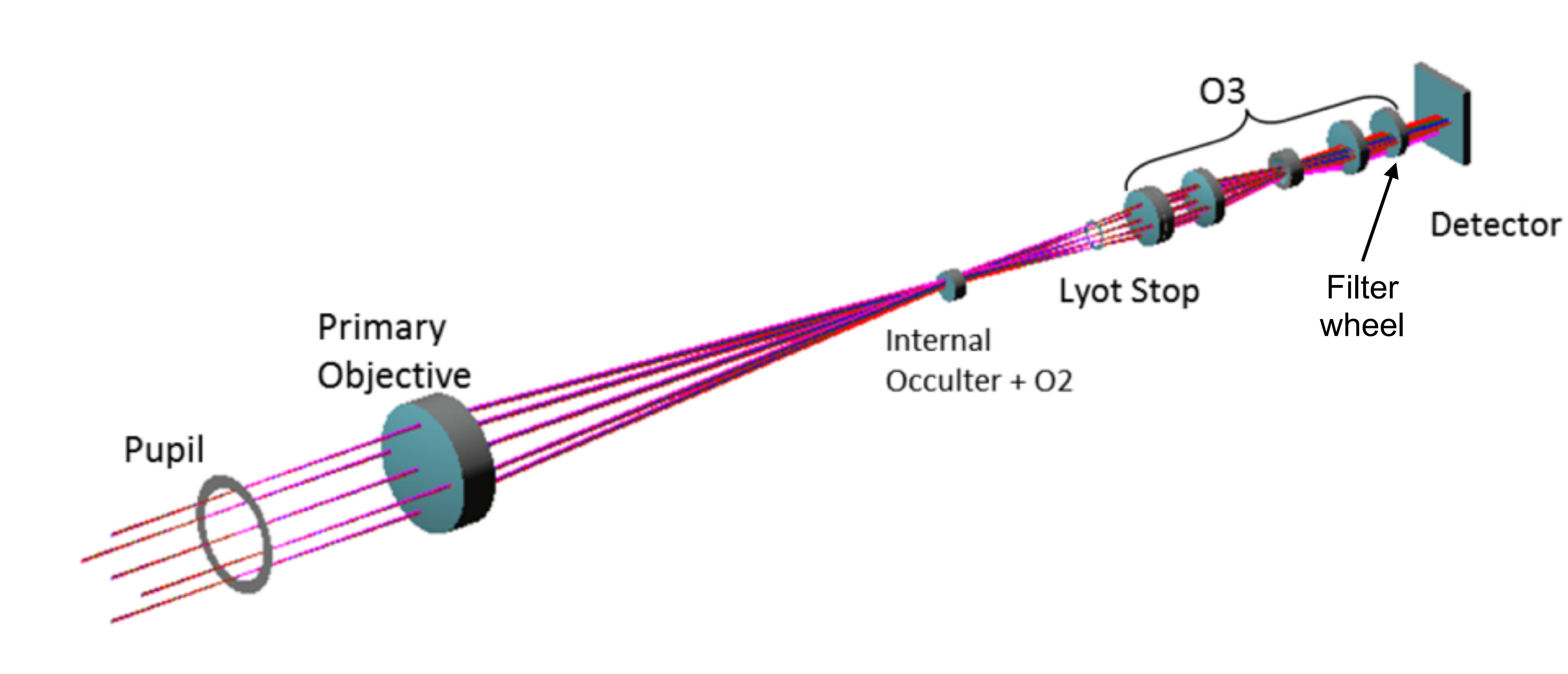


DARA
(Davos Absolute RAdiometer)

PI: Werner Schmutz (PMOD, Switzerland)

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

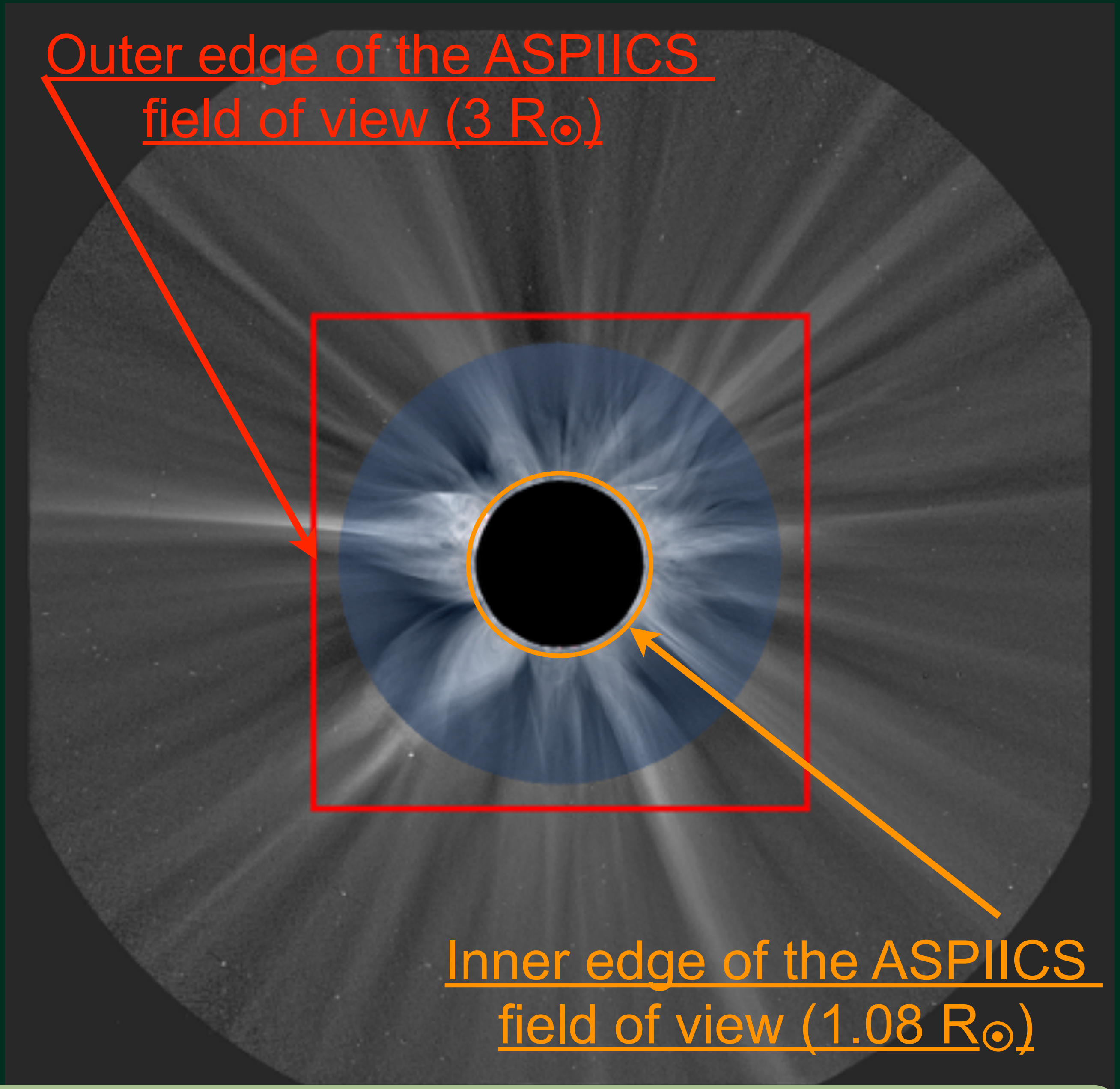
ASPIICS optical design



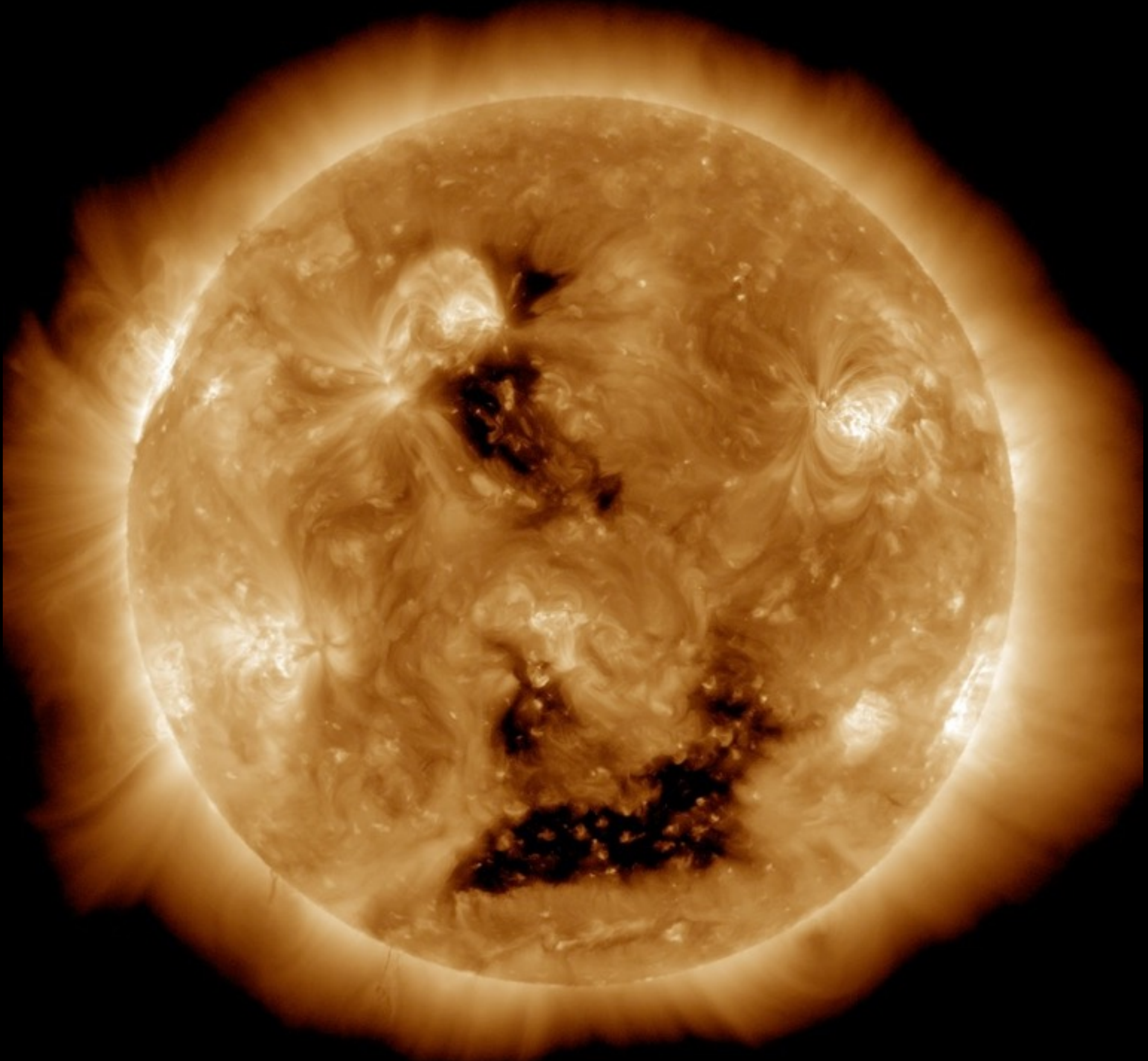
- An externally occulted coronagraph with the occulter placed about 150 m in front of the pupil.
- The optical design of ASPIICS follows the principles of the classic Lyot coronagraph.

ASPIICS characteristics

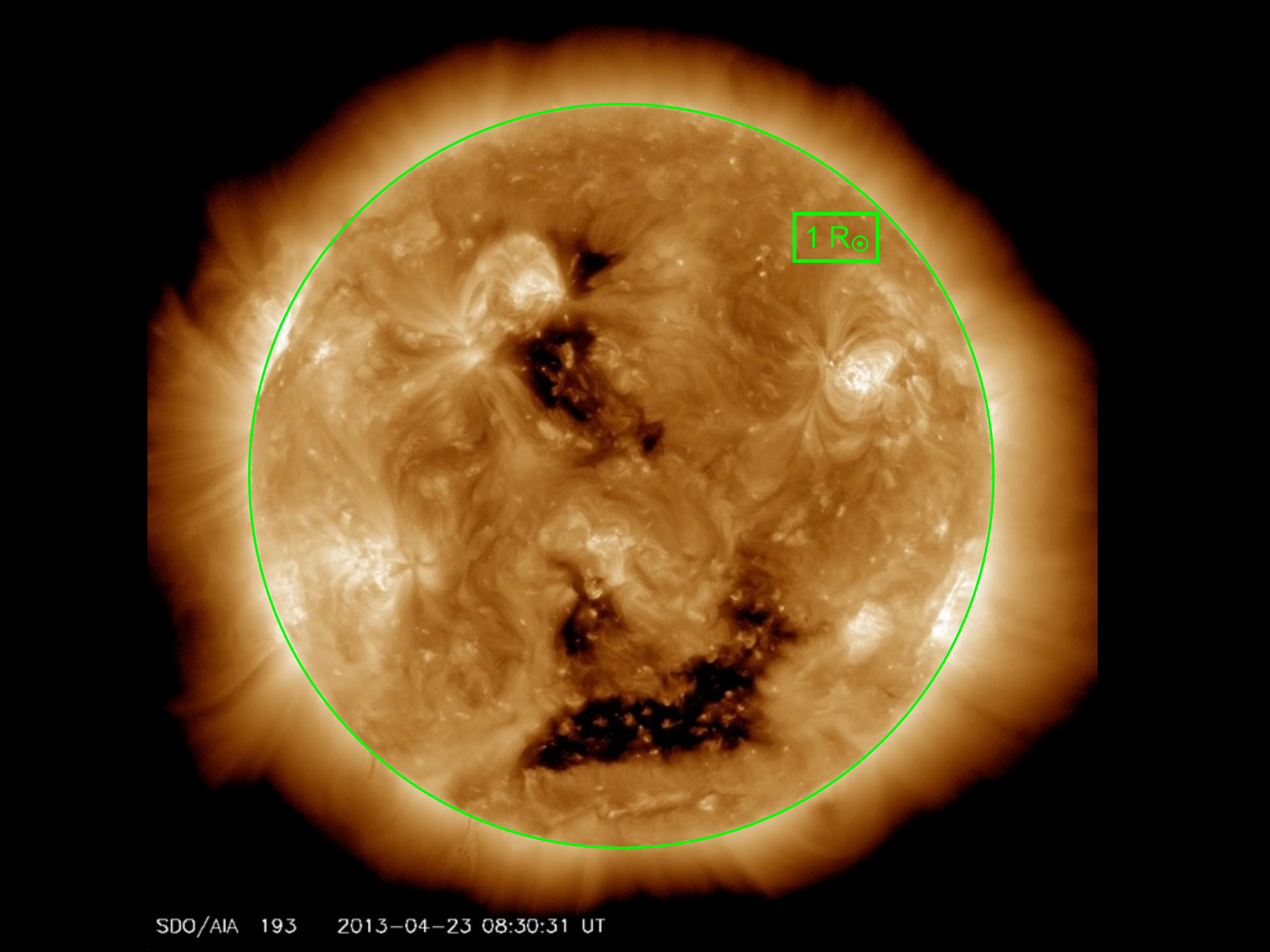
- 6 channels:
  - 1 white light (5400-5700 Å),
  - 3 polarized white light,
  - 1 narrow-band filter centered at the Fe XIV line at 5305 Å.
  - 1 narrow-band filter centered at the He I D3 line at 5876 Å.
- 2048x2048 pixels
  - 2.8 arc sec per pixel
- Outer edge of the field of view: 2.99 $R_\odot$
  - 4.20 $R_\odot$ in the corners
- 60 s nominal cadence
  - 2 s using a quarter of the field of view



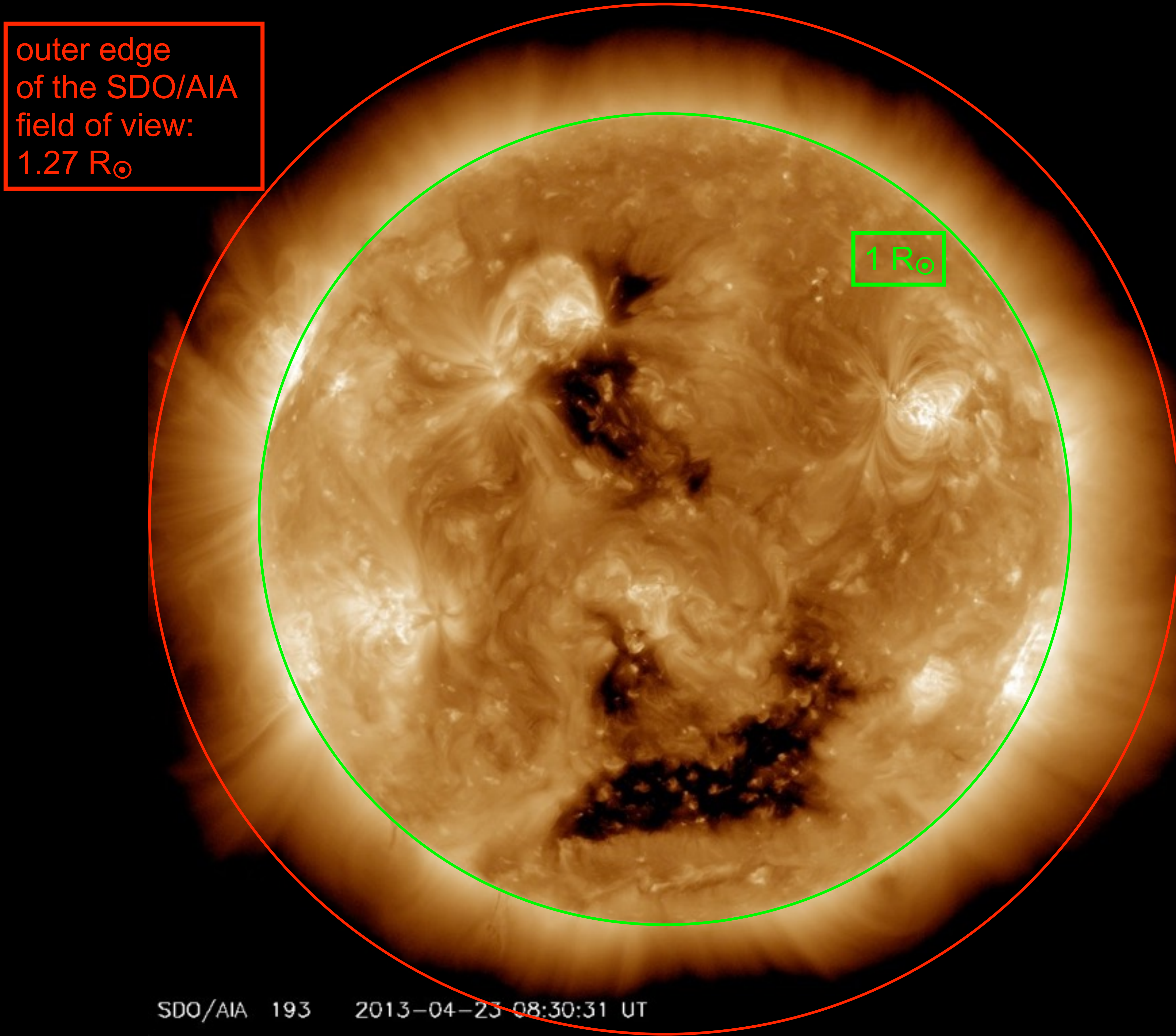
ASPIICS will cover *The Gap* between the typical fields of view of EUV imagers and externally occulted coronagraphs!

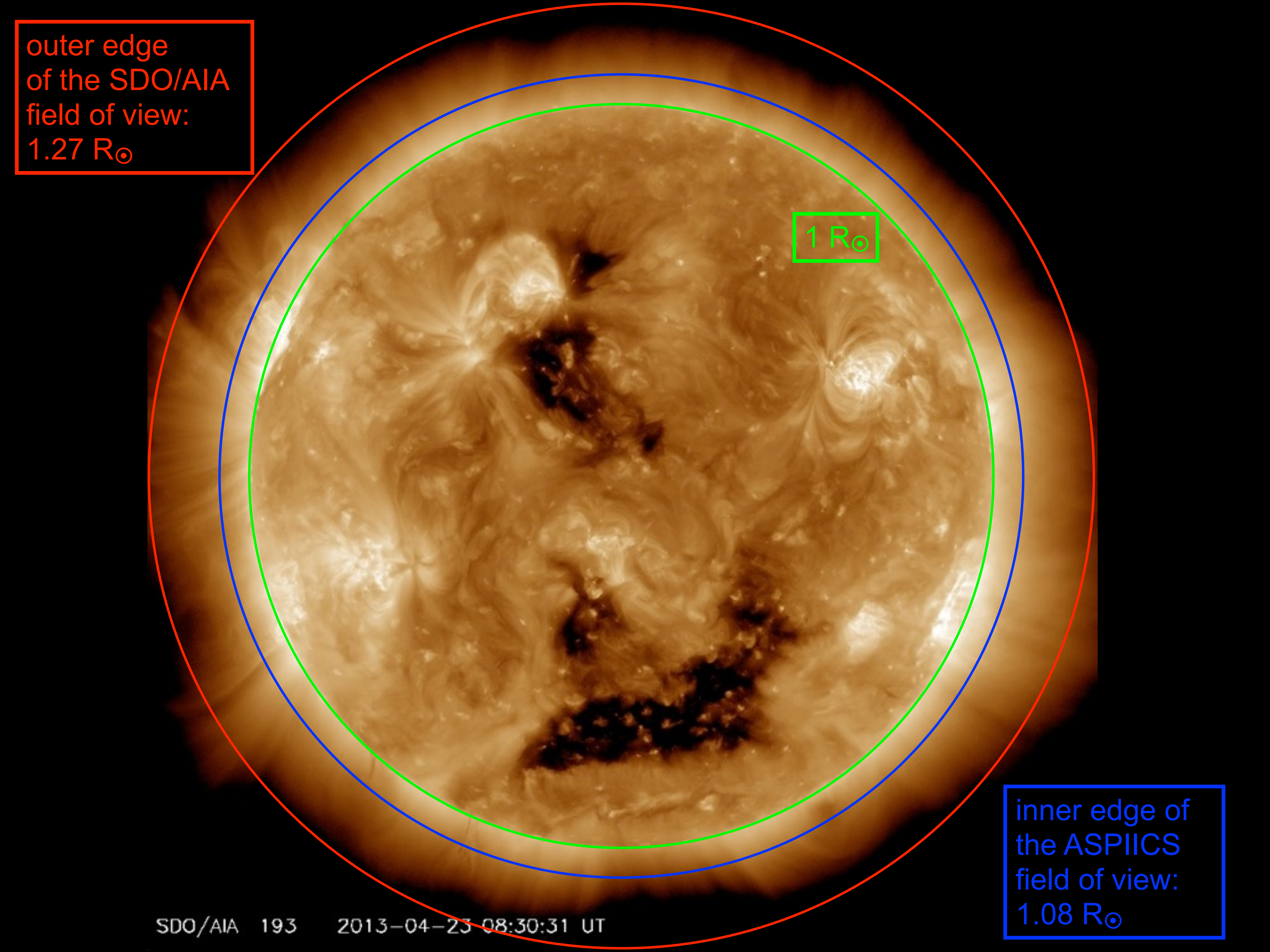


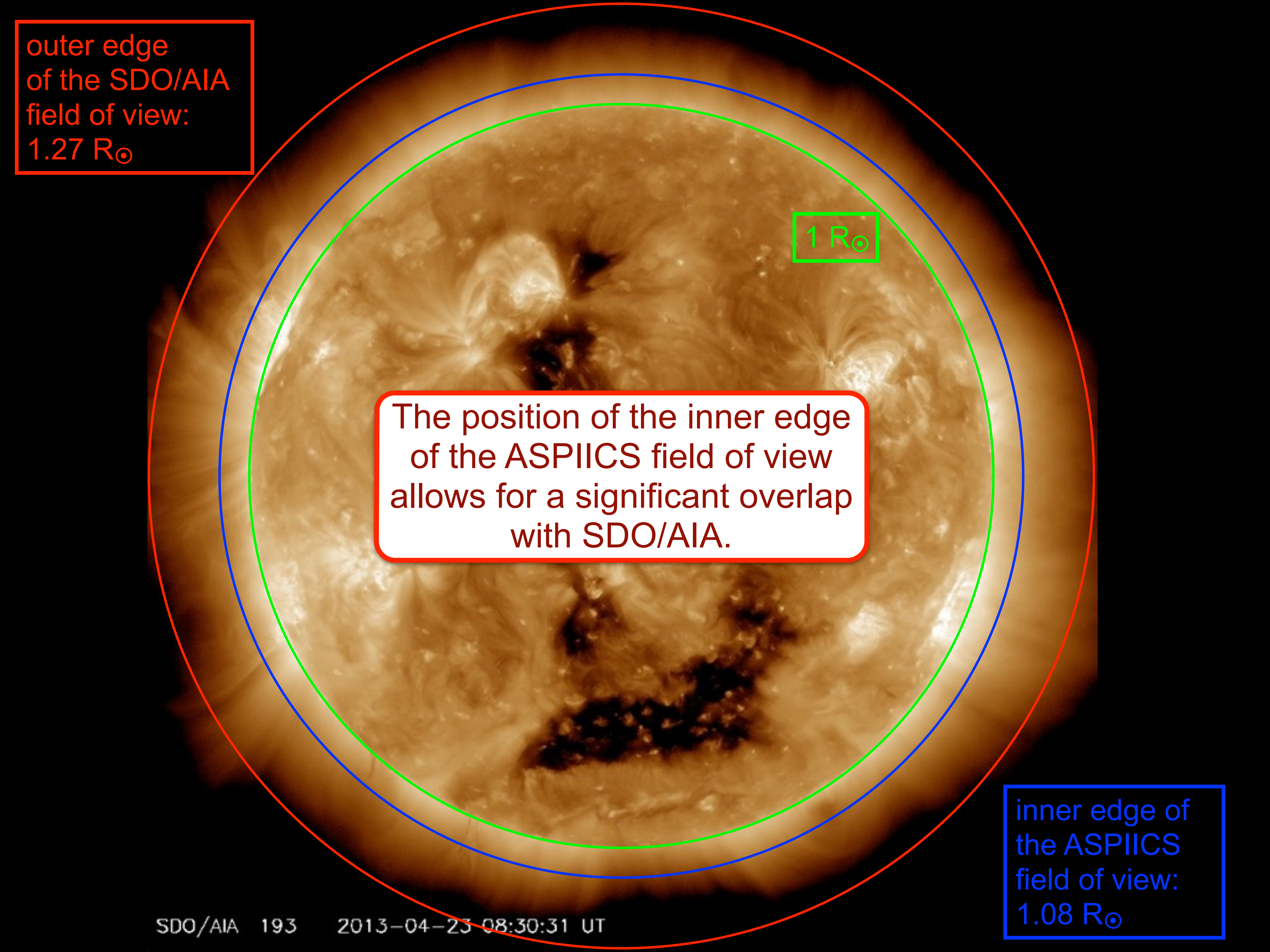
SDO/AIA 193 2013-04-23 08:30:31 UT



1 $R_\odot$
SDO/AIA 193 2013-04-23 08:30:31 UT


outer edge
of the SDO/AIA
field of view:
1.27 R⊙
1 R⊙
SDO/AIA 193 2013-04-23 08:30:31 UT


outer edge
of the SDO/AIA
field of view:
1.27 R⊙
1 R⊙
inner edge of
the ASPIICS
field of view:
1.08 R⊙
SDO/AIA 193 2013-04-23 08:30:31 UT


outer edge of the SDO/AIA field of view: 1.27 $R_\odot$
1 $R_\odot$
The position of the inner edge of the ASPIICS field of view allows for a significant overlap with SDO/AIA.
inner edge of the ASPIICS field of view: 1.08 $R_\odot$
SDO/AIA 193 2013-04-23 08:30:31 UT

ASPIICS scientific objectives

- The top-level scientific objectives of ASPIICS are:

  1. Understanding the physical processes that govern the quiescent solar corona by answering the following questions:

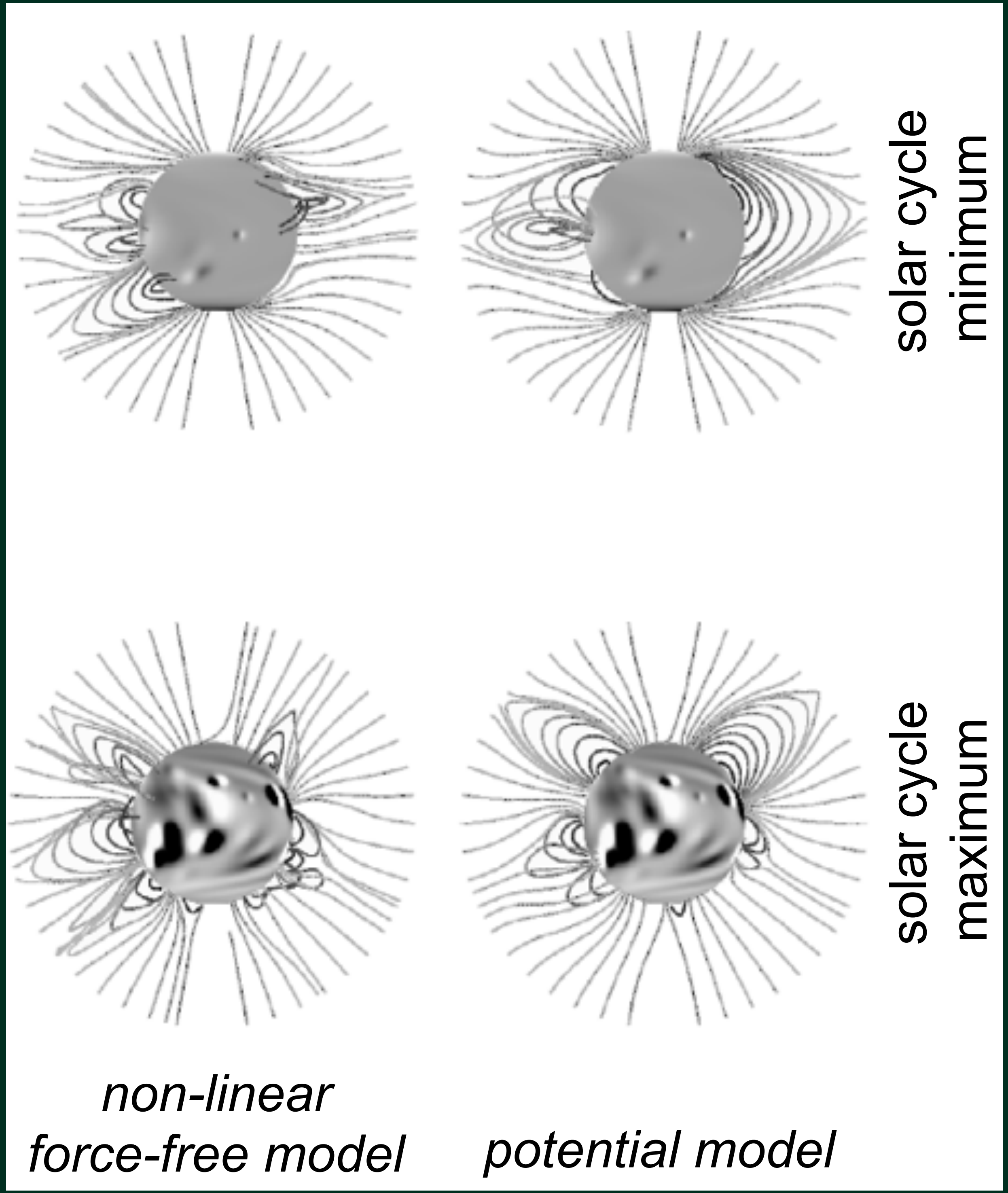
     - What is the nature of the solar corona on different scales?
     - What processes contribute to the heating of the corona and what is the role of waves?
     - What processes contribute to the solar wind acceleration?

  2. Understanding the physical processes that lead to CMEs and determine space weather by answering the following questions:

     - What is the nature of the coronal 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?

Coronal magnetic field

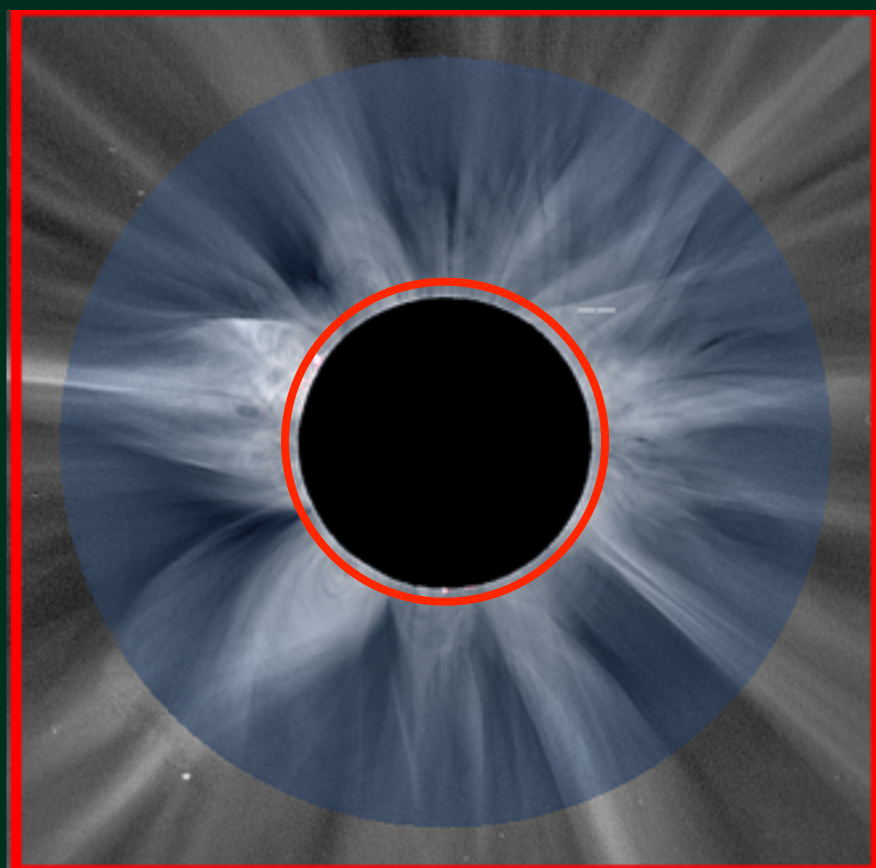
- The magnetic field often plays a dominant role in the structuring and dynamics of plasma in the solar corona (low plasma beta regime: $\beta = 8\pi p/B^2 < 1$).
- However, the coronal magnetic field cannot be routinely measured at the moment. Instead, it is extrapolated from photospheric magnetograms.
- The extrapolated field is strongly model-dependent.
- The extrapolated field cannot always reproduce the complex magnetic configuration of the solar corona.



(Yeates et al. 2010)

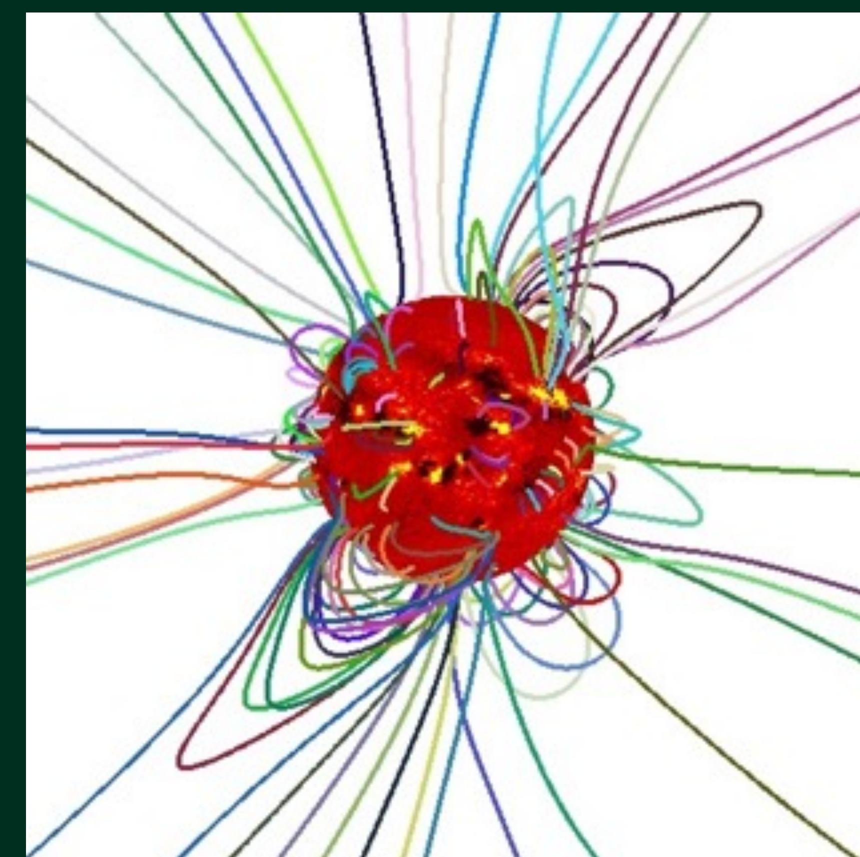
What is the nature of the solar corona on different scales?

ASPIICS
Formation Flying Coronagraph



ASPIICS field of view

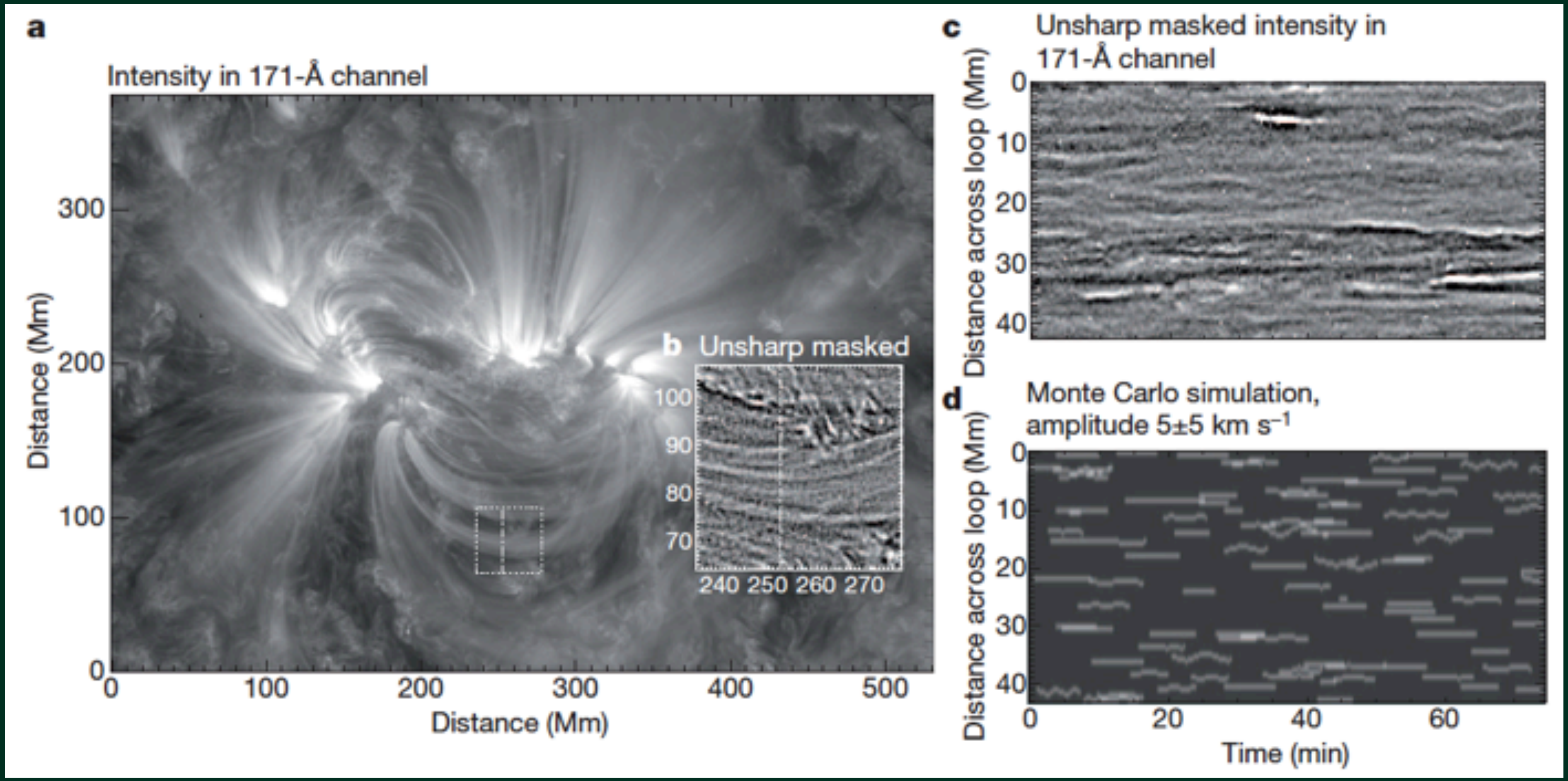
?



MHD model
of the coronal magnetic field

ASPIICS will answer questions about the structuring and dynamics of the solar corona on different scales, as well as constrain coronal magnetic field models.

What processes contribute to the heating of the corona?

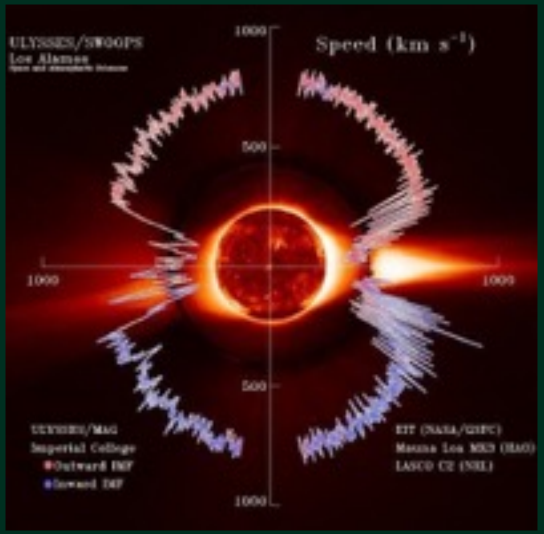


(McIntosh et al. 2011)

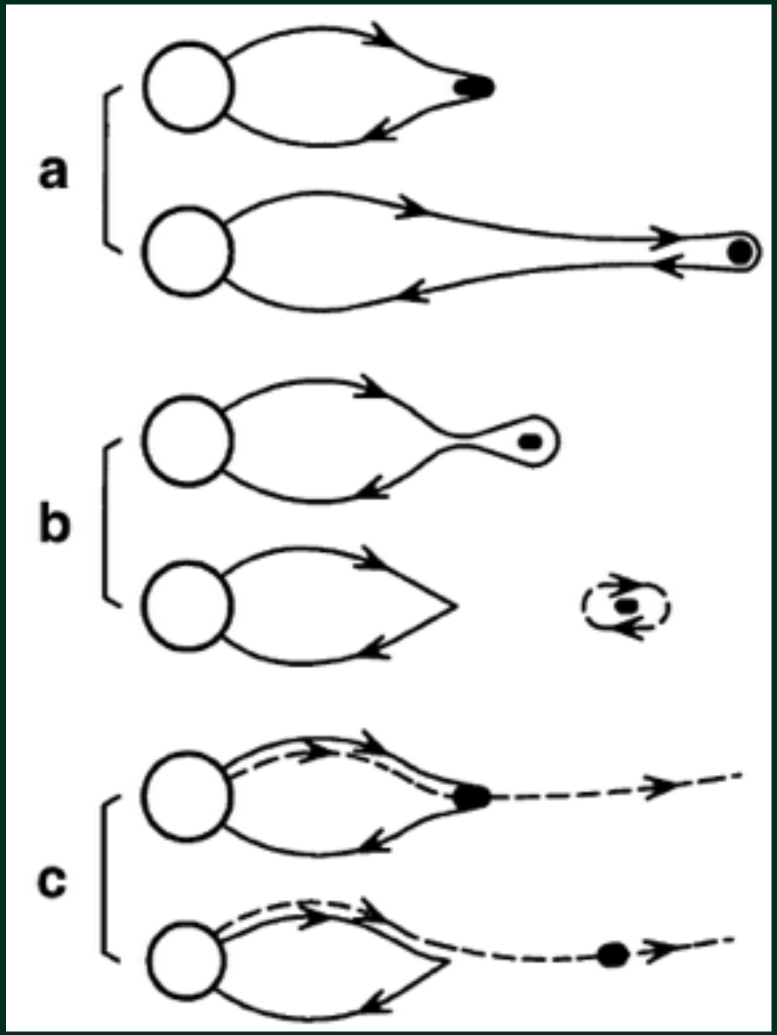
High spatial and temporal resolution of ASPIICS is perfectly suited to detect coronal waves (via observations of quasi-periodic perturbations), and to assess their contribution to the coronal heating.

What processes contribute to the solar wind acceleration?

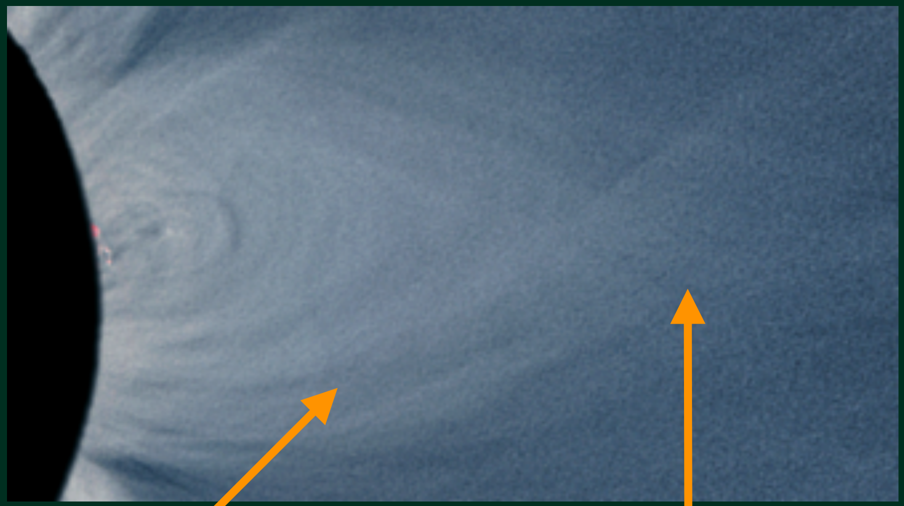
- The origin of the slow solar wind is still debated, mainly due to its non-stationary, inhomogeneous character.
- Dynamic processes at the streamer cusps are considered to be a viable mechanism to produce the slow solar wind.
- However, the cusp region is very difficult to observe as it is situated in *The Gap* between the low and high corona.



(McComas et al. 1998)

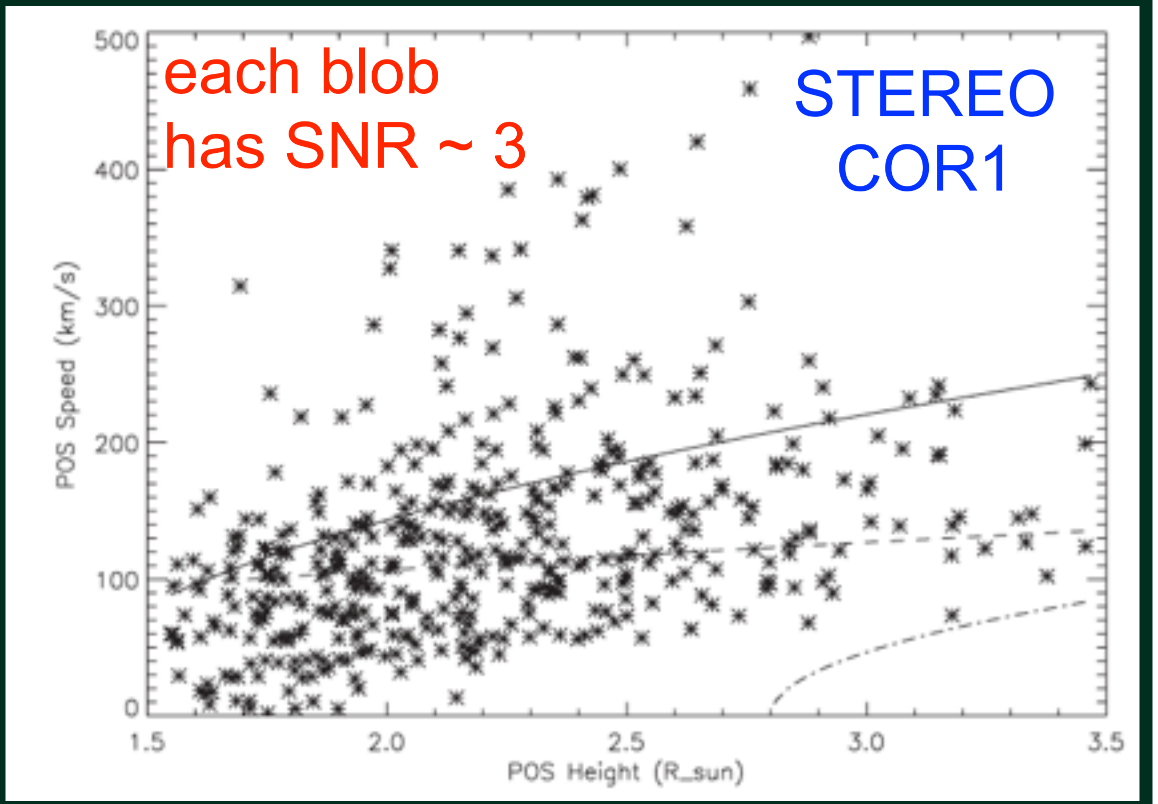


(Y.-M. Wang et al. 2000)

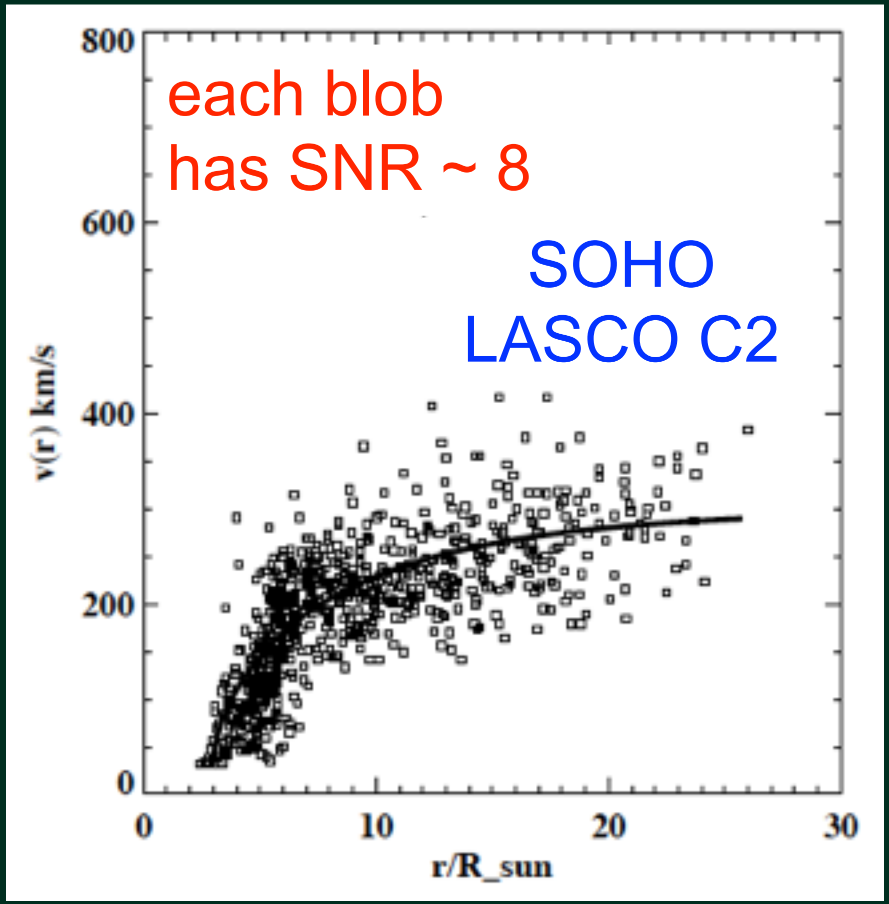


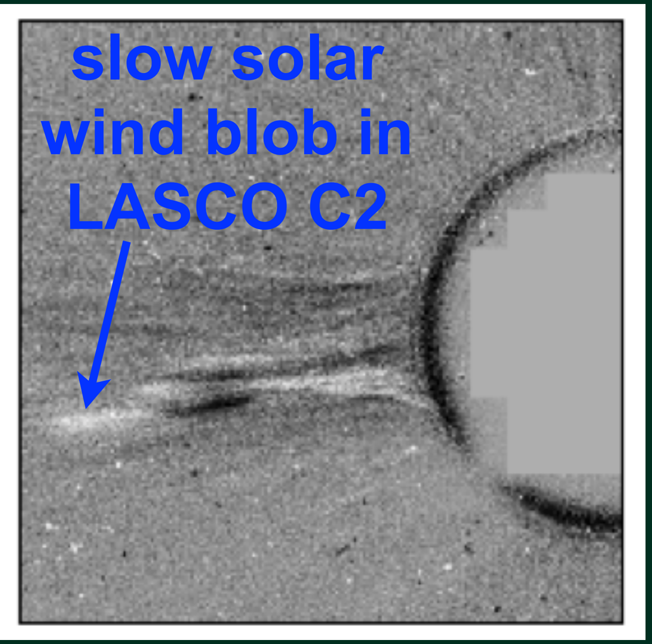
streamer cusp

What processes contribute to the solar wind acceleration?



(Jones & Davila 2009)





(Sheeley et al. 1997)

ASPIICS
Formation Flying Coronagraph

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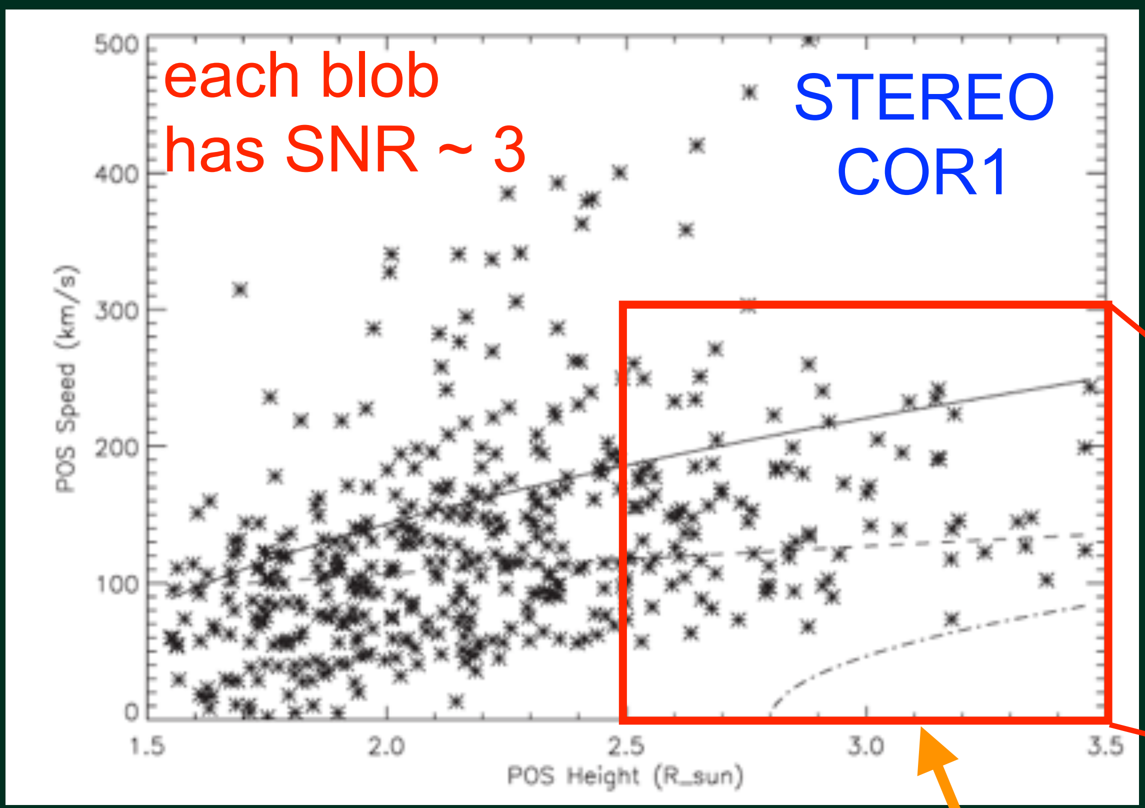
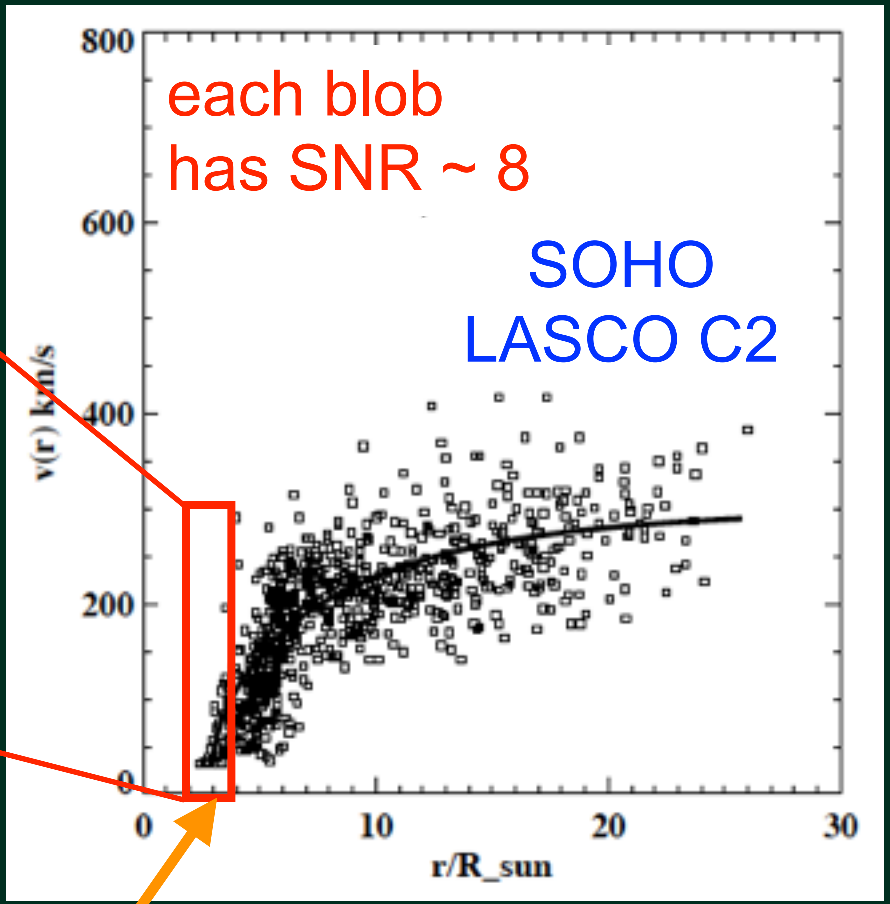
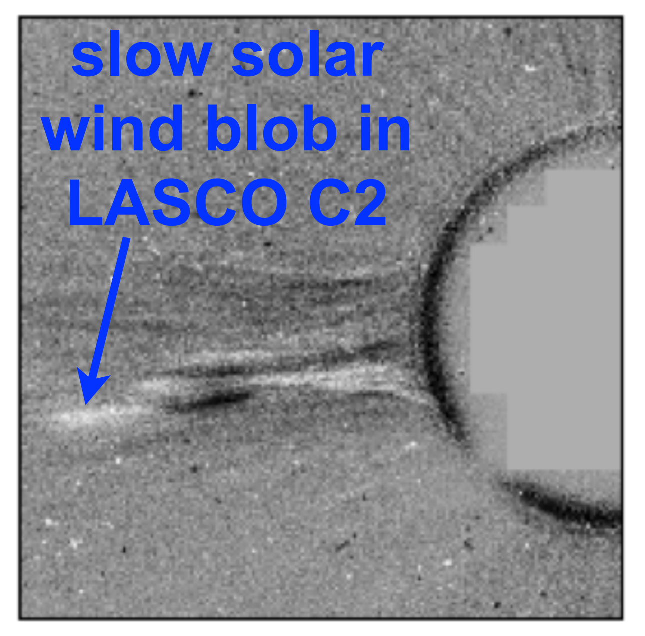


(Jones & Davila 2009)

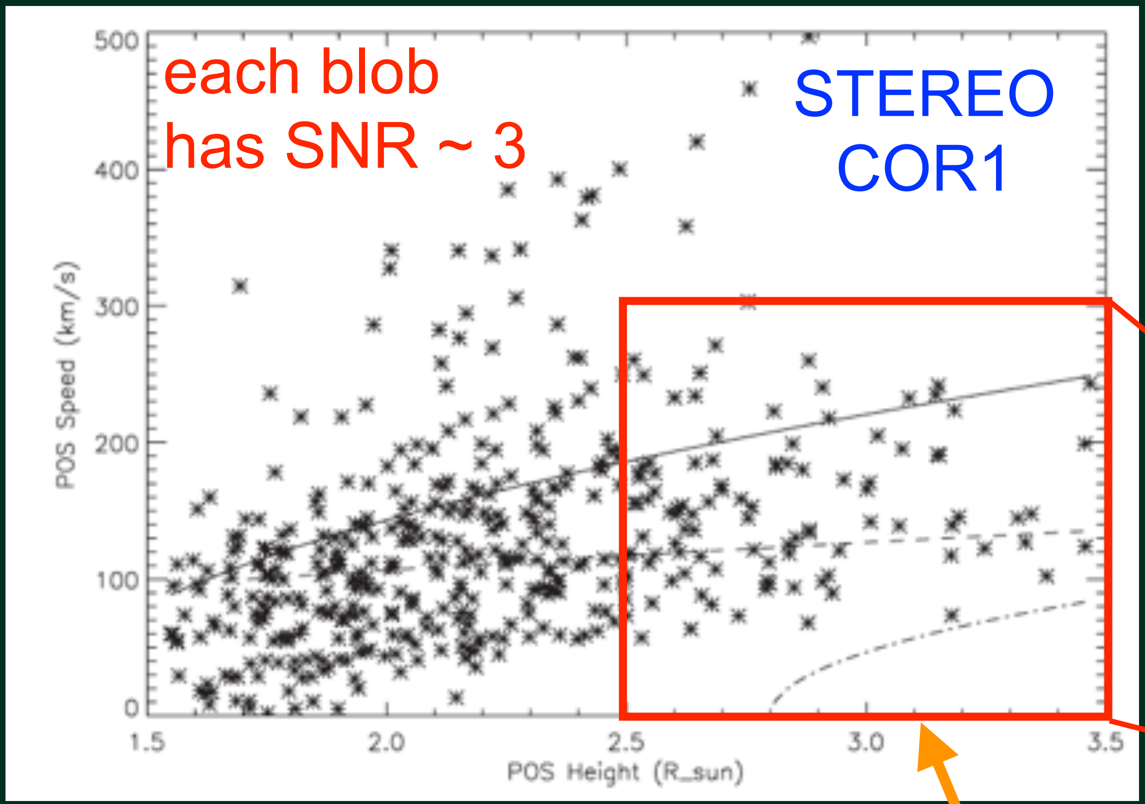




(Sheeley et al. 1997)

A discrepancy between measurements made by different coronagraphs!

What processes contribute to the solar wind acceleration?



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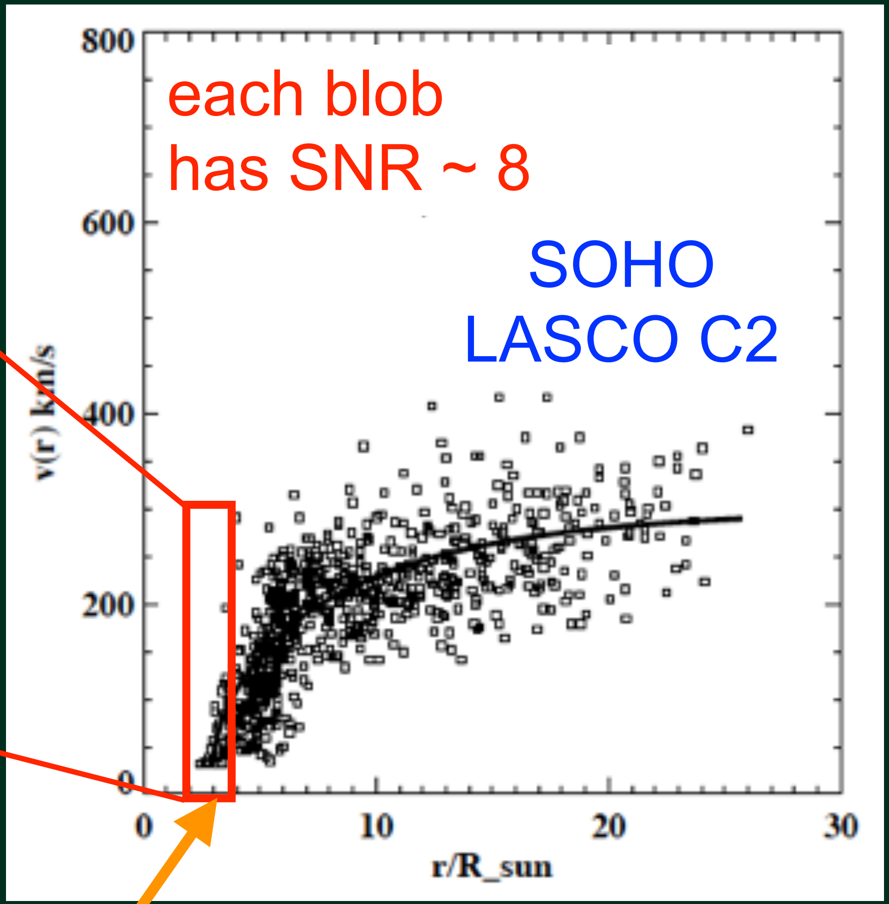
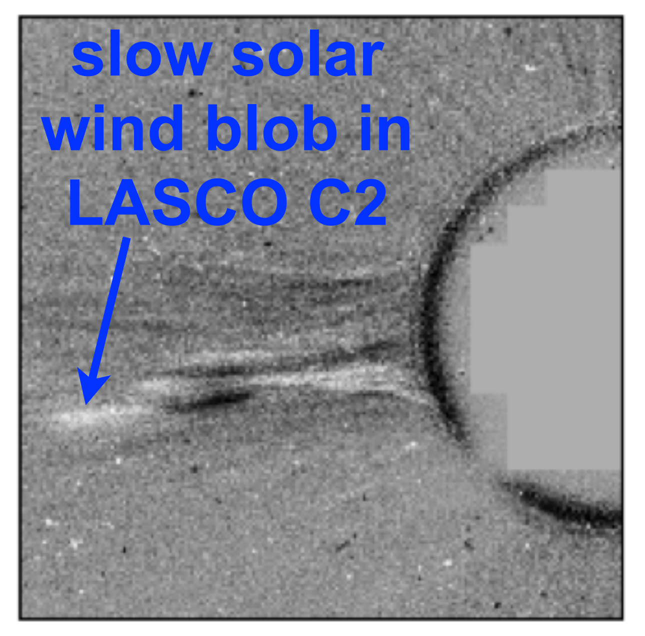


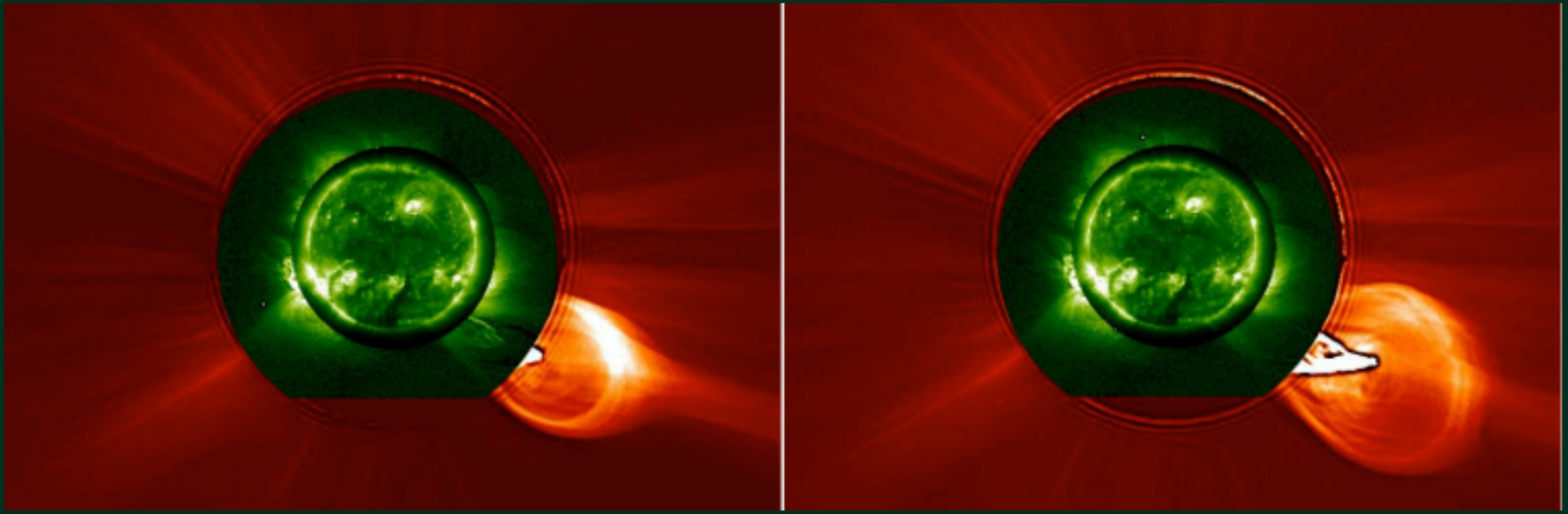


(Sheeley et al. 1997)

A discrepancy between measurements made by different coronagraphs!

ASPIICS, with its high signal-to-noise ratio (SNR ~ 20), will allow us to make detailed investigations of small-scale dynamic phenomena in the solar wind source region, in particular at the interface between fast and slow streams.

What is the nature of the structures that form the CME?

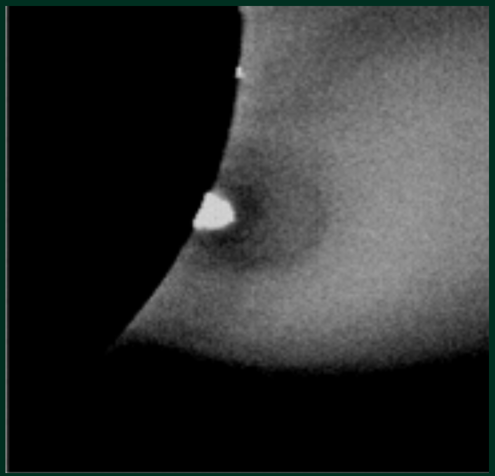


ASPIICS will be an ideal instrument to investigate coronal cavities and their evolution into CMEs.

ASPIICS
Formation Flying Coronagraph

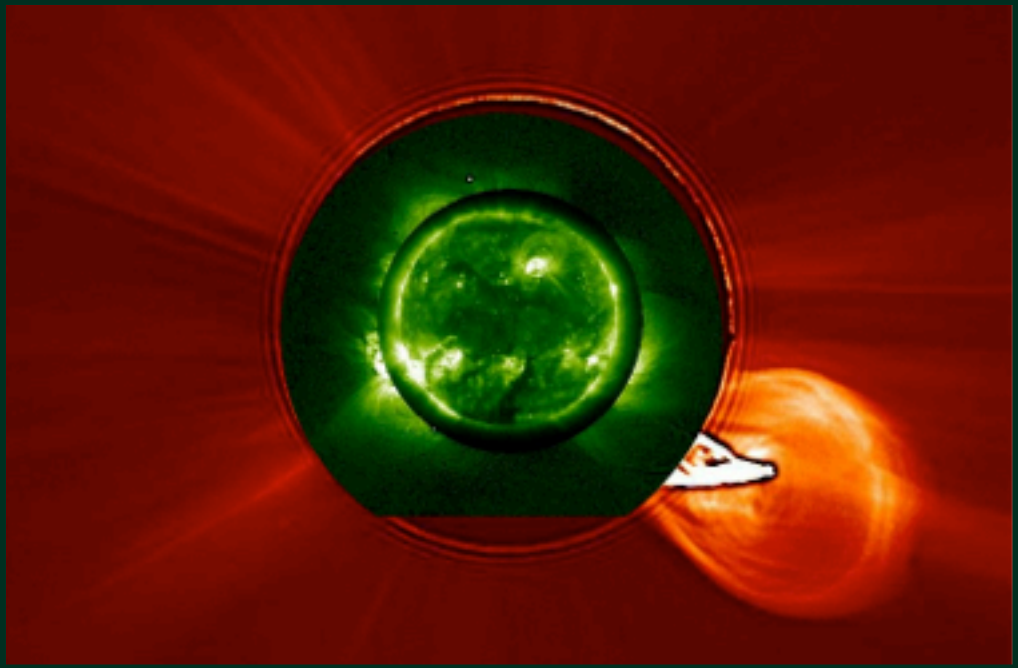
How do CMEs erupt and accelerate in the low corona?

quiescent state

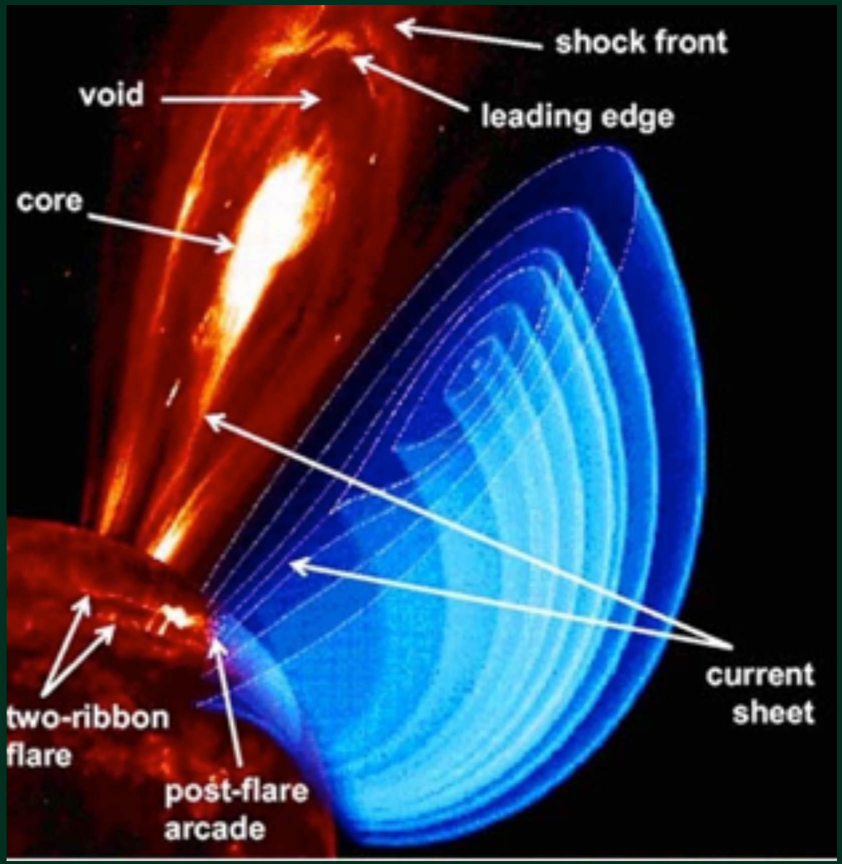


?

erupting state



interpretation



(Adapted from the Solar Sentinels STDT Report)

ASPIICS
Formation Flying Coronagraph

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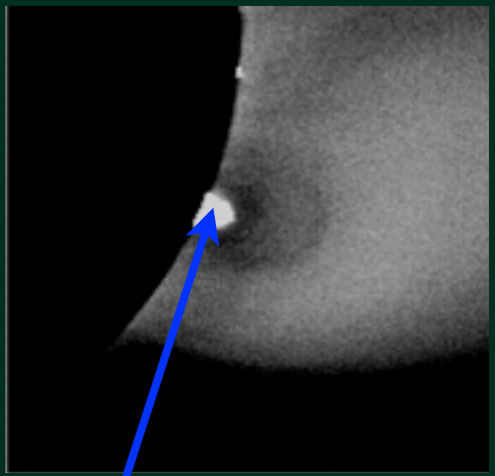

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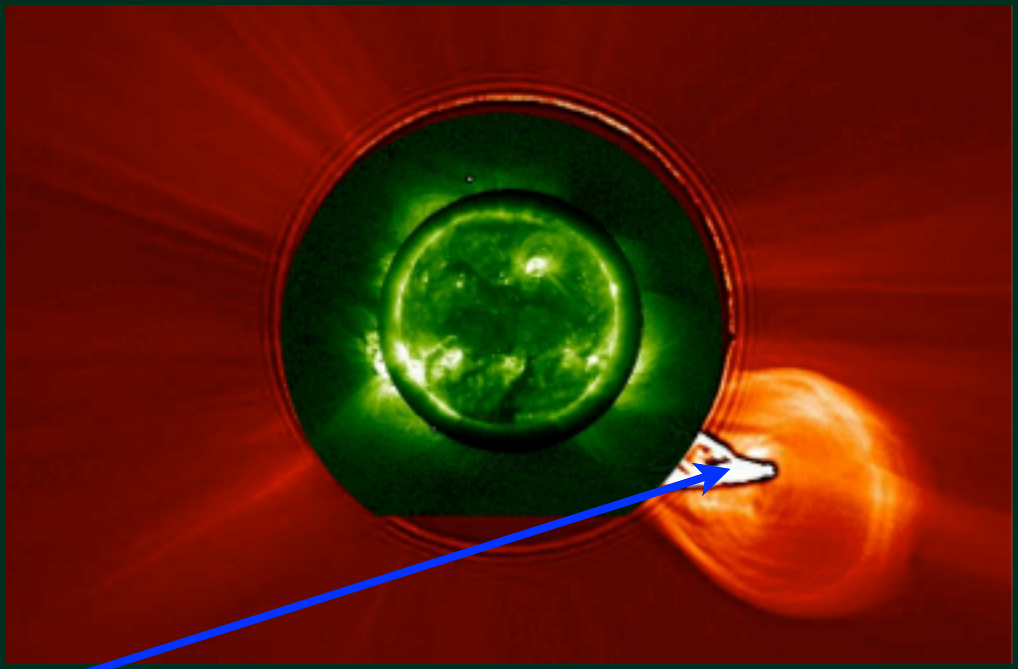
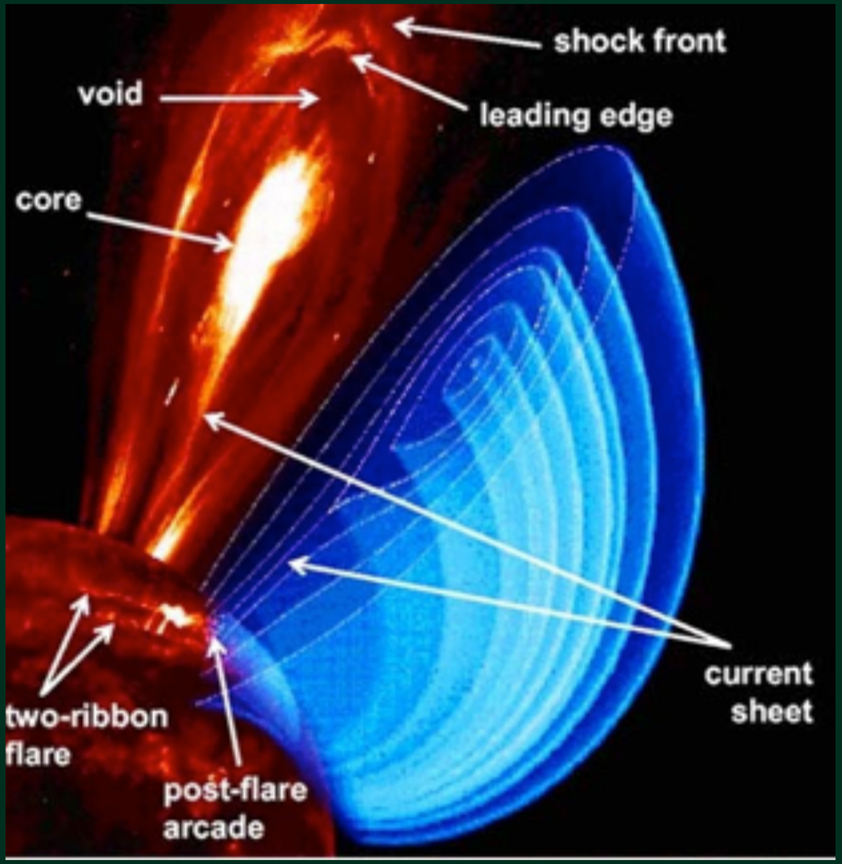
erupting state



interpretation



prominence

(Adapted from the Solar Sentinels STDT Report)

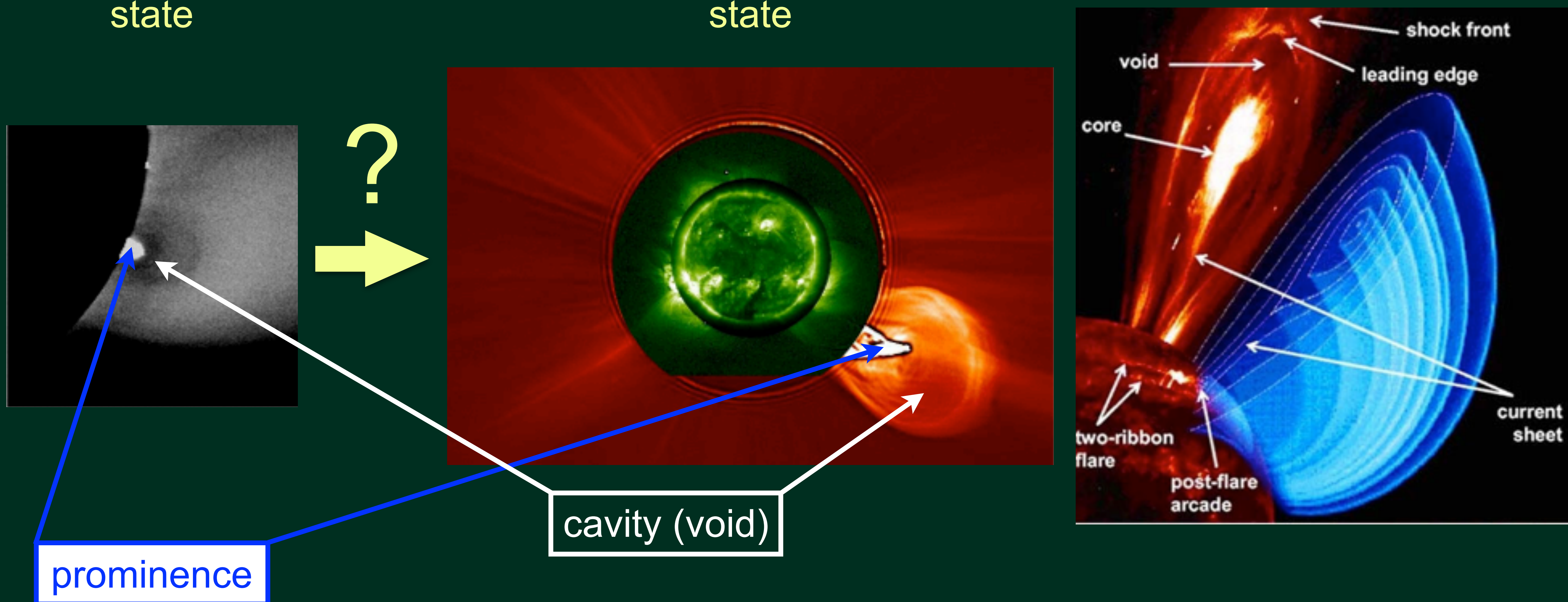
ASPIICS
Formation Flying Coronagraph

How do CMEs erupt and accelerate in the low corona?

quiescent state

erupting state

interpretation

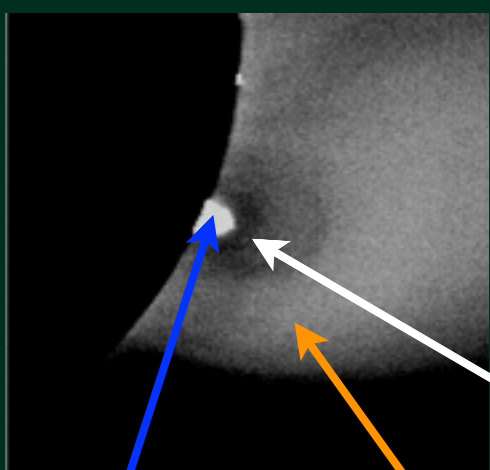


(Adapted from the Solar Sentinels STDT Report)

ASPIICS Formation Flying Coronagraph

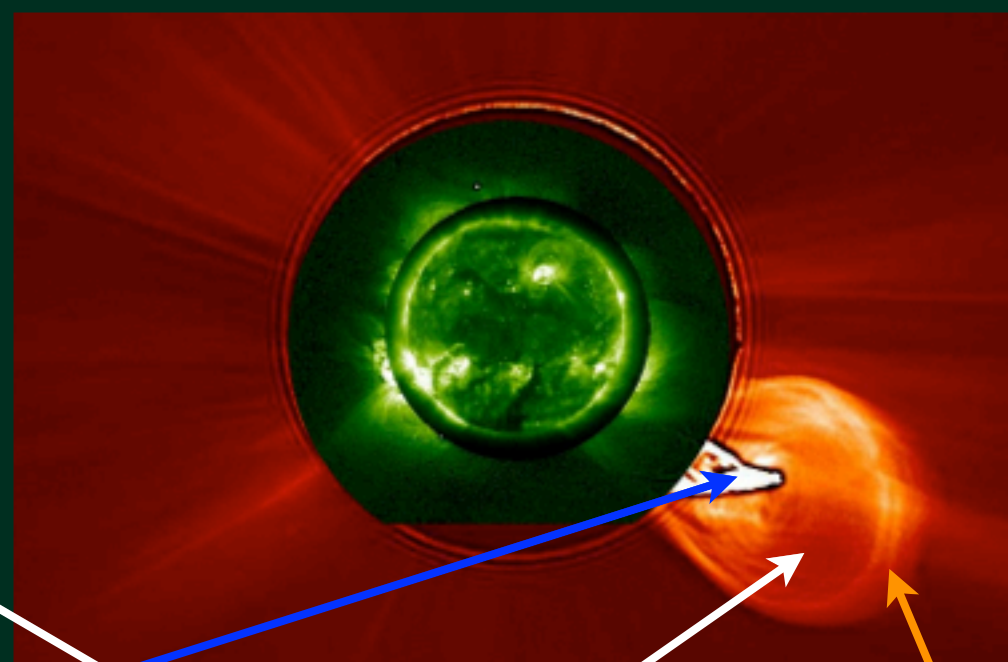
How do CMEs erupt and accelerate in the low corona?

quiescent state

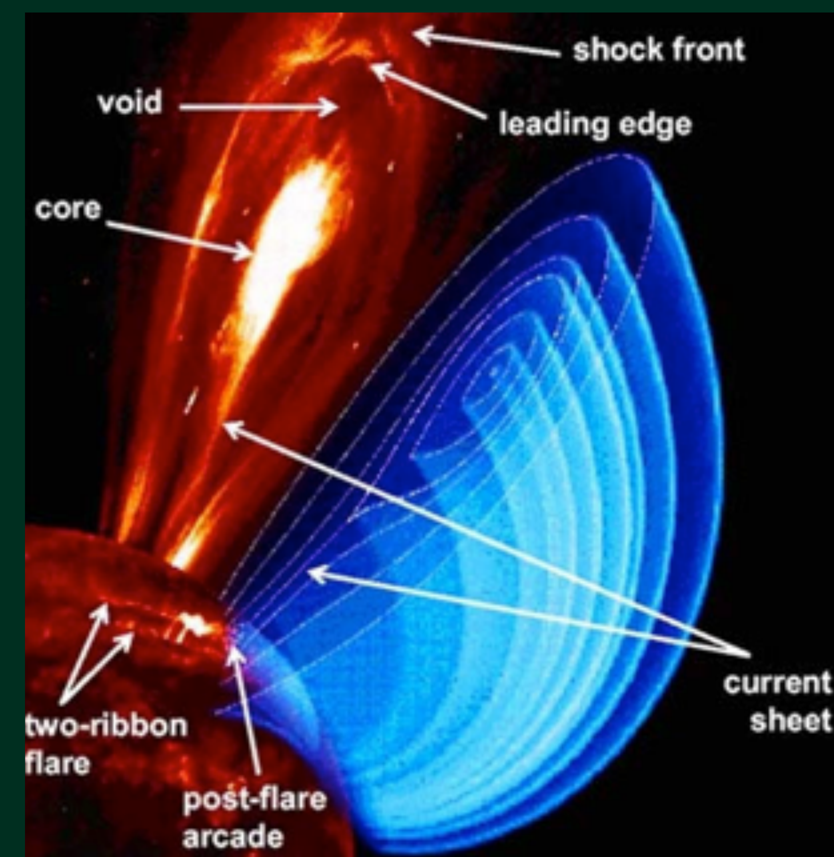


?

erupting state



interpretation



(Adapted from the Solar Sentinels STDT Report)

cavity (void)

prominence

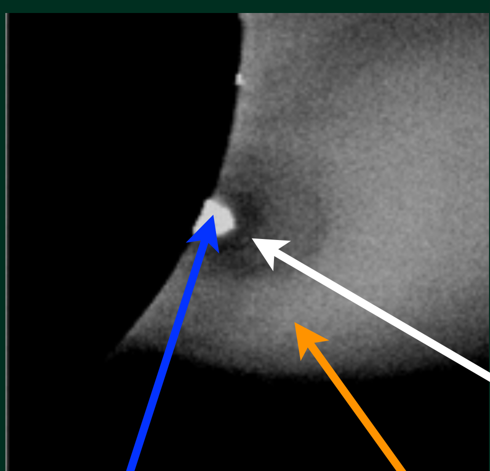
bulk of the streamer

?

CME frontal structure

How do CMEs erupt and accelerate in the low corona?

quiescent state



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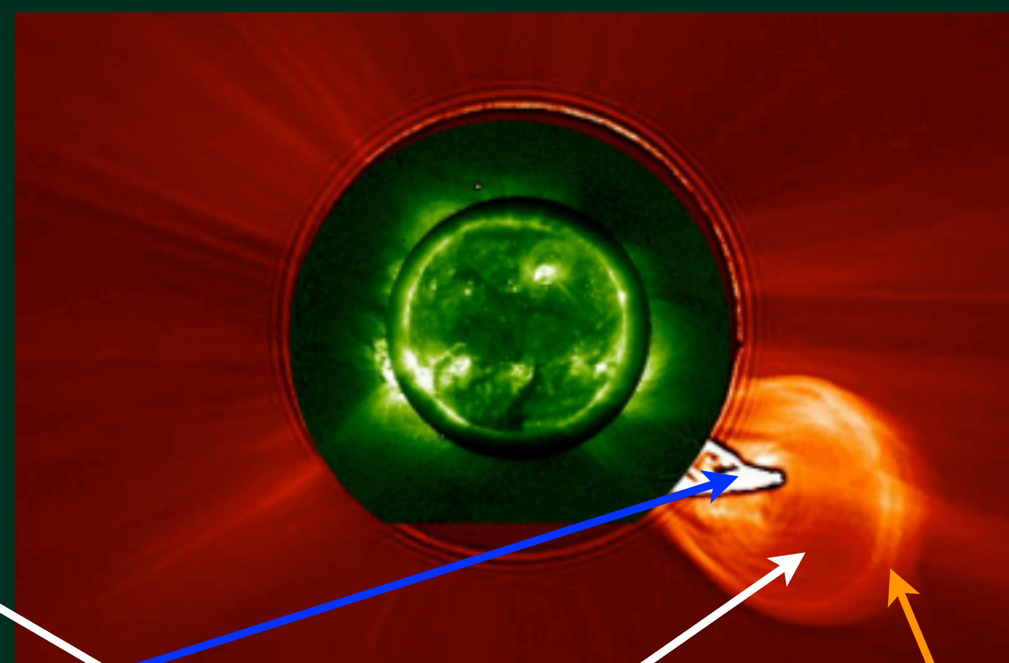
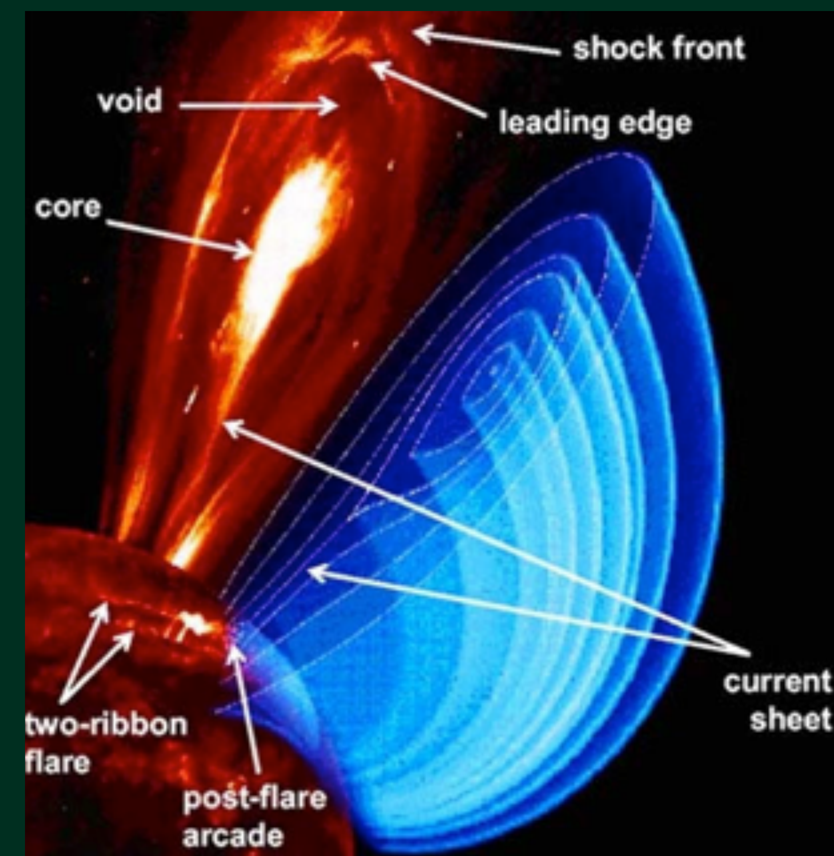
erupting state



interpretation



(Adapted from the Solar Sentinels STDT Report)

prominence

cavity (void)

bulk of the streamer

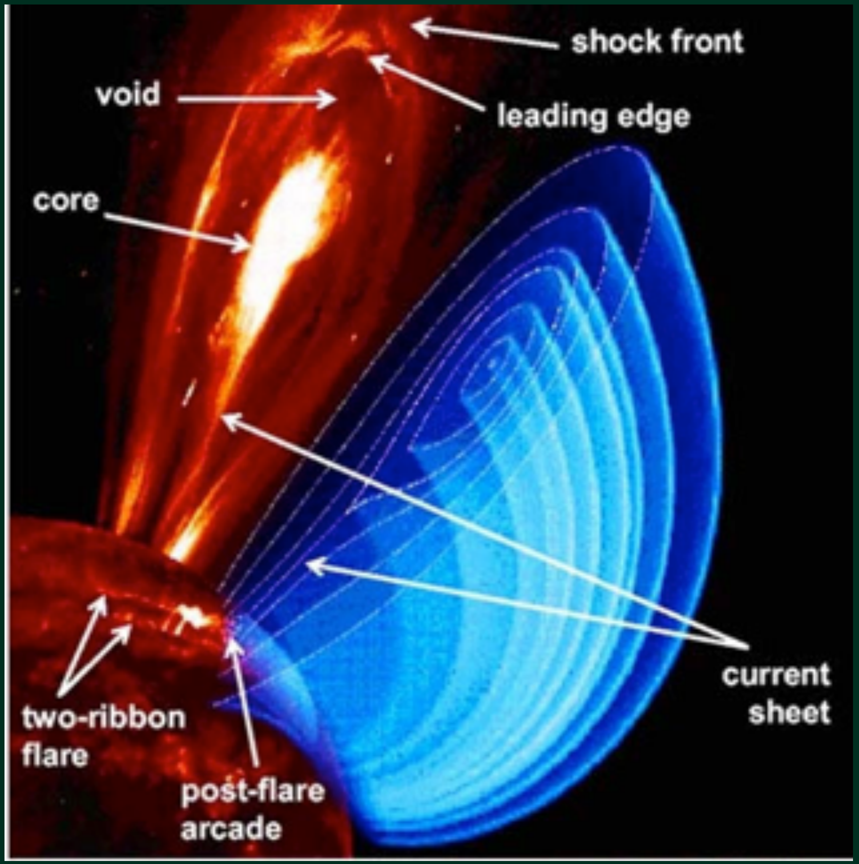
?

CME frontal structure

ASPIICS will be an ideal instrument to investigate the onset, acceleration, and early evolution of CMEs inside *The Gap*.

ASPIICS
Formation Flying Coronagraph

How do CMEs erupt and accelerate in the low corona? What is the connection between CMEs and active processes close to the solar surface?



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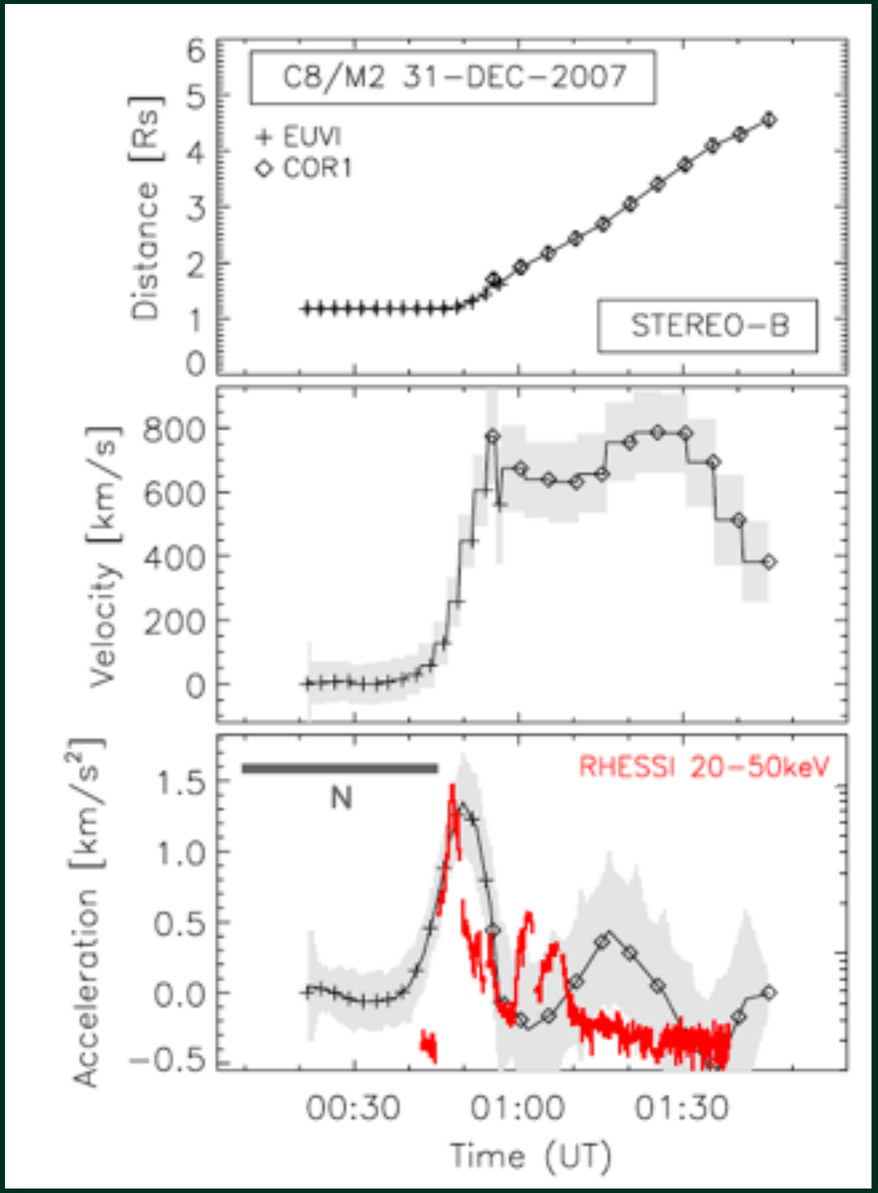
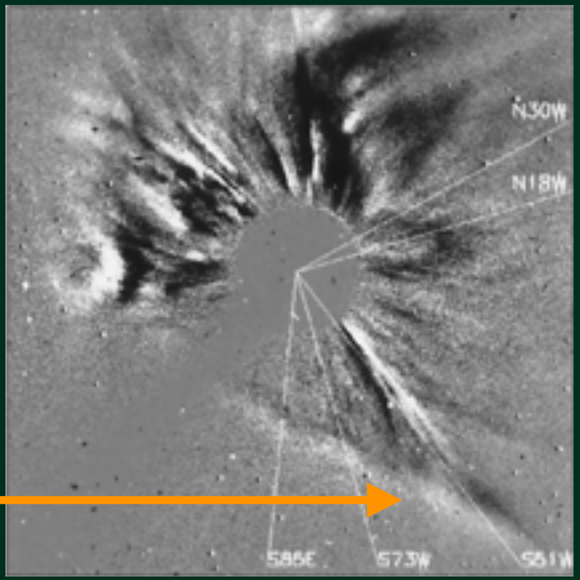


(Temmer et al. 2010)

ASPIICS will investigate the onset and early evolution of CMEs inside The Gap, as well as their link with flares, coronal dimmings and post-CME current sheets.

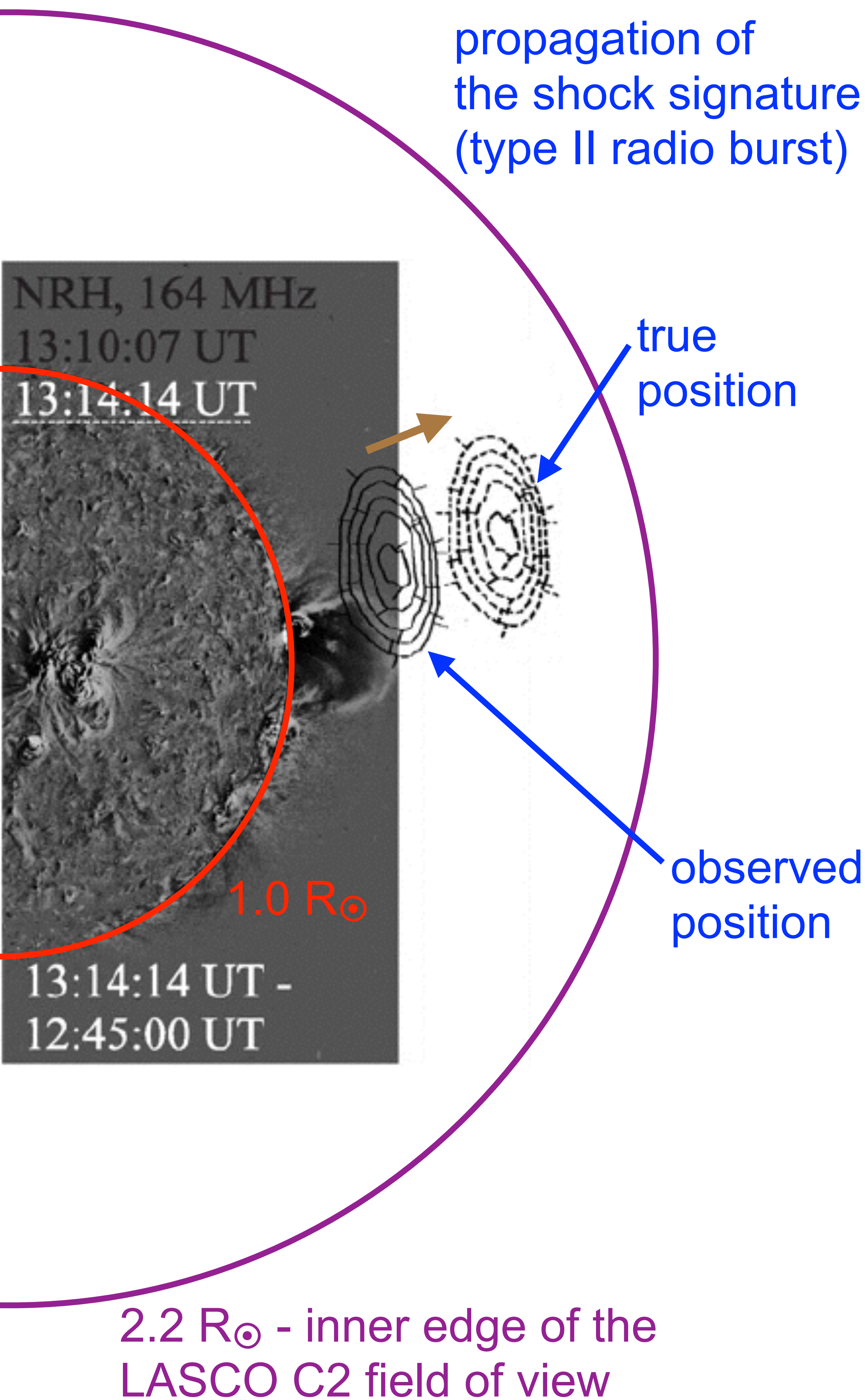
Where and how can a CME drive a shock in the low corona?

Coronal shocks can be observed by coronagraphs in white light observations.



(Sheeley et al. 2000)

(after Magdalenić et al. 2010)



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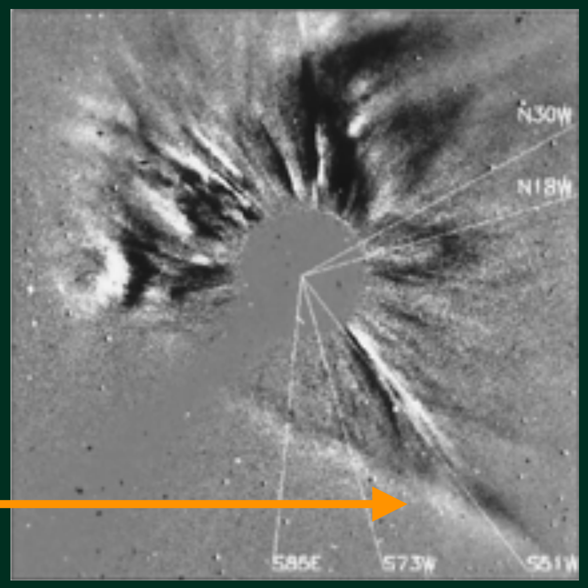

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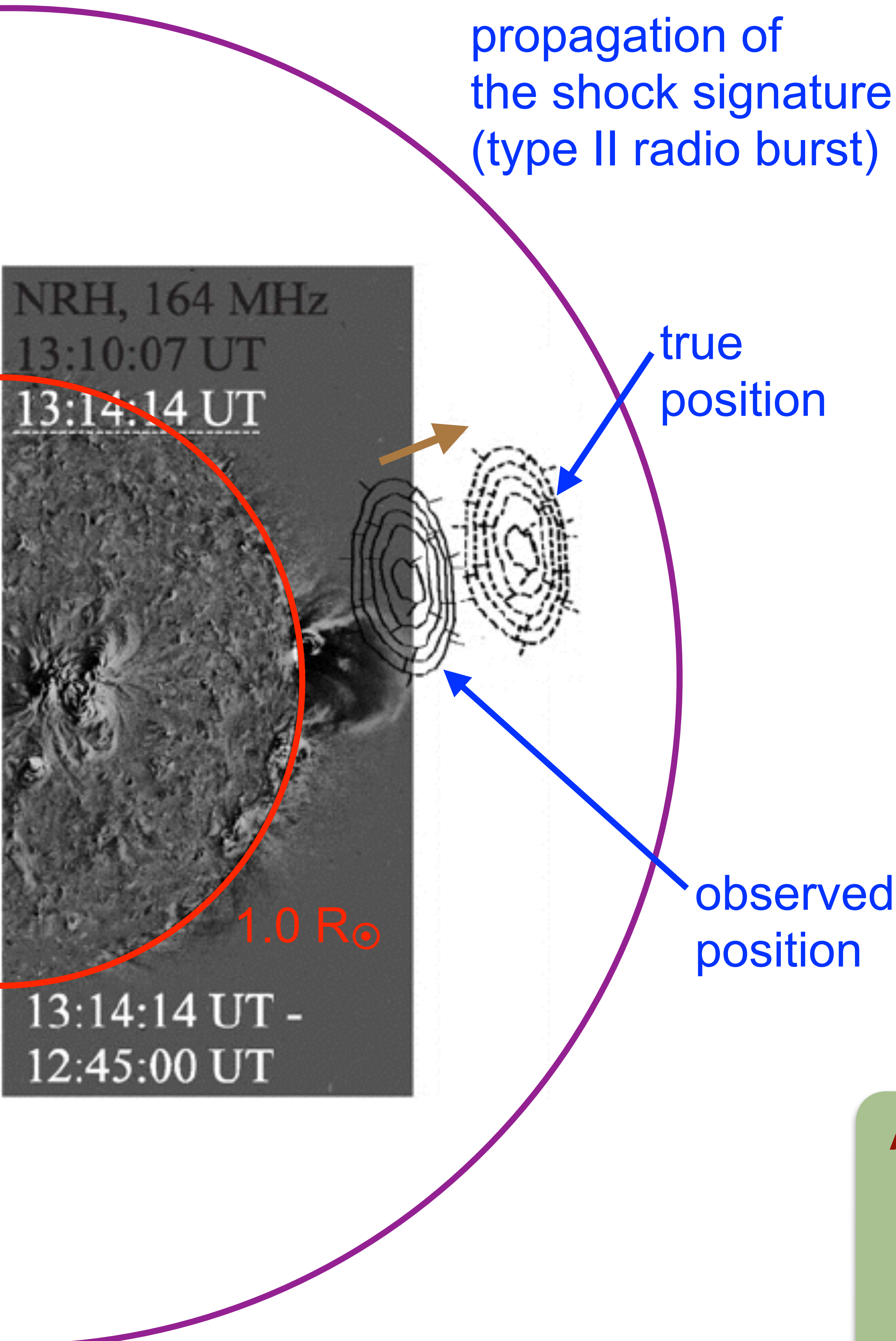

2.2 R⊙ - inner edge of the LASCO C2 field of view

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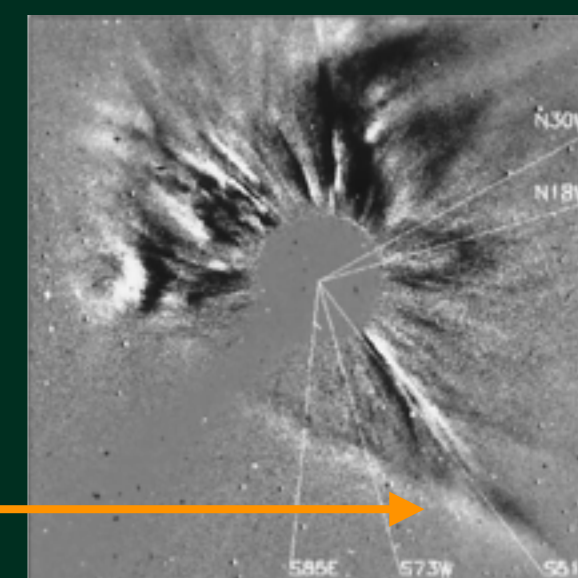


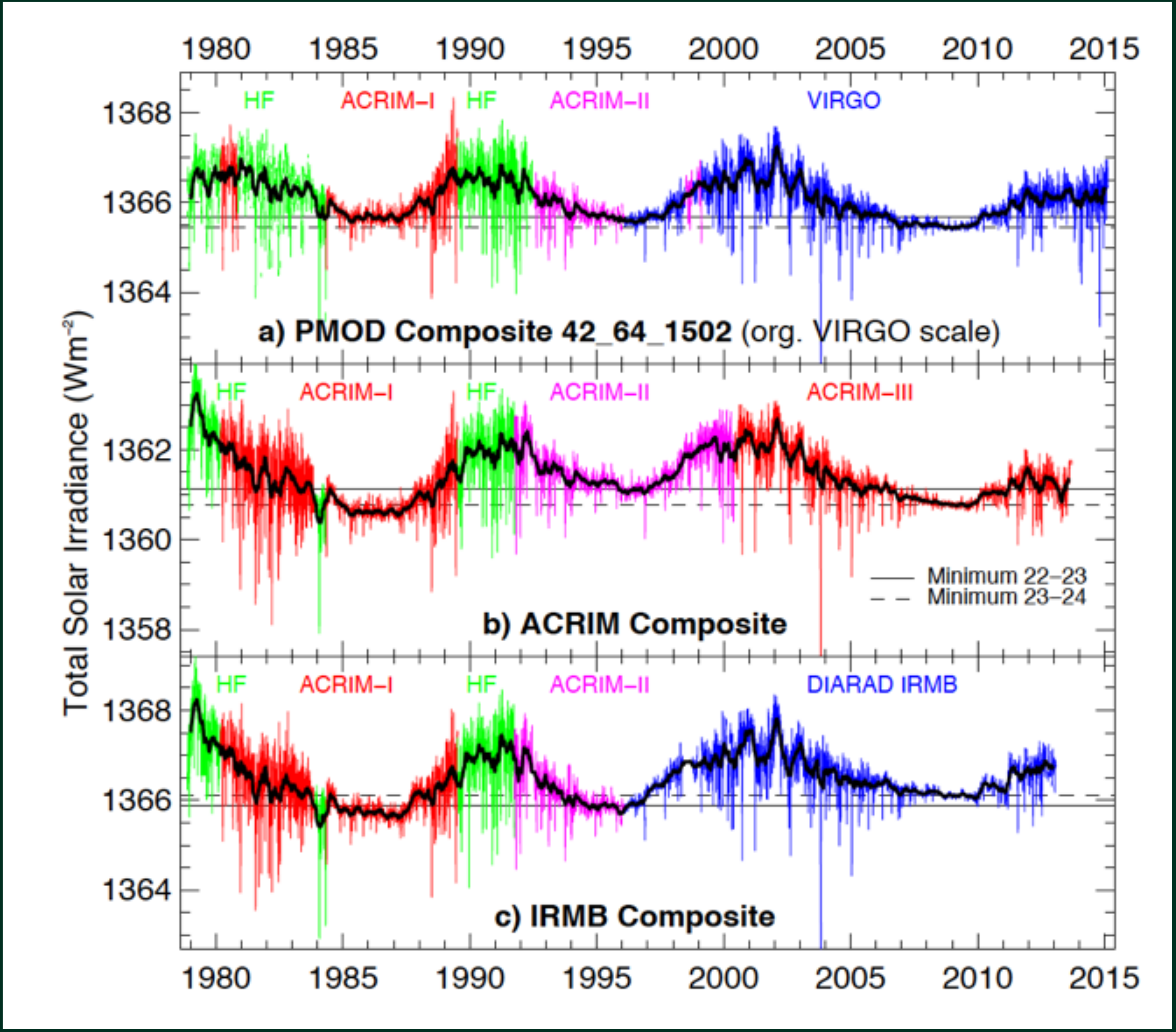
(Sheeley et al. 2000)

ASPIICS will observe the CME dynamics in *The Gap* providing us with conclusive evidence for the origin of coronal shocks observed concurrently by ground-based radio instrumentation.

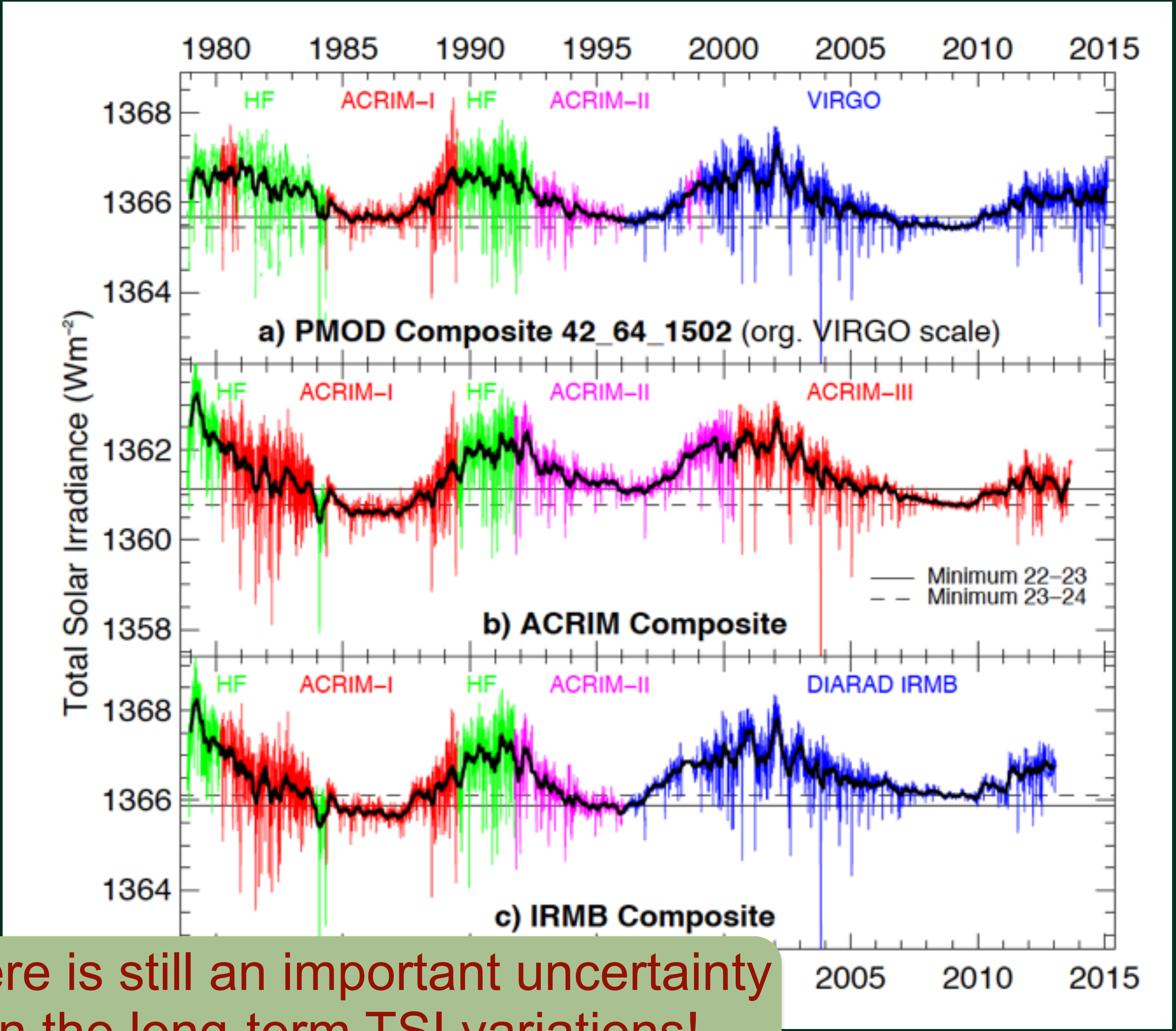
DARA scientific objectives

1. Radiometry
    - Confirm the scale offset found with PMO6/PREMOS.
    - Confirm design improvements (optical/thermal and weight reduction).
    - Meet or exceed highest currently achievable uncertainty level (by PMO6/PREMOS).
2. Climate Research
    - Extend the Total Solar Irradiance (TSI) data record for solar atmosphere and climate modelers (solar variability, global warming).
3. Helioseismology
    - Assess the acoustic energy carried into the solar atmosphere by high-frequency sound waves (above the acoustic cut-off frequency).

TSI variations



TSI variations



There is still an important uncertainty in the long-term TSI variations!

Contribution of PROBA-3 to space weather studies

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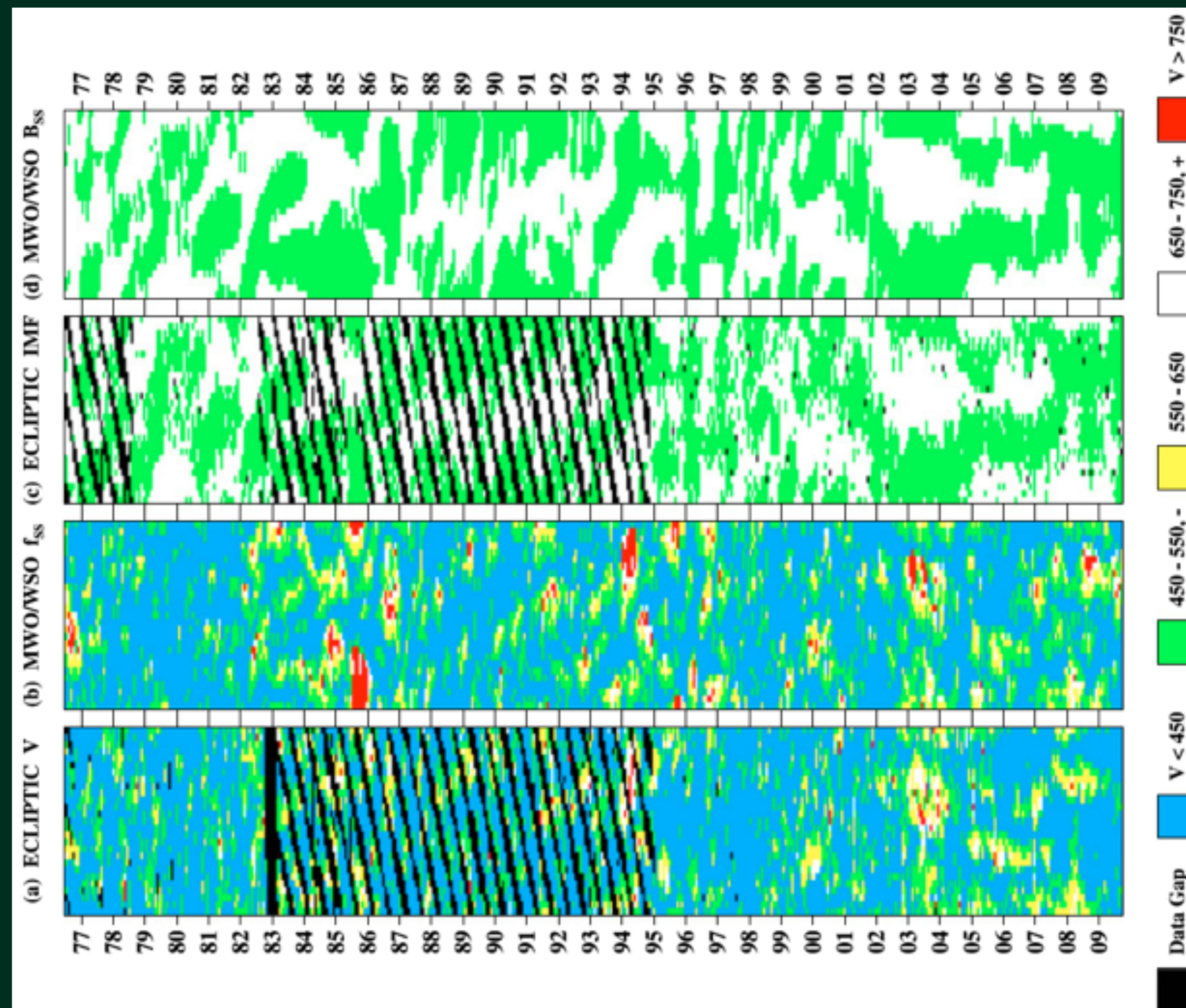
- ASPIICS will, however, give a scientific insight into the physics of CMEs.
- ASPIICS will provide important constraints to the models of the coronal magnetic field and therefore to the modeling of the solar wind and of the interplanetary magnetic field.

Modern solar wind models: a success?

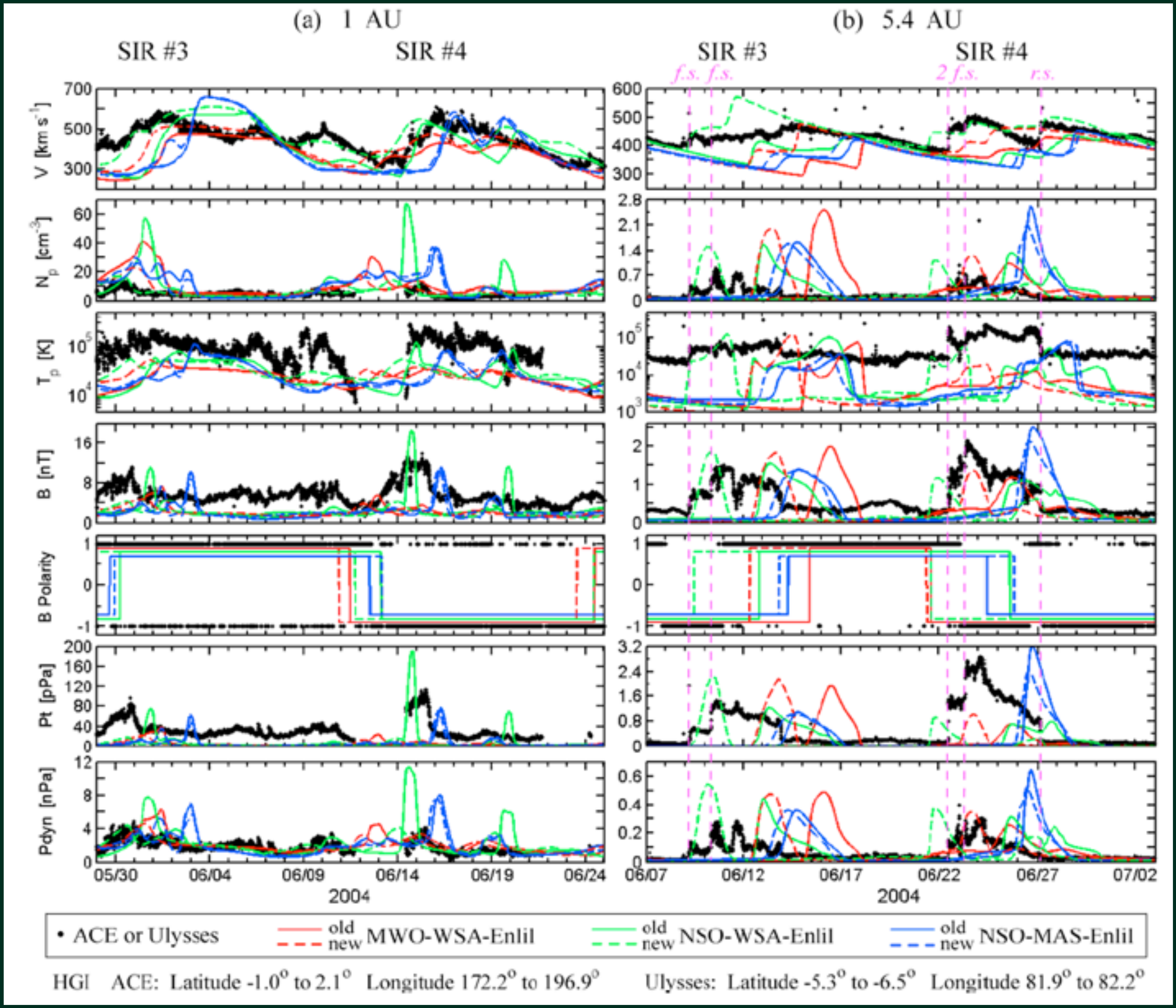
- The Wang-Sheeley-Arge (WSA) and ENLIL models (both eventually based on photospheric extrapolations) were found successful to describe the sector structure of the interplanetary magnetic field and the general configuration of the fast/slow solar wind in the heliosphere.
- The agreement holds both for low and high solar activity.



(Y.-M. Wang 2011)

Solar wind prediction by the WSA-ENLIL and MAS-ENLIL models

The predicted arrival times of stream interaction regions can be offset from reality by up to 2 days at 1 AU and up to 4 days at 5.4 AU *(Jian et al. 2011)*.



Field line connection errors in different models: impulsive SEP events

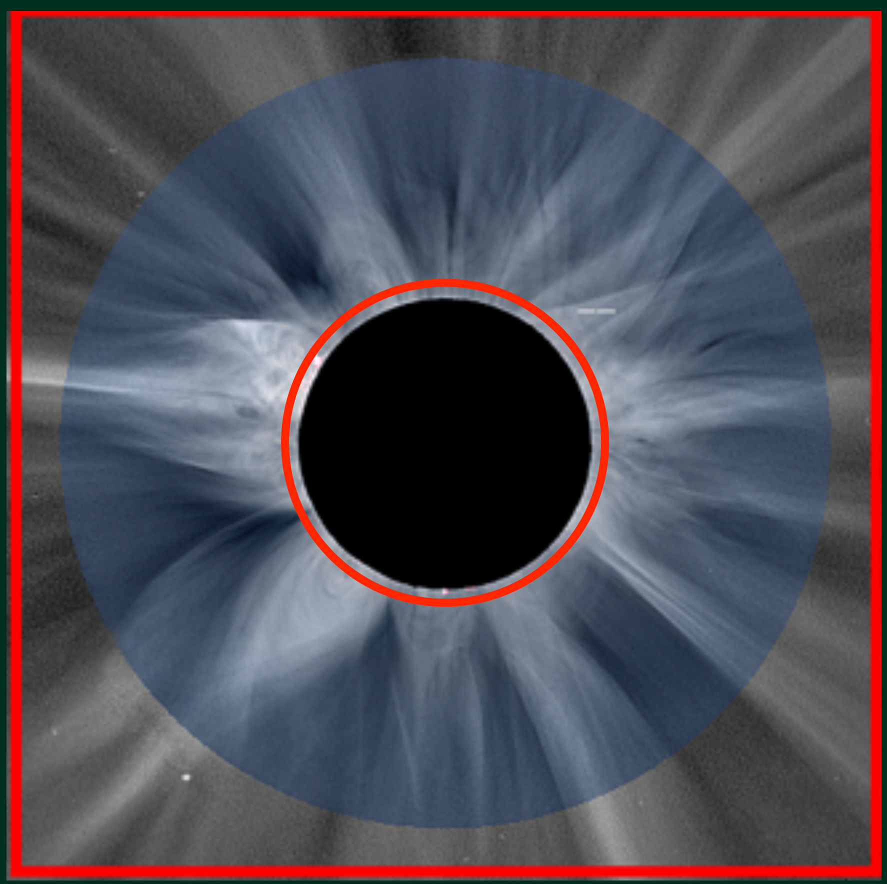
Table 6. Difference in Longitude and Latitude Between the Models' Foot Point Forecasts and the Identified SEP Source Locations[a]

SEP Event Number	Longitude Offset				Latitude Offset			
	ASM	PFSS + Spiral	WSA	WSA/ENLIL	ASM	PFSS + Spiral	WSA	WSA/ENLIL
1	2°E	20°E	1°E/10°E	20°E	30°N	38°N	93°N/91°N	29°N
2	44°W	56°W	56°W/57°W	56°W	22°N	6°N	6°N	8°N
3	10°E	13°W	7°W	5°W	11°N	32°N	38°N	46°N
4	12°E	9°E	22°W/19°W	8°E	11°N	8°S	6°S	1°S
5	29°E	37°E	13°W/14°W	2°W	24°S	52°S	56°S	58°S
6	30°W	32°W	35°W	47°W	26°S	11°S	11°S	12°N
7	15°E	12°E	9°E	7°E	8°N	17°N	29°N	42°N
8	10°E	2°W	34W°/32W	20°W	10°N	2°S	0°S	0°S
9	6°E	1°W	5°E/34°E	34°E	23°S	3°S	1°N/7°S	16°N
10	10°E	0°	9°W/13°W	5°W	10°S	8°S	8°S	16°N
11	95°W	88°W	93°W/78°W	88°W	10°N	25°N	27°N/40°N	27°N
11*	46°W	39°W	44°W/29°W	39°W	16°N	31°N	33°N/46°N	33°N
12	24°W	26°W	32°W/31°W	26°W	15°S	24°S	26°S/25°S	23°S
13	28°E	13°E	38°W	20°W	16°N	1°S	13°S	41°S
14	10°E	50°E	68°E/66°E	56°E	26°S	30°S	29°S	22°S
15	27°W	3°E	16°E	16°E	16°S	27°S	24°S	24°S
Average	23	25	27/32	24	17	19	27/24	25
Average Excl. 2, 11, 14	17	14	18/22	18	17	19	29/25	26

[a]Event 11* is our proposed alternative source location (at 31°W, 18°S) for event 11.

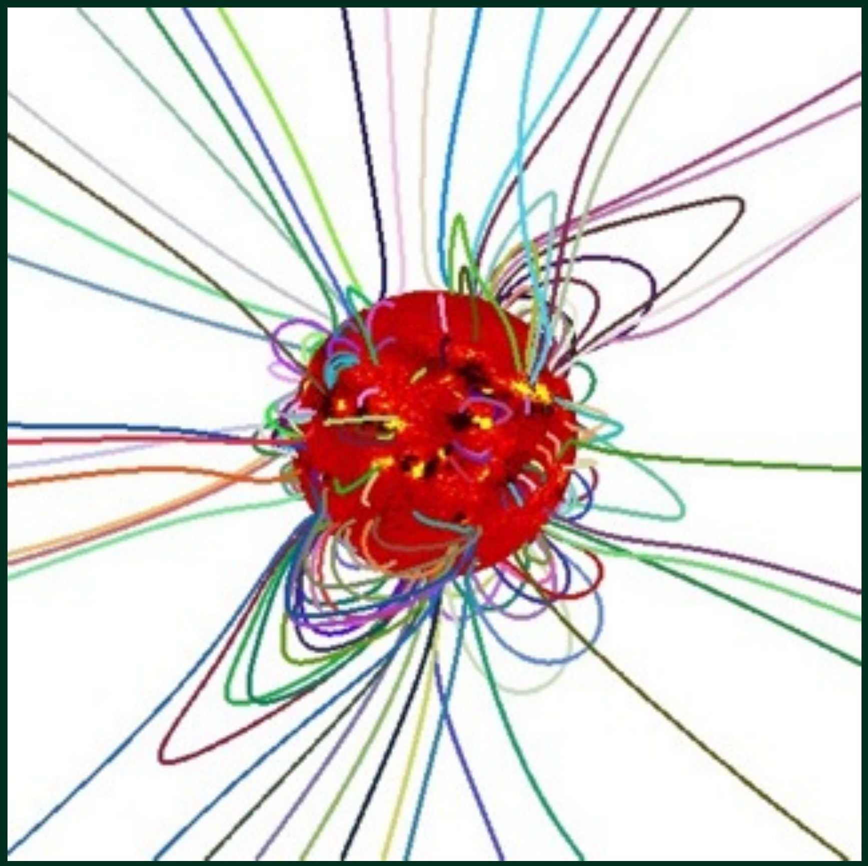
- The performance of modern models is not better than that of the simplest Archimedean spiral model (ASM in the table), according to current validation studies *(MacNeice et al. 2011)*.
- The main source of error seems to be the models' inability to reproduce low-latitude open flux.

ASPIICS observations vs coronal magnetic field models



ASPIICS field of view

?



MHD model
of the coronal magnetic field

ASPIICS observations of the large-scale coronal structure (streamers, pseudo-streamers, coronal holes) will provide us with important constraints to the models of the coronal magnetic field and therefore to the modeling of the solar wind and of the interplanetary magnetic field.

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- PROBA-3 and its payload are currently in phase C of the project.

ASPIICS
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