SAG 24
Exploring the Complementary Science Value of Starshade Observations

Sara Seager, Massachusetts Institute of Technology,

and

Stuart Shaklan, Jet Propulsion Laboratory, California Institute of Technology

ExoPAG 33

Jan 3, 2026

Phoenix, AZ

OUTLINE

- Participants
- Starshade 101
- Starshade Technology
- SAG 24 Goals
- Progress toward each goal:
  - Why: Broadband characterization is important!
  - What: Starshade design achieves broadband with high throughput
  - How well: UV imaging simulations: How well does it work?
  - How many: Exoplanet yield: How many planets can we characterize?

SAG 24 PARTICIPANTS

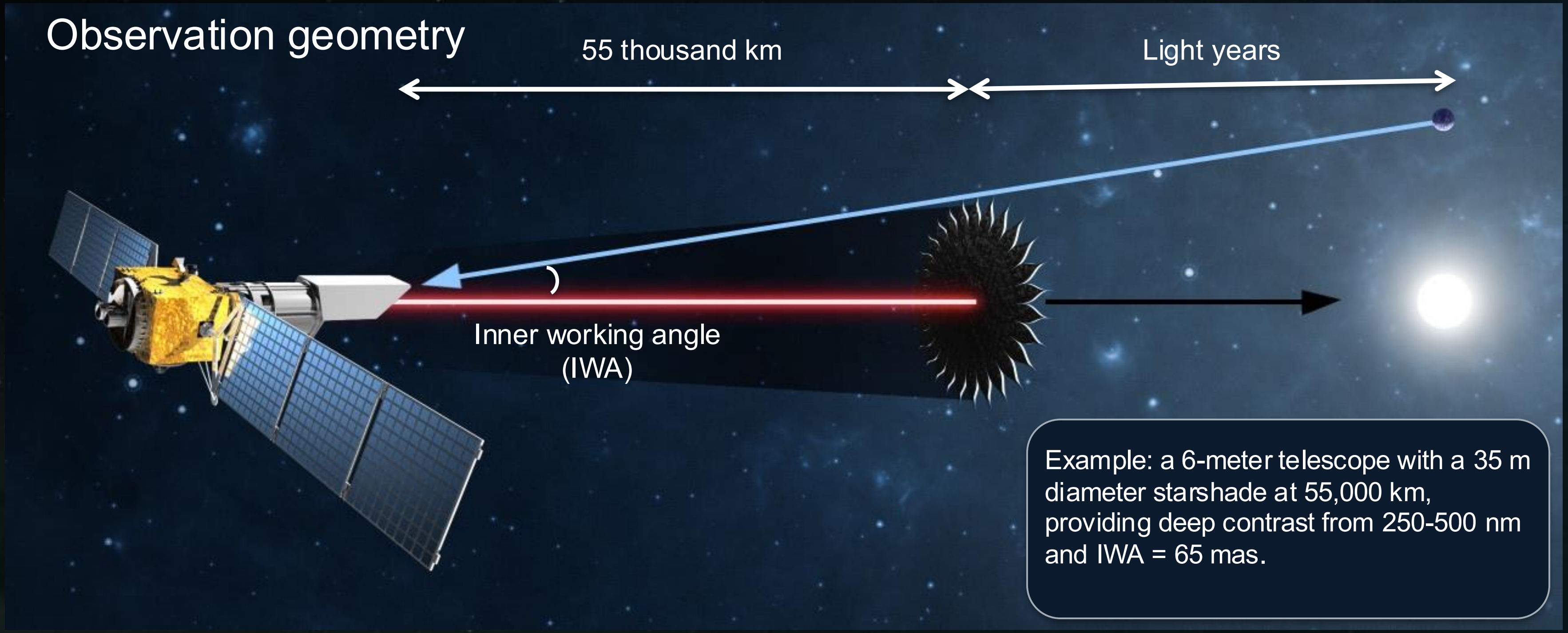
Co-Leads

Sara Seager (MIT)
Stuart Shaklan (JPL)

Participants

Renyu Hu (JPL)
Rhonda Morgan (JPL)
Mario Damiano (JPL)
Zahra Ahmed (Stanford)
Manan Arya (Stanford)
Matt Greenhouse (GSFC)
John Mather (GSFC)
Angelle Tanner (MSU)
Keith Warfield (JPL)
Eliad Peretz (NASA)
Jamila Taaki (U Michigan)
Katie Bennett (JHU)
Gangandeep Kaur (SGAC)
Josh Vaudrey (BYU)
Eddie Schwieterman (UC Riverside)
Ahmed Soliman (JPL)
Andres Romero-Wolf (JPL)
Russ Belikov (Ames)
Simone D’Amico (Stanford)
Ty Robinson (U of Arizona)
Dmitri Savransky (Cornell)
Dan Sirbu (Ames)
Jeremy Kasdin
Doug Lisman

STARSHADE 101

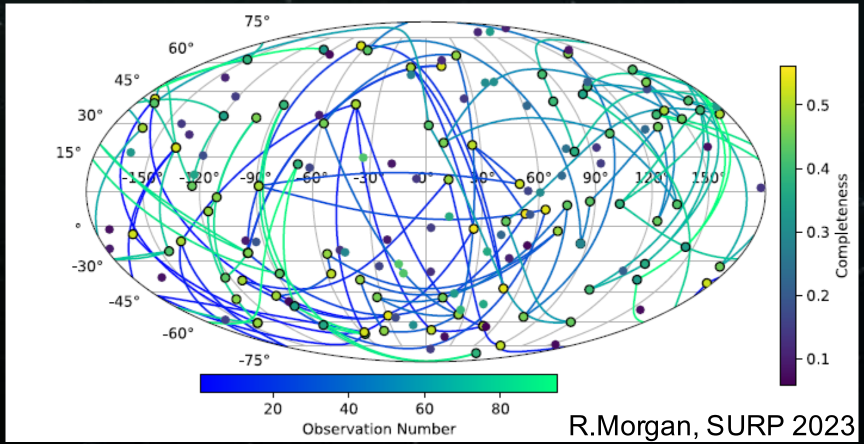


The starshade is filters out starlight in space where the signal from the planet and the signal from the star do not overlap.

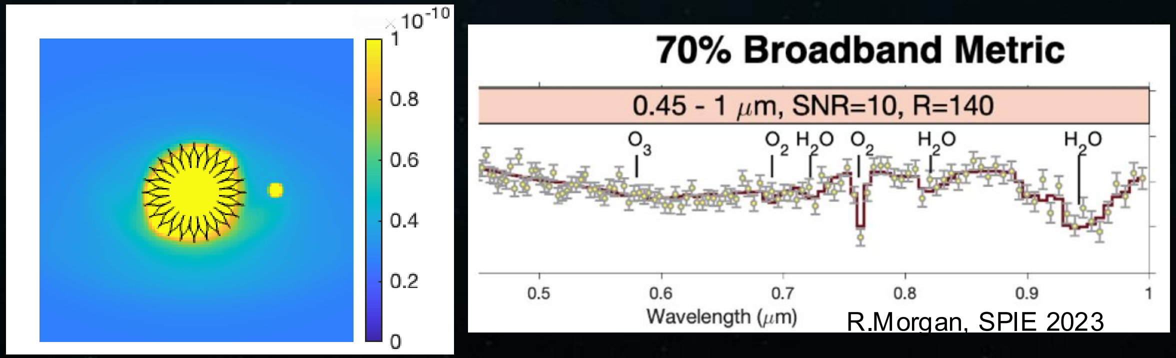
Starshades attributes:

- 100% throughput
- Wide bandwidth
- Excellent in the UV
- Small Inner Working Angle
- Standard Machine Tolerances, no picometers
- Works with any telescope, e.g. on- or off-axis, segmented or monolithic

Slew from target to target, 1-2 weeks/slew

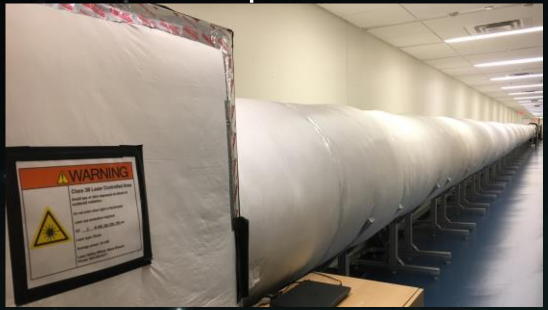


Science products are direct images and spectra



STARSHADE TECHNOLOGY: S5 COMPLETED SPRING 2025

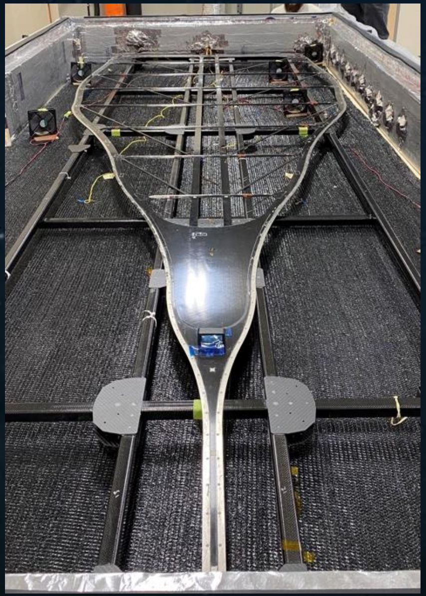
Princeton optical testbed



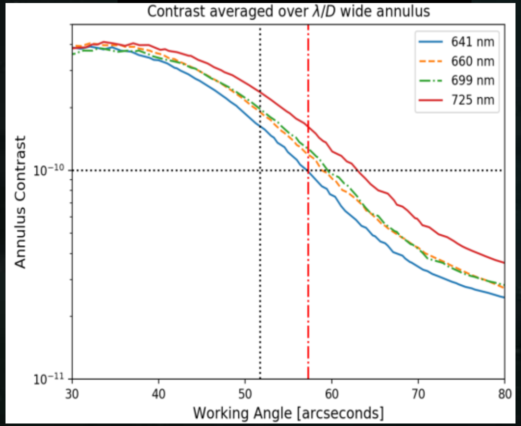
Precision mask

10 m disk with petals

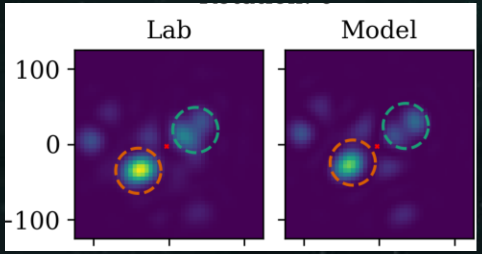
Half-scale precision petal



10^-10 contrast

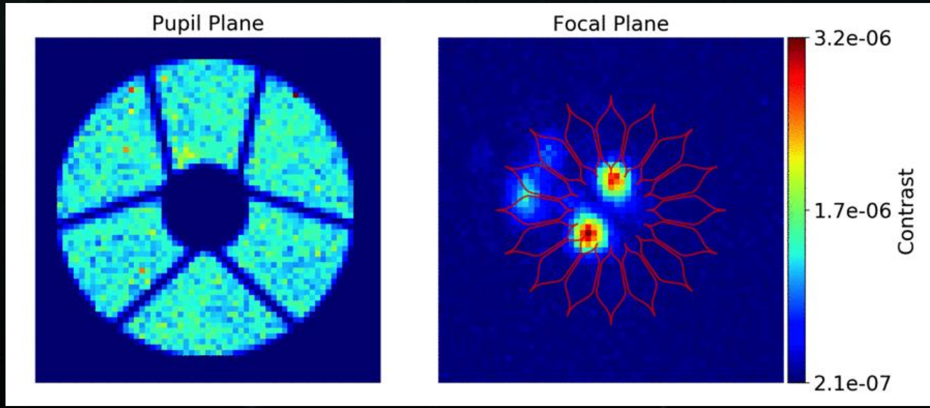


Model Validation

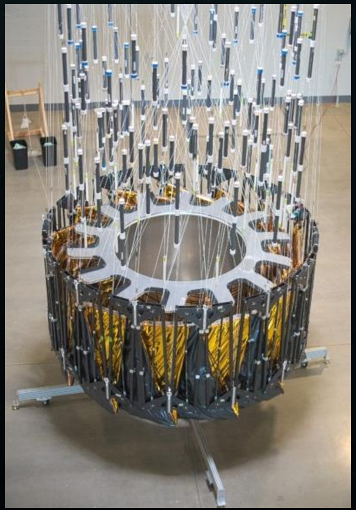


Demonstrated deep contrast, formation sensing and control, stowage, deployment, accurate petals, thermal stability

Hardware in the loop formation sensing and control

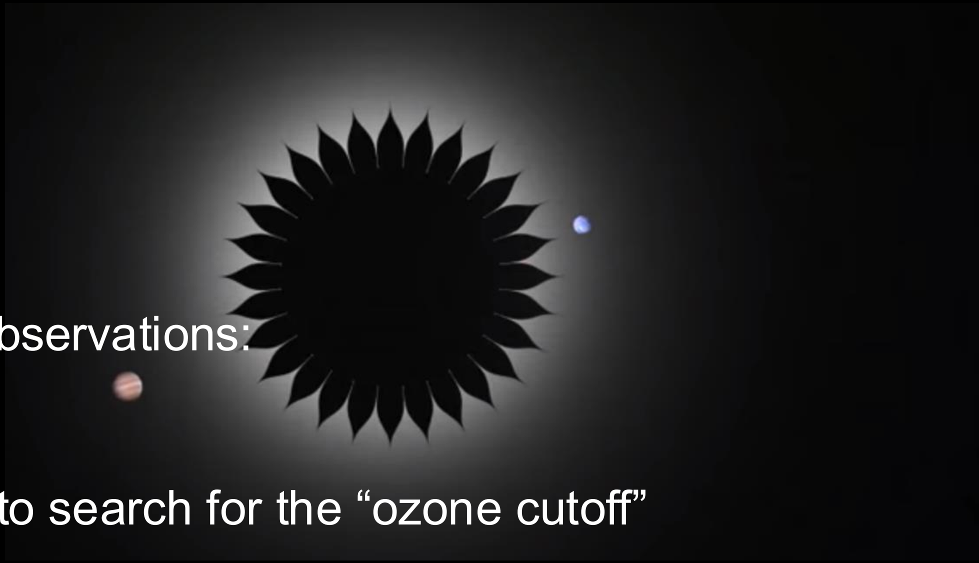


Stowed and partially deployed 10 m disk with optical shield



Petal position and shape Tolerancing is 0.1 – 1 mm.

SAG 24 GOALS



1. Observations: Assess the scientific value of access to the following observations:
   a. Broad, instantaneous spectral bandwidth (~100%)
   b. Unrestricted outer working angle
   c. Low resolution UV spectroscopy down to <= 250nm, with the ability to search for the “ozone cutoff”
   d. High throughput observations.

2. Yield: Estimate the exoplanet detection/characterization yield of a notional Starshade for HWO covering 250 nm to 2 um, e.g., to be used in conjunction with a visible-only HWO coronagraph.

3. Role: Identify methods for the critical or complementary role of Starshade for exoplanet characterization, incl: determining the rocky nature of any planet found by the HWO; determining the bulk composition of rocky planet atmospheres; characterizing biosignature gases on potentially habitable rocky planets.

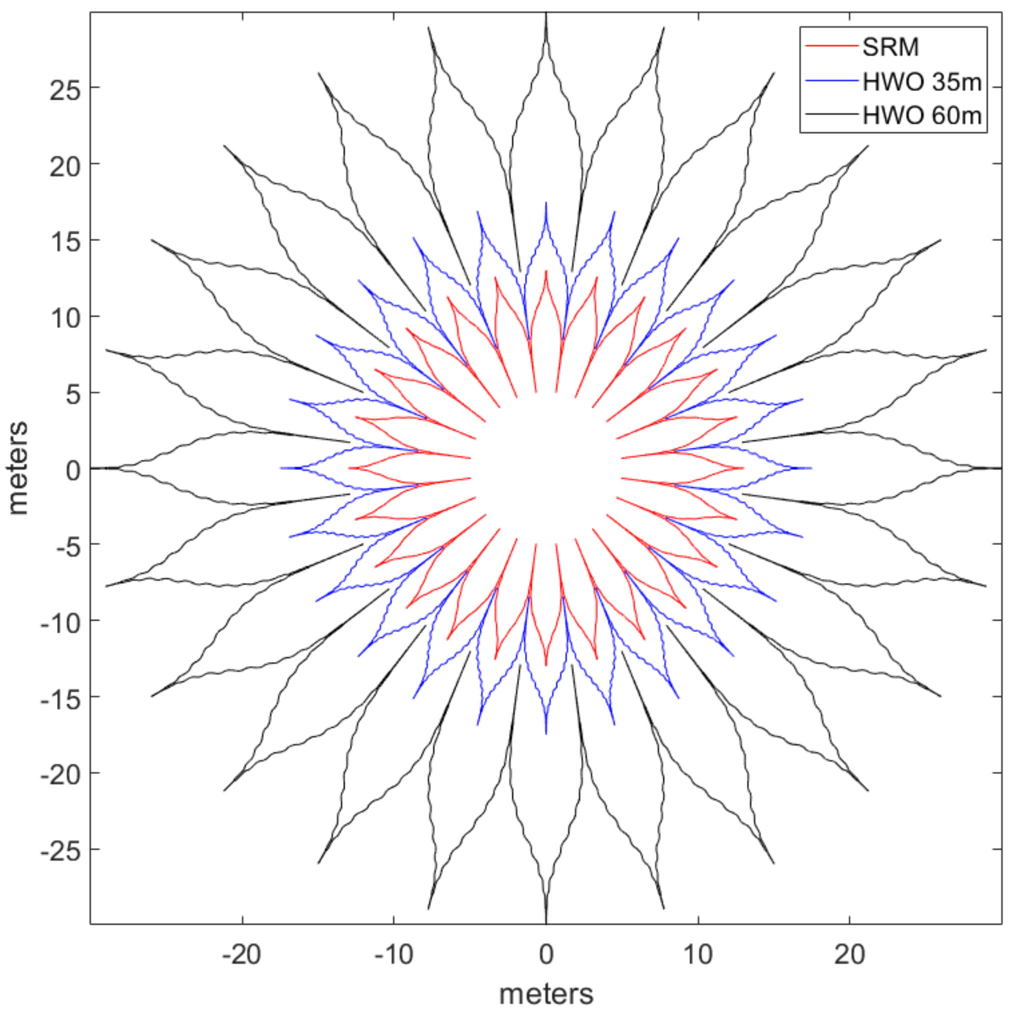
4. Simulations: Simulate end-to-end Starshade images including exozodi, and perform atmospheric spectral retrieval on the simulated images, to support Goal 3.

5. Design: Starshade point design to support Goals 2-4.

S5 Baseline (SRM) and HWO Starshades

"S5" is the name of the Starshade to TRL-5 activity (2018-2024)

	S5 Baseline	HWO (UV-VIS)	HWO (VIS-NIR)
Starshade Diameter	26 m	35 m	60 m
Disk/Petals	10 m, 8 m	17 m, 9 m	28 m, 16 m
Telescope	2.4 m	6 m	6 m
Wavelength	616-800 nm	250-500 nm	500-1000 nm
IWA_{tip} (λ_{max}/D), mas	1.5 λ/D, 103 mas	3.8 λ/D, 65 mas	1.9 λ/D, 65 mas
Separation	26.0 Mm	55.5 Mm	95.2 Mm
Fresnel Number	8.1-10.5	11.0 – 22.1	9.5-19.9
Diam/Sep^2 (m/Mm^2)	0.039	0.011	0.006



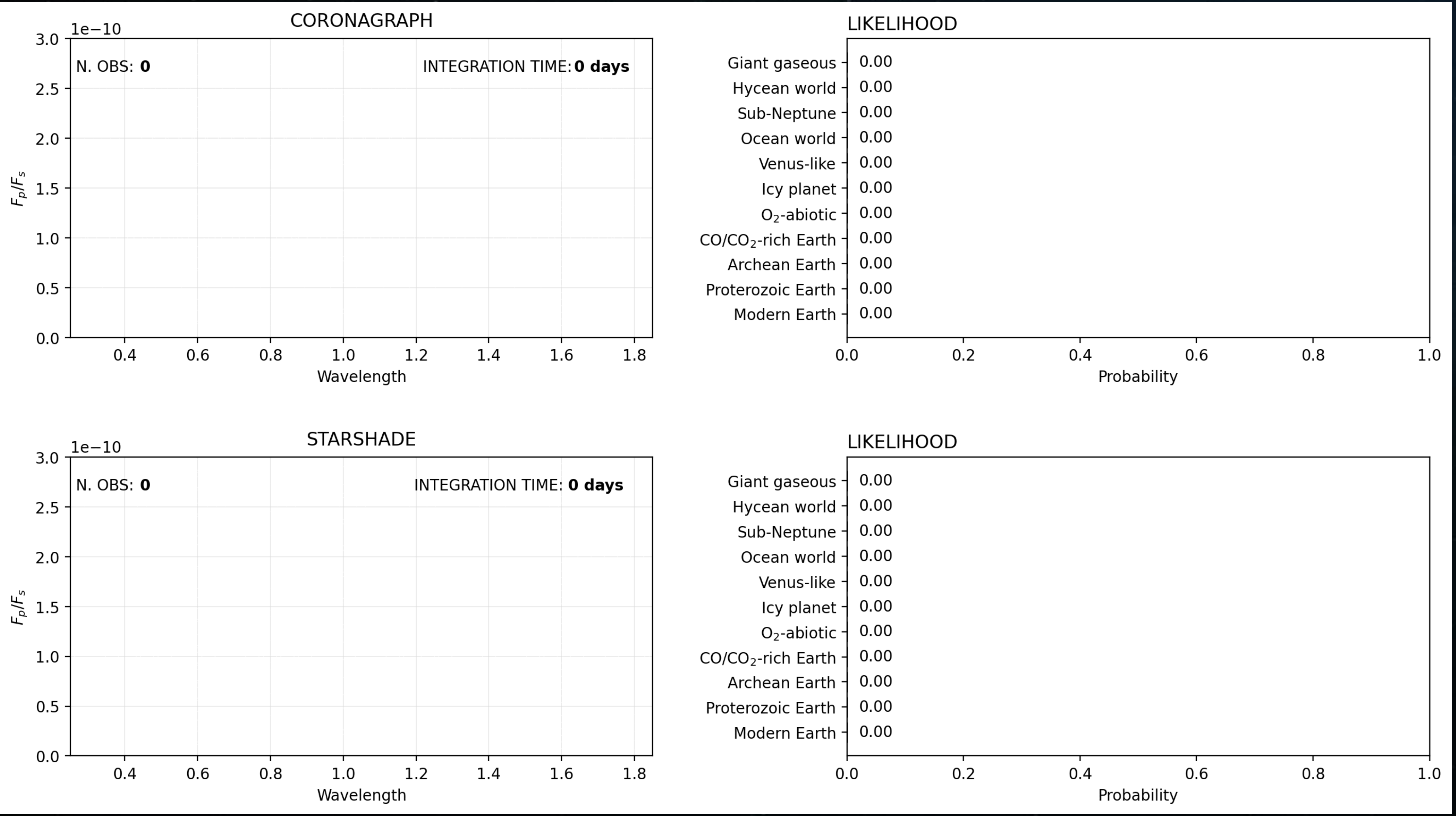
We also have a 30 m diameter design for a bandpass of 250-440 nm and IWA = 65 mas.

The HWO UV-VIS starshade is comparable in size to the baseline starshade that we have extensively studied. And it has better performance with relaxed tolerances (Shaklan SPIE 2024).
Note: the design is significantly smaller and simpler than the planned HWO sunshield (EAC-4,5).

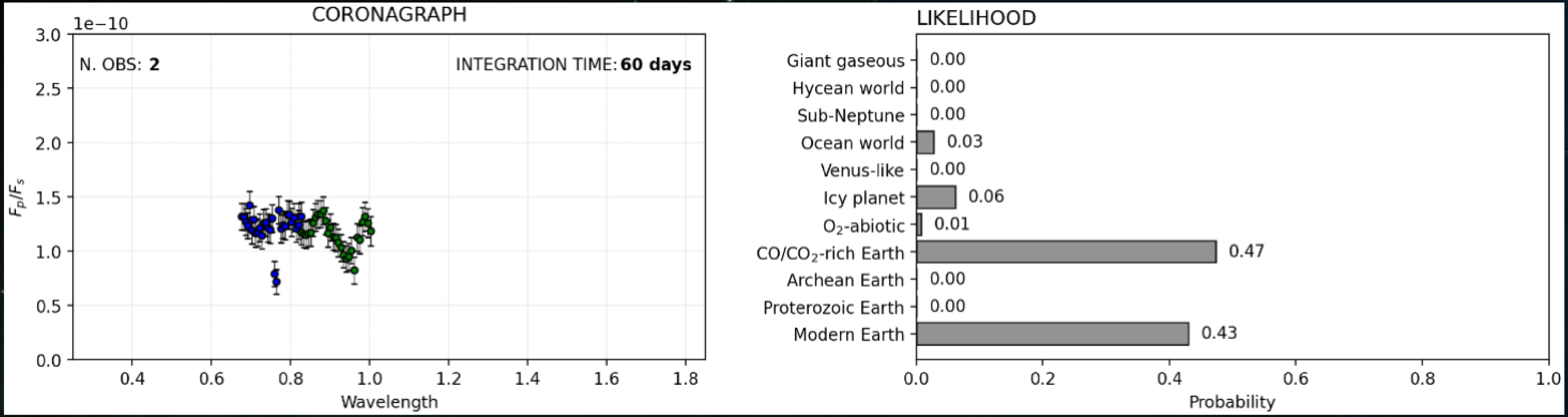
Goals 1 and 3 Progress: Low-resolution broadband spectra including UV

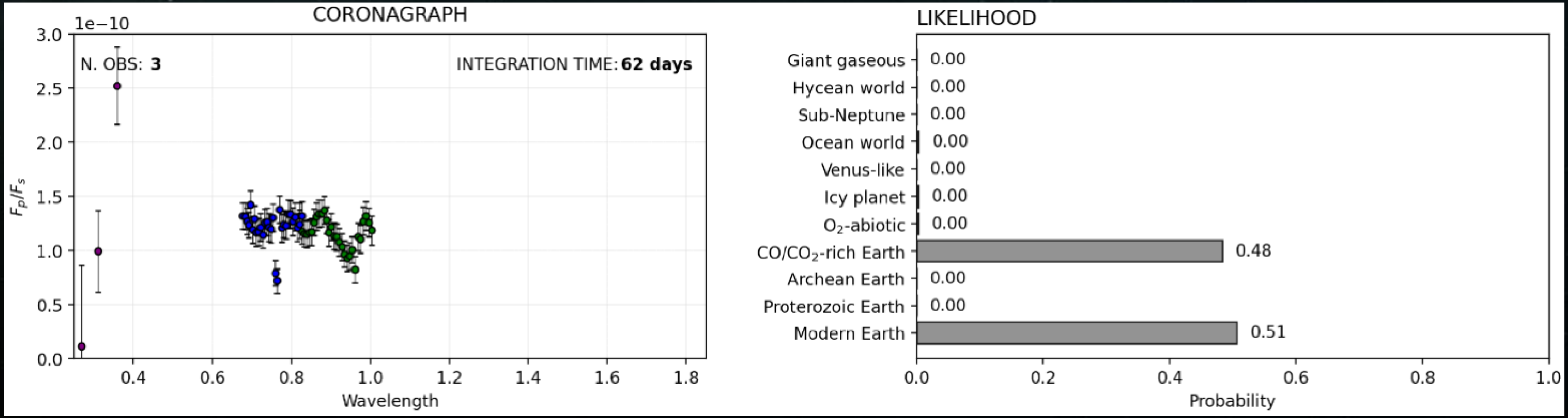
HWO Planet Template Matching: Coronagraph and Starshade

Credit: Mario Damiano, JPL. Bayesian Information Criterion is used to match observations to spectral templates.



Likelihood Function with and without UV Observation: Coronograph





INVESTIGATE THE ABILITY TO CHARACTERIZE EARTH-LIKE EXOPLANETS USING AN HWO STARSHADE IN THE ULTRAVIOLET

Investigations:

- 2024: What SNRs can we achieve for starshade observations of an Earth-twin in the UV?
- New work: How accurately can we constrain the 0.25 μm ozone feature in modern Earth atmosphere as a function of SNR?

Observing conditions to vary:

- Planet phase angle, system inclination, exozodi density, observing time

Realistic starshade model:

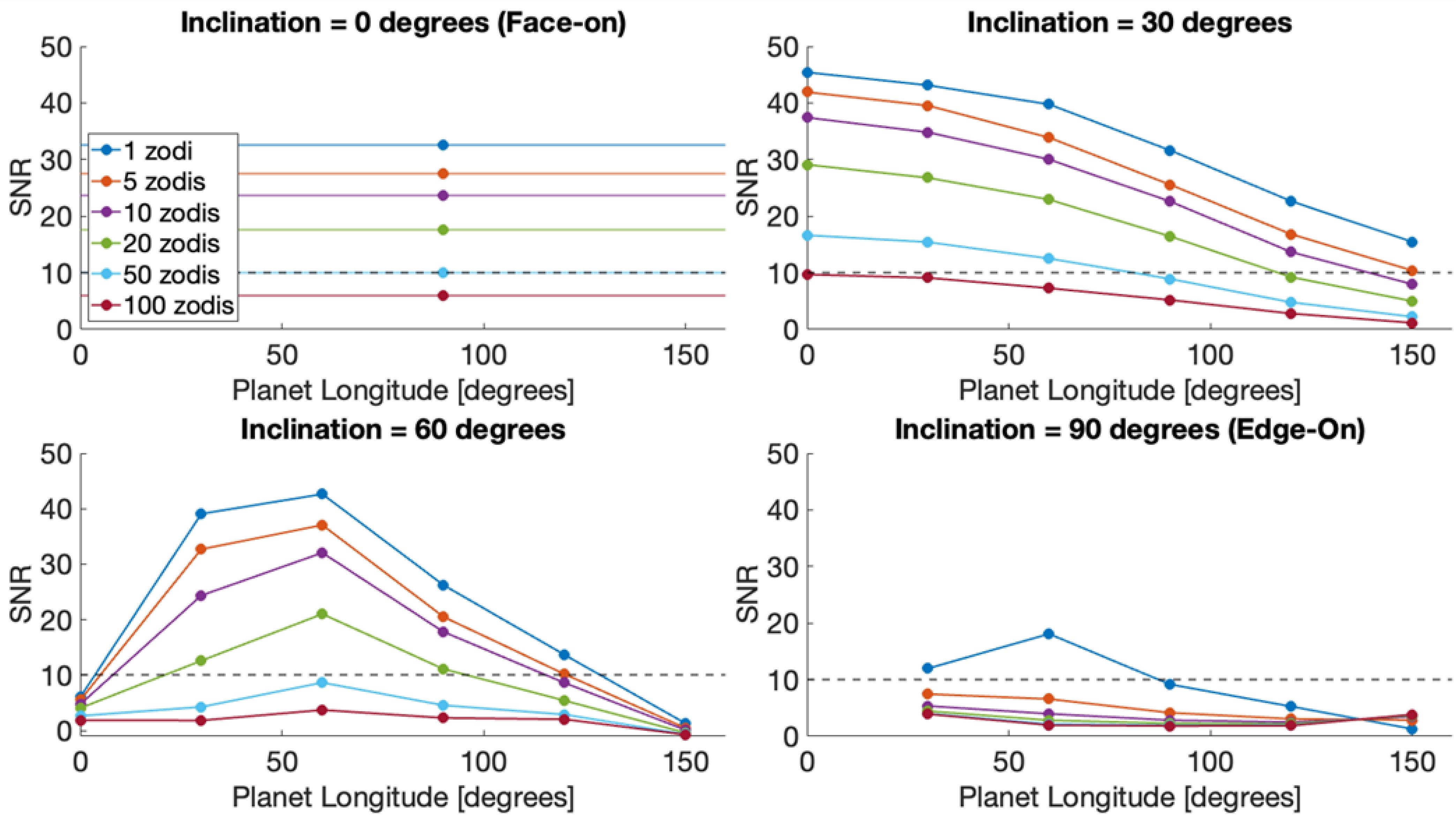
- Imperfect starshade, solar glint on edges and petal faces, micrometeoroid leakage, formation flying

Parameter	Value(s)
Imaging Bandpass	250 - 500 nm with 25 nm bands
System Distance	10 pc
Target Star	Solar-type star
Planet	Modern Earth-twin in a circular orbit
Planet Orbital Position	0, 30, 60, 90, 120, 150, 180 degrees
Disk Inclination	0, 30, 60 degrees
Exozodi Density	1, 5, 10, 20, 50, 100 zodi

Study Lead: Zahra Ahmed, Stanford University. With Simone d'Amico and Stuart Shaklan. Exozodi models provided by M. Currie, based on dustmap (Stark 2011).

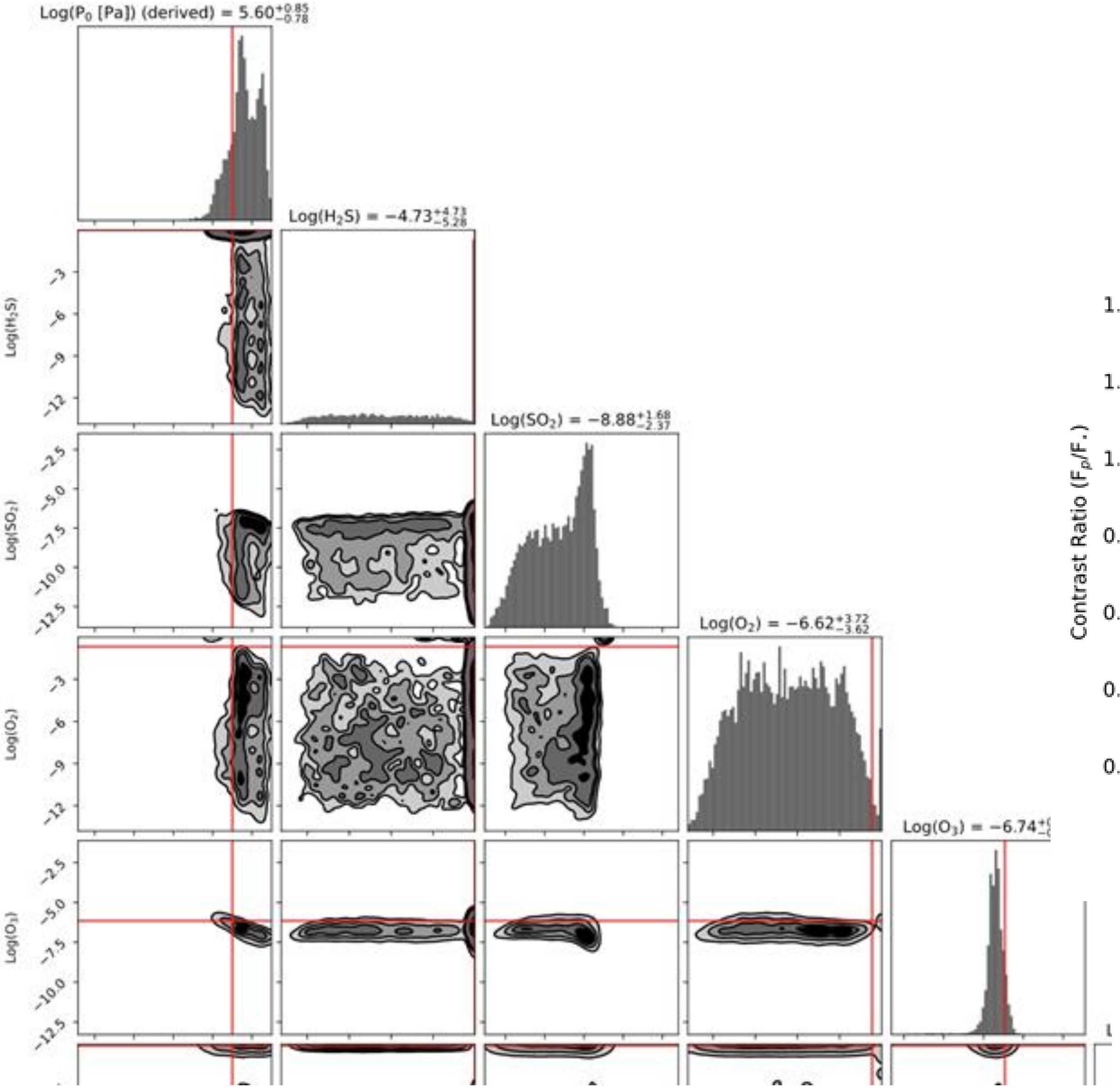
Results from JATIS 2024 paper: Achievable SNR for 3-day Observations

Stanford Space Rendezvous Laboratory

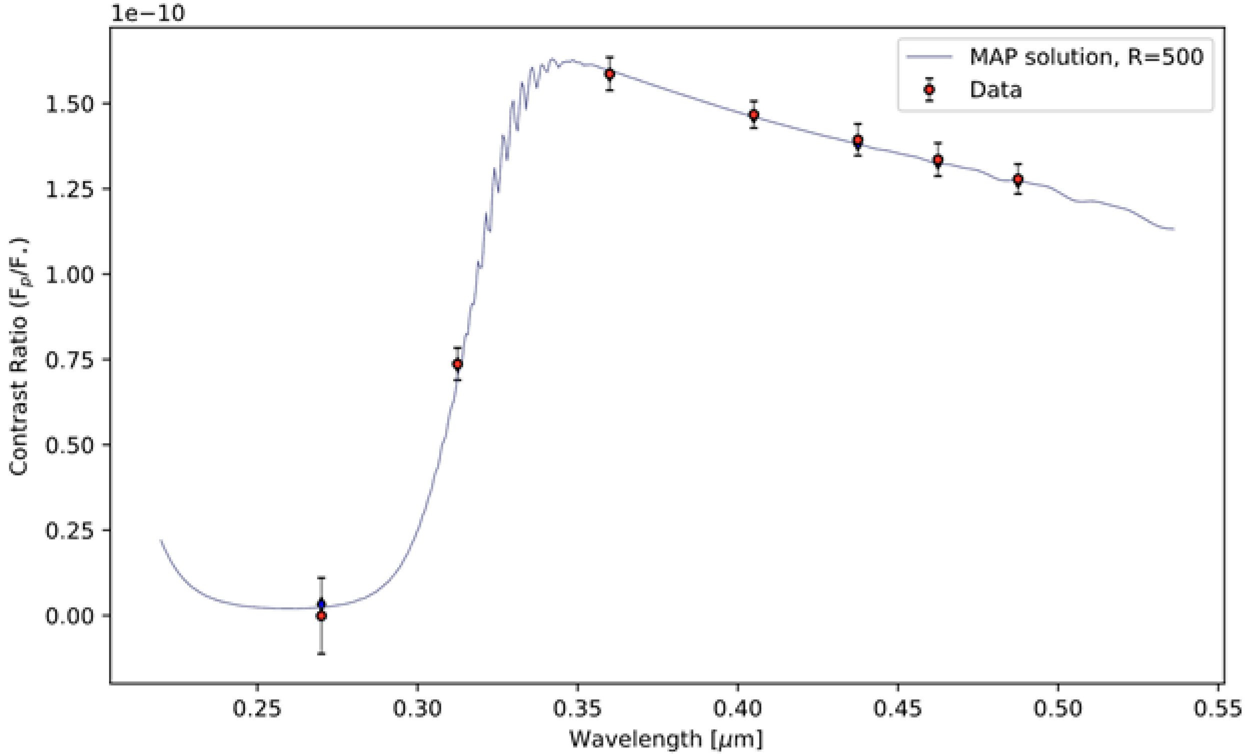


Retrieval Results - Clear Detection

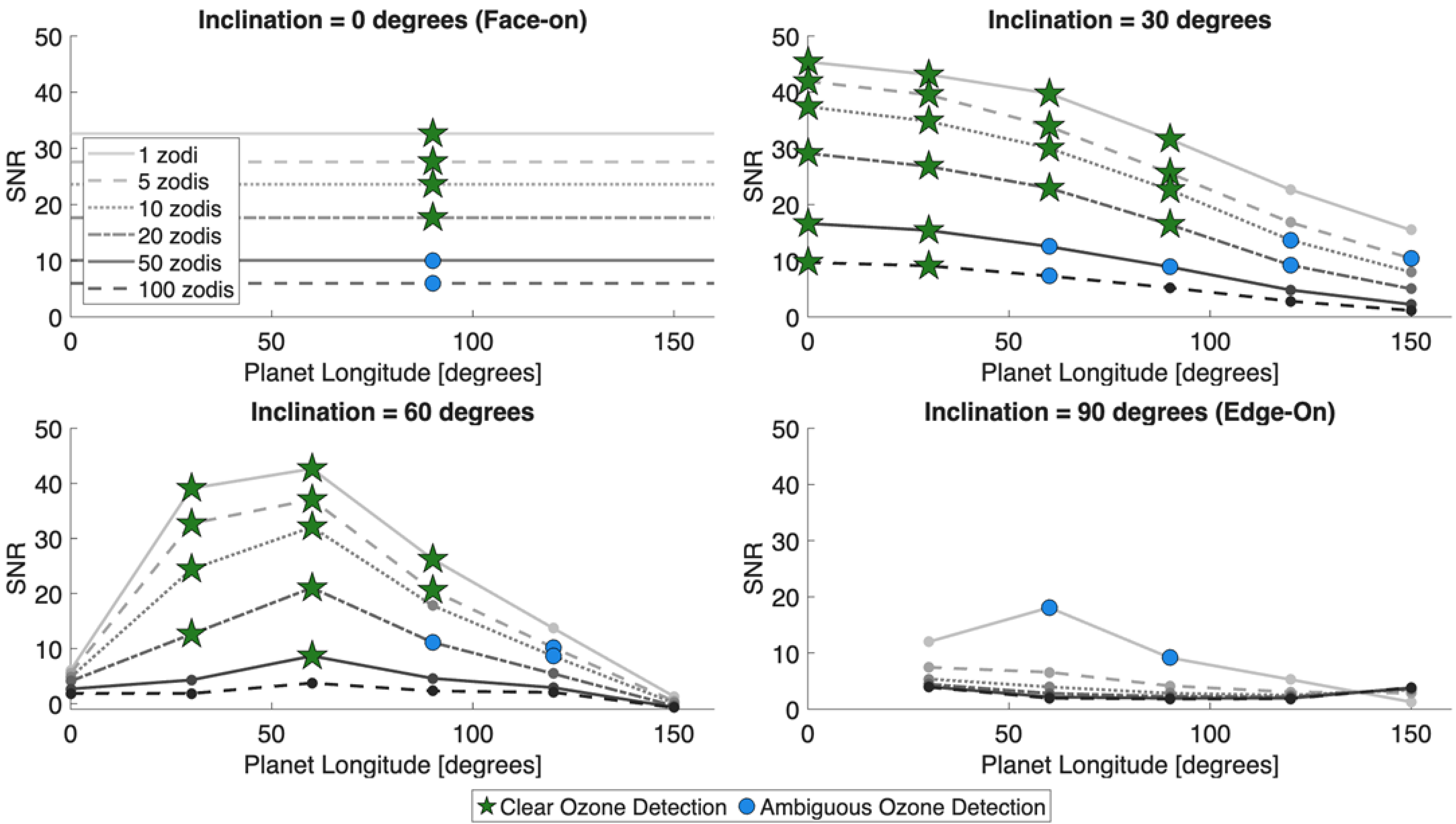
Stanford Space Rendezvous Laboratory



Face-On, Planet at Quadrature, 10 zodis



Retrieval Results (in progress): 3-day Integration

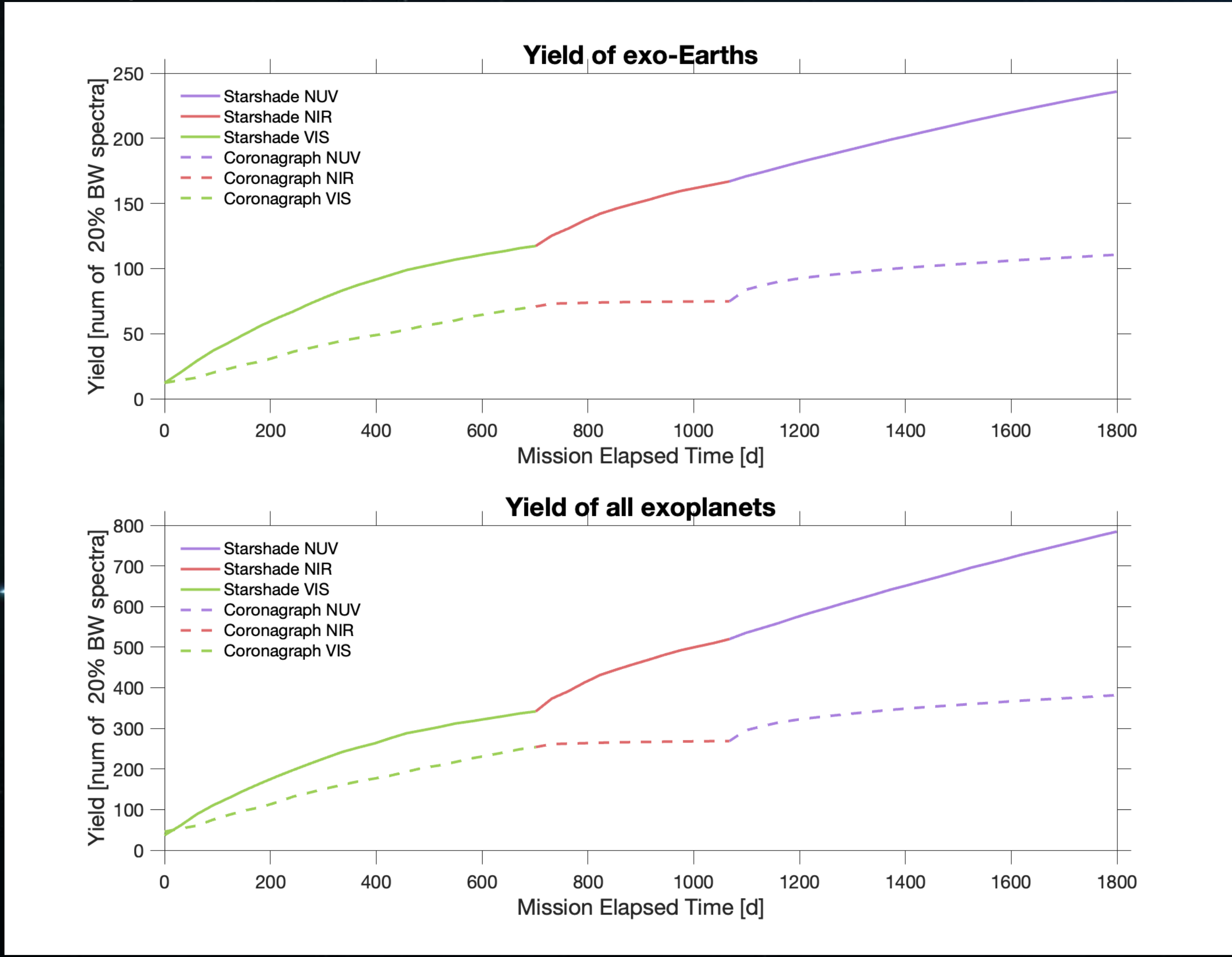


Goals 2 Progress: Yield

Number of Spectra Measured

Credit: Rhonda Morgan, JPL

- These charts show cumulative HWO Spectral yield in 5 years assuming:
  - planets are known (no search phase)
  - Two simultaneous Vis coro's (40% total bw, single NIR and single UV coronagraph, each 20% bw)
  - 35 m UV starshade, 60 m Vis/NIR starshade, 67% bw. No refueling.
  - Use < 50% of HWO on-sky time.
  - The usual ExoSIMS parameters for throughput, IWA, and contrast, including coronagraphs at IWA = 2.5 lambda/D.
- Starshade yield is higher because of:
  - Inst. Bandwidth, IWA, contrast and noise floor.
- Yield for all exoplanets is higher because of the above AND because of the starshade's large OWA (limited only by the detector size).
- To quote Rhonda, **the starshade is a "Spectral Hoover"**

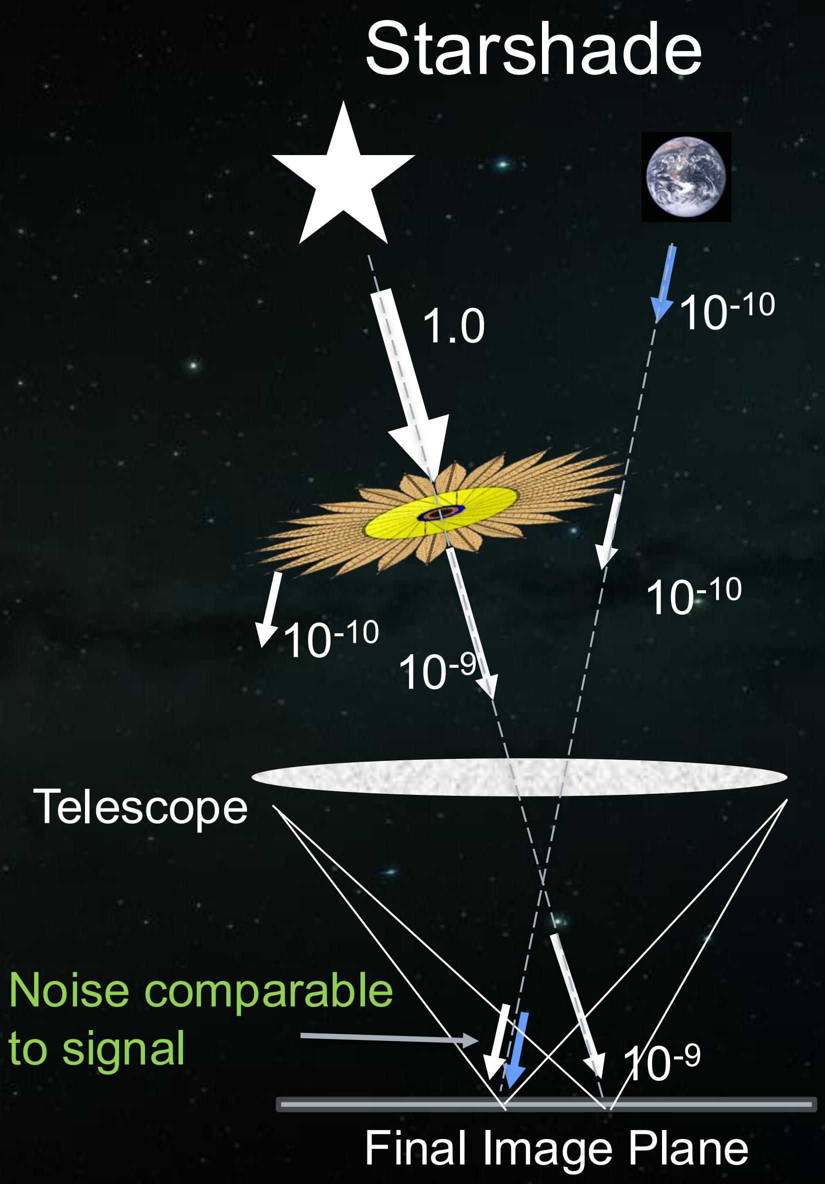


Conclusions

- Starshade technology has advanced to TRL-5 for a 26-35 m starshade. Some work to extend results to larger petals is needed for a 60 m starshade.
- With precursor knowledge of planet orbits, and without refueling, the starshade can make ~ 180 characterizations over 10 years.
- The Hartley-Huggins Ozone band can be retrieved with a "clear detection" in just 3 days of observation over a wide range of planet phases, exozodi levels, and system inclinations.
- A template matching simulation illustrates the importance of broad-band spectral characterization.
  - It shows the much more rapid characterization of a starshade compared to a coronagraph.
- The starshade is an efficient spectral machine!

Backup Slides

THE STARSHADE IS AN EFFICIENT FILTER

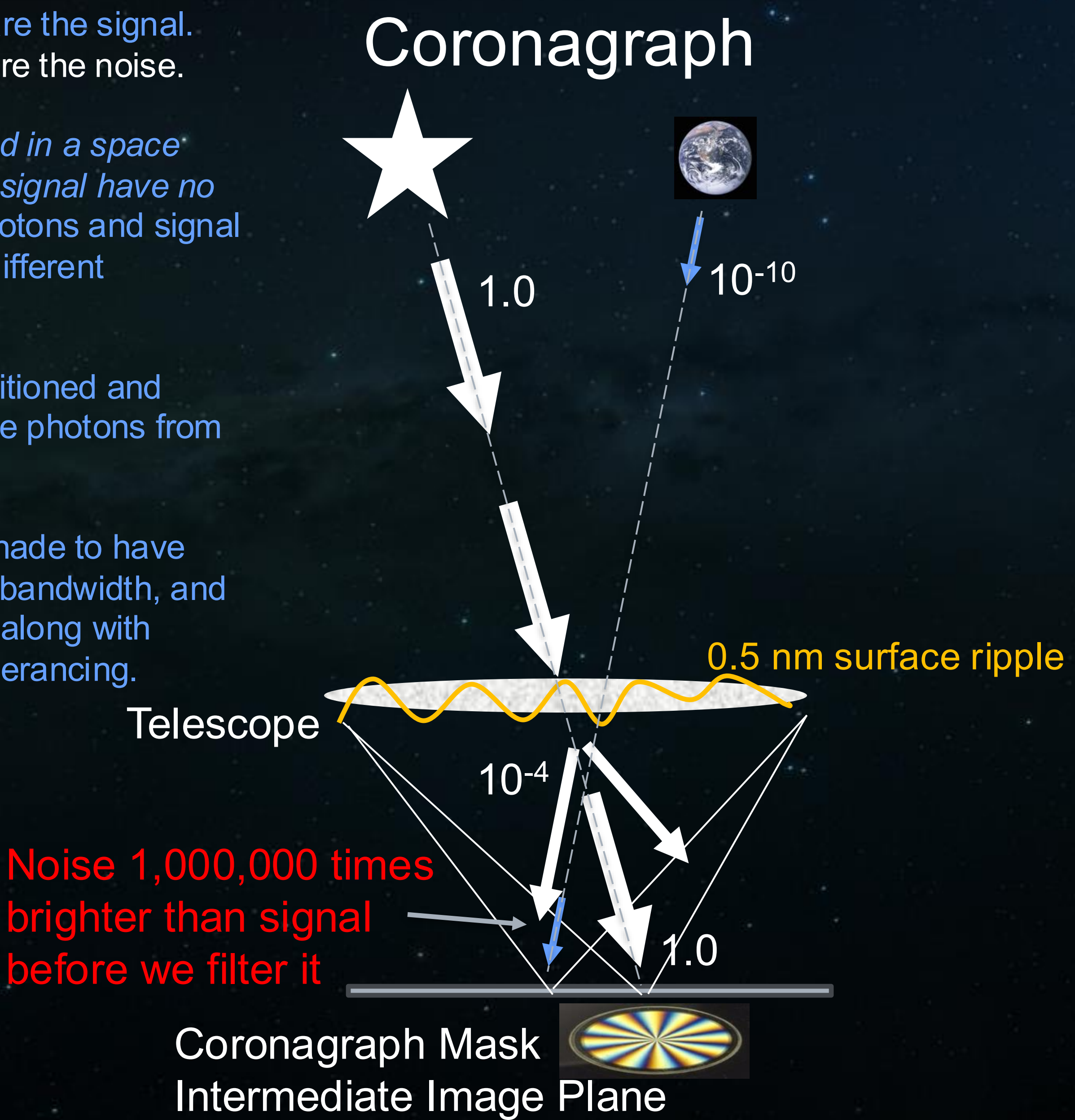


The planet photons are the signal.
The stellar photons are the noise.

The starshade is used in a space where the noise and signal have no overlap: the noise photons and signal photons come from different directions.

The starshade is positioned and sized to block only the photons from the star.

This allows the starshade to have high efficiency, large bandwidth, and small working angle, along with readily achievable tolerancing.

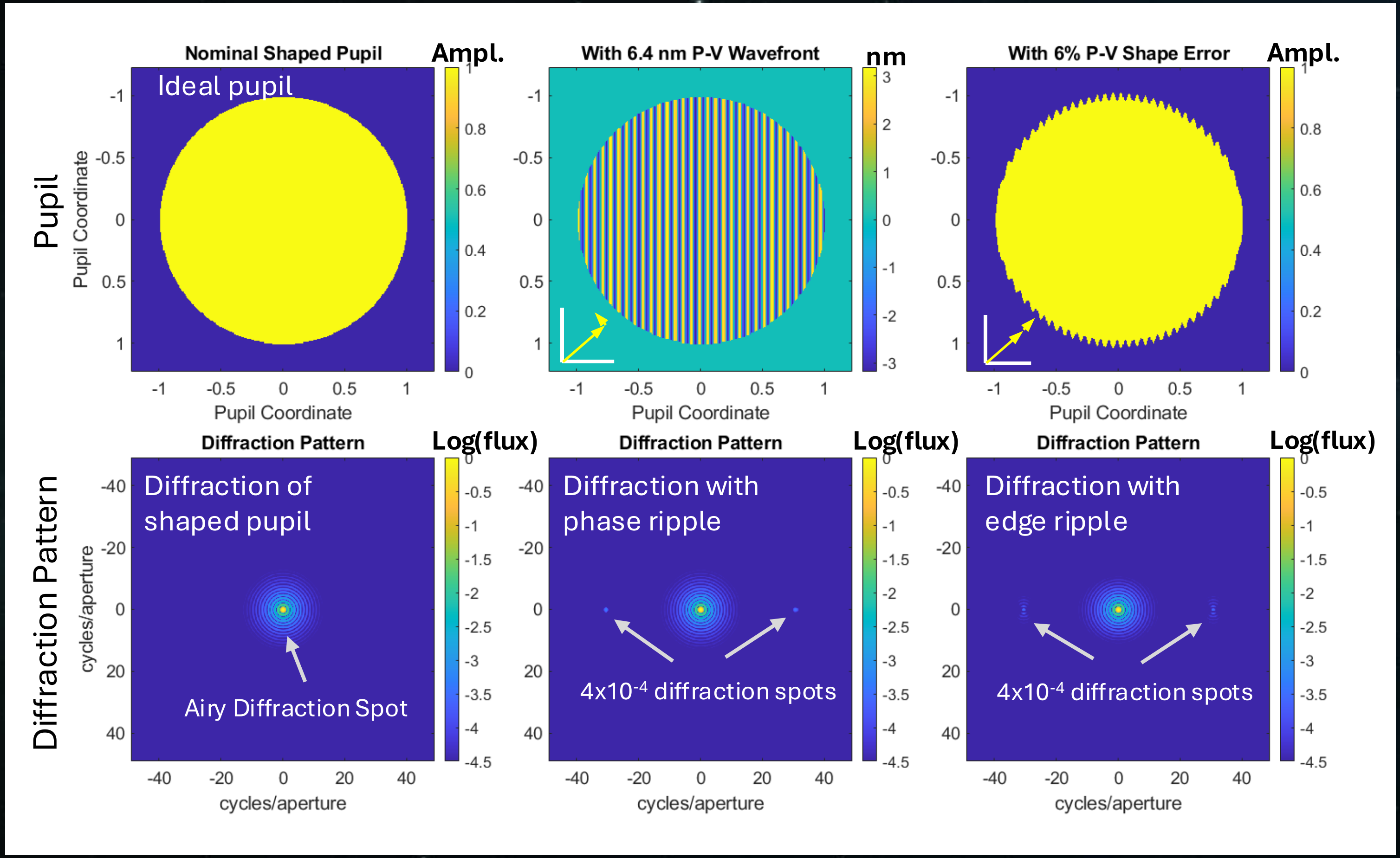


Shape Control is Easier than Wavefront Control

An example using a shaped-pupil coronagraph

Pupil

Diffraction Pattern (log scale)



Speckle Contrast:

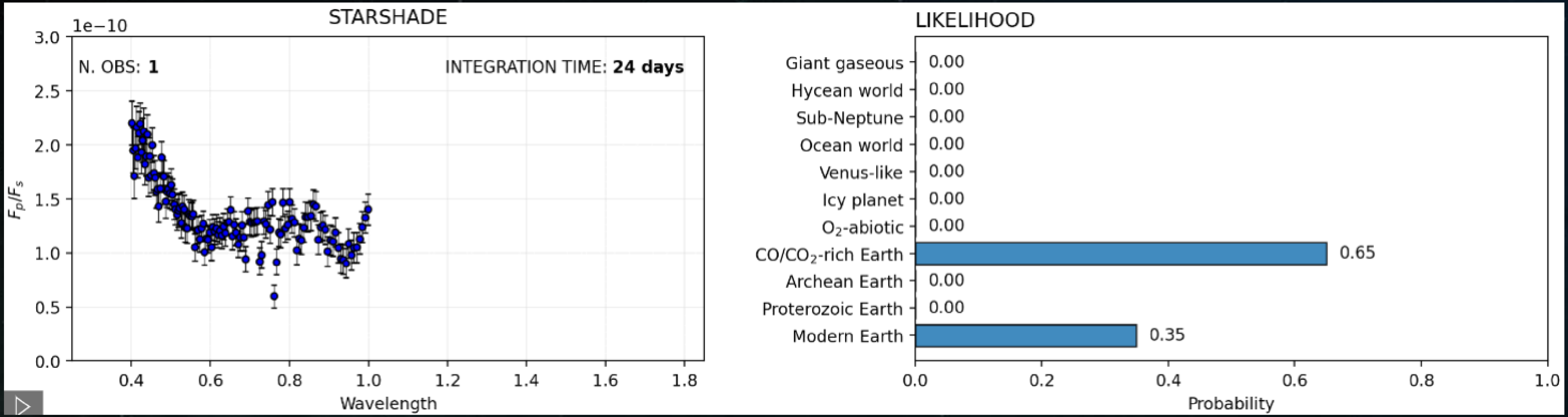
$$C = \frac{\sigma^2}{2}$$

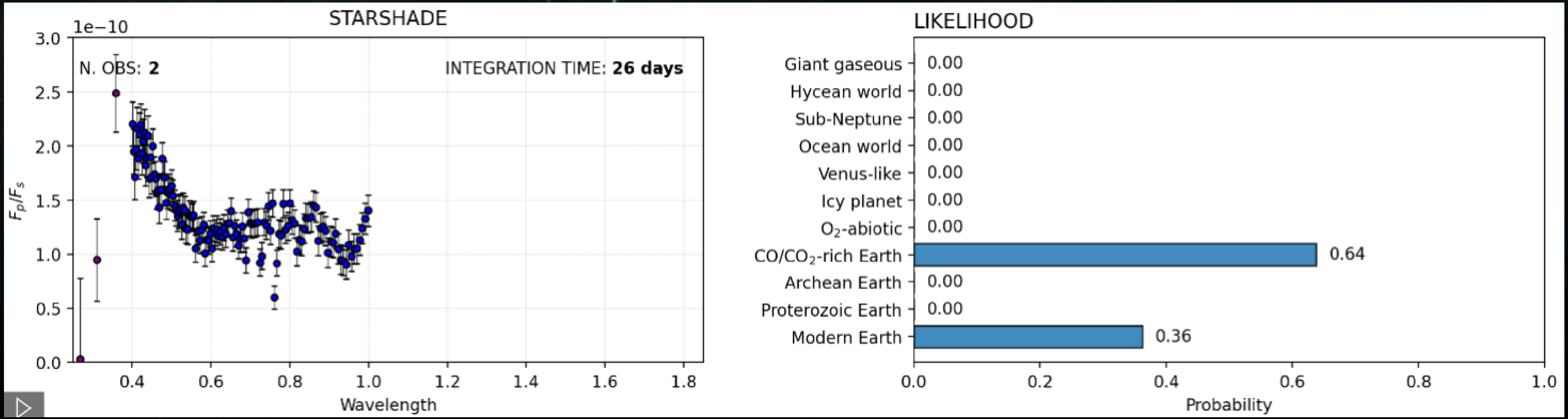
σ is std. dev of phase in radians or, std. dev of fractional shape error.

Diffraction control using a shape is highly robust to errors.
As shown above, a few nm of wavefront error is equivalent to a few % shape error.

For 10^{-10} contrast, 1 picometer of telescope wavefront is equivalent to 0.5 mm of starshade shape error.

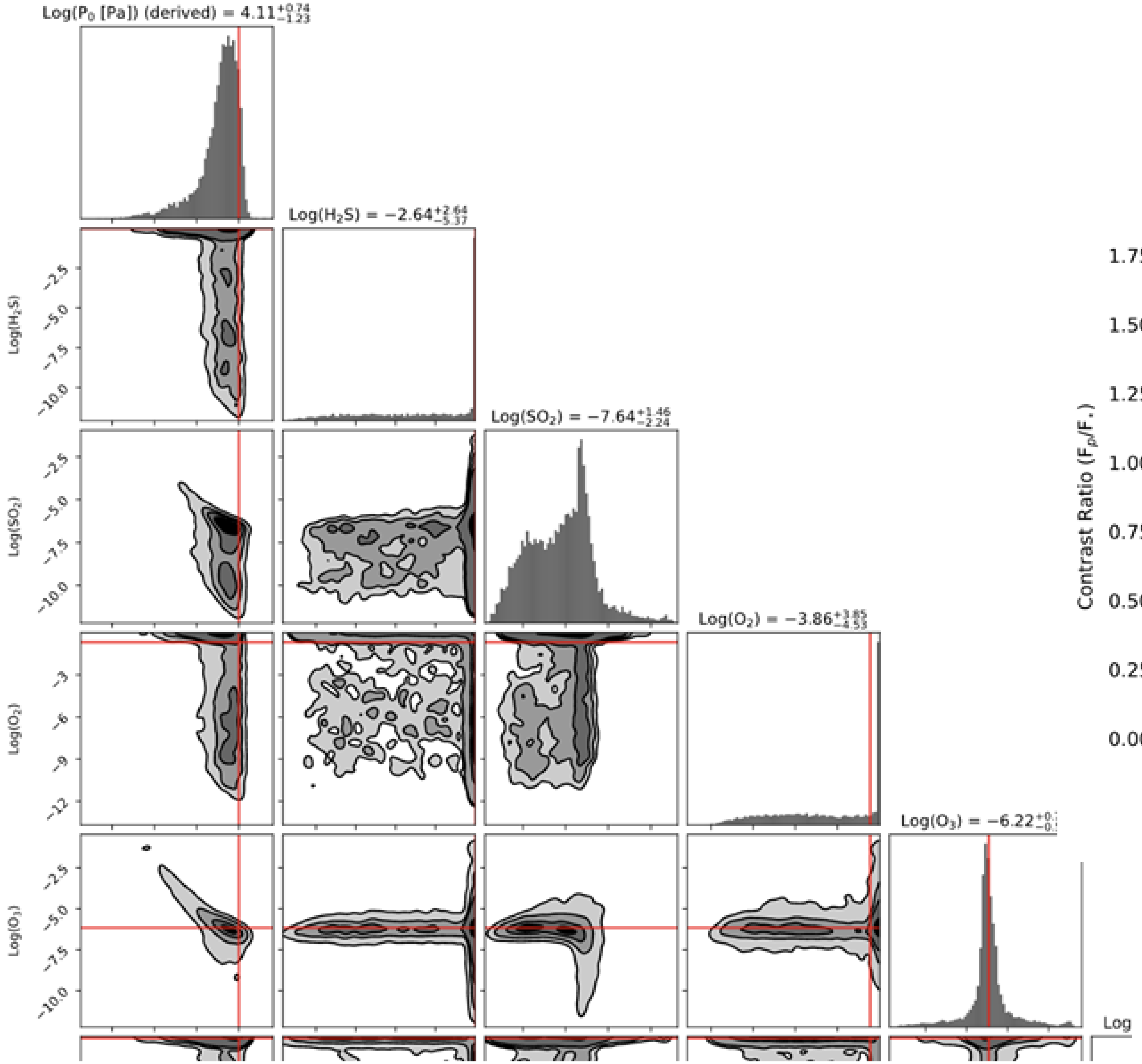
LIKELIHOOD FUNCTION WITH AND WITHOUT UV OBSERVATION: STARSHADE



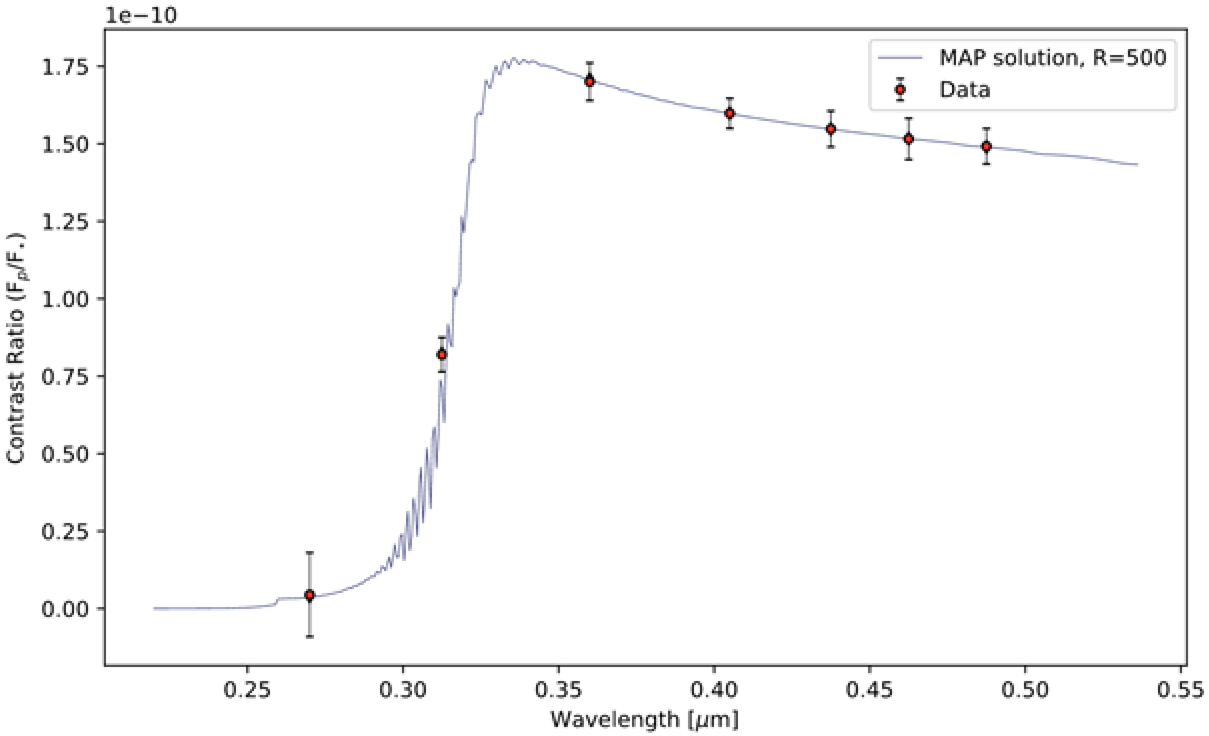


Retrieval Results - Ambiguous Detection

Stanford Space Rendezvous Laboratory



60deg inc, Planet at Quadrature, 50 zodis



Bayes Factor Analysis

- Determining ozone detection significance via Bayes Factor analysis
- 4 retrievals:

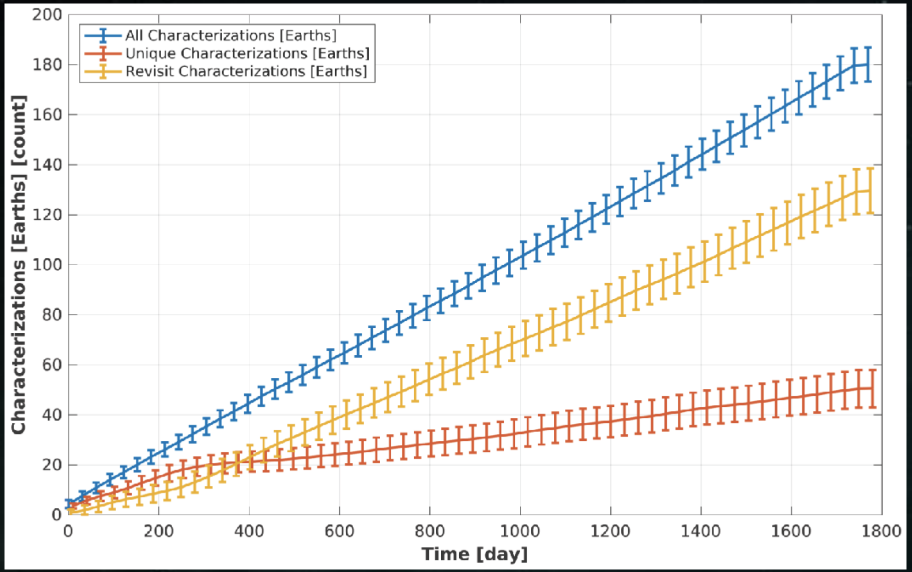
Case	SO_2	H_2S	N_2	O_2	O_3
Baseline	X	X	X	X	X
No O3	X	X	X	X	
No SO2		X	X	X	X
No O3 or SO2		X	X	X	

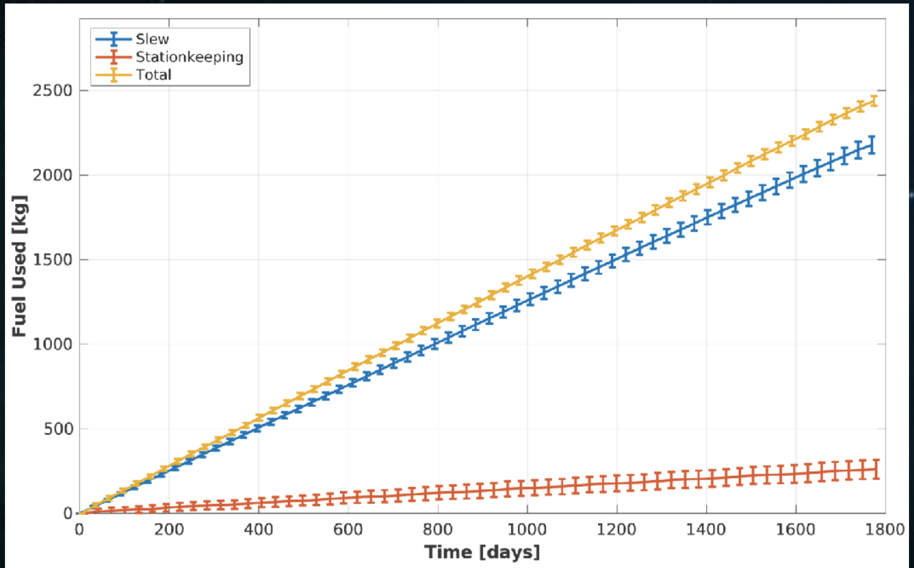
- Calculate 3 Bayes Factors by comparing the baseline model to the other three models:
  - BF_noO3
  - BF_noSO2
  - BF_noO3_SO2
- Use Kass-Rafferty scale to define clear detection or not (BF > 3)
- Clear Detection: BF_noO3 > 3 && BF_noSO2 < 3
- Ambiguous Detection: BF_noO3 < 3 && BF_noO3_SO2 > 3
- Nondetection: BF_noO3 < 3 && BF_noO3_SO2 < 3

Goals 2 Progress: Yield

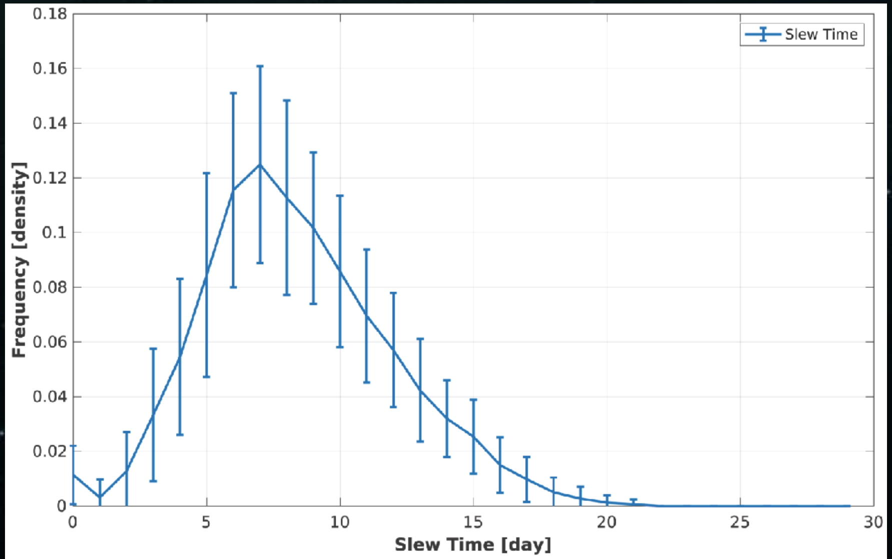
NUMBER OF TARGETS, FUEL USED, SLEW TIME FOR 35 M STARSHADE

Credit: Mario Damiano and Rhonda Morgan, JPL





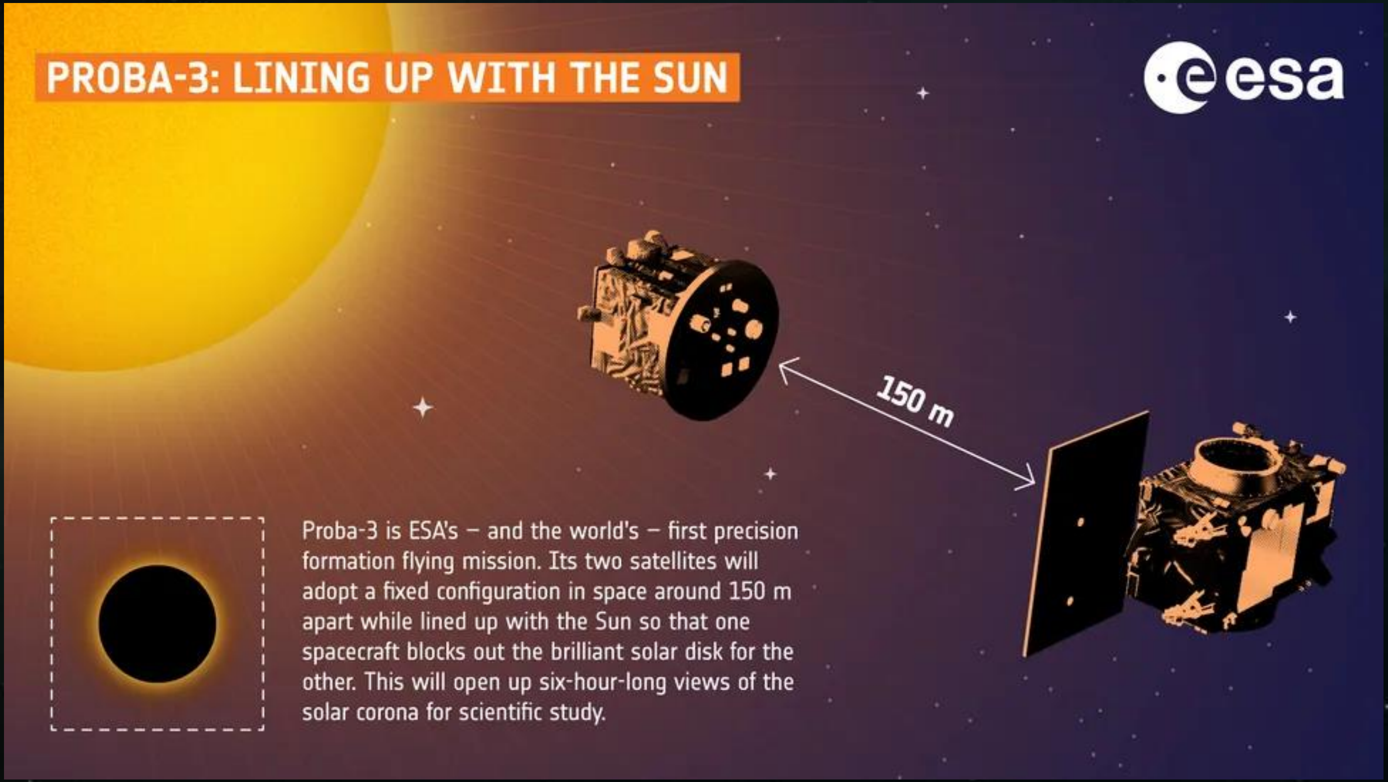
- Improvement over results reported last year by optimizing fuel tank size and fractional slew time. These results do not include refueling.
- With a total of 2500 kg of fuel, we get 35 unique and 130 revisit characterizations in 5 years.
- Assumes:
  - AEPS Hall Thrusters
  - Slewing: Total thrust 600 mN, Isp = 2900 s
  - Station keeping: Aerojet HiPAT biprop, thrust 445 N, Isp = 329 s



PROBA-3: An External Occulter on Orbit

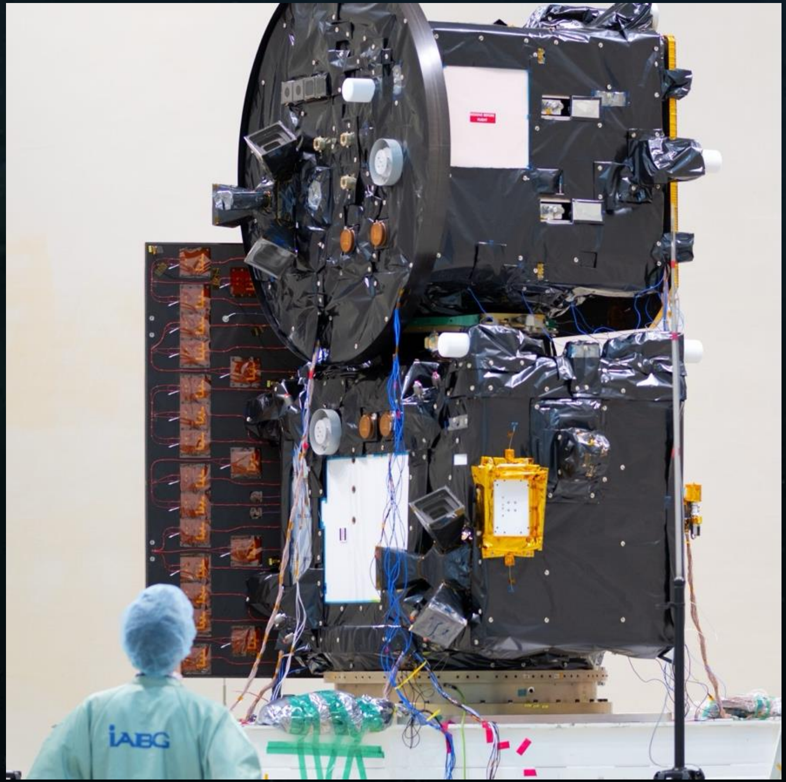
PROBA = PRoject for On Board Autonomy

Developed by ESA, launched by Indian Space Agency, December 2024. 20 hour highly-elliptical orbit. Autonomous formation flying to 1 mm over a distance of 150 m, for up to 6 hours of each orbit.



Configuration Overview

Image credit: ESA – F. Zonno



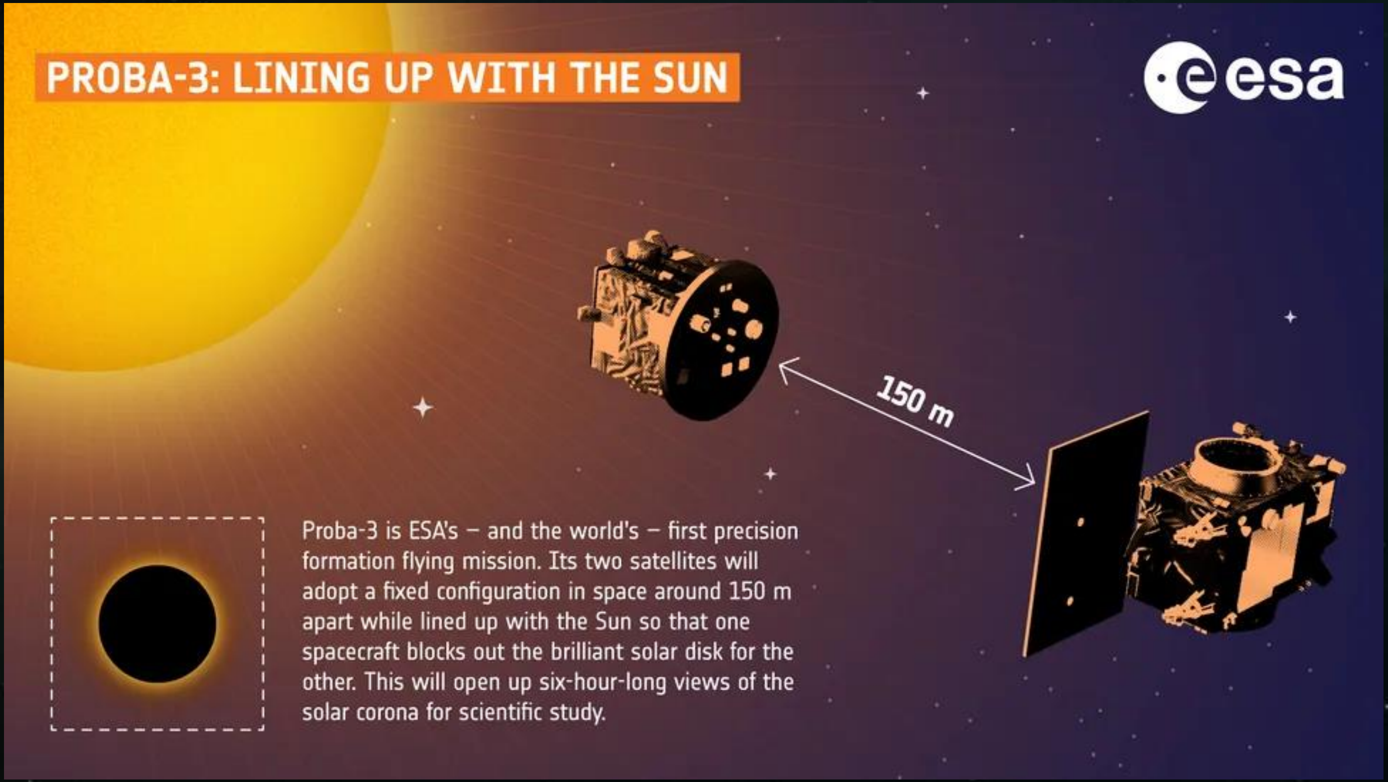
The two spacecraft stacked in launch configuration.

Image credit: https://www.group.sener/en/project/proba-3-formation-flying-mission/

PROBA-3: An External Occulter on Orbit

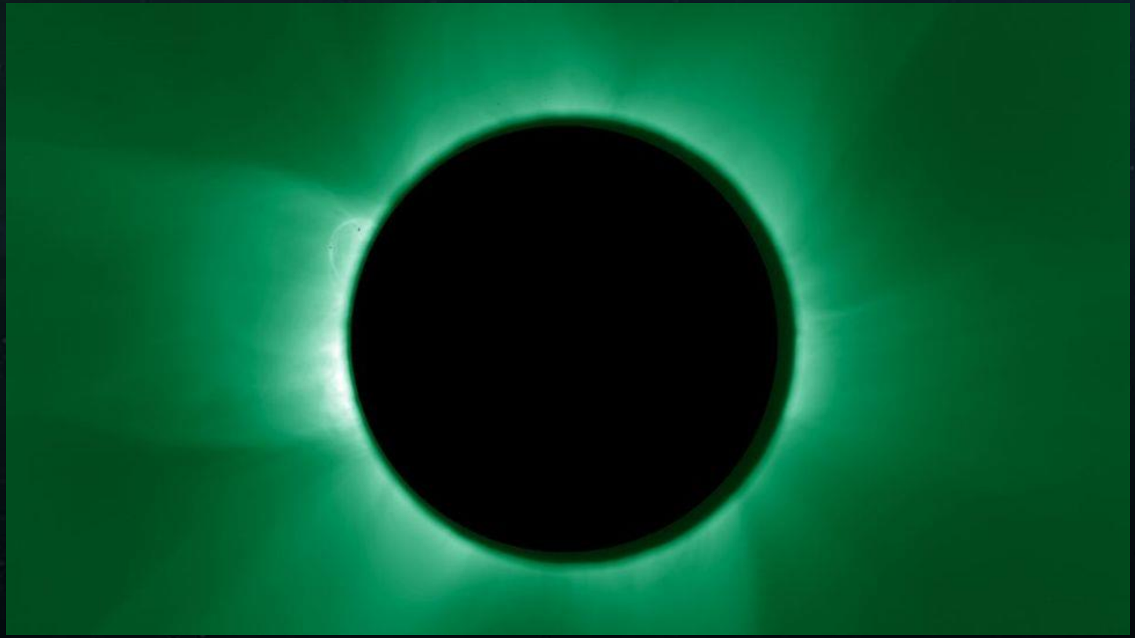
PROBA = PRoject for On Board Autonomy

Developed by ESA, launched by Indian Space Agency, December 2024. 20 hour highly-elliptical orbit. Autonomous formation flying to 1 mm over a distance of 150 m, for up to 6 hours of each orbit.



Configuration Overview

Image credit: ESA – F. Zonno



The coronal green line — the hottest part of the sun's inner corona — and a loop following a solar flare, in an image taken on May 23, 2025, by the ASPIICS coronagraph aboard Proba-3. (Space.com, Image credit: ESA/Proba-3/ASPIICS)