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 31

Jan 11, 2025

National Harbor, MD

Government Sponsorship Acknowledged. CL#25-0164

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)

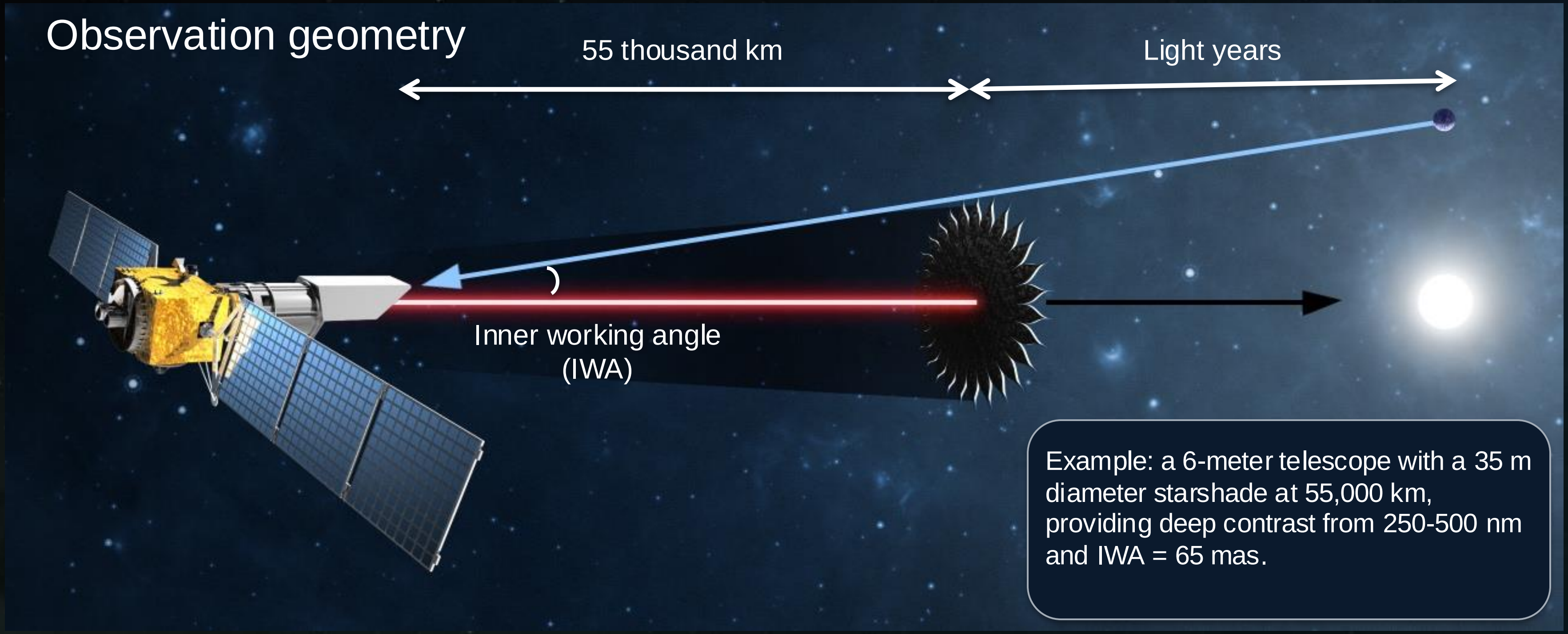
Participants

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

YOUR NAME HERE

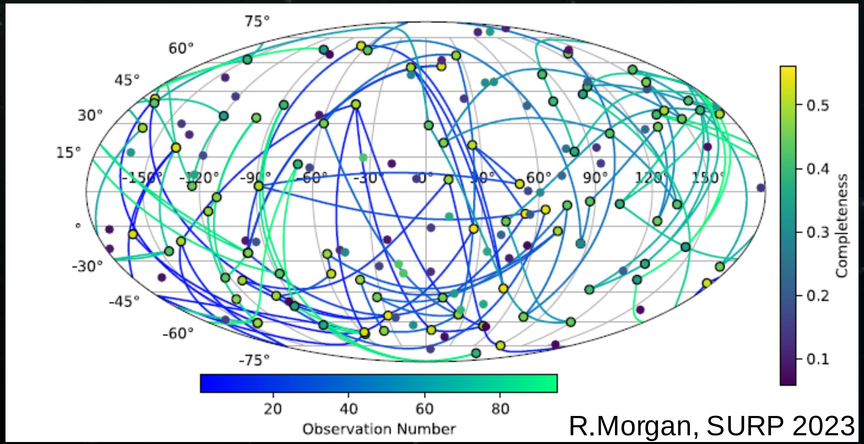
STARSHADE 101



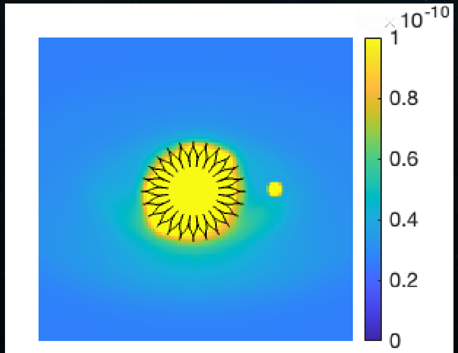
Starshades attributes:

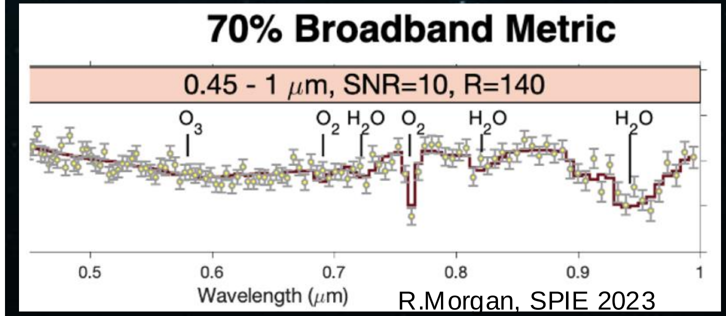
- 100% throughput
- Wide bandwidth
- Deep Contrast
- Excellent in the UV
- Small Inner Working Angle
- Standard Machine Tolerances
- Work with any telescope, e.g. on- or off-axis, segmented or monolithic

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



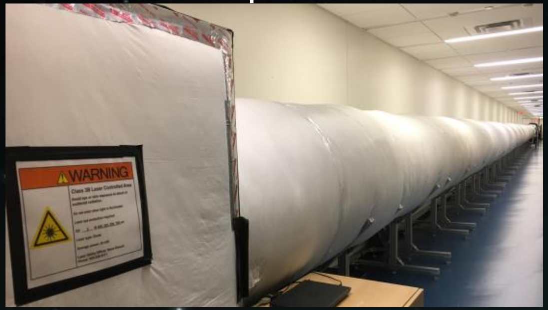
Science products are direct images and spectra





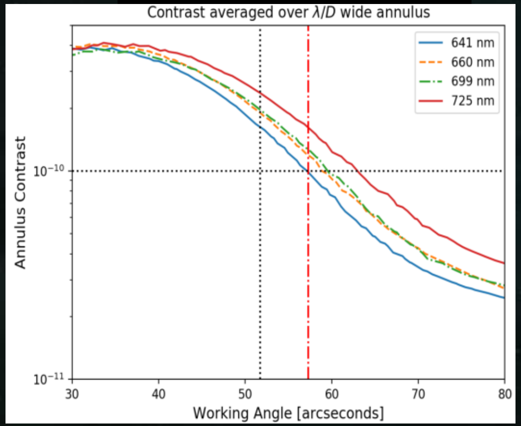
STARSHADE TECHNOLOGY

Princeton optical testbed

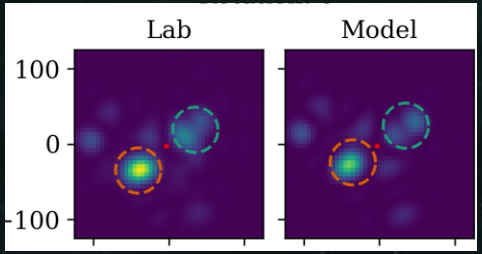


Precision mask

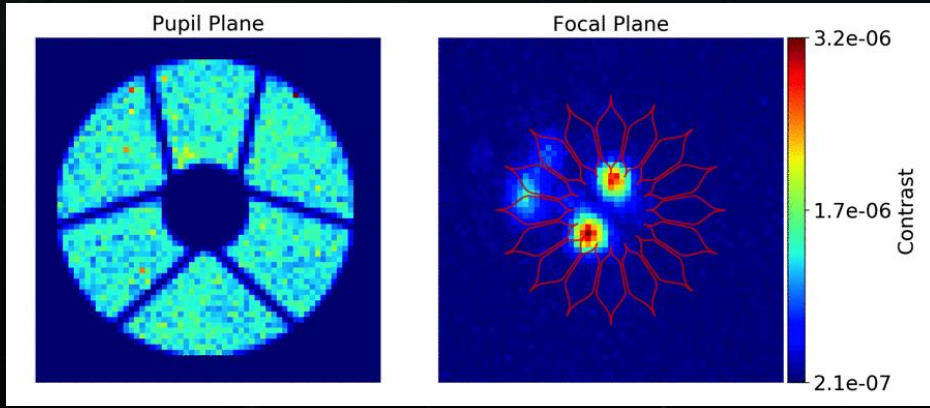
10^-10 contrast



Model Validation

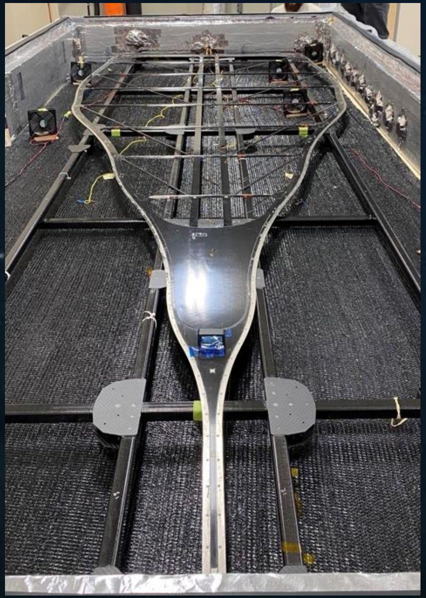


Hardware in the loop formation sensing and control



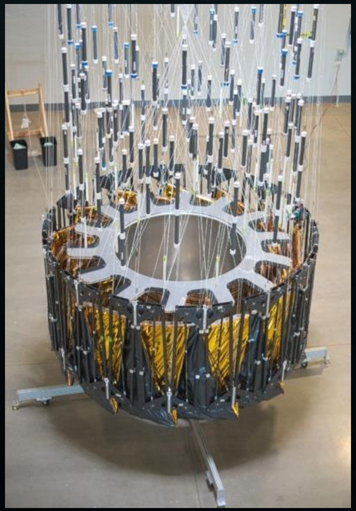
10 m disk with petals

Half-scale precision petal

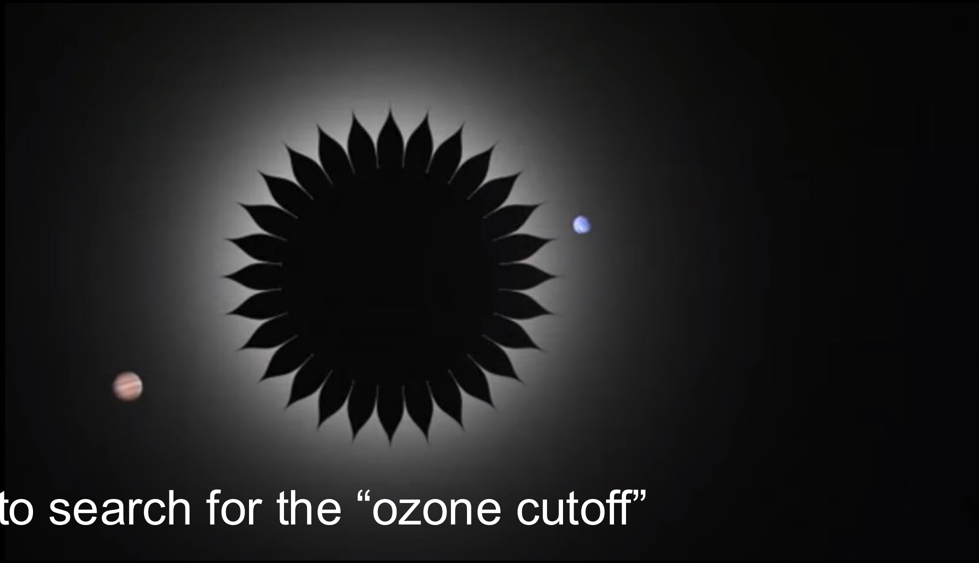


Demonstrated deep contrast, formation sensing and control, stowage, deployment, accurate petals, thermal stability

Stowed and partially deployed 10 m disk with optical shield



SAG 24 GOALS



1. 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. 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. 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.

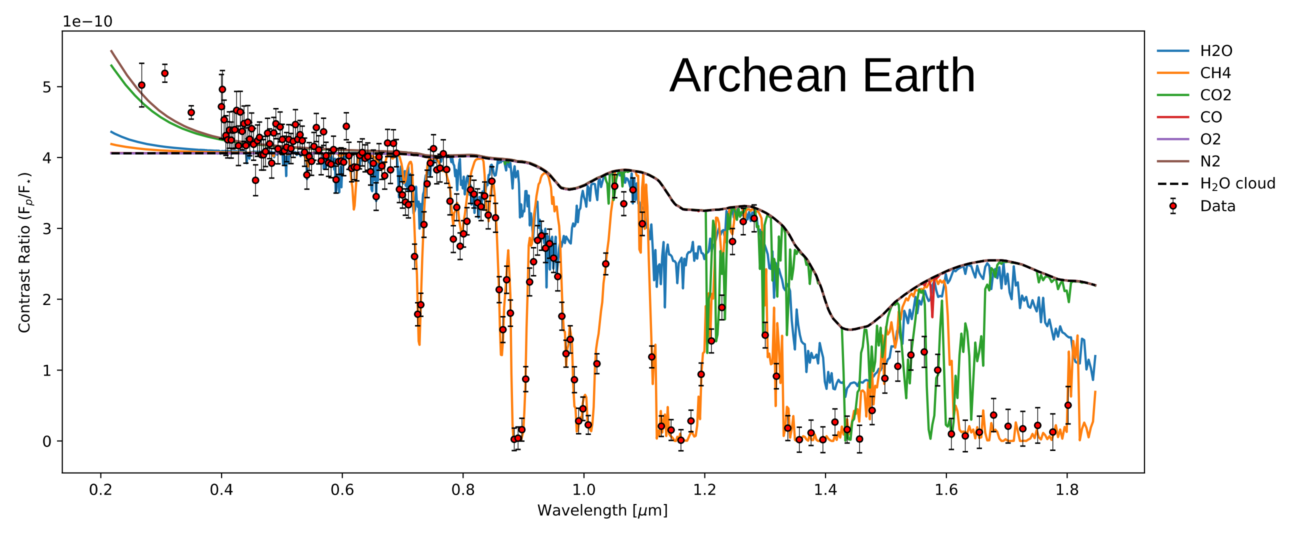
4. Simulate end-to-end Starshade images including exozodi, and perform atmospheric spectral retrieval on the simulated images, to support Goal 3.

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

Panchromatic Spectral Coverage Is Essential

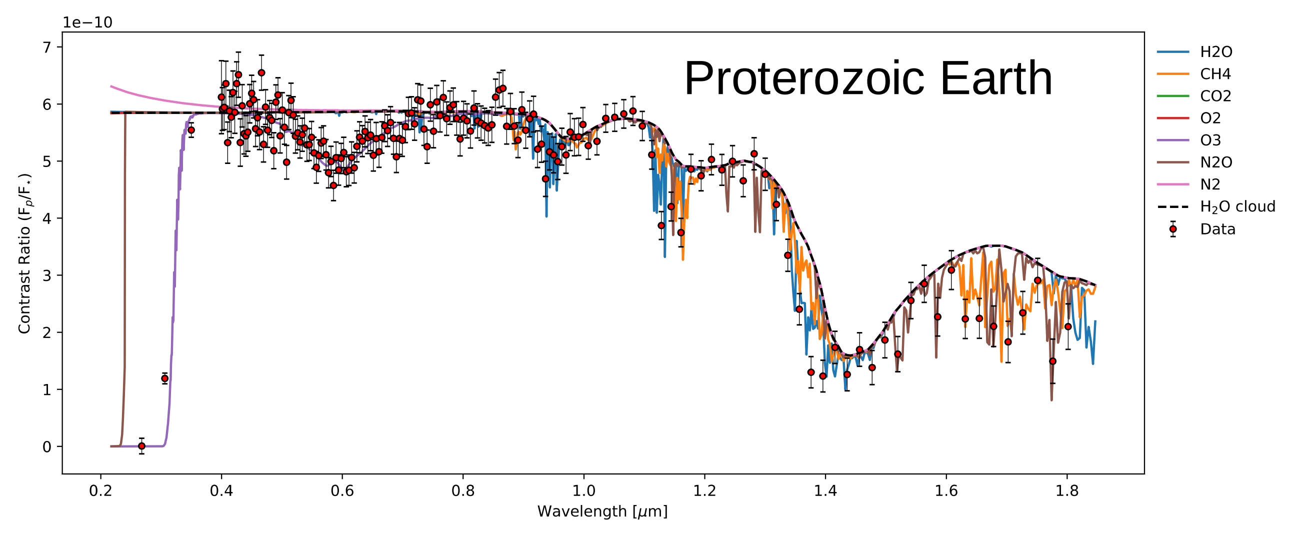
Archean Earth (Feng et al. 2018; Damiano & Hu 2022; Hall et al. 2023)

- Many strong features, but multiple bands are required to distinguish molecules



Proterozoic Earth (Damiano et al. 2023; Tokadjian et al. 2024)

- Weaker features in the visible
- Deep, easily detectable O_3 features



- Need multiple features for each molecule.
- Biosignature gases must be measured in the context of other gasses, e.g. want CH_4 and O_2 (O_3 proxy) together.
- O_3 is an important, easily detectable discriminator.

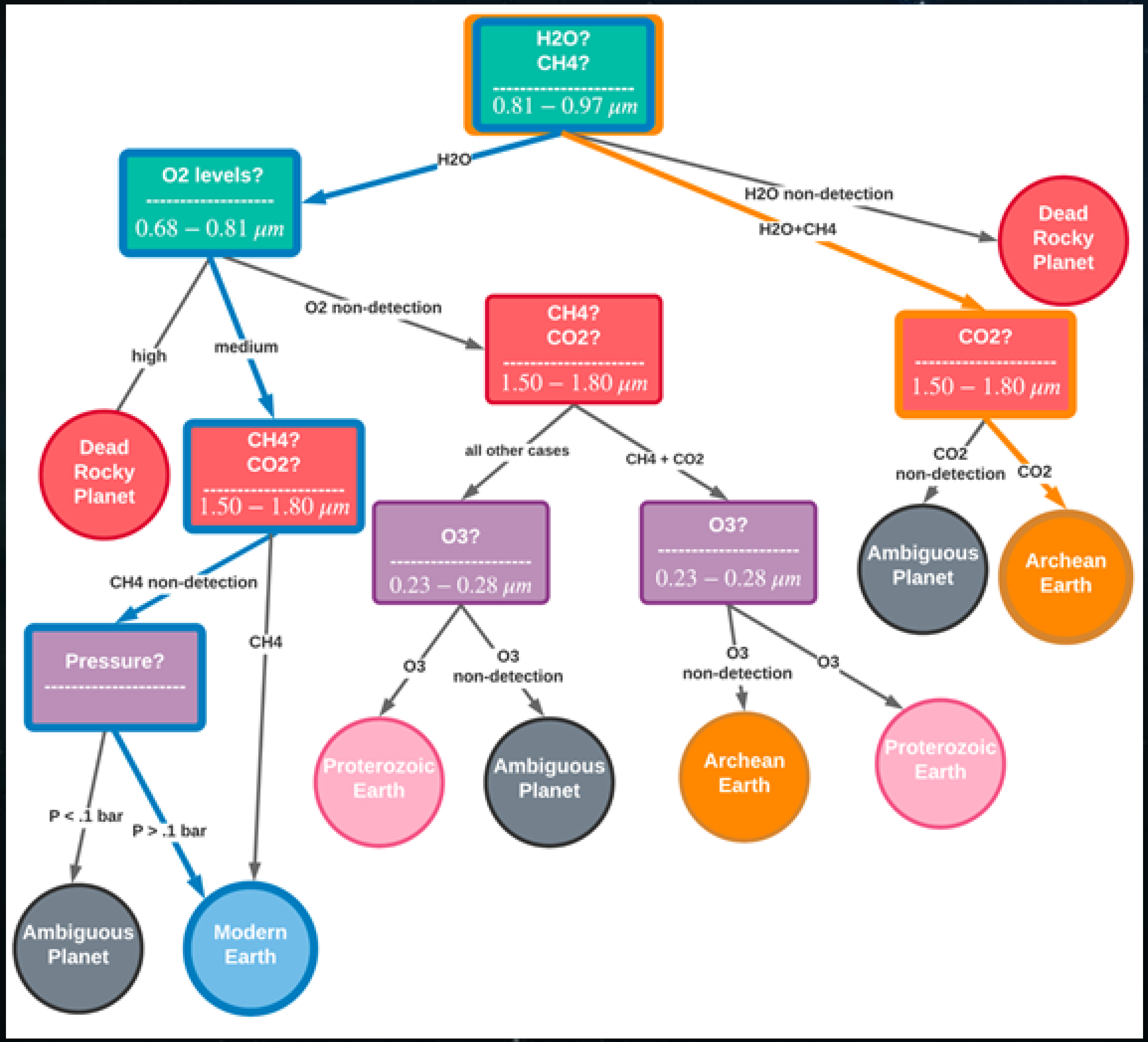
Goals 1 and 3 Progress: Low-res UV and Complementary Role

Multiple Bands from UV to NIR Are Necessary to Distinguish Planets

This decision tree highlights the measurements that distinguish Archean, Proterozoic, and Modern Earths.

Ozone is employed only after O_2 non-detection.

It would be interesting to reformulate the chart with O_3 at the top. Immediately determine if O_2 is present via O_3, which can be done quickly.

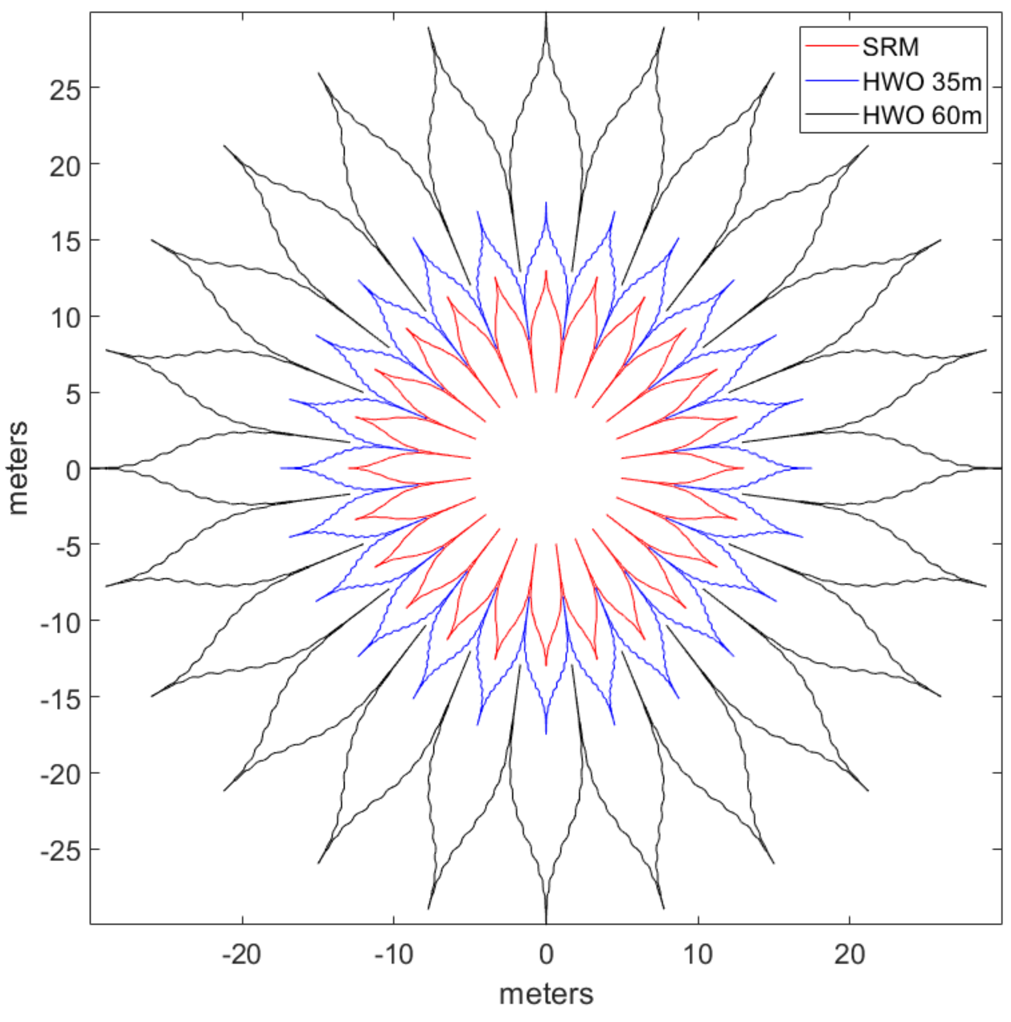


Young et al. PSJ 5:7, 2024

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).

Investigate the ability to characterize Earth-like exoplanets using an HWO starshade in the ultraviolet

Investigations:

- What SNRs can we achieve for starshade observations of an Earth-twin in the UV?
- 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:

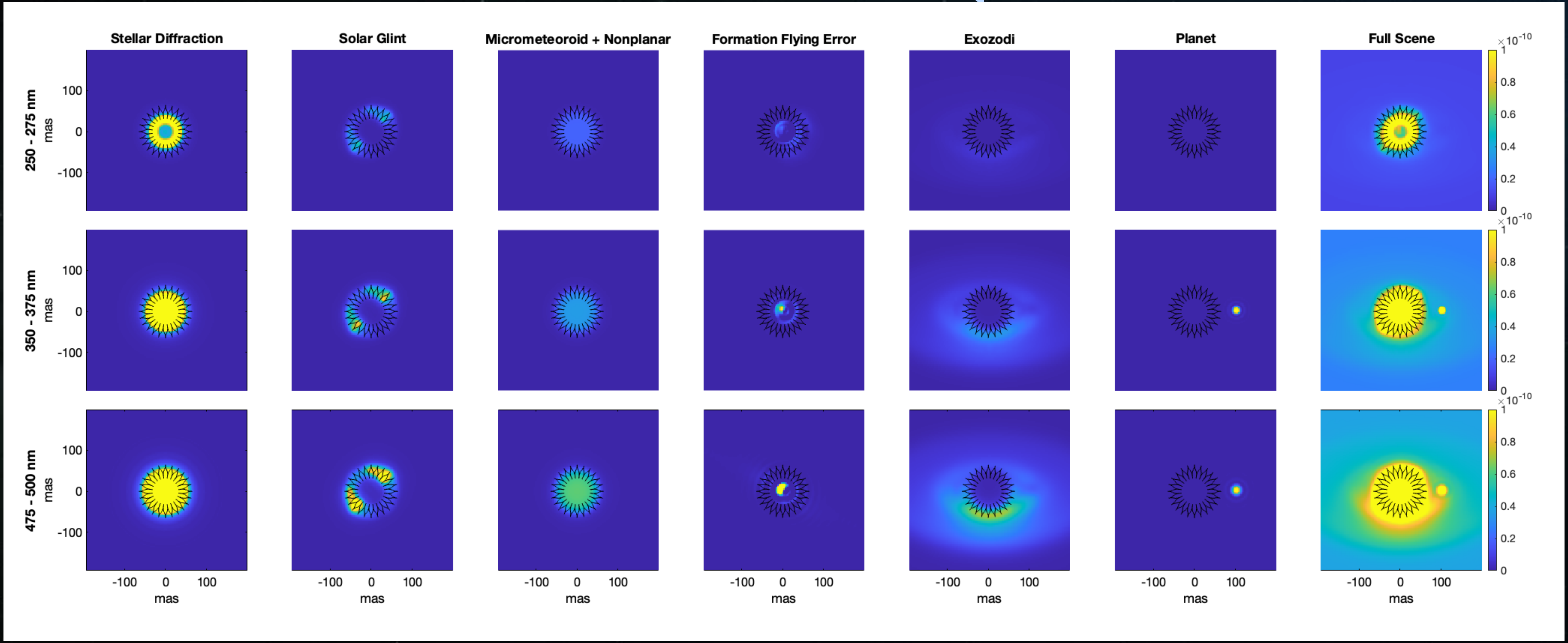
- Imperfect starshade, solar glint on edges and petal faces, micrometeoroid leakage, formation flying

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).

Simulated Scene with 35 m starshade

3 of 10 bands shown with an Exo-earth at quadrature and incl = 60º

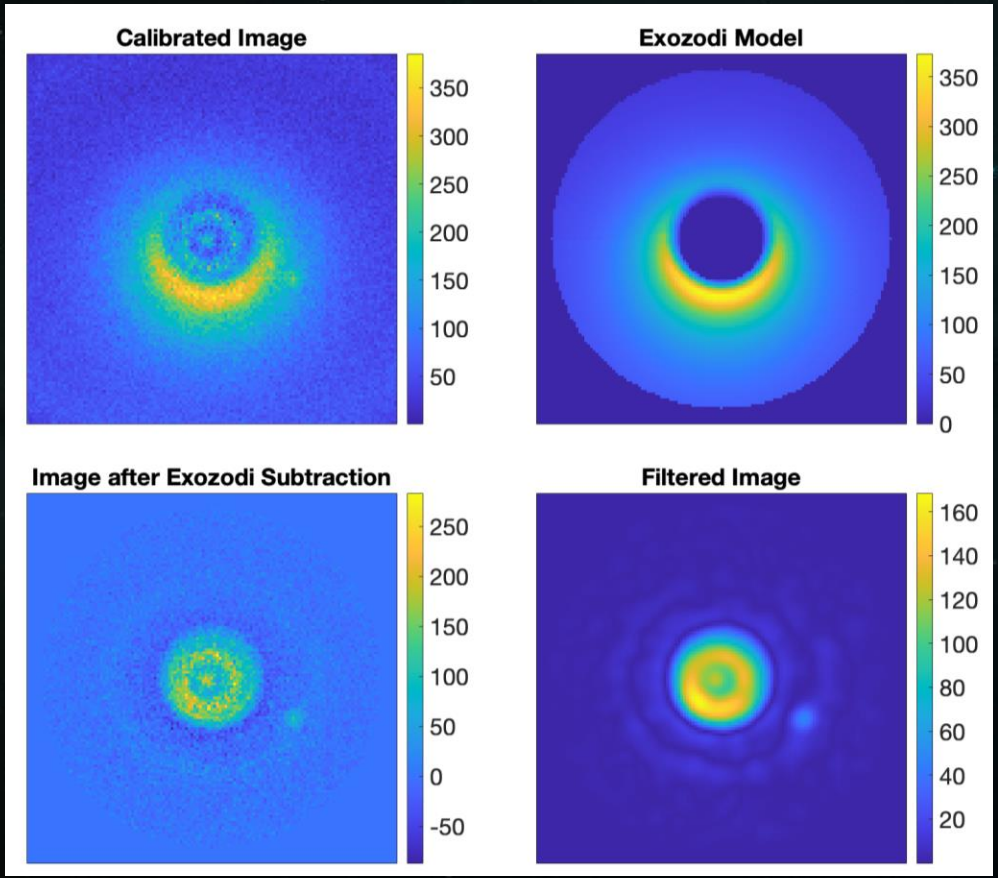


Realistic simulations show that the HWO 35 m will enable deep, accurate, NUV characterization of exo-earths. SNR will be limited by the Exozodi, not instrument systematics.

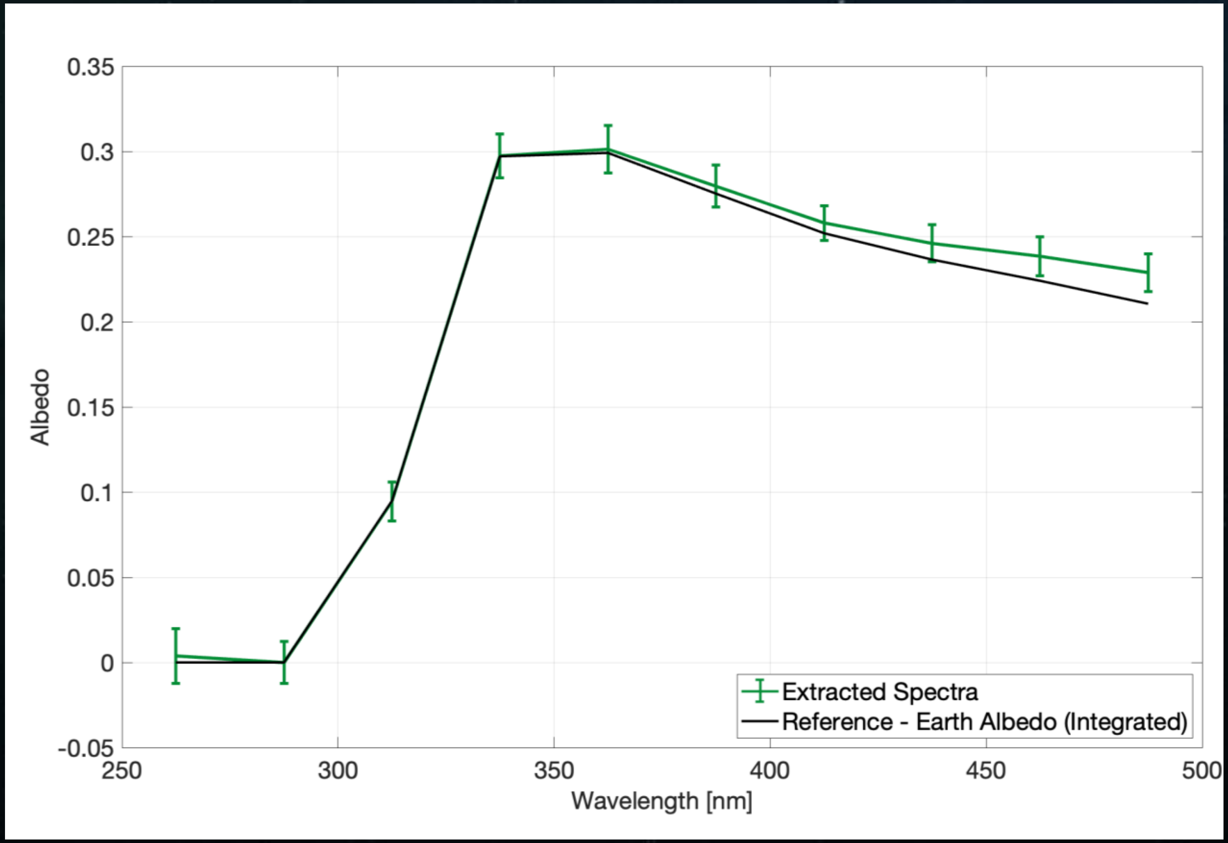
EXAMPLE: POST-PROCESSED SPECTRUM

- Inclined **30** degrees, 10 zodis, 3-day integration, planet at 120 degrees

475– 500 nm



Extracted Spectrum

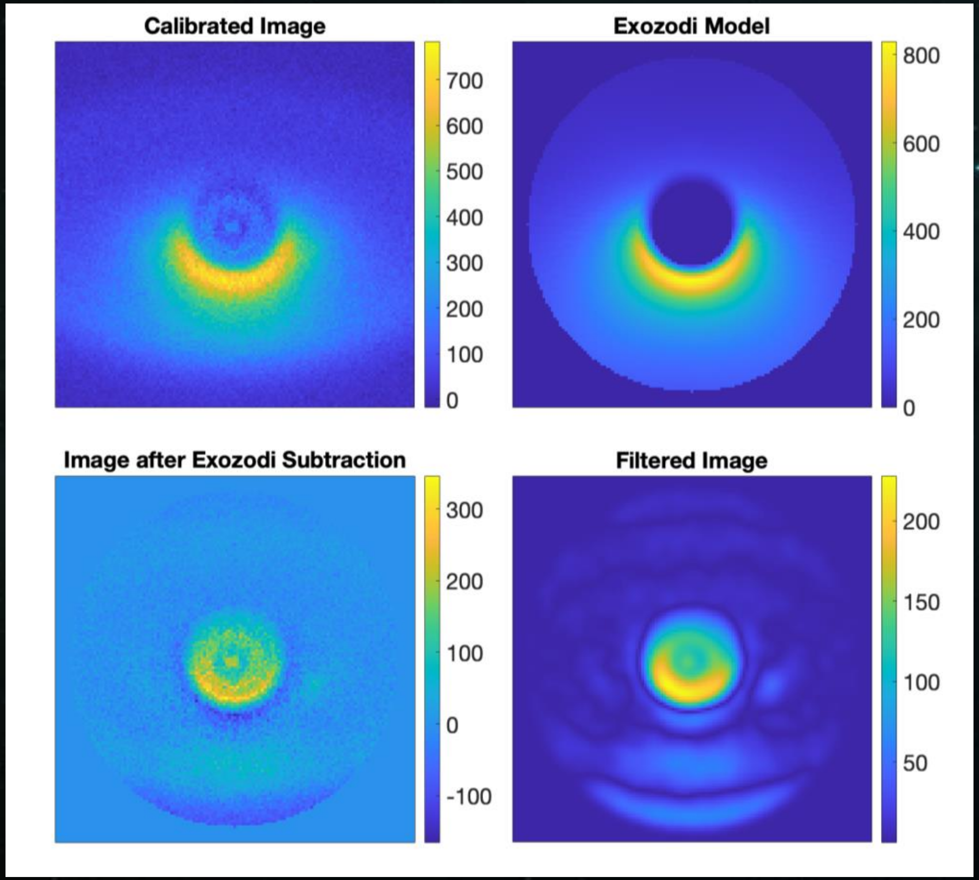


Using a simple post-processing pipeline, we are able to recover the planet signal in the presence of starshade systematics and resonant exozodi structures.

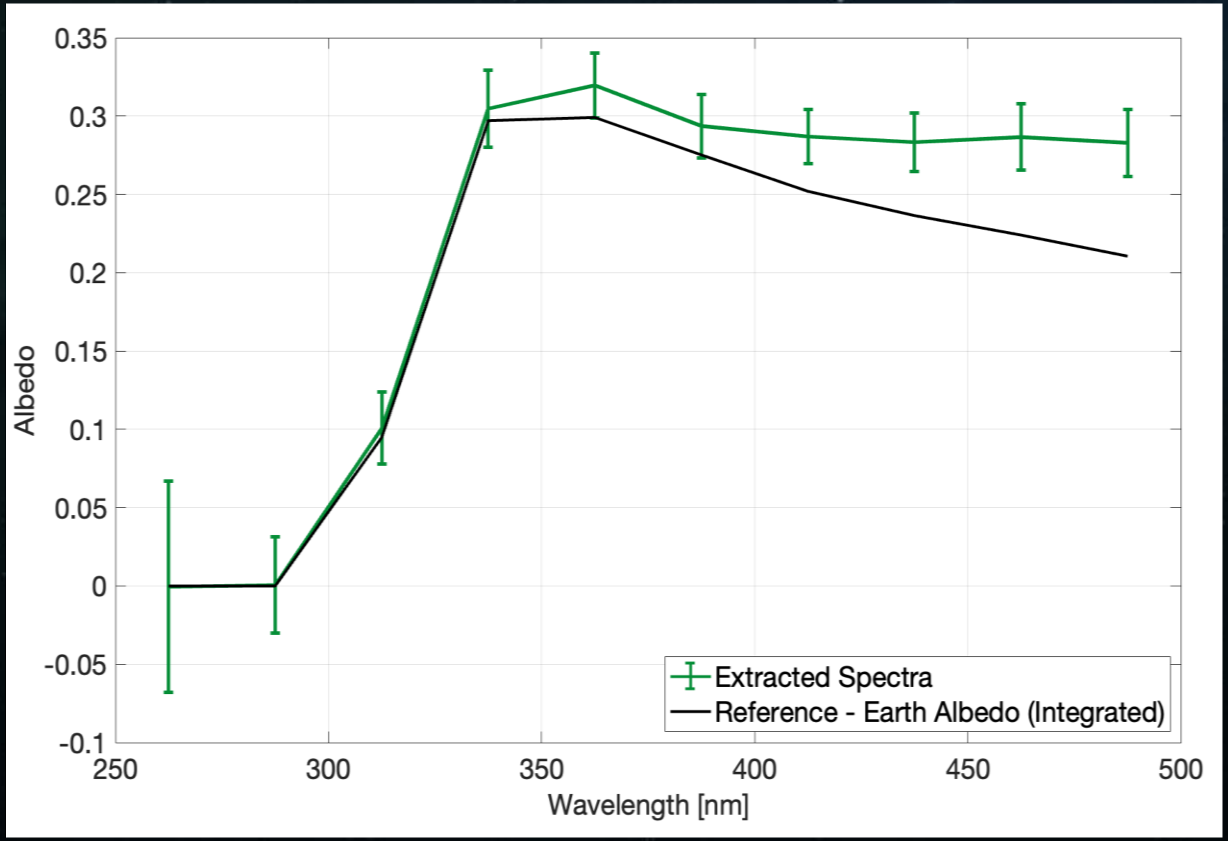
Example: Post-processed Spectrum

- Inclined **60** degrees, 10 zodis, 3-day integration, planet at 120 degrees

475– 500 nm



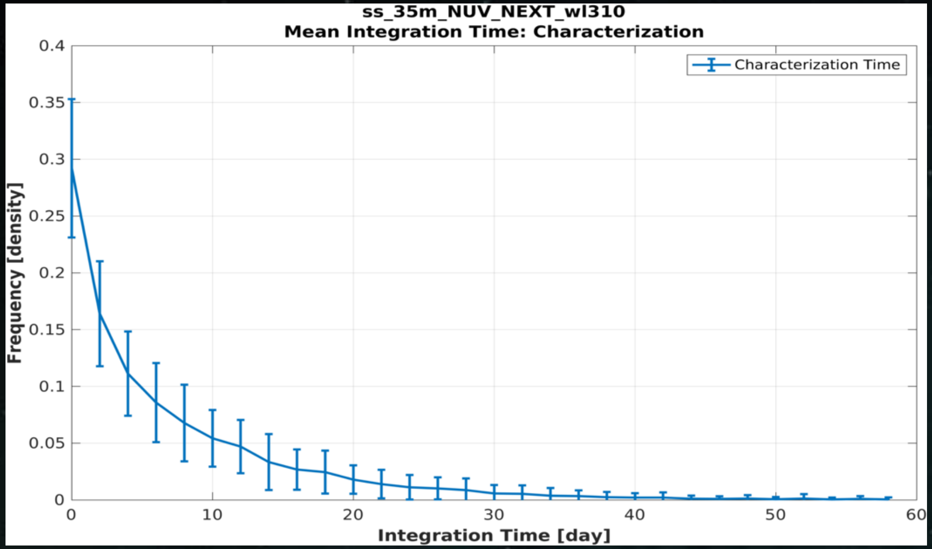
Extracted Spectrum

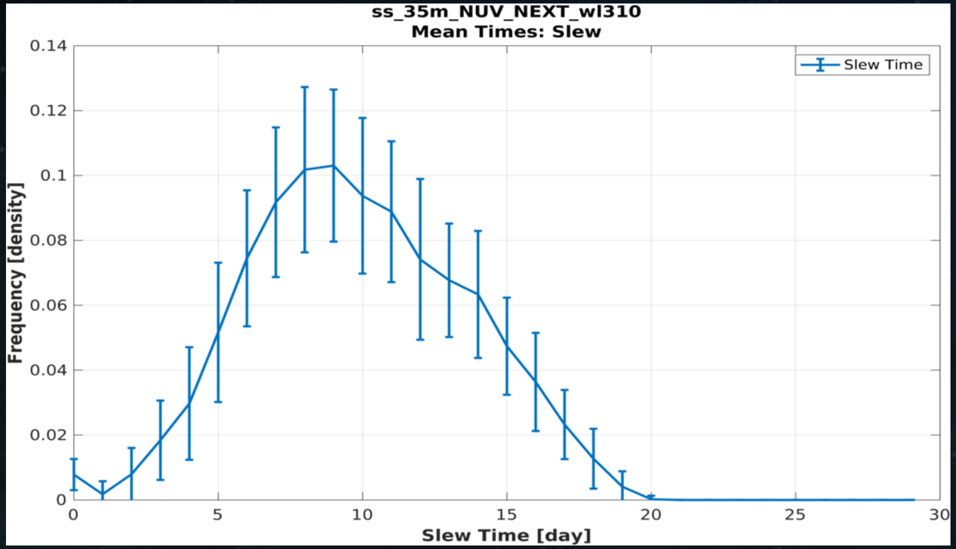


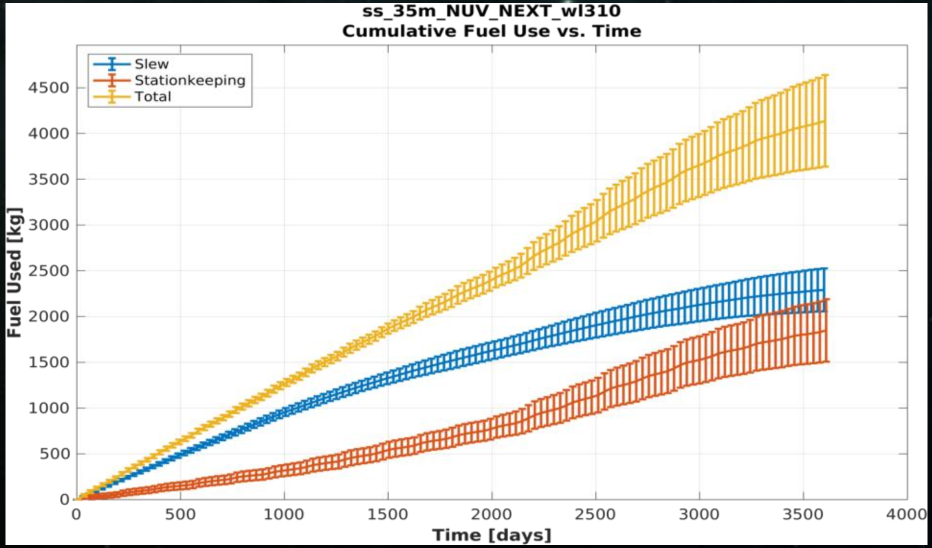
Using a simple post-processing pipeline, we are able to recover the planet signal in the presence of starshade systematics and resonant exozodi structures.

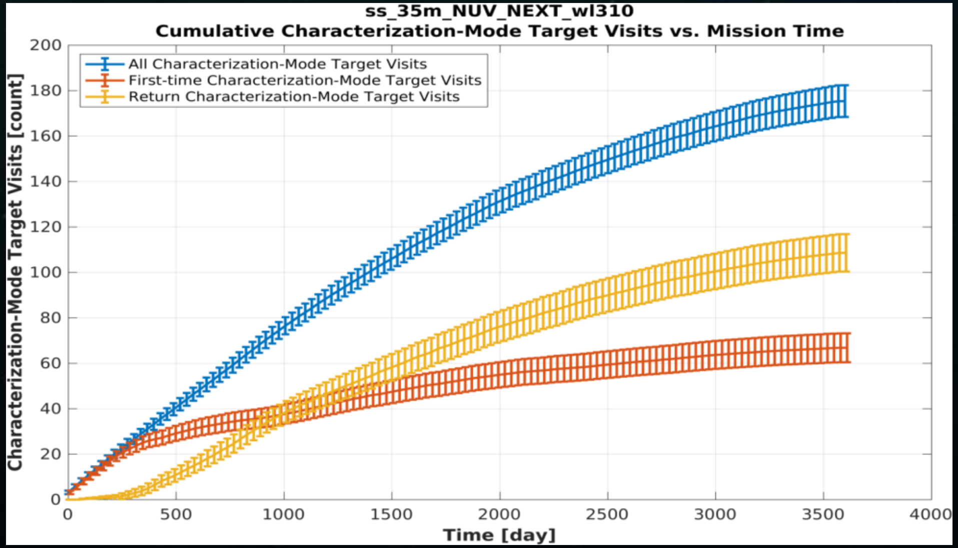
Goal 2 Progress: Exoplanet Yield

35 m with Solar Electric Propulsion (NEXT) Thrusters



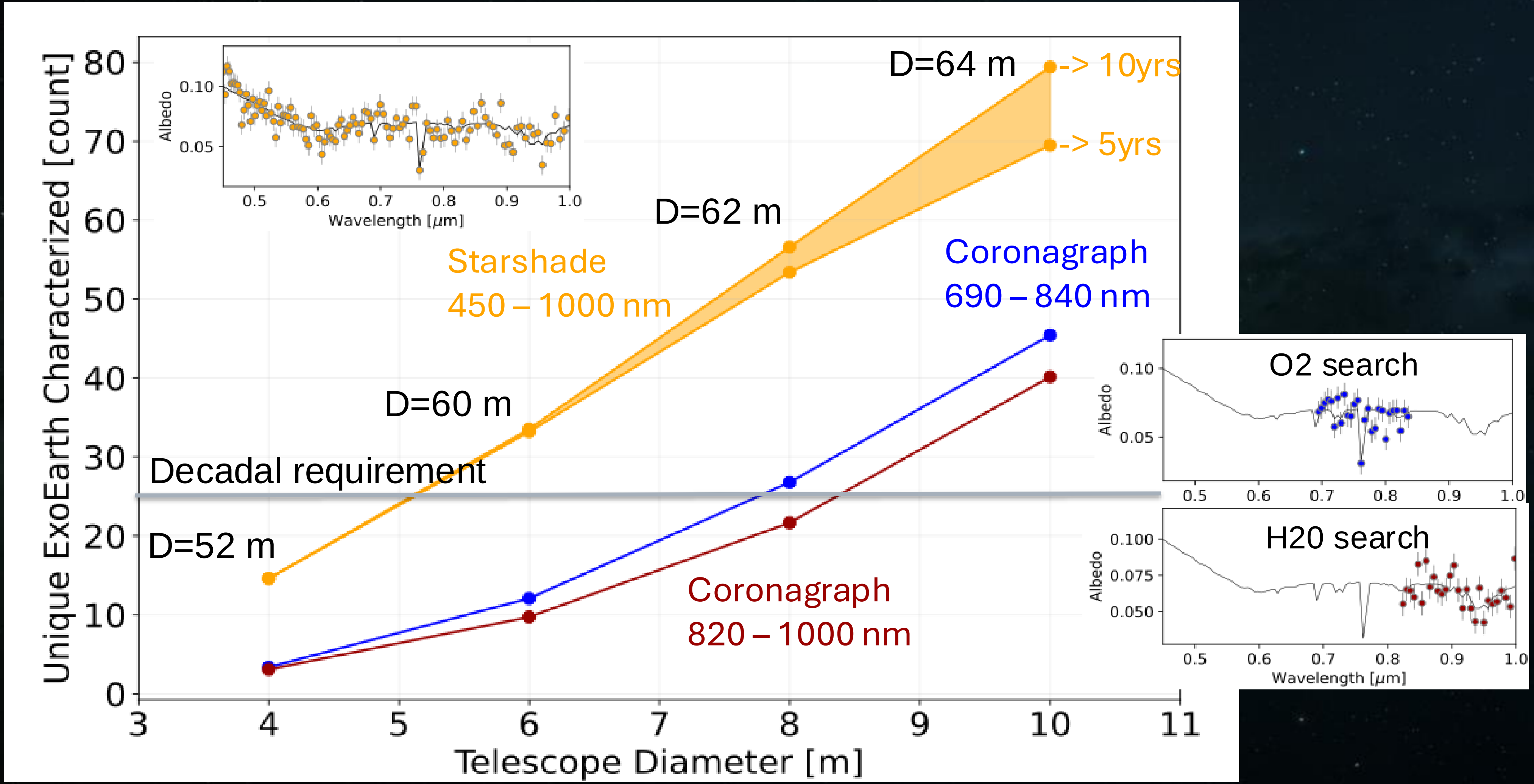






The 35 m starshade can observe 180 targets over 10 years without refueling.

Characterization Yield vs. Telescope and Starshade Diameter, Assuming Planets/Orbits are known.



Detection Assumptions:
- SR = 140
- SNR = 8.5
- 60 day observation cap

Starshade Assumptions:
- Diameter matched to telescope as shown.
- IWA_{tip} = 65 mas
- Planet orbits known.

Coronagraph Assumptions:
- 20% bandwidth
- Bands observed simultaneously
- 5 yr mission
- Planet orbits known

Starshade can meet the Decadal requirement with a 5-m telescope if the planet orbits are known.
It has the capacity to perform multiple characterization of the exoplanets.

Conclusions

- A 35 m starshade provides deep contrast and high throughput over a band from 250-500 nm with Inner Working Angle = 65 mas.
  - It is highly effective at measuring low-resolution spectra in the UV/Vis.
- With precursor knowledge of planet orbits, and without refueling, the starshade can make ~ 180 characterizations over 10 years.
- Broad bandwidth observations are crucial. Spectral “snippets” are not sufficient.
  - O_3 250-400 nm determines whether the planet is Proterozoic vs. archaic Earth.

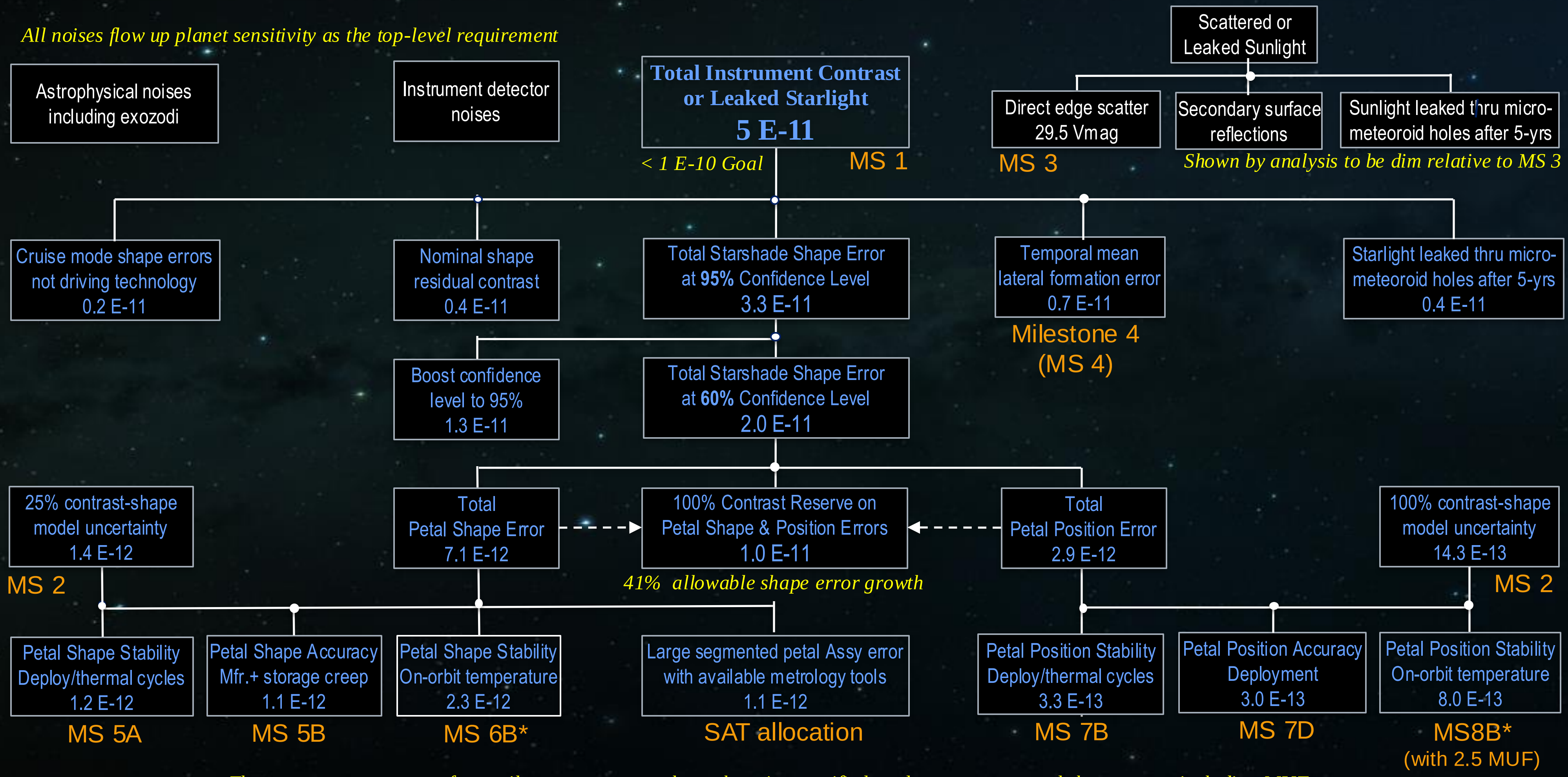
Backup Slides

Telescope diameter study (coronagraph vs starshade)

INSTRUMENT CONTRAST ROLLUP FOR 2.4M ROMAN TELESCOPE

Prime bandpass = 615-800 nm (26%)

IWA at tips = 103-mas = 1.5 λmax / D



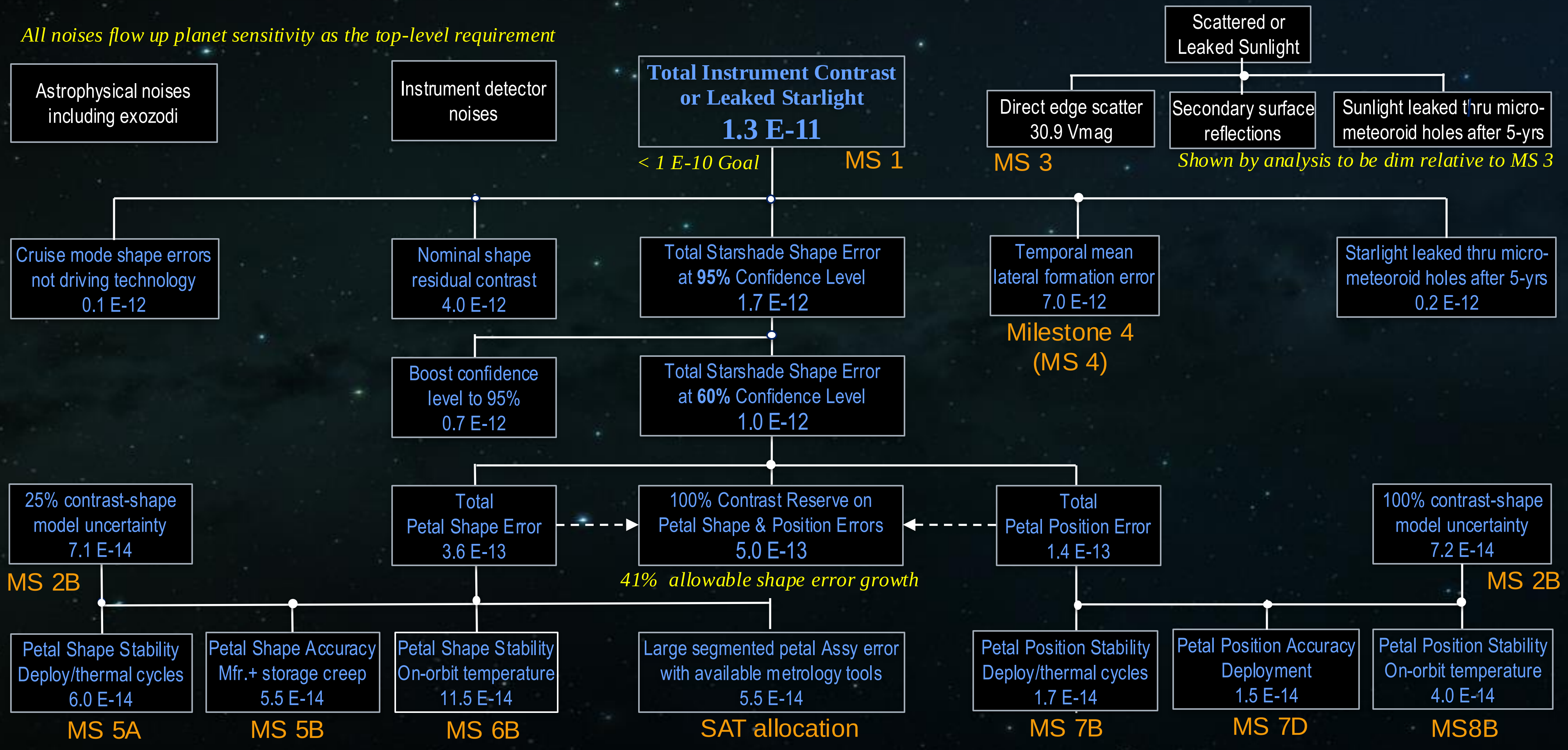
These are mean contrasts from milestone reports, unless otherwise specified, and per max expected shape errors including MUFs.

** Contrast is relative to MS8A results.*

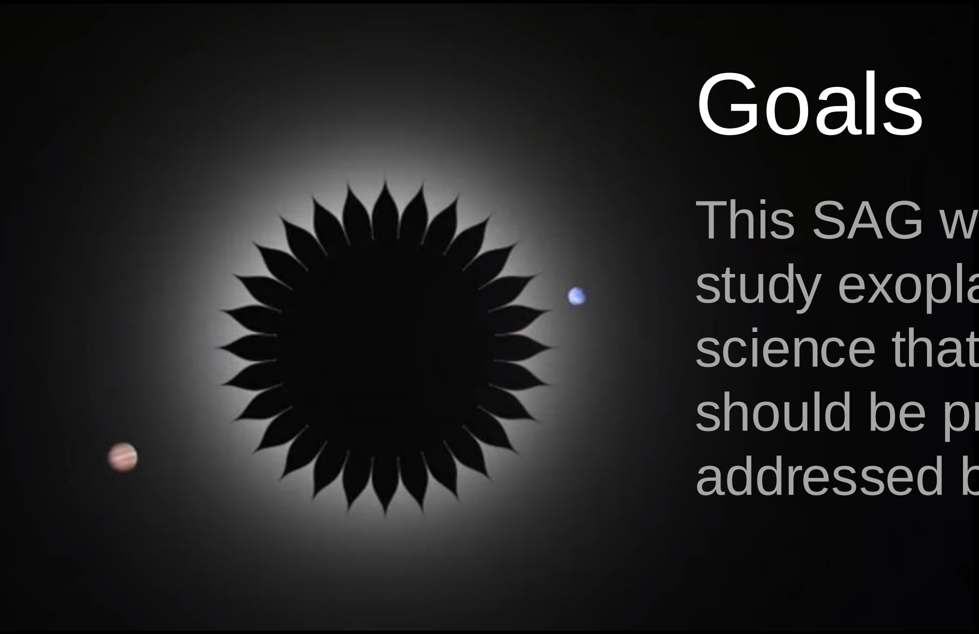
INSTRUMENT CONTRAST ROLLUP FOR 6M HWO TELESCOPE

Prime bandpass = 250-440 nm (55%)

IWA at tips = 65-mas = 4.3 $\lambda max / D$

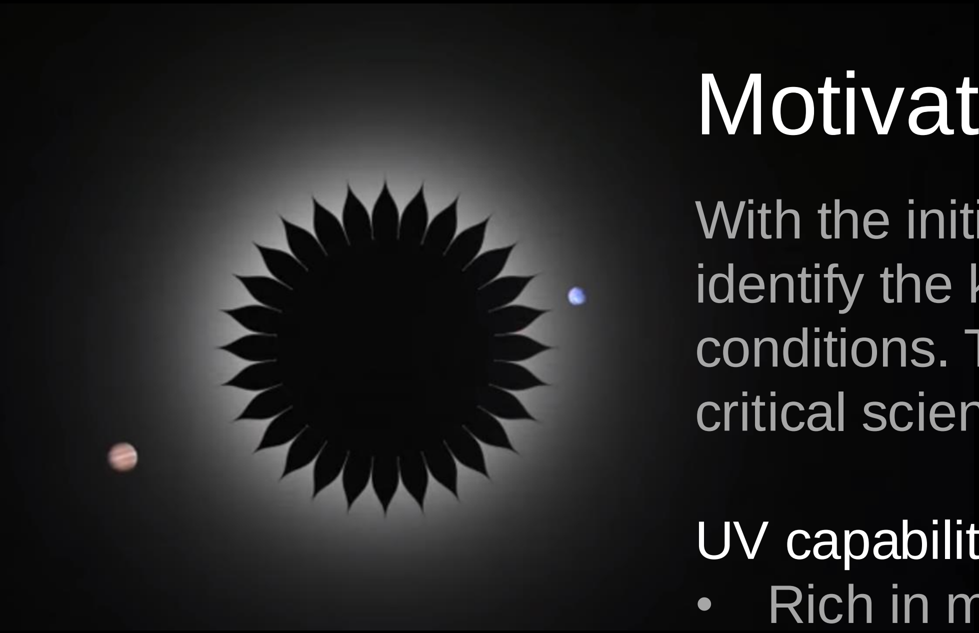


These are mean contrasts scaled from the Roman case by 1/20 per the n λ/D IWA indicated contrast sensitivity to shape errors.



Goals

This SAG will bring together an interdisciplinary team of scientists who study exoplanet characterization in order to flesh out areas of Starshade science that are unique and complementary to the coronagraph and should be prioritized in the coming years. The goals that will be addressed by this SAG are as follows.



Motivation

With the initiation of the Habitable Worlds Observatory (HWO) we must identify the key measurements needed to establish exoEarth habitable conditions. The Starshade SAG motivation is to elucidate the unique and critical science Starshade enables, complementary to the coronagraph.

UV capability

- Rich in molecular diagnostics not accessible at visible and near-IR wavelengths
- Contains the “ozone cut off”

Simultaneous broad-band spectral coverage

- Identification of multiple gases for characterizing the planet types
- Identification of individual gases by more than one spectral feature.

High throughput

- Necessary for gathering spectra of numerous faint exoEarths
- Can efficiently optimize a general observatory schedule
- Enables polarization measurements

Goal 5

S5 Baseline vs. HWO Starshades

S5 = Starshade to TRL5 Activity, funded 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

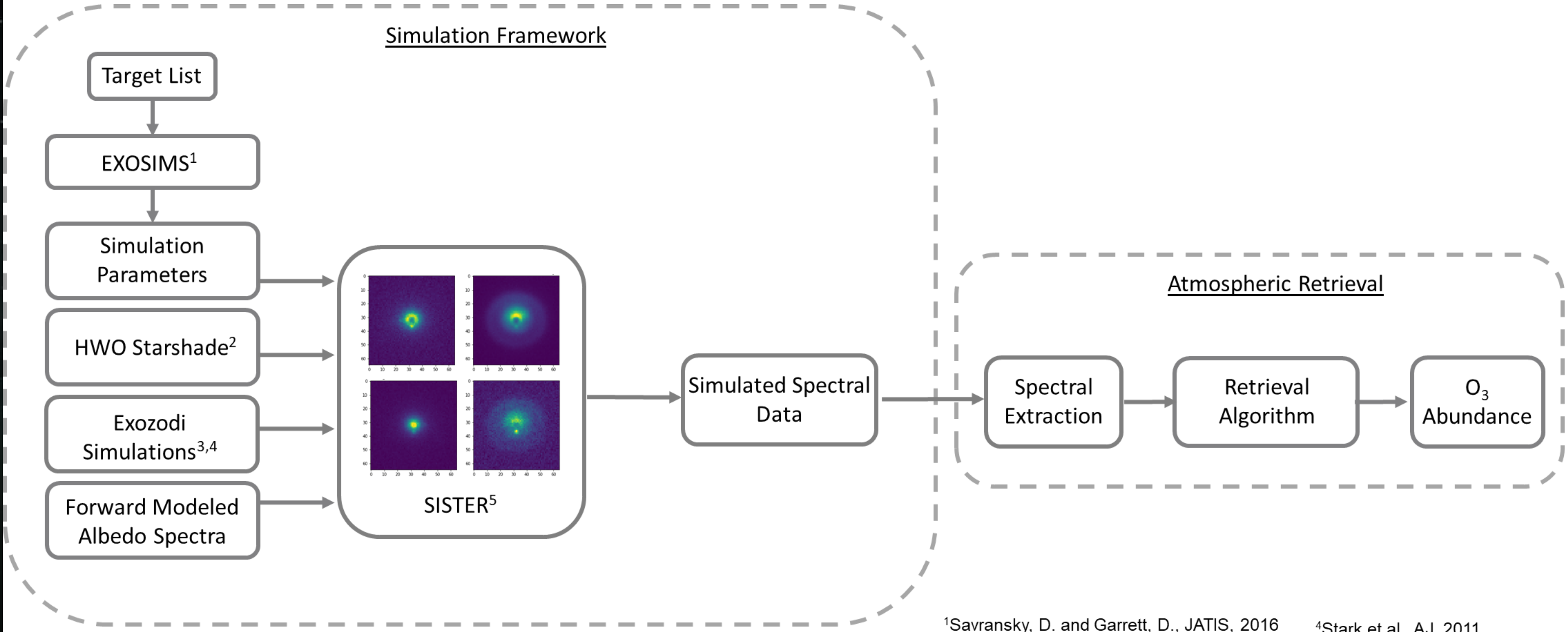
Resolving the starshade

Bigger is more ‘geometric’

Well-resolved IWA, **3.8 λ/D**: telescope resolves perturbations away from the planet.
Large Fresnel Number, **11-22**: easier to form a shadow, reduced sensitivity to perturbations.
D/Separation^2, **0.011**: Solar glint scales as edge length / distance^2. Smaller means fainter glint.

Given the same quality of build and same materials, HWO UV-VIS has 4x better contrast (1.3e-11) than the 26-m starshade that we have studied in the S5 program

PROJECT OVERVIEW

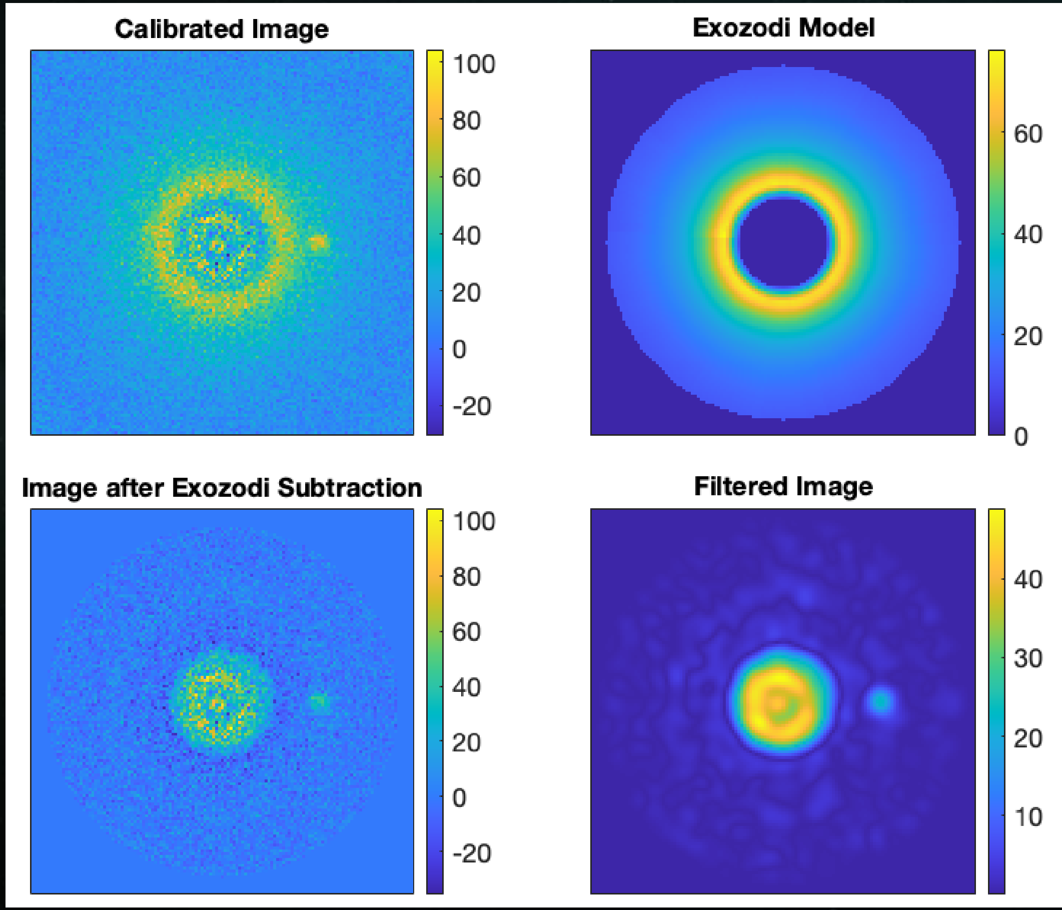


[1]Savransky, D. and Garrett, D., JATIS, 2016
[2]Shaklan, S. et al, SPIE Proc. 12680, 2023
[3]Currie et al., AJ, 2023
[4]Stark et al., AJ, 2011
[5]Hildebrandt, S. et al. JATIS, 2021

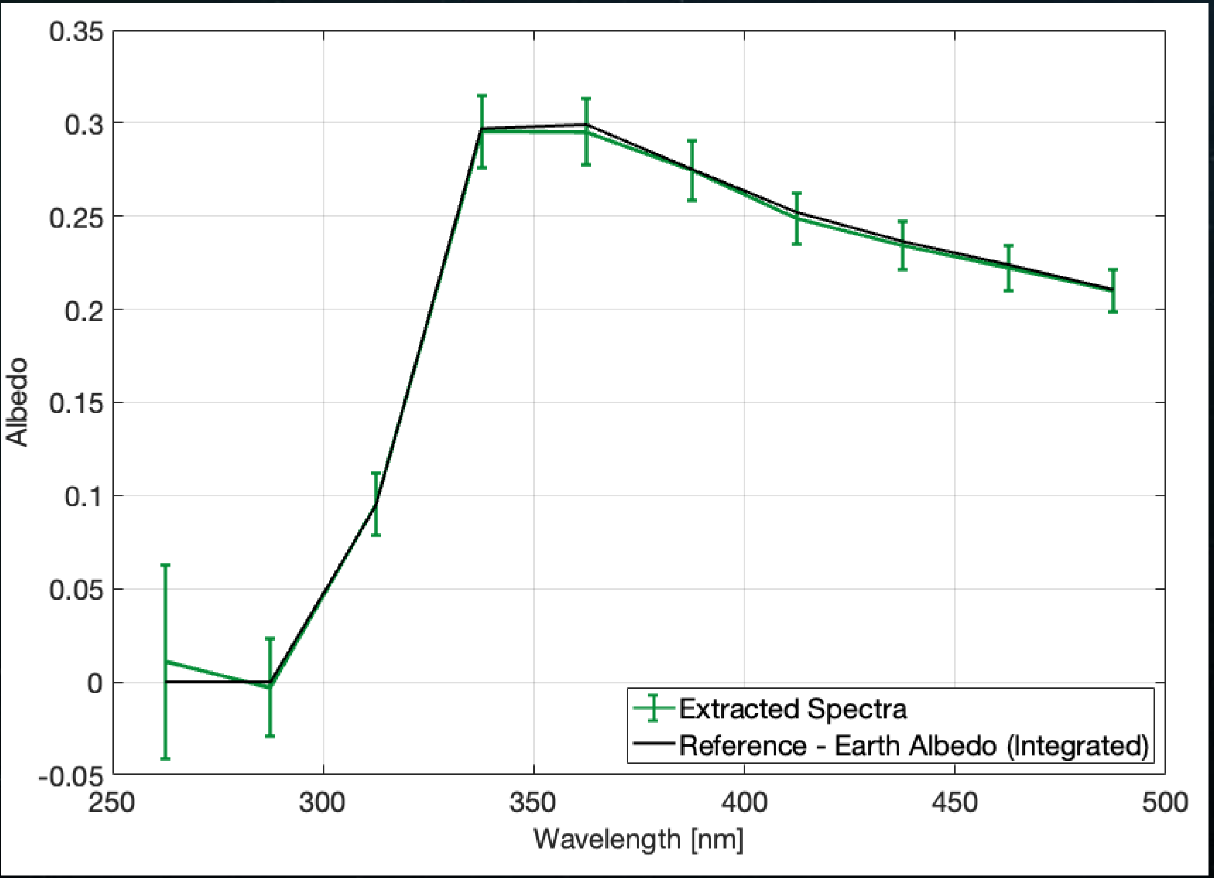
EXAMPLE: POST-PROCESSED SPECTRUM

- Face-on system, 10 zodis, 1-day observation

475– 500 nm



Extracted Spectrum



Why Starshades?

Starshades remove the starlight before it can scatter into the telescope.

Parameter	HWO 35-m UV/VIS Starshade concept	Demonstrated
IWA	65 mas = 3.8 λ/D @ 500 nm	1.8 λ/D
OWA	Unlimited	3.6 λ/D
Bandwidth	67%	12.5%
Instrument Contrast	< 4e-11	<1e-10 (75% search area)
Throughput	100%	90%
Telescope stability, shape, segmentation	Works equally well with any aperture: on- or off-axis, segmented or monolith, does not drive stability, does not drive coating uniformity.	Circular aperture