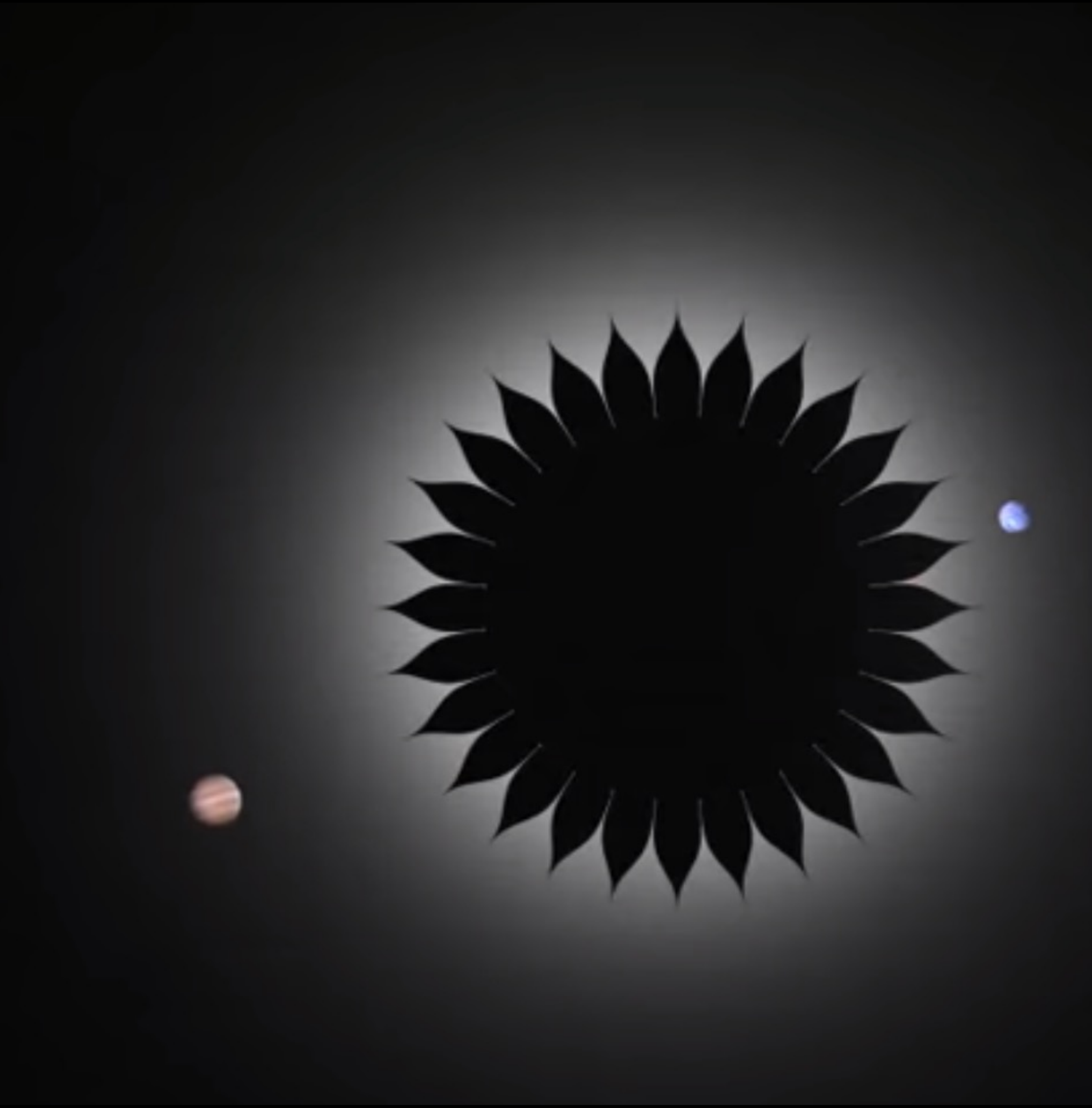

SAG 24

Exploring the Complementary Value of Starshade Science Observations

Co leads S. Seager, S. Shaklan

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.

https://exoplanets.nasa.gov/exep/exopag/sag/#sag24

SAG 24 Participants

Co-Leads

Sara Seager (MIT)
Stuart Shaklan (JPL)

Leadership Team

Renyu Hu (JPL)
Doug Lisman (JPL)
Rhonda Morgan (JPL)

YOUR NAME HERE

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Zahra Ahmed (Stanford)
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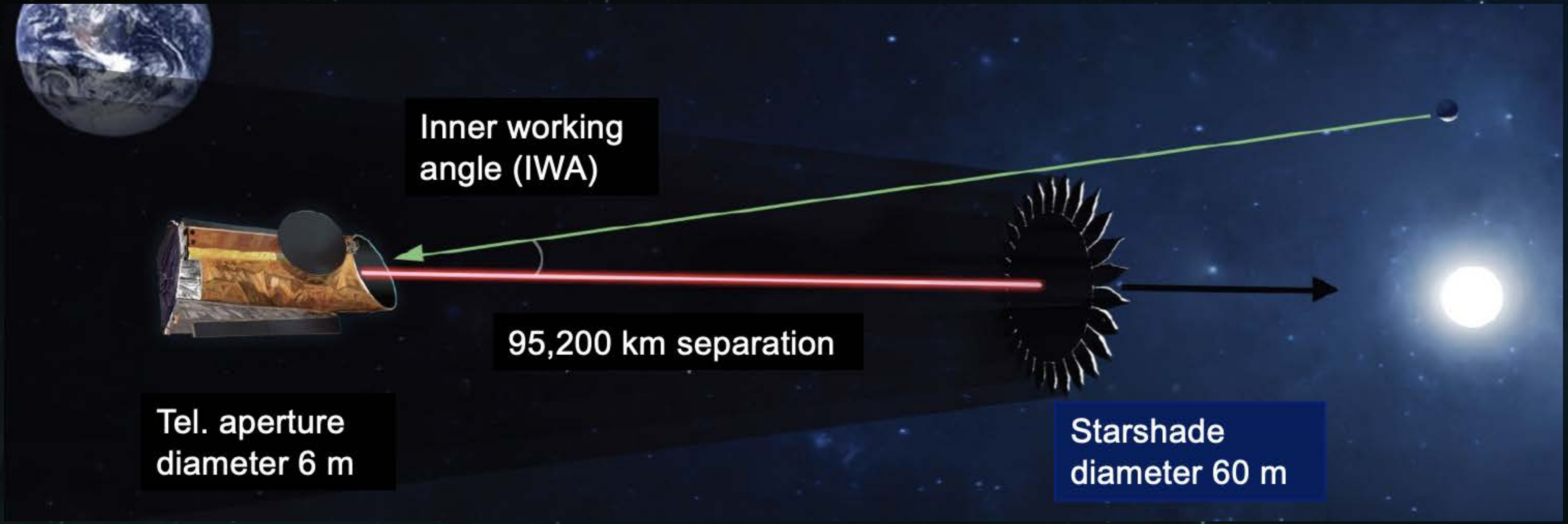
Angelle Tanner (MSU)
Keith Warfield (JPL)

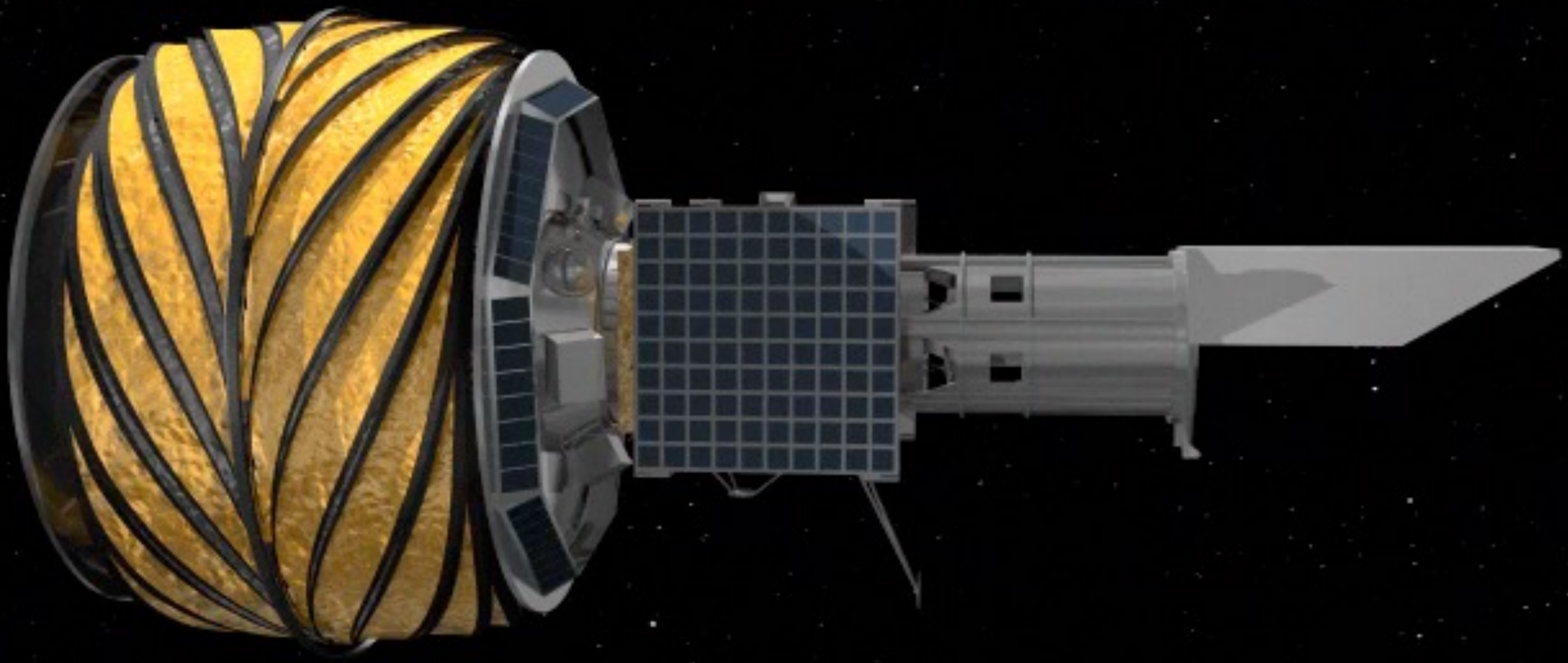
YOUR NAME HERE

WHAT IS A STARSHADE?



- Flower-shaped screen, 10s of meters in diameter
- Flies in formation with a telescope, aligning with a target star
- Controls diffraction, forms a deep shadow where the telescope is positioned

- Inner working angle (IWA) is the starshade radius divided by its distance
- For the HWO concept, r = 30 m, D = 95.2 Mm, IWA_{tips} = 65 mas
- Repositioning requires ~ 7 – 15 days
- Highly efficient planet characterizer



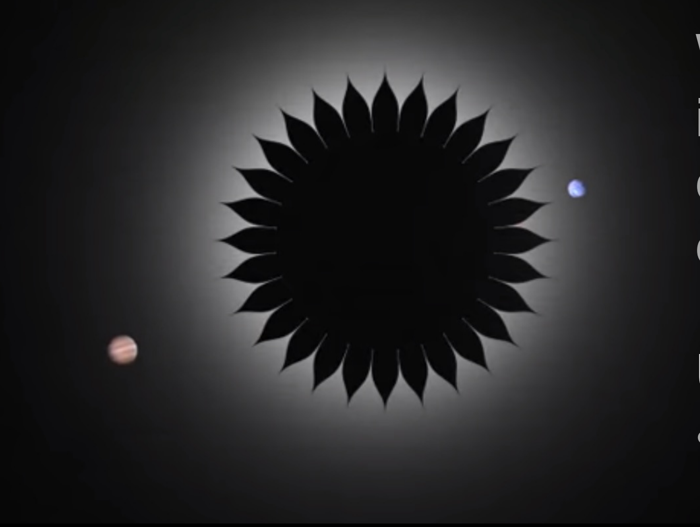
Exoplanet Probe – Starshade Mission Concept, circa 2014

Why Consider a Starshade?

Starshades remove the starlight before it can scatter into the telescope. This allows the system to achieve the ultimate high-contrast sensitivity.

Parameter	HWO Starshade concept
Inner Working Angle	1.9 λ/D
Outer Working Angle	Unlimited
Bandwidth	One octave
Instrument Contrast	Better than 4e-11 at tips
Throughput	100% beyond the tips
Telescope stability, shape, segmentation	Works equally well with any aperture, segmented or monolithic, on- or off-axis. Does not drive stability.

SAG 24 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

https://exoplanets.nasa.gov/exep/exopag/sag/#sag24

SAG 24 Goal 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"

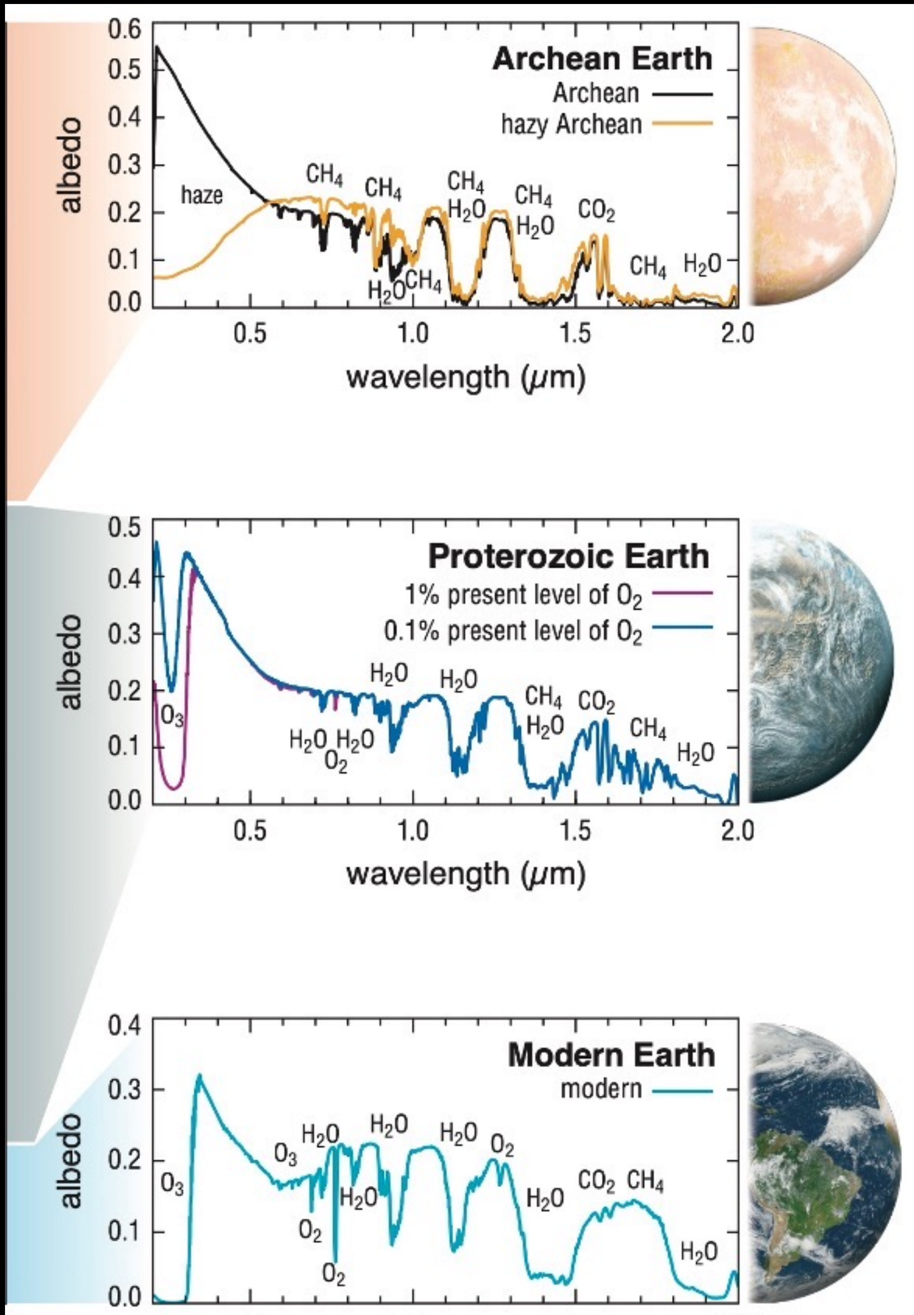
d. High throughput observations

Lead Renyu Hu and Sara Seager

Atmospheric retrieval of simulated data

Use lessons learned from JWST

Work with proposed SAG on HWO Exoplanet Reflectance Spectroscopy



Credit: LUVOIR Report; G. Arney, S. Domagal-Goldman, T.B. Griswold (NASA GSFC).

SAG 24 Goal 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.

Detection yield from notional CONOPS

↓

Detection and characterization yield from full end-to-end simulation

Lead Rhonda Morgan and Sara Seager

HWO exoplanet detection and characterization yield from starshades

Inclusion of outer working angle for planetary system detection

A hierarchy of yield calculations towards more realistic simulations

SAG 24 Goal 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.

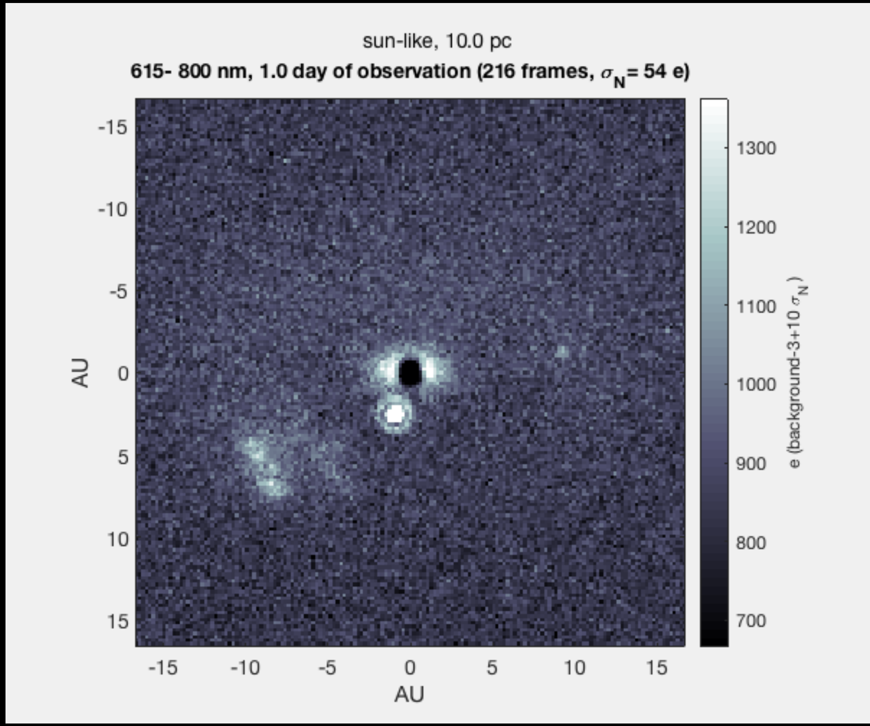
Intertwined with Goals 1 and 2

Additional focus on binary stars Lead TBD

- What Starshade and coronagraph configurations are needed and how well would they work?
- How deep a suppression and what Starshade design?
- Small Starshade with UV would be adequate for binary star investigations.

SAG 24 Goal 4

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



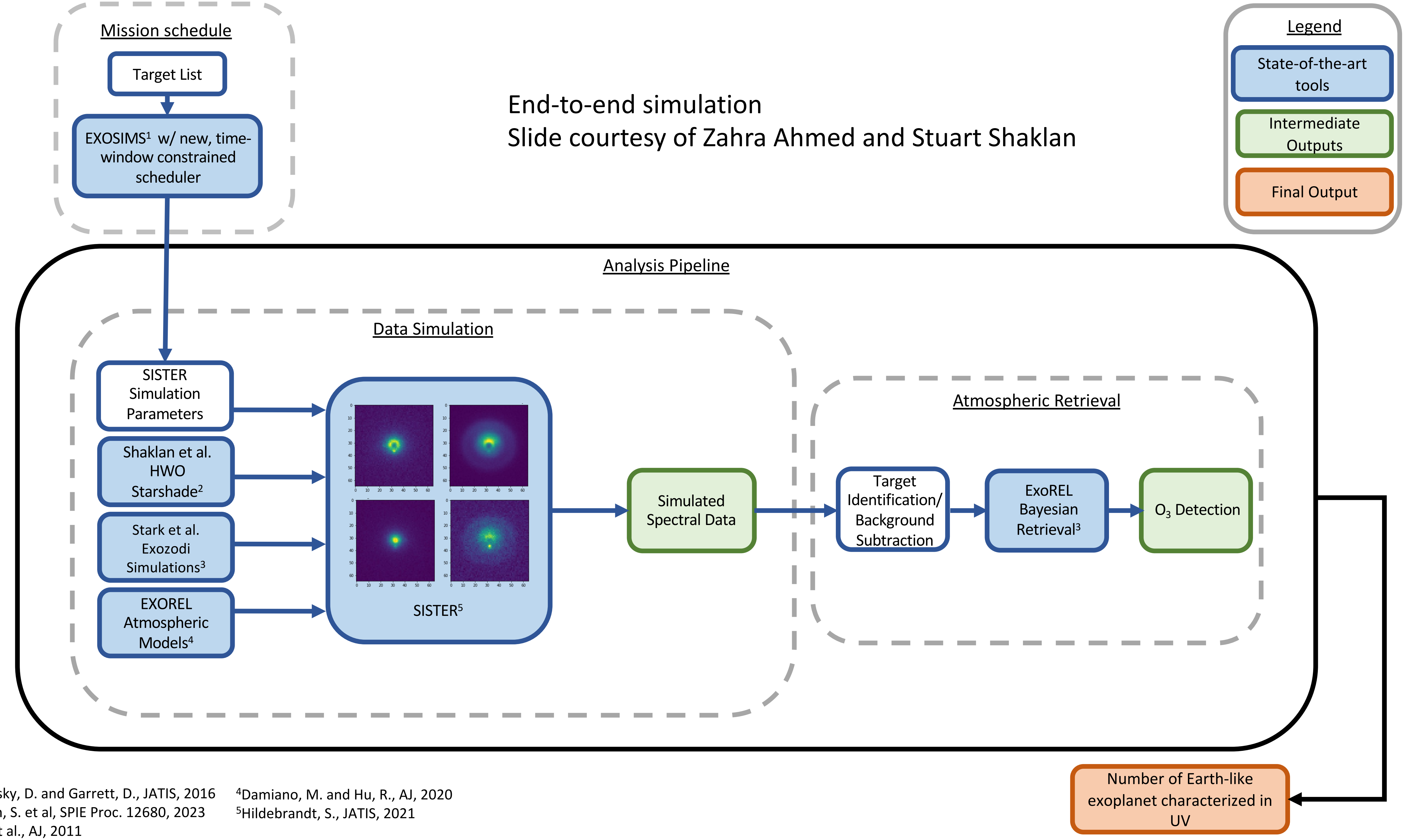
http://sister.caltech.edu/

Lead Stuart Shaklan and Zahra Ahmed

Initial focus on UV

Subsequent extension to the full UV-VIS-NIR range

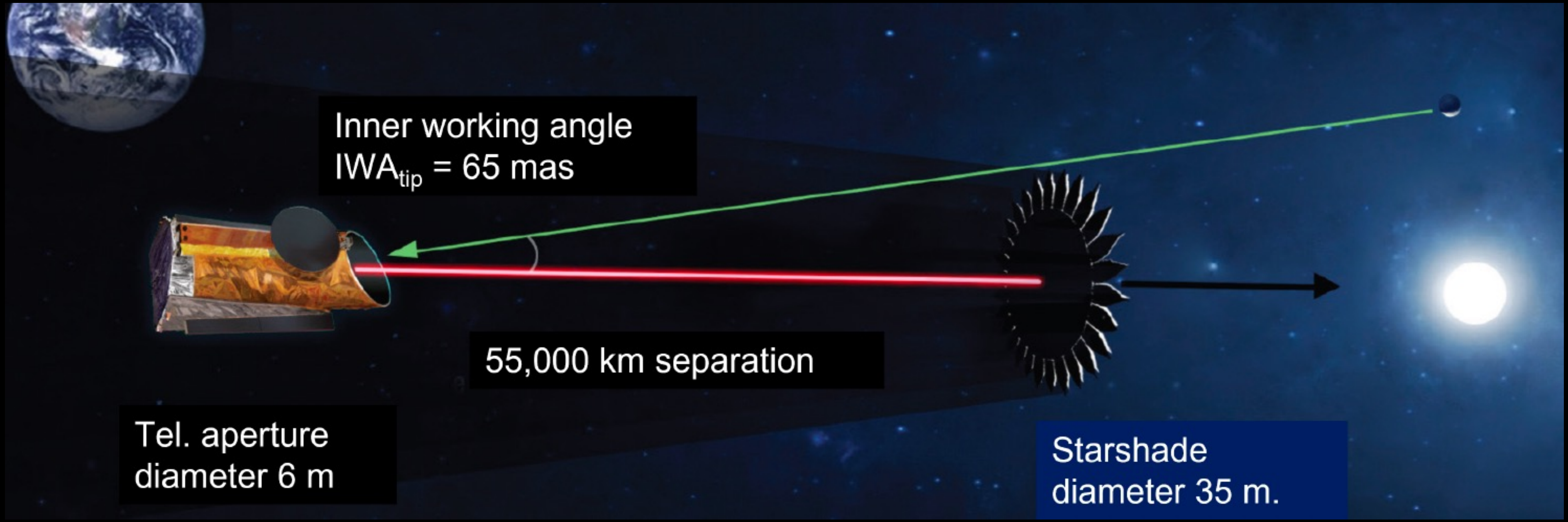
End-to-end simulation
Slide courtesy of Zahra Ahmed and Stuart Shaklan



[1]Savransky, D. and Garrett, D., JATIS, 2016
[2]Shaklan, S. et al, SPIE Proc. 12680, 2023
[3]Stark et al., AJ, 2011
[4]Damiano, M. and Hu, R., AJ, 2020
[5]Hildebrandt, S., JATIS, 2021

SAG 24 Goal 5

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



Lead Doug Lisman and Stuart Shaklan

Initial focus on UV

- Small Starshade
- Build on work in Shaklan et al. 2023

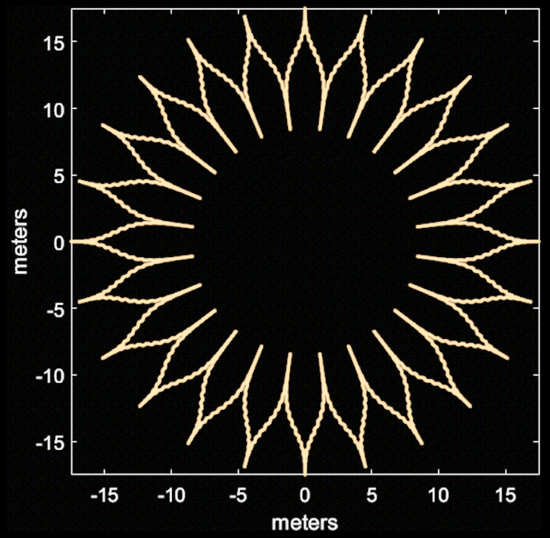
Subsequent extension to the full UV-VIS-NIR range

SAG 24 Goal 5

Starshade point design to support Goals 2 to 4.

HWO UV concept 35 m diameter starshade:

- Tip width: 3 mm
- Gap width: 2 mm
- Petals: 9 m long, 24 petals
- Disk Diameter: 17 m
- Separation: 55,000 km



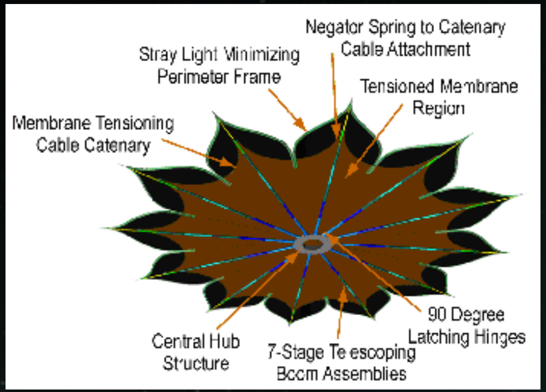
Lead Doug Lisman and Stuart Shaklan

Initial focus on UV

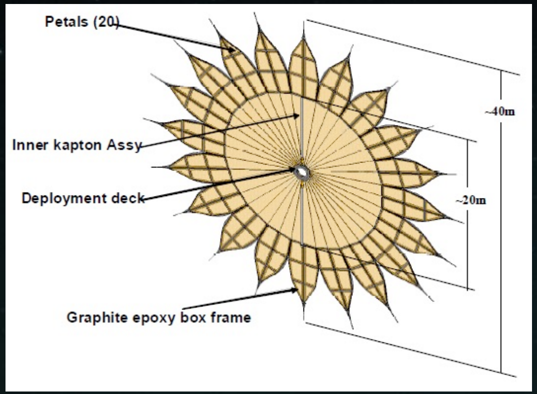
- Small Starshade
- Build on work in Shaklan et al. 2023

Subsequent extension to the full UV-VIS-NIR range

‘Modern’ History of Starshade Studies

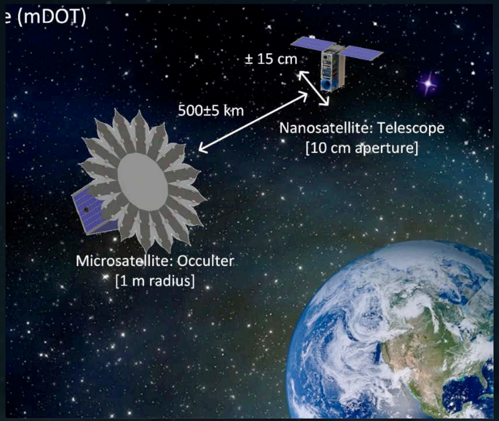


New Worlds Observatory, 50 m, Cash 2008

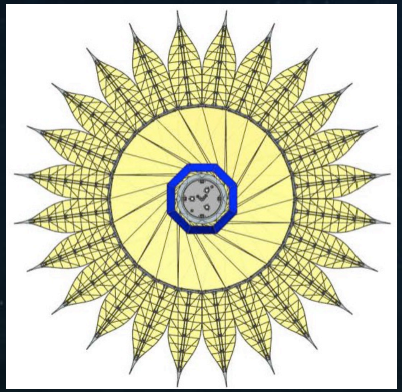


THEIA, 40 m, Kasdin 2009

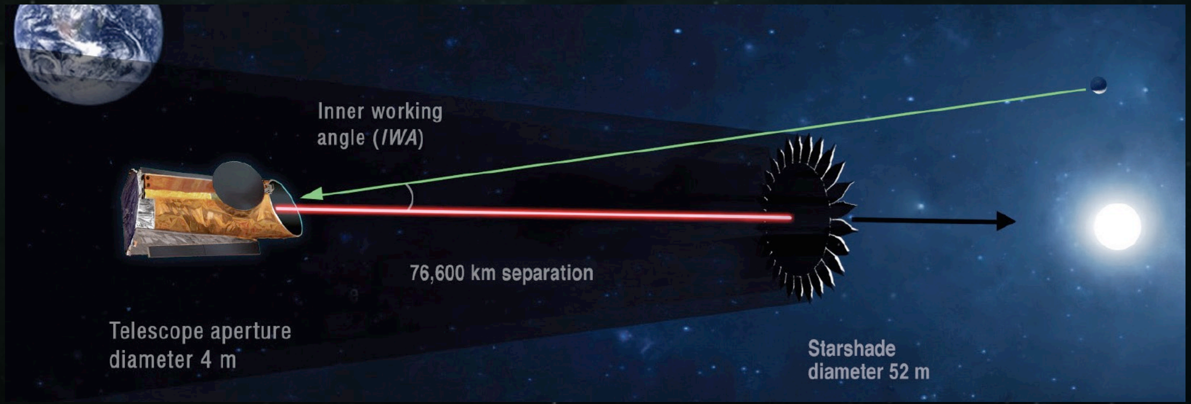
Exo-S Dedicated, 2014



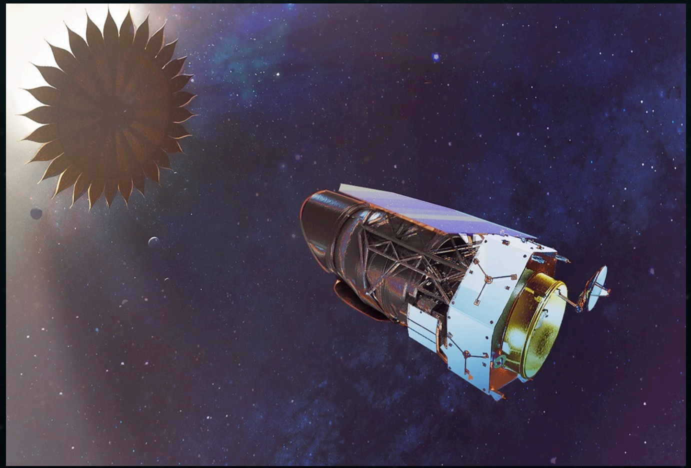
mDot, 3 m, Koenig 2015



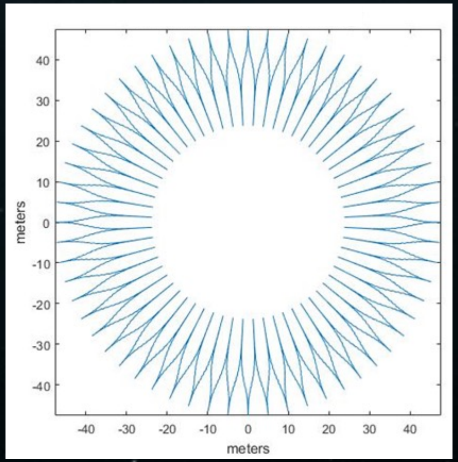
O3, 16 m, Lisman 2019



HabEx, 52 m, 2019



SRM, 26 m, Seager & Kasdin 2019

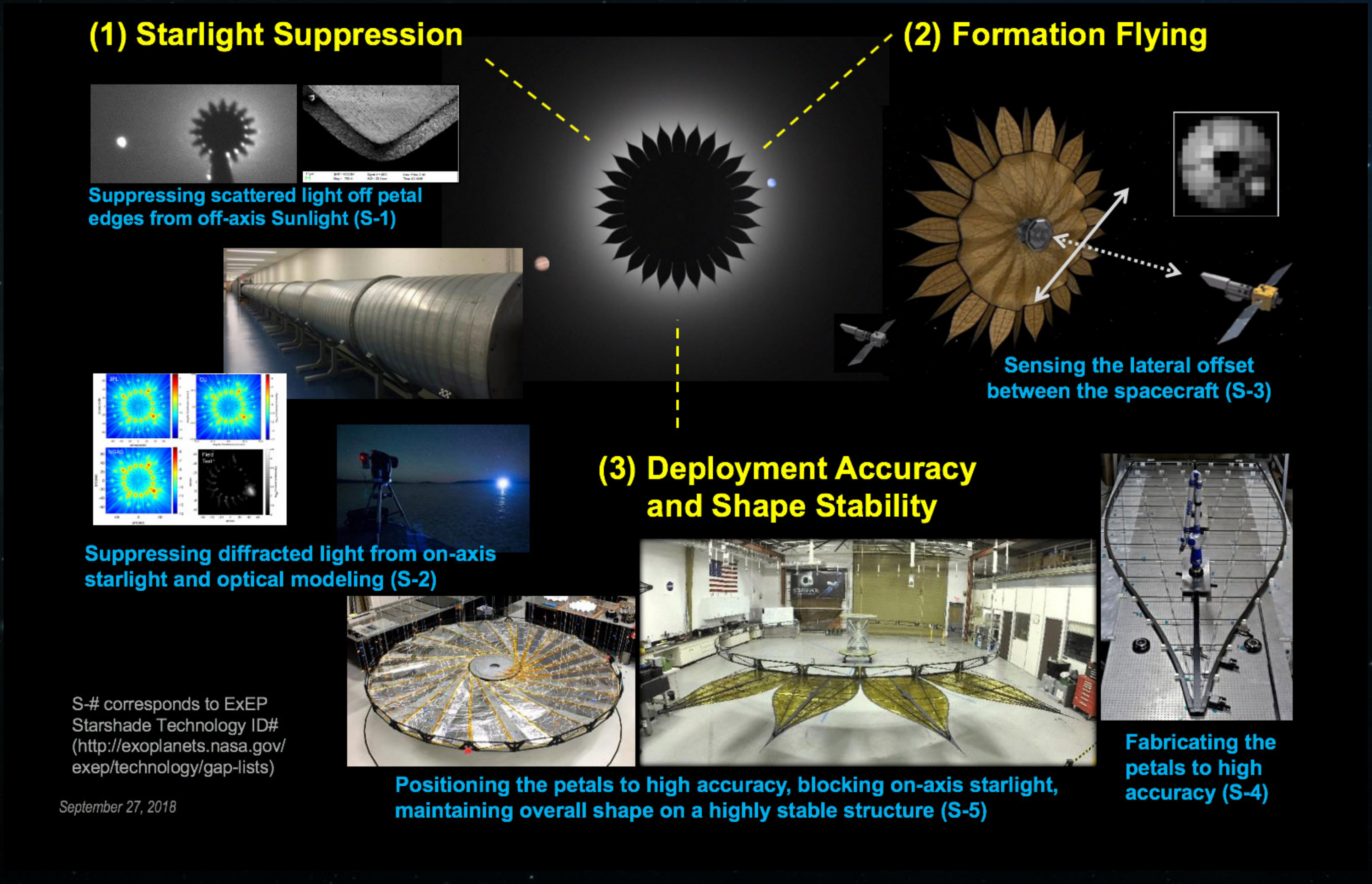


HOEE, 100 m
Mather 2020

Starshade mission concepts of various sizes have been studied for over for over 15 years

STATUS: STARSHADE TECHNOLOGY

See talks by Gary Blackwood and Brendan Crill, this session.



Starshade ExEP TRL Assessment Board Findings

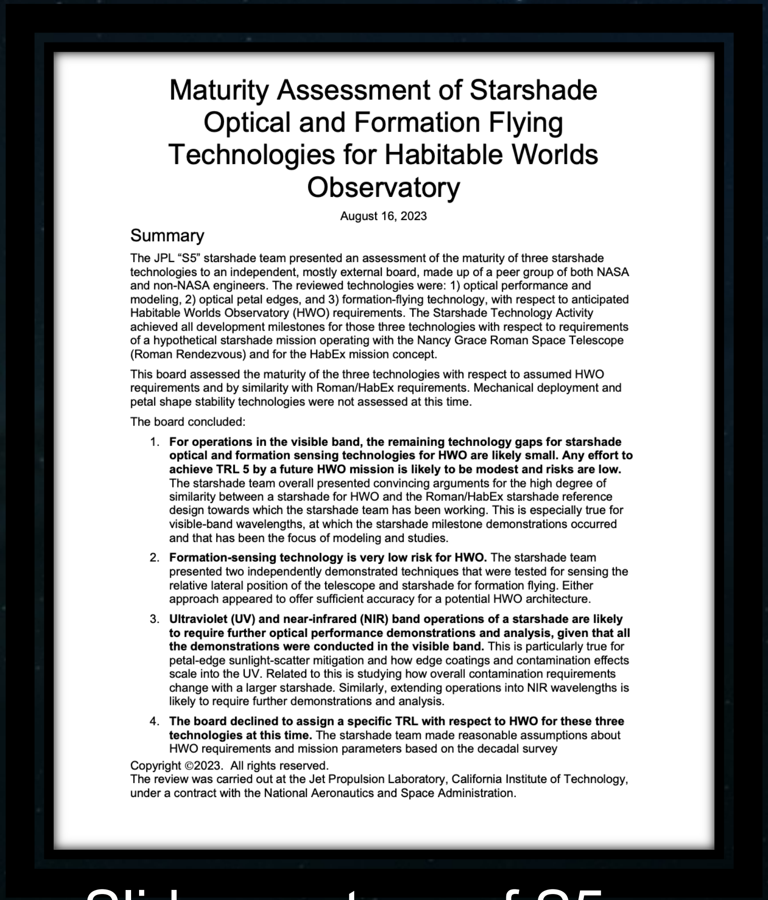
1. The remaining technology gap associated with **formation-flying sensing**, developed and demonstrated for HabEx, is likely small for a HWO.

2. The remaining gap associated with **starlight suppression and model validation**, developed and demonstrated for HabEx, is likely small for a HWO. *Subscale demonstrations at a larger physical size (~42 mm starshade) to demonstrate scaling of vector diffraction effects would build further confidence in models.*

3. The remaining technology gap associated with **petal edges**, developed and demonstrated for HabEx, is likely small for HWO.

4. Ultraviolet (UV) and near-infrared (NIR) band operations of starshade petal edges and starlight suppression were not demonstrated and are likely to require future performance demonstrations and analysis if required for science.

5. The board declined to assign specific TRLs for these three technologies given that the HWO architecture and requirements have not yet been established.



Maturity Assessment of Starshade Optical and Formation Flying Technologies for Habitable Worlds Observatory

August 16, 2023

Summary

The JPL "S5" starshade team presented an assessment of the maturity of three starshade technologies to an independent, mostly external board, made up of a peer group of both NASA and non-NASA engineers. The reviewed technologies were: 1) optical performance and modeling, 2) optical petal edges, and 3) formation-flying technology, with respect to anticipated Habitable Worlds Observatory (HWO) requirements. The Starshade Technology Activity achieved all development milestones for those three technologies with respect to requirements of a hypothetical starshade mission operating with the Nancy Grace Roman Space Telescope (Roman Rendezvous) and for the HabEx mission concept.

This board assessed the maturity of the three technologies with respect to assumed HWO requirements and by similarity with Roman/HabEx requirements. Mechanical deployment and petal shape stability technologies were not assessed at this time.

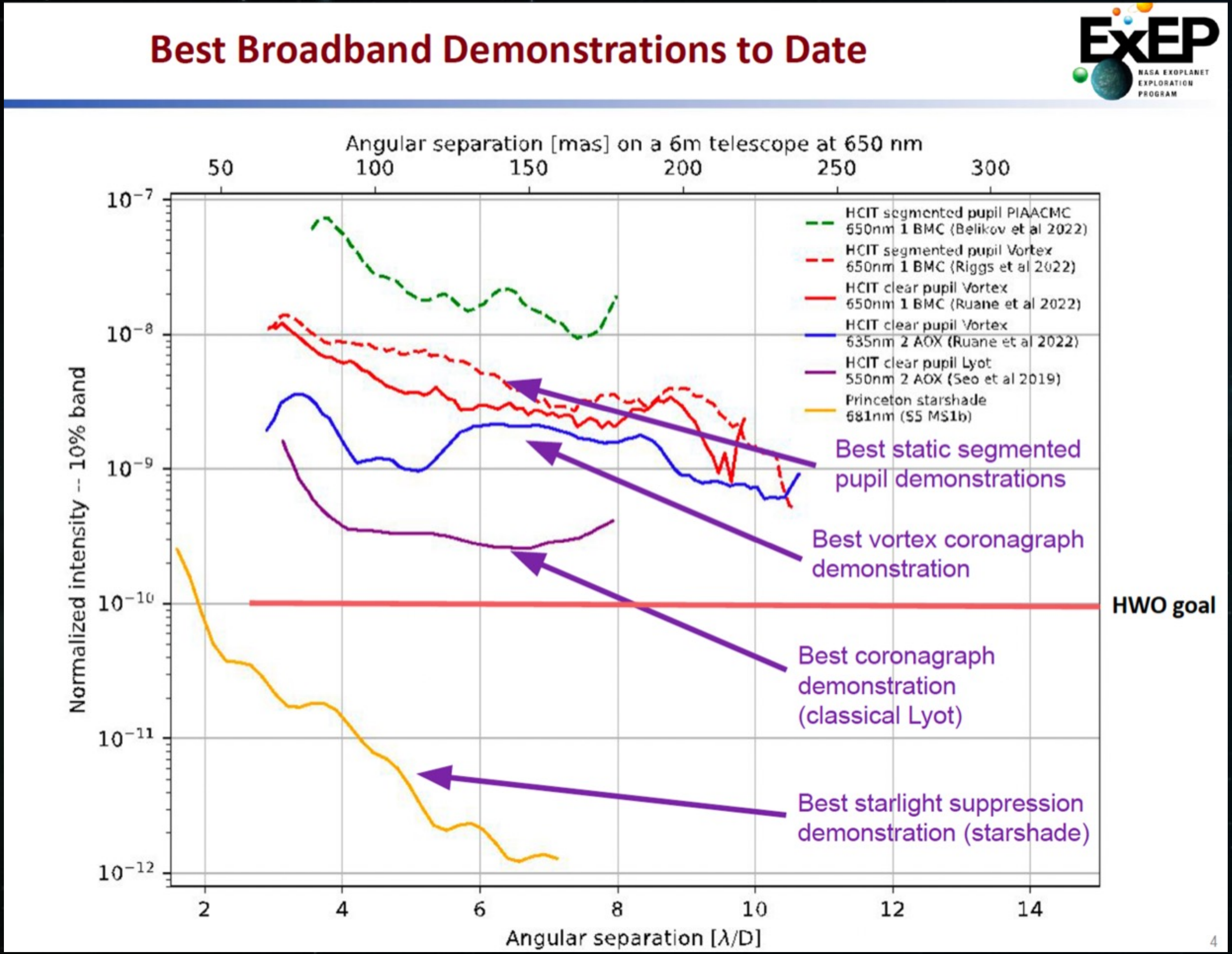
The board concluded:

1. **For operations in the visible band, the remaining technology gaps for starshade optical and formation sensing technologies for HWO are likely small. Any effort to achieve TRL 5 by a future HWO mission is likely to be modest and risks are low.** The starshade team overall presented convincing arguments for the high degree of similarity between a starshade for HWO and the Roman/HabEx starshade reference design towards which the starshade team has been working. This is especially true for visible-band wavelengths, at which the starshade milestone demonstrations occurred and that has been the focus of modeling and studies.
2. **Formation-sensing technology is very low risk for HWO.** The starshade team presented two independently demonstrated techniques that were tested for sensing the relative lateral position of the telescope and starshade for formation flying. Either approach appeared to offer sufficient accuracy for a potential HWO architecture.
3. **Ultraviolet (UV) and near-infrared (NIR) band operations of a starshade are likely to require further optical performance demonstrations and analysis, given that all the demonstrations were conducted in the visible band.** This is particularly true for petal-edge sunlight-scatter mitigation and how edge coatings and contamination effects scale into the UV. Related to this is studying how overall contamination requirements change with a larger starshade. Similarly, extending operations into NIR wavelengths is likely to require further demonstrations and analysis.
4. **The board declined to assign a specific TRL with respect to HWO for these three technologies at this time.** The starshade team made reasonable assumptions about HWO requirements and mission parameters based on the decadal survey

The review was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

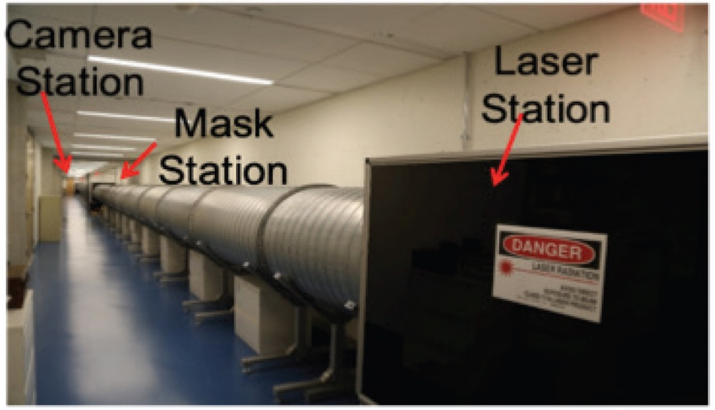
Slide courtesy of S5 team. See talks by Gary Blackwood and Brendan Crill, this session

Overall "Starshade to TRL5" (S5) plan for closing technology gaps and S5 Milestone reports accessible at https://exoplanets.nasa.gov/exep/technology/starshade/



https://exoplanets.nasa.gov/internal_resources/2664/

See talk by Brendan Crill, this session



Starshade test bed at Princeton University.

SAG 24 SUMMARY

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.

Meetings

Monthly online meetings starting January 2024
Virtual workshop planned for Summer 2024

All participants welcome. Contact seager@mit.edu