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Hybrid Observatory for Earth-like Exoplanets (HOEE)

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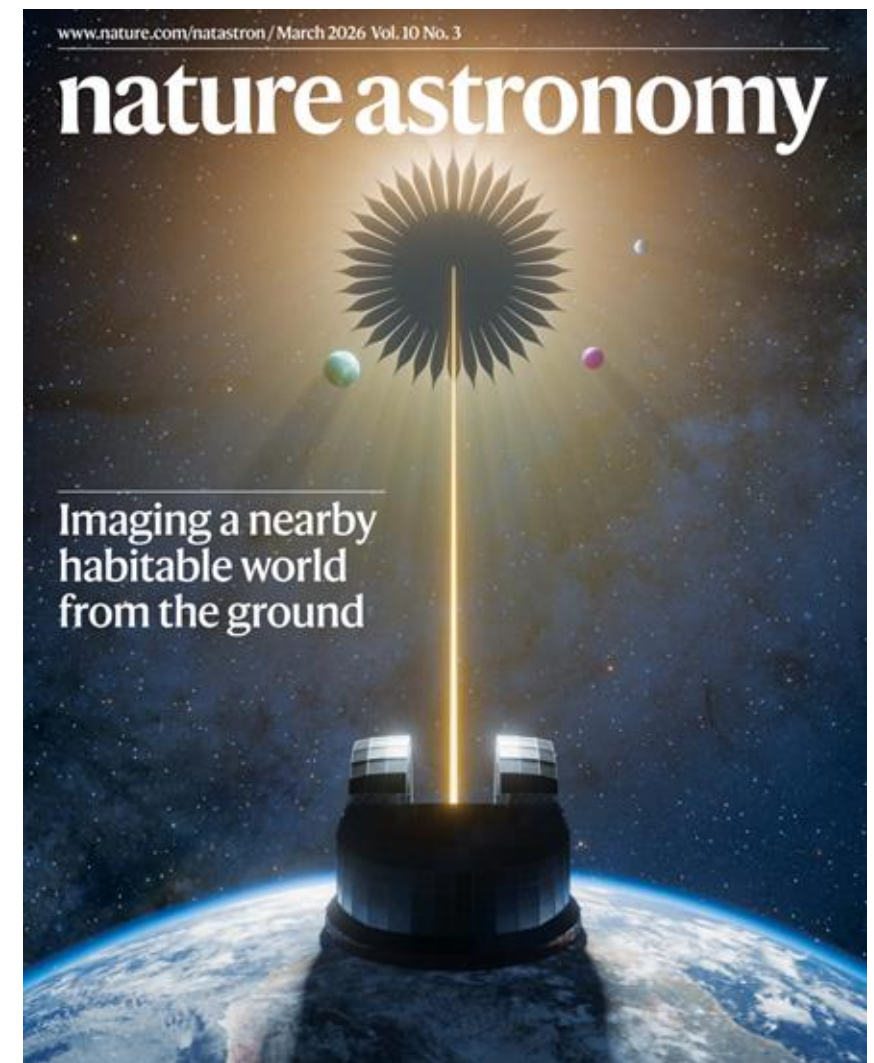
Christine Gregg

NASA Ames Research Center

Ad ASTRA Workshop

2 September 2026

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Soliman, A., Mather, J., Shaklan, S., Peretz, E., et al. *The observation of Earth-like exoplanets with ground-based telescopes and a shared orbiting starshade*. Nat Astron (2026).

<https://doi.org/10.1038/s41550-026-02787-9>

- Caltech Keck Institute for Space Studies (KISS) Program. March 9-13, 2026:

<https://www.kiss.caltech.edu/workshops/hybrid/hybrid.html>

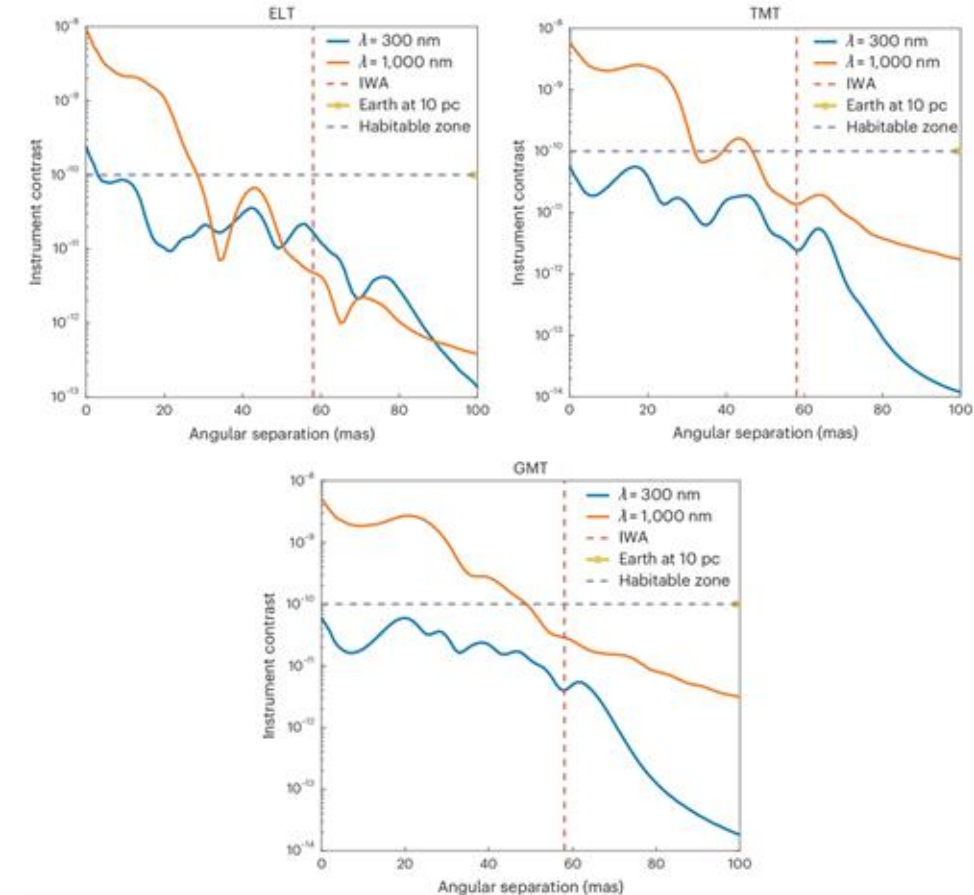
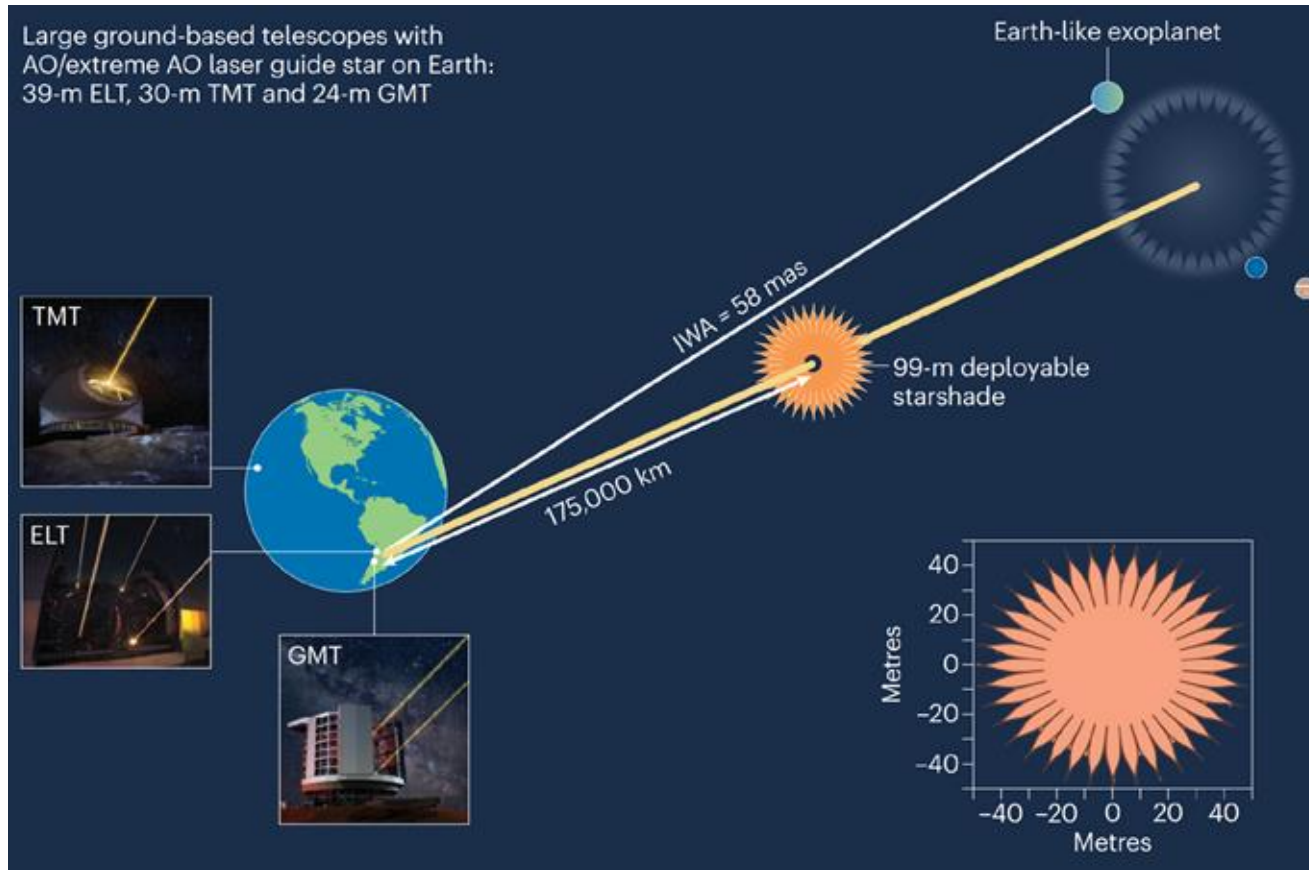
- Cover of Nature Astronomy Journal, March 2026:

<https://www.nature.com/natastron/volumes/10/issues/3>

- NASA STMD and NIAC office news: <https://www.nasa.gov/directorates/stmd/nasa-research-proposes-technology-to-look-for-earth-like-exoplanets/>

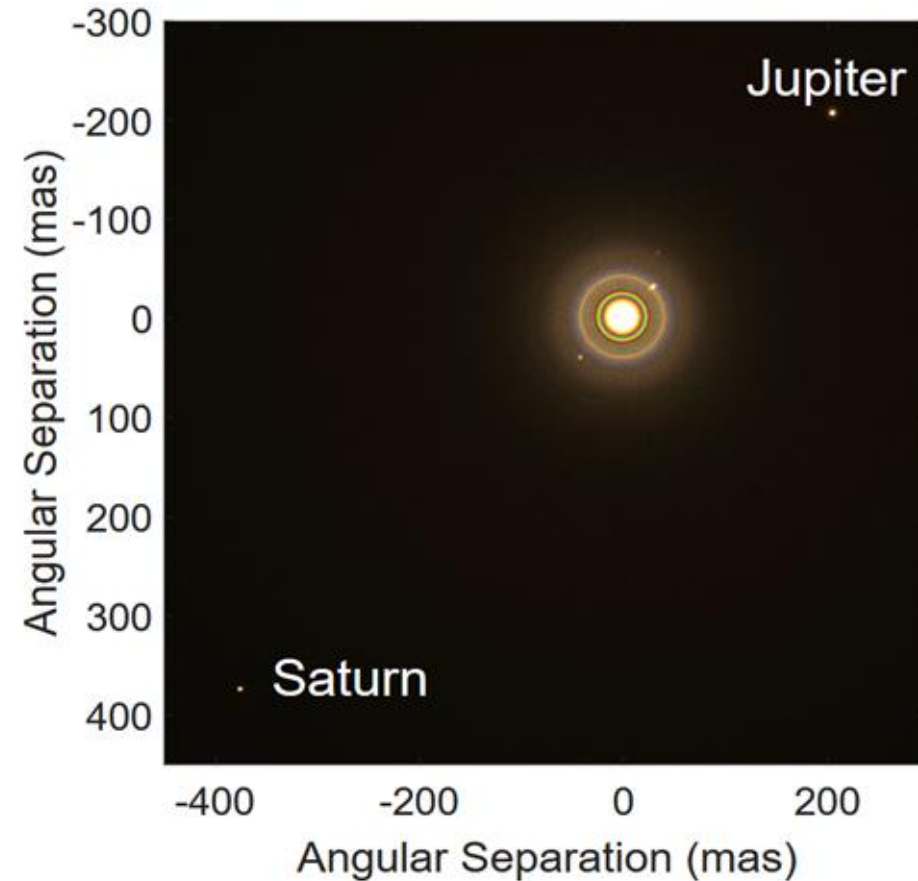
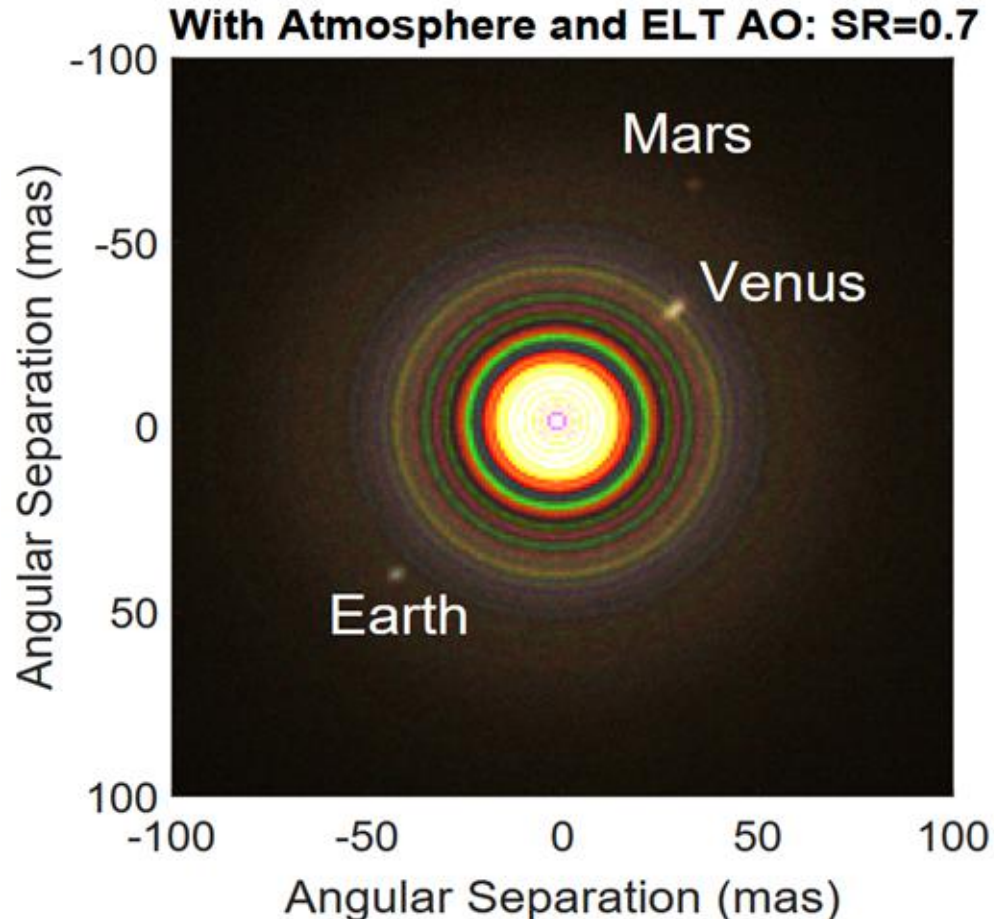
Hybrid Ground-Space Exoplanet Observatory

- Mather, et al, Hybrid Observatory for Earth Like Exoplanets - HOEE NIAC study, 2022.
- HOEE proposes a 99-m-diameter orbiting starshade to block the glare of the host stars in combination with existing large ground-based telescopes to detect faint Earth-like exoplanets and search for signs of life.
- Blocking the starlight before it can enter the telescope has many advantages: high throughput, small working angle, broad bandwidth, and deep contrast. The shadow is formed above the Earth's atmosphere.



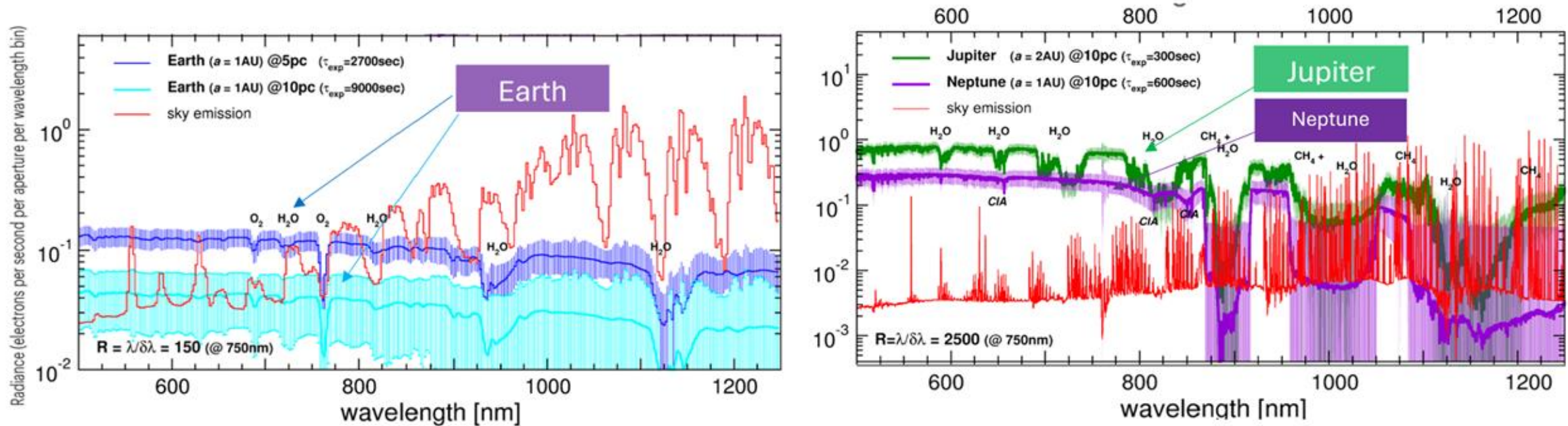
Key capabilities: Full solar system observation

1- Image the full Solar System, including Earth-like Exoplanets, within minutes - We can image planets from Venus to Saturn at 17 pc and detect them within minutes, even under atmospheric conditions - Strehl Ratio (SR) = 0.7 (ELT PCS Instrument), demonstrating the ELT Adaptive Optics (AO)'s ability to mitigate the atmospheric turbulence.



Key capabilities: Spectroscopy

2- Detect key biosignatures within hours of observation – Our simulated spectra show that water and oxygen molecular features are clearly observable for exo-Jupiters, exo-Neptunes, and exo-Earths.



Through Earth's Atmosphere and Telluric Interference.

The first HOEE block diagram with ELT telescope optical path

Based on the **ELT-PCS** Planetary Camera and Spectrograph architecture that integrates AO and XAO with natural guide stars, with key integrated subsystems.

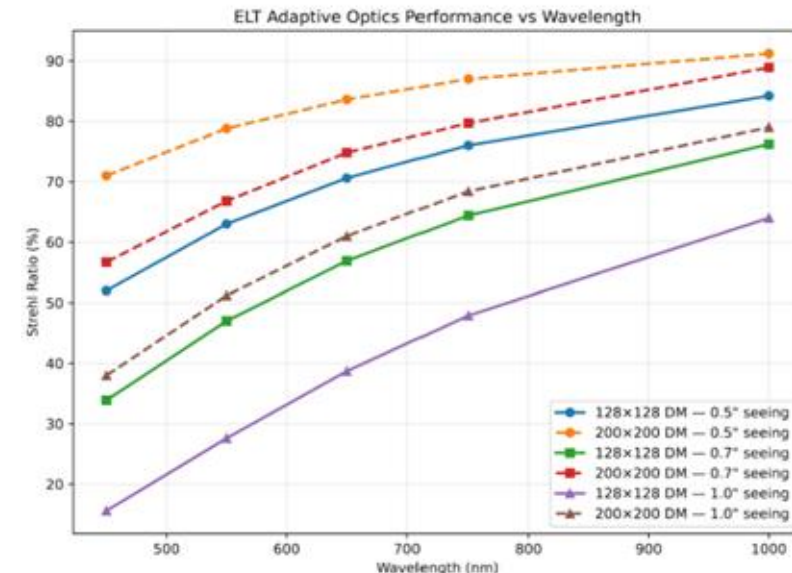
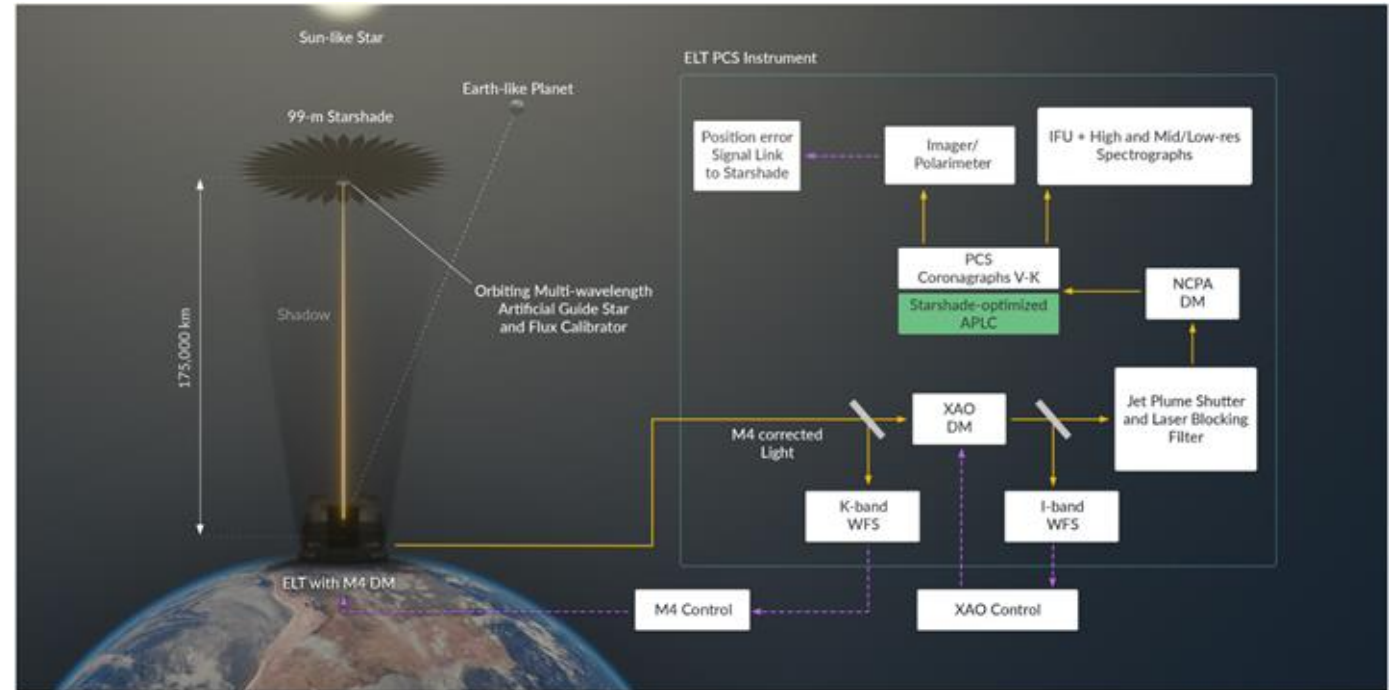
Starshade-centered multi-wavelength orbiting laser beacon provides an artificial guide star for adaptive optics (AO).

NIR pupil-plane sensor measures positioning errors and sends continuous feedback to maintain star–starshade–telescope alignment.

NIR stellar light leakage from a visible-optimized starshade enables direct spacecraft positioning feedback for precise line-of-sight control.

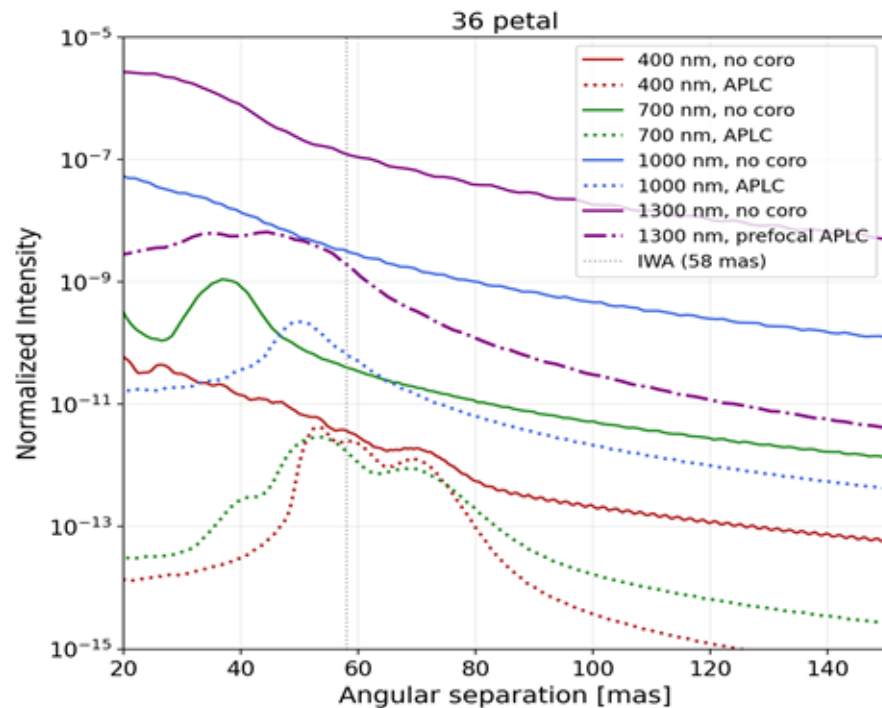
New: Starshade-optimized coronagraph further suppresses starshade leakage and relaxes alignment tolerances.

A **multiobject spectrometer** with a choice of resolution from 150 to up to $R \approx 10,000$ in the near-infrared.

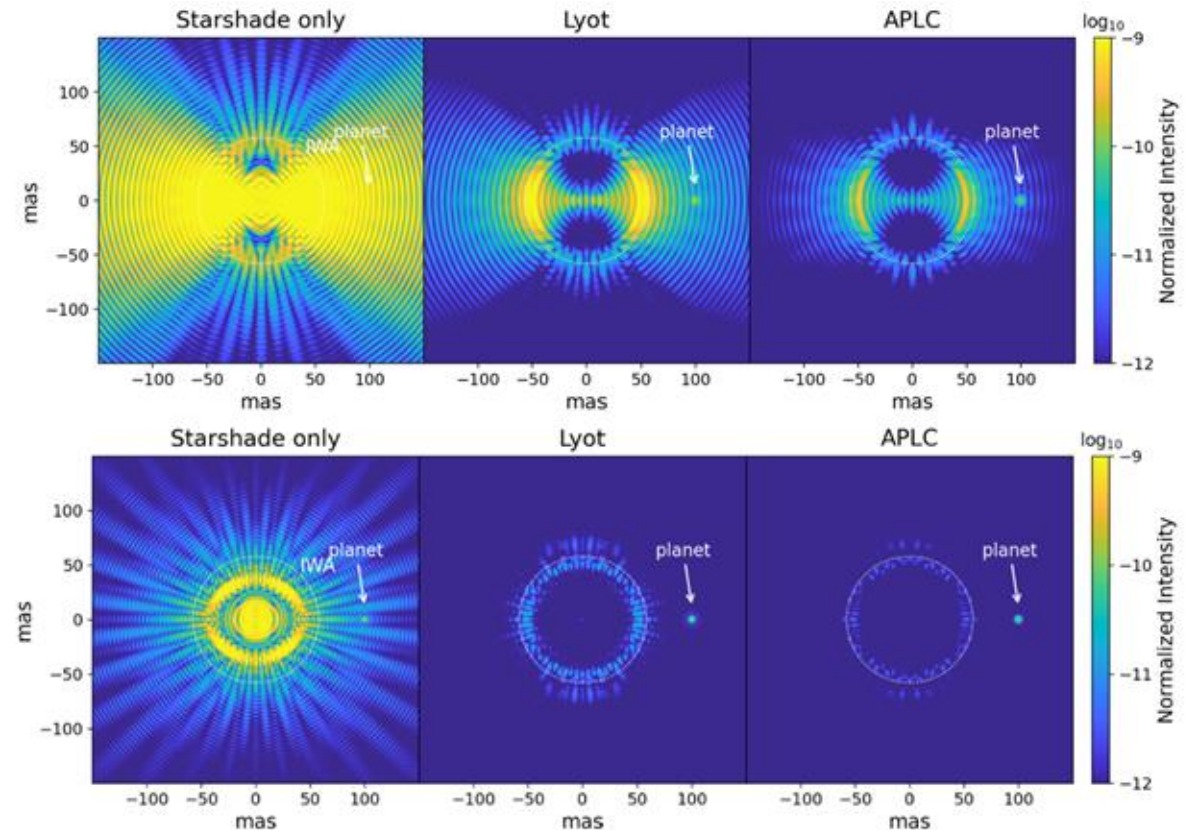


Key finding: ELT with simple APLC Coronagraph APLC

- Increase sky coverage by tilting coronagraph away from Sun. The coronagraph reduces the leakage from the tilted, foreshortened starshade.
- 100x looser tolerance on shape errors > **100 m scale starshade can be built.**
- Enable new science cases >1 μm (O₂ at 1.25 μm).



Starshade tilted 30 deg to LOS



Leakage at the short end, middle, and long end of the bandpass, with and without the coronagraph. Starshade tilt is 29° and lateral offset is 1 m.

Capabilities to build the 99-m starshade

JPL Starshade furled Design

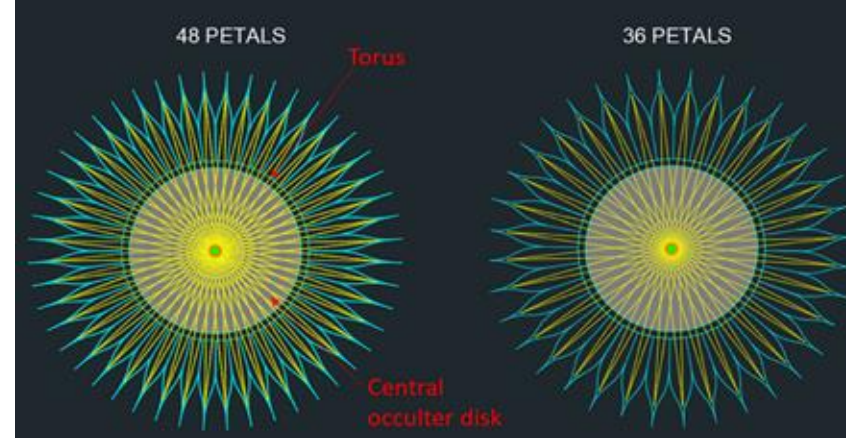
Starshade concept will be stowed within rocket fairings for launch and then deployed in space.



Manan Arya, et, al., "Demonstration of deployment repeatability of key subsystems of a furled starshade architecture" JATIS 2021

NASA NIAC study : Inflatable Starshade

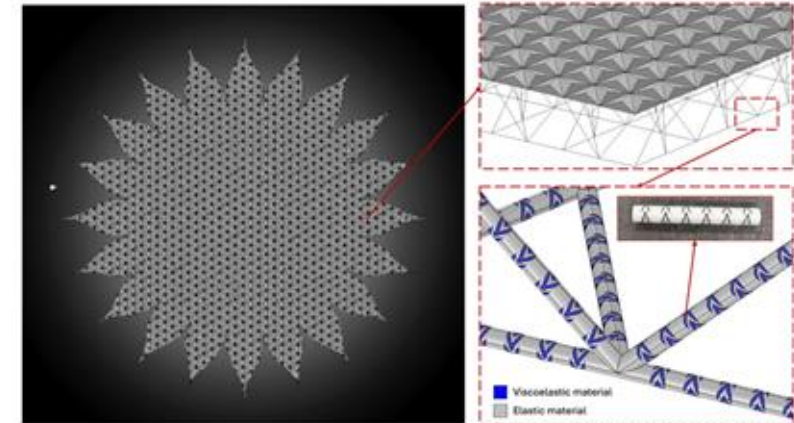
Design the first family of ISEE's (Inflatable Starshade for Earthlike Exoplanets) with sizes from 35 to 100 m diameter.



John Mather, Eliad Peretz, et, al., "Inflatable Starshade for Earthlike Exoplanets" NASA NIAC, 2025.

NASA NIAC study : Metashade

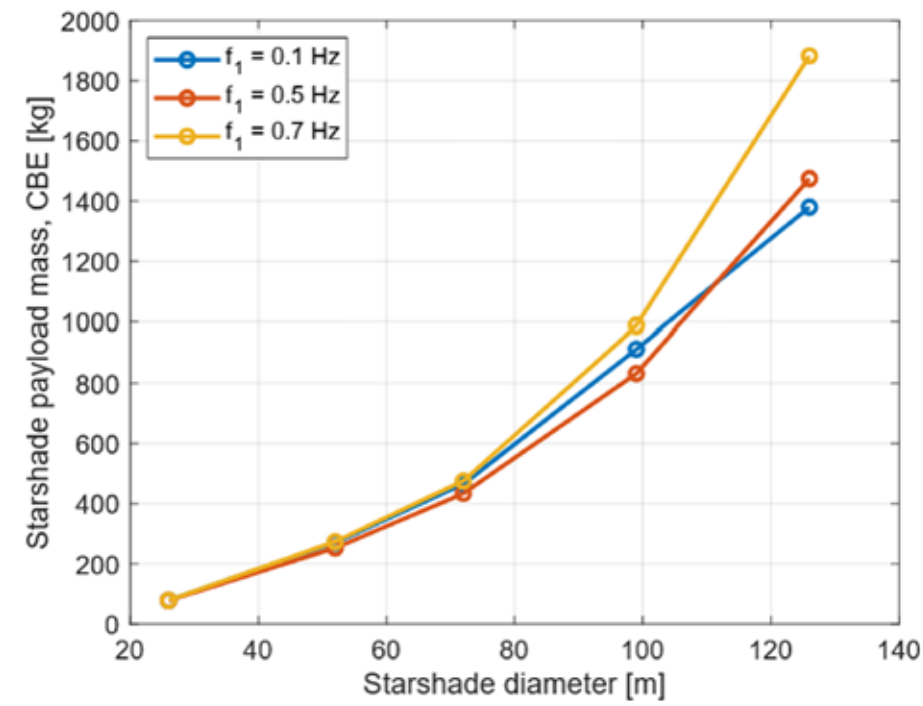
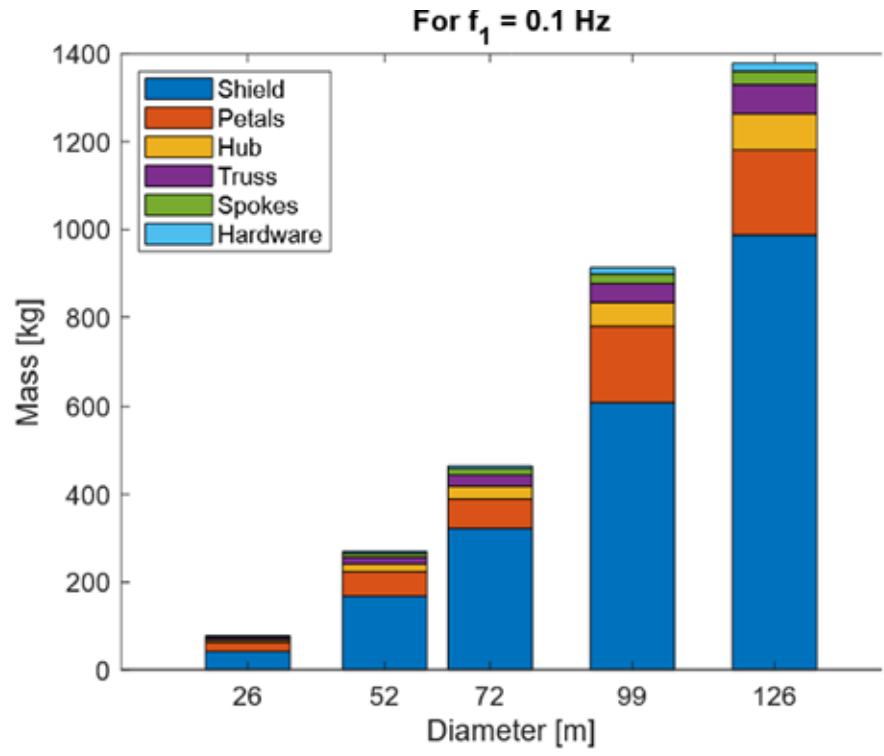
The structure will be assembled on orbit, combining metamaterial modules, creased-plate occulting layers, and petal structures that may use a hybrid assembly -deployment approach.



Christine Gregg, et al., "Dynamically Stable Large Space Structures via Architected Metamaterials" NASA NIAC, 2025.

Key finding: JPL Starshade Furled Design preferred with the most advanced TRL

The wrapped-furled starshade design was optimized to reduce total mass while meeting all required tolerance, accuracy, and shape specifications. Masses between 800 kg and 1000 kg for the 99 m-diameter case are possible toward an ultra light-weight design.



Key finding: Tech Demo Roadmap

Status Quo Demo

- TRL-5 for 10 m disk and 8 m petals based upon completion of the S5 Technology development program
- Meets requirements and demonstrated repeatability

Deployment sequence of the wrapped starshade architecture:

1- M. Arya, et al, (JATIS). DOI: 10.1117/1.JATIS.7.2.021202
2- M. Arya, et al, (Proc. SPIE). DOI:10.1117/12.2275086

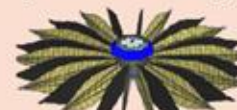
Petal Unfurling



(a)



(b)



(c)

Inner Disk Unfolding



(d)



(e)



Petal length 8 m
Inner disk diameter 10 m

(f)

Scale up

On-orbit demo

- 50 m mid-fidelity shape-accurate starshade
- Ground testing (found various lab facilities to fit)
- Prove accurate deployment on orbit , but no astronomy
- Validates large deployable models

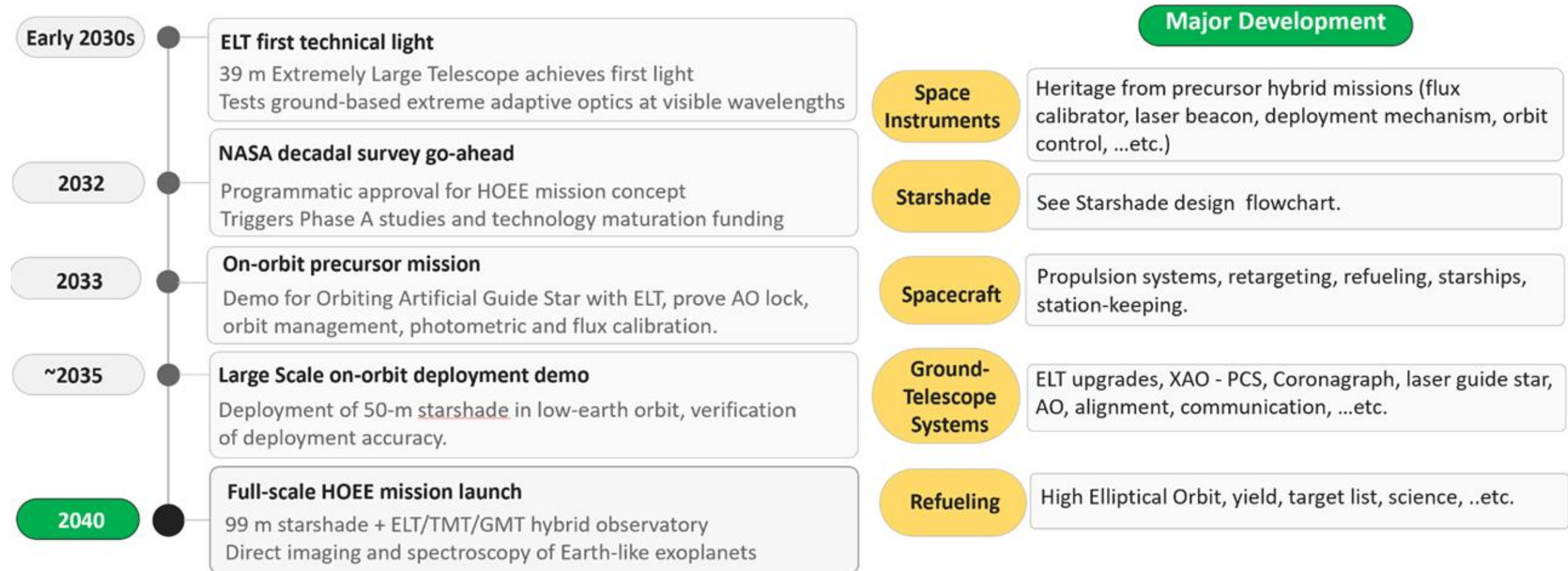
Scale up

Science

- Full-scale 99-m HOEE starshade
- Test inner disk and petals separately on the ground
- Ground deployment demo may be possible at specialized facilities (e.g., Hangar One at NASA Ames)

Mission Timeline

- With first light planned for 2030, the Extremely Large Telescope (ELT) should be ready to operate with a starshade soon after.
- HOEE can serve as a scientific precursor, technology demonstrator, and follow-on to NASA's planned flagship mission, the Habitable Worlds Observatory.
- Compared with a 6-m HWO, HOEE delivers $\sim 1000\times$ faster observations and $6\times$ higher angular resolution, enabling exoplanet measurements through exozodiacal dust and cloud obscuration.
- Precursor missions include ORCAS with an orbiting laser guide star at 200,000 km, and LANDOLT, a multi-laser GEO flux calibrator.



Summary and next steps

- Stay tuned for the final KISS report for further details - https://www.kiss.caltech.edu/final_reports.html
- HOEE provided a unique path for the detection of Earth-like Exoplanets soon (Cost ~\$1B).
- The concept enables the first detection of Earth-like Exoplanets orbiting Sun-like stars, along with key biosignatures such as oxygen and water.
- Advances the fundamental question - “Are we alone in the universe?”
- This concept supports the highest priority recommendation of the Exoplanet Strategy report: search for signs of life by observing reflected light from Earth-like Exoplanets.
- See Dr. Becky Smethurst video about our work - Oxford (<https://rebeccasmethurst.co.uk/public/#youtube>)
- Stay tuned for HOEE NIAC Phase II.



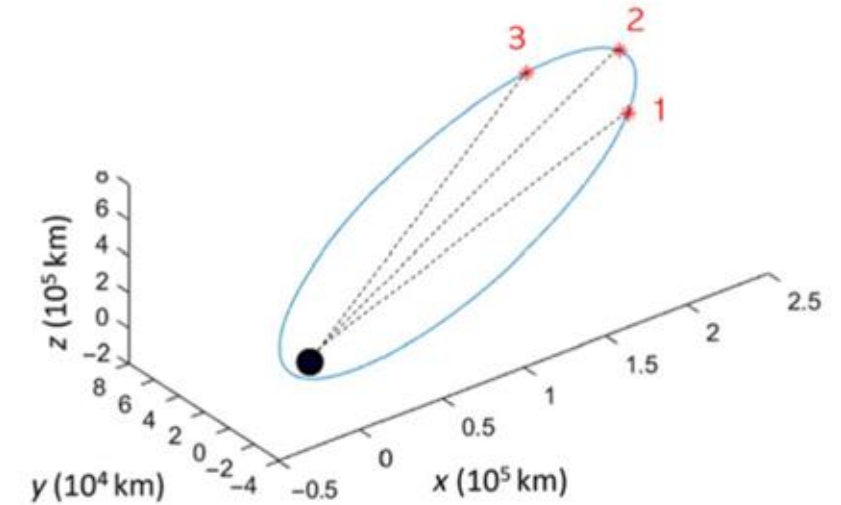
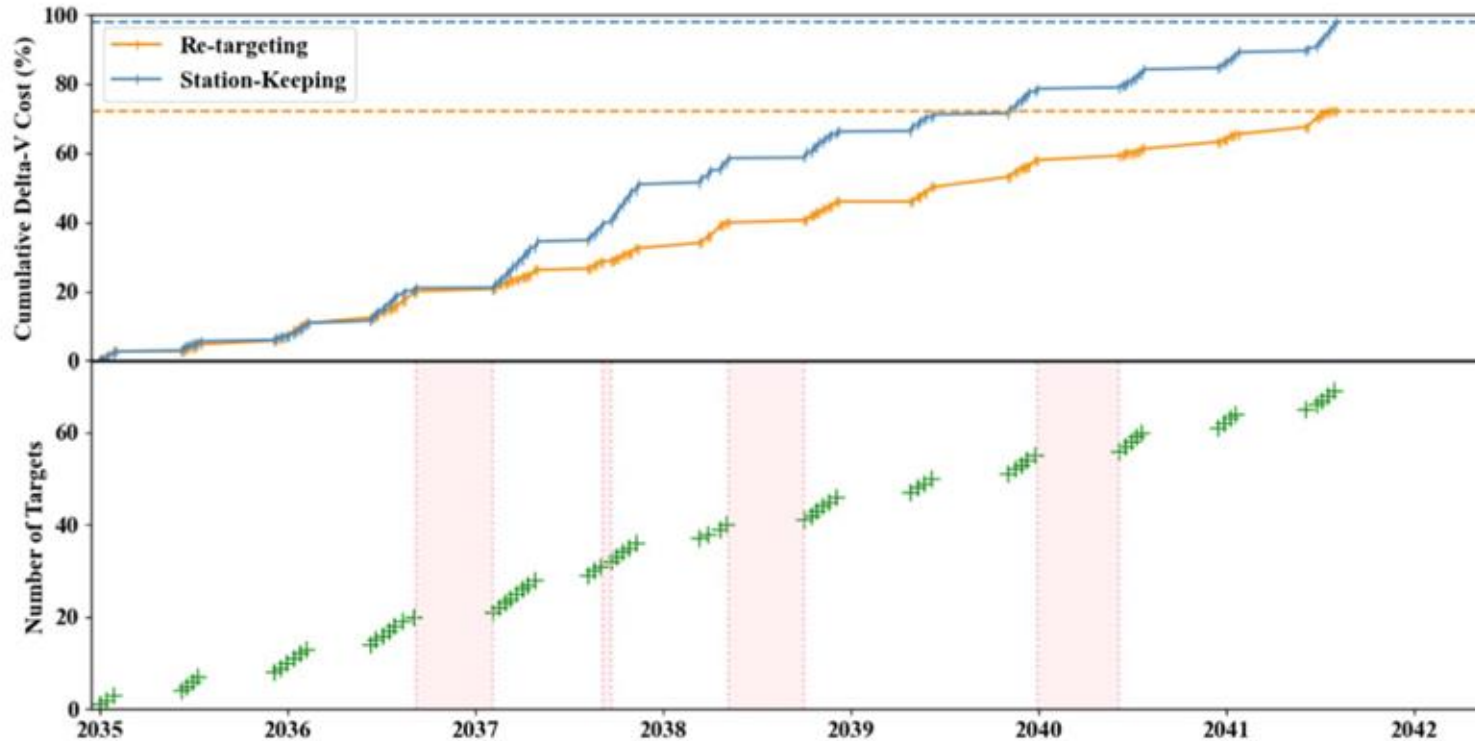
Backup slides

HOEE vs HWO

Category	HOEE	HWO Coronagraph
Advantages	• Highest sensitivity • Highest contrast against exo-zodi • 6× high angular resolution (5.3 mas a 1 μm) • Precise astrometry of orbits • 1000× faster observations • Time-dependent observing capability • Access to high-<i>R</i> spectrometers • Reduced IWA possible via orbit choice (distance) • Potential IR and UV access (depending on telescope details, airglow, and starshade size) • Much Lower Cost • Few minutes for full solar system obs., and couple hours for spectroscopy.	• Can observe roughly half the sky continuously • Good for detecting objects temporarily hidden by the star or inside the IWA • No telluric interference
Disadvantages	• Observations are short and occur only every $N \geq 5$ days; requires careful planning • Fuel-limited for targeting and observing • Earth atmospheric interference for O₂ and H₂O	• Lower contrast, especially near the IWA • Lower spatial and spectral resolution • Cannot perform close-in IR observations

Feasibility of the orbit

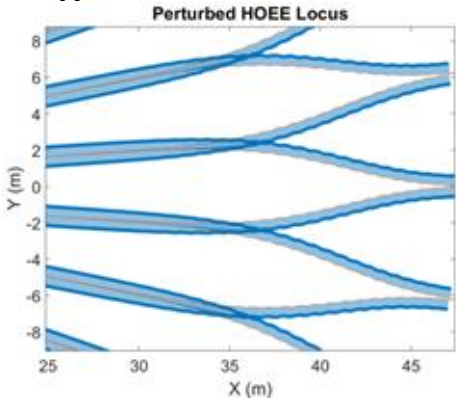
The HOEE mission uses an Astrostationary, highly elliptical orbit (HEO) to remain on target for up to 3 hours, with a minimal use of fuel for station-keeping. It orbits with an apogee at least 170,000 km from Earth, to match its motion with the motion of the observatory as the Earth rotates.



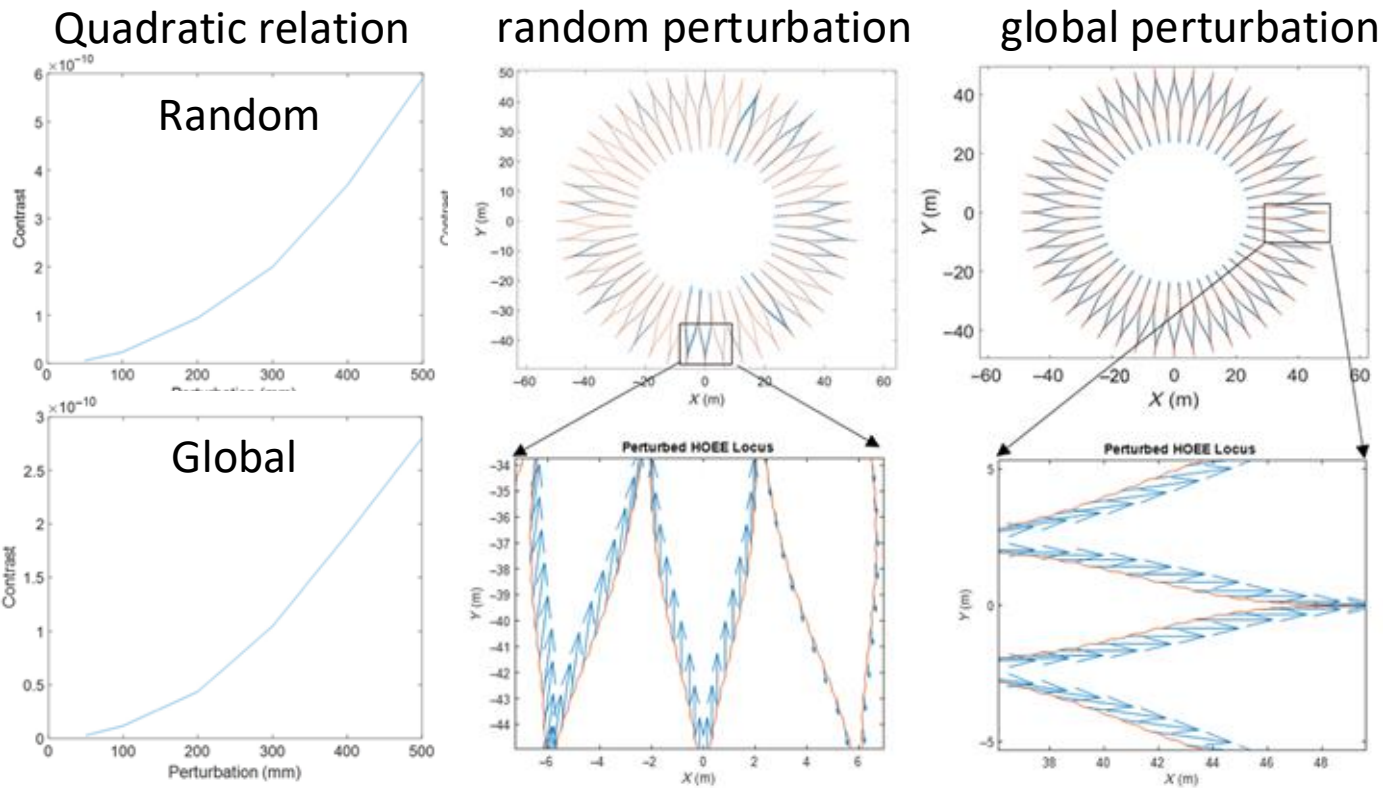
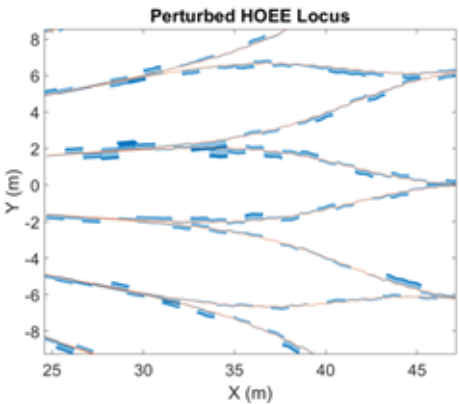
The 99-m starshade design requirements

- Our study shows that these errors are highly tolerable: 10's of mm in petal position and hundreds of microns in petal shape- demonstrating the robustness of the design.

Global



Random



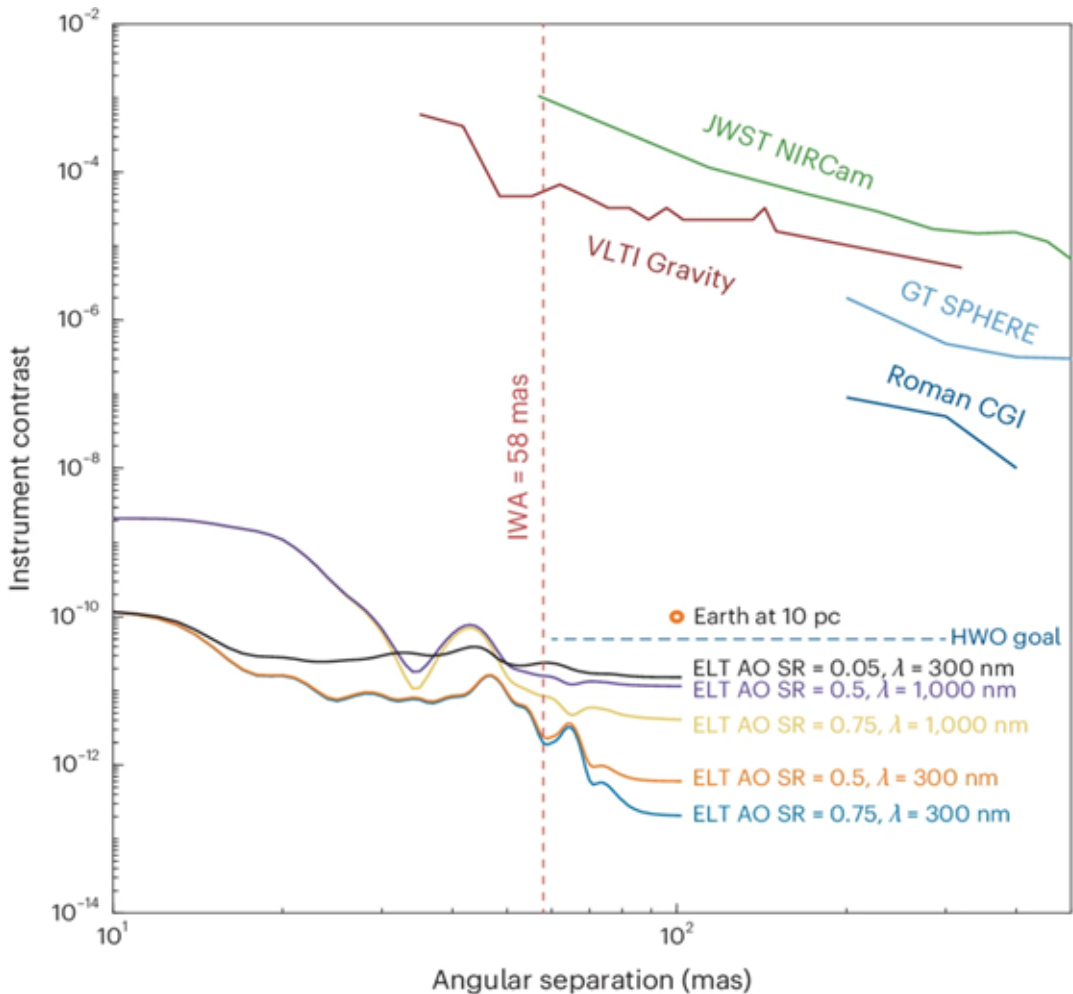
Allowable perturbations resulting in a contrast increase of 5×10^{-12} per perturbation at IWA = 58 mas.

Perturbation list	Perturbation type	Amplitude
Petal displacement	Radial/global	46 mm (fixed)
	Radial/random	66 mm (1σ)
Segment displacement	Vertical direction	280 μ m
Petal clocking	Random	4.2 mradians (1σ)
Formation offset error (RA and DEC)		Shift = 1.65 mas

Soliman, A., Mather, J., Shaklan, S. *et al.* " Optical Performance of Hybrid Observatory for Earth-like Exoplanets", *JATIS*, Vol. 11, Issue 1, 014002 (March 2025). <https://doi.org/10.1117/1.JATIS.11.1.014002>

HOEE compared to others

Our model predicts an imaging contrast after ELT AO atm., sufficient model to detect the Earth-like Exoplanets at $\sim 1 \times 10^{-10}$.



Category	HOEE	HWO Coronagraph
Advantages	• Highest sensitivity • Highest contrast against exozodi • 6× high angular resolution (5.3 mas a $1 \mu\text{m}$) • Precise astrometry of orbits • 1000× faster observations • Time-dependent observing capability • Access to high-R spectrometers • Reduced IWA possible via orbit choice (distance) • Potential IR and UV access (depending on telescope details, airglow, and starshade size) • Much Lower Cost • Few minutes for full solar system obs., and couple hours for spectroscopy.	• Can observe roughly half the sky continuously • Good for detecting objects temporarily hidden by the star or inside the IWA • No telluric interference
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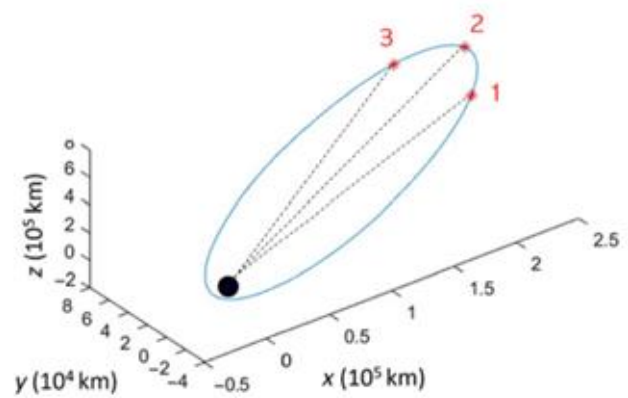
Outline

- Hybrid Ground-Space Exoplanet Observatory - HOEE
- Science cases that HOEE could uniquely enable.
- Key capabilities
 - Full solar system observation in few minutes.
 - Spectroscopy in couple hours.
- Observation, targets, orbit, and Launch vehicles.
- Capabilities to build the 99-m starshade
- Starshade Tech demo roadmap
- Summary of Caltech KISS Study Key findings, March 9-13, 2026 (Final in-progress KISS Report).



Observational (when we look) , targets, and orbit

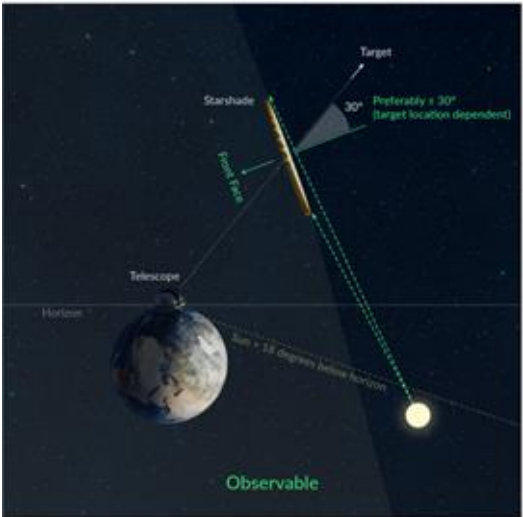
- HOEE uses an Astrostationary, highly elliptical orbit (HEO) with an apogee $\geq 170,000$ km to remain on target for up to 3 hours while minimizing station-keeping fuel. The mission targets >80 randomly distributed LUNAR FGK stars, enabling 160 observations over 7 years with four refueling missions (2-year baseline). Key drivers are $<2,000$ kg spacecraft mass and deployment of a 100 m starshade. Updated DRM details are in the final KISS report.



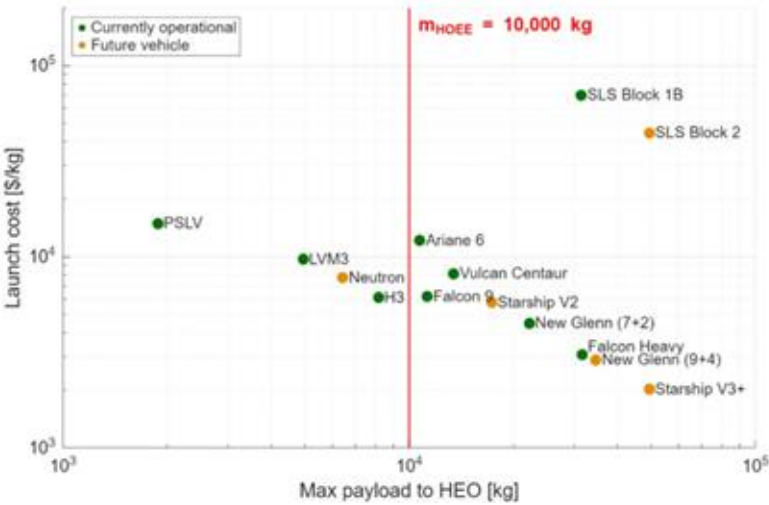
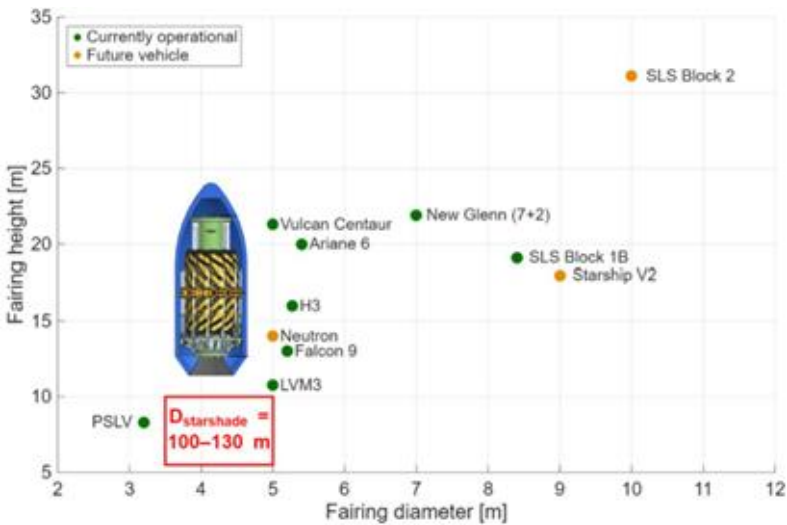
HEO - Ref: Peretz, et al, JATIS, 2021.

System	Sp. Type	# Total Planets	# HOEE Planets	# $<M_{Nep}$ HOEE planets
G 192-15	M5.0 V	2	1	1
GJ 1151	M4.5 V	1	1	1
GJ 229A*	M1.5 V	2	2	2
GJ 514	M1 V	1	1	1
GJ 667	M1.5 V	5	1	1
GJ 876	M2.5 V	4	1	1
GJ 887*	M1 V	4	1	1
HD 180617	M3 V	1	1	1
HD 20794	G6 V	4	3	3
HD 219134	K3 V	6	2	1
HD 95735	M1.5 V	2	1	1
Kapteyn	M2.0 V	1	1	1
Wolf 1061	M3.5 V	3	1	1
tau Cet*	G8.5 V	4	3	3

Known Planets for HOEE



Observational Geometry



Launch vehicle characteristics

Science cases that HOEE could uniquely enable (STM)

Science goal	Science objective	Measurement requirement	Observatory implication
Atmospheric habitability and oxygen-bearing biosignature characterization, including complementary out-of-band science at 1.0–1.7 μm enabled by the ELT coronagraph (Section 4.2)	Detect H_2O , search for O_2 and O_3 , and assess atmospheric composition, clouds, hazes, and plausible abiotic alternatives	Reflected-light spectra over 400–1000 nm with sufficient SNR to constrain the O_2 A-band near 0.76 μm , the O_3 Chappuis band, H_2O , CH_4 where detectable, Rayleigh scattering, cloud properties, and pressure-sensitive spectral features; CO and CO_2 require extended wavelength coverage or complementary observations	Low- to moderate-resolution spectroscopy with stable photometric calibration; preserve sensitivity near the O_2 A-band and across the O_3 Chappuis band; define complementary 1.0–1.7 μm observations for H_2O , CH_4 , CO_2 , and CO context
Methane and atmospheric disequilibrium, including high-resolution spectroscopy at $\lambda > 1 \mu\text{m}$	Detect CH_4 -bearing atmospheres and distinguish biological, geological, and volatile-rich sub-Neptune scenarios	Interpret CH_4 jointly with H_2O , O_2/O_3 , pressure-sensitive scattering features, planetary radius and mass, stellar irradiation, and CO/CO_2 constraints where available	Require broad wavelength coverage, complementary near-infrared spectroscopy, and external mass and radius constraints; prioritize CO and CO_2 measurements for the most compelling CH_4 detections
Surface and cloud variability	Detect rotational and phase-dependent variability caused by clouds, surface heterogeneity, ice, land-ocean contrast, and broad albedo features	Time-resolved photometry and spectroscopy over multiple rotational and orbital phases, with sufficient precision and cadence to distinguish persistent surface signals from evolving clouds and measurement noise	Plan repeated observations across rotational and orbital phases; require stable relative photometric calibration; evaluate polarimetry as a complementary capability
Comparative planetology and population-level science enabled by efficient broadband observations	Measure trends in atmospheric retention, cloud and haze occurrence, surface diversity, and biosignature-candidate occurrence across the accessible target sample	Quantified selection functions for detections and non-detections, with consistent retrievals and hierarchical analysis of atmospheric and planetary properties across targets	The DRM must preserve detection completeness, achieved sensitivity, integration time, exozodiacal background, stellar properties, observing geometry, and cadence for each target
Planetary-system architectures enabled by wide angular coverage	Detect multiple planets, constrain their orbits, relate system architecture to habitability, and test planet-formation theories through the relative occurrence and co-occurrence of inner rocky planets and outer gas giants	Multi-epoch astrometry, angular separations, broadband colors or spectra, and orbital motion for multiple planets over the mission lifetime	Provide a sufficiently wide field of view for multi-planet imaging and repeated astrometric observations; use precursor radial-velocity and astrometric constraints to optimize target selection and scheduling
Exozodiacal dust and planet detection in dusty systems	Resolve habitable-zone dust, quantify its impact on planet detection and characterization, and investigate disk structures that trace planetary-system dynamics	Visible scattered-light imaging of disk surface brightness, morphology, color, and spatial structure at contrasts relevant to exo-Earth observations	Require high angular resolution, stable background calibration, and disk-planet separation methods; include exozodiacal brightness and structure in the DRM completeness and noise models

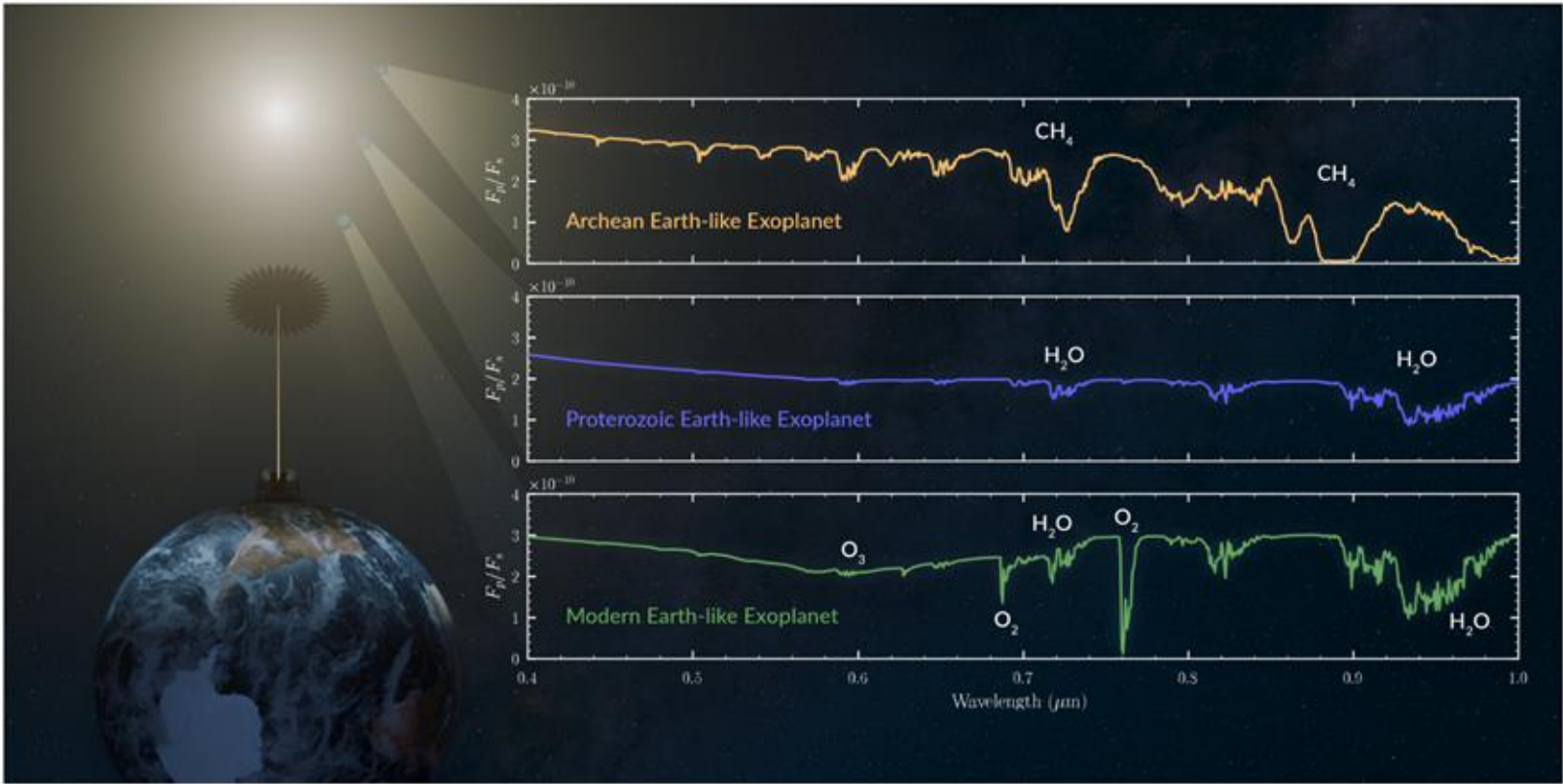


Image credit: Keck Institute for Space Studies / Keith Miller (Caltech/IPAC – SELab)

Caltech KISS study – March 9-13, 2026.



- Caltech KISS study: <https://www.kiss.caltech.edu/workshops/hybrid/hybrid.html>
- NASA STMD and NIAC office news: <https://www.nasa.gov/directorates/stmd/nasa-research-proposes-technology-to-look-for-earth-like-exoplanets/>
- Stay tuned for the final KISS report soon.
- Our SPIE KISS manuscript: Ahmed Soliman, Stuart Shaklan, John Mather, et al. "Toward a hybrid ground-space exoplanet observatory: summary of Caltech Keck Institute for Space Studies (KISS) report", Proc. SPIE 14145, Space Telescopes and Instrumentation 2026: Optical, Infrared, and Millimeter Wave, 141455U (21 Aug 2026); <https://doi.org/10.1117/12.3105590>