Recent Advances in Established Starlight Suppression Technologies

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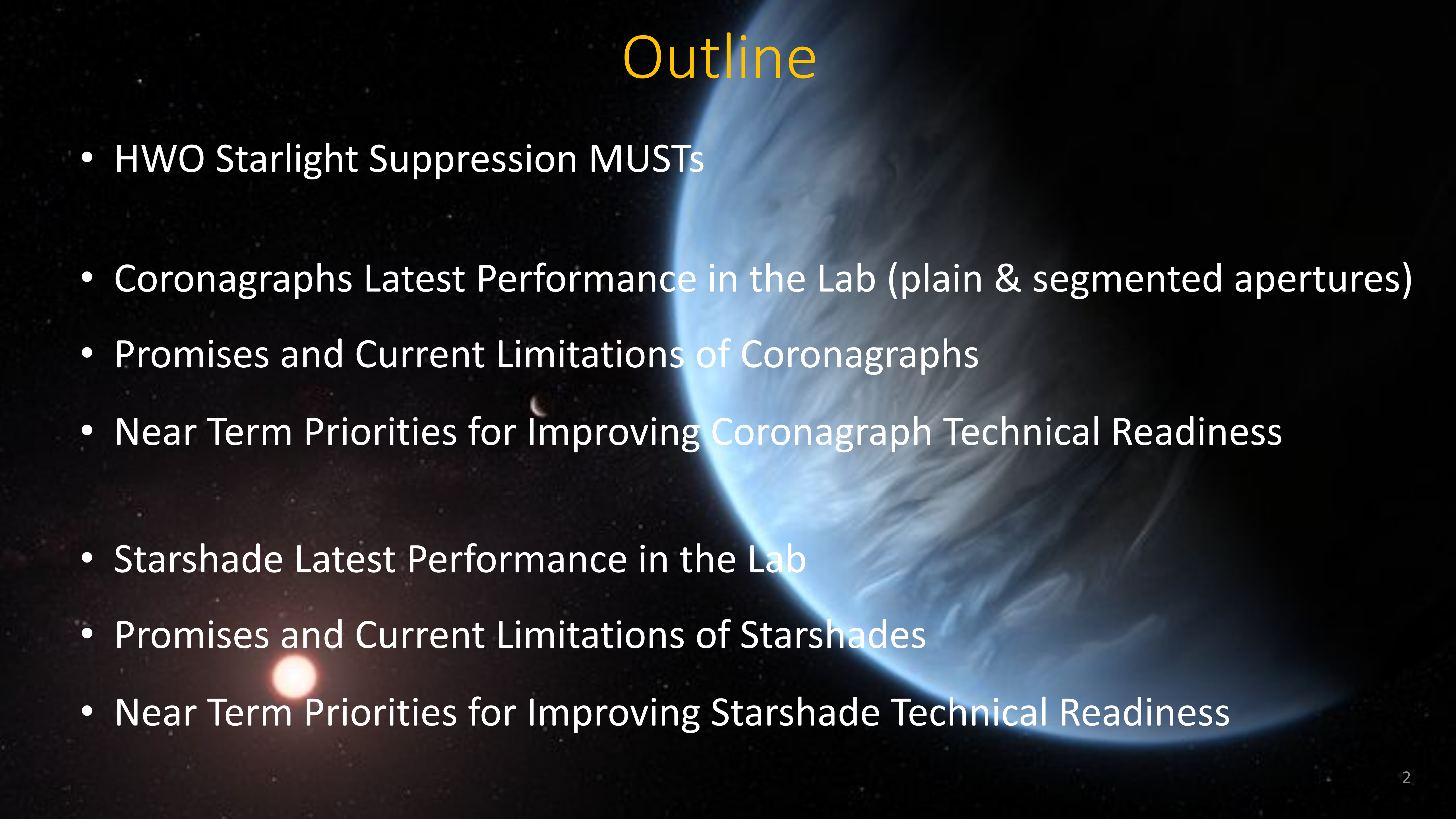
The research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. CL#23 0197

Starlight Suppression Technologies for HWO Flagship
Seattle AAS meeting Splinter Session January 10, 2023

Image credit: Mark Garlick, space-art.co.uk

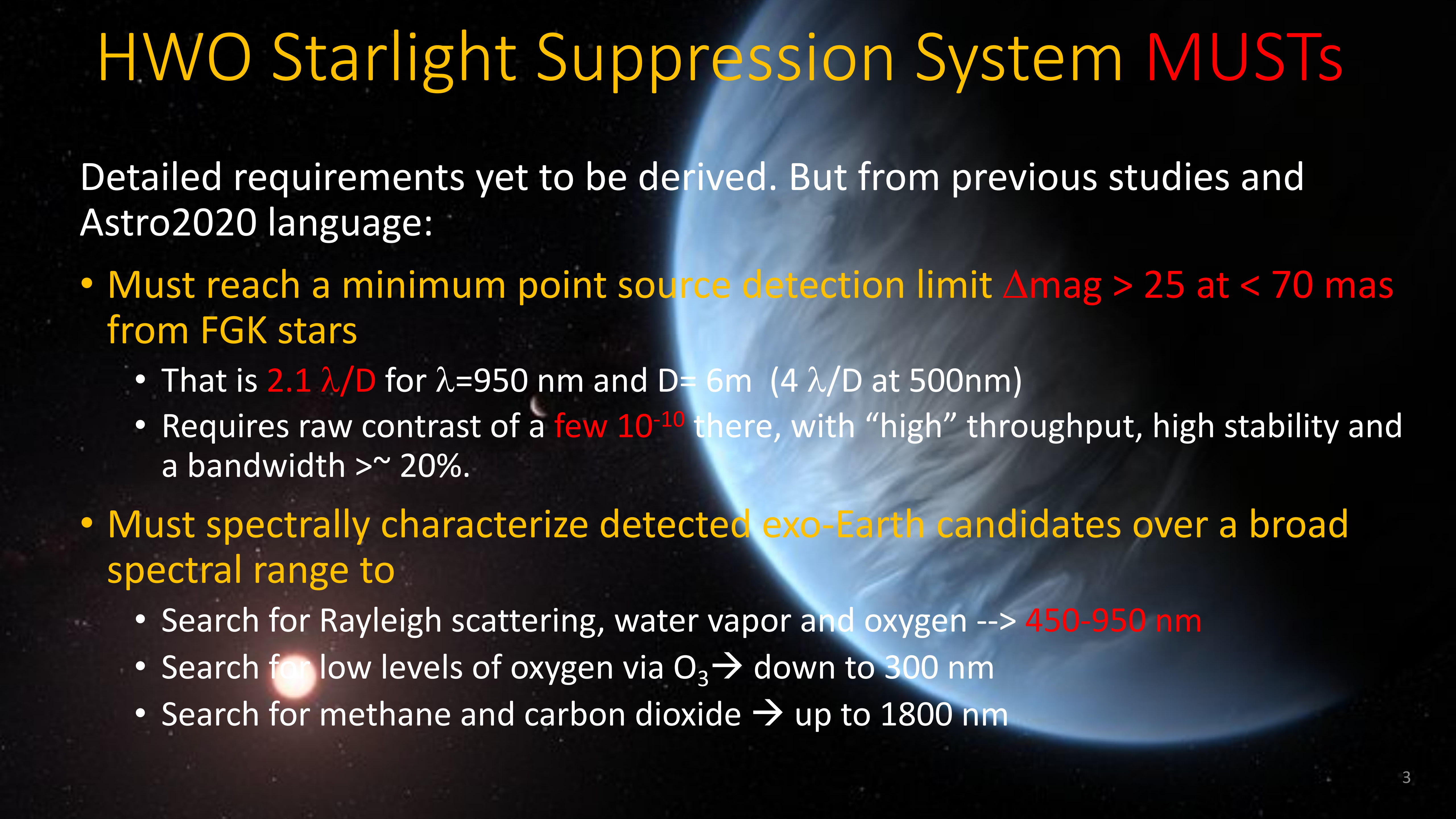
Outline



- HWO Starlight Suppression MUSTs

- Coronagraphs Latest Performance in the Lab (plain & segmented apertures)
- Promises and Current Limitations of Coronagraphs
- Near Term Priorities for Improving Coronagraph Technical Readiness

- Starshade Latest Performance in the Lab
- Promises and Current Limitations of Starshades
- Near Term Priorities for Improving Starshade Technical Readiness



HWO Starlight Suppression System MUSTs

Detailed requirements yet to be derived. But from previous studies and Astro2020 language:

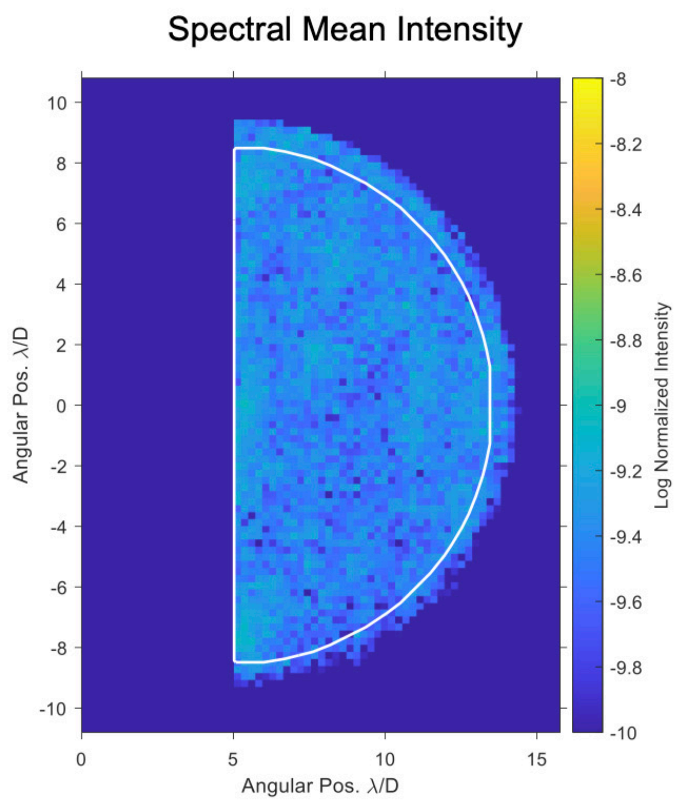
- Must reach a minimum point source detection limit Δmag > 25 at < 70 mas from FGK stars
  - That is 2.1 λ/D for λ=950 nm and D= 6m (4 λ/D at 500nm)
  - Requires raw contrast of a few 10^{-10} there, with “high” throughput, high stability and a bandwidth >~ 20%.
- Must spectrally characterize detected exo-Earth candidates over a broad spectral range to
  - Search for Rayleigh scattering, water vapor and oxygen --> 450-950 nm
  - Search for low levels of oxygen via O_3 → down to 300 nm
  - Search for methane and carbon dioxide → up to 1800 nm

Coronagraphs Current Lab Performance: unobscured aperture

Unobscured circular pupil with simple Lyot Coronagraph in vacuum:

4 x 10 ^{10} contrast (1 polar), JPL HCIT Team – Decadal Survey Testbed (DST)

- Over 10% BW, averaging from 3-10 λ/D, 360° DH *(Seo, B.J. et al SPIE 2019)*
- Over 20% BW, from 5.5-13 λ/D, one-sided DH

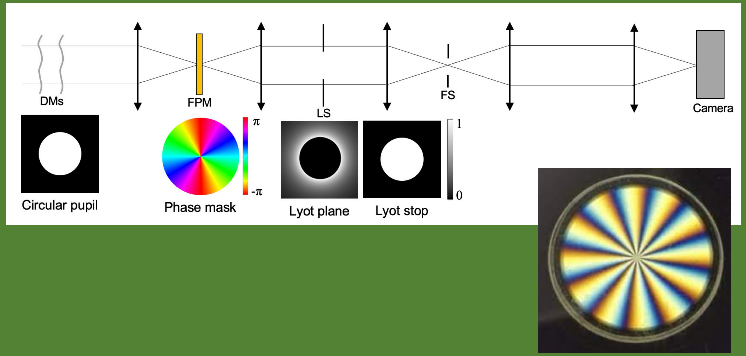

Spectral Mean Intensity

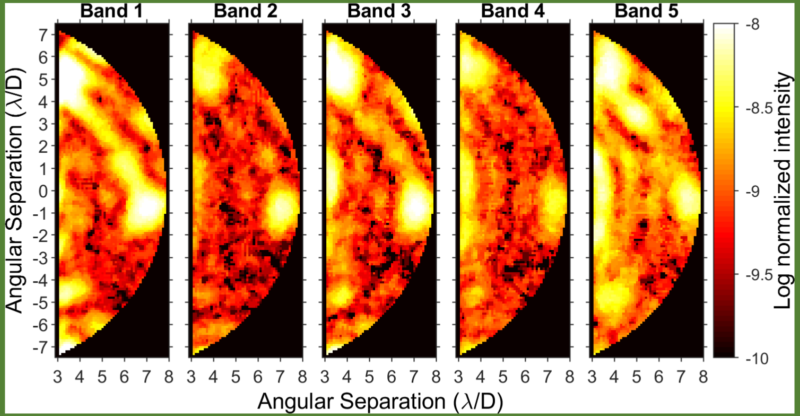
Smaller IWA, higher throughput and resilience to aberrations

Unobscured circular pupil with Vector Vortex (VVC6) Coronagraph in vacuum:

JPL HCIT Team DST *(Ruane, G. et al. SPIE 2022)*:

- 5.9 x 10 ^{9} contrast over 20% BW, averaging from 3-8 λ/D, one-sided DH, 1 polar
- 1.6 x 10 ^{9} contrast over 10% BW, averaging from 3-8 λ/D, one-sided DH, 1 polar



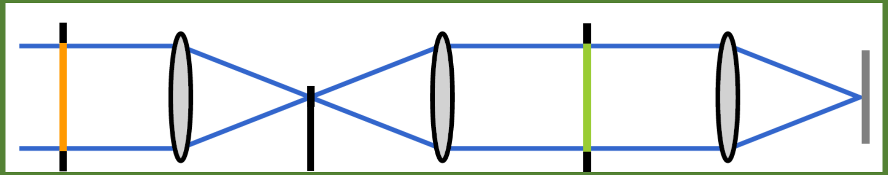


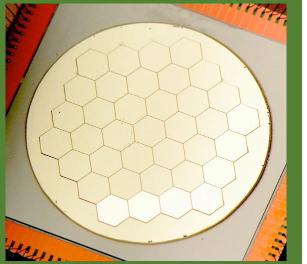
Coronagraphs Current Lab Performance: obscured apertures

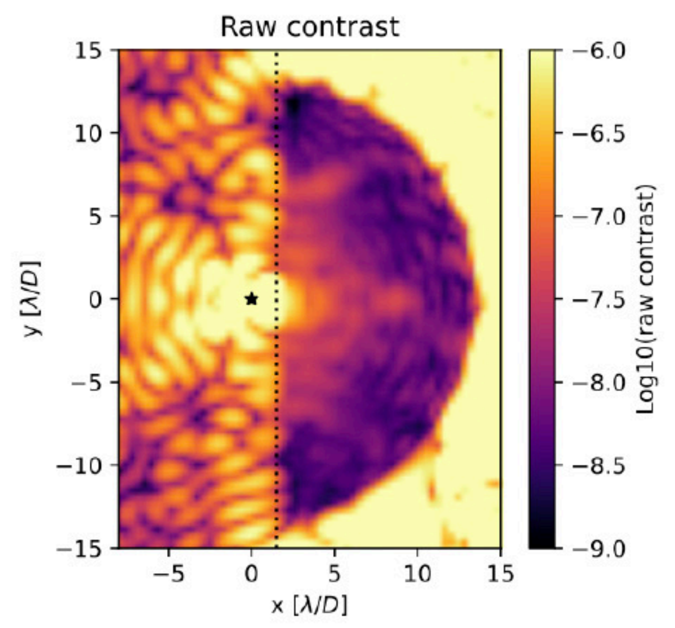
Segmented Pupil: 37 hexagons, no central obscuration Phase Apodized Pupil Lyot Coronagraph (PAPLC) in air:

STScI HiCAT Testbed *(Soummer et al. SPIE 2022, Por, E.H. et al. ApJ 2020)*:

- 2 x 10^{8} monochromatic contrast averaging from 2-13 λ/D, one-sided DH, unpolarized light







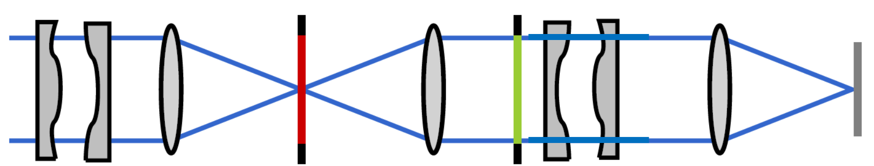
Off-axis to on axis

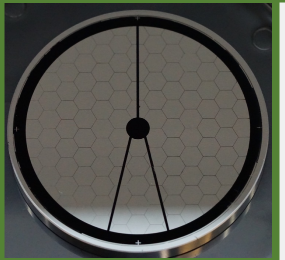
In air to vacuum

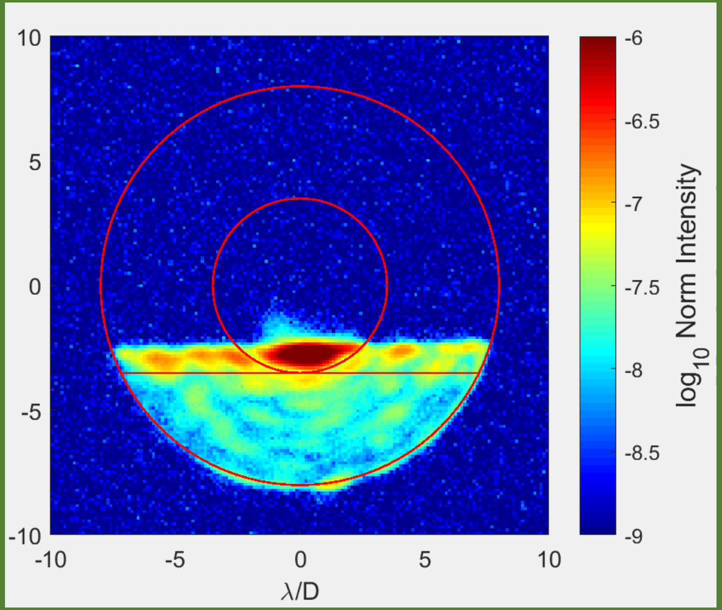
Segmented Pupil: 120 hexagons, central obscuration and spiders - Phase Induced Apodization Complex Mask Coronagraph (PIAACMC) in vacuum:

JPL HCIT Testbed *(Belikov, Sirbu, Marx et al. 2021)*:

- 1.8 x 10^{8} monochromatic contrast averaging from 3.5-8 λ/D, one-sided DH, polarized light





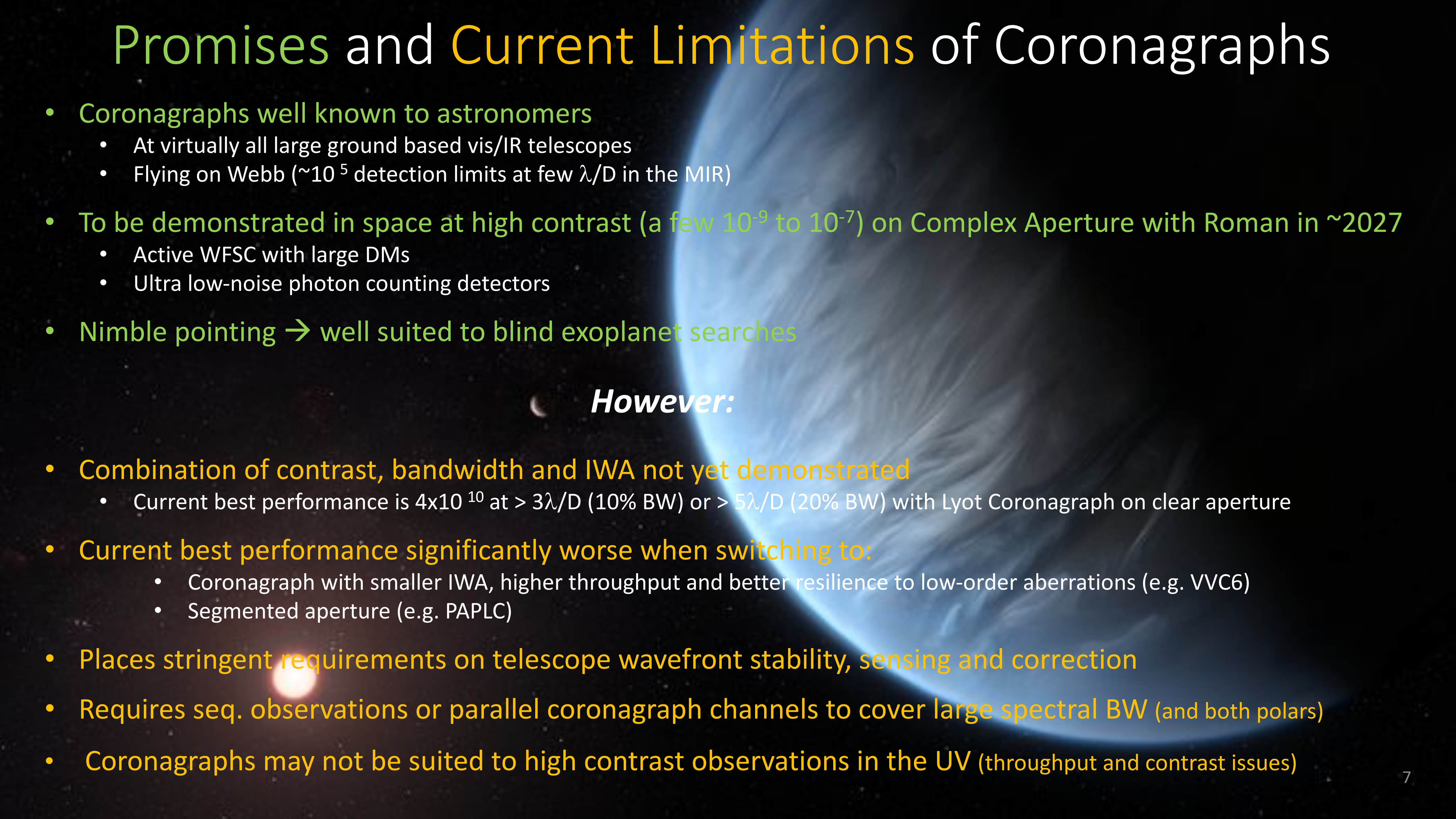


Coronagraph Current Performance in the Lab (vs 2020)

Coronagraph Type	**Classical Lyot**	**Vector Vortex charge 6**	**Phase Apodized Pupil Lyot Coronagraph**	**Phase Induced Amplitude Apodization Coronagraph**
Aperture Type	**Circular unobscured (= off-axis Monolith)**		**Off-axis Segmented**	**Circular on-axis segmented**
Deformable Mirrors	2 AOX (each 48 x 48)	2 AOX (each 48 x 48)	2 BMC MEMs (each 952 actus)	1 BMC MEMs (952 actus)
Separation Range	5-13.5 λ/D (vs 3-10 l/D)	3-8 λ/D	2 – 13 λ/D	3.5 – 8 λ/D
Dark Hole Azimuthal Extent (deg)	180 (vs 360)	180	180	180
Mean Raw Contrast over Sep. Range	4×10^{-10} (idem)	5.9×10^{-9} (10^{-8})	2×10^{-8}	1.8×10^{-8}
Central wavelength (nm)	550	635	638	650
Spectral bandwidth	20% (10%)	20% (10%)	Monochromatic	10%
Number of polarizations	1	1	2	1
Off-axis Throughput	medium	high	high	high
Sensitivity to low order aberrations	medium	low	medium	medium
Facility	JPL HCIT Testbed	JPL HCIT Testbed	STScI HiCAT Testbed	JPL HCIT Testbed
Vacuum Operation	Y	Y	**N**	Y

Currently demonstrated static contrast performance degrades when moving toward coronagraphs with higher throughput and lower sensitivity to aberrations, moving from monolithic to segmented apertures, and from off-axis to on-axis

Promises and Current Limitations of Coronagraphs



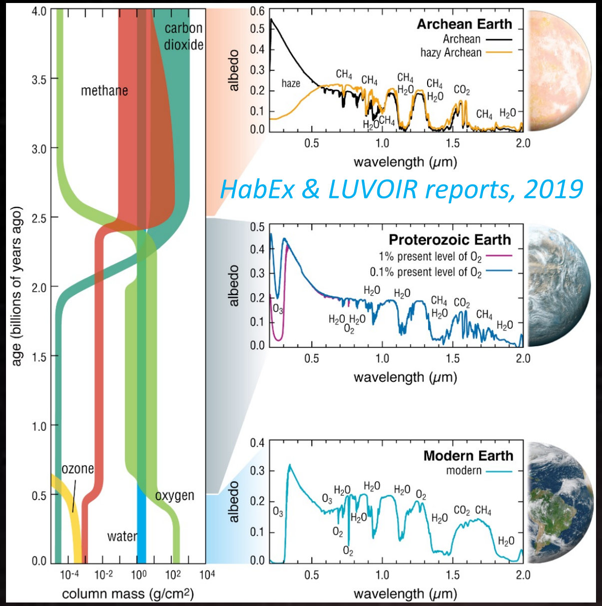
- Coronagraphs well known to astronomers
  - At virtually all large ground based vis/IR telescopes
  - Flying on Webb (~10^{5} detection limits at few λ/D in the MIR)
- To be demonstrated in space at high contrast (a few 10^{-9} to 10^{-7}) on Complex Aperture with Roman in ~2027
  - Active WFSC with large DMs
  - Ultra low-noise photon counting detectors
- Nimble pointing → well suited to blind exoplanet searches

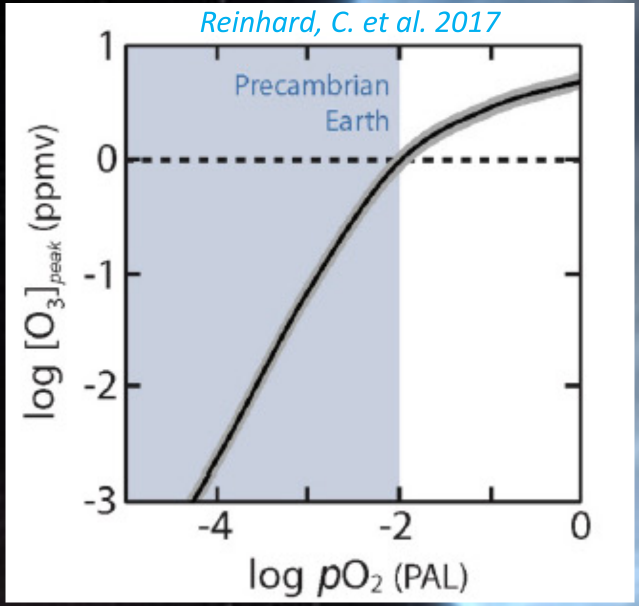
However:

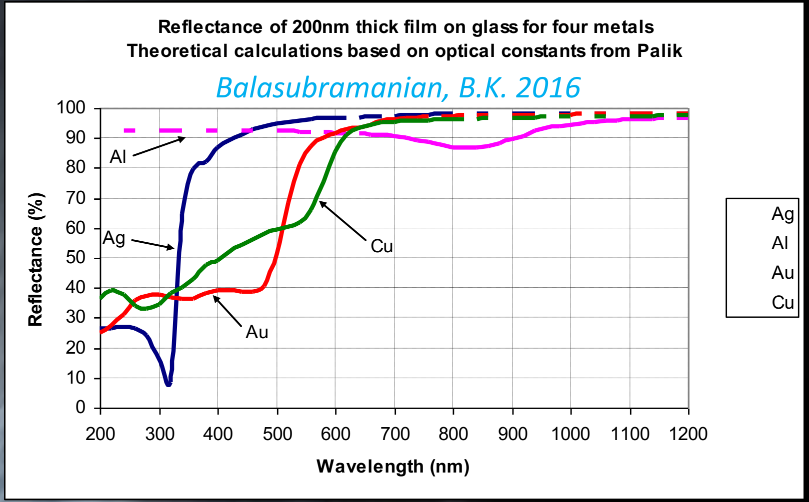
- Combination of contrast, bandwidth and IWA not yet demonstrated
  - Current best performance is 4x10^{10} at > $3\lambda/D$ (10% BW) or > $5\lambda/D$ (20% BW) with Lyot Coronagraph on clear aperture
- Current best performance significantly worse when switching to:
  - Coronagraph with smaller IWA, higher throughput and better resilience to low-order aberrations (e.g. VVC6)
  - Segmented aperture (e.g. PAPLC)
- Places stringent requirements on telescope wavefront stability, sensing and correction
- Requires seq. observations or parallel coronagraph channels to cover large spectral BW (and both polars)
- Coronagraphs may not be suited to high contrast observations in the UV (throughput and contrast issues)

Benefits and Challenges of UV Coronagraphy

- “The most sensitive indicator of atmospheric O_2 is the UV O_3 (Hartley-Huggins) band, which would have created a measurable impact on Earth’s spectrum for ~50% of its history to date, versus ~10% for O2”. *Schwieterman, E. et al. 2019*


HabEx & LUVOIR reports, 2019

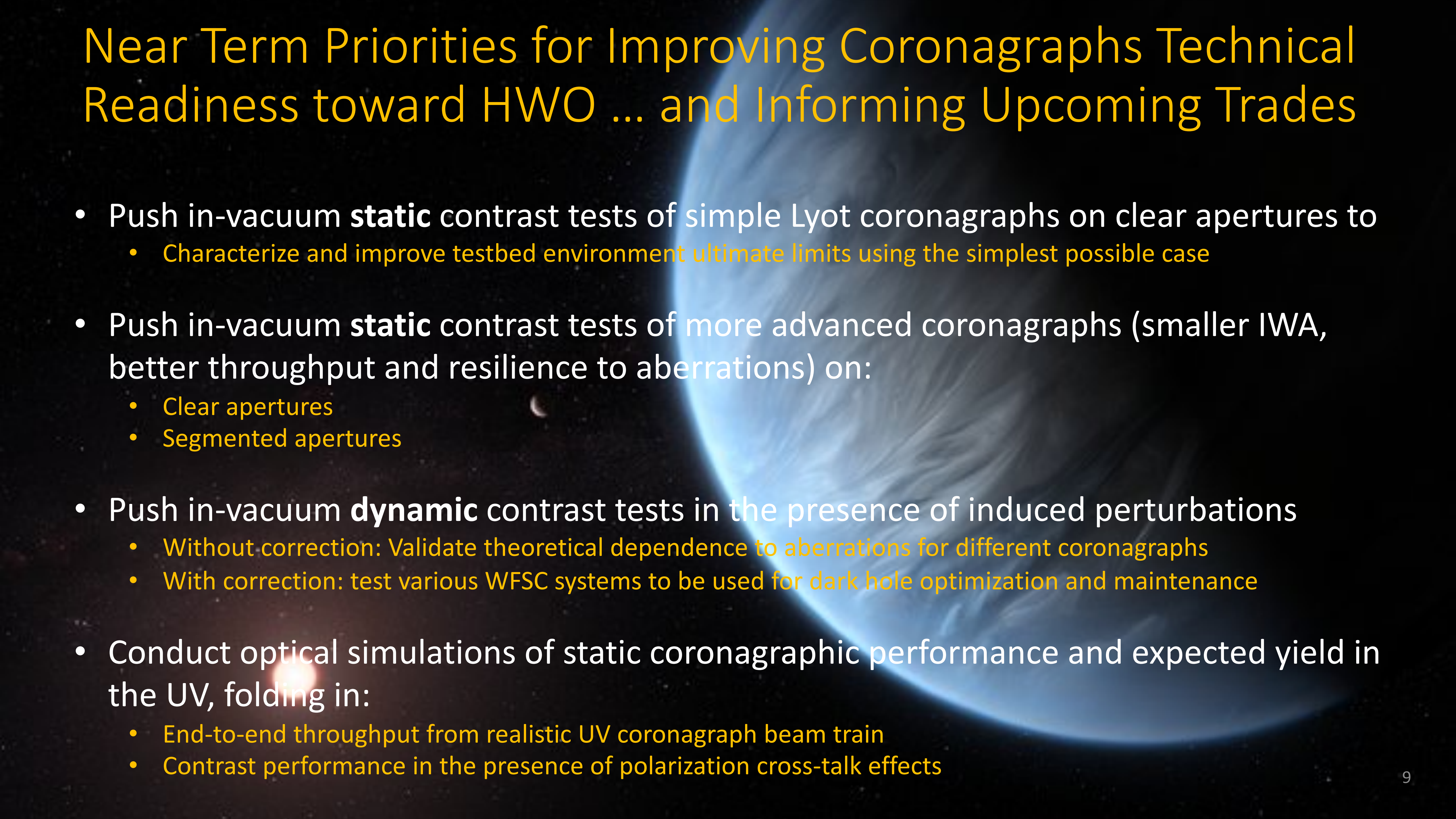

Reinhard, C. et al. 2017


Reflectance of 200nm thick film on glass for four metals
Theoretical calculations based on optical constants from Palik
Balasubramanian, B.K. 2016

However

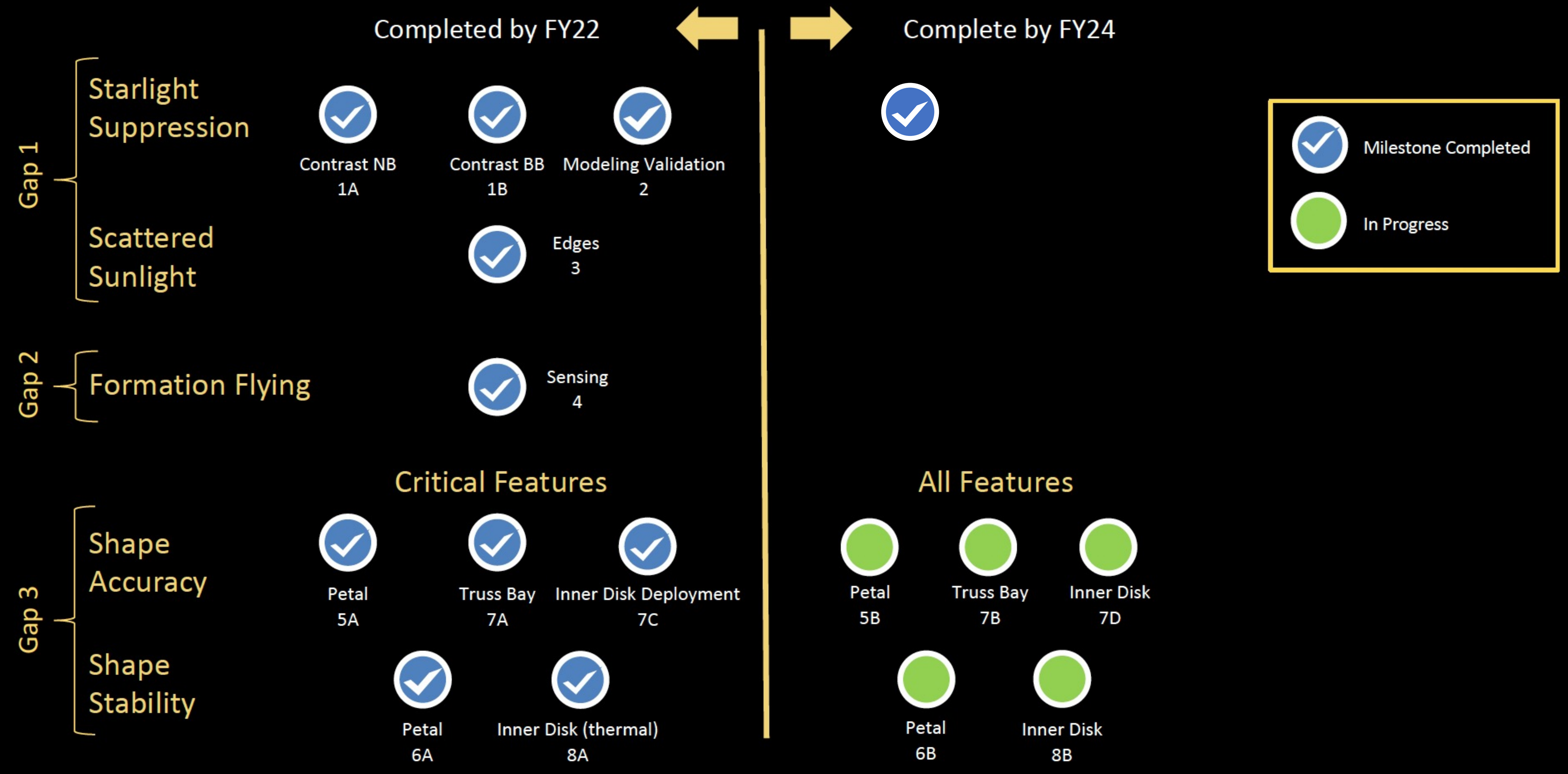
- Planets are much fainter in the UV!
- UV Throughput is low! UV reflectivity per surface is no better than 92% (for bare Al) and coronagraphs need many optics (15 on CGI)
- WFC reqts scale as λ
- Birefringence is generally higher in the UV, inducing incoherent “polarization aberrations”

Near Term Priorities for Improving Coronagraphs Technical Readiness toward HWO … and Informing Upcoming Trades



- Push in-vacuum **static** contrast tests of simple Lyot coronagraphs on clear apertures to
  - Characterize and improve testbed environment ultimate limits using the simplest possible case
- Push in-vacuum **static** contrast tests of more advanced coronagraphs (smaller IWA, better throughput and resilience to aberrations) on:
  - Clear apertures
  - Segmented apertures
- Push in-vacuum **dynamic** contrast tests in the presence of induced perturbations
  - Without correction: Validate theoretical dependence to aberrations for different coronagraphs
  - With correction: test various WFSC systems to be used for dark hole optimization and maintenance
- Conduct optical simulations of static coronagraphic performance and expected yield in the UV, folding in:
  - End-to-end throughput from realistic UV coronagraph beam train
  - Contrast performance in the presence of polarization cross-talk effects

Starshades Current Performance in the Lab



		Completed by FY22	Complete by FY24
Gap 1	Starlight Suppression	✓ Contrast NB 1A ✓ Contrast BB 1B ✓ Modeling Validation 2	✓
	Scattered Sunlight	✓ Edges 3	
Gap 2	Formation Flying	✓ Sensing 4	
		Critical Features	All Features
Gap 3	Shape Accuracy	✓ Petal 5A ✓ Truss Bay 7A ✓ Inner Disk Deployment 7C	● Petal 5B ● Truss Bay 7B ● Inner Disk 7D
	Shape Stability	✓ Petal 6A ✓ Inner Disk (thermal) 8A	● Petal 6B ● Inner Disk 8B

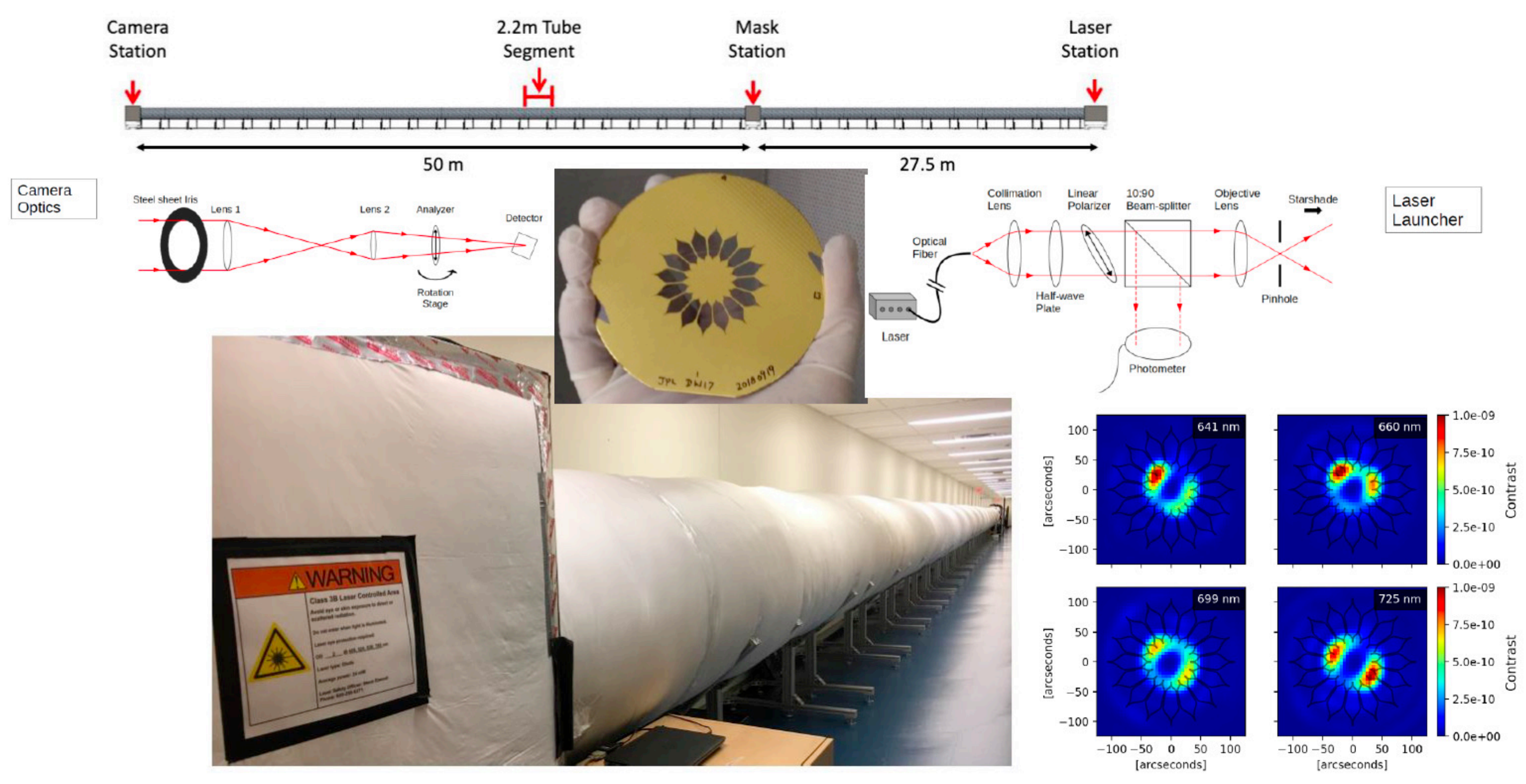
✓ Milestone Completed

● In Progress

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

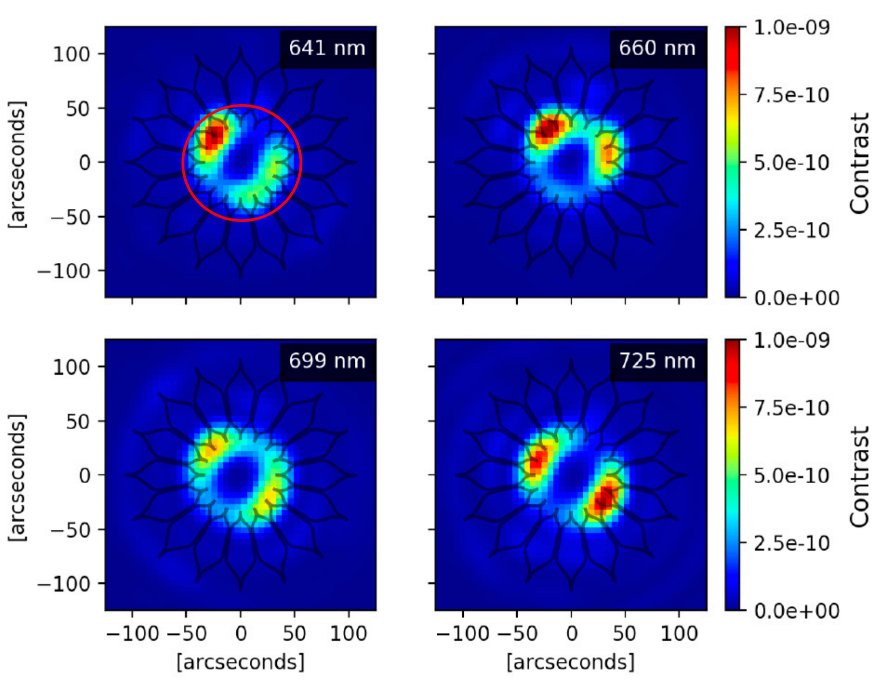
Starshades Current Performance in the Lab

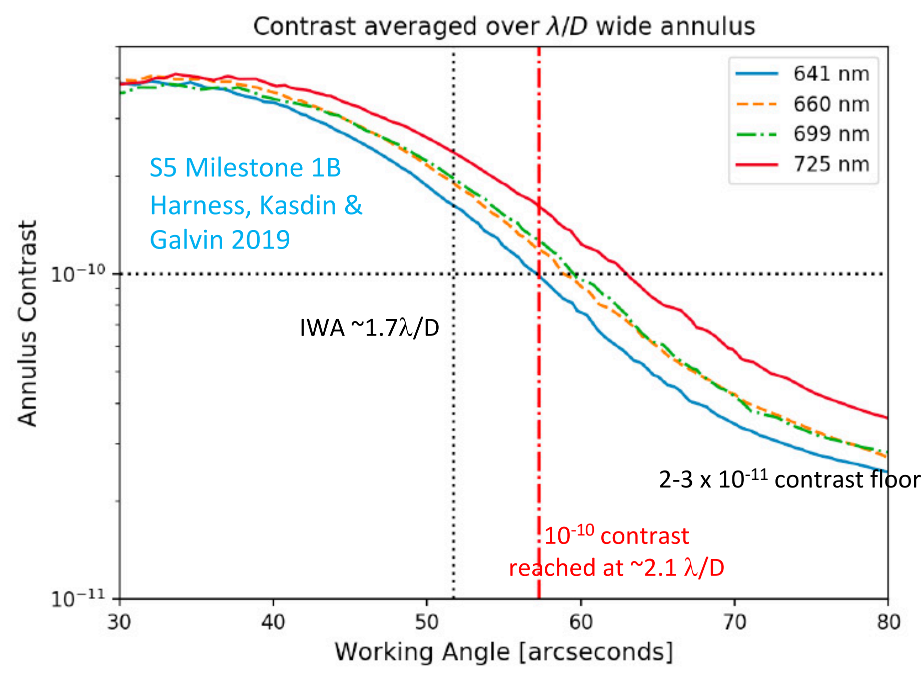
Princeton Starshade testbed demonstrated 10^{10} broad-band contrast (12%BW) at a flight-like Fresnel Number (F=13)



Starshades Current Performance in the Lab

- Princeton Starshade testbed (S5 Milestone 1B) demonstrated ~2x10 ^{10} contrast over a 12% BW (640 to 725 nm) at an IWA of 1.7λ_{max}/D, using 1 polar (96% polarized source) and a flight-like Fresnel Number (F=13)




Contrast averaged over λ/D wide annulus

S5 Milestone 1B
Harness, Kasdin &
Galvin 2019

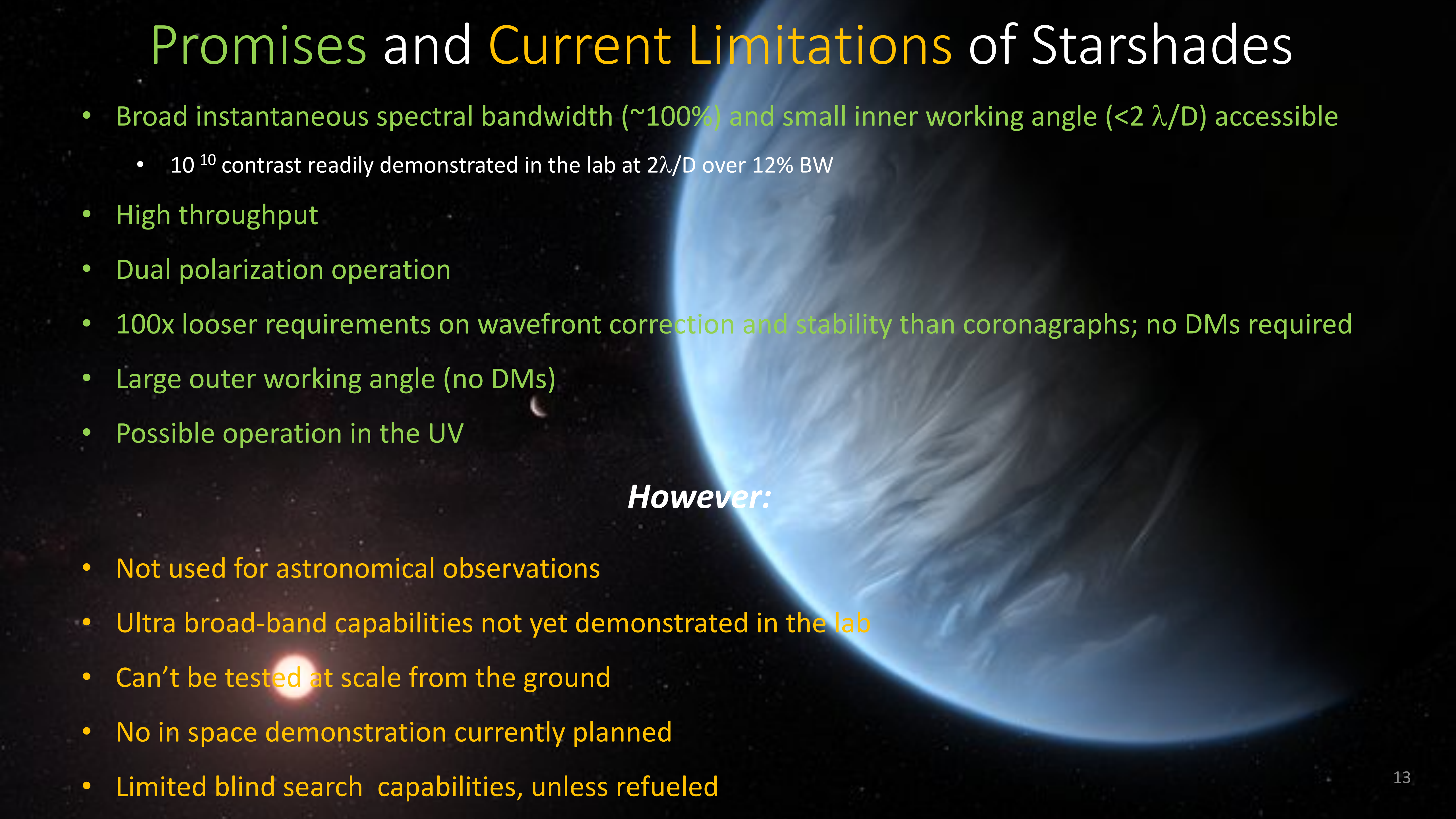
IWA ~1.7λ/D

2-3 x 10^{-11} contrast floor

10^{-10} contrast
reached at ~2.1 λ/D

- Observed ~2x 10 ^{10} raw contrast at tip IWA - and optical model residual error - limited by non-scalar diffraction (thick screen) effects where polarized light interacts with the edges of the 50 mm starshade mask.
- Such effects are completely negligible (> 1000x lower) on a > 10m diameter flight starshade.
- Performance at larger angles is limited by Rayleigh scattering by air molecules to ~10 ^{11} contrast
- Validated Contrast performance vectorial optical model to better than a factor of 2 for petal position error and 1.25 for petal shape errors (S5 Milestone 2, Harness, Kasdin & Galvin 2022)

Promises and Current Limitations of Starshades

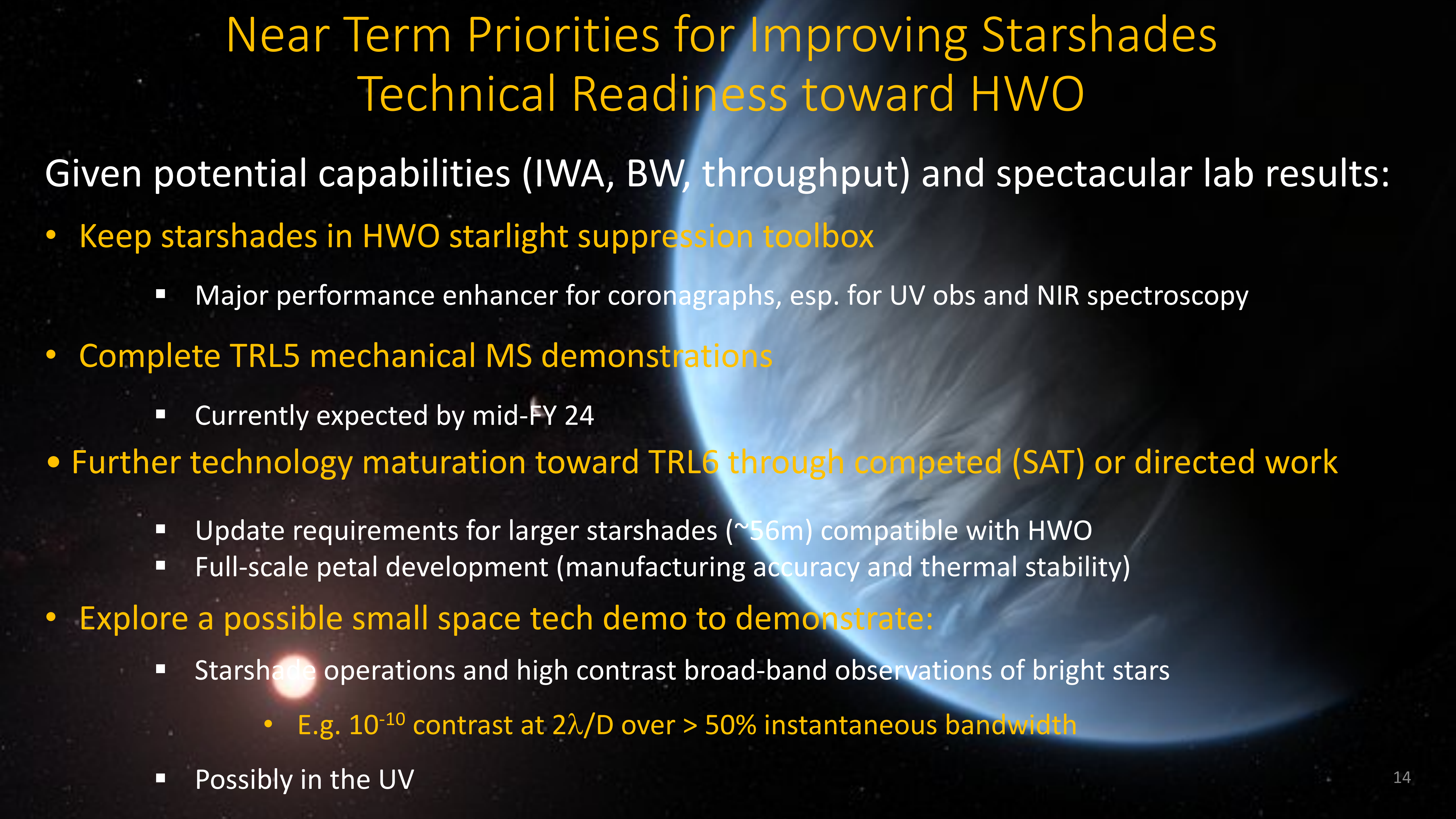


- Broad instantaneous spectral bandwidth (~100%) and small inner working angle (<2 λ/D) accessible
    - 10^{10} contrast readily demonstrated in the lab at 2λ/D over 12% BW
- High throughput
- Dual polarization operation
- 100x looser requirements on wavefront correction and stability than coronagraphs; no DMs required
- Large outer working angle (no DMs)
- Possible operation in the UV

However:

- Not used for astronomical observations
- Ultra broad-band capabilities not yet demonstrated in the lab
- Can’t be tested at scale from the ground
- No in space demonstration currently planned
- Limited blind search capabilities, unless refueled

Near Term Priorities for Improving Starshades Technical Readiness toward HWO

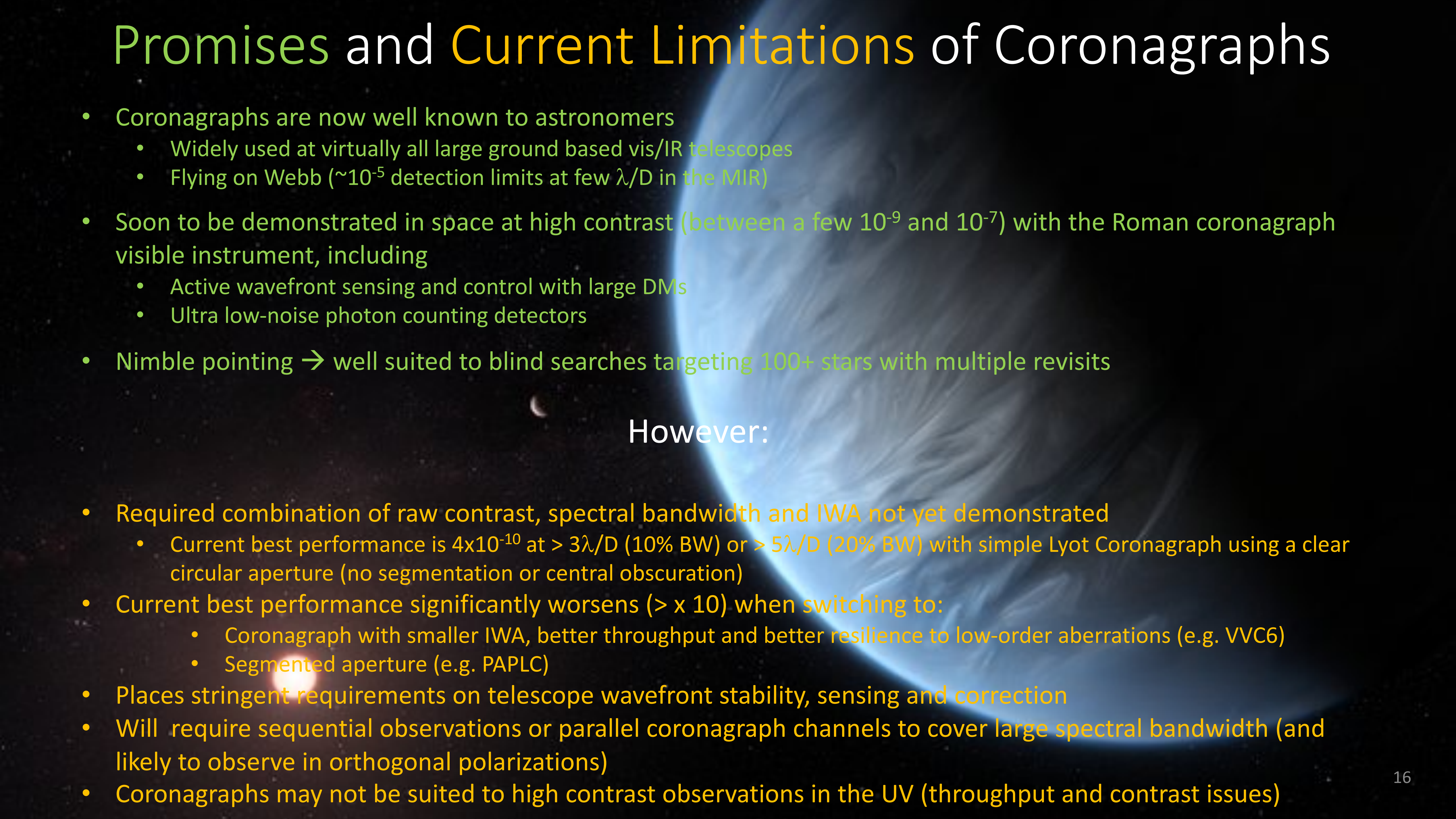


Given potential capabilities (IWA, BW, throughput) and spectacular lab results:

- Keep starshades in HWO starlight suppression toolbox
  - Major performance enhancer for coronagraphs, esp. for UV obs and NIR spectroscopy
- Complete TRL5 mechanical MS demonstrations
  - Currently expected by mid-FY 24
- Further technology maturation toward TRL6 through competed (SAT) or directed work
  - Update requirements for larger starshades (~56m) compatible with HWO
  - Full-scale petal development (manufacturing accuracy and thermal stability)
- Explore a possible small space tech demo to demonstrate:
  - Starshade operations and high contrast broad-band observations of bright stars
    - E.g. 10^{-10} contrast at $2\lambda/D$ over > 50% instantaneous bandwidth
  - Possibly in the UV

Back-up

Promises and Current Limitations of Coronagraphs



- Coronagraphs are now well known to astronomers
  - Widely used at virtually all large ground based vis/IR telescopes
  - Flying on Webb (~10^{-5} detection limits at few λ/D in the MIR)
- Soon to be demonstrated in space at high contrast (between a few 10^{-9} and 10^{-7}) with the Roman coronagraph visible instrument, including
  - Active wavefront sensing and control with large DMs
  - Ultra low-noise photon counting detectors
- Nimble pointing → well suited to blind searches targeting 100+ stars with multiple revisits

However:

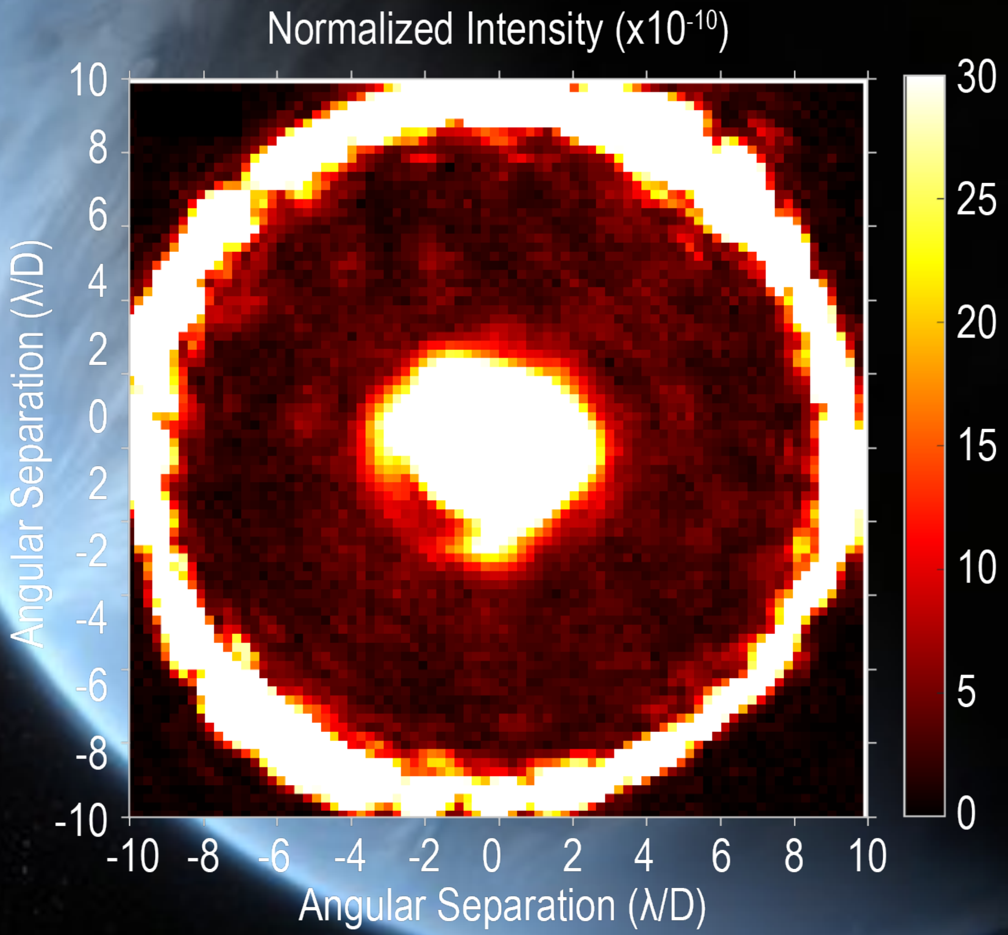
- Required combination of raw contrast, spectral bandwidth and IWA not yet demonstrated
  - Current best performance is 4×10^{-10} at > $3\lambda/D$ (10% BW) or > $5\lambda/D$ (20% BW) with simple Lyot Coronagraph using a clear circular aperture (no segmentation or central obscuration)
- Current best performance significantly worsens (> x 10) when switching to:
  - Coronagraph with smaller IWA, better throughput and better resilience to low-order aberrations (e.g. VVC6)
  - Segmented aperture (e.g. PAPLC)
- Places stringent requirements on telescope wavefront stability, sensing and correction
- Will require sequential observations or parallel coronagraph channels to cover large spectral bandwidth (and likely to observe in orthogonal polarizations)
- Coronagraphs may not be suited to high contrast observations in the UV (throughput and contrast issues)

Coronagraph Current Best Performance in the Lab

- Unobscured circular aperture

2019:

- 10% bandwidth
- 360 deg dark hole
- 4×10^{-10} mean contrast
- between 3 and 9 λ/D
- with classical Lyot Coronagraph (or HLC?)



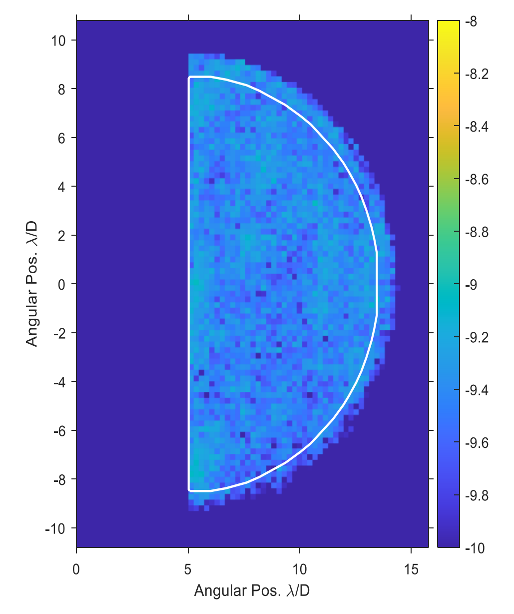
NASA-JPL HCIT Decadal Survey Testbed (DST) Single-polarization Results: Seo, B. et al. 2019

Coronagraph Current Best Performance in the Lab

- Unobscured circular aperture

2022: improved spectral bandwidth

- 20% bandwidth
- 180 deg dark hole
- 4×10^{-10} mean contrast
- between 5 and 13.5 λ/D
- with classical Lyot Coronagraph
  2.7 λ/D spot radius with aggressive Lyot Stop (0.28-0.675 D)

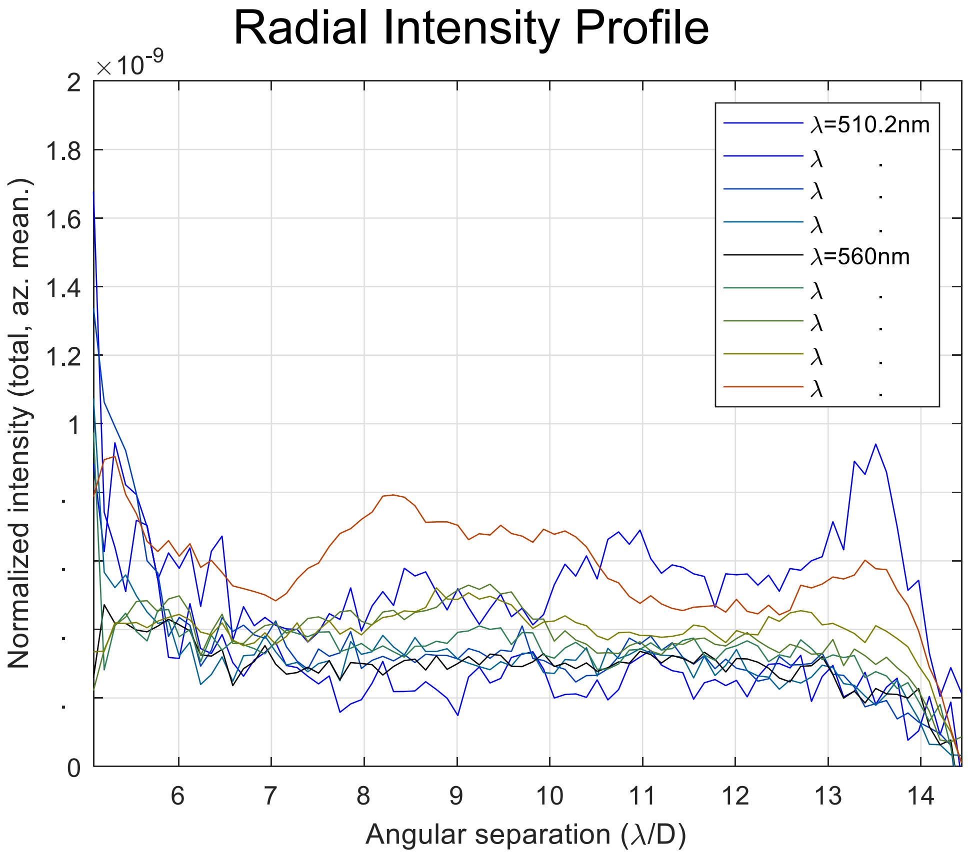


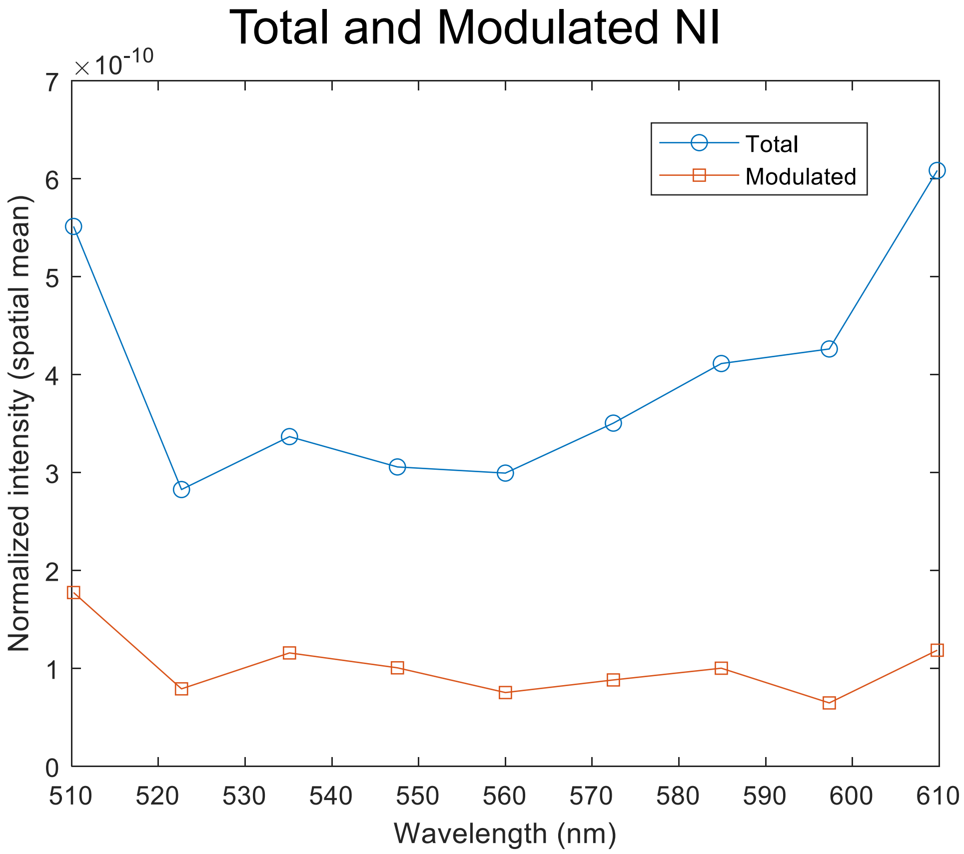
Mean Raw NI	**3.97E-10**
λ_0	560 nm
Bandwidth	20%
Scoring Zone	5-13.5λ_0/D
DMs	2x AOX 2k
Single Polarization	

NASA-JPL HCIT Team Decadal Survey Testbed (DST) Single-polarization Results

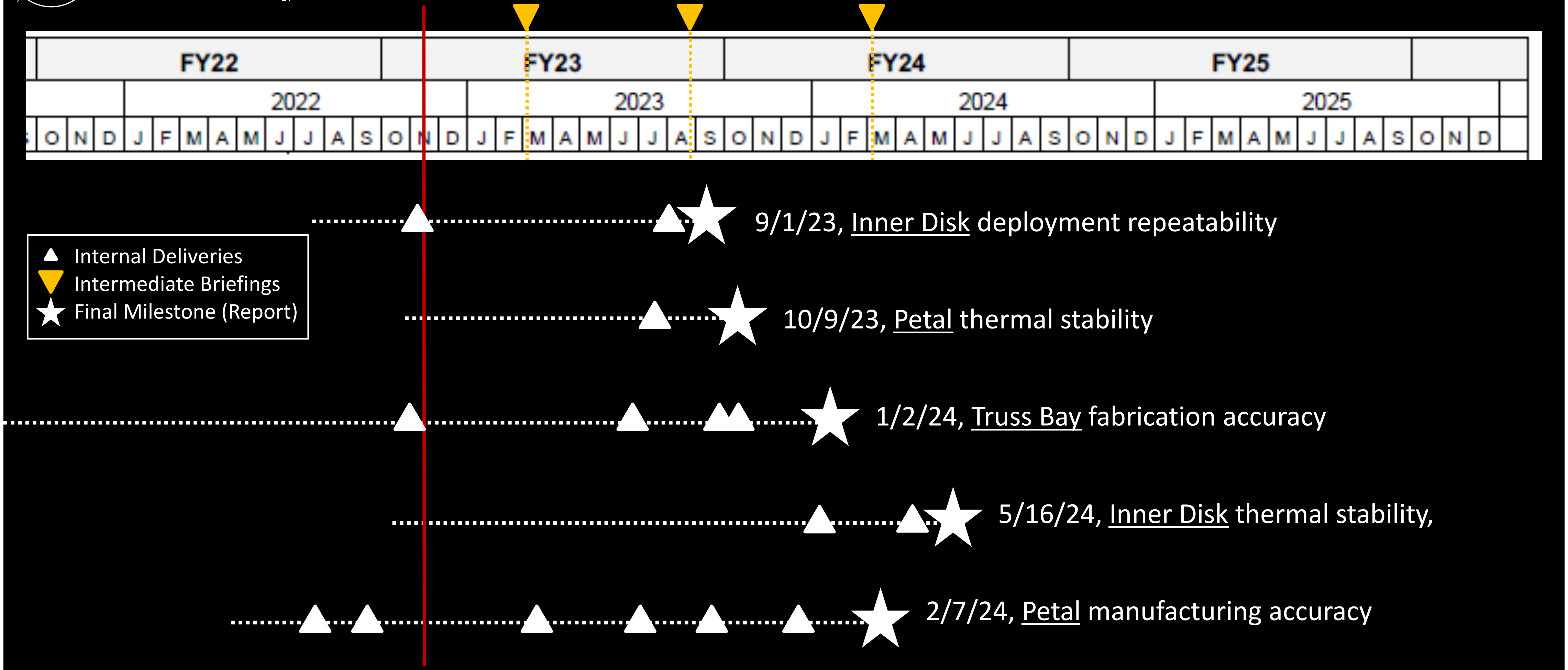
Initial emphasis on demonstrating broader bandwidth. Will now push toward reaching smaller separations

Wide-band contrast on the Decadal Survey Testbed (cont.)


Radial Intensity Profile


Total and Modulated NI

Mechanical Milestone Path to TRL5



△ Internal Deliveries
▼ Intermediate Briefings
★ Final Milestone (Report)

9/1/23, Inner Disk deployment repeatability

10/9/23, Petal thermal stability

1/2/24, Truss Bay fabrication accuracy

5/16/24, Inner Disk thermal stability,

2/7/24, Petal manufacturing accuracy

Each of these milestones is a conclusion of a previous activity. We are repeating design/fabrication/analysis for a higher-fidelity full-featured version of a component that has already been demonstrated with critical features.