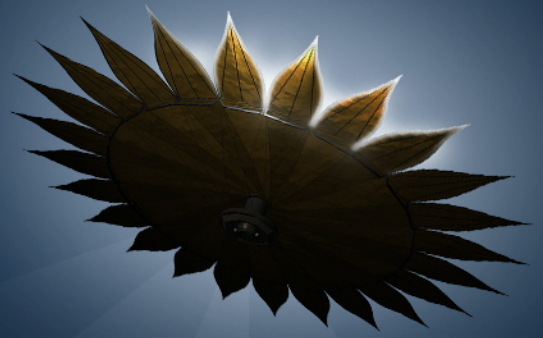
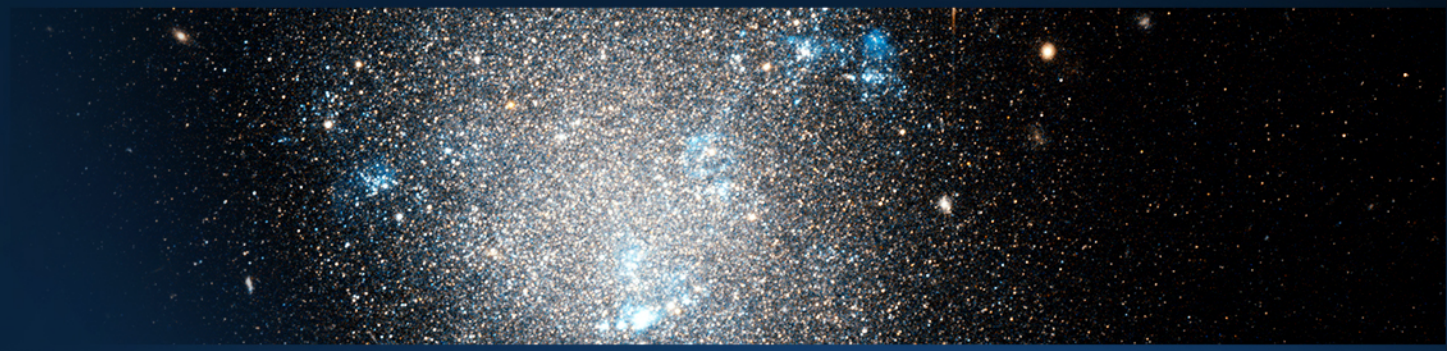


HabEx

Habitable Exoplanet Observatory



Baseline Architecture and Alternatives

Bertrand Mennesson, Study Scientist
Jet Propulsion Laboratory,
California Institute of Technology

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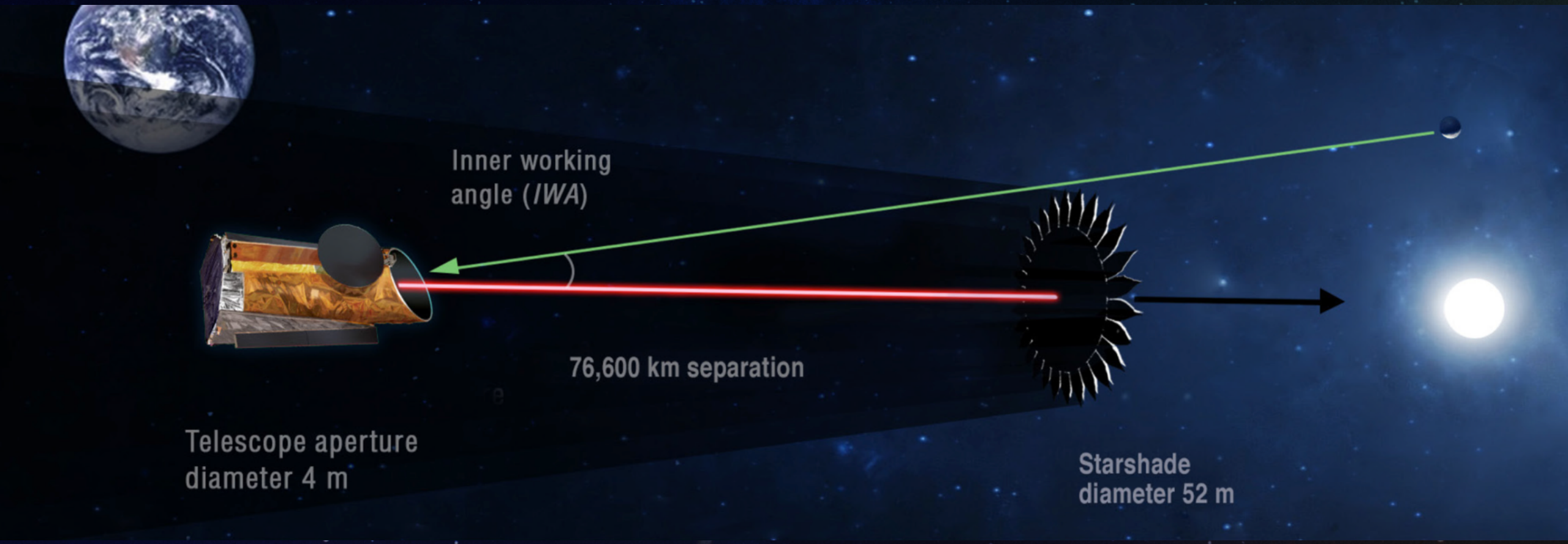
Government sponsorship acknowledged

Pre-Decisional Information – For Planning and Discussion Purposes Only

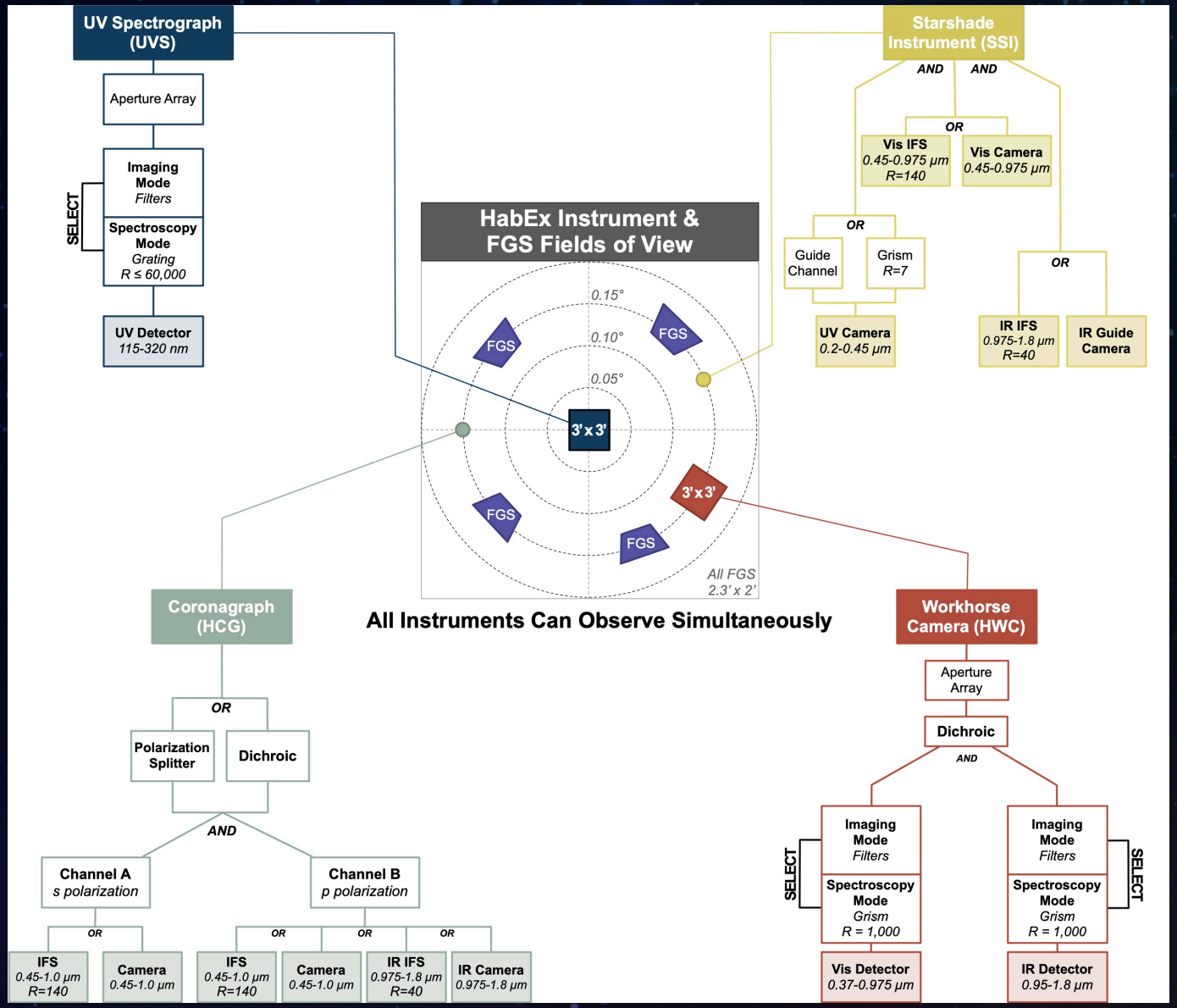
Outline

- Top Level Description of Baseline (preferred?) Architecture [WHAT?]
- Main Design Drivers [WHY?]
- Performance Expectation (illustrative examples) [HOW?]
  - From modeling
  - From the lab
- Mapping the Architecture Landscape [WHAT IF?]

HabEx Baseline Architecture at a glance

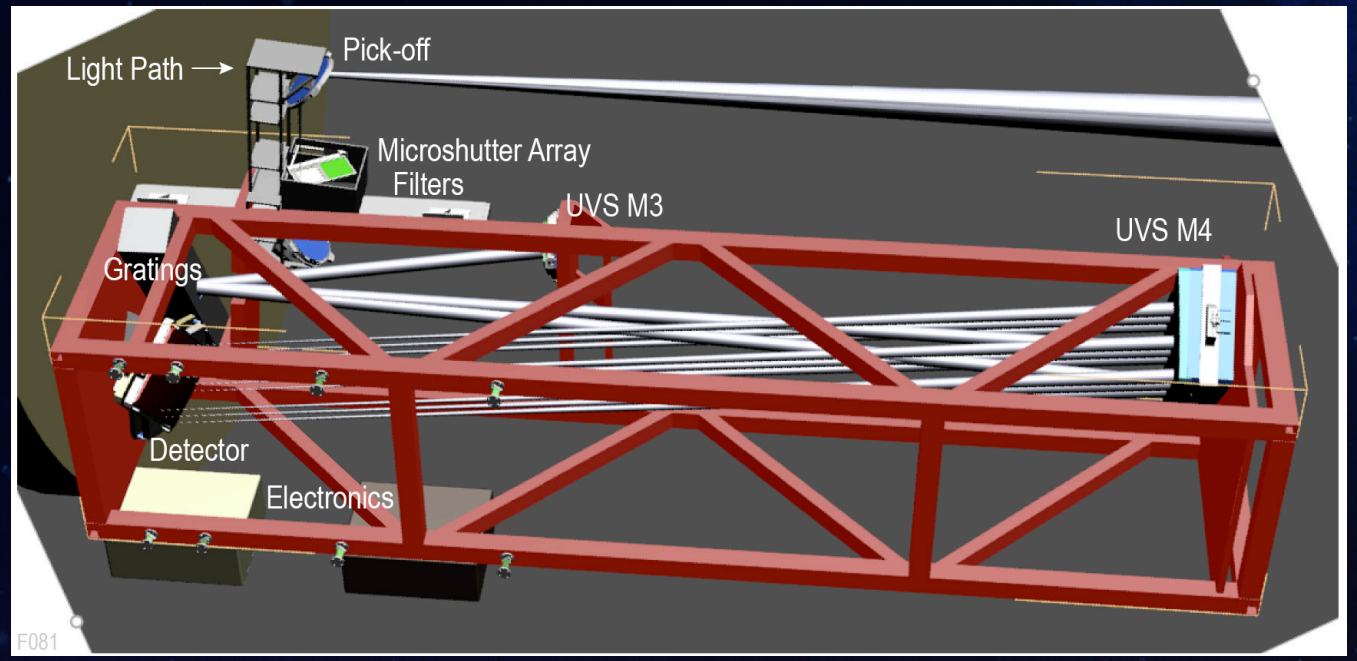


HabEx Instruments



Four Instruments

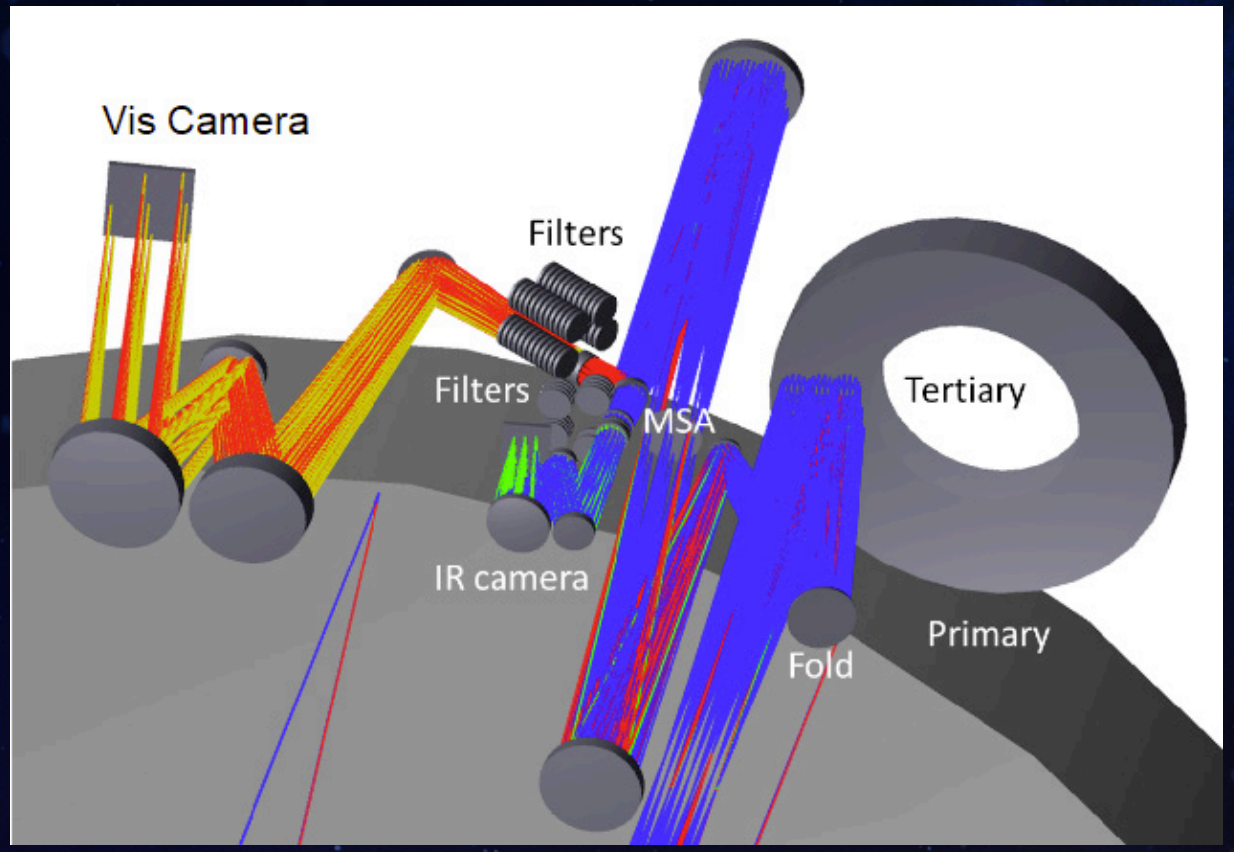
- HabEx UV Spectrograph and Imager (UVS)



- Wavelength range:
  - Imaging: 115 - 370 nm
  - Spectroscopy
    - 115-320 nm with R=60,000; 25,000, 12,000, 6000; 3,000, 1,000, and 500
    - 320-370nm with R =500 or 1000
- Field of View:
  - 3 x 3 arcmin2
  - Micro-shutter array for MOS: 2 x 2 array, each with 171 x 365 apertures

Four Instruments

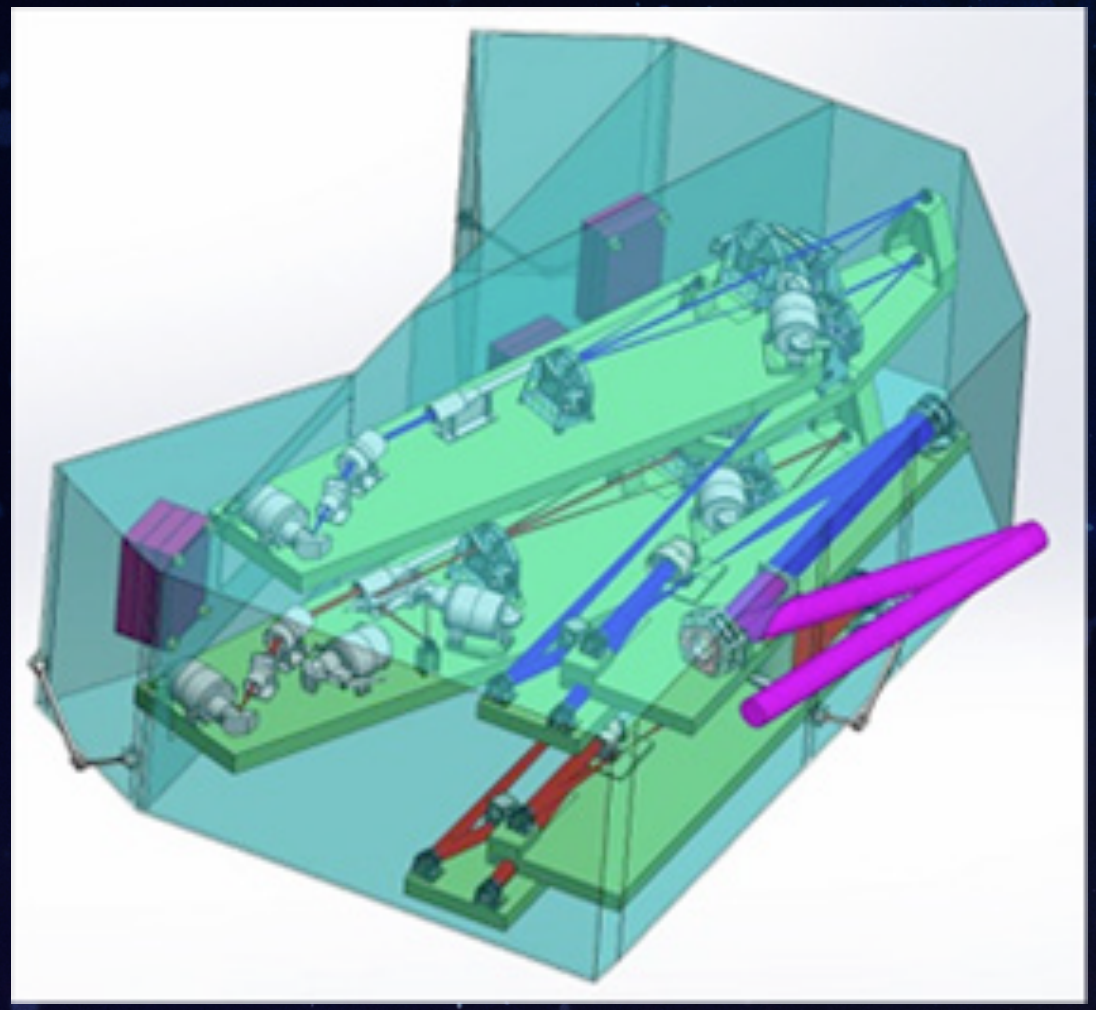
- HabEx Workhorse Camera (HWC Imager and Spectrograph)



- Wavelength range:
  - Visible Channel 0.37 – 0.975 μm Imager + grism with R=1000
  - Near IR Channel: 0.975 - 1.8 μm Imager + grism with R=1000)
- Field of View:
  - 3 x 3 arcmin2
  - Micro-shutter array for MOS: 2 x 2 array, each with 171 x 365 apertures

Four Instruments

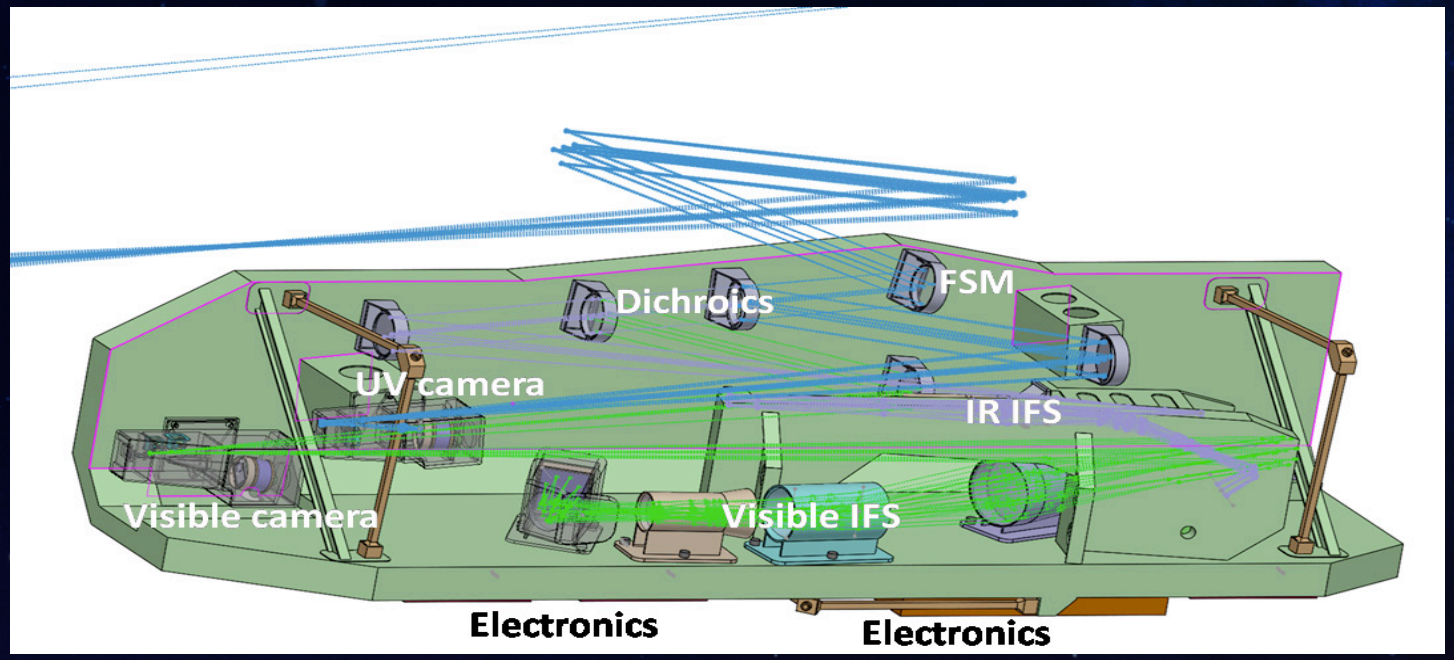
- HabEx Coronagraph (HCG)



- Wavelength range:
  - Visible Channel 0.45 - 1.0μm (Imager + IFS with R=140)
  - Near IR Channel: 0.975 - 1.8 μm (Imager + IFS with R=40)
- High Contrast Field of View:
  - IWA = 2.4 λ/D (62 mas at 0.5 μm)
  - OWA = 32 λ/D (830 mas at 0.5 μm)
- Raw Contrast: 2.5×10^{-10} at IWA
- Spectral BW per (polarized) channel: 20%
- Active LOWFS&C with two 64 x 64 DMs per channel

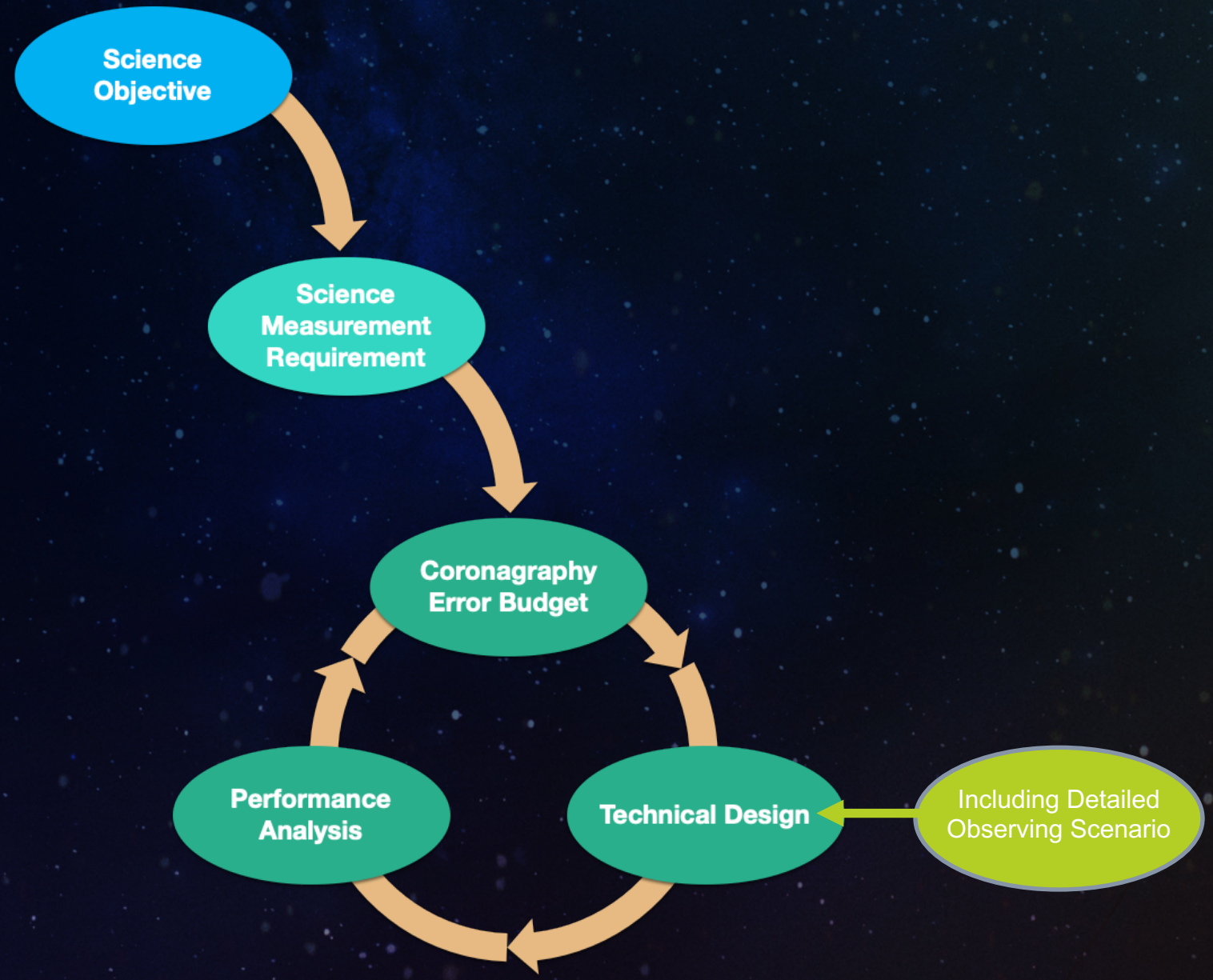
Four Instruments

- HabEx Starshade Instrument (SSI)



- Wavelength range:
  - UV Channel 0.2 – 0.45 μm (Imager + grism with R=7)
  - Visible Channel 0, 45 – 0.975 μm (Imager + IFS with R=140)
  - Near IR Channel: 0.975 - 1.8 μm (Imager + IFS with R=40)
- High Contrast Field of View:
  - IWA = 58 mas from 0.3 to 1.0 μm
  - OWA = 6” (Imager)
  - OWA = 1” (IFS)
- Raw Contrast: 10^{-10} at IWA
- Spectral BW per channel: 107%

Design Process



See report STM and Chapter 5

Design Drivers: Starlight Suppression System

Most driving science measurement requirement:

"HabEx shall be able to detect, determine the orbit and spectrally characterize over the full 0.3 to 1μm range at least one Earth-size habitable zone planet ("exo-Earth candidate") with > 95% confidence."

Design Drivers: Starlight Suppression System

Exoplanet Detection

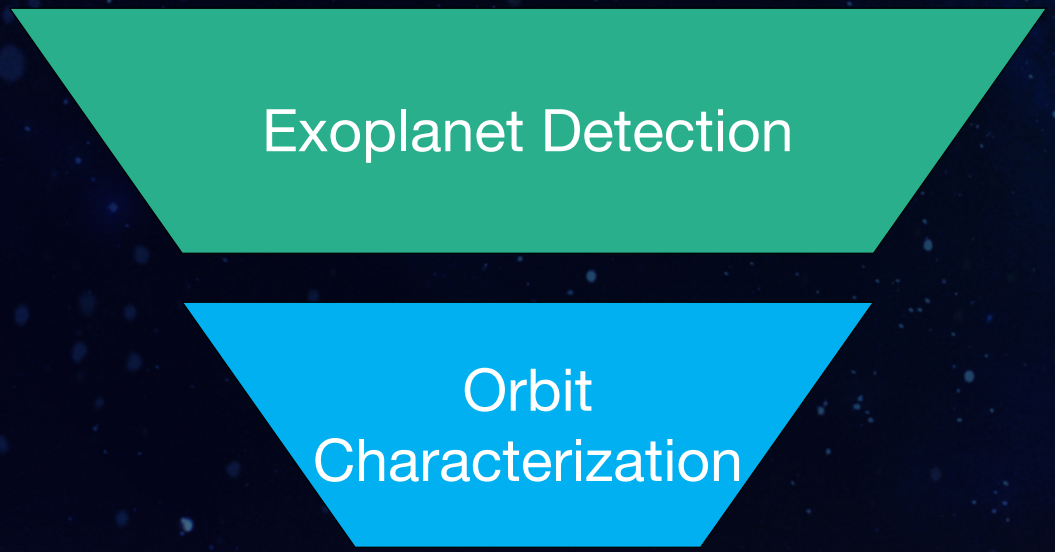
[redacted]

- Must detect HZ rocky planets 10^{-10} fainter than their host star in reflected light
  → drives instrument contrast and throughput

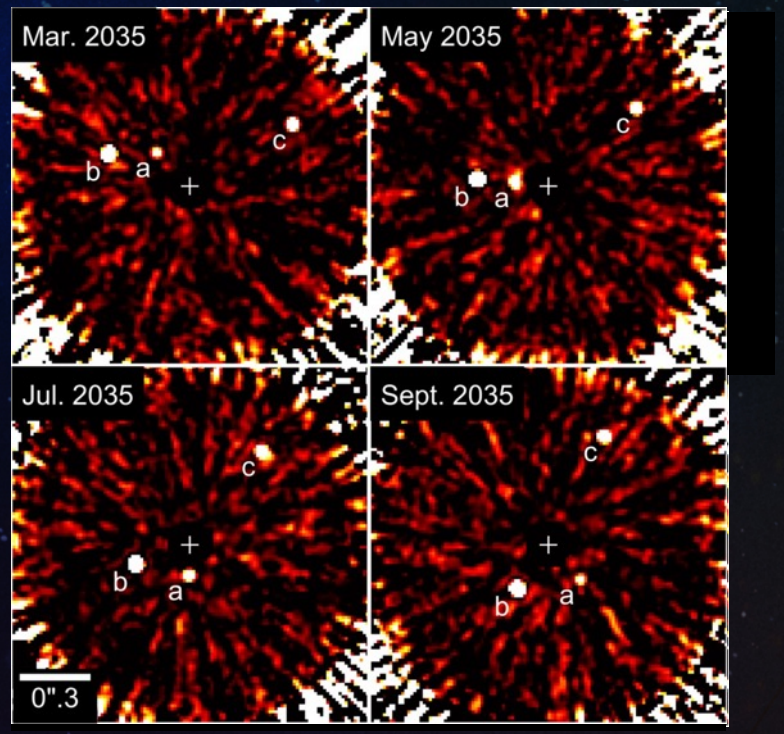
- At separations of 80 mas or less
  → drives instrument “inner working angle” (IWA)

Solution: Internal Coronagraph or Starshade

Design Drivers: Orbit Determination

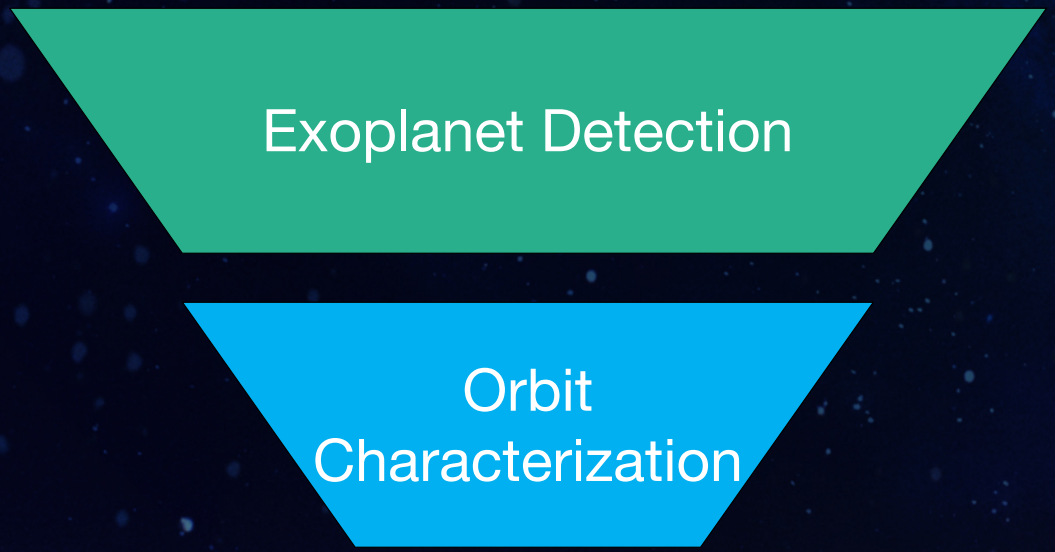


- *If* no prior knowledge exists:
  - must visit systems multiple times to increase completeness
  - Must *detect* planets >=4 times to accurately constrain planetary orbits



See report Chapter 3.1

Design Drivers: Orbit Determination



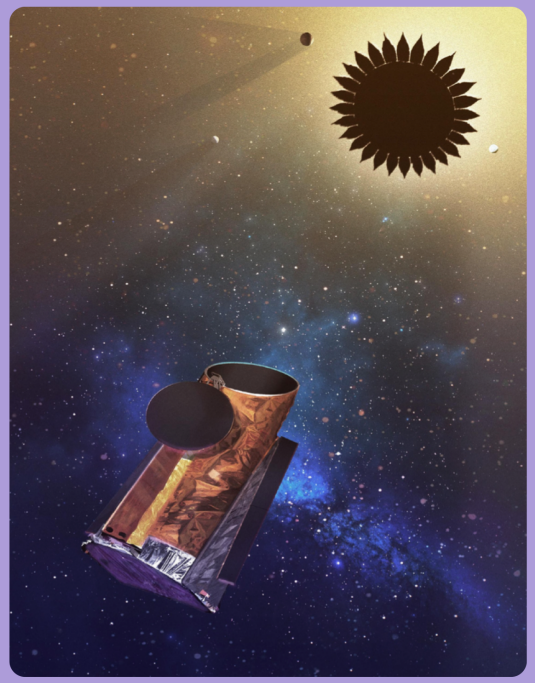
- *If* no prior knowledge exists:
  - must visit systems multiple times to increase completeness
  - Must *detect* planets >=4 times to accurately constrain planetary orbits and estimate their sizes
  - $F_{pl}/F^*(t) = \text{Albedo} \times (R_{pl} / d(t))^2 \times \Phi(\text{inclination},t)$

Calls for Internal Coronagraph rather than slew-limited starshade

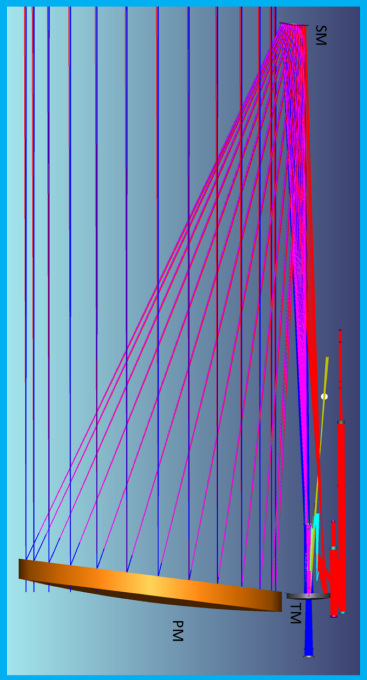
See report Chapter 3.1

Designing for High Contrast Coronagraphy

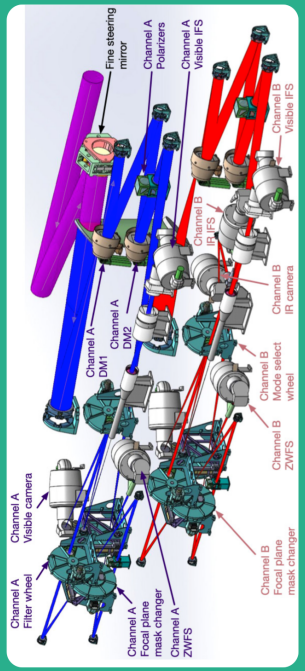
Spacecraft



Telescope



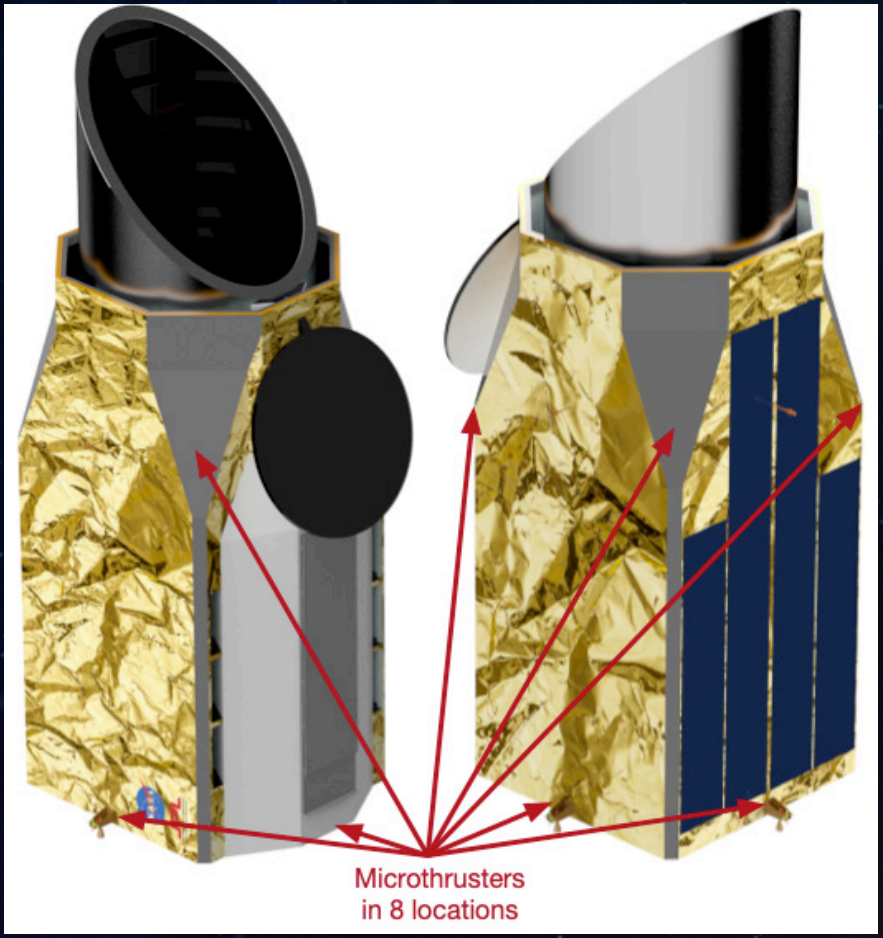
Coronagraph

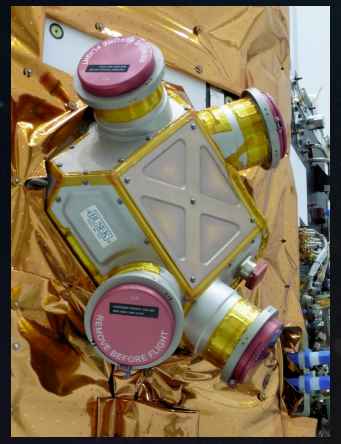


Spacecraft Accommodations

- L2 orbit
  - Thermal stability
- (Micro)Thrusters
  - Slewing with thrusters
  - Fine pointing control with micro-thrusters
    - Provides much lower dynamical disturbances than reaction wheels
    - Positioned for optimum slewing efficiency and counterbalancing of solar pressure

Add figure comparing RWs and microthrusters noise levels vs frequency

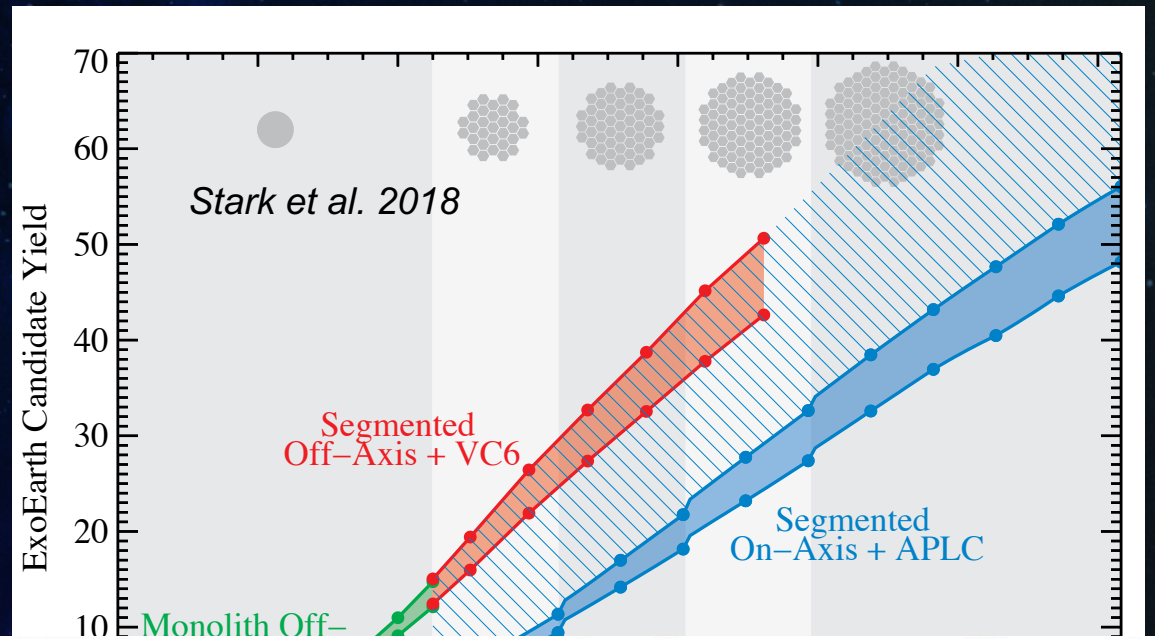


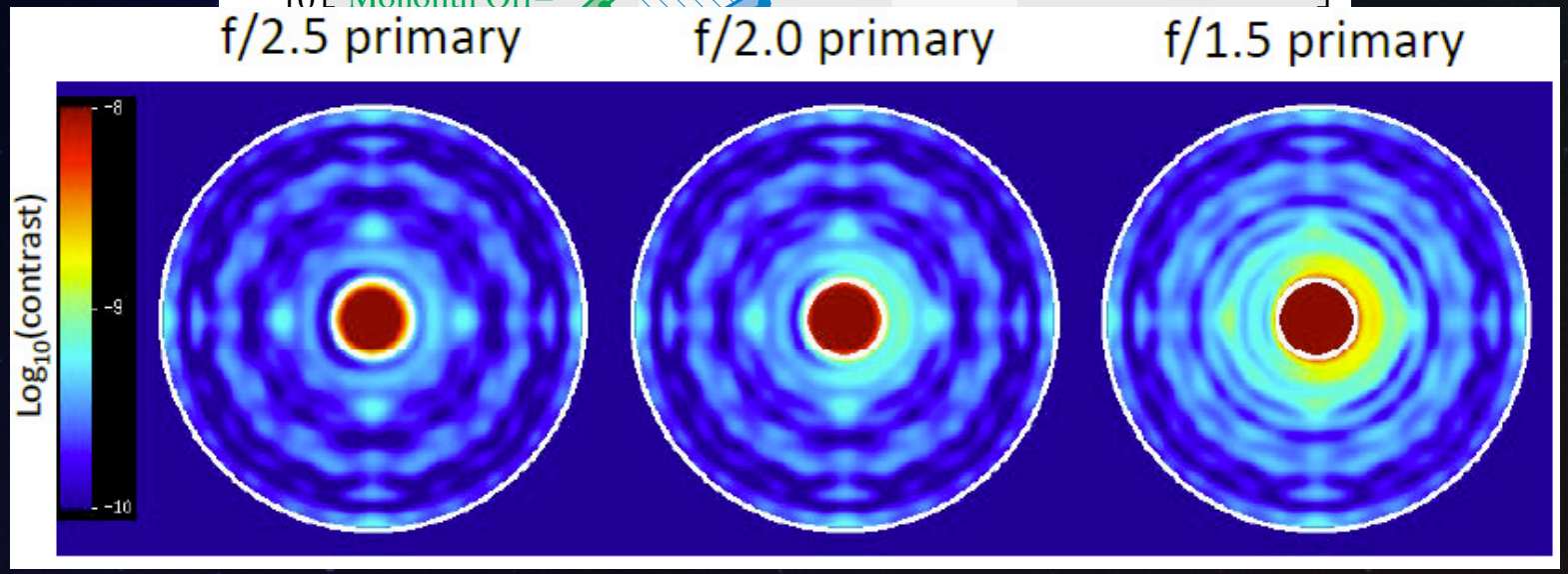


LISA Pathfinder micro-thrusters

Telescope Accommodations

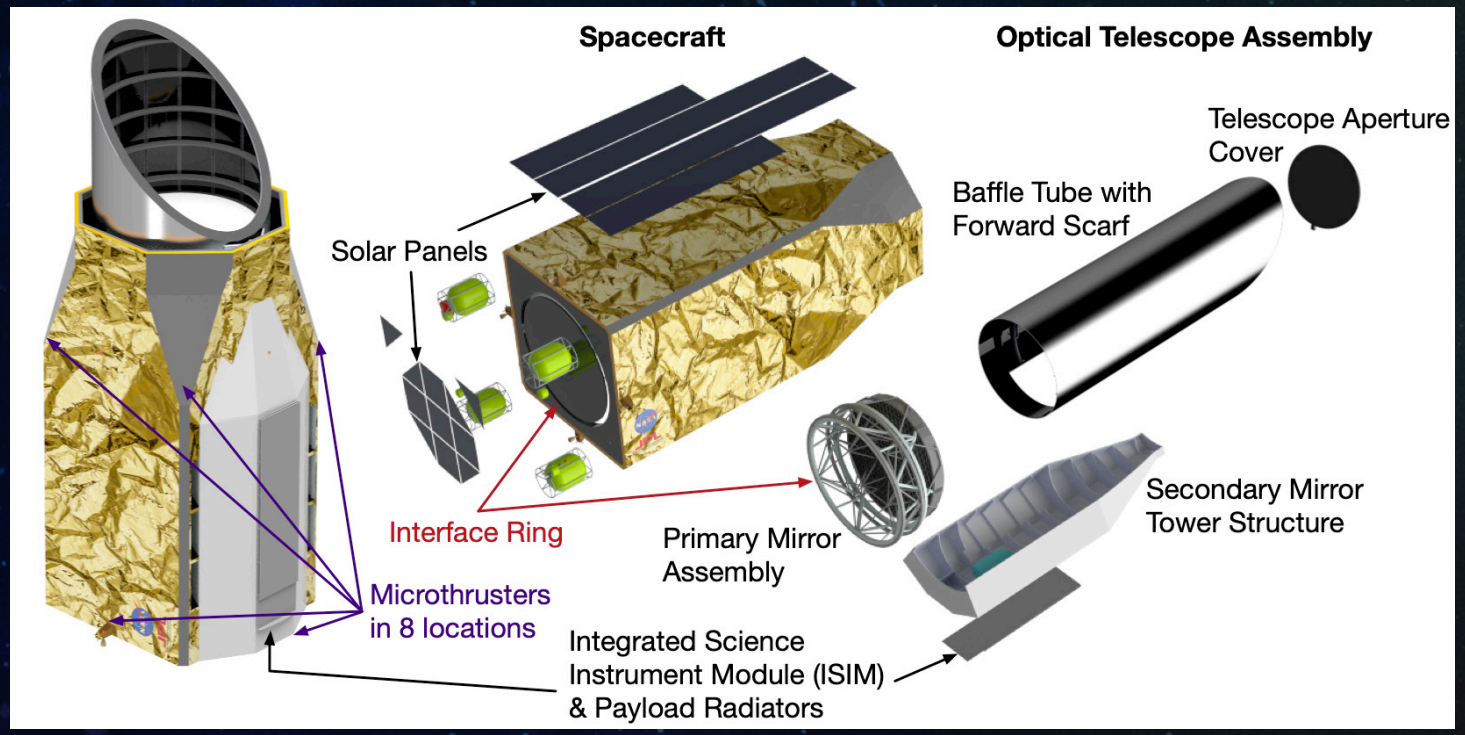
- Coronagraph-friendly Optical Telescope Assembly:
  - Off-axis Primary → Unobscured aperture
  - Monolith → Continuous aperture with no gaps
  - F/2.5 → Minimizes polarization effects



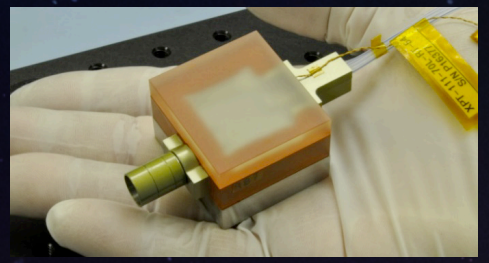


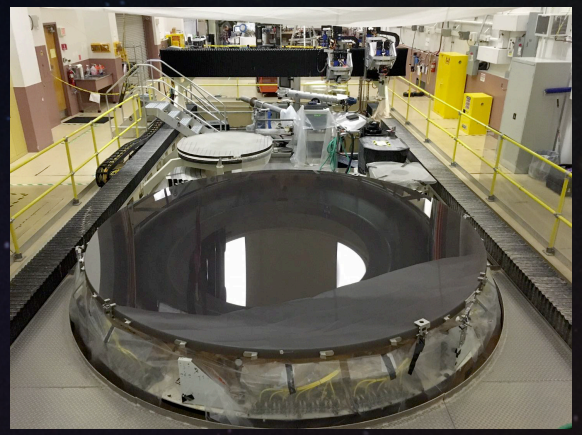
Telescope Accommodations

- High Mechanical Stability
  - Stiff Opto-Mechanical Structure (>20Hz)
  - Monolithic primary
    - No segment dynamic phasing issues
  - Ultra low pointing jitter (<0.7 mas rms pre-correction)
  - Laser Metrology to rigidify M1-M2-M3



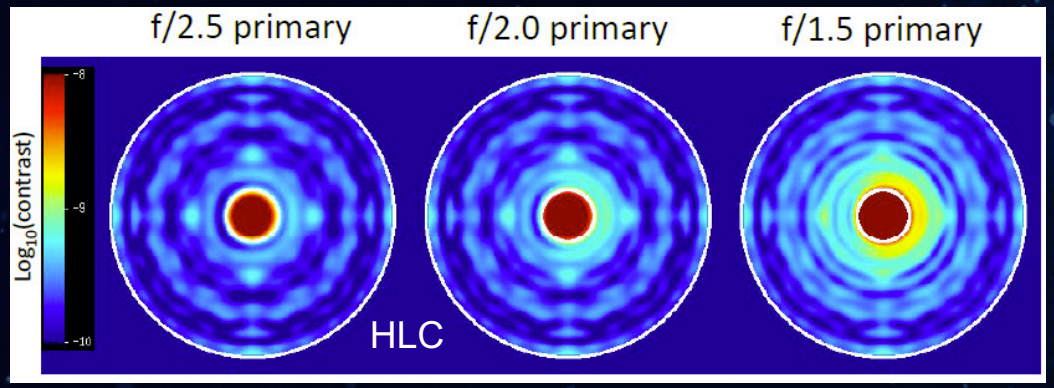
- High Thermal Stability
  - Zerodur Primary Mirror (< 5 ppb/K CTE)
  - Large Thermal Inertia (1400 kg PM)
  - Thermal insolation provided by spacecraft structure
  - Active thermal control

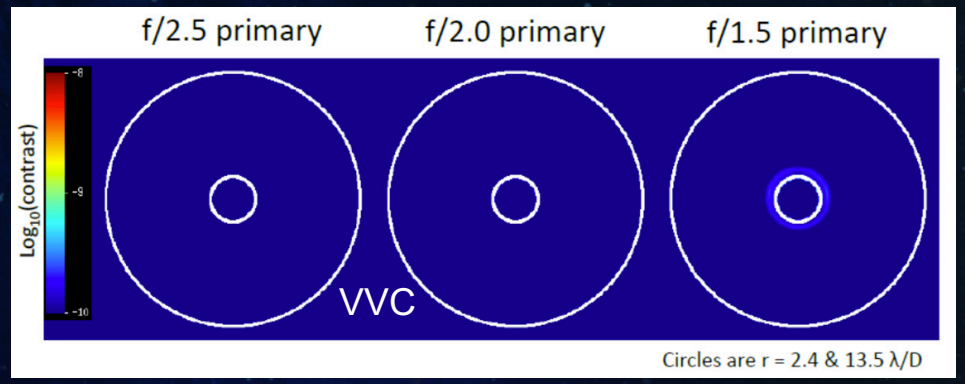




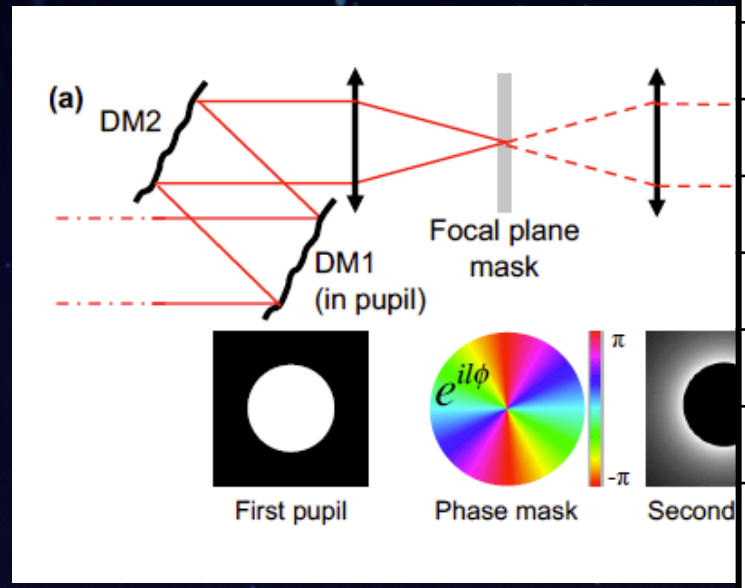
Coronagraph Accommodations and Trades

- Selecting among different coronagraph masks:





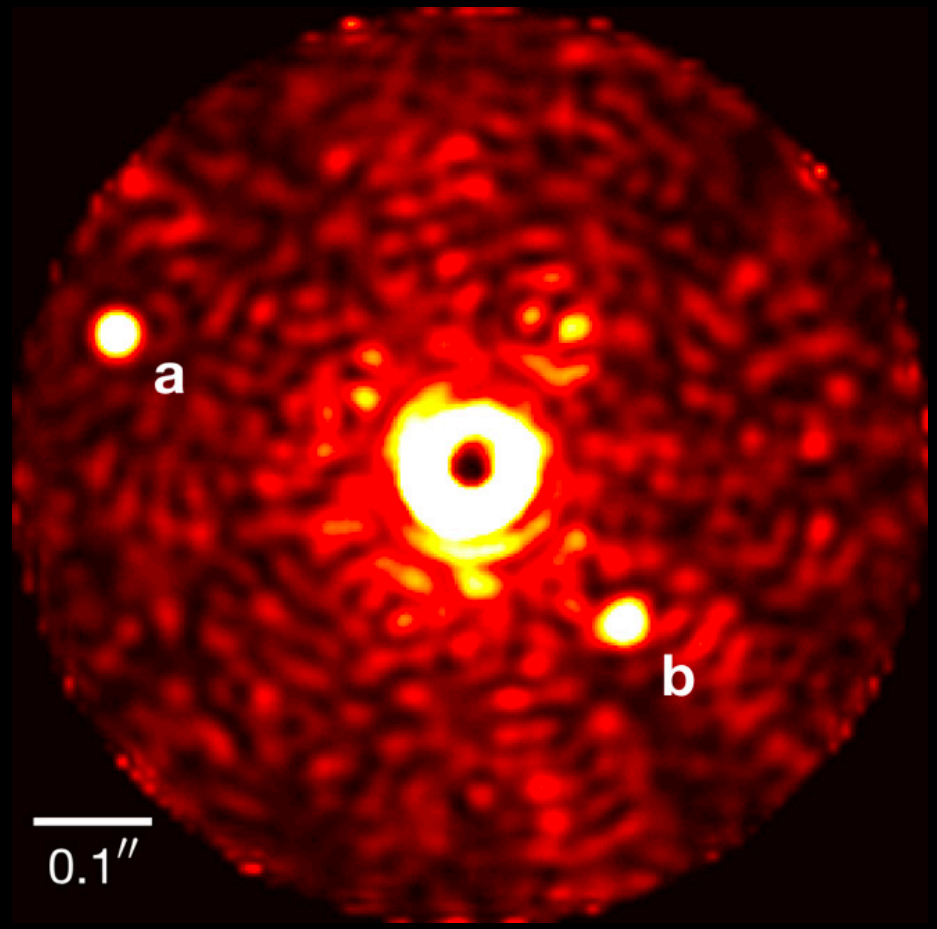
- Selecting from different VVC

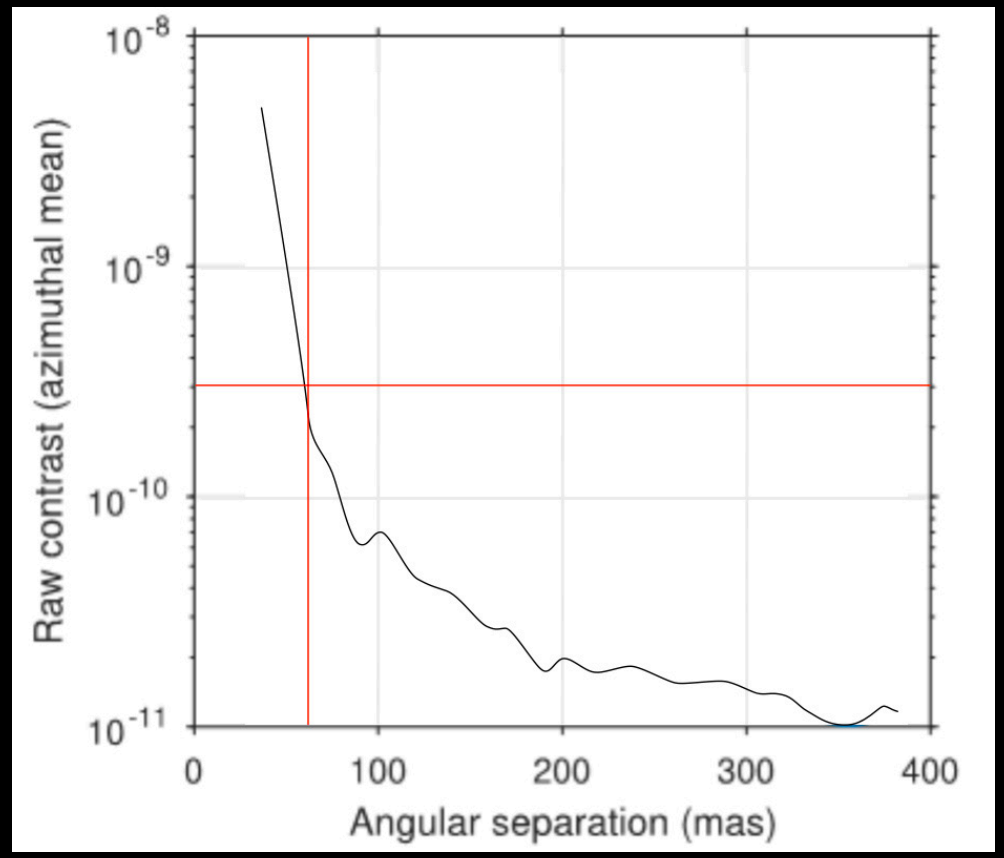


Aberration	Indices		Allowable RMS wavefront error (nm) per mode			
	n	m	charge 4	charge 6	charge 8	charge 10
Tip-tilt	1	±1	1.1	6.1	16	29
Defocus	2	0	0.8	4.6	13	32
Astigmatism	2	±2	0.0068	1.1	0.92	4.8
Coma	3	±1	0.0064	0.69	0.84	5.4
Spherical	4	0	0.0049	0.53	0.75	7
Trefoil	3	±3	0.0073	0.0064	0.59	0.68
Exo-Earths Spectra			**8**	**7**	**5**	**3**

Verifying the Telescope- Coronagraph System: Static Modeling (Krist 2019)

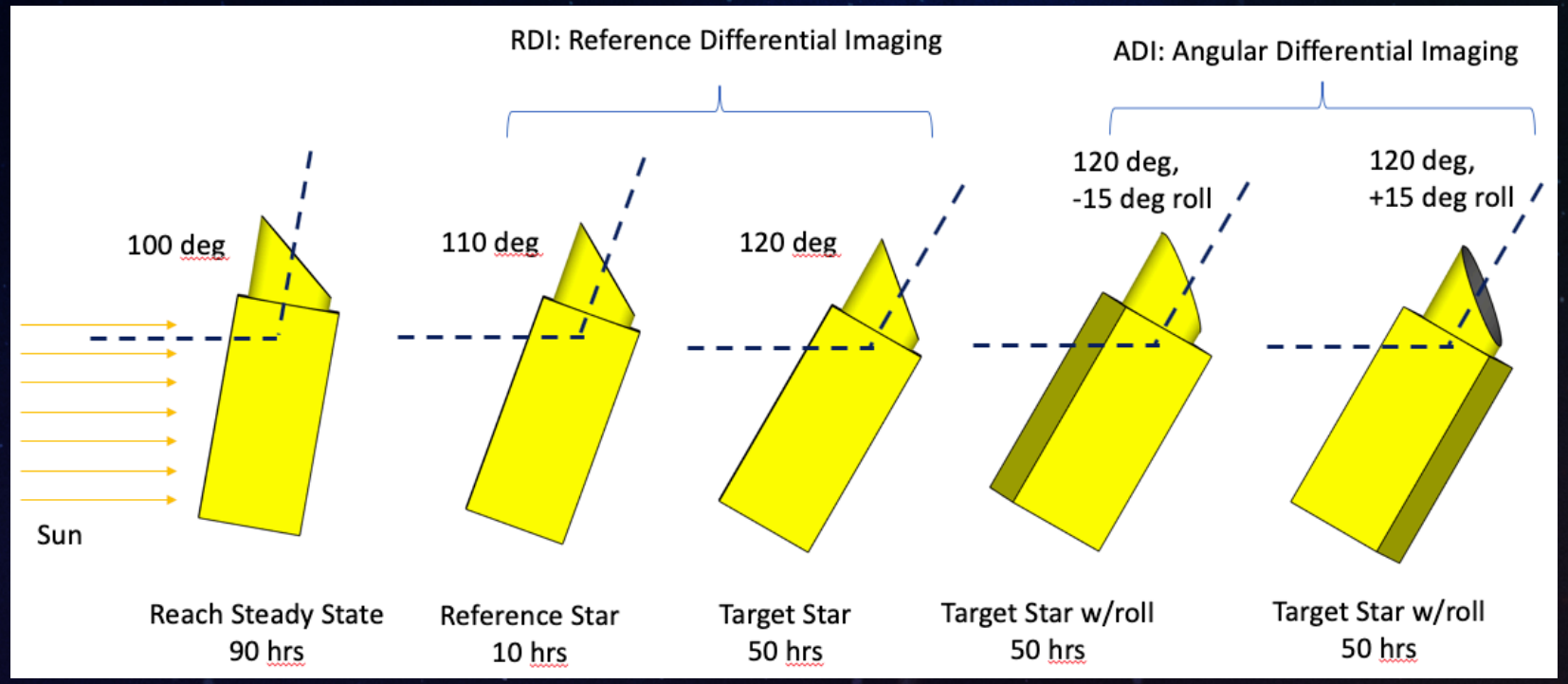
End-to-end dual polarization numerical modeling tools (PROPER) developed for previous studies and missions (e.g. TPF-C, Exo-C) and lab-validated on WFIRST-CGI





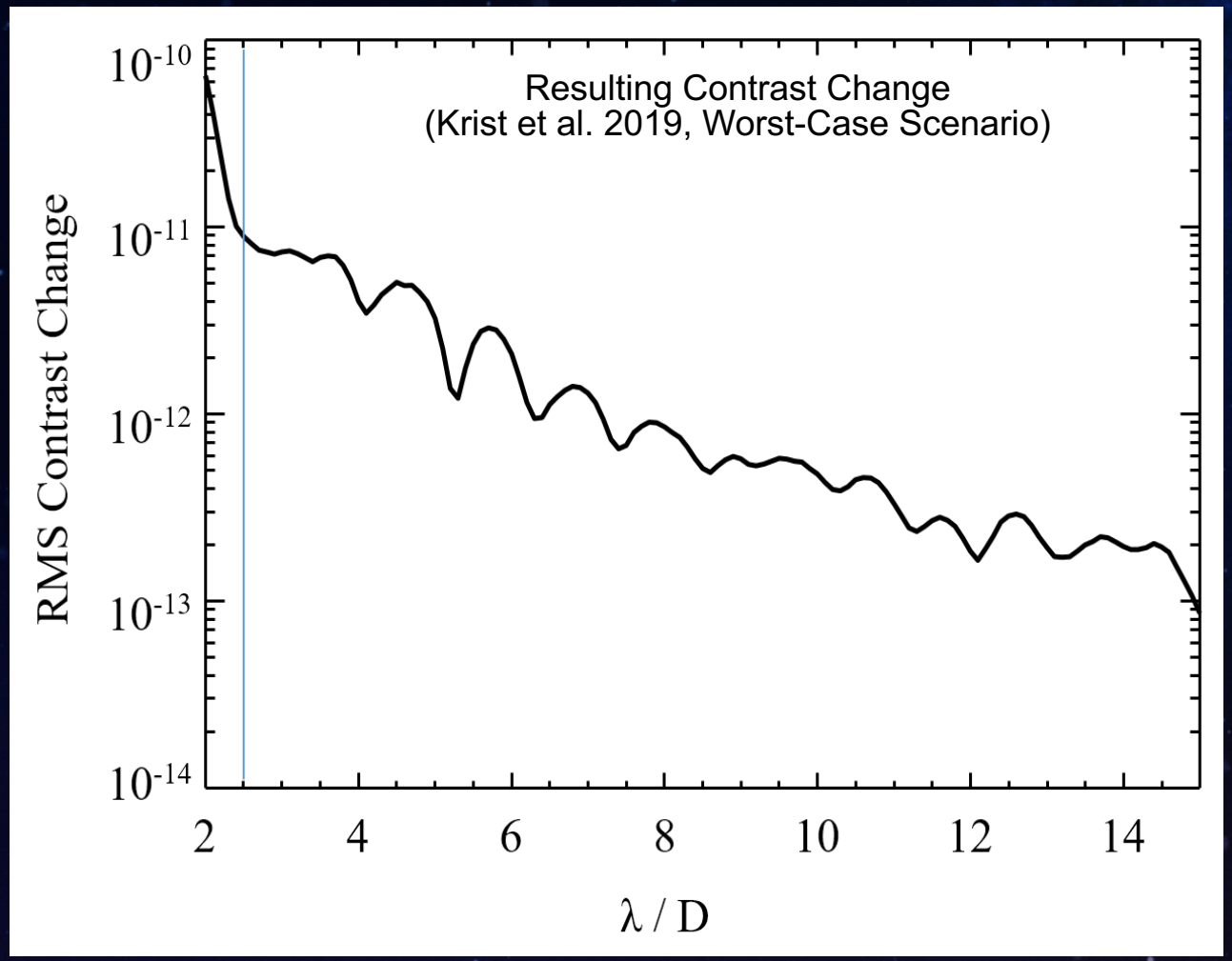
Verifying the Telescope-Coronagraph System Dynamic Modeling (STOP) Results

- Structural (NASTRAN), Thermal (Thermal Desktop), and OPtical (Sigfit & Code V) codes (WFIRST STOP model pipeline) produce wavefront changes vs time for observing scenario (OS)
- Realistic OS (250h RDI and rolls) defines solar angles and timescales for STOP run
- Wavefront changes propagated through whole system using PROPER to produce speckle fields



Verifying the Telescope – Coronagraph System: Dynamic Modeling (STOP) Results

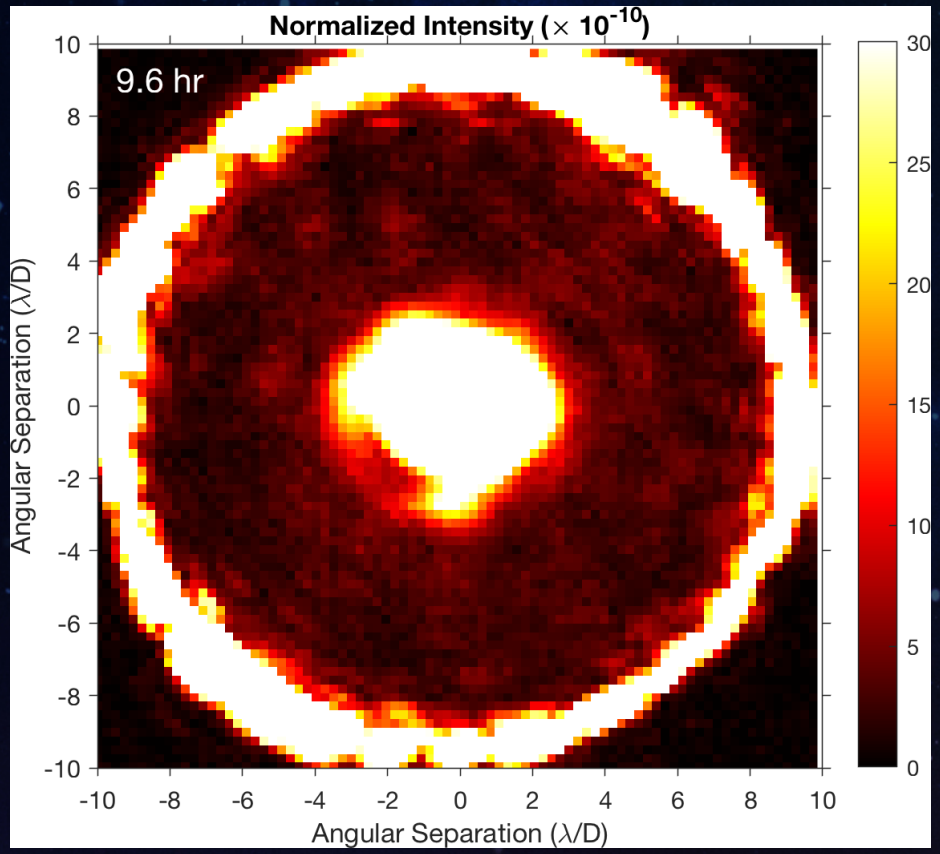
Predicted HabEx WFE vs time meets contrast stability requirements



- Modeling demonstrates required high-contrast performance (static and dynamic) when including
  - realistic optical surface errors
  - polarization-induced aberrations
  - reduced (x3) BMC DM surface errors
  - finite stellar diameter and pointing errors
  - WFE drifts predicted from STOP analysis
  - VVC 6 sensitivity to wavefront aberrations

Capitalizing on the DST lab results

10% bandwidth dark holes reach 4×10^{-10} mean contrast with HabEx-like unobscured monolithic aperture and simple Lyot Coronagraph

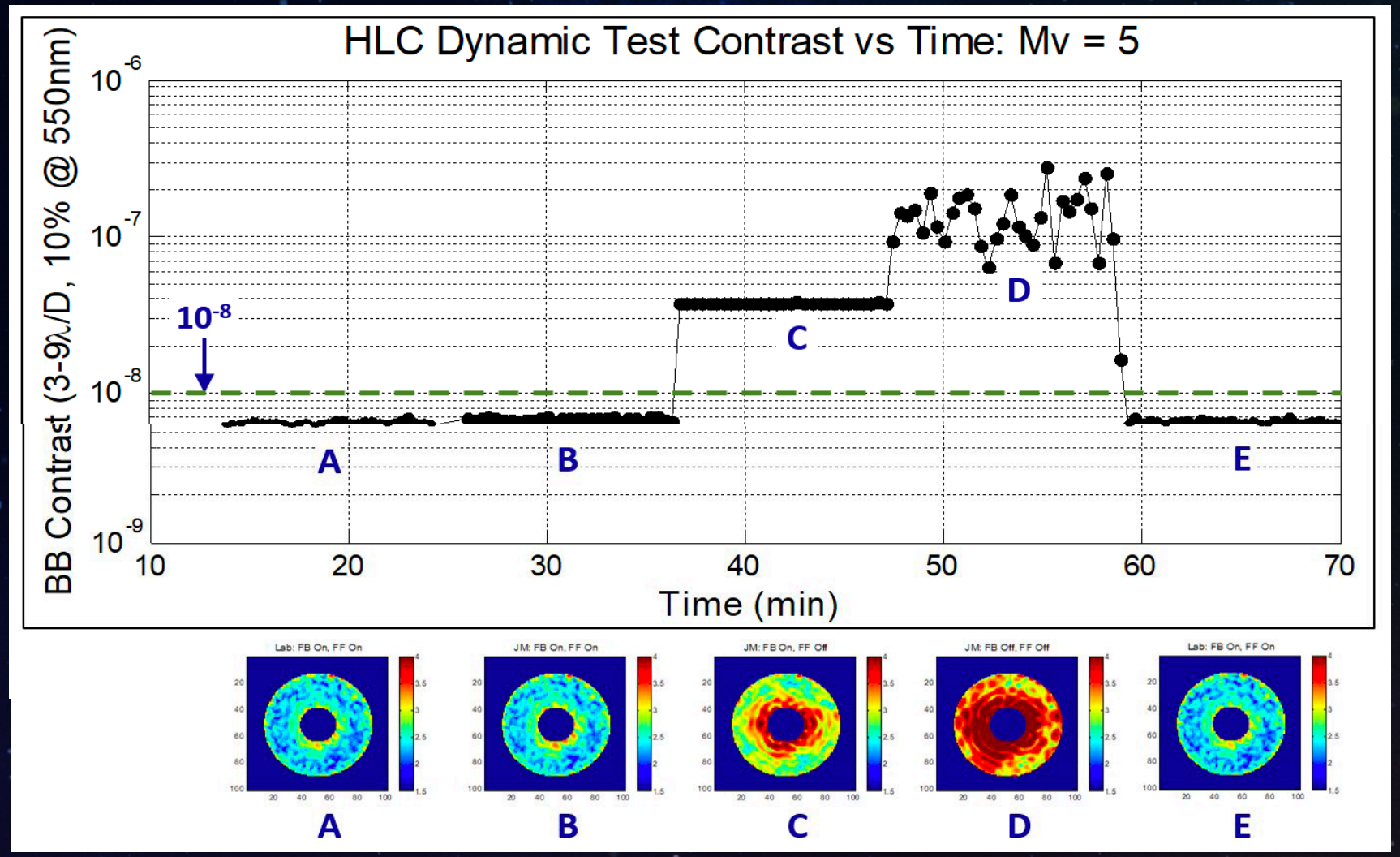


Decadal Survey Testbed Results: Seo, B. et al. 2019

Also see Coronagraphy State-of-the-art Presentation by Dimitri Mawet

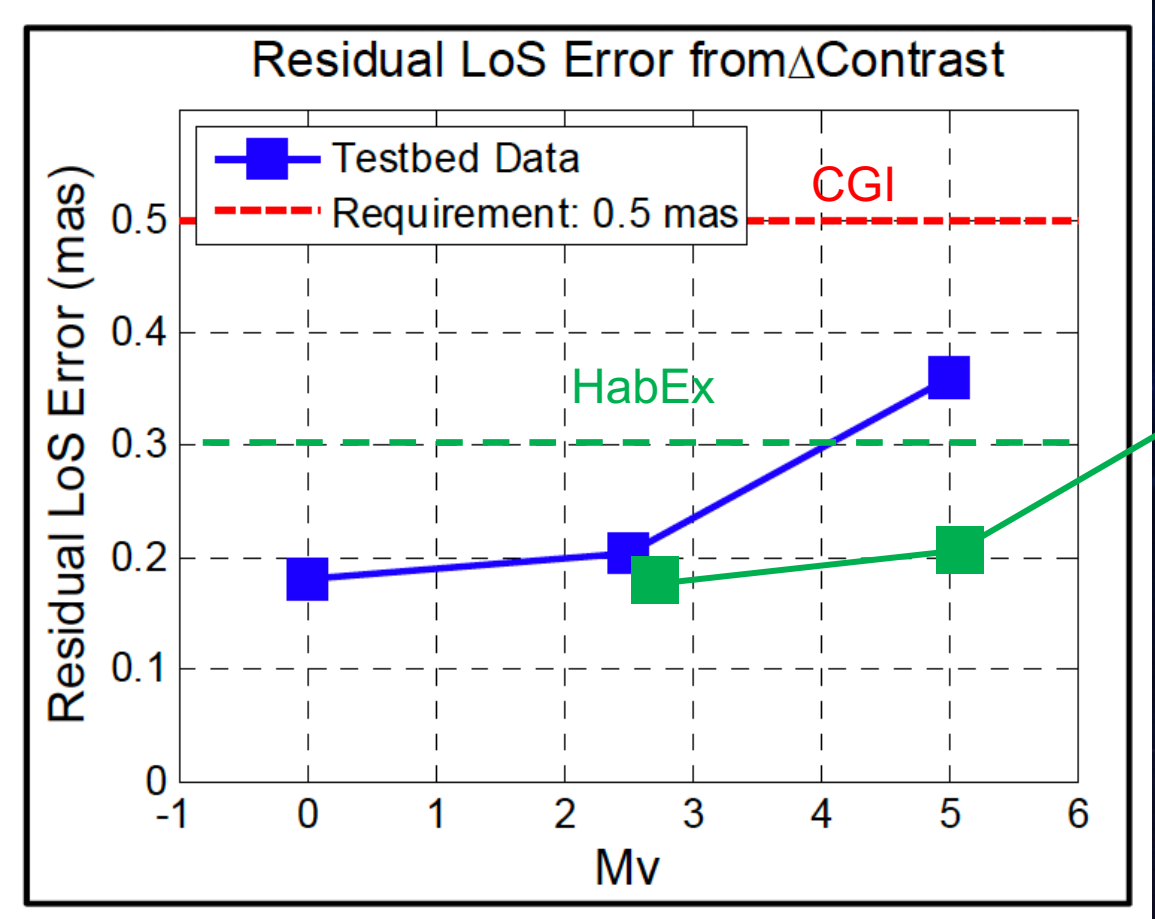
Capitalizing on WFIRST CGI lab results

CGI Low Order Wavefront Sensing & Control (LOWFSC) Demonstration (Shi et al. 2018)



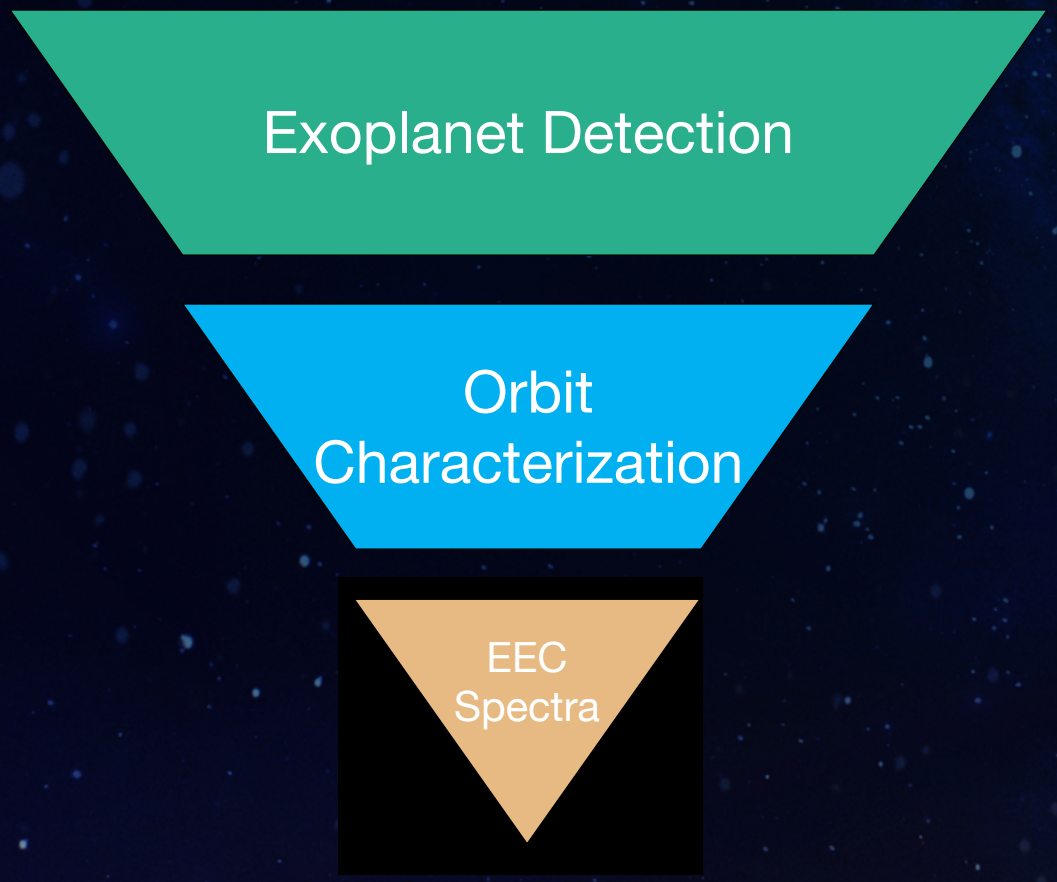
Capitalizing on WFIRST CGI lab results

CGI Line of Sight Sensing & Control Demonstration (Shi et al. 2018)



- Compared to WFIRST CGI, HabEx has:
  - larger collecting area (x3.5) & core throughput (x4)
  - much smaller telescope LOS jitter (0.7mas rms)
- CGI LOWFSC system* already meets HabEx LOS stability requirement !

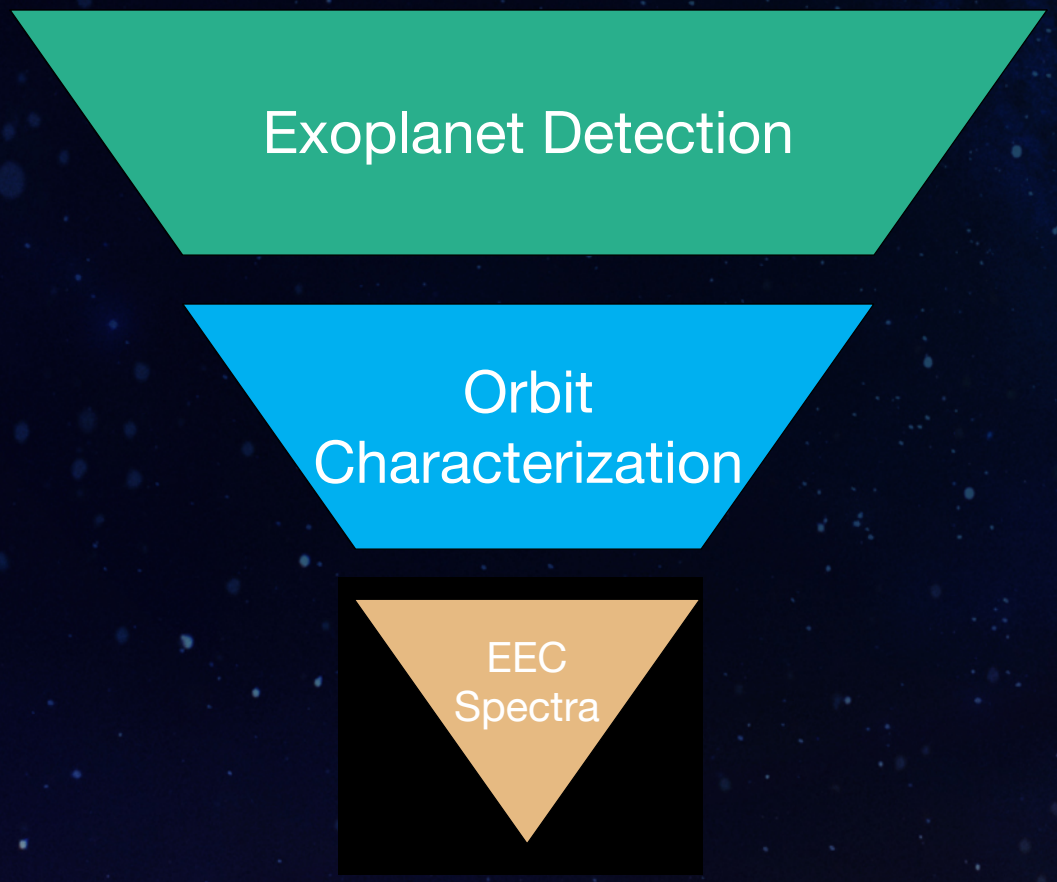
Design Drivers: Exoplanet Spectroscopy



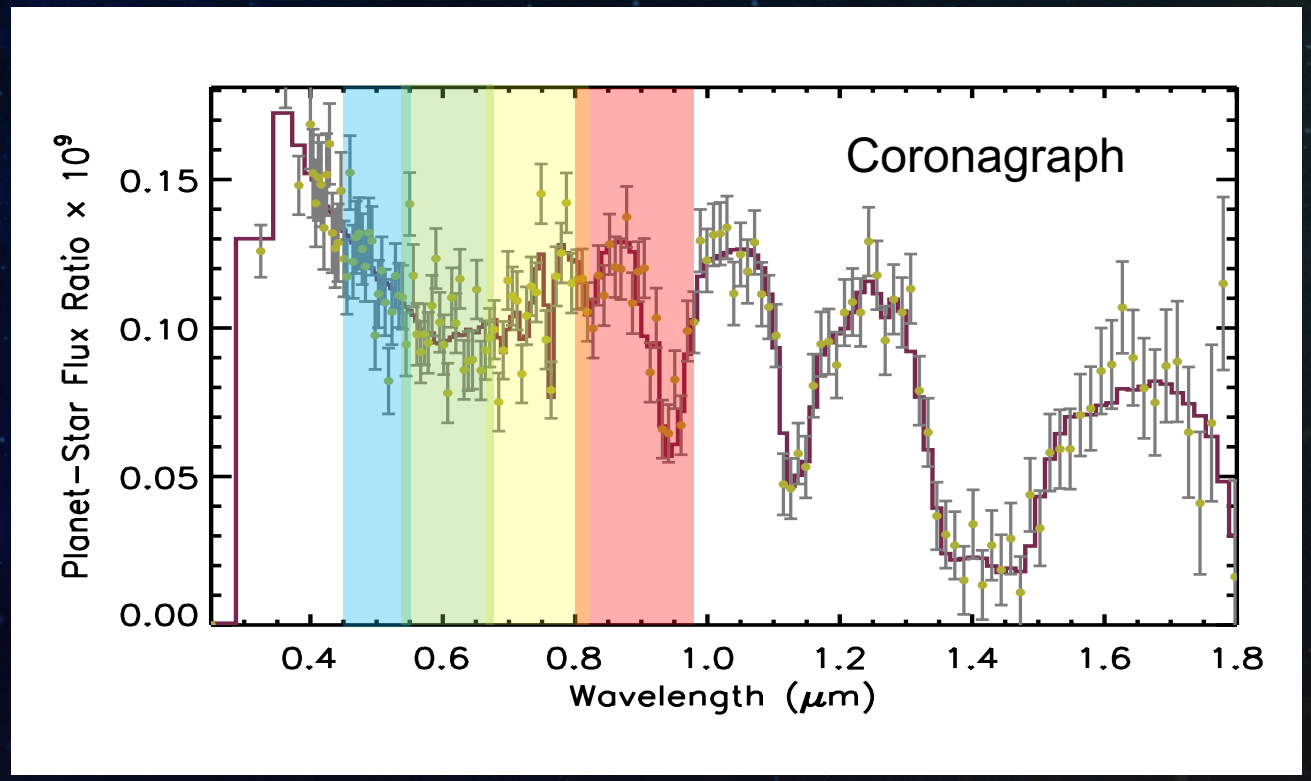
- Must measure high SNR spectra of
  - All systems with planets detected
  - All “exo-Earth candidates”
    - With sensitivity to water vapor, oxygen, ozone at levels << modern Earth levels
  - Covering at least 0.3 – 1 μm for all planets
    - with R>70 from 0.45-1 μm
  - Covering 0.2 to 1.8 μm for favorable targets

See report Chapter 3.1

Design Drivers: Exoplanet Spectroscopy

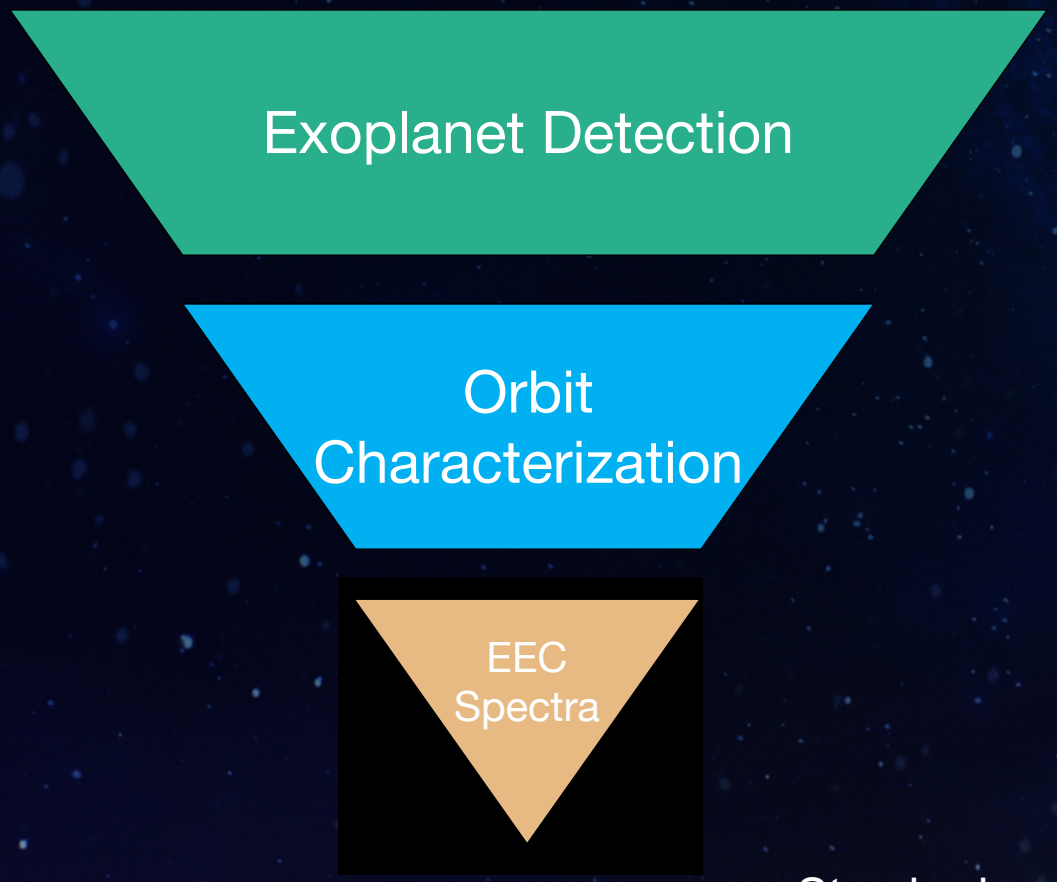


- Coronagraph vs Starshade Spectroscopy Trade

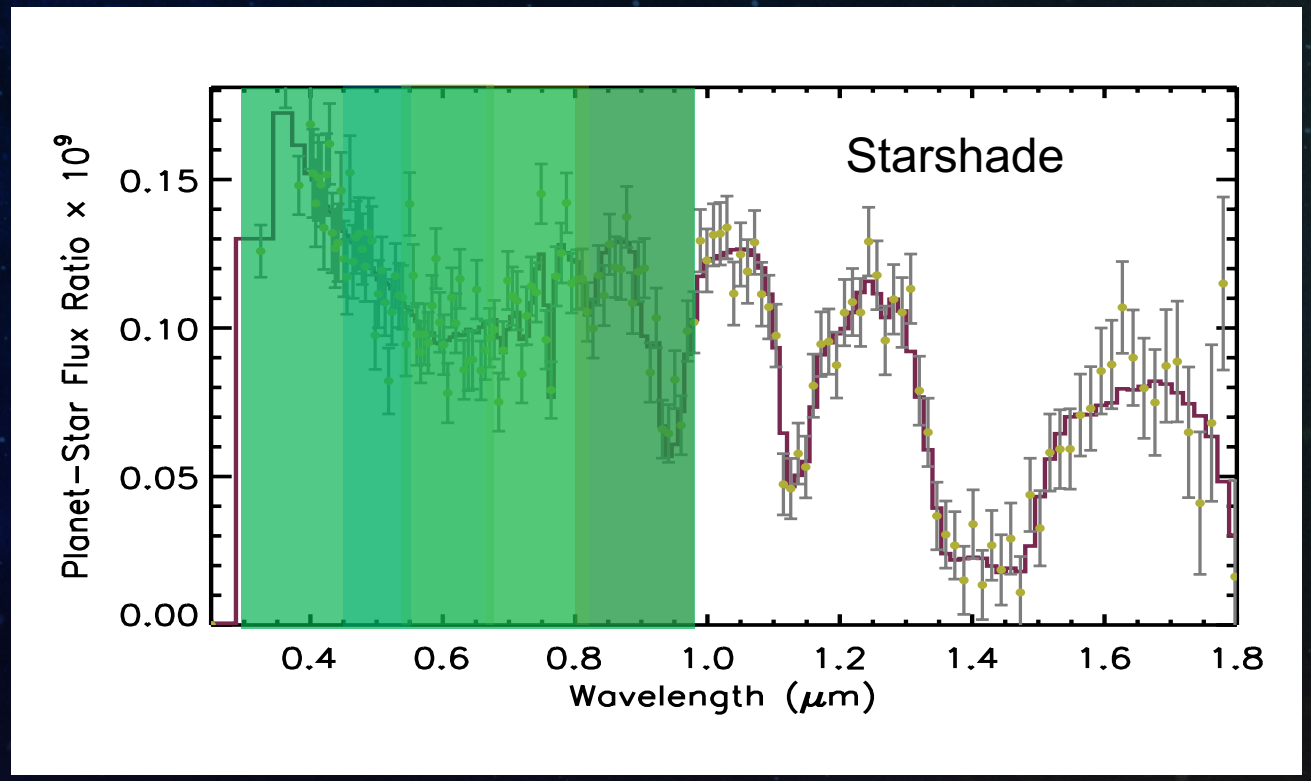


See report Chapter 3.1

Design Drivers: Exoplanet Spectroscopy



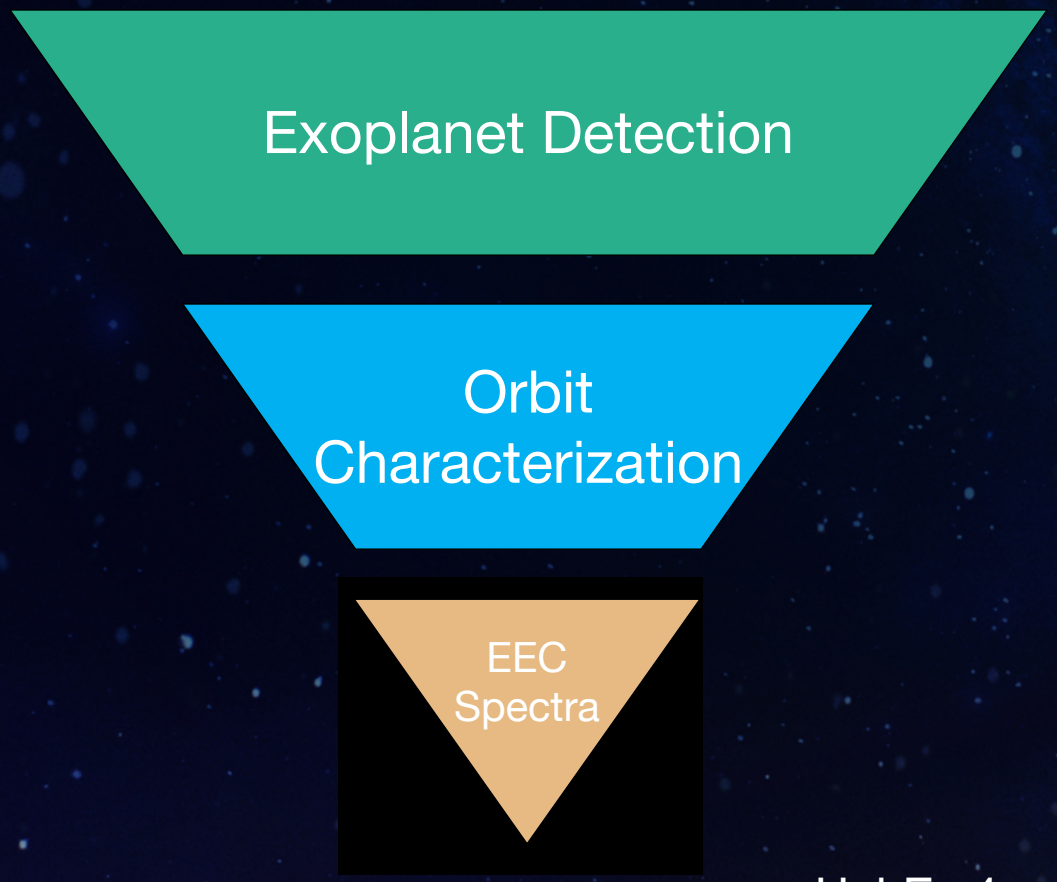
- Coronagraph vs Starshade Spectroscopy Trade



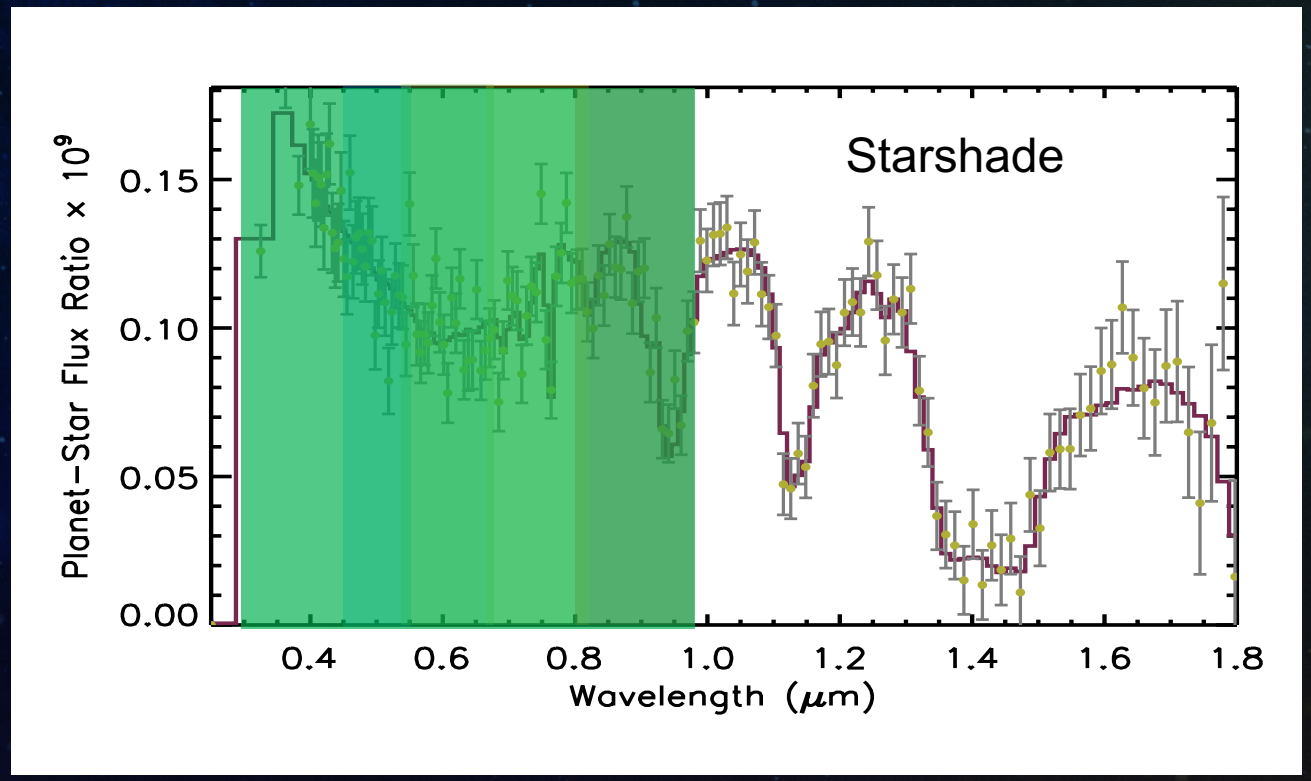
- Starshade offers much broader instantaneous spectral range
  - HabEx Starshade designed to cover 107% BW vs 20% for coronagraph (x5.3)
  - With both polarizations (x2) and higher end-to-end optical throughput (x1.5)

See report Chapter 3.1

Design Drivers: Exoplanet Spectroscopy



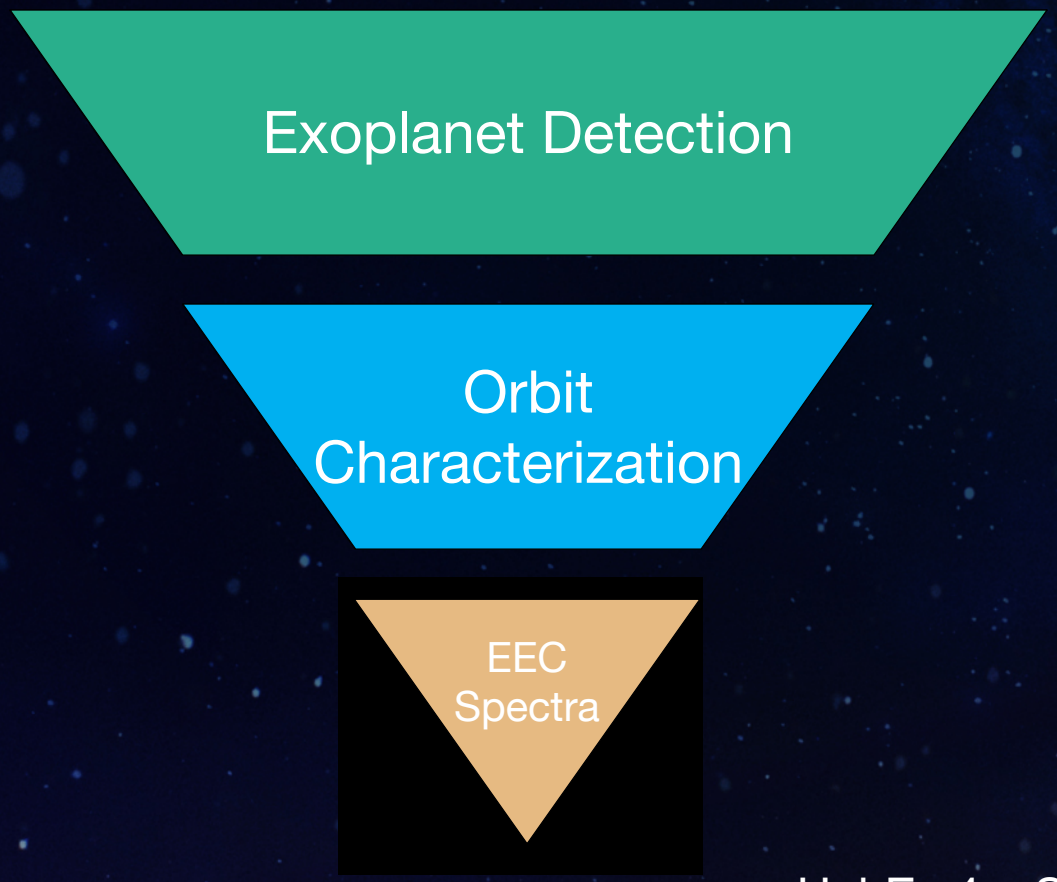
- Coronagraph vs Starshade Spectroscopy Trade



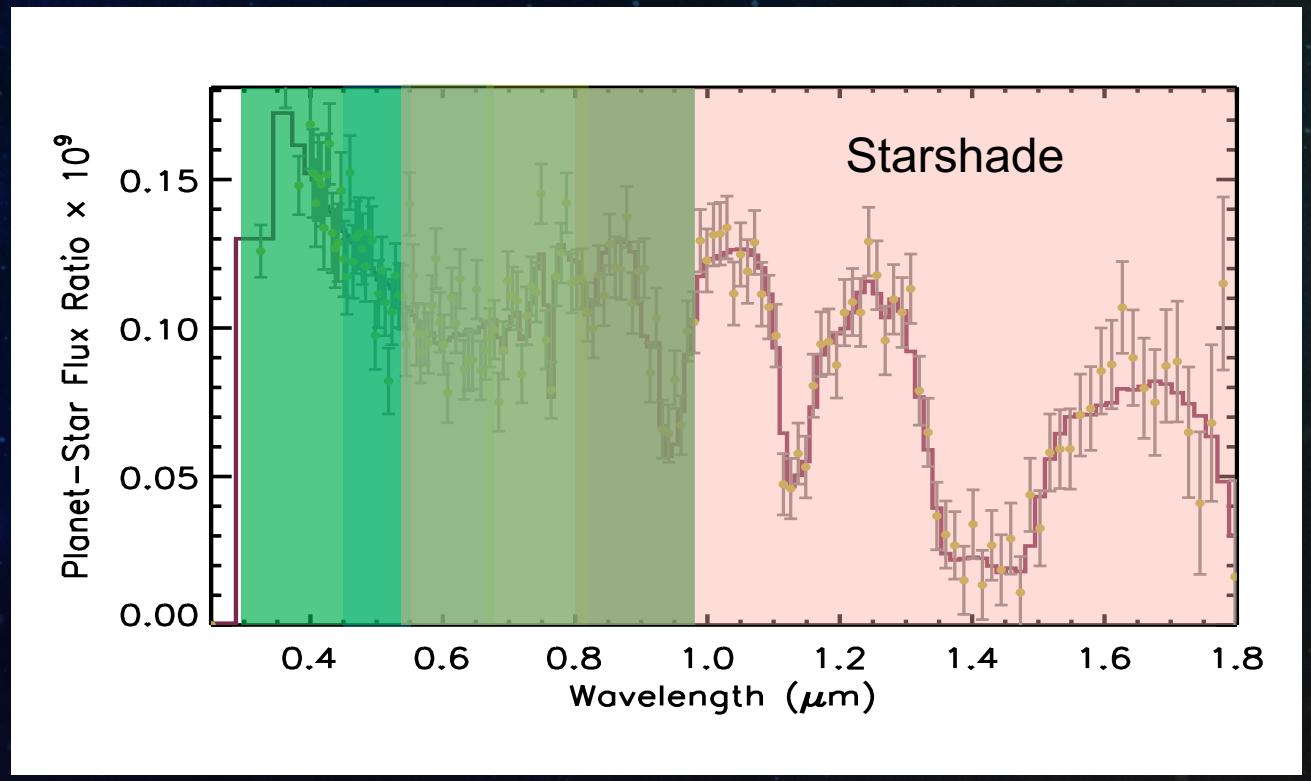
- HabEx 4m + Starshade gathers as many planetary photons per second in the vis/ near UV as a single HabEx coronagraph channel on a 16m telescope.

See report Chapter 3.1

Design Drivers: Exoplanet Spectroscopy



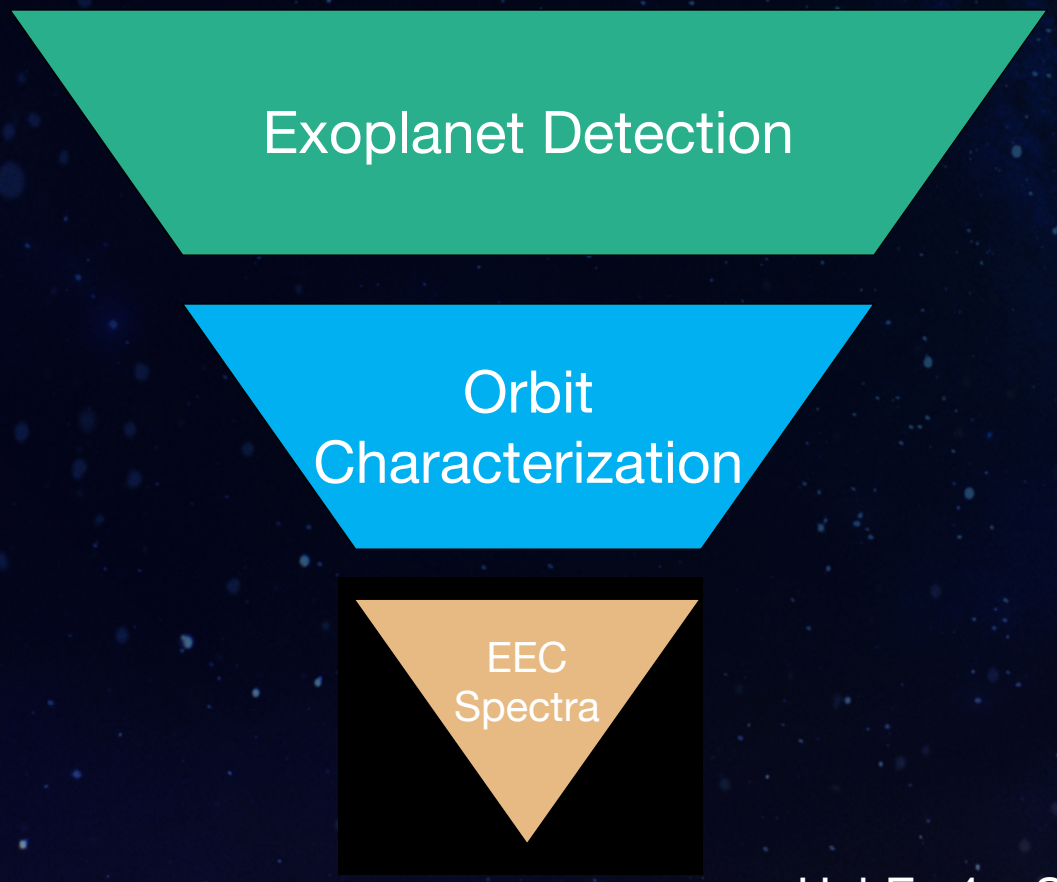
- Coronagraph vs Starshade Spectroscopy Trade



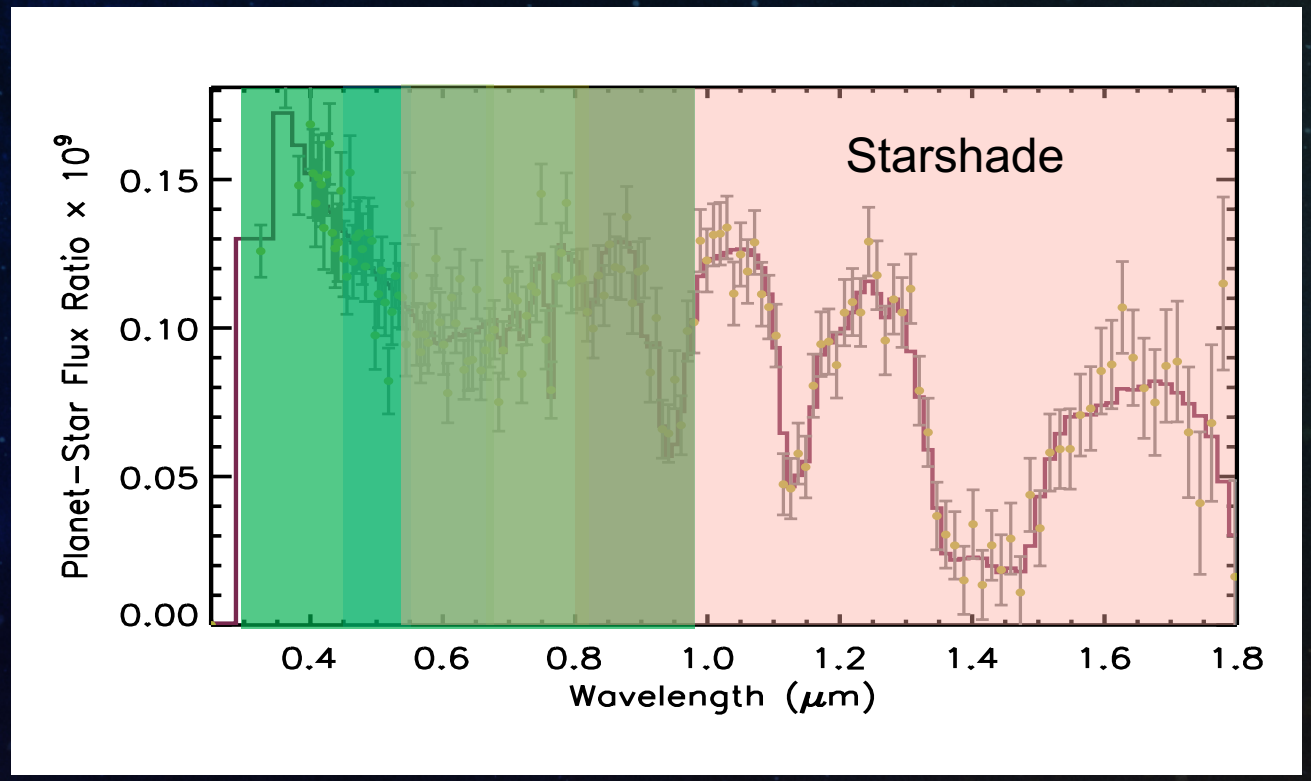
- HabEx 4m Starshade is designed to provide the ~ same (58 mas) IWA from 0.3 to 1um as the HabEx coronagraph at 0.5 um (62 mas)
  - Guarantees 0.3-1um spectra of all planets detected
  - Still provides ~100 mas IWA at 1.8 μm, equivalent to 2.8λ/D on a 10m

See report Chapter 3.1

Design Drivers: Exoplanet Spectroscopy



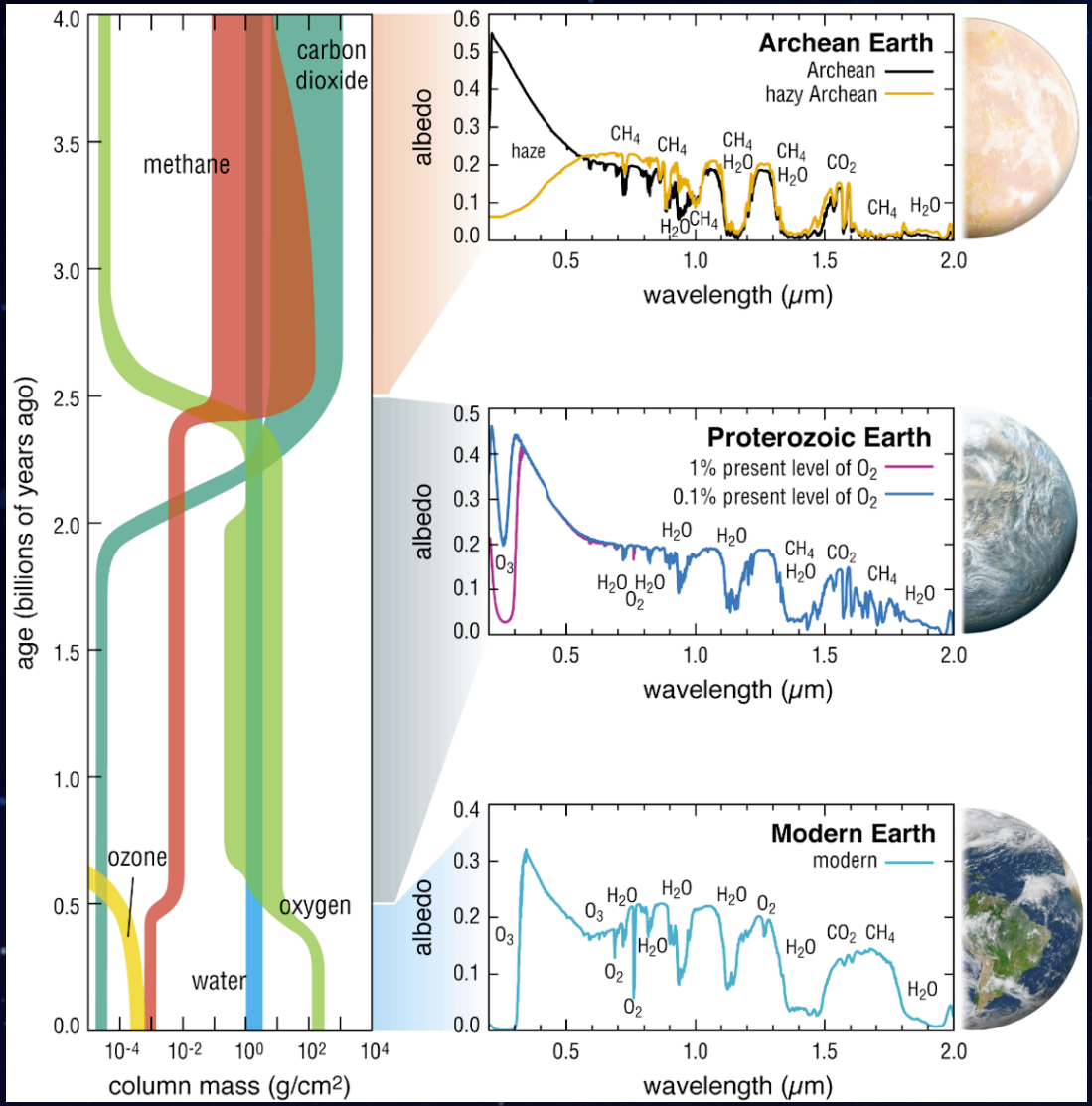
- Coronagraph vs Starshade Spectroscopy Trade

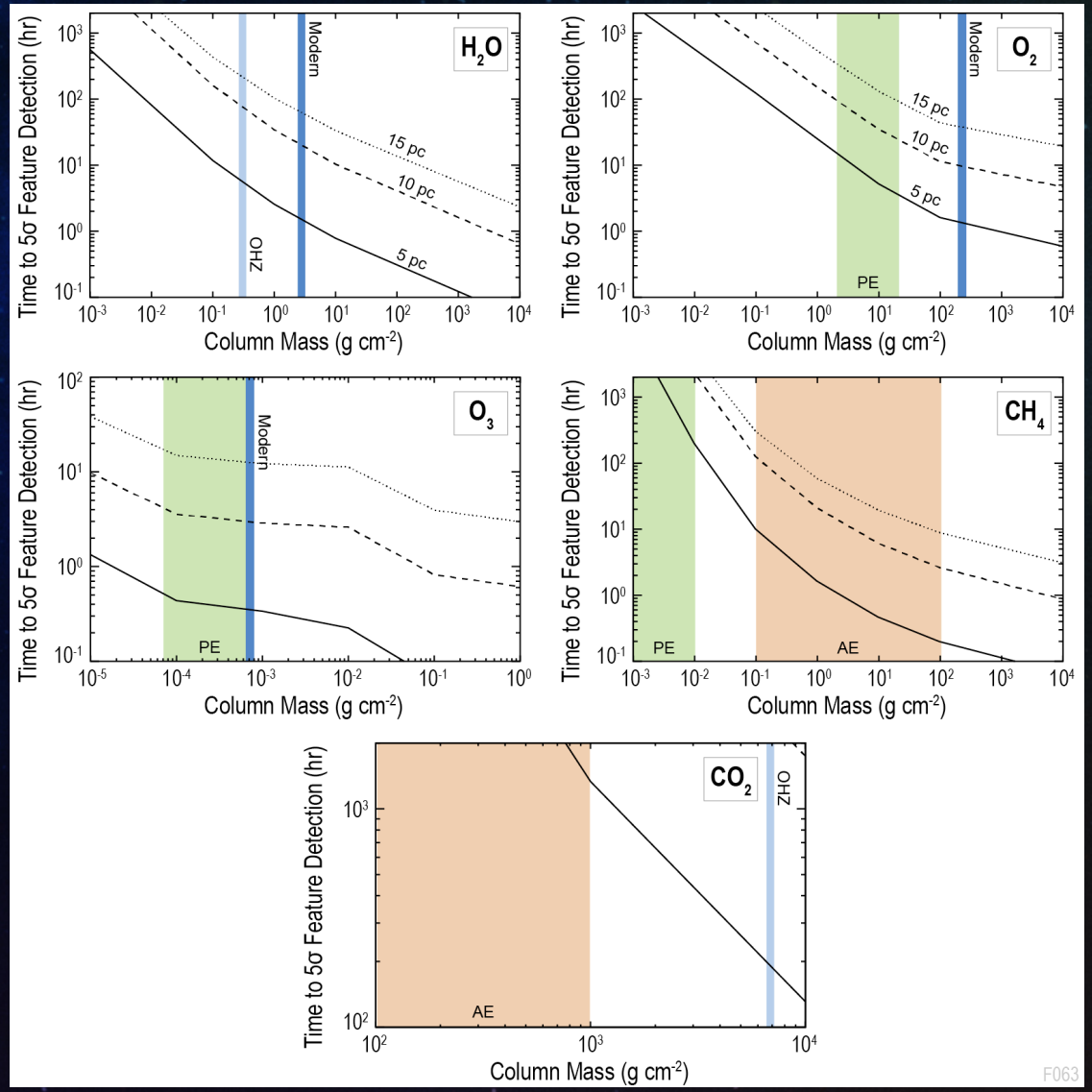


- HabEx 4m Starshade emulates a much larger telescope (throughput, IWA)
- Starlight Suppression System of choice for exoplanet spectroscopy

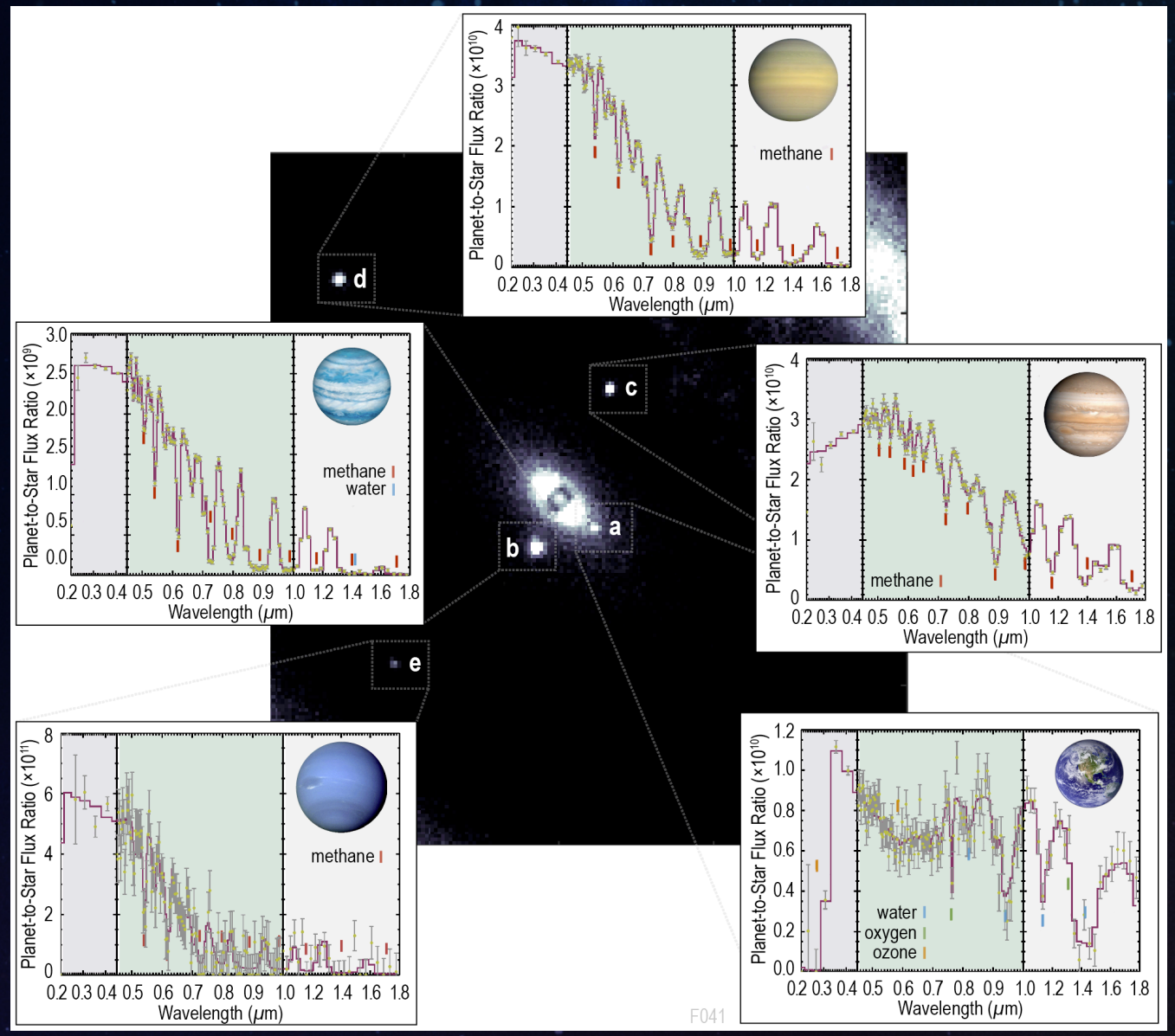
See report Chapter 3.1

A lot more than just Modern Earth spectra



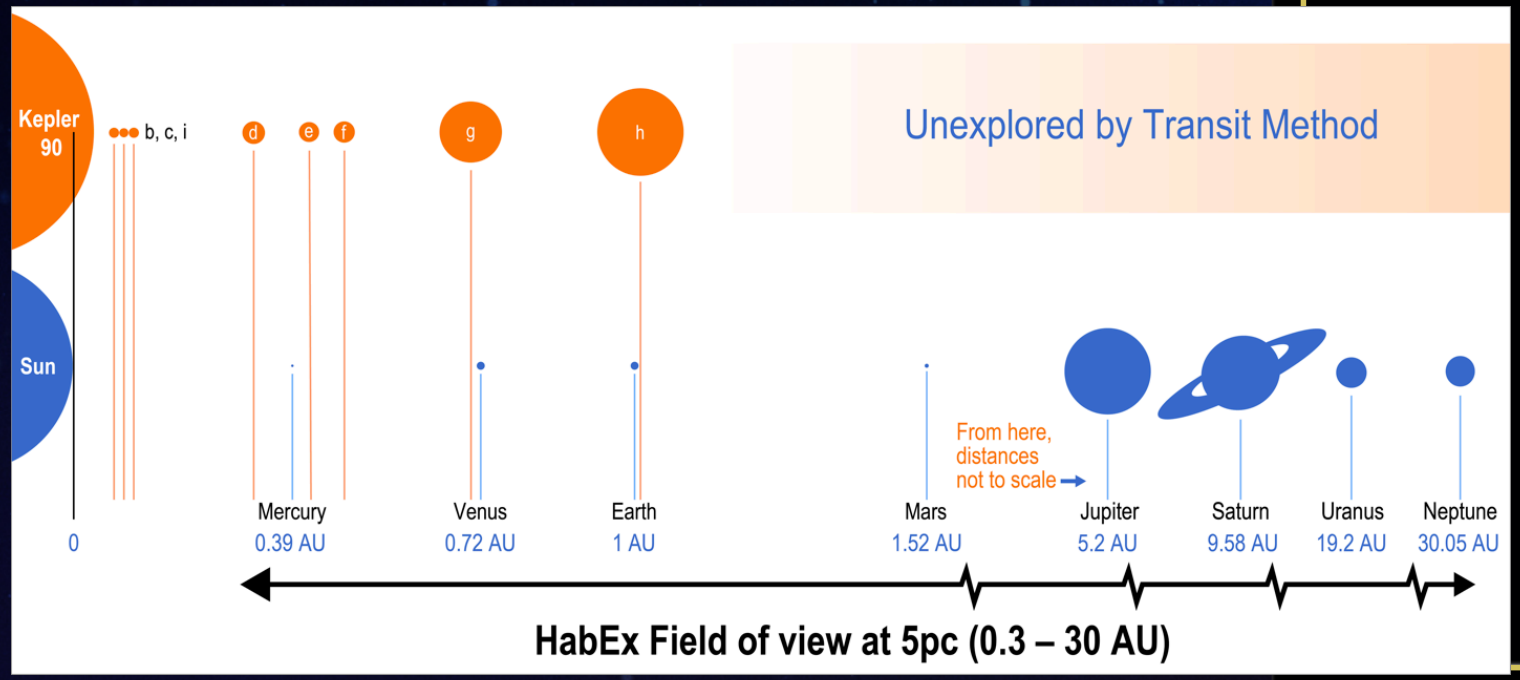


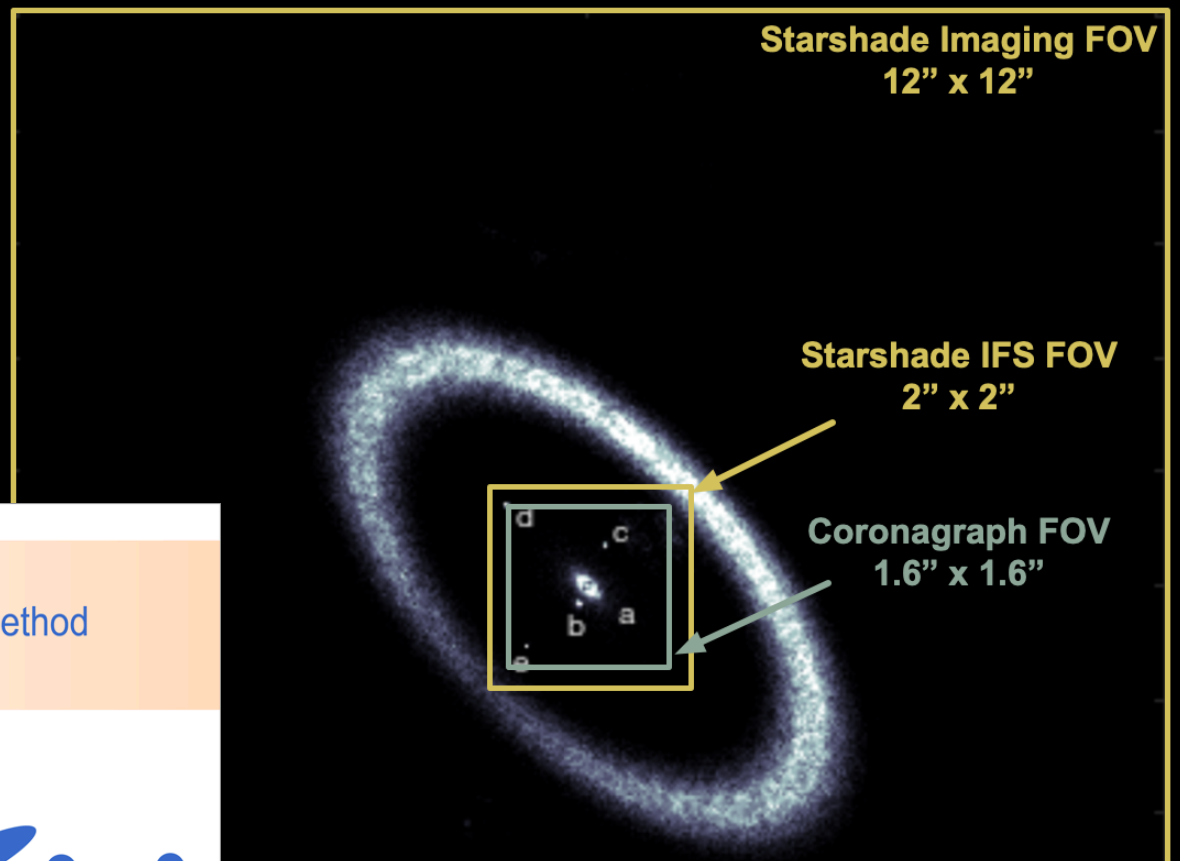
A high diversity of exoplanet spectra



Starshades offer more complete family portraits of exoplanets in nearest systems

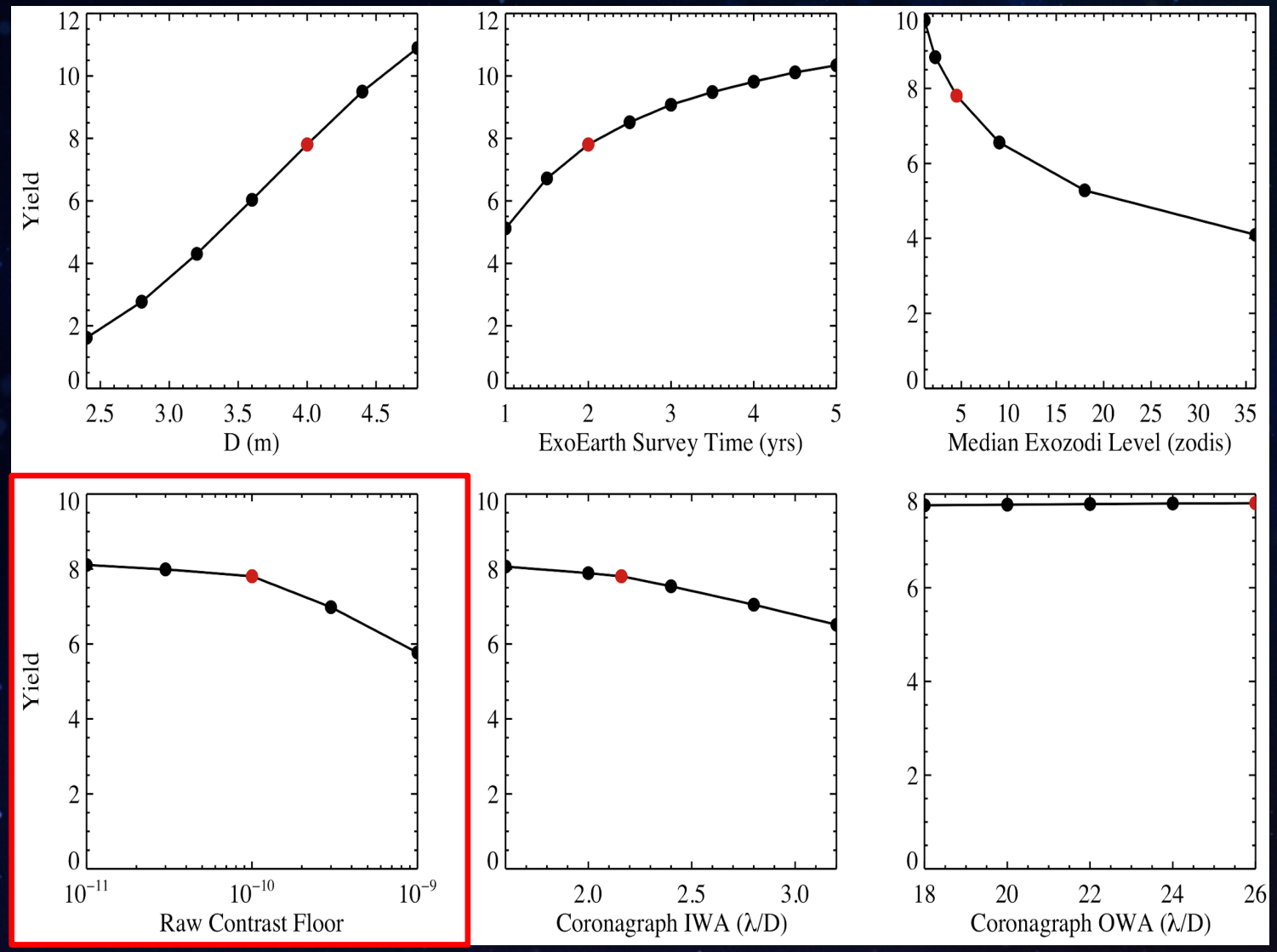
- Starshades high contrast field-of-view (OWA) limited by detector format
  - independent of wavelength, telescope D and # of DM actuators
- Starshades cover a much larger range of physical separations in nearest (most favorable) systems





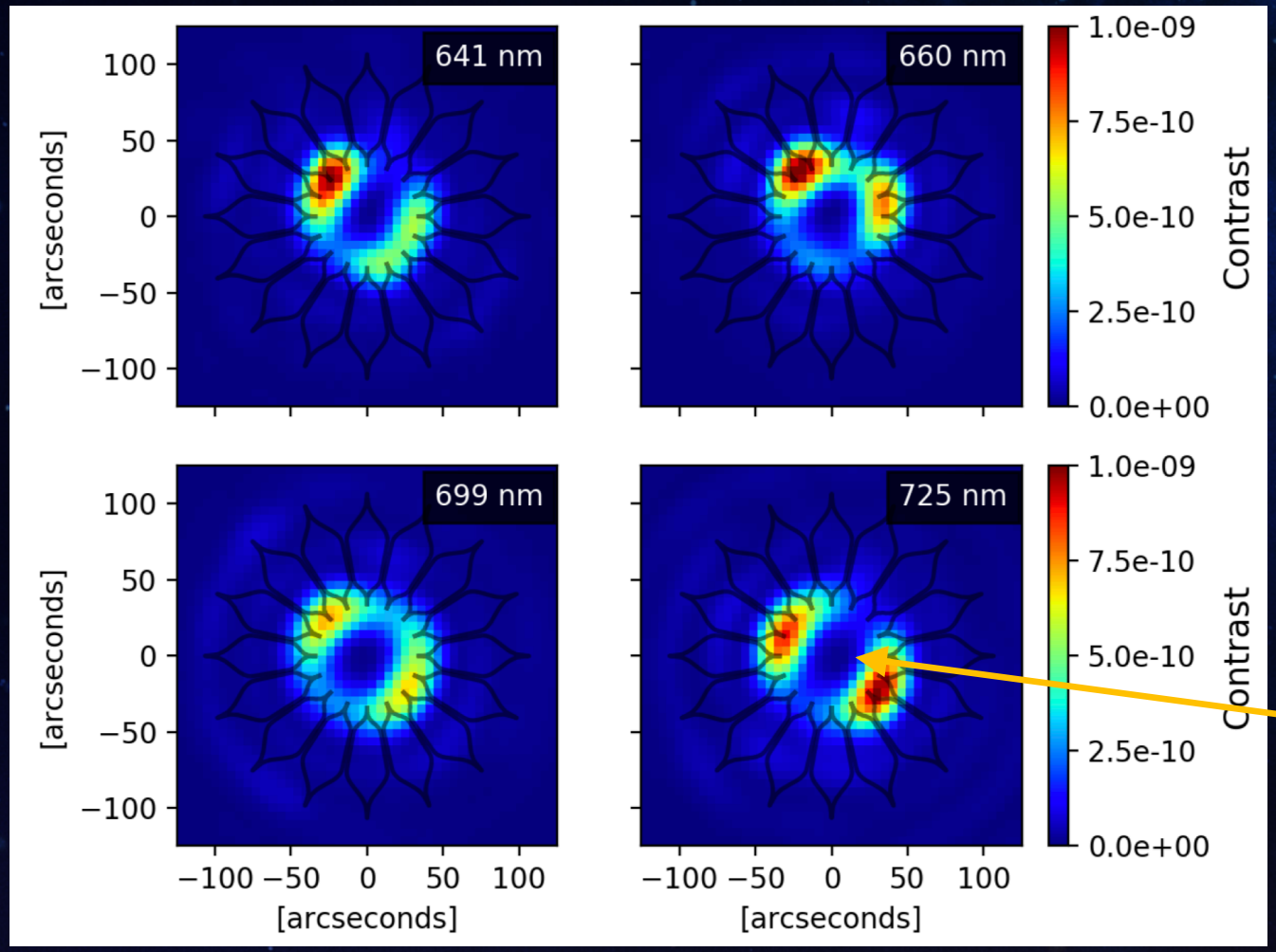
- Study planetary architecture diversity
- Assess “architecture habitability”
- Study variation of atmospheric properties

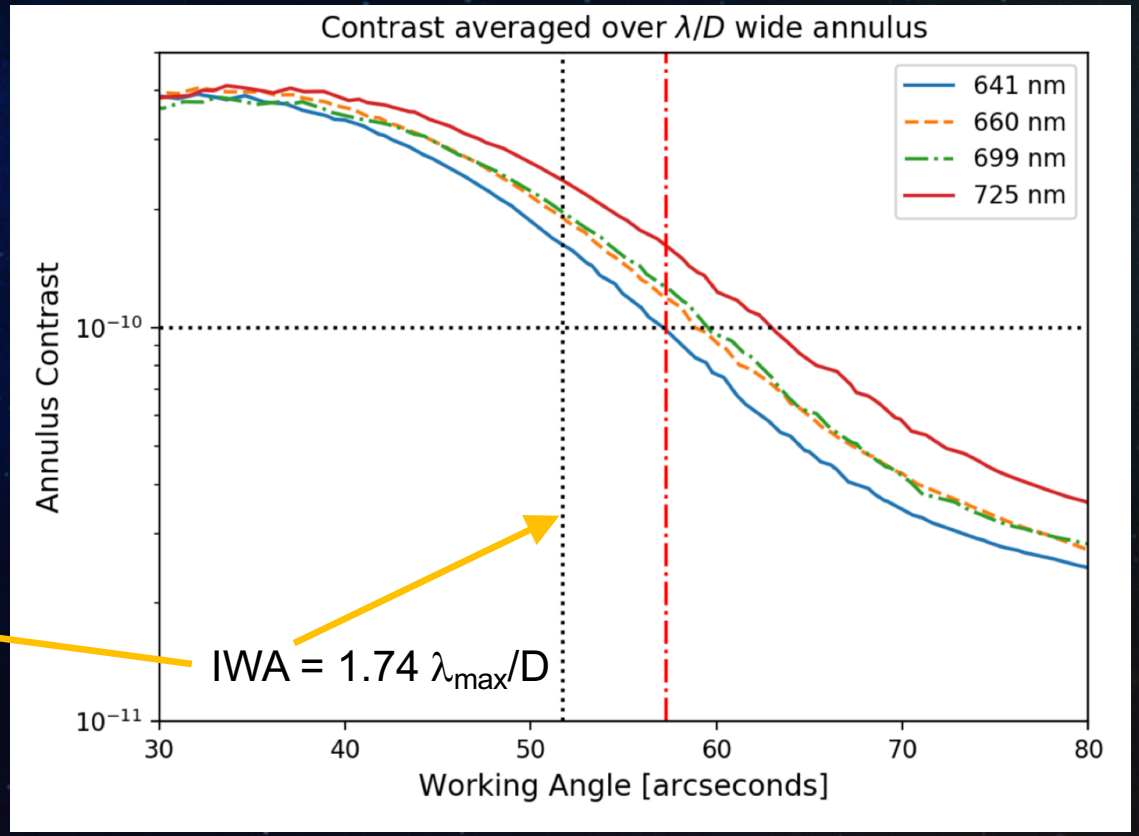
Designing the HabEx Starshade

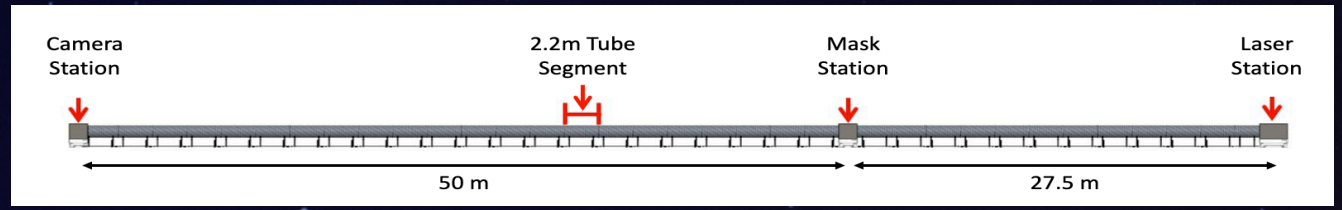


Sensitivity to Astrophysical and Instrument Parameters

Capitalizing on ExEP Starshade Technology Activity (S5) Results







(Harness et al. 2019, Princeton Lab Testbed https://exoplanets.nasa.gov/exep/technology/starshade/)
Also see Kendra Short "S5" presentation to this committee.

Capitalizing on the HabEx Architecture

- Designing for high contrast exoplanet imaging at the system level provides an unmatched platform for general astrophysics and planetary science observations in the UV to near IR

- Ultra-stable visible/near IR 4m space telescope diffraction limited at 400nm
  - HabEx visible to near IR imager & spectrograph (HWC) is designed to rip the benefits
    - plus improved detectors and multi-object spectroscopic capabilities over HST / WFPC3 instrument

- UV coated M1-M2-M3 opens up potential for far UV observations
  - HabEx UV imager and spectrograph (UVS)
    - plus improved detectors and multi-object spectroscopic capabilities over HST / COS instrument

- Very high (> 90%) observational efficiency
  - L2 orbit with small keep-out zones and no eclipse
  - Fast slews and settle times (thrusters and ultra-stable structure)
  - Phased array antennas for data downlink during observations
  - All instruments can observe simultaneously
    - Parallel deep field obs. during week-long exoplanet pointings

Architectures vs Science, Cost and Technical maturity

HabEx Science Goals & Objectives			HabEx Mission Architectures								
			4H	4C	4S	3.2H	3.2C	3.2S	2.4H	2.4C	2.4S
Habitable Exoplanets	O1	Exo-Earth candidates around nearby sunlike stars?									
	O2	Water vapor in rocky exoplanet atmospheres?									
	O3	Biosignatures in rocky exoplanet atmosphere?									
	O4	Surface liquid water on rocky exoplanets?									
Exoplanetary Systems	O5	Architectures of nearby planetary systems?									
	O6	Exoplanet atmospheric variations in nearby systems?									
	O7	Water transport mechanisms in nearby planetary systems?									
	O8	Debris disk architectures in nearby planetary systems?									
Observatory Science	O9	LIfecycle of baryons?									
	O10	Sources of reionization?									
	O11	Origins of the elements?									
	O12	Discrepancies in measurements of the cosmic expansion rate?									
	O13	The nature of dark matter?									
	O14	Formation and evolution of globular clusters?									
	O15	Habitable conditions on rocky planets around M-dwarfs?									
	O16	Mechanisms responsible for transition disk architectures?									
	O17	Physics driving star-planet interactions, *e.g.* auroral activity?									
Estimated Cost ($B FY20)			6.8	4.8	5.7	5.7	3.7	5.0	4.8	3.1	4.0
Number of TRL4 technologies			13	10	9	12	9	9	11	8	8

- *Orange does not mean "no science"*
- *S-only architectures have on-axis telescopes*
- *At a given aperture size, exoplanet science is best with Hybrid architectures*
- *C-only: no exoplanet observations in the UV. Reduced spectral characterization*
- *S-only: Reduced number of planetary orbits*

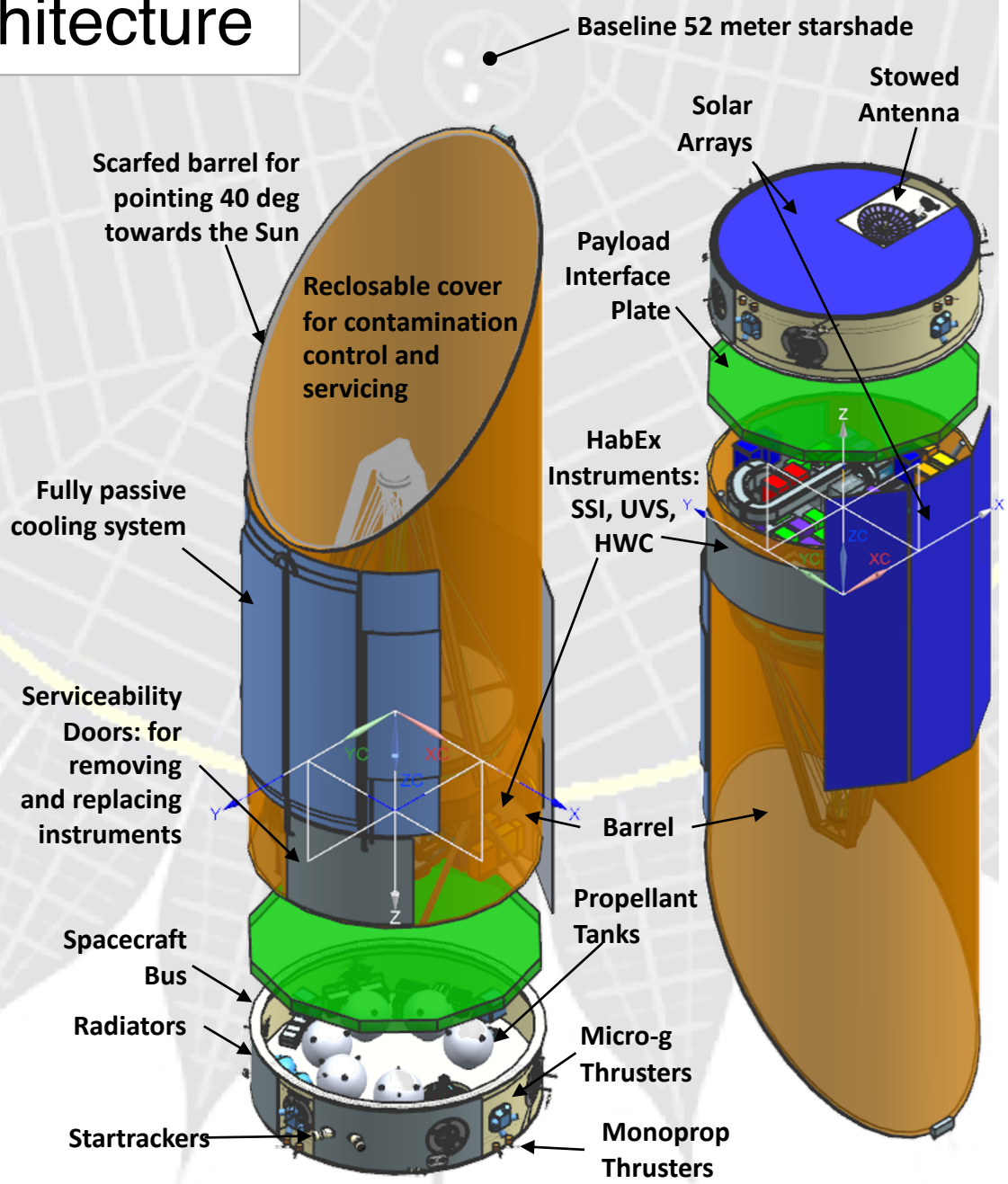
- *Observatory Science is primarily a function of telescope size*

- *STDT's preferred architecture is 4H*
- *Architectures 4H (4C) and 3.2S designed in detail*

HabEx Starshade-Only 3.2S Architecture

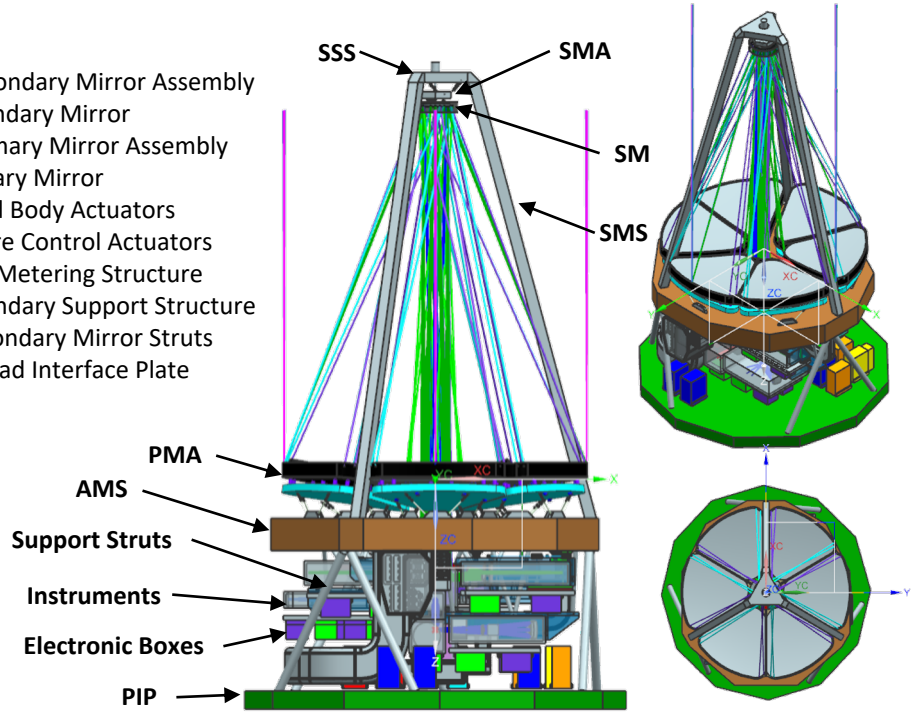
- HabEx without a coronagraph
  - Starshade provides the highest quality exoplanet imaging and spectroscopy
  - Supports the full HabEx General Astrophysics program
  - *But* – lower yield of exo-Earths *unless detected prior to HabEx via e.g. PRV or astrometry*
- Lower cost telescope
  - Eliminates one instrument
  - Telescope tolerances relaxed 1000 times
  - On-axis configuration
    - Light weight (5cm thick) Primary Mirror
    - Telescope Mass = 7.3 T vs. 19 T
    - More compact OTA (f/1.3)
    - Non deployable telescope architecture a priori scalable above 4m
    - Segmented telescope to stay within current practice and largest ULE mirrors.

Estimated Cost Reductions	HabEx 4H	HabEx 3.2S
Smaller Telescope	–	-0.6 $B
No Coronagraph	–	-0.4 $B
Smaller Launch Vehicle	–	-0.4 $B
Same Starshade System	–	–
Lower Reserves	–	-0.4 $B
Total Estimated Cost	**6.8 $B**	**5.0 $B**



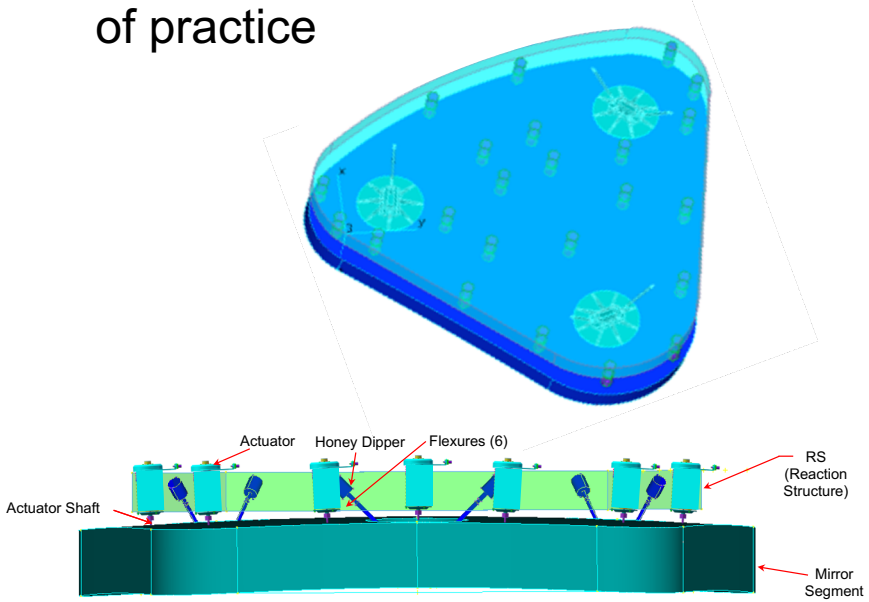
Active Optics Telescope

SMA: Secondary Mirror Assembly
SM: Secondary Mirror
PMA: Primary Mirror Assembly
PM: Primary Mirror
RBA: Rigid Body Actuators
FCA: Figure Control Actuators
AMS: Aft Metering Structure
SSS: Secondary Support Structure
SMS: Secondary Mirror Struts
PIP: Payload Interface Plate



- Wavefront Sensing and Control establishes initial 30 nm RMS WF error
  - Rigid-body control of PM segments and SM phase and collimate the telescope
  - PM segment figure control assures performance while relaxing fabrication requirements.
- **Laser Metrology is used to continuously maintain optical alignments**

- **Corrects optical errors on-orbit**
- Mirror fabrication within current state of practice



Requirement	**18.0** nm rms WFE			
	Nominal	**Corrected**	**Margin**	**8** nm
	56.0	**16.0** nm		
		Nominal	**Corrected**	
	Segment Figure	**108.0**	**12.0** nm	
	Includes effects of polishing, testing, gravity sag prediction, temperature change, coating, and matching radius of curvature			
		Nominal	**Corrected**	
	Mounting Errors	**26.0**	**10.0** nm	
	Includes effects of bonding mounts and devices, material creep, desorption, etc.			

See Report Appendix B for full details