Starlight suppression technologies from the LUVOIR and HabEx reports

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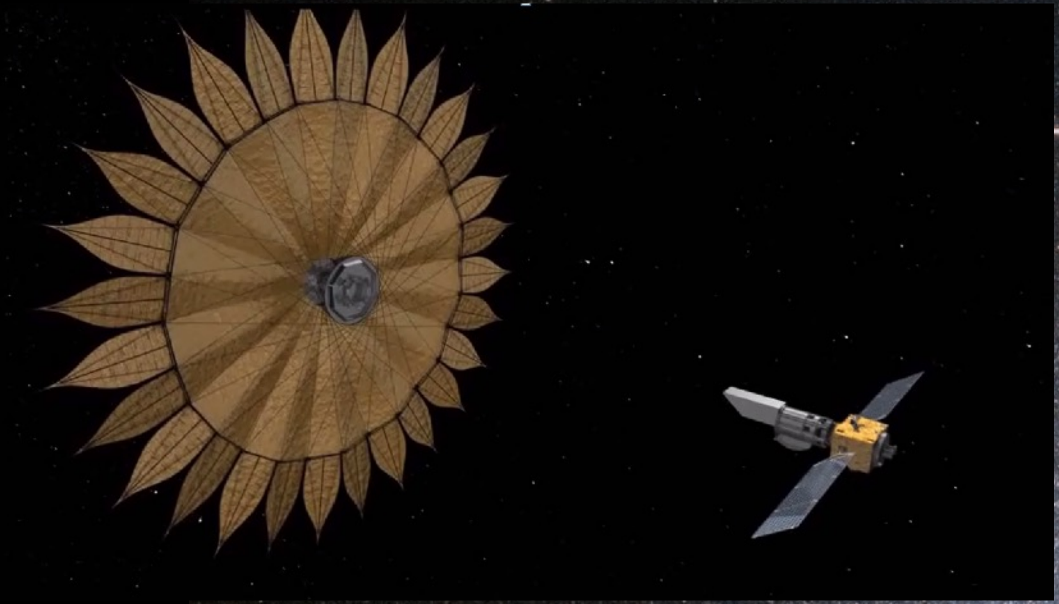
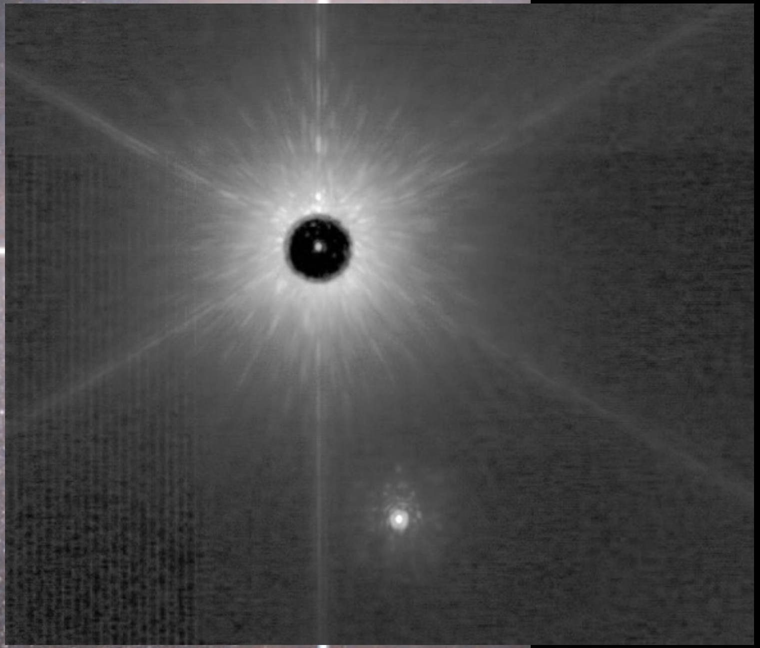
Acknowledgements to the LUVOIR and HabEx Design Teams

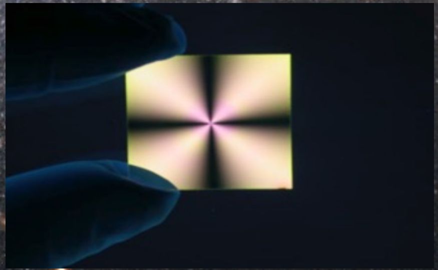
Starlight Suppression Technologies for HWO Flagship
Seattle AAS meeting Splinter Session January 10, 2023

External Occulters (Starshades)





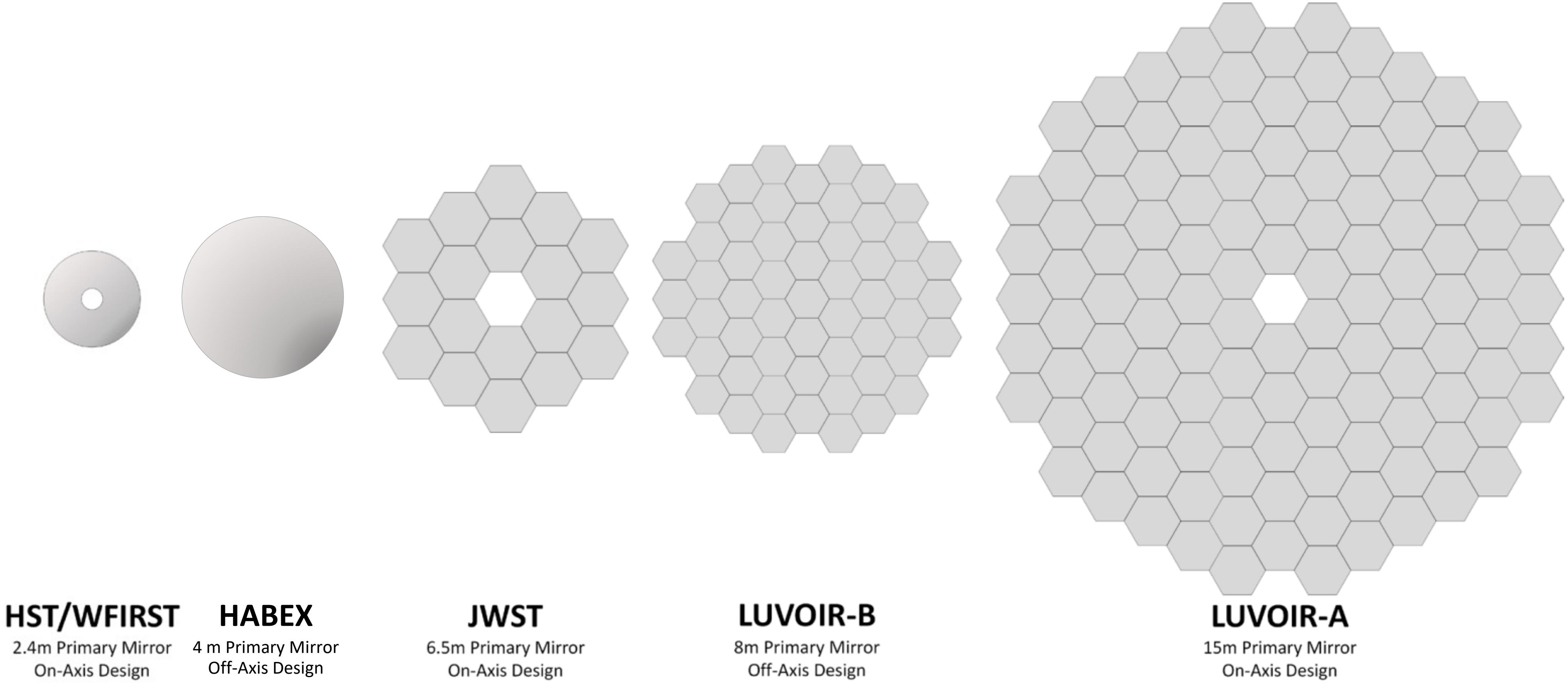
Internal Occulters (Coronagraphs)



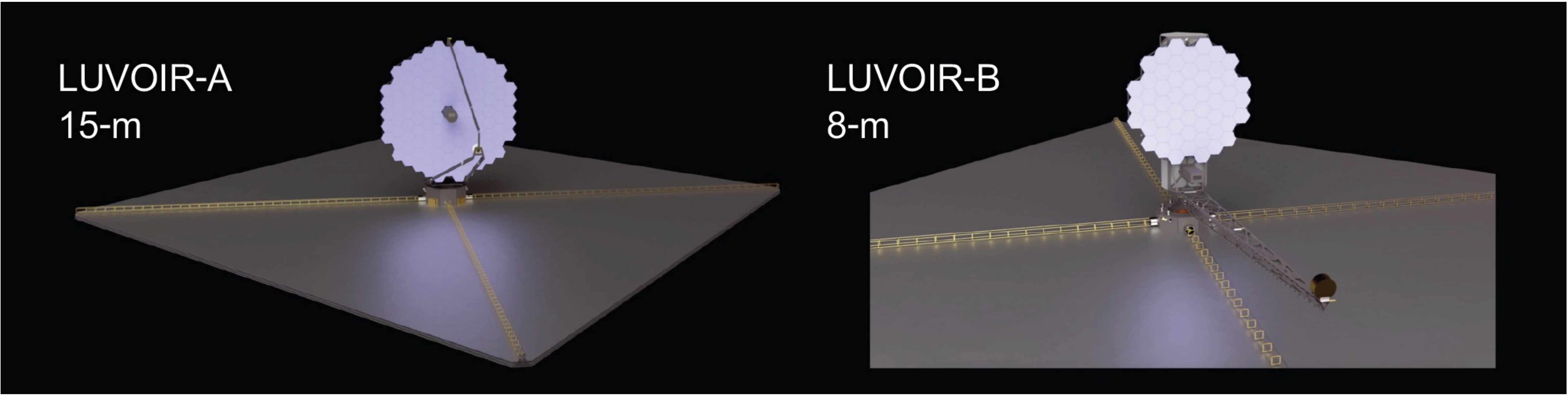
ExEP

In-space high contrast imaging architectures

	HST	WFIRST	HabEx	JWST	LUVOIR-B	LUVOIR-A
Coronagraph contrast	10^{-5}	10^{-8}	10^{-10}	10^{-6}	10^{-10}	10^{-10}
Starshade diameter		(26 m)	52 m			



LUVOIR architectures



On-axis obscuration is challenging for coronagraph

Coronagraph with 10^{-10} raw contrast

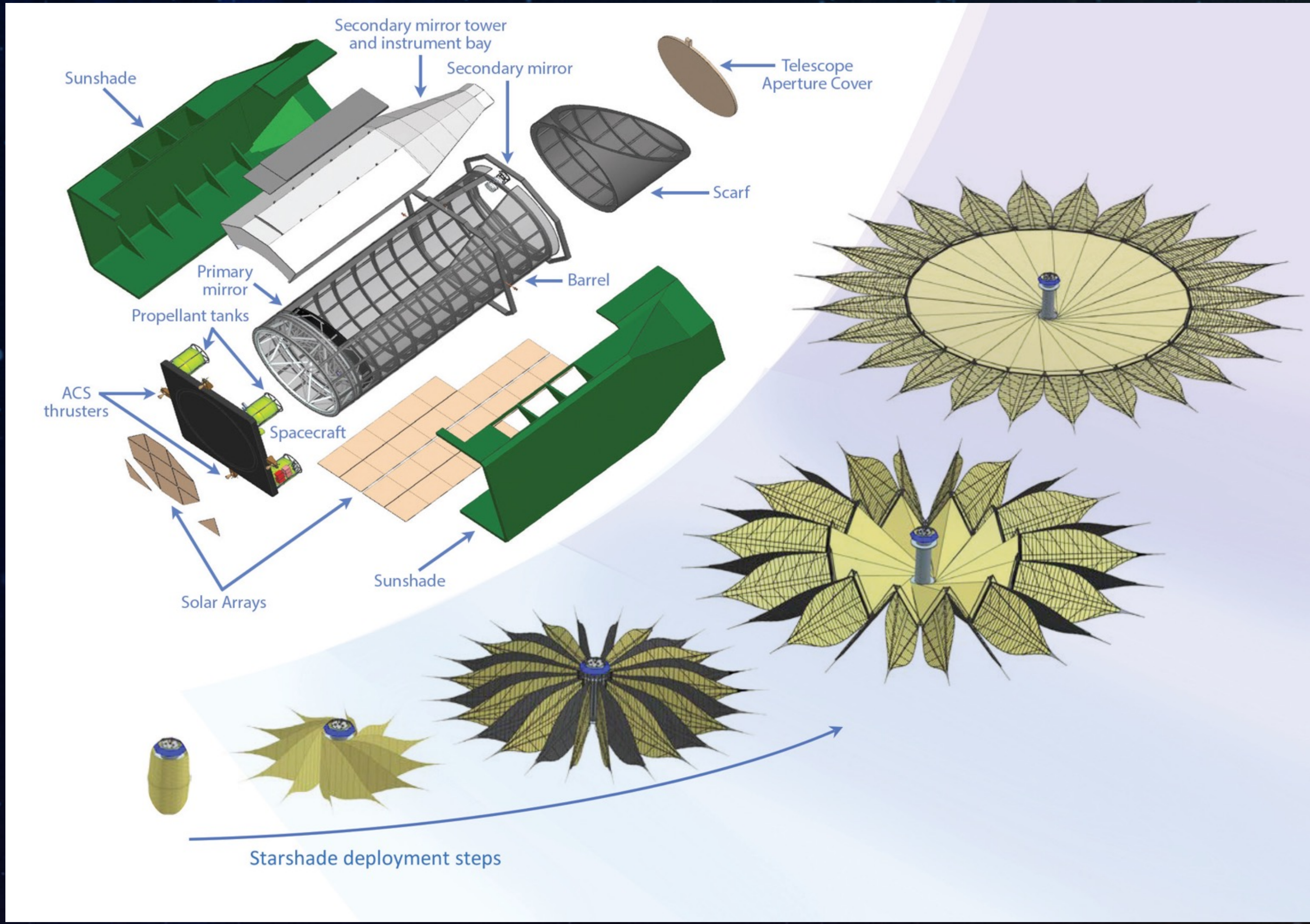
- LUVOIR-A: APLC, LUVOIR-B: VVC
- DM: 128 x 128 MEMS
- Imager: 1024 pixels, IFS: 4096 pixels
- IWA – OWA: 3.5 – 64 l/D
- Wavelengths: 200-525, 515-1030, 1000-2000 nm

Ultra-stable segmented mirror

- Closed back ULE glass segments
- Rigid body actuated segments
- Edge sensors
- Laser metrology truss
- Vibration isolation

HabEx Baseline Architecture: coronagraph + starshade

Mission Duration	**5 years (10 years consumables)**
Orbit	Earth-Sun L2 Halo
Telescope Type	Off-axis three-mirror anastigmat
Primary Mirror	4-meter monolith glass-ceramic (Zerodur) substrate with Al+MgF_2 coating
Attitude Control	Slewing: hydrazine thrusters Pointing: micro-thrusters
Launch Vehicles	Telescope: SLS Block 1-B Starshade: Falcon Heavy
Science Instruments	• Exoplanet Science - Coronagraph - Starshade • Observatory Science: - UV Spectrograph - Workhorse Camera



Coronagraph IWA – OWA: 2.4 – 32 l/D, Vis, NIR
Starshade IWA -OWA: 58 mas – 6” for 300-1000 nm
IFS detector: 4096 pixels

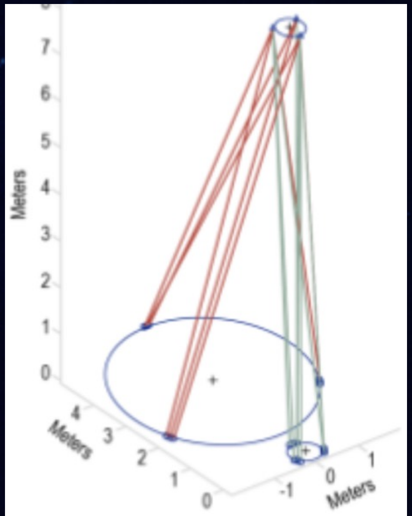
The complementary strengths of coronagraphs and starshades

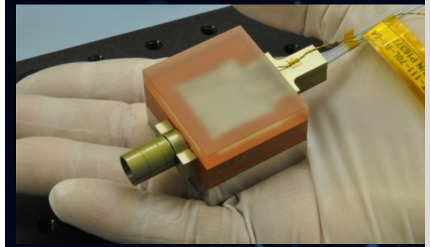
	coronagraph	starshade
Bandwidth	20%	>100%
Throughput	20-40%	~100%
Polarization	Single channel	Unaffected
IWA	2.4 λ/D	1.5 λ/D
OWA	64 λ/D	>235 λ/D
Slew time	<1 hr	~1 week
Starlight suppression	Inside telescope	In front of telescope
Strength	Search survey	High quality spectra

- **Coronagraphs are agile and well-suited for search surveys**
- **Starshades are optimal for high quality spectra due to their smaller IWA, higher throughput, and very broad bandwidth**

Telescope Technology Advances

Laser Metrology





TRL 5

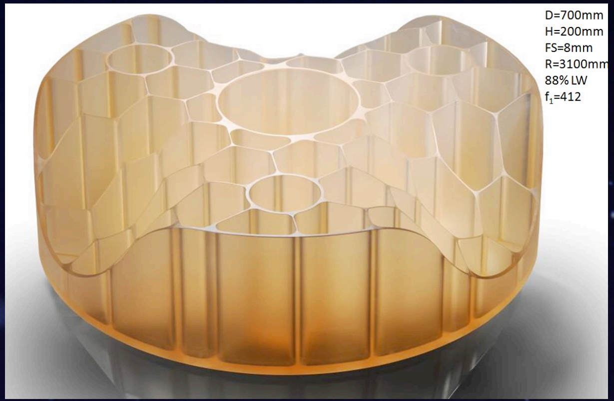
Laser Metrology System: Beam launcher, ring laser, and phase meter

TRL 4

Systems level solutions required for coronagraph

Microthrusters

ESA/LISA Pathfinder



Large Monolith Mirror Fabrication

2.4 m Coating Chamber

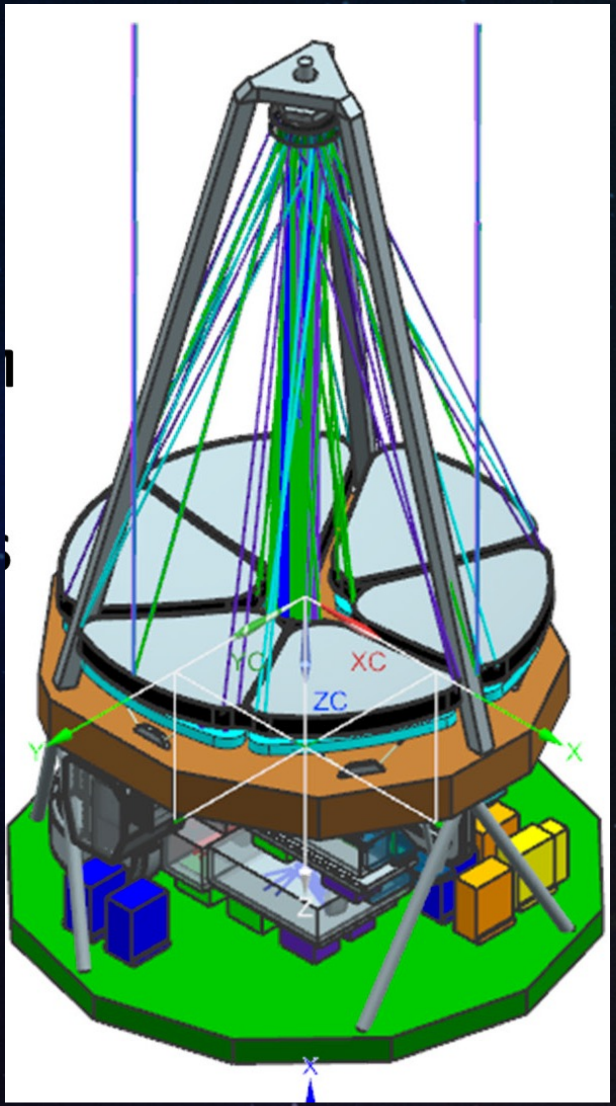
TRL 4

Coating Uniformity

Starshade-Only 3.2S Architecture

- No coronagraph
  - –Telescope WFE stability tolerances relaxed 1000 times
  - –Starshade provides the highest quality exoplanet spectroscopy
  - –*But* – lower yield of exo-Earths *unless detected before HabEx*
- Active Optics On-axis Telescope
  - –Corrects Static PM WFE in orbit
  - –Segmented to stay within current practice and largest ULE mirrors
  - –Laser MET to continuously maintain optical alignment
  - –Lighter (2T) & Smaller Telescope
    - Light weight ULE (5cm thick) Primary Mirror
    - *Total* launch Mass = 7.3 T, fits in Delta IV Heavy or Vulcan Centaur
    - More compact (f/1.3)
    - Non deployable OTA a priori scalable to 4m and above
- Lower cost option

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**



HabEx Report Appendix B, Fig B.1-6

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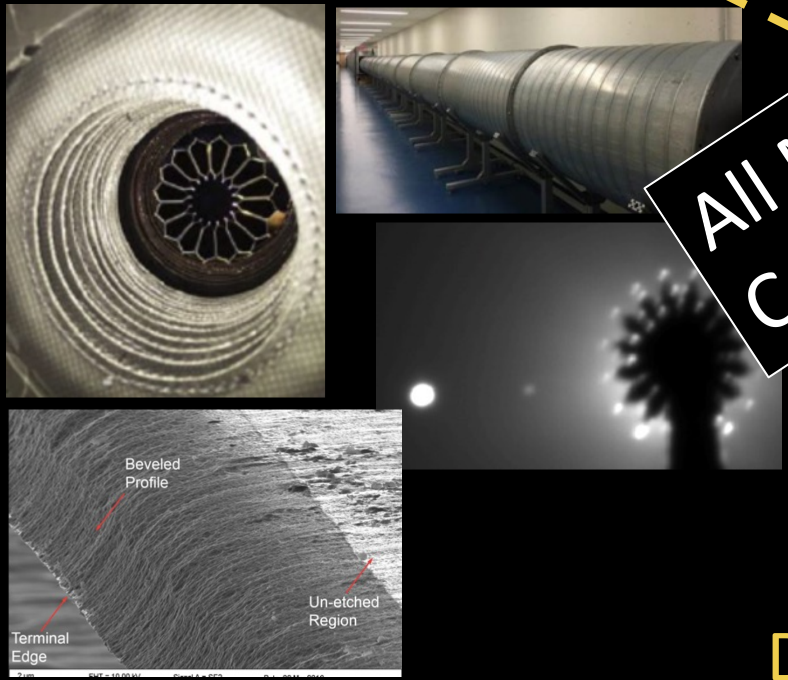
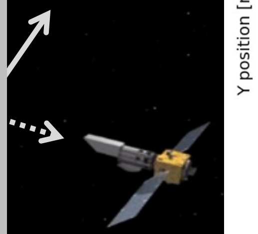
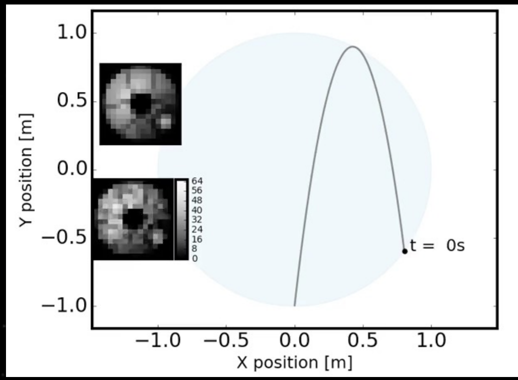
Starshade Technology Gaps

Starlight Suppression



Formation Sensing and Control





Is a starshade required for UV?

Deployment Accuracy and Shape Stability

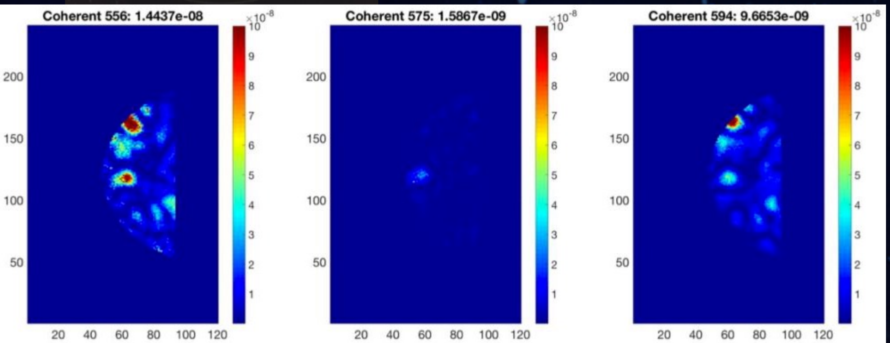
Critical Milestones Complete, High-Fidelity Milestones In Progress!

HabEx

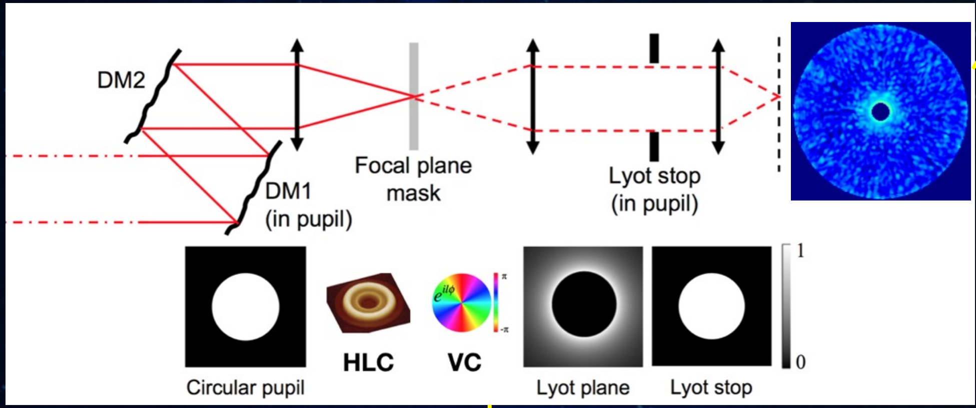
Instrument Technology Advances

Contrast

TRL 4



Coronagraph Architecture

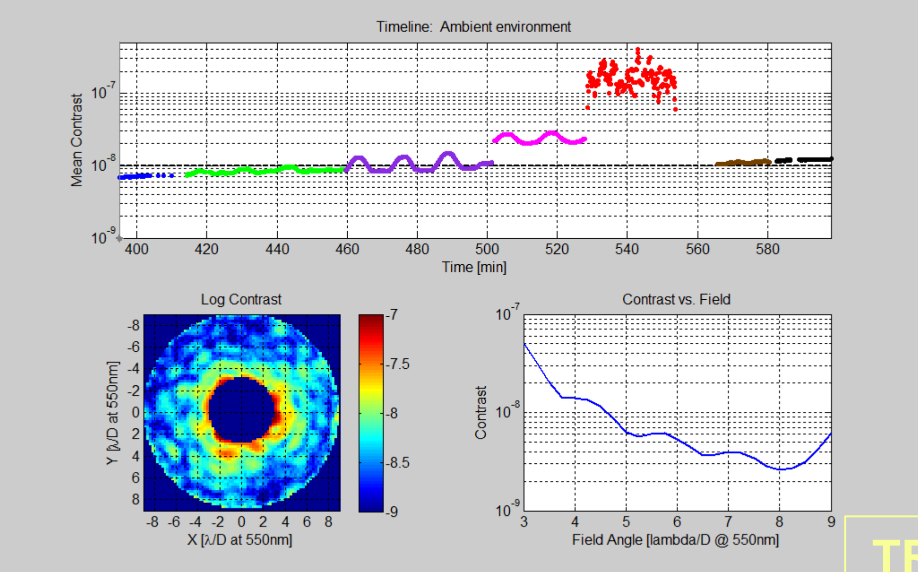


TRL 5

TRL 4

Deformable Mirrors

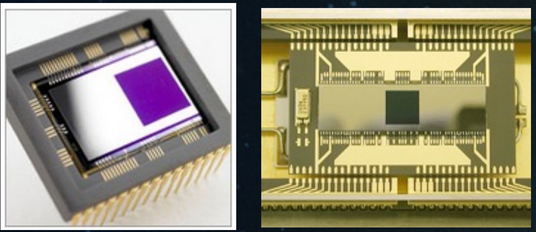
Contrast Stability



TRL 4

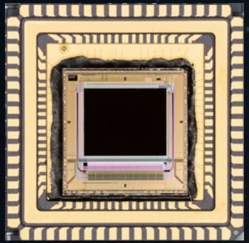
Low-Order Wavefront Sensing and Control

Detection Sensitivity



TRL 4

Ultra-low Noise UV and Visible EMCCD



TRL 5
320x256

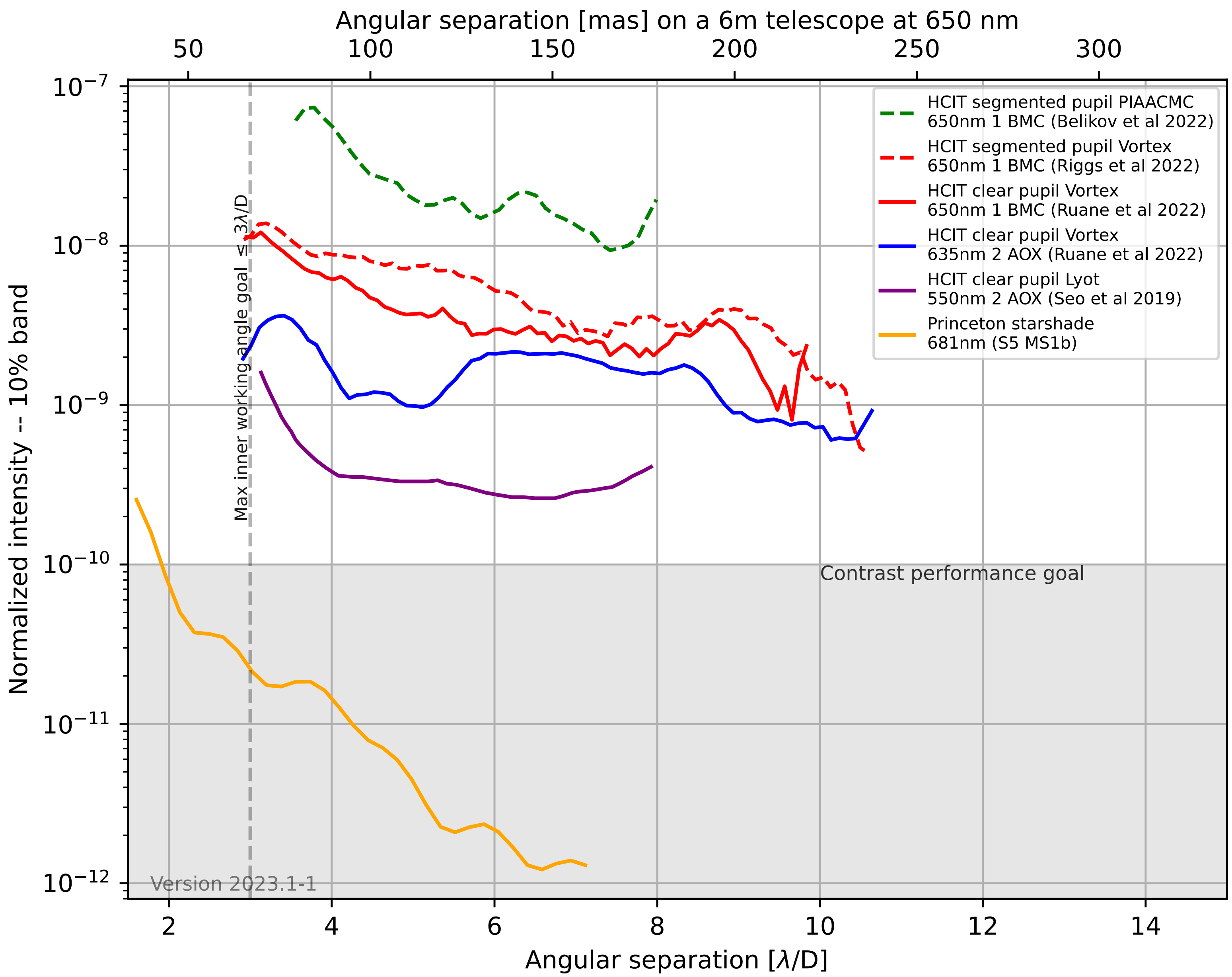
TRL 4
1k x 1k

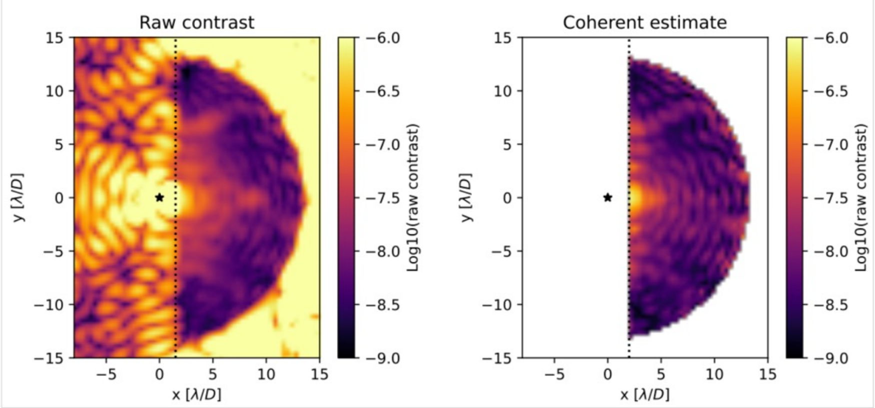
LMAPD NIR photon counting

TRL 4

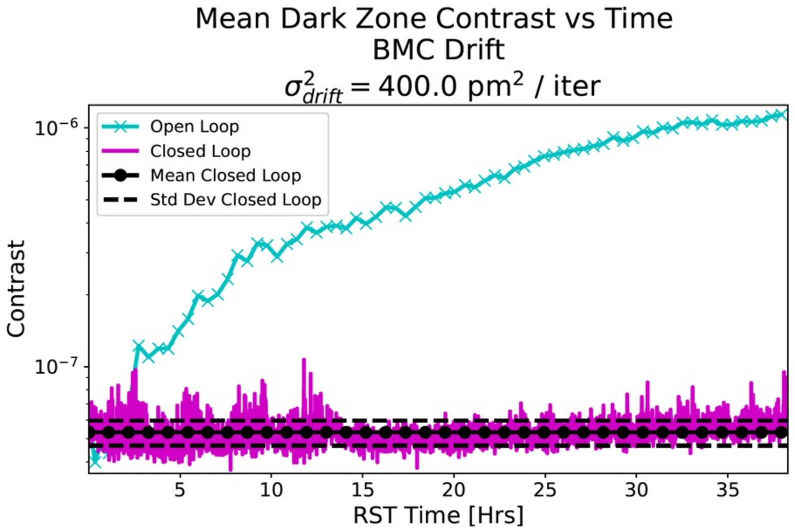
Microchannel Plate Detector for UVS

Starlight Suppression Performance



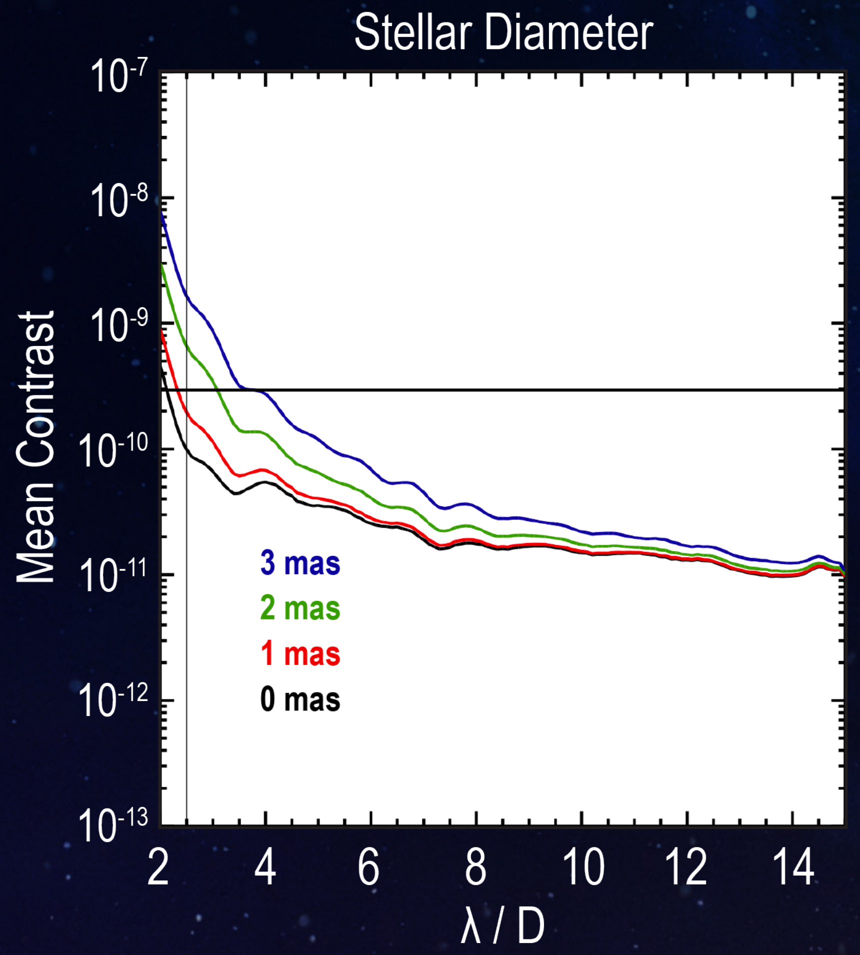


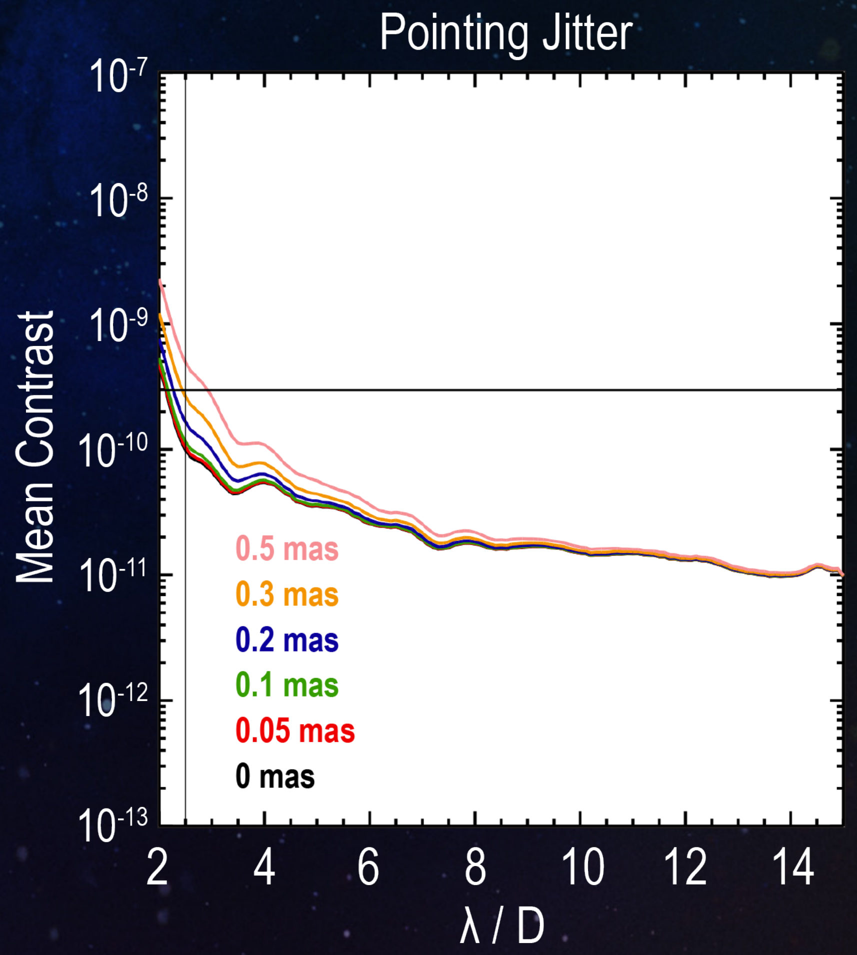
open-air HiCAT, segmented pupil PAPLC monochromatic, 1 BMC (Soummer et al 2022)



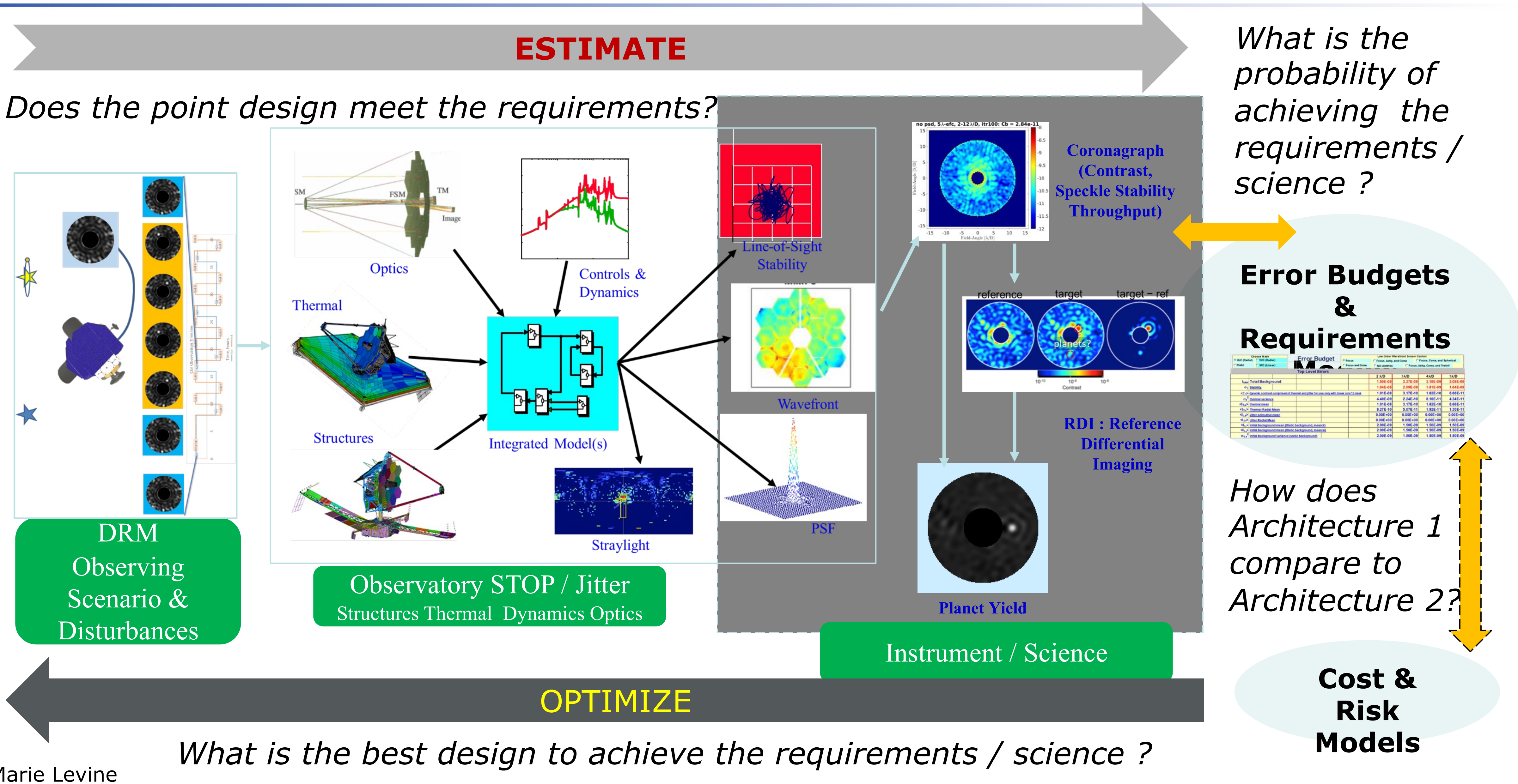
PAPLC active WFSC in dark hole (Redmond et al 2022)

HabEx Coronagraph Modeling Results





Modeling Threads to be Integrated for System Modeling



Credit: Marie Levine

Different yield metrics reveal different sensitivities

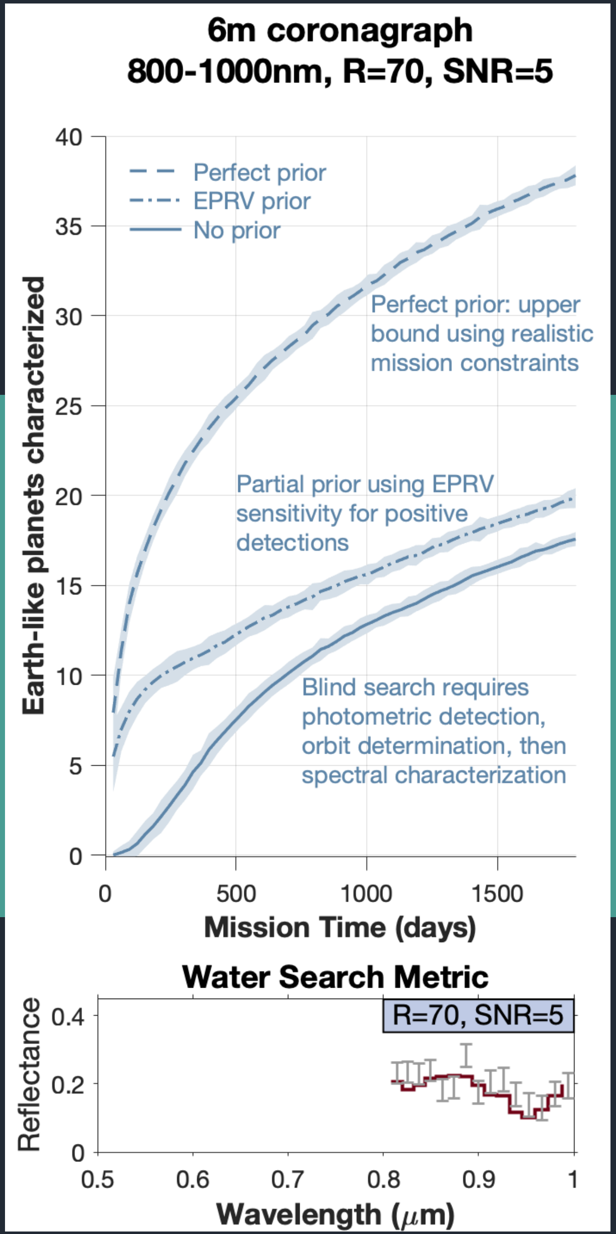
Metrics

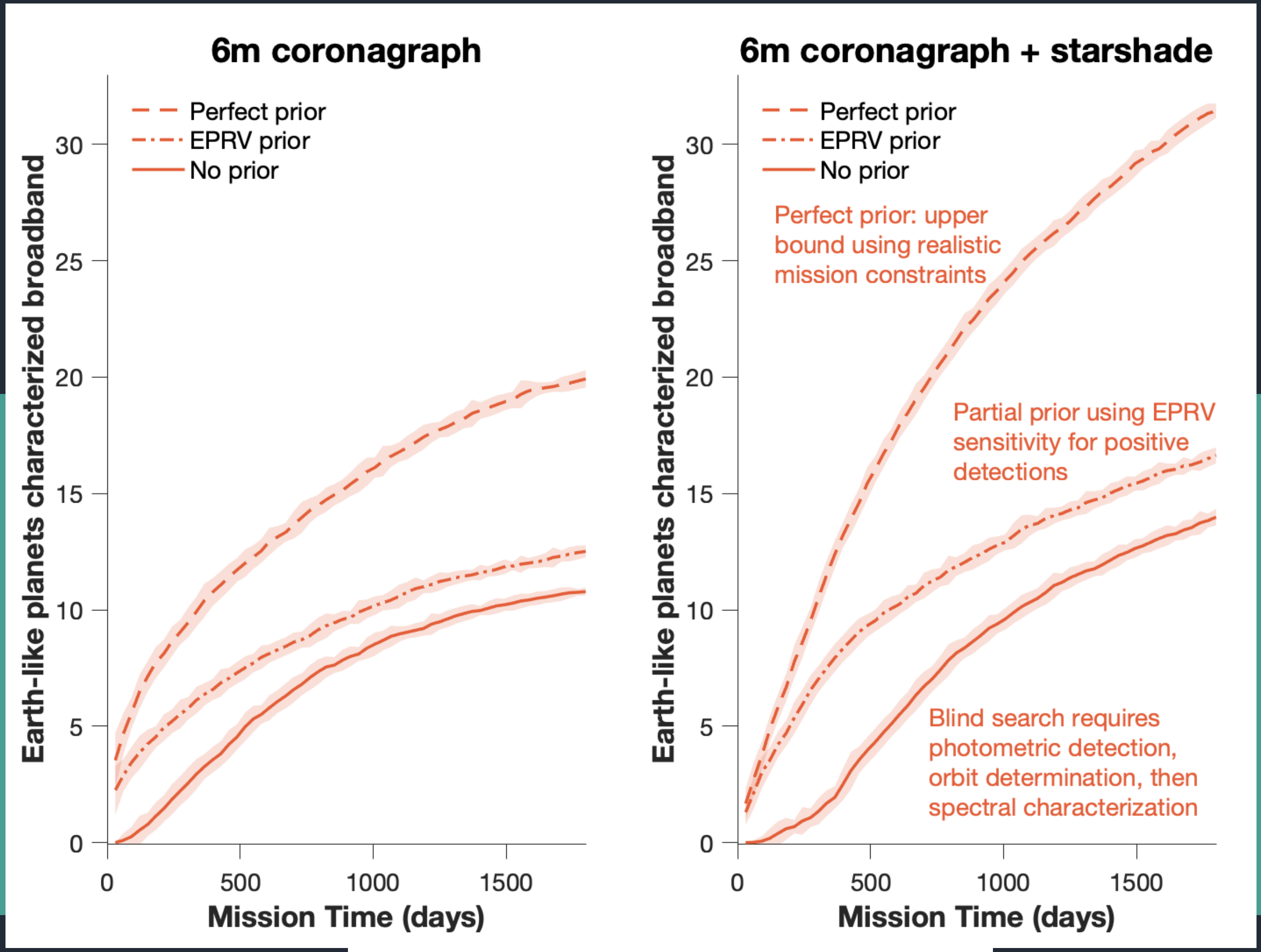
Bandwidth, SNR, R_s

Architecture

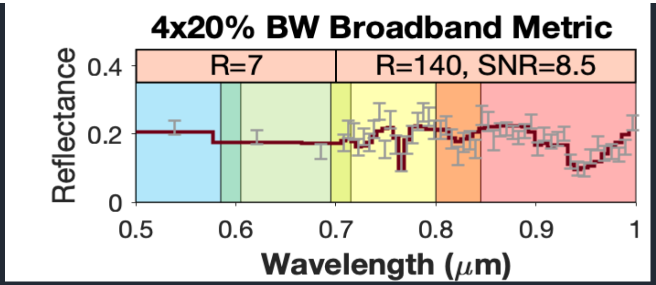
Observing Scenario

Prior Knowledge

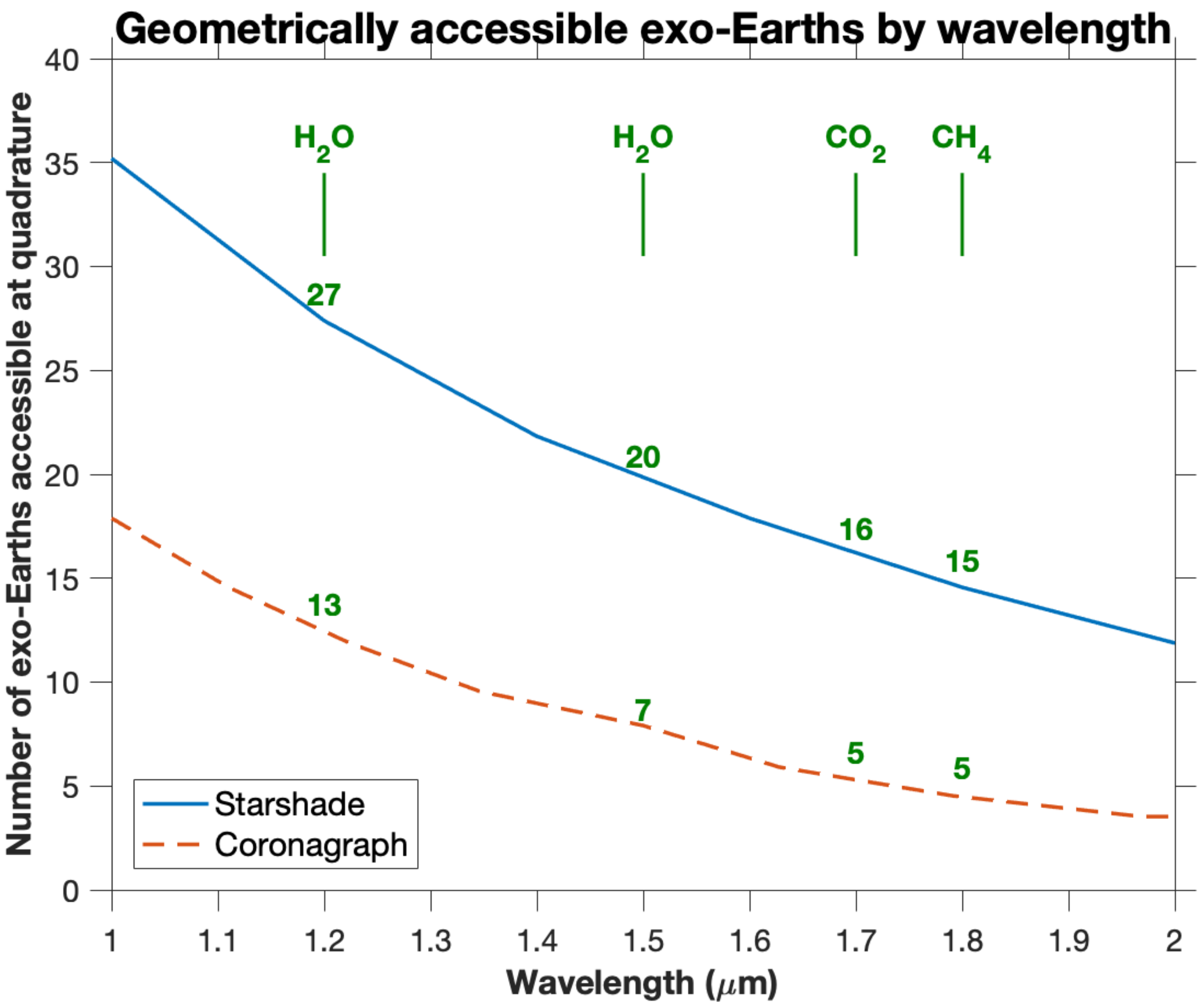




Morgan et al 2022



Upper bound on yield at NIR wavelengths



Morgan et al AAS 2023

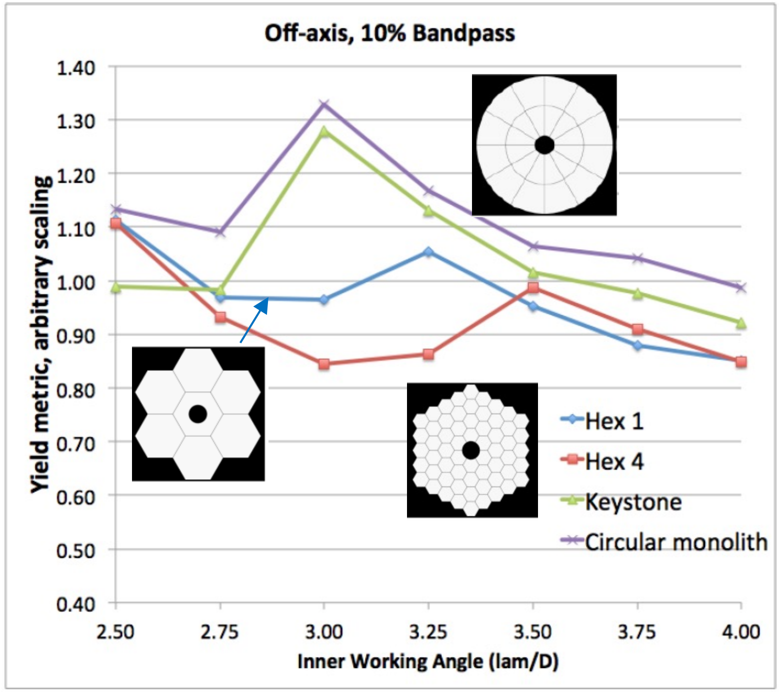
Modeled using EXOSIMS https://github/dsavransky/EXOSIMS

- Molecular species wavelength indicated where the red edge returns to the continuum
- Relative yield is due to IWA:
  - 1.56 l/D starshade
  - 2.5 l/D coronagraph

Conclusions

- **Coronagraphs require a system level solution**
- **Coronagraph contrast AND throughput are important, as robustness to aberrations and dynamics**
- **Inner working angle (IWA) strongly improves yield**
- **Size of DM sets the outer working angle (OWA)**

- **New possibilities**
  - Scalar Vortex coronagraphs for manufacturability
  - Photonic Lanterns (could they mature in time for HWO?)
  - Incorporate EPRV
  - Multi-star wavefront control
  - Segment shape for throughput and dynamics resilience
  - Detailed study of UV and NIR coronagraphs
  - Evaluate NIR and UV science requirements



ExEP Segmented Design Activity 2016 Report https://exoplanets.nasa.gov/exep/technology/tech_colloquium/

BACKUP

HabEx 4 Instruments

UV Imager & Spectrograph (UVS)

Section 6.5

Imaging Channel	115 - 370 nm
Spectroscopy Channel	• 115 - 320 nm with R=500 to 60,000 • 320 - 370 nm with R=500 or 1,000
Field of View	• 3 x 3 $arcmin^2$ • Micro-shutter Array for MOS: 2 x 2 array of 171 x 365 apertures
Effective Collecting Area	10x HST/COS

Starshade Instrument (SSI)

Section 6.4

UV Channel	200 to 450 nm Imager + Grism at R=7
Visible Channel	450 - 975 nm Imager + IFS with R=140
Near Infrared Channel	975 - 1800 nm Imager + IFS with R=40
High Contrast Region	IWA = 58 mas (from 300 to 1000 nm) OWA = 6" (Imager) / 1" (IFS)
Raw Contrast	10^{-10} at IWA over **107%** Bandwidth (nominally 300 to 1000 nm)

Baseline	Vector Vortex (Charge 6)
Visible Channels (1 per Polarization)	450 - 975 nm Imager + IFS with R=140
Near Infrared Channel	975 - 1800 nm Imager + IFS with R=40
High Contrast Region	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 x 10^{-10} at IWA over **20%** Bandwidth 40x better than WFIRST CGI
Features	Active Low Order Wavefront Sensing & Control with two 64x64 DMs

Coronagraph (HCG)

Section 6.3

FGS: Fine Guidance Sensor

Visible Channel	370 - 975 nm Imager + Grism with R=1000 >2x better resolution than HST < 600 nm
Near Infrared Channel	975 - 1800 nm Imager + Grism with R=1000
Field of View	• 3 x 3 $arcmin^2$ • Micro-shutter Array for MOS: 2 x 2 array of 171 x 365 apertures

Workhorse Camera & Spectrograph (HWC)

Section 6.6

Architectures vs Science, Cost and Technical Maturity

HabEx Science Goals & Objectives		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?	Green	Green	Green	Green	Green	Yellow	Yellow	Red	Red
	O2 Water vapor in rocky exoplanet atmospheres?	Green	Green	Green	Green	Yellow	Yellow	Yellow	Red	Red
	O3 Biosignatures in rocky exoplanet atmosphere?	Green	Yellow	Green	Green	Yellow	Yellow	Yellow	Red	Red
	O4 Surface liquid water on rocky exoplanets?	Green	Yellow	Green	Green	Red	Yellow	Yellow	Red	Red
Exoplanetary Systems	O5 Architectures of nearby planetary systems?	Green	Yellow	Red	Green	Yellow	Red	Yellow	Red	Red
	O6 Exoplanet atmospheric variations in nearby systems?	Green	Yellow	Yellow	Green	Red	Red	Yellow	Red	Red
	O7 Water transport mechanisms in nearby planetary systems?	Green	Yellow	Green	Green	Yellow	Yellow	Yellow	Red	Red
	O8 Debris disk architectures in nearby planetary systems?	Green	Yellow	Green	Green	Yellow	Green	Green	Yellow	Green
Observatory Science	O9 Lifecycle of baryons?	Green	Green	Green	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow
	O10 Sources of reionization?	Green	Green	Green	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow
	O11 Origins of the elements?	Green	Green	Green	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow
	O12 Discrepancies in measurements of the cosmic expansion rate?	Green	Green	Green	Green	Yellow	Green	Yellow	Yellow	Yellow
	O13 The nature of dark matter?	Green	Green	Green	Yellow	Yellow	Yellow	Red	Red	Red
	O14 Formation and evolution of globular clusters?	Green	Green	Green	Green	Green	Green	Yellow	Yellow	Yellow
	O15 Habitable conditions on rocky planets around M-dwarfs?	Green	Green	Green	Yellow	Yellow	Yellow	Red	Red	Yellow
	O16 Mechanisms responsible for transition disk architectures?	Green	Green	Yellow	Green	Green	Green	Yellow	Yellow	Yellow
	O17 Physics driving star-planet interactions, *e.g.* auroral activity?	Green	Green	Green	Green	Green	Green	Green	Green	Green
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		13	10	9	12	9	9	11	8	8
Exo-Earths Characterized		8	5	5	5	3	4	3	1	2
Exoplanet Detections (all)		178	114	140	105	83	119	76	27	67

- *STDT's preferred architecture is 4H*
- *Red does not mean "no science"*
- *At a given size, Hybrid architectures maximize exoplanet science*
- *C-only*
  - *no UV exoplanet observations*
  - *Vast majority of planets with orbits*
  - *Reduced spectroscopy*
- *S-only:*
  - *High Quality spectra*
  - *Limited # of orbits measured*

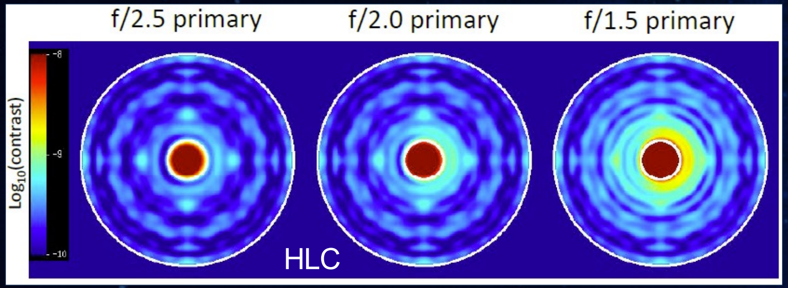
- *Observatory Science is primarily a function of telescope size*

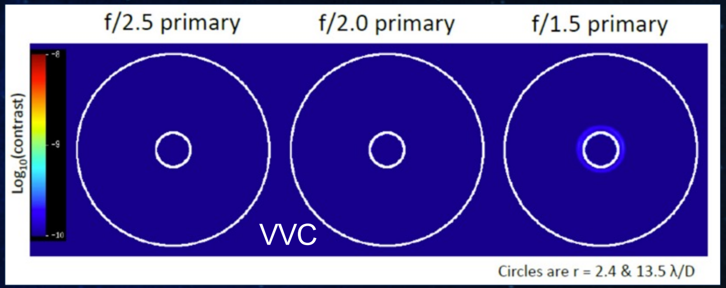
- *Architectures 4H (4C) and 3.2S studied in detail and "TRACEable"*

Coronagraph Accommodations and Trades

- Selecting among different coronagraph masks:

Figure 5.4-1





- 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			9	8	5	3

4H OTA Specifications are within current State of Practice

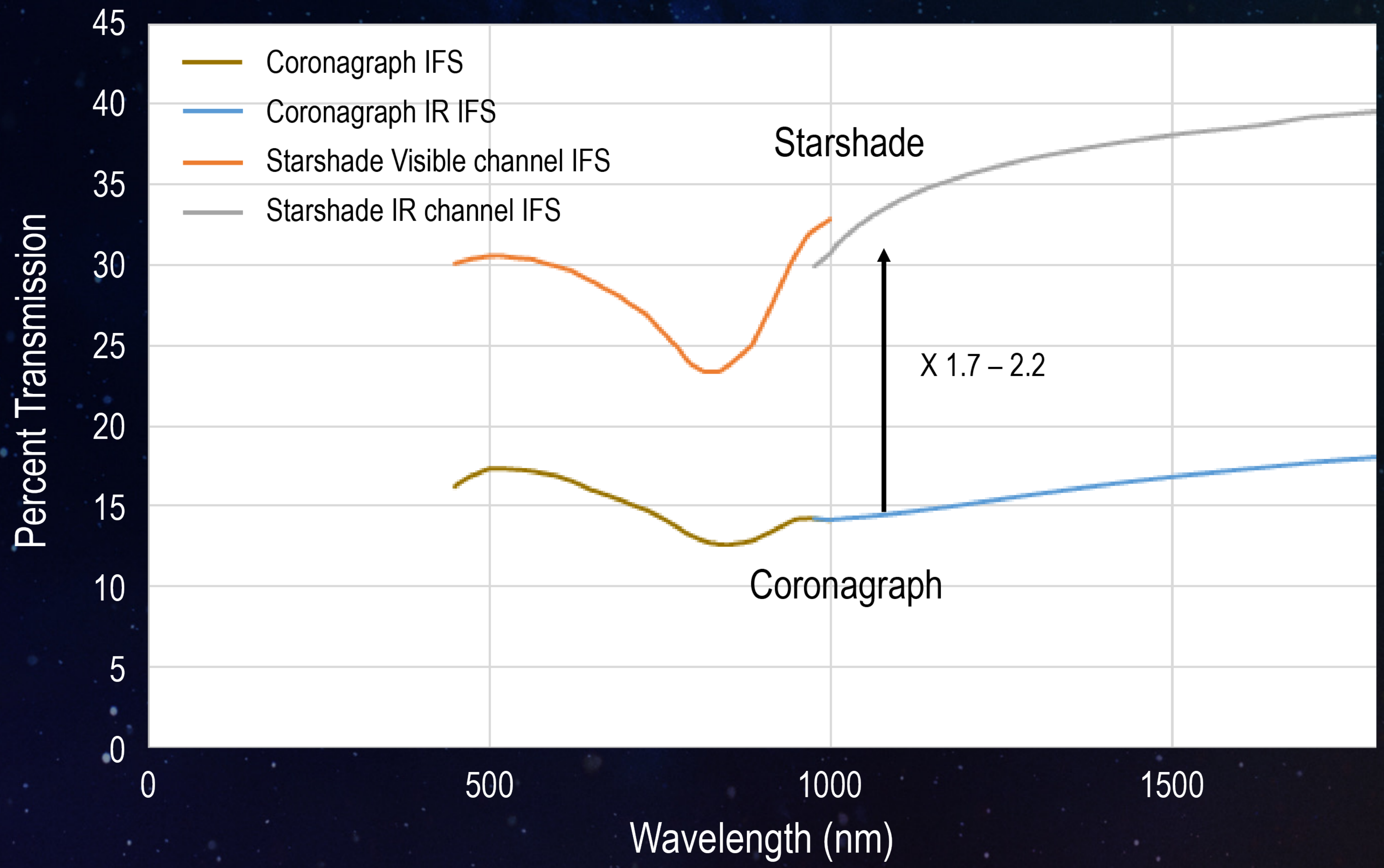
Aperture Diameter	4.0 meters
Diffraction Limited Wavelength	400 nm
Total Wavefront Error	30 nm rms (wavefront)
Total Primary Mirror Figure Error	5.6 nm rms (surface)
Low Spatial SFE (<30 cycles/dia)	4.3 nm rms
Mid Spatial SFE (30 to 100 cycles/dia)	3.3 nm rms
High Spatial SFE (>100 cycles/dia)	1.4 nm rms
Roughness	0.3 nm rms
Line of Sight Stability (Jitter)	< 0.7 milli-arcseconds
Wavefront Error Stability	1 to 250 pm (spatial frequency dependent)
Spectral Range	115 nm to 1700 nm

Specification	Predicted Margin	Enabling Design Elements
LOS Mechanical Jitter	20X	Telescope Structure Stiffness Low-Noise Micro-Thrusters
LOS Thermal Drift	3.5X	Laser Metrology System
Diffraction-Limited Transmitted Wavefront	1X	Demonstrated Mirror Fabrication Capability Laser Metrology System for Alignment
Wavefront Stability	4X	Telescope Structure Stiffness PM Substrate Stiffness, CTE and Thermal Mass Active Thermal Control, Low-Noise Micro-Thrusters

Verifying the HabEx Starshade: Modeling Results

Parameter	Requirement	Expected Performance	Margin
Observational band	0.30–1.7 µm	0.20–1.80 µm	Met by design
IWA	≤64 mas (0.87 µm) ≤80 mas (1.0 µm)	57 mas (0.87 µm) 58 mas (1.0 µm)	12% (0.87 µm) 38% (1.0 µm)
Raw contrast	$\leq 1.0 \times 10^{-10}$	6.0×10^{-11}	67%
Raw contrast stability	$\leq 2.0 \times 10^{-11}$	1.0×10^{-11}	100%
Pointing control	≤1°	<<1°	Met by design
Solar edge scatter	V > 25 mag/arcsec^2	V > 25 mag/arcsec^2	Met by design
Sunlight leakage	>32 V_{mag}	>32 V_{mag}	Met by design
Micrometeoroid holes	≤500 ppm	5 ppm	9900%
Petal position (manufacture)	≤±600 µm	±340 µm	76%
Petal shape (manufacture)	≤±140 µm	±80 µm	75%
Petal position (thermal)	≤±400 µm	±62 µm	545%
Petal shape (thermal)	≤±160 µm	±50 µm	220%

Transmission Curves
Coronagraph and Starshade IFS



National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

S5: Closing Starshade Technology Gaps

https://exoplanets.nasa.gov/exep/technology/starshade/

Completed by FY22 | Complete by FY24

Starlight Suppression

Contrast NB 1A

Contrast BB 1B

Modeling Validation 2

Scattered Sunlight

Edges 3

Formation Flying

Sensing 4

Critical Features

Shape Accuracy

Petal 5A

Truss Bay 7A

Inner Disk Deployment 7C

Shape Stability

Petal 6A

Inner Disk (thermal) 8A

All Features

Petal 5B

Truss Bay 7B

Inner Disk 7D

Petal 6B

Inner Disk 8B

Milestone Completed

In Progress

What is Integrated Modeling (IM) ?

- IM refers to the pipeline of engineering model and analyses required to verify observatory performance based on Systems Error Budget (EB) Metrics
- IM provides inputs as estimates into Systems Error Budget allocations and Science yield for Architecture Trades
- Typical IM Disciplines in the pipeline:
  - Thermal, structures, dynamics, attitude control, optics with wavefront sensing and control, straylight, coronagraph models
- Typical Error Budget Metrics computed with IM
  - WFE, WFE stability (thermal drift & jitter), Pointing stability, Alignments, PSF, Contrast
- Note: Science Yield models could also be integrated into the IM pipeline