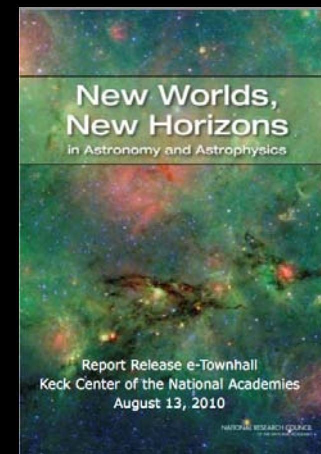
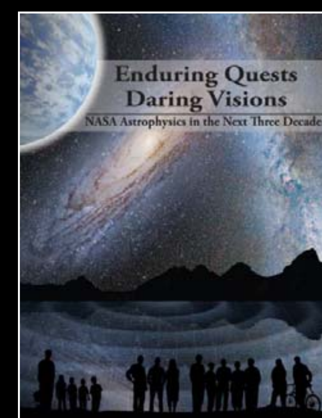
Exploring New Worlds—Understanding Our Univers

National Academies Planetary Science and Astrobiology Decadal Survey
Panel on Giant Planet Systems
April 16, 2021

History of the Large Mission Concept Studies

- January 2015 – Paul Hertz (NASA ApD Director) charged the three Astrophysics PAGs to solicit community input on a small set of large mission concepts to study. Four candidates were suggested:
  - Far-IR Surveyor (NASA Roadmap)
  - Habitable Exoplanet Imaging Mission (Astro2010 DS)
  - UV/Optical/IR Surveyor (NASA Roadmap)
  - X-ray Surveyor (NASA Roadmap)
- November 2015 – Consensus report of the PAGs that these four (and only these four) should be studied.
- Early 2016 – Study centers selected, and Science and Technology Definition Teams were assembled.
- March 2018 - Interim report submitted.
- June 2018 – External, independent review by the Large Mission Concept Studies Report Team (LRT).
- July 2019 - Large Mission Concept Studies Independent Team (LCIT) performed an independent analysis to assess if the cost, technical, and schedule requirements were reasonable and credible.
- August 2019 – Final Reports submitted.
- October 2019 – Presentations to the Astro2020 Decadal Survey Panels (EOS1 and EOS2).
- Nearly four years of effort by hundreds of team members with broad community representation:
  - Hundreds of team members from academia, NASA centers, industry, foreign agencies, …
  - Astronomers, astriobiologists, planetary scienctists, engineers, instrumentationalists, technologists, …

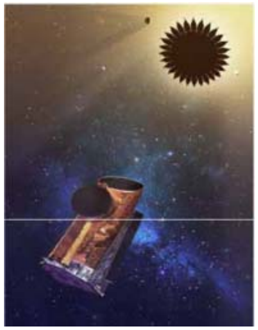




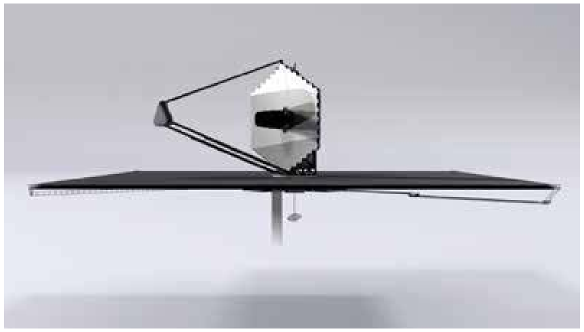
Paul Hertz's Presentation to Astro2020 on July 15

Large Mission Concepts

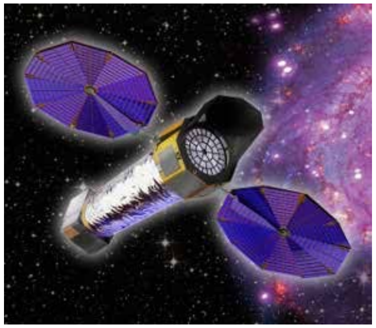
"NASA should ensure that robust mission studies that allow for trade-offs (including science, risk, cost, performance, and schedule) on potential large strategic missions are conducted prior to the start of a decadal survey. These trade-offs should inform, but not limit, what the decadal surveys can address." – Powering Science: NASA's Large Strategic Science Missions (NAS, 2017)



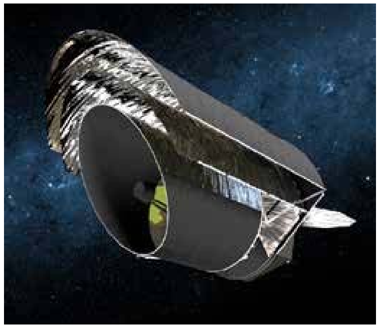
HabEx



LUVOIR



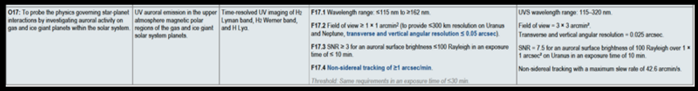
Lynx



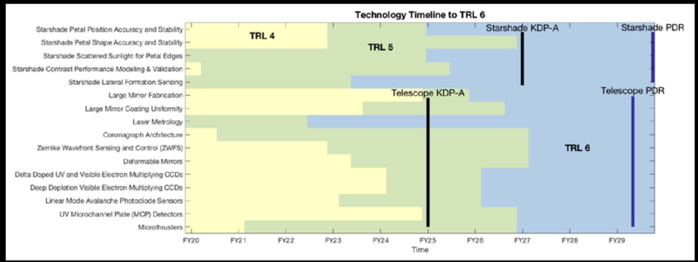
Origins

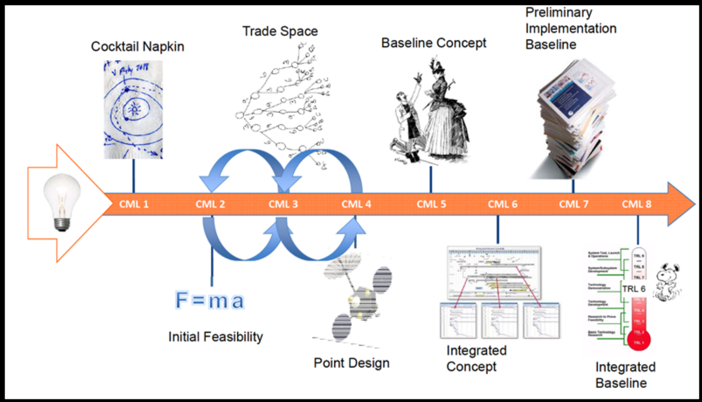
Detailed and Mature Mission Concepts

- Each study was tasked to identify and develop a *strong*, *compelling*, and *executable* science case.
- Comprehensive trade studies (science, cost, capabilities, risk).
- Science requirements → Mission requirements
  - Science and mission traceability matrices.
- Detailed assessment of needed technology and cost, and creation of a technology maturation plan and schedule.
- Achieved tailored Concept Maturity Level 4 (point design).



O17: To probe the physics governing star-planet interactions by investigating auroral activity on gas and ice giant planets within the solar system.	UV auroral emission in the upper atmosphere magnetic polar regions of the gas and ice giant solar system planets.	Time-resolved UV imaging of H_2 Lyman band, H_2 Werner band, and H Lyα.	**F17.1** Wavelength range: ≤115 nm to ≥162 nm. **F17.2** Field of view ≥ 1 × 1 arcmin² (to provide ≤300 km resolution on Uranus and Neptune, transverse and vertical angular resolution ≤ 0.05 arcsec). **F17.3** SNR ≥ 3 for an auroral surface brightness ≤100 Rayleigh in an exposure time of ≤ 10 min. **F17.4** Non-sidereal tracking of ≥1 arcsec/min. *Threshold: Same requirements in an exposure time of ≤30 min.*	UVS wavelength range: 115–320 nm. Field of view = 3 × 3 arcmin². Transverse and vertical angular resolution = 0.025 arcsec. SNR = 7.5 for an auroral surface brightness of 100 Rayleigh over 1 × 1 arcsec² on Uranus in an exposure time of 10 min. Non-sidereal tracking with a maximum slew rate of 42.6 arcmin/s.





the new GREAT OBSERVATORIES

Credit: Grant Trembley

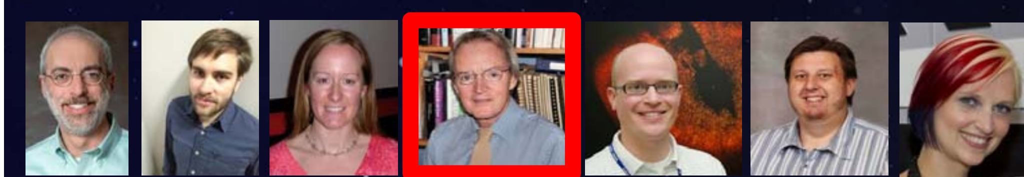
https://www.greatobservatories.org/

https://www.jpl.nasa.gov/habex/pdf/HabEx-Final-Report-Public-Release-LINKED-0924.pdf

Science and Technology Definition Team

HabEx

HabEx STDT Meeting, May 16-17 2016, Washington, DC. Team members from left to right: Rachel Somerville, David Mouillet, Shawn Domagal-Goldman, Leslie Rogers, Martin Still, Olivier Guyon, Paul Scowen, Kerri Cahoy, Daniel Stern, Scott Gaudi, Bertrand Mennesson, Lee Feinberg, Karl Stapelfeldt, Sara Seager, Dimitri Mawet. Missing STDT members (unable to attend meeting in person): Jeremy Kasdin, Tyler Robinson and Margaret Turnbull.



17 STDT Members

6 International Observers (ESA, JAXA, DLR, CNES, CSA, SRON)

HabEx Study Philosophy

Maximize

↑ Science return for both
- Exoplanet direct imaging
- General astrophysics & planetary science

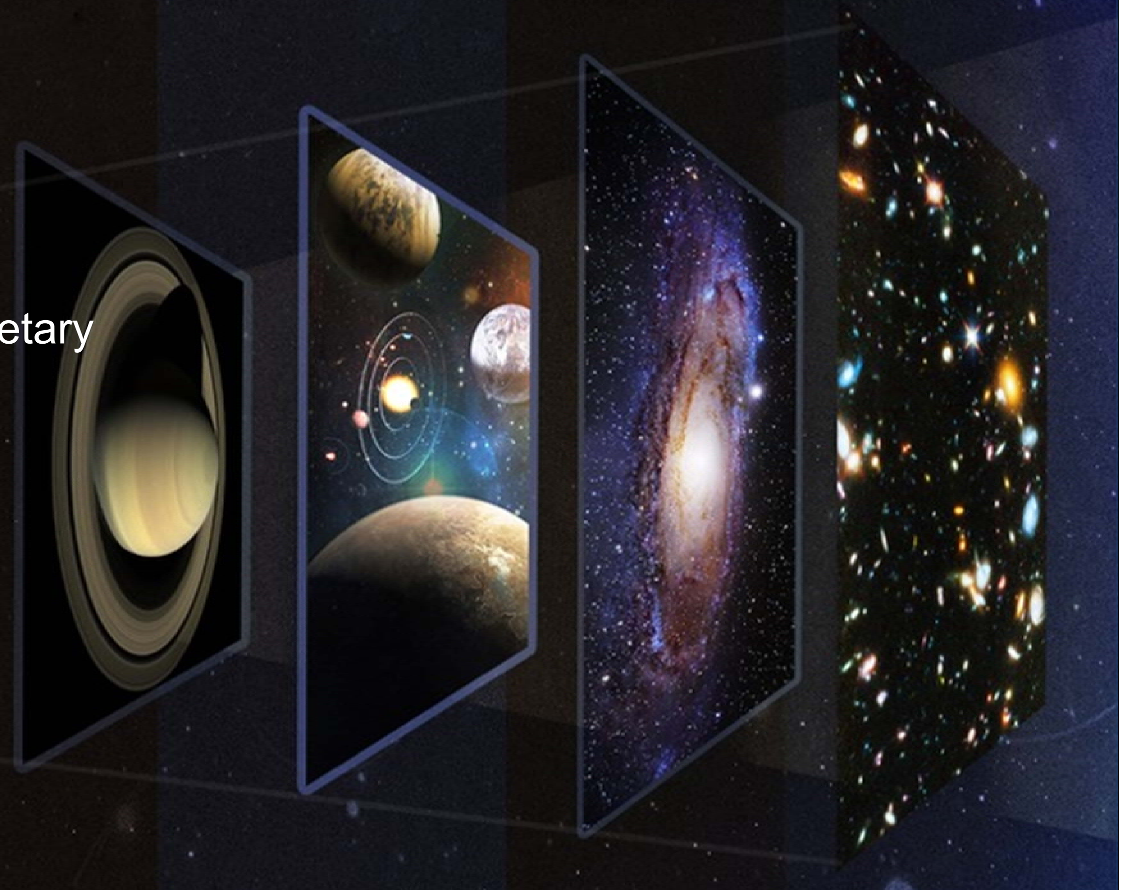
↑ Flexible mission architecture

Minimize

↓ Cost

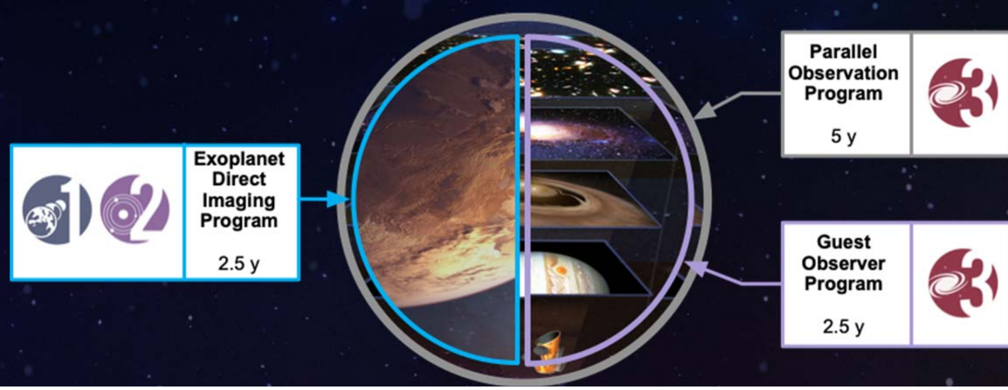
↓ Risk

↓ Technology development



The Great Observatory for the 2030s & Beyond

- Directly detecting and characterizing Earth-like exoplanets orbiting sunlike stars in reflected visible light requires an ultra-stable telescope in space
- Such a telescope also enables a broad portfolio of transformative general observatory science including stellar, Galactic, extragalactic, and solar system science
- Thus, HabEx will be a great successor to Hubble but with:
  - A much larger effective collecting area, particularly in the UV;
  - Modern instrumentation, such as microshutter arrays; and
  - Better resolution than existing or planned facilities including HST, JWST, and Roman for wavelengths less than roughly 1 micron.
- At least **50%** of HabEx's primary 5-year mission is dedicated to Guest Observer Science
- Fully **100%** of an extended mission will be dedicated to Guest Observer Science



Preferred Architecture - 4H

HabEx

Telescope:

- 4m off-axis f/2.5 Al-coated monolith

Instruments:

- Coronagraph Instrument (HCG)
- Starshade Instrument (SSI, used with a 52 m Starshade)
- UV Spectrograph (UVS)
- HabEx Workhorse Camera (HWC)

Launch:

- SLS Block 1B (Telescope)
- Falcon Heavy (Starshade)
- L2 orbit

Timeline:

- Launch: Mid-2030s
- Nominal operation: 5 years, Capability: 10 years

Studied a total of 9 architectures:
4 m/3.2 m/2.4 m × Hybrid/Starshade-Only/ Coronagraph-Only

Why a Starshade and a Coronagraph?

Coronagraph:

Pro: Nimble, on-board, good for blind searches and orbit determination

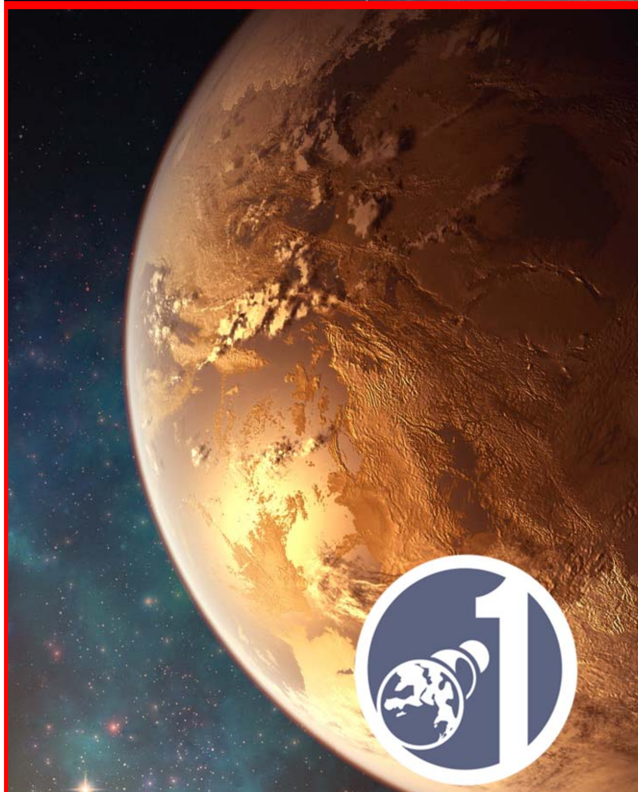
Con: Narrow instantaneous bandpass, not optimal for obscured primaries, typically have a limited outer working angle (OWA)

Starshade:

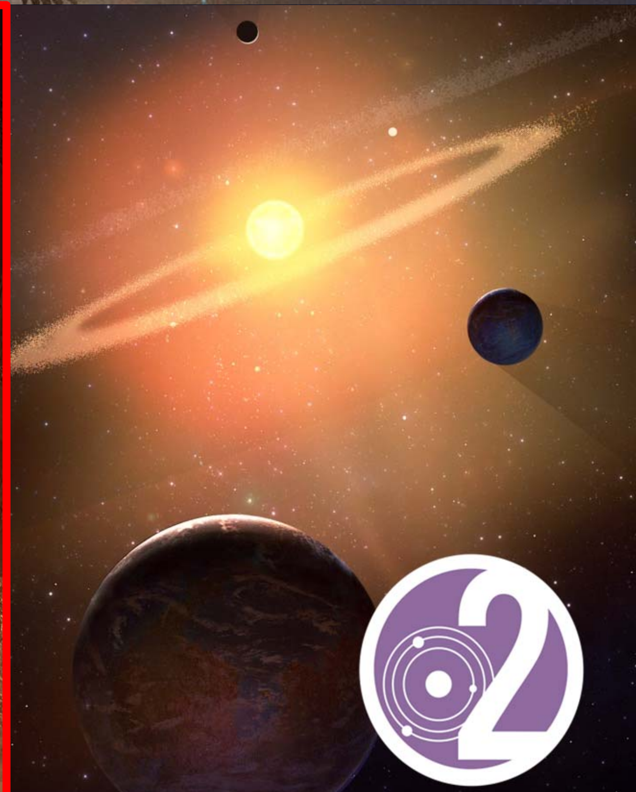
Pro: Wide bandpass, high throughput, large OWA, small inner working angle (IWA), good for spectral characterization

Con: Requires repositioning, fuel limited, requires a separate launch

Science Goals



Seek out nearby worlds and explore their habitability



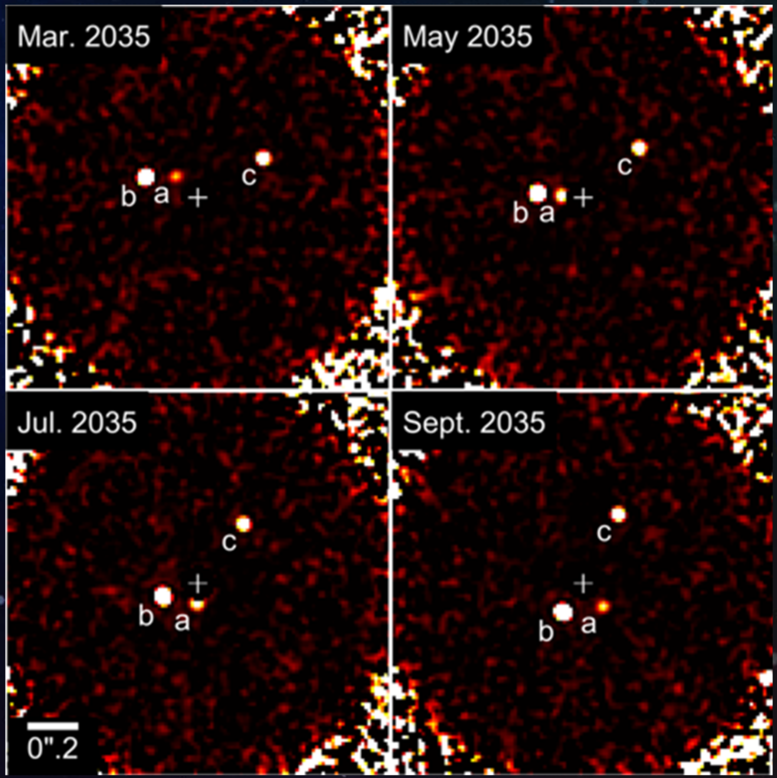
Map out nearby planetary systems and understand their diversity

Enable new explorations of astrophysical systems in the UV to near-IR

Broad Survey for Potentially Habitable Worlds

"Seek out Habitable Worlds"

- HabEx will survey ~50 stars with the coronagraph to search for potentially habitable worlds.
- HabEx will measure their orbits to determine if they are in the Habitable Zone.
- Promising systems will be studied in further detail with the coronagraph and starshade.

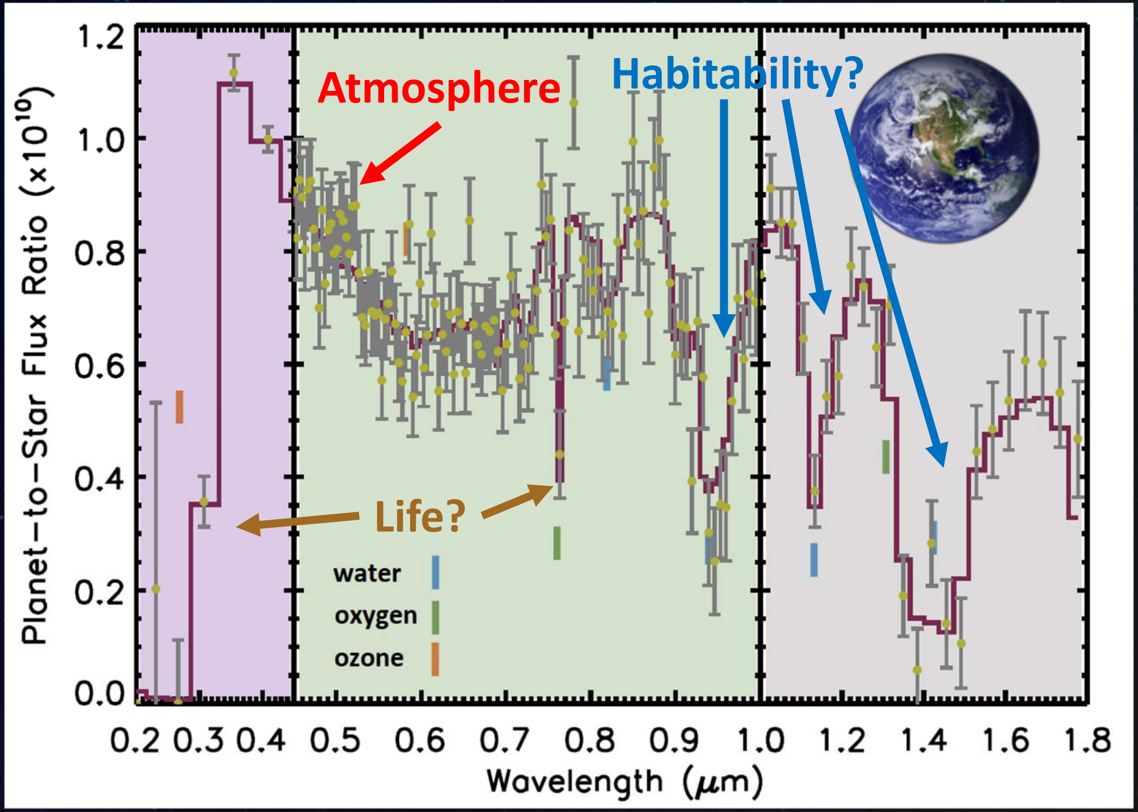


Simulated ExoEarth Spectrum

HabEx

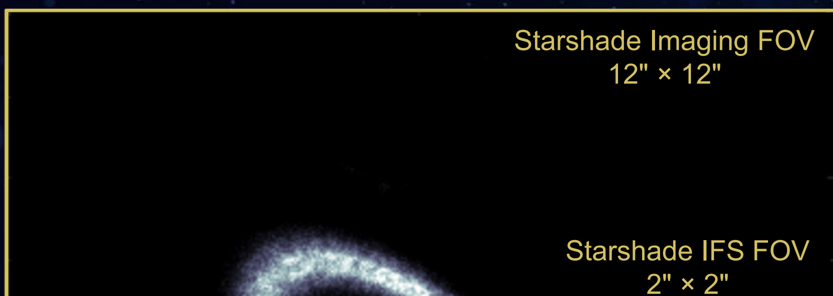
"Characterize Earths"

- Potentially rocky planets with orbits in the HZ of their stars will be characterized by the starshade.
- Simulated HabEx spectrum of exo-Earth around Beta CVn (Chara), a G0V star at 8.4 pc assuming 230h of observations (SNR=10 @ 0.55 mm & R=140)

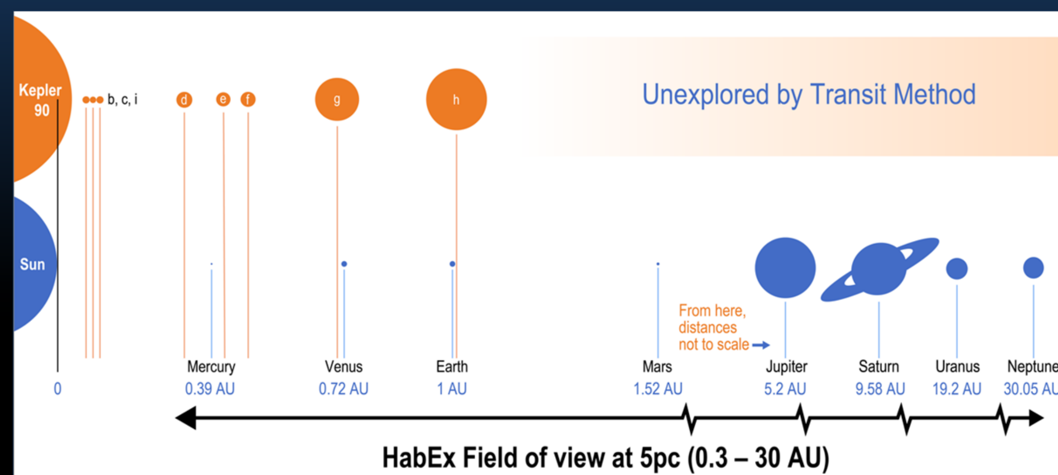



HabEx
Science Goals
Seek out nearby worlds and explore their habitability
Map out nearby planetary systems and understand their diversity
Enable new explorations of astrophysical systems in the UV to near-IR

Starshade's Wide Field of View

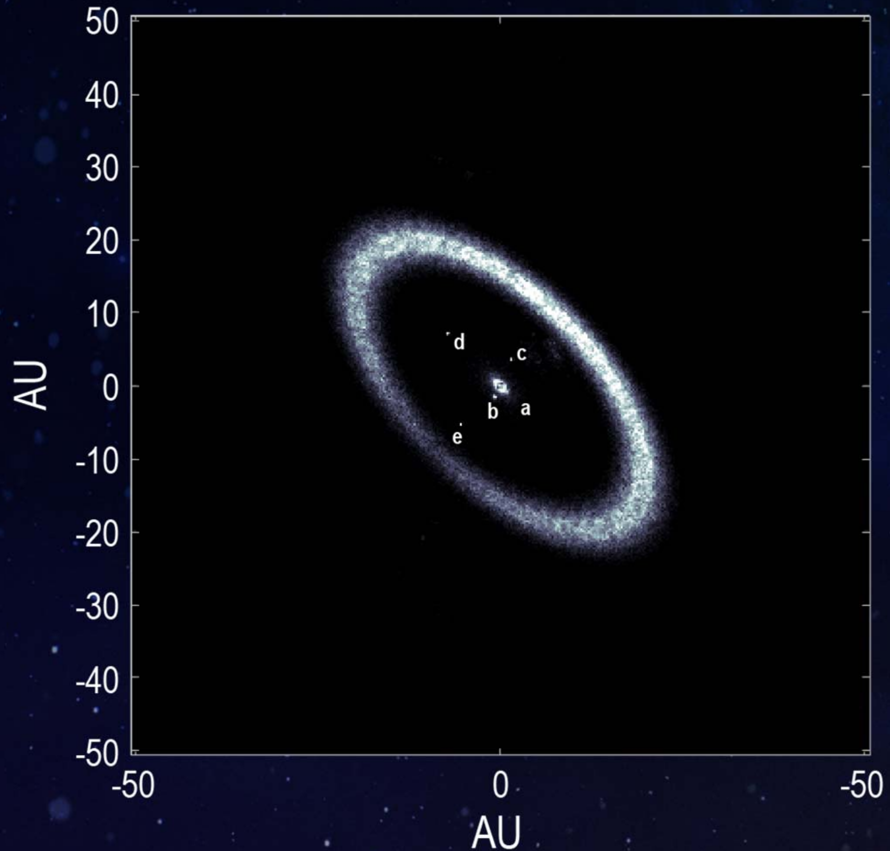


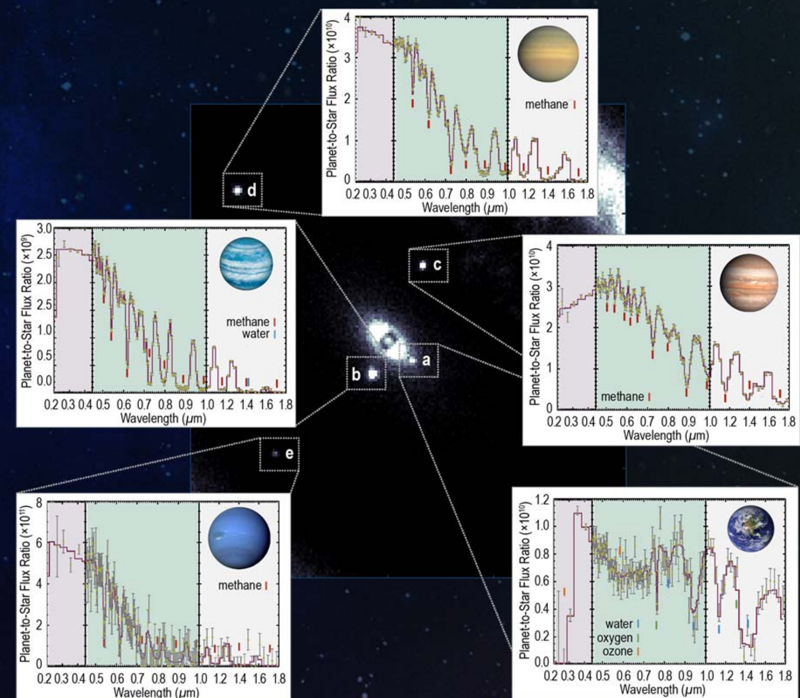
- Starshade has high contrast and a large field of view, with OWA only limited by the detector format.
- Starshade can cover a large range of physical separations in the nearest (most favorable) systems.
- Simultaneous 0.3-1.0 μm spectra with starshade for all planets within 2"x2" square.



- Study planetary architecture diversity
- Assess "architecture habitability"
- Study variation of atmospheric properties

Simulated Starshade Image and Spectra





R=7 (grism) 0.2 - 0.3 μm

R=7 (grism) 0.3-0.45 μm

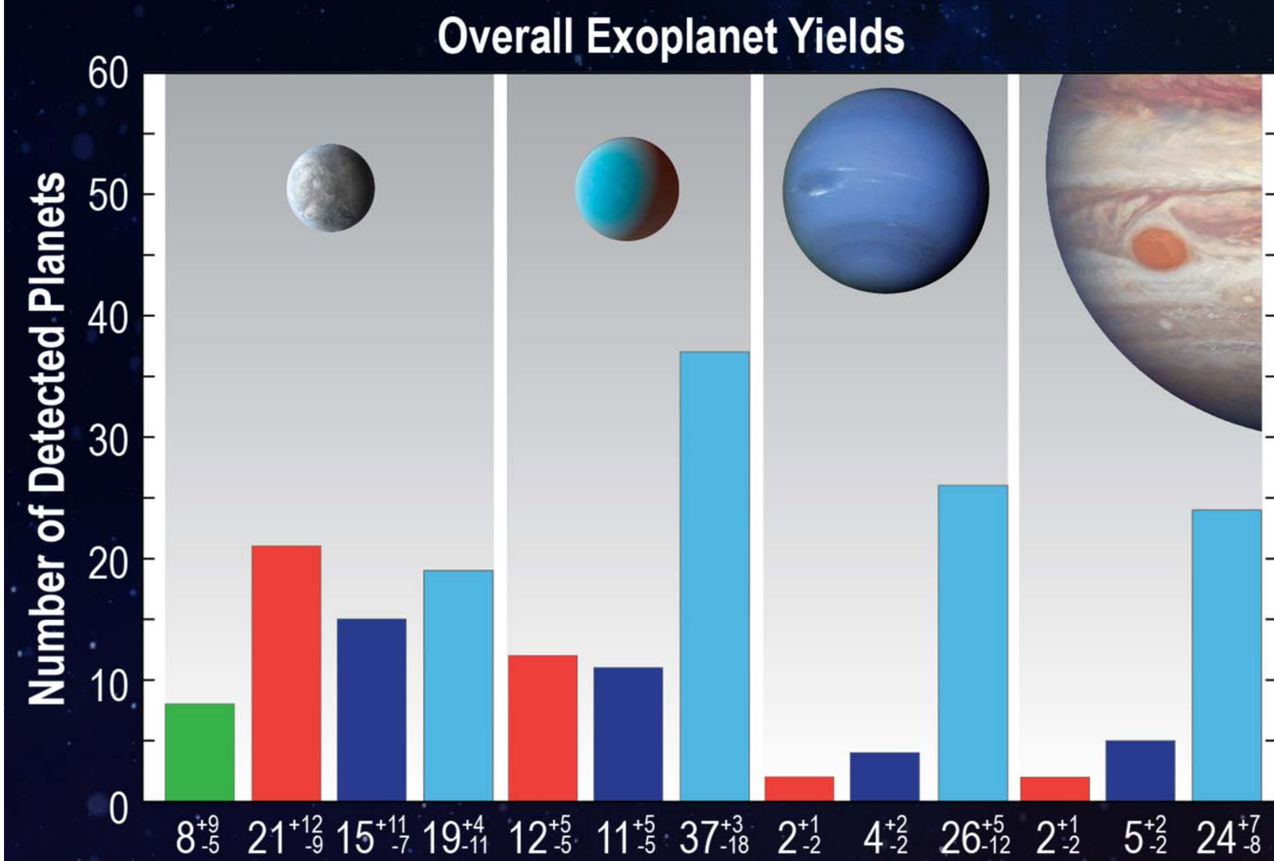
R=140 (IFS) 0.45-1.0 μm

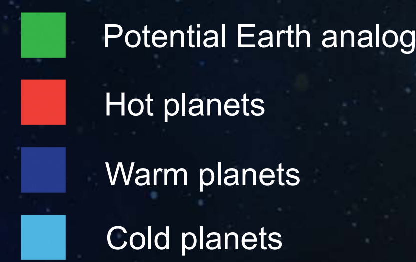
HabEx

Target List

Star	Type	Dist. (pc)	V-mag	Age (Gyr)	Notes
τ Ceti	G8V	3.7	3.5	5.8	**Astronomy:** closest solitary G-star, 4 confirmed planets (2 in HZ) plus debris disk **Popular culture:** homeport of *Kobayashi Maru* in *Star Trek* and location of *Barbarella* (1968)
82 Eridani	G8V	6.0	4.3	6.1–12.7	**Astronomy:** 3 confirmed planets (all super-Earths) plus dusk disk
40 Eridani	K1V	5.0	4.4		**Astronomy:** triple-system, with white dwarf and M-dwarf **Common name:** Keid **Popular culture:** in *Star Trek*, host star to Vulcan
GJ 570	K4V	5.8	5.6		**Astronomy:** quadruple-system, with 2 red dwarfs and brown dwarf
σ Draconis	K0V	5.8	4.7	3.0 ± 0.6	**Astronomy:** 1 unconfirmed planet (Uranus-mass) **Common name:** Alfasi **Popular culture:** visited in *Star Trek* episode "*Spock's Brain*" (1966)
61 Cygni A	K5V	3.5	5.2	6.1	**Astronomy:** wide-separation binary **Common name:** Bessel's star **Popular culture:** home system of humans in Asimov's *Foundation* series
61 Cygni B	K7V	3.5	6.1		
ε Indi	K5V	3.6	4.8	1.3	**Astronomy:** triple-system, with 2 brown dwarfs 1 unconfirmed planet (Jupiter-mass)

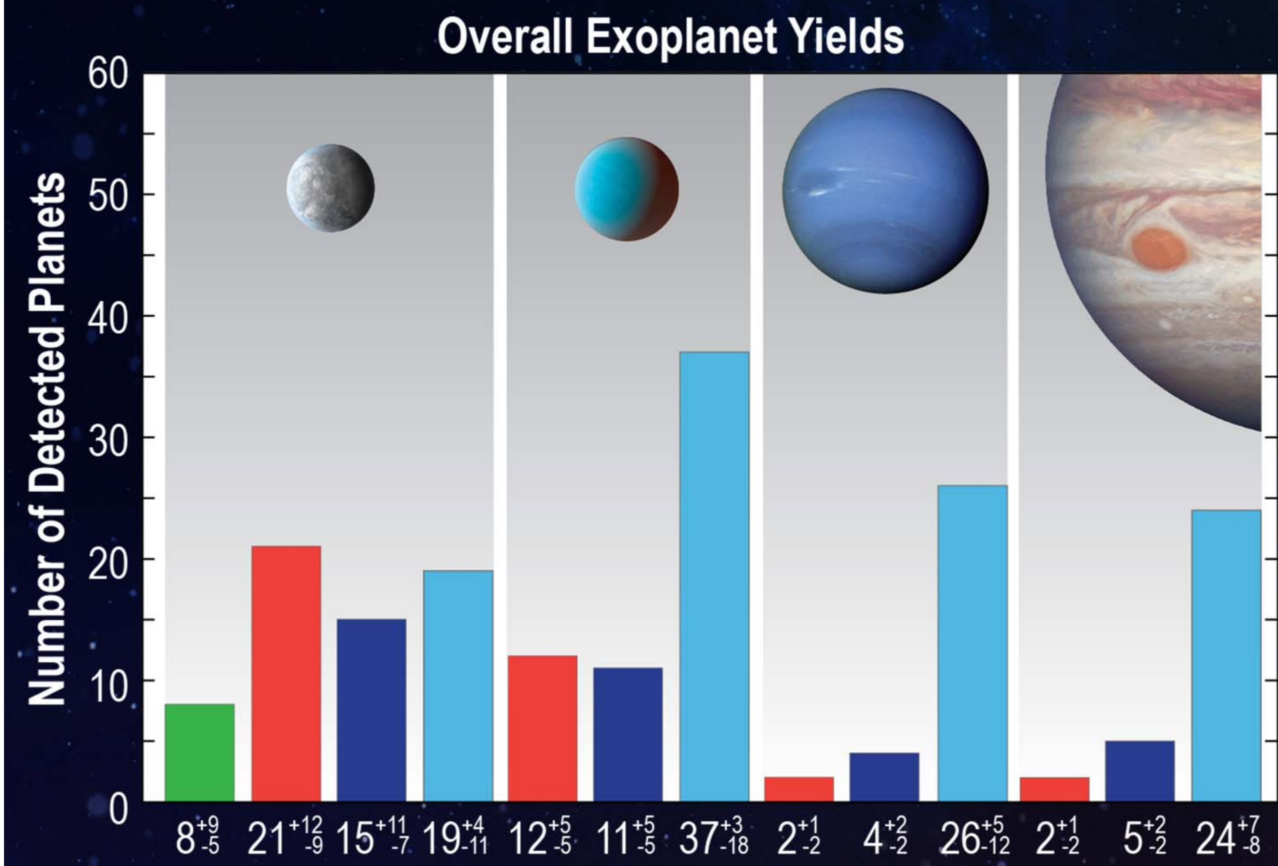
Planet Yield





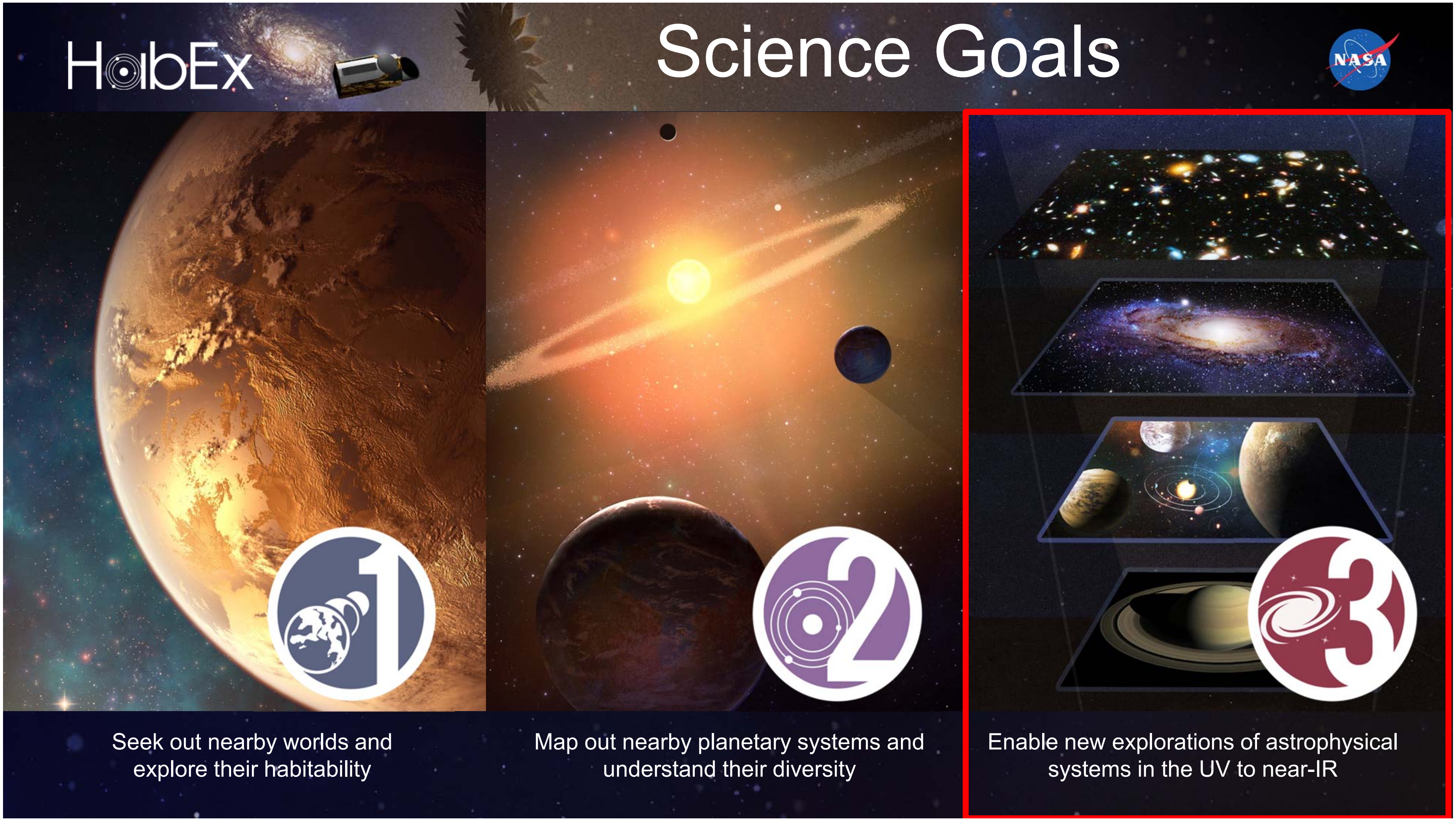
Planet yield is for a fiducial observing strategy and notional time allocation of 2.5 years during the 5 year prime mission.

Planet Yield



Every HabEx planet discovered can be characterized with a high-quality spectrum from 0.3 to 1.0 micron (and many from 0.2 to 1.8 micron).

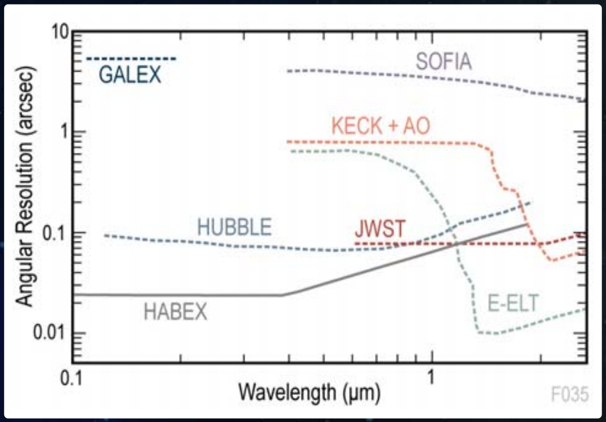
Nearly every HabEx planet will have its orbit determined.

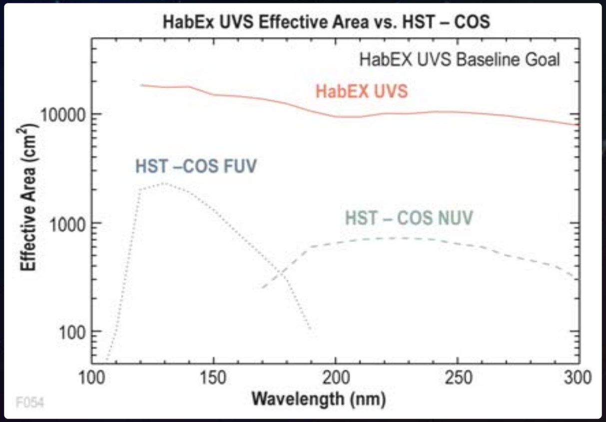

HabEx
Science Goals
NASA
1
2
3
Seek out nearby worlds and explore their habitability
Map out nearby planetary systems and understand their diversity
Enable new explorations of astrophysical systems in the UV to near-IR

Capabilities: Resolution and Effective Area

Imaging and Spectra

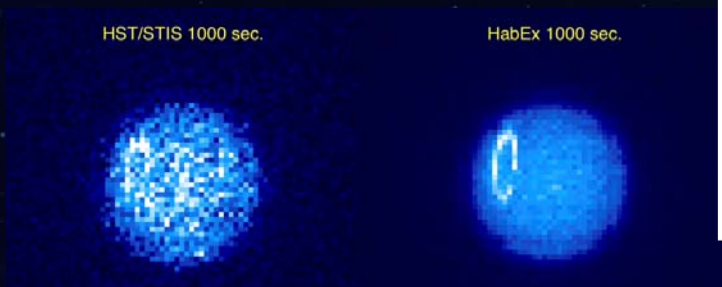
- **Key Details**
  - diffraction limited at 0.4 μm
  - non-sidereal (e.g., SS objects) tracking
  - wavelength coverage: 115 nm - 1.8 μm
- **UVS**
  - 3' x 3' FOV
  - 115-320 nm
  - spectral resolution up to 60,000
- **HWC**
  - 3' x 3' FOV
  - 450-950 nm and 950 nm - 1.8 μm
  - spectral resolution of 1000



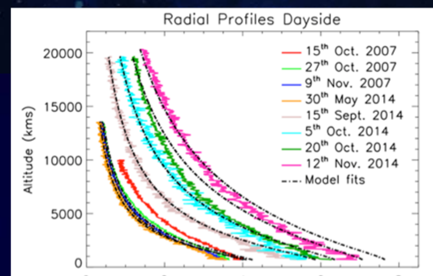


Other Exoplanet and Solar System Science

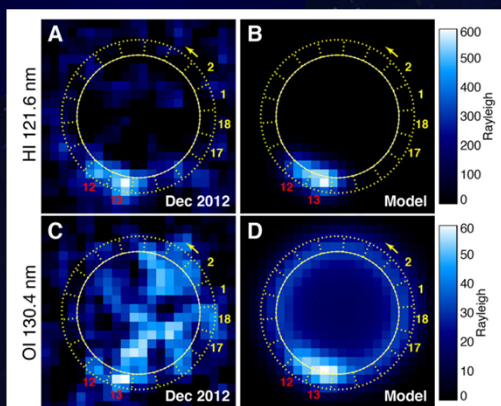
Solar System Science:
- Non-sidereal tracking up to 42''/s
- 0.025"@ 0.4 microns ~100 km @ Jupiter, ~200 @ Saturn, ~550 km @ Neptune
- >10x HST sensitivity in UV (150-300 nm)



Credit: John Clarke.

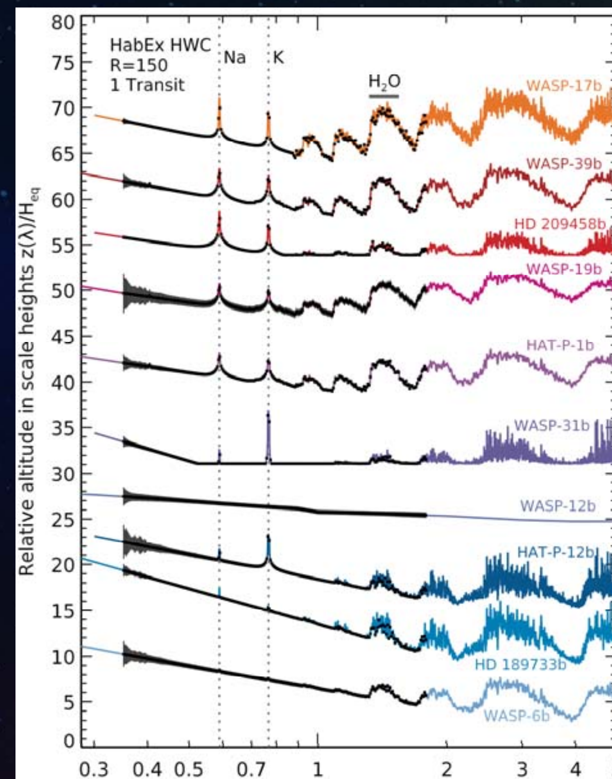


Bhattacharyya et al. (2015)



Roth et al 2014

Exoplanets:
Transmission Spectroscopy



Credit:Eric Lopez

Summary

Preferred Architecture Design:

- 4m off-axis monolith.
- Four instruments:
  - Coronagraph and Starshade.
  - UV Spectrograph and Workhorse Camera.

Studied 9 Architectures in Total:

- 4m/3.2m/2.4m x Hybrid/Starshade-Only/Coronagraph-Only

Science Goals:

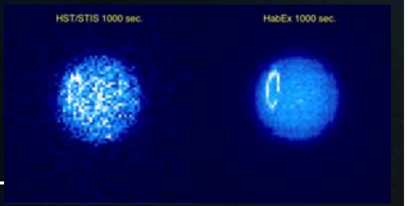
- To seek out nearby worlds and explore their habitability.
- To map out nearby planetary systems and understand the diversity of the worlds they contain .
- To carry out observations that open up new windows on the universe from the UV through near-IR.

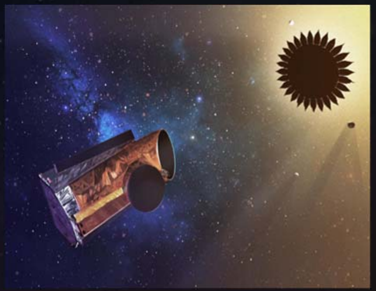
Technologies:

- Following the technology roadmaps, by 2023, HabEx will carry two TRL 4 enabling technologies and twelve TRL 5 technologies.

Cost:

- HabEx annual budgets would exceed current-level yearly allocations.
- However, this still assumes a diversified portfolio for NASA.






Thank you!

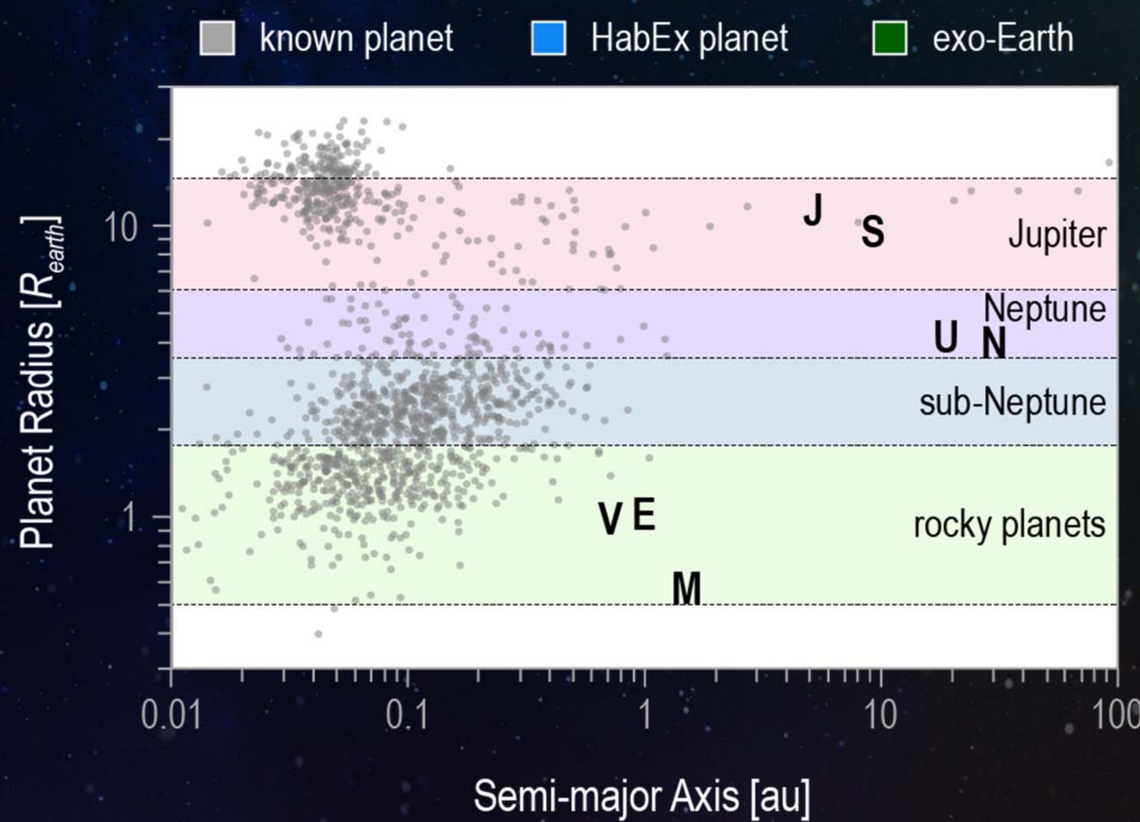
Backup Slides

Exoplanet Landscape

Thousands of exoplanets are known to exist…

…Yet selection effects have prevented discovery of small planets at and beyond 1 AU orbits.

HabEx stands to populate the missing part of the diagram.



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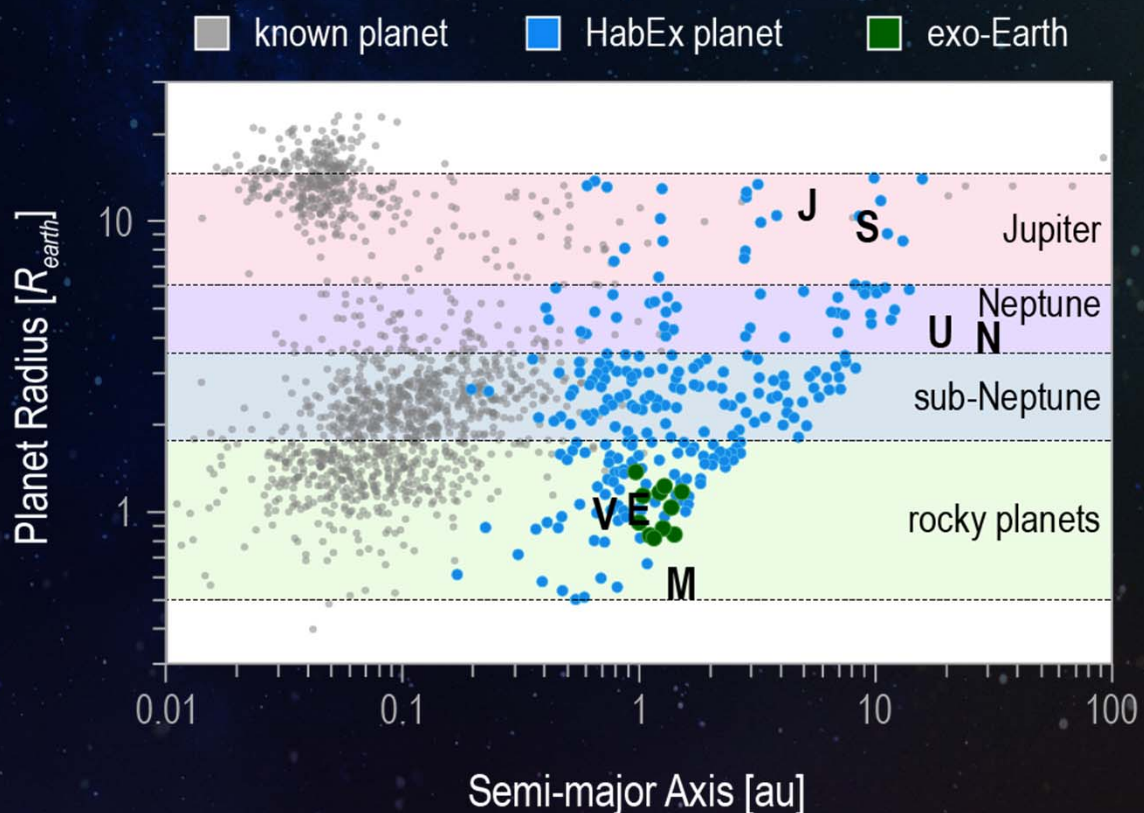
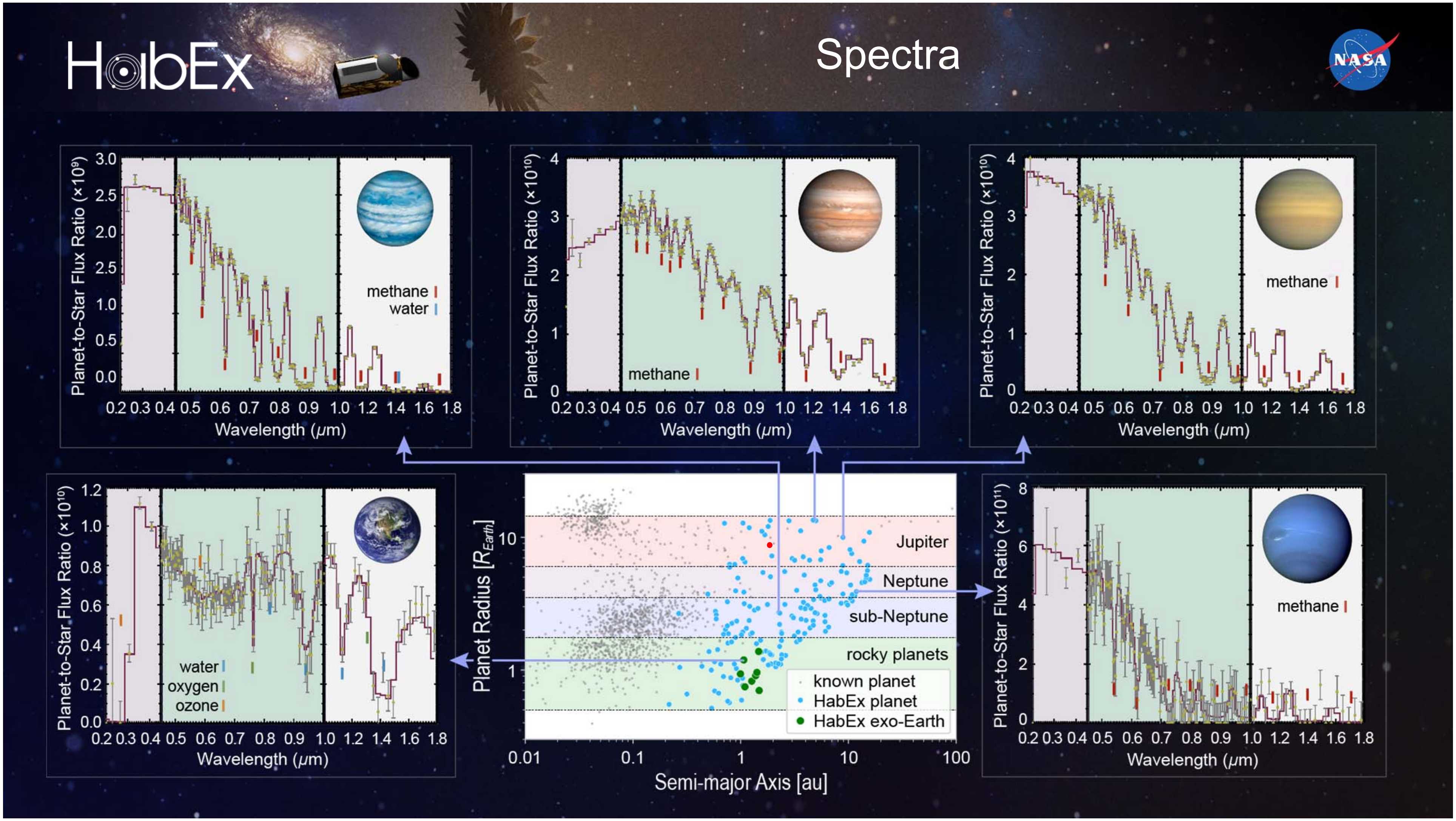
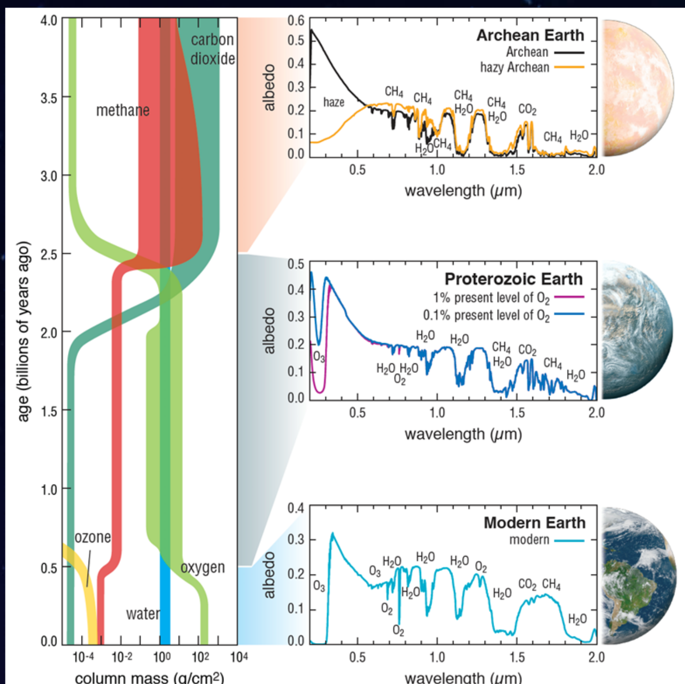
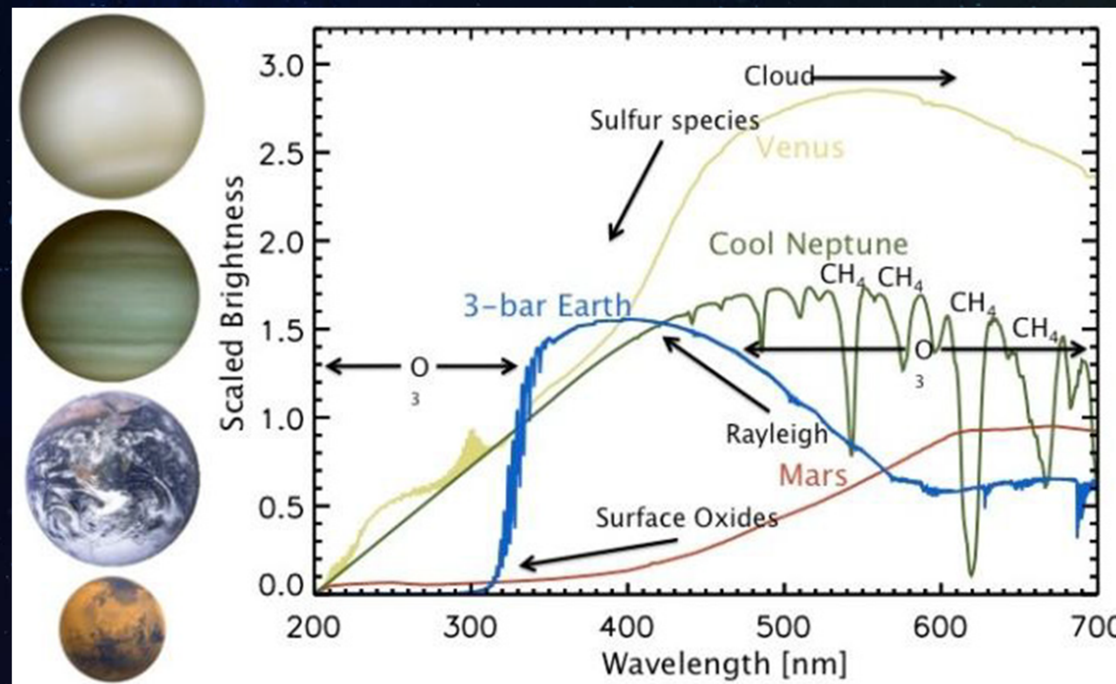




HabEx
Spectra
NASA
Planet-to-Star Flux Ratio (×10⁹)
methane
water
Wavelength (μm)
Planet-to-Star Flux Ratio (×10¹⁰)
methane
Wavelength (μm)
Planet-to-Star Flux Ratio (×10¹⁰)
methane
Wavelength (μm)
Planet-to-Star Flux Ratio (×10¹⁰)
water
oxygen
ozone
Wavelength (μm)
Planet Radius [R_Earth]
Jupiter
Neptune
sub-Neptune
rocky planets
known planet
HabEx planet
HabEx exo-Earth
Semi-major Axis [au]
Planet-to-Star Flux Ratio (×10¹¹)
methane
Wavelength (μm)

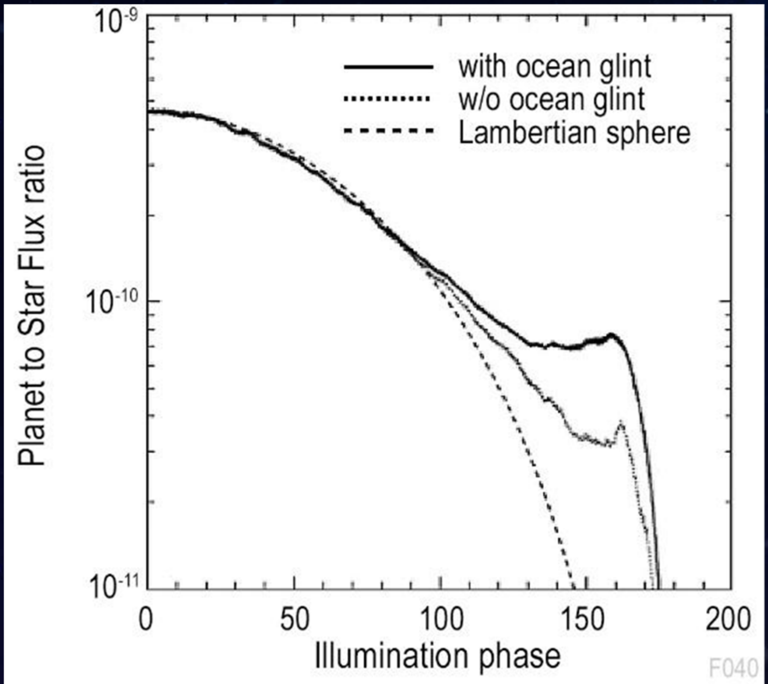
Not-Modern-Day-Earths

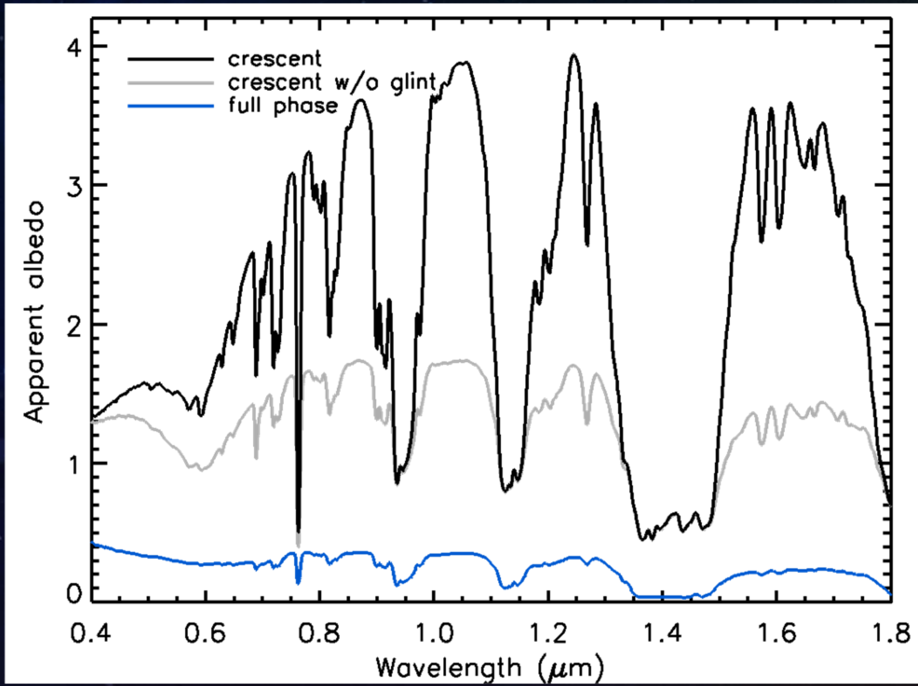




Credit: G. Arney, S. Domagal-Goldman, T. B. Griswold

Global Surface Water

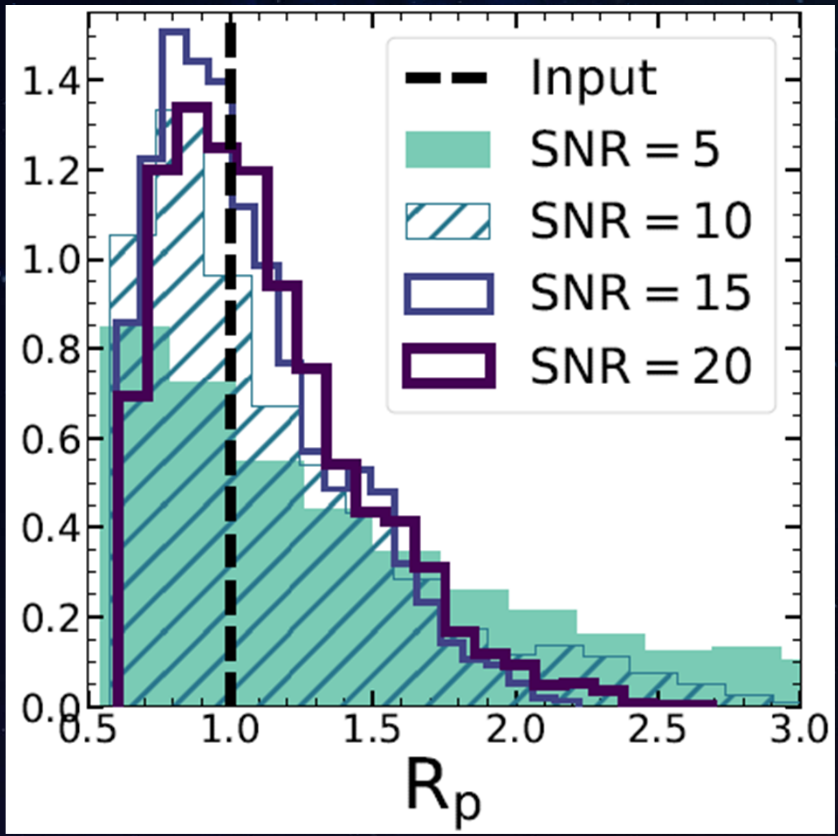




Robinson et al. 2011, 2014, 2018

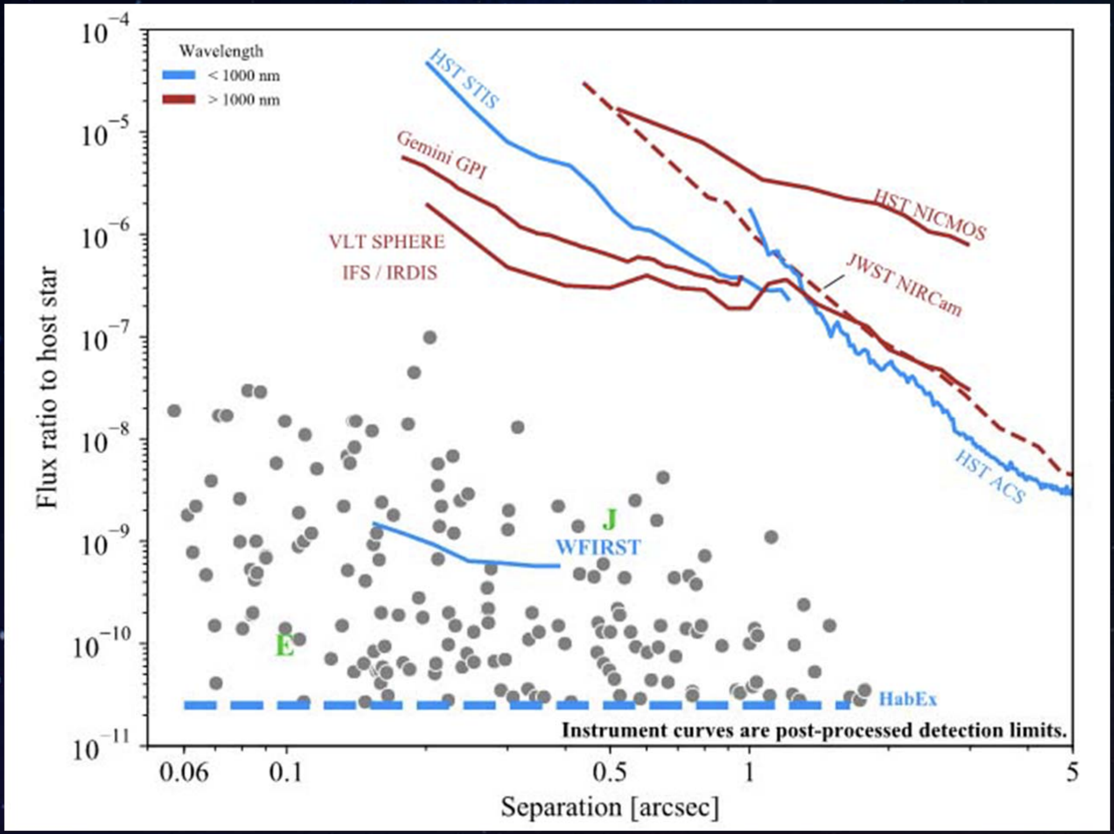
HabEx

Spectroscopic Radius Constraint



Feng et al. 2018

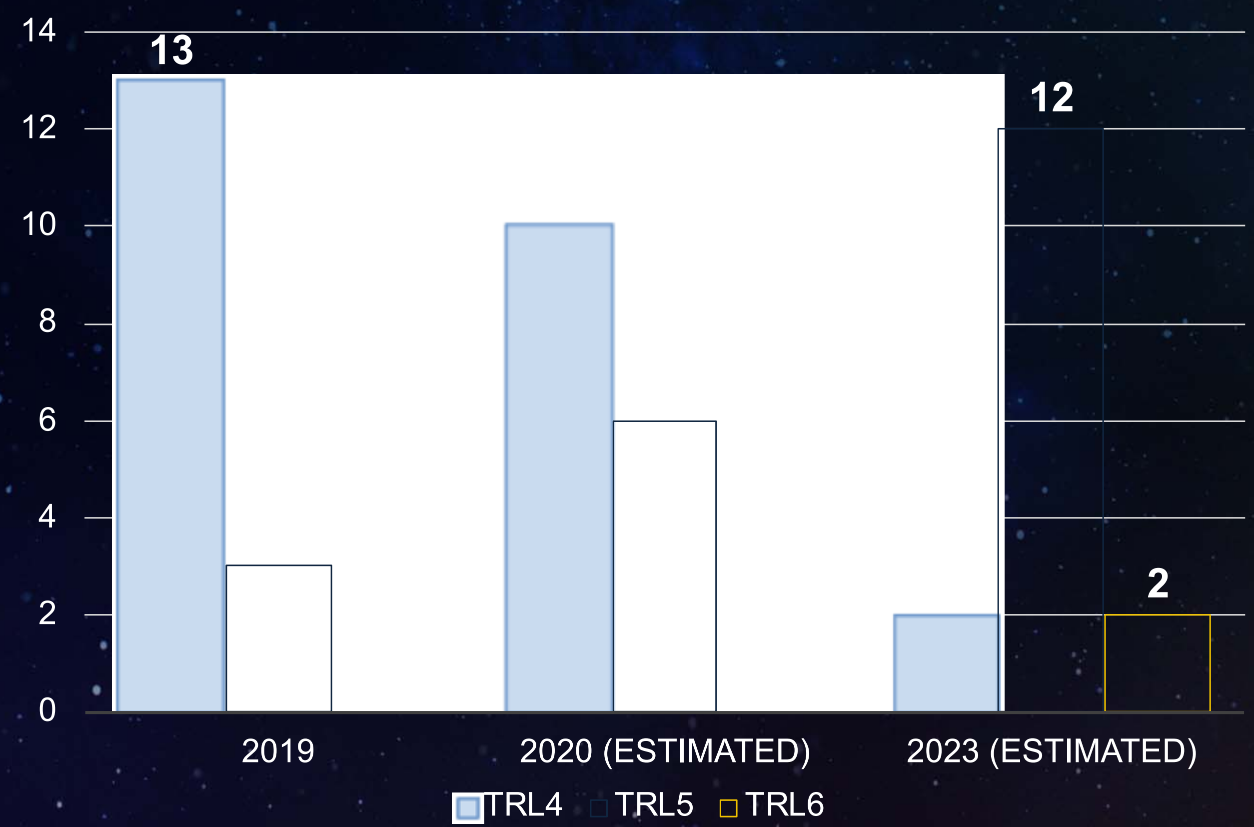
Contrast Requirements



Two Teams, One Vision
Statement by the LUVOIR & HabEx STDTs

- The HabEx and LUVOIR (and Lynx and *Origins*) Science and Technology Definition Teams have devoted over three years and many thousands of person-hours to studying future large strategic space mission concepts.
- Together, HabEx and LUVOIR will present eleven different architectures.
- ***The HabEx and LUVOIR teams have collaborated since their initiation,*** and as a result are offering a ‘buffet’ of options, with corresponding flexibility in budgeting and phasing.
- The studies agree that a joint astrophysics – exoplanet UV/optical/near-IR space observatory provides a bold, compelling, and achievable vision for space astronomy.

Technology Maturation



Technology Maturation

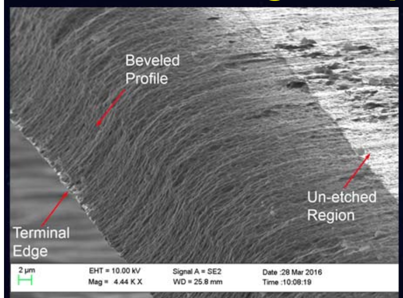
Technology Item	TRL Nov 2019	Progress up to 4/21	TRL 5 Expected
Starshade Petal Position Accuracy and Stability	4		2025
Starshade Petal Shape Accuracy and Stability	4		2025
Starshade Scattered Sunlight from Petal Edges	5		
Starshade Contrast Performance and Model Validation	4		July 2021
Starshade Lateral Formation Sensing	5		
Large Mirror Fabrication	4		
Large Mirror Coating Uniformity	4		
Laser Metrology	5		
Coronagraph Architecture	4		
Zernike Wavefront Sensing and Control	4		
Deformable Mirrors	4		
Delta Doped UV and Vis EMCCDS	4		
Deep Depletion EMCCDS	4		
LMAP Sensors	4		
Microthrusters	4		

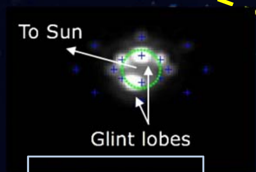
NASA directed slowdown

Delayed due to COVID restrictions

Starshade Technology

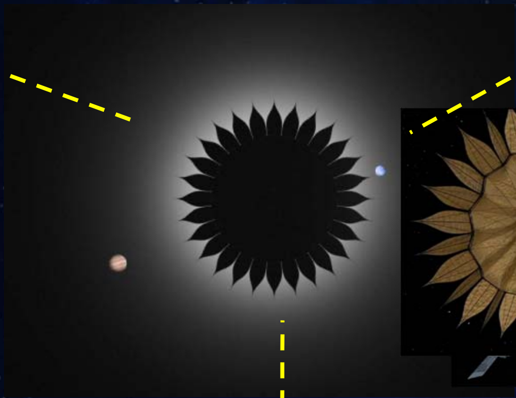
Starlight Suppression





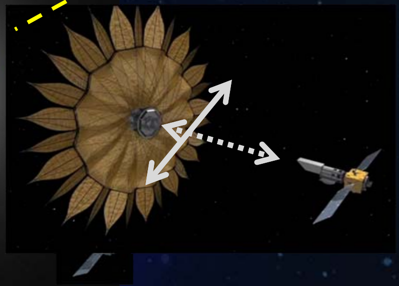
TRL 5
summer
2019

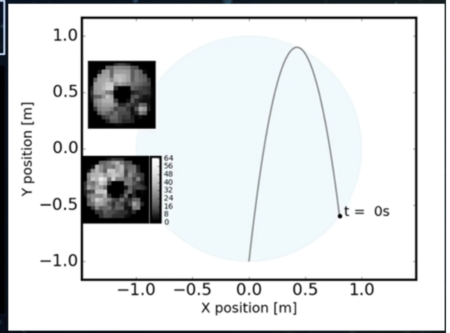
Controlling Scattered Sunlight



Formation Sensing

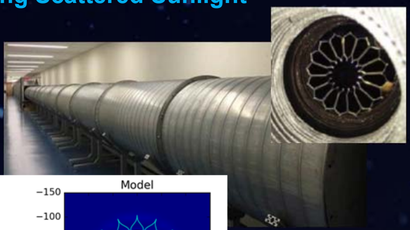
TRL 5

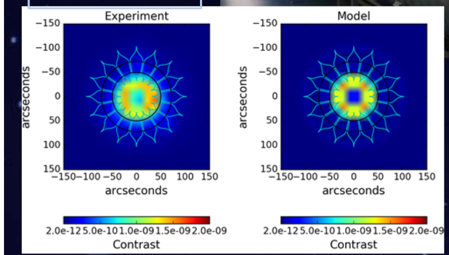




Lateral Formation Sensing

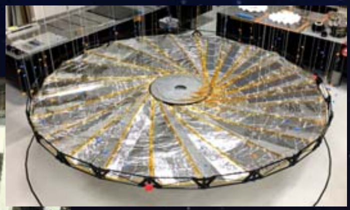
TRL 5
January
2020





Contrast Performance and Model Validation

Deployment Accuracy and Shape Stability



TRL 4

Petal Positioning Accuracy and Opaque Structure

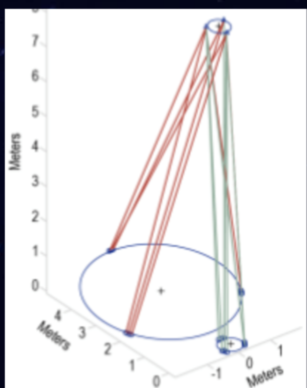
TRL 4

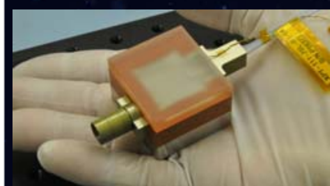
Petal Shape And Stability

Telescope Technology

HabEx

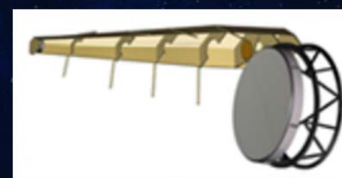
Laser Metrology





TRL 5

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



Microthrusters

TRL 5

ESA/LISA Pathfinder

Large Monolith Mirrors

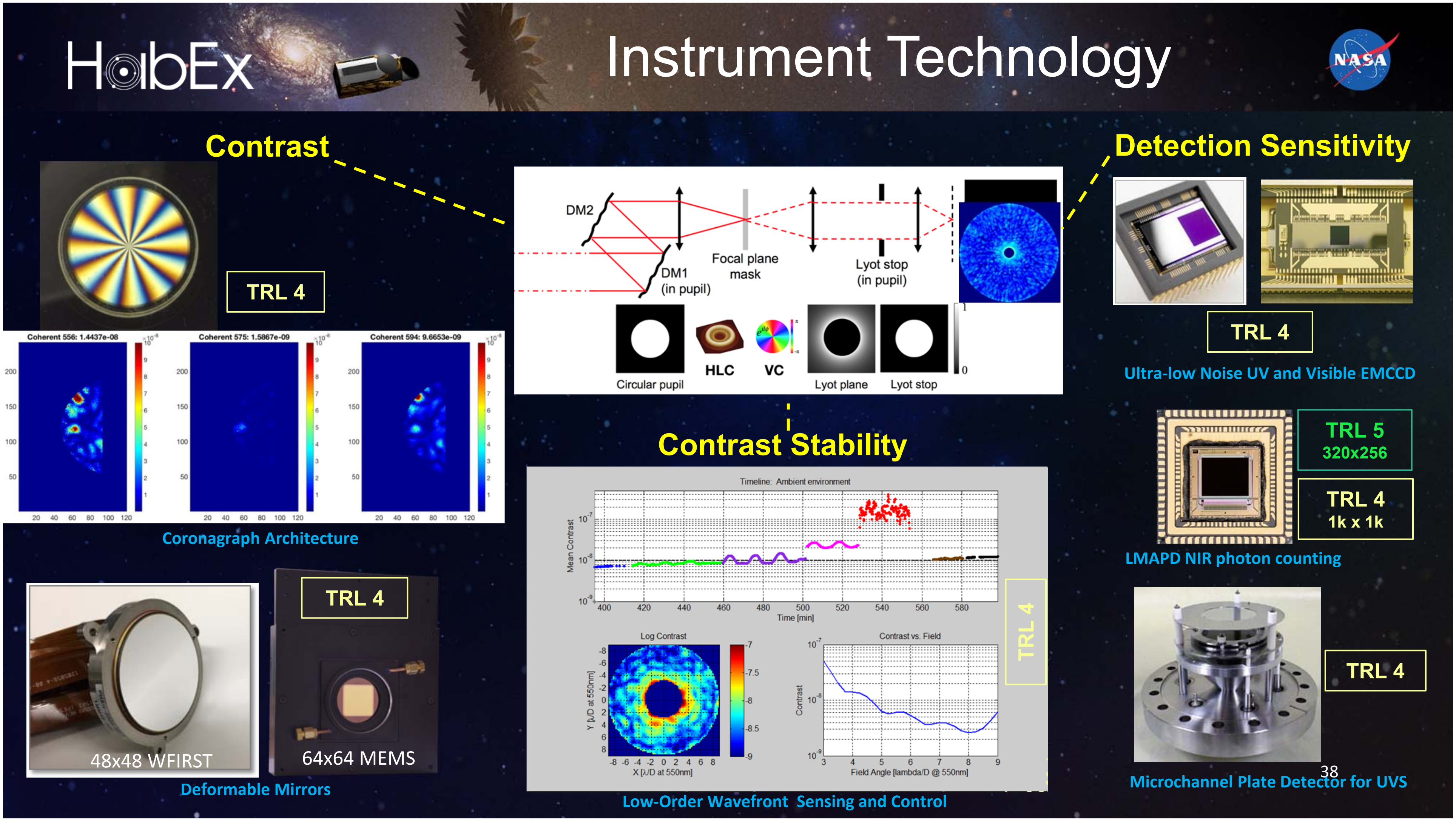
TRL 4

Large Monolith Mirror Fabrication

2.4 m Coating Chamber

TRL 4

Coating Uniformity



HabEx
Instrument Technology
NASA
Contrast
TRL 4
DM2
DM1
(in pupil)
Focal plane
mask
Lyot stop
(in pupil)
Circular pupil
HLC
VC
Lyot plane
Lyot stop
Coherent 556: 1.4437e-08
Coherent 575: 1.5867e-09
Coherent 594: 9.6653e-09
Coronagraph Architecture
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
Contrast Stability
Timeline: Ambient environment
Mean Contrast
Time [min]
Log Contrast
Y [λ/D at 550nm]
X [λ/D at 550nm]
Contrast vs. Field
Contrast
Field Angle [lambda/D @ 550nm]
TRL 4
Low-Order Wavefront Sensing and Control
TRL 4
48x48 WFIRST
64x64 MEMS
Deformable Mirrors
38

Technology Development

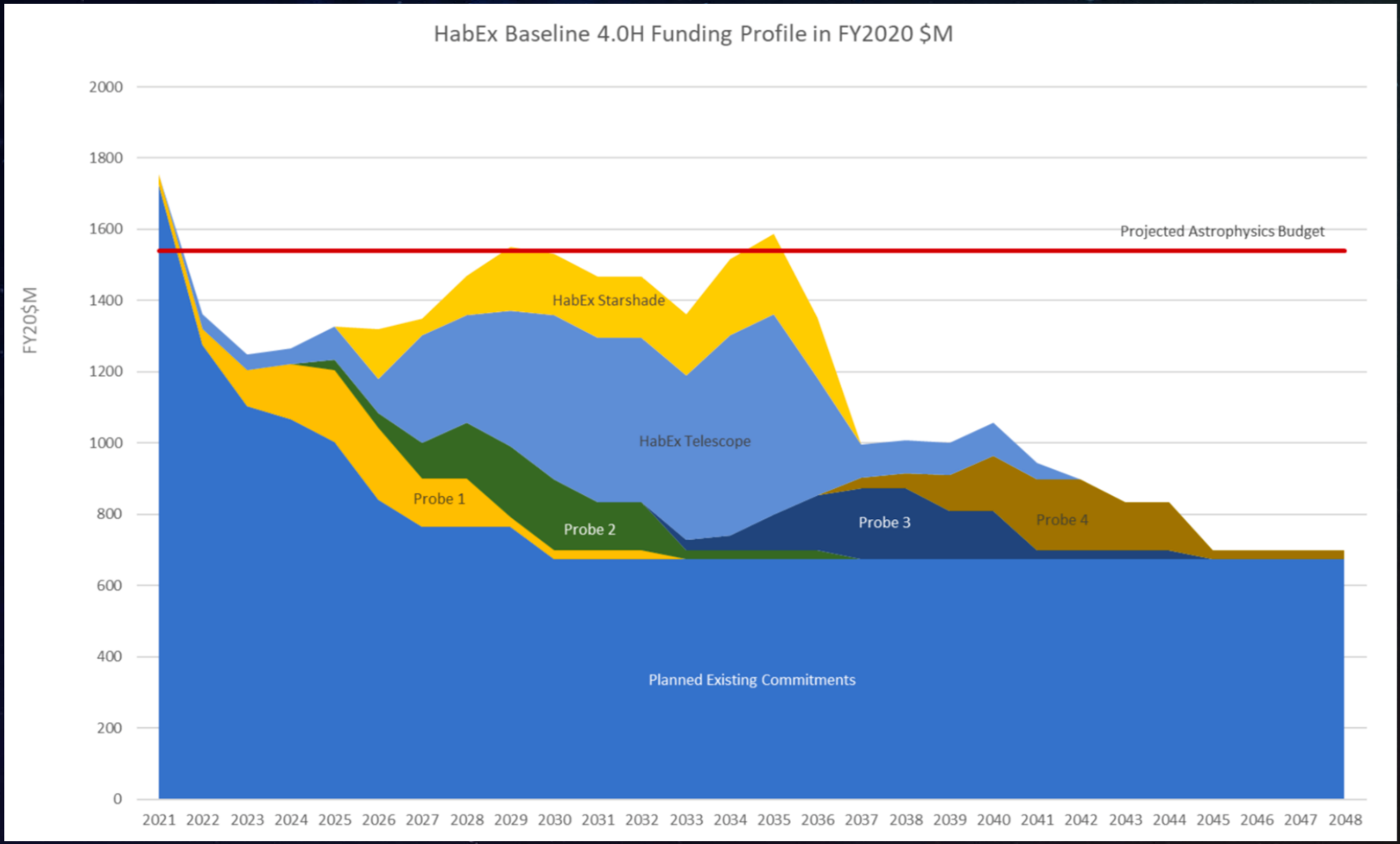
# of Enabling Tech. / Category	2019		2020 (estimated)		2023 (estimated)		
	TRL 4	TRL 5	TRL 4	TRL 5	TRL 4	TRL 5	TRL 6
Starshade	3	2	2	3	0	4	1
Large Mirror	2	0	2	0	1	1	0
Metrology	0	1	0	1	0	0	1
Coronagraph	3	0	2	1	0	3	0
Detectors	4	0	4	0	1	3	0
Microthrusters	1	0	0	1	0	1	0
Total	**13**	**3**	**10**	**6**	**2**	**12**	**2**

- Following the technology roadmaps, by 2023, HabEx will carry two TRL 4 technologies and twelve TRL 5 technologies.
- Two technologies will be at TRL 6 and will have completed technology development one year before the start of Phase A.

Cost

Baseline concept funding profile.

- For a flat astrophysics budget projection, HabEx annual budgets would exceed current-level yearly allocations.
- However, such a profile would still assumes a diversified portfolio for NASA, including existing commitments (like Explorers, R&A), and the inclusion of a new line of Probes ($1B).



HabEx

Cost

Alternative delayed funding profile.

- If the starshade launch is delayed, HabEx would fit into the current-level yearly allocations.

Alternative delayed funding profile.
If the starshade launch is delayed, HabEx would fit into the current-level yearly allocations.