Designing the Future of Exoplanet Exploration: Mission Studies for the 2020 Decadal Survey

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and the LUVOIR & HabEx study teams for much of this material

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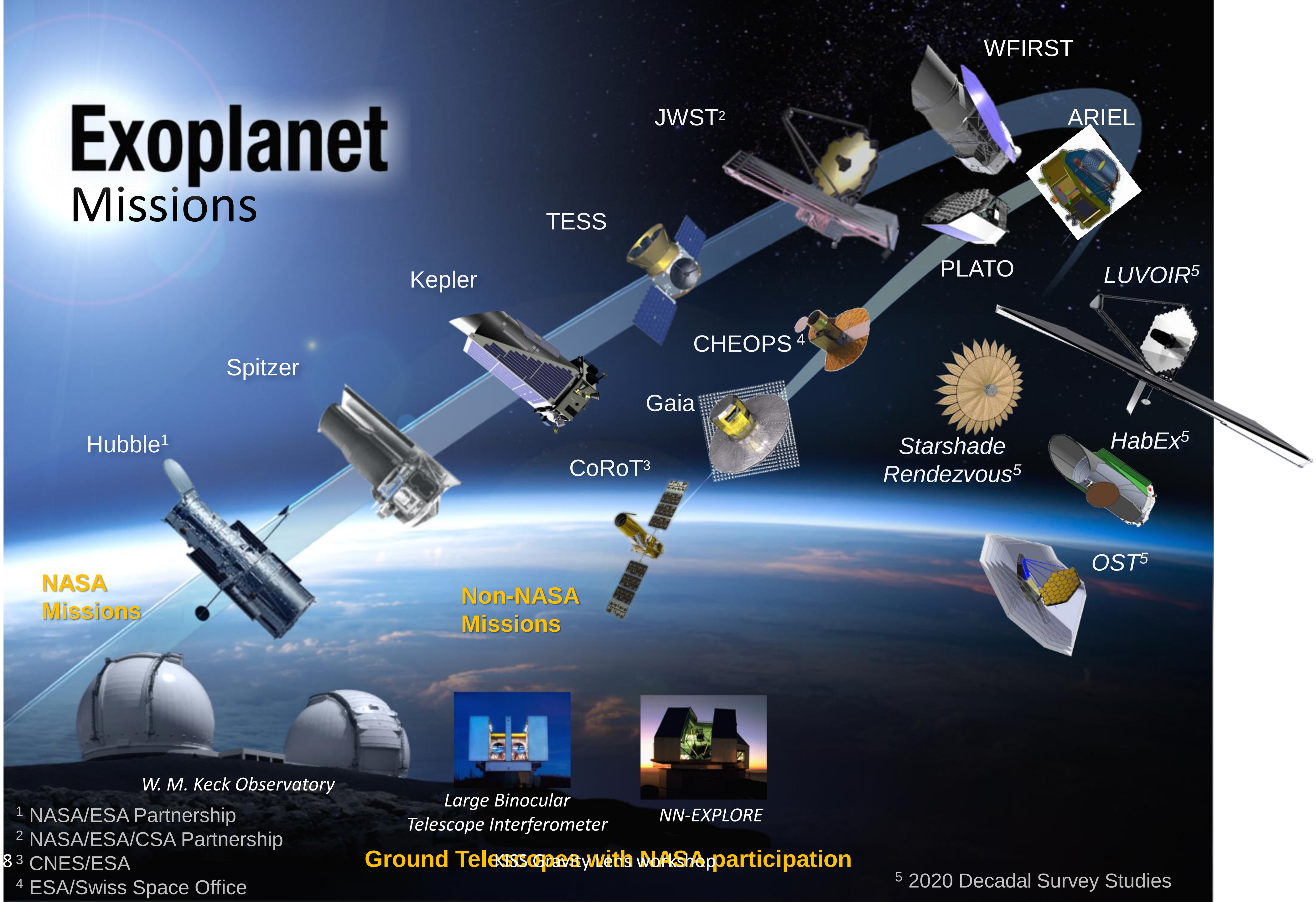
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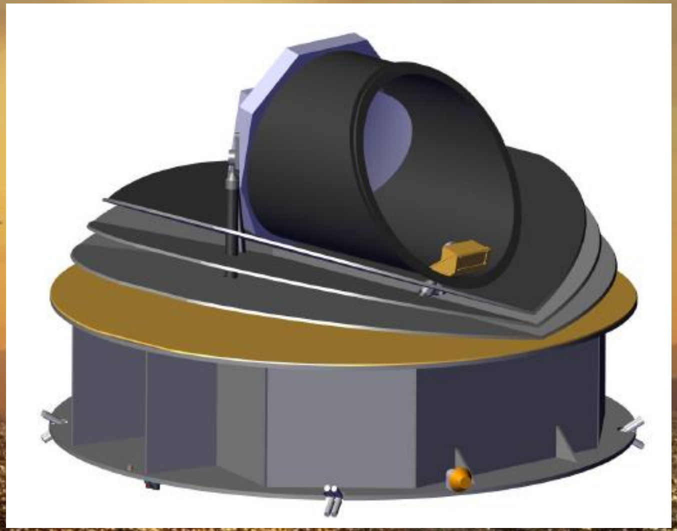
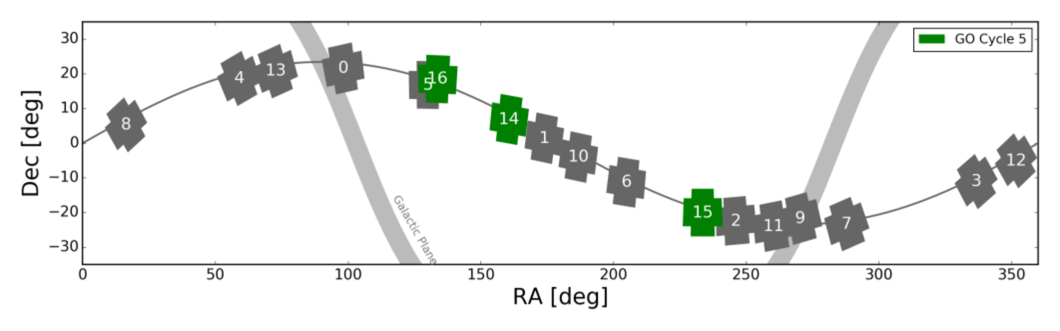
Exoplanet Mission News

- TESS mission launched a month ago, all OK so far
- ESA selected ARIEL transit spectroscopy mission for 2028 launch. U.S. expected to contribute hardware



Kepler and K2:

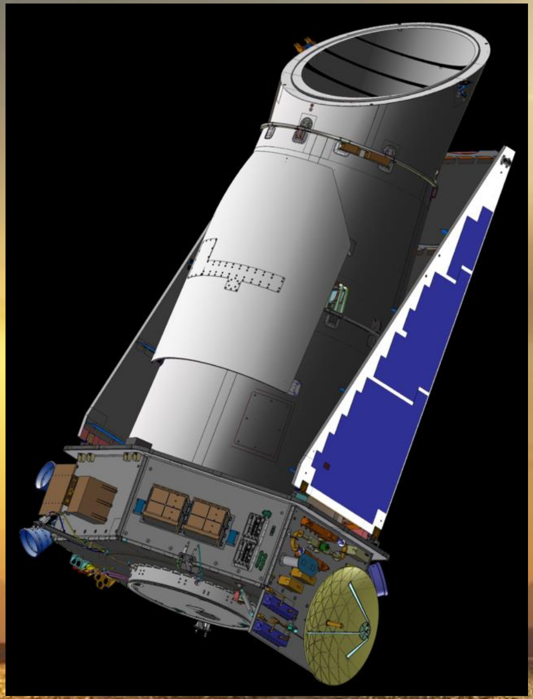
Frequency of rocky planets



- Kepler prime mission concluded in FY 17

  Final data Products delivered.   2327 confirmed exoplanets, ~2000 additional candidates. Roughly 20 confirmed Earth-sized exoplanets in HZ.

- K2 has found 309 confirmed exoplanets with 500 additional candidates. These include high value small planets around bright stars
- K2 microlensing campaign has found > 600 events, number of planets TBD
- K2 will exhaust its fuel in summer 2018 leading to loss of fine pointing

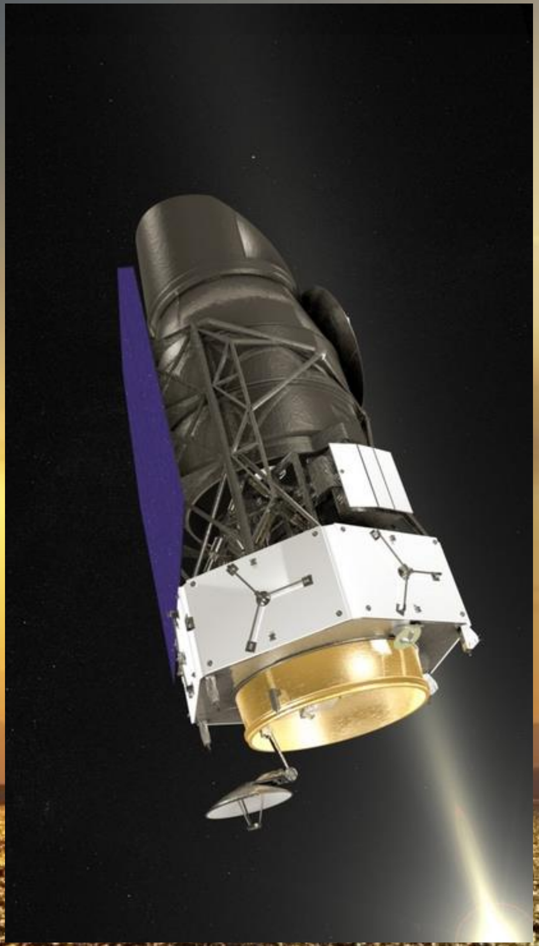


The TESS Mission in One Slide

- TESS will monitor the brightness of 200,000 stars for ~26 days to search for transiting exoplanets
  - *Target: Earths, super-Earths, and sub-Neptunes*
- TESS will provide images of every object in every observed field at a 30 minute cadence
  - *Anticipated result: Photometric data for ~20 million stars and ~10 million galaxies*
- Ground analyses of TESS data will reveal transiting planets by looking for regular dips in the brightness of each star
- Ground follow-up observations will:
  - *Confirm the presence of a transiting planet*
  - *Determine the mass of the planet*

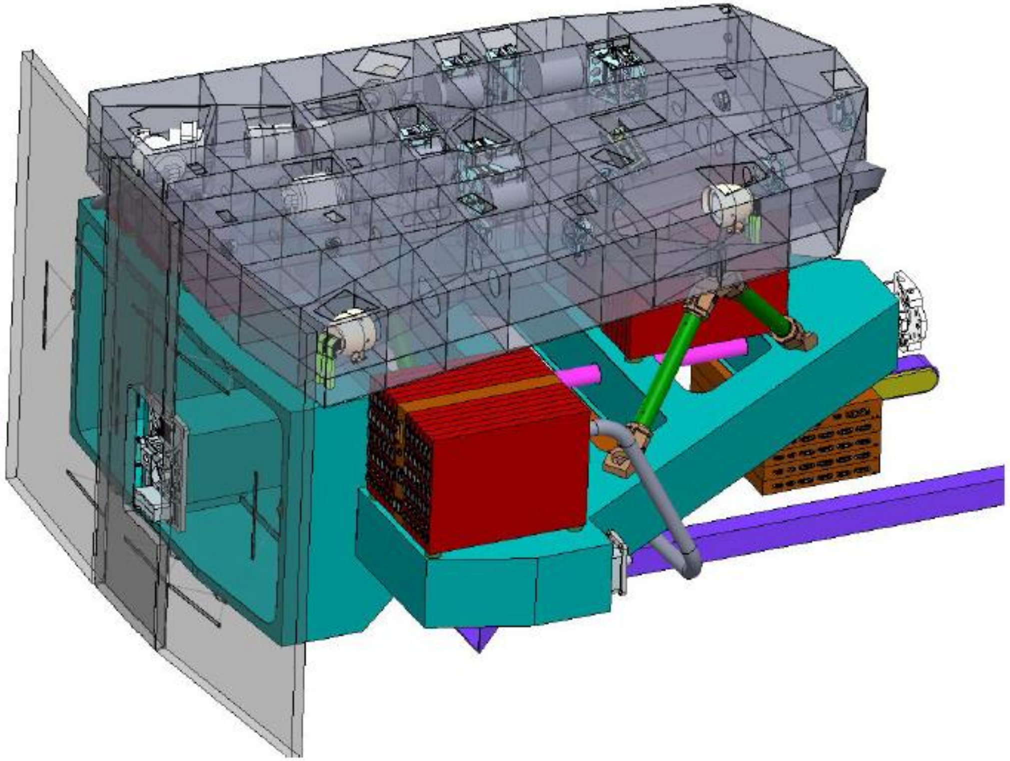
FUTURE EXOPLANET SPECTROSCOPY: WFIRST MISSION, 2025 ?

- Surplus space telescope with 2.4 m aperture for wide field near-infrared imaging (dark energy, exoplanet microlensing). #1 priority for space astronomy in 2010 Decadal Survey.
- Coronagraph will be first flight of wavefront-correcting deformable mirrors that should enable 10^{-9} contrast, 130 milliarcsec inner working angle at 0.55 μm
- Coronagraph is a key technology demo that could image & make spectra of known RV planets, dust disks, and maybe a couple super-earths. R= 50.
- Starshade option is under consideration
- WFIRST not included in President's FY 19 budget



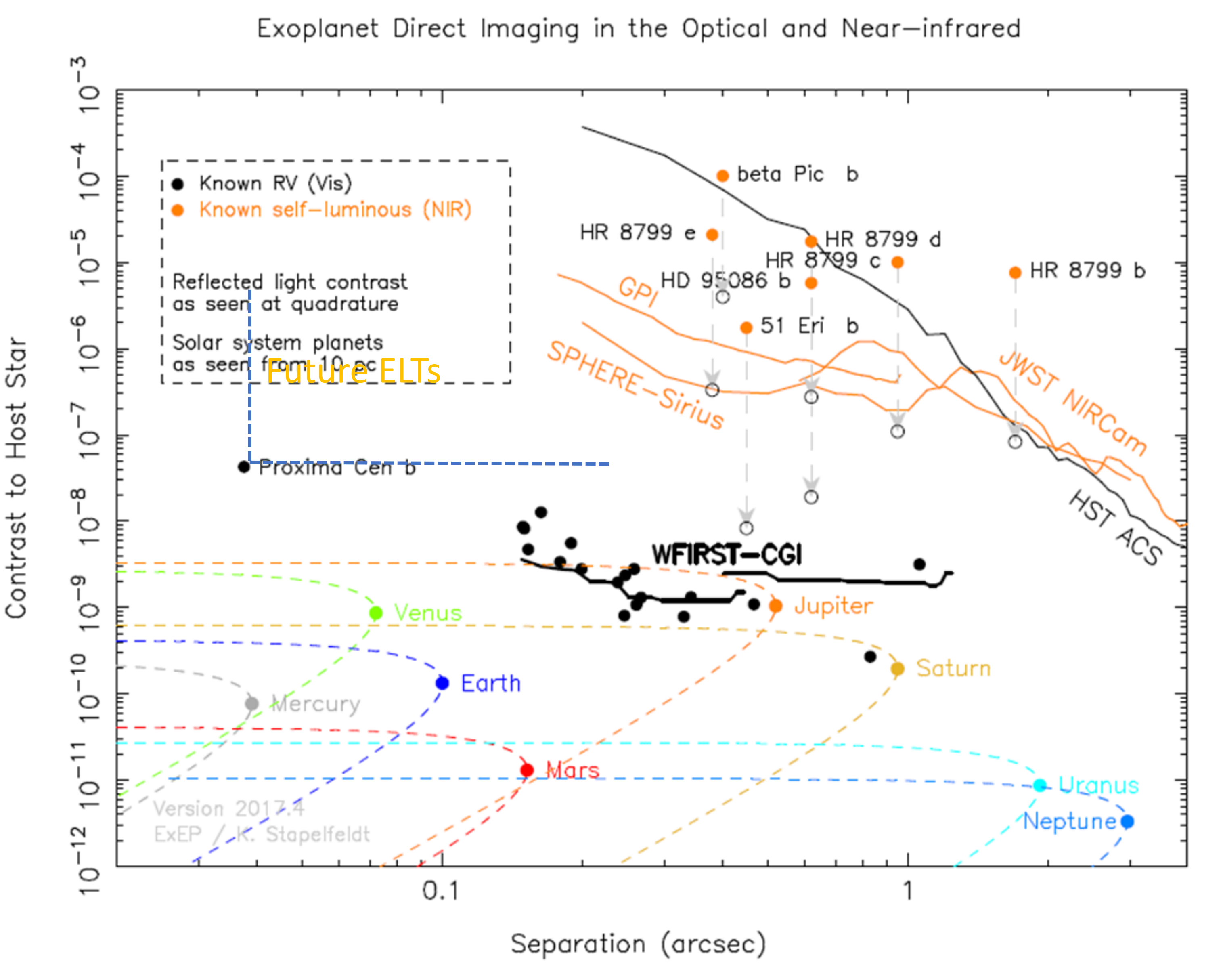
WFIRST Coronagraph layout

- 2 PbMgNb Deformable Mirrors (48x48 actuators)
- Direct Imaging channel with Photon-Counting EMCCD passively cooled to 165 K
- Integral Field Spectrograph (R = 50, cooled EMCCD camera)
- Low-Order Wavefront Sensor (Rejected starlight, EMCCD camera)
- Active thermal control for bench, DM, and electronics
- Robotically serviceable payload interface
- Starshade accommodation



WFIRST Coronagraph Performance

(preliminary)

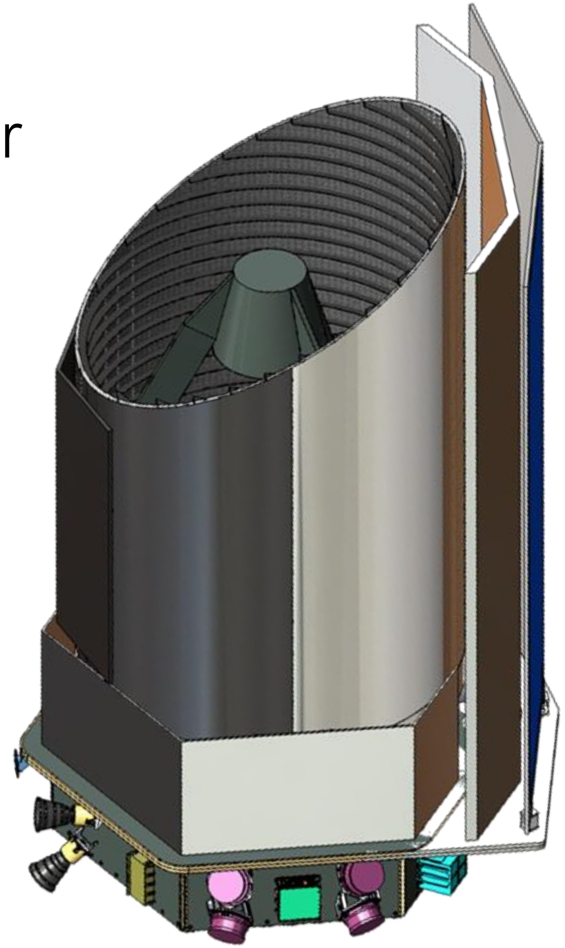


NASA-sponsored decadal mission studies for exoplanets

- In 2015 NASA Astrophysics Director Paul Hertz asked the community to suggest large mission studies that he should fund. PAGs considered this and requested four.
- A X-ray mission, a far-IR mission, an exoplanet direct imaging mission, and an exoplanet + general astrophysics mission were recommended
- In early 2016 the large mission studies were assigned to NASA Centers and STDT members were selected after a community self-nominations
- In late 2016 a less-well-funded call for “probe mission” concepts was issued. Two related to exoplanets were “partially selected”
- <u>In the rest of this talk I’ll quickly review these 2+4 mission concepts as they relate to exoplanets</u>

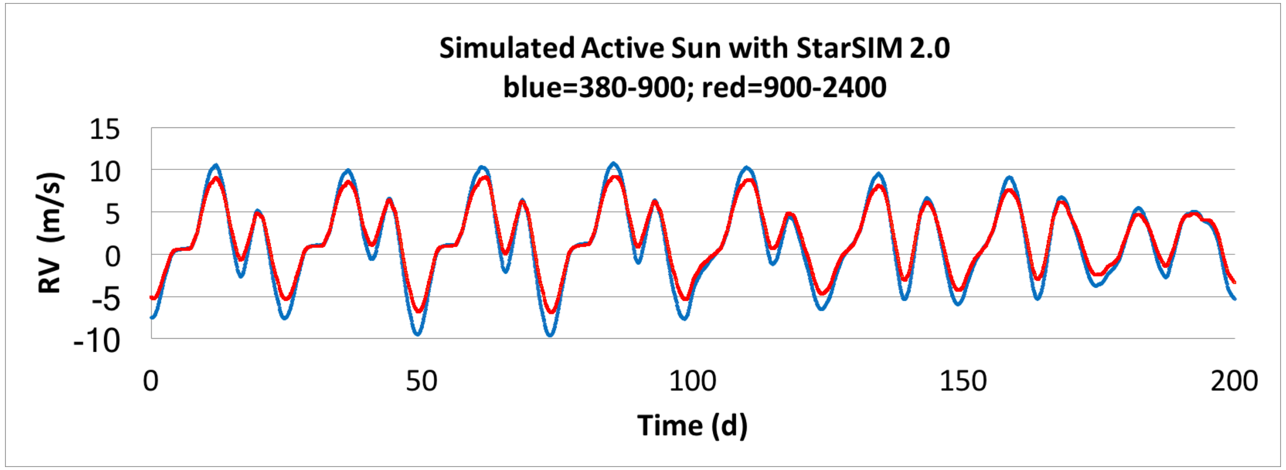
"Earthfinder" RV Probe Study

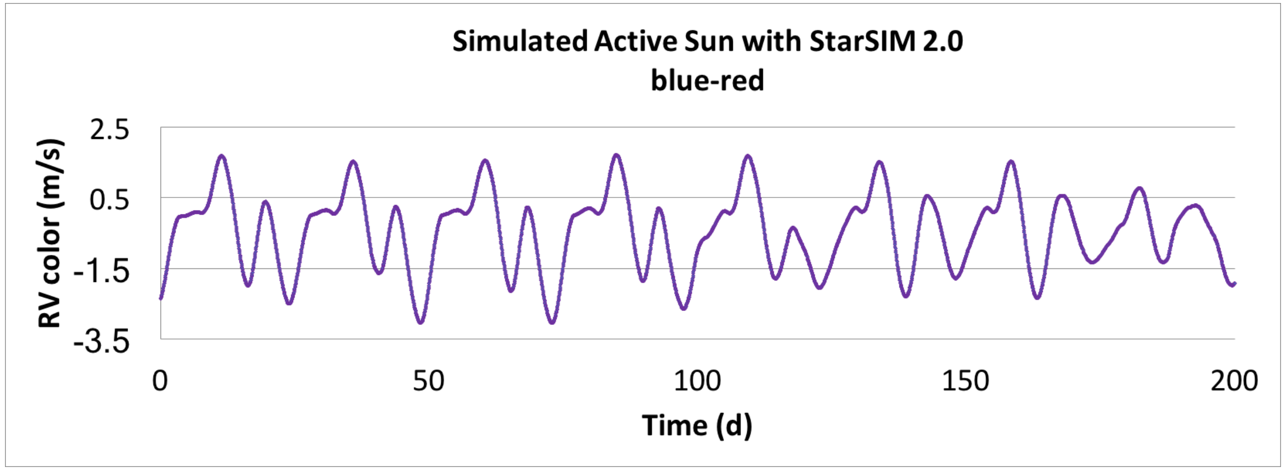
- EarthFinder is a space-based 1-1.4 m observatory Probe mission concept. Peter Plavchan (GMU) is PI, JPL partner
- Extremely precise and stabilized high-resolution UV-VIS-NIR spectrograph, targeting 1 cm/sec precision
- Developing scientific rationale for measuring stellar velocities of the nearest FGKM dwarf stars from space
- <u>Absence of the Earth's atmosphere improves the obtainable radial velocity precision</u>
- Unique combination of space advantages aid in mitigating stellar activity:
  - Uninterrupted wavelength coverage
  - Uninterrupted cadence
  - Diffraction-limited
  - Extreme spectral resolution



Stellar Activity

Wavelength coverage into near-IR reveals stellar jitter systematics, enabling their removal



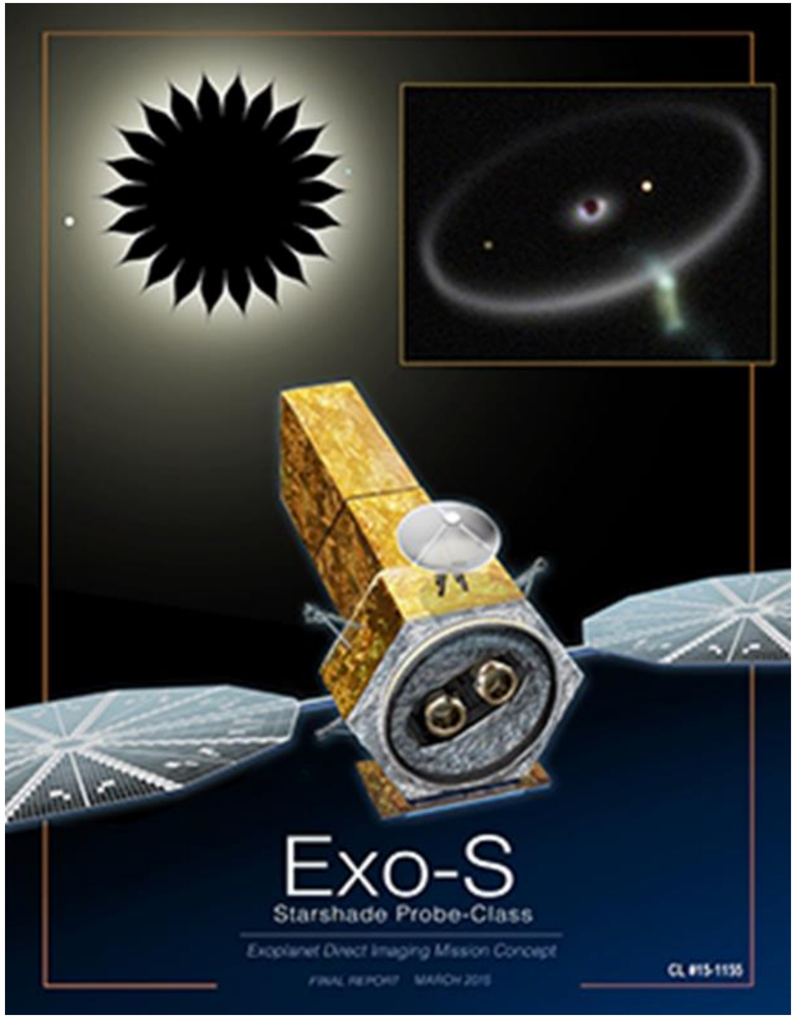


Earthfinder promise and challenge

- Imaging missions can’t determine planet mass, would require supporting measurements of stellar reflex motion
  - Planet mass determines bulk composition, and is crucial for interpreting atmospheric spectra,
- If RV (or astrometry) could identify in advance the targets with HZ planets, an imaging mission might avoid searches and save considerable observing time for other uses (exoplanet characterization, general astrophysics).
- Tradeoff between cost of the additional probe mission and the cost of search time on the large mission. But mass values are required regardless.
- Can advantages of space RV overcome the 100-1000x collecting area advantage of VLTs / ELTs ?

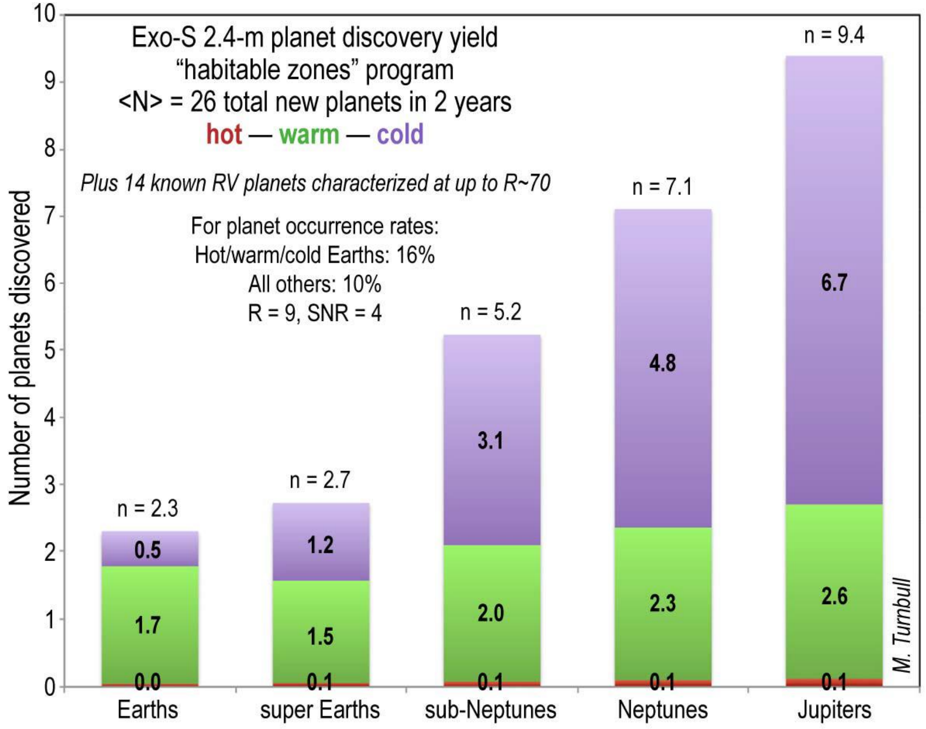
Starshade Probe Mission Options

- Seager+ 2015 studied two mission concepts utilizing a starshade for detecting & characterizing Earth analogs in a sample of ~2 dozen nearby stars. JPL strongly involved.
- Current probe study is updating that report for the 2020 decadal.
- "Rendezvous" concept would use 2.4m WFIRST telescope + CGI focal planes, is preferred option
- "Dedicated" concept includes its own 1.1 m telescope, backup in case WFIRST Rendezvous does not proceed



Starshade mission key points

- Would enable smaller inner working angles, higher throughput/bandwidth than coronagraphic starlight suppression
- Opens up nearby HZs to 1-2 m class telescopes such as WFIRST, along with giant planets & disks
- Spectroscopy of exo-Earths would require finding them around the brightest targets; otherwise characterization via broad colors
- Technology is progressing since 2015 study: model validation, formation flying, smaller 26 m starshade now baselined
- This study report is THE crucial input to Decadal decision on WFIRST Rendezvous
- Would be a pathfinder for larger HabEx starshade



Predicted detection yields for Rendezvous mission vs. exoplanet type (Seager+ 2015)

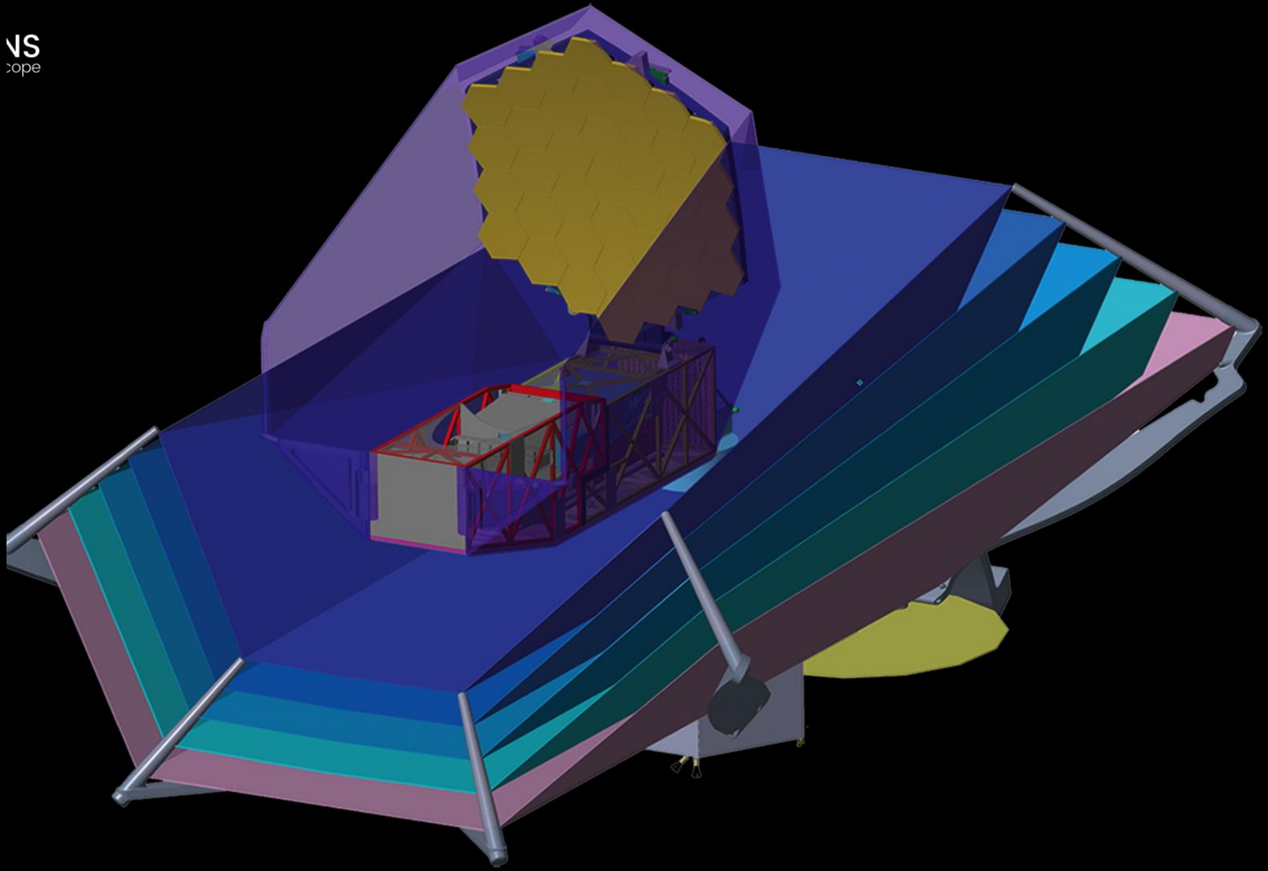
- L2 orbit

Lynx Exoplanet Summary:

- Primary use would be for characterizing the levels of stellar high energy radiation incident on nearby exoplanets
- Transit spectroscopy of exospheres for brighter stellar hosts
- Results would support interpretation of exoplanet spectra from other facilities
- General astrophysics would dominate mission utilization, exoplanets would have small niche

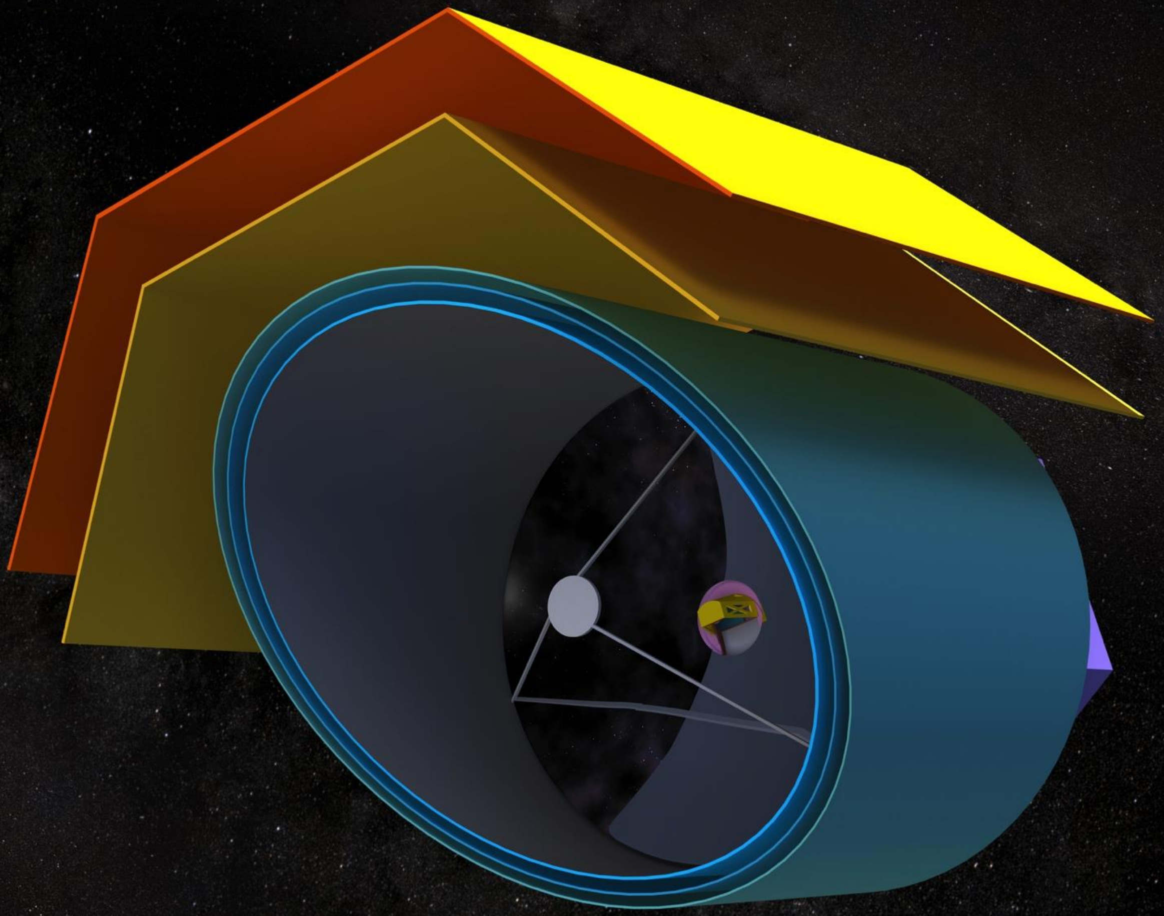
Origins Space Telescope Mission Concept 1

- 9.1 m off-axis primary mirror
- Cold (4 K) telescope
- Wavelengths 5-660 μm
- Diffraction limited at 30 μm
- 5 science instruments:
  - MISC - 5-38 μm
  - MRSS 30-660 μm
  - HERO 63-66; 111-610 μm
  - HRS 25-200 μm
  - FIP 40, 80, 120, 240 μm
- 100 arcseconds/second mapping
- Launch 2030s, Sun-Earth L2 orbit
- Launch vehicle SLS with 8.4m fairing
- 5 year lifetime, 10 year goal



OST Mission Concept 2

- 5.9-m circular aperture
- Cold (4 K) primary
- Spitzer-like baffle, with Sun shield
- Minimal deployment
- Fewer (≤4), science-optimized instruments
- Preliminary designs started, to be completed by end of summer 2018

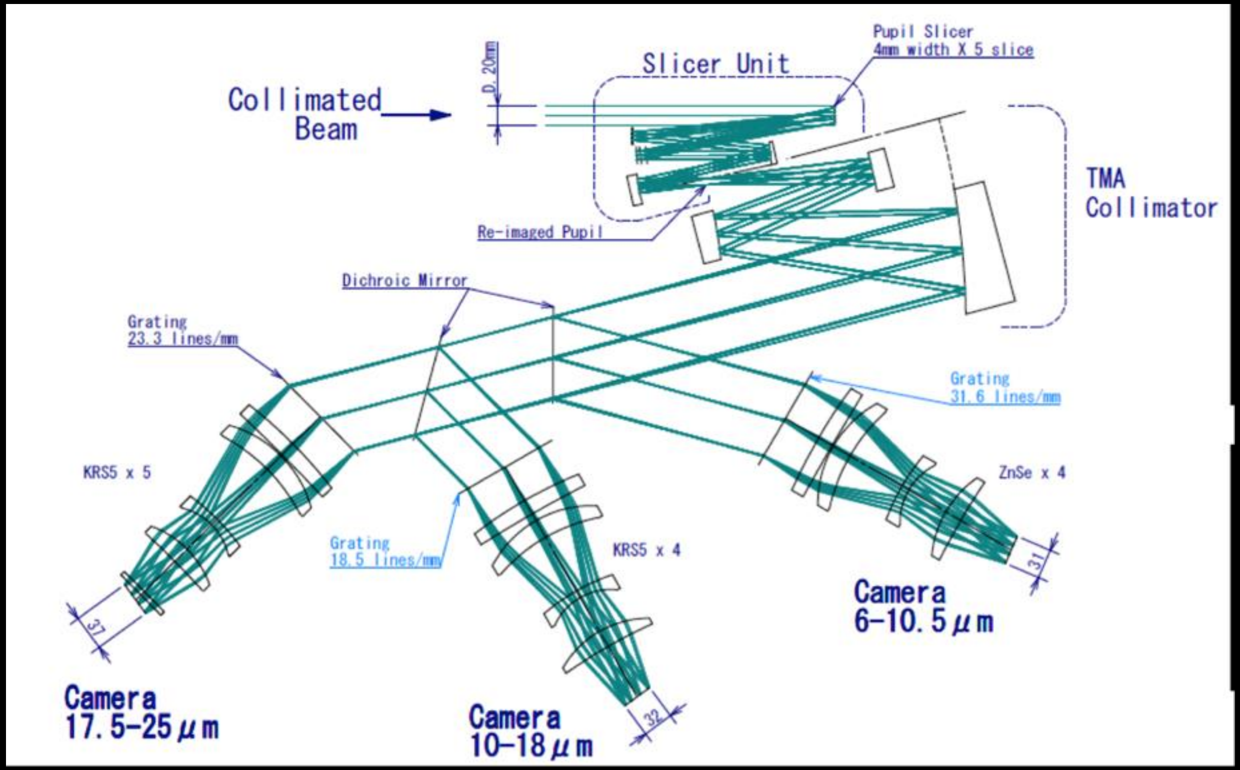


The Mid-Infrared Imager, Spectrometer, and Coronagraph (MISC) instrument

- Suite of spectroscopic and imaging modes from 5-38 microns
- lambda/delta lambda ~ 15, 300, 1200, 10^4
- Instruments for exoplanet science
  - Transit Spectrometer: < 5 ppm stability
  - Coronagraph: 10^{-5} contrast

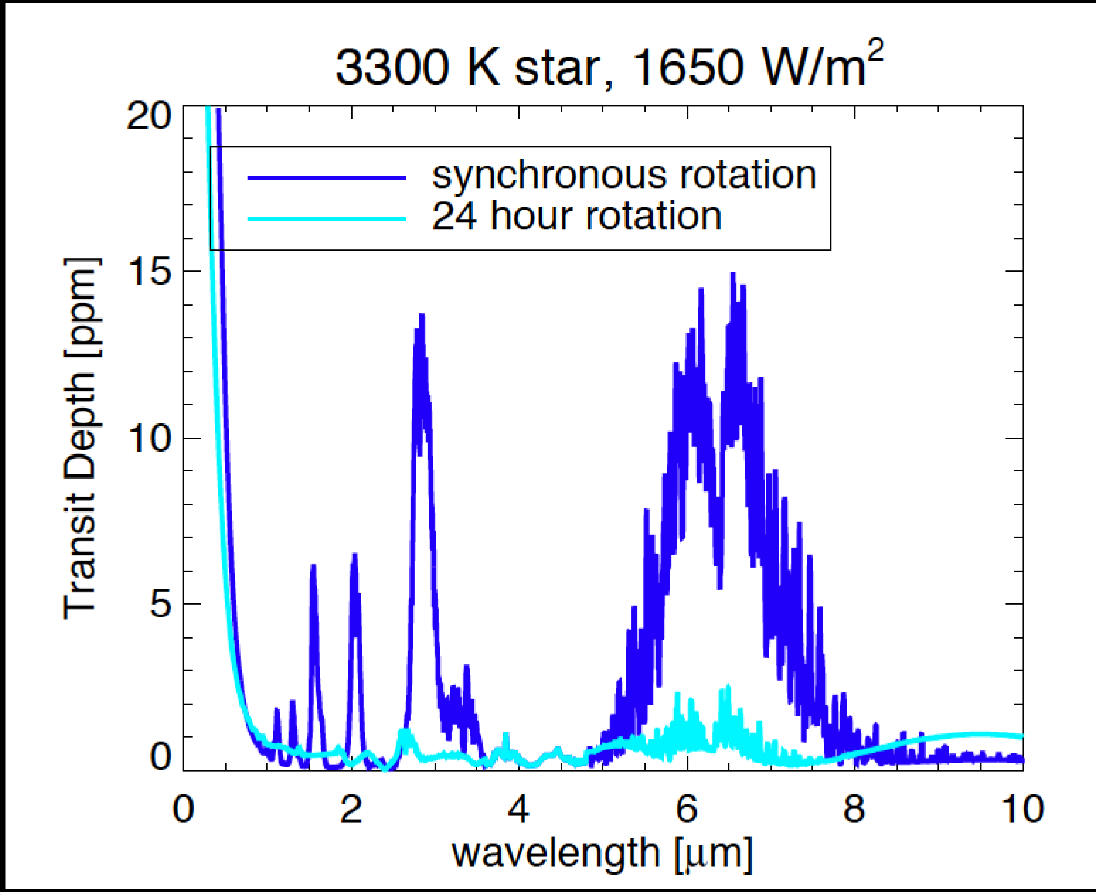
MISC Transit Spectrometer

- Gets entire 5-28 micron spectrum *simultaneously*
- Densified Pupil Spectrometer (Matsuo et al. 2016)
- Spreads light over multiple pixels to mitigate minor telescope pointing and jitter issues
- Has reference pixels to remove detector gain drifts
- Mid-IR detectors will be developed to meet requirements



Transmission Spectra

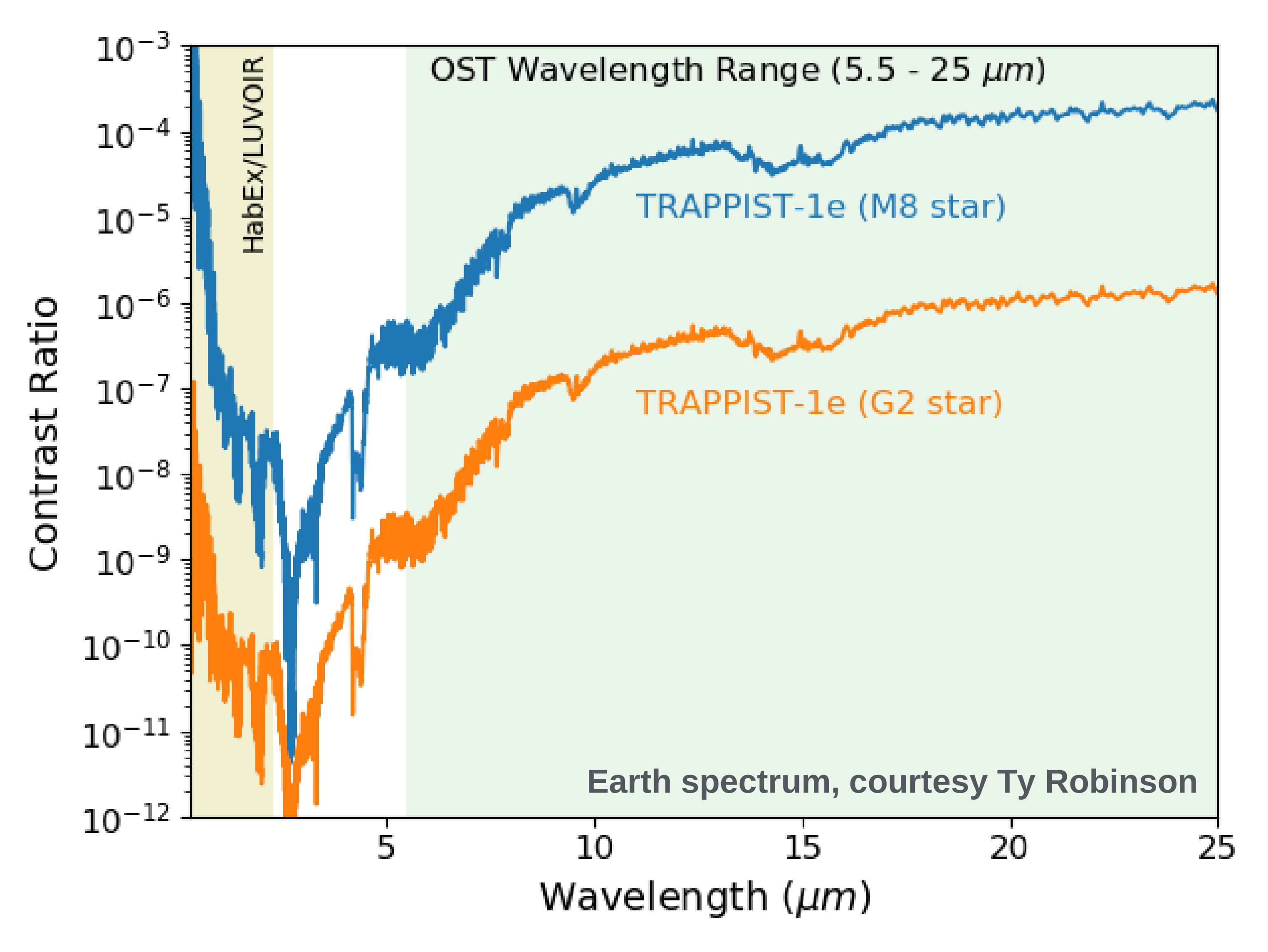
- Molecular detections at the atmospheric terminator
- Pressure level of any opaque clouds
- Long wavelengths may allow for seeing through the clouds, depending on particle size, yielding additional cloud constraints
- Spectral resolution of MISC + concurrent ground-based monitoring + long wavelengths will mitigate effects of inhomogeneous stellar photosphere (Rackham et al., 2018) on H_2O features



Kopparapu et al. 2017, ApJ

Emission Spectra

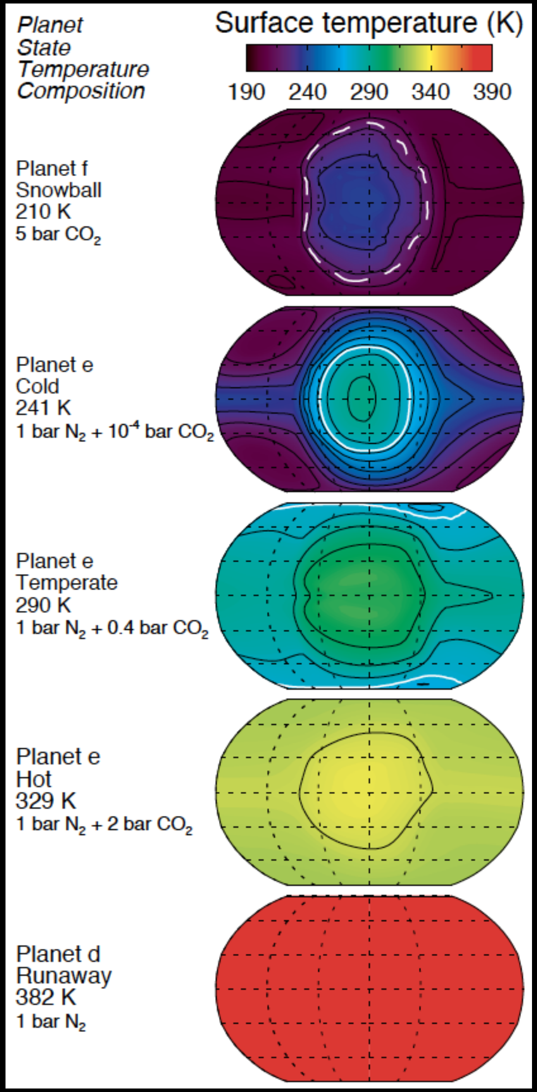
- Planet-to-star flux ratios are favorable at thermal infrared wavelengths
- Ability to determine temperature structure

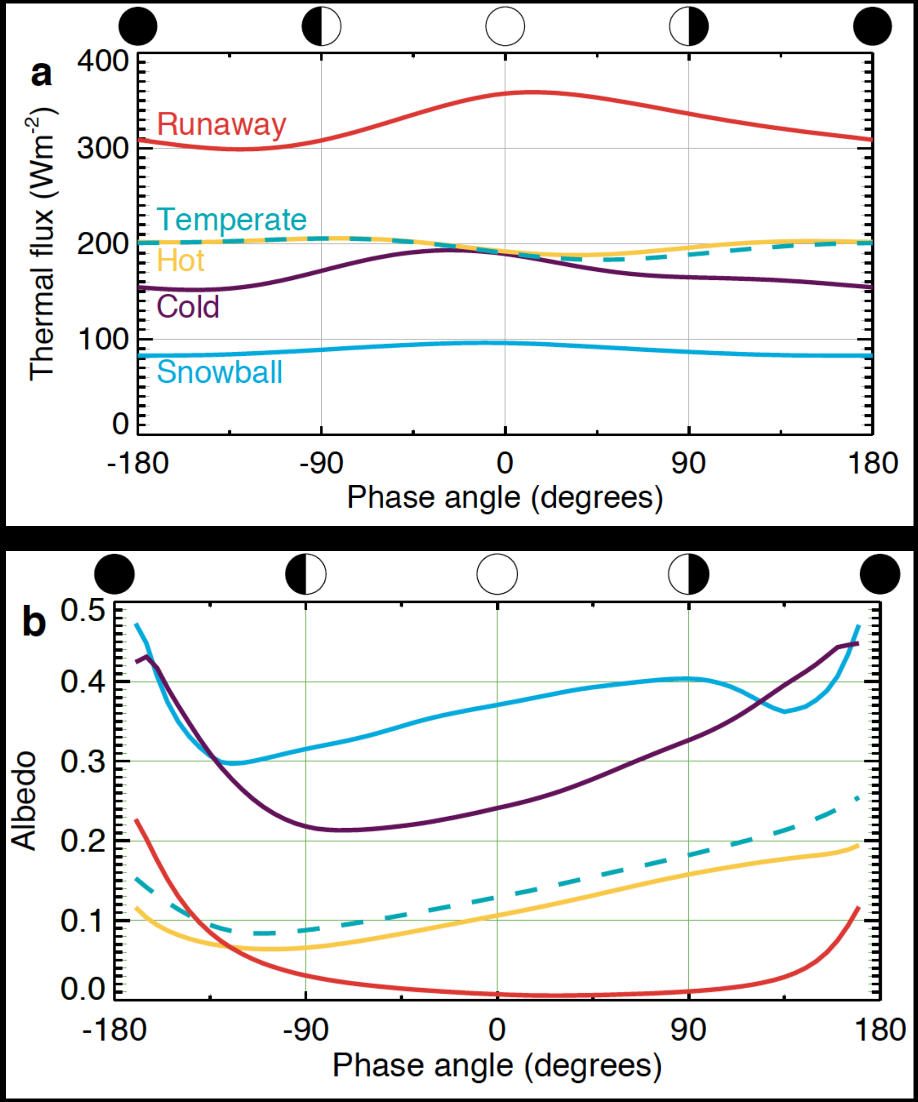


Phase Curves

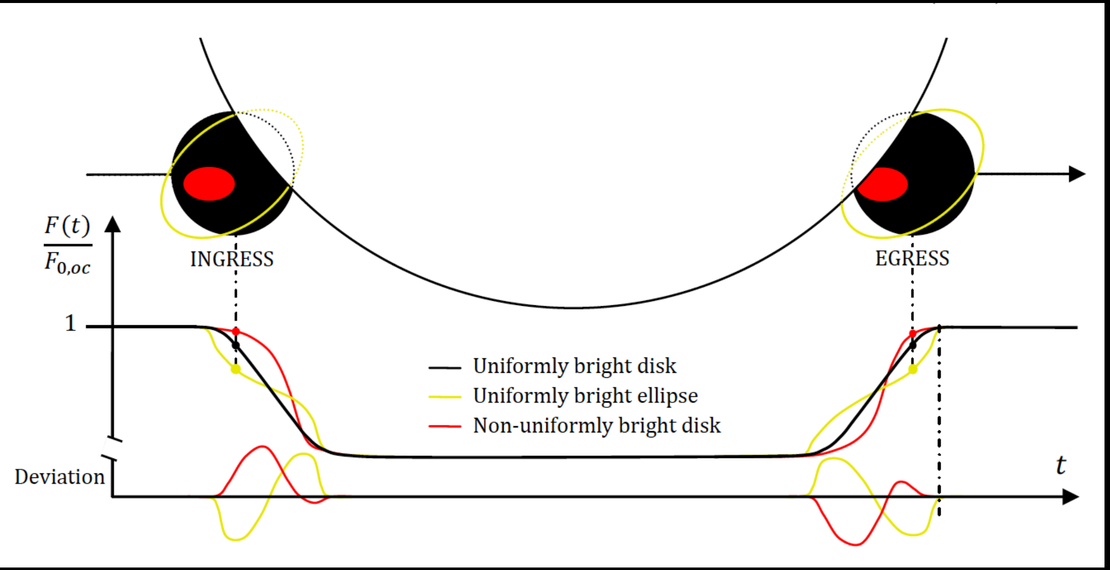
Thermal phase-curve observations in the mid-IR, we have the opportunity to probe the 3D properties of rocky planets that could be habitable
—Also constrain A_{Bond}

TRAPPIST 1 d,e,f: Wolf 2017



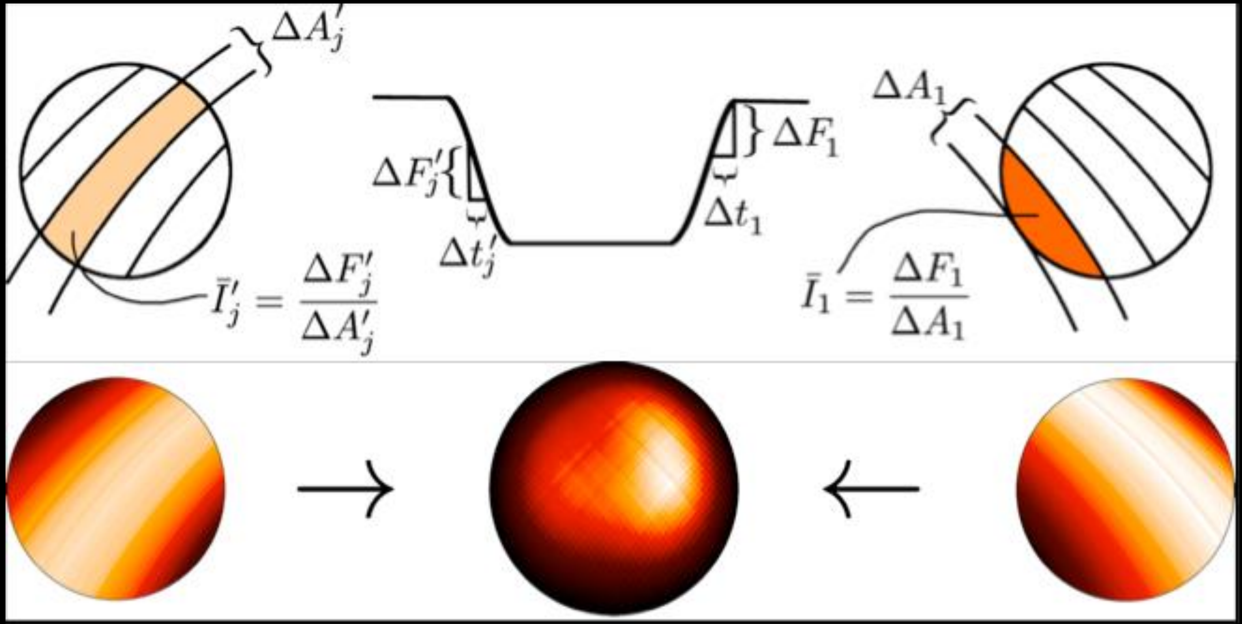


Eclipse Mapping

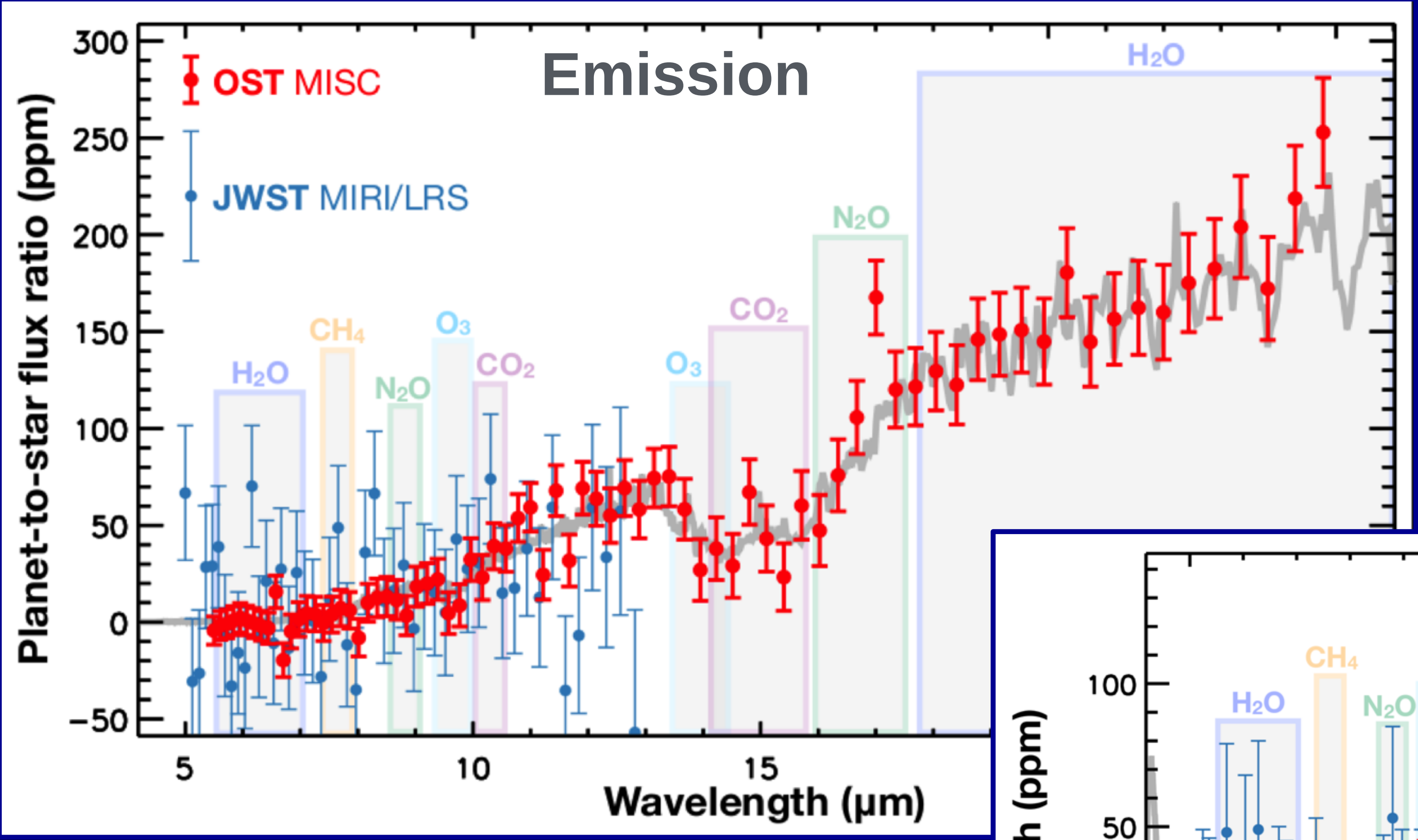


de Wit et al. (2012)

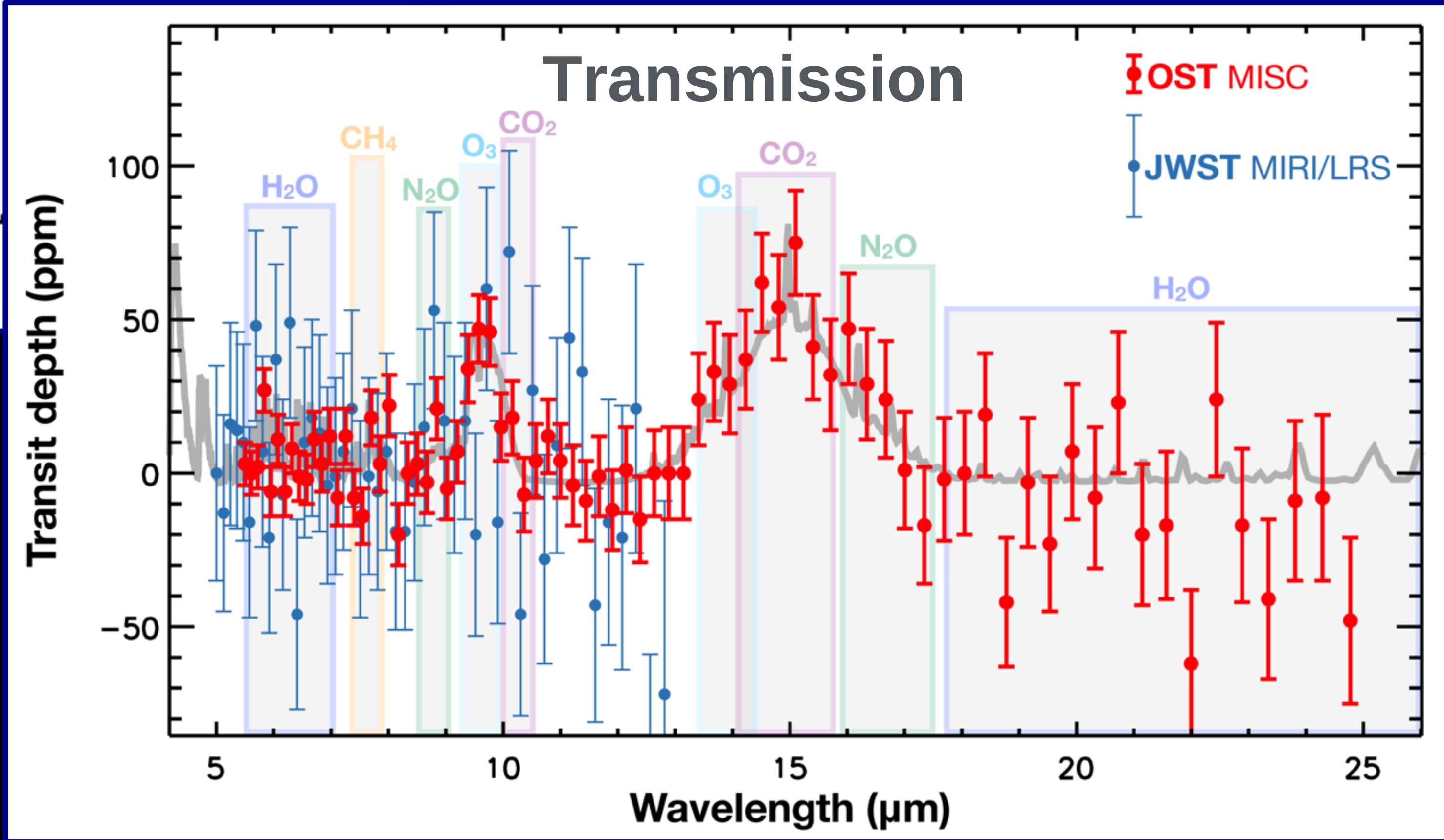
- Spectroscopic eclipse mapping
  - 3D map of planetary dayside
  - Latitudinal information



Majeau et al. (2012)



- Model TRAPPIST-1e-*like* emission/transmission spectra with simulated uncertainties
- 30 visits each, $K_{mag} = 8$
- Optimistic 30 ppm noise floor for MIRI/LRS

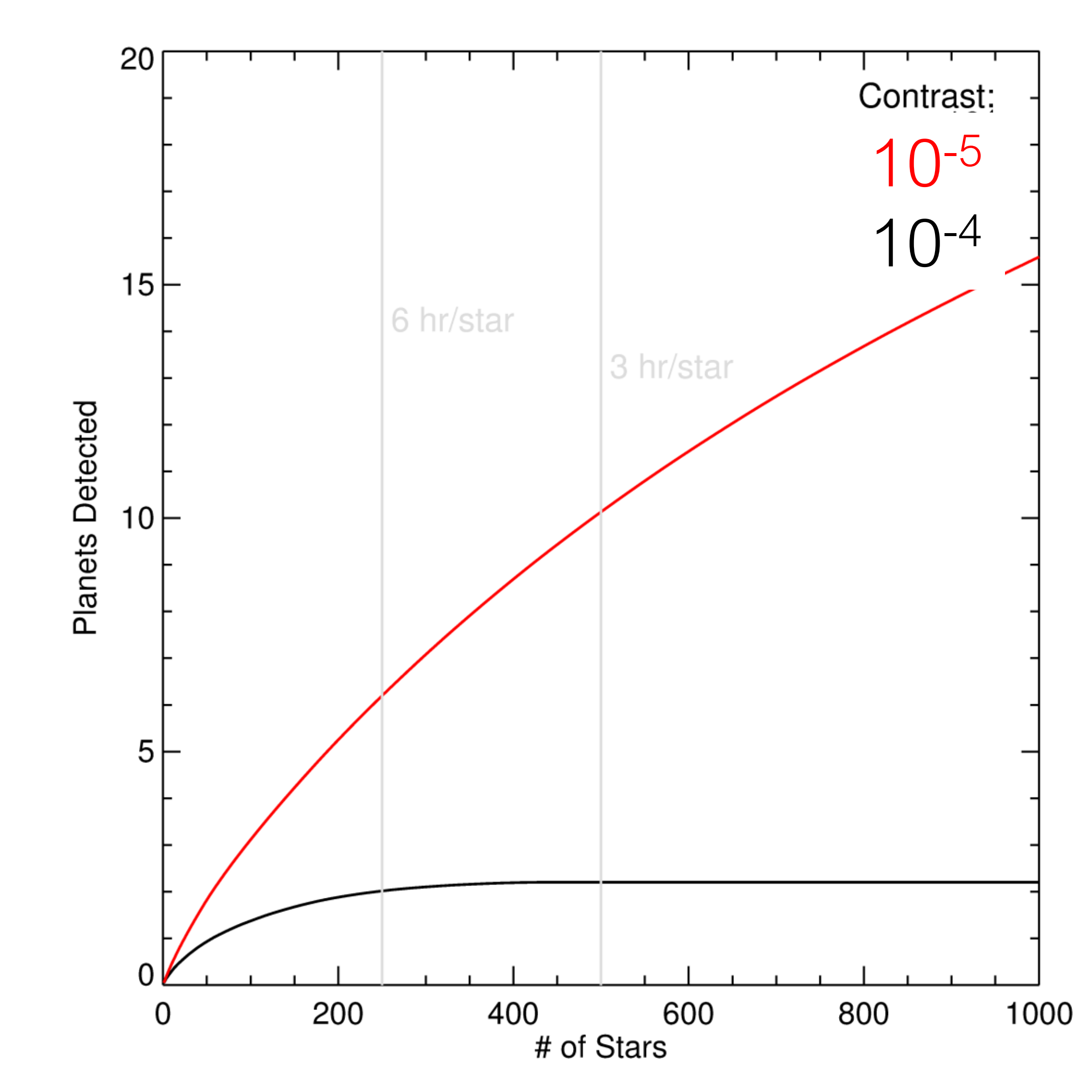


What Would an OST Exoplanet Transit Survey Look Like?

- Reconnaissance of all suitably-bright targets within 15 pc
- Measure planetary thermal emission
  - Constrain dayside equilibrium temperature
- Further investigations to detect molecular absorption of CO_2 and/or H_2O
  - Determine presence of substantial atmosphere, confirm presence of bio-indicators
  - Disregard planets with tenuous atmospheres
- Perform in-depth study of remaining planets in search for biosignatures
  - O_3/N_2O & CH_4

OST Coronagraph

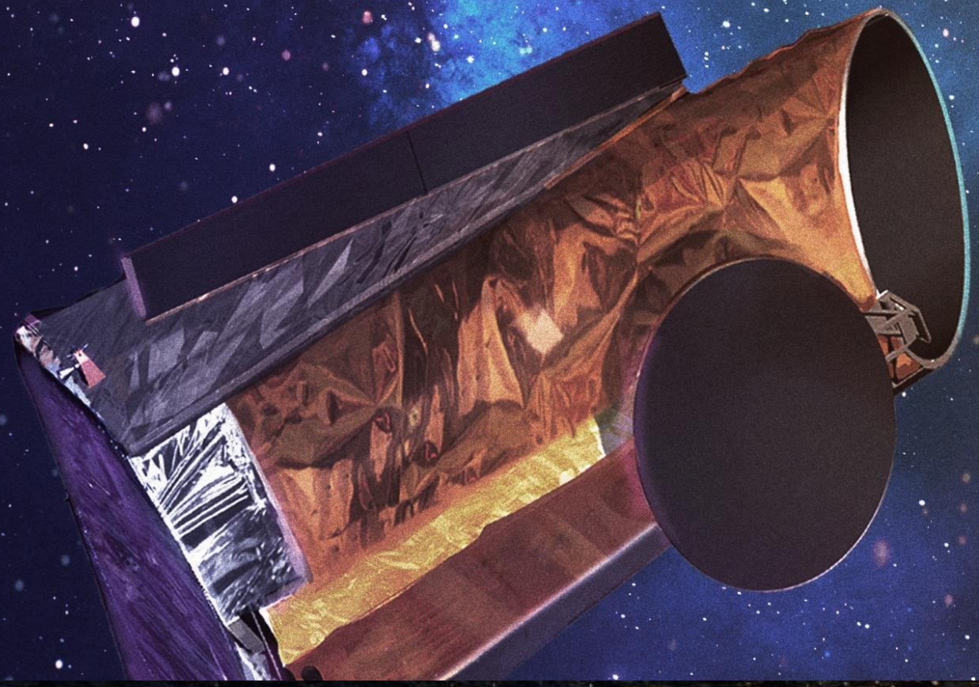
- Motivation
  - Gas giant planet formation and evolution
- Goals
  - Determine occurrence rates of gas giants (down to Saturn masses)
  - Trace planet evolution during first 1 Gyr after formation
- Advantages of mid-IR thermal emission
  - Higher contrast ratio than optical/near-IR
  - Planets accessible in larger stellar population fraction (~17% vs youngest 1-2%)
- Disadvantage of mid-IR thermal emission
  - Larger inner working angle



OST Exoplanet Summary:

- Primary application is to extend JWST's mid-IR exploration of transit spectroscopy to longer wavelengths & greater sensitivity
- As for JWST, OST spectra would require many coadded transits to realize
- Mid-IR coronagraphy could image long-period giant planets orbiting stars within a few pc, if present; or hot young planets in associations
- Strong disk capabilities including debris disk imaging at 2″ resolution, and measurement of H_2O & HD lines in protoplanetary disks
- Other astrophysics would dominate mission utilization

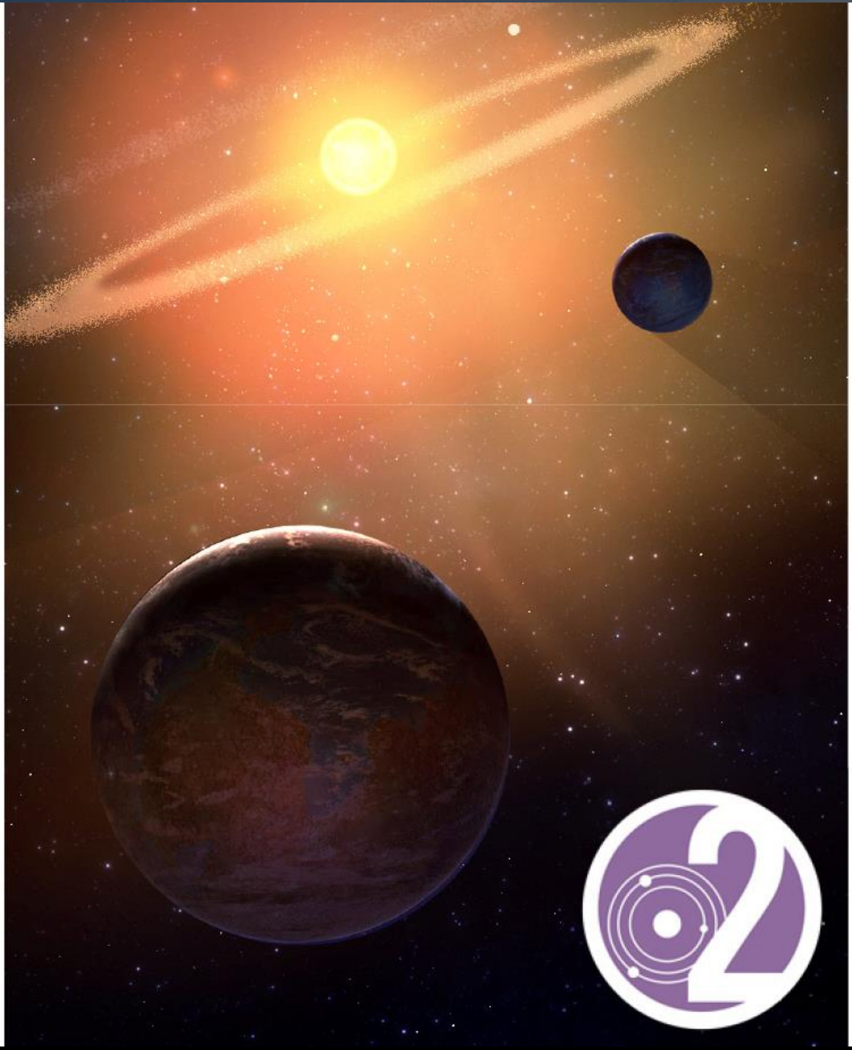
The Habitable Exoplanet Observatory Mission Concept



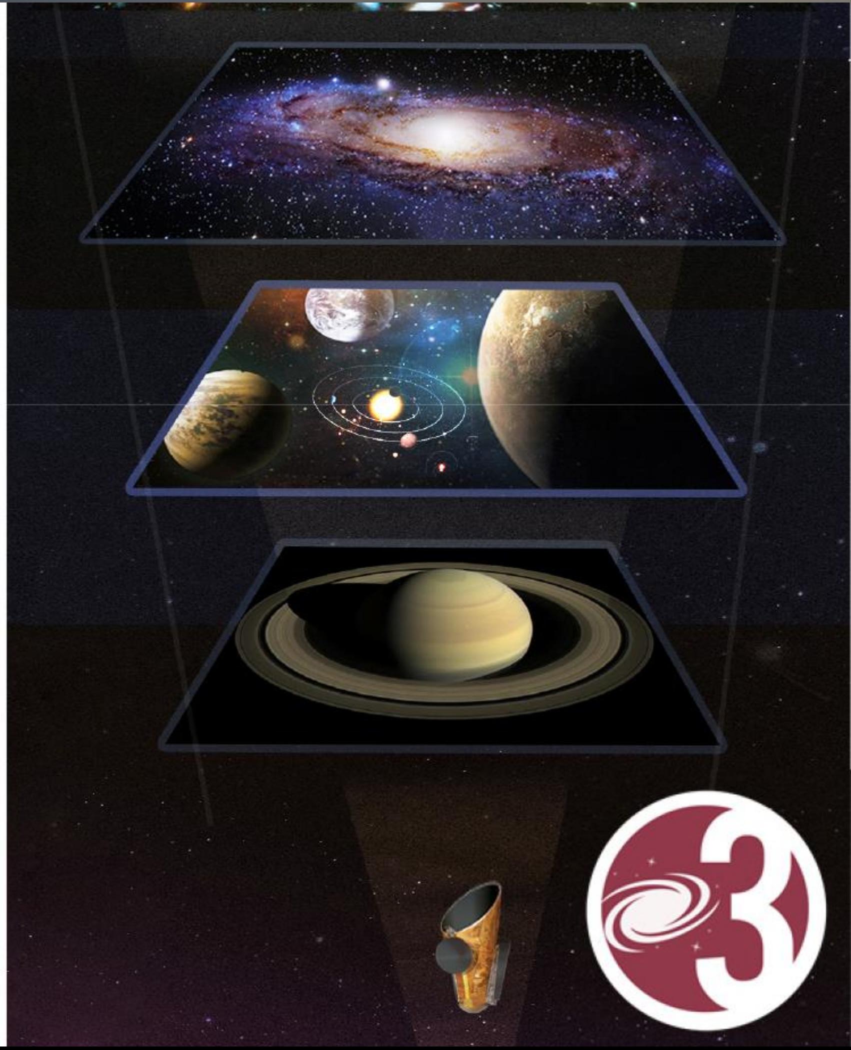
Exploring planetary systems around our neighboring sun-like stars and enabling a broad range of observatory science from the UV through the near-IR

HabEx Science Goals

Seek out nearby worlds and explore their habitability



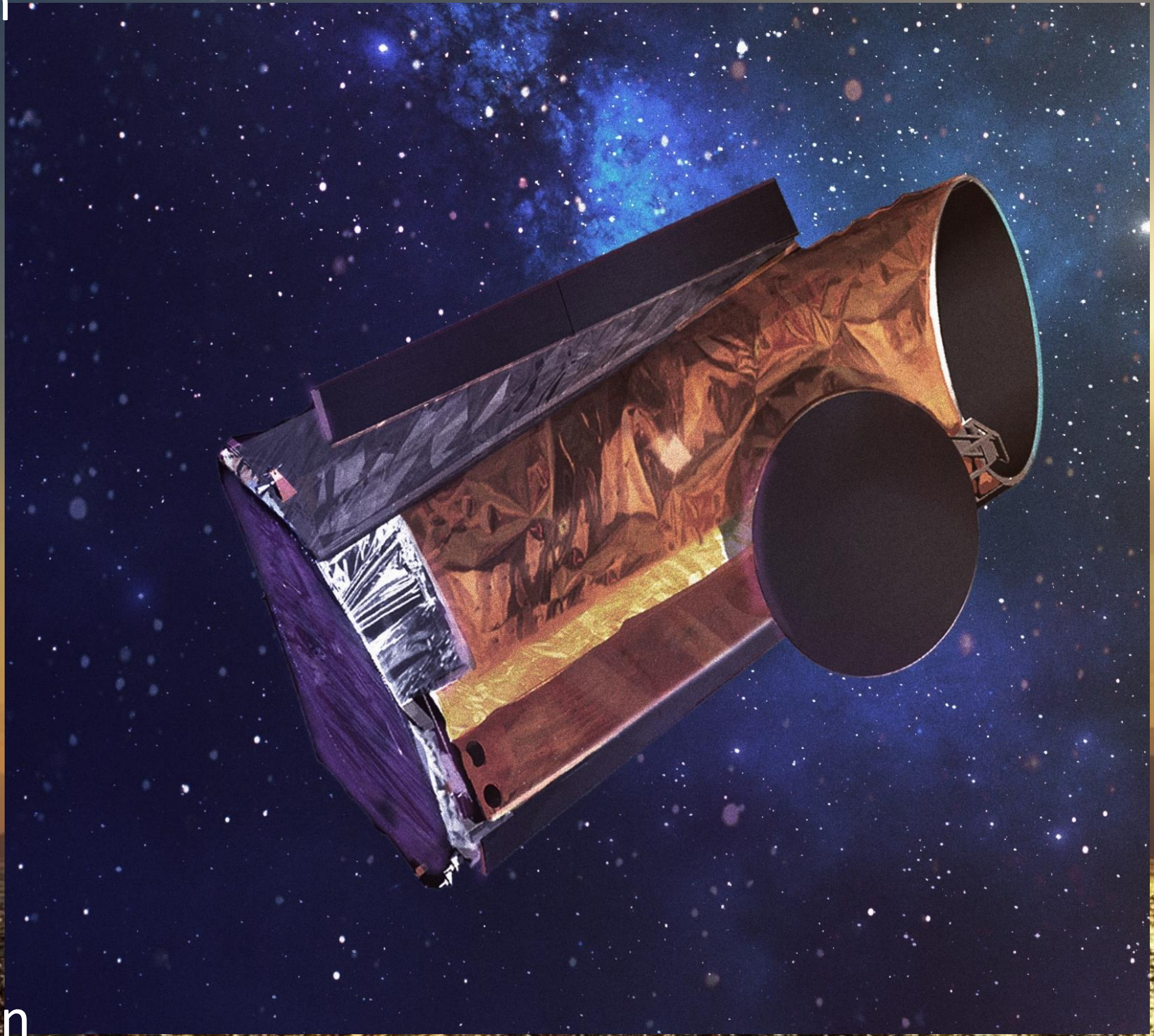
Map out nearby planetary systems and understand their diversity.



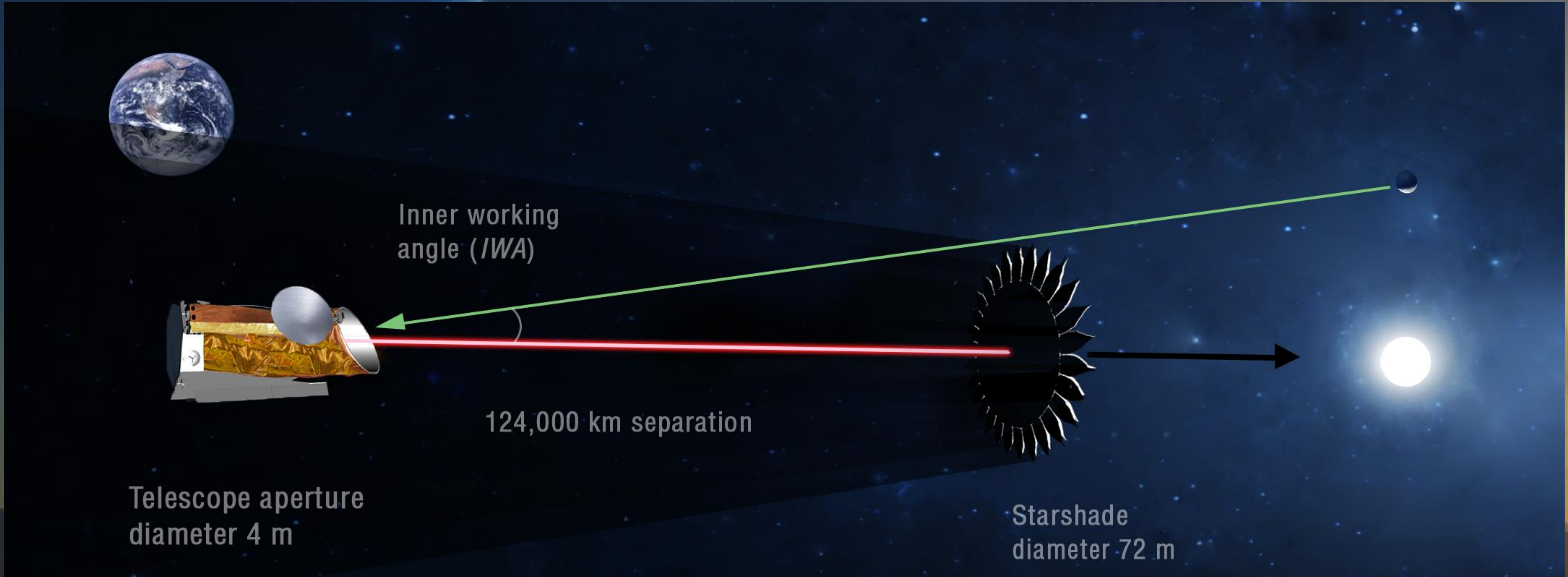
Open up new widows in the Universe from the UV to NIR.

HabEx Mission Concept Architecture:

- 4 m off-axis f/2.5 primary mirror, monolith
  - preliminary design completed.
- Four Instruments:
  - Coronagraph Instrument
  - Starshade Instrument
  - UV Spectrograph (UVS)
  - HabEx Workhorse Camera (HWC)
- 72 m diameter starshade (tip-to-tip)
  - Co-launched with telescope
- Design heritage from Exo-C and Exo-S
- Launch vehicle & orbit:
  - SLS Block 1B to Earth-Sun L2
- Launch by mid-2030s, 5 year prime mission



HabEx Starshade Concept:



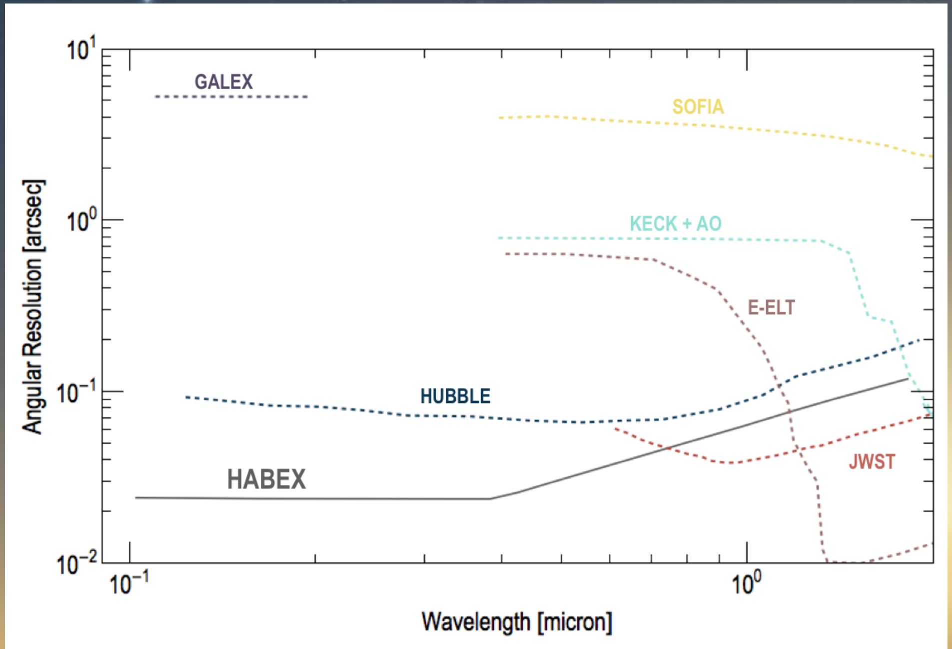
- Number of targets limited by available fuel
- Use for most spectroscopy, and for imaging of nearest target systems

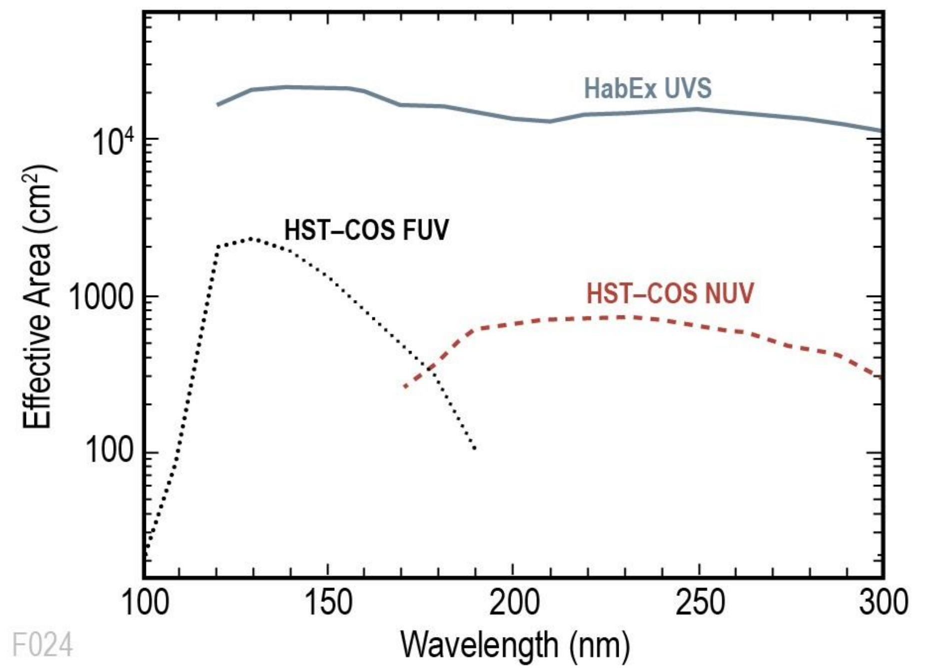
HabEx Coronagraph:

- For unobscured apertures, a more mature starlight suppression technology
- Vector Vortex Charge 6 coronagraph (shown)
  - Mostly insensitive to low-order aberrations: relaxes telescope stability requirements
- And also the Hybrid Lyot Coronagraph:
  - Demonstrated $<10^{-9}$ suppression in the laboratory with unobscured pupil
  - Heritage with WFIRST CGI demonstrations, including active correction of low-order disturbances
- Use for initial exoplanet searches & orbit tracking

General Astrophysics Capabilities: Imaging and Spectra

- Diffraction limited at 0.4 µm: better than all current or planned facilities for $\lambda < 0.7$ µm
- Non-sidereal (i.e. solar system) tracking
- Wavelength coverage 115 nm-1.8 µm
- Effective Area >10x better than HST for 115-300 nm
- UVS: FOV 3’ x 3’, 115-300 nm, resolution up to R=60,000
- HabEx Workhorse Camera:
  - Area 3’ x 3’
  - 150-400nm, 400-950nm, 950-1.8nm
  - R=2000





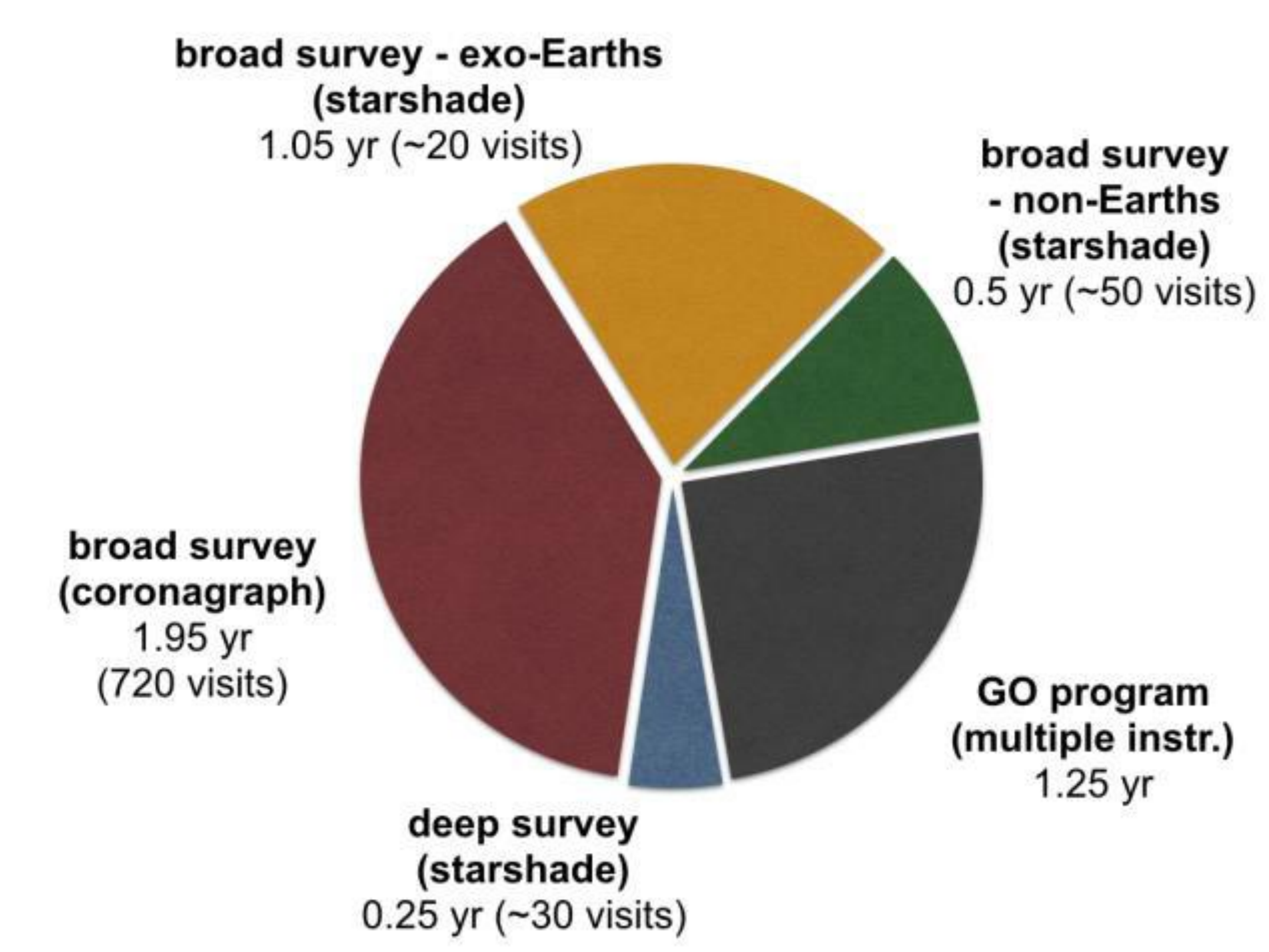
HabEx Mission Time Allocation

Deep Exoplanet Survey

- Nine nearby high-priority sunlike stars
- 3 months total with starshade
- Deep broadband image to the systematic floor
- Spectra
  - R=7 (grism) 0.3-0.45 μm
  - R=140 (IFS) 0.45-1.0 μm

Broad Exoplanet Survey

- ~110 stars with coronagraph
- Roughly 6 observations of each
- 50% completeness for exo-Earths
- Spectra with starshade covering 0.3-1.0 μm at once

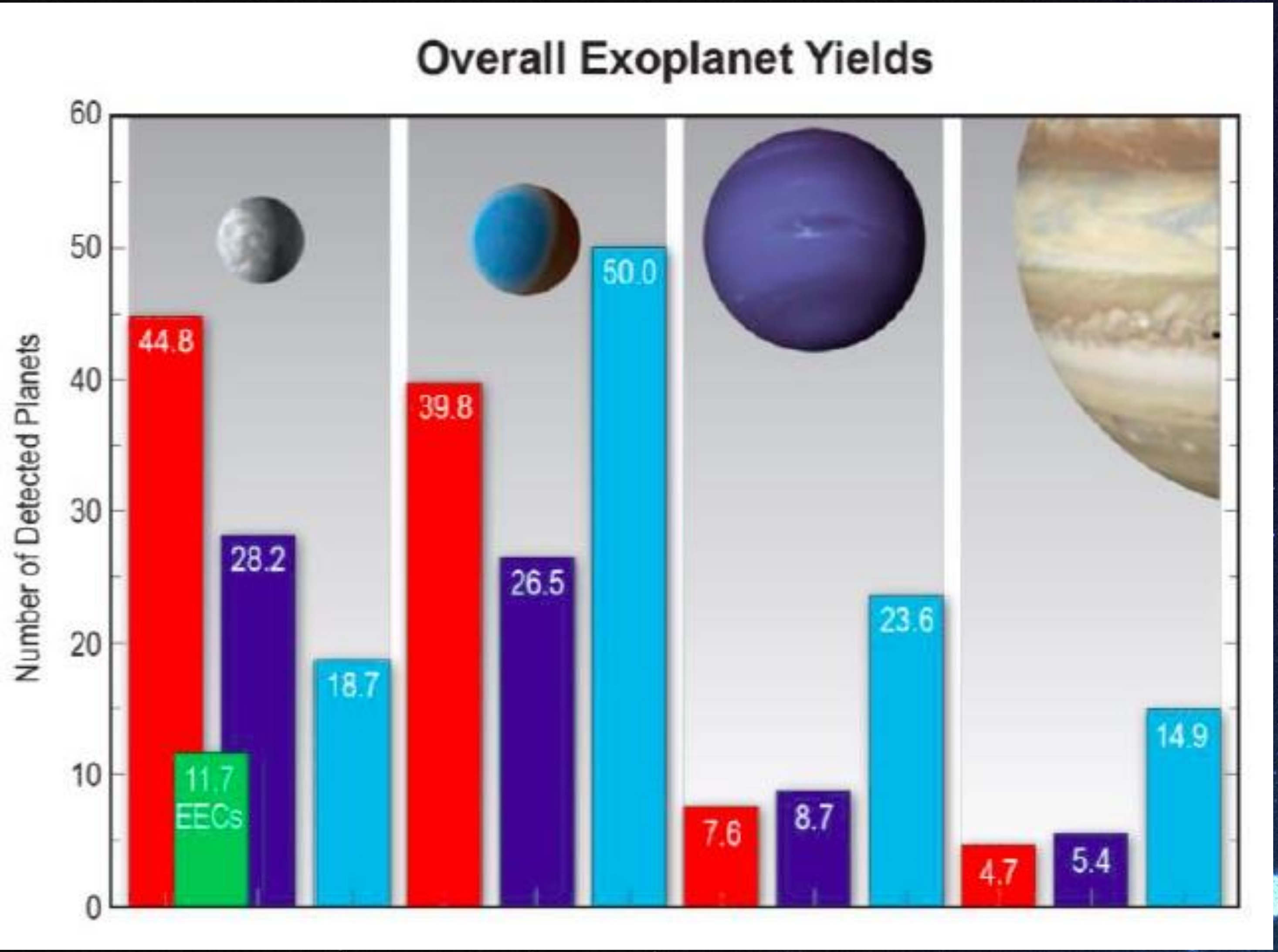


Yields of Characterized Planets **preliminary**

Yields*

Detect and characterize the orbits and atmospheres of:

- Rocky planets:
  - 92 rocky planets (0.5-1.75 R_E)
  - Includes 12 Earth Analogs (0.5-1.4 R_E)
- Sub Neptunes:
  - 116 sub-Neptunes (1.75-3.5 R_E)
- Gas Giants
  - 62 gas giants (3.5-14.3 R_E)

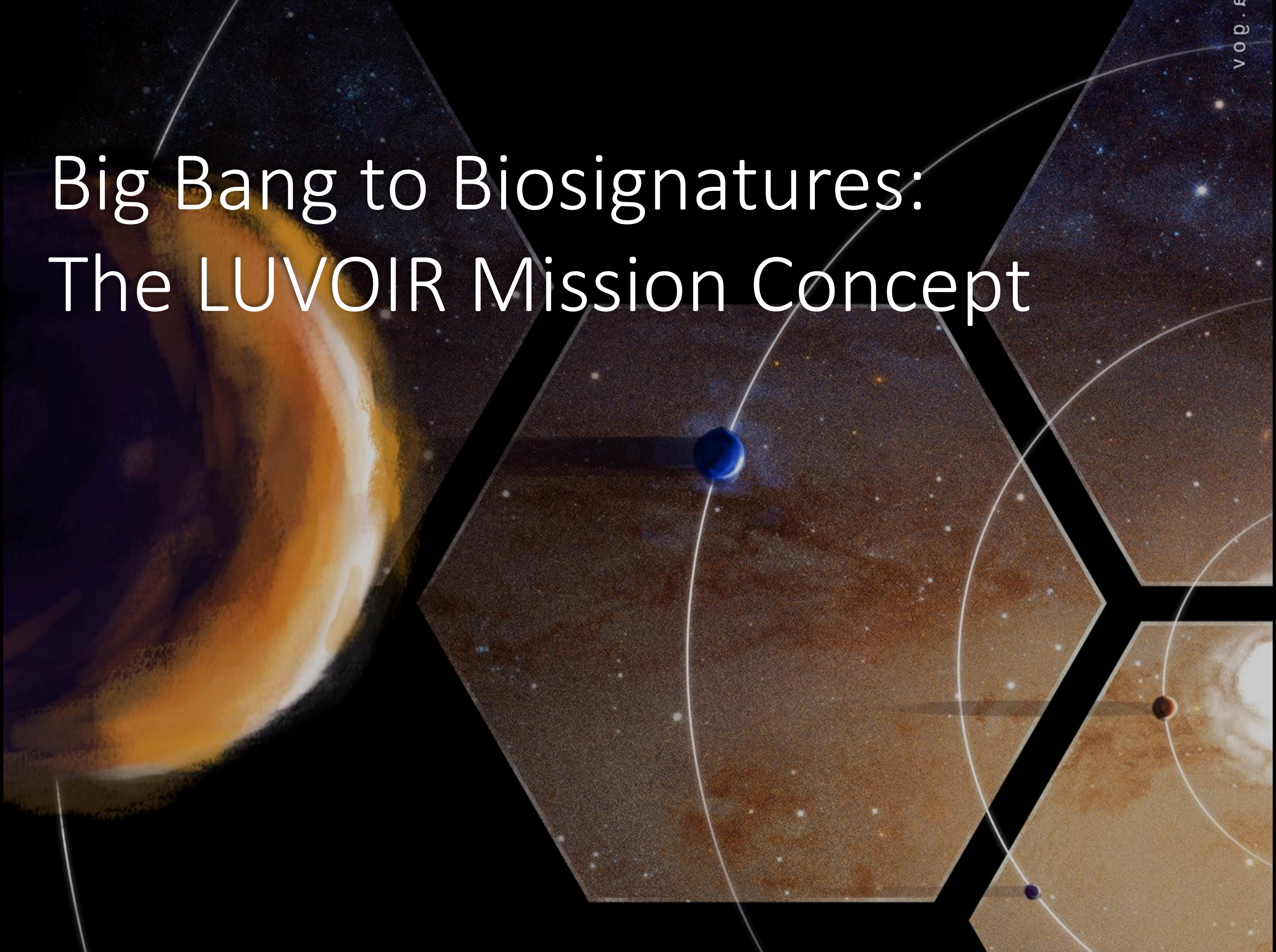


*Assumes SAG13 Occurrence Rates.

HabEx Technologies

	Starshade	Coronagraph	Technology Gap	ExEP TRL Assessment at P&L	Our Assessment at Final Report	
Enabling	■		Petal Shape stability	3	3	**High priority. Needs a plan.**
	■		Petal Position Accuracy	3	3	**High priority. Needs a plan.**
		■	LOWFS and control	3	4	**High Priority. Once we can demonstrate that we need only the same LOWFS implementation as WFIRST we can move to TRL 4.**
	■		Starshade Starlight Suppression	3	4	Technology being advanced in the S5 project
	■		Starshade Edge Scattering	3	4	Technology being advanced in the S5 project
		■	Micro-Thrusters	3	5	ExEP needed analysis that demonstrated that the existing thrusters would work for HabEx. We are doing this now. Once complete, the technology moves to TRL 5 since already demonstrated in space.
		■	Coating Uniformity on Large Optics	4	4	**High priority. Needs a plan.**
		■	Coronagraph Architecture	4	4	
	■	■	Large Aperture Primary	4	4	
	■		Formation Flying	4	5	Technology being advanced in the S5 project.
		■	Deformable Mirrors	5	5	
	■	■	Visible Detectors	5	5	
Enhancing	■	■	NIR Detectors	3	4 or 5	ExEP needs analysis showing that the current SOA will meet HabEx needs. May be able to leverage work in JWST to show HgCdTe detectors are suitable for the HabEx environment.

Big Bang to Biosignatures: The LUVOIR Mission Concept



What is LUVOIR ?

Large UV / Optical / Infrared Surveyor (LUVOIR)

A space telescope concept in tradition of Hubble

- Broad science capabilities
- Far-UV to near-IR bandpass
- Two architectures: 8-m and 15-m telescopes
- Suite of imagers and spectrographs
- Serviceable and upgradable for decades of operation
- Guest Observer driven

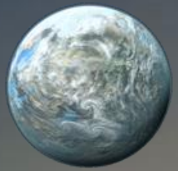
"Space Observatory for the 21st Century"

Ability to answer the questions of the 2030s and beyond

What is the difference between LUVOIR and HabEx ?

Both LUVOIR and HabEx have two primary science goals:

- Habitable exoplanets & biosignatures
- Broad range of general astrophysics



The two architectures are driven by a difference in focus

- For LUVOIR, both goals are on equal footing. LUVOIR would be a general purpose "great observatory", a successor to HST and JWST in the ~ 8 – 15 m class
- HabEx would be optimized for exoplanet imaging, but also enable a range of general astrophysics. It is a more focused mission in the ~ 4 – 6 m class

Similar exoplanet goals, differing in quantitative levels of ambition

- HabEx would *explore* the nearest stars to "search for" signs of habitability & biosignatures via direct detection of reflected light
- LUVOIR would *survey* more stars to "constrain the frequency" of habitability & biosignatures and produce a statistically meaningful sample of exoEarths

<u>The two studies provide a continuum of options for a range of futures</u>

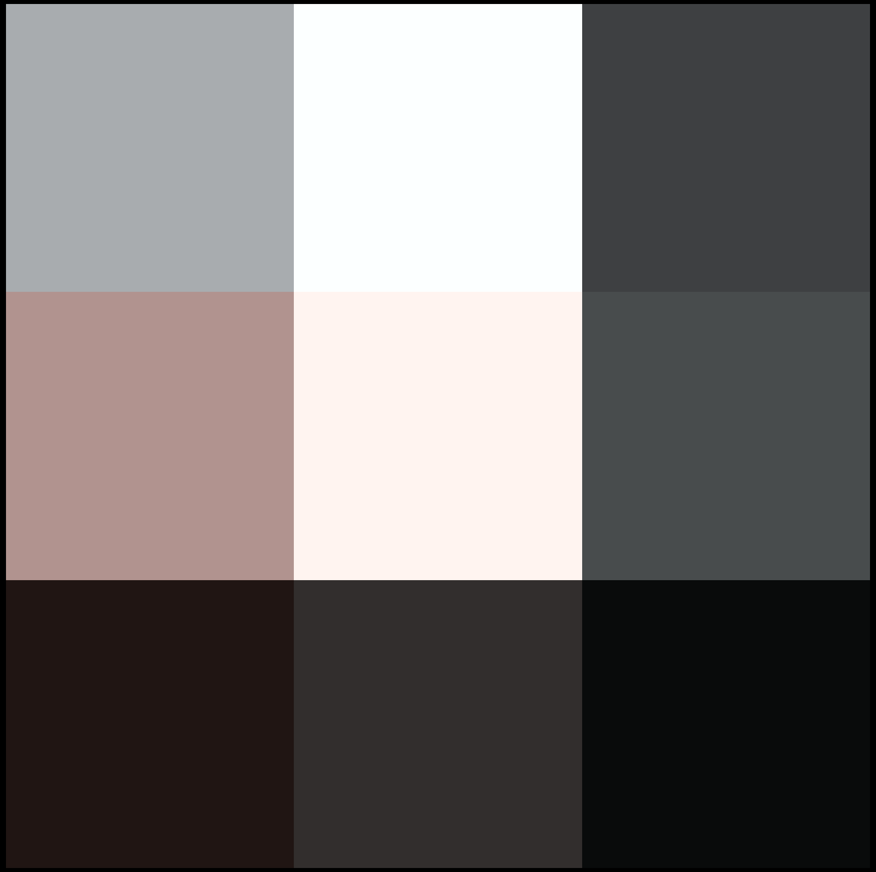
Imagine Astronomy with LUVOIR …

Low-mass galaxy at z = 2
with HST

Low-mass galaxy at z = 2
with 15-m LUVOIR

Credit: G. Snyder (STScI)

Imagine Astronomy with LUVOIR …

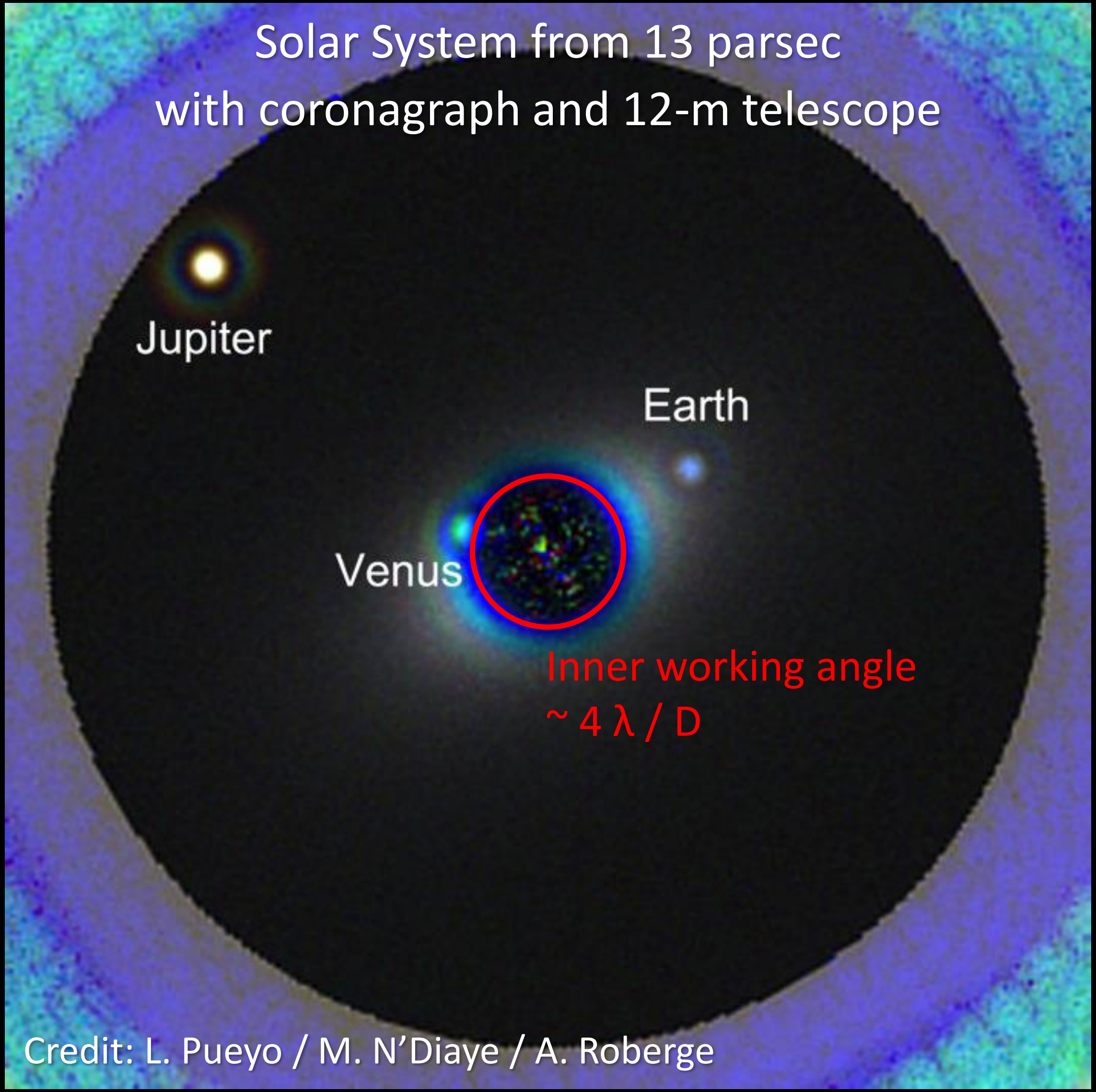


Pluto with HST

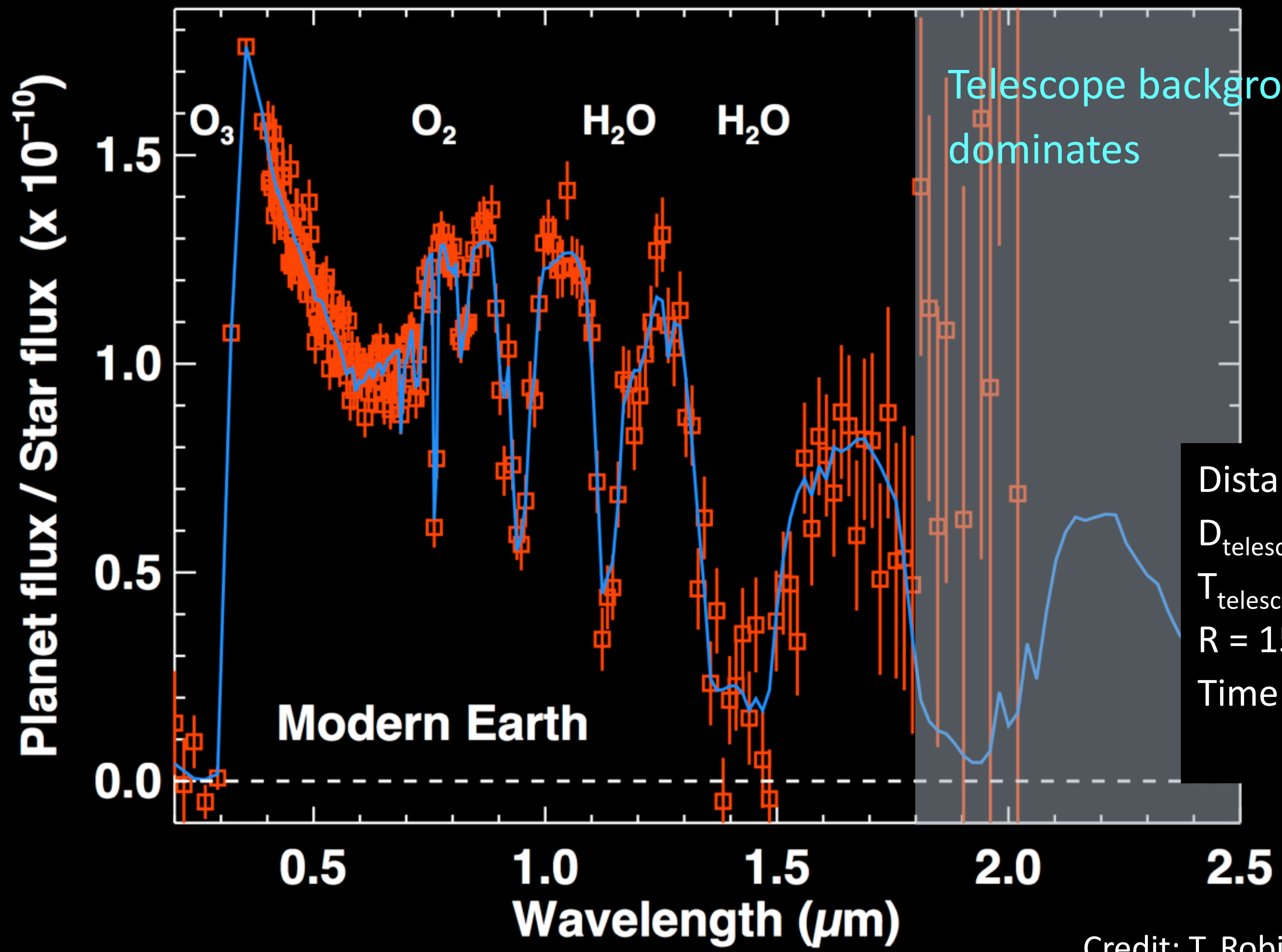
Pluto with 15-m LUVOIR

Credit: NASA / New Horizons / R. Parramon

Imaging Earthlike Planets



Simulated LUVOIR Observation

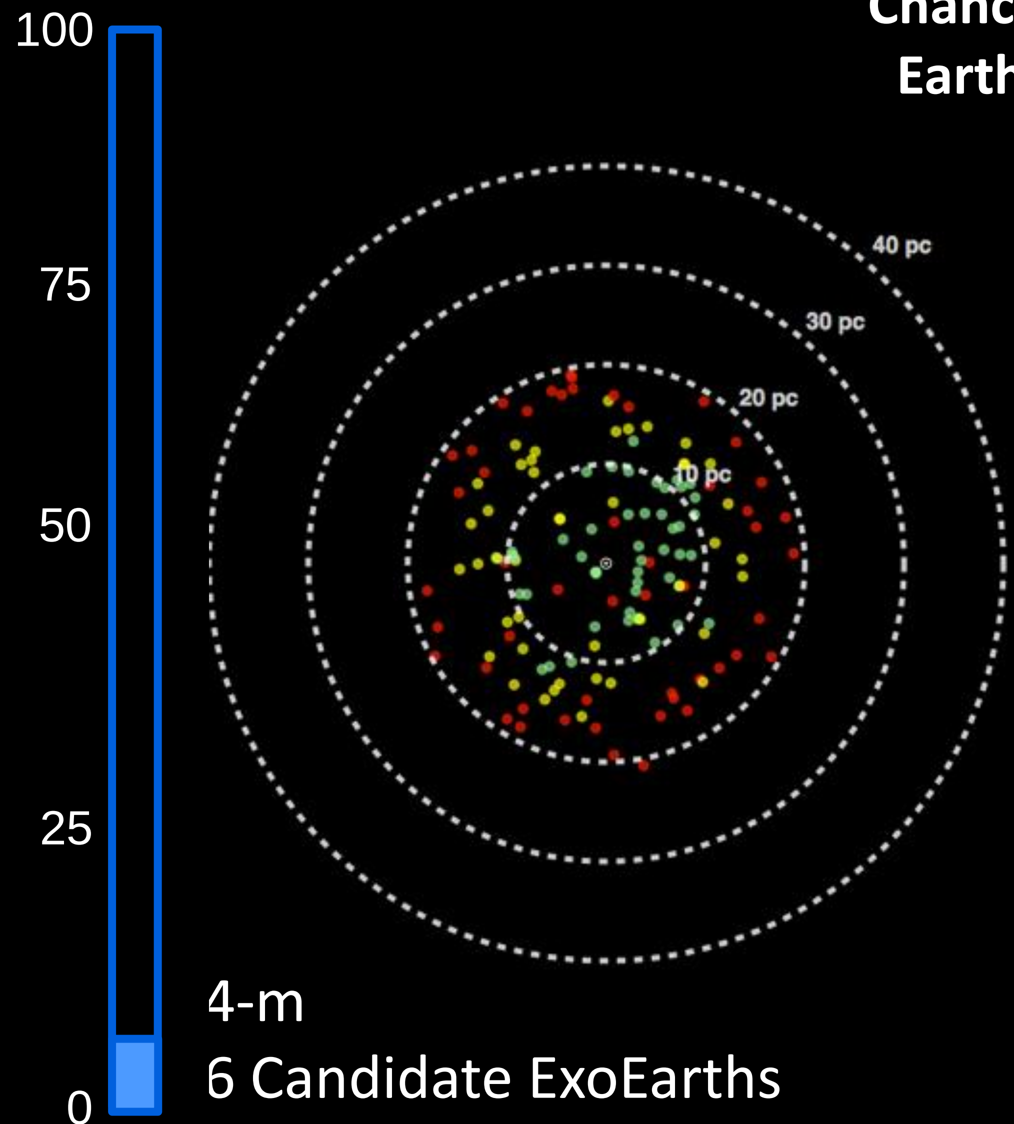


Distance = 10 pc
$D_{telescope}$ = 15-m
$T_{telescope}$ = 270 K
R = 150
Time = 96 hrs per band

Credit: T. Robinson / G. Arney

Larger Telescopes Survey More Stars

ExoEarth Yield



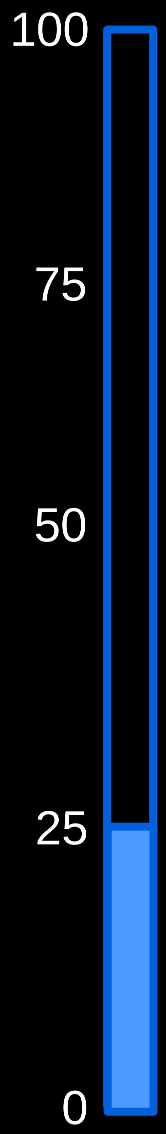
Chance of Detecting an Earth Twin if Present

80-100%
50-80%
20-50%

Stark et al. (2014)

Larger Telescopes Survey More Stars

ExoEarth Yield



8-m

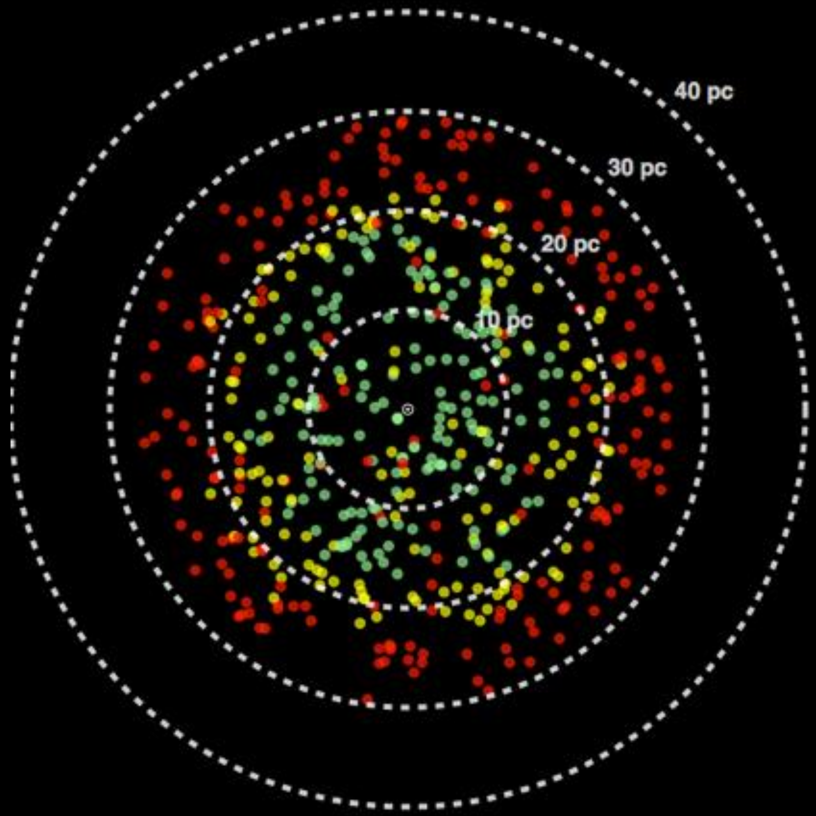
25 Candidate ExoEarths

Chance of Detecting an Earth Twin if Present

80-100%

50-80%

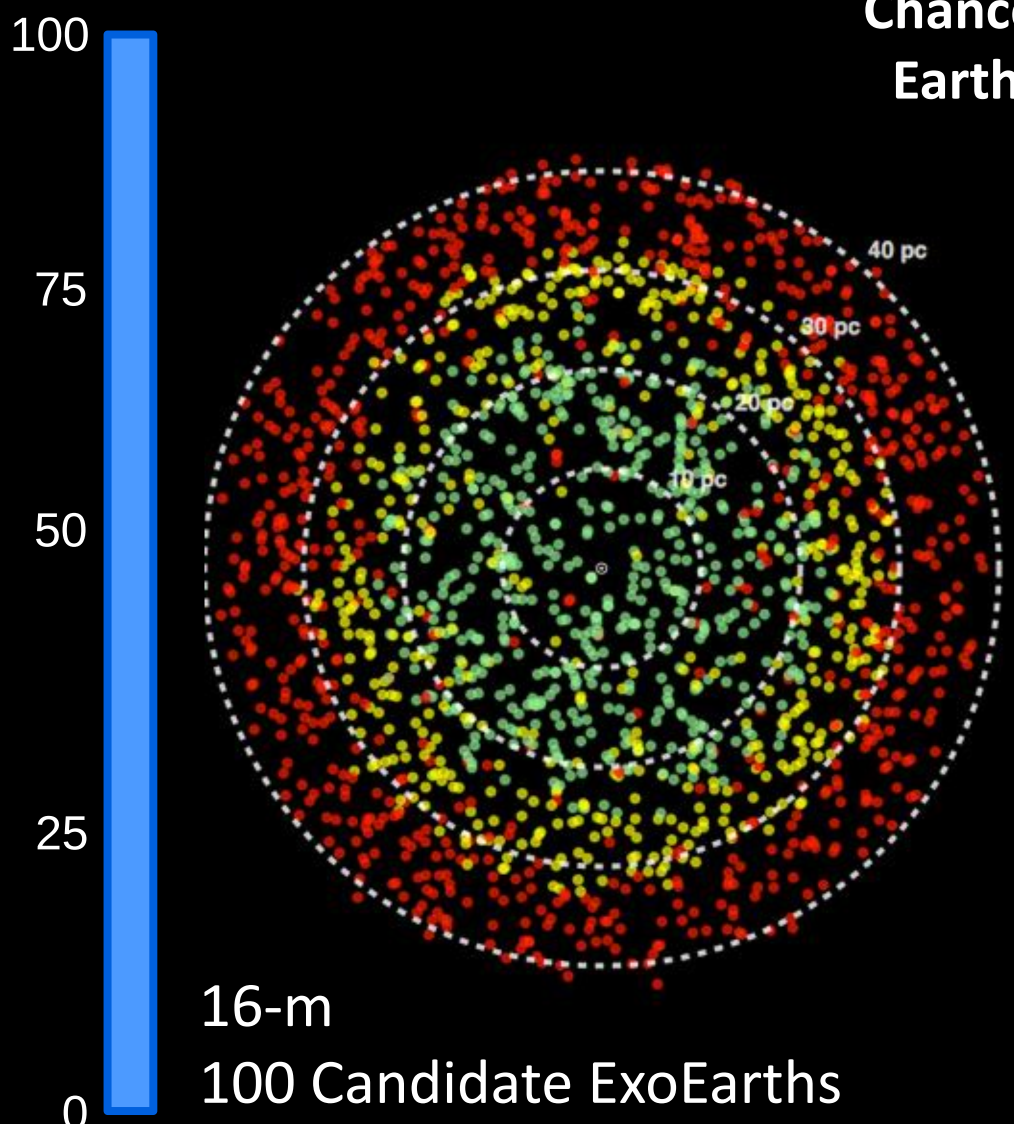
20-50%



Stark et al. (2014)

Larger Telescopes Survey More Stars

ExoEarth Yield



Chance of Detecting an Earth Twin if Present

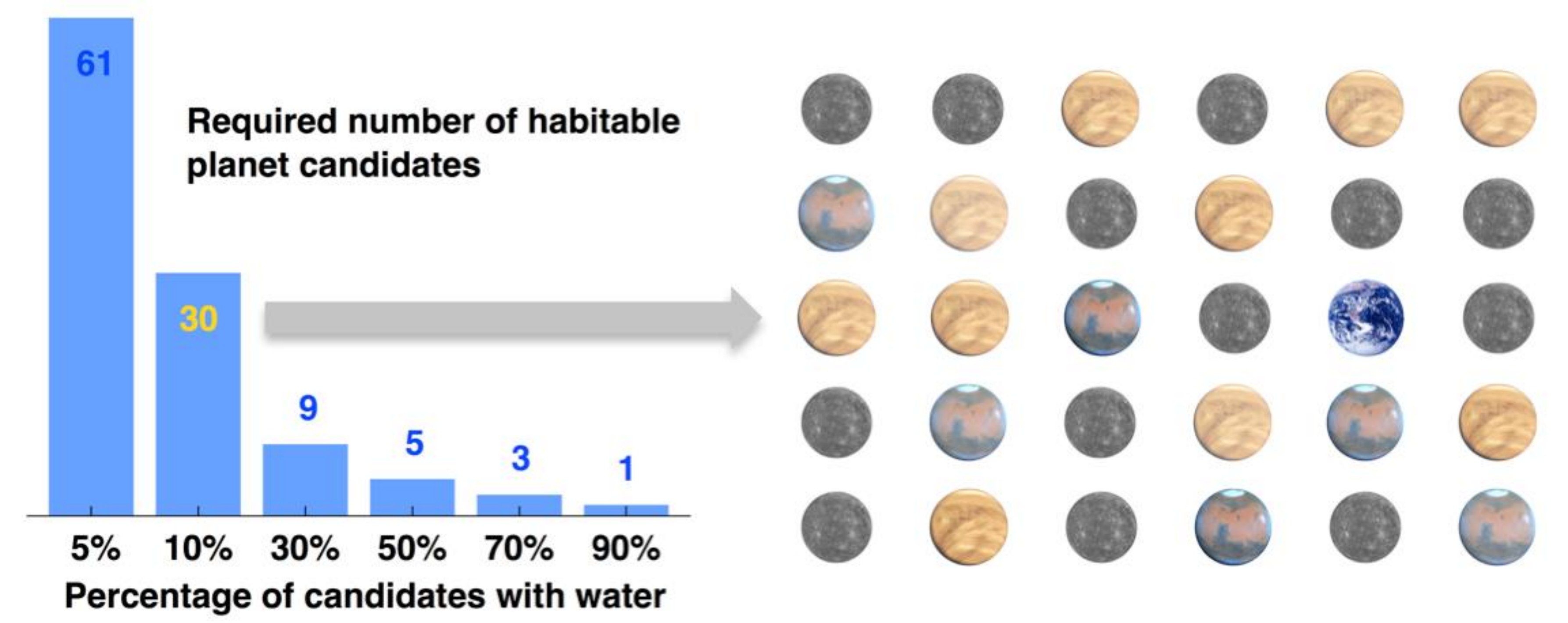
80-100%

50-80%

20-50%

Stark et al. (2014)

How Many Candidate Habitable Planets Do We Need to Observe to Find One With Water?



Credit: C. Stark / A. Roberge

The LUVOIR Architectures

Architecture A

- 15-m diameter obscured telescope
- Fits in 8.4-m fairing
  - *Space Launch System Block 2*
- Bulk of work completed
- Refinements in progress

Instruments
ECLIPS A
LUMOS A
High-Definition Imager
POLLUX

Architecture B

- 8-m diameter unobscured telescope
- Fits in 5-m fairing
  - *e.g., Delta IV Heavy, Falcon Heavy*
- Work began in September 2017

Instruments
ECLIPS B
LUMOS B
HDI B

The LUVOIR Instruments

Observational challenge

Faint planets next to bright stars

Extreme Coronagraph for LIving Planetary Systems (ECLIPS)

Inner working angle ≤ 40 mas

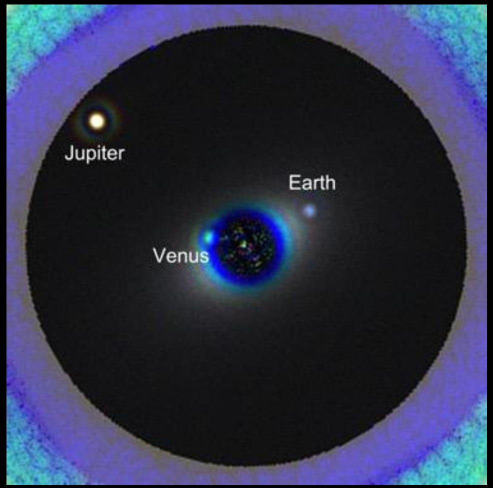
Contrast < 10^{-10} after post-processing

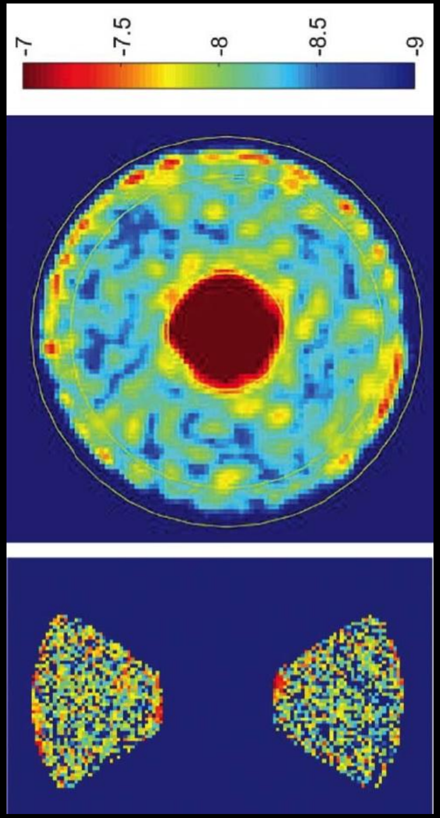
Low resolution imaging spectroscopy

Bandpass: 0.2 µm to 2.0 µm

Apodized Pupil Lyot Coronagraph (15m), possibly vector vortex charge 6 for 9 m

Tech development via WFIRST coronagraph





WFIRST HLC

WFIRST SPC

The LUVOIR Instruments

Observational challenge

Imaging the ultra faint and very small at high resolution

High-Definition Imager (HDI)

2 x 3 arcmin field-of-view

Bandpass: 0.2 µm to 2.5 µm

Nyquist sampled

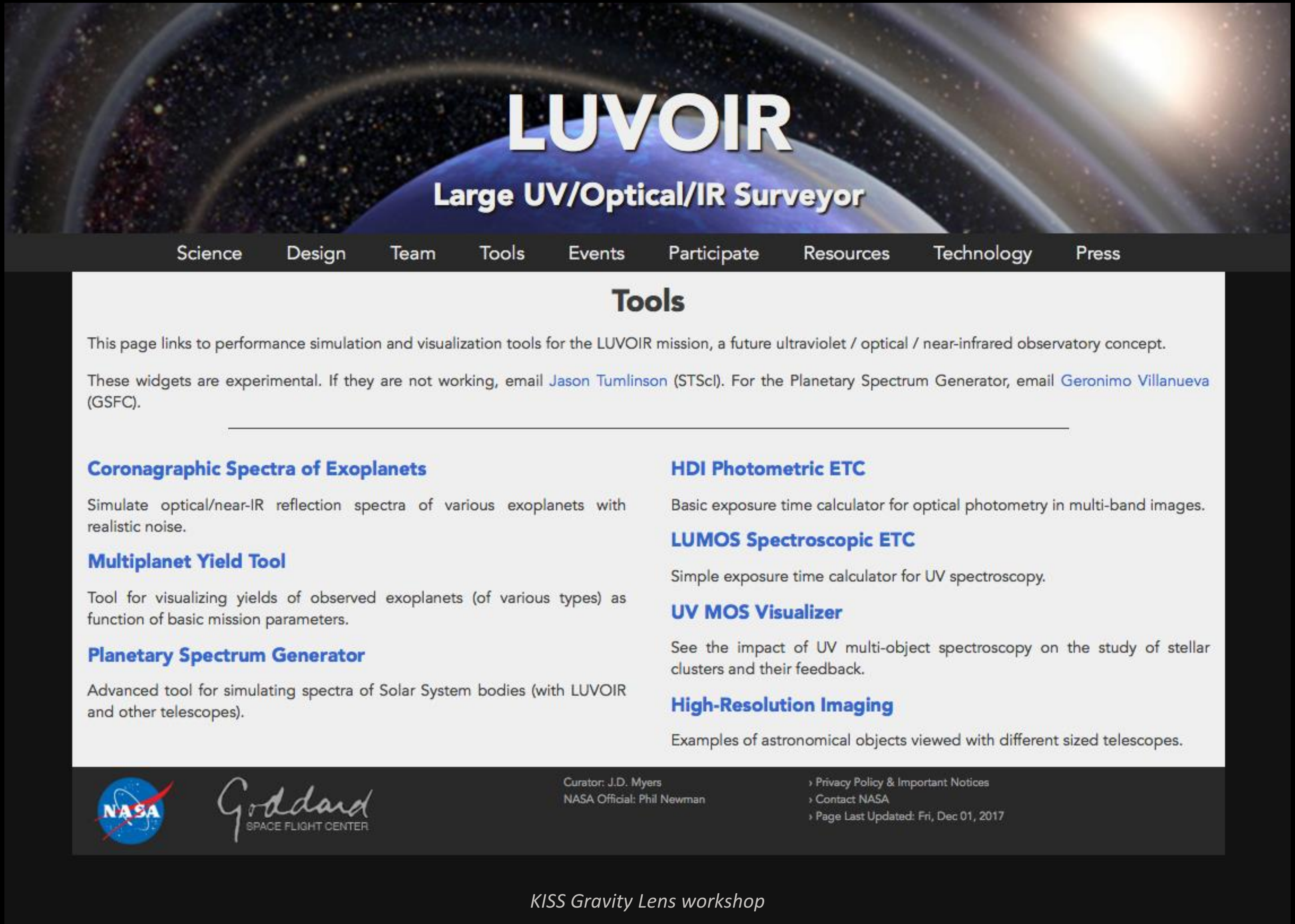
Micro-arcsec relative astrometry capability
    (measure planet masses, etc.)

Heritage from HST WFC3 & WFIRST

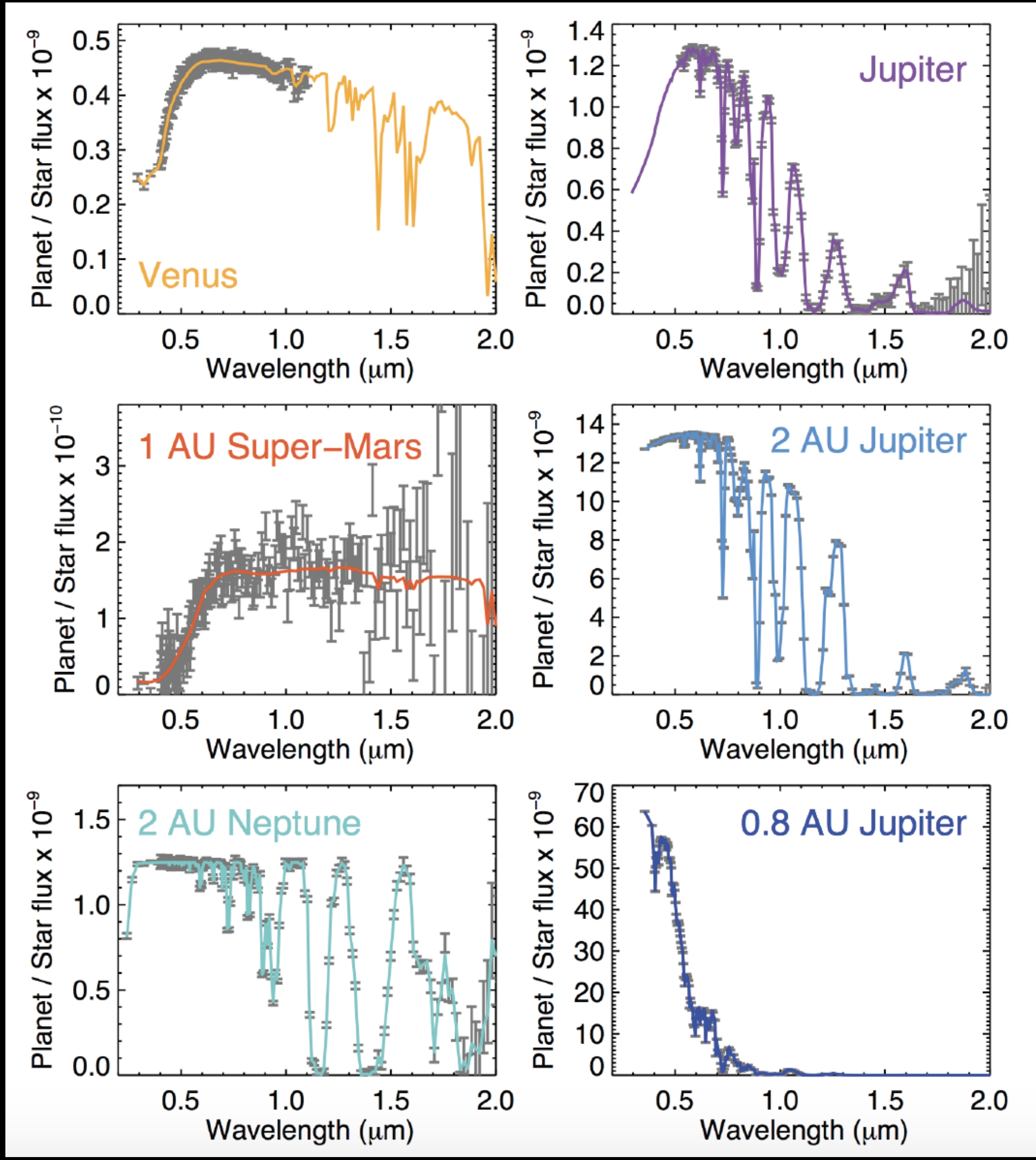
HST Wide Field Camera 3

Design Your Own Observations Using Online Tools

http://asd.gsfc.nasa.gov/luvoir/tools/



Sample Observations: An “Exoplanet Zoo”



Technological Challenges

Deployment of large segmented telescope

To be demonstrated by JWST

LUVOIR Architecture A (15-m)

Credit: A. Jones (GSFC)

Technological Challenges

LUVOIR

Need heavy lift launch vehicle with large fairing

Suitable vehicles (SLS and commercial) in development

Compatibility of UV and coronagraphy

New lab work shows UV reflective mirrors are just fine for coronagraphy

Ultra-high contrast observations with a segmented telescope

Coronagraphs can be designed for segmented telescopes. Working hard to demonstrate needed system stability

Series of short, readable "LUVOIR Tech Notes" available at http://asd.gsfc.nasa.gov/luvoir/tech/

HabEx/LUVOIR Exoplanet Summary:

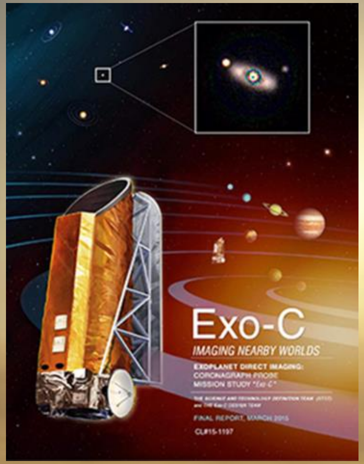
- Similar requirements, different architectures, different scales
- Larger aperture enables larger exoplanet sample and fractional mission time for general astrophysics
- LUVOIR accepts low TRL of segmented aperture coronagraphy, while HabEx is accepting starshade development issues
- Both are adopting SLS launch vehicle
- Teams regularly consult with each other, have held joint meetings, have 5 joint members, and have mutually supported each other.
- Each team acknowledges the need for the other study and looks for one or the other to be selected

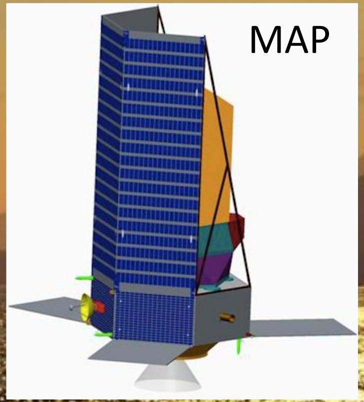
Upcoming Milestones
(assuming nominal 2020 Decadal Survey)

- March 2018: Large mission studies delivered interim reports to NASA
  - After internal HQ review, public versions available summer 2018
  - Please read these and give feedback to the teams !
- Dec 2018: Probe Study whitepapers delivered to NASA HQ
- January 2019: Large mission study draft final reports delivered to HQ
- May 2019: Independent cost estimates provided back to teams
- June 2019: Large mission studies deliver final reports to HQ
- July 2019: NASA submits final reports to Decadal Survey
- Late 2020: Decadal Survey recommendations released

Other exoplanet mission concepts
(not funded by HQ)

- **Exo-C** dedicated coronagraph probe mission, an option for imaging characterization of 2 dozen giant exoplanets if WFIRST+CGI did not proceed (Stapelfeldt+ 2015, 2017)
- **Microarcsecond Astrometry Probe** would find Earth analogs in the HZs of ~90 nearest FGK stars using a well-calibrated wide field camera, 1m telescope (Shao+ 2017)
- **Mission to the Solar Gravitational Lens** at 550 AU may enable resolved images of exoplanets in one highest-priority system, decades after launch (Turyshev+ 2017)





Next step after HabEx/LUVOIR ? Mid-infrared nulling Interferometry

Needed for high contrast with sparse apertures. Combine two telescope beams with 180° phase shift. On-axis starlight nulls out, leaving off-axis planets or dust visible in constructive areas of null pattern

Was a major NASA thrust 1999-2011. Investments have largely stopped in favor of single apertures and visible wavelengths. Eventual revival recommended by 2013 NASA Astrophysics Roadmap

In-use at LBTI in Arizona @ 10 μm, broadband suppression of 10^{-3} to 10^{-4}. Lab tests have achieved 10^{-6} in narrow bands

Concluding thoughts

- Kepler results came too late to affect Astro2010 recommendations. Since then exoplanets is on a roll: the last three medium-scale missions to be selected are in our field (TESS, PLATO, ARIEL). Can we keep this up ?
- Cost numbers will be very important to the fate of the large mission concepts, but they are not released/available now
- "Exoplanets will be unstoppable in the next Decadal"
  – Bill Oegerle, former Director of Astrophysics at Goddard
- But it's not a given that the Decadal will endorse any large mission
- Spread the word in the community about how exciting these missions would be for the field, and what they would enable across astrophysics