HabEx: The Habitable Exoplanet Observatory (A Concept Study)

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http://www.jpl.nasa.gov/habex/

(Most of) the HabEx STDT

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.

18 STDT Members, Study Scientist, Study Manager, 2 HQ Liaisons, 5 International Observers, 8 Working Groups

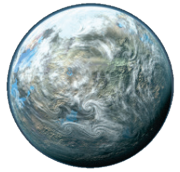
http://www.jpl.nasa.gov/habex/

HabEx Study Goals:

“Develop an optimal mission concept for characterizing the nearest planetary systems, and detecting and characterizing a handful of ExoEarths.”

“Given this optimal concept, maximize the general astrophysics science potential without sacrificing the primary exoplanet science goals.”

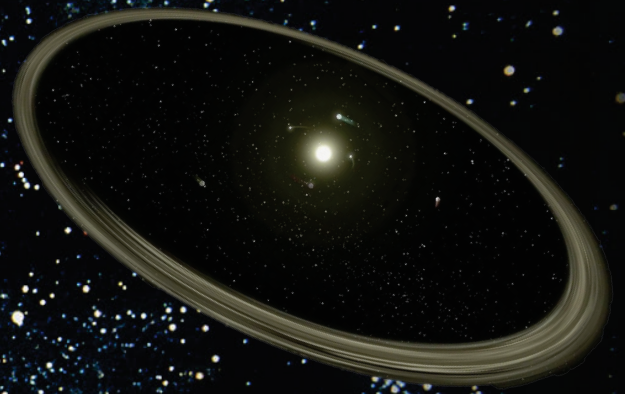
Difference between LUVOIR and HabEx?



- Both LUVOIR and HabEx have two primary science goals
  - Habitable exoplanets & biosignatures
  - Broad range of general astrophysics
- The two architectures will be driven by difference in focus
  - For LUVOIR, both goals are on equal footing. LUVOIR will be a general purpose “great observatory”, a successor to HST and JWST in the ~ 8 – 16 m class
  - HabEx will be optimized for exoplanet imaging, but also enable a range of general astrophysics. It is a more focused mission in the ~ 4 – 8 m class
- Similar exoplanet goals, differing in quantitative levels of ambition
  - HabEx will *explore* the nearest stars to “search for” signs of habitability & biosignatures via direct detection of reflected light
  - LUVOIR will *survey* more stars to “constrain the frequency” of habitability & biosignatures and produce a statistically meaningful sample of exoEarths
- The two studies will provide a continuum of options for a range of futures

HabEx Architecture Overview

- 4m monolithic primary mirror, off-axis secondary
- Micro-thrusters, instead of reaction wheels
- Wavelengths 120nm – 1800nm
- SLS Launch Vehicle
- Earth-Sun L2
- 5 year Nominal Mission Lifetime (at least 25% GO)

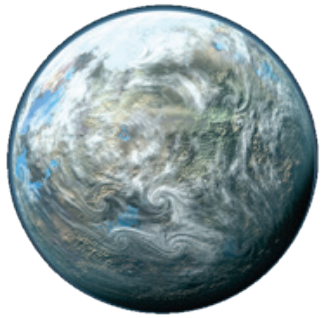


charge 6
vector vortex
coronagraph
IWA ~60 mas at 500 nm

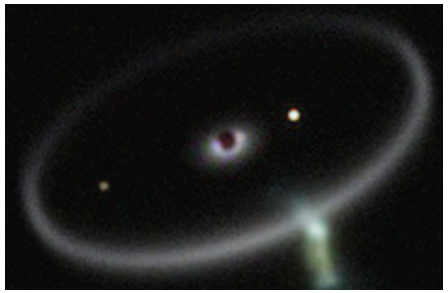
~124,000 km

72-m starshade
IWA ~60 mas
from 300-1000 nm

HabEx Science Goals



1. To seek out nearby worlds and explore their habitability



2. To map out nearby planetary systems and understand the diversity of the worlds they contain

3. To carry out observations that open up new windows on the Universe from the UV through NIR

We have already found a lot of Exoplanets

3550 Confirmed Planets as of 11/02/17

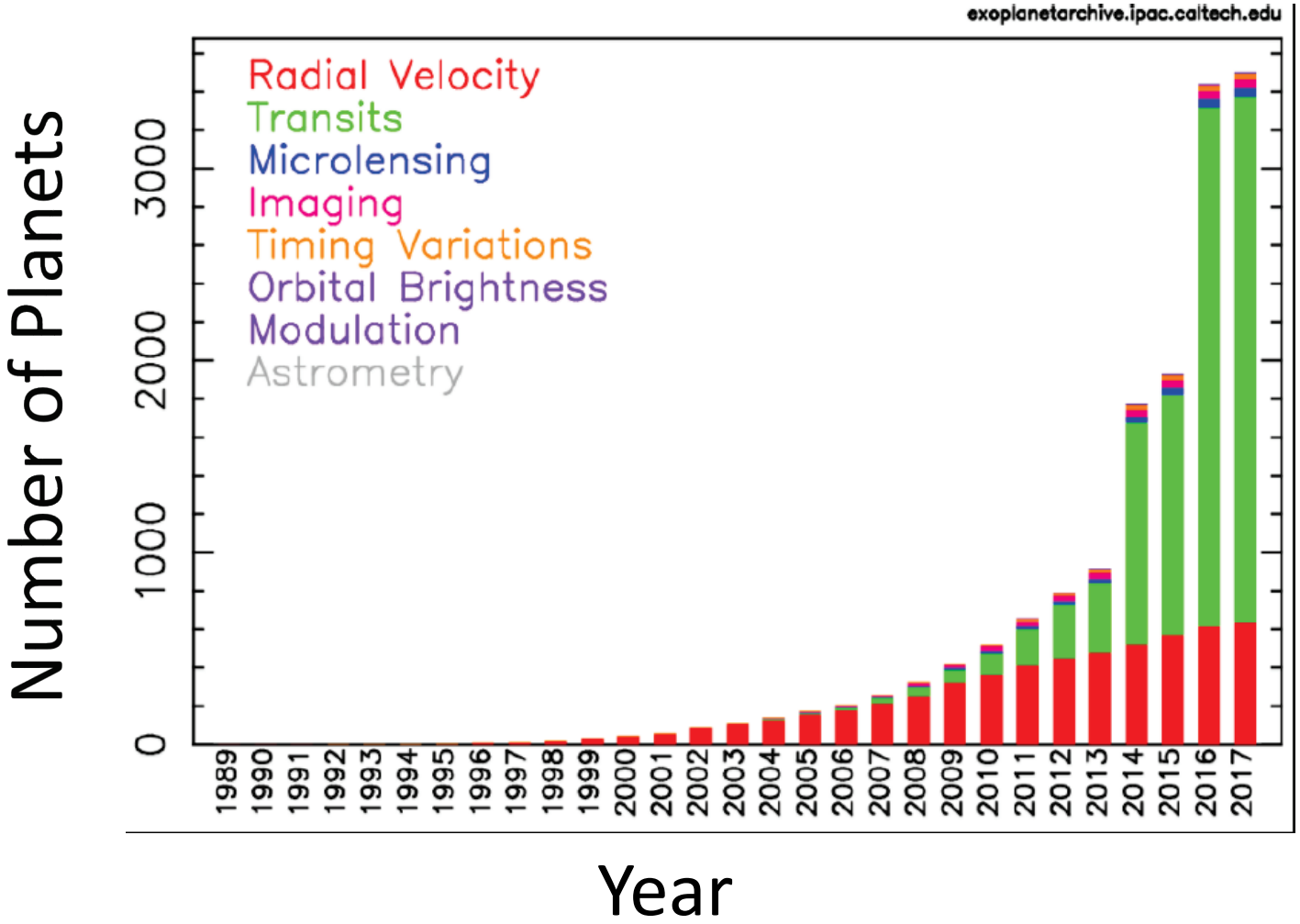
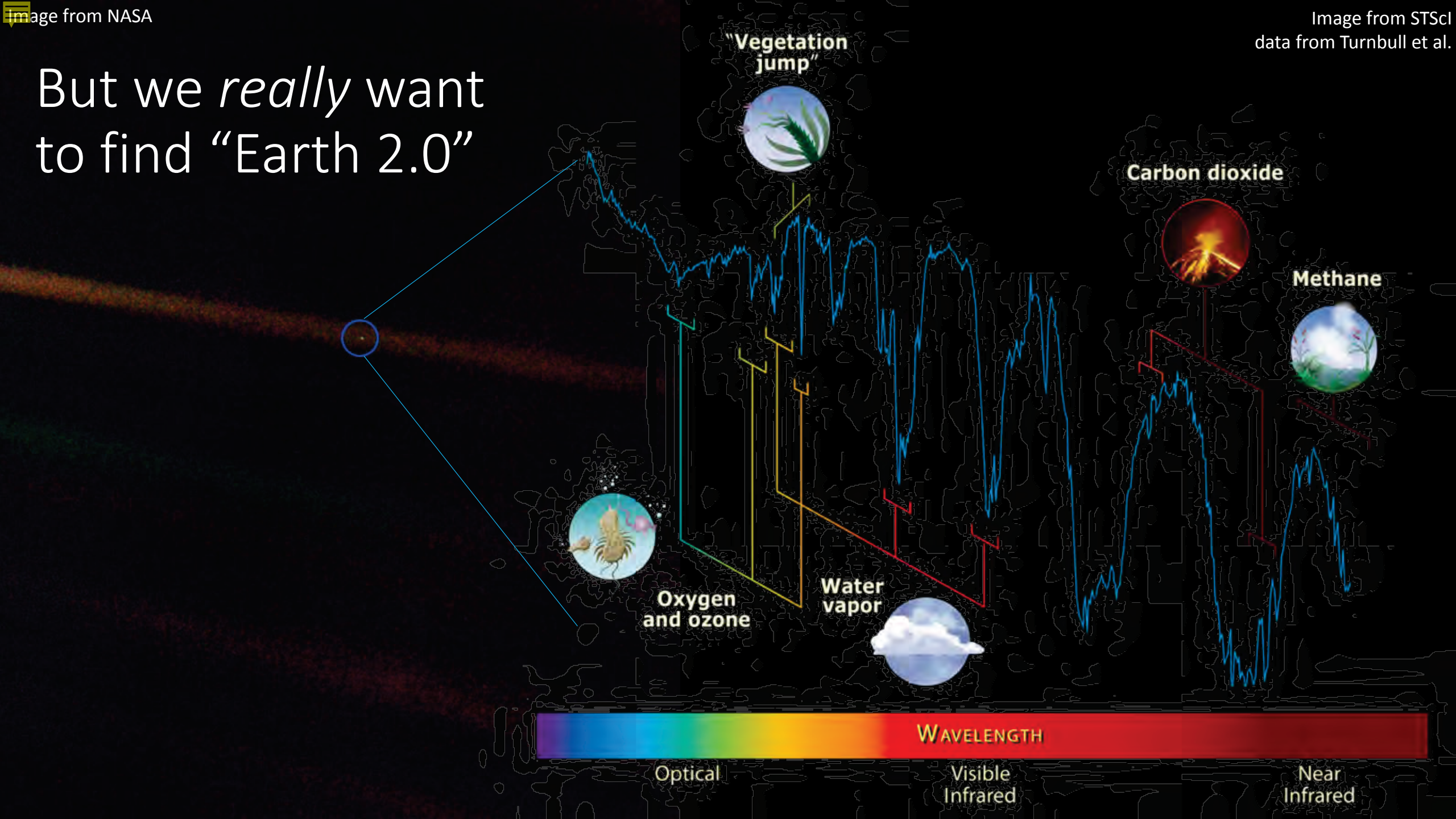


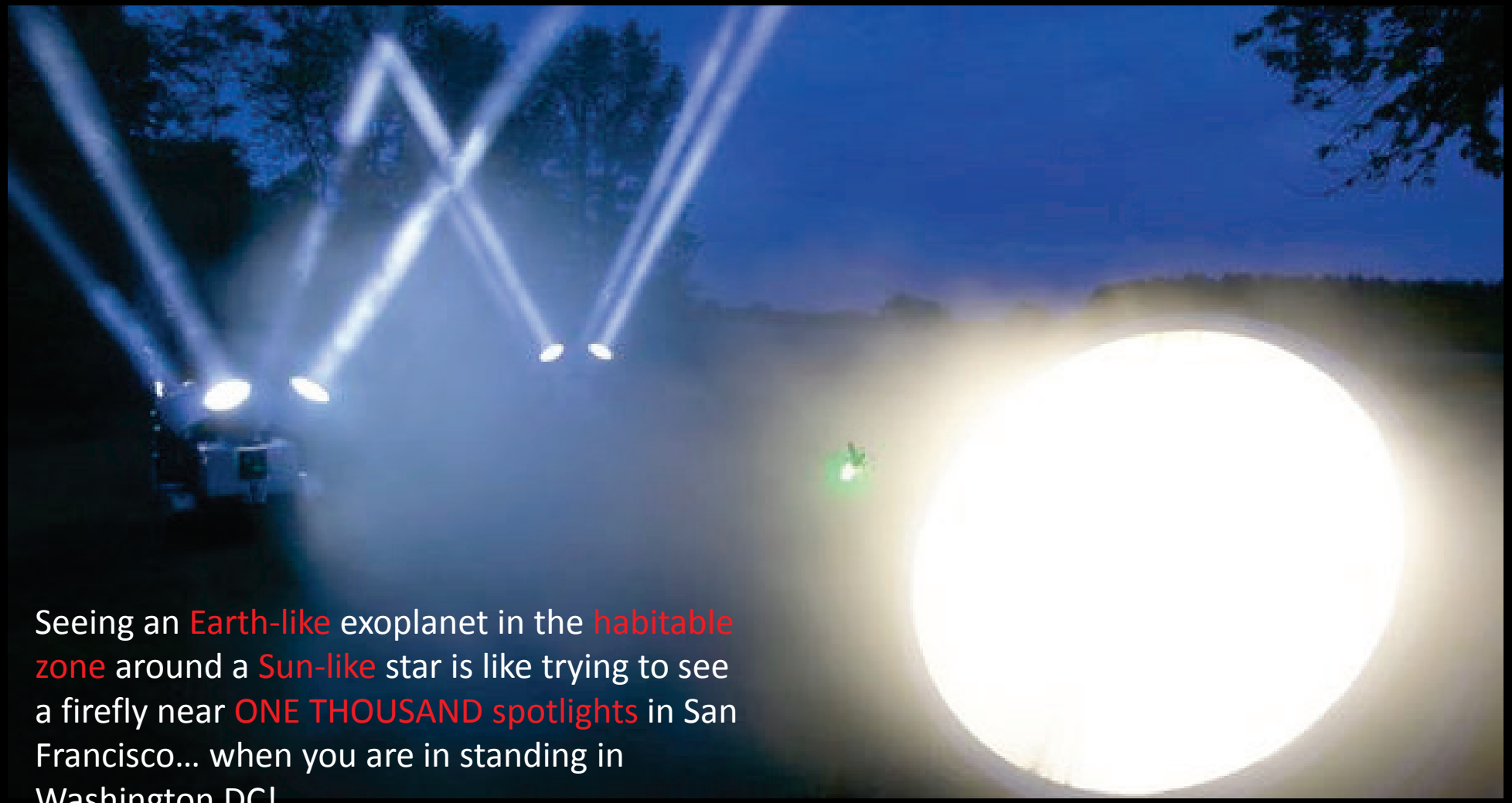
Image from NASA

Image from STScI
data from Turnbull et al.

But we *really* want to find “Earth 2.0”

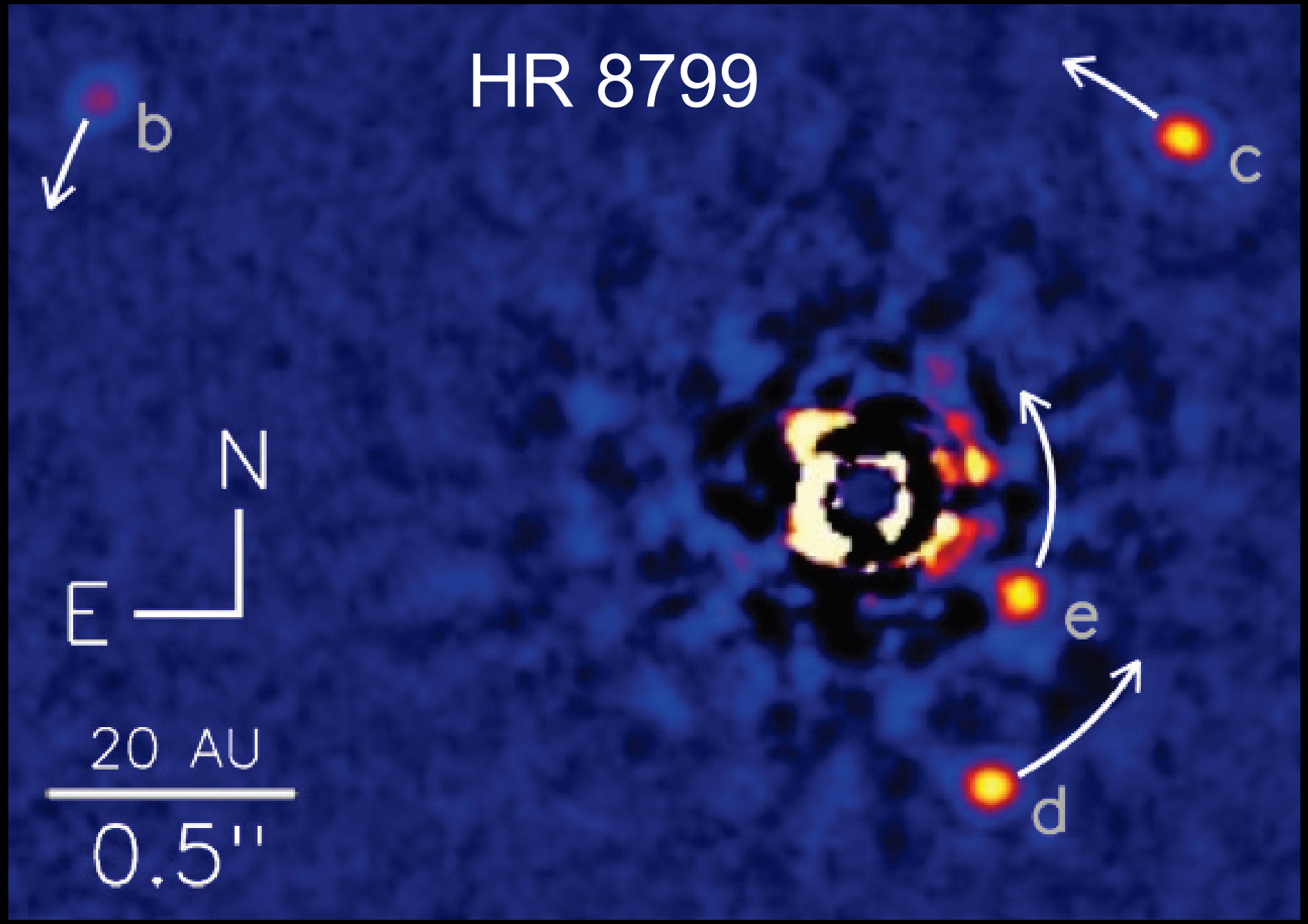


Imaging Planets is Challenging!

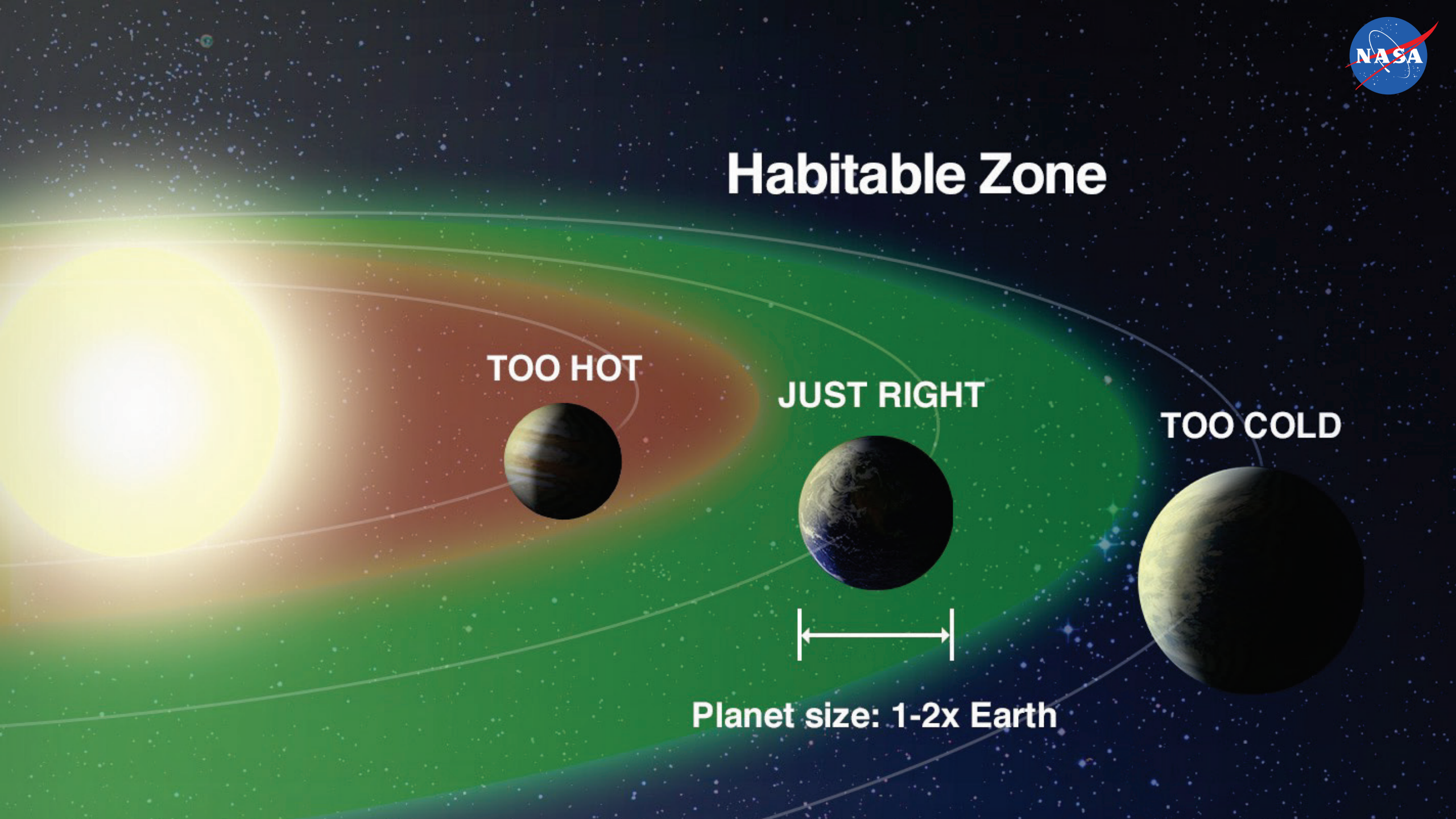


Seeing an Earth-like exoplanet in the habitable zone around a Sun-like star is like trying to see a firefly near ONE THOUSAND spotlights in San Francisco… when you are in standing in Washington DC!

Image Credit: National Geographic



Marois et al. (2011)


Habitable Zone
TOO HOT
JUST RIGHT
TOO COLD
Planet size: 1-2x Earth

Challenging Contrast Requirements

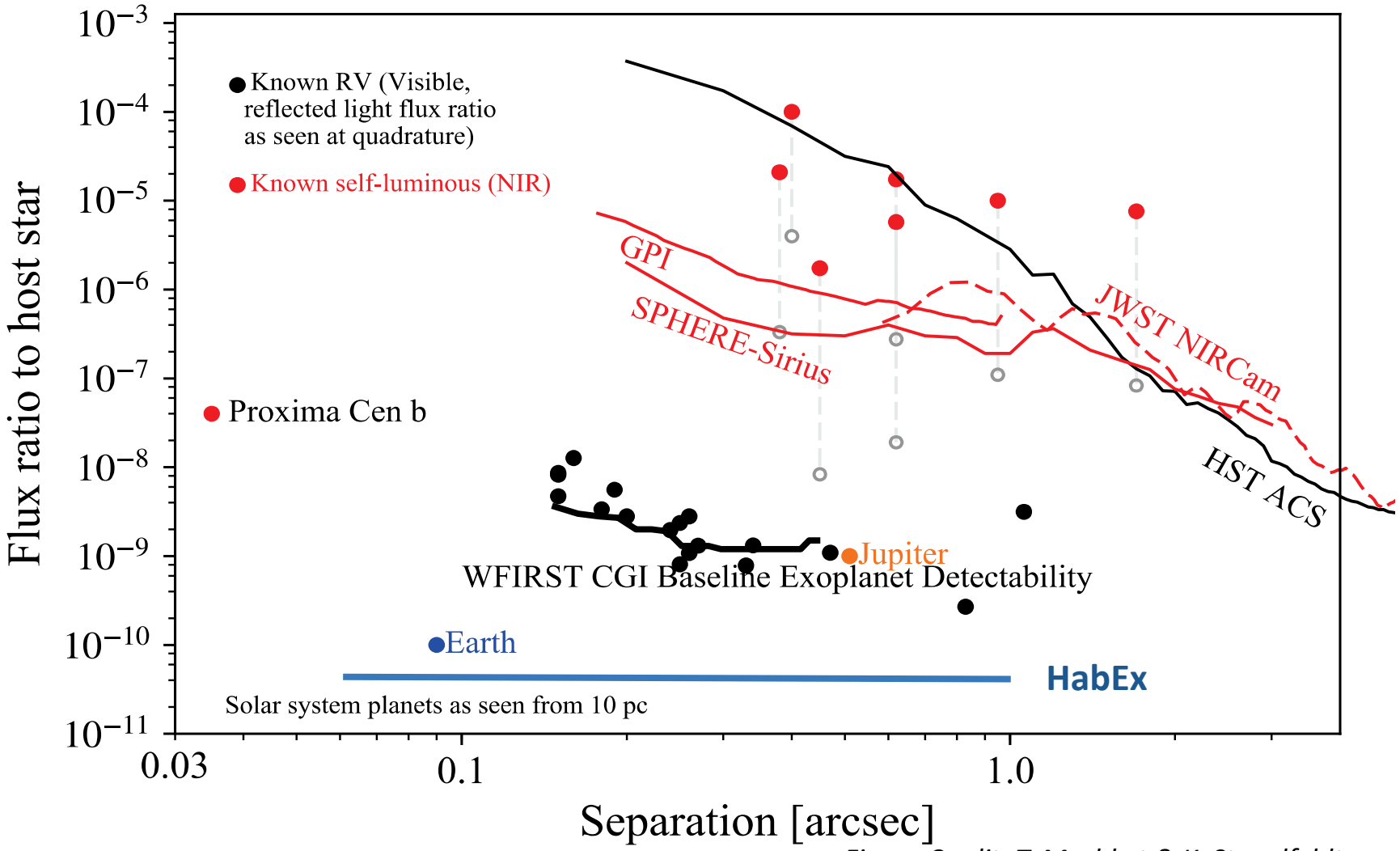
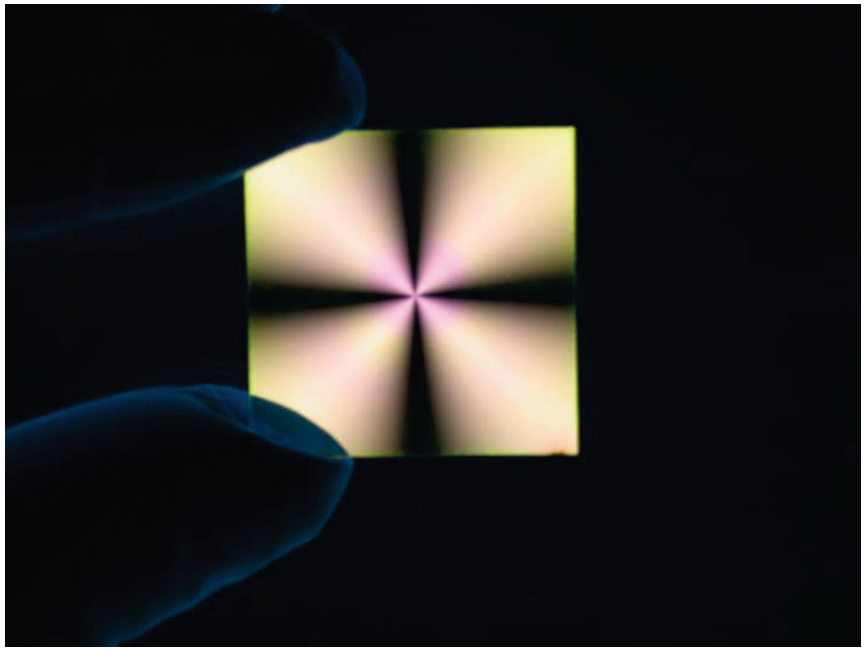


Figure Credit: T. Meshkat & K. Stapelfeldt

The 4-m HabEx design employs two starlight suppression systems

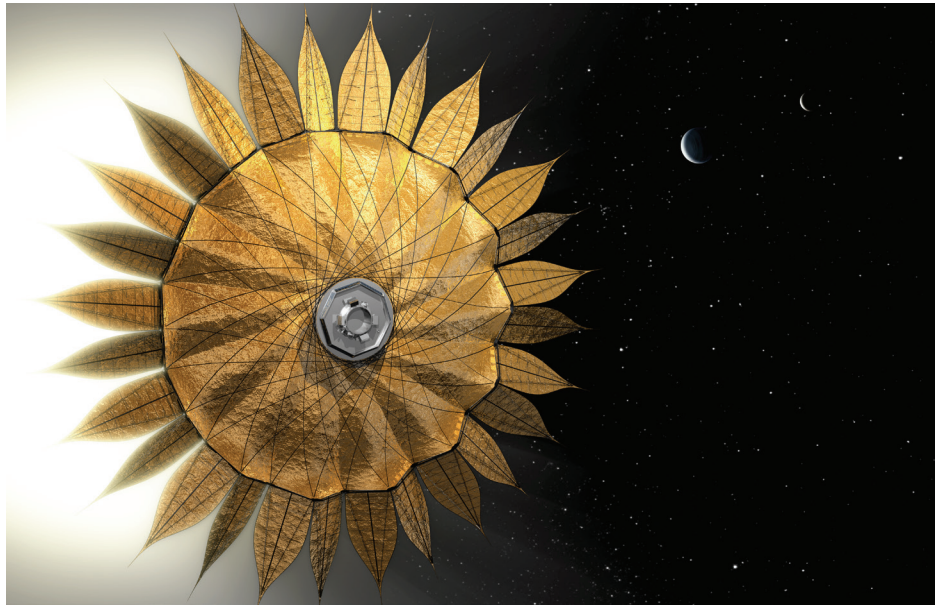
Internal CORONAGRAPH



- Very nimble
- Large field of regard
- Planet Yield limited by time (not fuel)
- Searches for planets around many stars
- Takes images at multiple visits to measure orbits

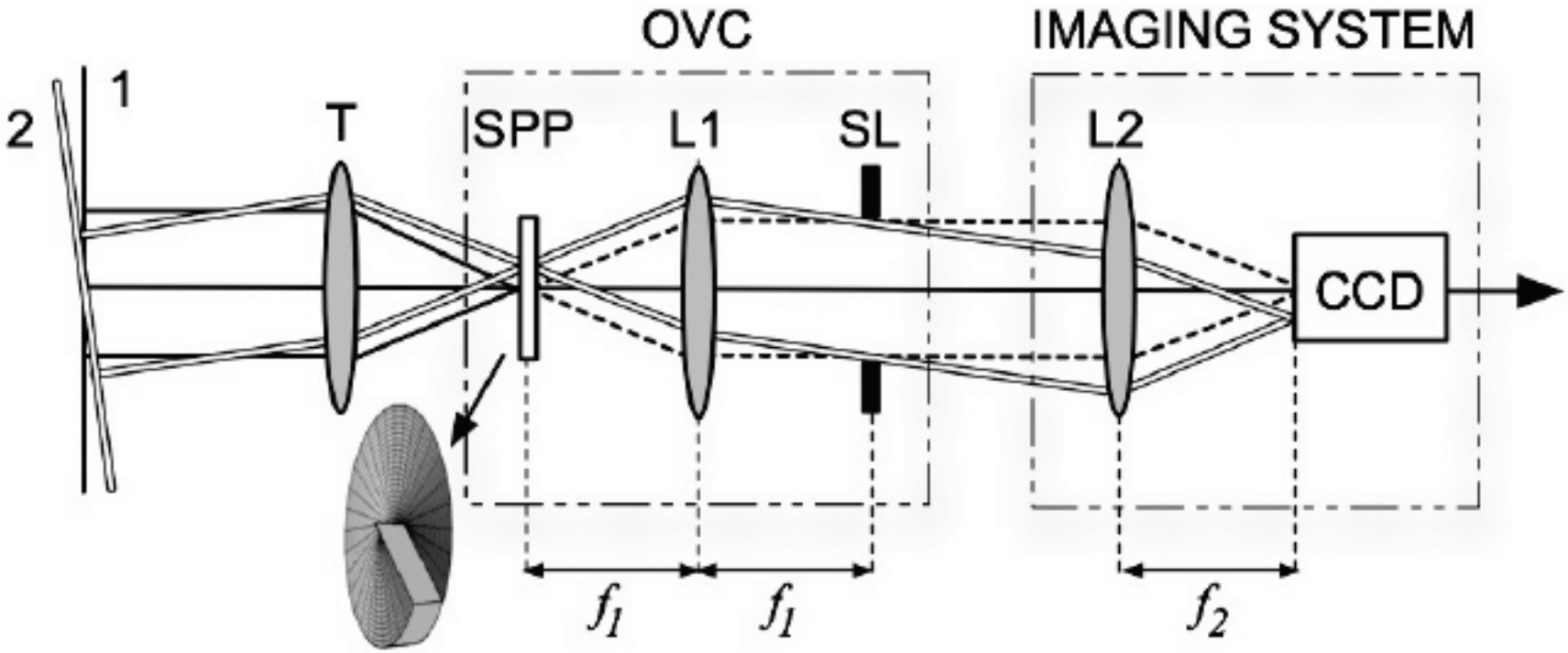
+

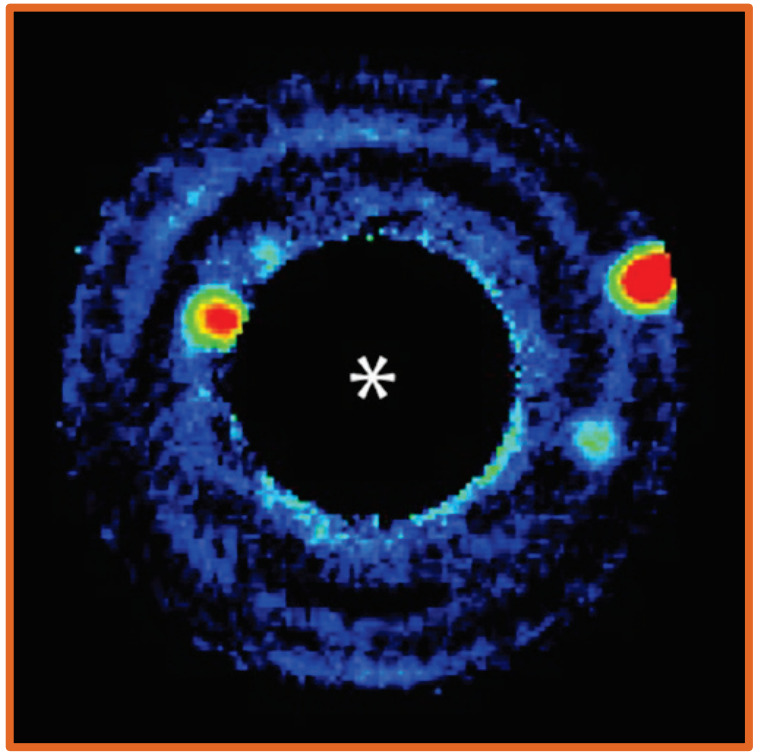
External STARSHADE



- Wide instantaneous bandpass
- High throughput
- No OWA
- Accesses closer-in planets at a given λ
- Takes broad spectra of all planets found in ~50-100 most interesting systems

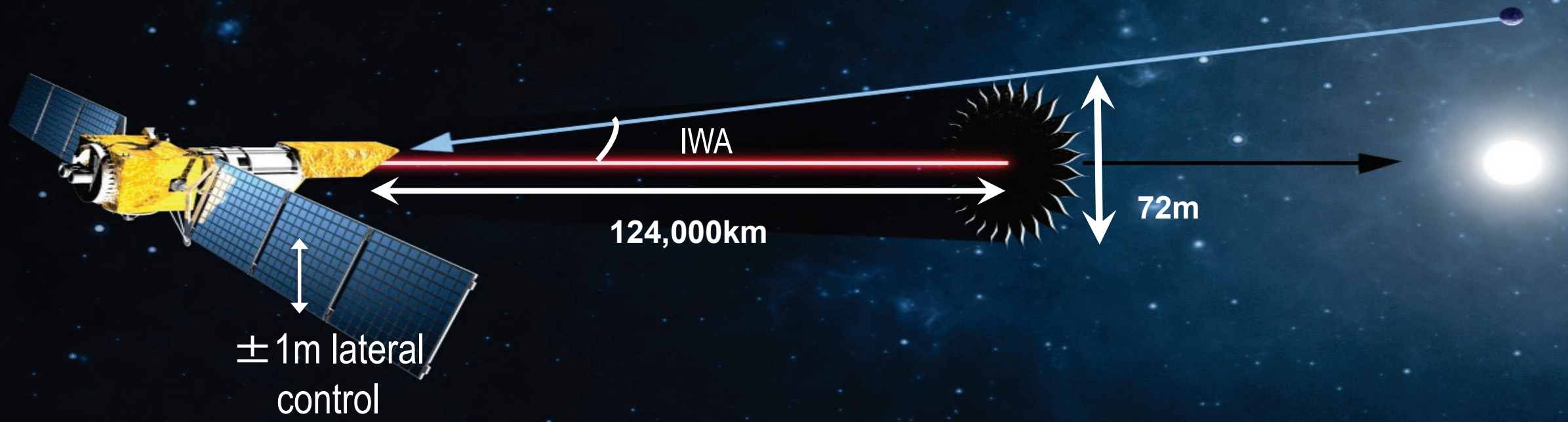
Coronagraph





Starshade

IWA = Inner Working Angle



Not to scale

Starshade

Starshade

Coronagraphs and starshades make great partners…

one is nimble while the other enables deep, broad observations.

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But both technologies present key engineering challenges…

coronagraphs require ultra-stable telescopes, while starshades must unfurl to great precision!

Technology Gaps and TRL Assessments

	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.

TRADE STATEMENT: Recommend a 4m exoplanet direct detection architecture for HabEx study concept development

	Requirements and figures of Merit (MUSTs, WANTs, Risks and Opportunities)	Assignee/ Working Group	Weights		3		4		9		10		
Description					Large Starshade (UV to NIR) & Coronagraph (Vis/NIR)		Small (Vis) Starshade & Large Starshade (UV to NIR)		Coronagraph Only Vis/ NIR		Large Starshade Only UV to NIR		
					Off-axis; single SLS launch; 300-1800nm Starshade is 72m diameter and does 300-1000nm at 124Mm with 60mas IWA, and 1000-1800nm at 69Mm with 138 mas IWA Coronagraph is used primarily for visible detection and starshade for Near UV/VIS/NIR characterization. Coronagraph will enable multiple revisits for verification and possibly orbit determination		On-axis; no coronagraph; 300nm-1800nm; 2 Falcon H launches The small starshade does all detection in the 300nm-500nm The large stareshade does characterization in 300nm-1800nm Large Starshade is 72m diameter and does 300-1000nm at 124Mm with 60mas IWA, and 1000-1800nm at 69Mm with 138 mas IWA Small starshade is 32m diameter and does 300-500nm at 55Mm with 60mas IWA		Off axis; 450-1800nm only; SLS launch EMCCD and HgCdTe detectors. Multiple bands covered with filters.		On-axis; 300-1800nm , no coronagraph; 2 Falcon H launches; Starshade is 72m diameter and does 300-1000nm at 124Mm with 60mas IWA, and 1000-1800nm at 69Mm with 138 mas IWA		
Evaluation	*MUSTS*												
	Science/Technical												
M1a	Can search for exo-Earths in the HZ of enough nearby single stars to reach a total HZ cumulative completeness greater than 40	WG1-			66 to 88	Yes	73	Yes	66 to 88 (1 Pc	Yes	65	Yes	
M1b	Shall be able to detect and characterize planets located between Xau and Yau around at least N stars between 450nm and 1000 nm.	WG2 Defines IWA and OWA. Need to quantify "Deep Dive" and "Explore"				Yes		Yes				Yes	- write a separate went extension to 1800nm - Check out OWA against detectors array size and TRL
M3	Can spectrally characterize HZ earth-like planets to R 140 resolution and SNR 10 around at least 10 stellar systems (no orbits)	WG 1&2 Ty, Shawn. Consider the oxygen A band.			36	Yes	~30	Yes	25	Yes	33	Yes	
M4.1	Can determine the orbits of the best 10 habitable zone planet candidate systems (no spectra)	WG3. Might not be able to get orbits for planets with low observation al completene ss			58	Yes	32	Yes	58	Yes	16	Yes	Note: "Best" stars = highest completeness nearby stars
M4.3	Can characterize both orbits and spectral properties of HZ planets around at least 1 stellar target				5.0 to 39	Yes	3.2 to 32*	Yes	2.7 to 23	Yes	2.2 to 16	Yes	low number is for eta=0.1 ; large numbe ifs for eta=1
M7	No more than 3 enabling new technologies (TRL 3 or less)	WG 5,6,7&8			3-4	Likely	2-3	Yes	1-2	Yes	2-3	Yes	Is it TRL 3 or 4
	Schedule												
M8	Ready for KDP-A by 2025					Unknown		Unknown		Unknown		Unknown	
	WANTS (DISCRIMINATORS)	Grand Total		100		716		682		642		628	
	Technical			*70*		*658*		*624*		*532*		*540*	
W0	Measure orbits of all detected planets with periods < 3x mission duration	AEIWG	High	5		10		8		10		5	best if 96x96 DM
W0b	Maximize the number of orbits measured for habitable zone planets			5		10		5	5.8	10		2	
W4	Maximize spectral characterization of all planet types	WG2	High	5		10		8		5		10	
W5	Can spectrally characterize and measure orbits of any potential exo-Earths discovered in the HZ of as many nearby stars as possible (more than 10)	WG1	High	5		10		8		5		5	
W1	Spectrally characterize up to 1800 nm in IR	WG1 &2	Me dHi gh	4		10		10		8		10	
W5i	Planet search capability for binary stars	WG 2 & 5	Med	4		10		10		5			
W2	Spectrally characterize to 250 nm or below in UV	WG 1&2	Med	2		10		10				10	
W2a	Spectrally characterize as many planets as possible to 250 nm or below in UV		Med	2		8		10				8	
W3	Minimize number of new technologies	Design Team	Med	2	3-4	2	2-3	8	1-2	10	2-3	8	
W7	Spectrally characterize measure orbits for as many systems as possible for giant planets and circumstellar disks for variety of stellar types.	WG 2	Med	2		10		8		5		8	
W5f	Maximize the outer working angle	WG 2	Med	2		8		10		5		8	
W5g	Maximize the magnitude at which we can perform high contrast imaging	WG 5&6		2		8		10		5		8	
W5h	Measure the spectrum of the host star in UV with GA instrument	WG 1	Med	2		10		10		10		10	IfUV spectrometer only
W8	*Telescope design allows for more than one GA instrument*	Gen astro	*High*	5		10		10		10		10	

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W9	*Maximize the 5 year mission time dedicated to a GO program above 25%*	Gen astro	*Med*	2		5		8		5		10
W10	*Imaging and Spectroscopy over at least 300nm - 1um (100nm - 2um goal)*	Gen astro	*High*	5		10		10		10		10
W11	*Short wavelength cutoff at 100nm*	Gen astro	*High*	5		10		10		10		10
W12	*FoV of at least 3x3 arcmin^2*	Gen astro	*Med*	2		10		10		10		10
W13	*Diffraction-limited performance longward of 400nm*	Gen astro	*Med*	2		10		10		10		10
W14	*Multi-object spectroscopy*	Gen astro	*Med*	2		10		10		10		10
W15	*Non-sidereal tracking*	Gen astro	*Med*	2		10		10		10		10
W6	Minimize number of launch vehicles	Design Team	Low	1	1 SLS	10	2 FH	5	1 SLS	10	1 SLS	10
W16	Graceful descopes		Med	2		8		8		5		5
	Schedule					*160*		*160*		*200*		*160*
W6b	Reach TRL 5 at earliest possible date	WG 5,6&7	Med	20		8		8		10		8
	Cost					*50*		*50*		*100*		*80*
W7	Minimize cost	Design Team	Low	10		5		5		10		8
	RISKS											
R1	Adding another low TRL technology if UV Coatings down to 100nm is required	Gen astro			Med L	High C	Med L	High C	Med L	High C	Med L	High C
R2	WFIRST starshade captures significant fraction of exoplanet science				LowL	High C	LowL	High C	Med L	High C	Med L	High C
R3	Low eta_earth value (<0.1)				LowL?		LowL?	Med C	LowL?	High C	LowL?	
R4	Not inferring the planet masses well enough to assess whether or not they are rocky	AEIWG										
R5	Confusing planets with one another when measuring orbits				LowL	High C	Med L	High C	LowL	High C	LowL	High C
	OPPORTUNITIES											
O1	Solar sytems science	WG2										
O2	Precursor / contemporaneous observations with astrometry or radial velocity that is sensitive to potential habitable planet	WG3				high		high		Med C		Best
O3	Some other mission does UV contemporary science	WG1										
O4	Amount of Parallel observations	Gen astro				Best L		medium L		Best L		medium L
O6	Higher performance (better IWA and bandwidth) NIR coronagraph for point sources				L=H	B=M	N/A		L=H	B=H	N/A	
O7	Permits faster telescope and better UV instrument design (General astrophysics FOV and throughput)							B=H				B=H
O5	Deep precursor imaging of HabEx fields	AEIWG				medium		medium		medium		medium
O8	High eta_earth value (>> 0.1)											
O9	Mission lifetime significantly exceeds 5 years				L=H	B=Highest	L=H	B=low	L=H	B=Highest	L=H	B=low

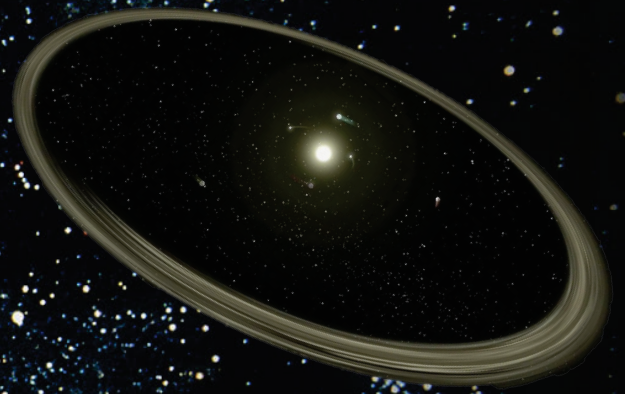
Risk Evaluation

Notes

Identify "Best" and others are:
Wash
-Small Difference
-Significant Difference
-Very Large Difference

HabEx Architecture Overview

- 4m monolithic primary mirror, off-axis secondary
- Micro-thrusters, instead of reaction wheels
- Wavelengths 115nm – 1800nm
- SLS Launch Vehicle
- Earth-Sun L2
- 5 year Nominal Mission Lifetime (at least 25% GO)



charge 6
vector vortex
coronagraph
IWA ~60 mas at 500 nm

~124,000 km

72-m starshade
IWA ~60 mas
from 300-1000 nm

HabEx Exoplanet Observing Strategy has 2 Components:

Broad Survey (Blind Exoplanet Search ~3.25 yrs mission time):

HabEx will survey ~120 FGK stars out to 16 pc. Each target will be observed with the coronagraph on average ~6 times, optimized for the detection of exo-Earth candidates. Using the starshade, HabEx will obtain R=7 spectra from 0.3-0.45 μm and R=140 spectra from 0.45-1.0 μm for each planetary system observed.

Deep Survey (Nearest Neighbors ~6 months mission time):

HabEx will use the starshade to observe 7-10 nearby high priority G&K stars 3 or 4 times each (regardless of whether an exo-Earth candidate exists) to obtain i) a deep systematic noise-floor limited broadband image, ii) an R=7 spectrum from 0.3-0.45 μm, and iii) an R=140 spectrum from 0.45-1.0 μm using the IFS.

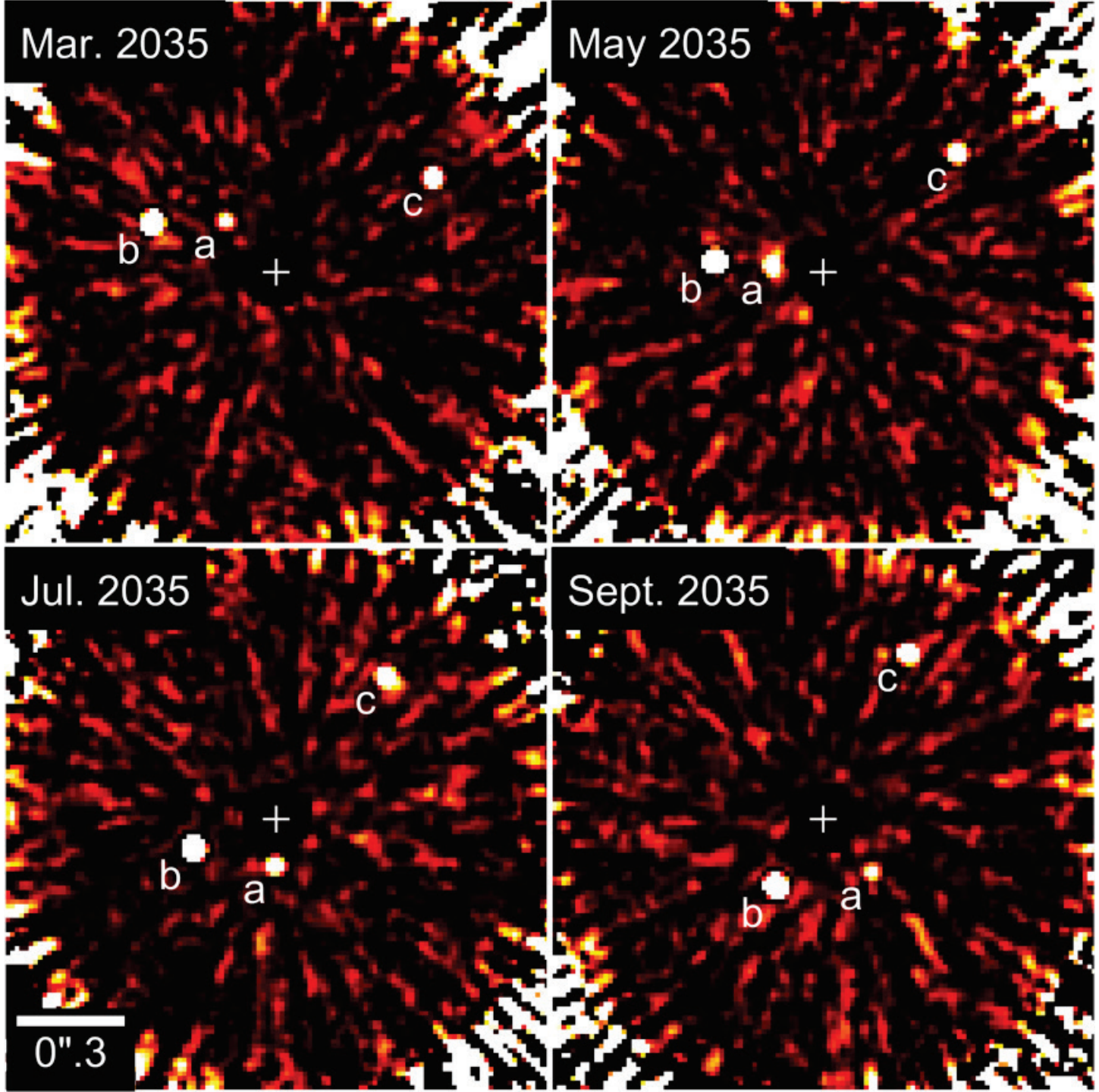


Figure Credit:
Garreth Ruane

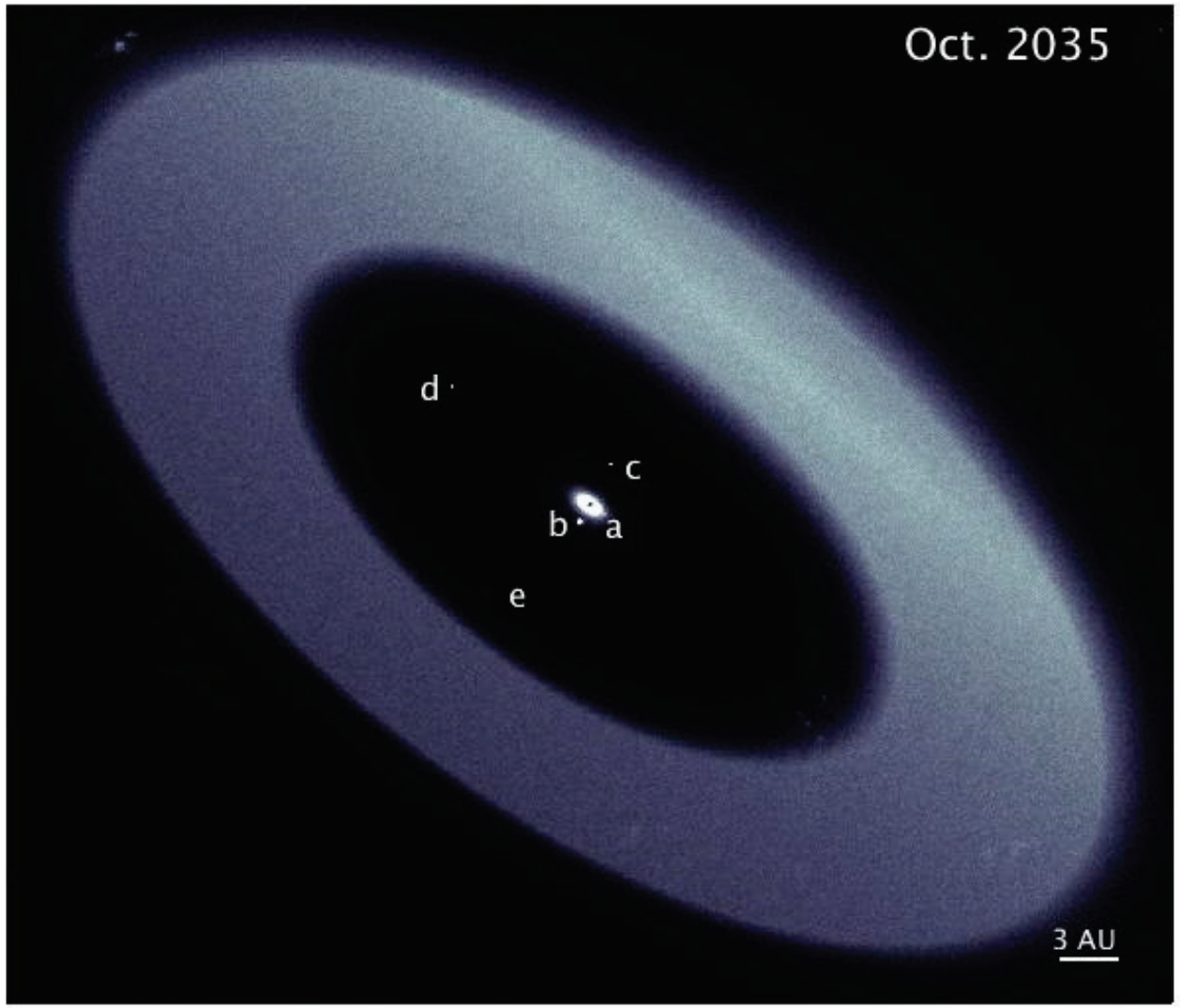
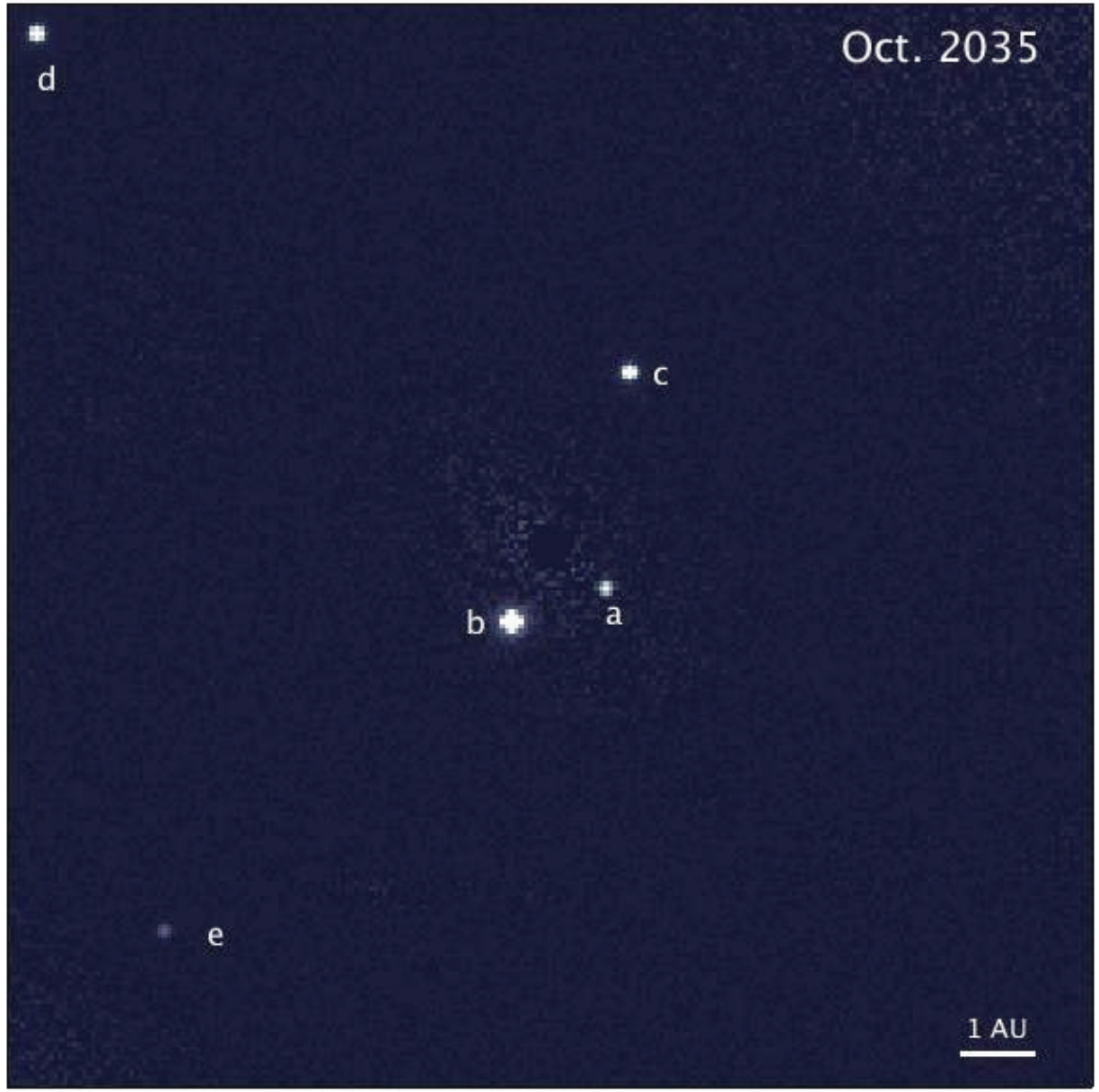


Figure Credit: Sergi Hildebrandt



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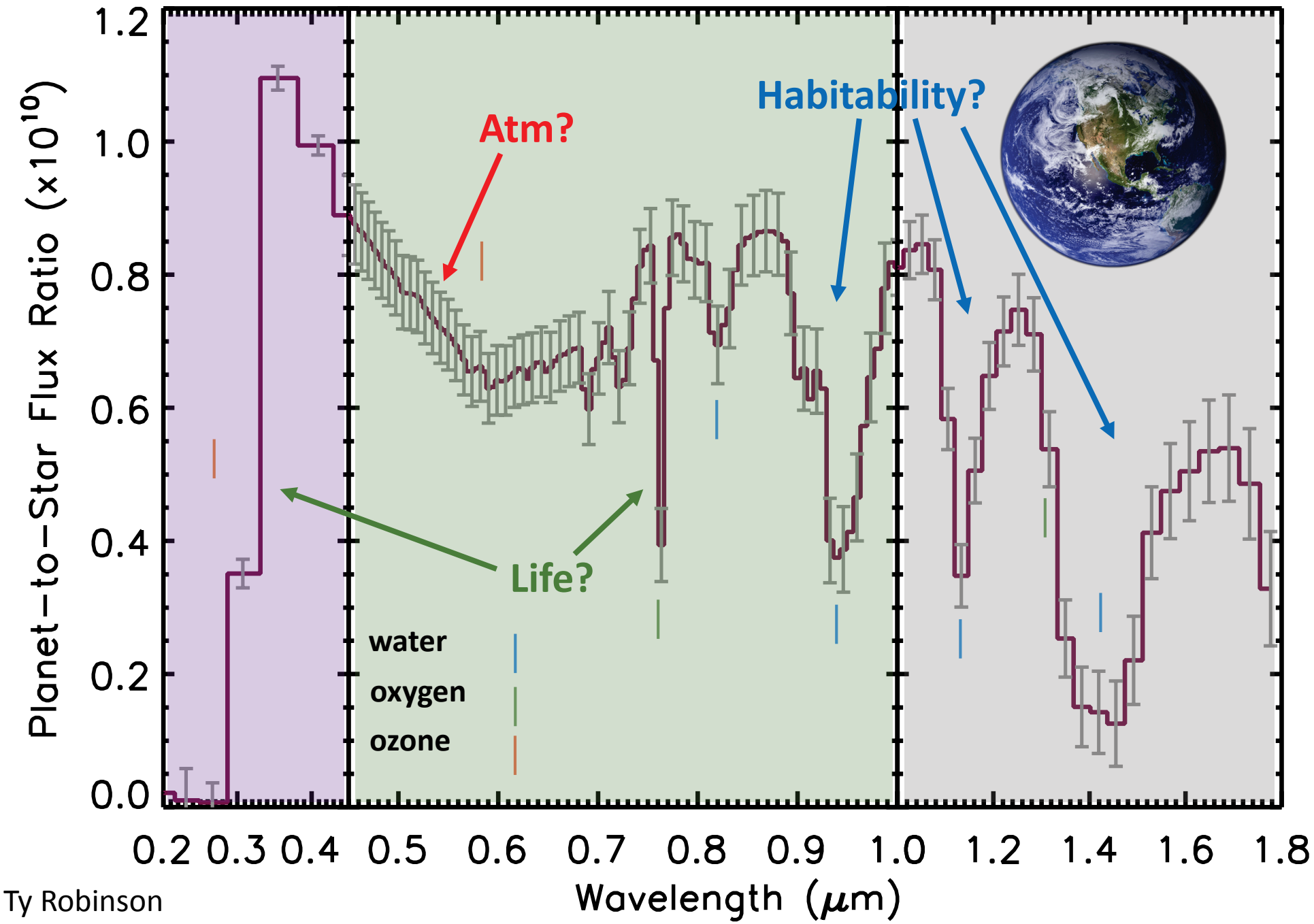
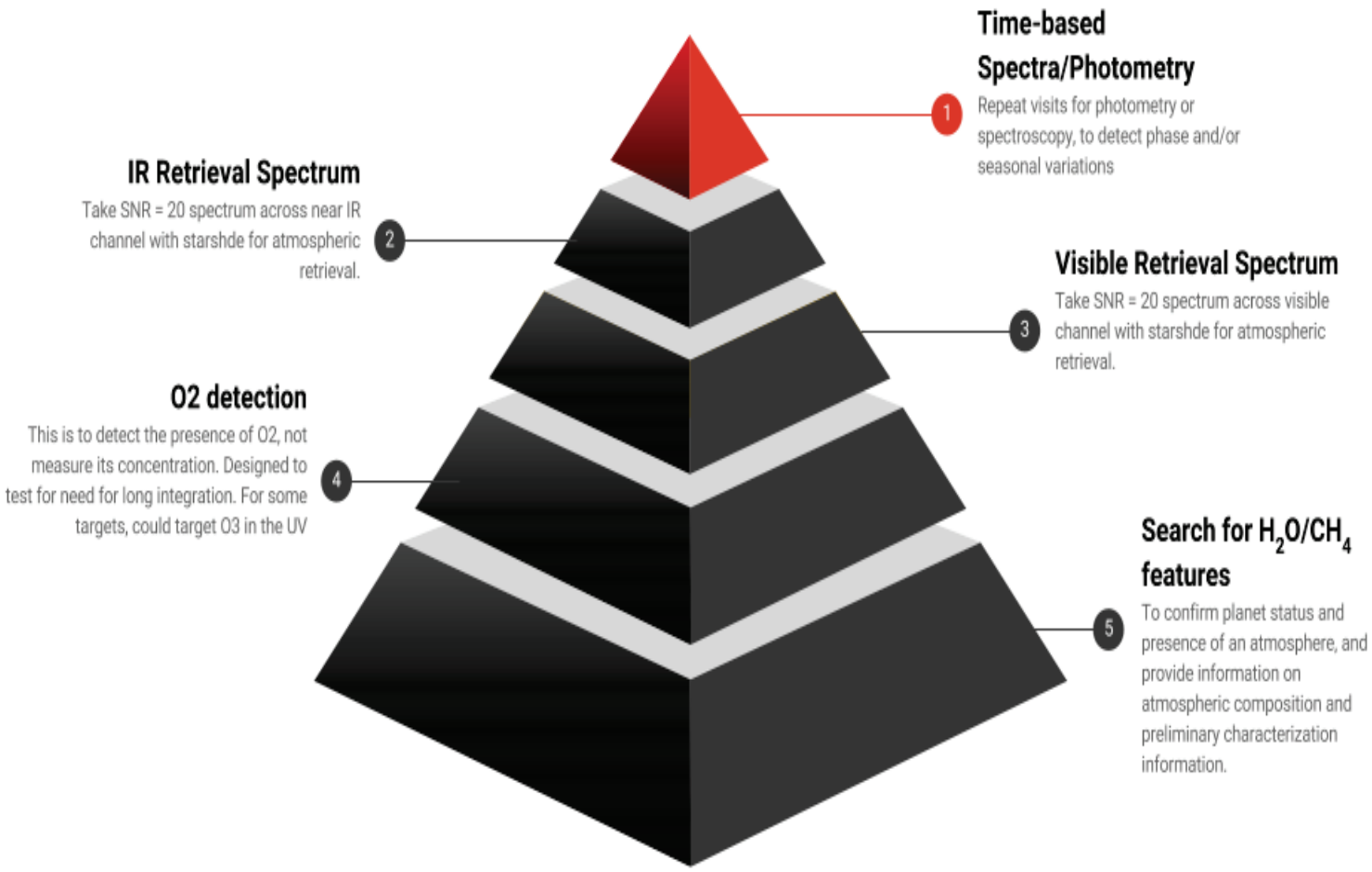


Figure Credit: Ty Robinson

HabEx Instrument Capabilities for High Contrast Imaging and Spectroscopy of Exoplanets

- Instrument raw contrast of <=10^{-10} , stable at a fraction of that level
- Can detect planets brighter than 4 x 10^{-11} of the visible stellar flux at separations > 60 mas
- Can measure orbit for all such planets with orbital periods < 15 years
- Can get 450nm to 1000nm R=140 spectra for all such planets
- Near UV (down to 200nm R=7) spectro-photometry for brightest planets
- Near IR (1000 to 1800nm R=40) spectra of brightest planets
- Time-based spectra and photometry (selected few): phase/ seasonal/ diurnal variations



Exoplanets Characterization "Pyramid"
(Figure Courtesy of S. Domagal-Goldman)

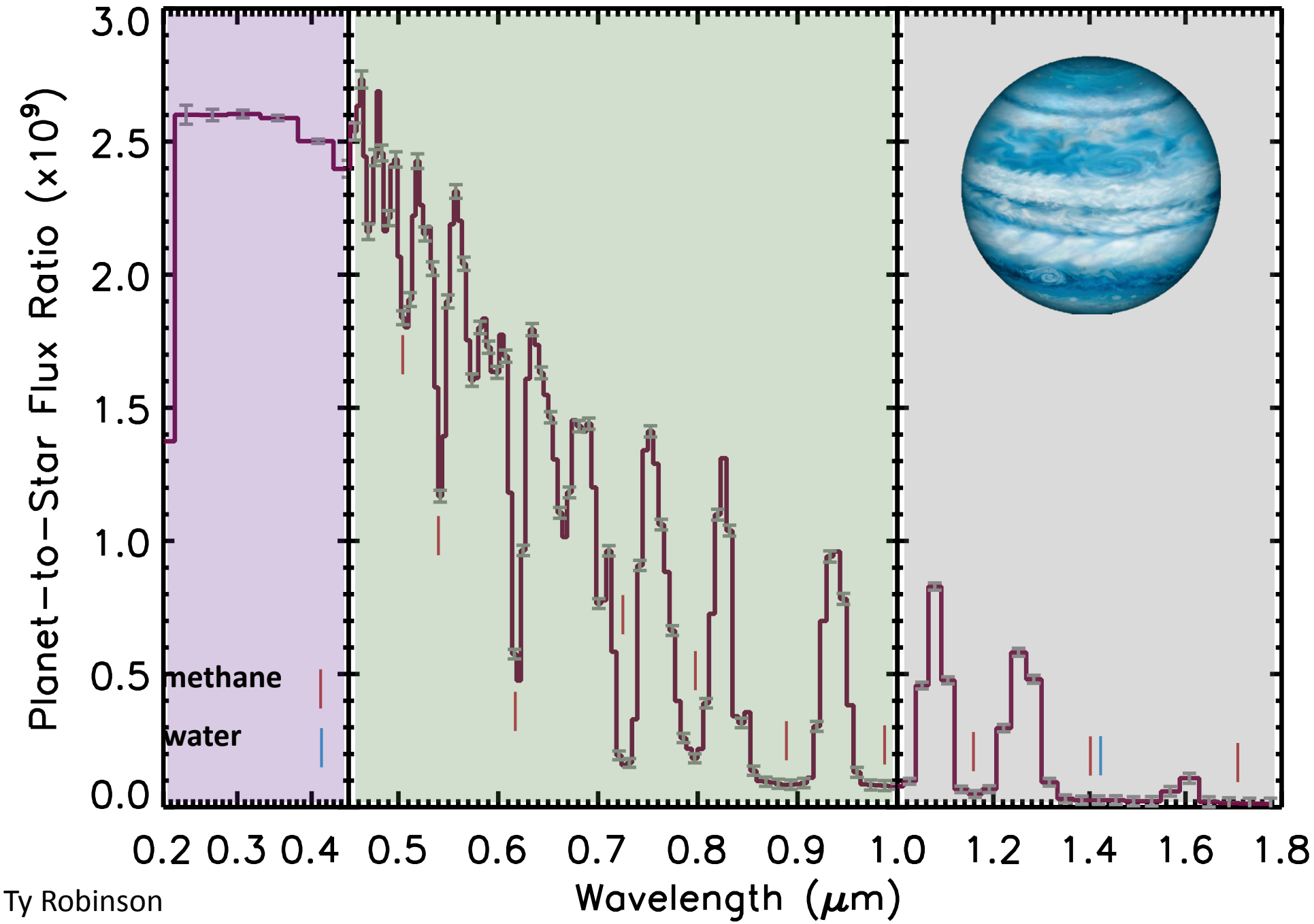
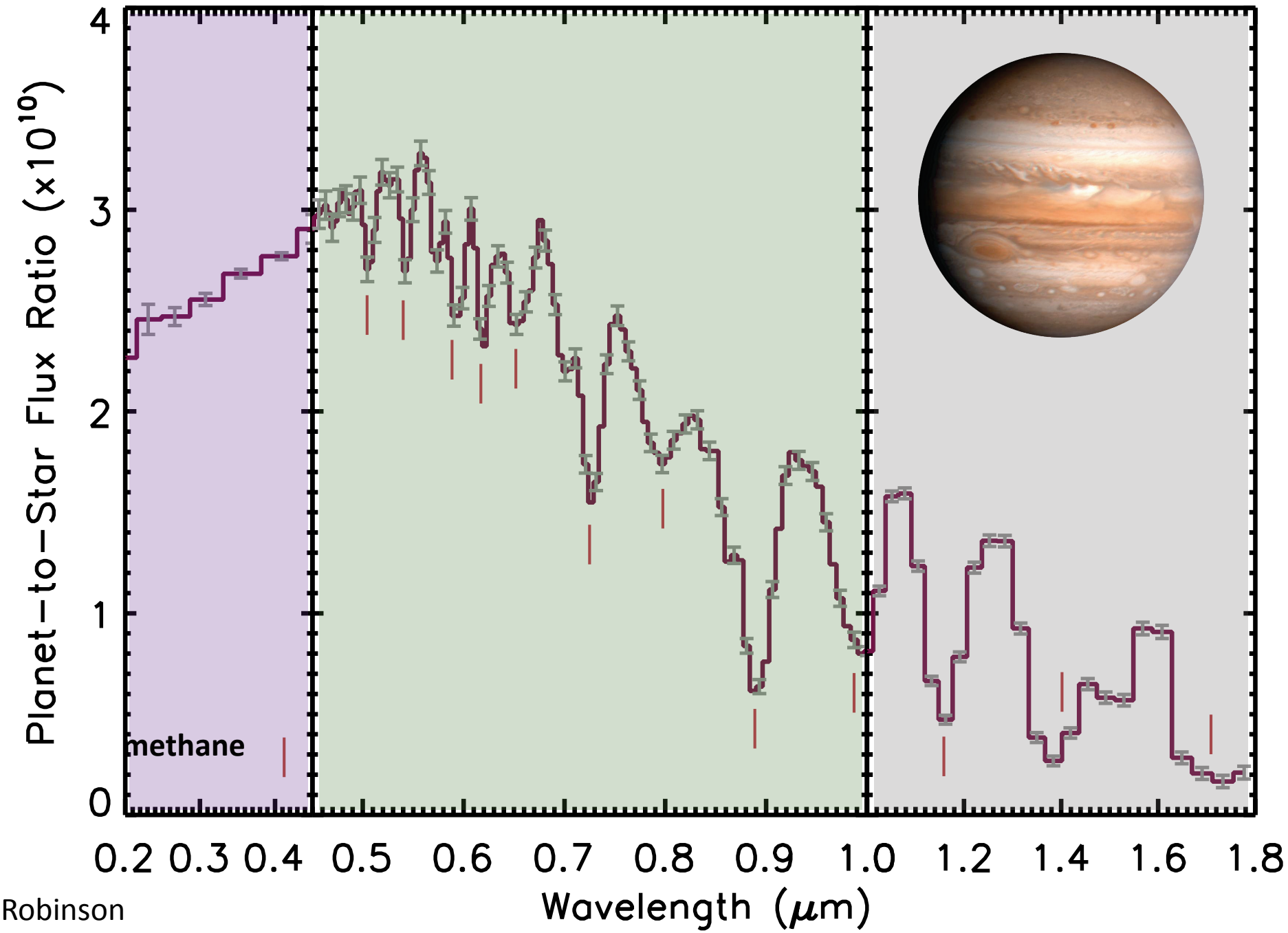


Figure Credit: Ty Robinson



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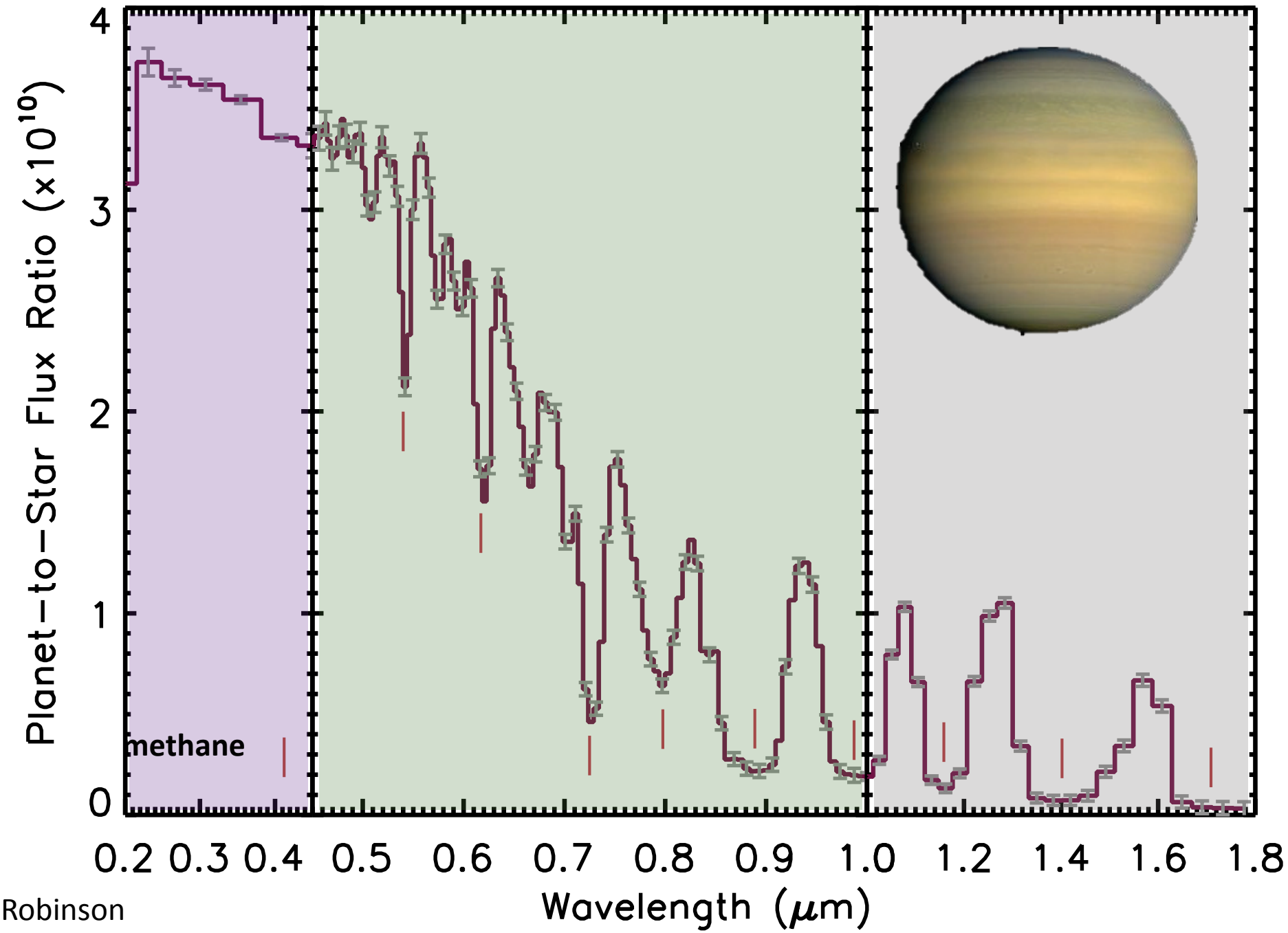

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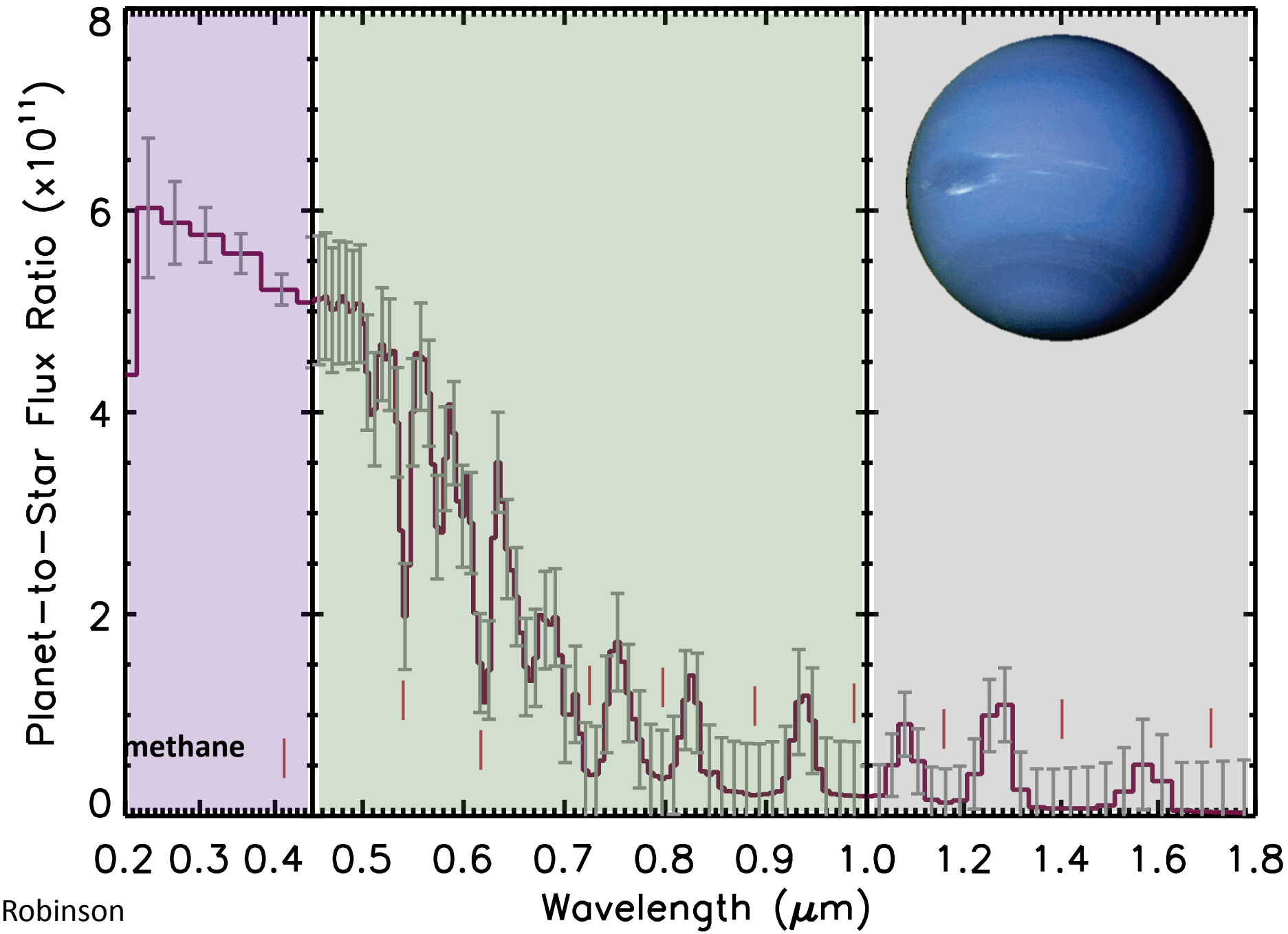
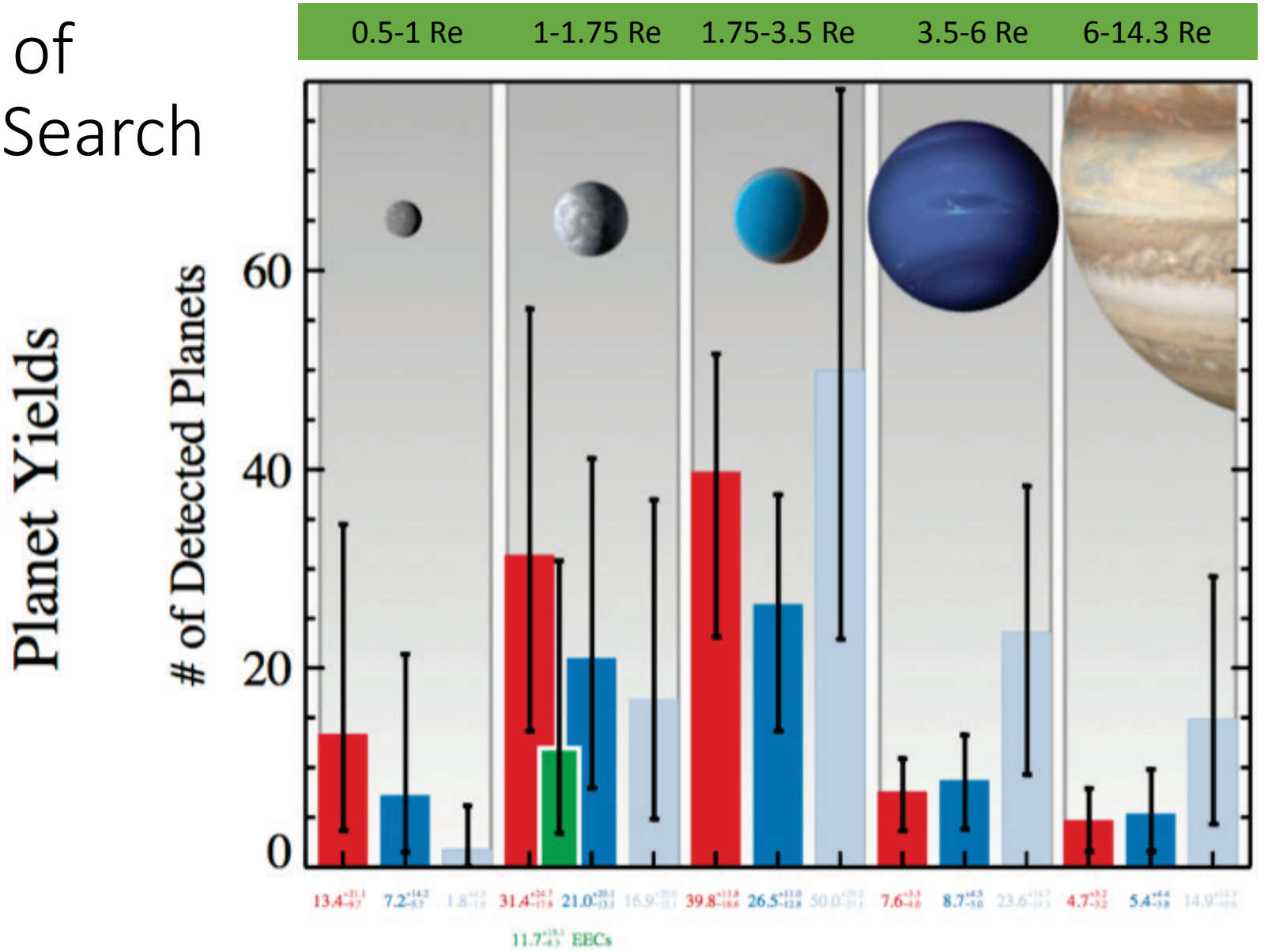


Figure Credit: Ty Robinson

Predicted Yields of Blind Exoplanet Search



92 rocky planets
Incl. 12 HZ exo-earths

116 sub-Neptunes

65 Neptunes and Jupiter analogs

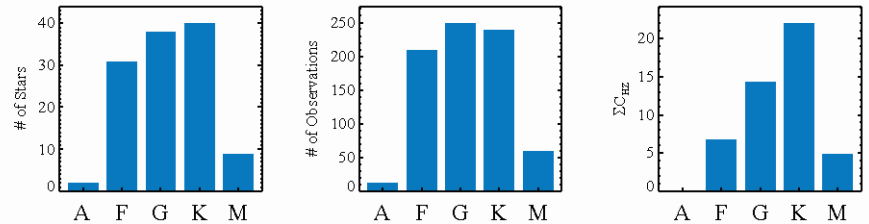
Figure Credit: Chris Stark

Target List

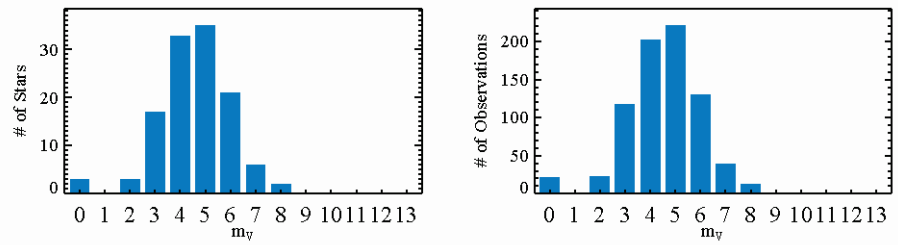
N_{stars} = 120 | $N_{observations}$ = 770

d_{max} = 16.3 pc | θ_{max} = 9.3 mas

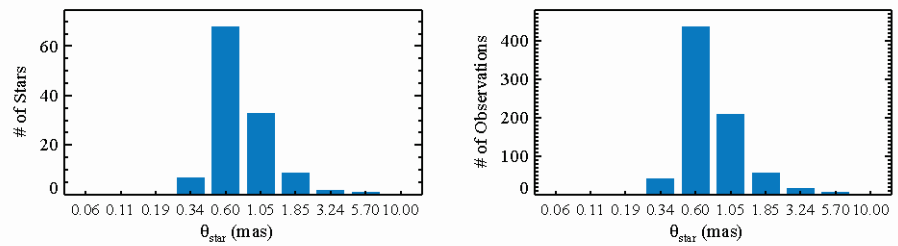
Spectral Type



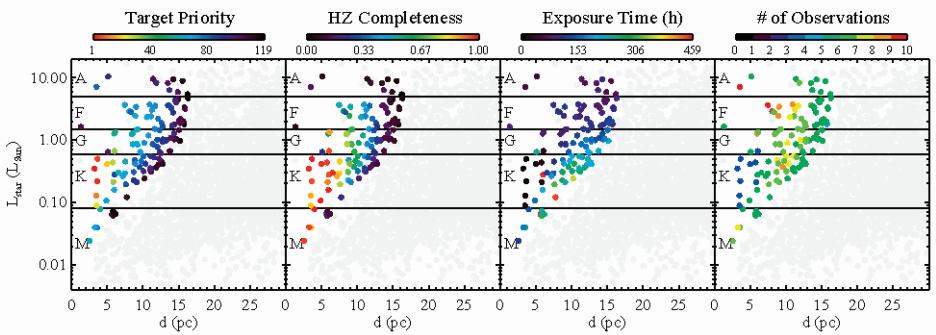
Apparent magnitude



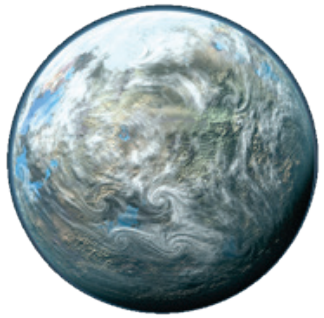
Stellar Diameter



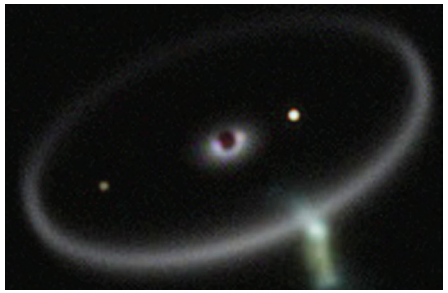
Luminosity–Distance Plots



HabEx Science Goals



1. To seek out nearby worlds and explore their habitability



2. To map out nearby planetary systems and understand the diversity of the worlds they contain

3. To carry out observations that open up new windows on the Universe from the UV through NIR

A Diversity of Planets on the Way to Earths

Designed to directly image habitable-zone Earth analogs around nearby sun-like stars, HabEx will also detect planets that are as bright or brighter than Earths at a range of orbital separations.

Giant Planets

- HabEx will determine whether there exist nearby solar-type stars with planetary system architectures that resemble the distribution of small rocky planets, giant planets and interplanetary dust found in the solar system.

- HabEx will also determine if the presence of giant planets is related to water vapor in the atmospheres of small planets within the snow line.

Grand Tack model of Solar System formation (Walsh et al. 2011)

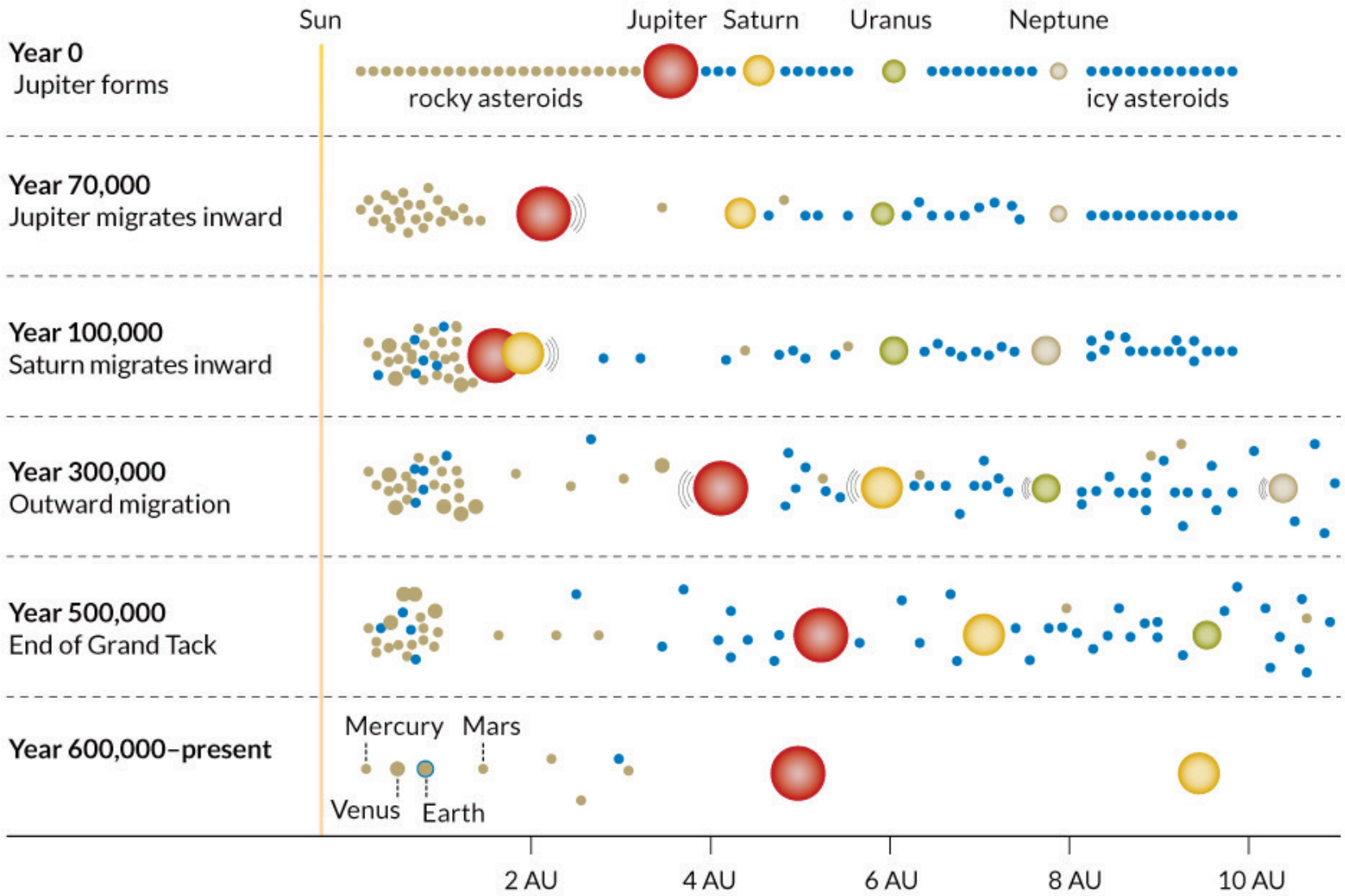
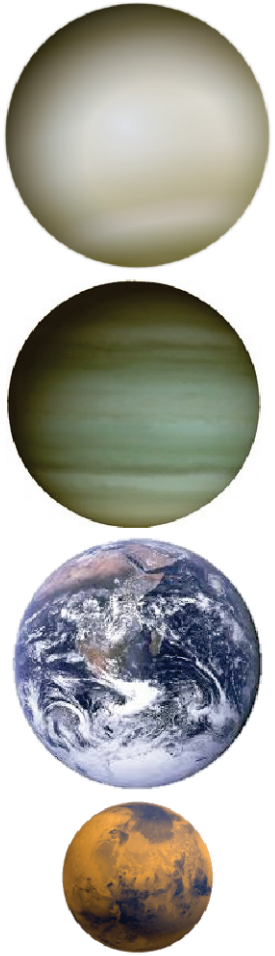


Figure Credit: exoclimes.com/F. Pont, Adapted by M. Telfer

Super-Earth and Sub-Neptune Size Planets

HabEx will determine the diversity of planetary atmospheric compositions in nearby planetary systems around solar-type stars, including (but not limited to) planets with sizes ranging from 1 to 3 Earth radii, encompassing the regime of super-Earths and sub-Neptunes.



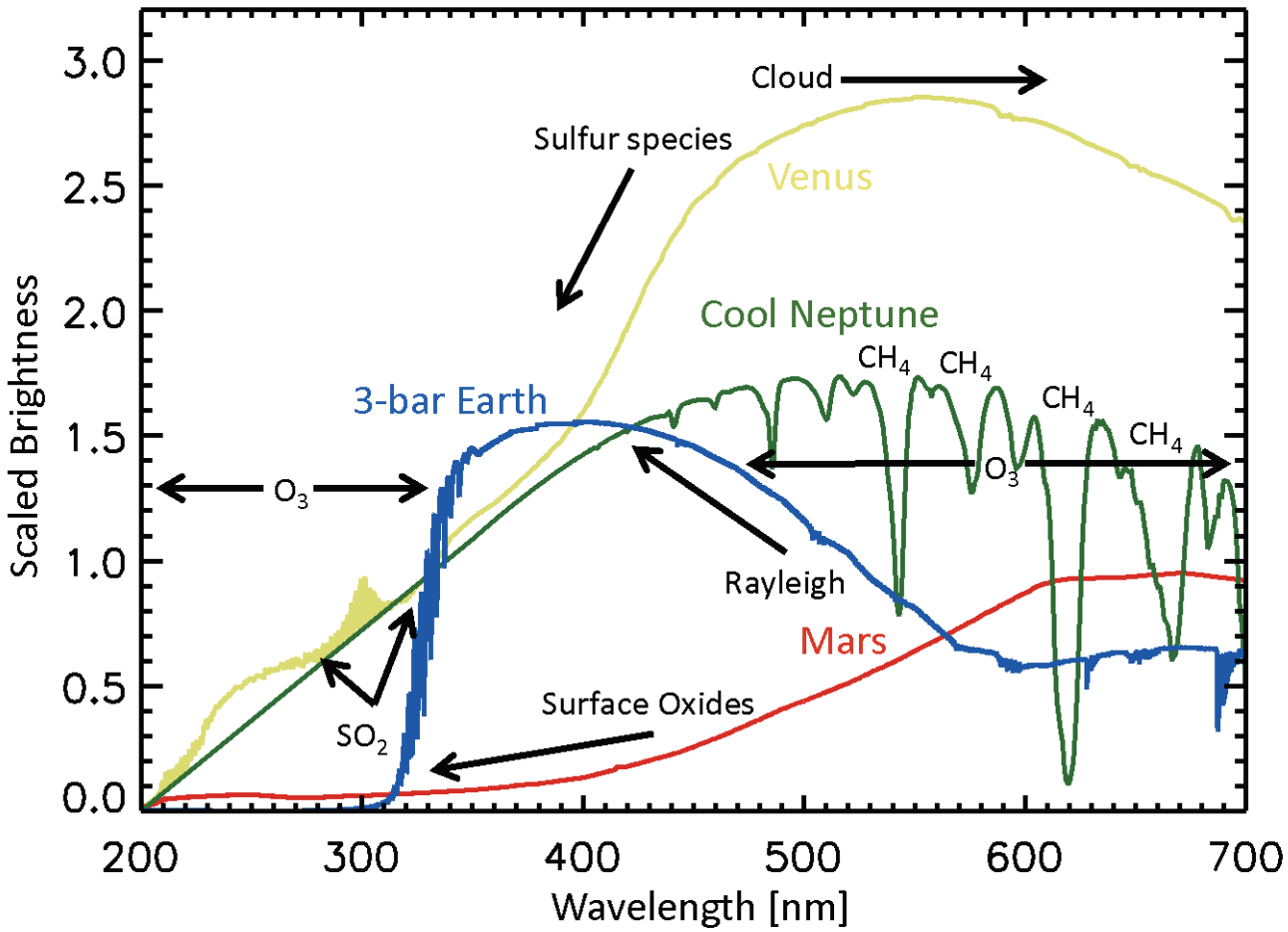


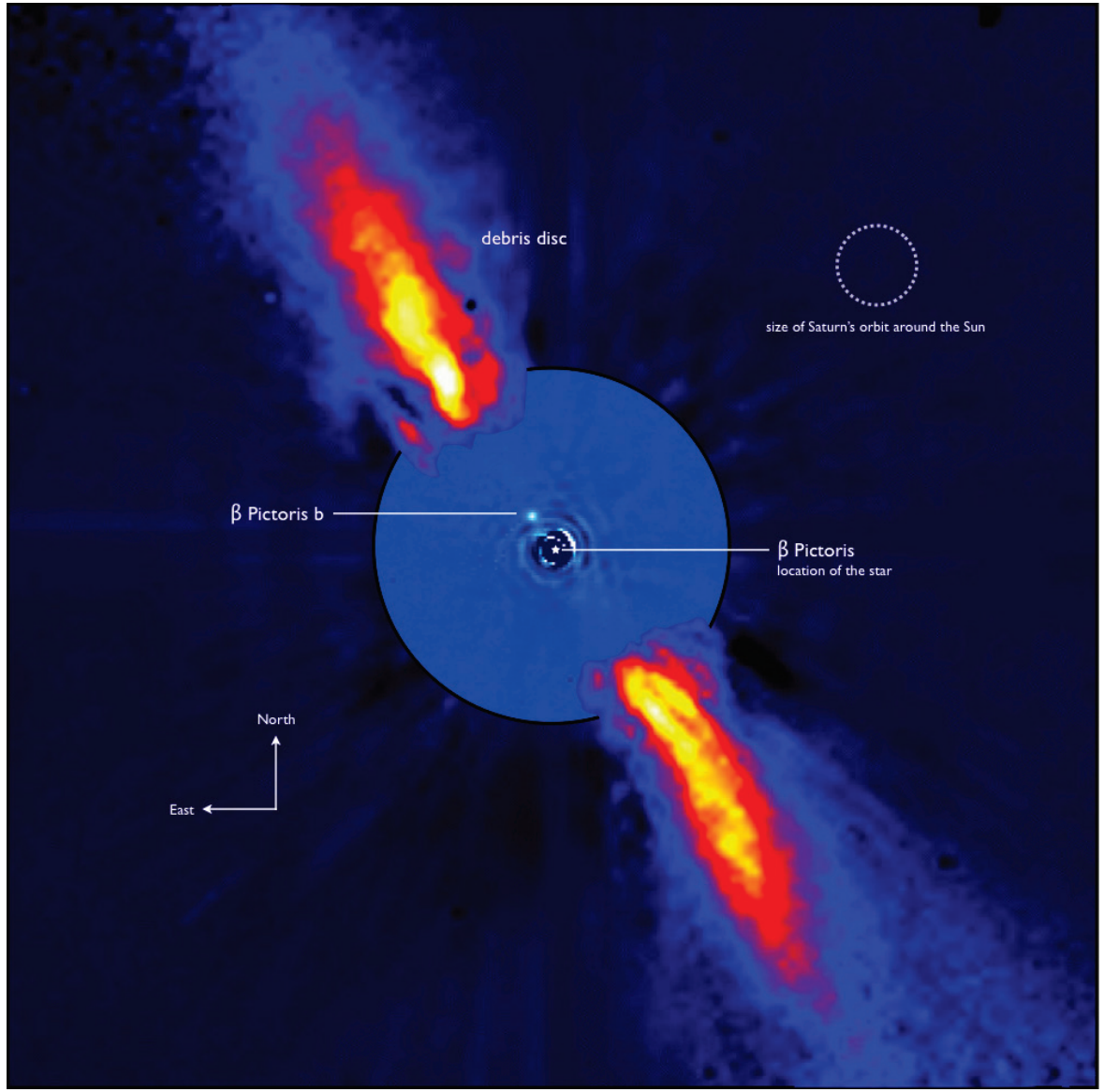
Figure Credit: T. D. Robinson

Circumstellar Dust

- HabEx optical observations are projected to be sensitive to ~0.3 times the solar system equivalent dust level around a solar twin at 10pc (10 to 100 times the sensitivity of LBTI for exozodiacal dust).

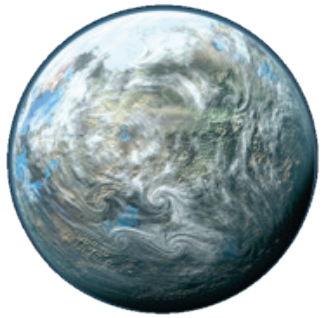
- HabEx will determine the dust origin in debris disks by observing whether dust disks are always associated with detectable planets (dynamical stirring by planets important) or not (self-stirred planetesimals).

- HabEx may also use dust structures driven by planetary perturbations to constrain planet masses.



Beta Pictoris planet in the NIR (at 3.6 microns with NACO on the VLT) and debris disk in reflected visible light. Credit: ESO/A.-M. Lagrange et al. (2008)

HabEx Science Goals



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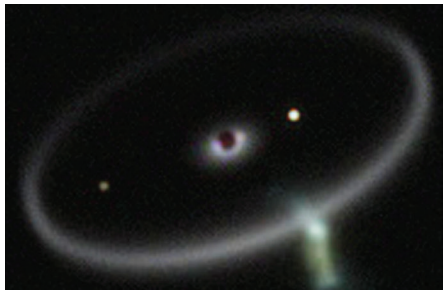

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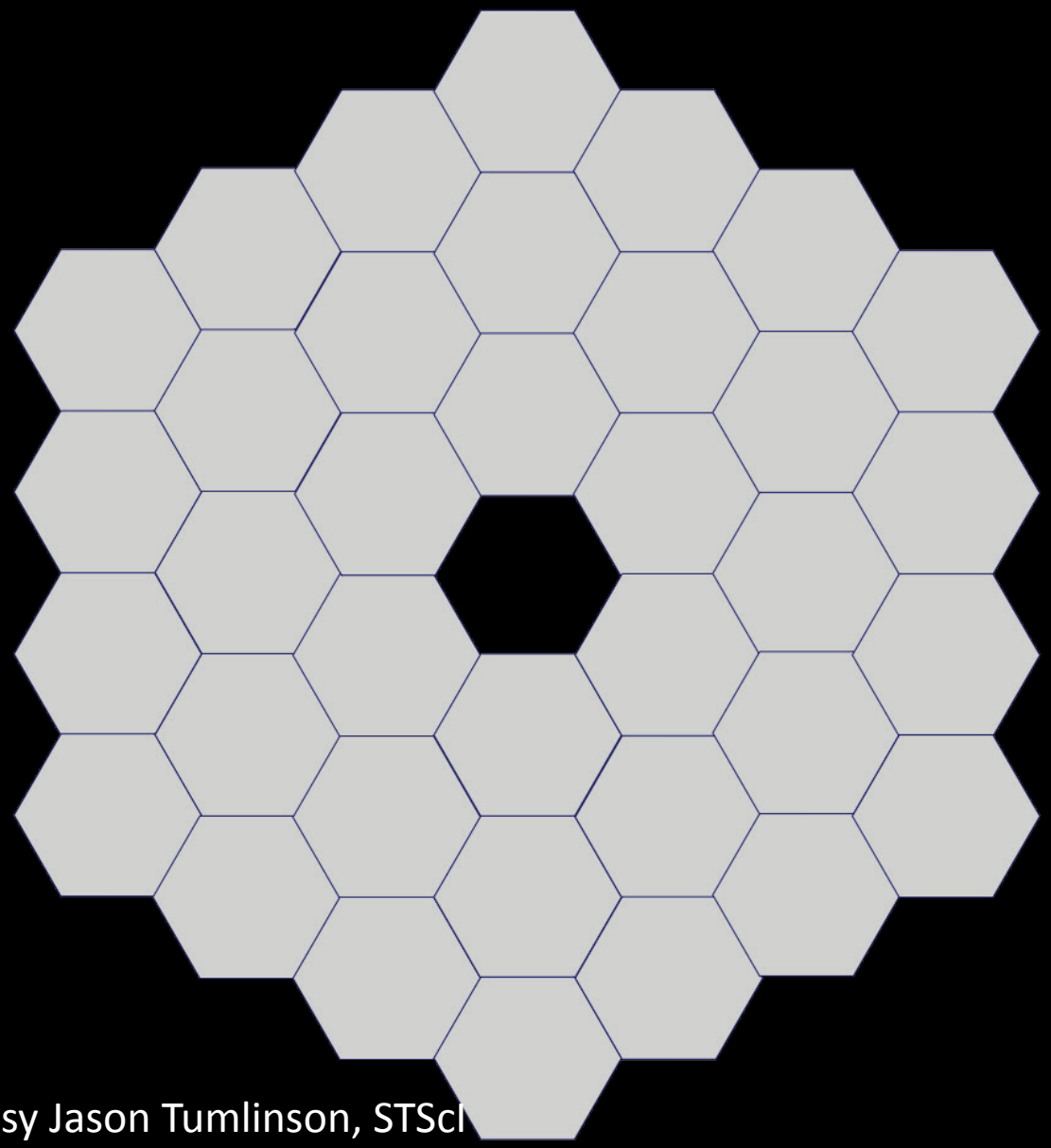
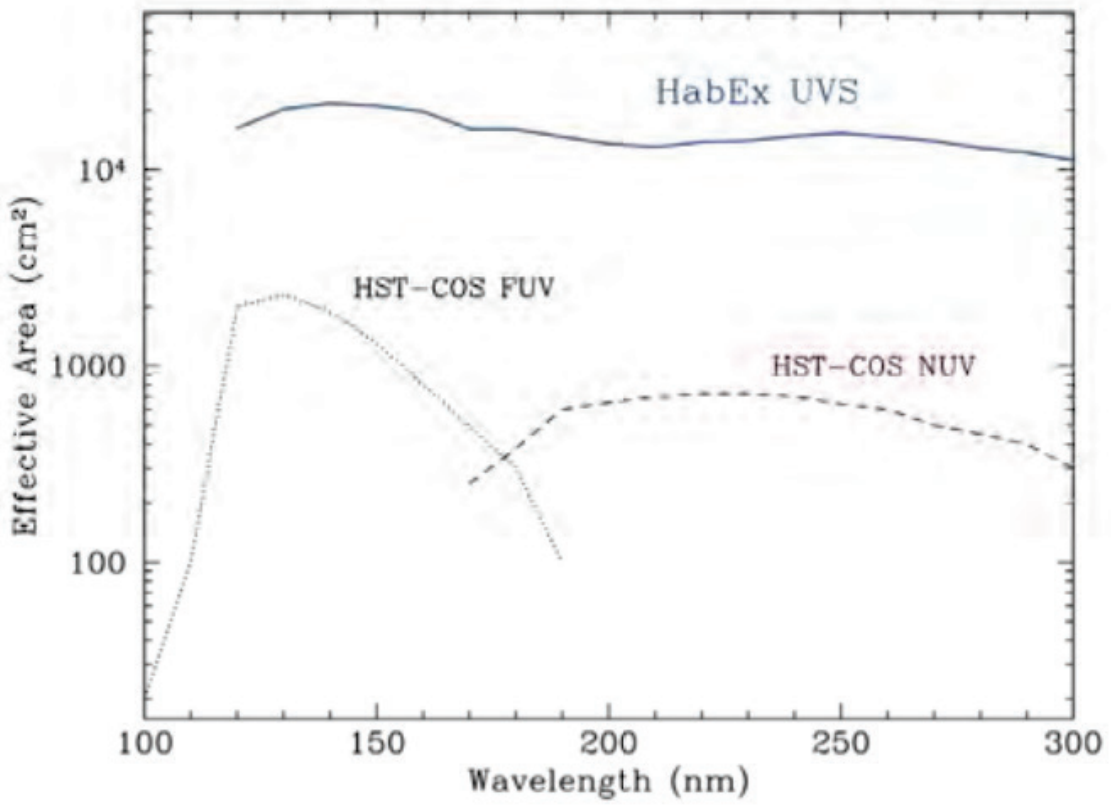
Observatory Science/General Astrophysics

- Consider existing/future telescopes: HST, JWST, WFIRST, Ground-based ELTs
- UV >2.5m provides a novel capability



Images Courtesy Jason Tumlinson, STScI

HabEx Includes Two “General Astrophysics” Instruments:



Workhorse Camera:

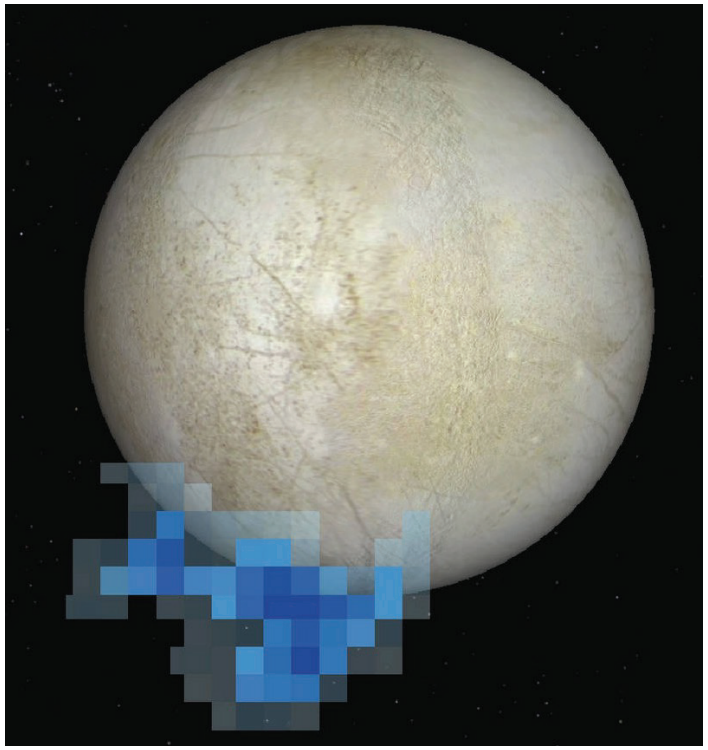
	UV/VIS channel	IR channel
FOV	3'x3'	3'x3'
Wavelength bands	150 nm - 400 nm	950 nm - 1800 nm
	400 nm - 950 nm	Stretch goal >=2.5 um
Pixel resolution	15.5 mas	24.5 mas
Telescope resolution	30.9 mas	49 mas
Design wavelength	600 nm	950 nm
Detector	3x3 CCD203	2 x2 H4RG10
Array width	12288 pixels	8192 pixels
Spectrometer	R=2000	R=2000
Aperture array	2x2 array 200x100 um 171x365 apertures	

High Resolution UV Spectrograph:

	UV channels
FOV	3'x3'
Wavelength bands	20 bands covering 120nm to 360 nm
Spectral resolutions	60,000 25,000 12,000 6000 3000 1000 500
Telescope resolution	Diffraction limited at 400 nm
Detector	6x6 MCP array, 100 mm sq each
Array width	60000 pixels
Aperture array	2x2 array 100x200 um 171x365 apertures

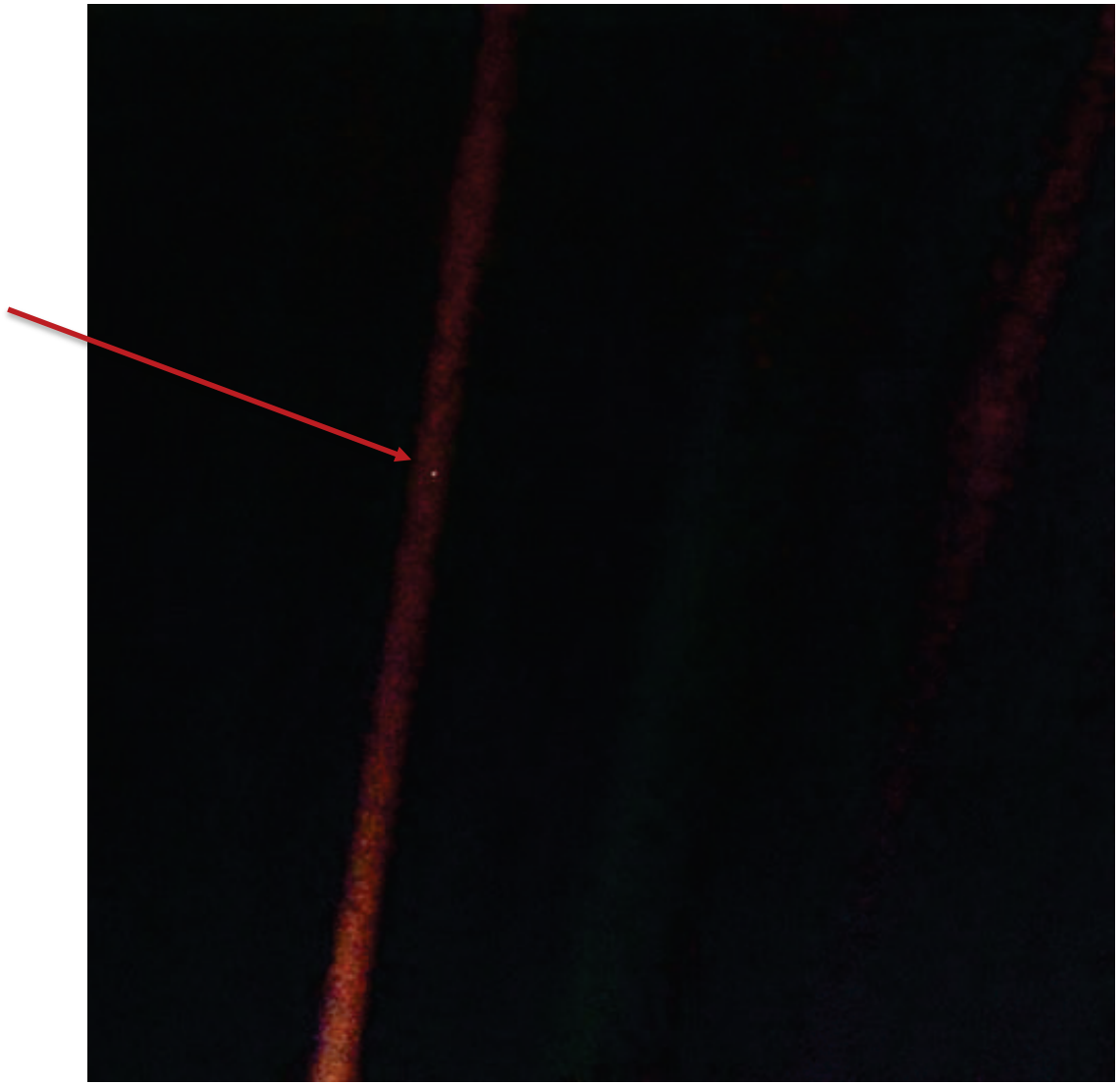
Observatory Science Themes:

- Hubble Constant
- Galaxy leakiness and reionization
- Cosmic Baryon Cycle
- Massive Stars & Feedback
- Stellar Archaeology
- Dark Matter (using Dwarf Galaxies)
- Planetary Aurora and Exospheres
- Plumes from Small Solar System Bodies
- Exoplanet Transit Spectra
- GO Observations of Bright Debris Disks



The Four Graces: John Clarke, Paul Scowen, Rachel Somerville, Dan Stern

Finding another pale blue dot



That's home. That's us. On it, everyone you ever heard of, every human being who ever lived, lived out their lives.
-Carl Sagan, 1994

HabEx