The Habitable Exoplanet Imaging Mission (HabEx):

Exploring our neighboring planetary systems, and searching for and characterizing potentially habitable Worlds.

Scott Gaudi (OSU – Community Chair)

Sara Seager (MIT – Community Chair)

Bertrand Mennesson (JPL – Center Study Scientist)

Keith Warfield (JPL – Study Manager)

(Figures and slides stolen from Maggie Turnbull, Paul Hertz, Ty Robinson, Chris Stark, Paul Scowen, Shawn-Domagal Goldman, Keith Warfield, and probably others…)

The HabEx STDT.
(mostly)

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 (+John Clarke and Chris Stark)

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

Communication Methodology.

- Regular, weekly STDT telecons: essential.
- Weekly leadership telecons: equally, if not more, essential.
- One community chair regularly attend the design team meetings enables a strong connection between the STDT and design team.
  - This facilitated the flow of information and aided in making informed design choices.

HabEx Study Goals.

- Highest-level goals:

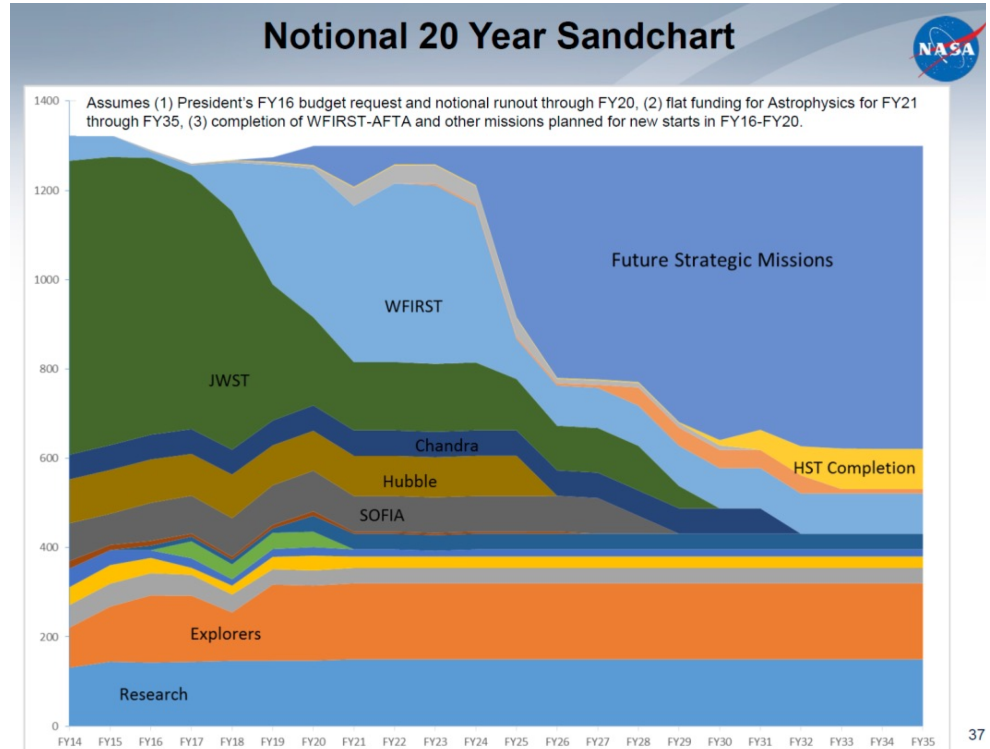
“Develop an optimal mission concept for characterizing the nearest planetary systems, and detecting and characterizing a handful of ExoEarths.”

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

- Optimal means:
  - Maximizing the science yield while maintaining feasibility, i.e., adhering to expected constraints.
- Constraints include:
  - Cost, technology (risk), time to develop mission.
- Thus some primary lower-level goals include:
  - Identify and quantify what science yields are desired and optimal.
  - Identify and quantify the range of potential constraints.

We have chosen to adopt convervative expectations.

- HabEx is adopting a *conservative* approach.
- From Keith Warfield's study of past decadal missions:
  - "All past missions prioritized by the Decadal Survey were thought to be under $3B"
  - Only allowed ~3 tooth fairies.

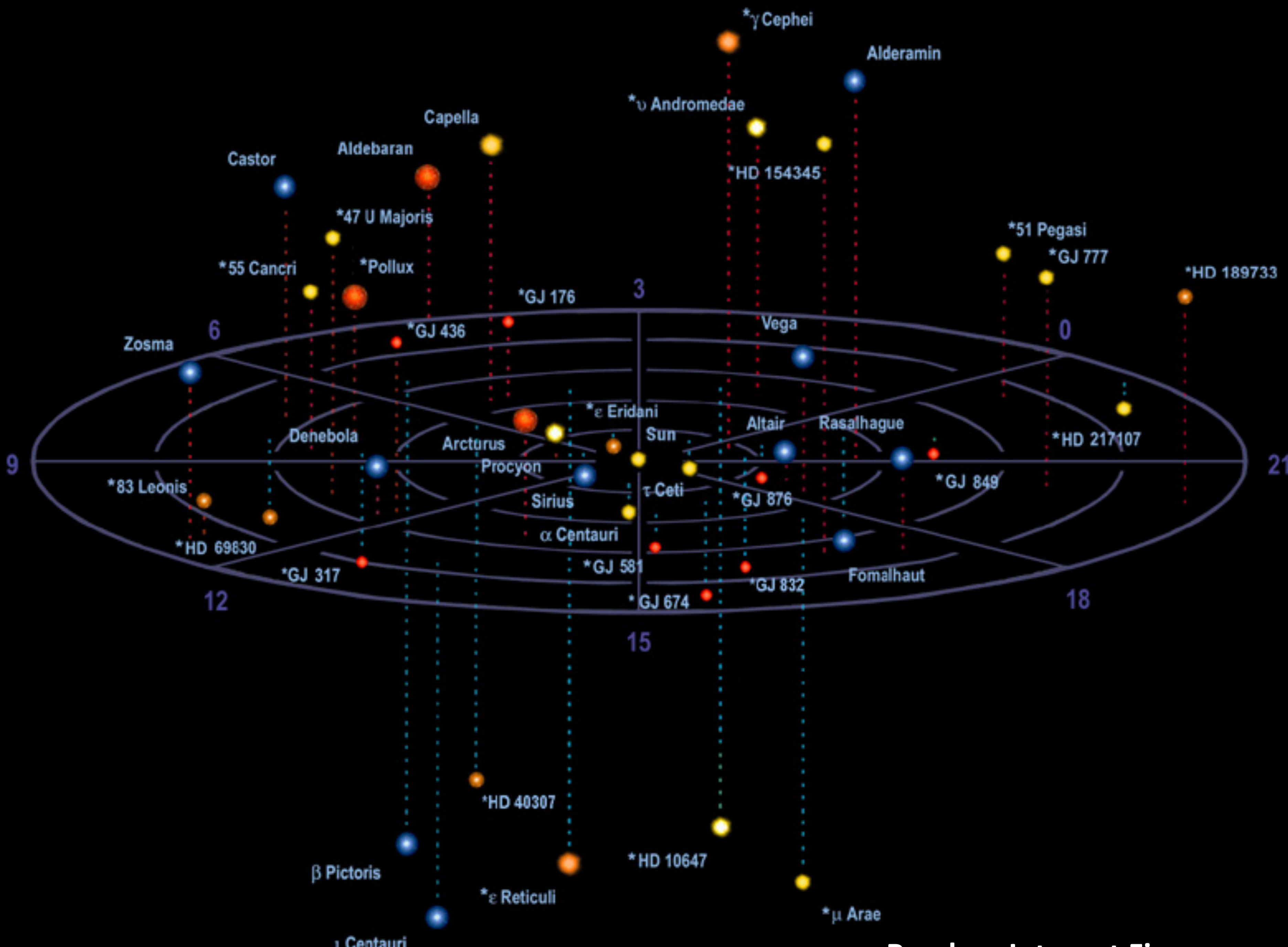


Paul Hertz

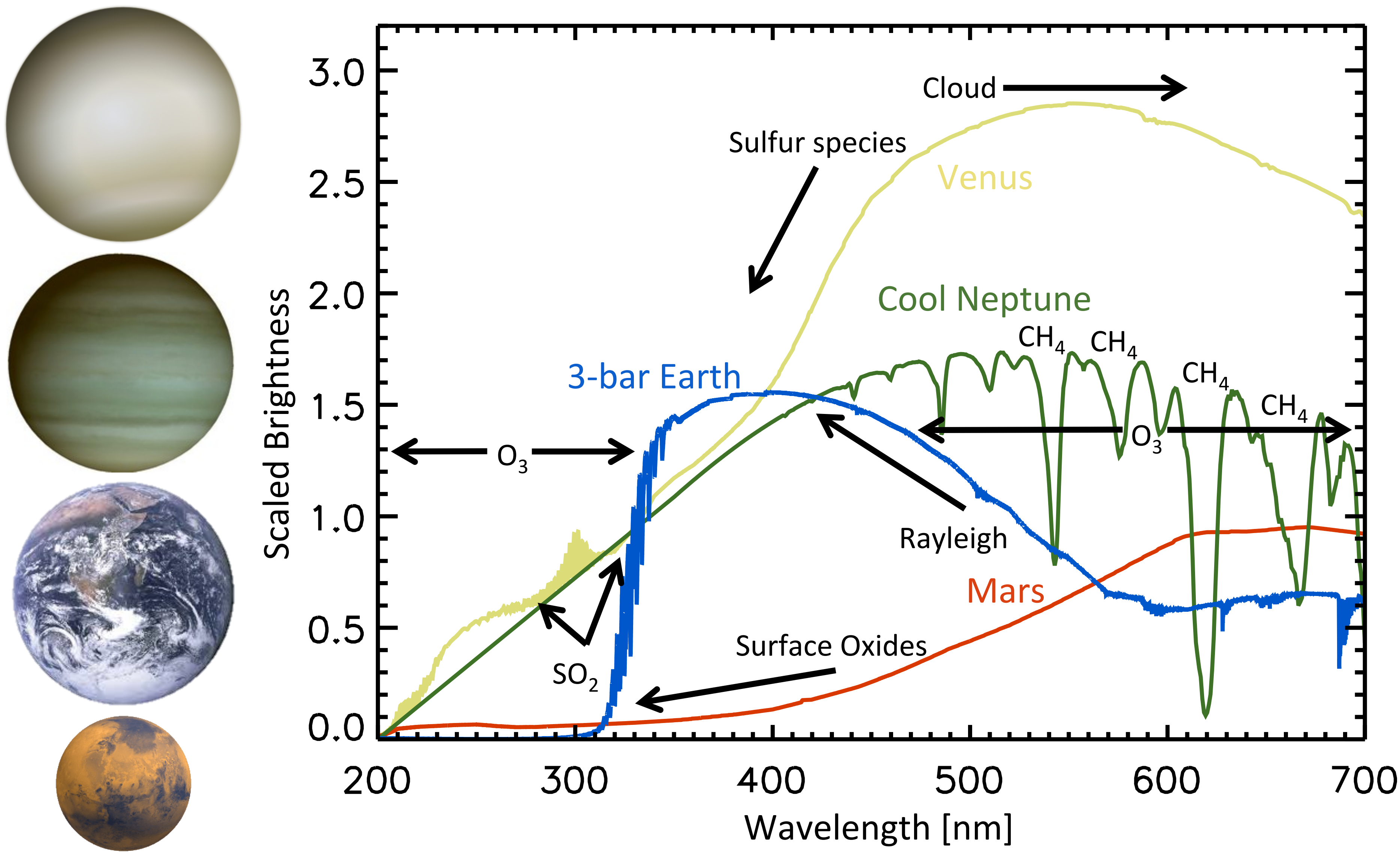
$7.0B by 2035 (likely out of date)

HabEx Science Goals.

- Exploration-based:
  - How many unique planetary systems can we explore in great detail, determine "their story", including finding and characterizing potential habitable worlds?
  - HabEx will explore N systems as systematically and completely as possible.
  - Leverage abundant pre-existing knowledge about our nearest systems, acquire as much additional information as possible.
  - Take the first step into the unknown!
- Search for Potentially Habitable Worlds
  - Detect and characterize a *handful* of potentially habitable planets.
  - Search for signs of habitability and biosignatures.
- Optimized for exoplanet imaging, but will still enable unique capabilities to study a broad range of general astrophysics topics.



Random Internet Figure



Courtesy of Ty Robinson

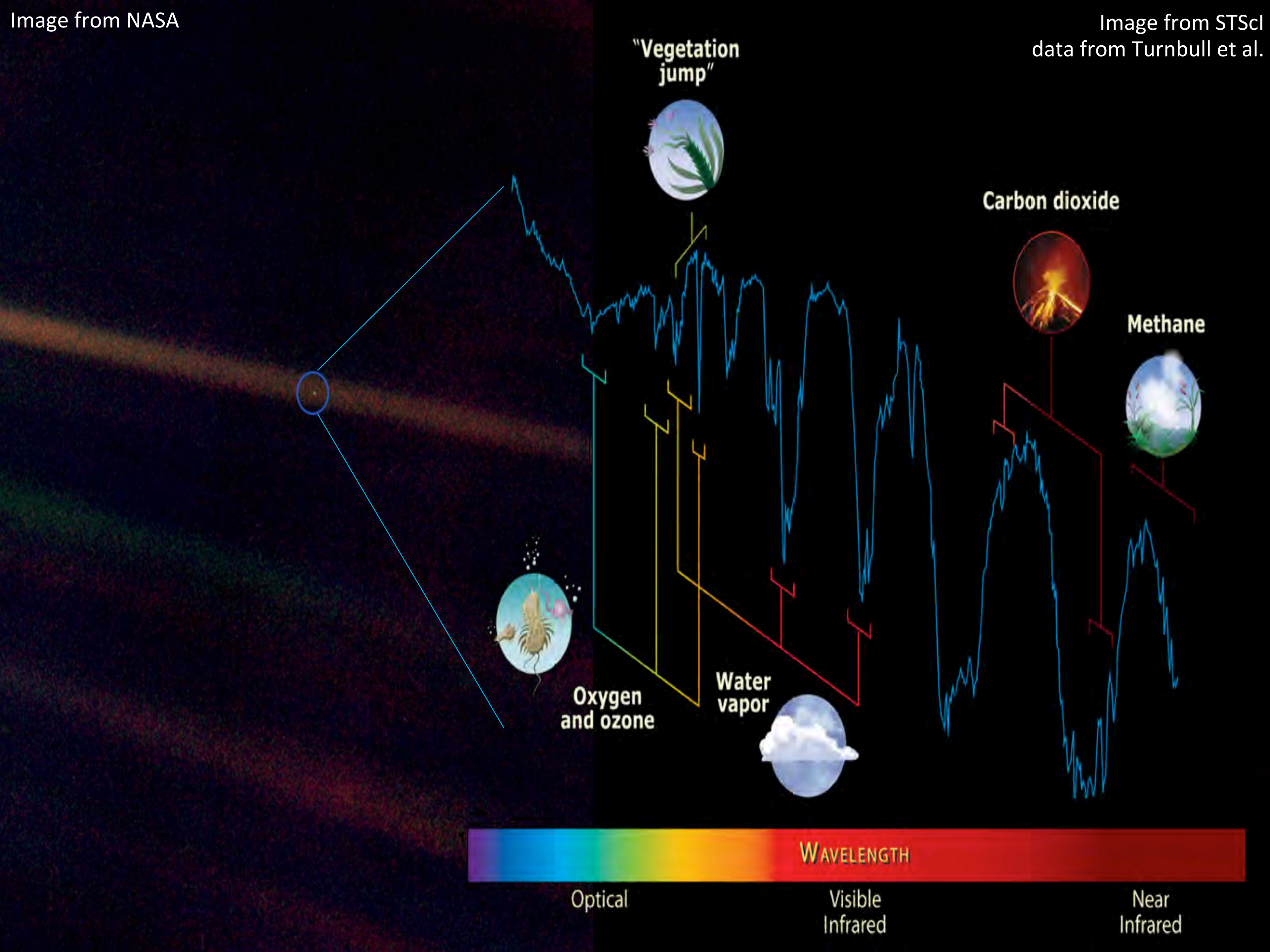
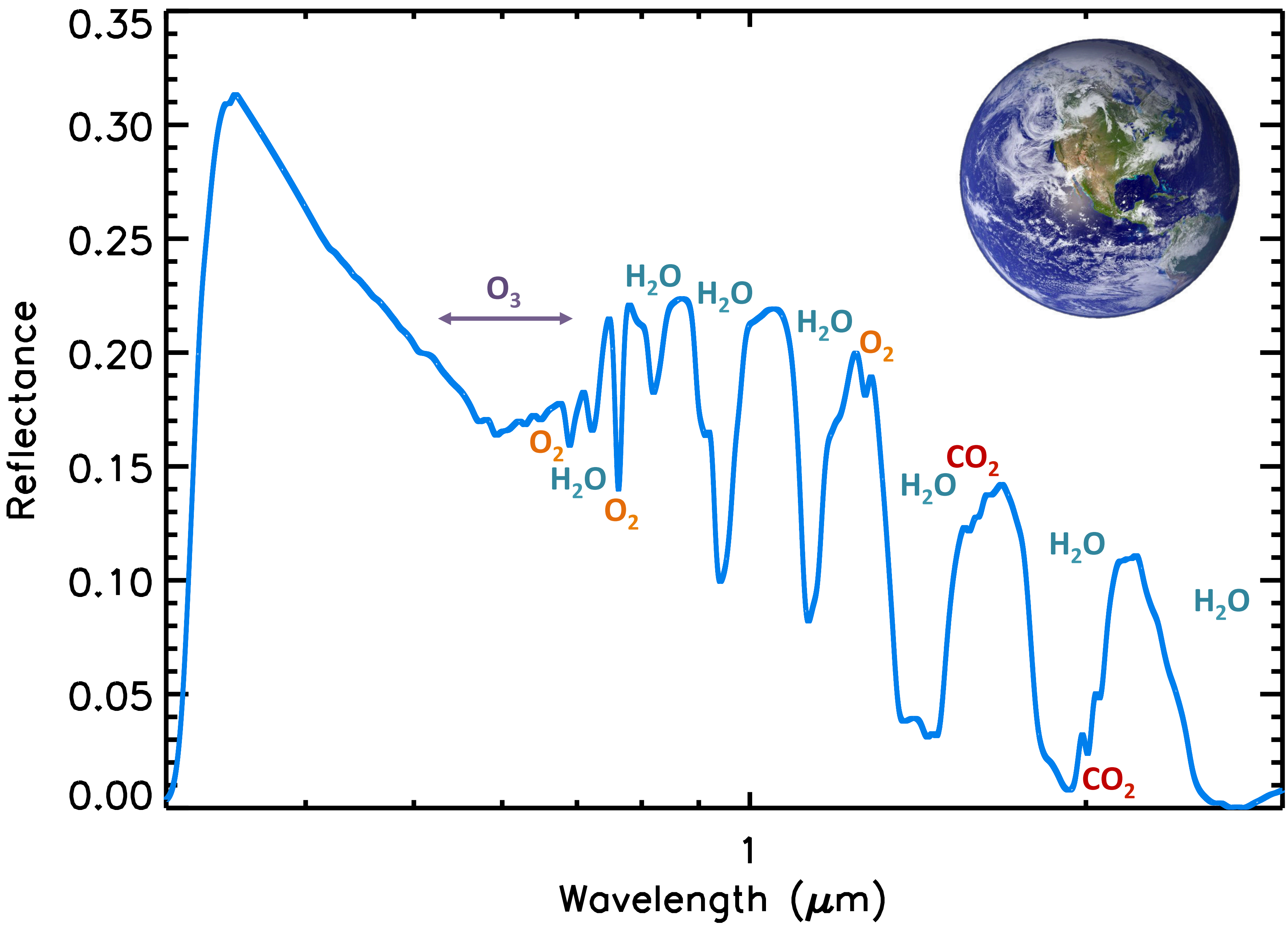


Image from NASA
Image from STScI
data from Turnbull et al.
"Vegetation jump"
Carbon dioxide
Methane
Oxygen and ozone
Water vapor
WAVELENGTH
Optical
Visible Infrared
Near Infrared



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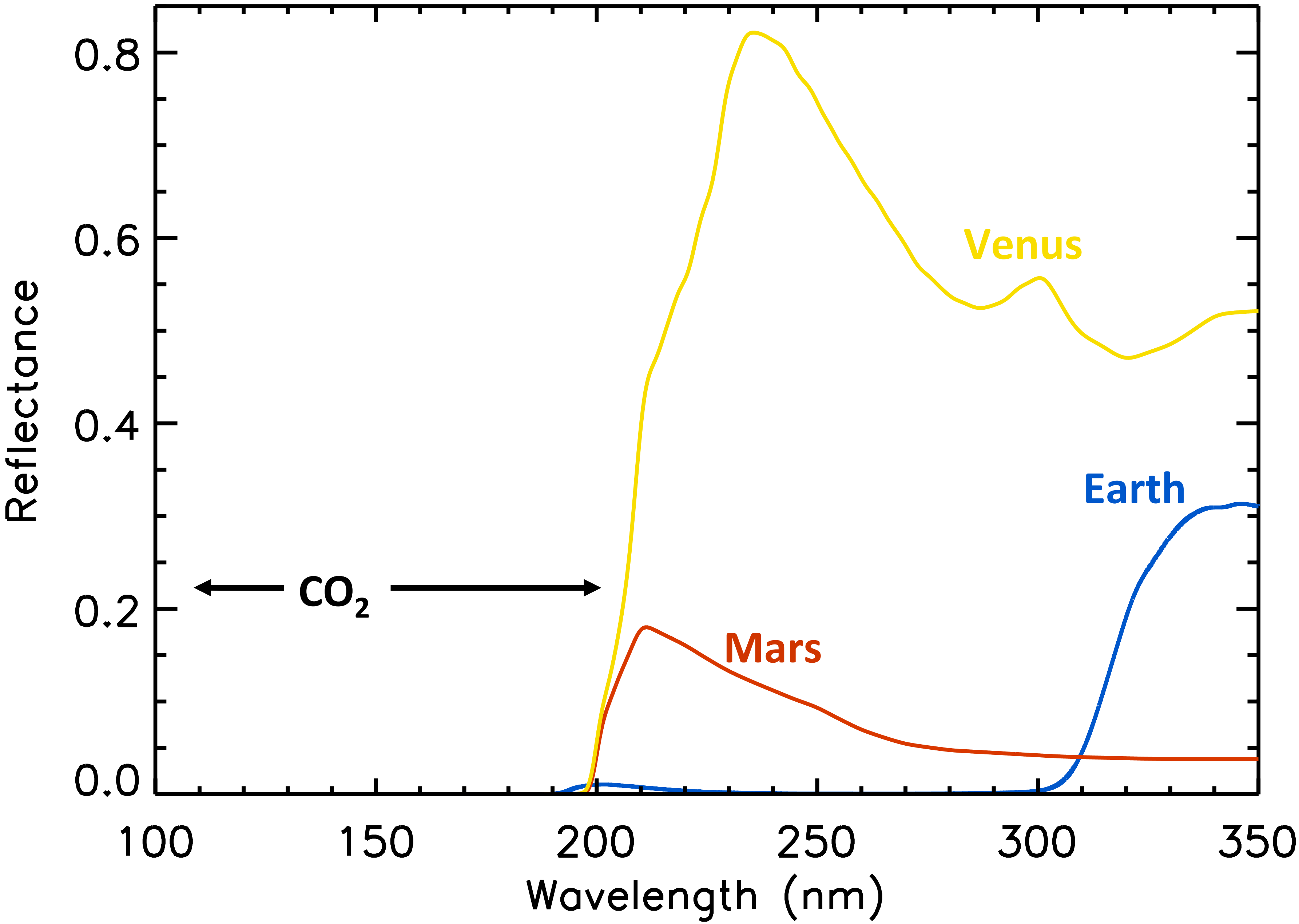
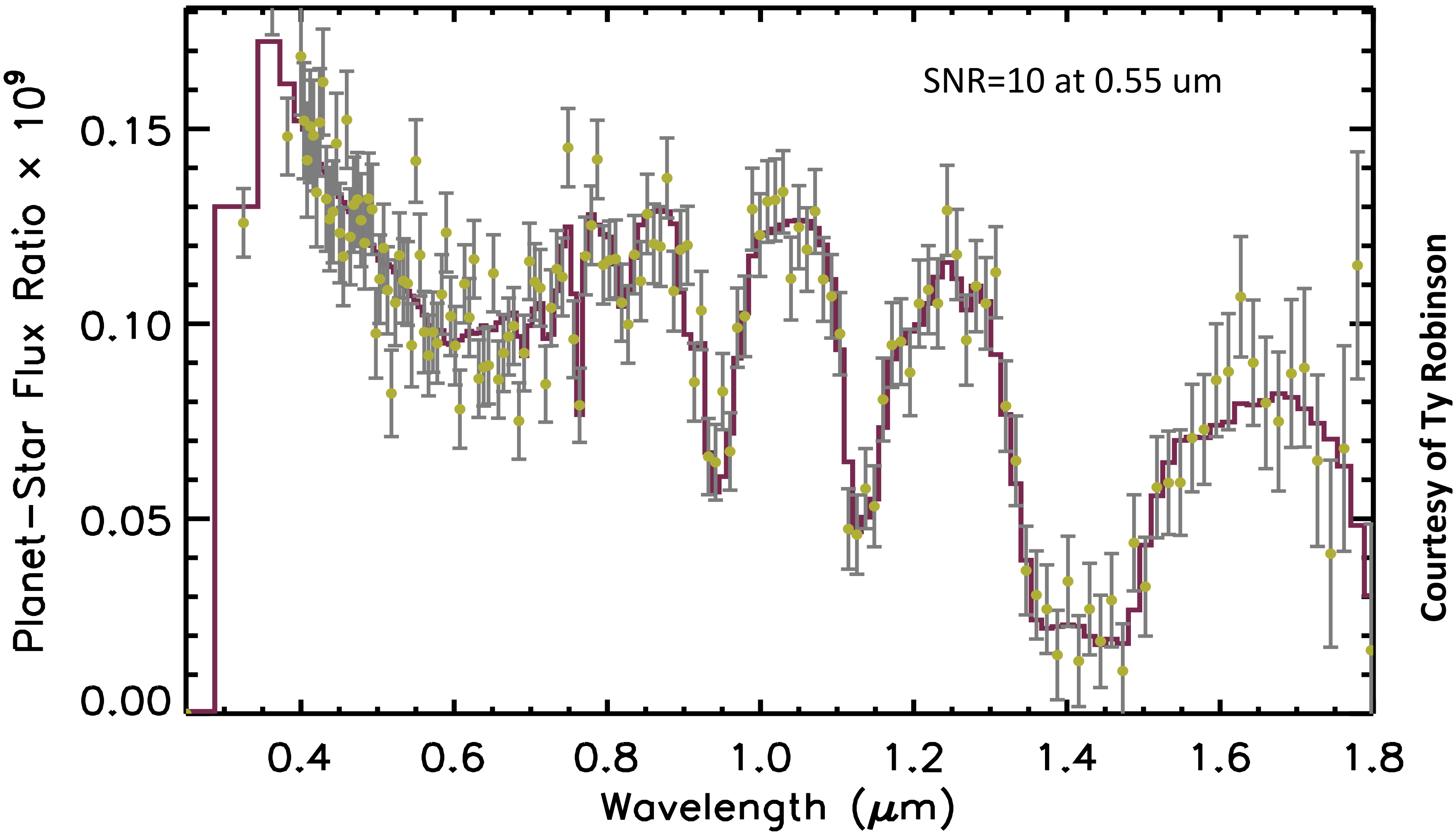


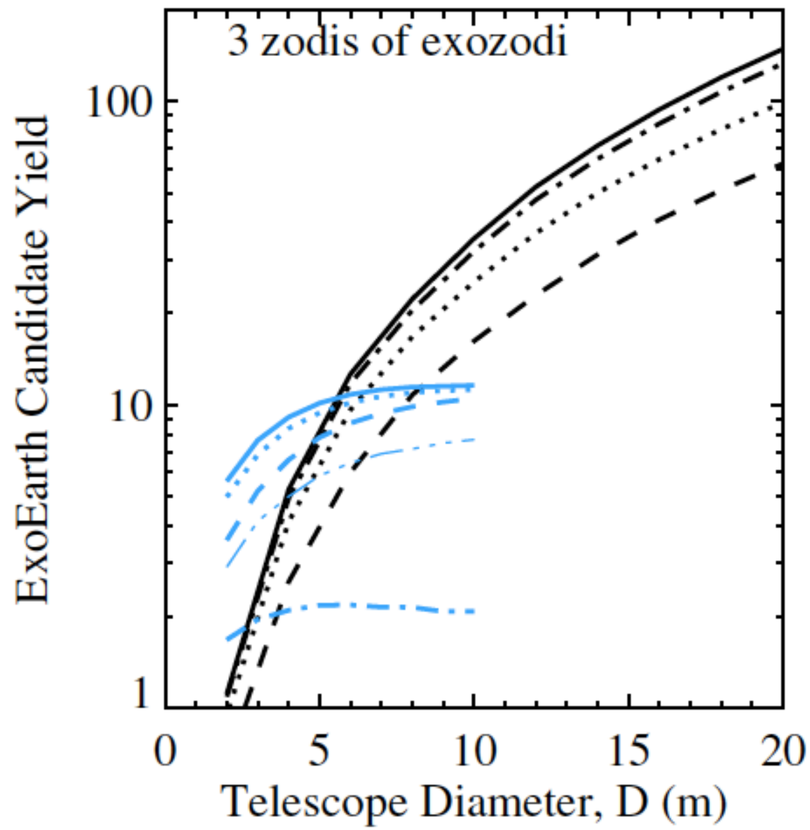
Courtesy of Ty Robinson



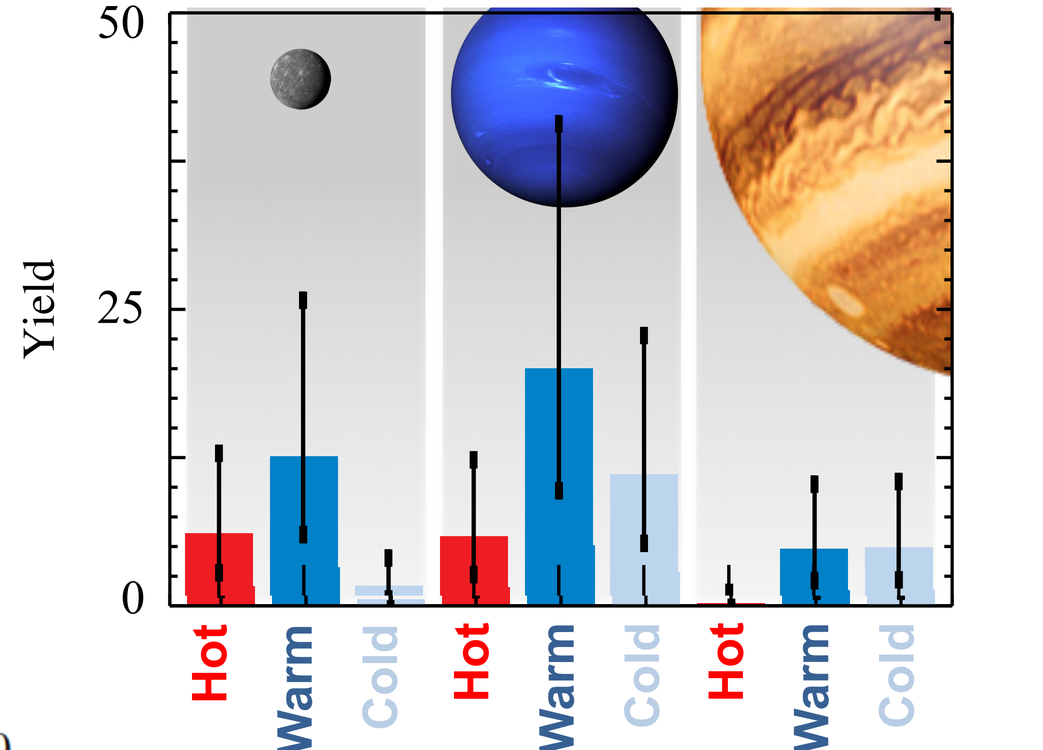
SNR=10 at 0.55μm
10^{-10} raw contrast
Constant 30% throughput
Integration time *per* bandpass

5m HabEx: 10 hr for a Earthlike planet at 5 pc
12m LUVOIR for a target at 12 pc.
5m HabEx: 30 hr at 7pc
12m LUVOIR: for a target at 17 pc.

Yields.



From Stark et al. 2016

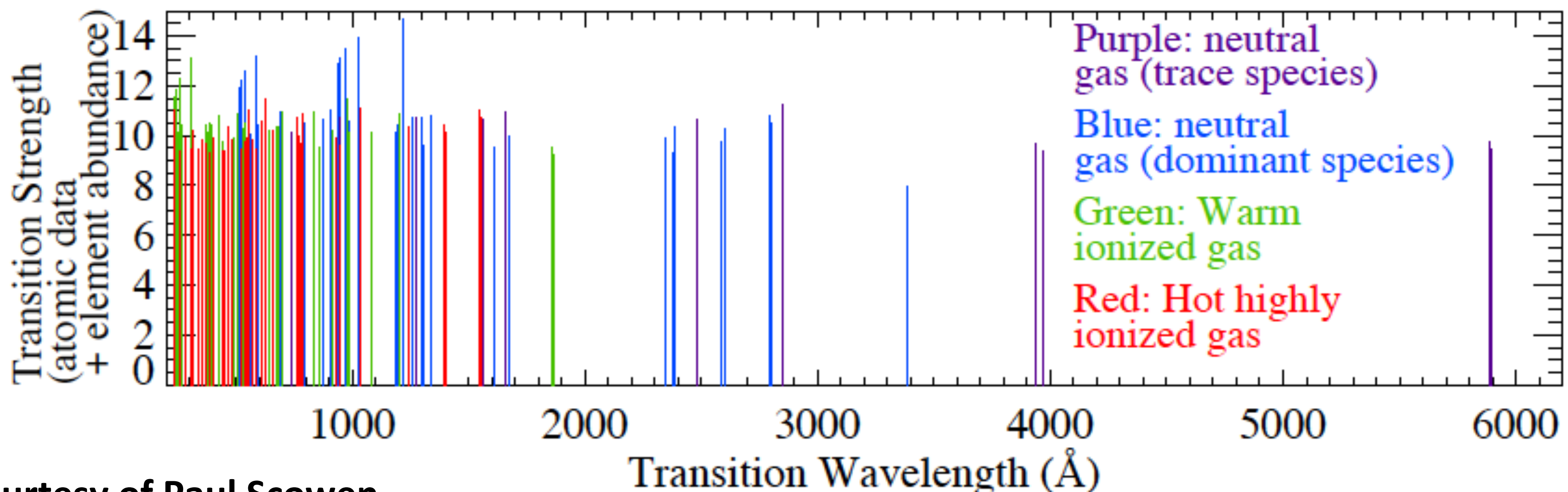


C. Stark, Using SAG13 Occurrence Rates

Solid: Detection only
Dotted: Three band detection, immediate characterization
Dashed: Detection and immediate characterization
Dot-Dashed: Full orbit before characterization
Triple-dot Dashed: Characterization, then orbits (starshade only)

General Astrophysics

- Consider what will be or has been available:
  - HST
  - JWST
  - Ground-based ELTs
- UV for >2.5m provides a novel capability
- UV Spectrometer and UVOIR Imager



Courtesy of Paul Scowen

General Astrophysics and Solar System Themes.

- Hubble Constant
- Escape Fraction
- Cosmic Baryon Cycle
- Massive Stars & Feedback
- Stellar Archaeology
- Dark Matter
- Planetary Aurora and Exospheres
- Plumes from Small Solar System Bodies

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

HabEx Design Team

Name	Role
Keith Warfield	Study Lead
Bertrand Mennesson	Study Center Scientist
Gary Kuan	Design Lead
Stefan Martin	Optics Lead
Joel Nissen	Systems & Structures; Stability
Rhonda Morgan	DRM & science yield
Stuart Shaklan	starshade & coronagraph expert
Doug Lisman	Starshade expert
David Webb	Starshade expert
Eugene Serabyn	coronagraph expert
John Krist	coronagraph expert
Alina Kiessling	associate center scientist
Bala Balasubramanian	coatings expert
Phil Stahl	MSFC - Telescope
Steve Warwick	Northrup Grumman - Starshade expert
Shouleh Nikzad	Detectors Lead
John Hennessy	detectors expert
Fang Shi	LOWFSC expert consultant

HabEx Design Status

- Completed several design trades before the 4m architecture trade
  - Polarization driven contrast vs. telescope F#
  - Coronagraph sensitivity to telescope induced wave front error
  - Starshade sizing vs bandwidth and inner working angle
  - Leveraged the LUVOIR Segmented Coronagraph Design and Analysis Study
  - Instrument sizing, cost and technical risk studies were conducted with Team X
  - Many technology assessments aimed at minimizing low TRL technology usage
- 4m Architecture trade is settled
  - Evaluated 4 architectures: starshade only, coronagraph only, starshade and coronagraph and two starshades
  - Baseline design is an unobscured telescope with a coronagraph and starshade
  - Primary general astrophysics instrument is a UV spectrograph with a wide field "workhorse" camera as a possible second contributed instrument

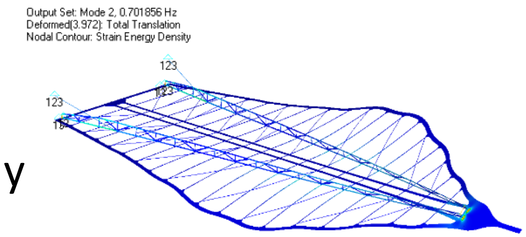
TRADE STATEMENT: Recommend a 4m exoplanet direct detection architecture for HabEx study concept development

	Requirements and figures of Merit (MUSTs, WANTs, Risks and Opportunities)	Assignee/ Working Group	Weight		3		4		9		10	
					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	
	WANTS (DISCRIMINATORS)	Grand Total		100		868		834		832		780
	Technical			***70***		***658***		***624***		***532***		***540***
W0	Measure orbits of all detected planets with periods < 3x mission	AEIWG	High	5		10		8		10		5
W0b	Maximize the number of orbits measured for habitable zone			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	Med /High	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	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	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
W8	*Telescope design allows for more than one GA instrument*	Gen astro	*High*	5		10		10		10		10
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	1SLS	10
W16	Graceful descopes		Med	2		8		8		5		5
	Schedule					***160***		***160***		***200***		***160***
W6b	Reach TRL 5 at earliest possible	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

Evaluation

Used Kepner-Tregoe (KT) Methology to settle on an architecture.

HabEx Design Status



- JPL and NGAS Starshade designs have been completed
  - Mechanical and thermal performance analyses are under way with the JPL design
- The telescope and instrument optical layouts have been completed
- Telescope design is well under way
- Team X designs of the starshade and telescope buses are in draft form
- Currently pursuing a telescope bus design without reaction wheels
  - Micro-thruster technology is flight proven
  - Simplifies the design and reduces risk
- Extensive technology TRL discussions with ExEP in advance of the P&L meeting and O2 delivery
- Working to complete instrument designs, micro-thruster/telescope stability modeling, and starshade thermal performance simulations

Architectures.

Property (Baseline)	Architecture #1	Architecture #2
Aperture	4m	6.5m
Primary Mirror	Monolithic, Al, f/2.5	Segmented (TBD)
Secondary Mirror	Off-axis	Off-axis (TBD)
Stabilization	Laser Metrology (M2)	TBD
Coatings	M1, M2, M3: Al	TBD
Coronagraph Instrument	HLC/VV6, Ag (OIR)	TBD
Wavelength (high contrast)	250nm-1.8µm	TBD
Wavelength (GA)	120nm-1.8µm (stretch 90nm-2µm)	TBD
Starshade	Yes, ~70m (TBR) UVOIR	TBD
General Astrophysics Instrument #1	Workhorse UVOIR Camera (10 arcmin^2 FOV, diff. limited at 400nm), Microshutter arrays	TBD
General Astrophysics Instrument #2	High Res; 60k UV Spectrograph, Microshutter arrays	TBD

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	4	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.

Lessons Learned: Decision Making

- Small working groups with strong leads are a productive way of focusing effort into answering specific questions, developing science cases, and exploring technology requirements
- The K-T matrix methodology was very useful for highlighting objective differences between different architectures and getting STDT buy-in on one specific architecture
- The K-T matrix methodology, combined with the working group products, was very helpful in building intuition about how survey strategy, science yield, risk, cost, and complexity play against the specific architecture trades.
- Limiting the Tradespace is a process
  - Trade constraints must not only be justified but their science consequences must also be understood
  - Technology risks require time to assess and to socialize
    - Effort is needed to gain acceptance inside and outside of the STDT
    - It takes time to get the STDT to recognize and accept only enabling technologies

Summary

Primary HabEx Science Goals:

- Develop an optimal mission concept for characterizing the nearest planetary systems, and detecting and characterizing a handful of ExoEarths.
- Enable a broad range of solar system and general astrophysics.

Our overall Approach:

- Maximizing the science yield while maintaining feasibility, i.e., adhering to *conservative* expectations on constraints: cost, technology, risk, time to develop mission.

Considering Two Architectures:

- 4m monolith.
- 6.5m segmented.
- This is a complex region of trade space.

For the 4m Architecture:

- Six enabling TRL 3 technologies that need to be matured: 4 starshade, 2 coronagraph.
- Expect two TRL 3 technologies by final report.