How Lonely (or not) is the Universe?
aka “future IROUV flagship”
aka Habitable Worlds Observatory

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Astrophysics Division, NASA Headquarters

Sagan Exoplanet Summer Workshops

The Sagan Exoplanet Summer Workshops are held annually and provide opportunities for students, postdocs, and researchers to learn about the engineering and scientific application of exoplanet-related techniques used in NASA's Exoplanet Exploration Program.

2023: **Characterizing Exoplanet Atmospheres: The Next Twenty Years**

2022: **Exoplanet Science in the Gaia Era**

2021: **Circumstellar Disks and Young Planets**

2020: **Extreme Precision Radial Velocity**

2019: **Astrobiology for Astronomers**

2018: **Did I Really Just Find an Exoplanet?**

2017: **Microlensing in the Era of WFIRST**

2016: **Is There a Planet in My Data? Statistical Approaches to Finding and Characterizing Planets in Astronomical Data**

2015: **Exoplanetary System Demographics: Theory and Observations**

2014: **Imaging Planets and Disks**

2013: *workshop cancelled due to federal government sequestration*

2012: **Working with Exoplanet Light Curves**

2011: **Exploring Exoplanets with Microlensing**

2010: **Stars as Homes for Habitable Planetary Systems**

2009: **Exoplanetary Atmospheres**

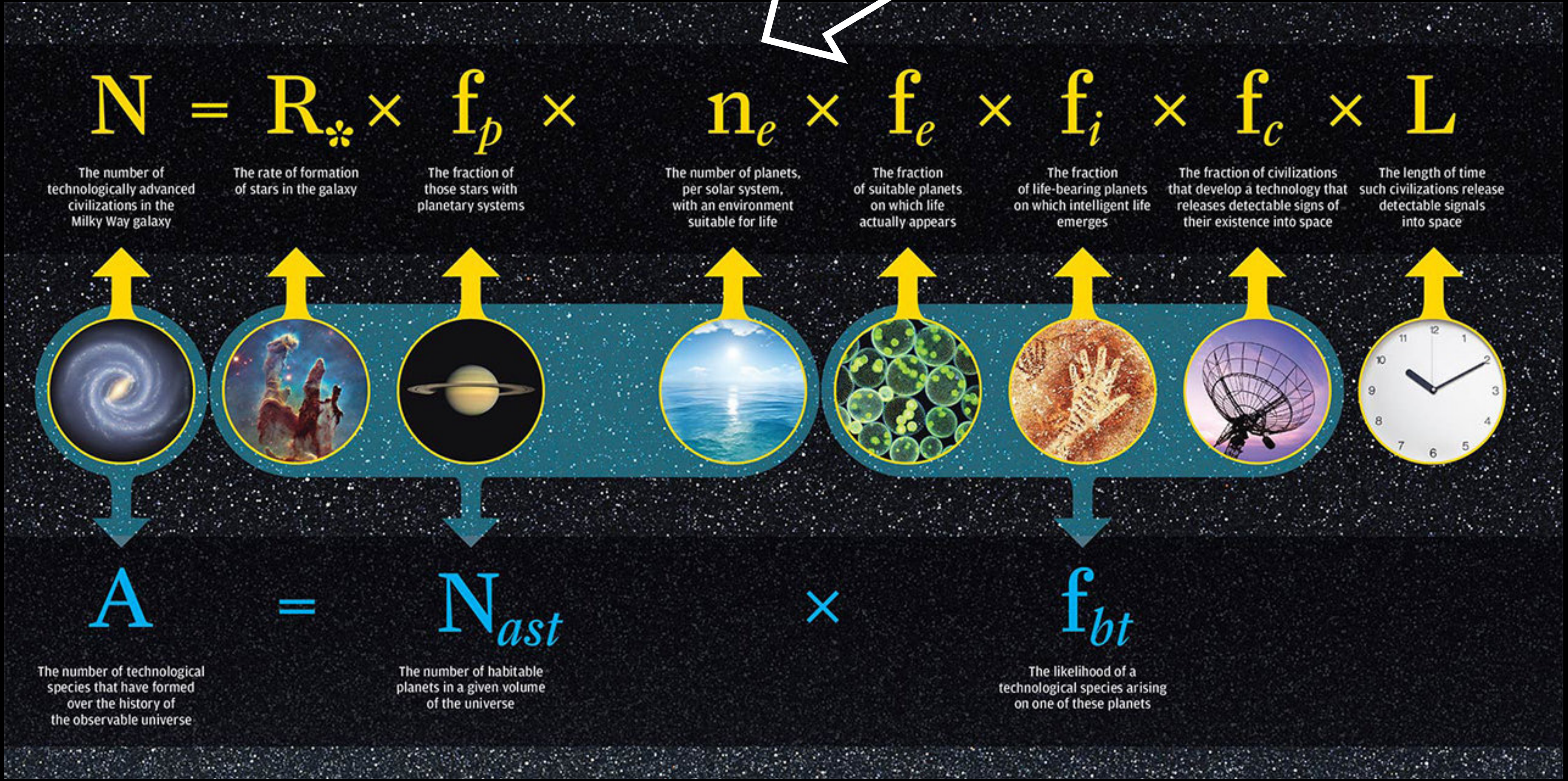
Tilt-a-Worlds: Effects of High Rates of Obliquity Change on the Habitability of Extrasolar Planets

Show affiliations

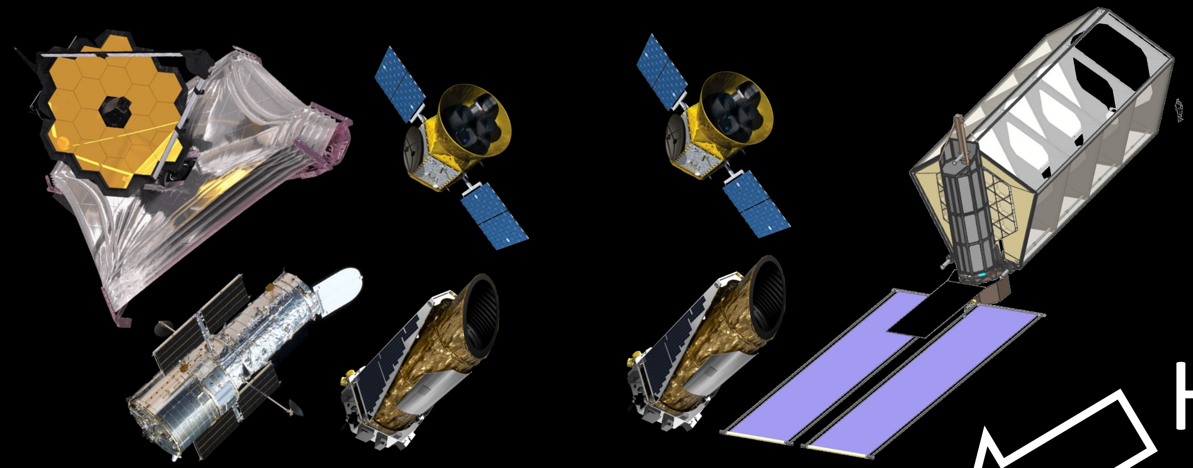
Domagal-Goldman, Shawn ; Barnes, R. ; Armstrong, J. C. ; Breiner, J. ; Meadows, V. S.

We explore the impact of obliquity variations on planetary habitability in hypothetical systems with high mutual inclination. For the hypothetical systems, we restrict our exploration to systems consisting of a solar-mass star, an Earth-mass planet at 1 AU, and 1 or 2 giant planets. We verify that these systems are stable for 10^8 years with N-body simulations. We then calculate the obliquity variations induced by the orbital architecture on the Earth-mass planets. We find that in some cases the spin axes can rotate through 360 degrees in as little as 10,000 years (John is that right? Can you look through the systems and find the most extreme case of obliquity variation?) Next, we run energy balance models (EBM) on the terrestrial planets to assess surface temperature and ice coverage on the planets' oceans. Finally, we explore differences in the outer edge of the habitable zone for planets with rapid obliquity variations. We run EBM simulations for a range of values for the semi-major axis, assuming that the obliquity variations of the nominal system (terrestrial planet at 1 AU) are typical for each orbital architecture. We find that planets undergoing extreme axial perturbations may be habitable at larger distances than those with static

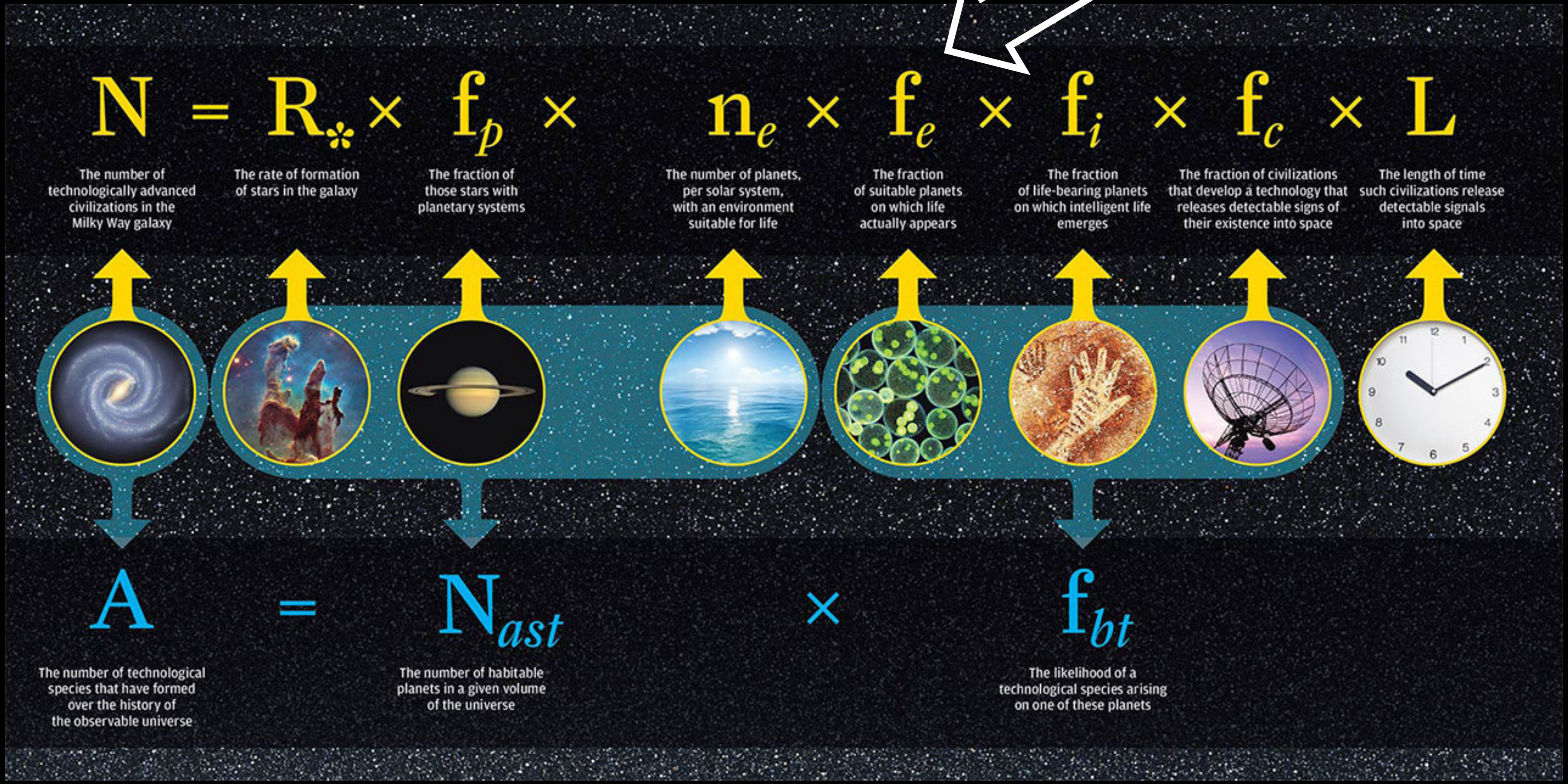
We are here.



N = R* × fp × ne × fe × fi × fc × L
The number of technologically advanced civilizations in the Milky Way galaxy
The rate of formation of stars in the galaxy
The fraction of those stars with planetary systems
The number of planets, per solar system, with an environment suitable for life
The fraction of suitable planets on which life actually appears
The fraction of life-bearing planets on which intelligent life emerges
The fraction of civilizations that develop a technology that releases detectable signs of their existence into space
The length of time such civilizations release detectable signals into space
A = Nast × fbt
The number of technological species that have formed over the history of the observable universe
The number of habitable planets in a given volume of the universe
The likelihood of a technological species arising on one of these planets



HWO takes us here.



National Aeronautics and Space Administration

Exoplanet Travel Bureau

While there is much debate over which exoplanet discovery is considered the "first," one stands out from the rest. In 1995, scientists discovered 51 Pegasi b, forever changing the way we see the universe and our place in it. The exoplanet is about half the mass of Jupiter, with a seemingly impossible, star-hugging orbit of only 4.2 Earth days. Not only was it the first planet confirmed to orbit a sun-like star; it also ushered in a whole new class of planets called Hot Jupiters: hot, massive planets orbiting closer to their stars than Mercury. Today, powerful observatories like NASA's Kepler space telescope, will continue the hunt of distant planets.

NASA's Exoplanet Exploration Program. Jet Propulsion Laboratory, Pasadena CA.
exoplanets.nasa.gov

www.nasa.gov

National Aeronautics and Space Administration

Exoplanet Travel Bureau

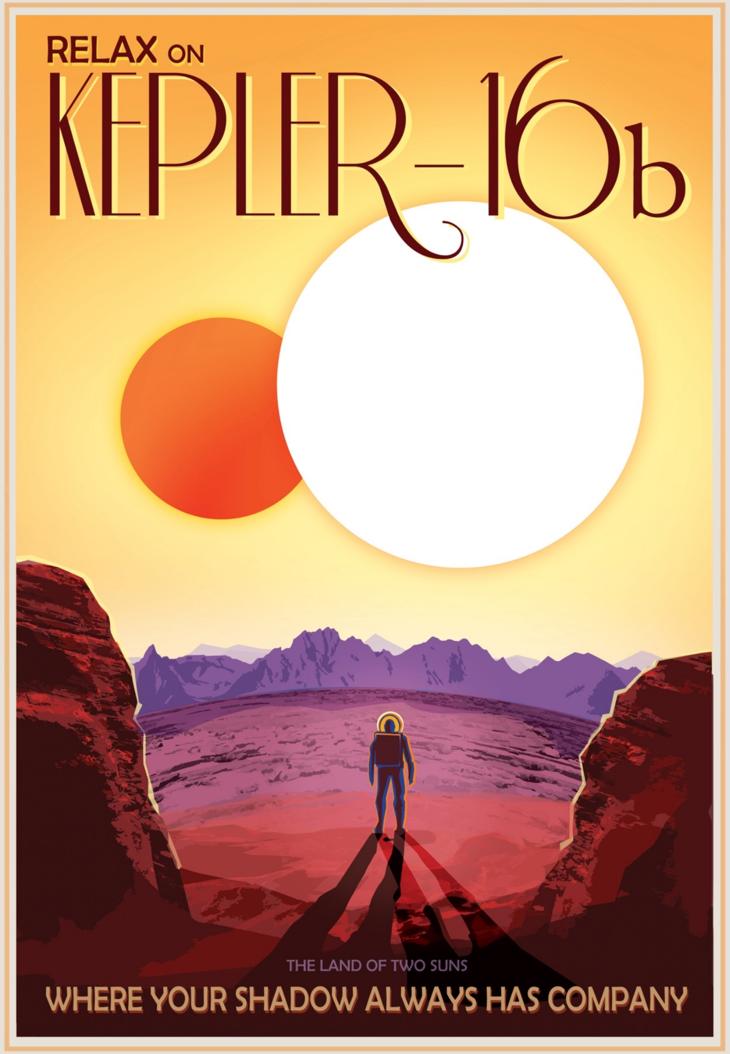
Discovered in October 2013 using direct imaging, PSO J318.5-22 belongs to a special class of planets called rogue, or free-floating, planets. Wandering alone in the galaxy, they do not orbit a parent star. Not much is known about how these planets come to exist, but scientists theorize that they may be either failed stars or planets ejected from very young systems after an encounter with another planet. These rogue planets glow faintly from the heat of their formation. Once they cool down, they will be dancing in the dark. Confirmed and candidate exoplanets and all available data are listed in the NASA Exoplanet Archive.

NASA's Exoplanet Exploration Program. Jet Propulsion Laboratory, Pasadena CA.
exoplanets.nasa.gov

www.nasa.gov

National Aeronautics and Space Administration

Exoplanet Travel Bureau



Like Luke Skywalker's planet "Tatooine" in *Star Wars*, Kepler-16b orbits a pair of stars. Depicted here as a terrestrial planet, Kepler-16b might also be a gas giant like Saturn. Prospects for life on this unusual world aren't good, as it has a temperature similar to that of dry ice. But the discovery indicates that the movie's iconic double-sunset is anything but science fiction.

NASA's Exoplanet Exploration Program. Jet Propulsion Laboratory, Pasadena CA.
exoplanets.nasa.gov

www.nasa.gov

National Aeronautics and Space Administration

Exoplanet Travel Bureau

Kepler-186f is the first Earth-size planet discovered in the potentially 'habitable zone' around another star, where liquid water could exist on the planet's surface. Its star is much cooler and redder than our Sun. If plant life does exist on a planet like Kepler-186f, its photosynthesis could have been influenced by the star's red-wavelength photons, making for a color palette that's very different than the greens on Earth. This discovery was made by *Kepler*, NASA's planet-hunting space telescope.

www.nasa.gov

NASA's Exoplanet Exploration Program. Jet Propulsion Laboratory, Pasadena CA.
exoplanets.nasa.gov

National Aeronautics and Space Administration

Exoplanet Travel Bureau

Some 40 light-years from Earth, a planet called TRAPPIST-1e offers a heart-stopping view: brilliant objects in a red sky, looming like larger and smaller versions of our own moon. But these are no moons. They are other Earth-sized planets in a spectacular planetary system outside our own. These seven rocky worlds huddle around their small, dim, red star, like a family around a campfire. Any of them could harbor liquid water, but the planet shown here, fourth from the TRAPPIST-1 star, is in the habitable zone, the area around the star where liquid water is most likely to be detected. This system was revealed by the TRAnsiting Planets and PlanetesImals Small Telescope (TRAPPIST) and NASA's Spitzer Space Telescope. The planets also are excellent targets for NASA's James Webb Space Telescope. Take a planet-hopping excursion through the TRAPPIST-1 system.

www.nasa.gov

NASA's Exoplanet Exploration Program. Jet Propulsion Laboratory, Pasadena CA.
exoplanets.nasa.gov

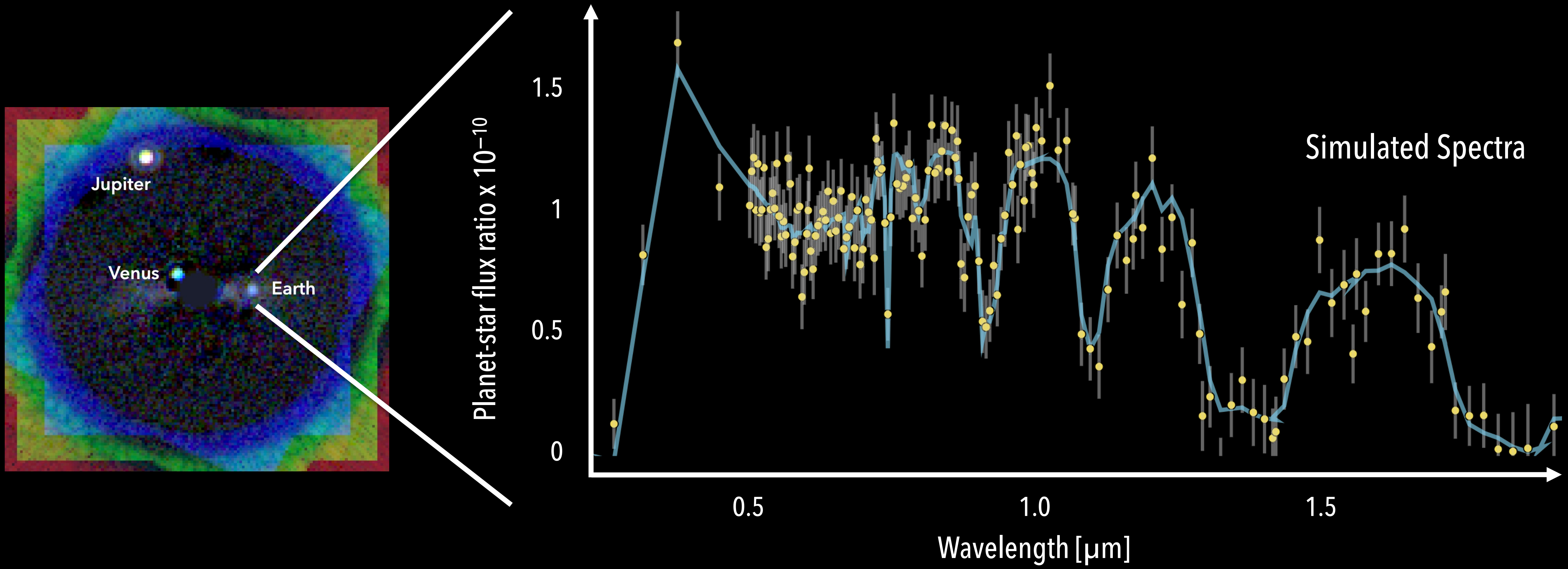
National Aeronautics and Space Administration

Exoplanet Travel Bureau

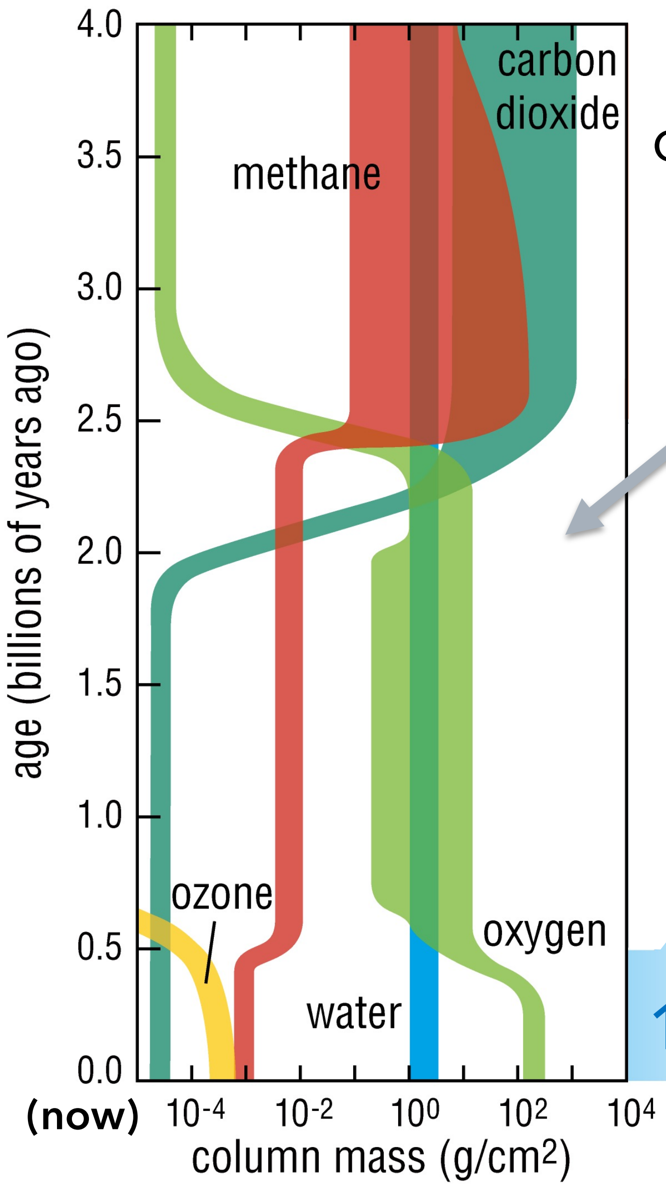
A global ocean of lava under sparkling, silicate skies reflecting the lava below: what better choice for an extreme vacation? Planet *Janssen*, or *55 Cancri e*, orbits a star called *Copernicus* only 41 light years away. The molten surface is completely uninhabitable, but you'll ride safely above, taking in breathtaking views: the burning horizon, *Janssen's* sister planet *Galileo* hanging in a dark sky, and curtains of glowing particles as you glide across the terminator to *Janssen's* dark side. Book your travel now to the hottest vacation spot in the galaxy, *55 Cancri e*.

www.nasa.gov

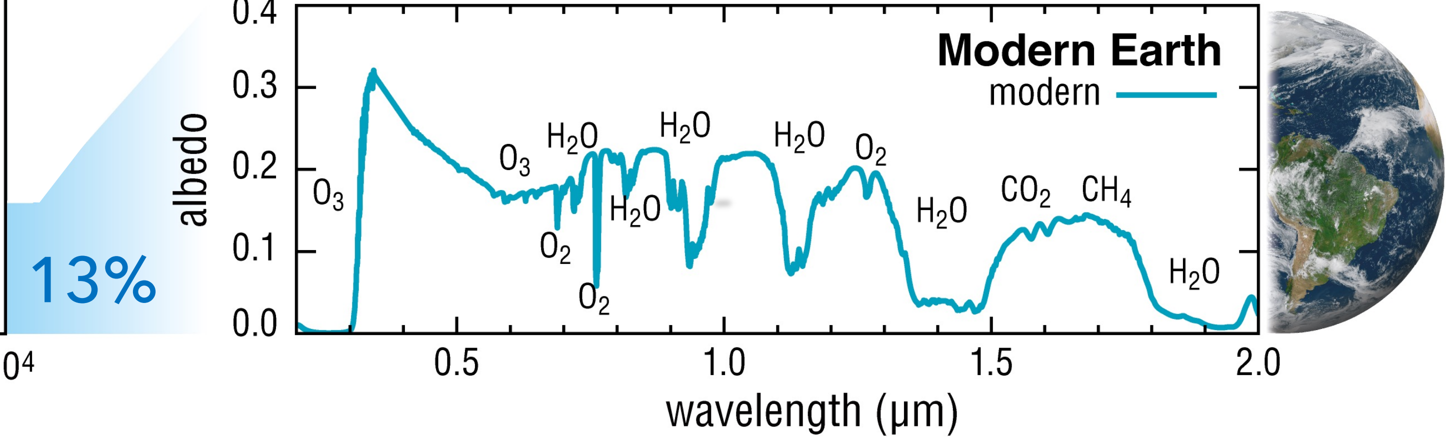
NASA's Exoplanet Exploration Program. Jet Propulsion Laboratory, Pasadena CA.
exoplanets.nasa.gov


Jupiter
Venus
Earth
Planet-star flux ratio x 10⁻¹⁰
1.5
1
0.5
0
0.5
1.0
1.5
Wavelength [μm]
Simulated Spectra

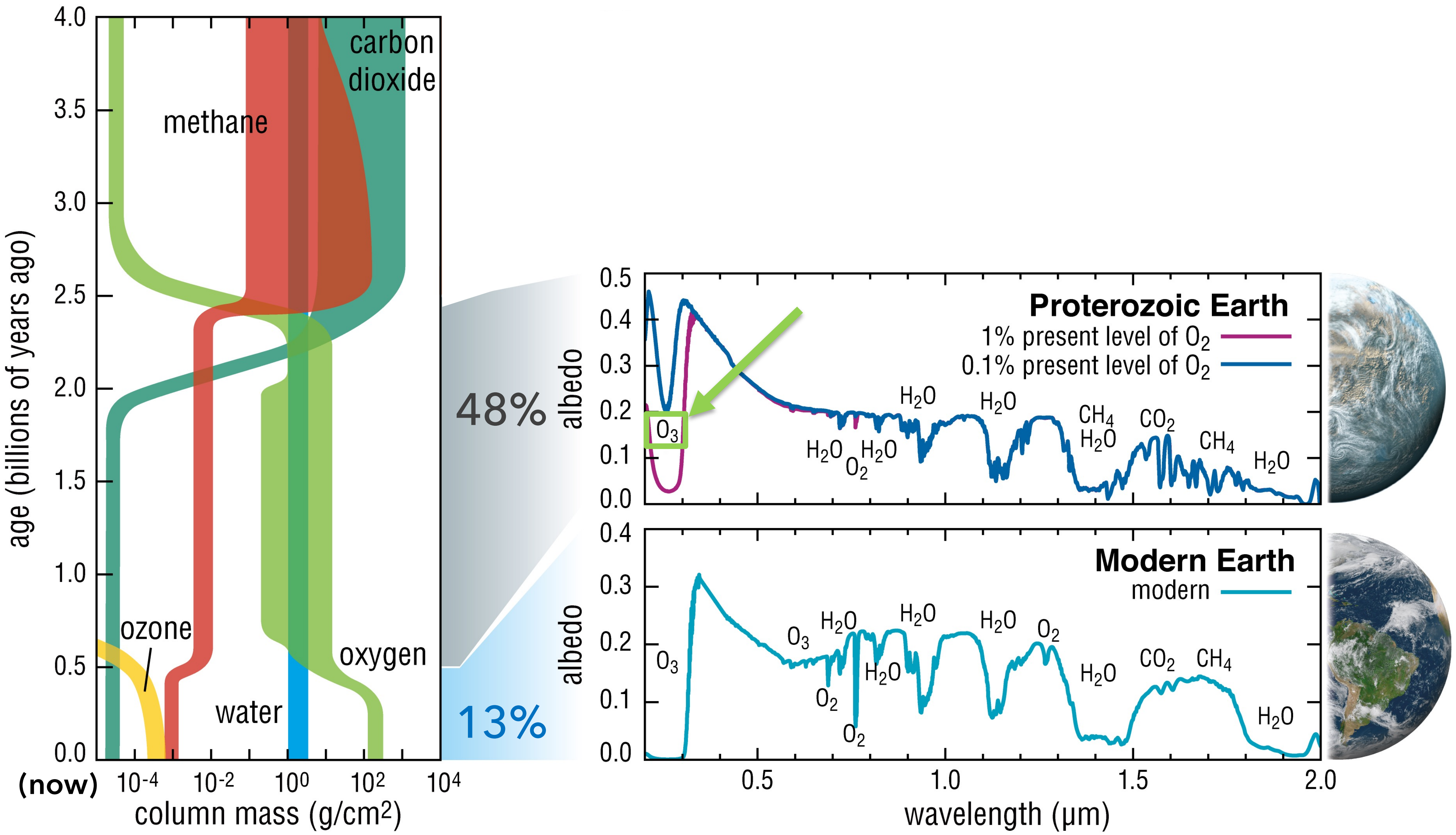
EARTH IS MORE THAN ONE PLANET



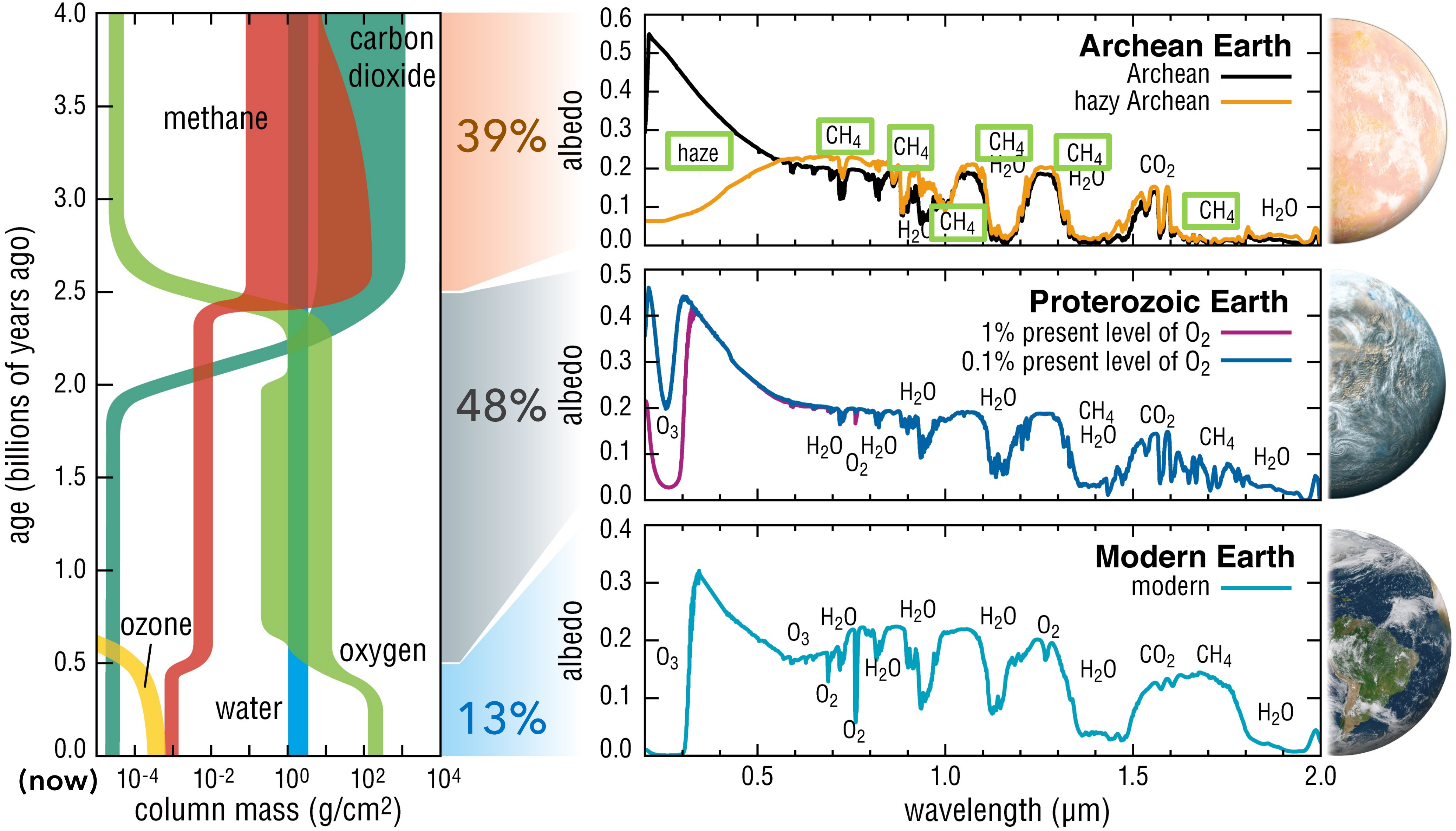
Earth's atmospheric composition through time



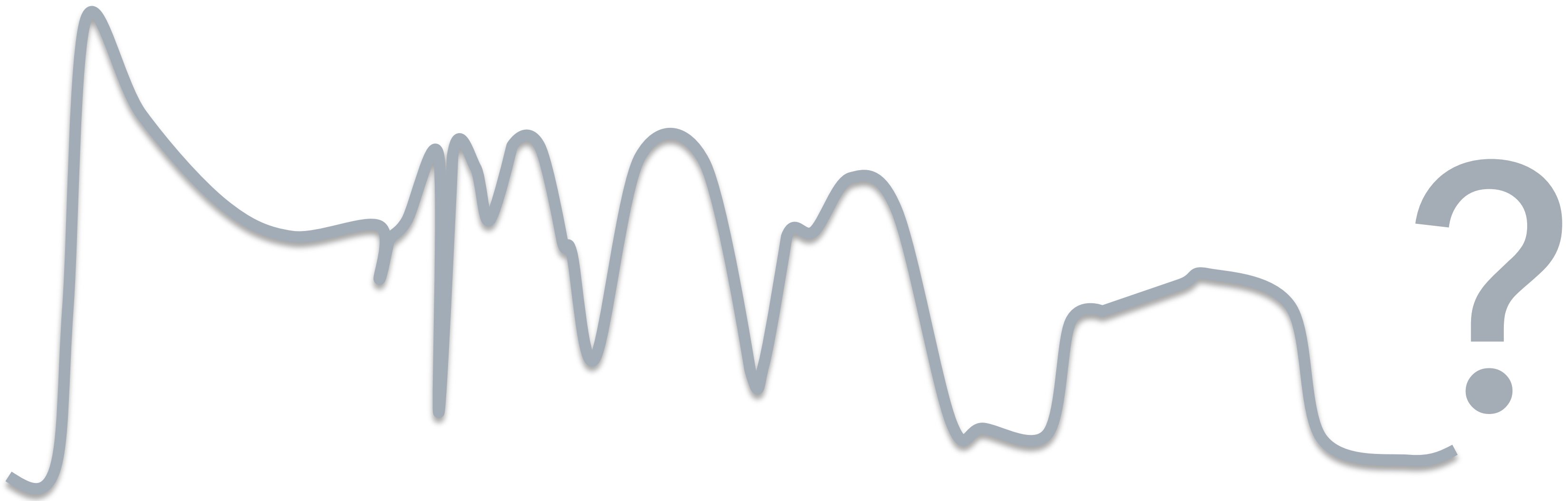
Earth is more than one planet



EARTH IS MORE THAN ONE PLANET



Biosignatures need context

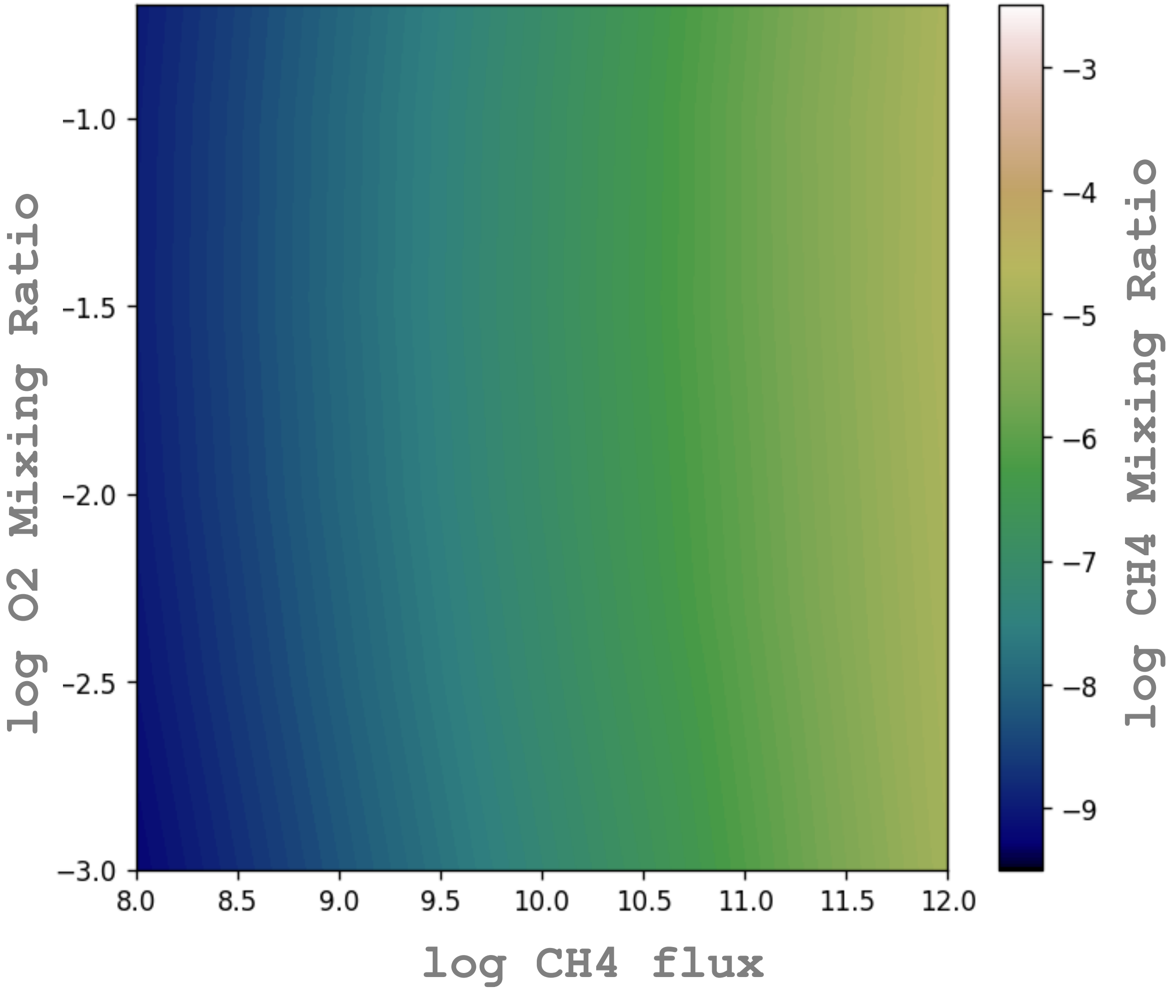


False positive?

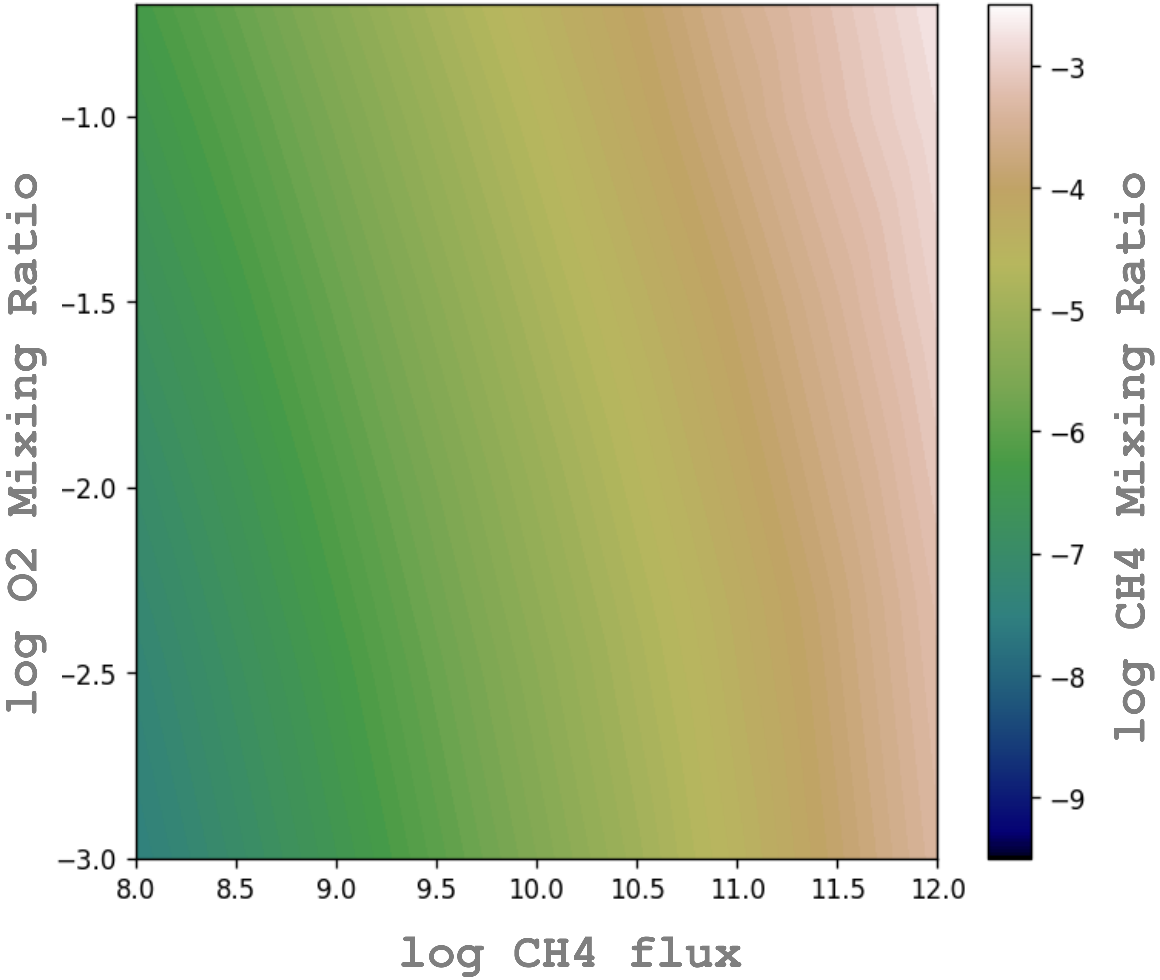
True biosignature?

BIOSIGNATURES DEPEND ON CONTEXT…

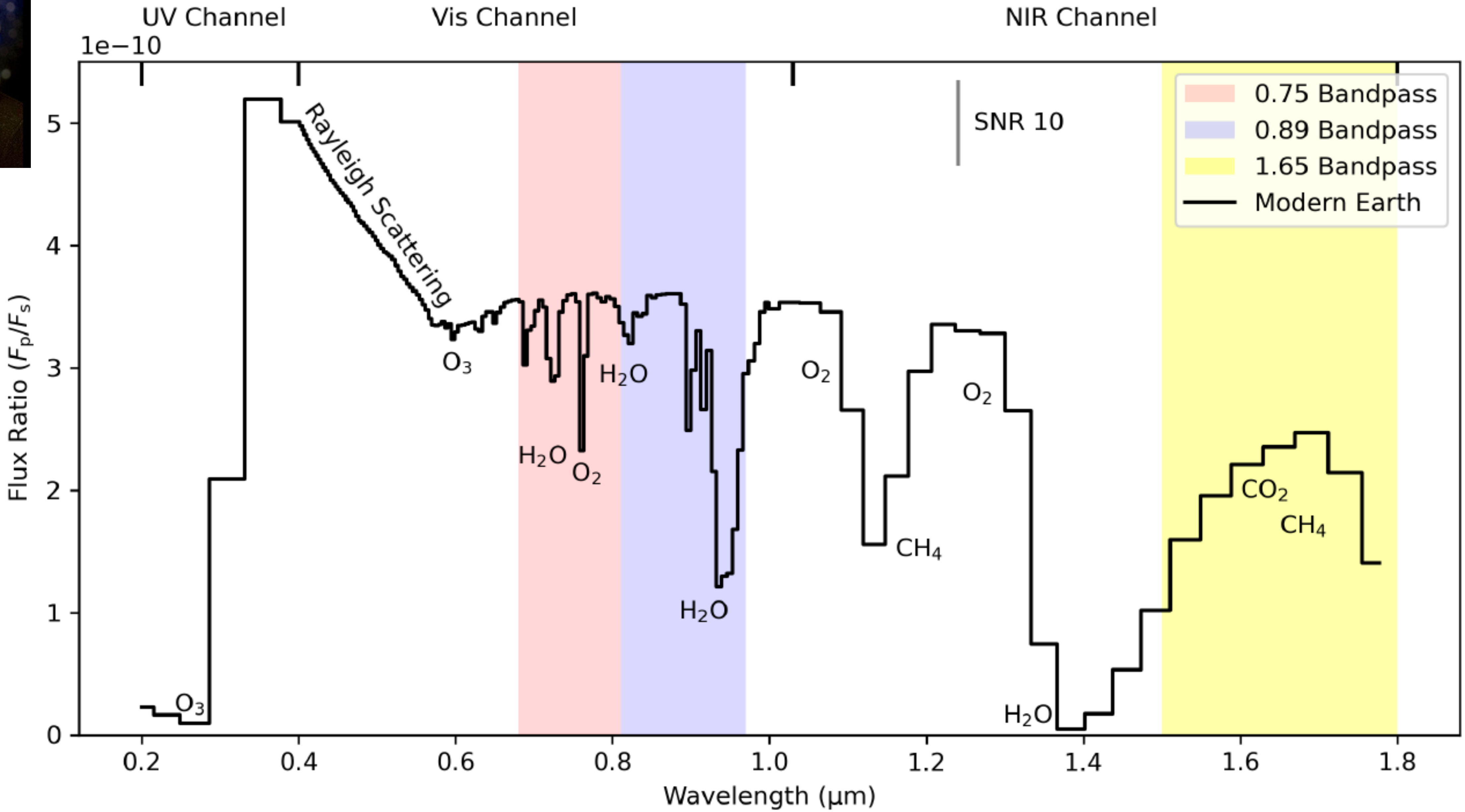
Modern Sun



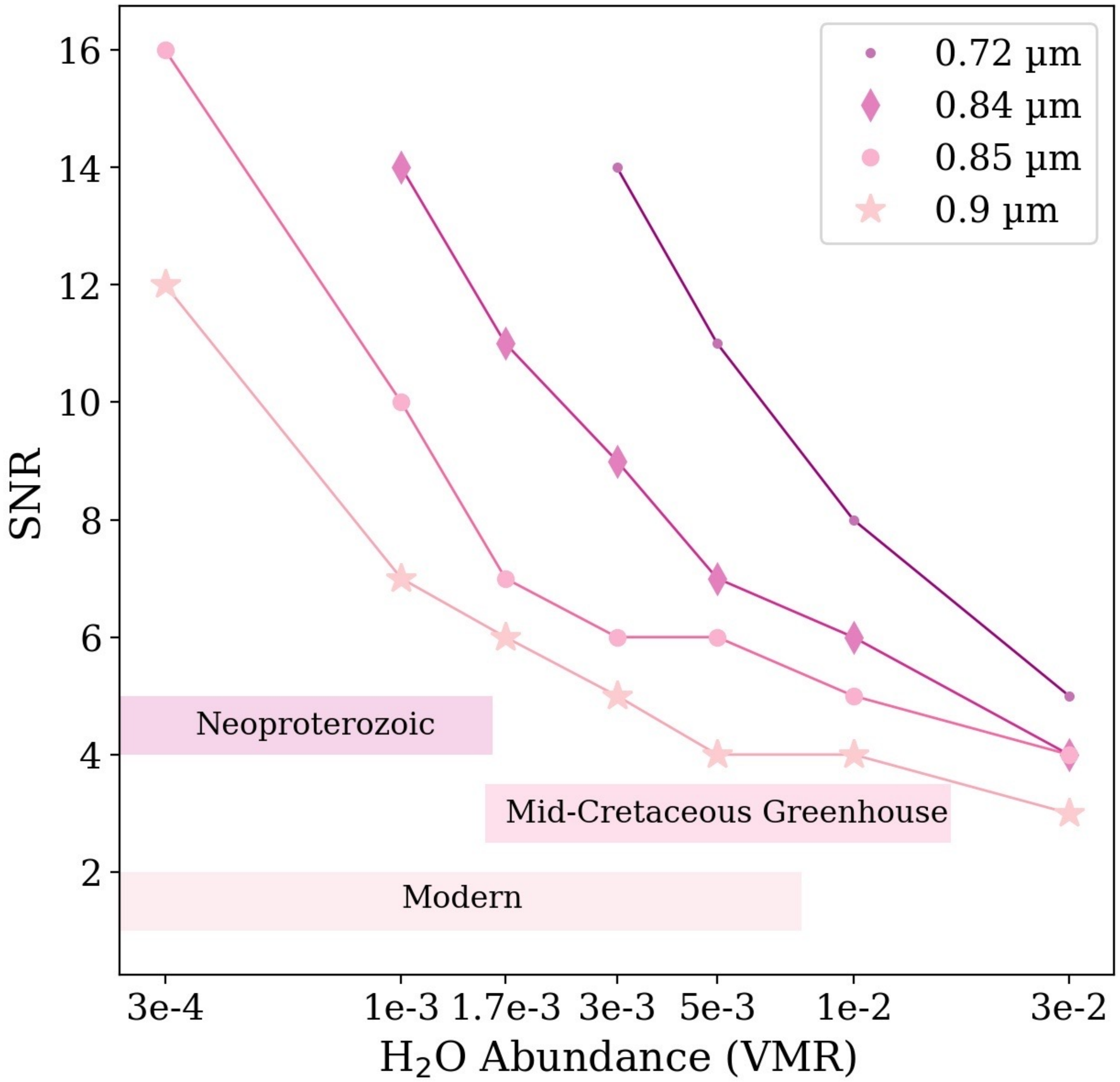
Proxima Centauri



… AND HWO CAN OBTAIN THAT CONTEXT!




This Barbie is available for questions!
Barbie

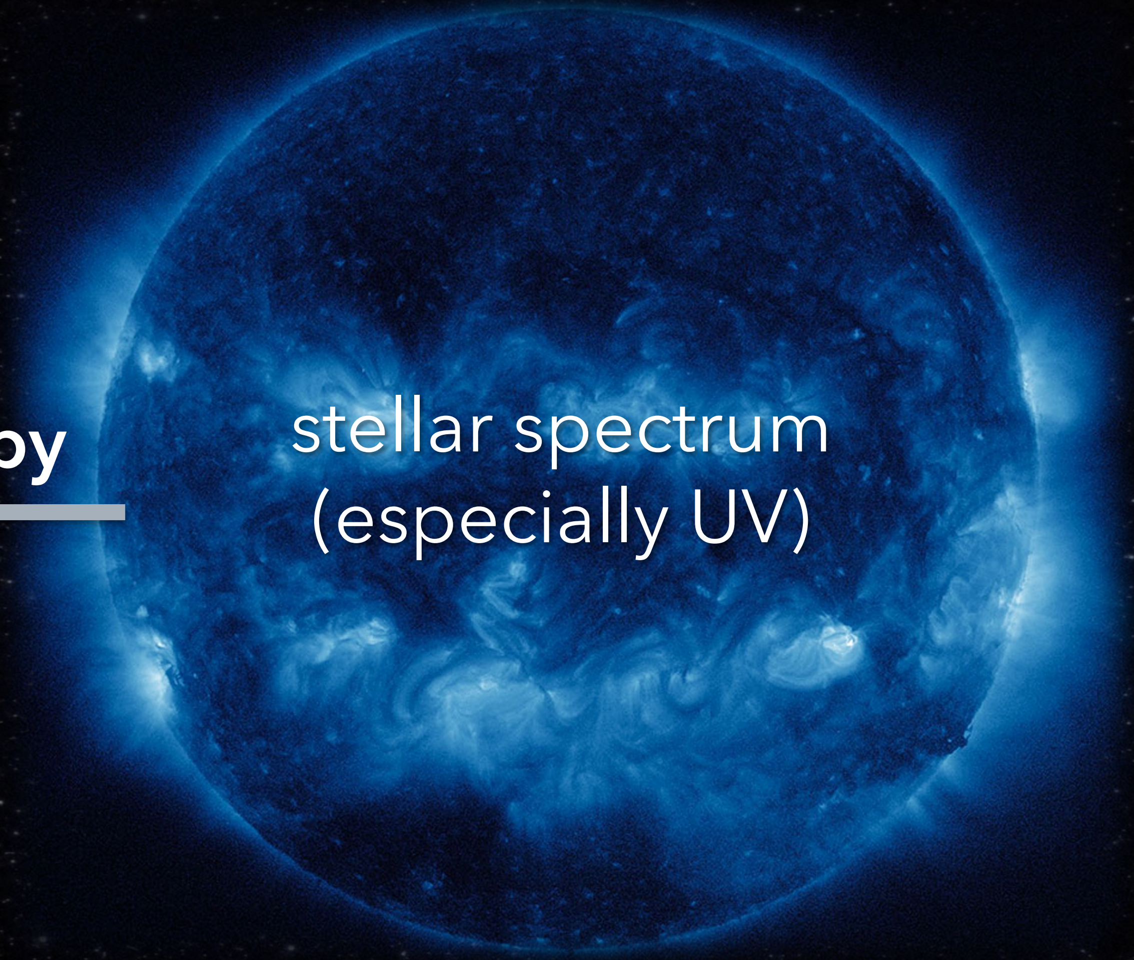

0.72 μm
0.84 μm
0.85 μm
0.9 μm
SNR
16
14
12
10
8
6
4
2
Neoproterozoic
Mid-Cretaceous Greenhouse
Modern
3e-4
1e-3
1.7e-3
3e-3
5e-3
1e-2
3e-2
H_2O Abundance (VMR)

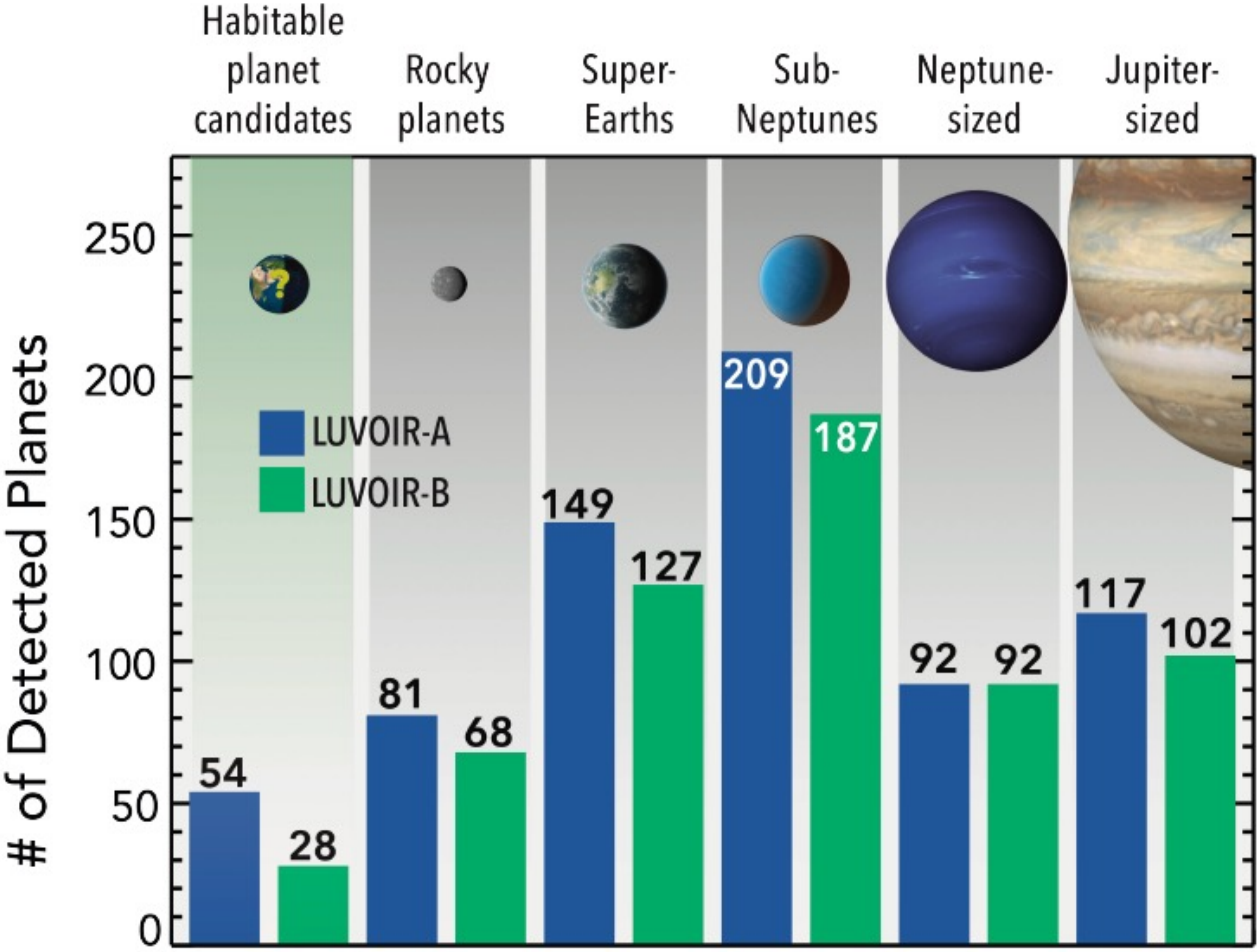
HWO WILL NEED TO GIVE US THE NEEDED CONTEXT

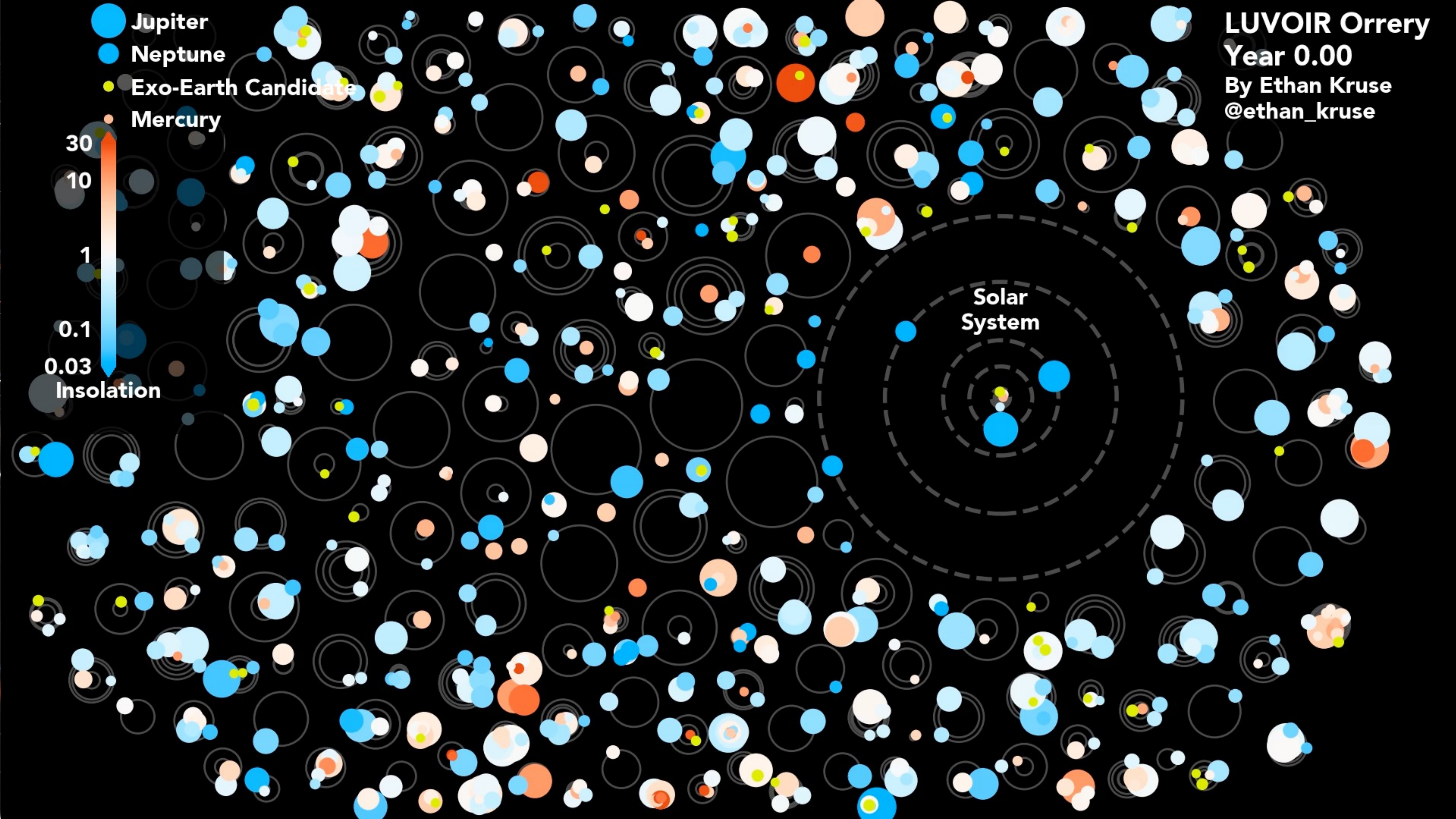
UV instrument
100-1000 nm spectra

enabled by ←

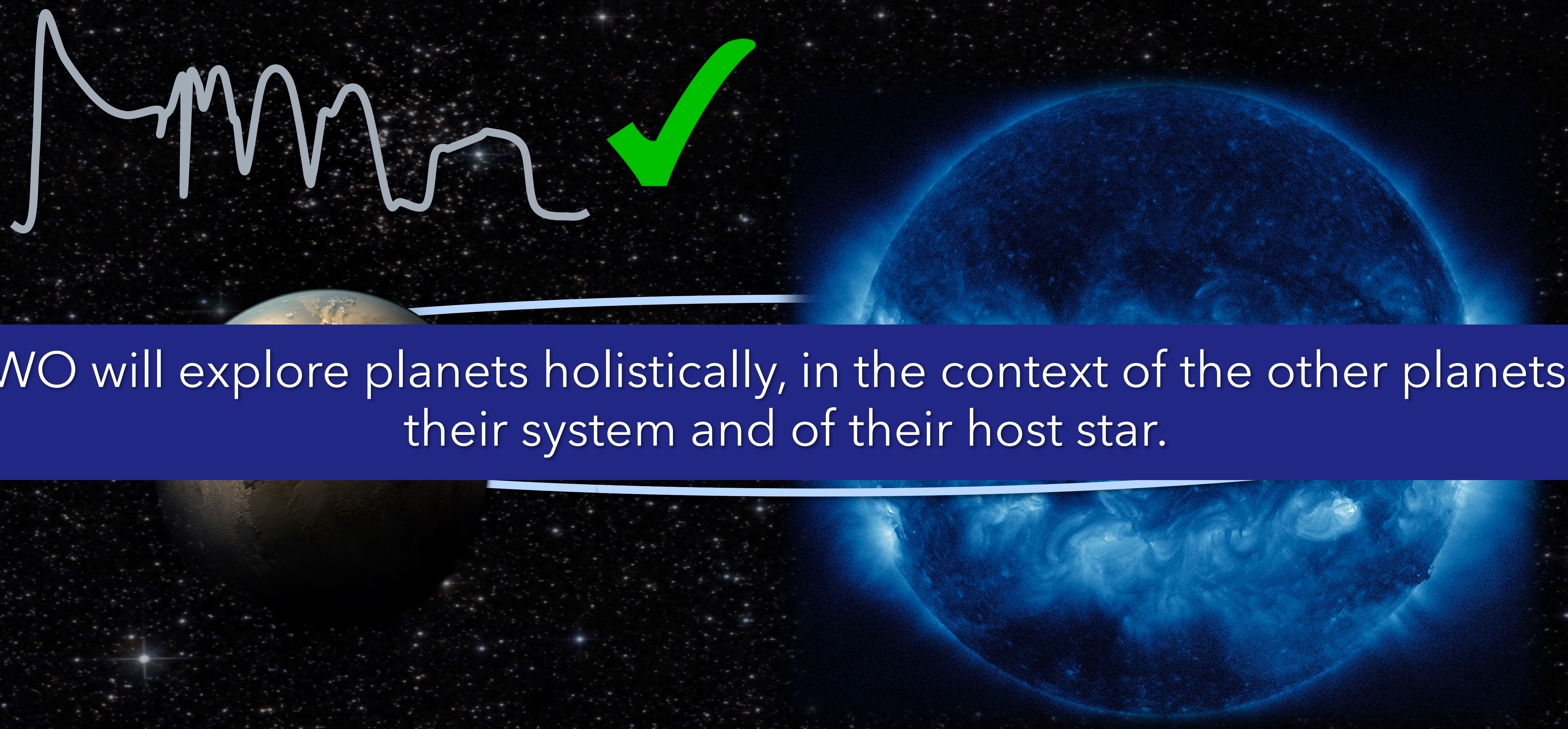
stellar spectrum
(especially UV)



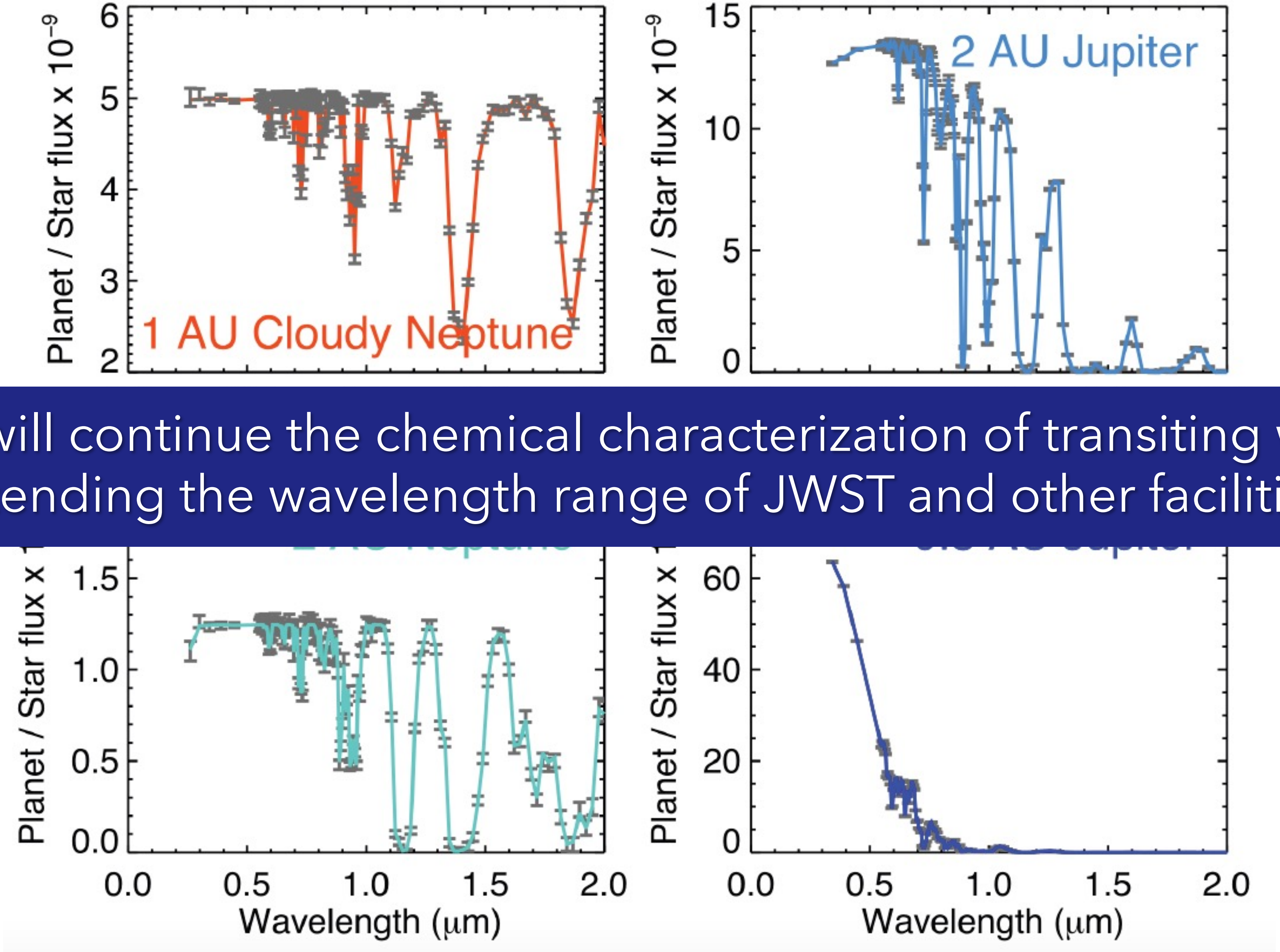

Habitable planet candidates
Rocky planets
Super-Earths
Sub-Neptunes
Neptune-sized
Jupiter-sized
# of Detected Planets
0
50
100
150
200
250
LUVOIR-A
LUVOIR-B
54
28
81
68
149
127
209
187
92
92
117
102


Jupiter
Neptune
Exo-Earth Candidate
Mercury
30
10
1
0.1
0.03
Insolation
LUVOIR Orrery
Year 0.00
By Ethan Kruse
@ethan_kruse
Solar
System

HWO WILL NEED TO GIVE US THE NEEDED CONTEXT



HWO will explore planets holistically, in the context of the other planets in their system and of their host star.

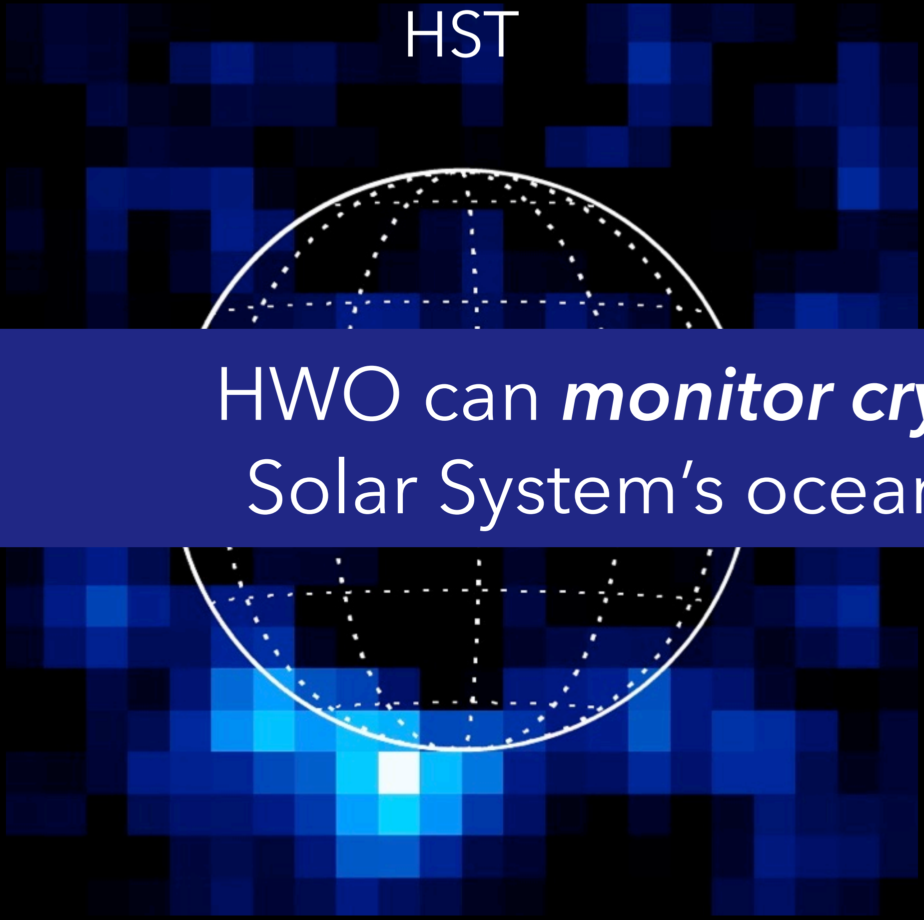


HWO will continue the chemical characterization of transiting worlds, extending the wavelength range of JWST and other facilities.

Habitable environments? Solar System ocean moons

Europa in far-UV Lyman-α emission

HST



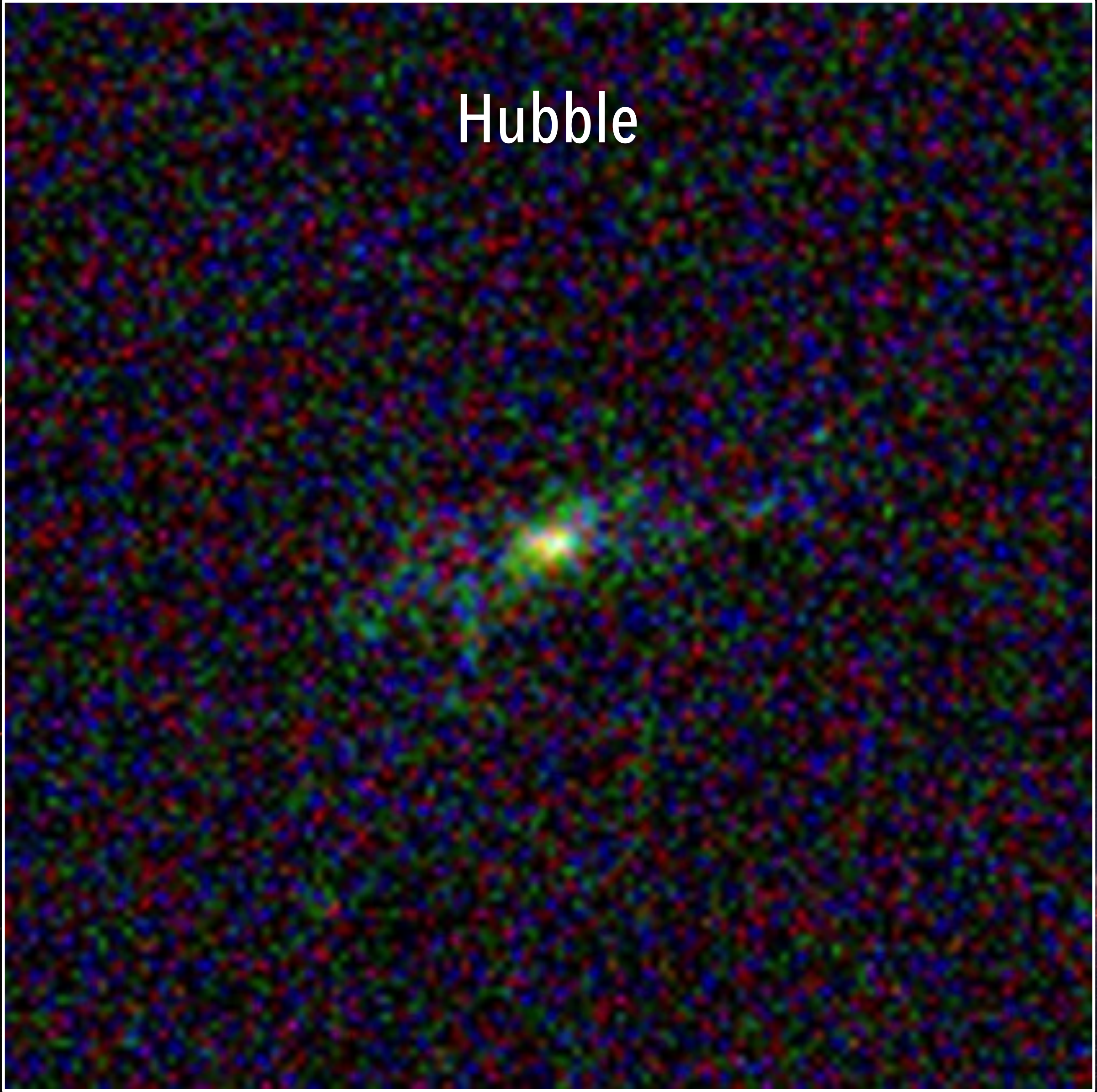
HWO

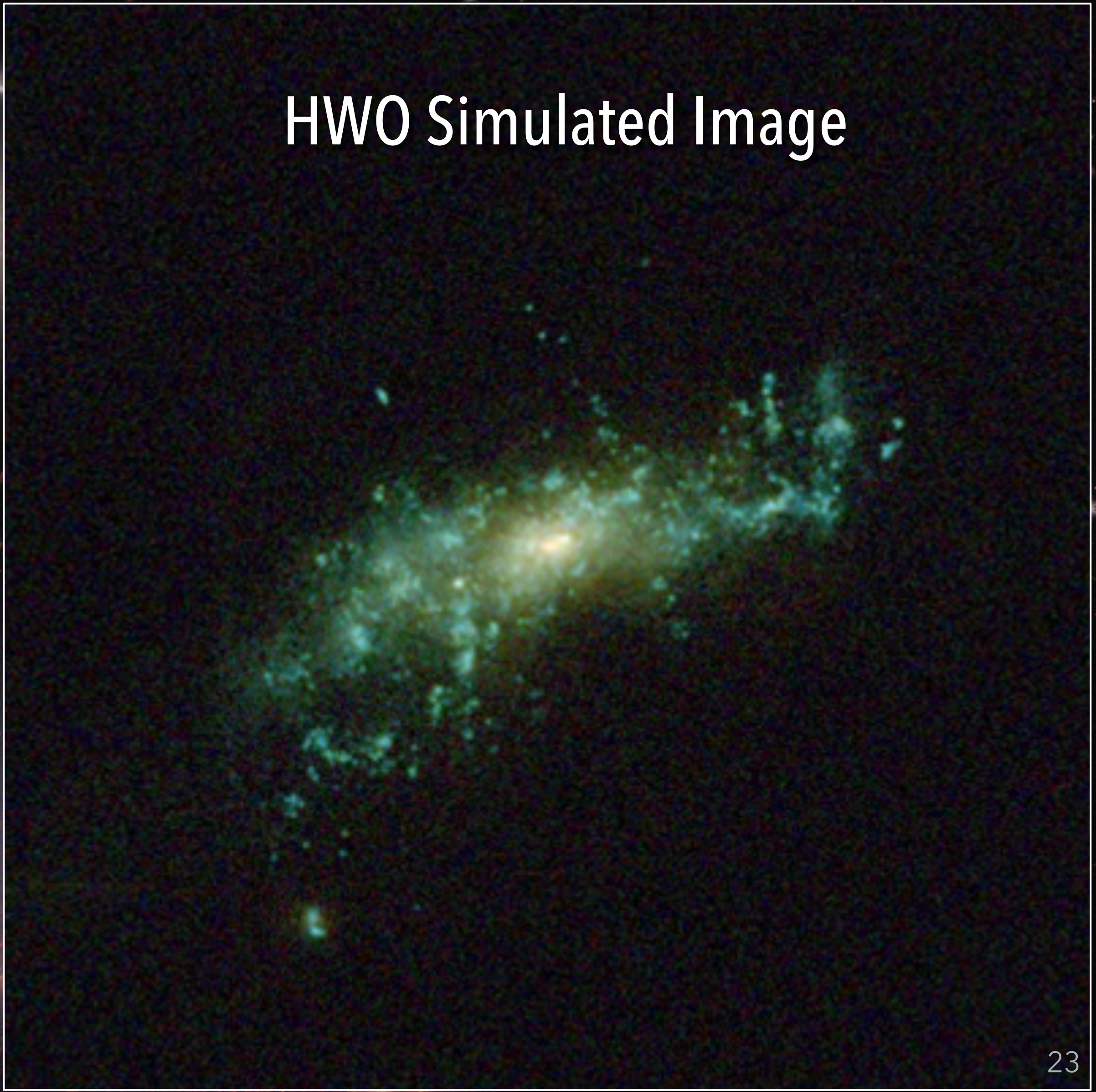
HWO can ***monitor cryovolcanic activity*** from the Solar System's ocean worlds at high resolution

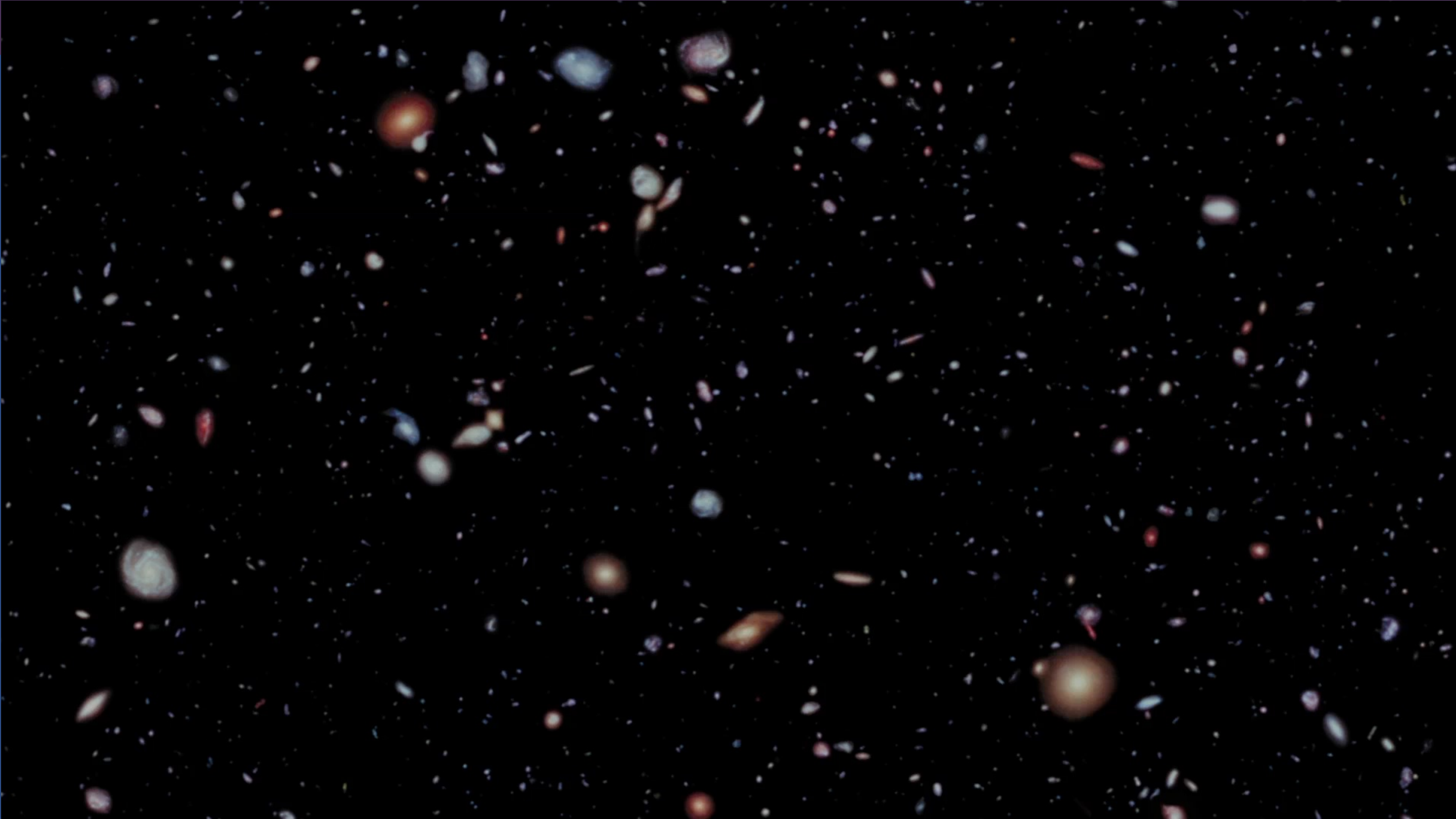
Roth et al. (2014)

Input model: G. Ballester

Probing the Properties of Dark Matter with Dwarf Galaxies







Why GOMAP? Decades of research-based consensus on megaprojects

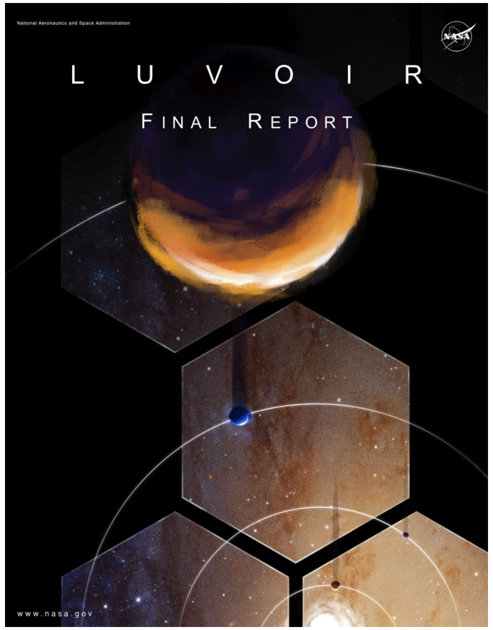
Independent Research Papers	Mission Concept Reports	GAO Report on Major Projects	SMD Internal Study on Flagship Projects	National Academy Recommendations

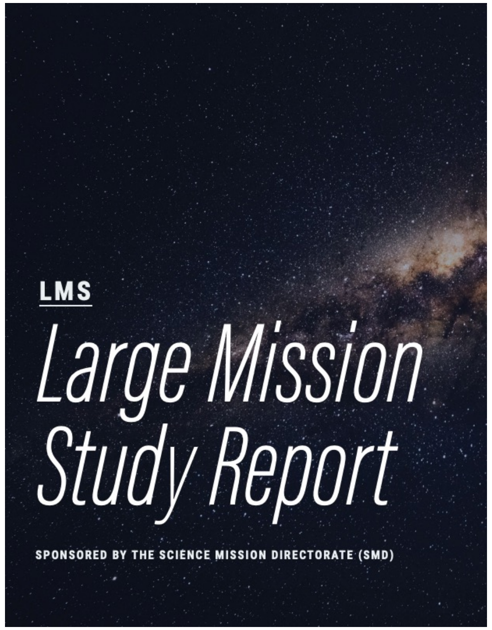
Challenges and Potential Solutions to Develop and Fund NASA Flagship Missions

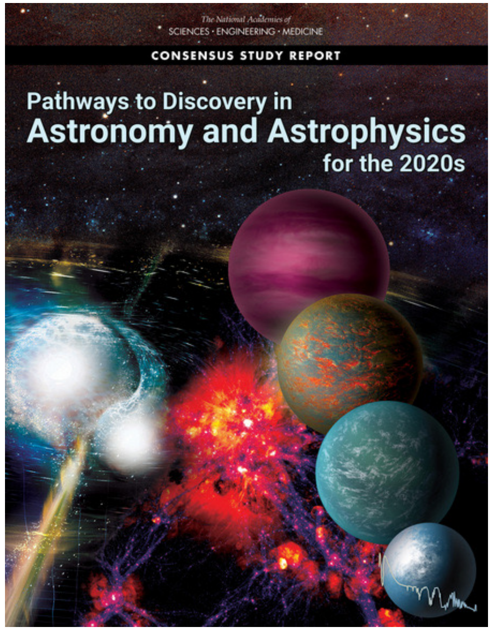
Robert E. Bitten, The Aerospace Corporation, 2310 E. El Segundo Blvd., El Segundo, CA 90245, 310-336-1917, robert.e.bitten@aero.org

Stephen A. Shinn, NASA Goddard Space Flight Center, 8800 Greenbelt Road, Greenbelt, Maryland 20771, 301-286-5894, stephen.a.shinn@nasa.gov

Debra L. Emmons, The Aerospace Corporation, 2310 E. El Segundo Blvd., El Segundo, CA 90245, 310-418-7892, debra.l.emmons@aero.org

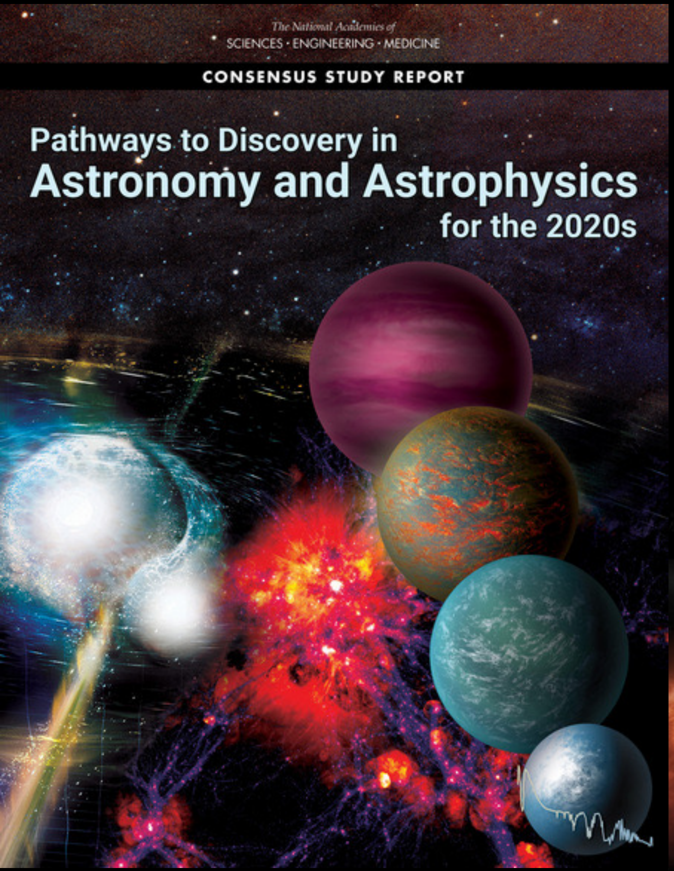


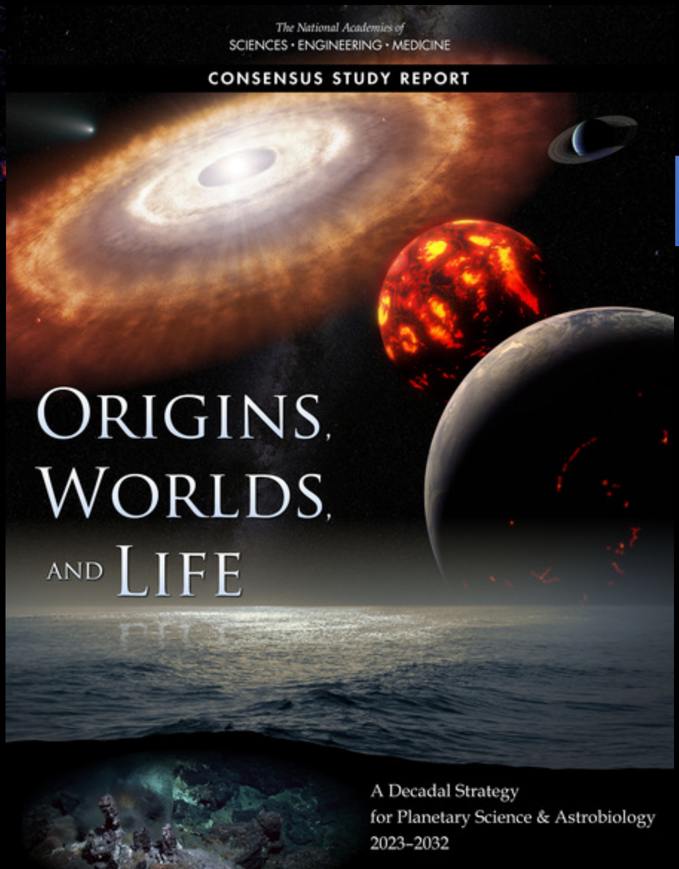




A variety of documents from internal, external, and oversight groups all point to a consistent set of problems & solutions for large/flagship projects, across sectors

Science, Technology, Architecture Review Team (START)





Which decadal science questions can HWO help address?

What observations do we need to answer those questions?

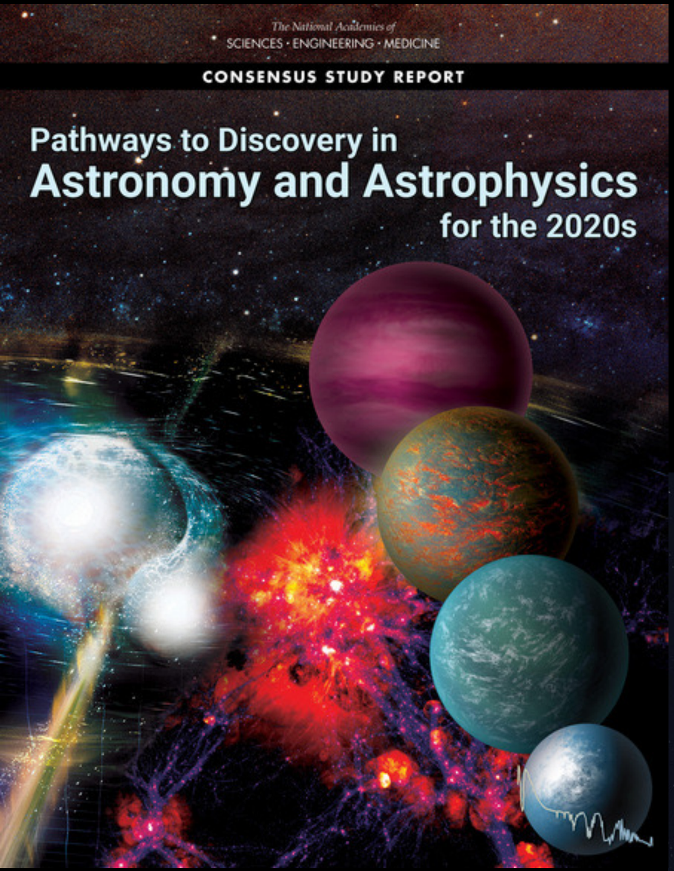
What capabilities will deliver those observations?

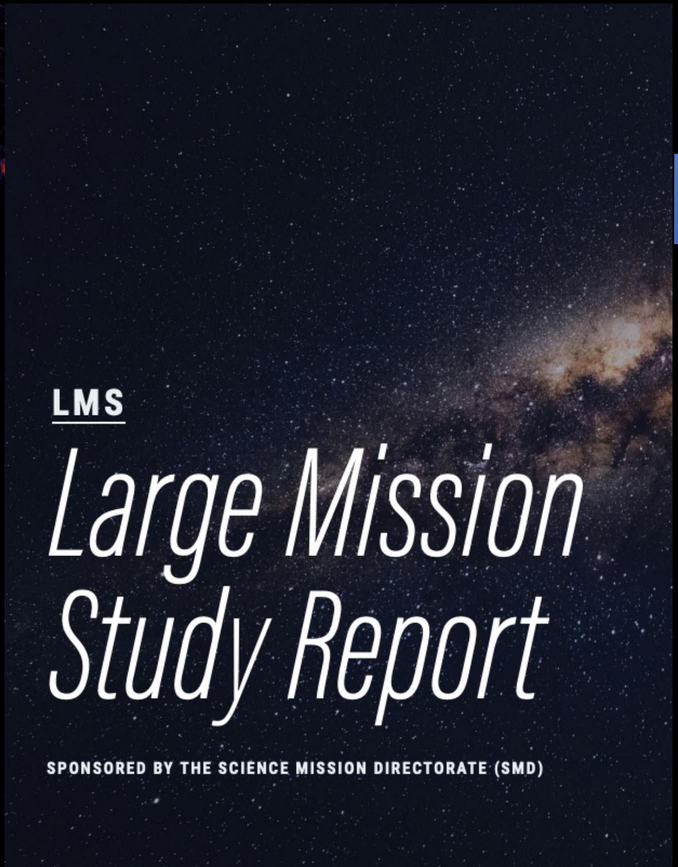
What performance can we expect?

Where do performance breakpoints exist?

What models do we need to predict performance?

Technical Assessment Group (TAG)





What architecture trades remain?

How are those trades related/coupled to each other?

Which trades are the most important to study now?

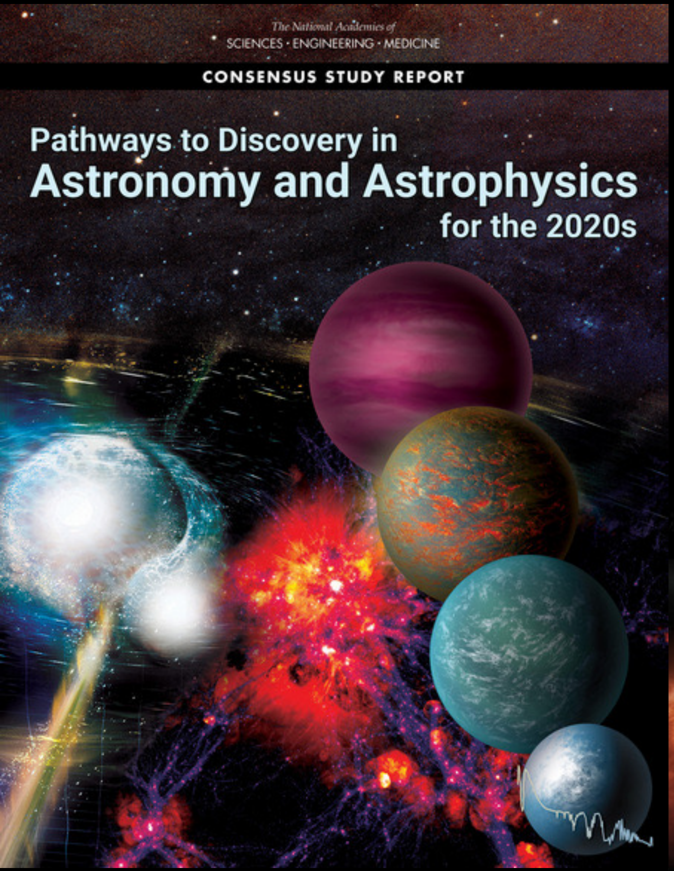
What are the technologies associated with those trades?

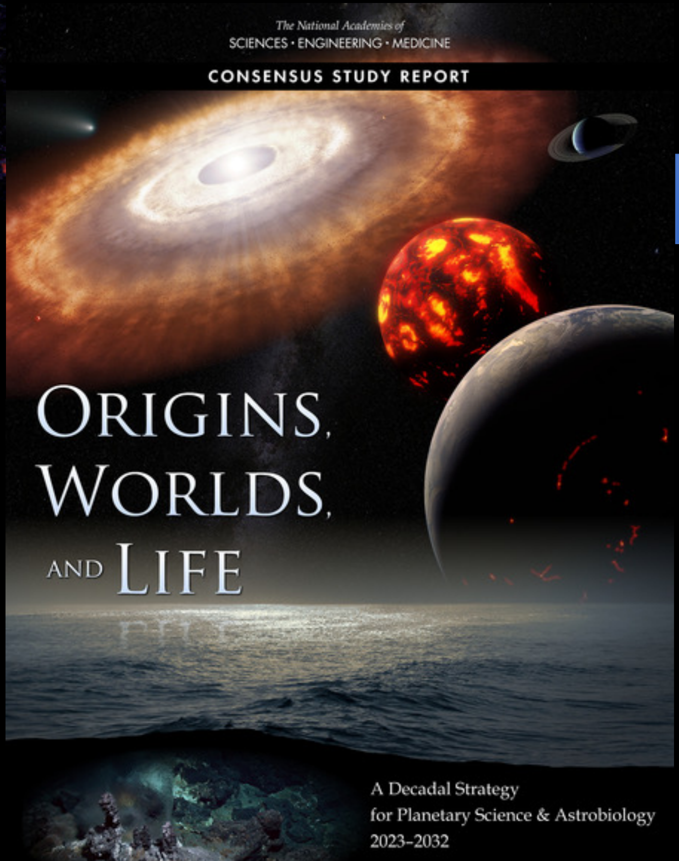
What cost/schedule risks exist for those trades?

How might those risks be mitigated?

How can external partners be involved?

Community Participation





Multi-generational approach to a multi-generation mission

Training/development/mentorship programs throughout lifecycle

Diversification of the HWO community

"Badgeless" culture that places expertise over institution

Safe and just team culture

Team culture that adapts to a changing culture

Changing leadership over time

Compensation for people's work

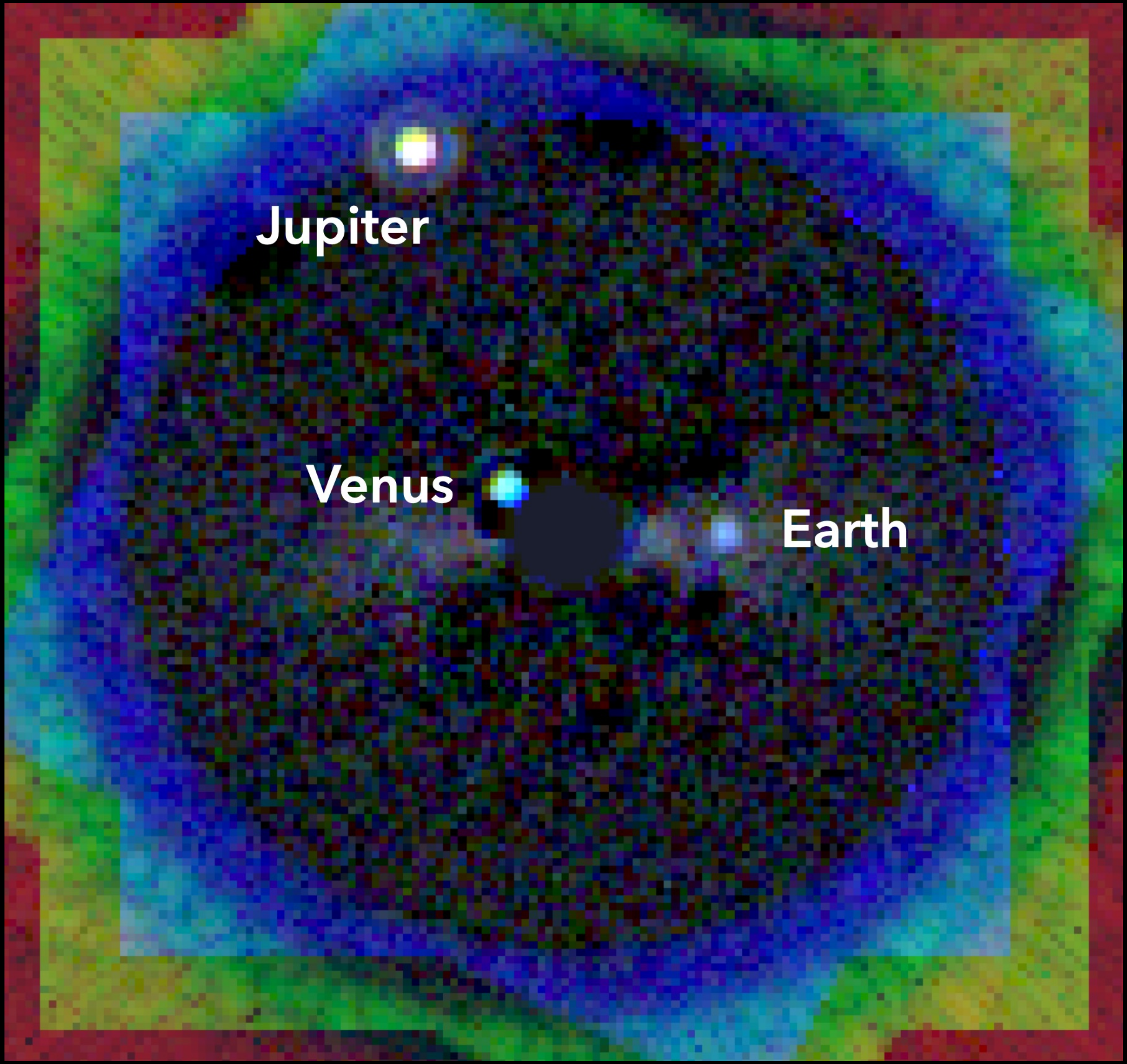
HWO Early Career Initiatives

START/TAG members will be allowed to include their institution/research group members in technical work related to the START

We will create an HWO mentorship program, focused on early career members from institutions not represented on the START

Creation of an HWO Early Career Community/Council for discussions within the HWO early career community, and for feedback on HWO culture from that community

We will have a workshop (date/location very TBD) to discuss plans for HWO workforce development. Will include ”primers” on HWO science/technology, networking/job fair to connect early career members to HWO-relevant institutions, and presentations and discussion on ideas for a welcoming, just, safe, and inclusive culture for HWO.


Jupiter
Venus
Earth


esa
#UnfoldTheUniverse
EssilorLuxottica
EssilorLuxottica
PLANET HOLLYWOOD

How do we get involved?

Is the telescope actually a real thing?

What is TAG?

What still needs to happen to make it a real thing?

How big is it?

How much of it is luvoir or habex?

What is START?

What’s the timeline?

Questions and more information

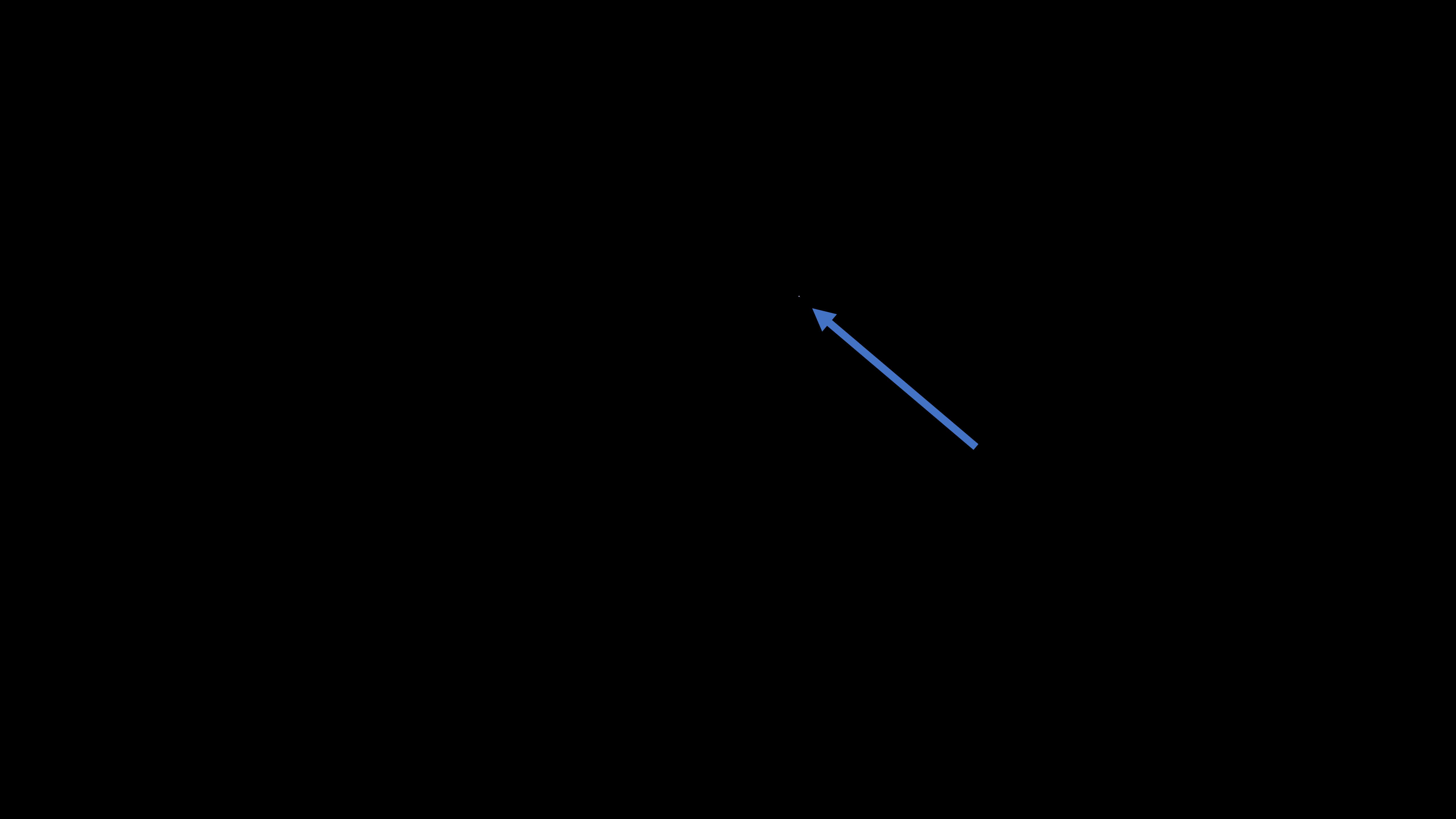
NASA Astrophysics Statement of Principles:
go.nasa.gov/3Kwn07s

NASA GOMAP website:
go.nasa.gov/4107ZzC

julie.a.crooke@nasa.gov
shawn.goldman@nasa.gov

The Habitable Worlds Observatory:
Big Picture Strategy

- **Build to schedule:** Mission Level **1 Requirement - like planetary**
- **Evolve technology from what we have done before:**
  - Build upon current NASA investments and TRL-9 technology
  - Segmented optical telescope system from JWST
  - Coronagraph from Roman‘s coronagraphic imager program
- **Next Generation Rockets:**
  - Larger telescope aperture sizes
  - Leverage opportunities for mass & volume trades
- **Planned Servicing:** Robotic servicing at L2
- **Robust Margins:** Large scientific, technical, and programmatic margins
- **Mature technologies first:** Reduce risk by fully maturing the technologies prior to development phase.



DESIGN DRIVER – CONTRAST STABILITY FOR EXOEARTHS

Corresponds to wavefront stability of “10 pm per 10 minutes”

How do we enable that level of ultra-stability?

Through **design**

Through **control**

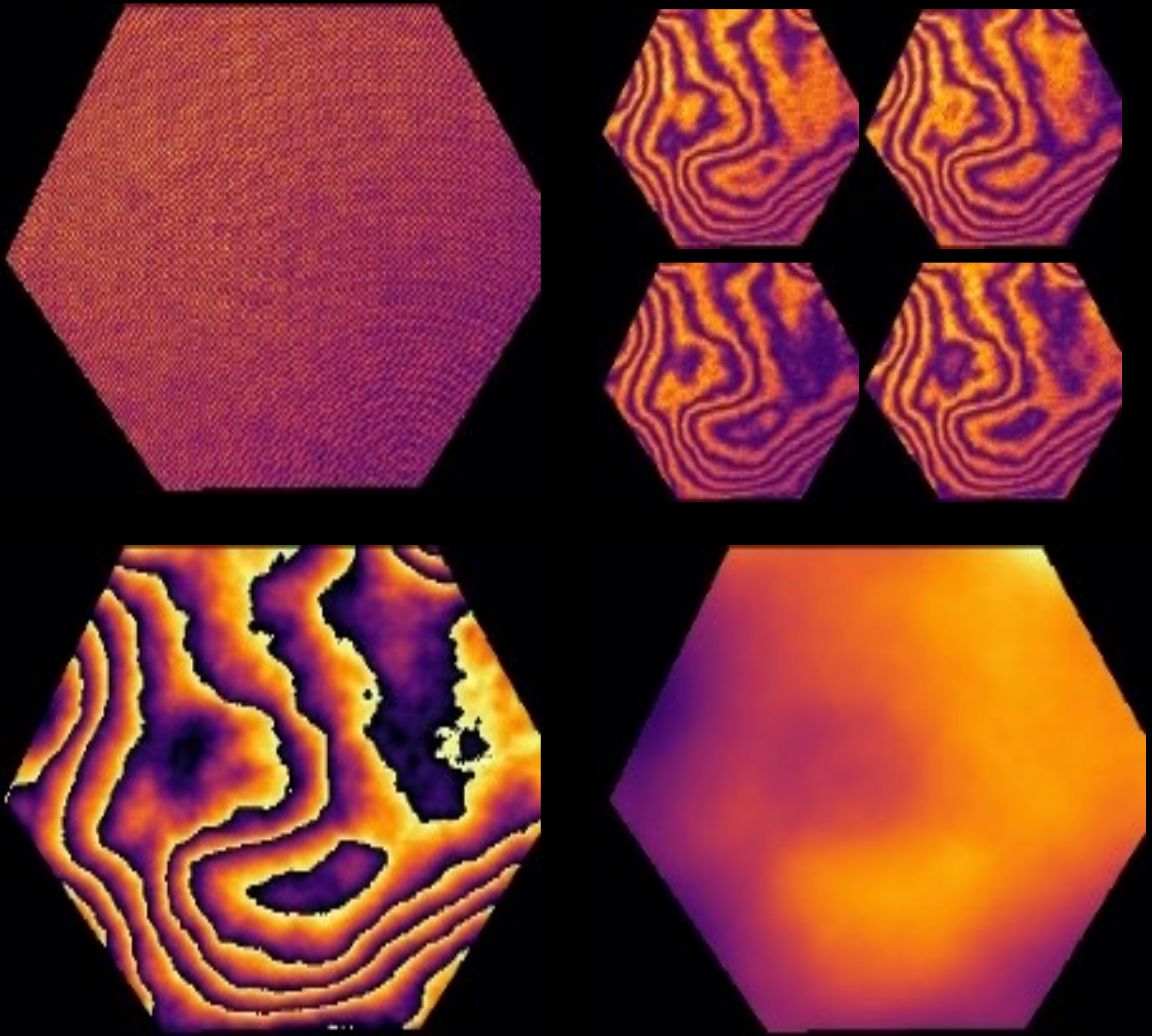
Through **tolerance**

ULTRA-STABILITY THROUGH DESIGN

Lightweight ULE mirror segment

Credit: L3/Harris

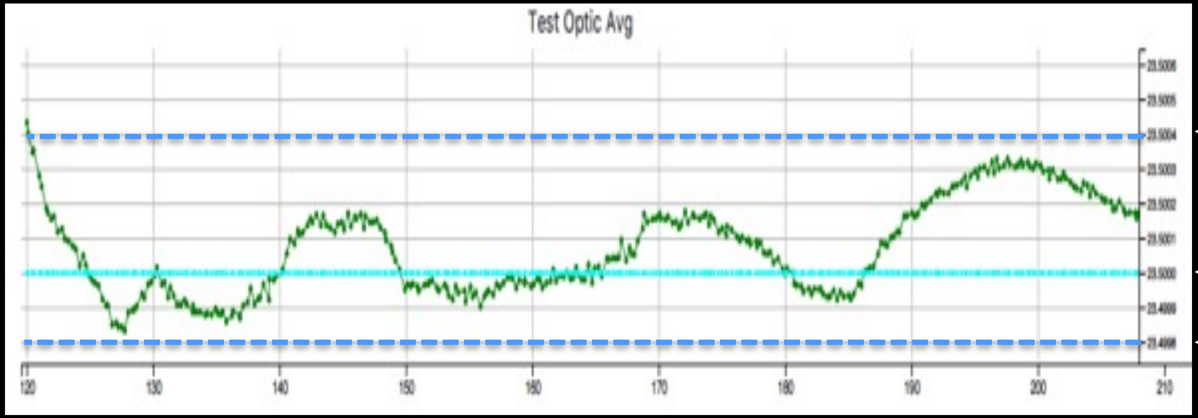
Picometer-scale dynamics measured with high-speed interferometry



Credit: NASA GSFC

ULTRA-STABILITY THROUGH CONTROL

Sub-milli-Kelvin thermal control

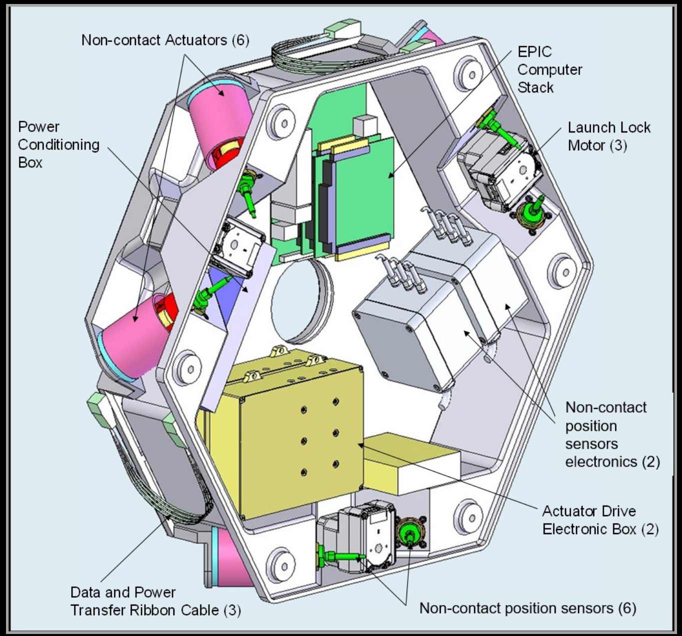


296.6504 K

296.6500 K

296.6408 K

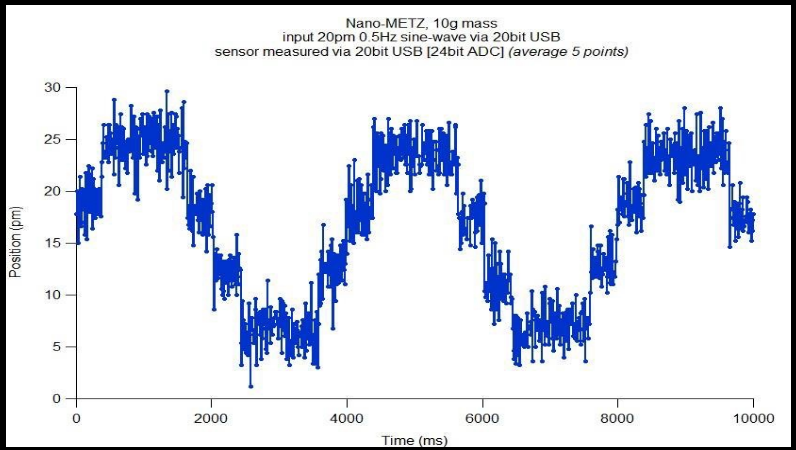
Credit: SAO / NASA GSFC



Credit: Lockheed Martin

Vibration-isolation and precision pointing system

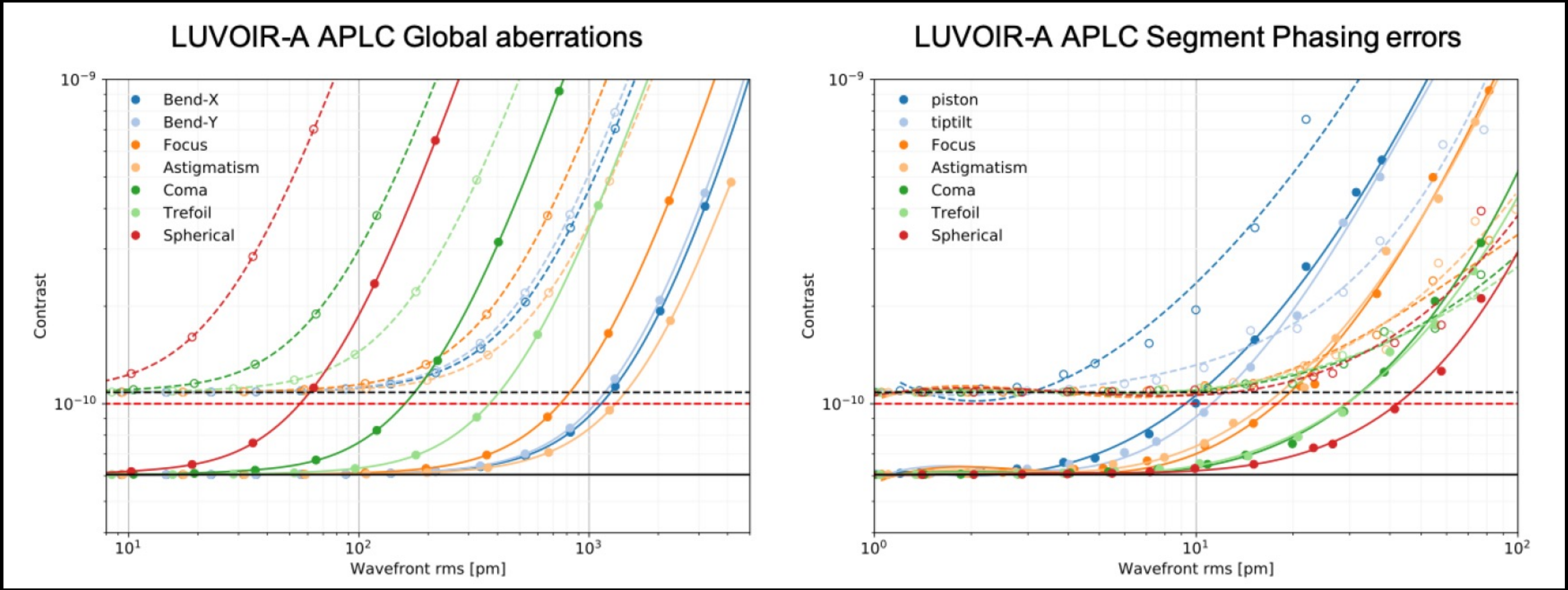
Measurement of 5 pm resolution piezo actuator at 1 Hz



Credit: NASA GSFC

Ultra-stability through tolerance

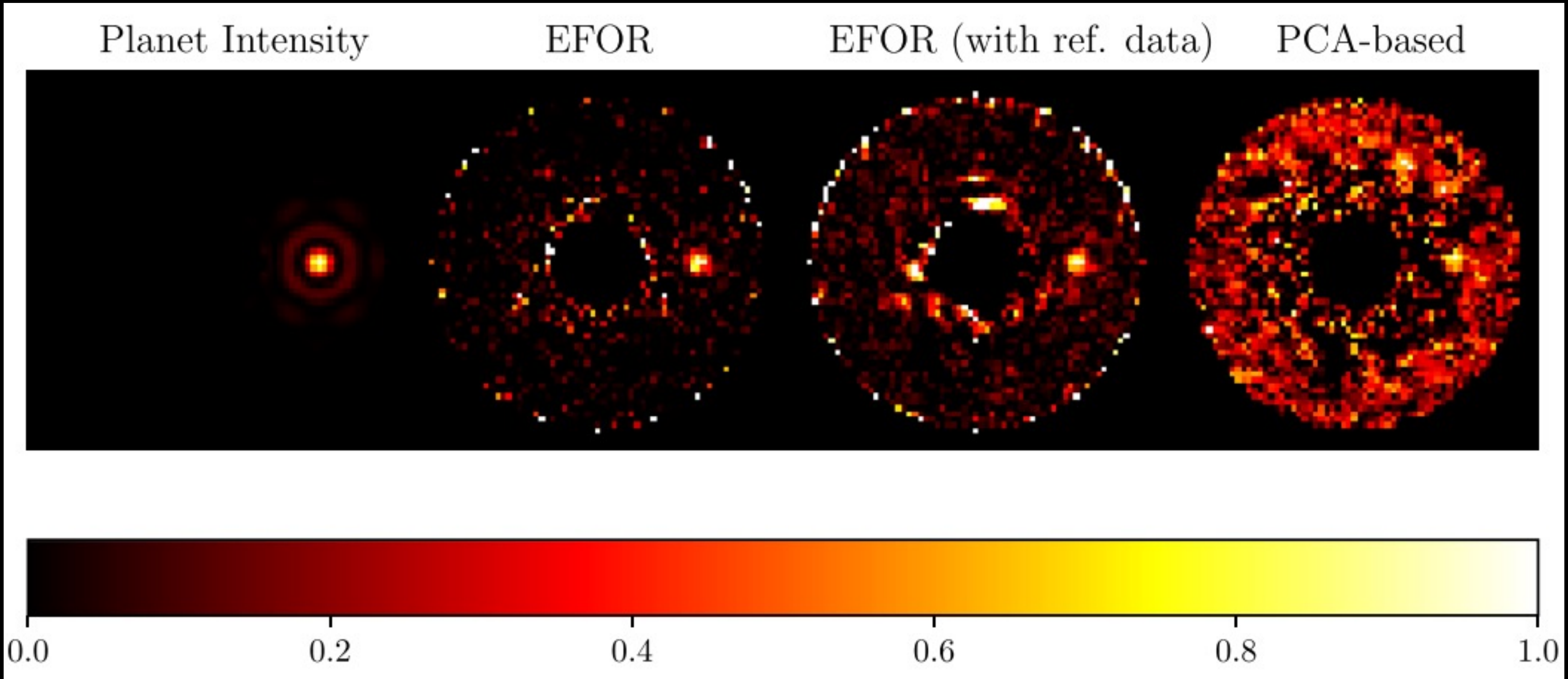
Contrast Sensitivity to Wavefront Errors



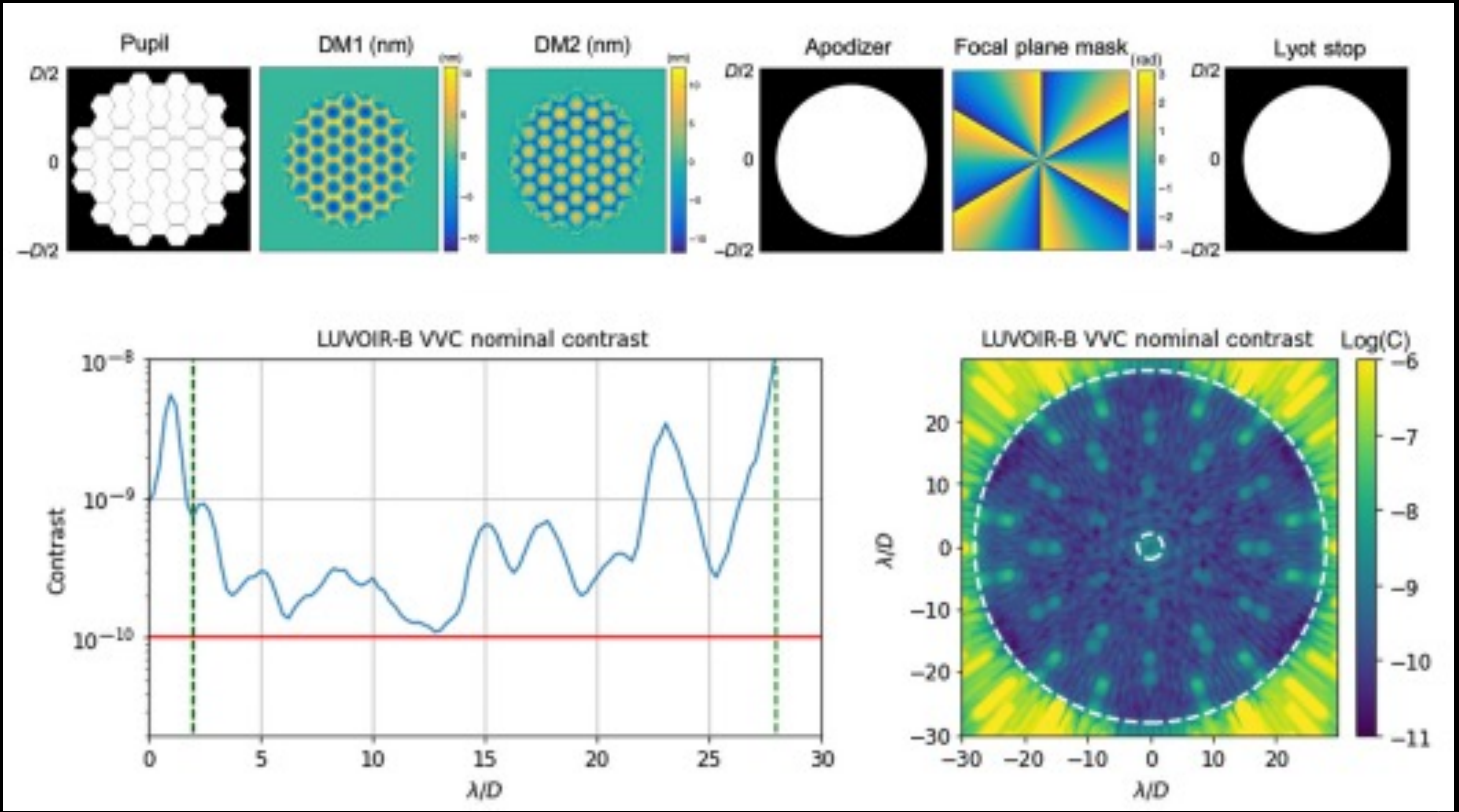
Credit: Juanola-Parramon / NASA GSFC

ULTRA-STABILITY THROUGH TOLERANCE

Post-processing Extraction of Exoplanet Image

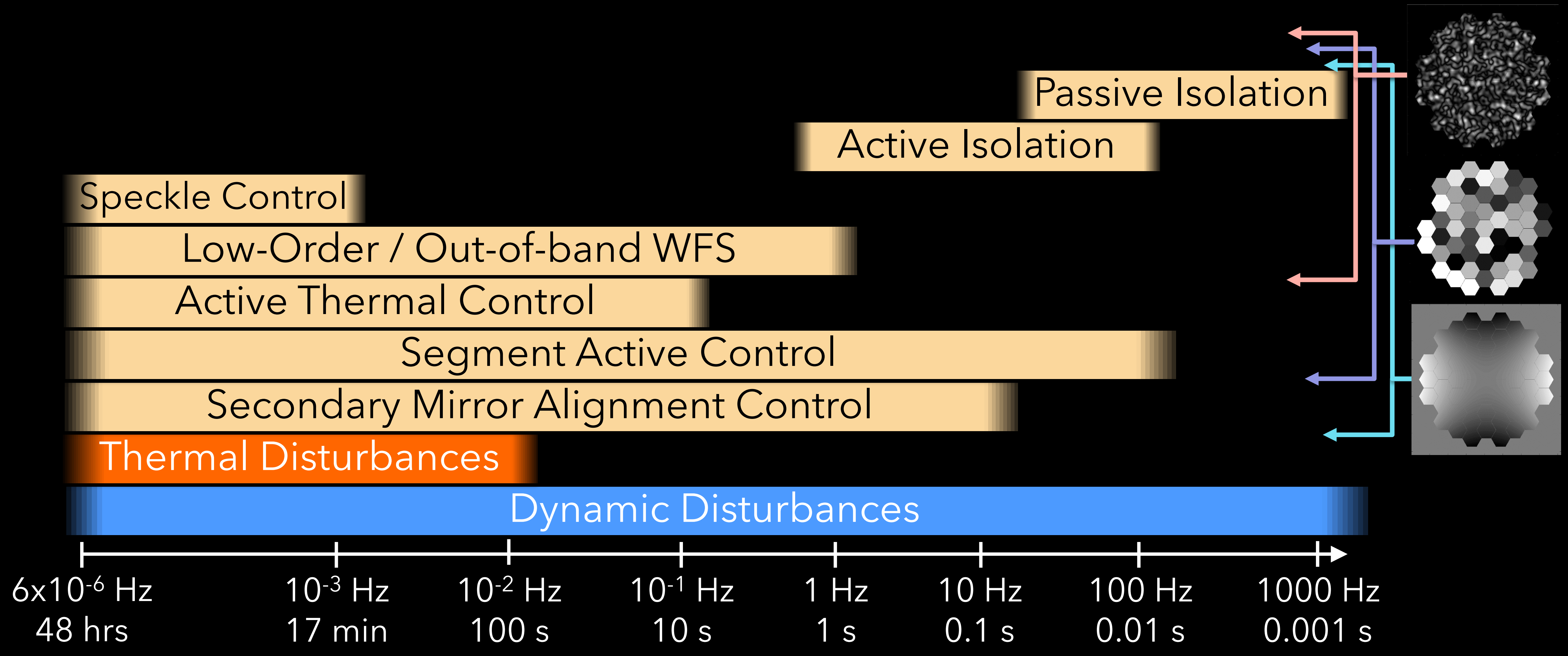


Credit: Pogorelyuk / Princeton University



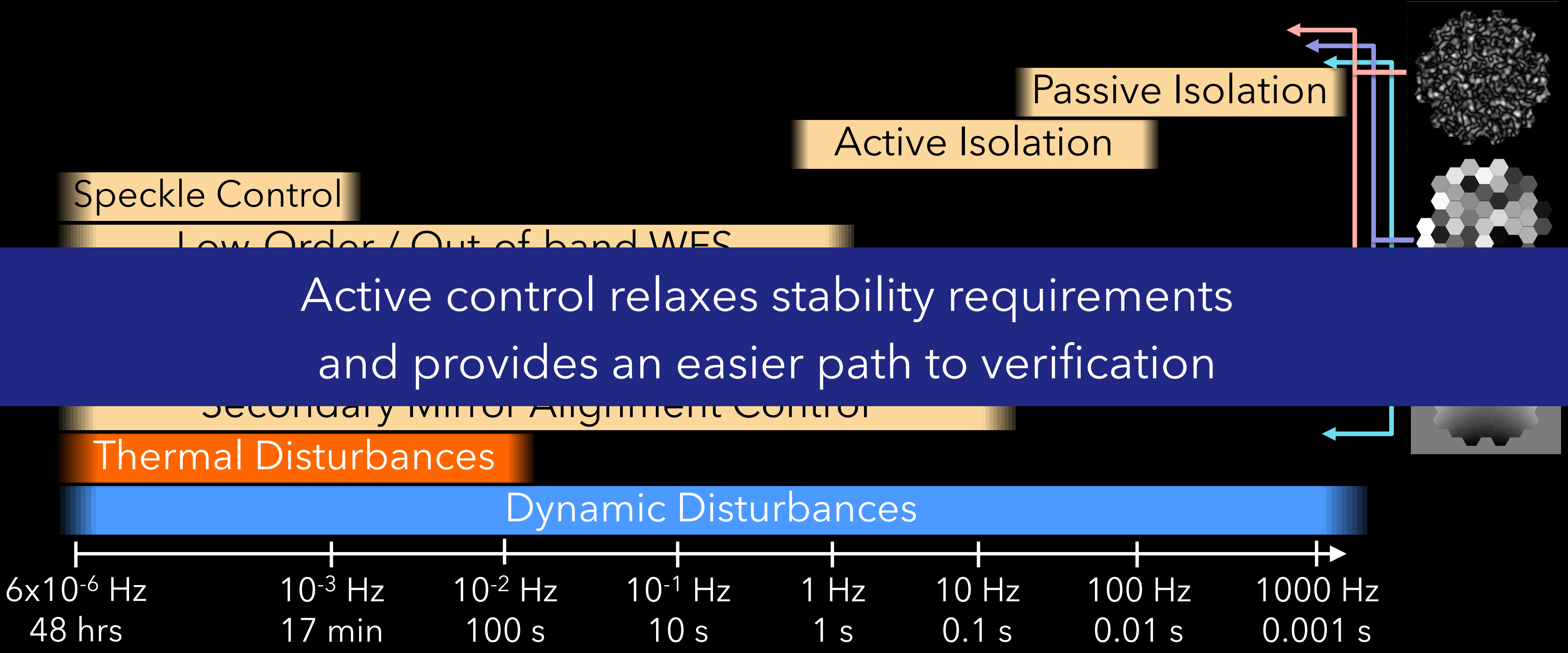
Pupil
DM1 (nm)
DM2 (nm)
Apodizer
Focal plane mask
Lyot stop
(rad)
D/2
0
−D/2
LUVOIR-B VVC nominal contrast
Contrast
10^{-8}
10^{-9}
10^{-10}
0
5
10
15
20
25
30
λ/D
LUVOIR-B VVC nominal contrast
Log(C)
−6
−7
−8
−9
−10
−11
20
10
0
−10
−20
−30
λ/D

ULTRA-STABILITY THROUGH CONTROL



See "Ultra-stable Telescope Research and Analysis (ULTRA) Program Phase 1 Report", Ball Aerospace, L3/Harris, Northrop Grumman, SGT, Space Telescope Science Institute

ULTRA-STABILITY THROUGH CONTROL



Active control relaxes stability requirements and provides an easier path to verification

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