Detecting Earths Directly and Indirectly

Aki Roberge

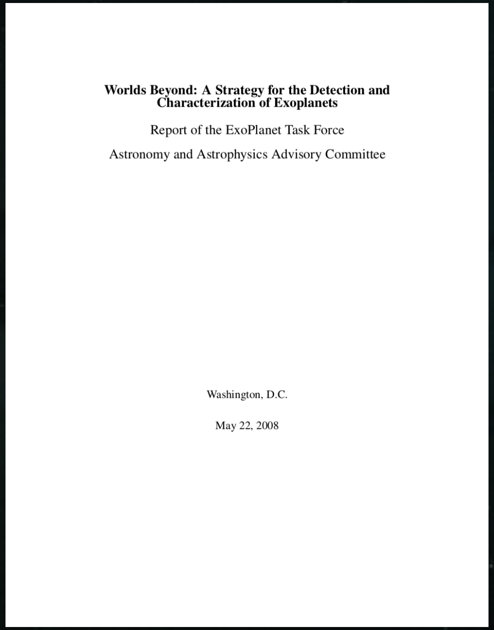
NASA Goddard Space Flight Center

Sagan Summer Workshop
July 29, 2022

The Search for Life

Finding Earth-like planets and life would be a momentous achievement

2008


Worlds Beyond: A Strategy for the Detection and Characterization of Exoplanets

Report of the ExoPlanet Task Force

Astronomy and Astrophysics Advisory Committee

Washington, D.C.

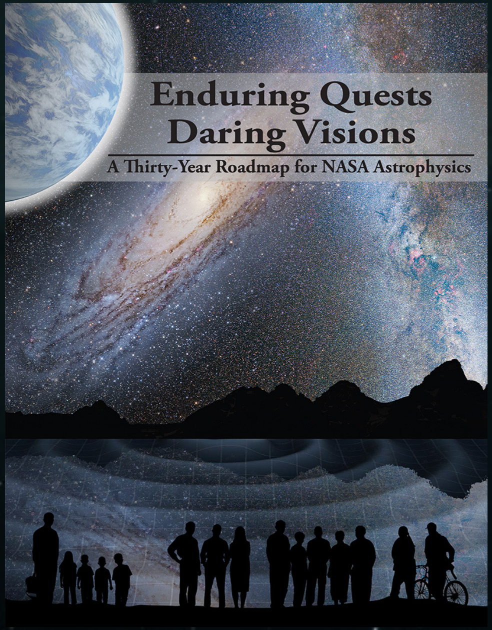
May 22, 2008

AAAC Exoplanet Task Force

2010

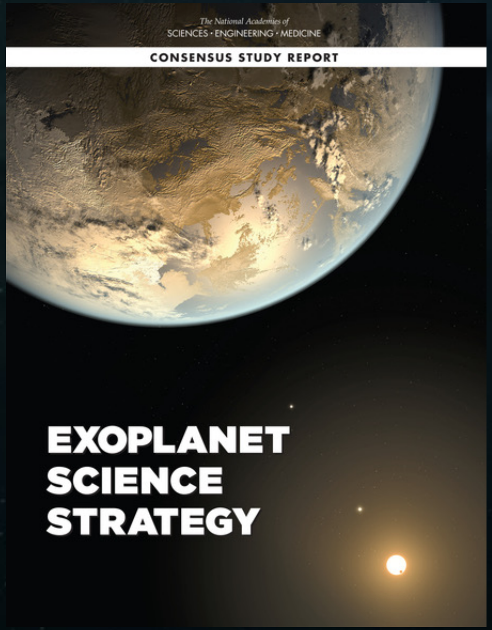
NAS Astro2010 Decadal

2013



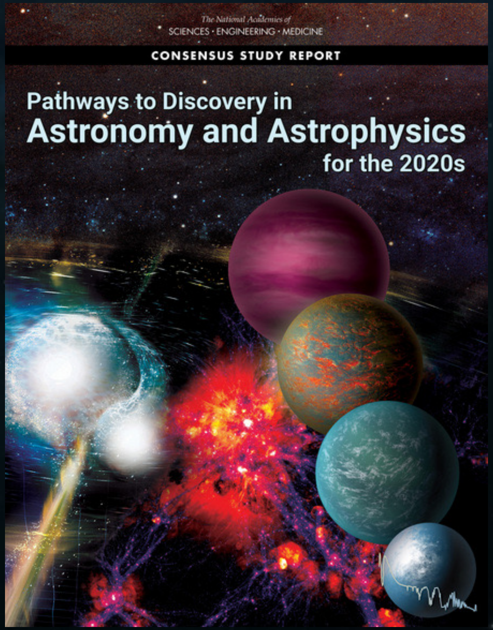
NASA Astro Roadmap

2018



NAS Consensus Study

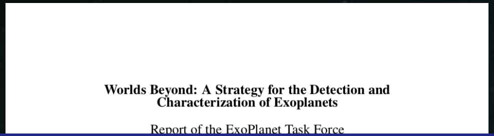
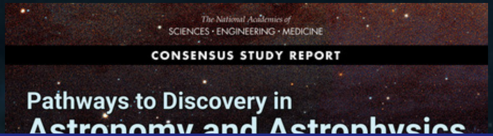
2021



NAS Astro2020 Decadal

The Search for Life

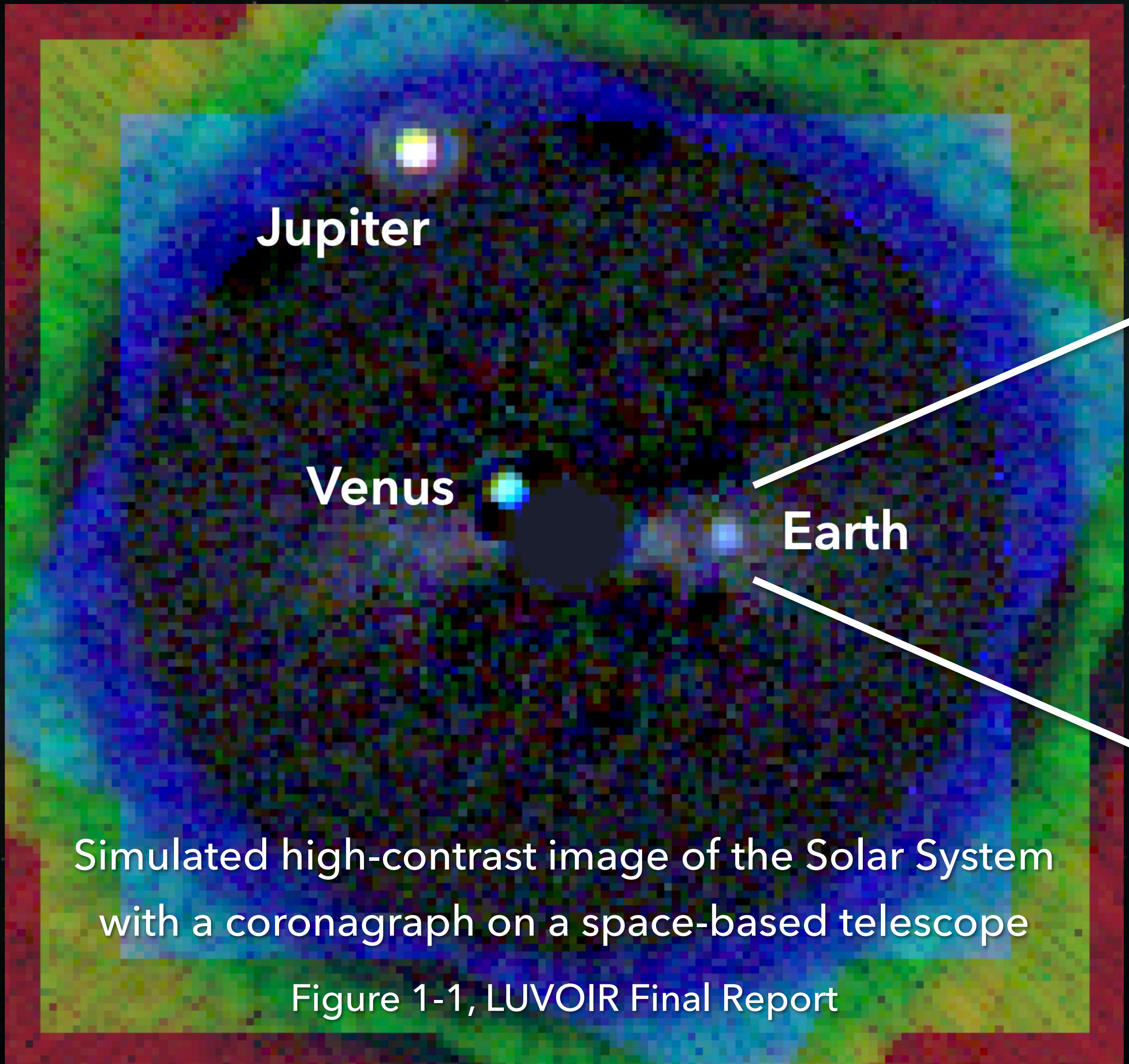
Finding Earth-like planets and life would be a momentous achievement

2008	2010	2013	2018	2021
				
AAAC Exoplanet Task Force	NAS Astro2010 Decadal	NASA Astro Roadmap	NAS Consensus Study	NAS Astro2020 Decadal

Two paths towards habitable exoplanets …

1. Space-based direct spectroscopy for Sun-like stars
2. Ground-based direct spectroscopy for low-mass stars

DIRECT OBSERVATIONS OF EXOEARTHS



Simulated high-contrast image of the Solar System with a coronagraph on a space-based telescope

Figure 1-1, LUVOIR Final Report

Light reflected or emitted by the planet, with little or no starlight mixed in

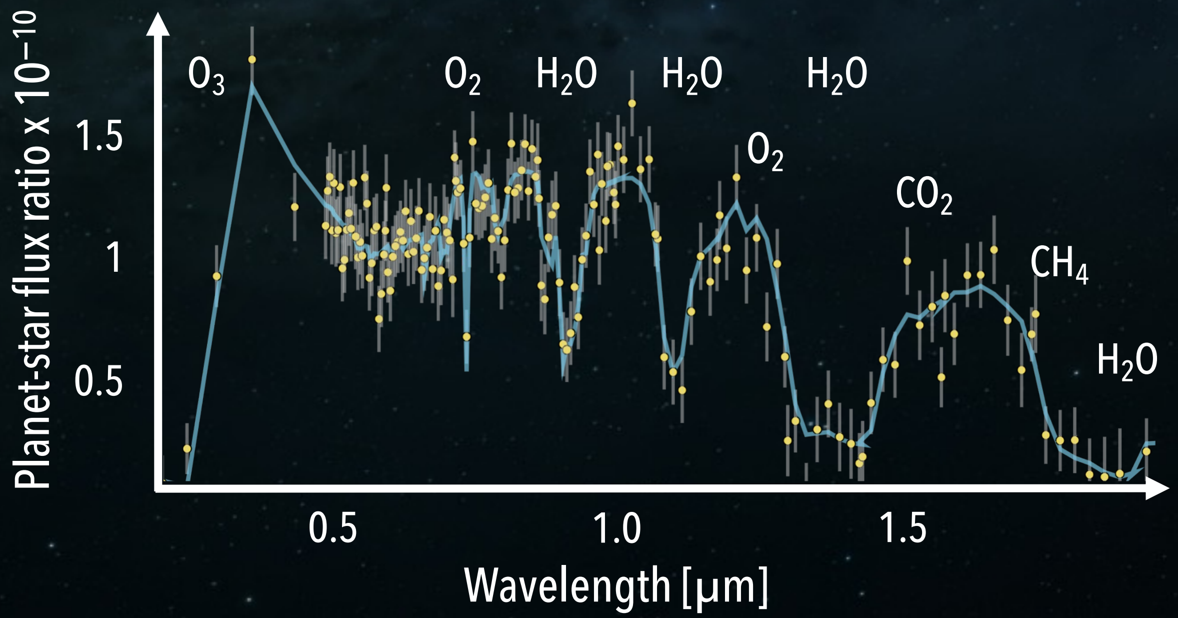


Figure 3-15, LUVOIR Final Report

Why direct spectroscopy?

Sun-like Stars

Small planet & small atmosphere

Large star

↓ ↓

Extremely small signals in transit spectroscopy

↓

Need direct spectroscopy

Required ultra-high contrast too challenging from ground
(even using ELTs, future extreme adaptive optics, & high dispersion technique)

↓

Need space-based direct spectroscopy

Why direct spectroscopy?

Sun-like Stars

Small planet & small atmosphere

Large star

↓

Extremely small signals in transit spectroscopy

↓

Need direct spectroscopy

Required ultra-high contrast too challenging from ground
(even using ELTs, future extreme adaptive optics, & high dispersion technique)

↓

Need space-based direct spectroscopy

Low-mass Stars

Small planet & small atmosphere

Small star

↓

Small possible signals in transit spectroscopy.
But … sensitive to planet's upper atmosphere

Some important molecules concentrated in Earth's lower atmosphere (e.g., water vapor)

↓

Need direct spectroscopy to probe lower atmosphere

Lower contrast requirements

↓

Try ground-based direct spectroscopy

Path 1

Earth-like Planets Around Sun-Like Stars

The once and future Great Observatories

The First Great Observatories

The once and future Great Observatories

The Future Great Observatories

HabEx
UV/Optical/NIR

LUVOIR
UV/Optical/NIR

Lynx
X-ray

Origins
Infrared

Astro2020 Decadal Survey recommended NASA work towards a new fleet of multi-wavelength Great Observatories

First New Great Observatory

UV / Optical / Infrared space telescope with ~ 6-m inscribed diameter

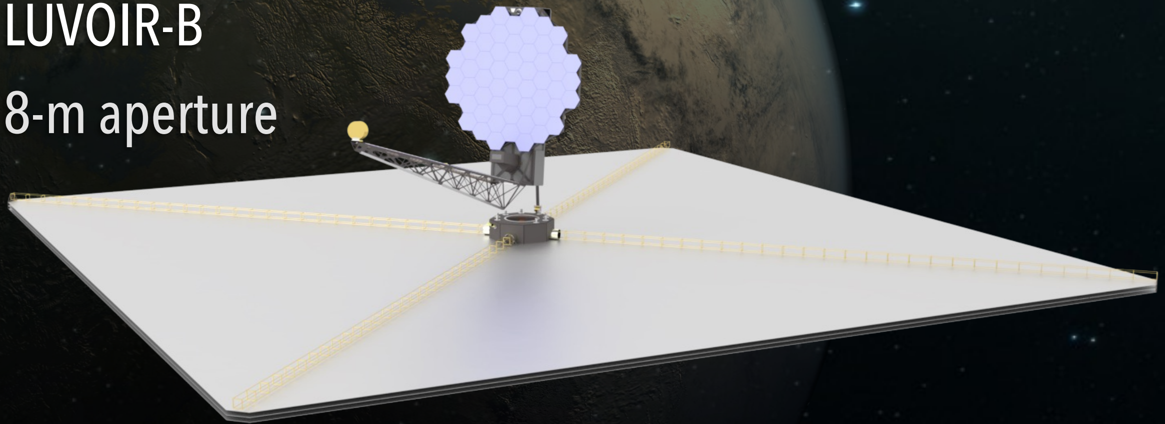
To search for life on exoplanets and enable transformative astrophysics

Blending of the LUVOIR and HabEx mission concepts (IROUV? LUVEx?)

Start maturing concept ASAP. Launch in early 2040s

LUVOIR-B

8-m aperture



Planet yields from LUVOIR & HabEx

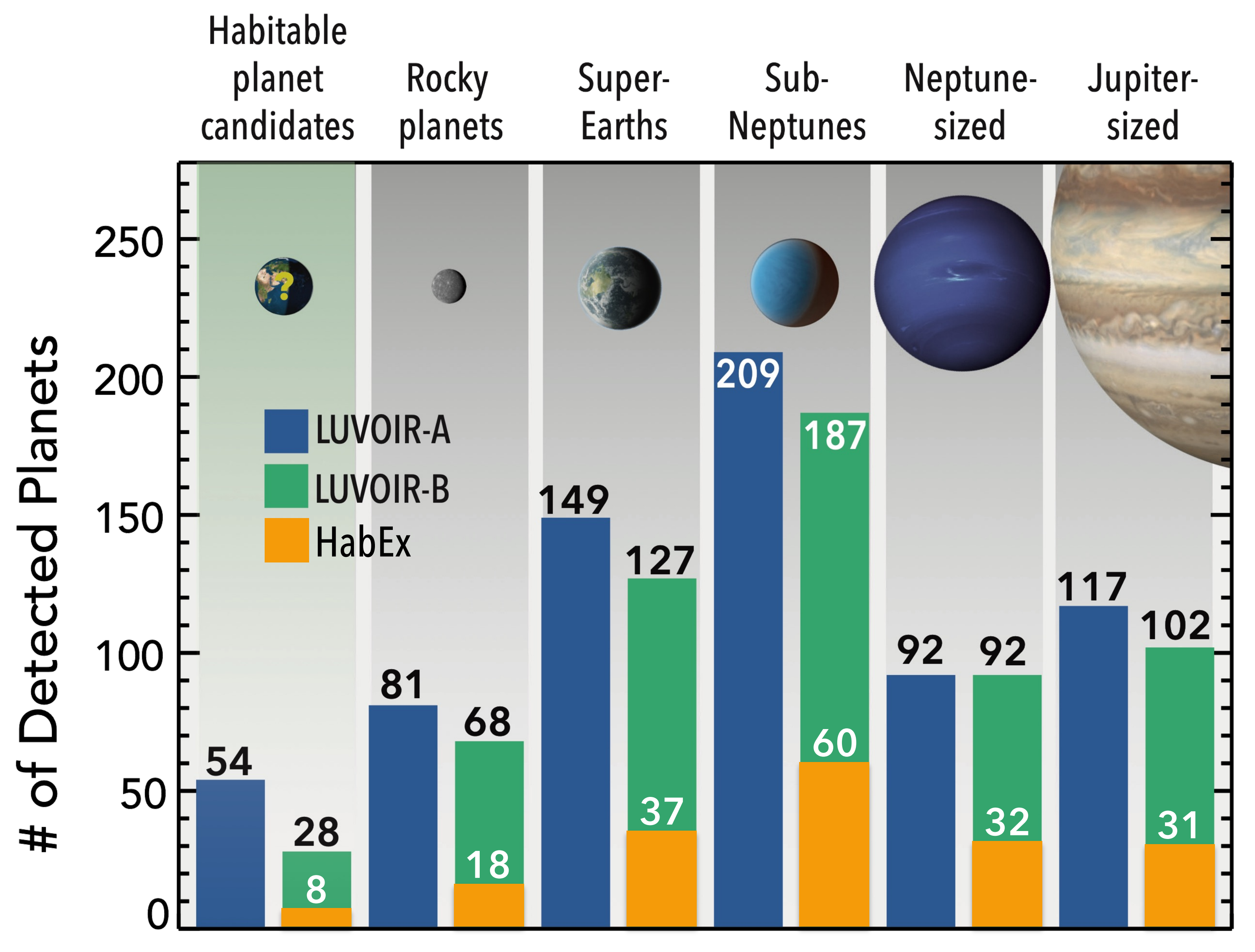
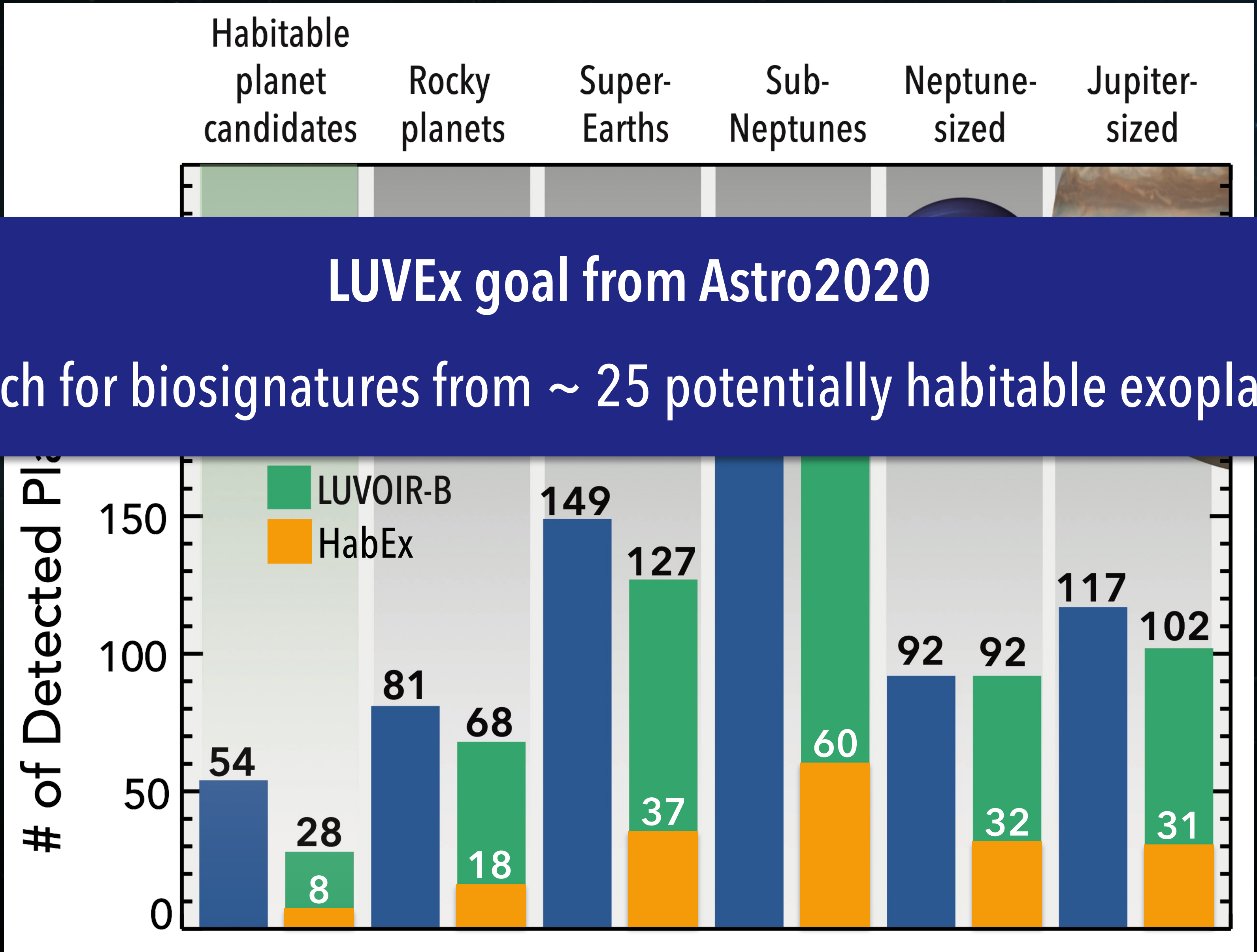


Figure 1-6, LUVOIR Final Report &
Figure ES-2, HabEx Final Report

Planet yields from LUVOIR & HabEx



LUVEx goal from Astro2020

Search for biosignatures from ~ 25 potentially habitable exoplanets

Three inhabited planets: the Earth through time

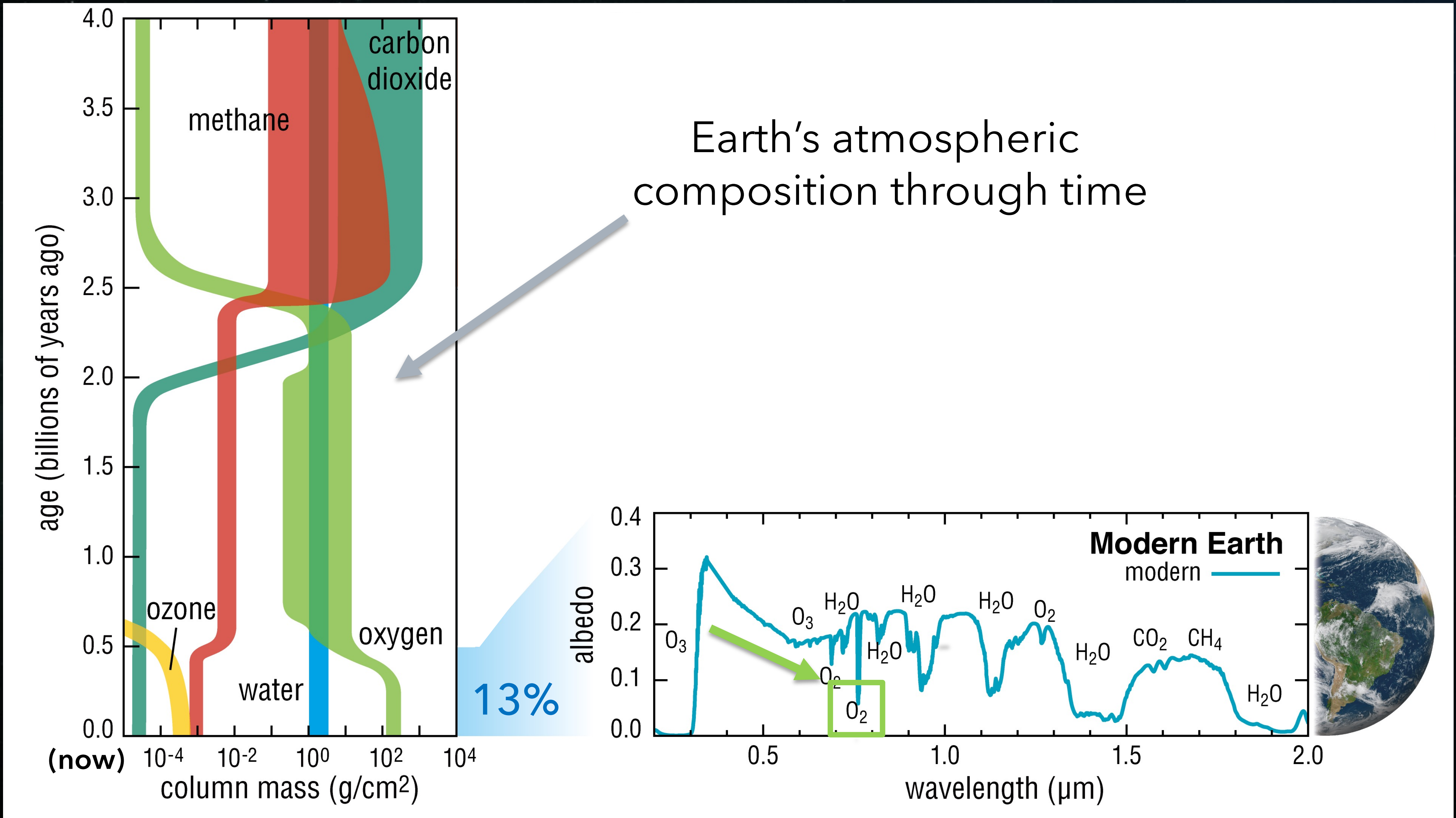


Figure 1-8, LUVOIR Final Report

Three inhabited planets: the Earth through time

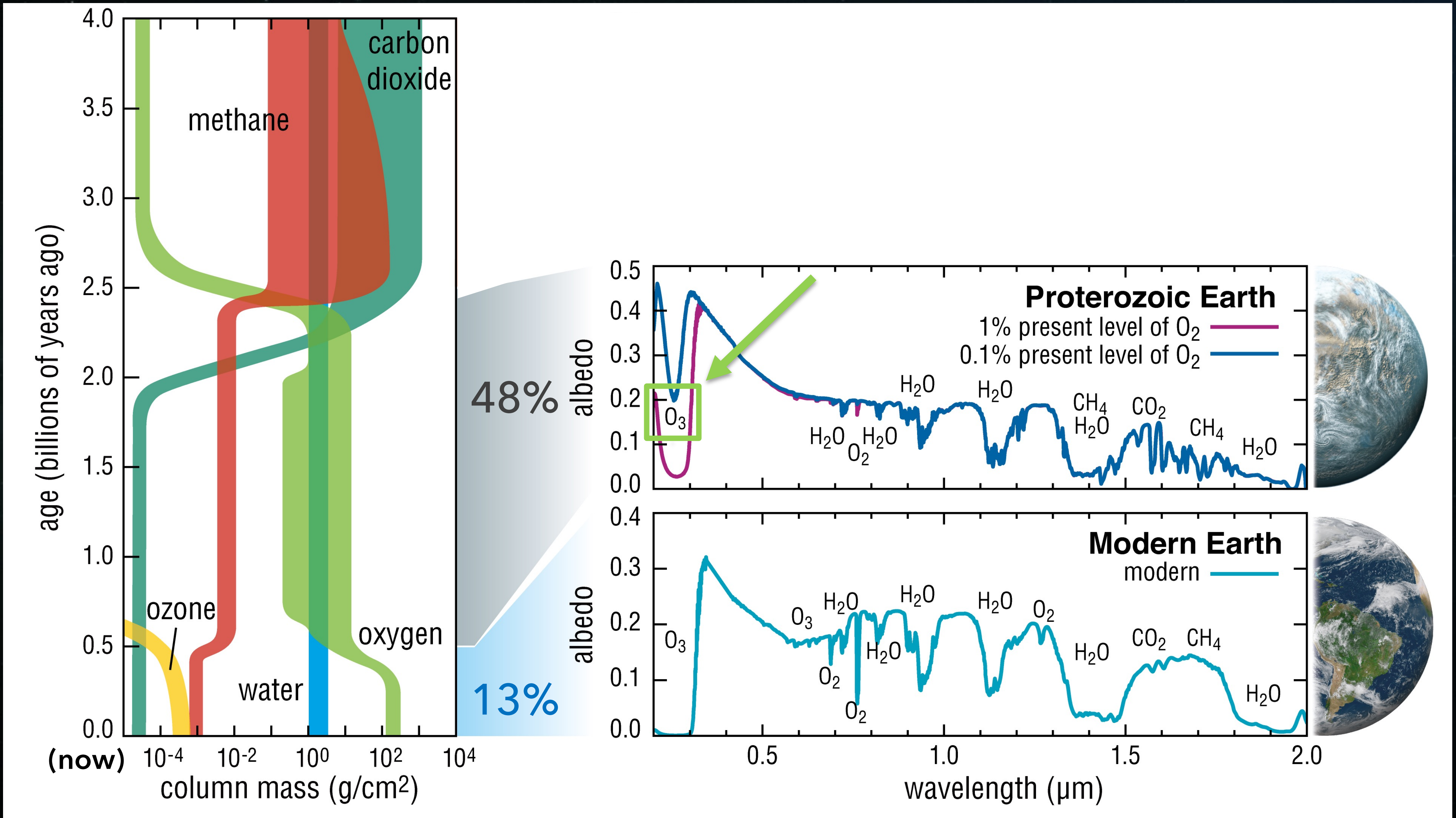


Figure 1-8, LUVOIR Final Report

THREE INHABITED PLANETS: THE EARTH THROUGH TIME

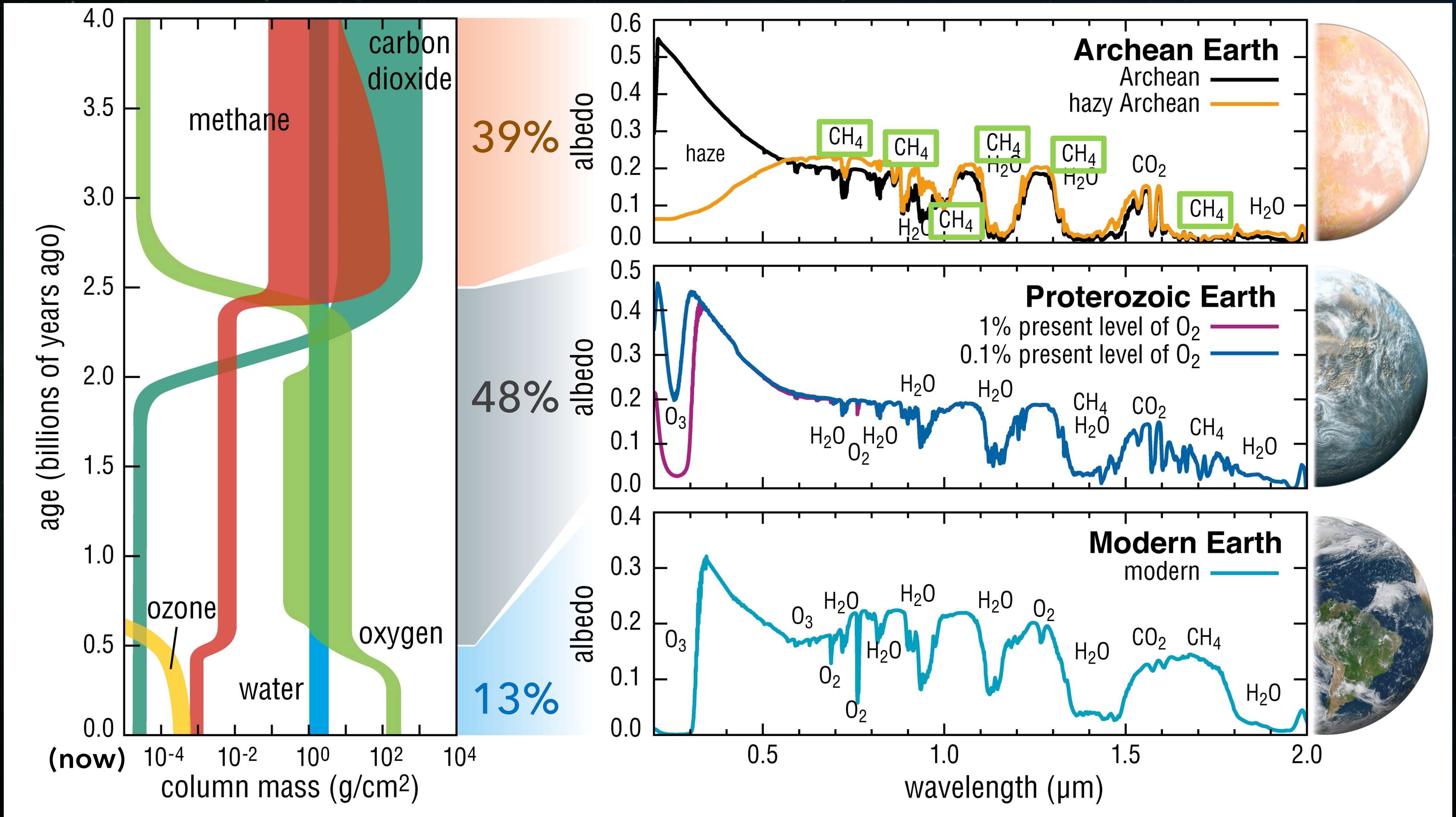


Figure 1-8, LUVOIR Final Report

Three inhabited planets: the Earth through time

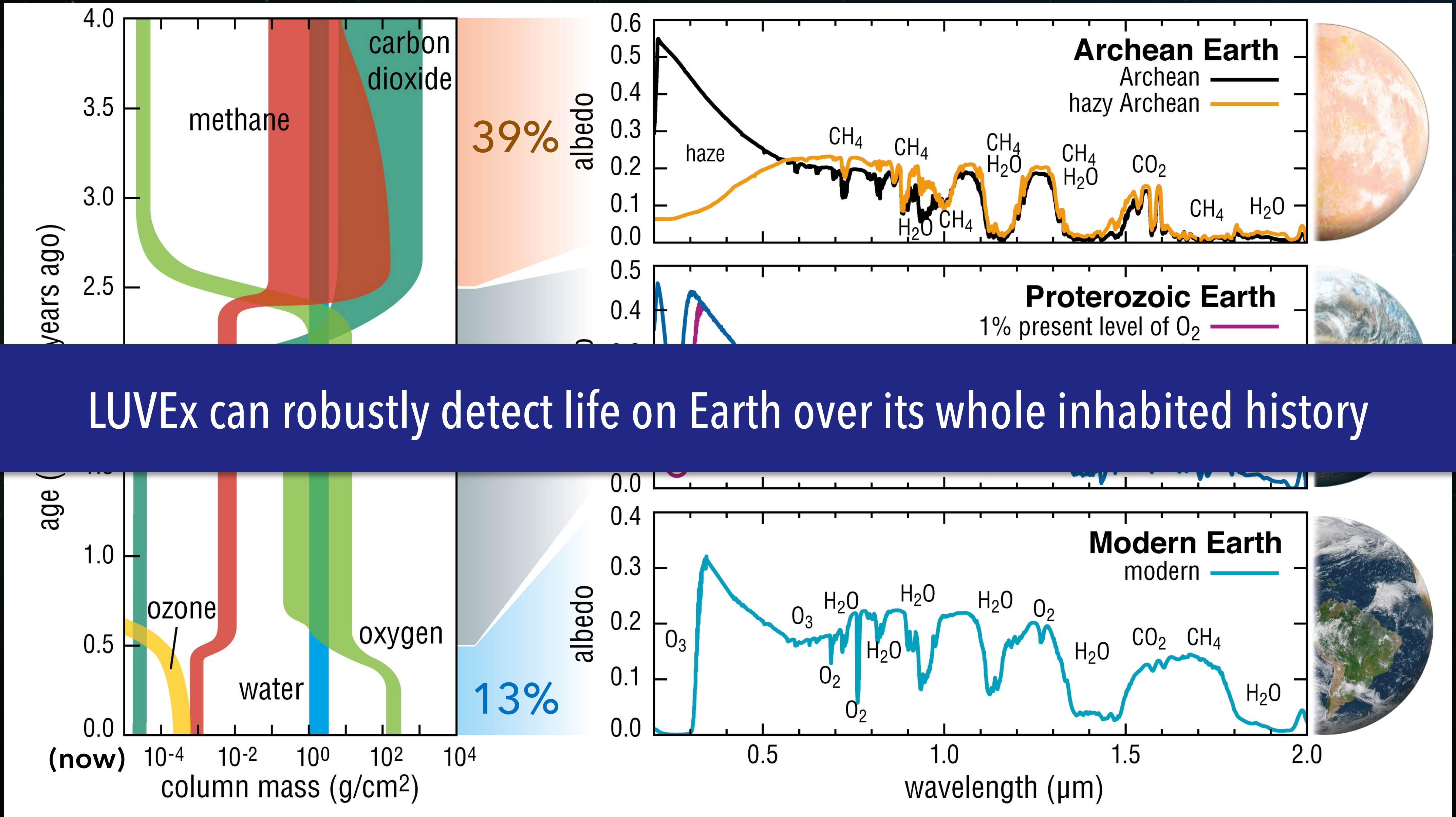
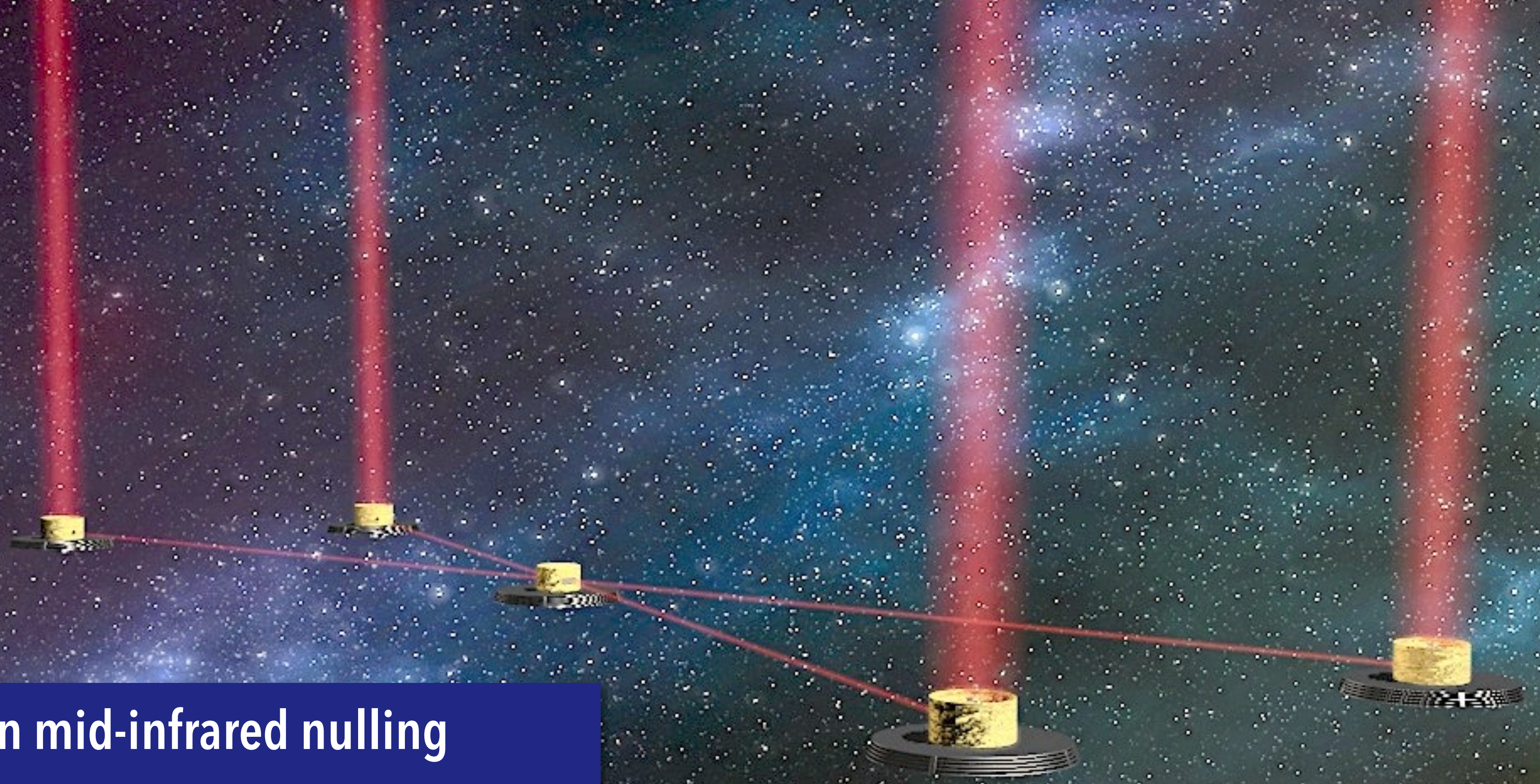


Figure 1-8, LUVOIR Final

LUVEx can robustly detect life on Earth over its whole inhabited history

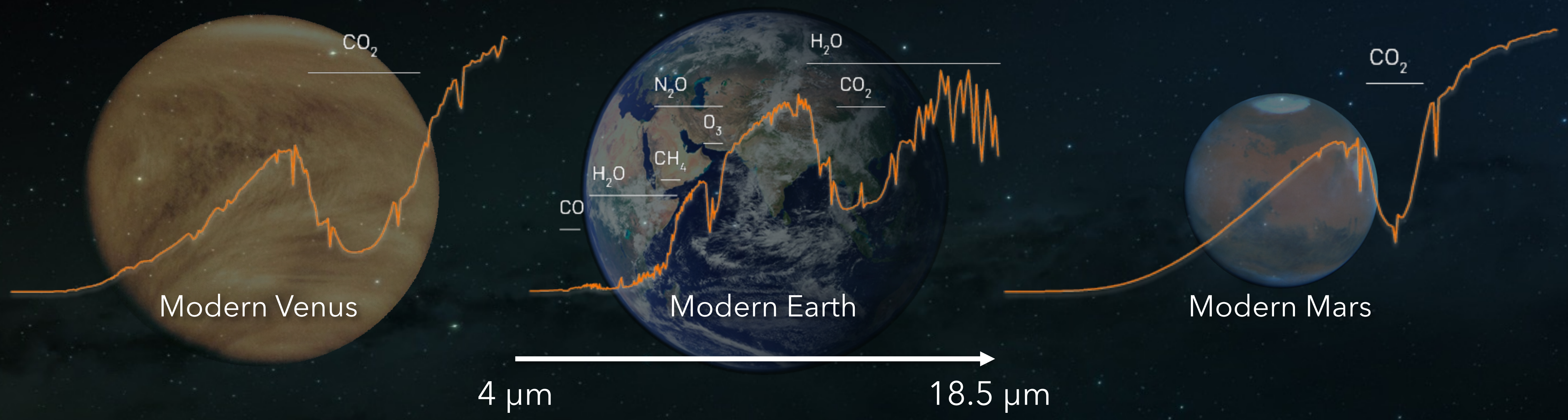
Large Interferometer for Exoplanets (LIFE) concept



European mid-infrared nulling interferometer mission concept

Heritage from ESA's Darwin & NASA's TPF-I mission concepts (early/mid 2000s)

The European LIFE mission concept



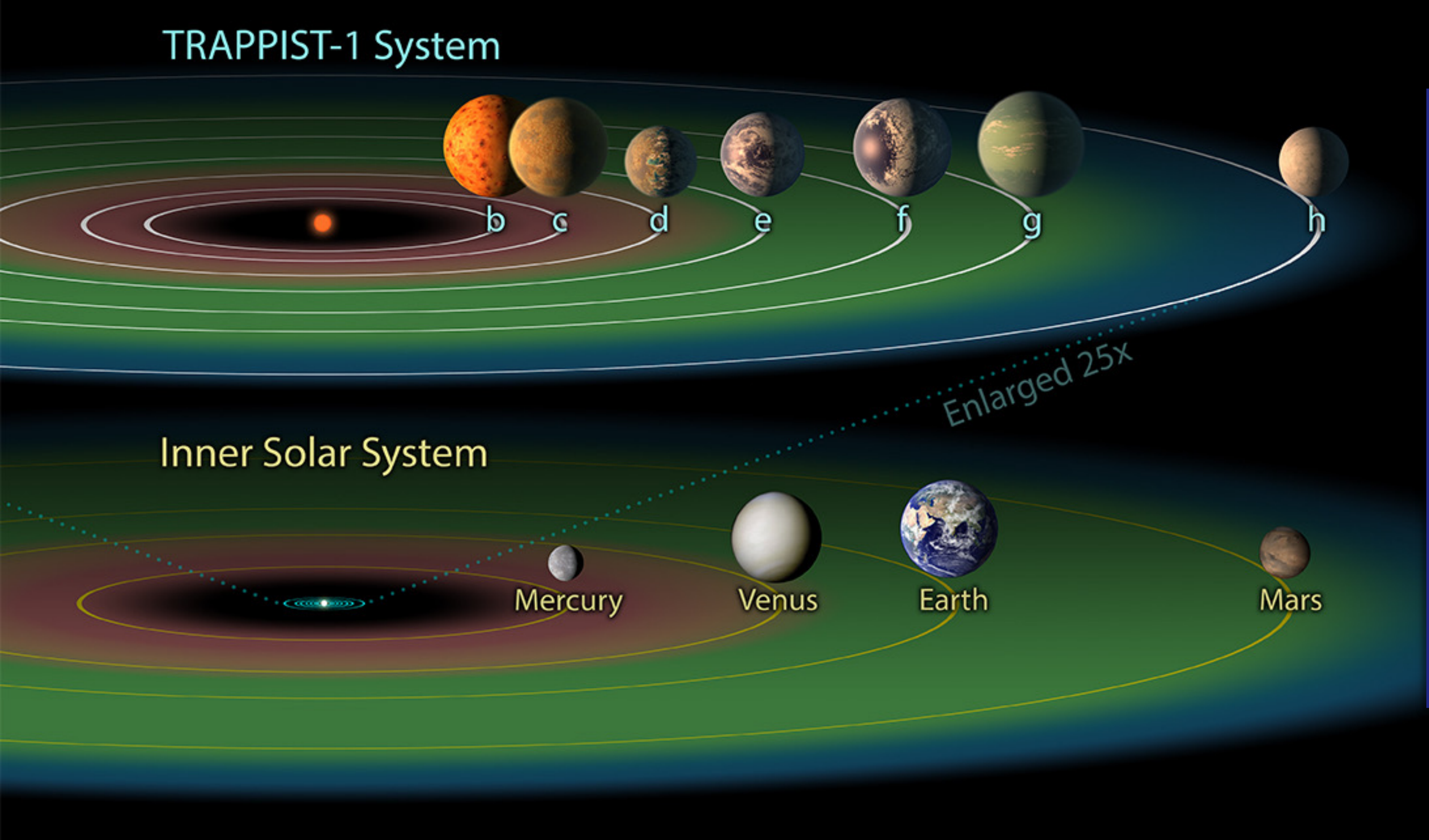
Science Objective

Biosignature search from 30–50 potentially habitable exoplanets orbiting early-M stars to late-F stars via high-contrast direct spectroscopy of thermal emission

Path 2

Earth-like Planets Around Low-Mass Stars

What can JWST do for habitable planets?



What we know about the TRAPPIST-1 planets

Innermost six do not have H-He dominated atmospheres

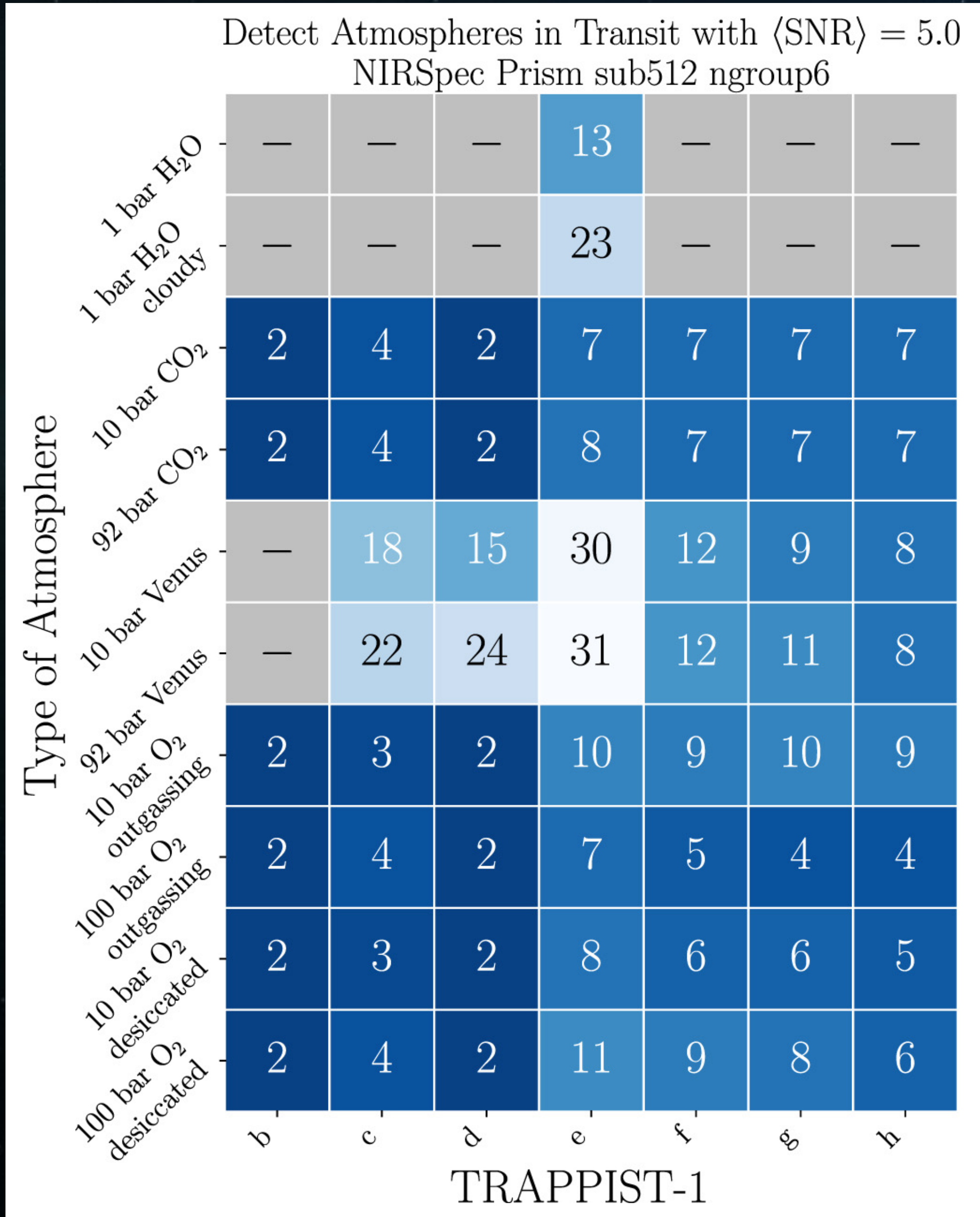
High-mean molecular weight atmospheres or airless rocks?

Terrestrial planet atmospheres with JWST

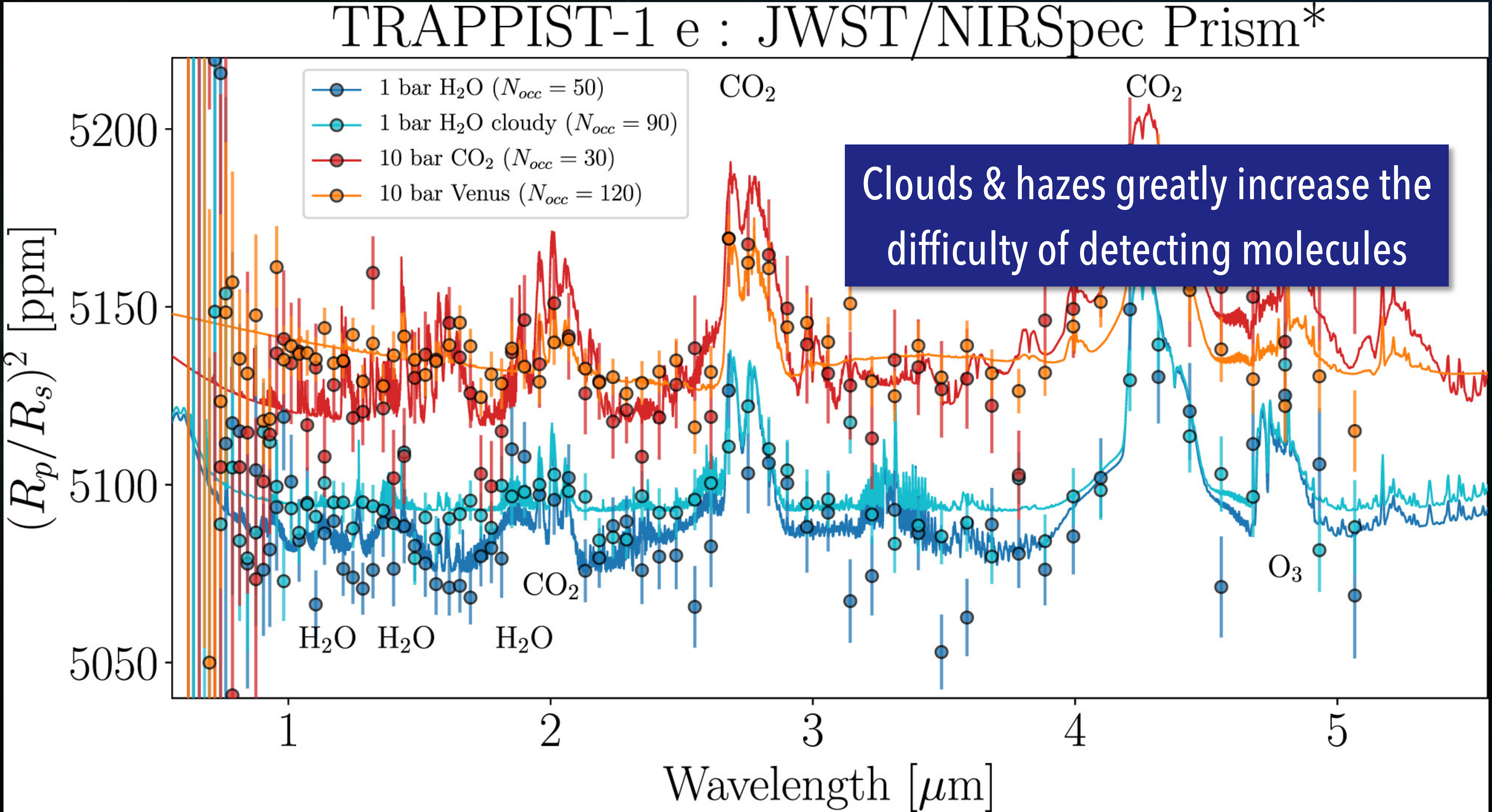
Cycle 1 search for atmospheres on TRAPPIST-1 b, c, g, & h

Number of transits for each TRAPPIST-1 planet needed to rule out a featureless spectrum

- For different self-consistent atmospheric compositions using *JWST* NIRSpec Prism (Lustig-Yaeger, Meadows, & Lincowski 2019)

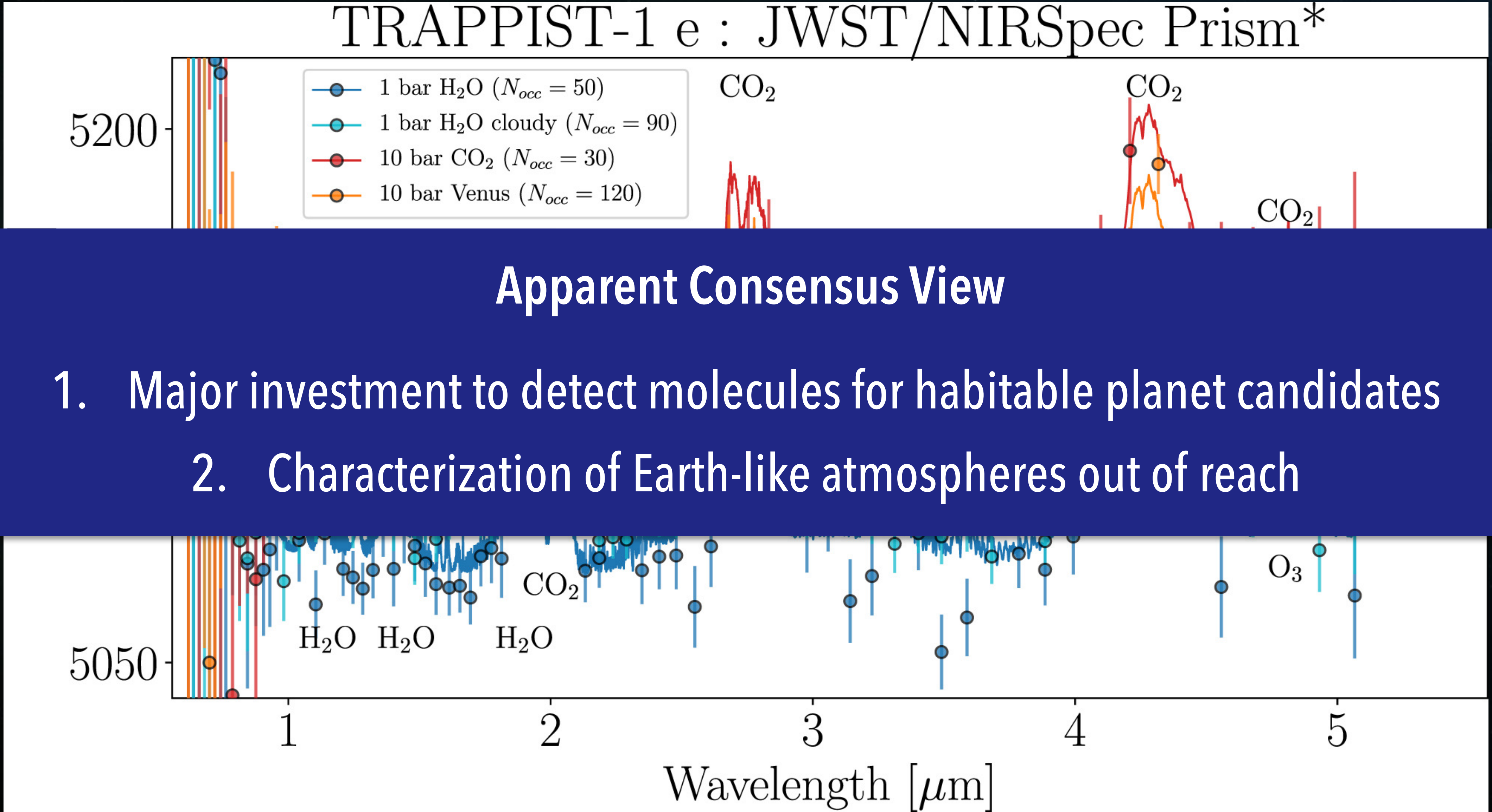


HABITABLE ZONE PLANET ATMOSPHERES WITH JWST



Lustig-Yaeger, Meadows, & Lincowski (2019)

HABITABLE ZONE PLANET ATMOSPHERES WITH JWST

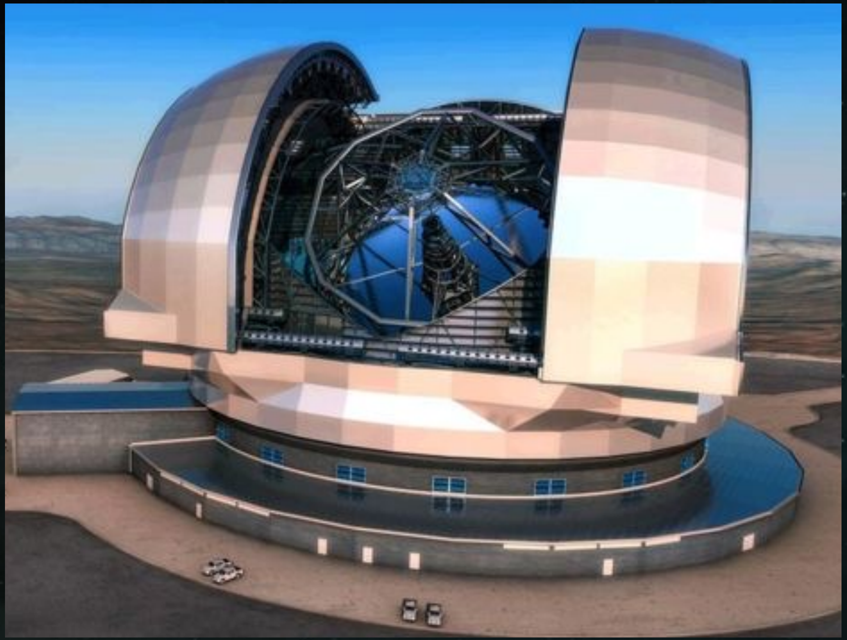


Lustig-Yaeger, ...ski (2019)

Apparent Consensus View

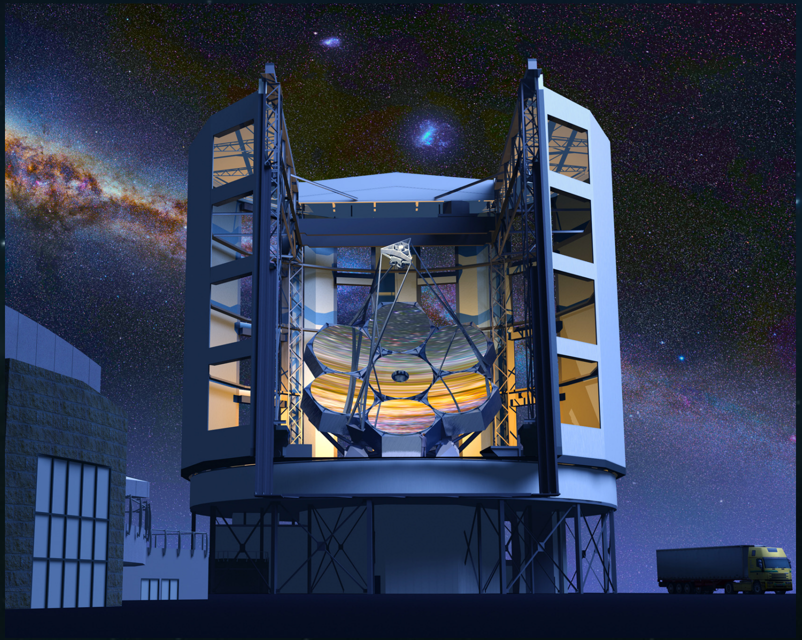
1. Major investment to detect molecules for habitable planet candidates
2. Characterization of Earth-like atmospheres out of reach

THE FUTURE EXTREMELY LARGE TELESCOPES ON THE GROUND



ELT (Chile)
39 meters

TMT (Hawaii?)
30 meters

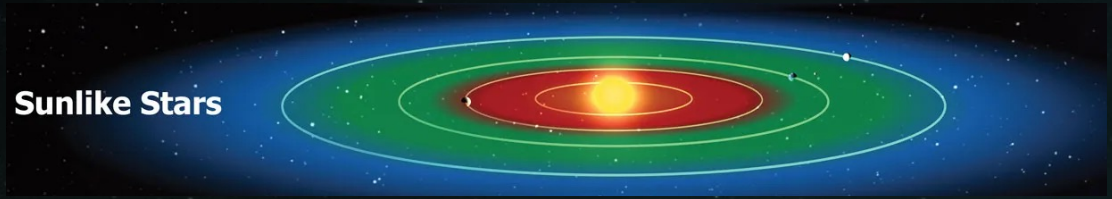


GMT (Chile)
25 meters

Astro2020 Decadal Survey recommended significant investment in TMT and GMT, as parts of a coordinated U.S. ELT program

WHY ELTs FOR HABITABLE PLANETS AROUND M STARS?

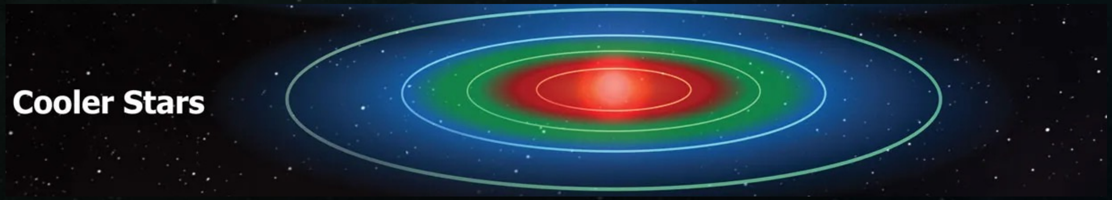
Sun-like Stars



Low planet-to-star flux ratio

Large habitable zone

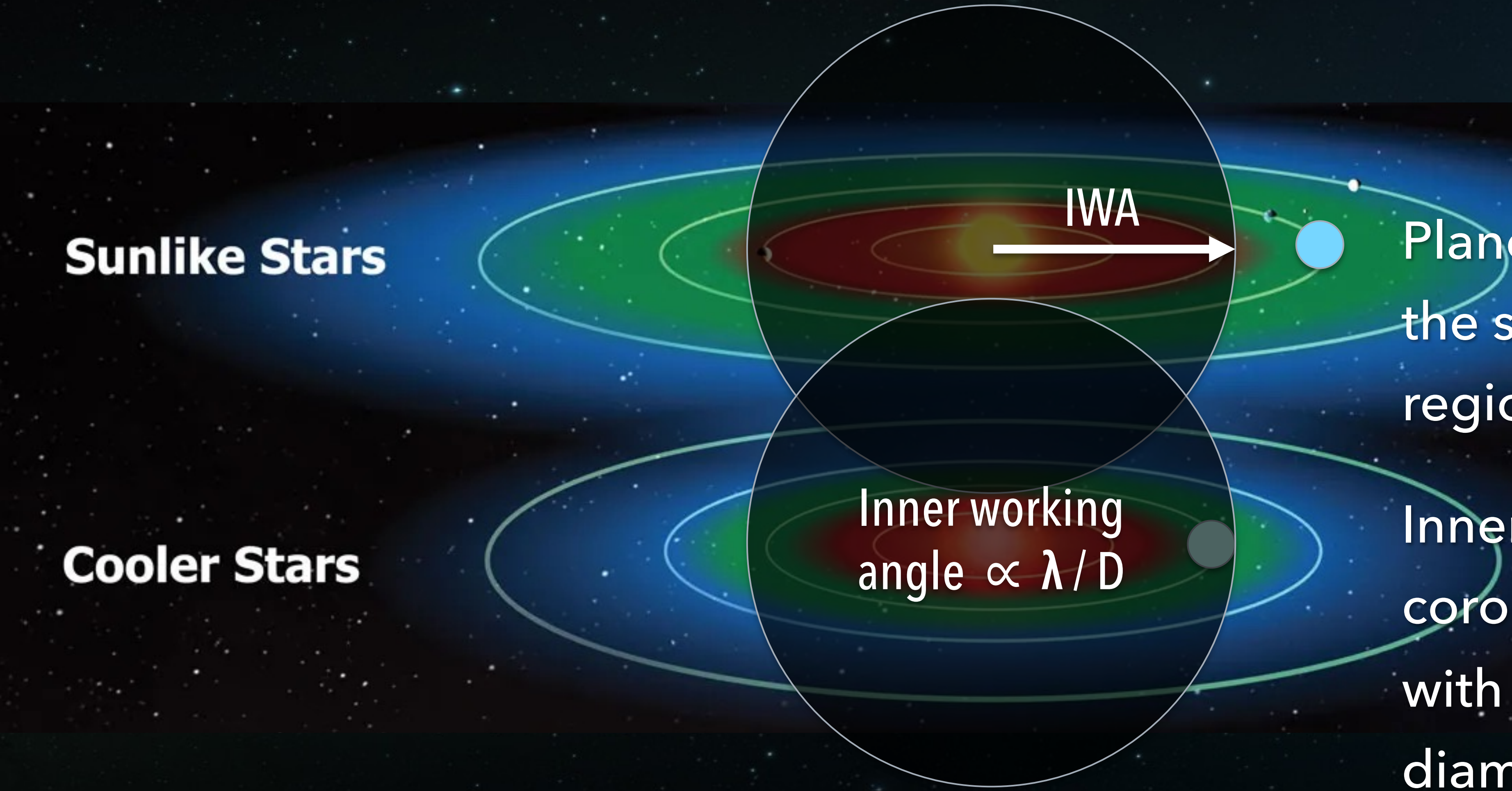
Low-Mass Stars



Higher planet-to-star flux ratio

Smaller habitable zone

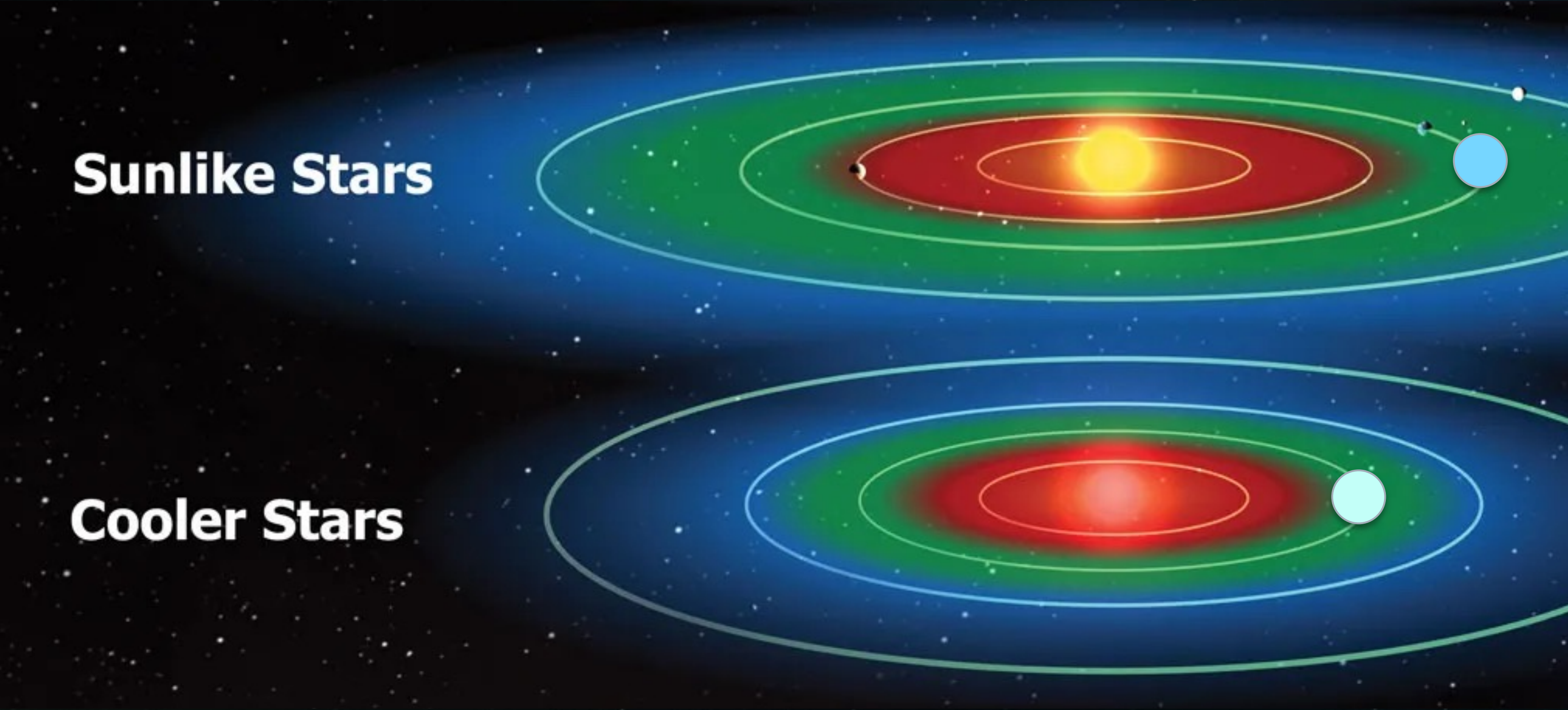
A WORD ABOUT CORONAGRAPHS



Planet must be outside the starlight suppression region to be seen

Inner working angle of a coronagraph gets smaller with increasing telescope diameter (D)

A word about starlight suppression

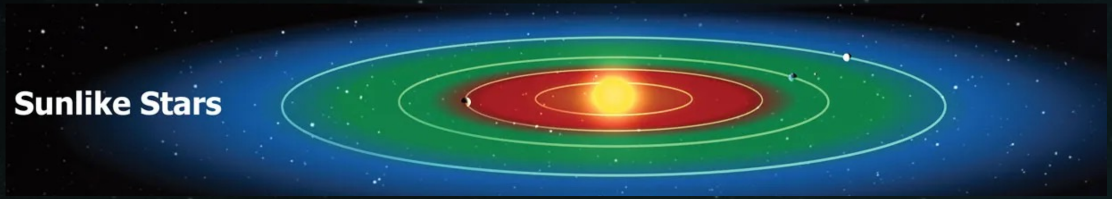


From space, can get higher contrast and observe planets with lower planet-to-star flux ratios

Variability of Earth's atmosphere limits contrast achievable from ground

THE TWO PATHS, AGAIN

Sun-like Stars → **Space**



Low planet-to-star flux ratio

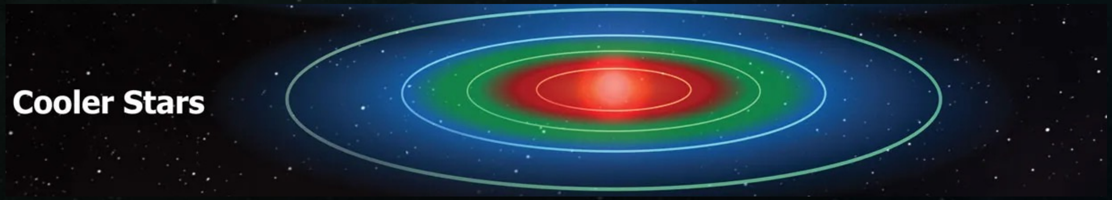
Large habitable zone

Better contrast

Modest telescope diameter

Larger central starlight suppression region (inner working angle)

Low-Mass Stars → **Ground**



Higher planet-to-star flux ratio

Smaller habitable zone

Worse contrast

Huge telescope diameters

Smaller central starlight suppression region (inner working angle)

ELT spectroscopy of M dwarf habitable planets

Quality spectra will likely need combination of …

- High-contrast coronagraph
- Extreme adaptive optics (AO)
- High-dispersion technique

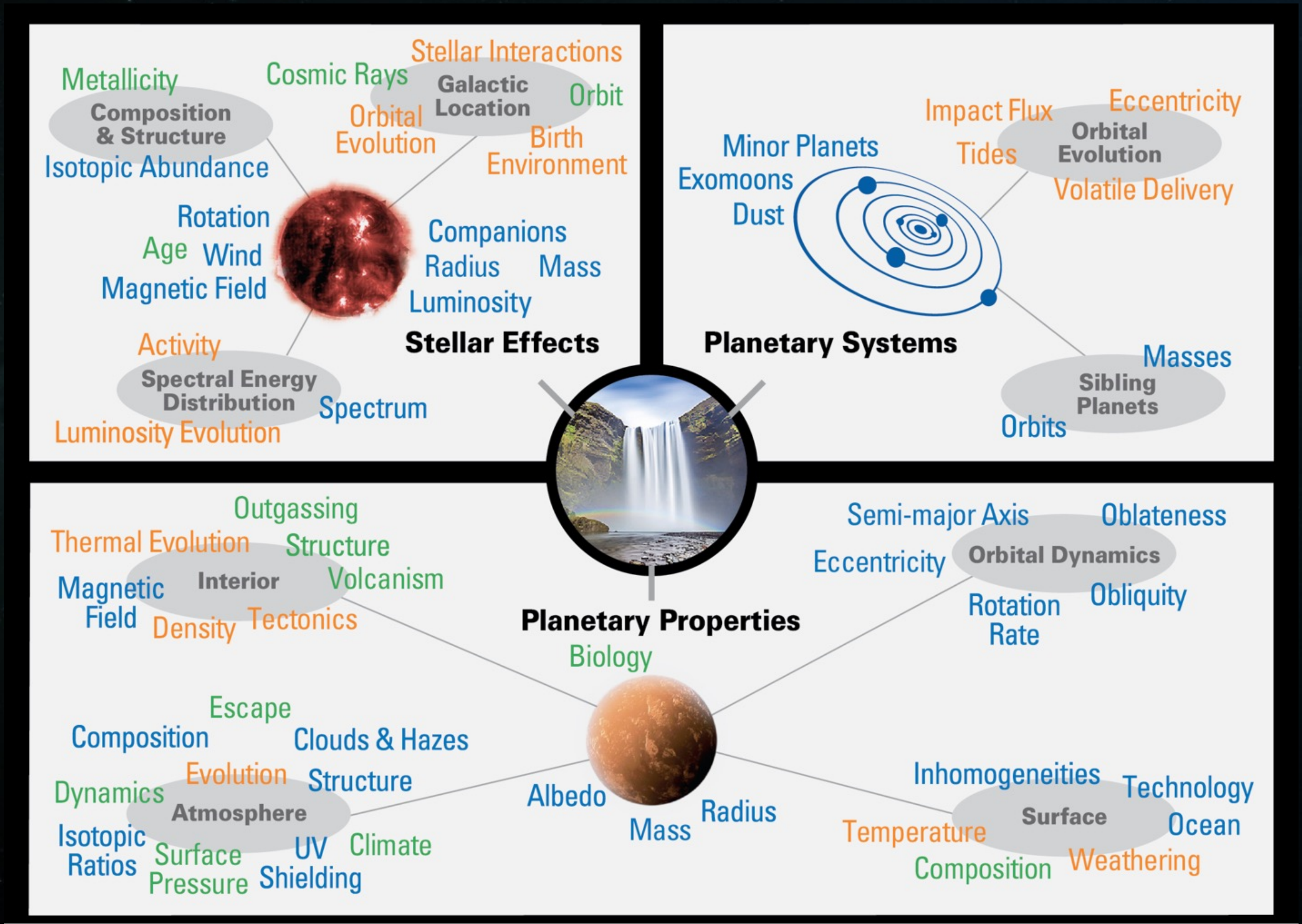
A first-generation instrument (METIS) for ELT appears to combine these features

- No coronagraphs in first-generation instrument suite for TMT or GMT

How many habitable planet candidates can be studied? TBD

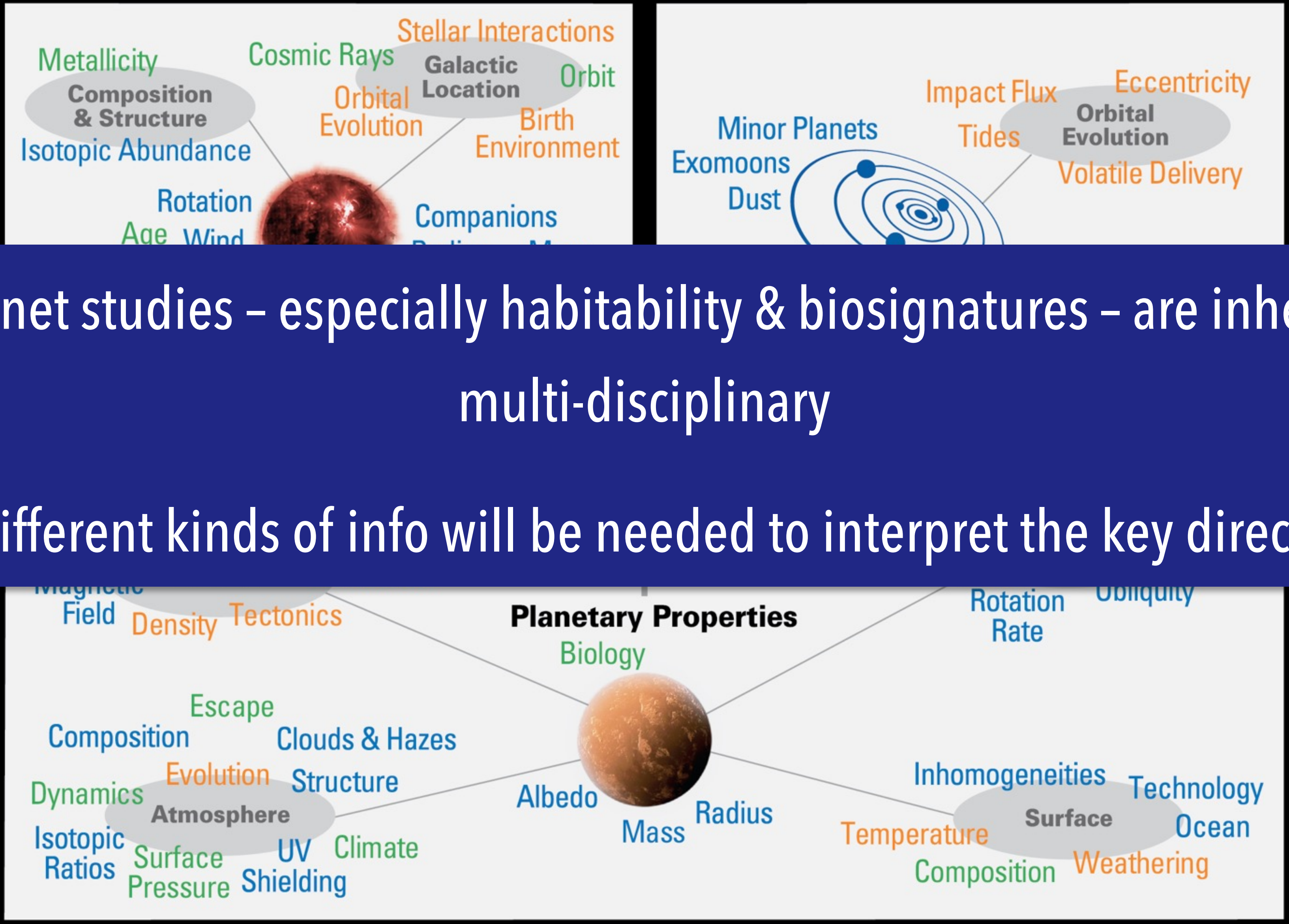
Indirect & Supporting Observations

Context is everything in the search for life



Meadows & Barnes 2018

Context is everything in the search for life



Meadows & B

Exoplanet studies – especially habitability & biosignatures – are inherently multi-disciplinary

Lots of different kinds of info will be needed to interpret the key direct spectra

LUVOIR SEARCH FOR LIFE OBSERVATIONAL STRATEGY

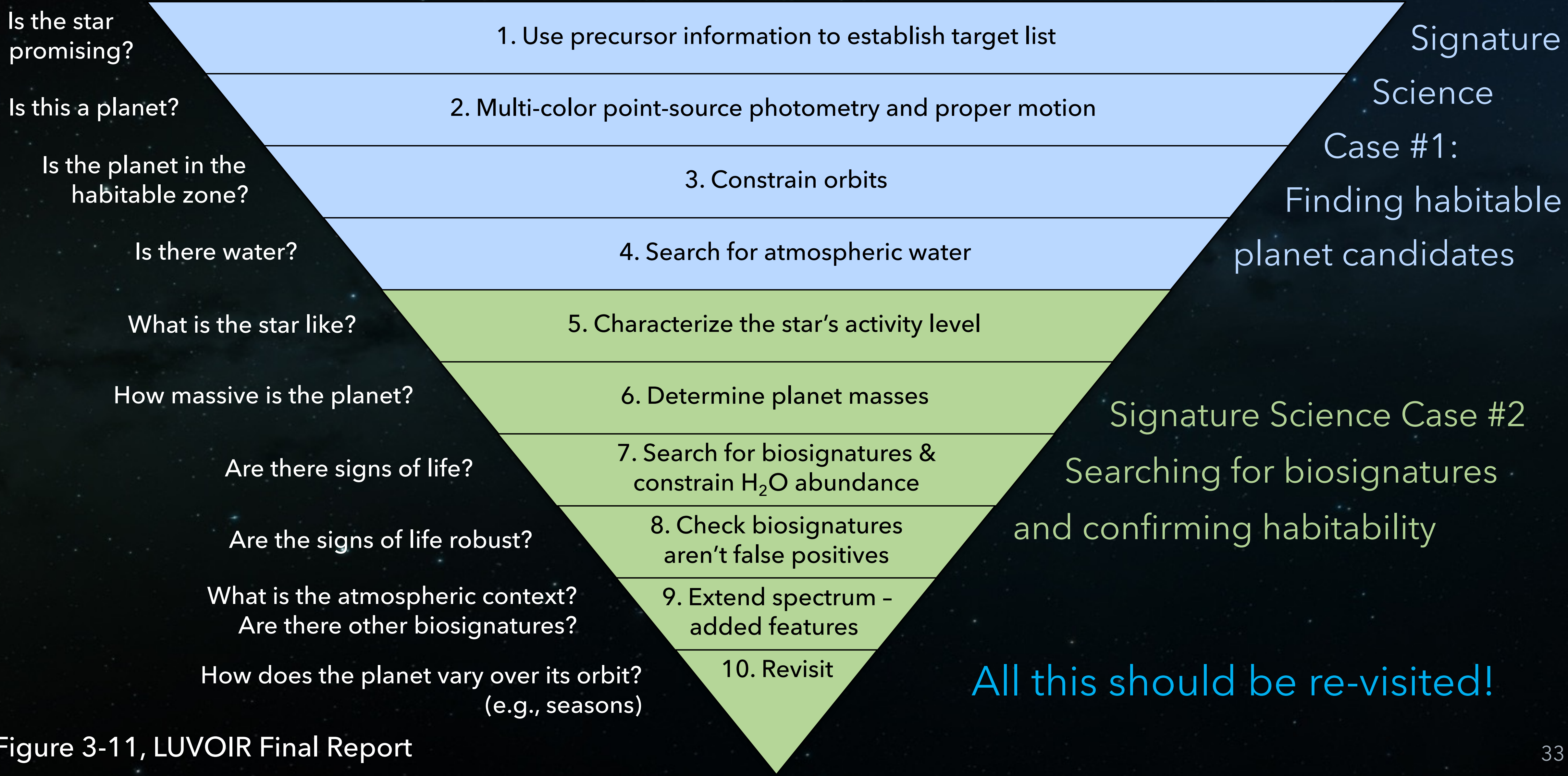
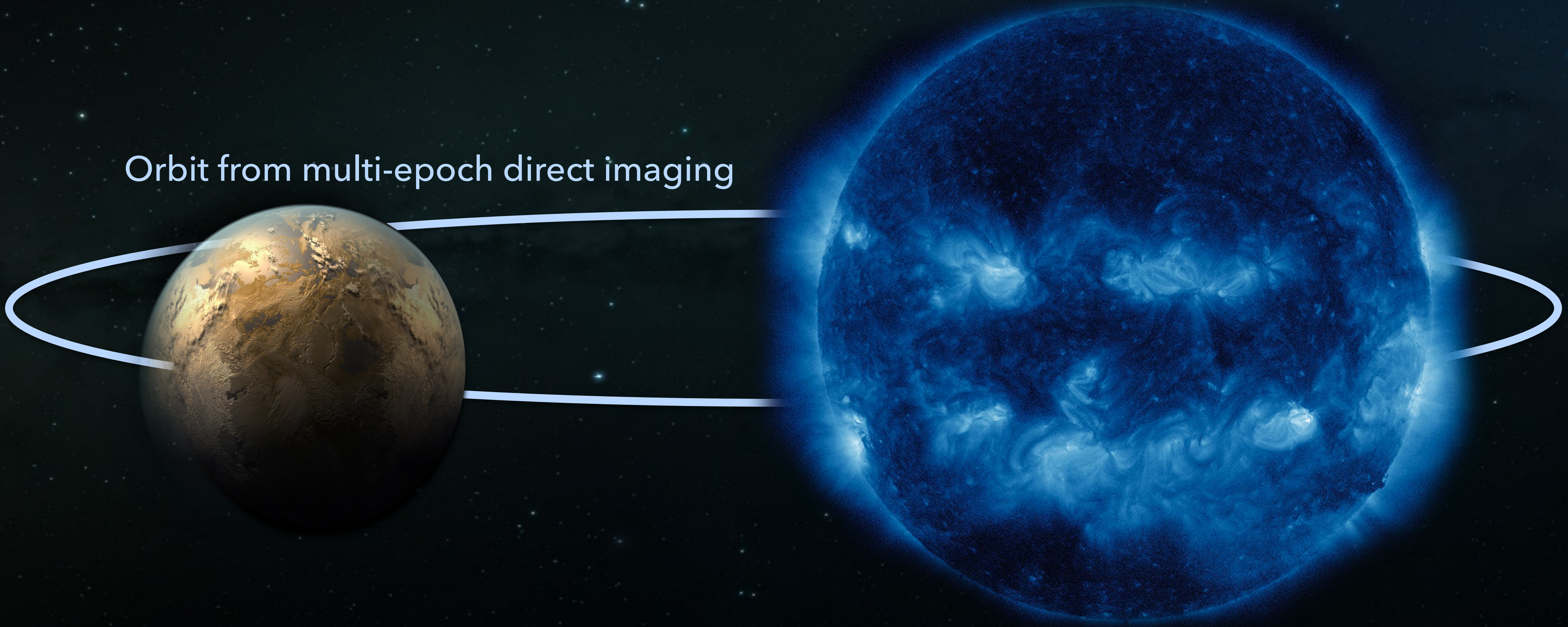


Figure 3-11, LUVOIR Final Report

Roles of indirect / supporting observations

Stellar characterization



Roles of indirect / supporting observations

Stellar characterization

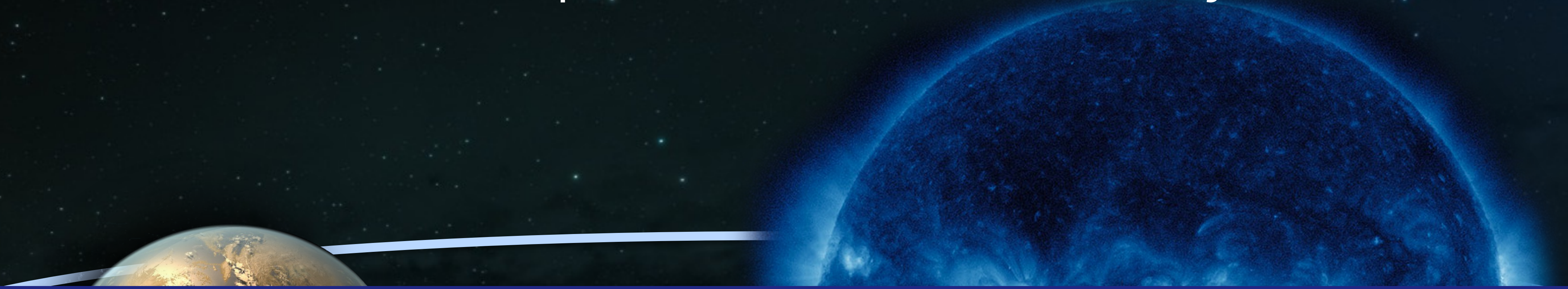
Stellar spectrum drives planet heating

Stellar UV drives UV photochemistry – key for biosignature interpretation

Stellar wind affects atmospheric mass loss

Roles of indirect / supporting observations

Planet masses – extreme precision radial velocity (EPRV)



Options

Current RV instruments for higher mass planets

Future ELT for lower mass planets

Can we get to Earth-mass around Sun-like stars from the ground for all stars of interest?

Roles of indirect / supporting observations

Planet masses – astrometry

Options

Gaia & Roman for higher mass planets

A new dedicated astrometry mission?

Wide-field camera on-board LUVEx for Earth-mass planets (< 1 µas precision)

Roles of indirect / supporting observations

Exozodiacal dust

Noise in direct exoplanet direct observations

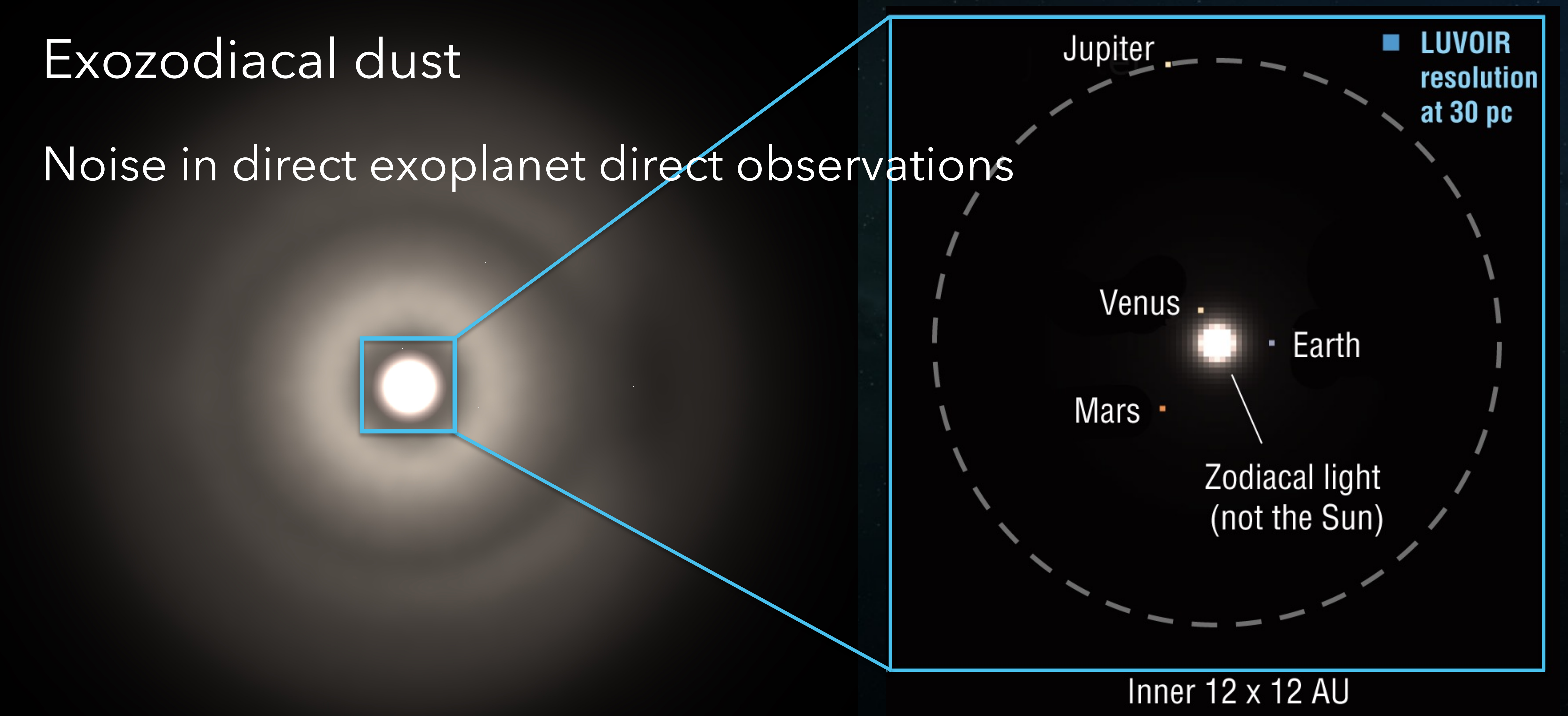
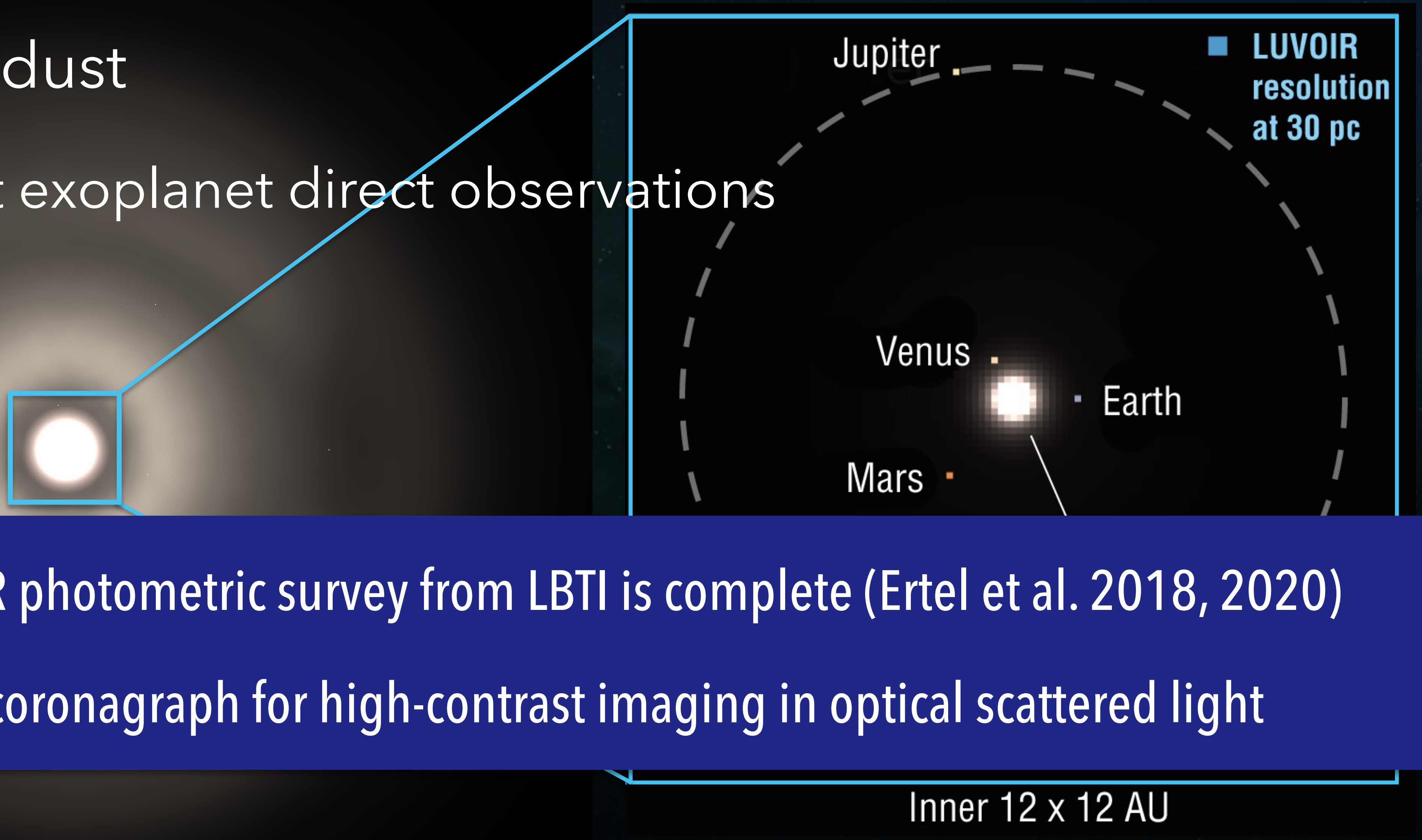


Figure 3-8, LUVOIR Final Report

Roles of indirect / supporting observations

Exozodiacal dust

Noise in direct exoplanet direct observations



Good mid-IR photometric survey from LBTI is complete (Ertel et al. 2018, 2020)

Roman coronagraph for high-contrast imaging in optical scattered light

Figure 3-8, LUVOIR Final Report

Aki's incomplete thoughts on useful near-term efforts

For LUVEx, we need to better simulate the whole diverse potential science portfolio

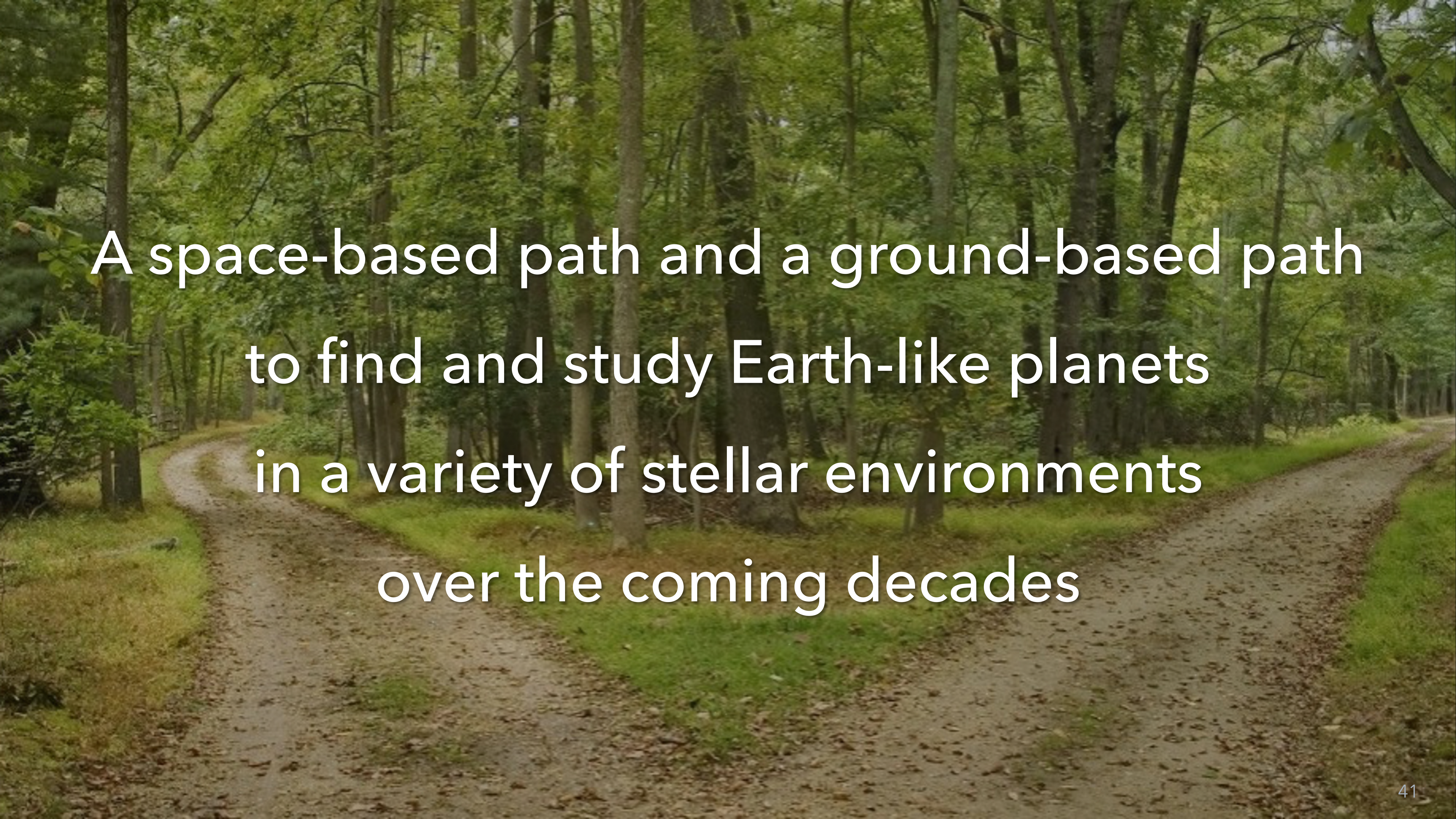
- Anyone want to code a LUVEx astrometry simulator?

Make sure prime LUVEx target stars are getting sustained RV monitoring

- Even if can't reach Earth-mass, we still want to know what else is in the system

Use Hubble to study the heck out of the exoplanet host stars targeted by JWST, before we lose far-UV spectroscopy for a while

- Some of this is happening. More!


A space-based path and a ground-based path
to find and study Earth-like planets
in a variety of stellar environments
over the coming decades