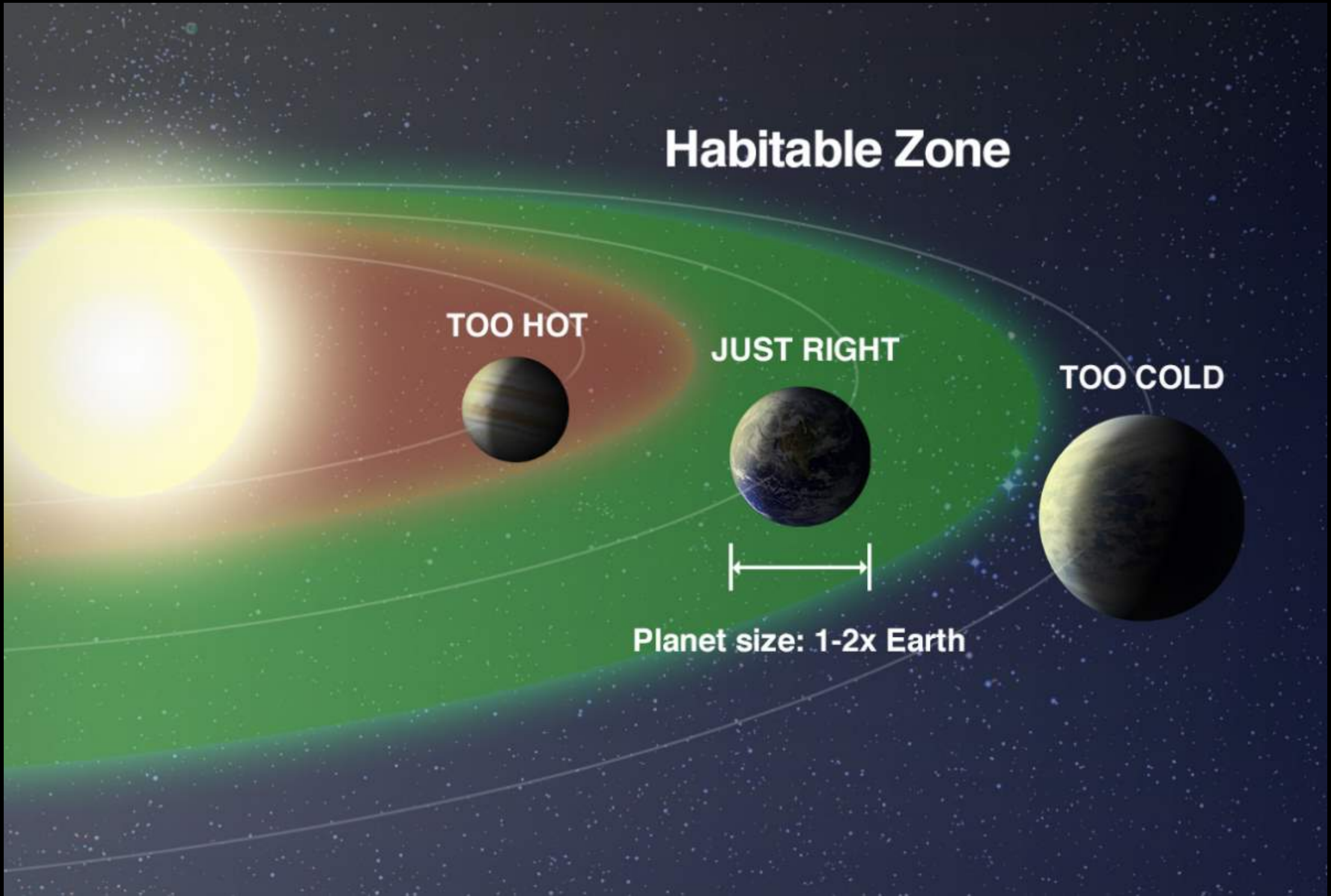
Exploring the boundaries of habitability and life on exoplanets

Dr. Aki Roberge

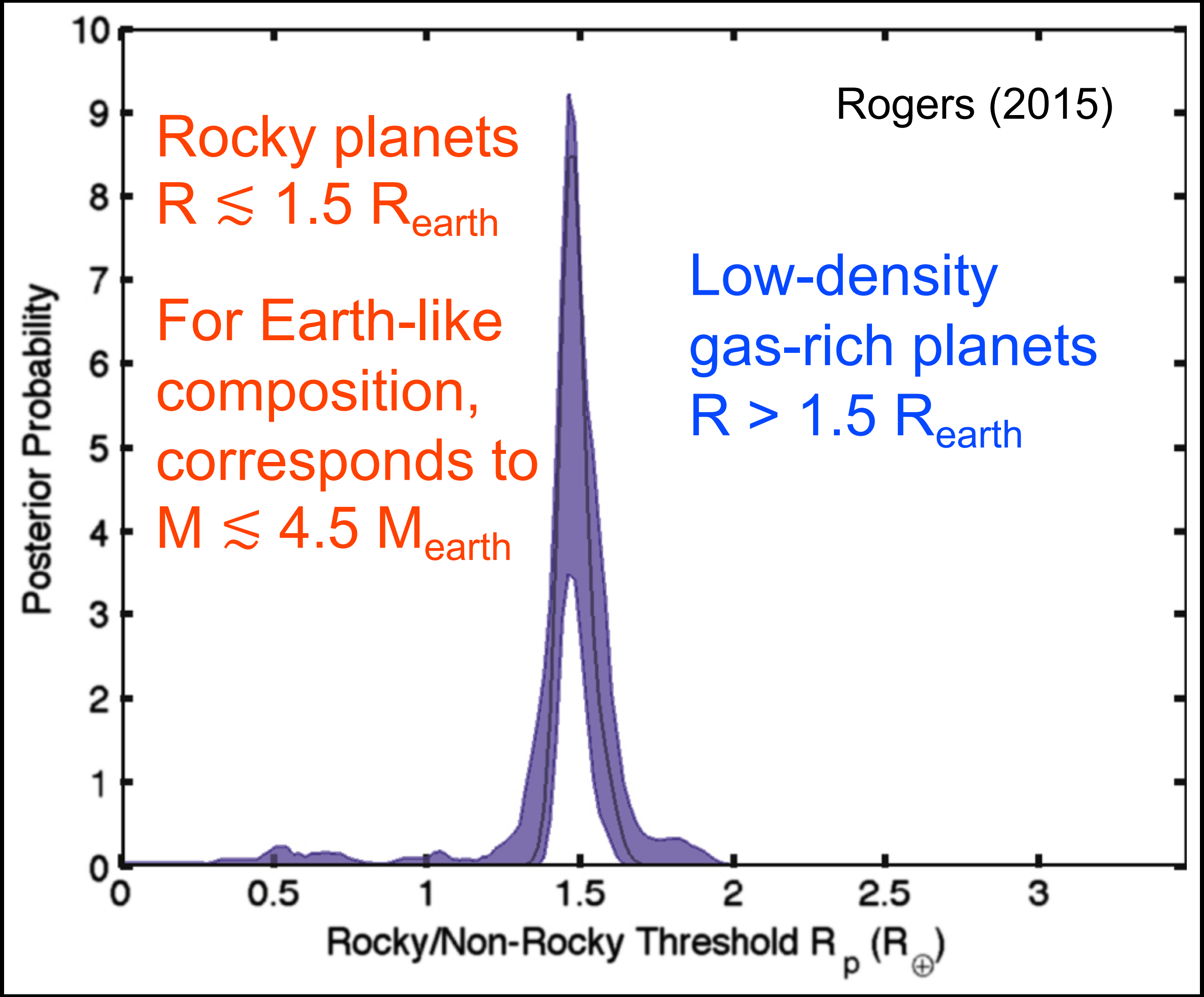
NASA Goddard Space Flight Center

What is the "habitable zone"?

The region around a star where a rocky planet ***could*** have liquid water on its surface

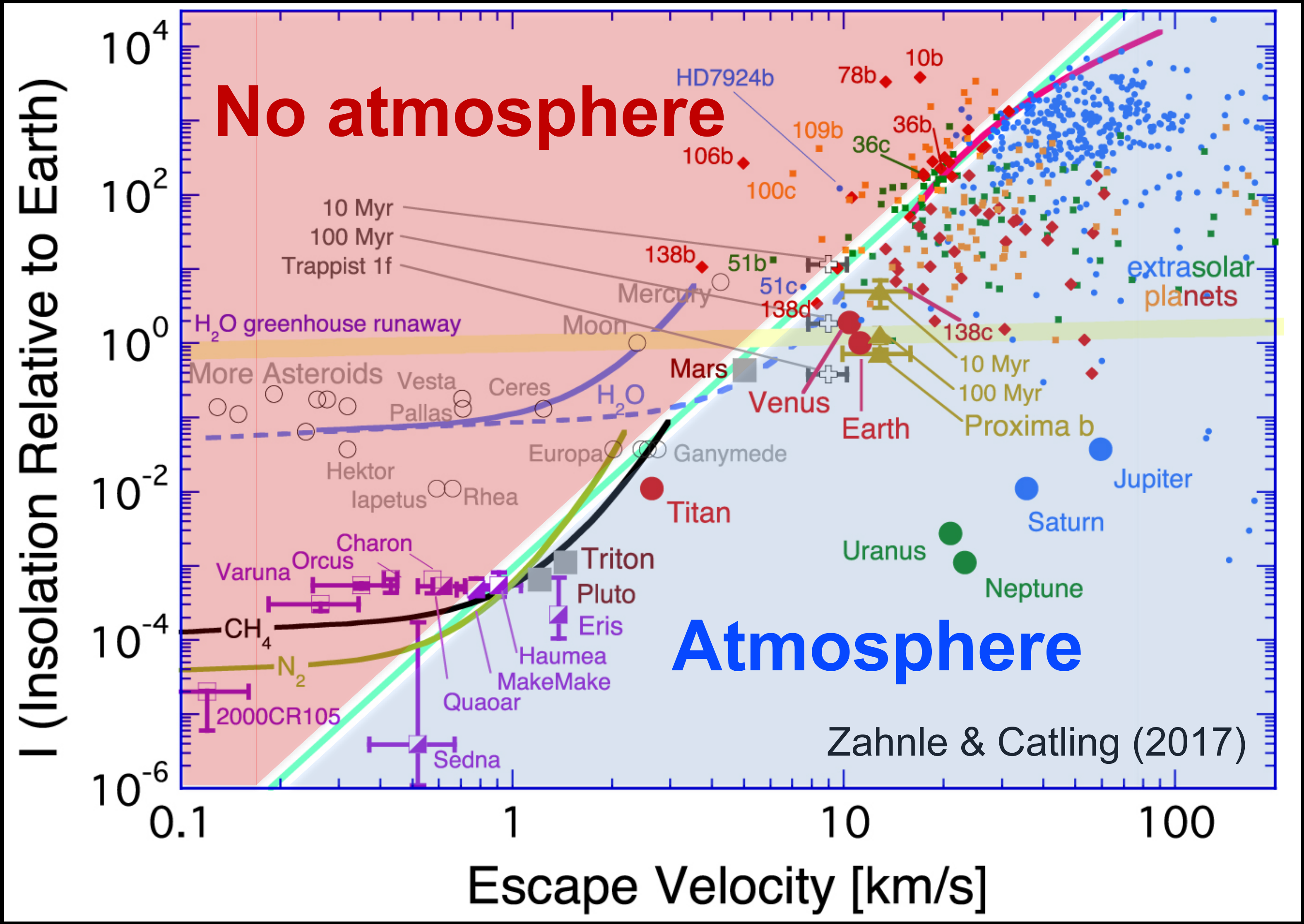


What is the largest planet than can be habitable?



What is the smallest planet than can be habitable?

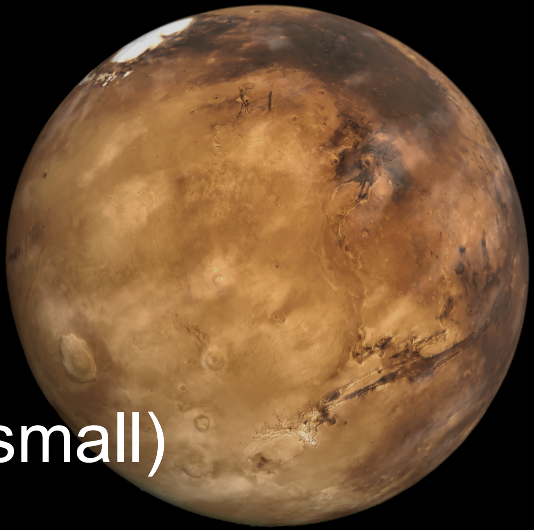
The "Cosmic Shoreline"



What is the smallest planet than can be habitable?

Cosmic shoreline function: $I \propto v_{esc}^{4}$

For rocky planet, converts to $R_{min} \approx 0.8\ a^{-0.5}$, where a = semi-major axis of planet orbit



Inner HZ: a ~ 0.75 AU, R_{min} ~ 0.9 R_{earth}

Outer HZ: a ~ 1.7 AU, R_{min} ~ 0.6 R_{earth}

Mars: a = 1.52 AU, R = 0.53 R_{earth} (too small)

Venus: a = 0.72 AU, R = 0.95 R_{earth} (big enough, but not in HZ)

Habitable exoplanet candidate characteristics : a theory

1. Rocky planet
2. Orbital semi-major axis in stellar habitable zone

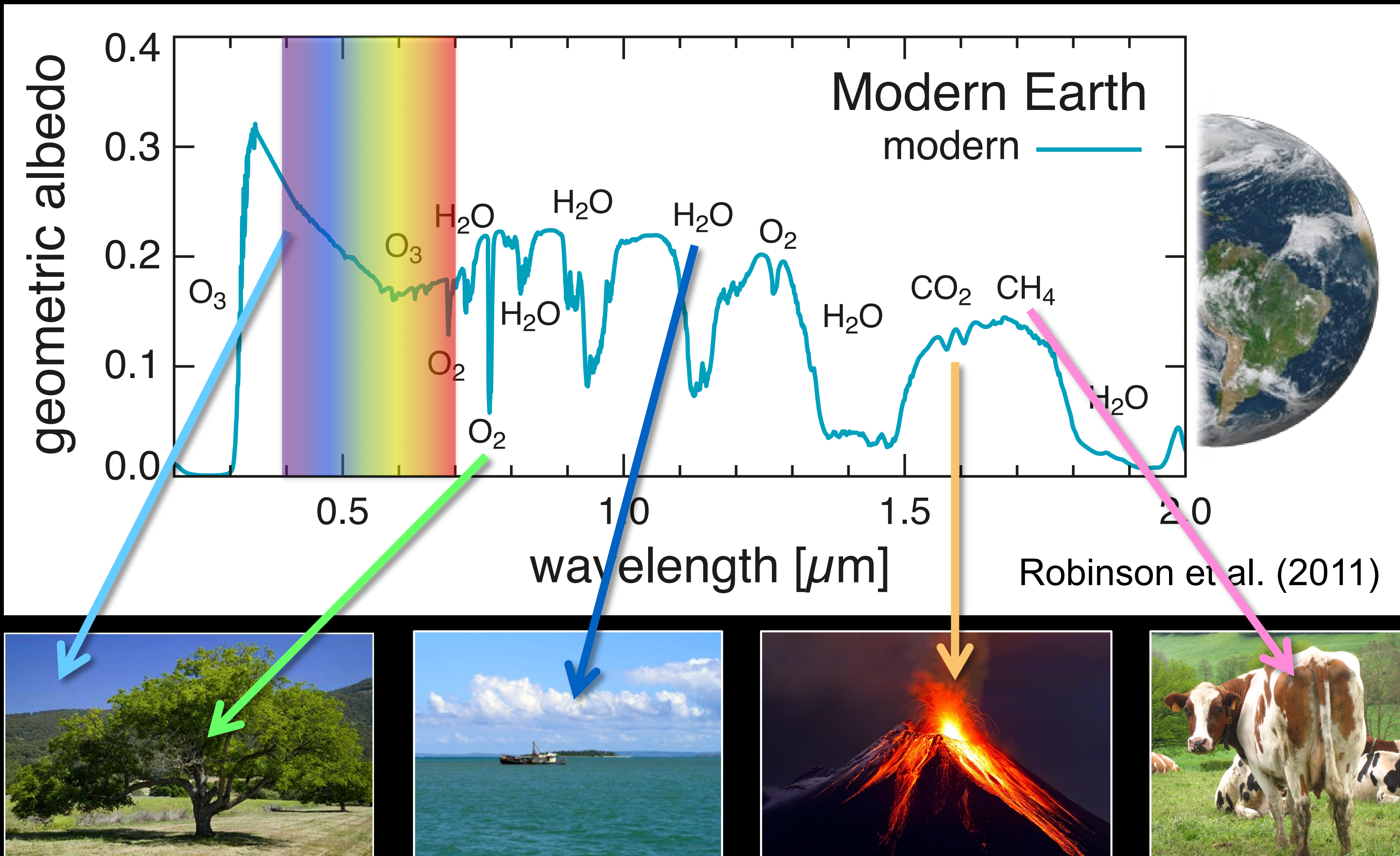
   For Sun-like star, roughly 0.75 AU to 1.7 AU

   Boundaries scale with $\sqrt{L_{Star}/L_{Sun}}$
3. Radius $\lesssim 1.5\ R_{earth}$
4. Radius $\gtrsim 0.6\ R_{earth}$ at outer HZ edge and $\gtrsim 0.9\ R_{earth}$ at inner HZ edge
5. What else? *Discussion on Friday morning*

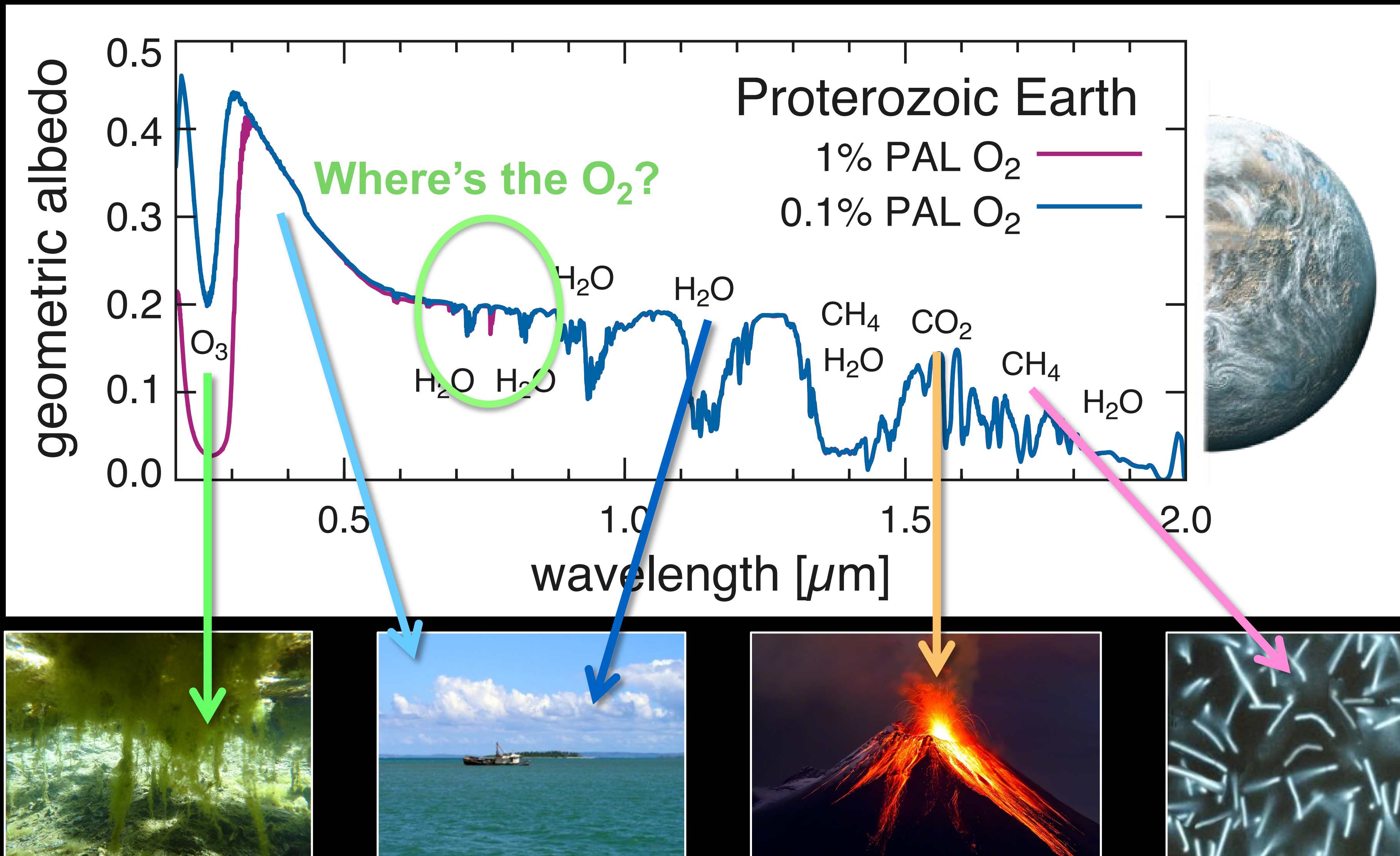
What does a habitable exoplanet look like?

Earth is the fundamental model

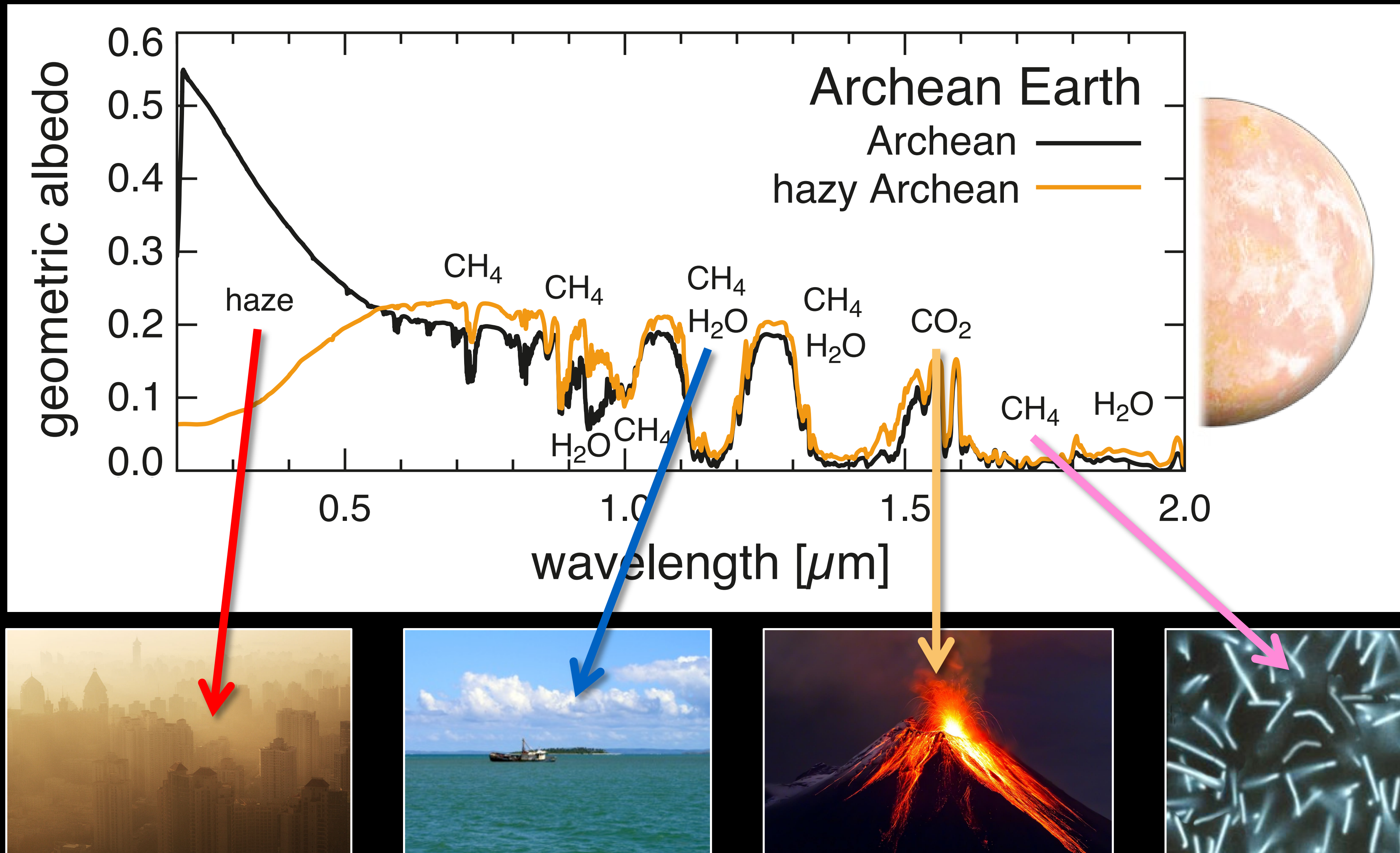
Modern Earth as an exoplanet



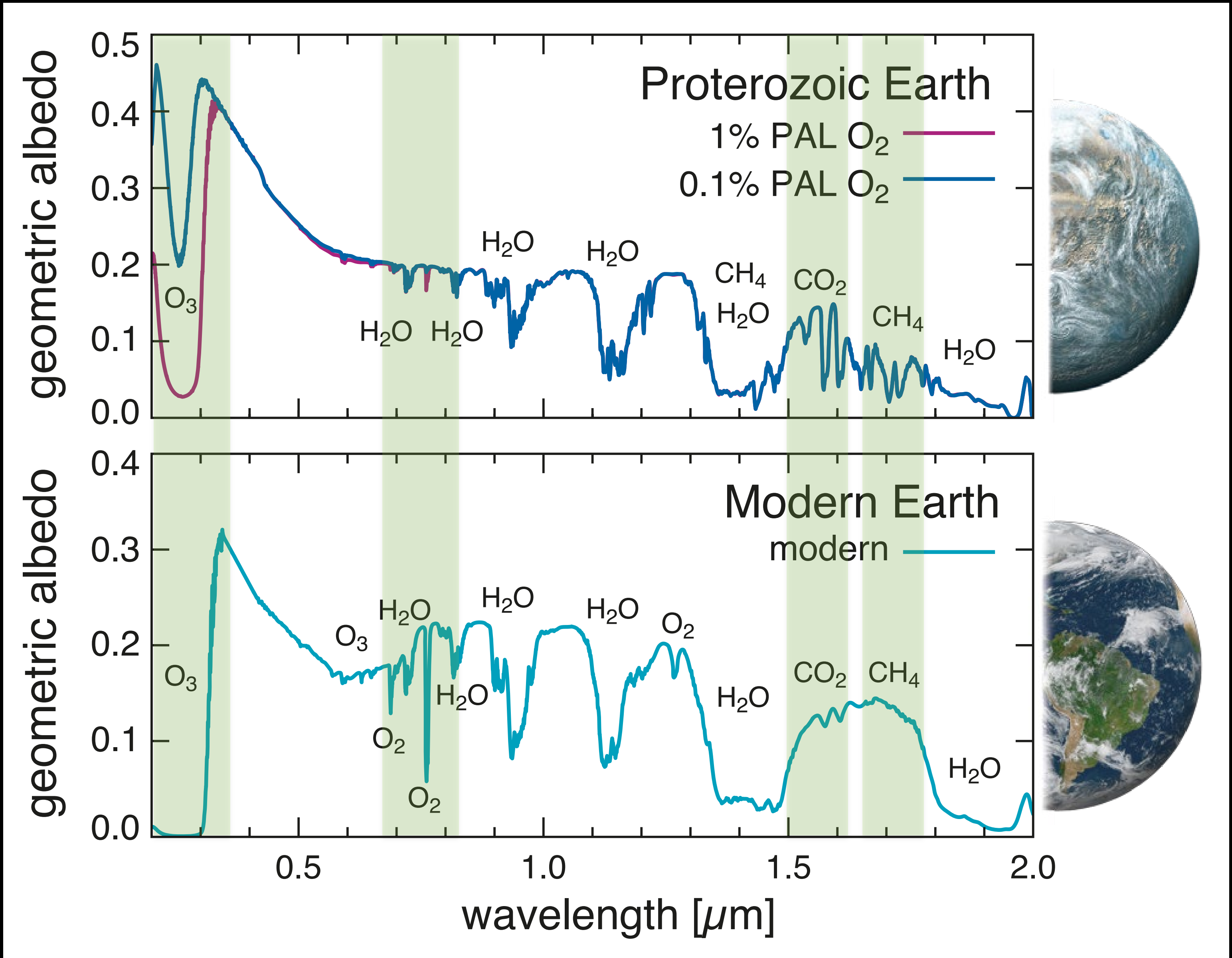
Proterozoic Earth as an exoplanet



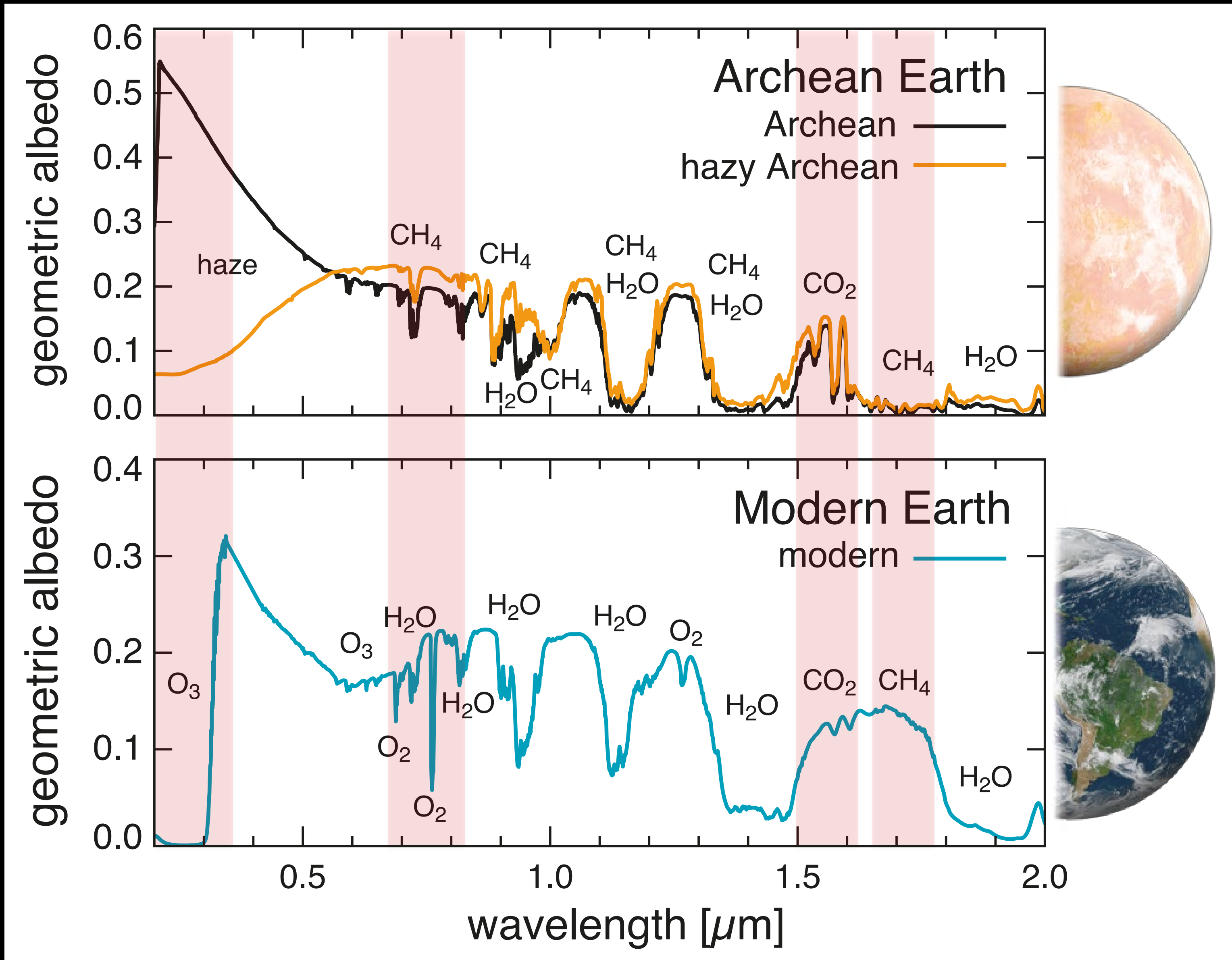
Archean Earth as an exoplanet



Modern vs. Proterozoic Earth



Modern vs. Archean Earth

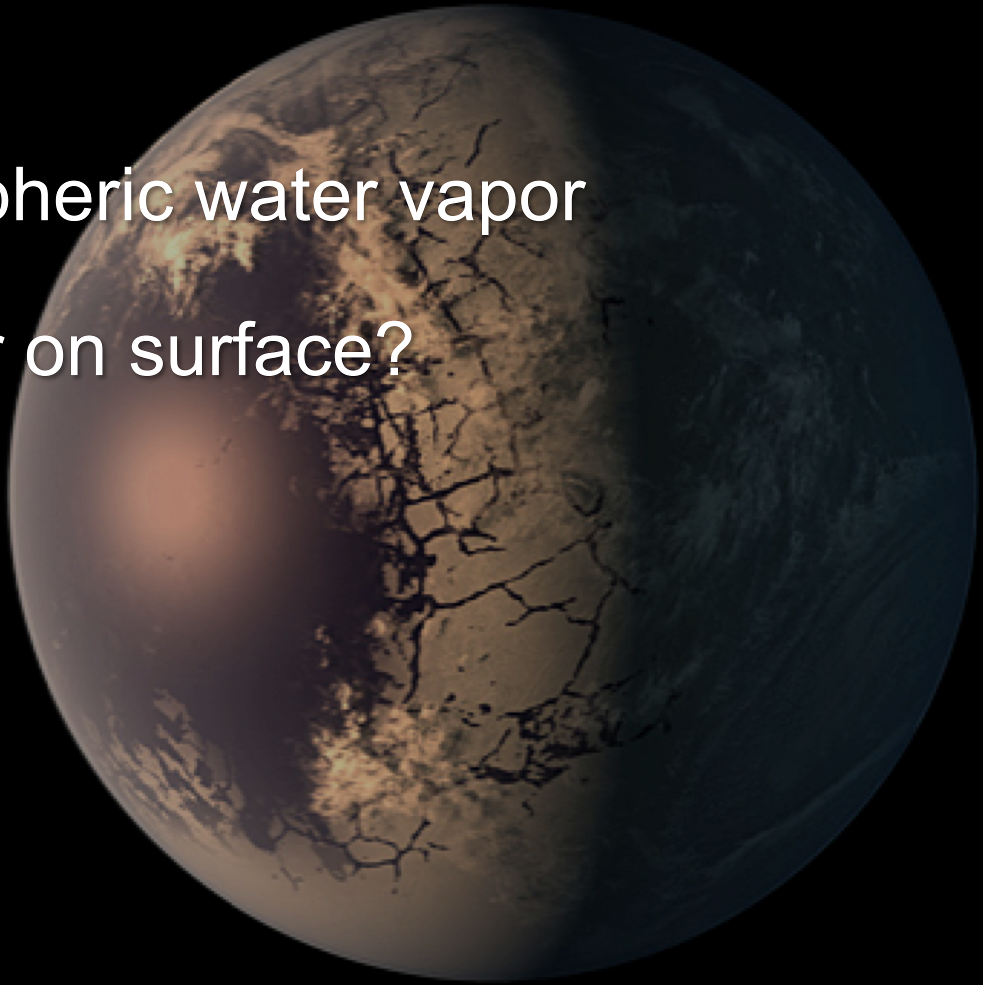


What does a habitable exoplanet look like?

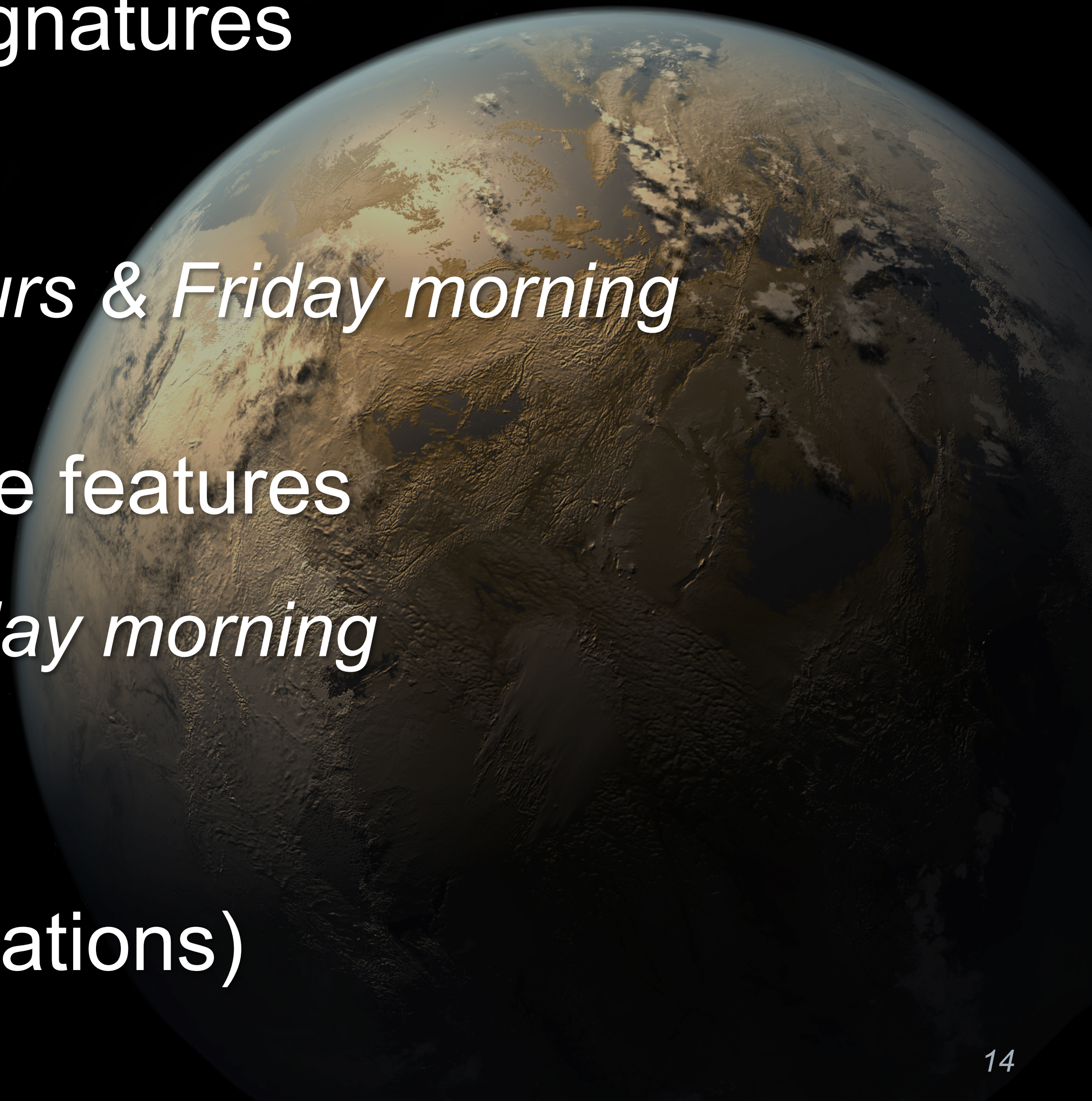
Modern, Proterozoic, and Archean Earth spectra all show water vapor

So, first look for atmospheric water vapor

But is there liquid water on surface?



Which exoplanets are inhabited?



Atmospheric biosignatures

Talks on Monday

More talks on Thurs & Friday morning

Surface reflectance features

Arney talk on Friday morning

Temporal changes
(e.g. seasonal variations)

Observing planets at interstellar distances

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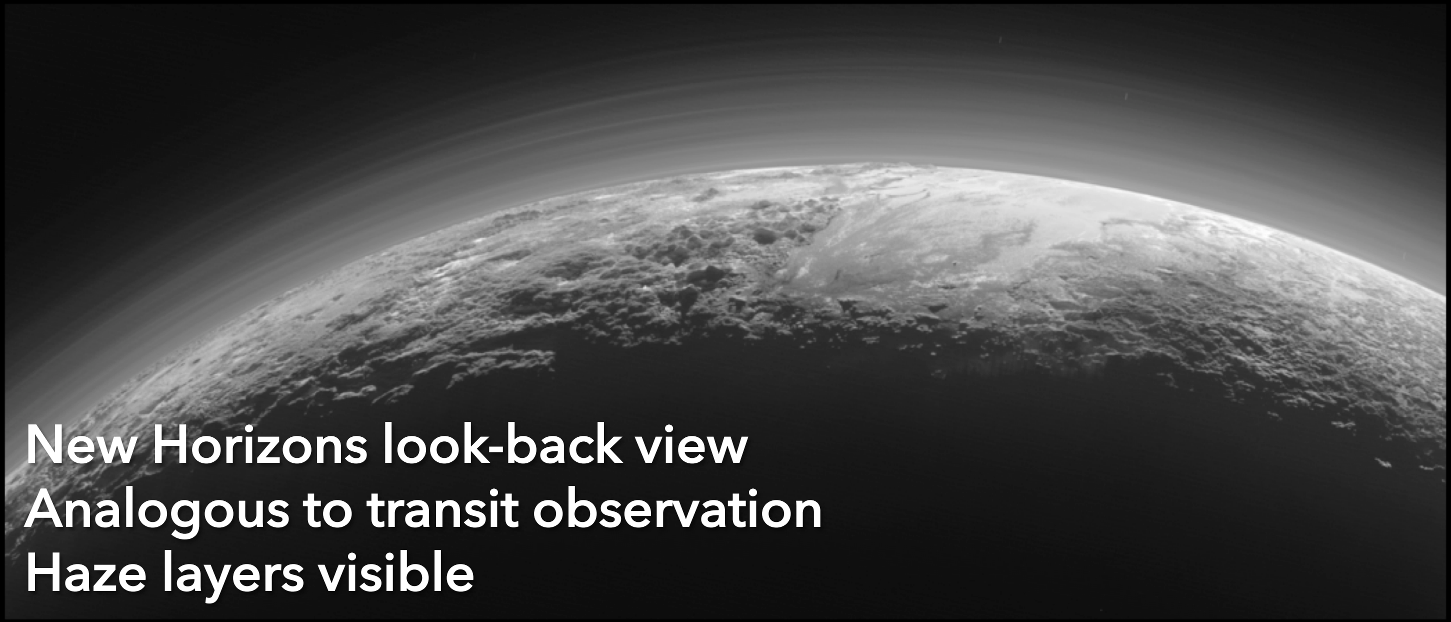
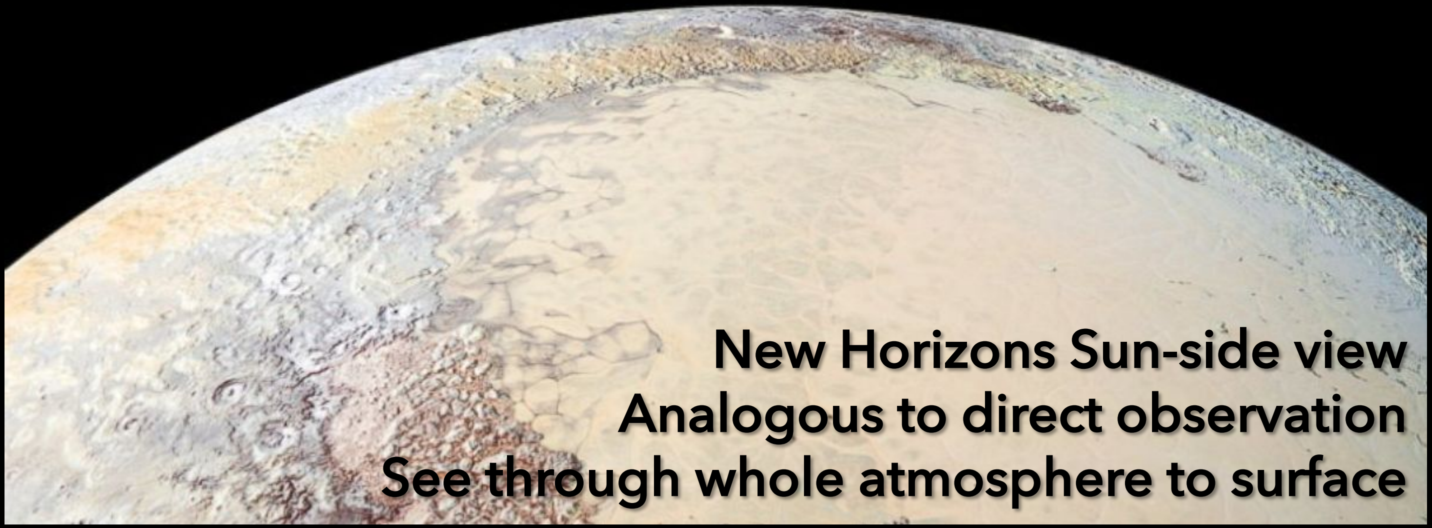
Indirect vs. direct case study – Pluto

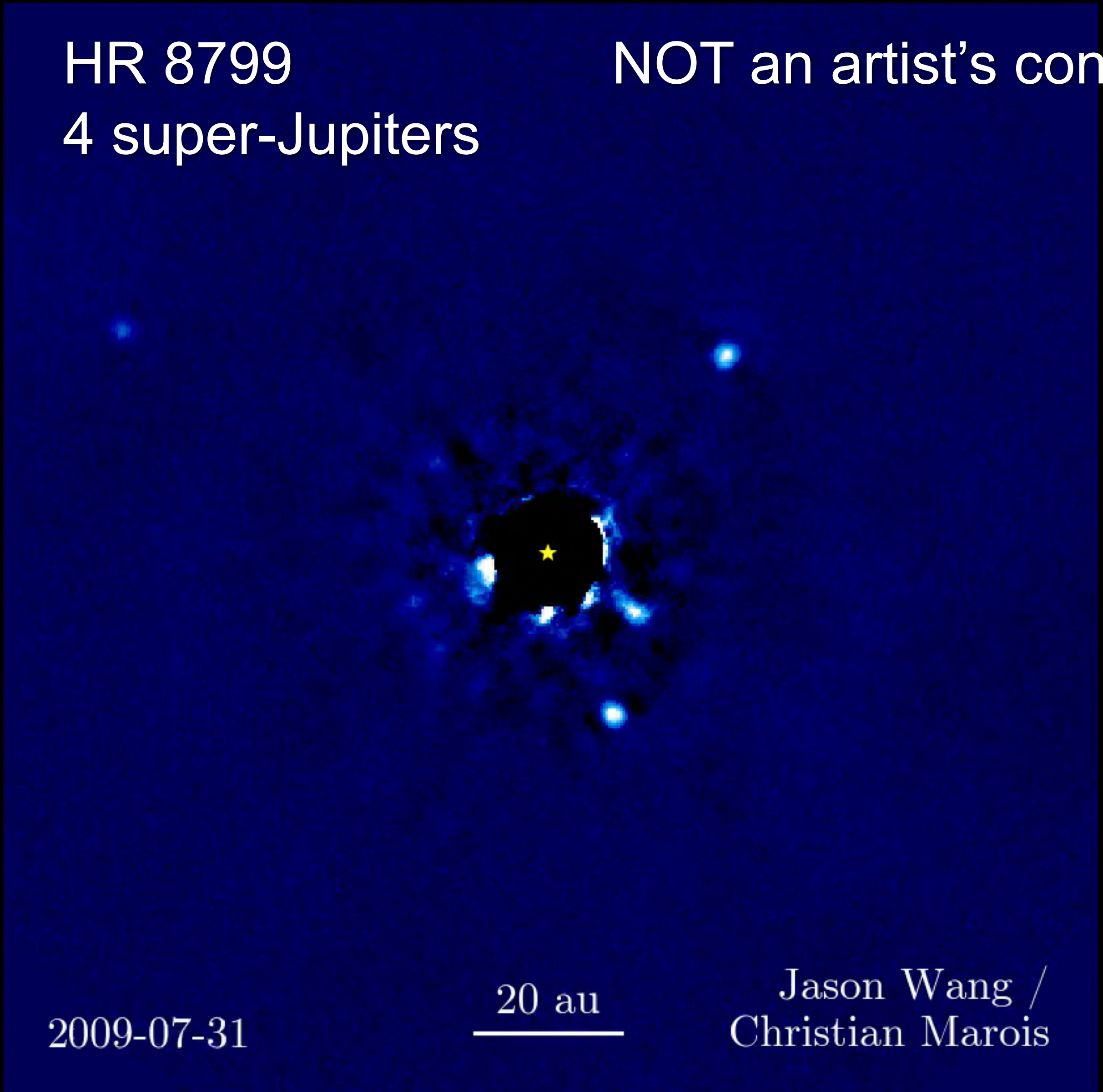




Today’s direct imaging of exoplanets

HR 8799
4 super-Jupiters

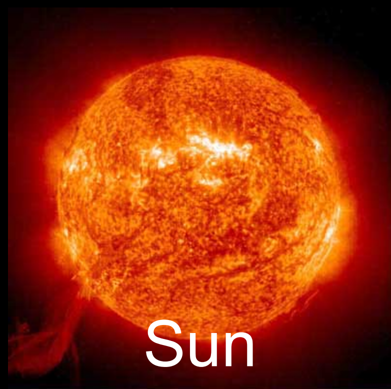
NOT an artist’s conception



Suppressing the star: coronagraphs

Challenges for directly imaging exoEarths

Earth is 10 billion times fainter than the Sun …



Sun

Earth

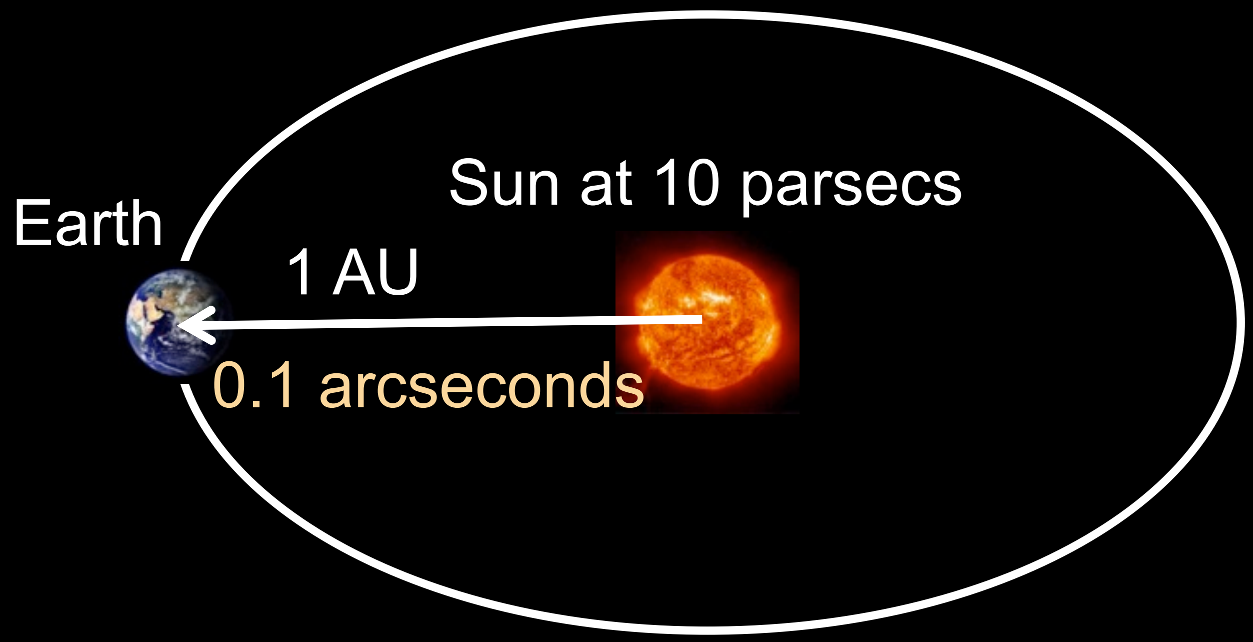
Luxor Sky Beam

Brightest artificial light in the world

Two fireflies

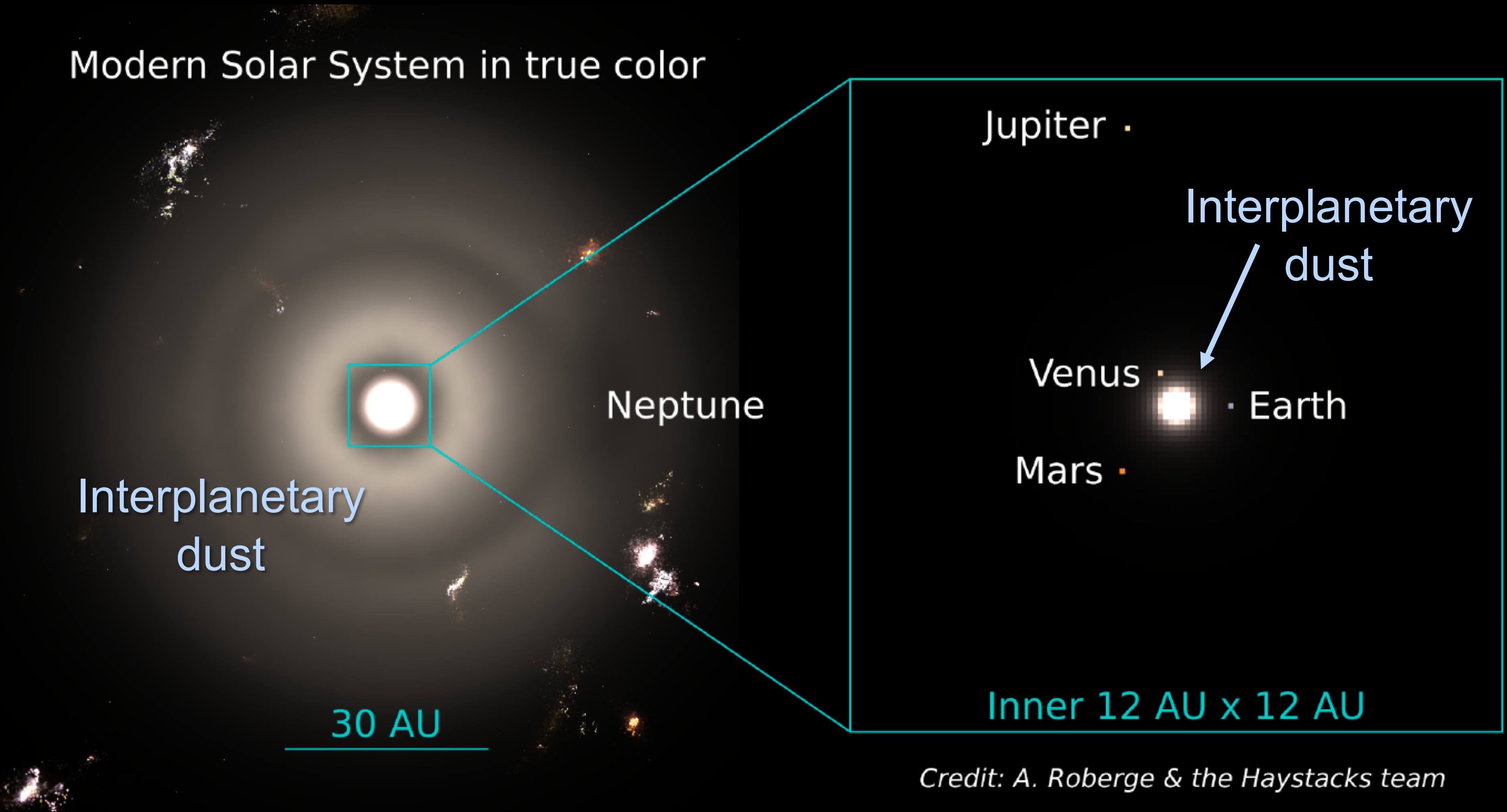
Challenges for directly imaging exoEarths

… and it's right next to the bright star



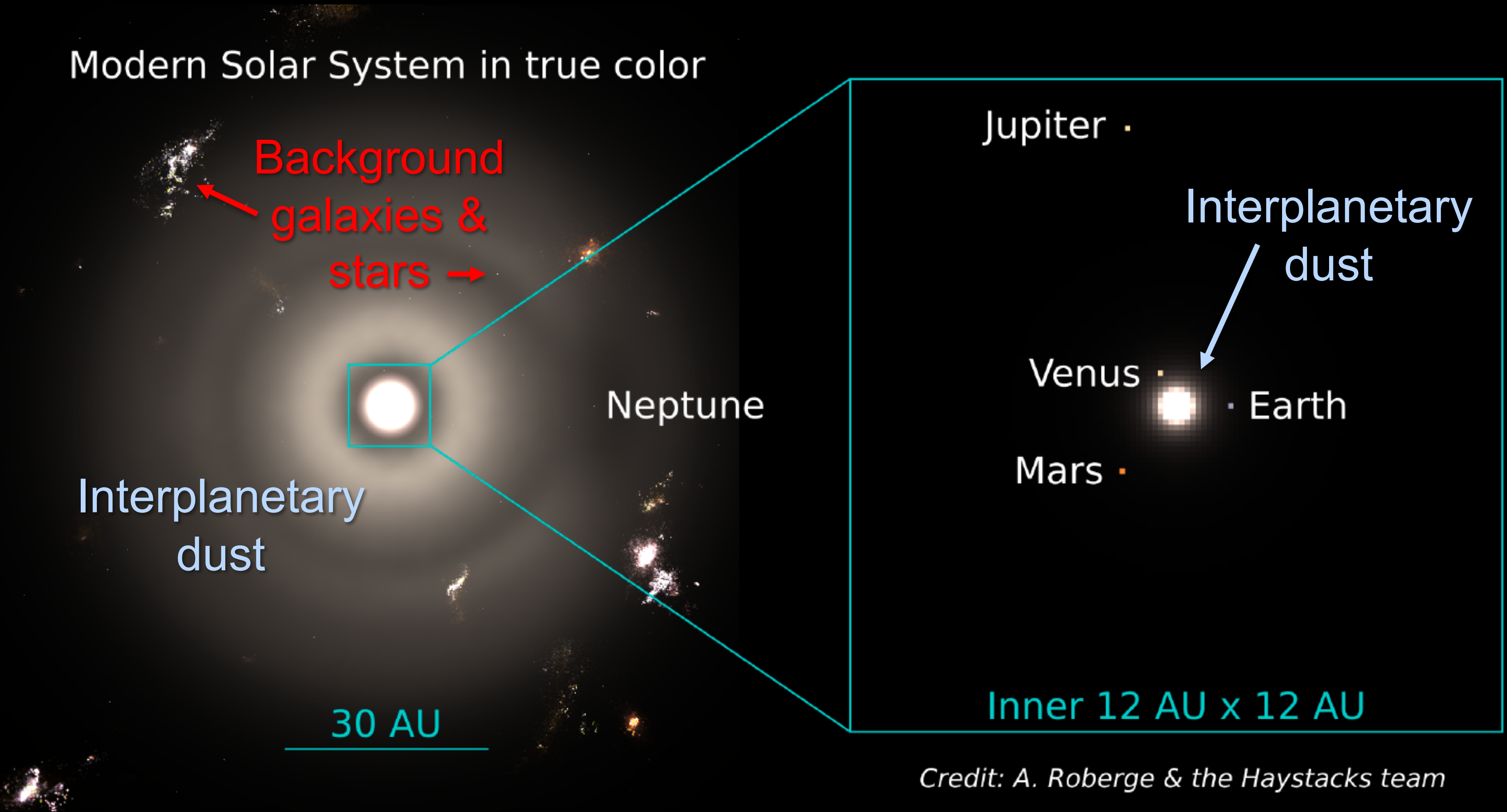
0.1 arcseconds is about the width of a human hair at the distance of two football fields

The Solar System from interstellar distance



Credit: A. Roberge & the Haystacks team

The Solar System from interstellar distance



Into space with the WFIRST coronagraph

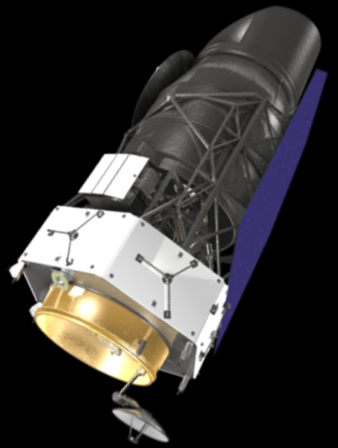
Next strategic mission after JWST

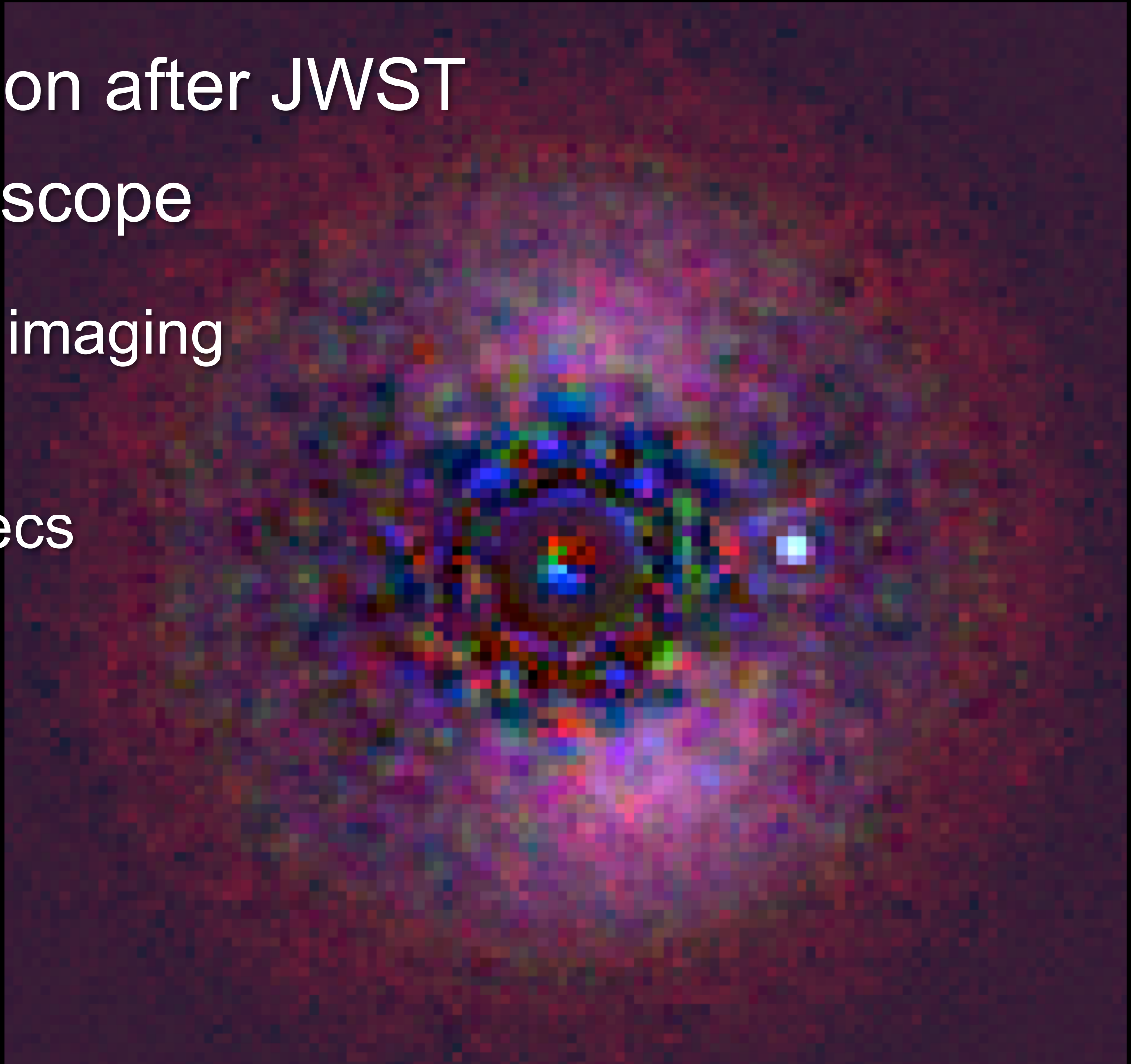
2.4-m diameter telescope

Preliminary multi-color imaging simulation

Sun-like star at 3 parsecs

Warm Jupiter at 2 AU





Credit: M. Rizzo / N. Zimmerman (NASA GSFC)

What could be next?

Earth-size planets around Sun-like stars with

LUVOIR

Courtesy of Bruce Macintosh (Stanford) & Dan Tell (CA Academy of Sciences)

CALIFORNIA ACADEMY OF SCIENCES

What happens next?

Four candidates for NASA's next large mission being studied now – almost done

Two (LUVOIR and HabEx) have key goal of studying Earth-like planets around Sun-like stars

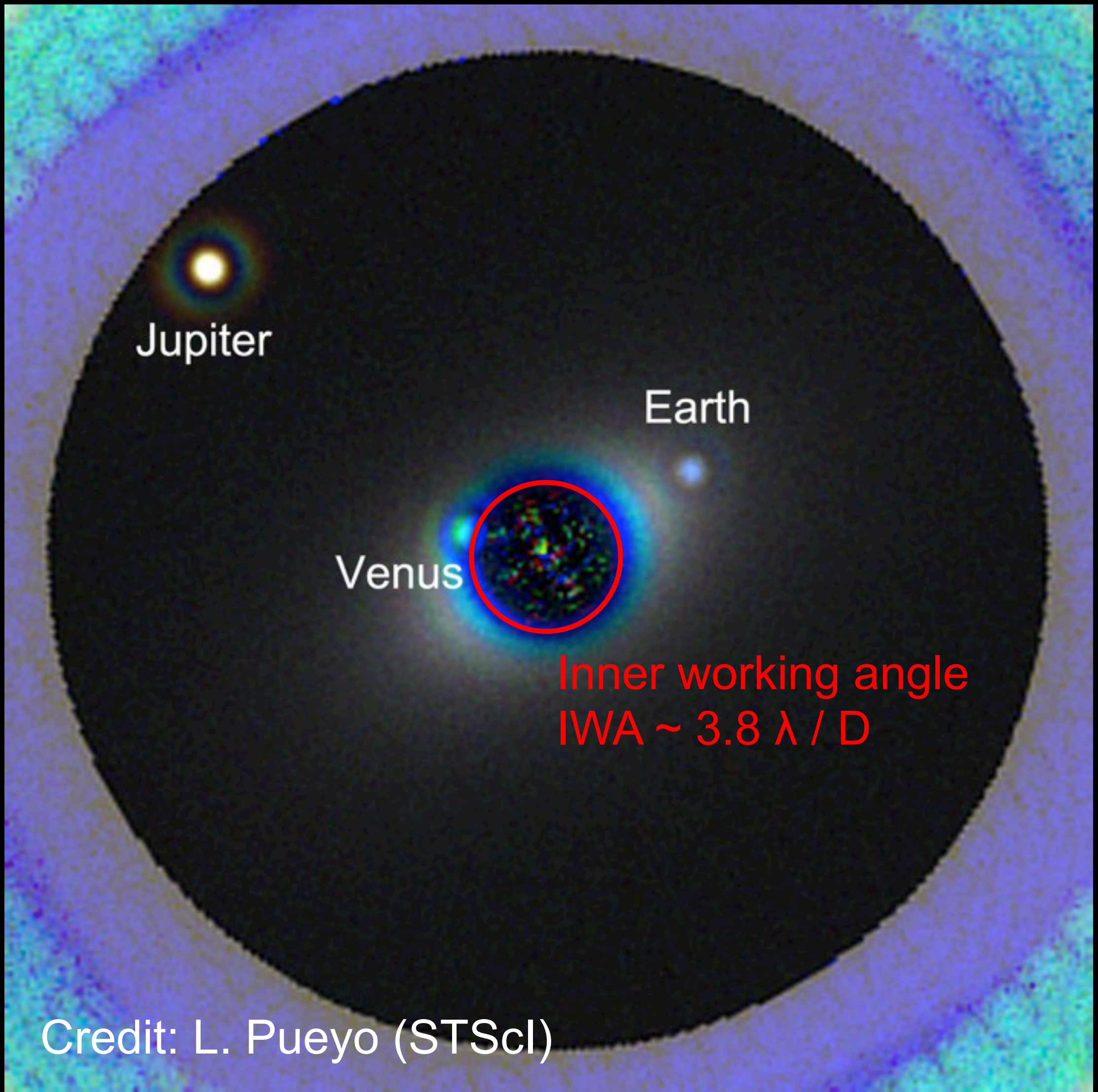
More on the mission concepts Friday from Scott Gaudi

Final Reports to NASA HQ in Aug 2019, and the National Academies of Sciences shortly thereafter

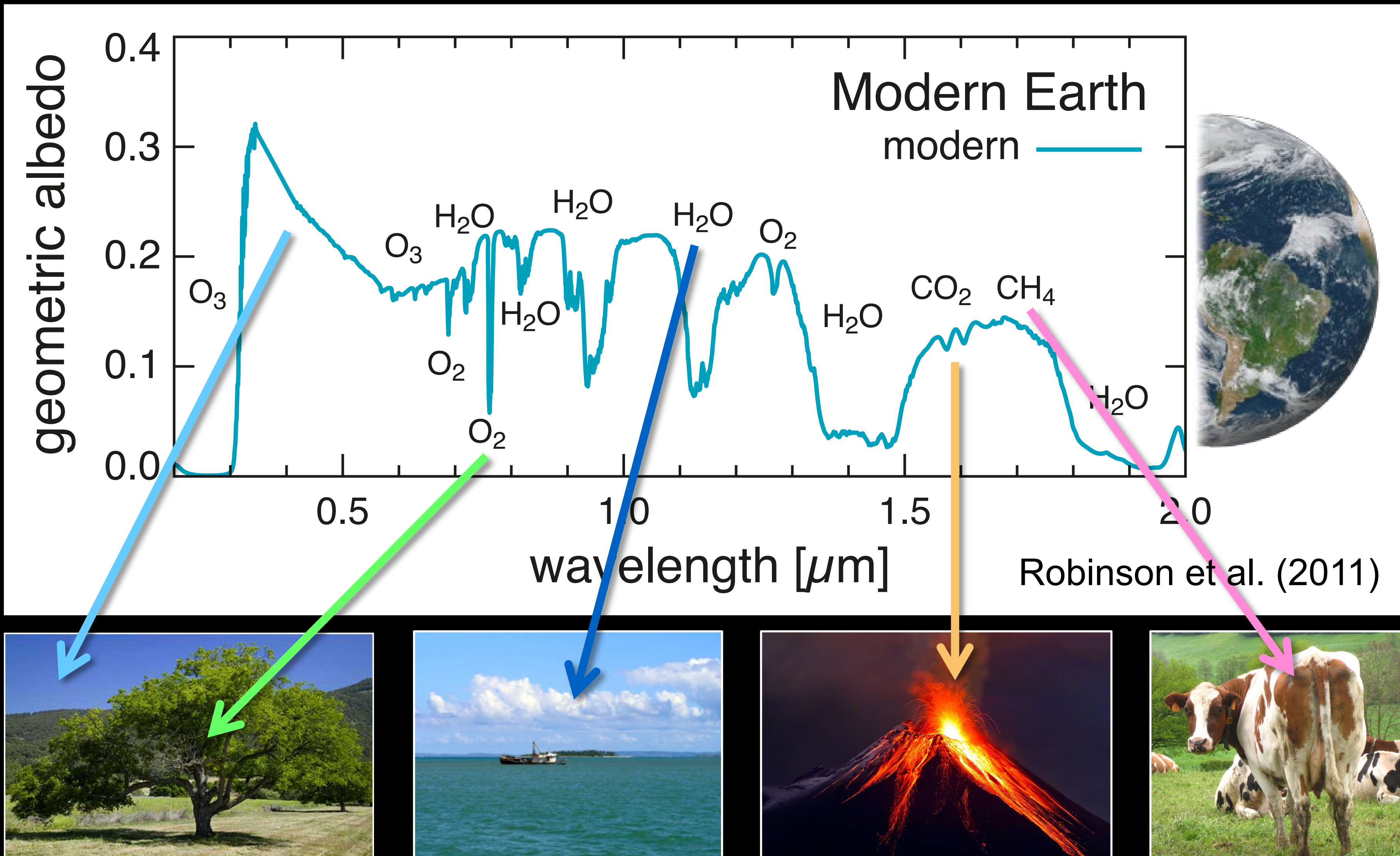
2020 Astrophysics Decadal Survey will prioritize all astrophysics activities – space & ground, large & small

Imaging Earth 2.0 in 2040

Simulated image of the Solar System with LUVOIR

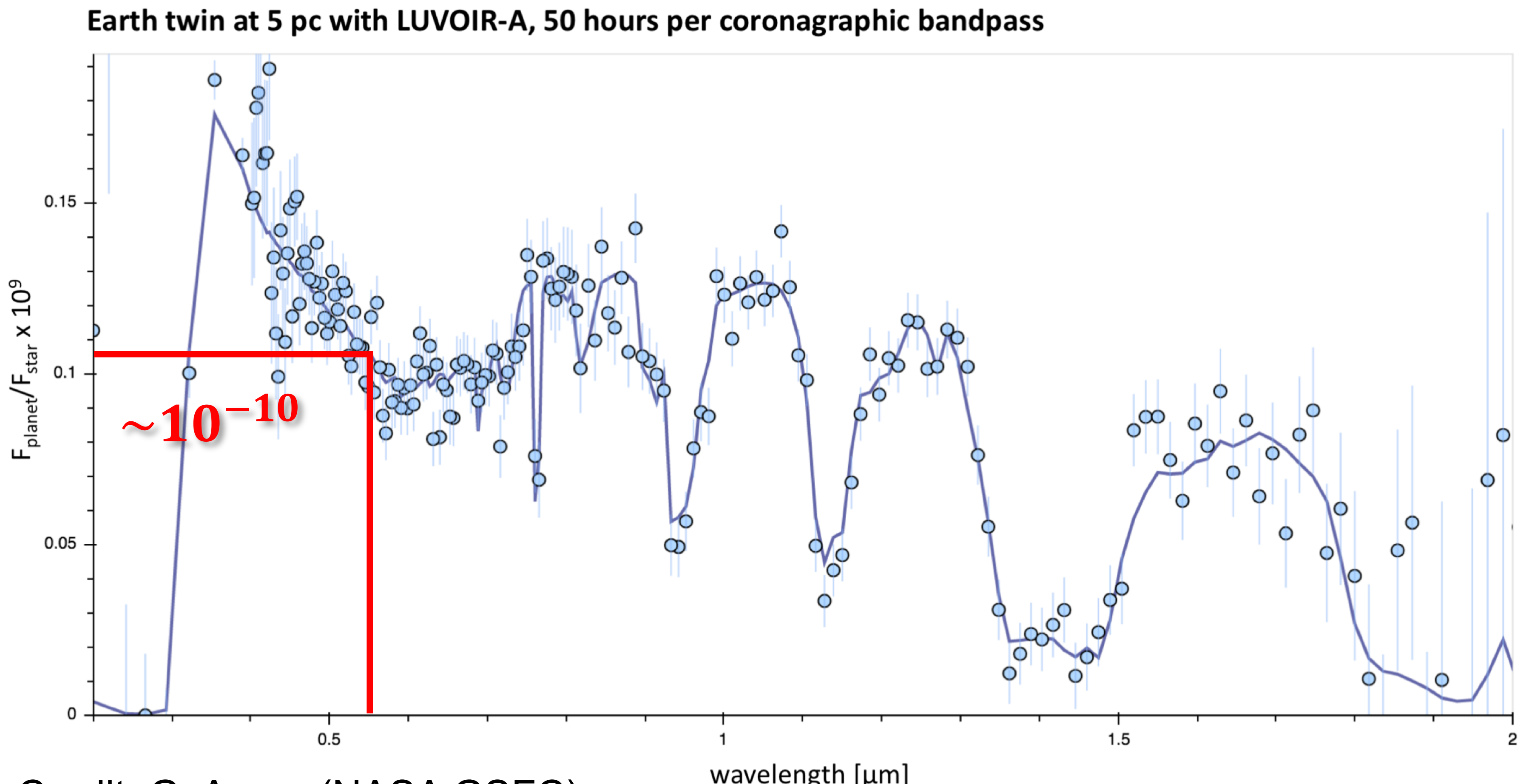


Modern Earth as an exoplanet



Robinson et al. (2011)

Simulated direct spectrum of modern Earth



Credit: G. Arney (NASA GSFC)

What does the planet-to-star flux tell you?

$$\frac{F_p}{F_s} = \Phi(\alpha)\, A(\lambda) \frac{r_p^2}{a_p^2}$$

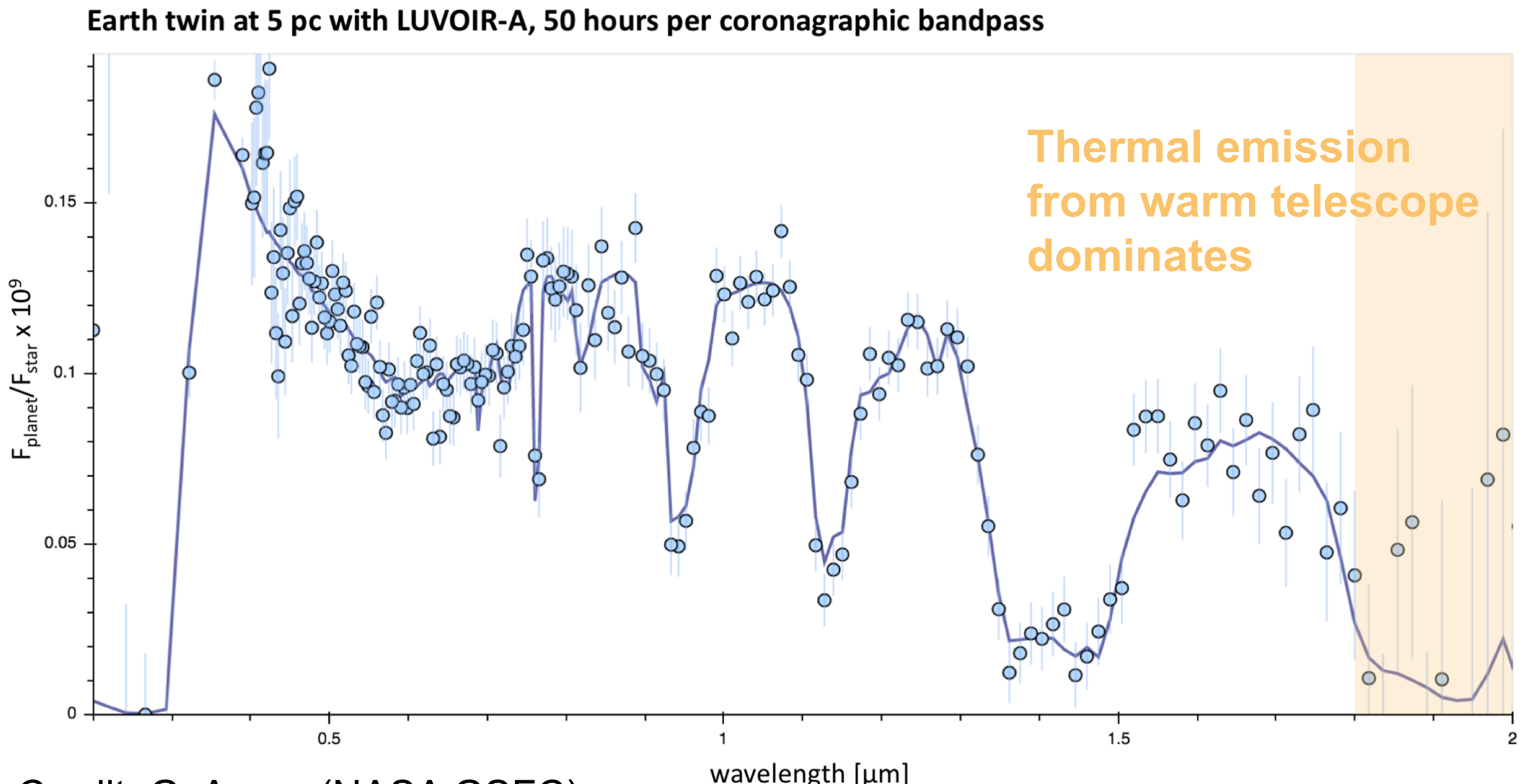
$\Phi(\alpha)$ = scattering function
α = star-planet-observer angle
$A(\lambda)$ = geometric albedo

r_p = planet radius
a_{HZ} = semi-major axis of planet orbit

Compare two planets with same $\Phi(\alpha)$, α, $A(\lambda)$, and a_p

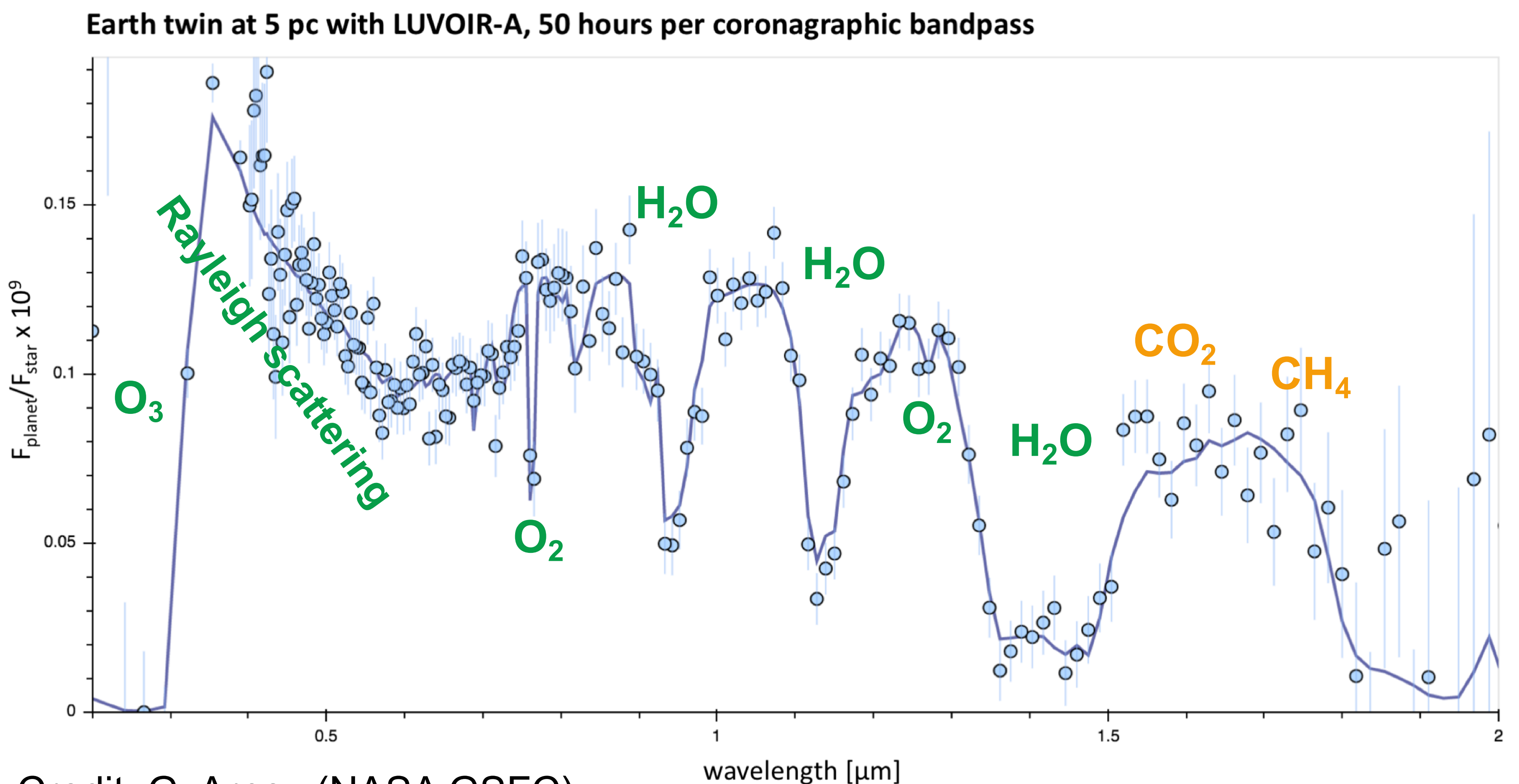
Planet-to-star flux ratio depends on planet size

Simulated direct spectrum of modern Earth



Credit: G. Arney (NASA GSFC)

Simulated direct spectrum of modern Earth

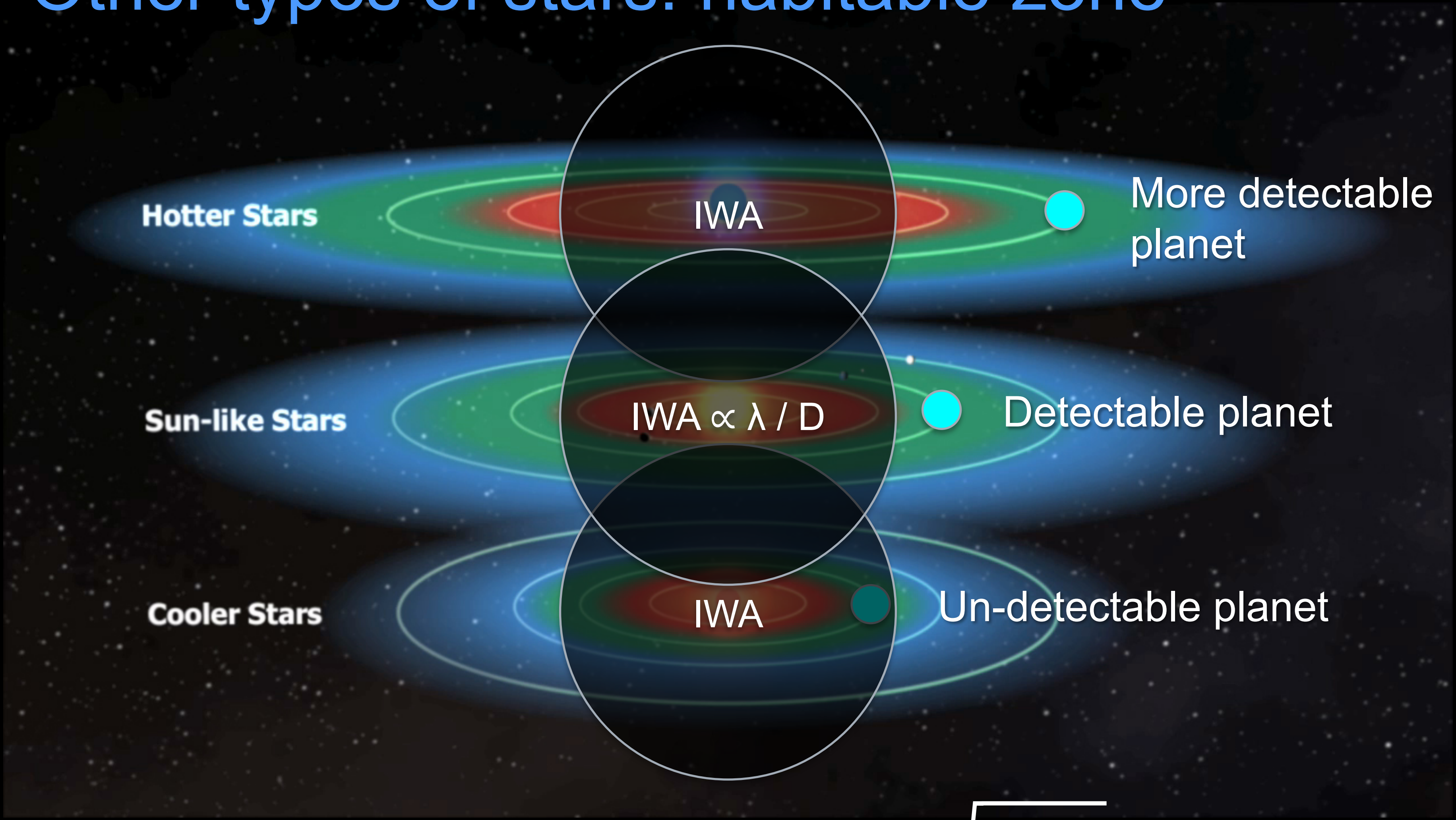


Credit: G. Arney (NASA GSFC)

VPL molecular spectra search engine

http://vplapps.astro.washington.edu

Other types of stars: habitable zone



$$r_{HZ,Star} = r_{HZ,Sun} \times \sqrt{\frac{L_{Star}}{L_{Sun}}}$$

Other types of stars: planet-to-star flux

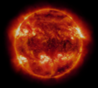
$$\frac{F_{p,HZ}}{F_{s,HZ}} = \Phi(\alpha)\, A(\lambda)\, \frac{r_p^2}{a_{HZ}^2} = (1.15 \times 10^{-10}) \times \frac{L_\odot}{L_s}$$

L_s = stellar luminosity
$L_\odot$ = solar luminosity

Cool, dim stars

Higher $\frac{F_p}{F_s}$

More detectable



Hot, bright stars

Lower $\frac{F_p}{F_s}$

Less detectable

Ground and space are complementary

Cool, dim stars

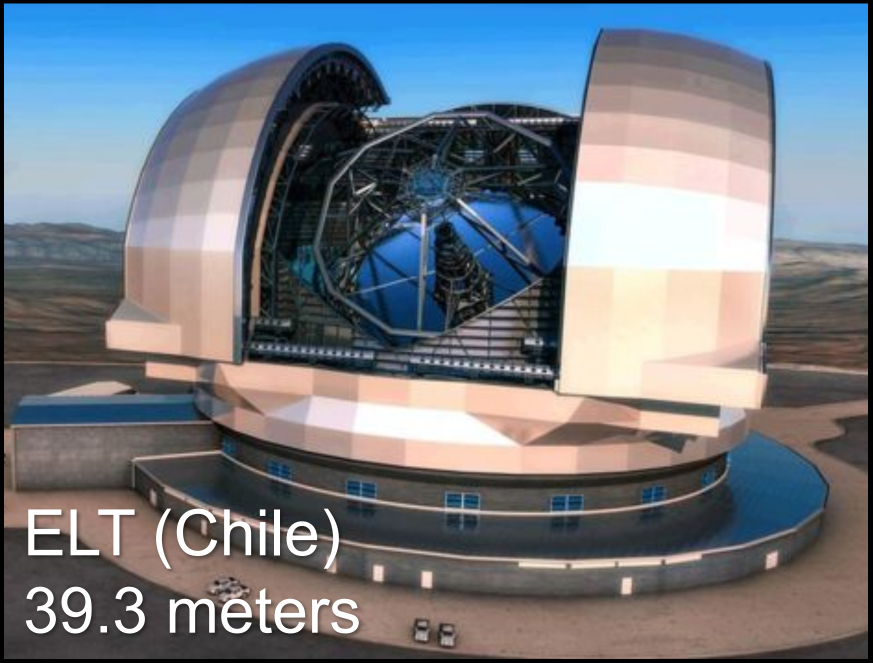
Small HZs, Higher $\frac{F_p}{F_s}$

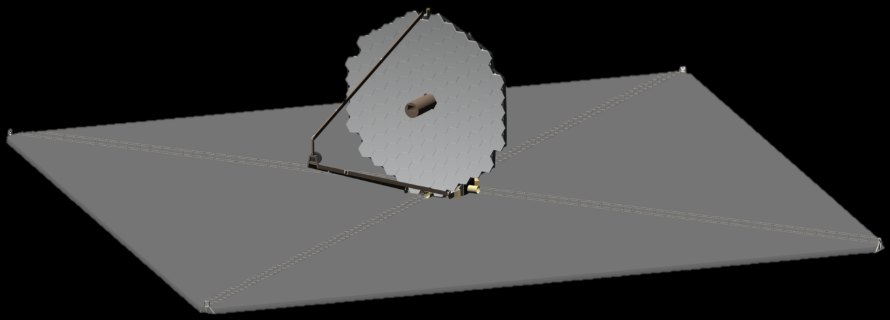
exoEarth candidates around M dwarfs

Hotter, brighter stars

Larger HZ, Lower $\frac{F_p}{F_s}$

exoEarth candidates around Sun-like stars

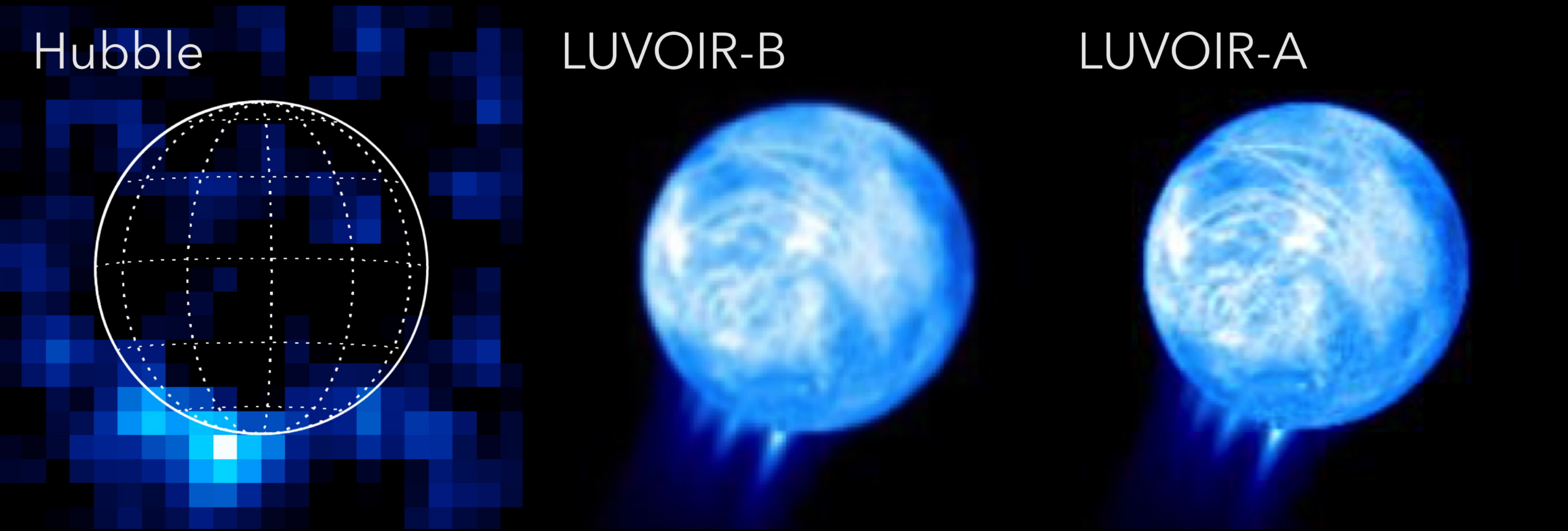




LUVOIR
15 meters

Search for life in the Solar System

UV hydrogen emission from plumes



Roth et al. (2014)

Credit: G. Ballester (LPL)

Final thoughts

Exoplanets offer exciting possibility of studying many different biospheres & multiple origins of life

Finding something that could be a biosignature is (relatively) easy

Convincing ourselves we have actually done so is hard

Multiple pieces of supporting evidence will be needed

It may be easier to show that a planet is inhabited than show that it is habitable but lifeless

Credit: Dan Durda