Decoding exoplanet atmospheres in the 2040s

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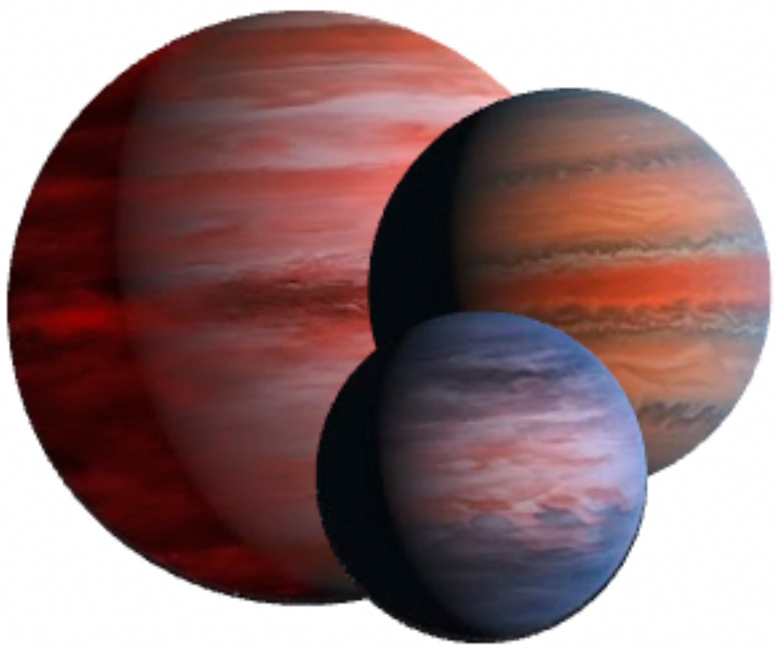
In the 2040s, we will study the atmospheres of rocky, temperate planets

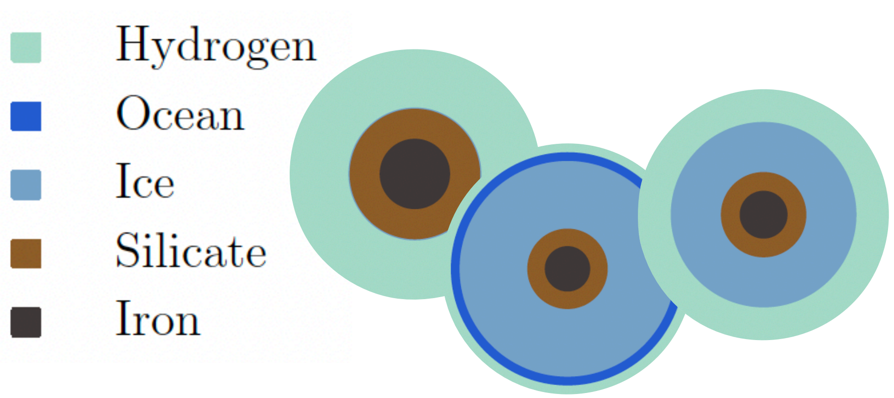
Answering the scientific questions related to unicity of our own planet requires ambitious measurements and context from previous decades

Context from current **transiting planets observations**
(HST-JWST-Ariel from space, high-res spectroscopy from the ground)



Giant and Neptunian planets
Very hot (>2000K): refractories, O/H, C/H
Warm-Hot (700-2000K): N/H, O/H, C/H, clouds

Probes of formation, early evolution, and available building blocks *even for rocky planets*

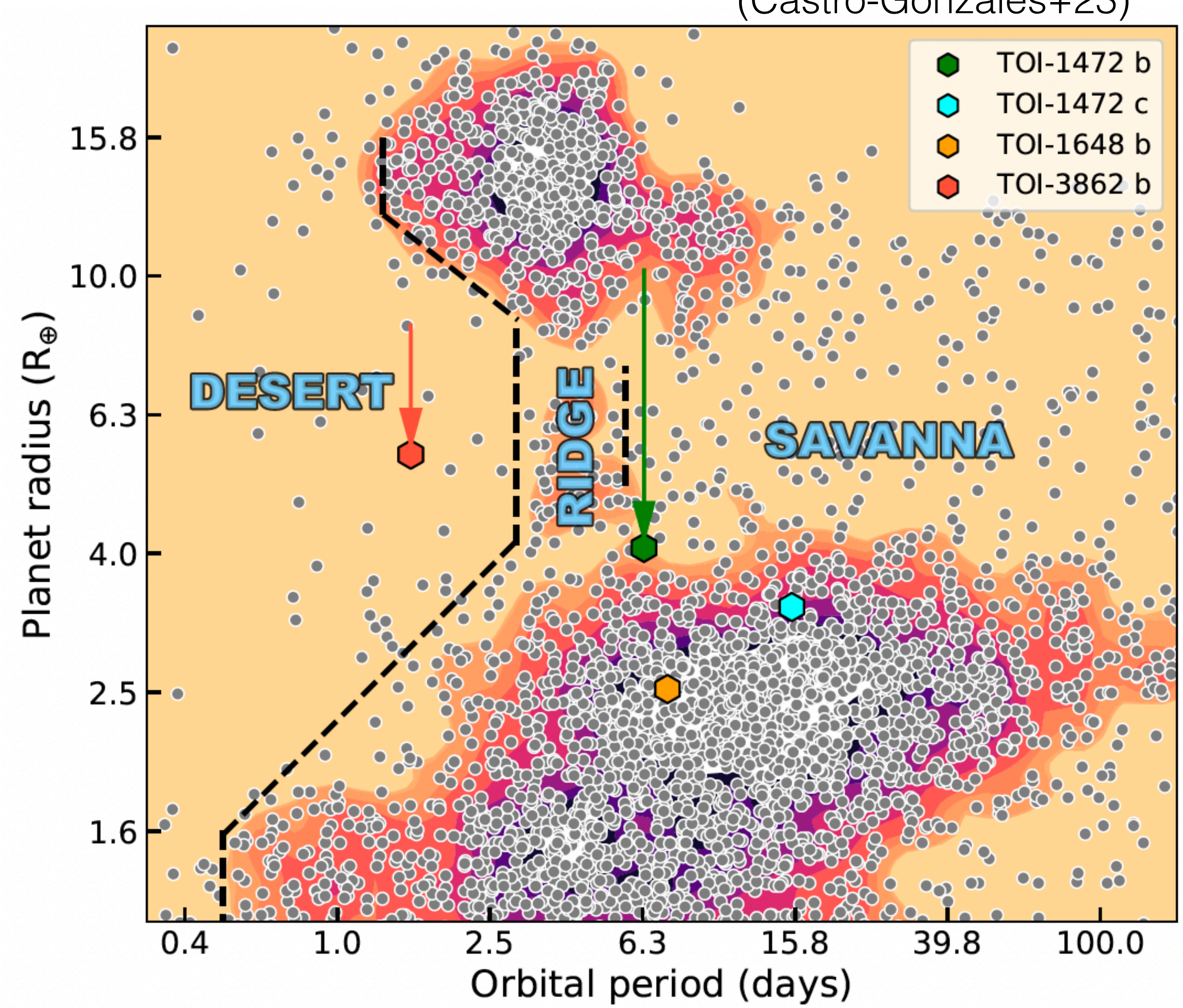


Unique population of 2-4 R_{Earth} planets
(none of them in the solar system!)
Many internal structures for the same density

Evaporating / molten rocky planets
Direct probes of composition in volatilised atmospheres

Before the 2040s, it is paramount to understand the rocky-gaseous transition

(Castro-Gonzáles+23)



Planets with radii > 1.5 R_{Earth} are mostly gaseous (Rogers, 2015)

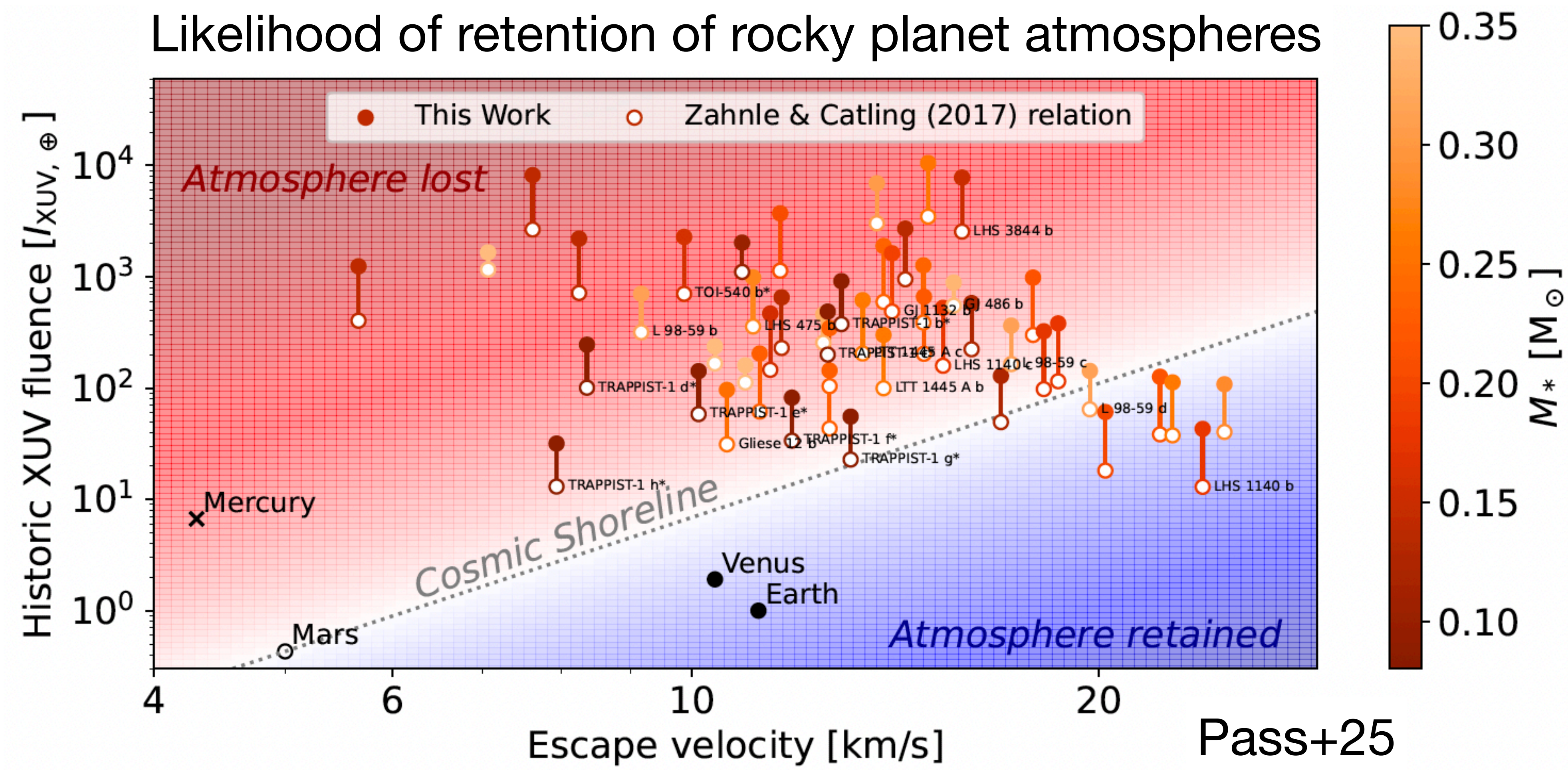
The rocky-gaseous transition can be a consequence of **formation** pathways or **atmospheric loss**

Transmission signals decrease by 10-30× at the transition

Gaseous exoplanets: targeted with <u>current/planned</u> instruments both from space (JWST, Ariel) and from the ground (VLT, Gemini, Keck)

Rocky exoplanets: upper limits on mean molecular weight with current instruments ⇒ detections possible with the <u>ELT in the 2030s</u>

Rocky planets around M dwarfs can lose their atmospheres entirely due to super-luminous pre-main sequence, XUV fluxes, flaring



Identifying the boundaries of the "Cosmic Shoreline" is a prime scientific case
(Zahnle & Catling 17; Pass+25; Berta-Thompson+25)

Current-generation (JWST): *limited* sample and measurements
(2 planets selected for JWST DDT, eclipse brightness at 15 μm)

A science case for the 2030s
(Needs ELT, might need HWO/LIFE to be fully addressed)

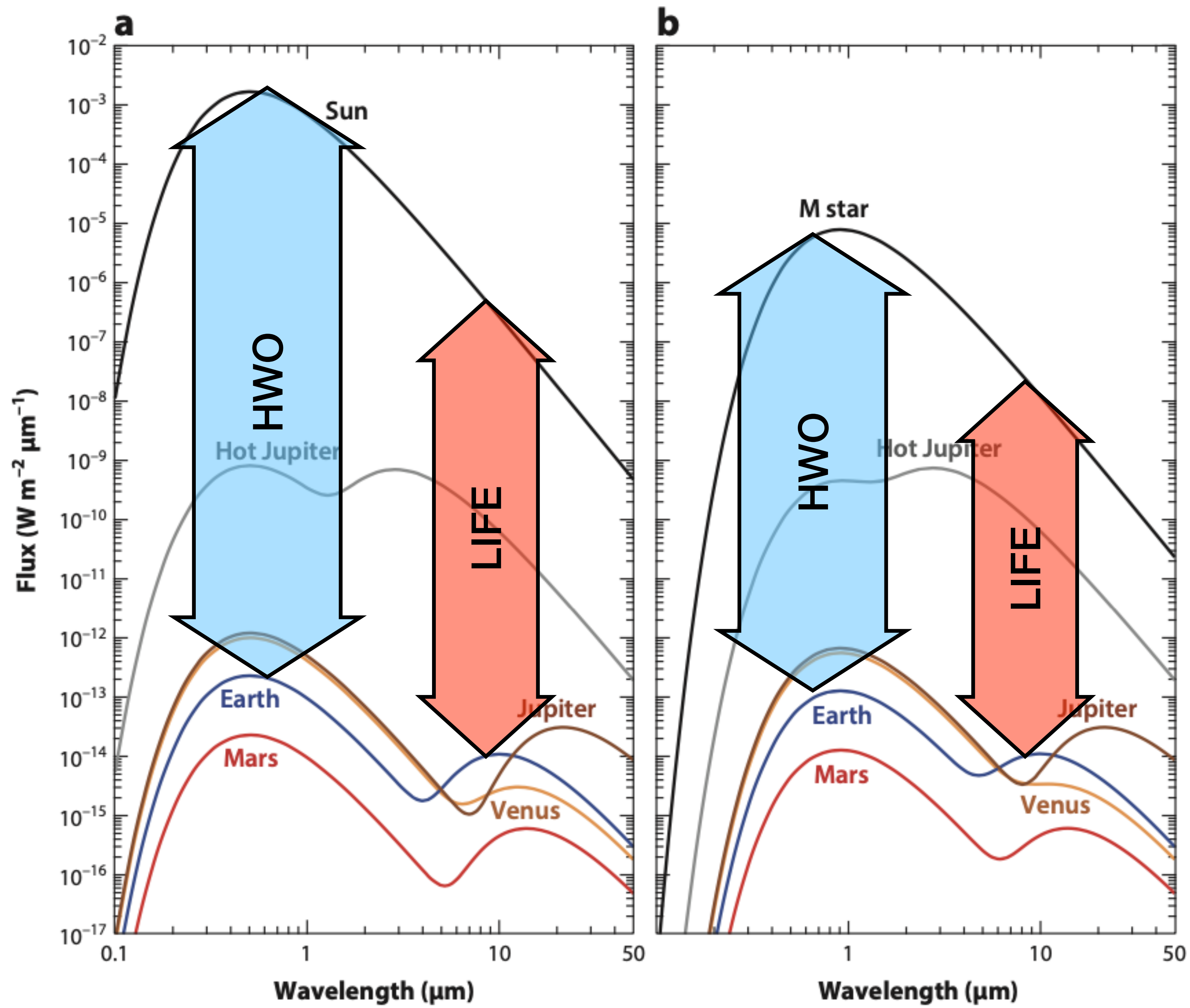
Observing temperate rocky exoplanets requires filling a gap of 2 to 5 orders of magnitude in contrast compared to current observations

Planet/star contrast in reflected light

10^{-10} (G stars)
10^{-8} (M stars)

Planet/star contrast in thermal emission

10^{-7} (G stars)
10^{-6} (M stars)

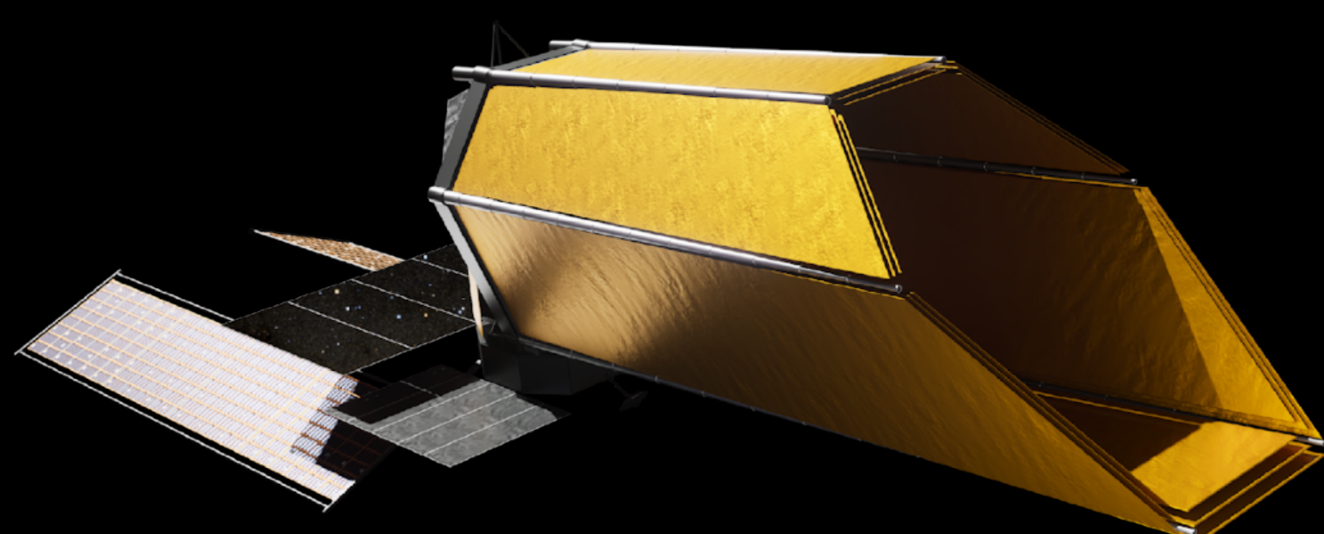


Contrast is "just" one of the challenges
As isolated objects, these planets are very faint (V = 30+ mag)

To detect a planet at such extreme contrasts,
planet and star must be spatially separated

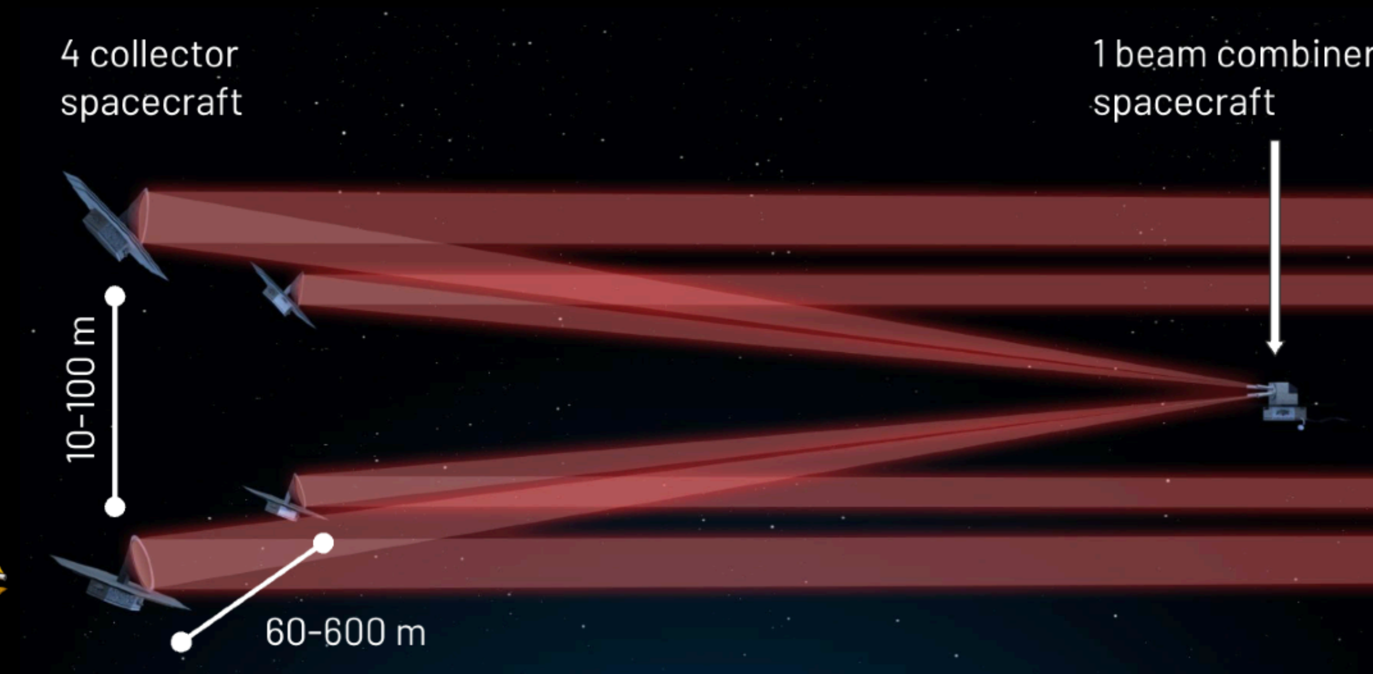
Transit spectroscopy is *not* a viable option
We must rely on *emission* and/or *reflected light* spectroscopy

Habitable Worlds Observatory (HWO)



6-8m mirror
Coronography
Reflected light
0.2-1.8 μm, *R* = 70-200

Large Interferometer For Exoplanets (LIFE)



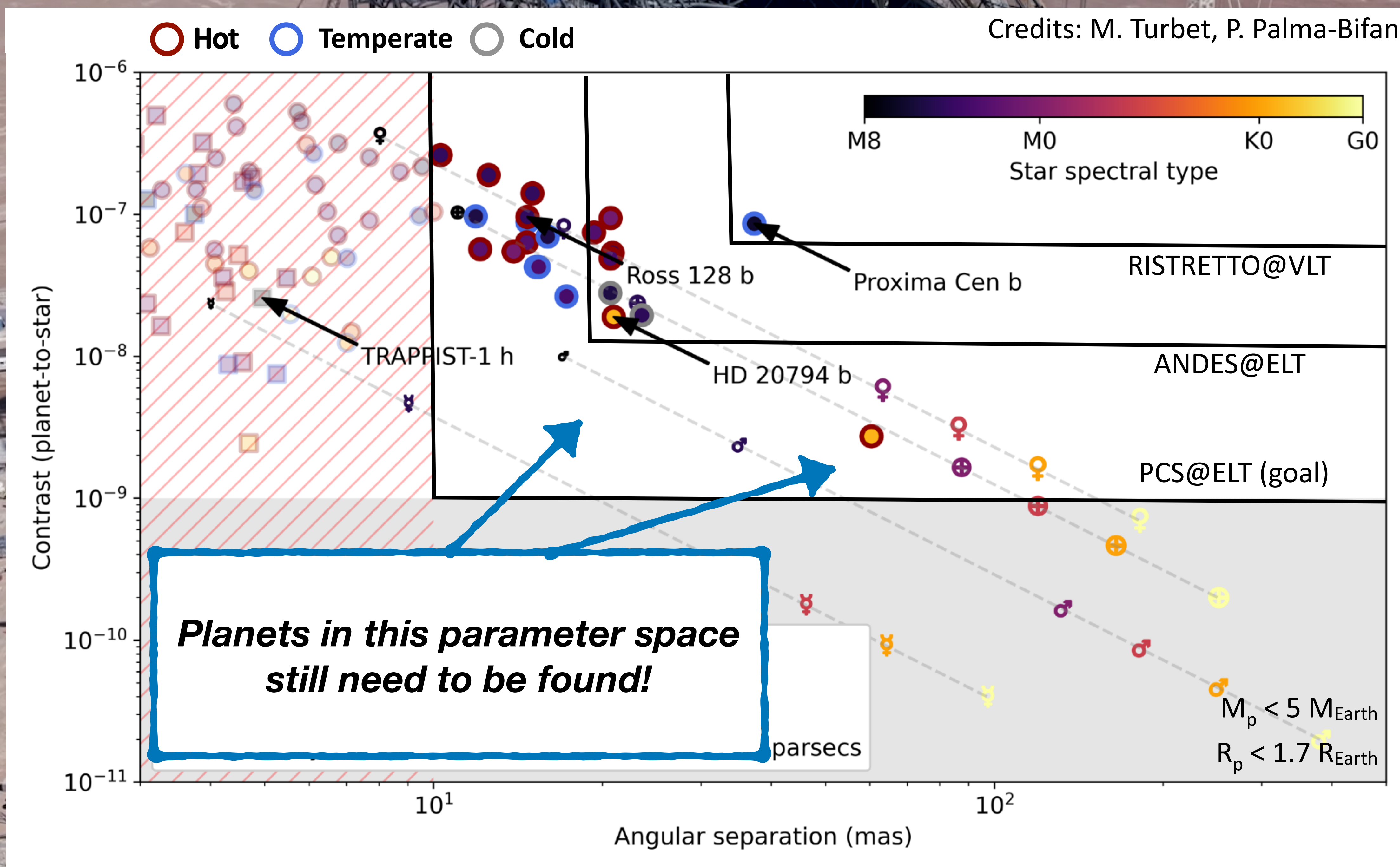
4 x (2.0-3.5m) mirrors
Nulling interferometry
Thermal emission
6-16 μm (4-18.5 μm goal), *R* = 100

Ground-based ELT observations can hit the 10^{-8} / 10^{-9} contrast, but with a combination of direct imaging and cross correlation techniques

ANDES (post-PDR)
R = 75-100k
full 0.4-1.8 µm

AO + Coronograph Integral Field Units

PCS (pre-phase A)
R ~ 100k
full 0.4-2.4 µm



Thermal emission and reflected light measurements offer highly-complementary views of a temperate rocky planet

Better constraints in <u>reflected light</u>	**Better constraints in <u>thermal emission</u>**
Chemical make up	*Chemical make up*
Clouds (coverage, composition)	*Abundances*
Planet albedo (land/ocean)	*Surface temperatures*

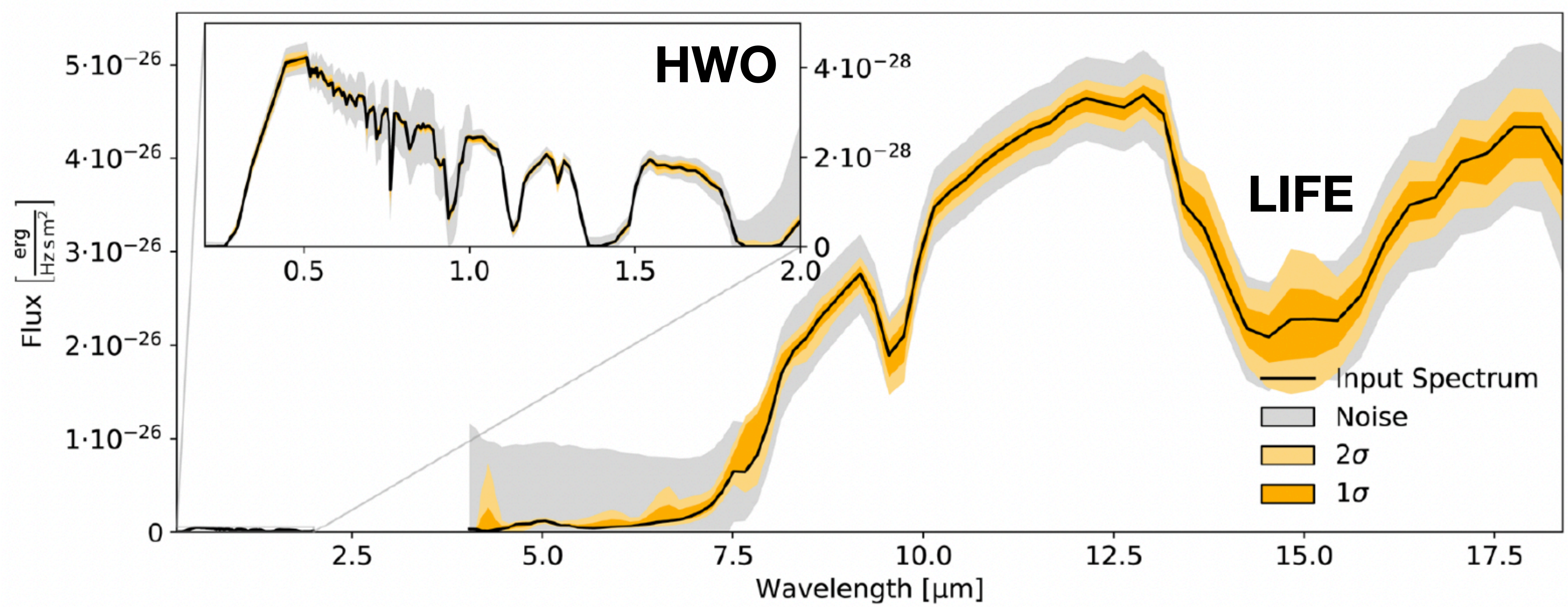
Some cases will strongly benefit from *polarimetry* (albedo vs phase)

Reflected light: a few photometric detections, no firm *spectroscopic* detection
Challenging **interpretation:** stellar spectrum modulated by albedo + starlight passing twice through the planet atmosphere

Known degeneracies between key physical parameters:
simulations w/ Bayesian retrievals needed to assess performances and yield.

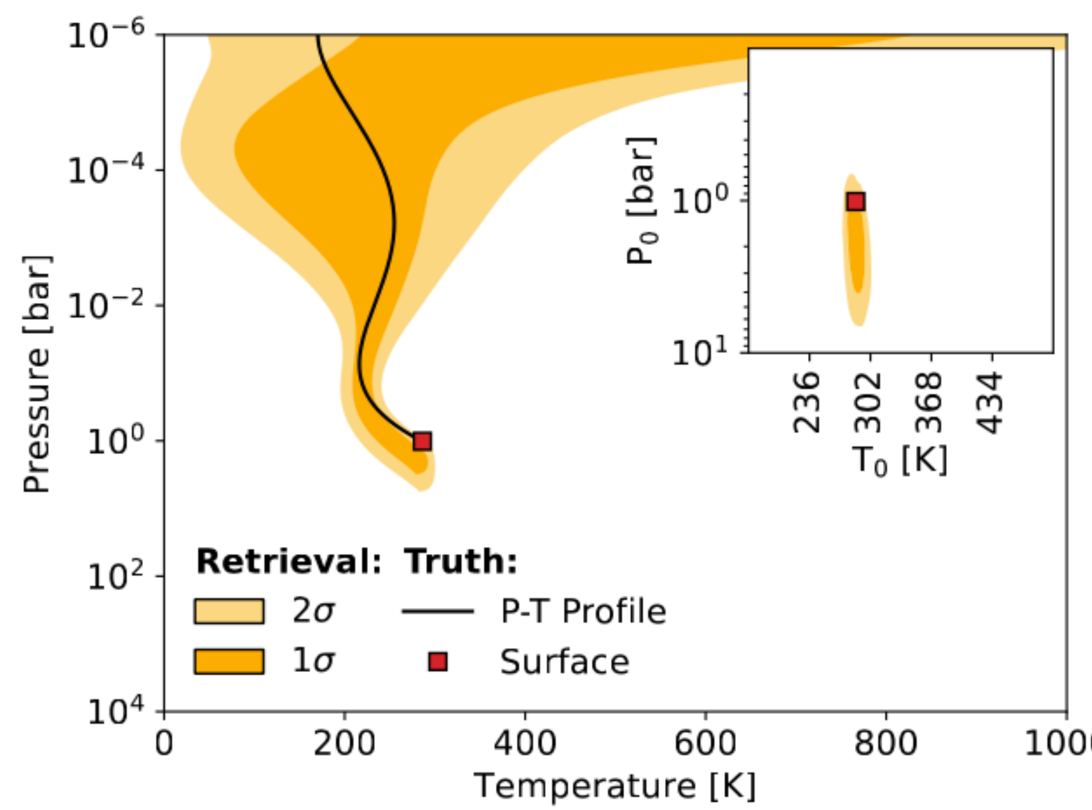
The maximum scientific yield of the 2040s can be obtained with both HWO and LIFE flying and their measurements combined

(Alei+24)



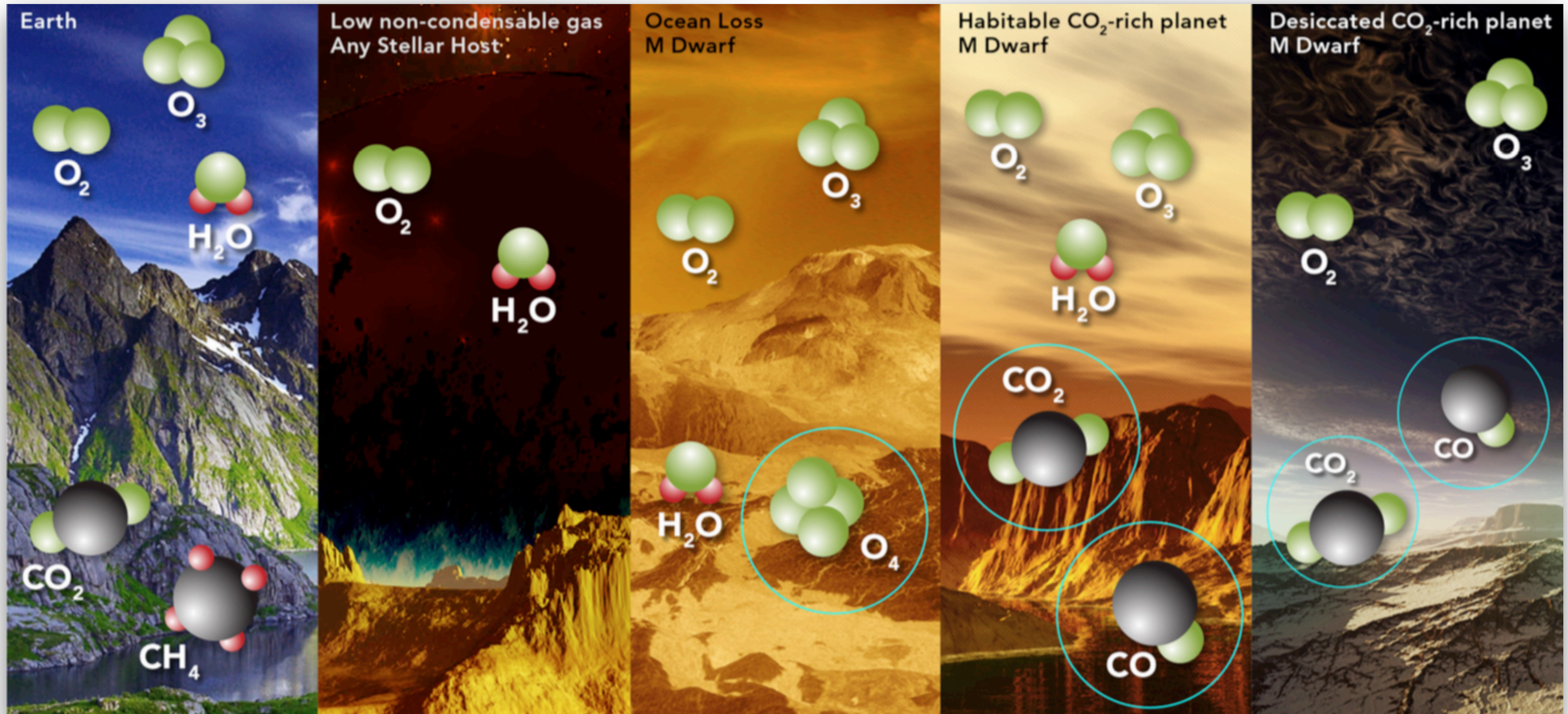
≤10 K uncertainty in surface temperature, ~1 dex uncertainty in abundances

	HWO	LIFE	HWO+LIFE
O_2	4σ	-	4σ
H_2O	>5σ	4σ	>5σ
CO_2	-	>5σ	>5σ
CH_4	-	-	-
O_3	5σ	3σ	>5σ
CO	-	-	-
N_2O	-	-	-



To rule out false-positive scenarios, we need the widest possible spectral coverage and the highest number of species detectable (H_2O, CH_4, CO, CO_2, O_2, O_3)

Schwieterman+16



Even HWO + LIFE lack sensitivity to CO (and CH_4)
The K-band (targeting CO) is *not* in the baseline of ANDES

Wrapping up

Exoplanet science in the 2040s promises to unveil the **prominence of habitable planets** by studying the atmospheres of **temperate rocky exoplanets**

It requires extremely challenging **measurements** of the **chemical makeup, temperature** and **reflectivity** at planet/star contrast ratio down to 10^{-10}

Instrument **design** (spectral range and resolution) happening now needs to anticipate (yet unknown) **false-positive scenarios**

Any putative biomarker detection and subsequent claim is contingent on fulfilling the main science goals of the next 15-20 years