How to Determine Whether M-Dwarf Terrestrial Planets Possess Atmospheres

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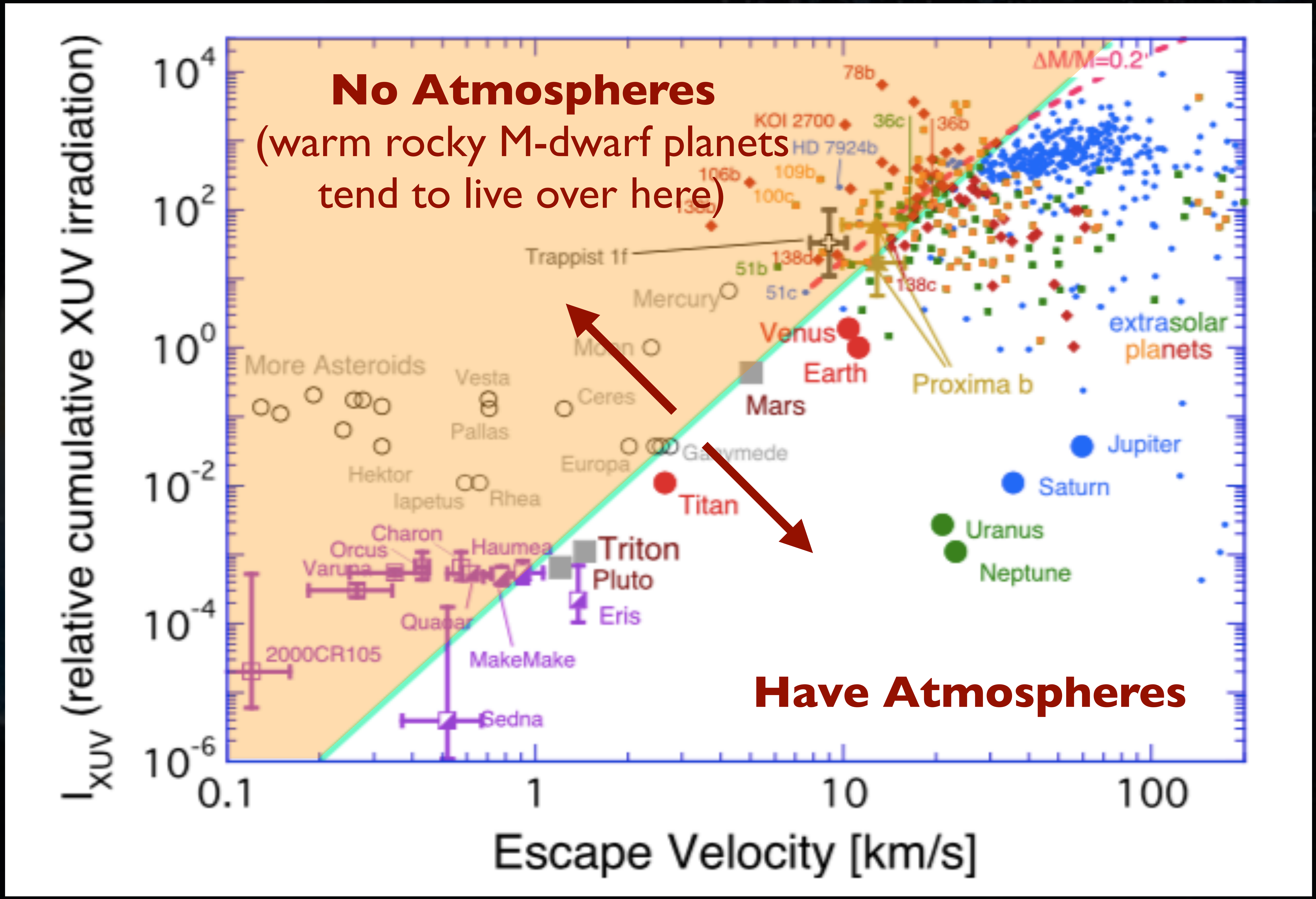
Based on:

Koll et al. (ArXiv: 1907.13138)
Malik et al. (ArXiv: 1907.13135)
Mansfield et al. (ArXiv: 1907.13150)
Koll (ArXiv: 1907.13145)

A major open question in characterizing the atmospheres of the rocky M-dwarf planets that *TESS* will find in large numbers, is whether such planets possess atmospheres at all



Zahnle and Catling., *ApJ*, 2017

The null hypothesis:

There is a maximum possible value for a rocky planet's dayside temperature that will be observed only if the planet lacks an atmosphere

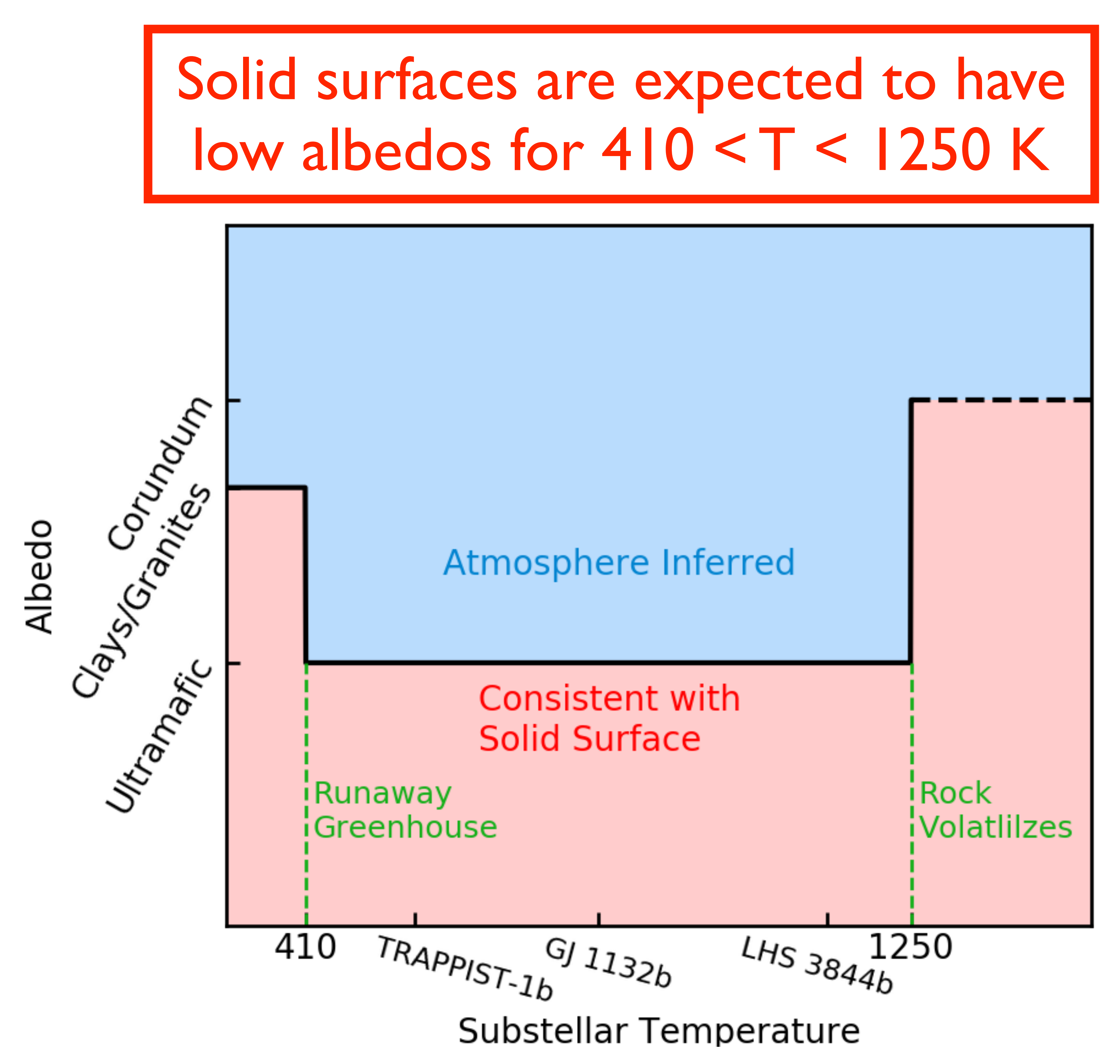
"Bare rock" temperature: $$T_{max} = T_\star \sqrt{\frac{R_\star}{d}} \left(\frac{2}{3}\right)^{1/4}$$

(Equilibrium temperature: $T_{eq} = T_\star \sqrt{\frac{R_\star}{d}} (1 - \alpha_B)^{1/4} f^{1/4}$)

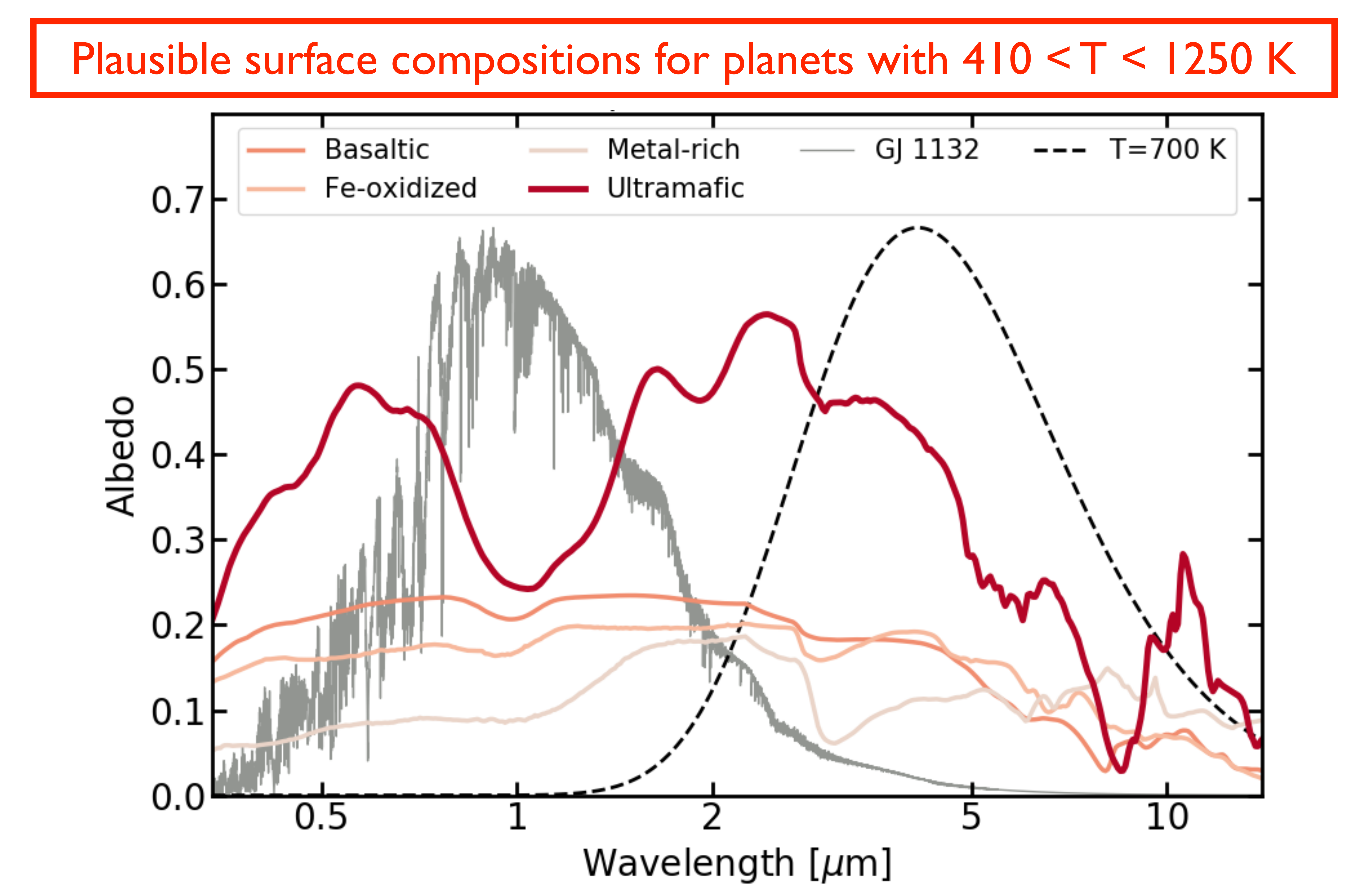
$T_\star$ = stellar temperature, $R_\star$ = stellar radius, d = orbital distance, α_B = Bond albedo, f = heat redistribution parameter

An ***atmosphere*** will serve to lower the dayside temperature by (i) increasing the planet's albedo, and (ii) transporting heat to the planet's night side

Testing the null hypothesis: The albedo effect



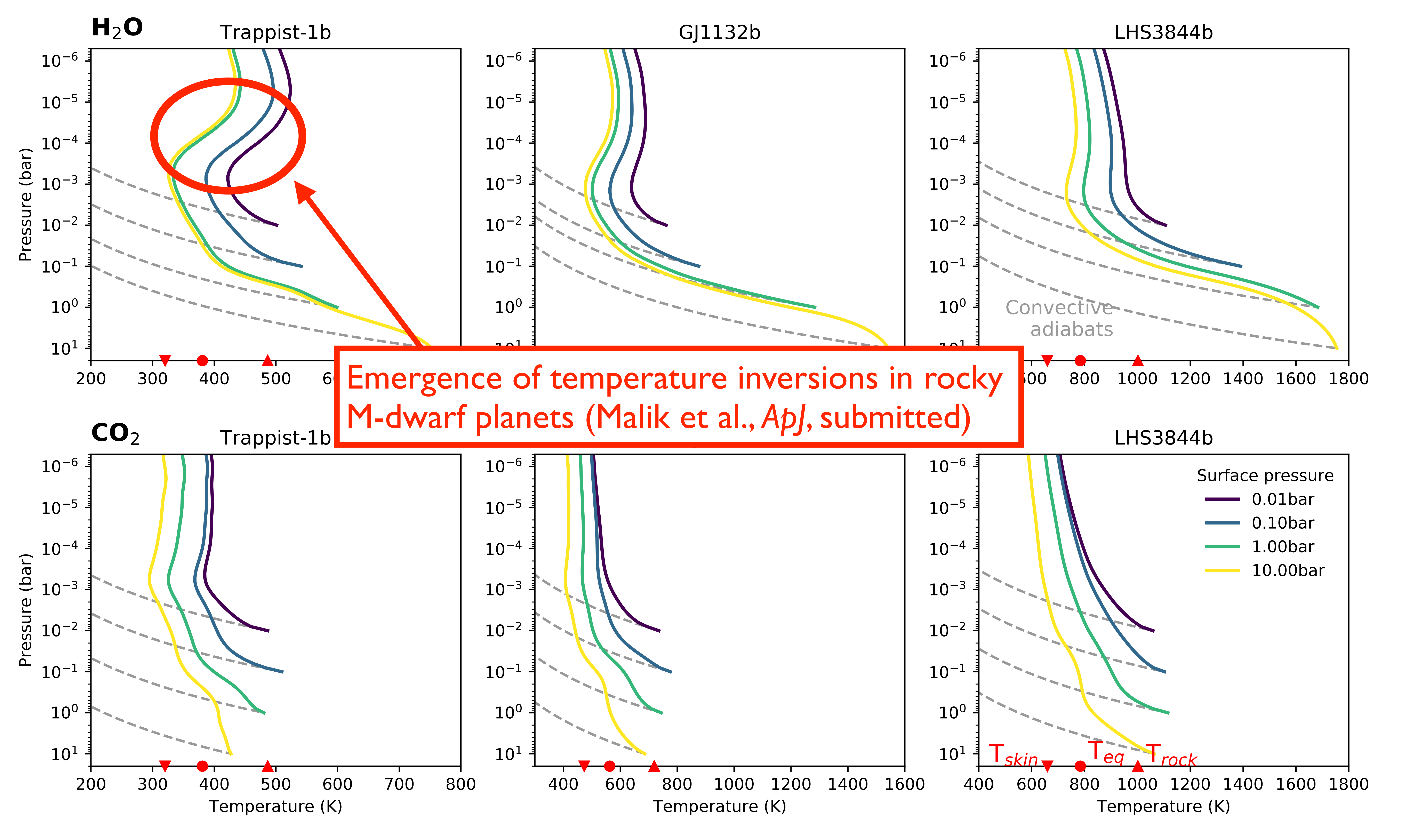
Mansfield et al. (submitted)



Mansfield et al. (submitted), albedo spectra from Hu, Ehlmann, & Seager, *ApJ* (2012)

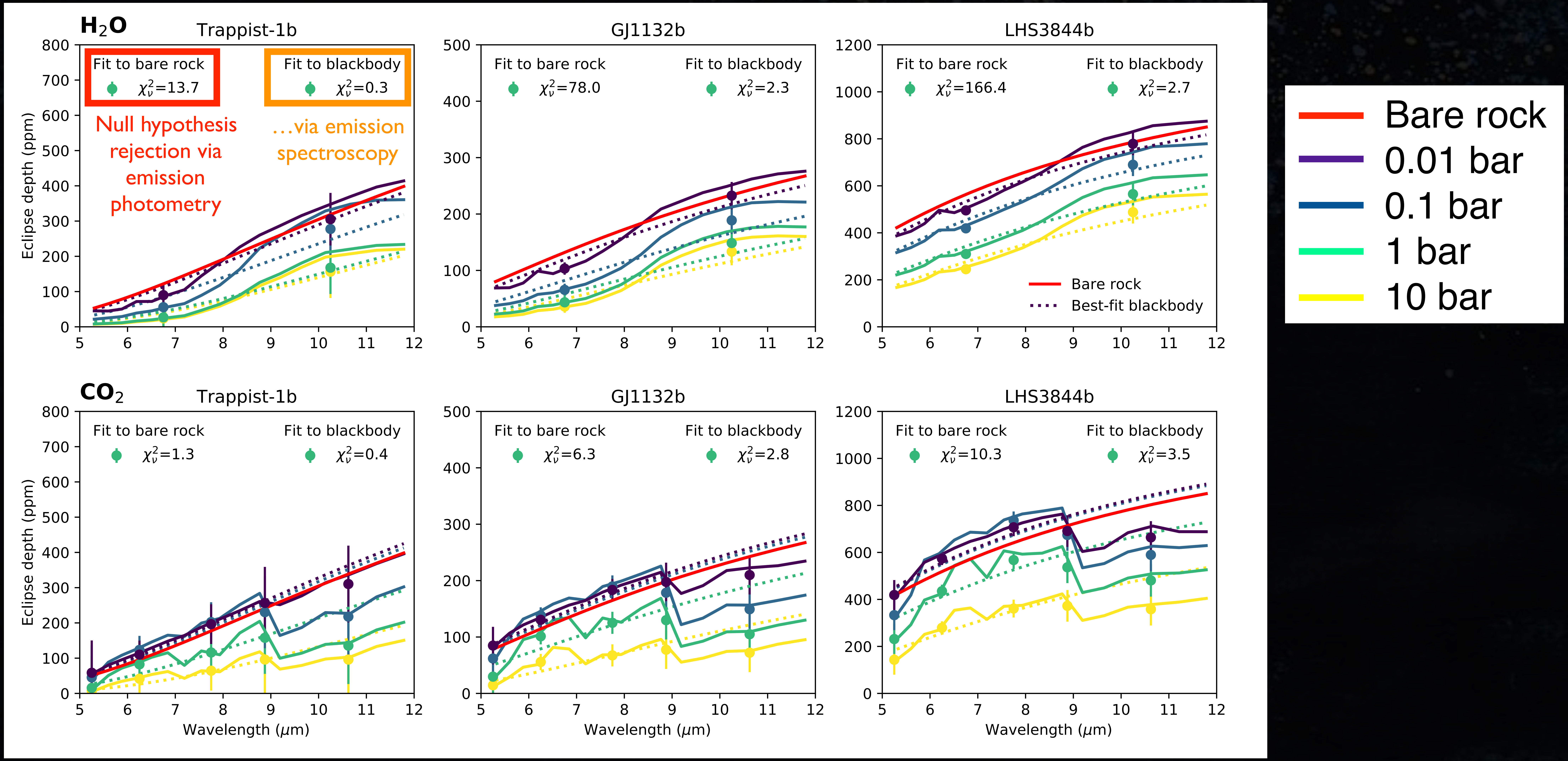
Testing the null hypothesis: 1-D atmosphere modeling

Radiative-convective equilibrium models for planets with solid surfaces from HELIOS (https://github.com/exoclime/HELIOS)



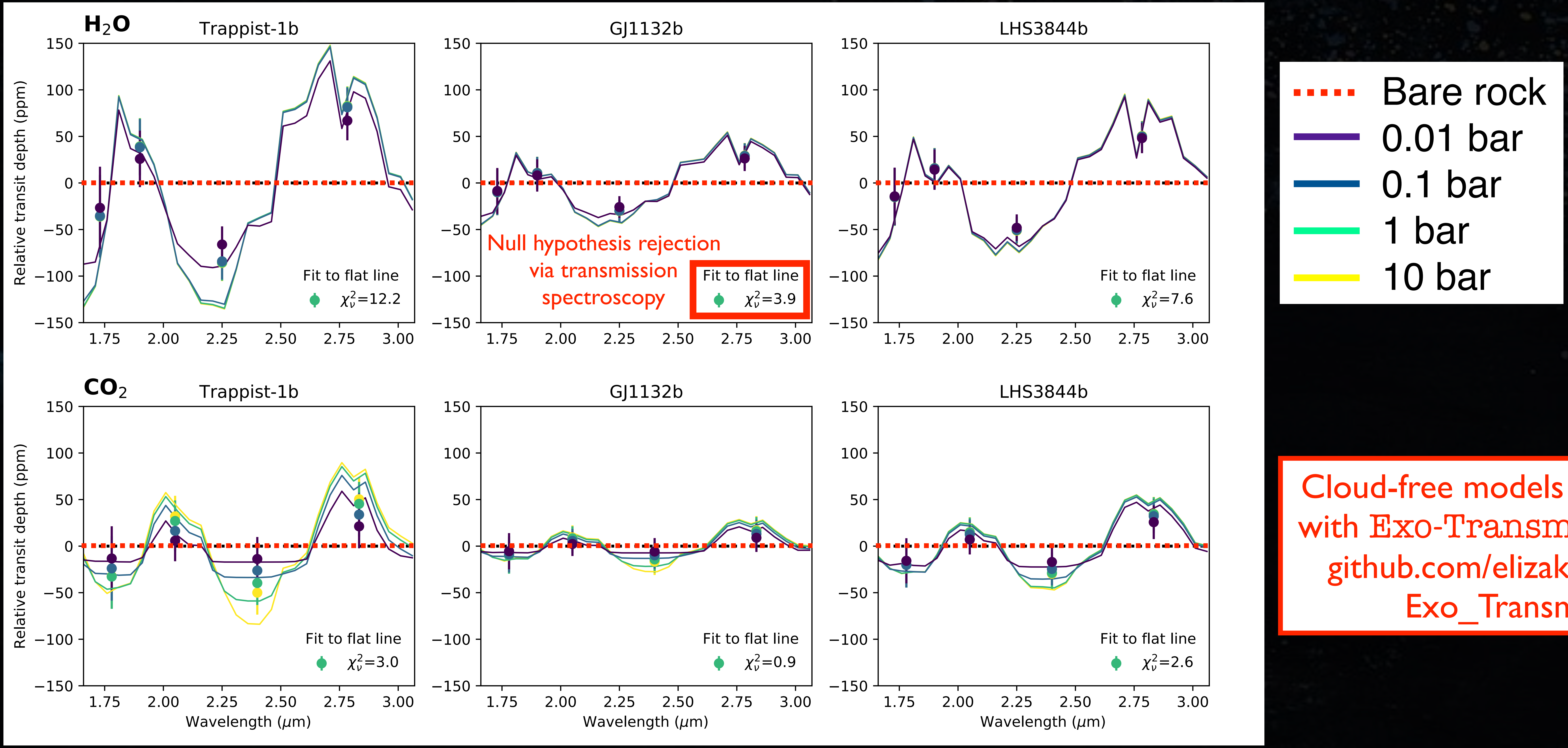
Koll et al. (submitted)

Testing the null hypothesis: Emission spectroscopy vs. photometry



Koll et al. (submitted)

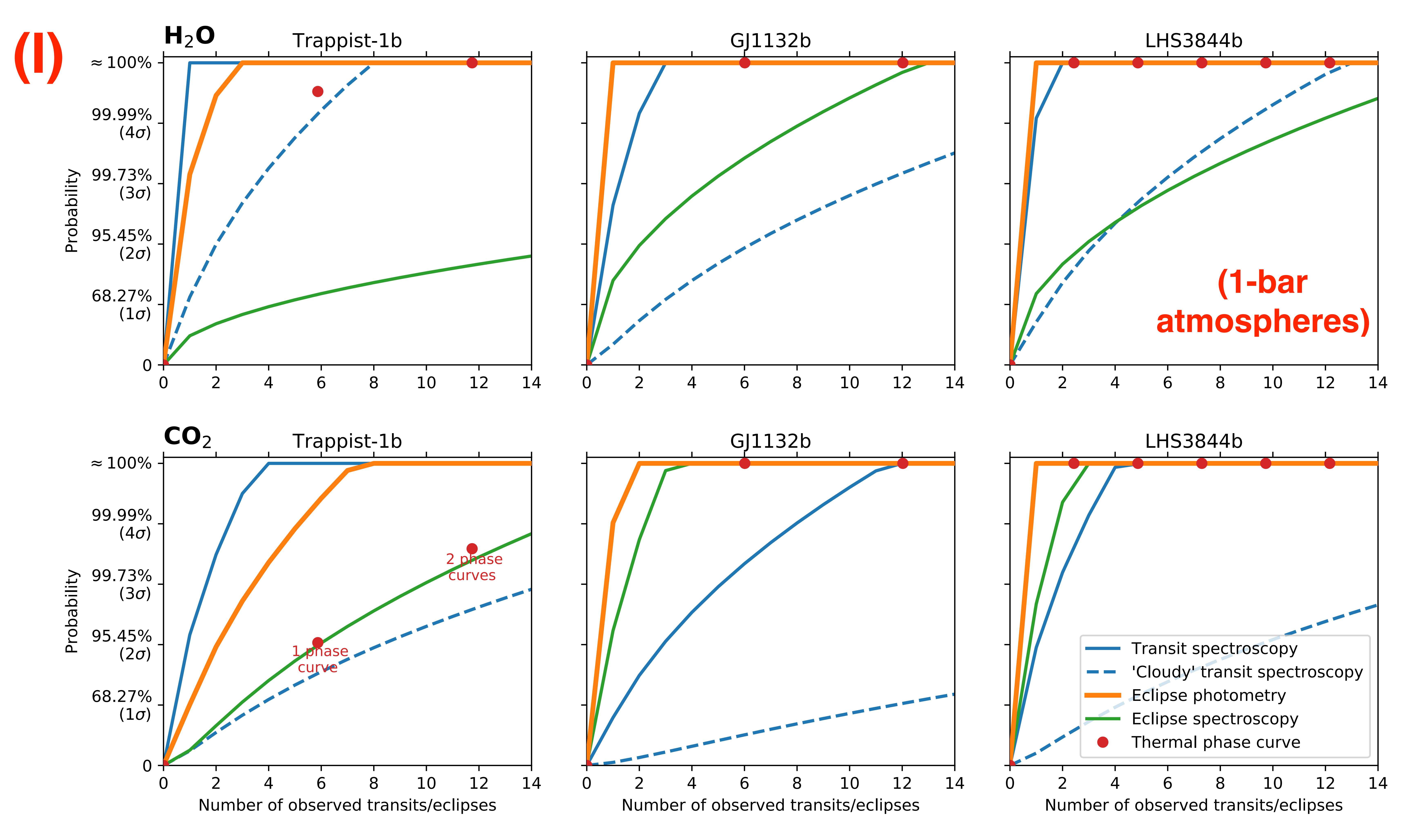
Testing the null hypothesis: Transmission spectroscopy



Cloud-free models generated with Exo-Transmit (https://github.com/elizakempton/Exo_Transmit)

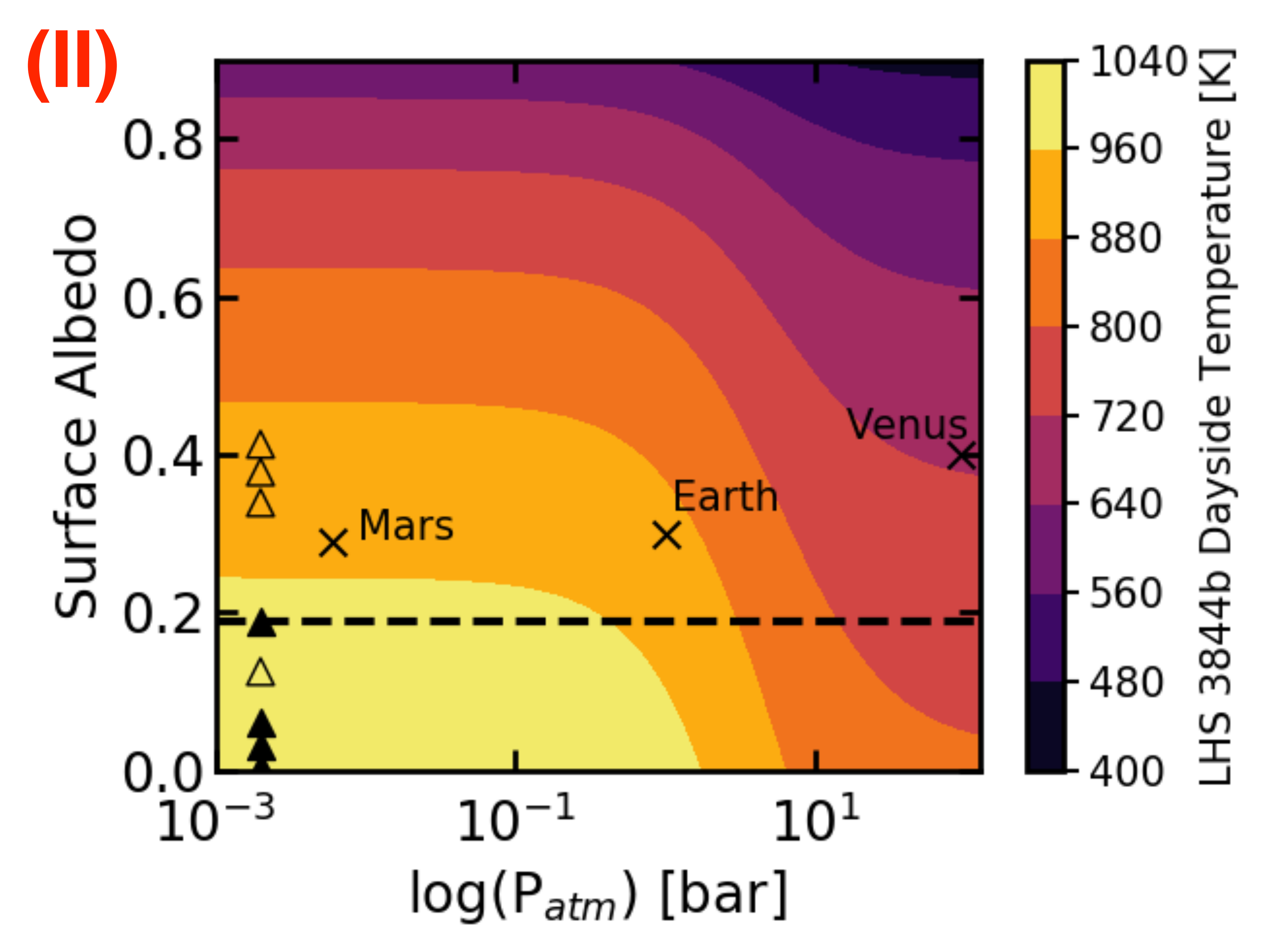
Koll et al. (submitted)

Results: (I) Eclipse photometry is typically the most economical technique to reject the null hypothesis and confirm a "candidate" atmosphere

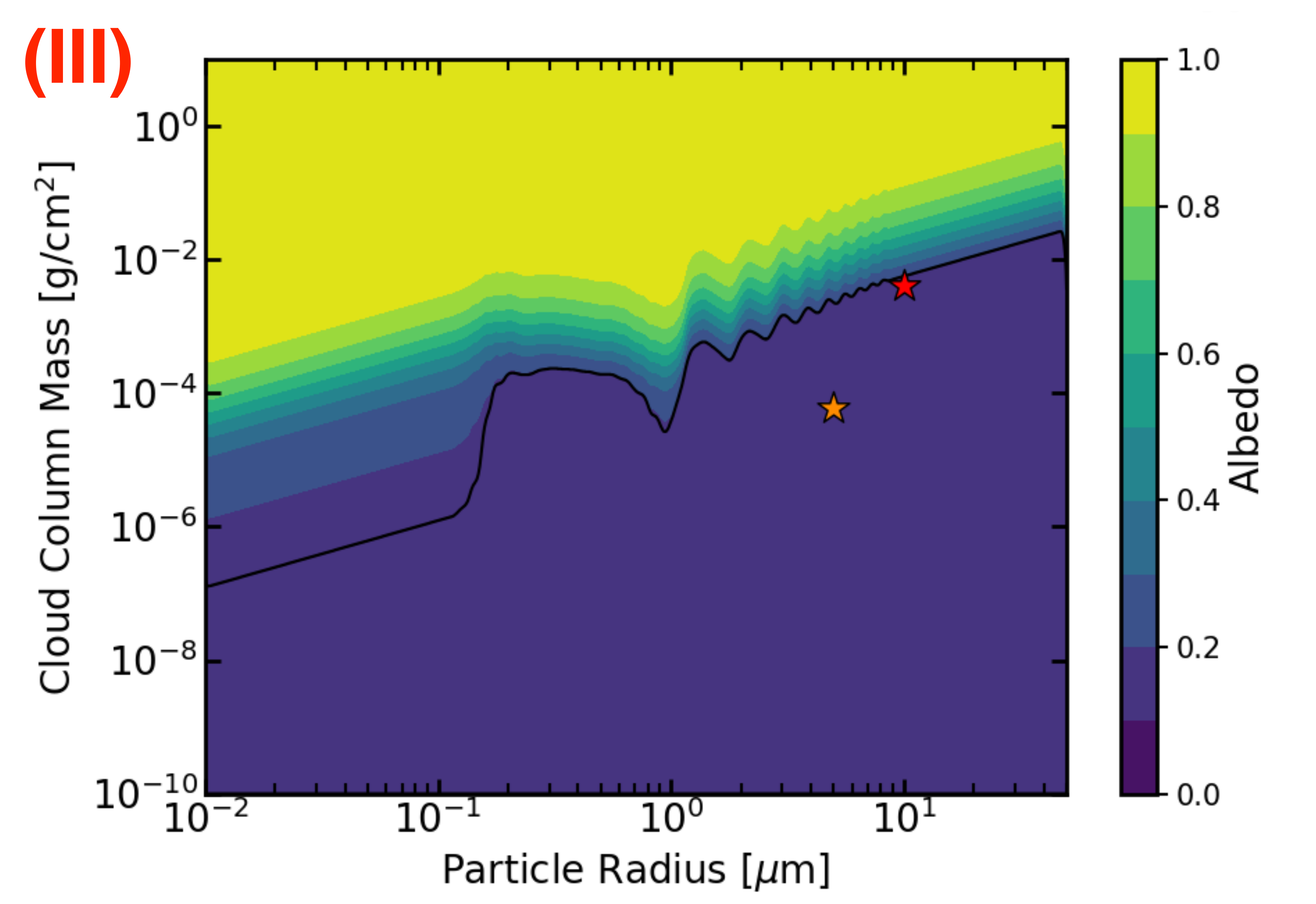


Koll et al. (submitted)

Results: (II) *Inferred* Bond albedos greater than ~0.2 are indicative of atmospheres on warm rocky M-dwarf planets
(III) Moderate cloud columns can raise the albedo well above this threshold, even for very thin atmospheres

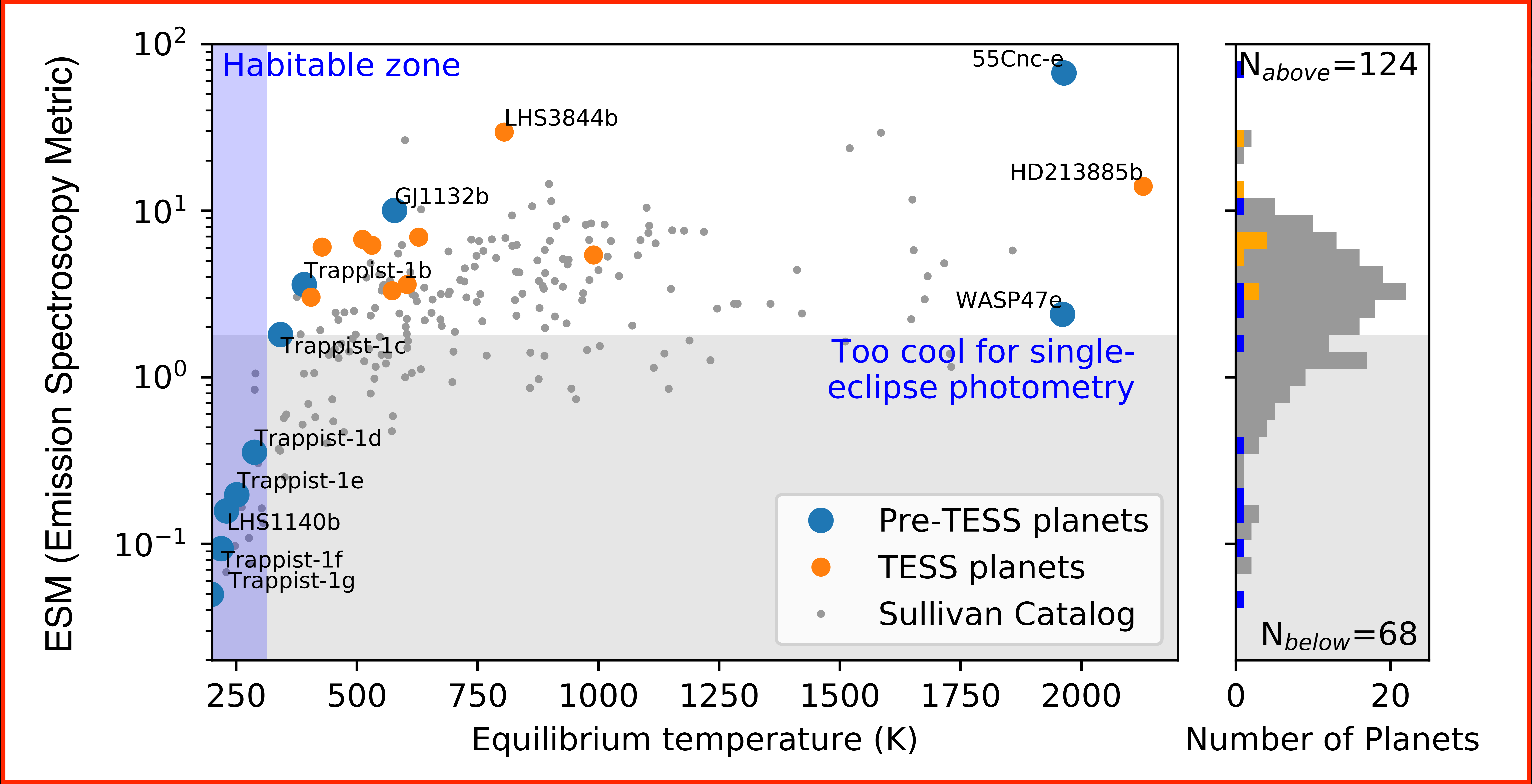


Mansfield et al. (submitted)



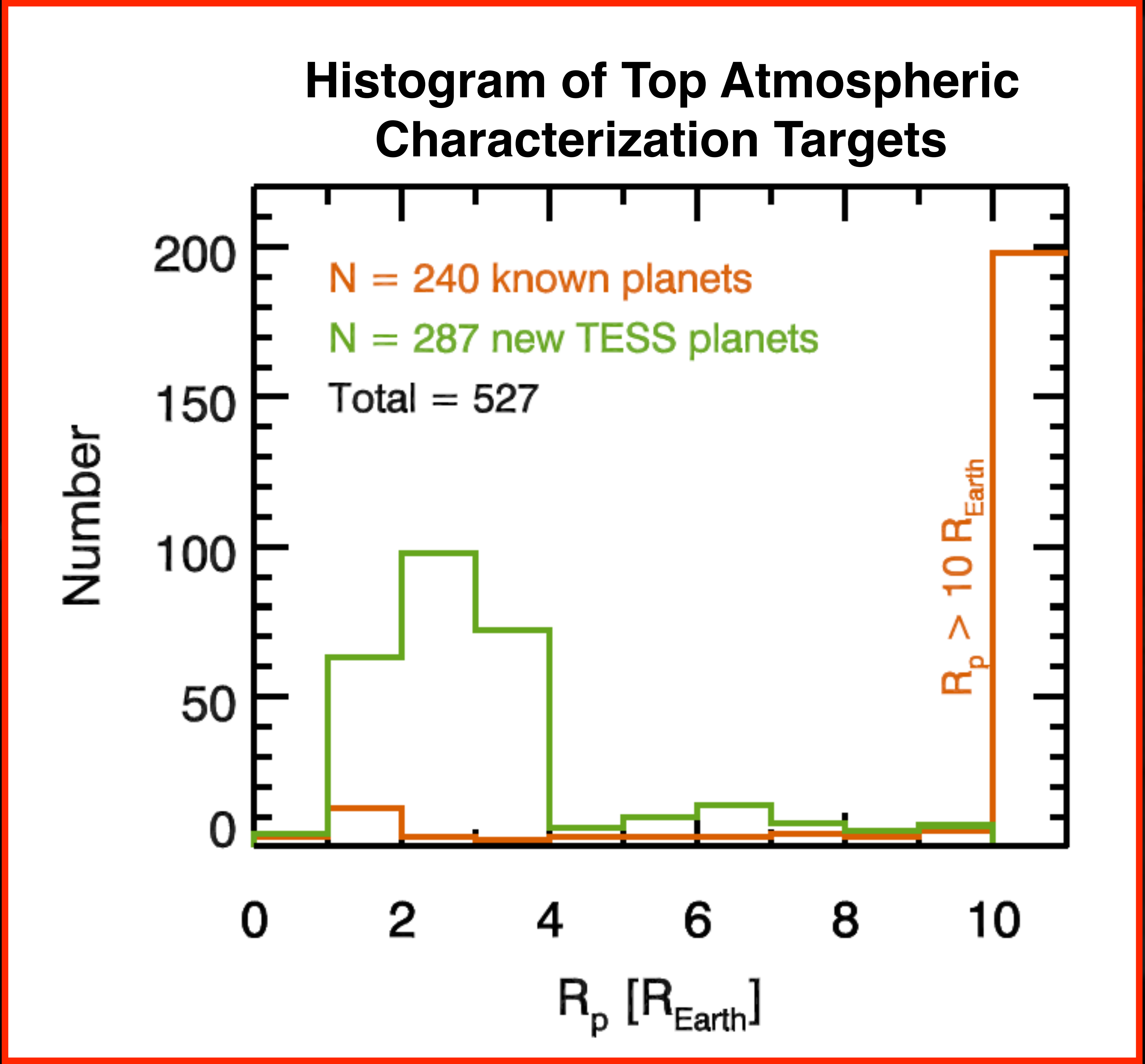
Mansfield et al. (submitted)

The secondary eclipse photometry test could be performed on ~100 rocky M-dwarf planets with JWST to determine the occurrence rate of atmospheres on such objects



Koll et al. (submitted)

Final thoughts: The exoplanet community requires a large statistical survey of exoplanet atmospheres to make good on the promise of the *TESS* mission



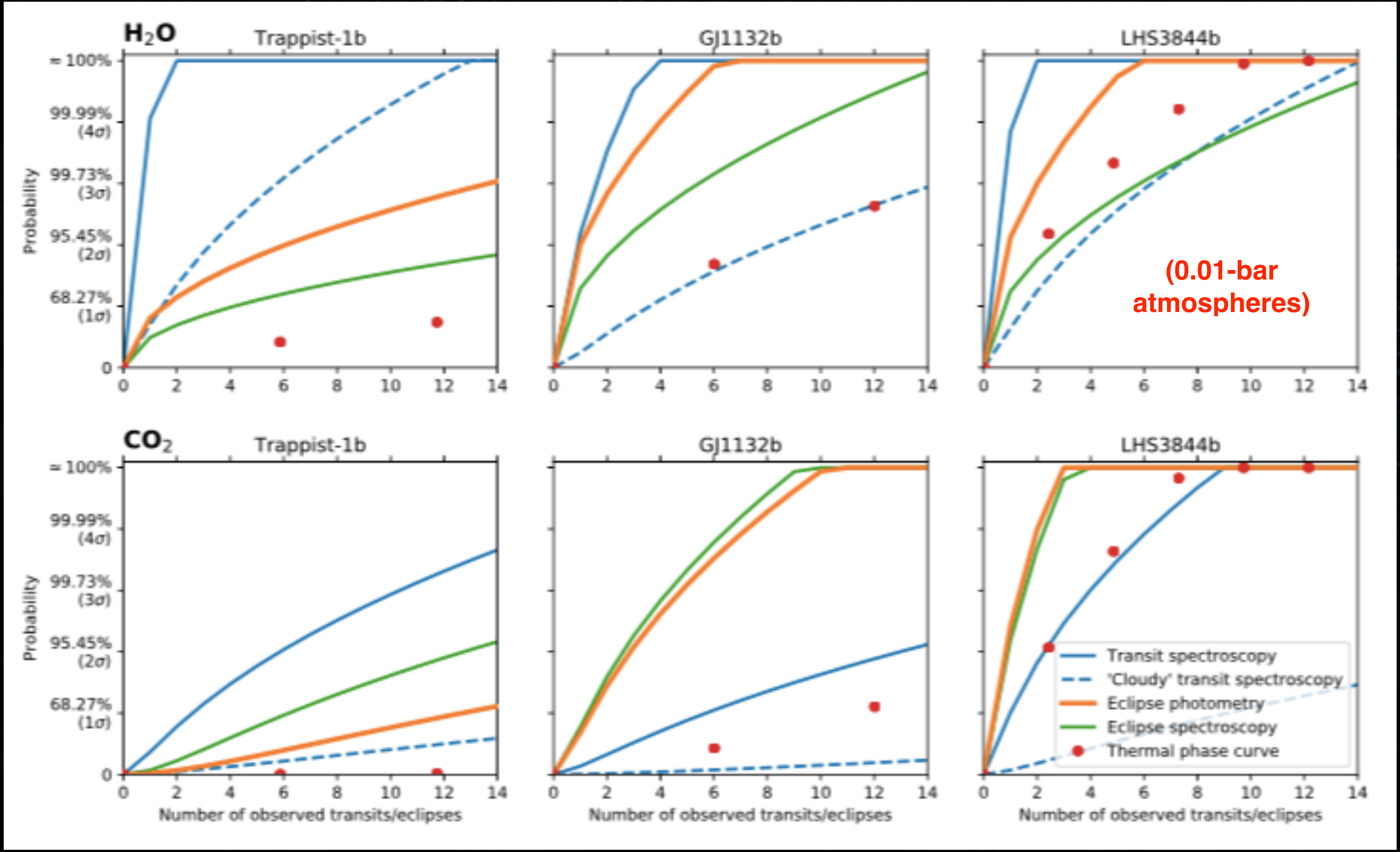
Kempton et al., *PASP*, 2018

"Recommendation: NASA should create a mechanism for community-driven legacy surveys of exoplanet atmospheres early in the JWST mission" - National Academy of Sciences Exoplanet Science Strategy Consensus Study Report (2018)

Summary:

- For rocky M-dwarf planets interior to the habitable zone, there is a maximum possible secondary eclipse depth (corresponding to low albedo and no day/night heat redistribution), which is representative of a bare rock planet.
- A smaller secondary eclipse depth is indicative of a *candidate* atmosphere because atmospheres scatter away incoming stellar light and transport heat to the planet's night side.
- Eclipse photometry is typically the most economical technique to identify a candidate atmosphere.
- Inferred Bond albedos greater than ~0.2 are indicative of atmospheres on warm rocky M-dwarf planets.
- Moderate cloud columns can raise the albedo well above this threshold, even for very thin atmospheres.

Backup slides

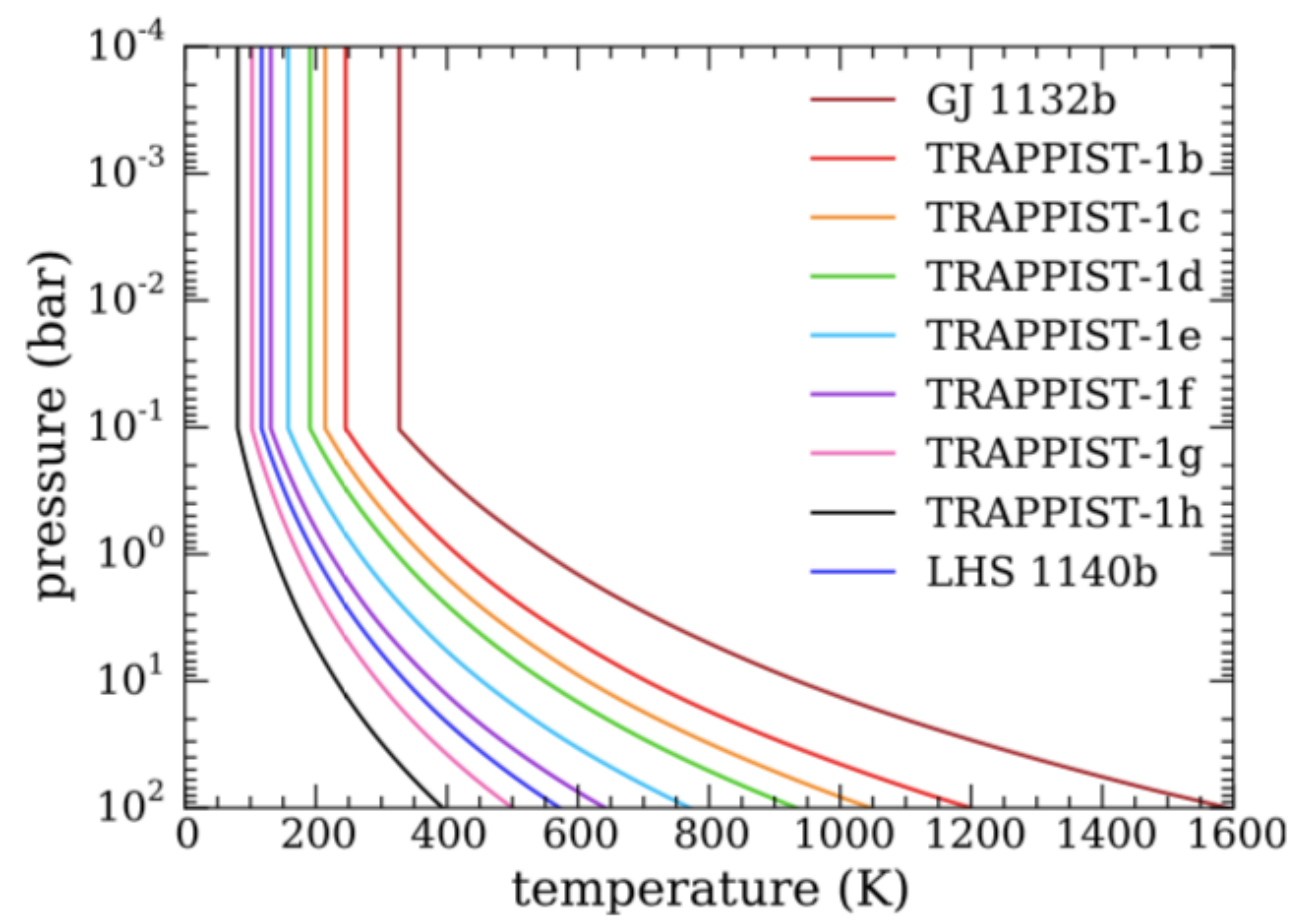


H_2O
Trappist-1b
GJ1132b
LHS3844b
≈ 100%
99.99% (4σ)
99.73% (3σ)
95.45% (2σ)
68.27% (1σ)
0
Probability
0 2 4 6 8 10 12 14
(0.01-bar atmospheres)
CO_2
Trappist-1b
GJ1132b
LHS3844b
Number of observed transits/eclipses
Transit spectroscopy
'Cloudy' transit spectroscopy
Eclipse photometry
Eclipse spectroscopy
Thermal phase curve

Number of Transits or Eclipses Required to Detect a Venus-like Atmosphere

Planet	Emission $P = 0.1$ bar	Emission $P = 1.0$ bar	Emission $P = 10.0$ bar	Transmission $P = 0.01$ bar	Transmission $P = 0.1$ bar	Transmission $P = 1.0$ bar
TRAPPIST-1b	6 (11)	9 (18)	17 (30)	23 (89)	11 (40)	6 (21)
TRAPPIST-1c	19 (37)	29 (58)	48 (92)	–	73 (50)	36 (25)
TRAPPIST-1d	–	–	–	59 (–)	25 (46)	13 (24)
TRAPPIST-1e	–	–	–	15 (–)	6 (66)	4 (71)
TRAPPIST-1f	–	–	–	73 (–)	27 (92)	17 (54)
TRAPPIST-1g	–	–	–	36 (–)	15 (–)	10 (76)
TRAPPIST-1h	–	–	–	16 (–)	6 (90)	4 (56)
GJ 1132b	2 (2)	2 (3)	3 (6)	27 (38)	13 (20)	11 (13)
LHS 1140b	–	–	–	–	–(96)	–(64)

Morley et al., *ApJ*, 2017



Morley et al., *ApJ*, 2017

	R_* ($R_\odot$)	T_* (K)	R_p ($R_\oplus$)	g (m/s^2)	T_{eq} (K)[a]	f_{CO_2}[b]	f_{H_2O}[b]
TRAPPIST-1b	0.121	2511	1.12	7.95	391	0.26	0.25
GJ1132b	0.207	3270	1.16	11.8	578	0.27	0.25
LHS3844b	0.189	3036	1.32	12.9[c]	805	0.27	0.26

[a] Equilibrium temperature, which assumes full heat redistribution and zero albedo.

[b] Heat redistribution factor, for 1 bar surface pressure.

[c] Assuming 2.3 $M_\oplus$, based on Chen & Kipping (2017).