Planets are Places:

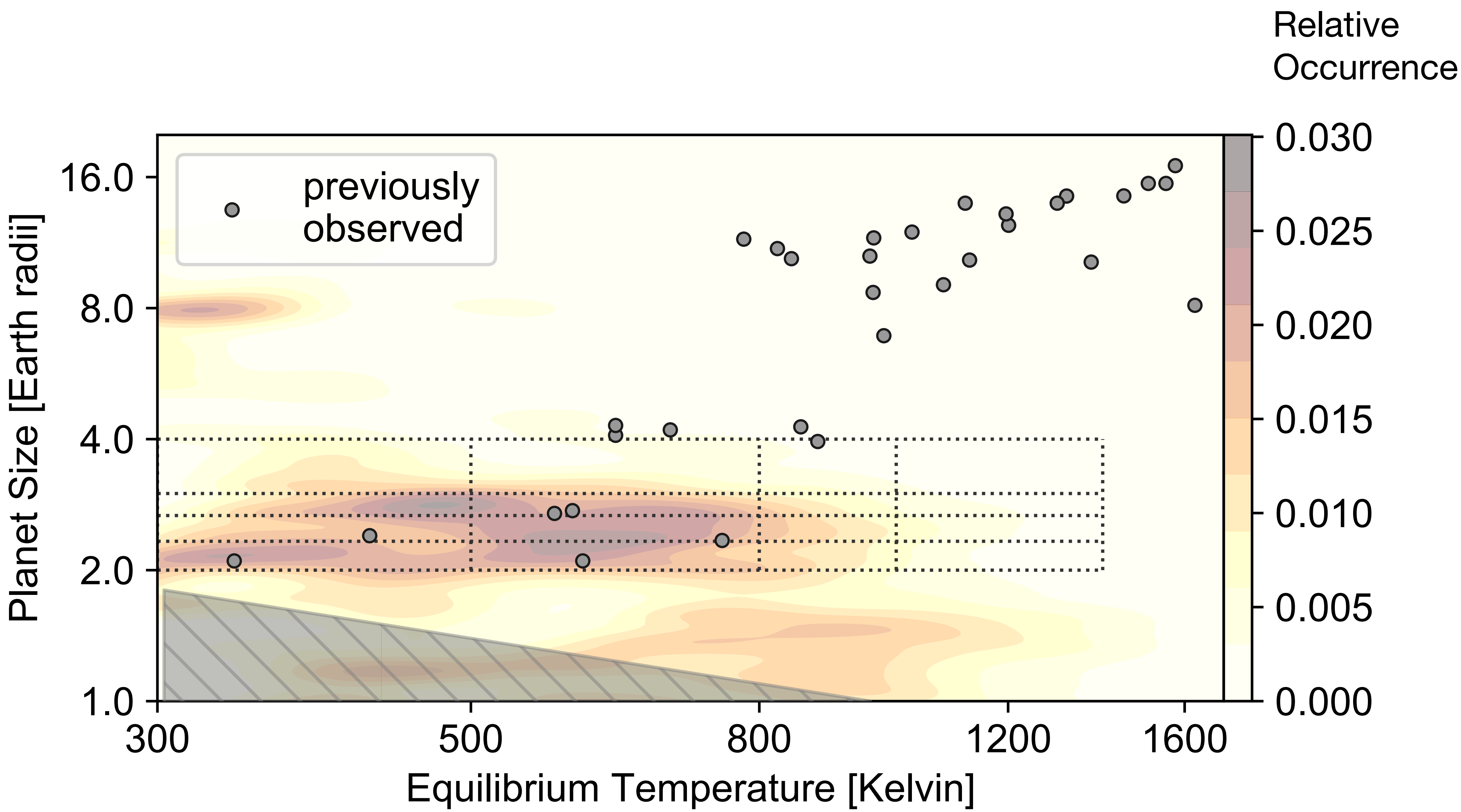
Characterization of Other Worlds in the 2020s and Beyond

Laura Kreidberg

Director, APEx Department

Max Planck Institute for Astronomy

The push towards atmosphere characterisation for Earth twins

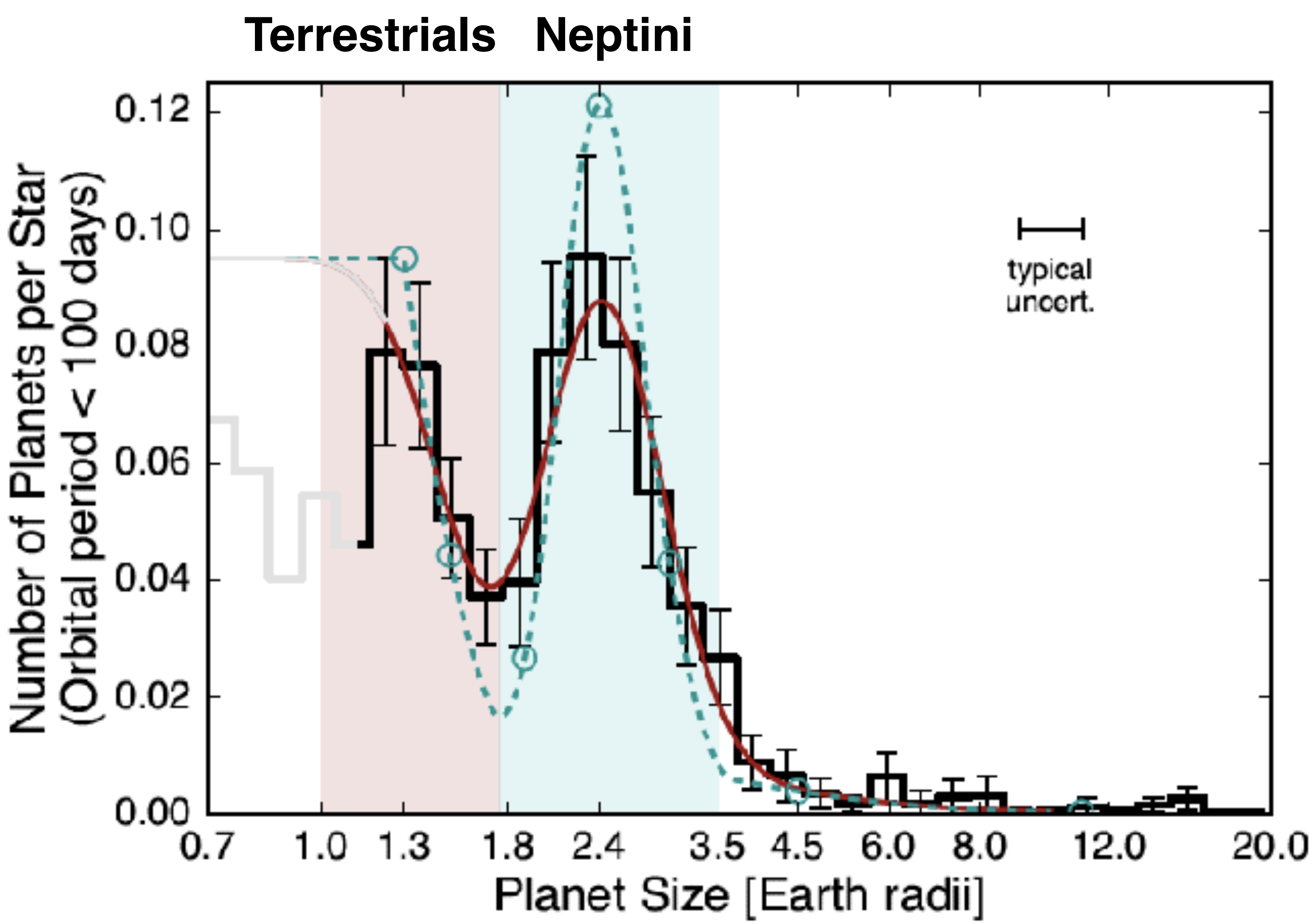


So far, most atmosphere studies are for hot Jupiters

The push towards atmosphere characterisation for Earth twins

Let’s start with Earth cousins, a planets a little ***bigger*** or a little ***hotter*** than Earth

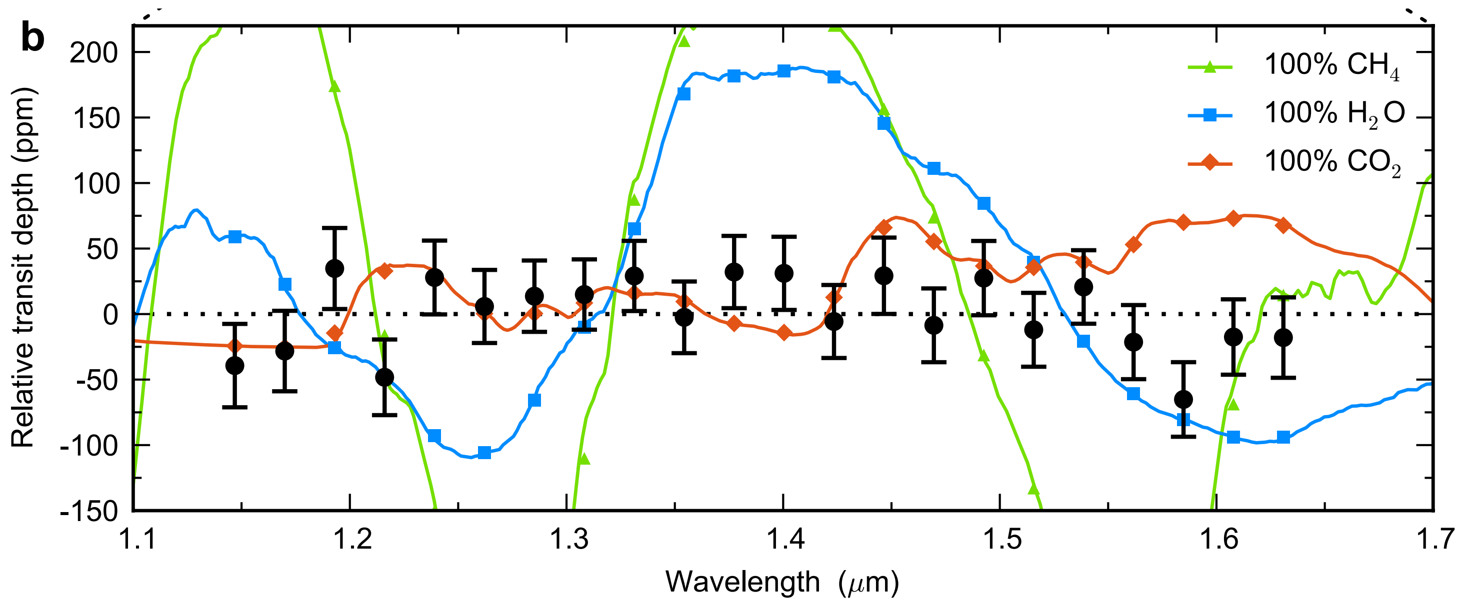
What can we learn from Earth cousins?
1. Neptini



- Planets in the 2-4 Earth radius range are expected to have H2-dominated envelopes
- They may be enhanced in volatiles such as water, carbon dioxide, and methane — but this cannot be determined from masses and radii alone

Definitive evidence for clouds on a warm Neptino

GJ 1214b: 2.7 Earth radii, 550 Kelvin



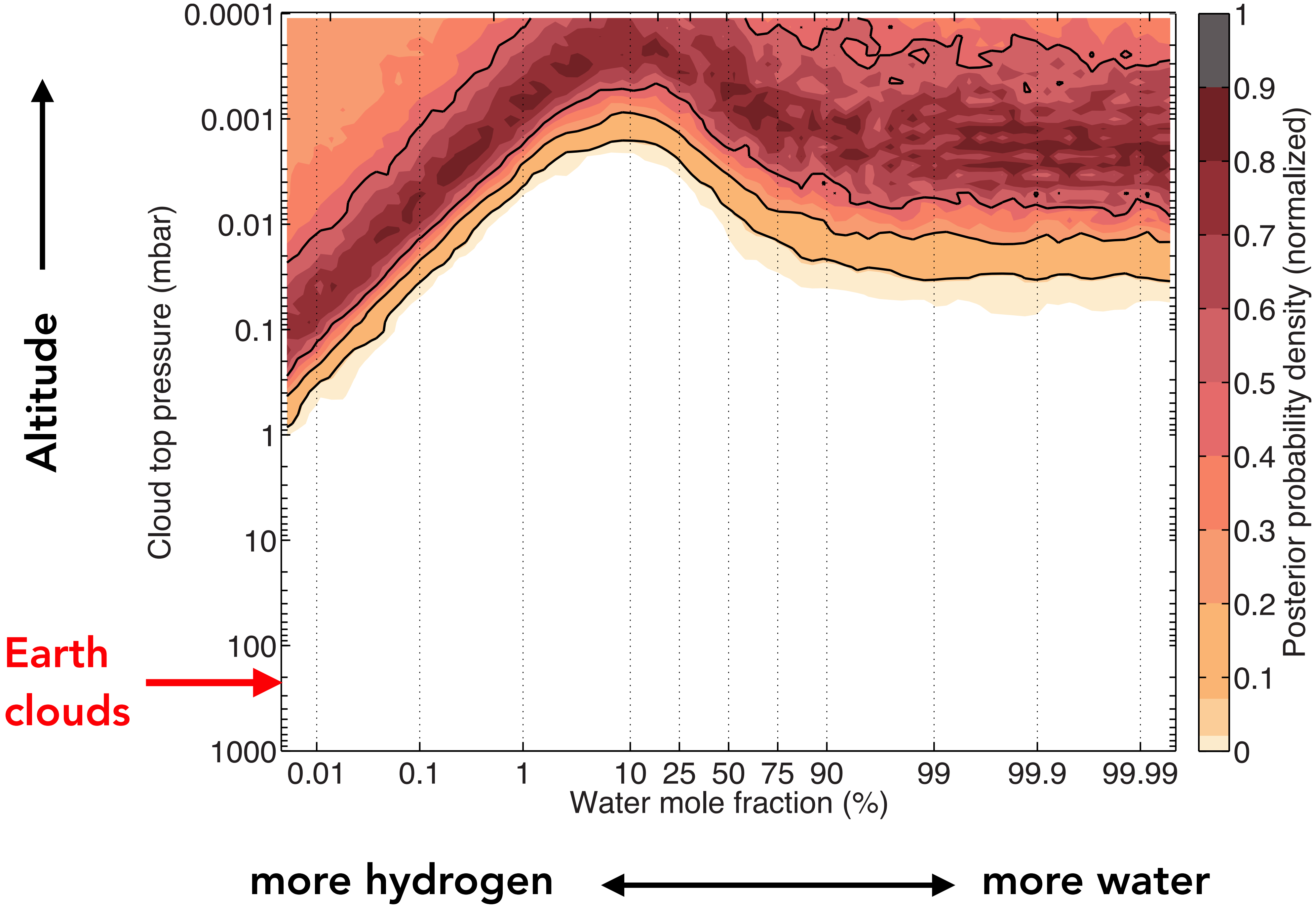
Kreidberg + 2014 (Nature)

15 transit observations with Hubble reveal a featureless spectrum —> clouds or haze **must** be present in the atmosphere

Cloud deck pressure is 0.1 mbar or lower

Possibly made of salts/sulfides, photochemical soots

Kreidberg + 2014 (Nature)



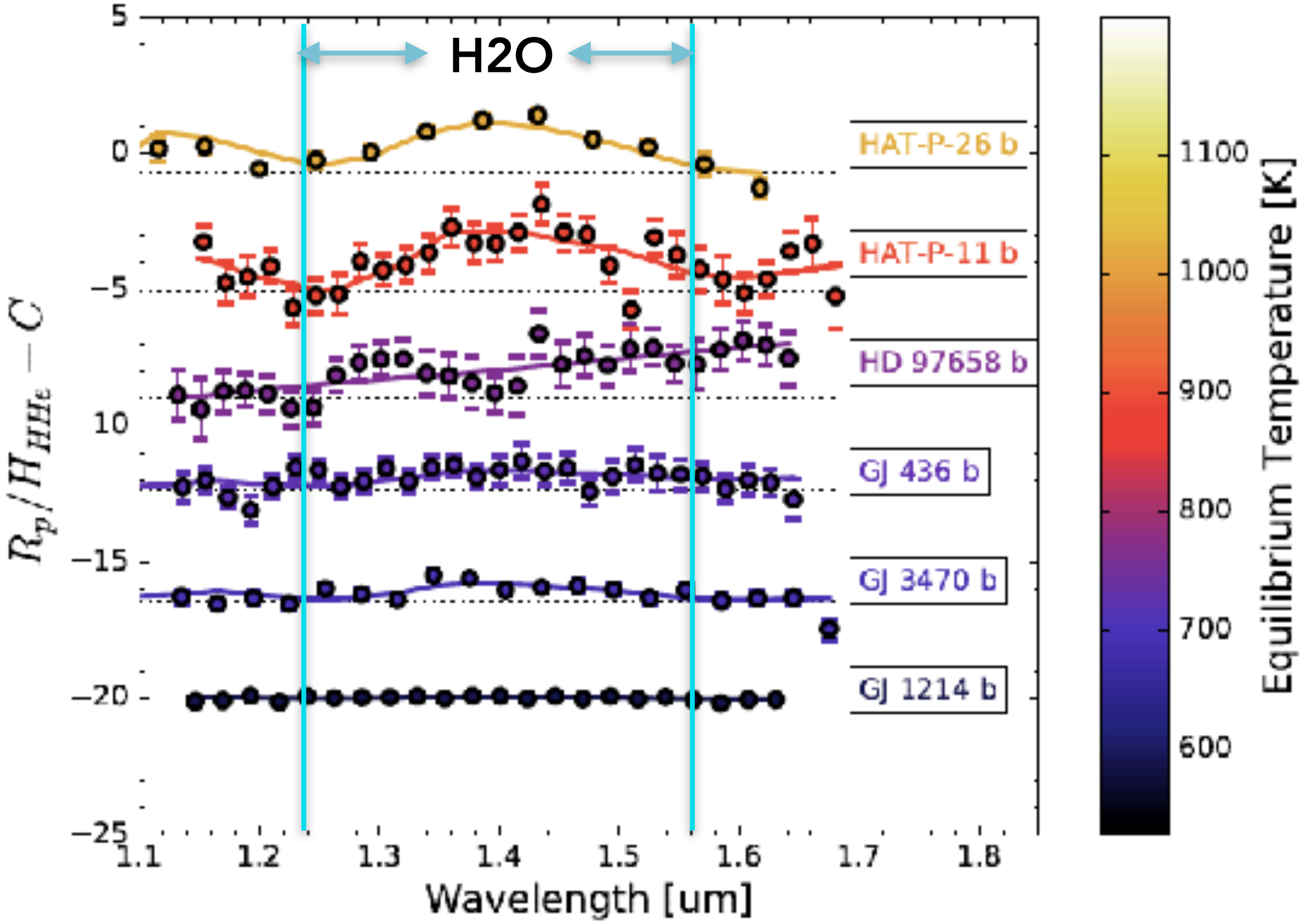
What colour is GJ 1214b?

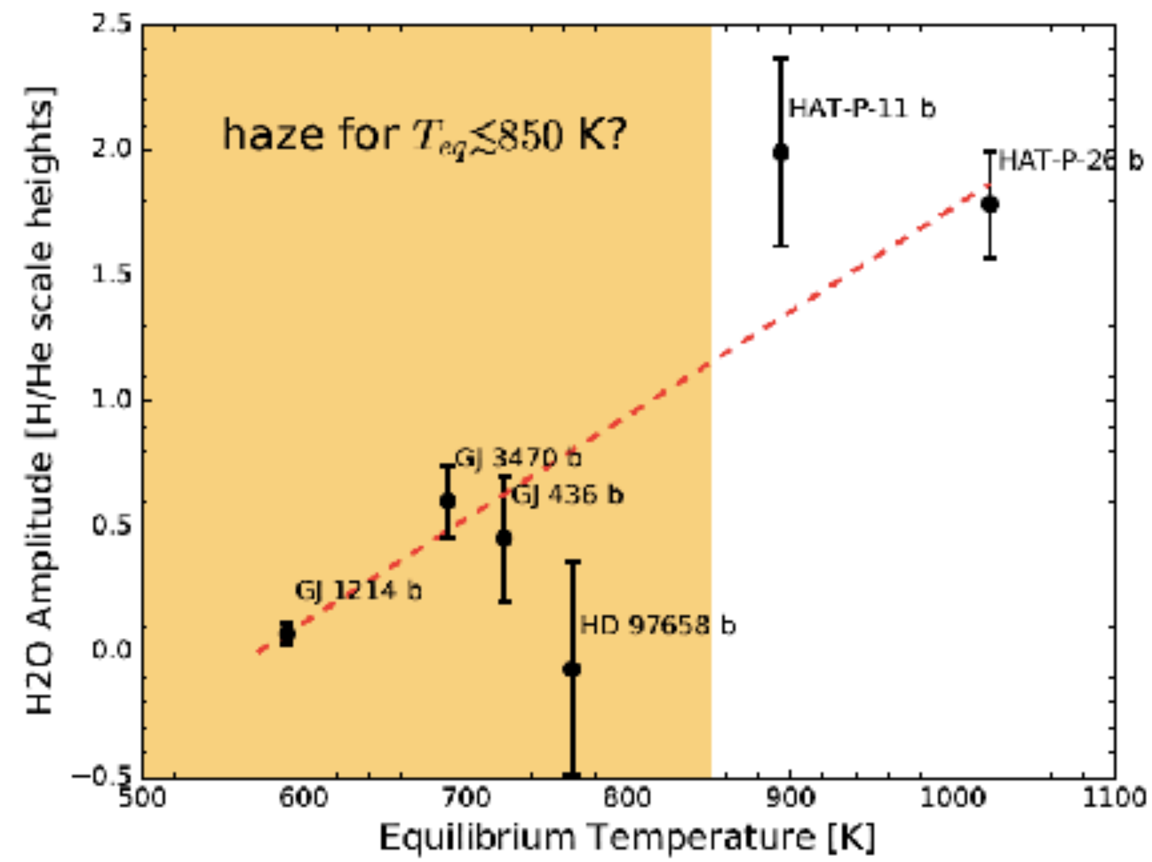
Model spectra convolved with the human eye response

Charnay et al. 2015

Not ALL Neptini have insurmountable clouds

Crossfield & Kreidberg 2017,
Libby-Roberts et al. 2019

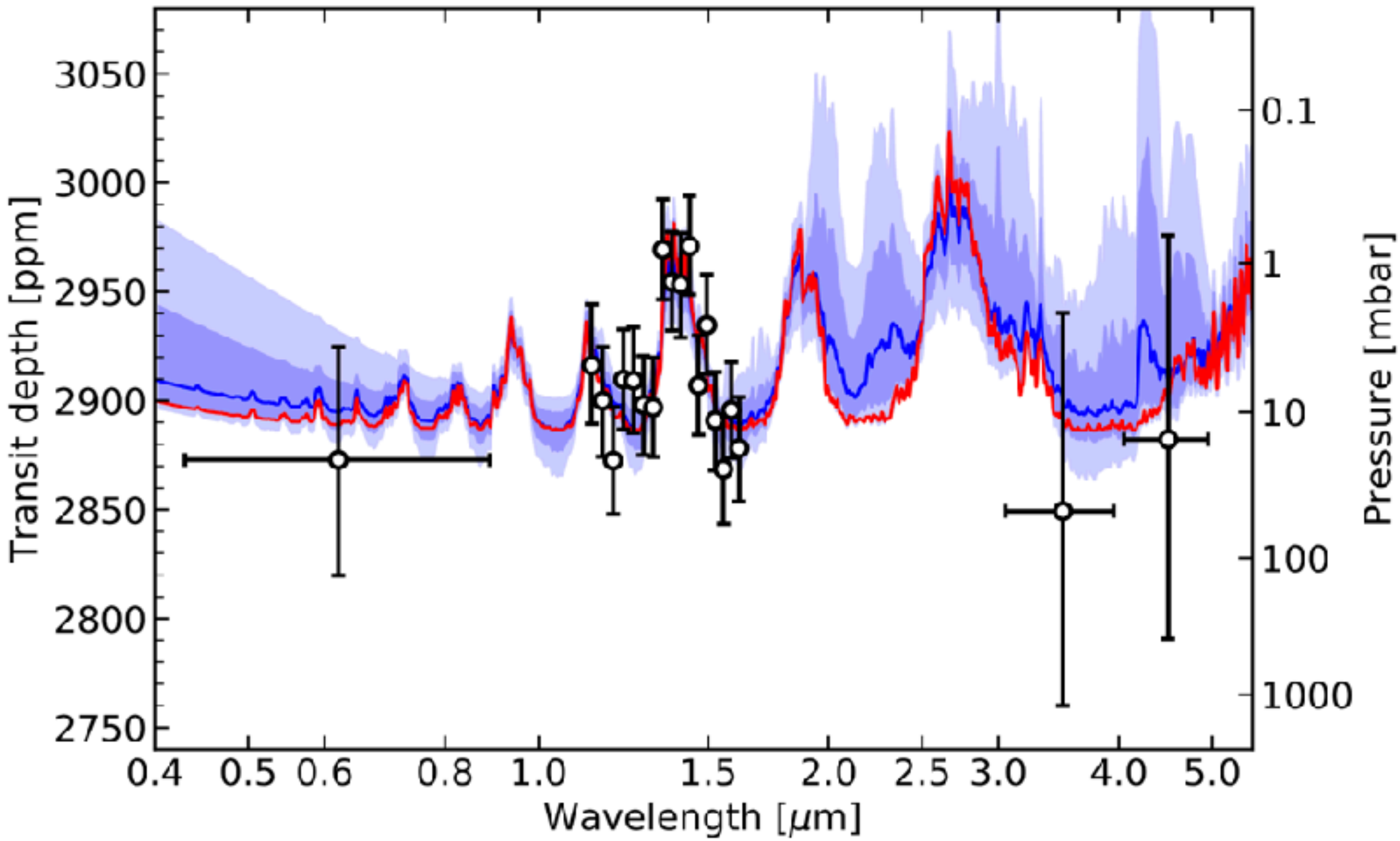




Tentative trend showing that hotter planets have clearer atmospheres with larger amplitude H2O features

Are the coolest atmospheres are free of clouds/haze?

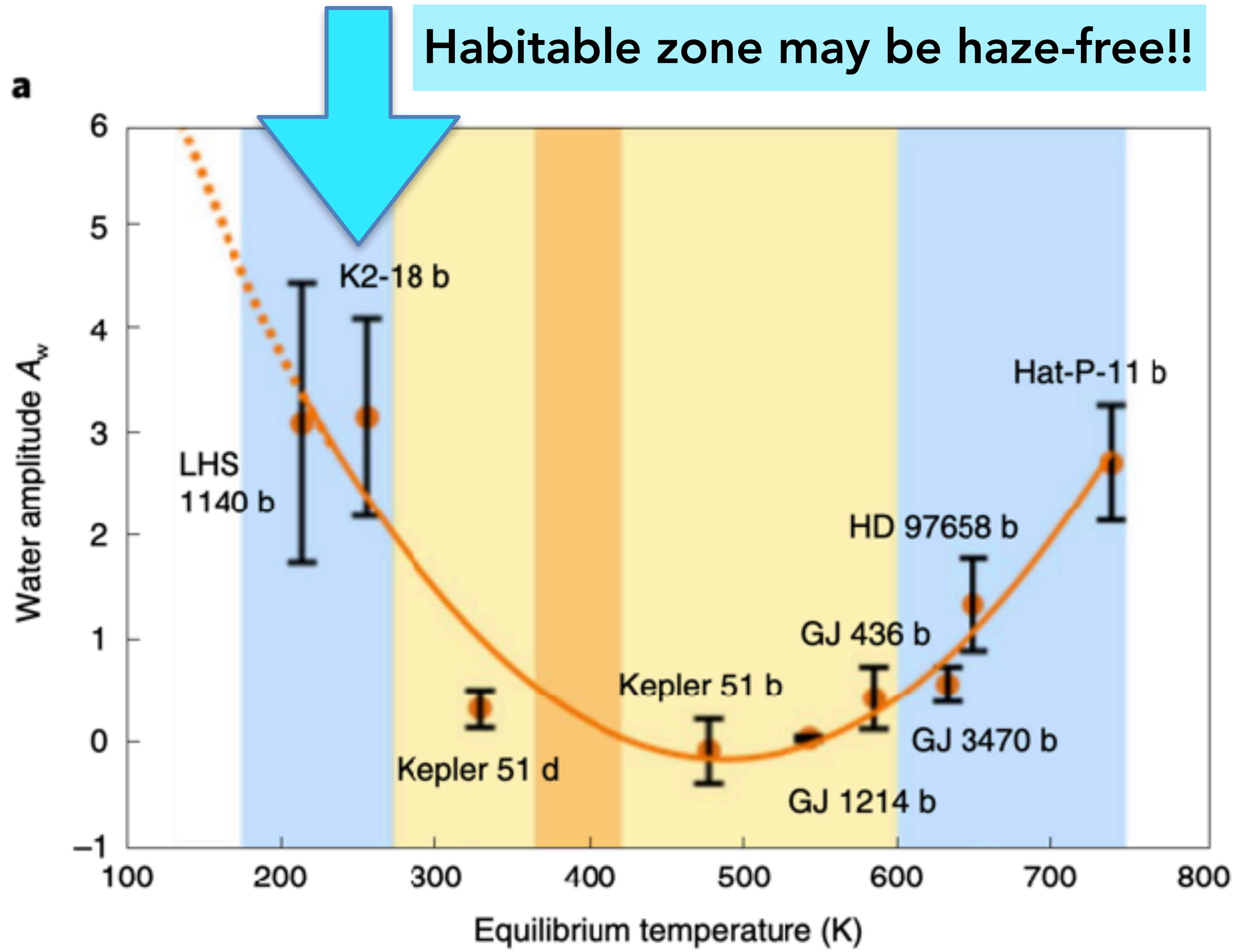
Large spectral features for the habitable zone sub-Neptune K2-18b**



Benneke et al. 2019, Tsiaras et al. 2019
(**see also Barclay et al. 2021!!)

Lab data can explain haziness trends

Experimental hazes have lowest surface energies near 400 K



High surface energy particles grow and rain out, low surface energy particles linger in upper atmosphere

Yu et al. 2021
Nature Astronomy

What can we learn from Earth cousins?
2. Hot rocky planets

Mercury ✗
(1e-15 bar)

Venus ✓
(100 bar)

Earth ✓
(1 bar)

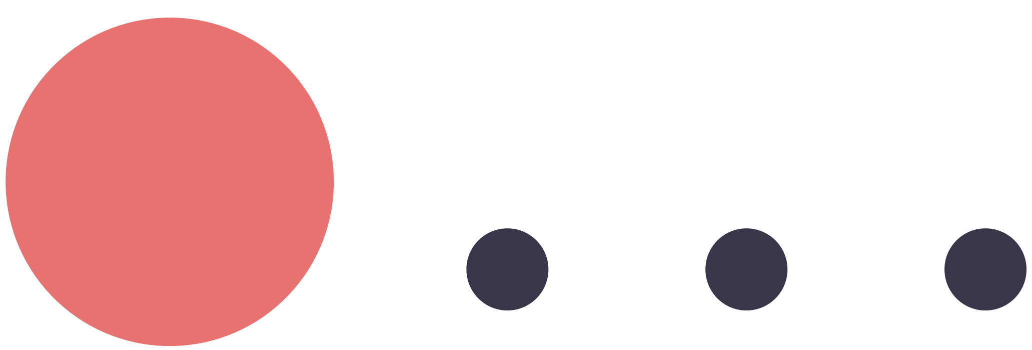
Mars ✗
(0.1 bar)

Can atmospheres survive on rocky planets around small stars?

The most numerous terrestrial planets in the Galaxy orbit small stars — Dressing & Charbonneau 2015

M-dwarf planets are easy to characterize thanks to their small host stars

But their atmospheres are endangered by photoevaporation and collapse!
— Wordsworth 2015, Luger & Barnes 2015, Bolmont et al. 2017

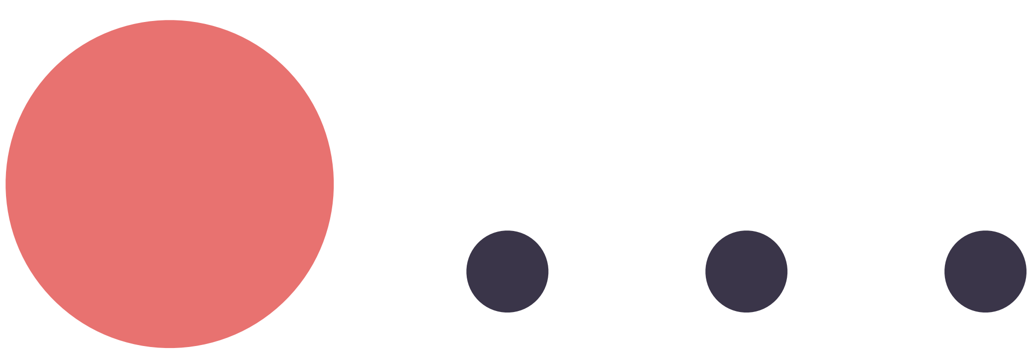


Current observations provide limits on composition

For several known terrestrial planets,

transmission spectroscopy rules out cloud-free, hydrogen-rich atmospheres

TRAPPIST-1b,c,d,e,f — de Wit et al. 2016, 2018
GJ 1132b — Diamond-Lowe et al. 2018



Current observations provide limits on composition

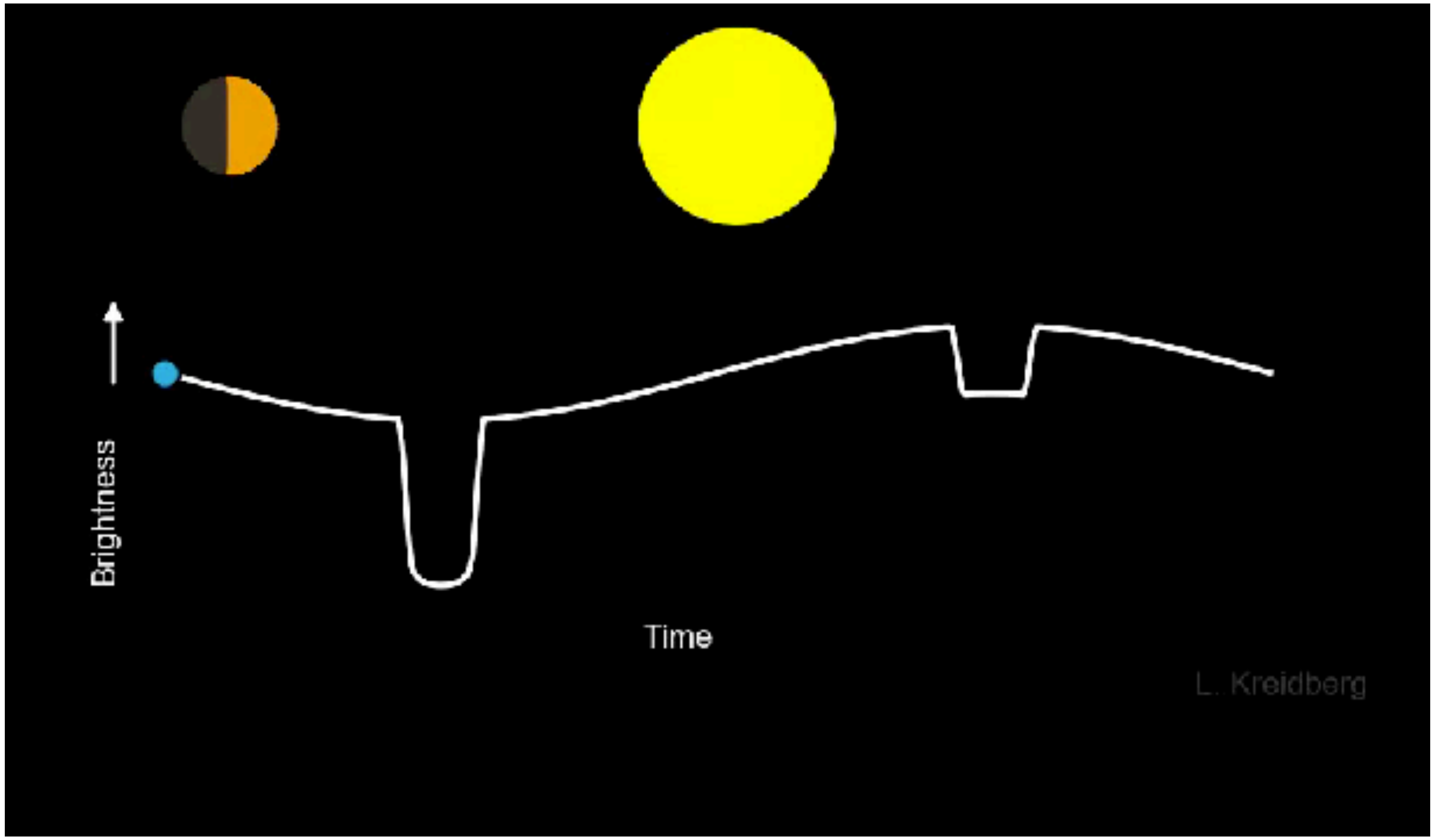
For several known terrestrial planets,

transmission spectroscopy rules out cloud-free, hydrogen-rich atmospheres

… but high mean molecular weight / cloudy compositions are still possible (or no atmosphere at all)

So how can we tell if an atmosphere is present?

Thermal phase curves to the rescue!



IDEA: thin atmospheres are bad at circulating heat.

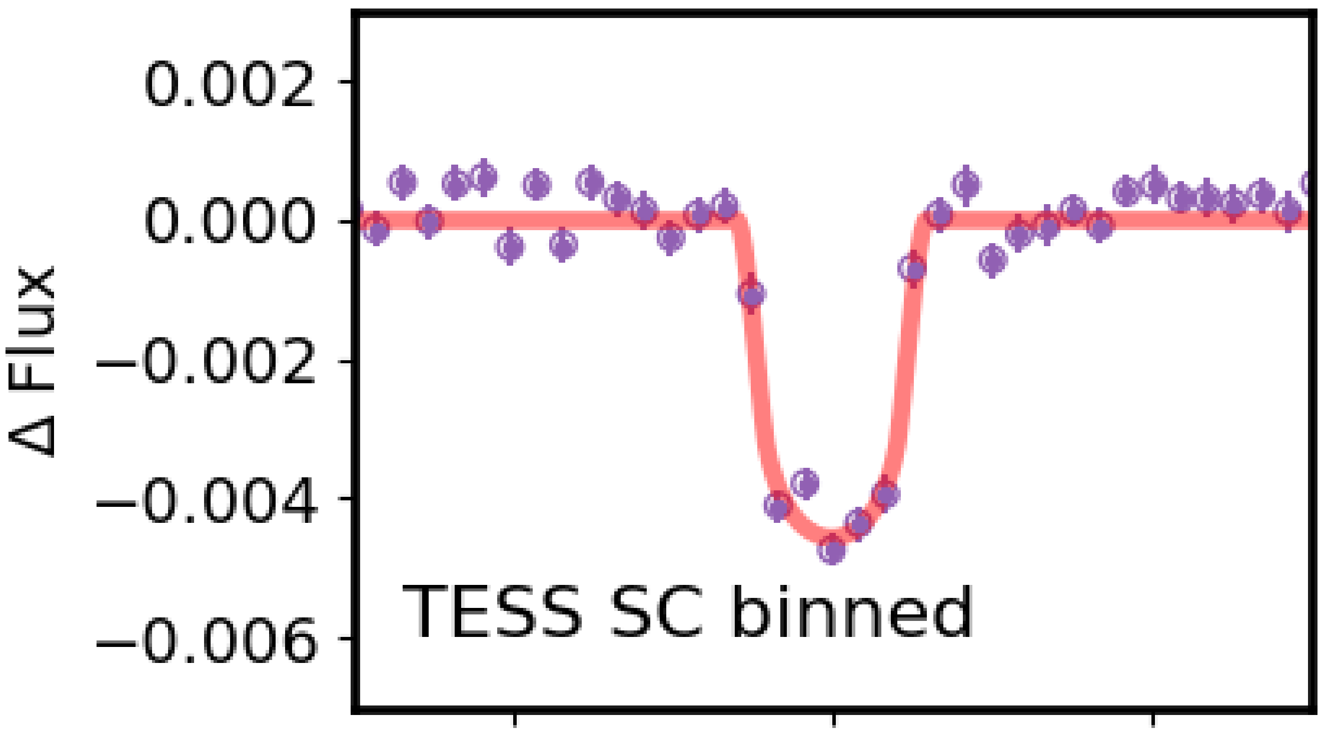
Large phase variation —> large temperature variation —> thin atmosphere.

(Seager & Deming 2009, Selsis et al. 2011, Koll & Abott 2015, Kreidberg & Loeb 2016)

TESS discovery LHS 3844b is the first terrestrial exoplanet accessible for phase curve observations

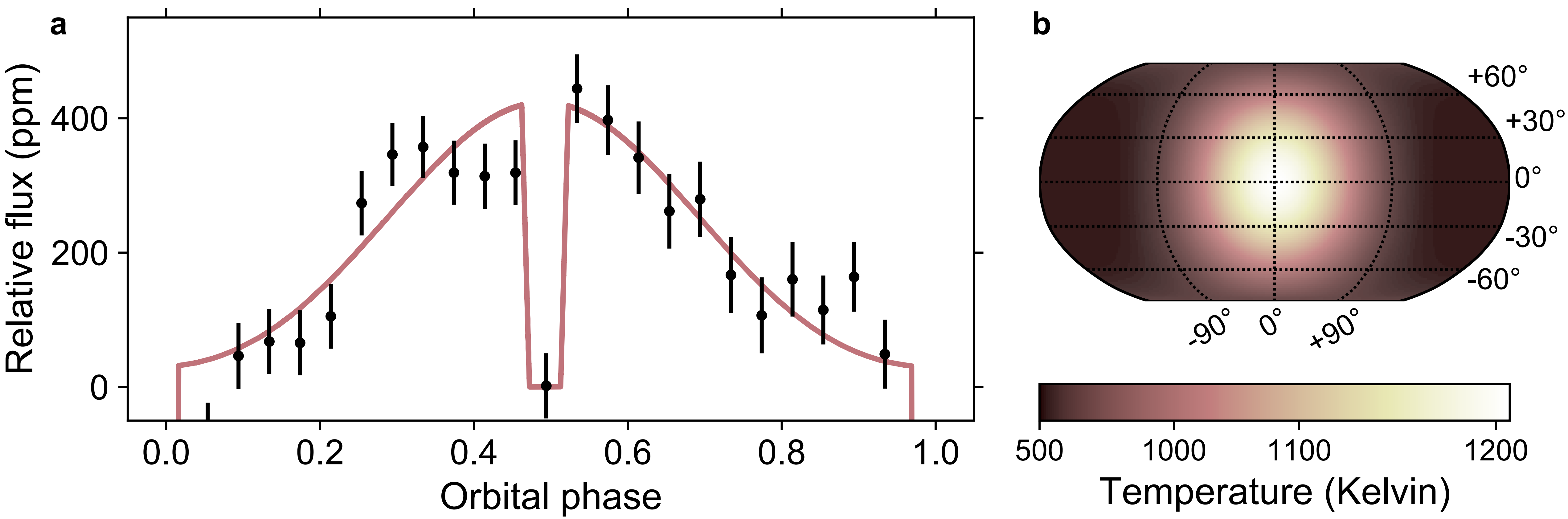
- Rp = 1.3 Re
- P = 11 hours
- Teq = 1000 K

- R* = 0.2 Rs
- D = 15 parsecs



Vanderspek et al. 2019

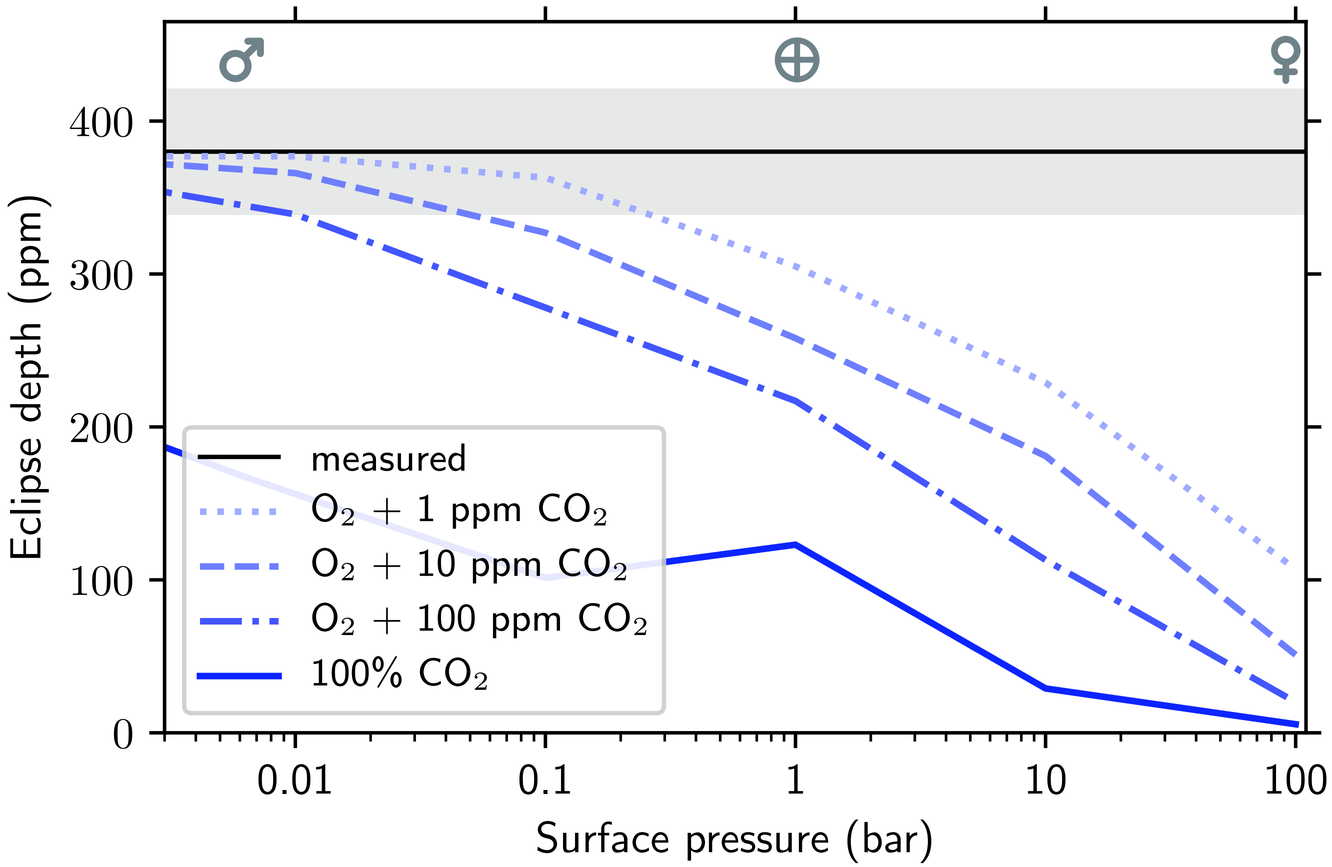
Ta da!



- T_day = 1080 +/- 40 K
- T_night is consistent with 0 K
- No hotspot offset

Kreidberg et al. 2019, Nature

Could LHS 3844b have an atmosphere?



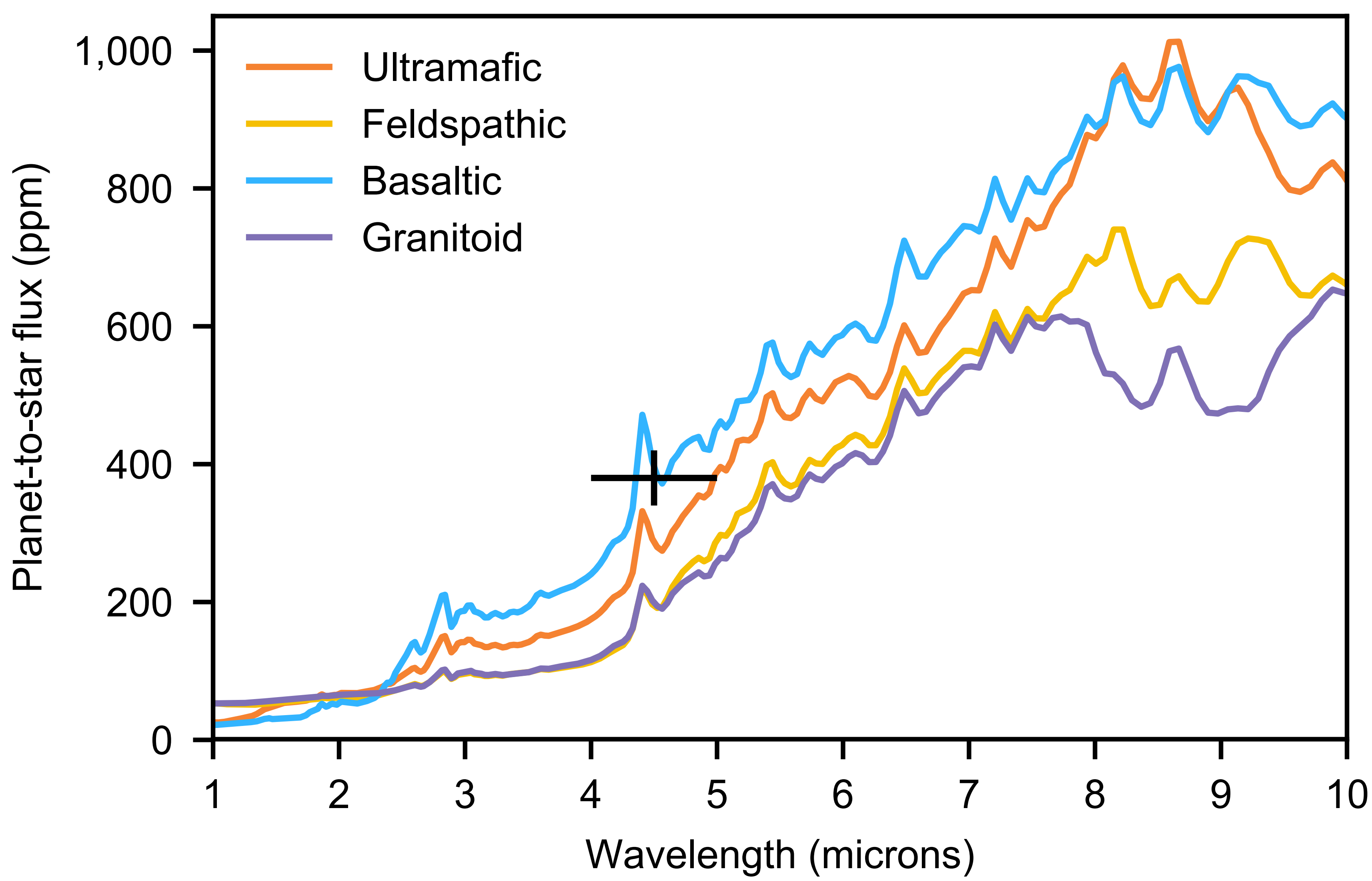
LHS 3844b eclipse depth

model atmospheres from **Daniel Koll & Caroline Morley**; analytic climate map + 1D radiative transfer

- Surface pressures > 10 bars are ruled out at 3 sigma
- Less massive atmospheres are unstable to erosion by stellar wind

Kreidberg et al. 2019, Nature

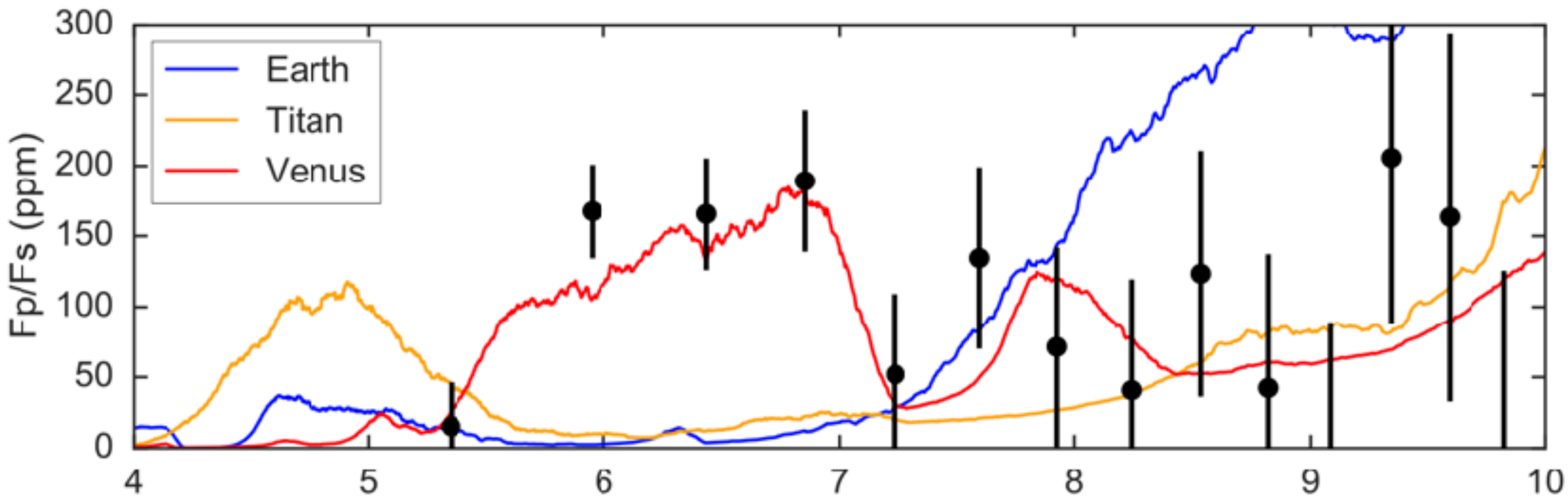
This is the *first time* we have seen thermal emission from the bare surface of a rocky exoplanet. What kind of rock is it?



Kreidberg et al. 2019, Nature

Best fit compositions are basaltic, similar to the lunar mare and Mercury

Upcoming JWST observations will explore the diversity of rocky planet atmospheres (around M-dwarfs)



Wavelength (microns)

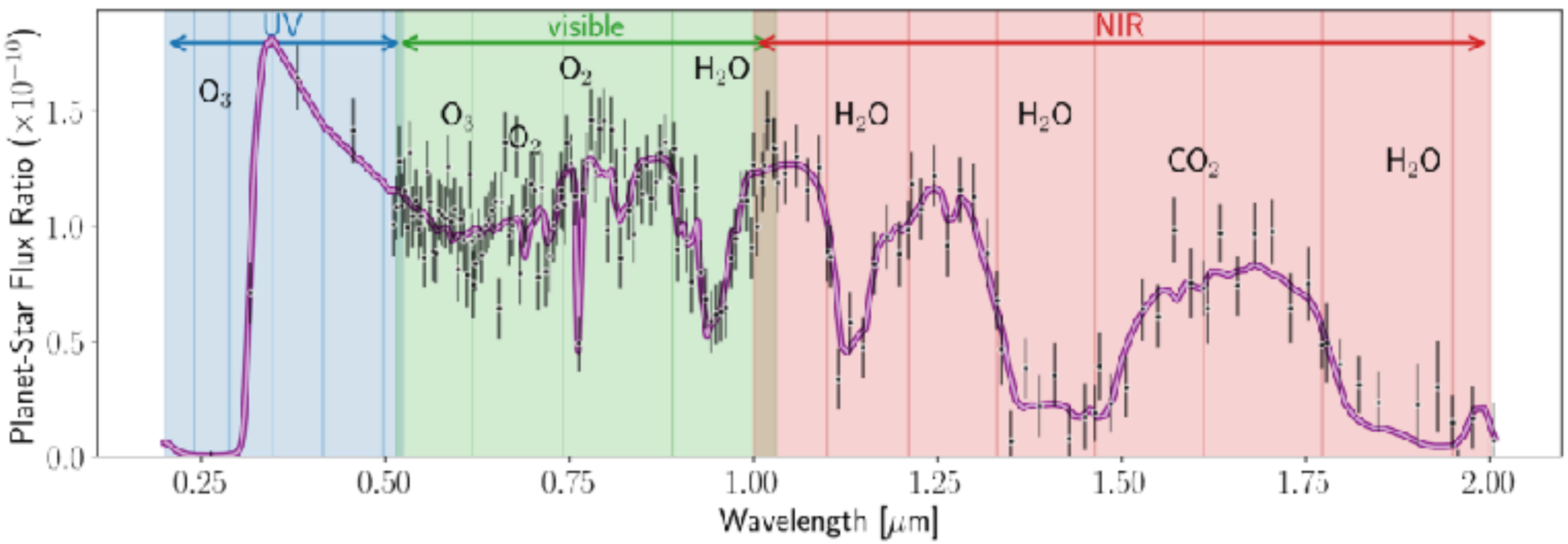
Morley et al. 2017

- >10 hot rocky planets are scheduled to be observed during JWST Cycle 1
- If atmospheres are present, we will be able to detect spectral features from the dominant chemical species.

What about true Earth twins?
We need a next generation space telescope

The smoking gun evidence for life on Earth is disequilibrium chemistry — the simultaneous presence of oxygen and methane

Atmosphere characterisation for rocky planets with Sun-like host stars requires a new telescope; Mission concepts include LUVOIR, HABEx, & LIFE



Simulated LUVOIR ECLIPS spectrum of an Earth twin