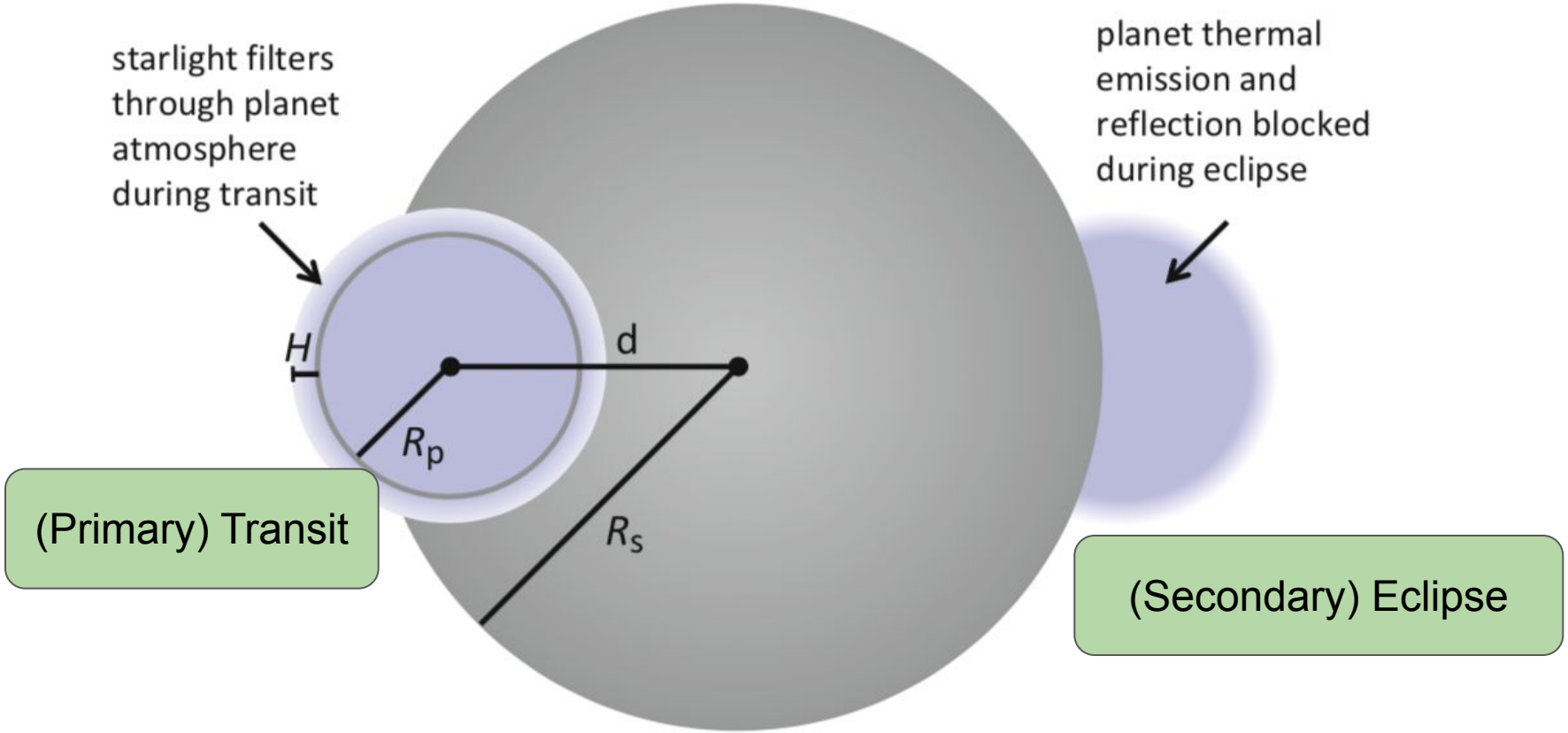
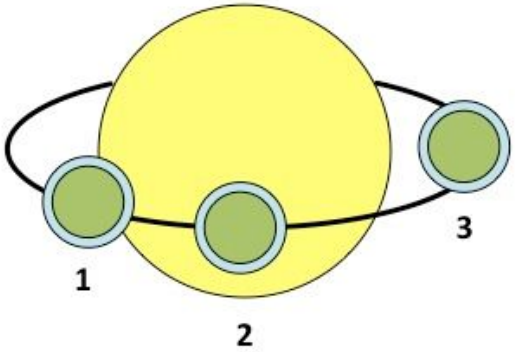
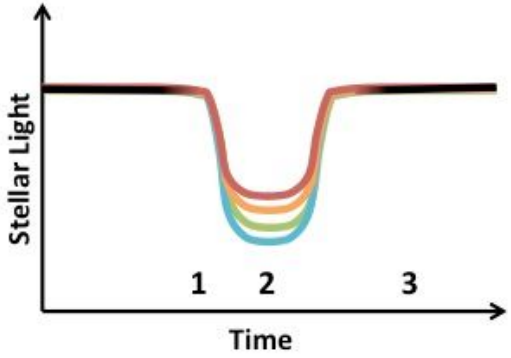

Observing
Exoplanet
Atmospheres

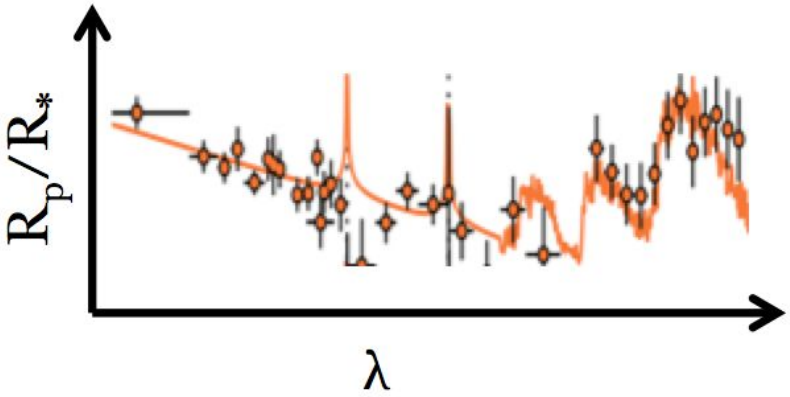
How do we measure atmospheres?



How do we measure atmospheres?

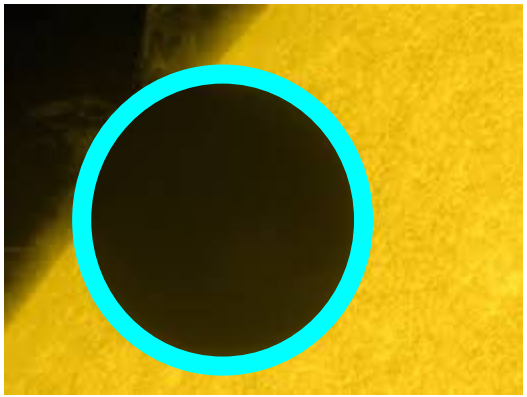






Transit is **larger** at some wavelengths: ones at which the planet absorbs/ scatters more light

How do we measure atmospheres?



How much extra area is blocked by the atmosphere?

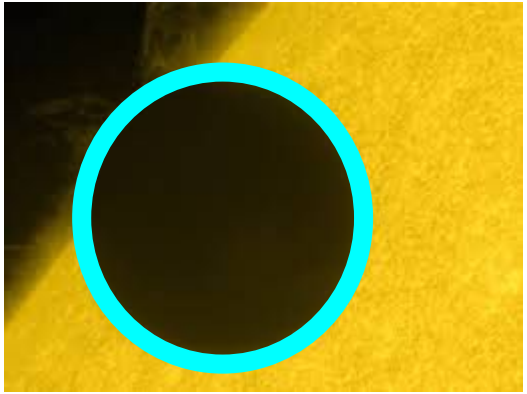
Let's derive it!

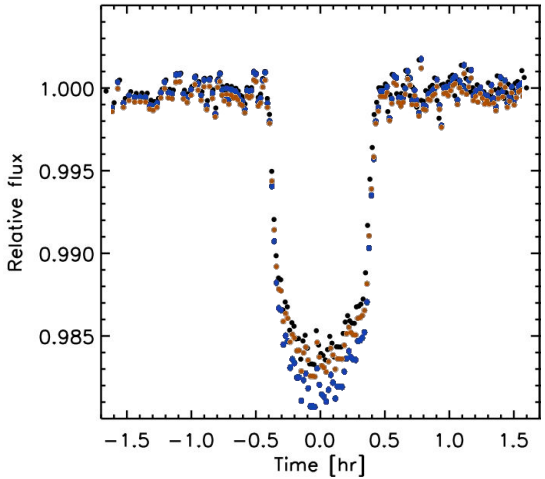
$$\frac{(R_p + H)^2 - R_p^2}{R_s^2} = \frac{R_p^2 + 2R_pH + H^2 - R_p^2}{R_s^2}$$

$$= \frac{2R_pH + H^2}{R_s^2} \approx \frac{2R_pH}{R_s^2}$$

$$H^2 \ll 2R_pH$$

How do we measure atmospheres?





What size features do we expect for hot Jupiters?

$$\text{signal} \sim \frac{2R_p H}{R_s^2} \qquad H = \frac{kT}{\mu_m m_H g}$$

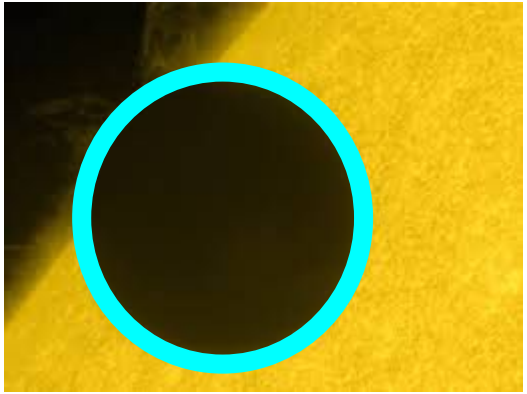
How can we improve the signal when selecting targets?

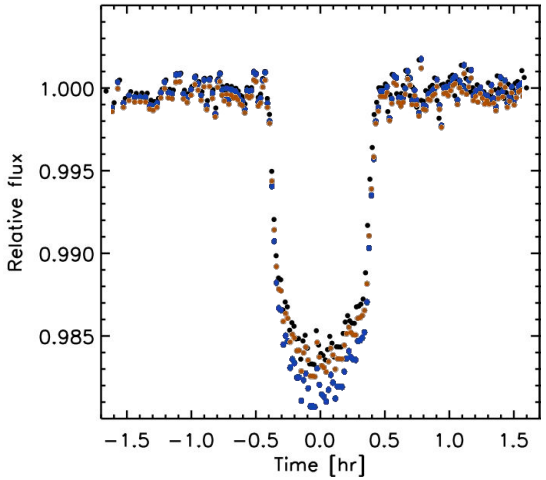
1. Smaller star ➡ M-dwarfs can have 0.2 R_{sun}
2. Low mean molecular weight ➡ H/He atmospheres
3. High temperature / low gravity

What type of exoplanet is ideal for characterisation?

- Hot Jupiters!

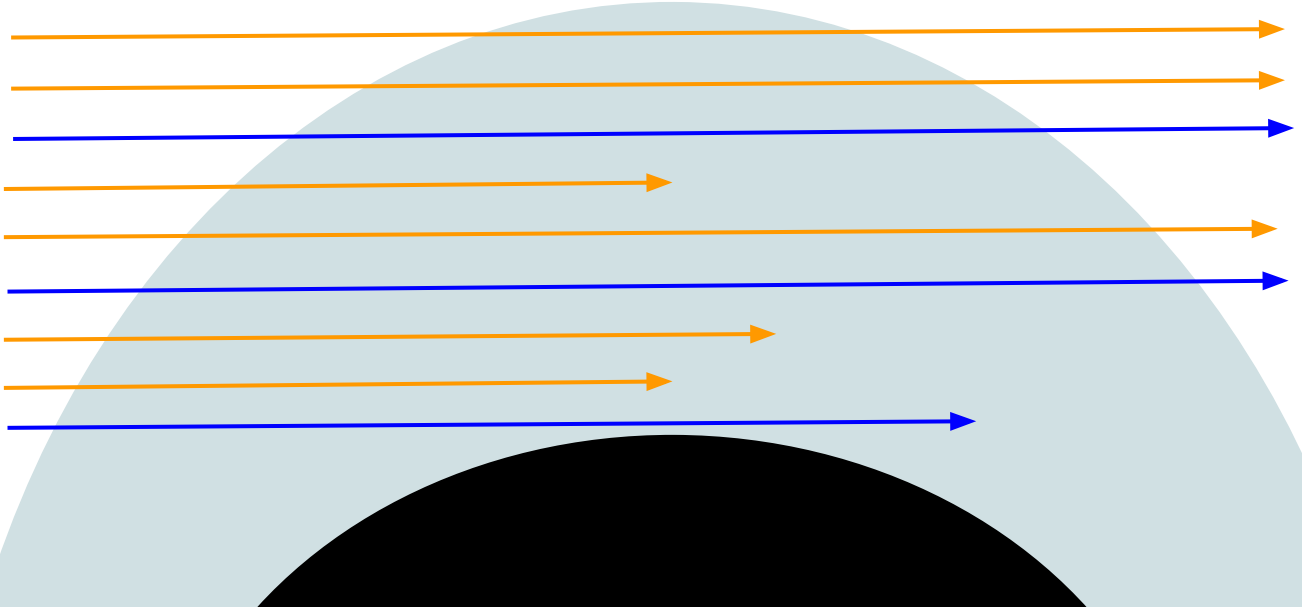
How do we measure atmospheres?





During transit, parts of the light goes through the atmosphere and is **partially** blocked.

These differences can be used to generate a spectra:



Small Exercise

What size features do we expect to see?

$$\text{signal} \sim \frac{2R_pH}{R_s^2}$$

R_S = 700,000 km

- Earth around Sun? Around an M-dwarf (0.2 R_S)?

H_E = 8.5 km
R_E = 6,400 km

Around Sun = 0.22 ppm
Around M dwarf = 5.6 ppm

- Hot Jupiter around a Sun like star? Around an M-dwarf?

H > 200 km
R_J = 70,000 km

Around Sun = 57 ppm
Around M dwarf = 1429 ppm

Small Exercise

What size features do we expect to see?

$$\text{signal} \sim \frac{2R_pH}{R_s^2}$$

R_S = 700,000 km

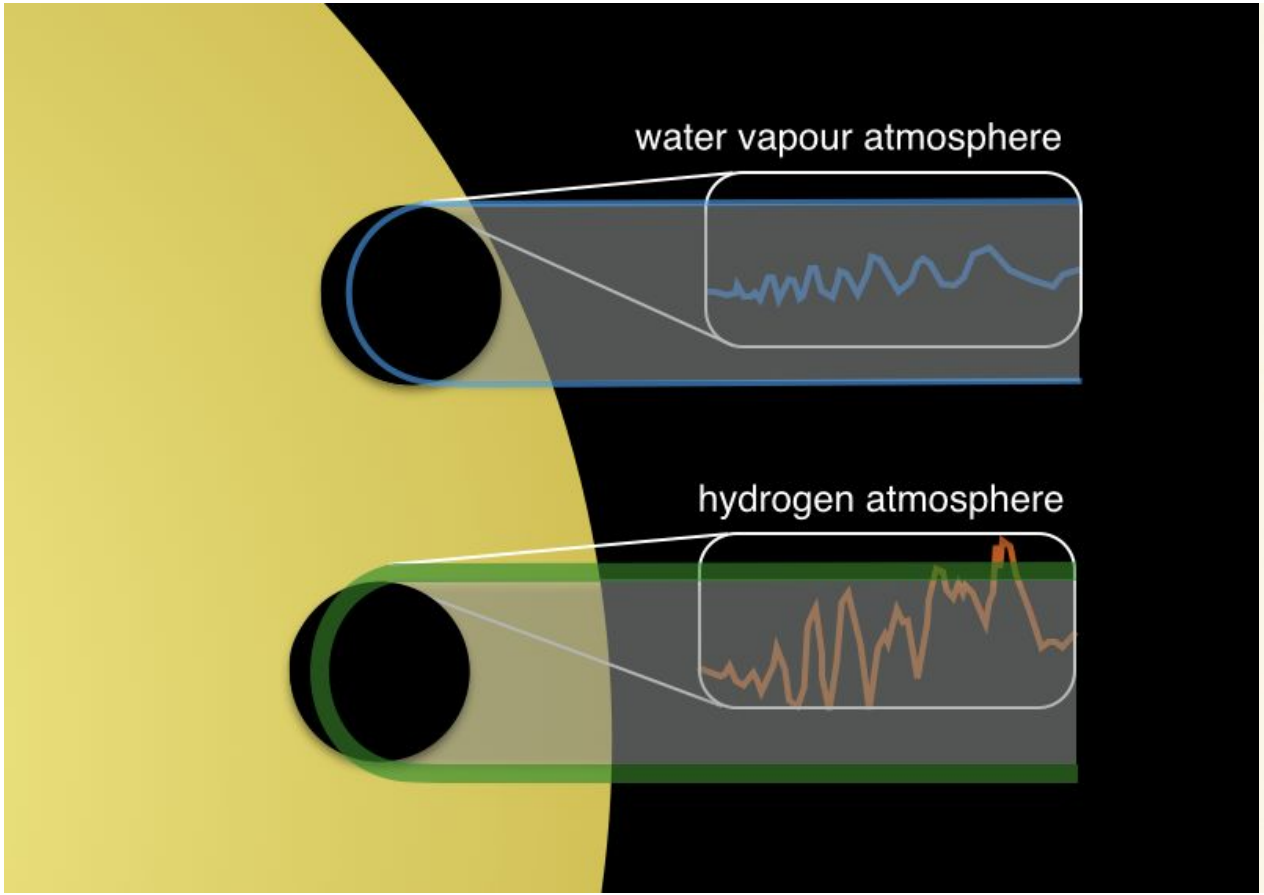
- Ea
- Hc

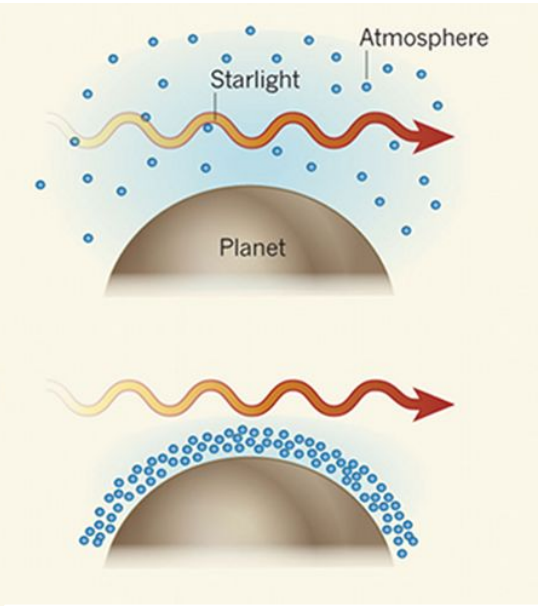
Take Away:
Hydrogen atmospheres are much easier to observe than higher mean molecular weight atmospheres

H > 200 km
R_J = 70,000 km

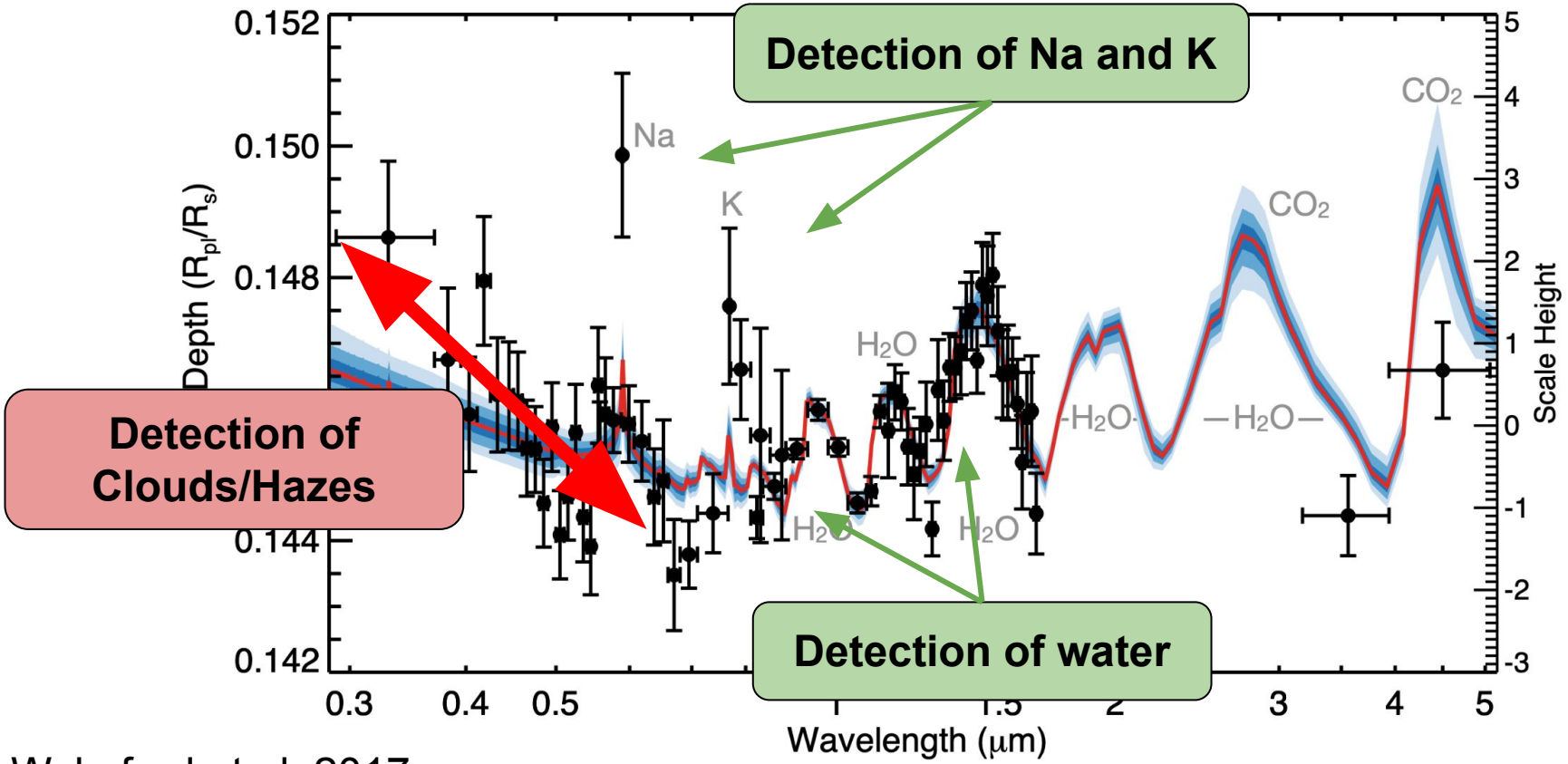
Around Sun = 37 ppm
Around M dwarf = 1429 ppm

How do we measure atmospheres?





State of the art: 2015 - 2020



Wakeford et al. 2017

What do we do with spectra like this?

Giant planets: all H/He-dominated, but with different amounts of “metals”

- measure compositions
- connect to planet formation
- understand how atmospheres work (clouds, chemistry, mixing, temperature structures)
- compare to our solar system

Sub-Neptune/super-Earth planets: in-between, a wide variety of bulk + atmosphere compositions possible

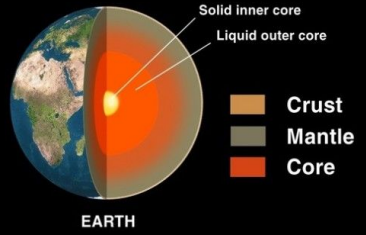
- measure bulk compositions
- understand how atmospheres work (clouds, chemistry, mixing, temperature structures)

Terrestrial planets: “secondary” atmospheres made of outgassed materials (water, CO2, etc.)

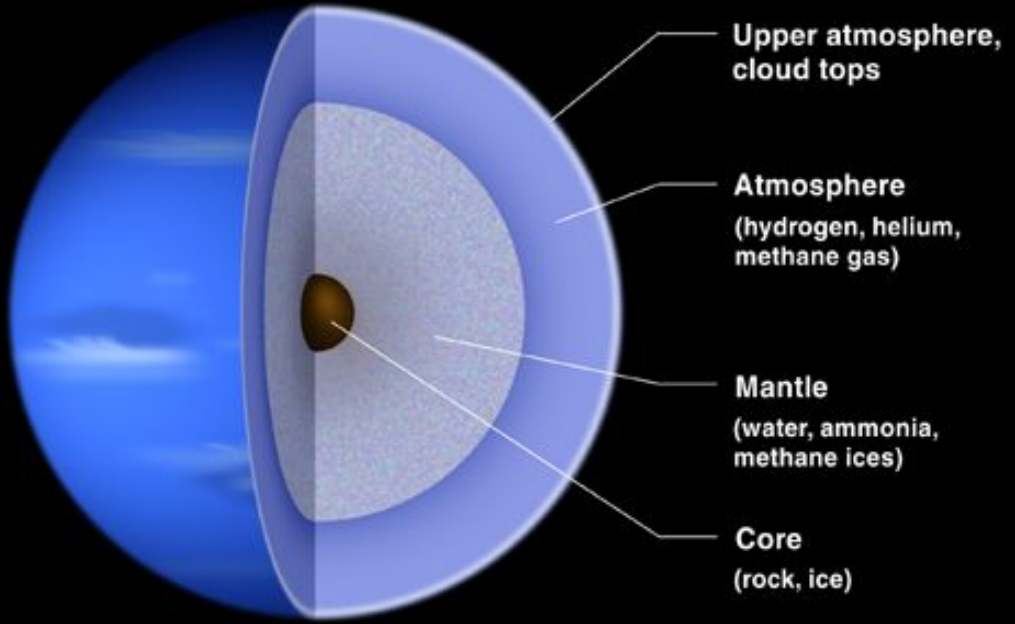
- measure bulk compositions
- compare to our solar system
- understand how volatiles are outgassed and potentially lost
- understand habitability, detect biosignatures

“Super-Earths” vs “Sub-Neptunes”

Key: Atmospheric Composition



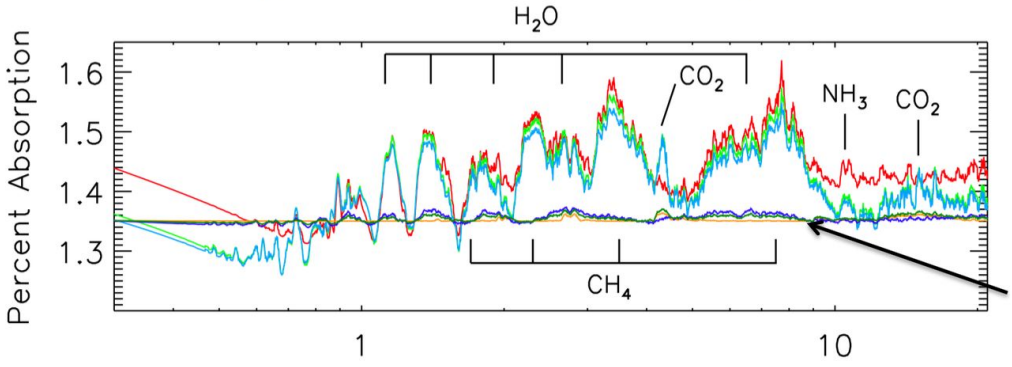
?



Mostly rocky with a H/He atmosphere?

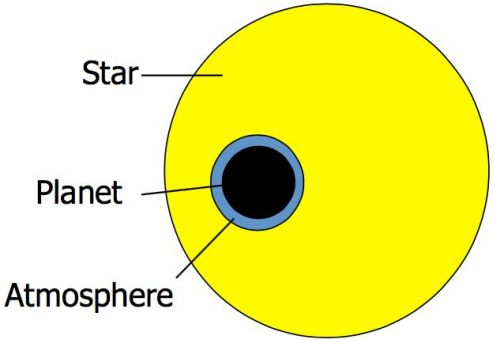
Mostly icy with a water-rich atmosphere?

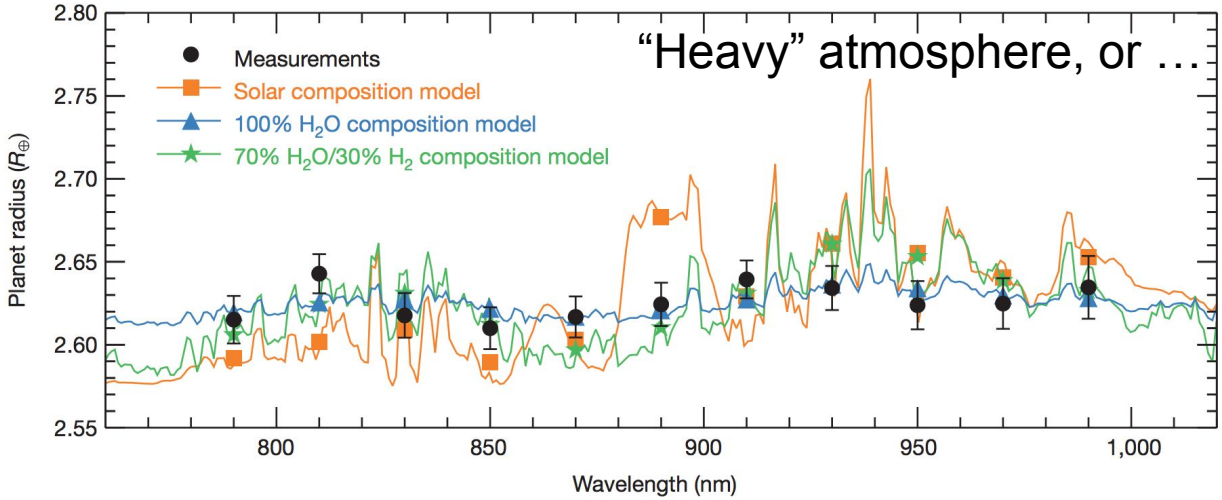
Transmission Spectroscopy of Super Earths



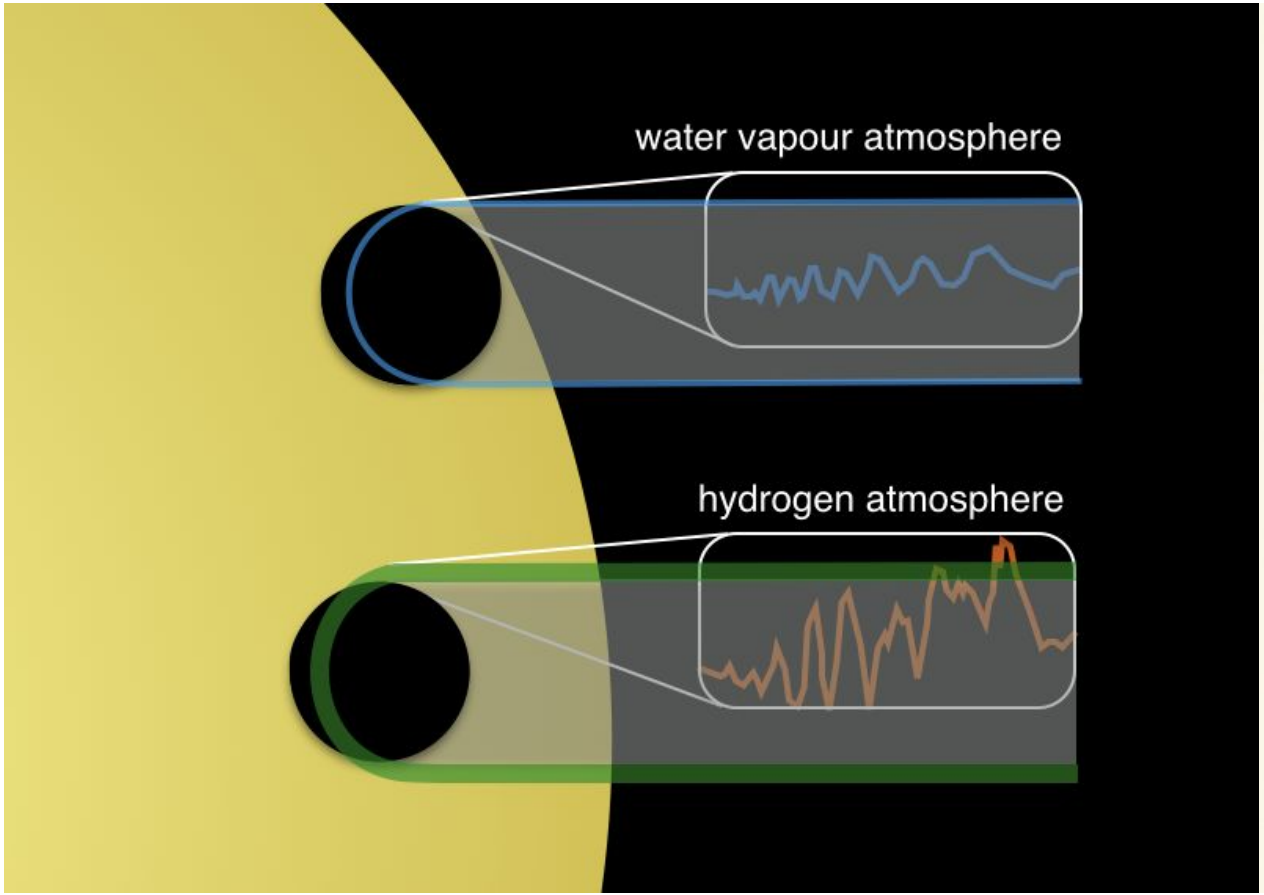
Compositions:
solar
30x solar
50x solar

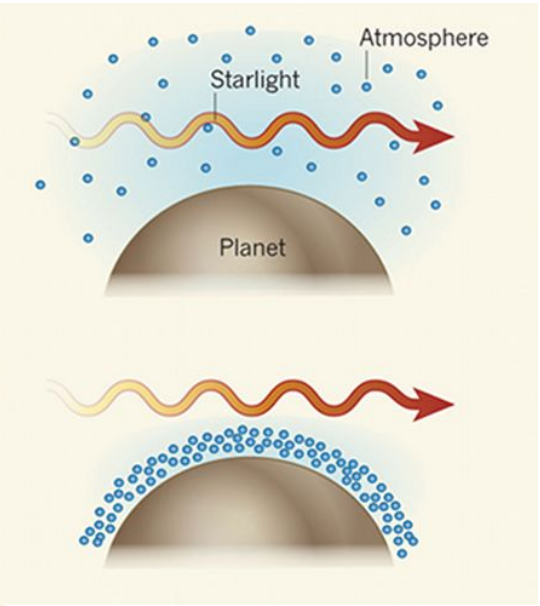
H_2O (steam)
50/50 H_2O, CO_2
CO_2 (Venus)



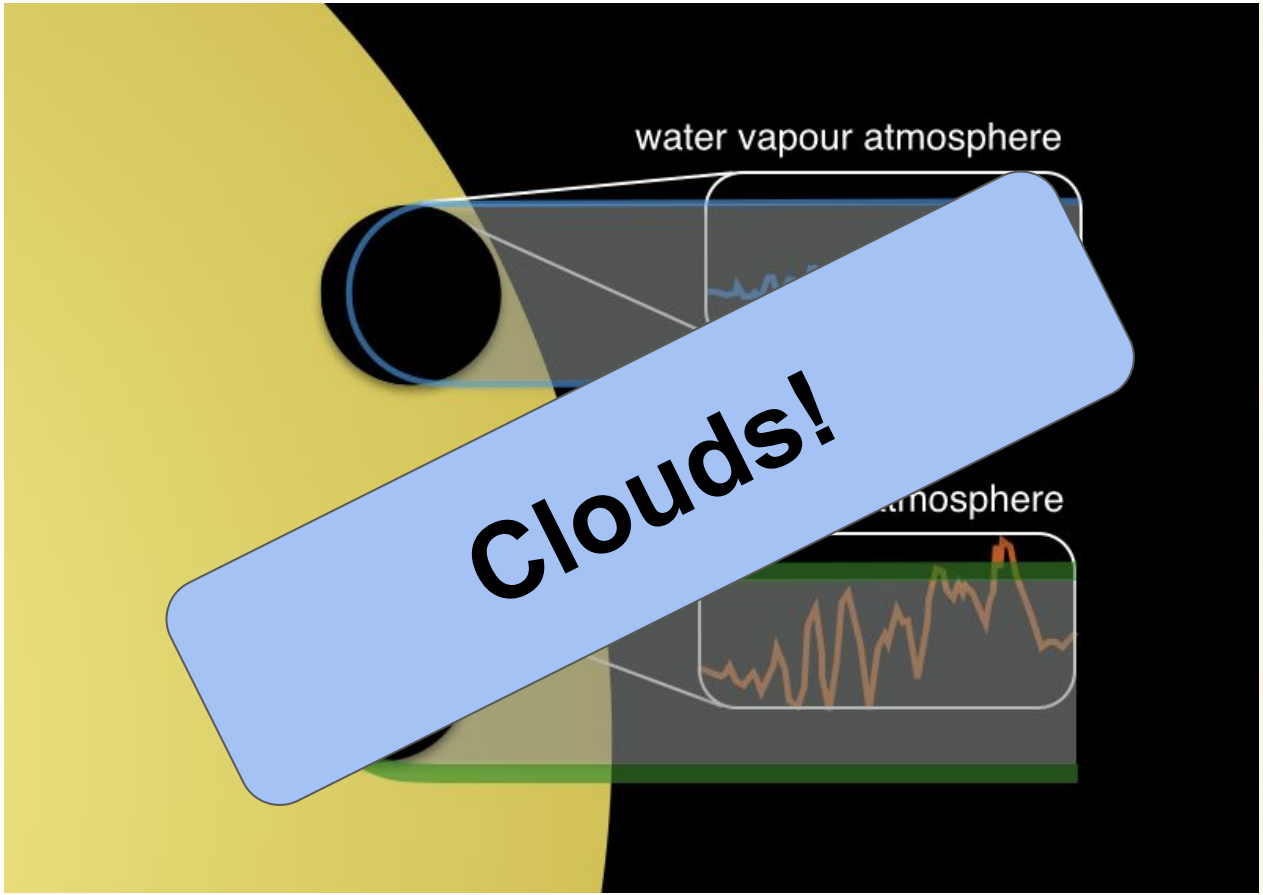


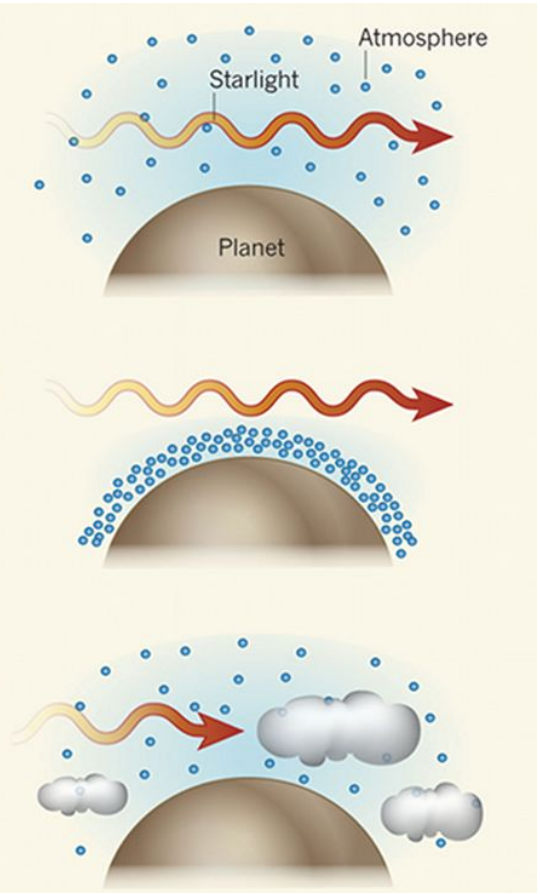
Transmission Spectroscopy of Sub Neptunes



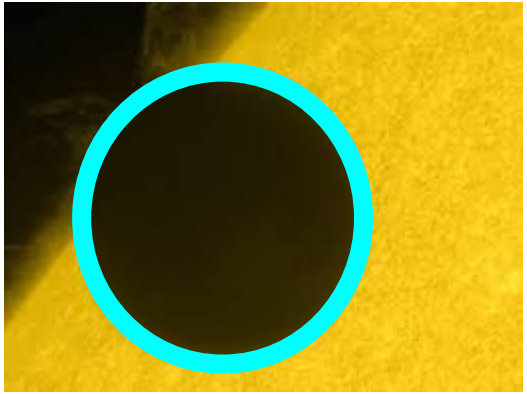


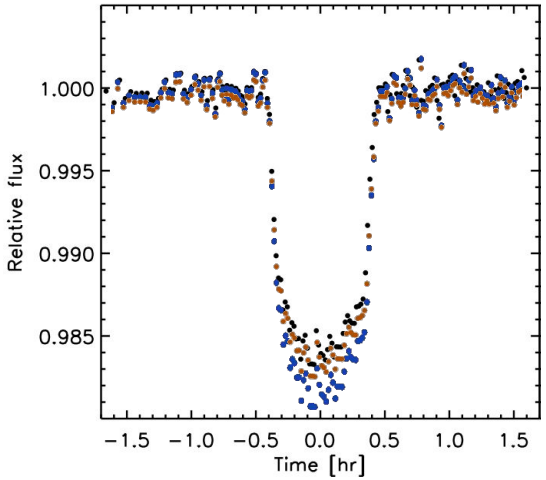
Transmission Spectroscopy of Sub Neptunes



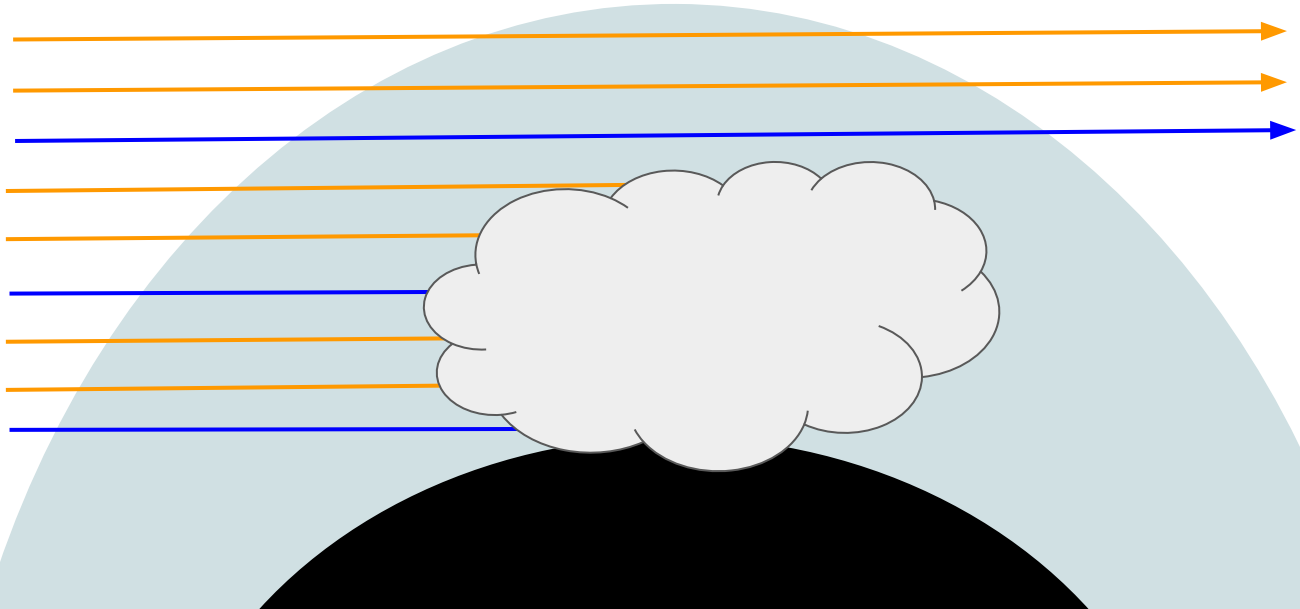


How do we measure atmospheres?



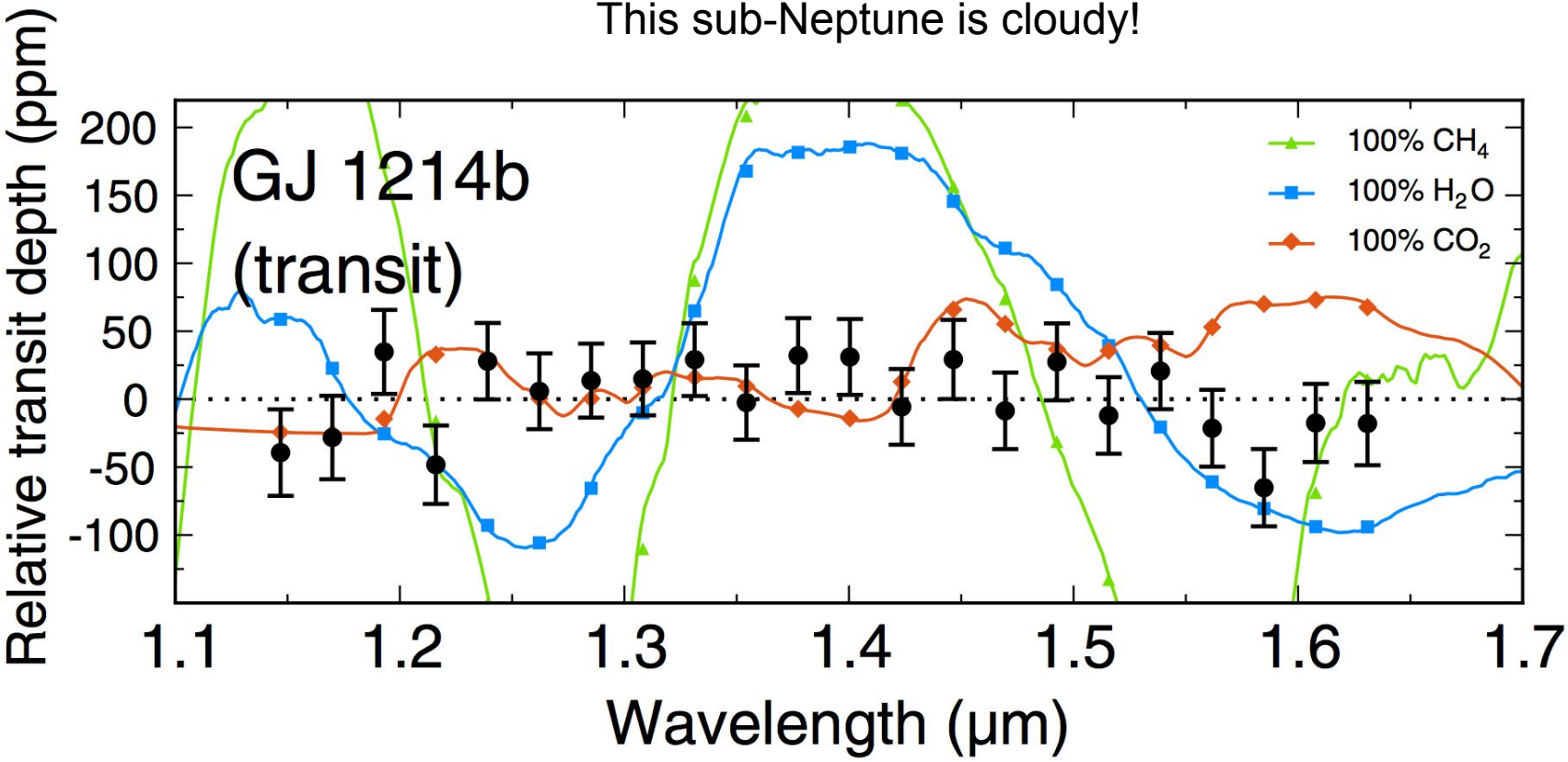


We can only observe above the clouds, effectively reducing the area of the atmosphere that we can probe.

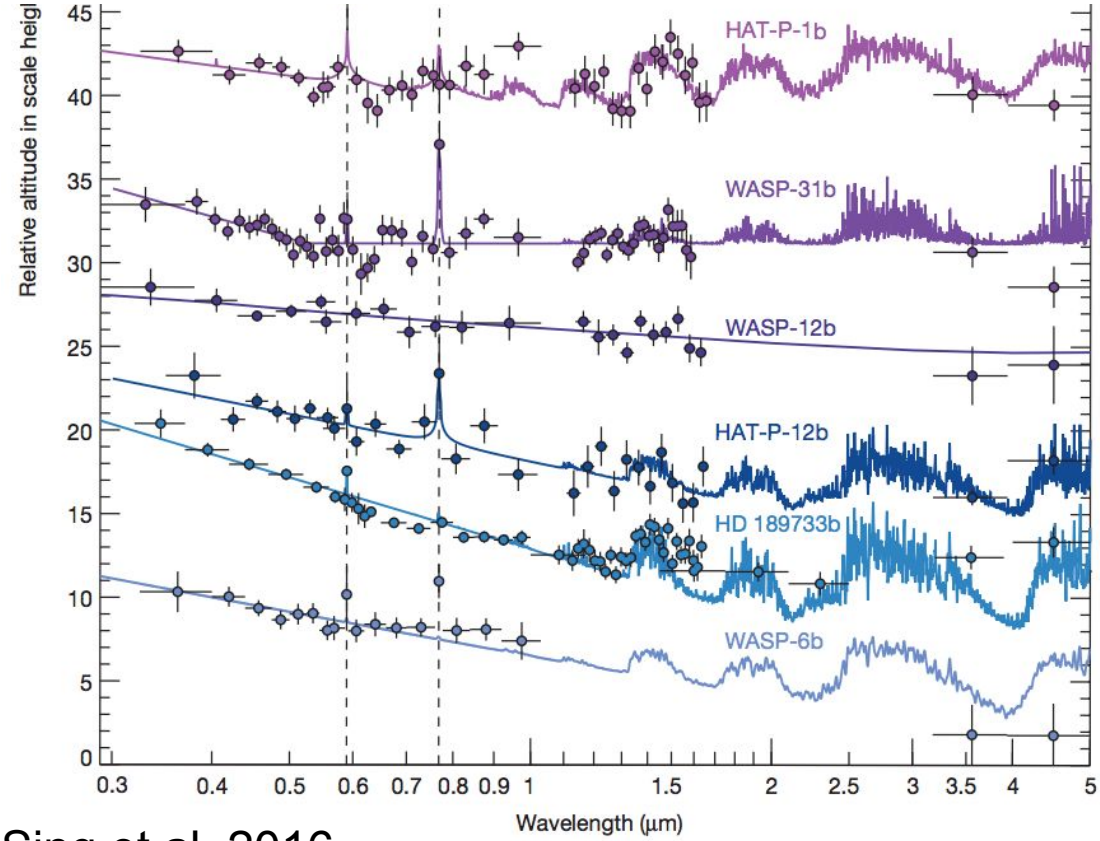


Transmission Spectroscopy of sub-Neptunes

This sub-Neptune is cloudy!



State of the art for hot Jupiters from 10 years ago



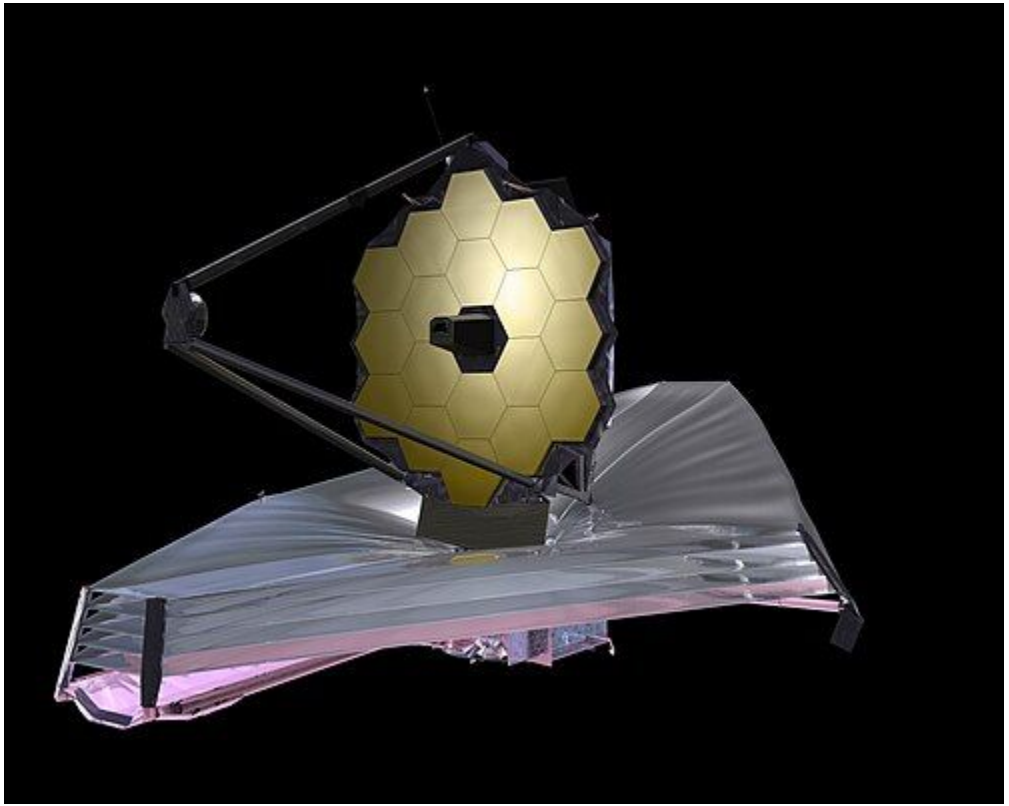
Sing et al. 2016

hot Jupiters are cloudy and hazy

lots of atoms/molecules, including water, sodium, potassium

Transmission spectra with JWST

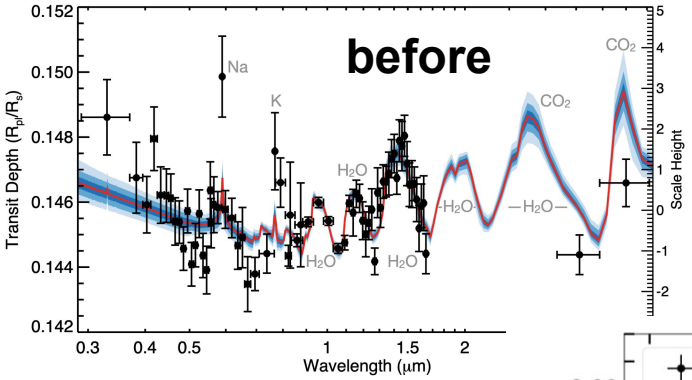
Highlights from ~5 years of JWST



What's exciting about JWST:

- 6.5m Mirror into space allows unprecedented accuracy
- Large wavelength range in the infrared: 0.6 to 28.5 micron
- Photometry and medium resolution spectrographs (R~3000)

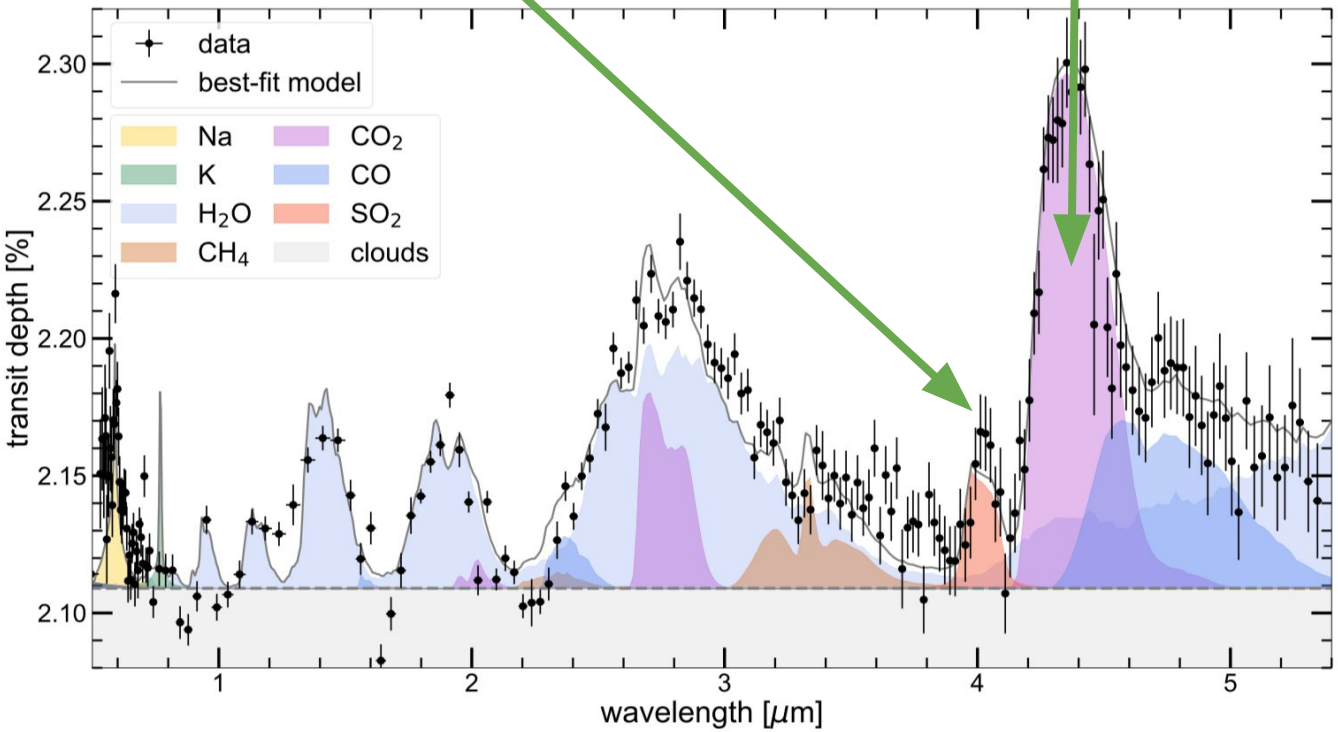
Highlights from ~5 years of JWST



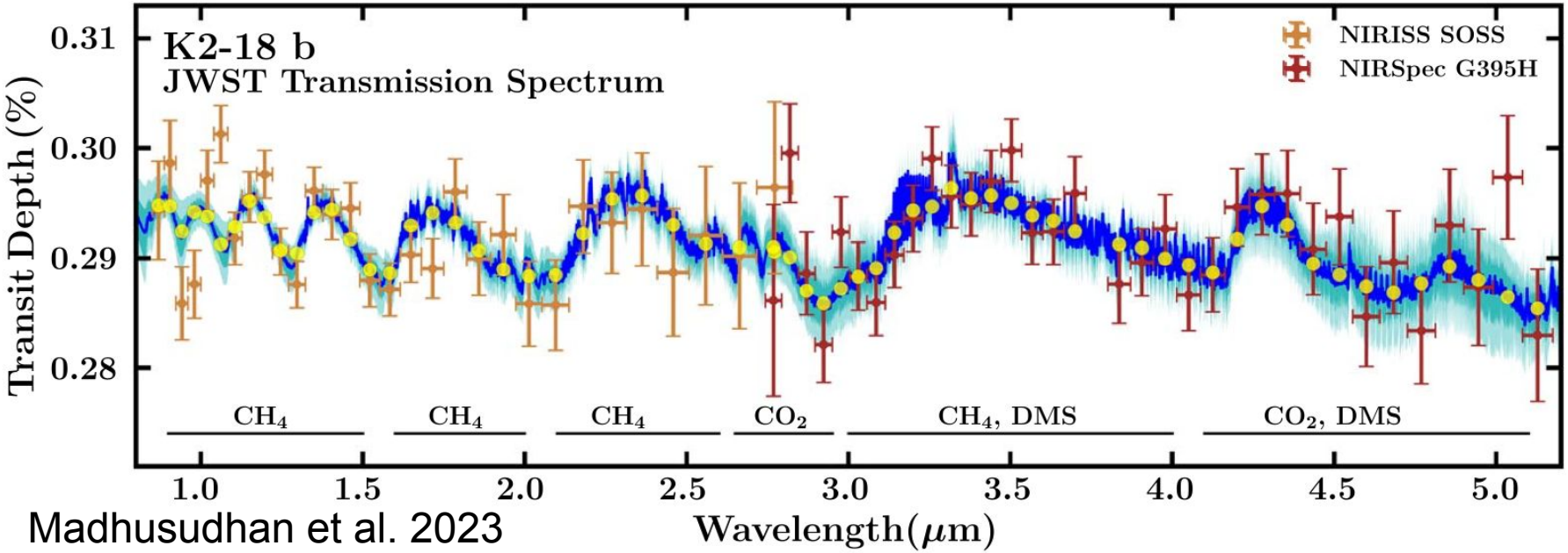
Transiting planet Early Release Science team

first photochemical feature (SO2)

first definitive detection of CO2



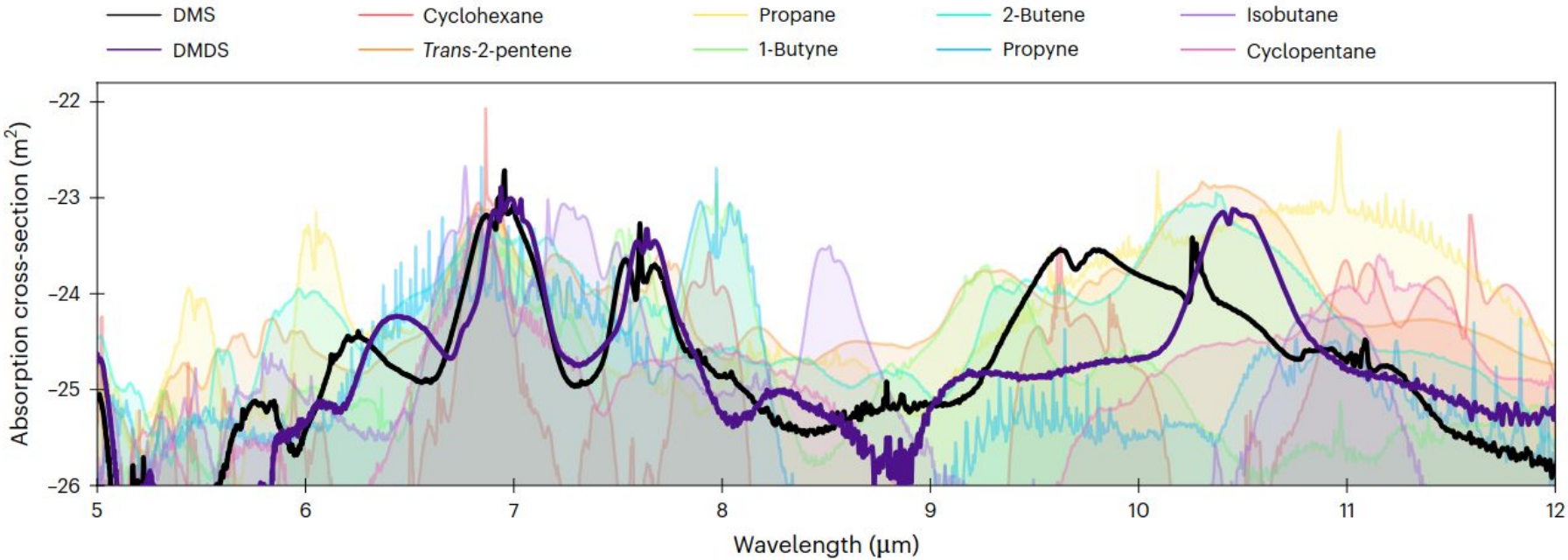
K2-18 b (a “habitable zone” sub-Neptune)



Madhusudhan et al. 2023

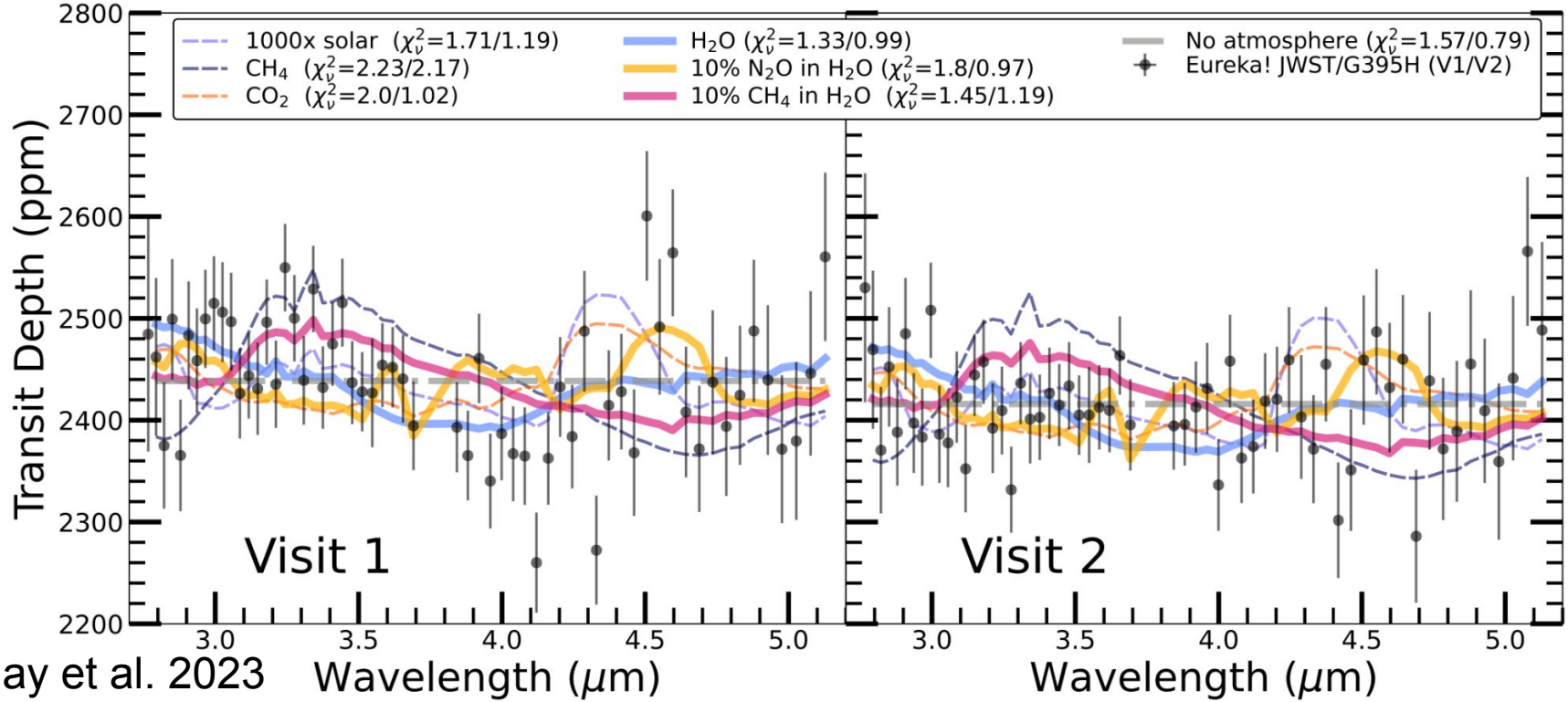
- Instead of detecting water as we expected, we detected CH4 and CO2
- This planet was in the press for a highly disputed DMS detection

K2-18 b (a “habitable zone” sub-Neptune)



DMS is a potential biosignature. However …

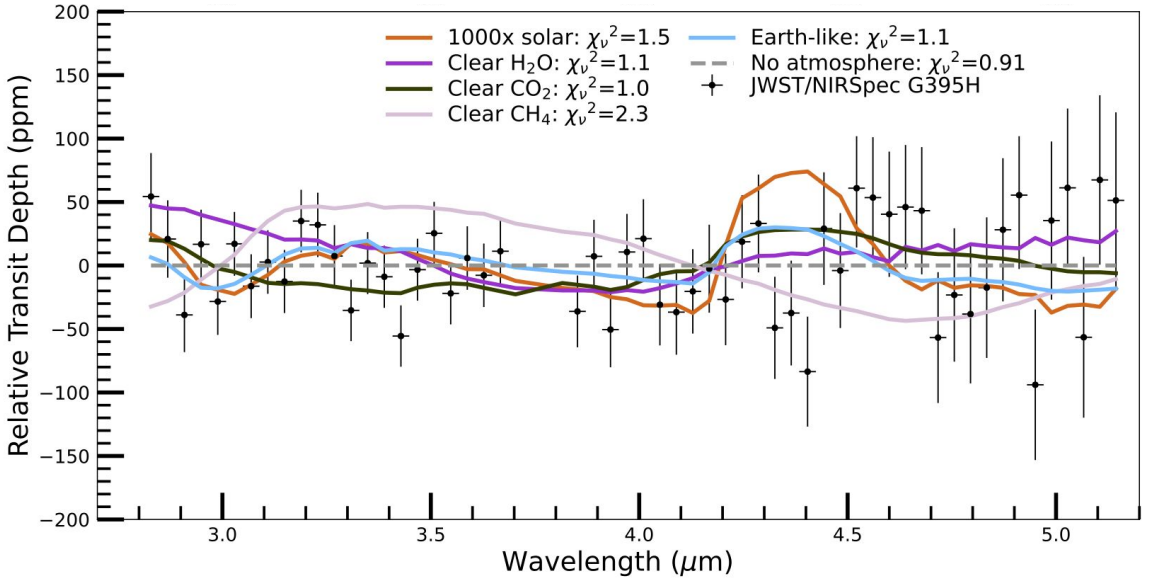
Terrestrial planets are still tricky! Why?

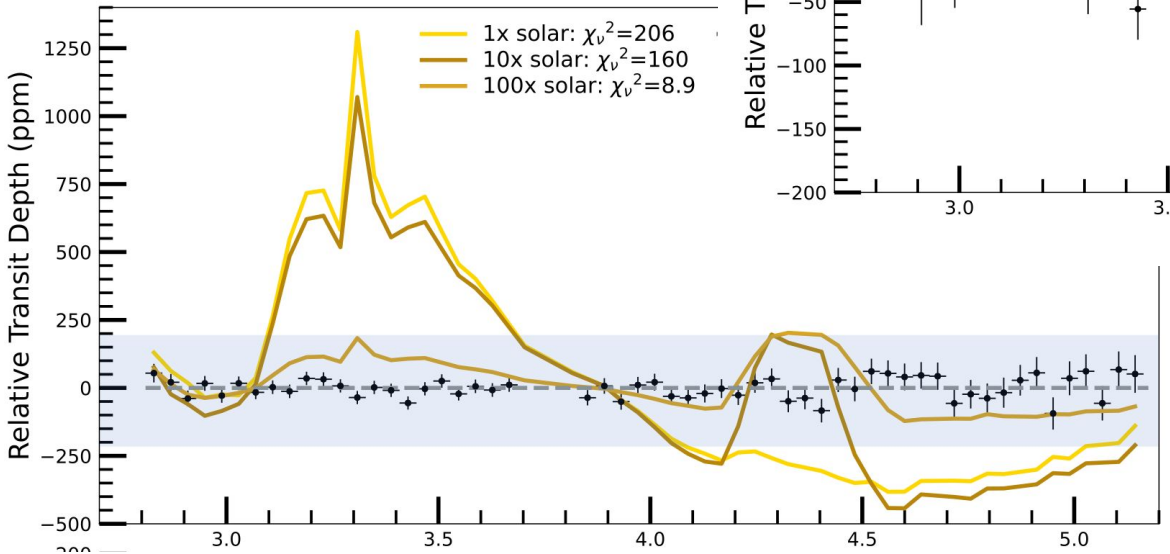


May et al. 2023

- GJ 1132b: a warm super Earth, consistent with no atmosphere

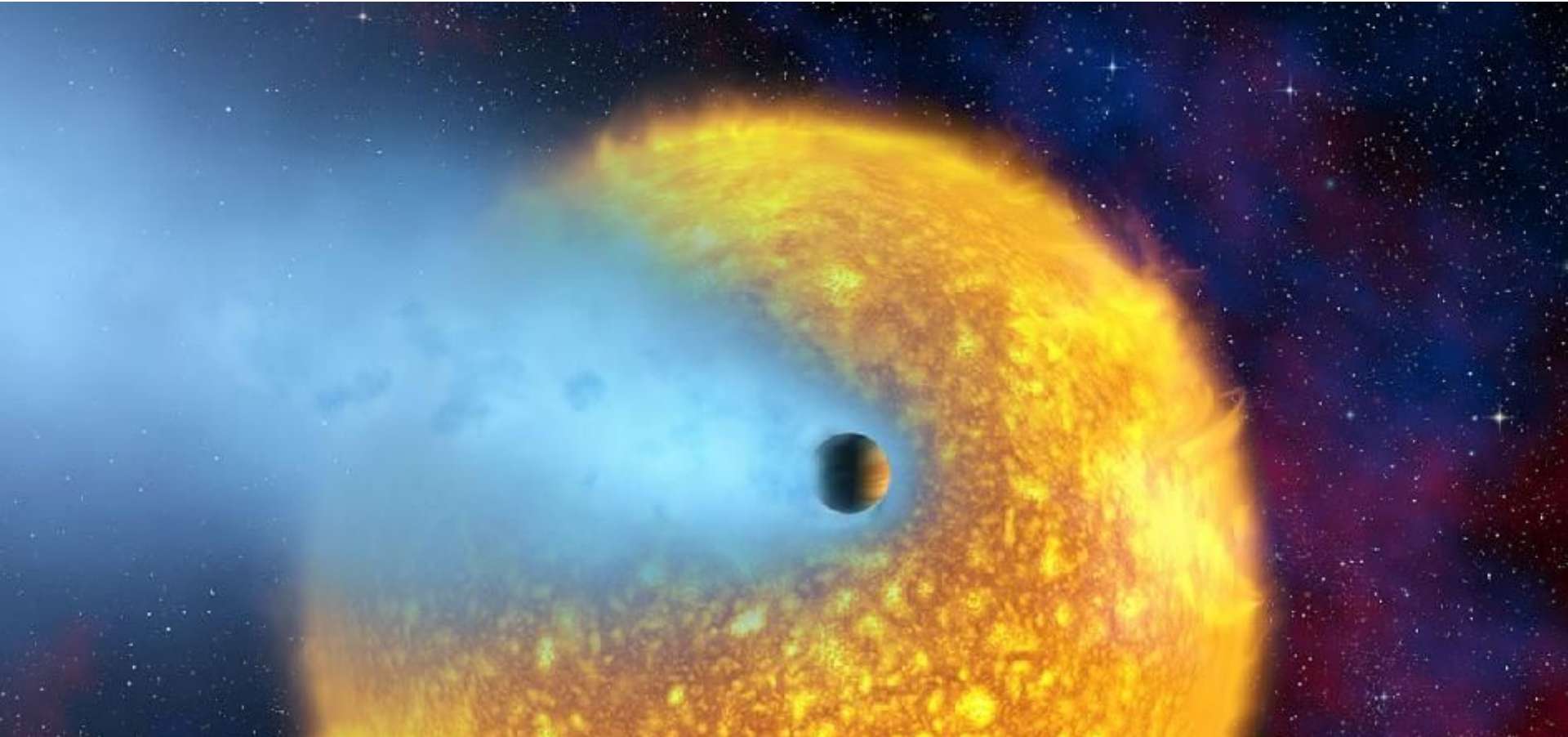
Terrestrial planets are still tricky! Why?



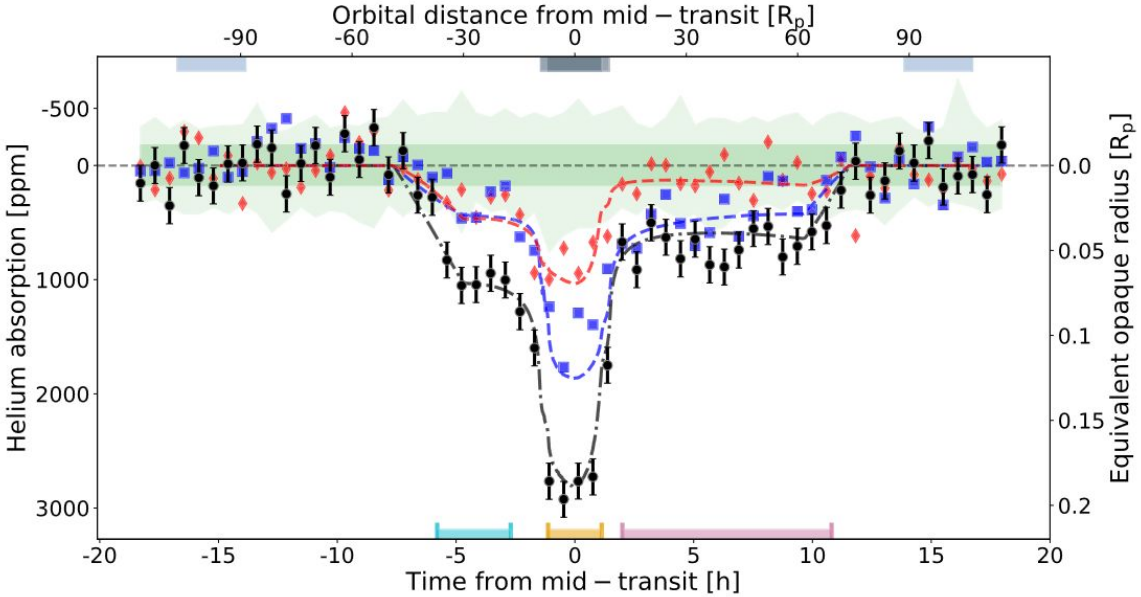


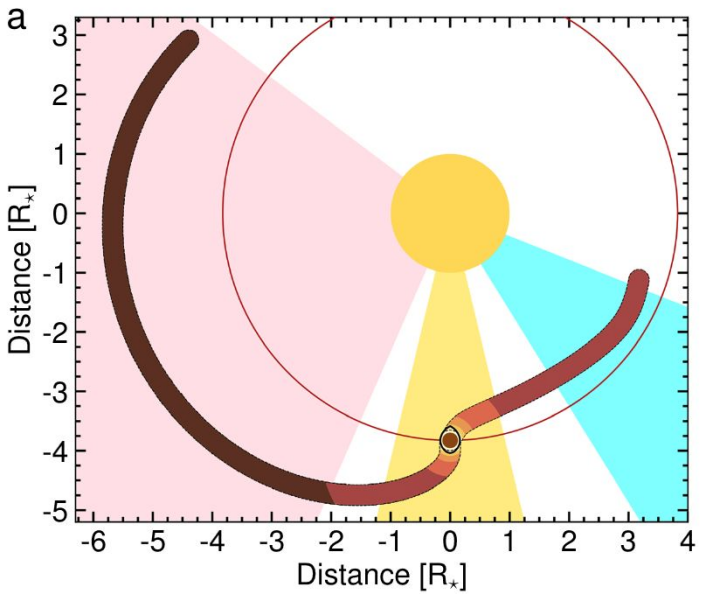
Lustig-Yaeger et al. 2023

Atmospheric escape - Helium



Atmospheric escape - Helium

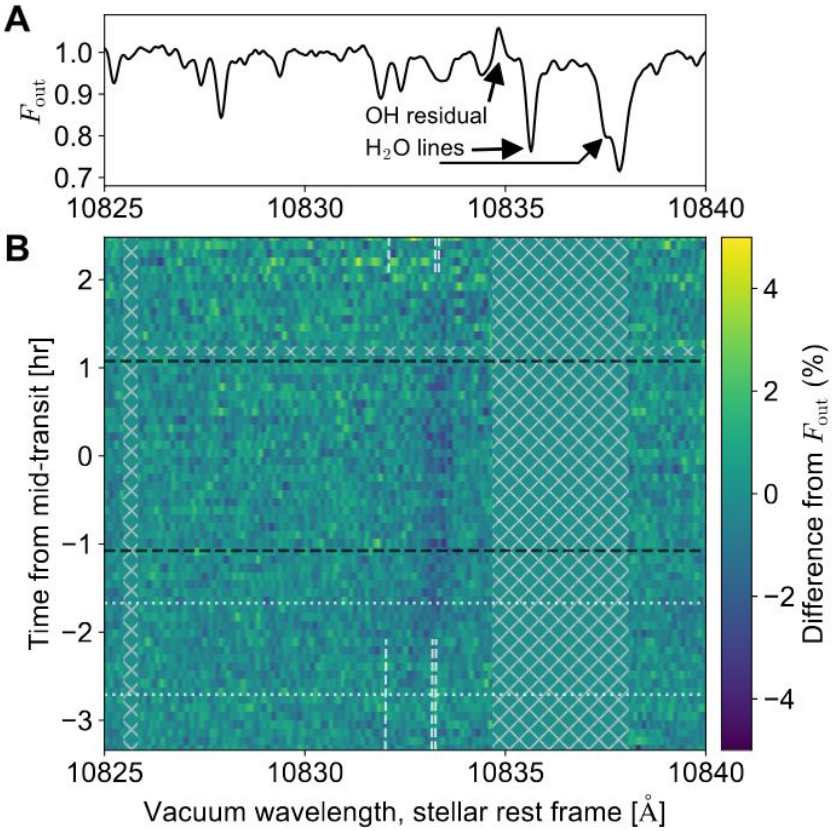




- Helium is the lightest element after Hydrogen and will escape over time
- Measurements of Helium are difficult and can be highly variable

Allard et al. 2025

Atmospheric escape - Helium



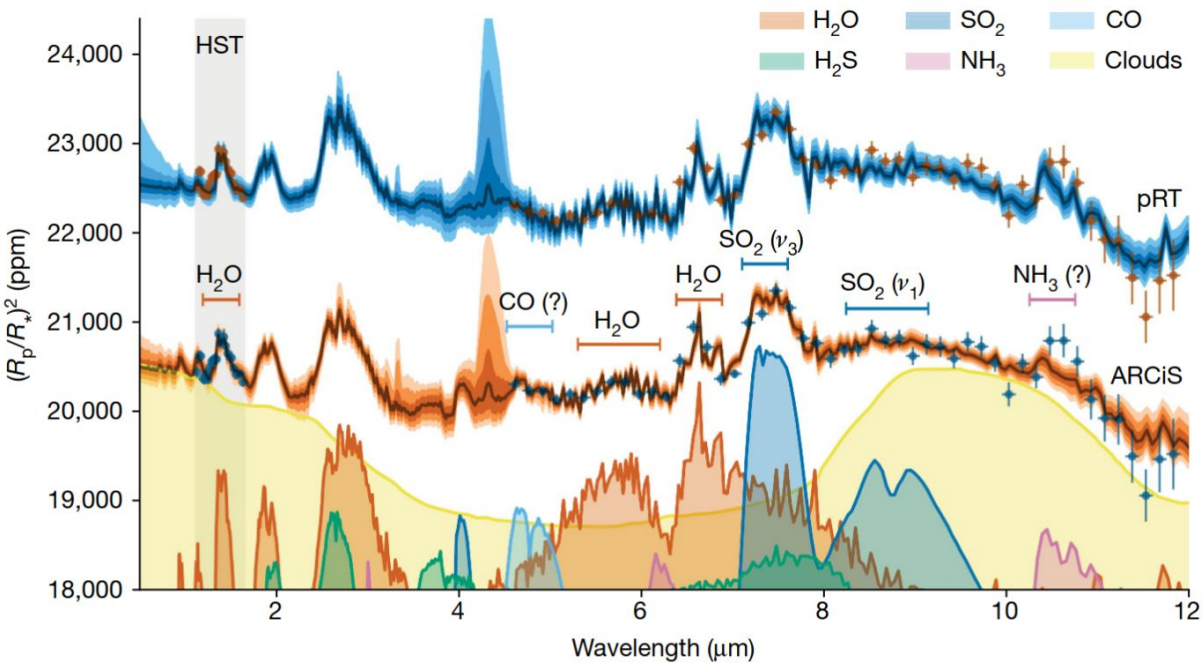
LHS 1140

- Potential Helium detection
- Could not be reproduced for now (future observations are scheduled)
- If true, this would be the first

Cherubim et al. 2026



Clouds



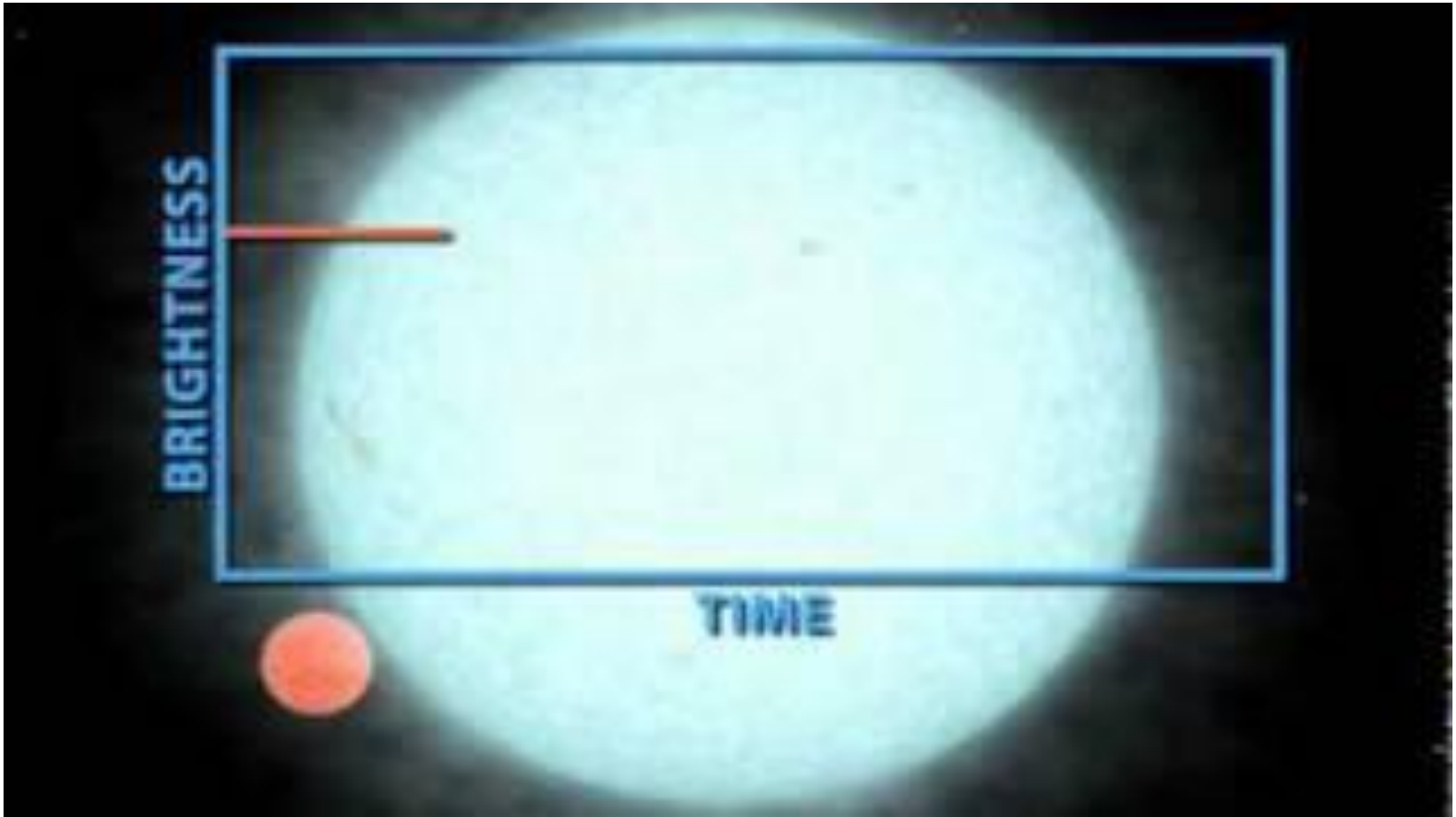
WASP 107 b

- First direct detection of clouds (not just flat lines)
- Surprising find: a lot of small silicate particles at high altitudes

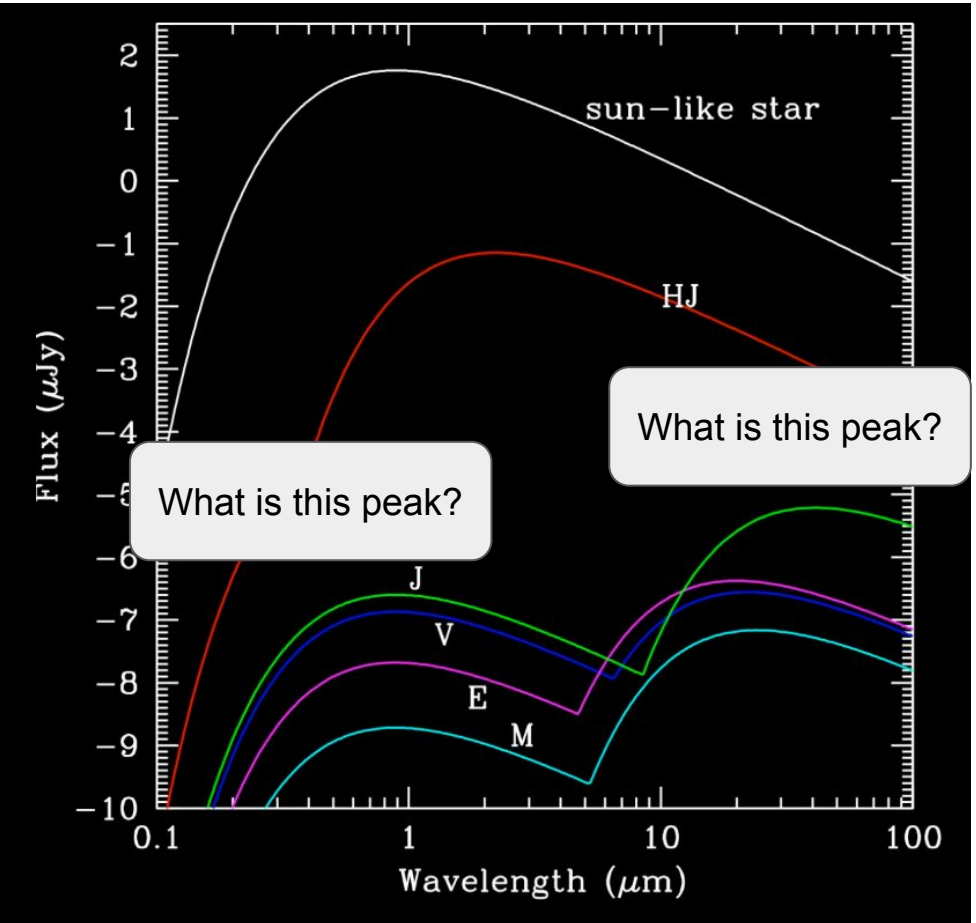
Dyrek et al. 2023

Eclipse spectra with JWST

Thermal emission flux ratio



Thermal emission flux ratio



Blackbody radiation:

$$B_\lambda(T) = \frac{2hc^2}{\lambda^5}\frac{1}{e^{hc/\lambda kT} - 1}.$$

For $\lambda >> hc/kT$: $B_\lambda \sim \lambda^{-4} T$

At Earth wavelengths we can approximate the flux ratio as:

$$\frac{F_p}{F_s}\Big|_{Earth(\lambda)} = \frac{T_p R_p^2}{T_s R_s^2}$$

Small Exercise

What size features do we expect to see?

$$\frac{F_p}{F_s}\Big|_{Earth(\lambda)} = \frac{T_p R_p^2}{T_s R_s^2}$$

T_S = 5800 K
R_S = 700,000 km

- Hot Jupiter?

T_J = 2000 K
R_J = 70,000 km

Fp/Fs = 3500 ppm

- Earth?

T_E = 300 K
R_E = 6,400 km

Fp/Fs = 4.3 ppm

Small Exercise

What size features do we expect to see?

$$\frac{F_p}{F}|_{Earth(\lambda)} = \frac{T_p R_p^2}{T_* R_*^2}$$

T_S = 5800 K
R_S = 700,000 km

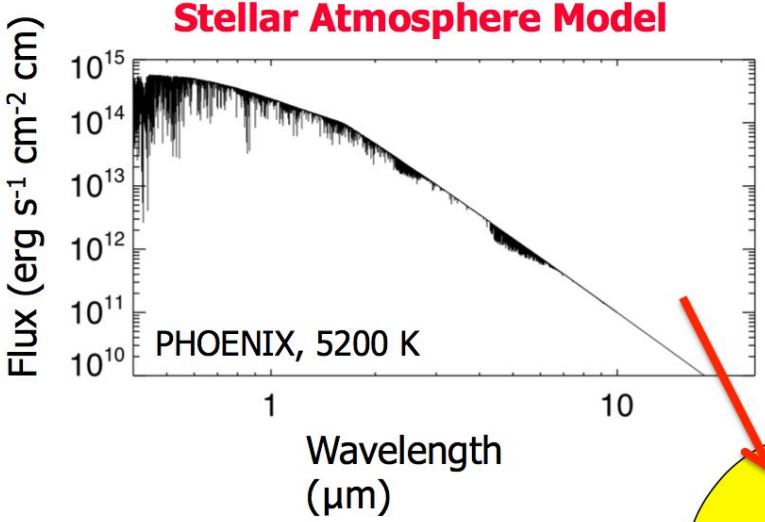
- Ho
- Ea

Take Away:
Large and hot planets are much easier to observe than cold and small ones

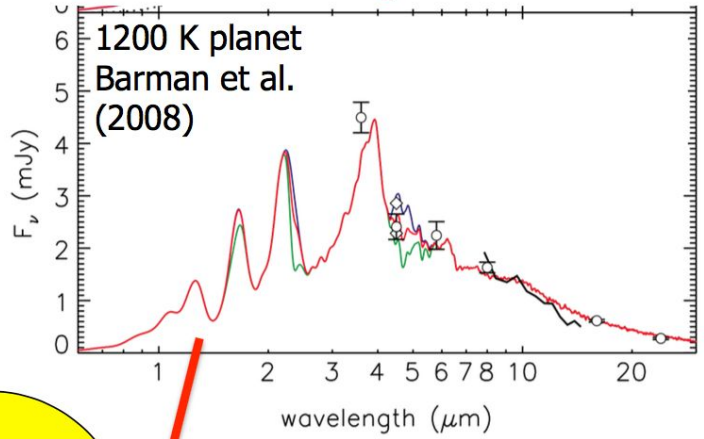
T_E = 300 K
R_E = 6,400 km

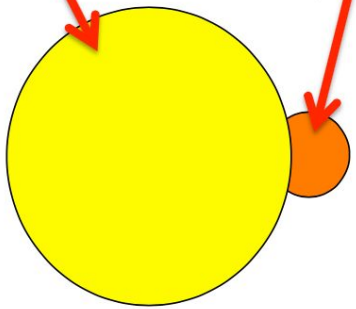
Fp/Fs = 4.3 ppm

Stellar Atmosphere Model

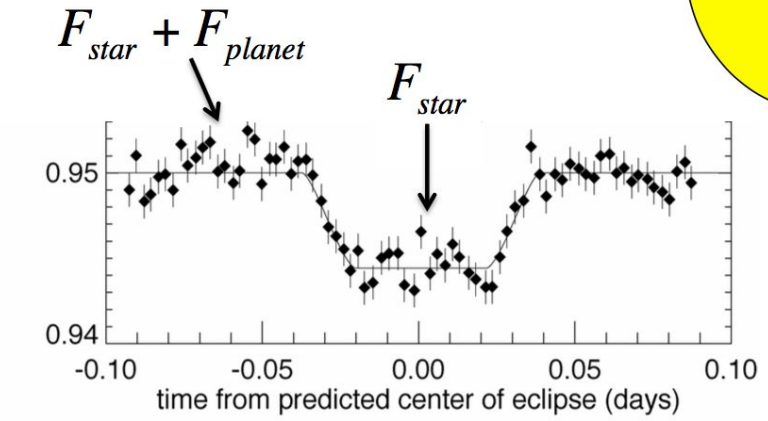


Planet Atmosphere Model





Model assumes solar composition atmosphere, chemistry in local thermal equilibrium.



$$depth(\%) = \frac{F_{planet}}{F_{star} + F_{planet}} \approx \frac{F_{planet}}{F_{star}}$$

Secondary Eclipse

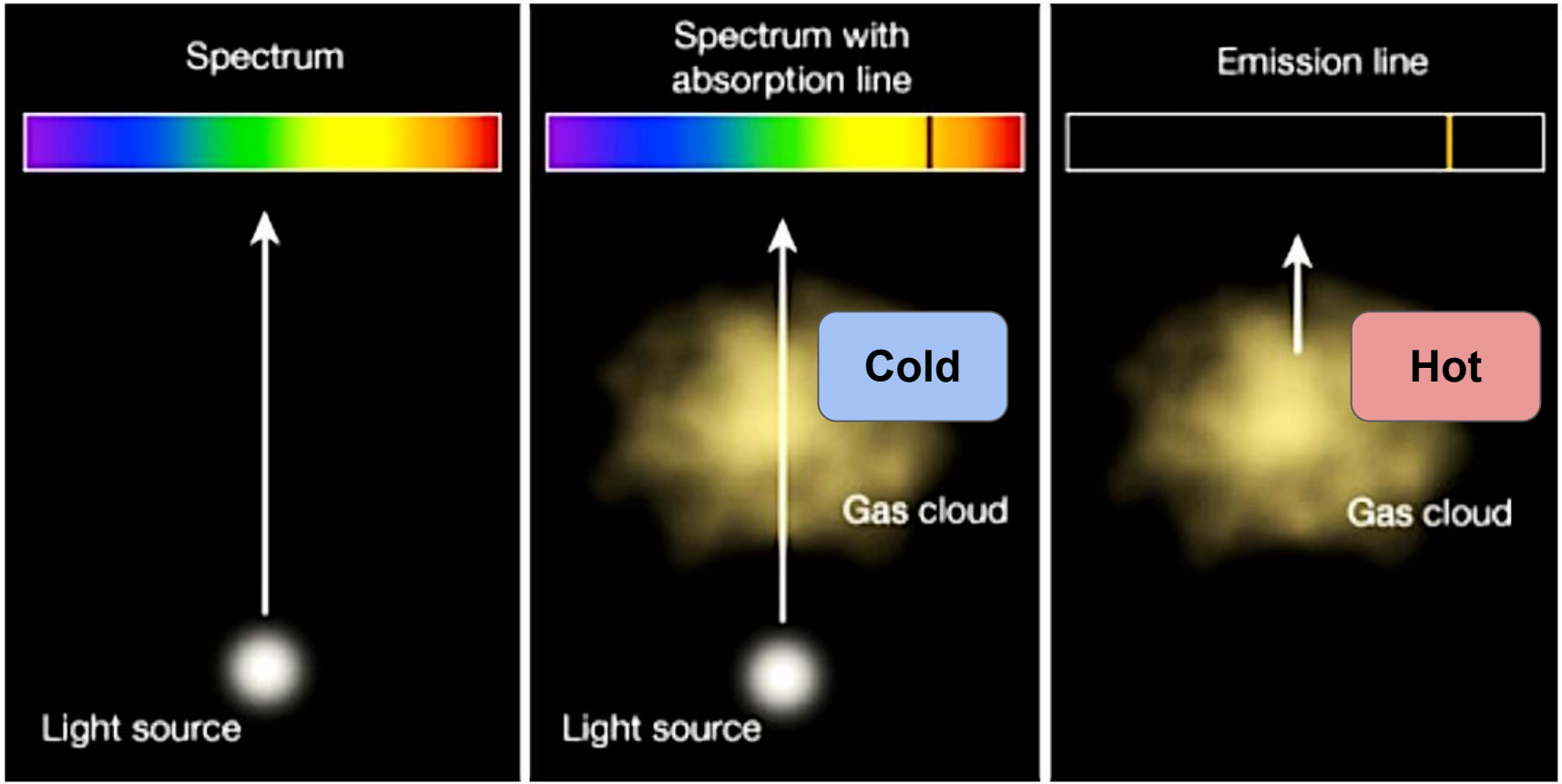
What temperature should we compare to?

- Compare to (zero Bond albedo) equilibrium temperature
- If the temperature is much lower, the planet might have a high albedo
  ➡ reflects more starlight

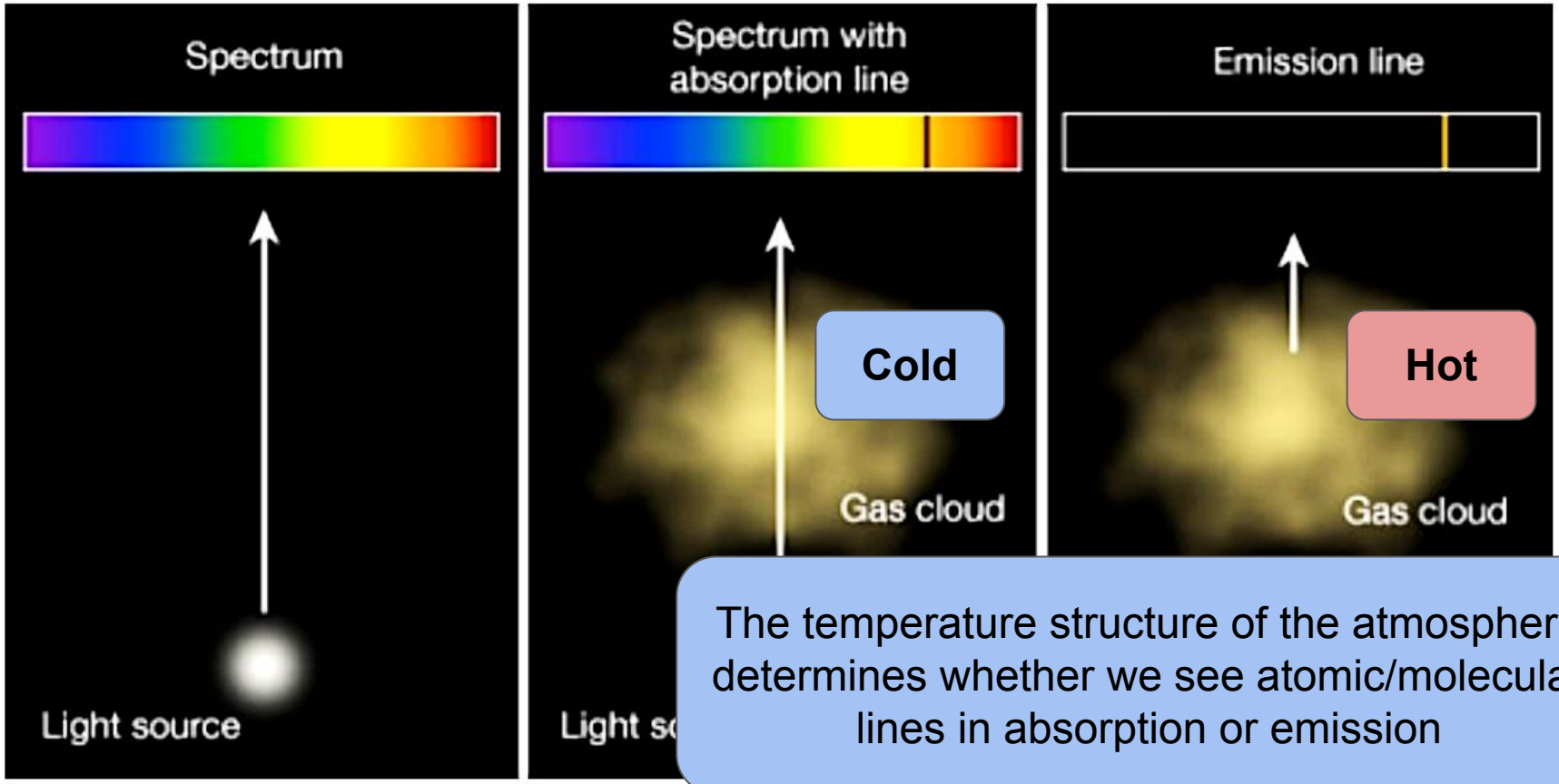
Gameplan for interpreting emission spectra

- Compare each wavelength's brightness temperature to equilibrium temperature
- Lower brightness temperature at that wavelength = "absorption" feature
- Higher brightness temperature at that wavelength = "emission" feature

Effect of the planet's temperature structure



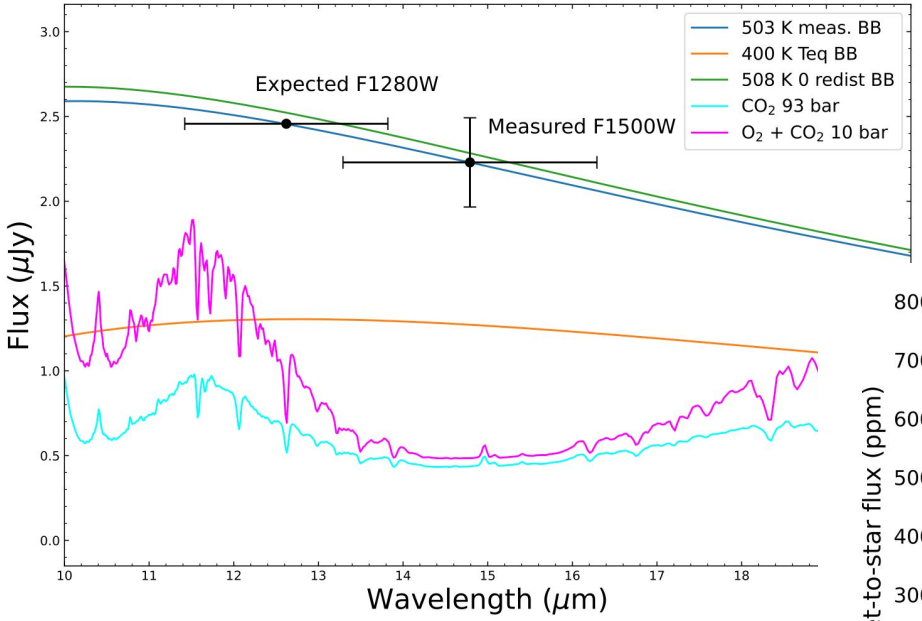
Effect of the planet's temperature structure



The temperature structure of the atmosphere determines whether we see atomic/molecular lines in absorption or emission

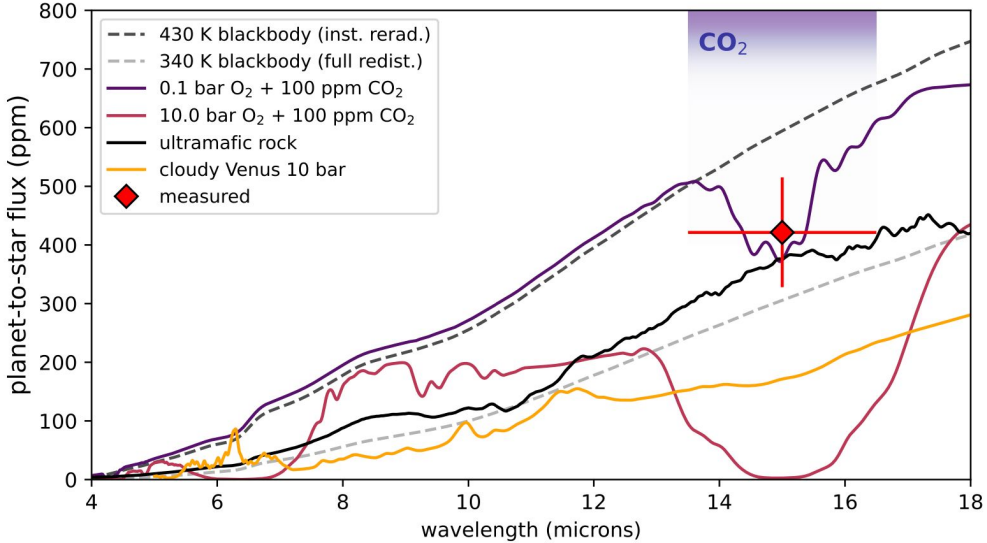
JWST Secondary Eclipse of Trappist 1 b & c

Greene et al. 2023

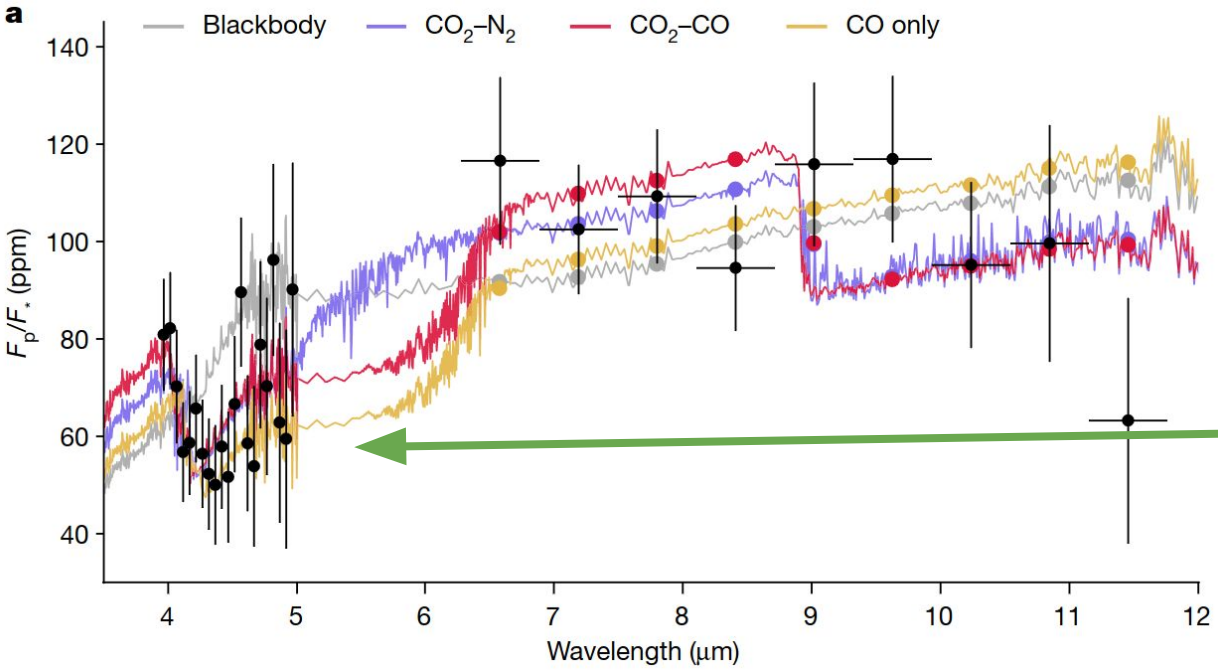


Neither of the Trappist planets have a confirmed atmosphere yet

Zieba et al. 2023



JWST Secondary Eclipse of 55 Cnc e



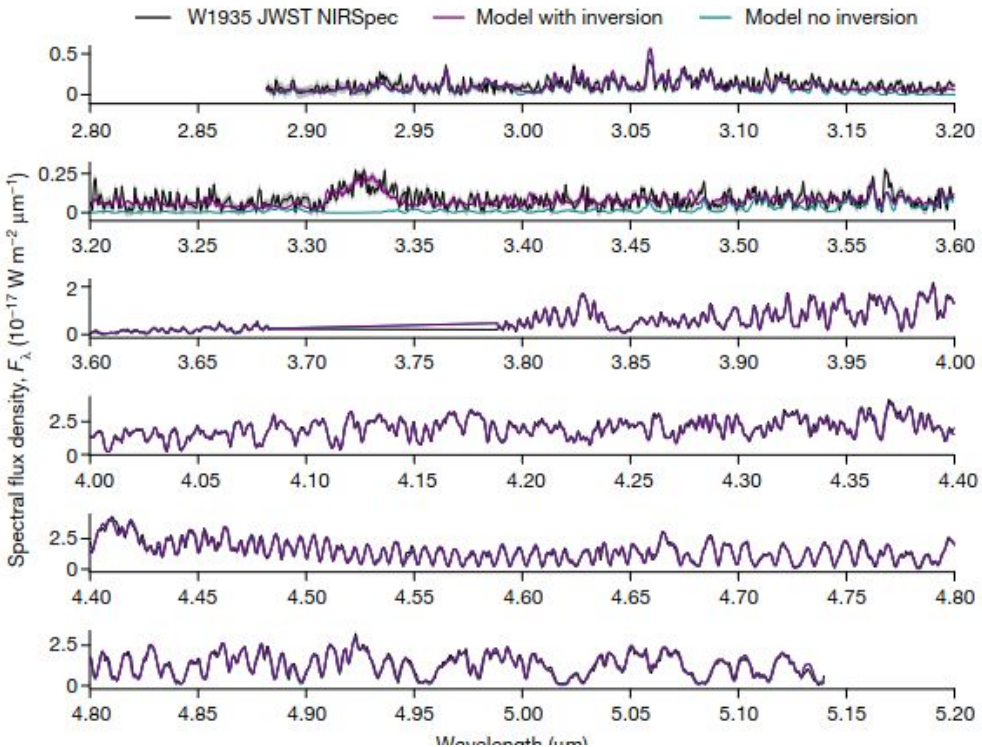
Hu et al. 2023

CO2 absorption feature

Detection of CO2 on a rocky planet through a secondary Eclipse.

This is a secondary atmosphere that outgassed after it lost its primordial atmosphere.

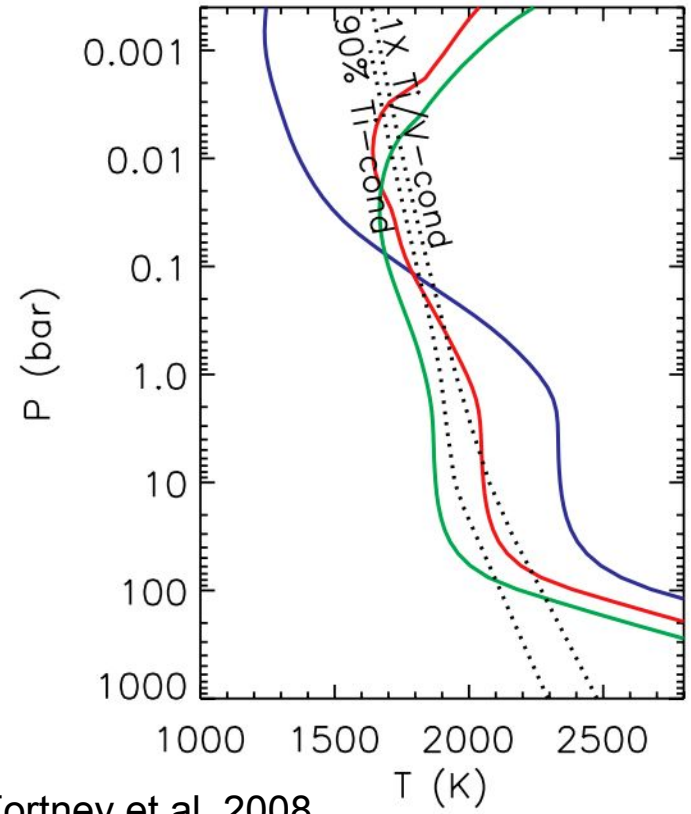
Effect of the planet's temperature structure

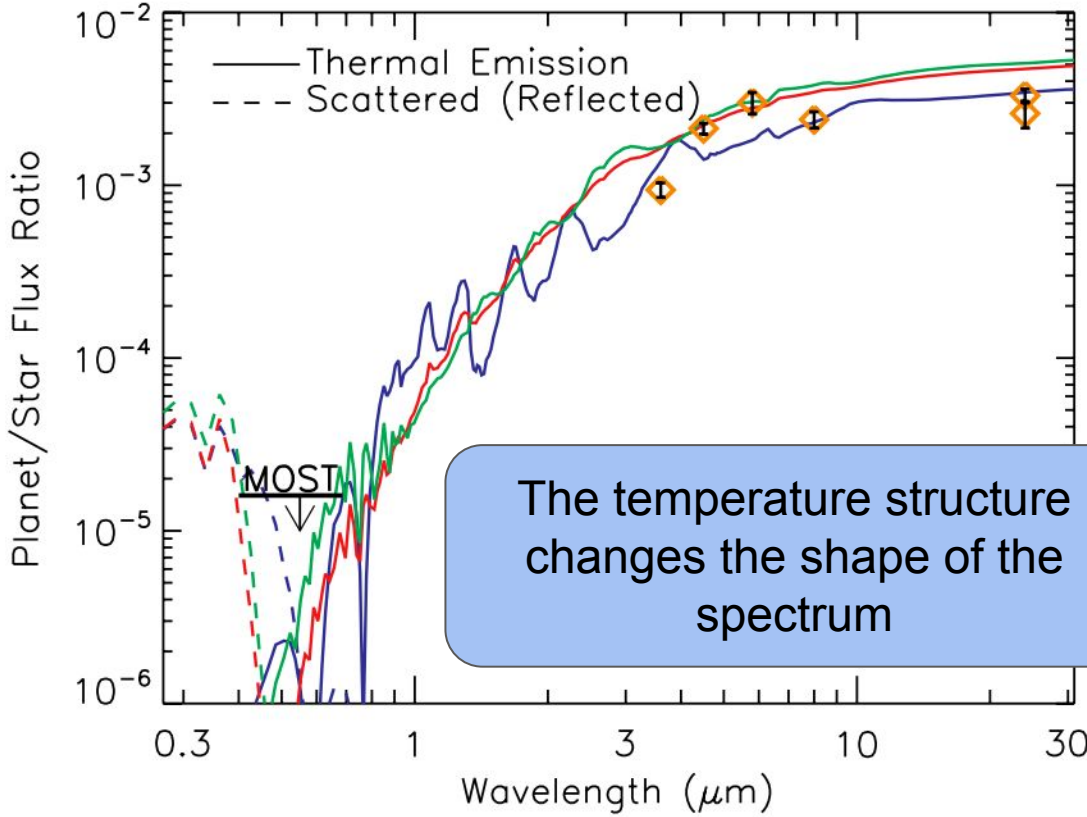


Methane in emission found in a brown dwarf
Temperature inversion?

Faherty et al. 2024

Effect of the planet's temperature structure



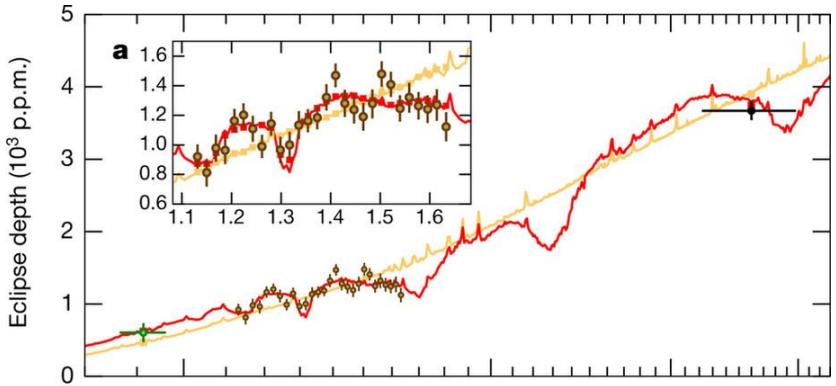


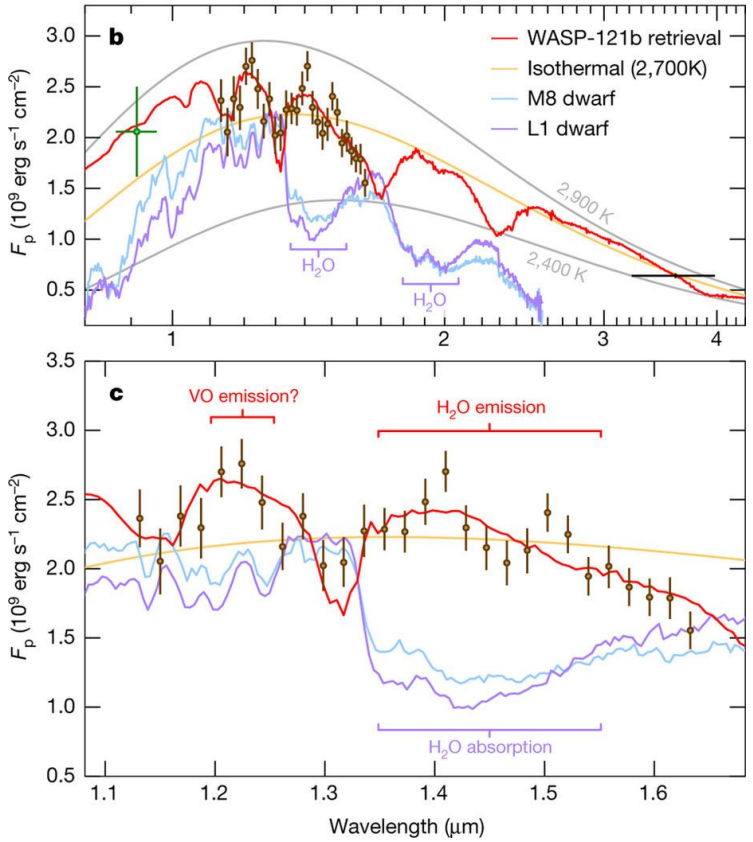
The temperature structure changes the shape of the spectrum

Fortney et al. 2008

Effect of the planet's temperature structure

There's evidence for temperature inversions in some of the hottest hot Jupiters





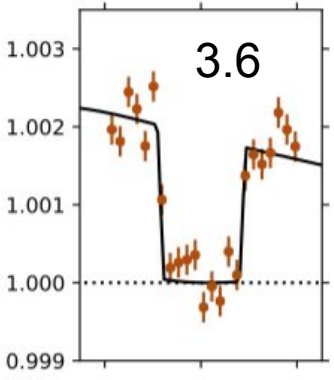
Fortney et al. 2023

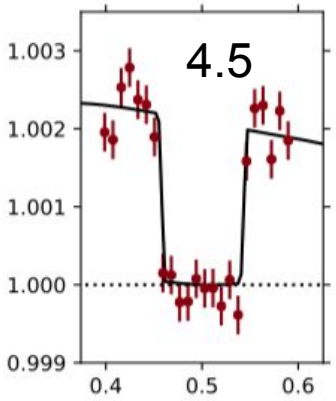
Small Exercise

Estimate the dayside brightness temperature at 3.6 and 4.5 microns based on this figure:

$R_P = 1.1\ R_J$
$R_S = 14.4\ R_J$
$T_S = 6500\ K$

$$\frac{F_p}{F_s}\Big|_{Earth(\lambda)} = \frac{T_p R_p^2}{T_s R_s^2}$$



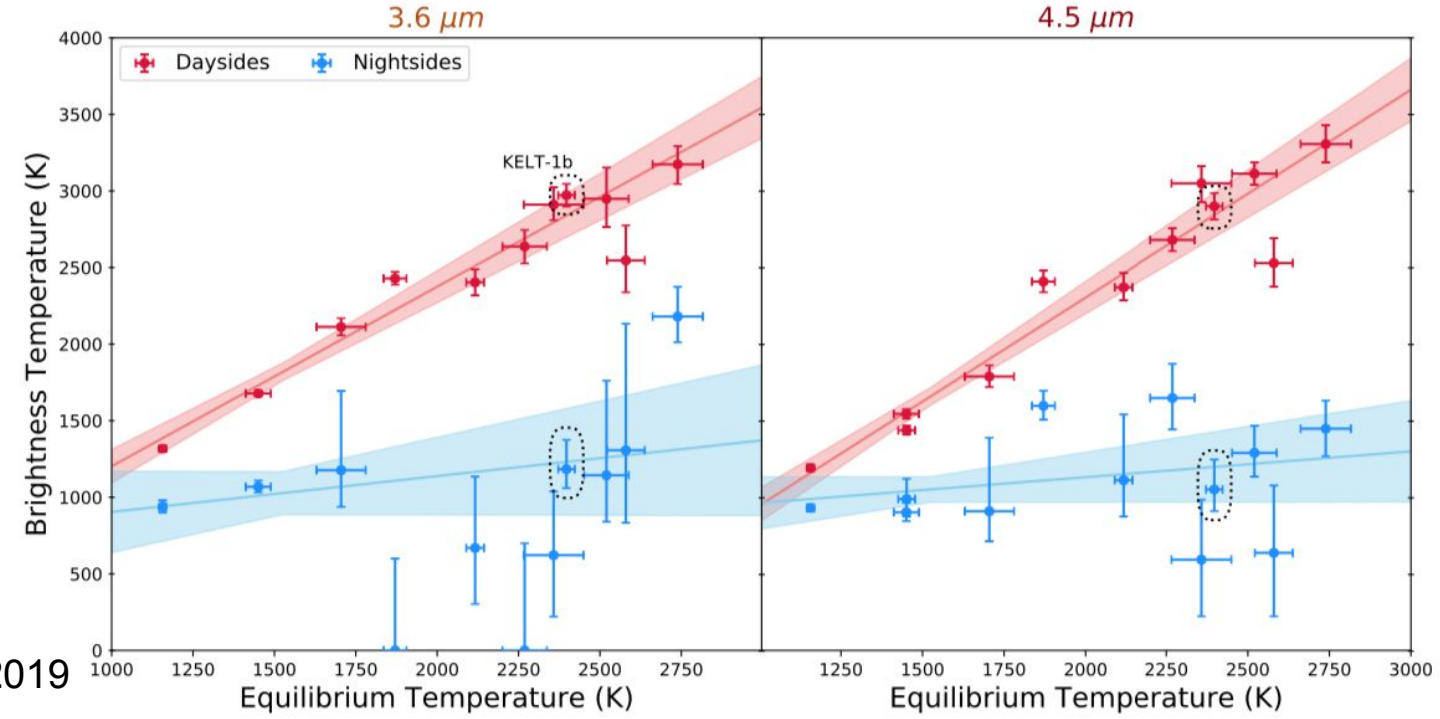


$T_P = 2200\ K$

$T_P = 2300\ K$

Effect of the planet's temperature structure

Dayside and nightside temperatures of hot Jupiters reveal daysides increase in temperature for higher equilibrium temperatures, while nightsides are ~constant



Beatty et al. 2019