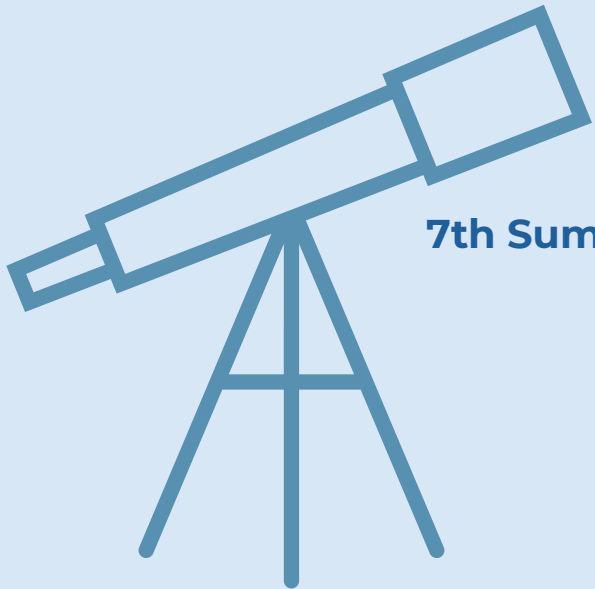


# Characterizing planetary atmospheres



7th Summer School - Multiwavelength approach to exoplanetary systems

Lisa Nortmann

# Why do we care about exoplanet atmospheres?

## Putting our Solar System into context

**Studying a large population of planets.** (Planet formation and evolution in many systems.)

Planets that have **no counterpart in our Solar System.**

Hotter planets allow us to **probe composition that has rained out in our cooler gas planets.**

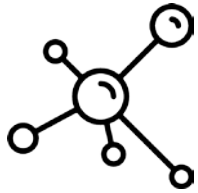
**Super-Earths to mini Neptunes:** may be gaseous, rocky or water worlds.  
Atmosphere is the only way to constrain the nature of these planets.

## Habitability

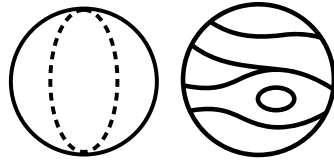
# What can we tell about a planet using its atmosphere?



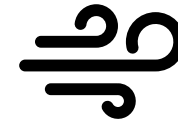
**Temperature**



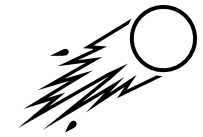
**Composition**



**3D structure**



**Winds**



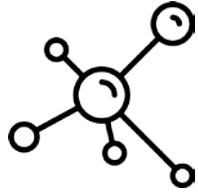
**Mass loss**



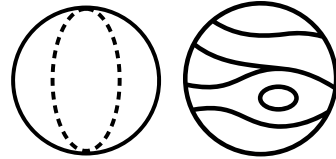
# What can we tell about a planet using its atmosphere?



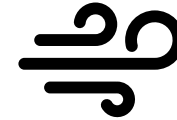
**Temperature**  
(-pressure profile)



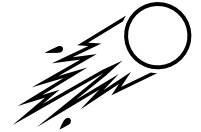
**Composition**  
C/O ratio  
Metallicity  
→ Formation  
→ and evolution



**3D structure**  
→ Day-to night side  
→ Hot spot-(offsets)  
→ Jets  
→ Cool poles

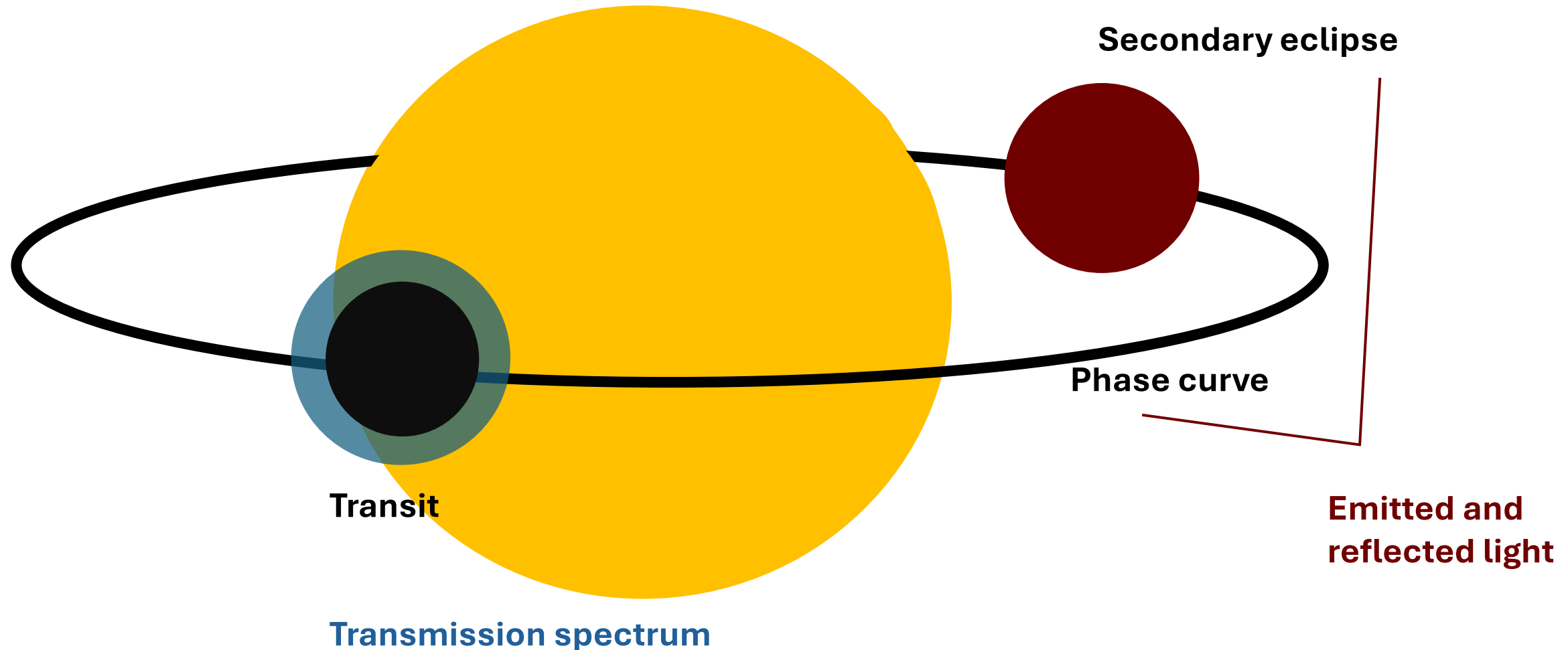


**Winds**  
→Supersonic  
Equatorial  
jets  
Day-to-  
nightside  
winds



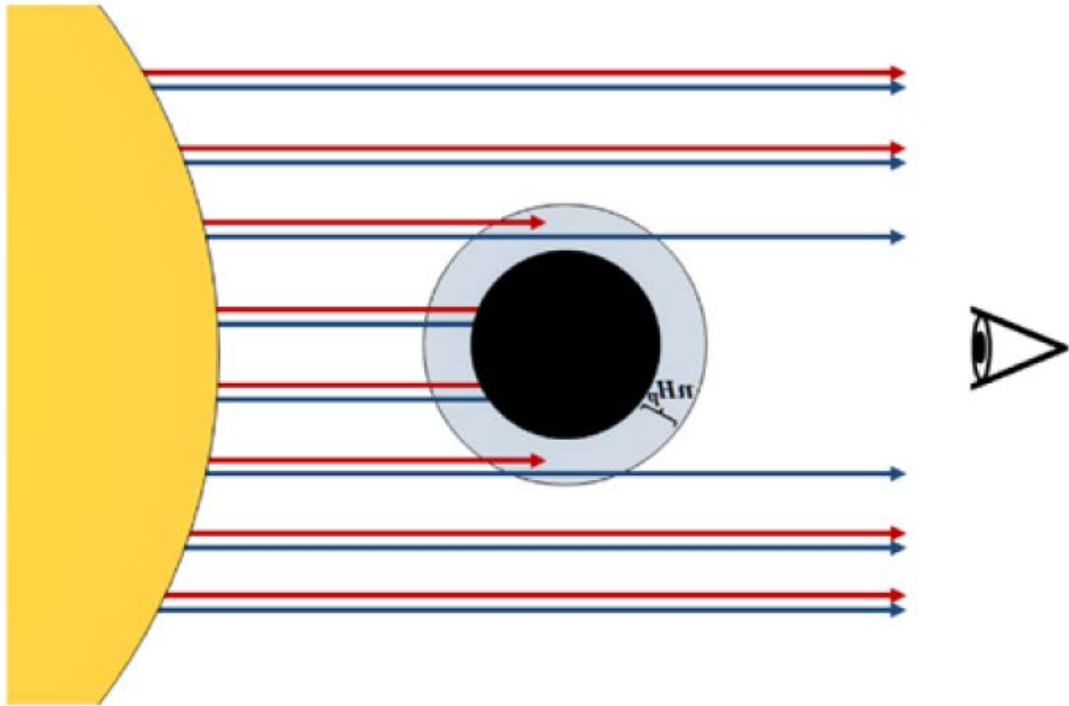
**Atmospheric  
loss**  
  
**Evolution**

# How do we measure exoplanet atmospheres?



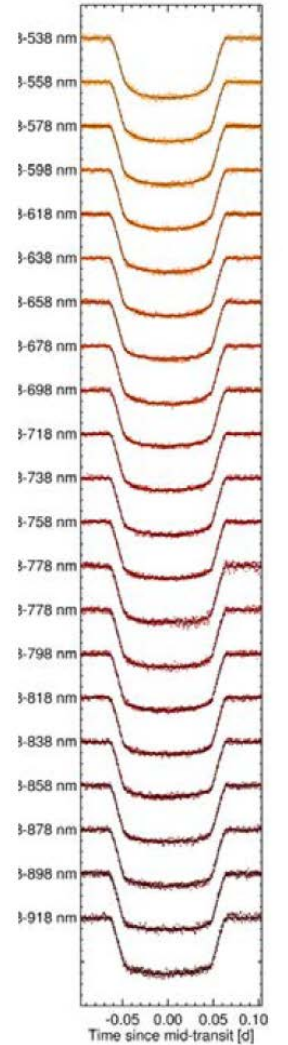
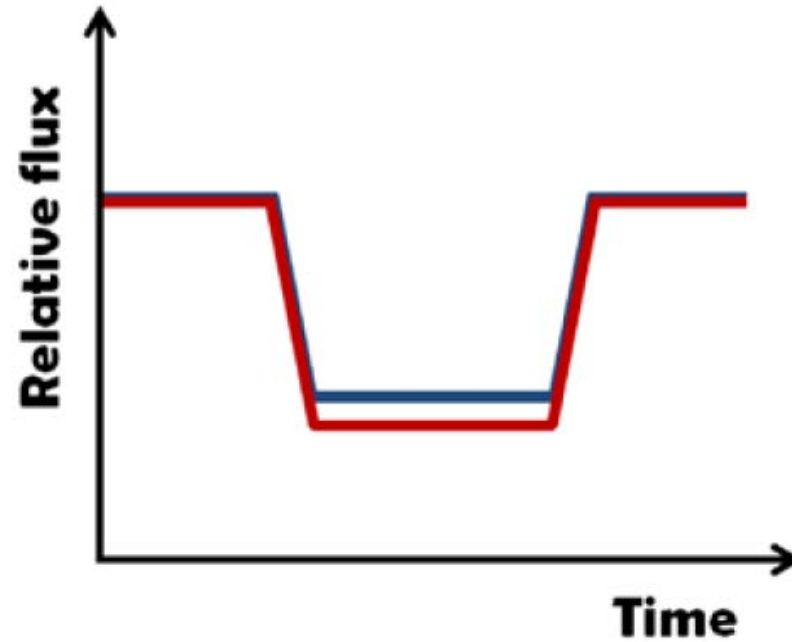
# Transmission spectroscopy

Transit

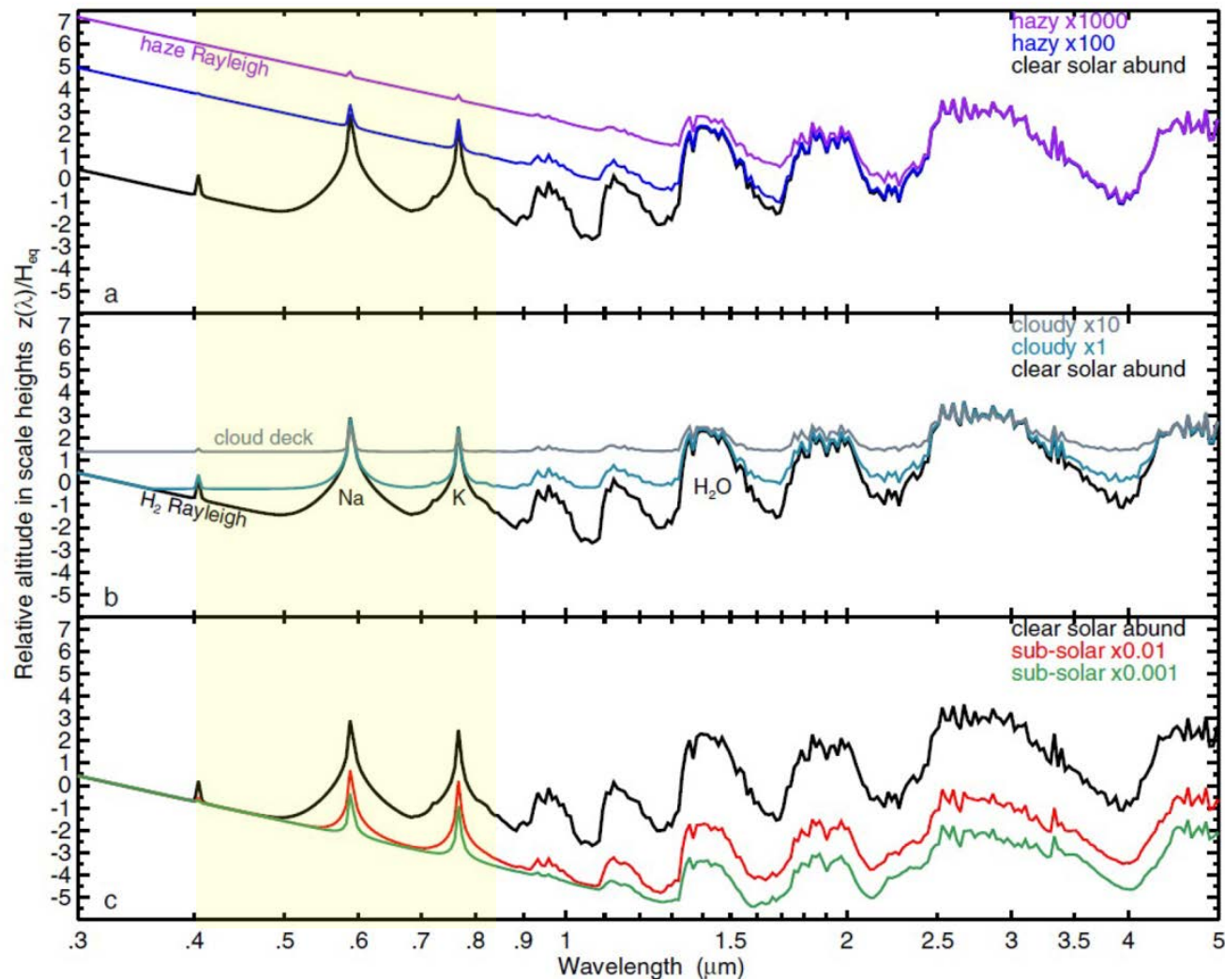


$$D = \frac{2R_p nH}{R_s^2}$$

$$H = \frac{kT}{Mg}$$

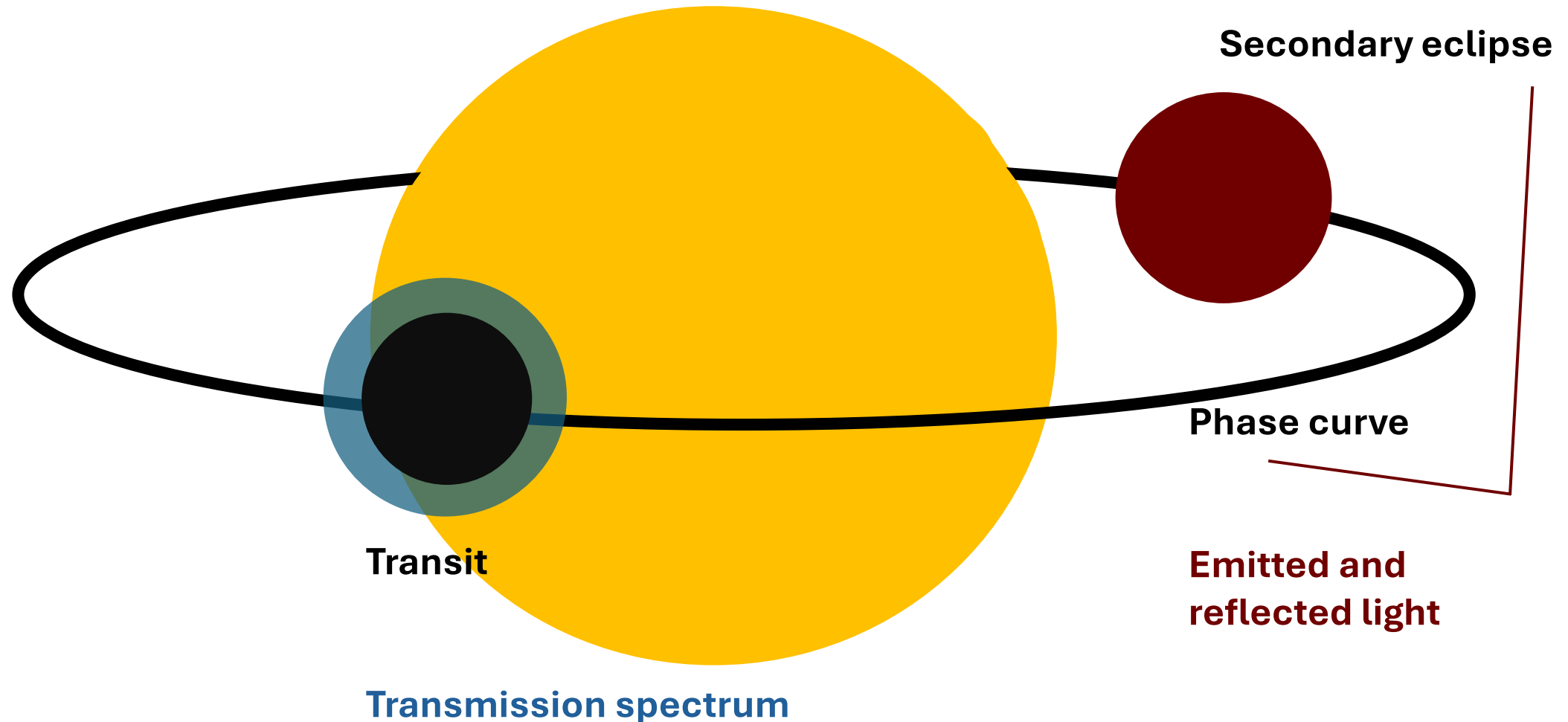


# Transit – Transmission spectroscopy



Sing et al. 2016

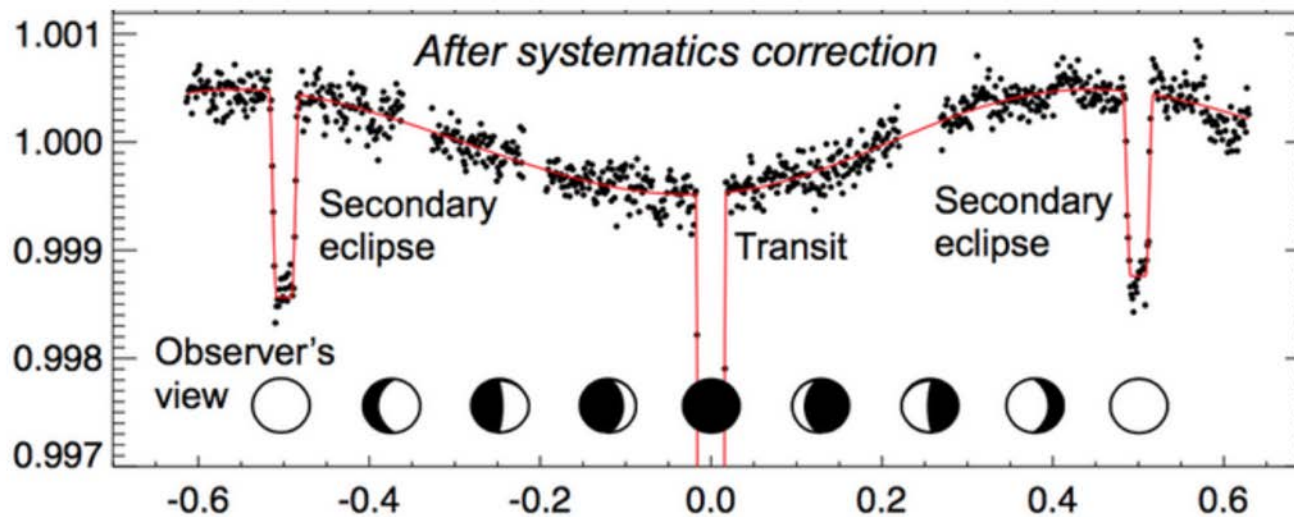
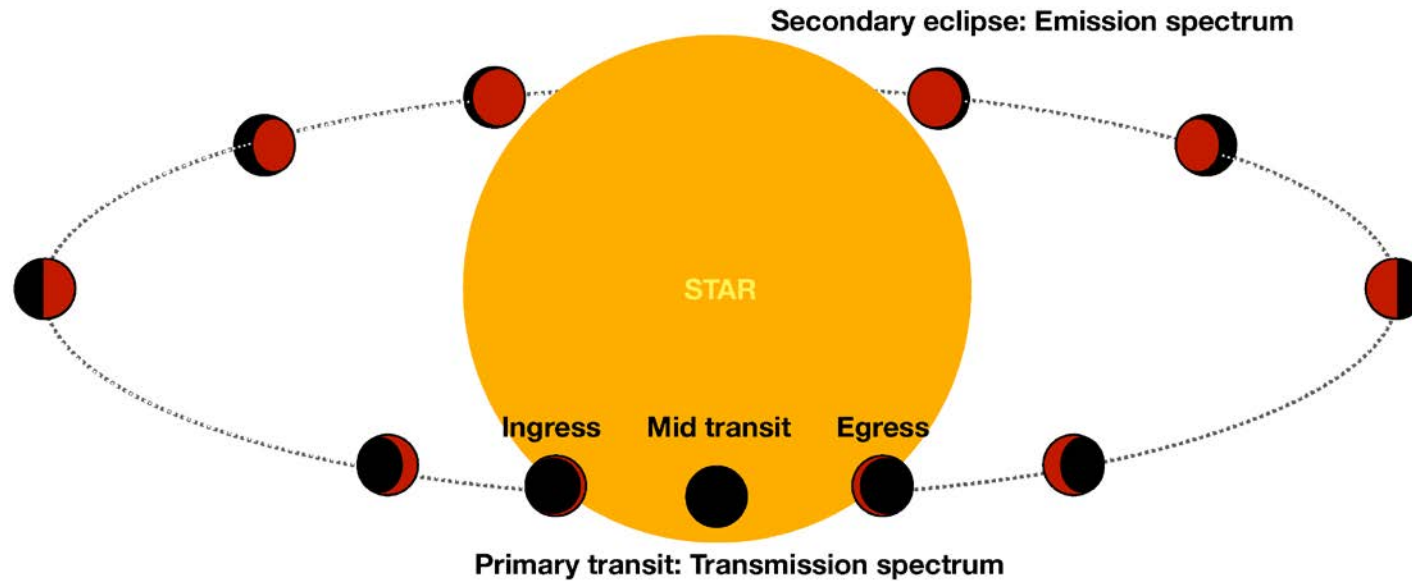
# How do we measure exoplanet atmospheres?





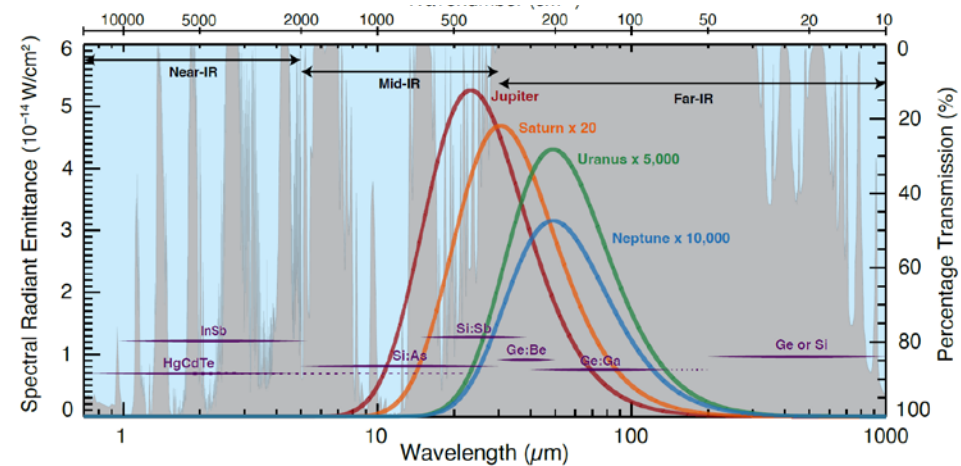
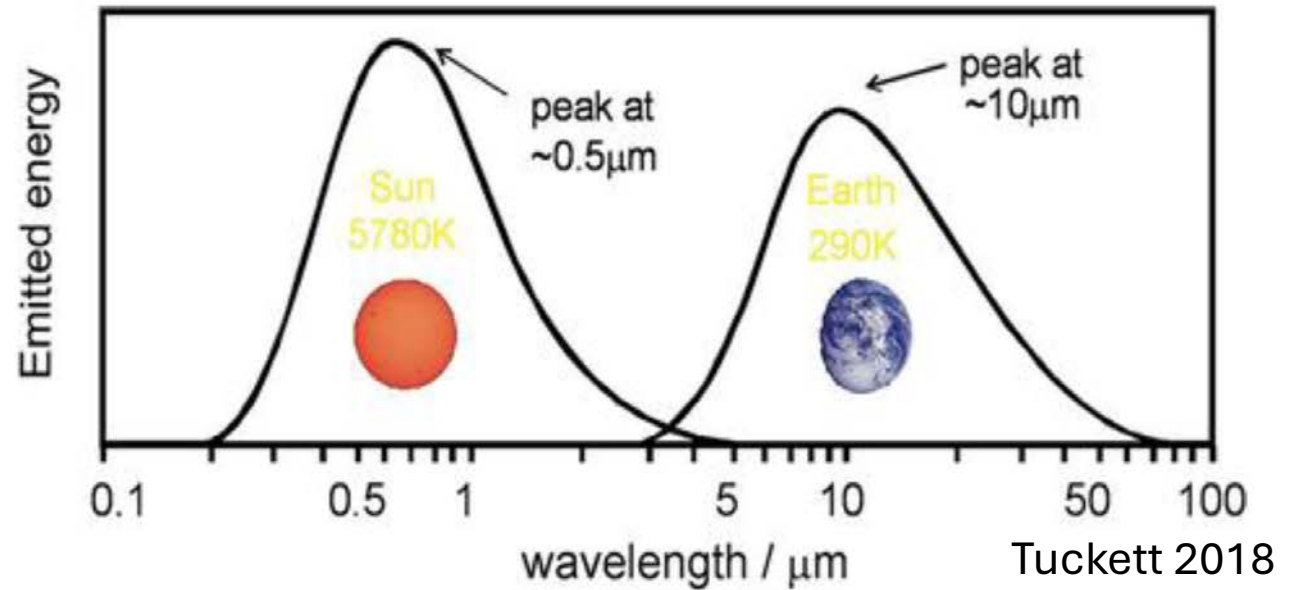
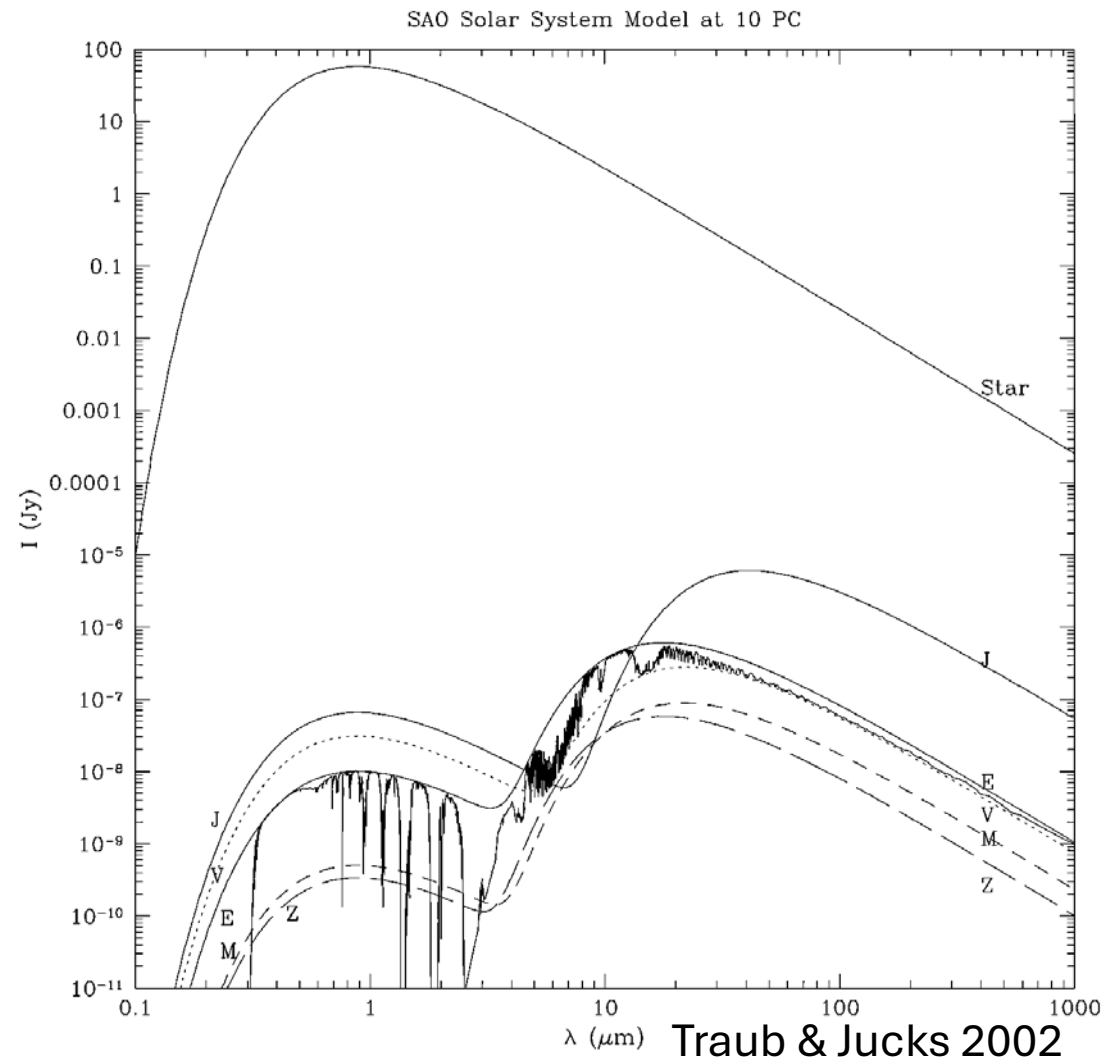
# Emitted light / Reflected light

Phase curve  
Secondary eclipse



Pluriel 2023;  
adapted from  
Seager & Deming 2010  
Knutsen et al. 2012

# Emitted vs. Reflected light



# How large are the signals?

$$\Delta\delta = \frac{(R_p + n H_p)^2}{R_*^2} - \frac{R_p^2}{R_*^2} = \frac{2 R_p n H_p + (n H_p)^2}{R_*^2}$$

$\sim n * 100\text{-}500 \text{ ppm}$

$$H_p = \frac{k_b T_{eq}}{\mu g_p}$$

$$\text{TSM} = (\text{Scale factor}) \times \frac{R_p^3 T_{eq}}{M_p R_*^2} \times 10^{-m_J/5}$$

$$\text{ESM} = 4.29 \times 10^6 \times \frac{B_{7.5}(T_{day})}{B_{7.5}(T_*)} \times \left(\frac{R_p}{R_*}\right)^2 \times 10^{-m_K/5}$$

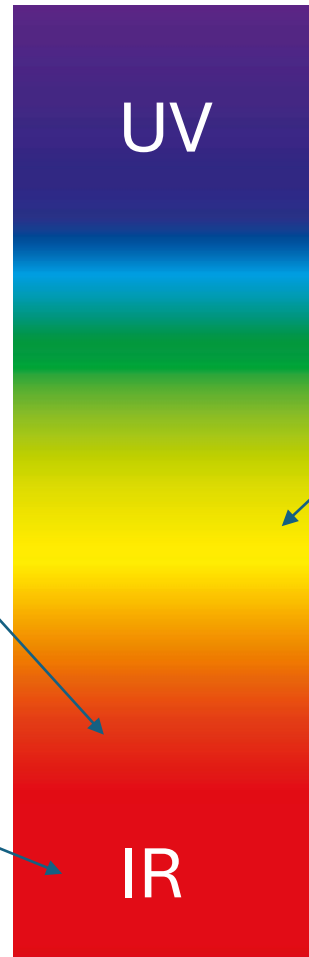
Kempton et al. 2018

# Where does the data come from – Low resolution:

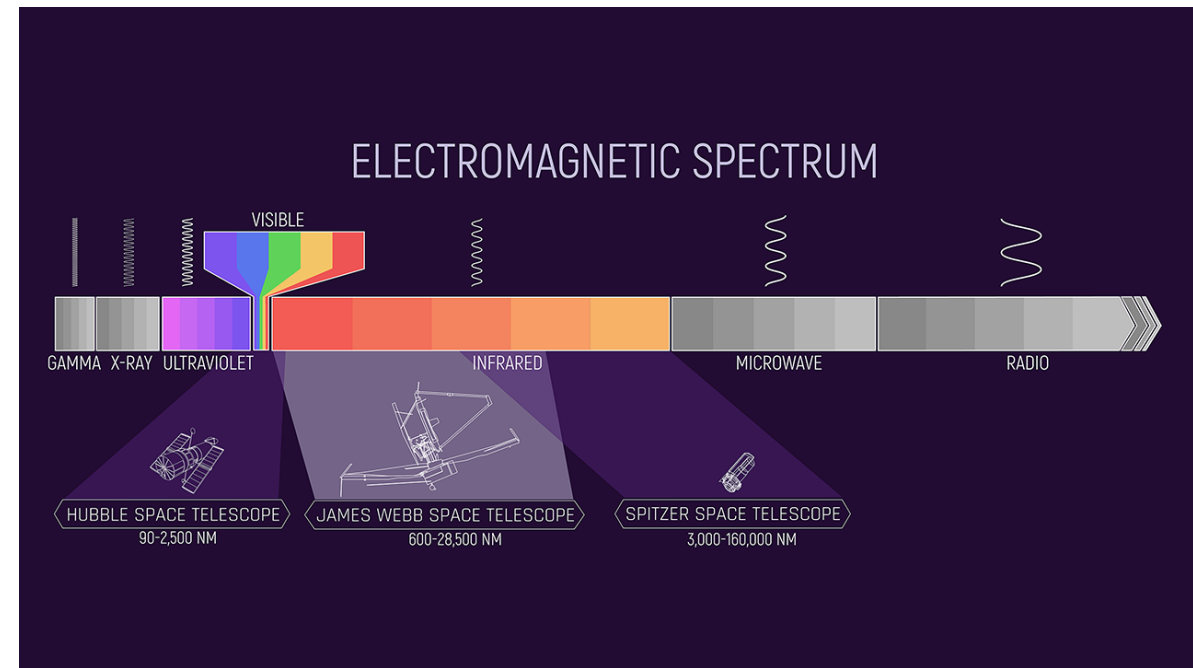
Space based:  
HST (STIS,  
WFC3)



Spitzer



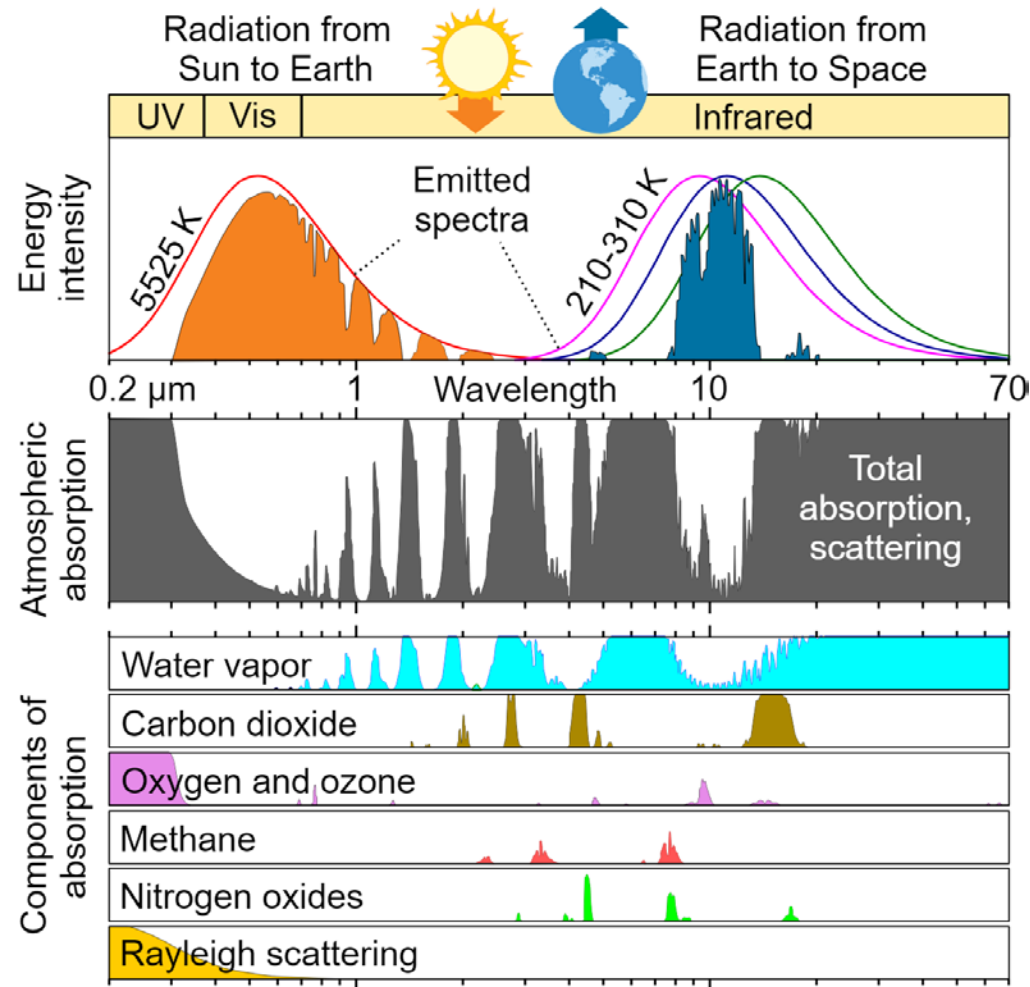
Ground-based:  
FORS2/VLT, OSIRIS/GTC,  
GMOS/GEMINI-South,  
...



NASA, ESA, CSA, Joseph Olmsted (STScI)

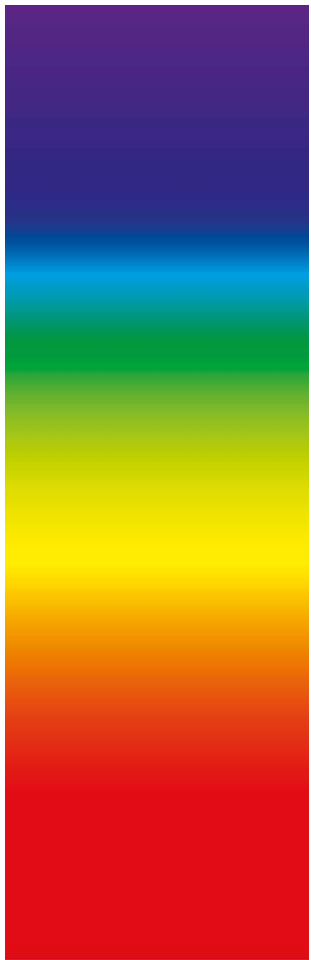
# What can be measured at which wavelength?

## Throughput Earth's atmosphere

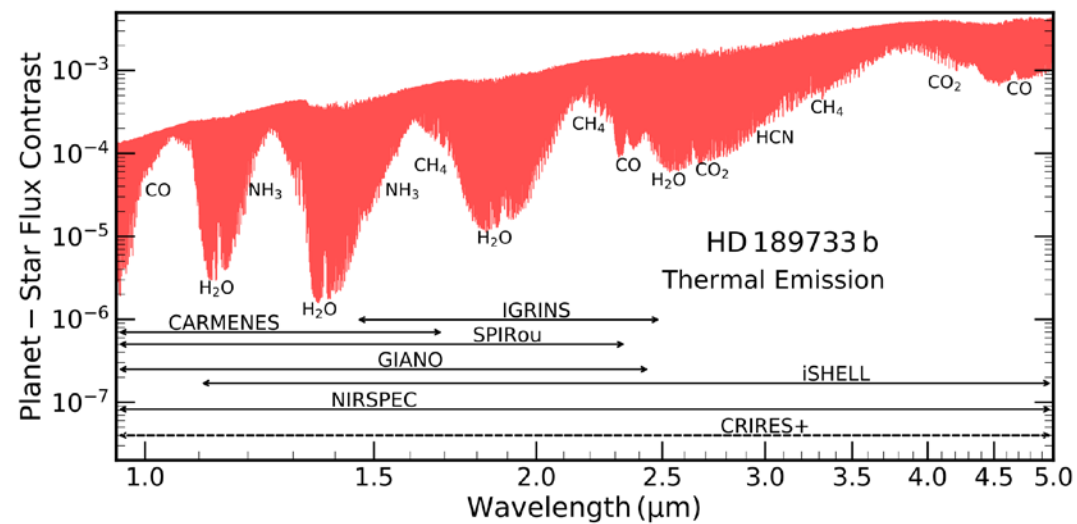
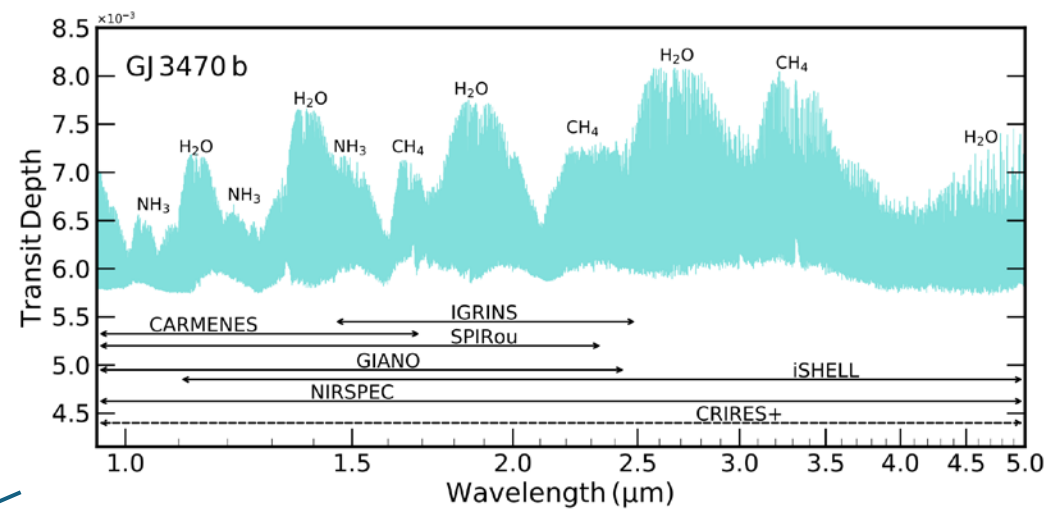


Credit: noaa.gov  
The atmospheric window

# Where does the data come from – High resolution:

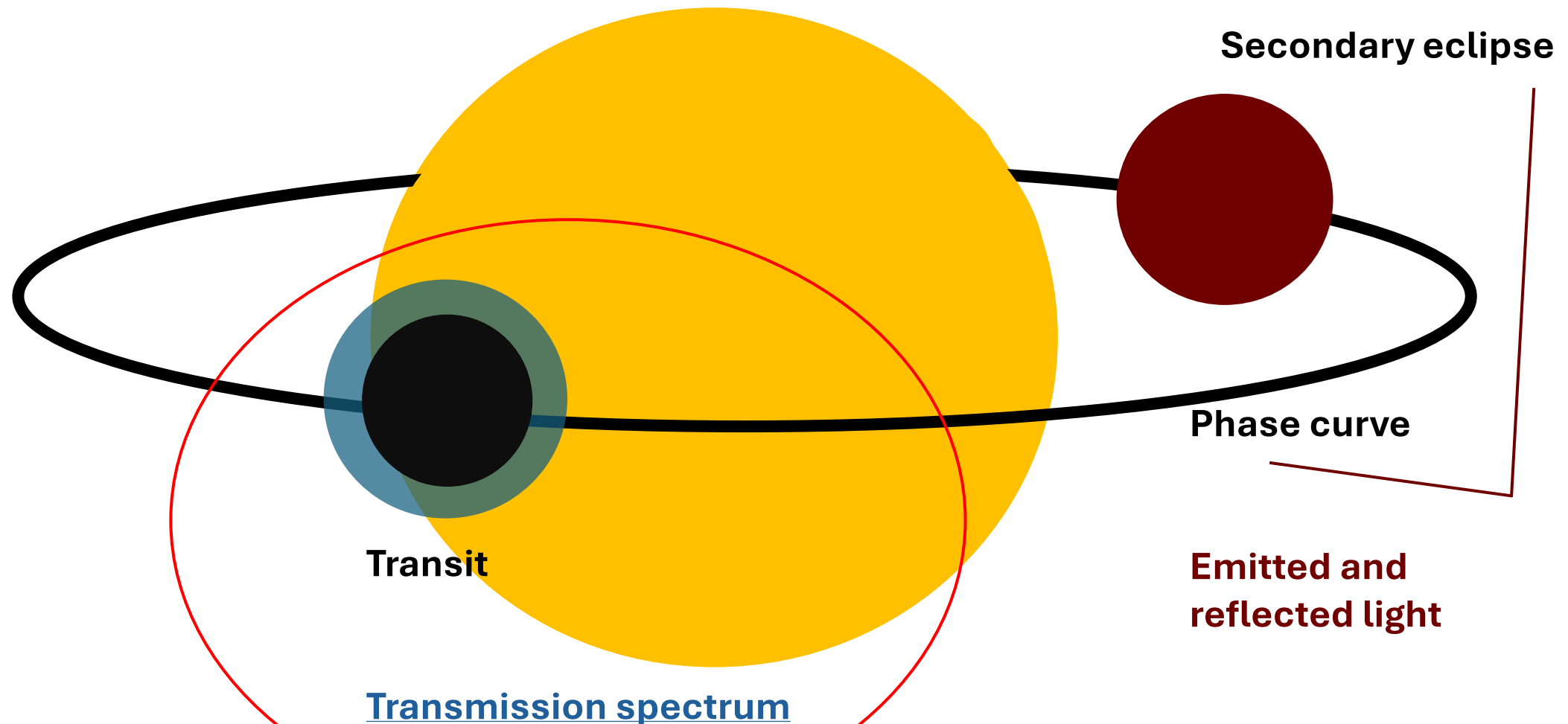


VLT/ESPRESSO  
HARPS-N  
CARMENES  
...



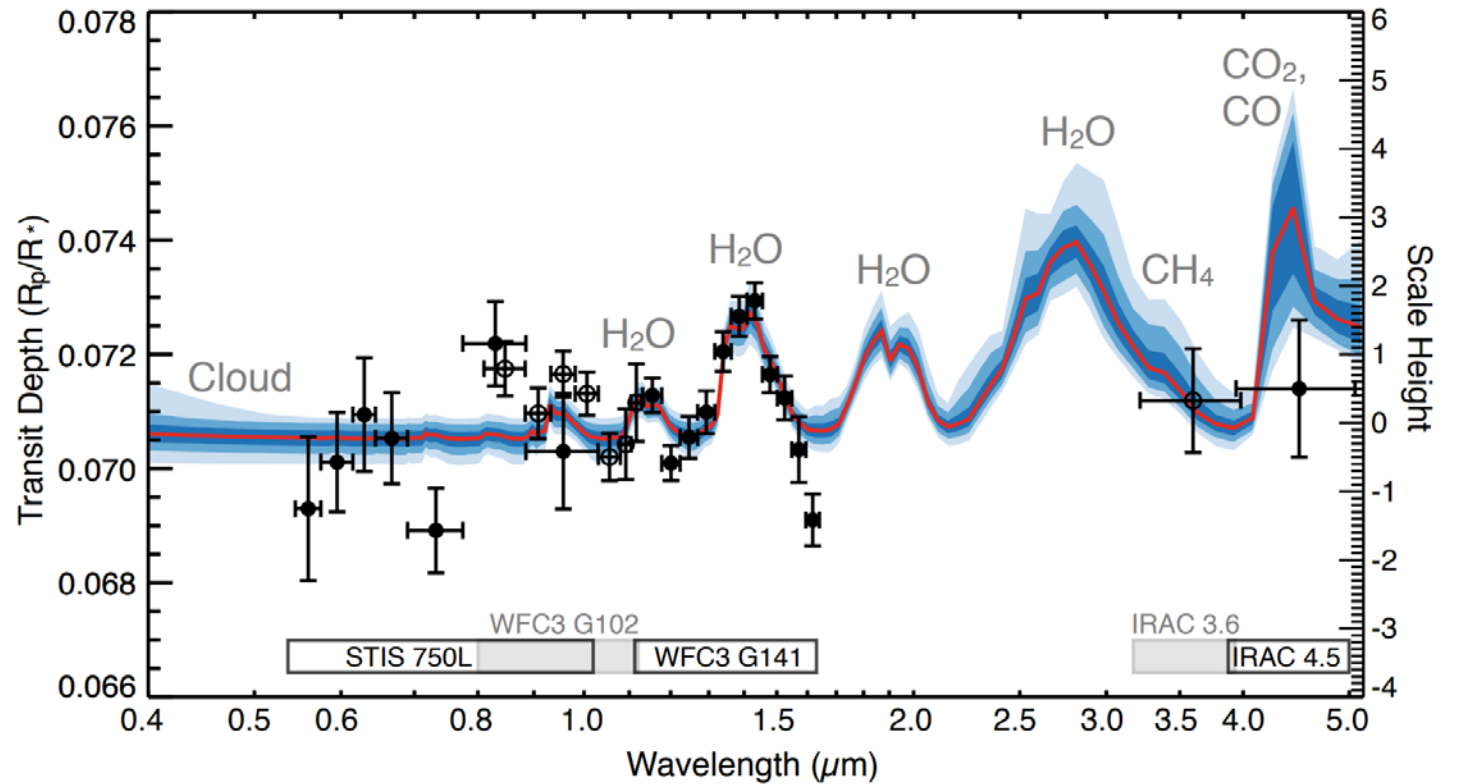
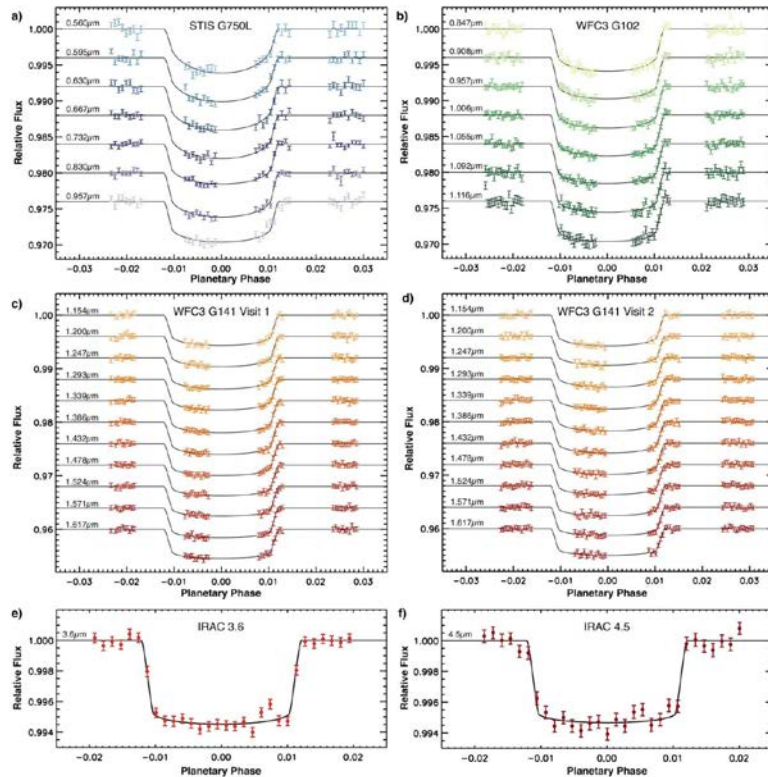
Ghandi et al 2020

# How do we measure exoplanet atmospheres?



# Transit – Transmission spectroscopy

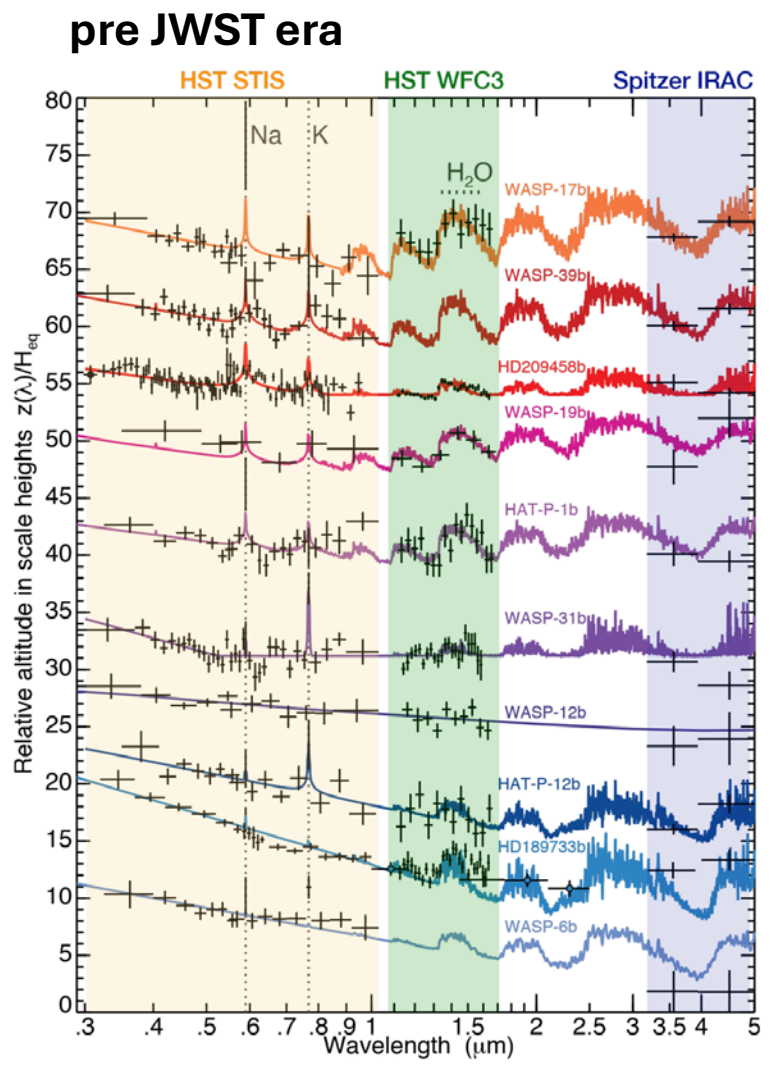
HAT-P26b, a Neptune mass planet with HST + Spitzer



Wakeford et al. 2022

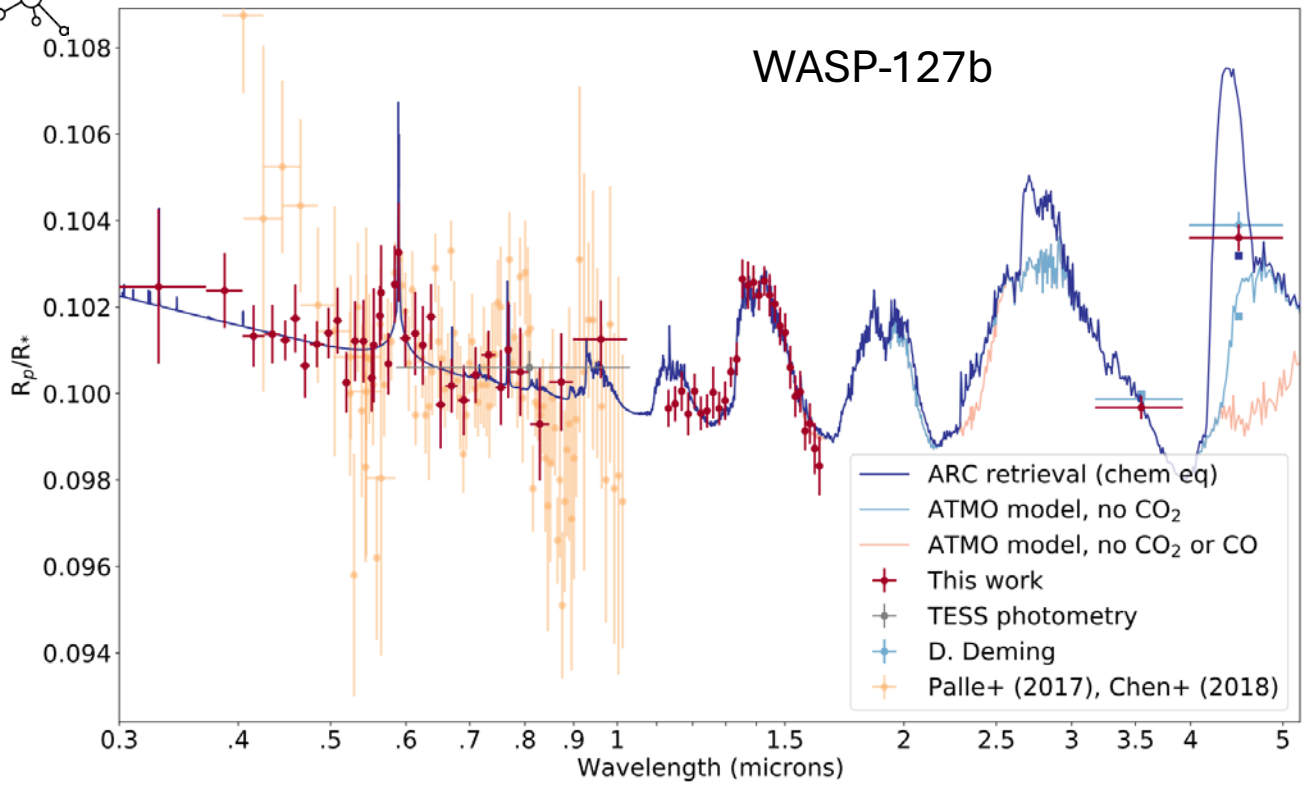
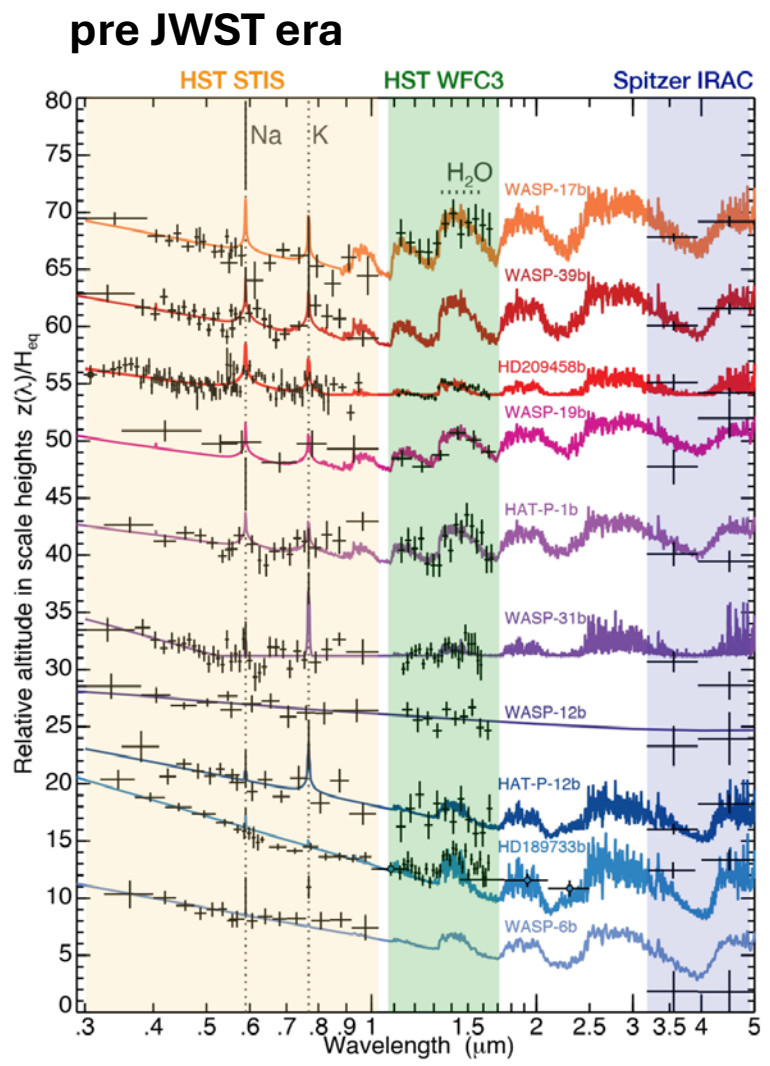


# Low resolution space based transmission spectra



Kempton & Knutson 2024; adapted from Sing et al 2010

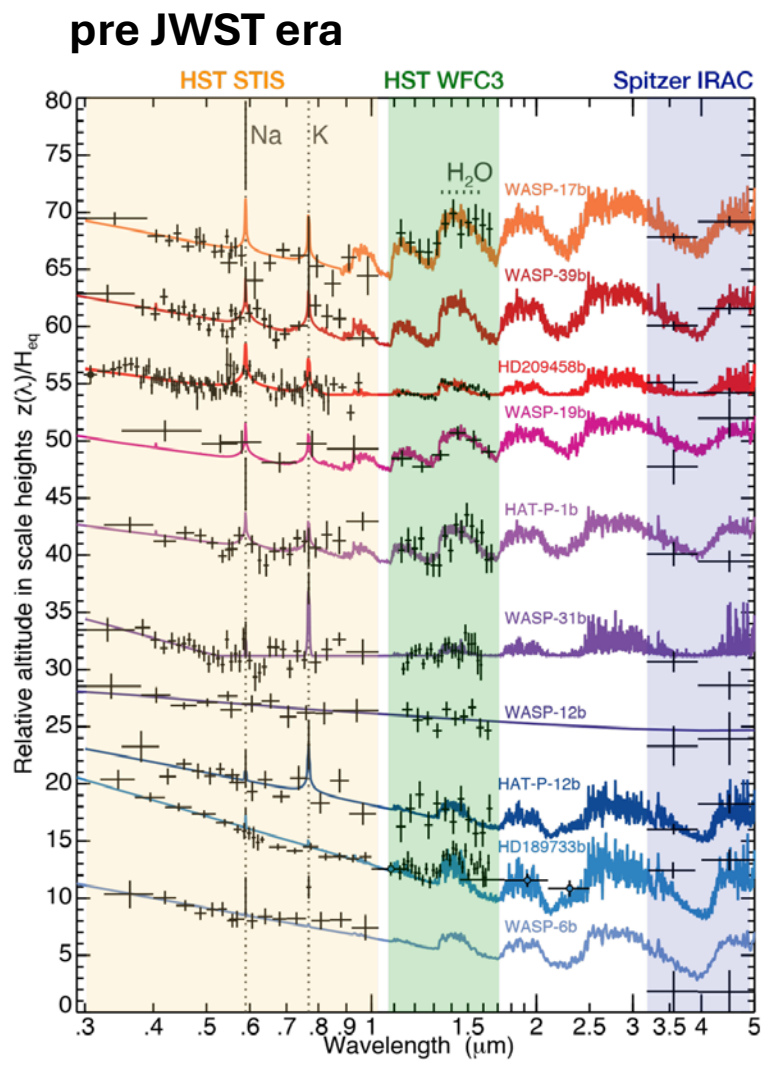
# Low resolution space based transmission spectra



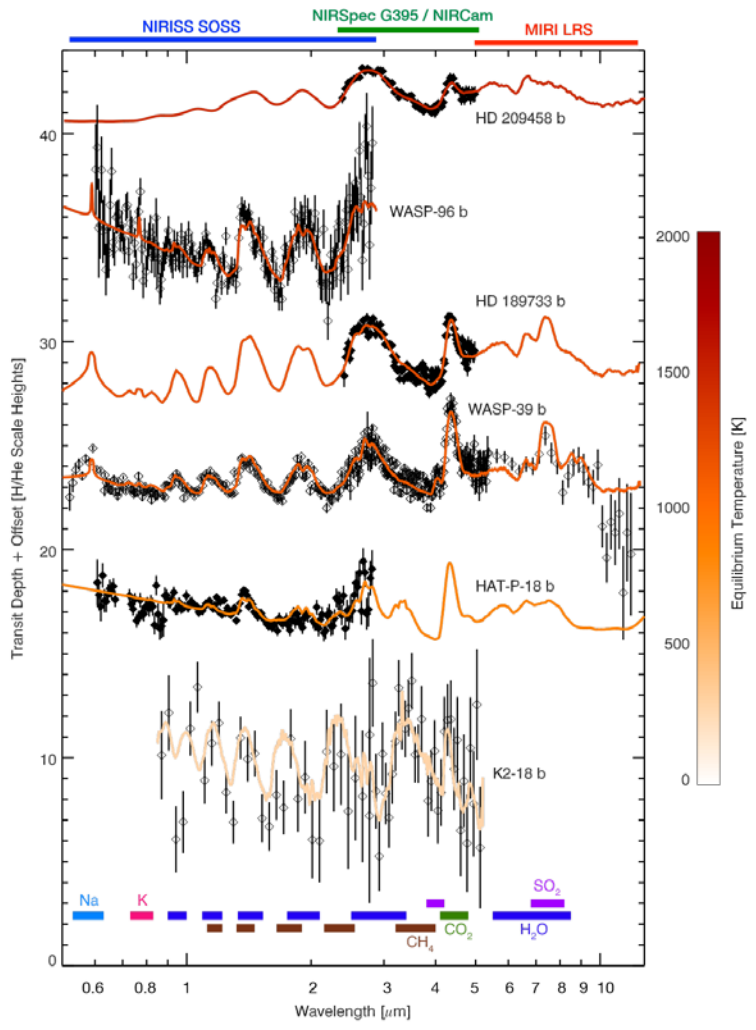
Spake et al 2019

Kempton & Knutson 2024; adapted from Sing et al 2010

# Low resolution space based transmission spectra

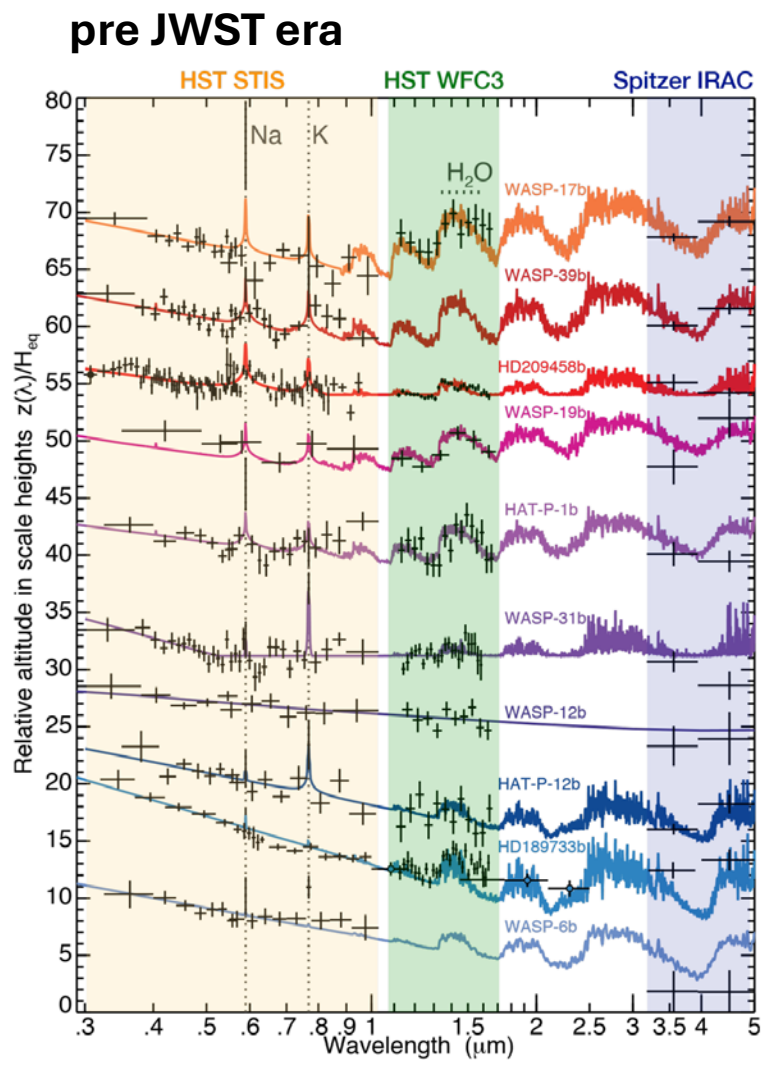


## JWST first results

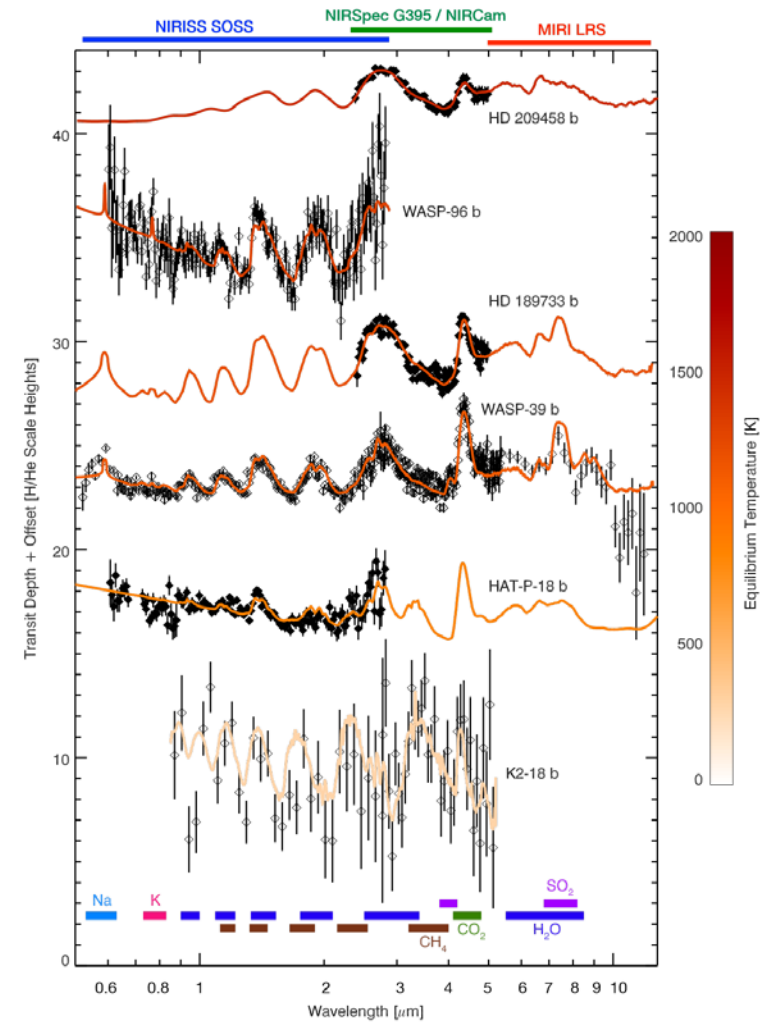


Kempton & Knutson  
2024; left: adapted  
from Sing et al 2010

# Low resolution space based transmission spectra

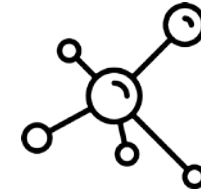
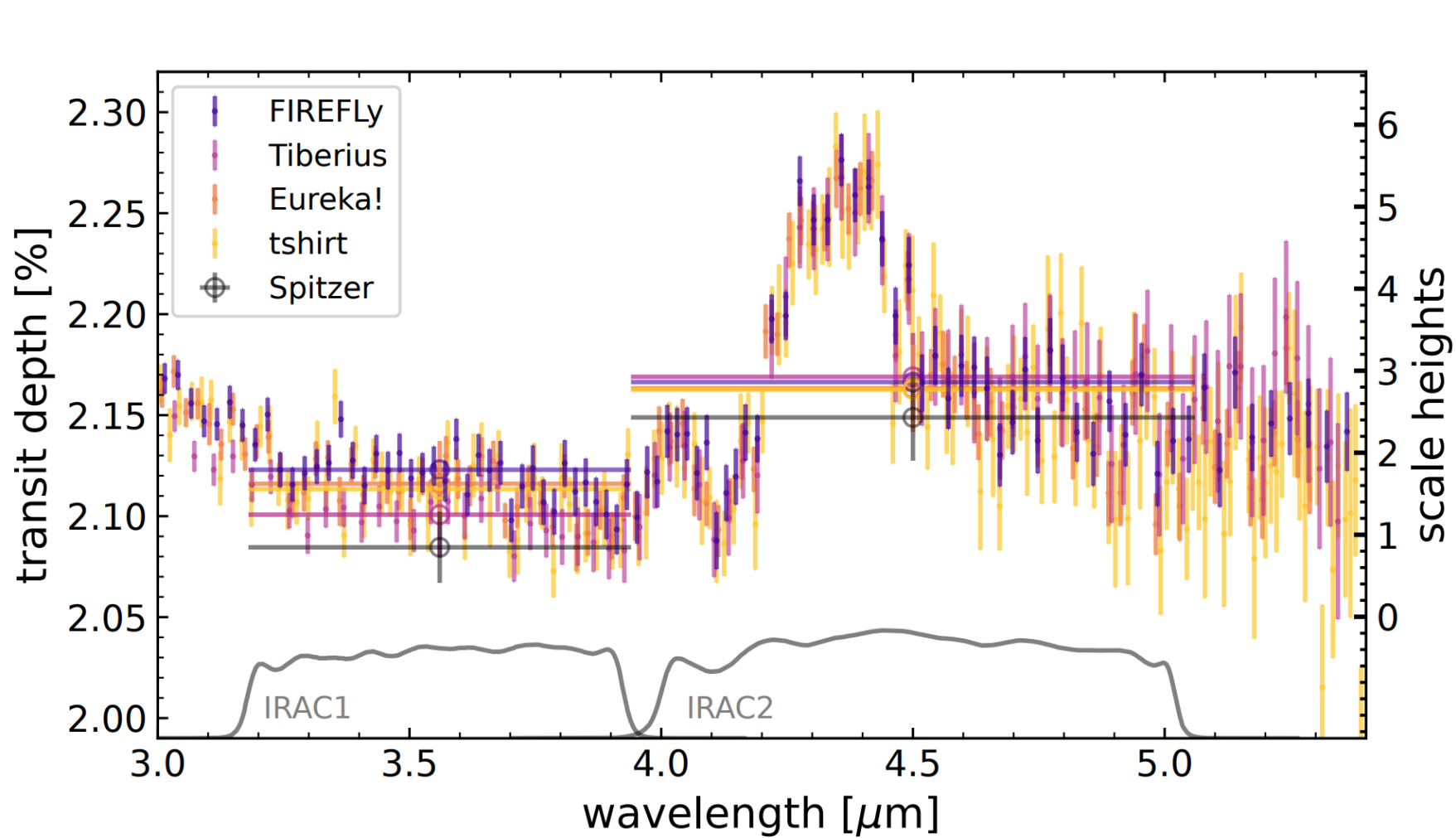


### JWST first results



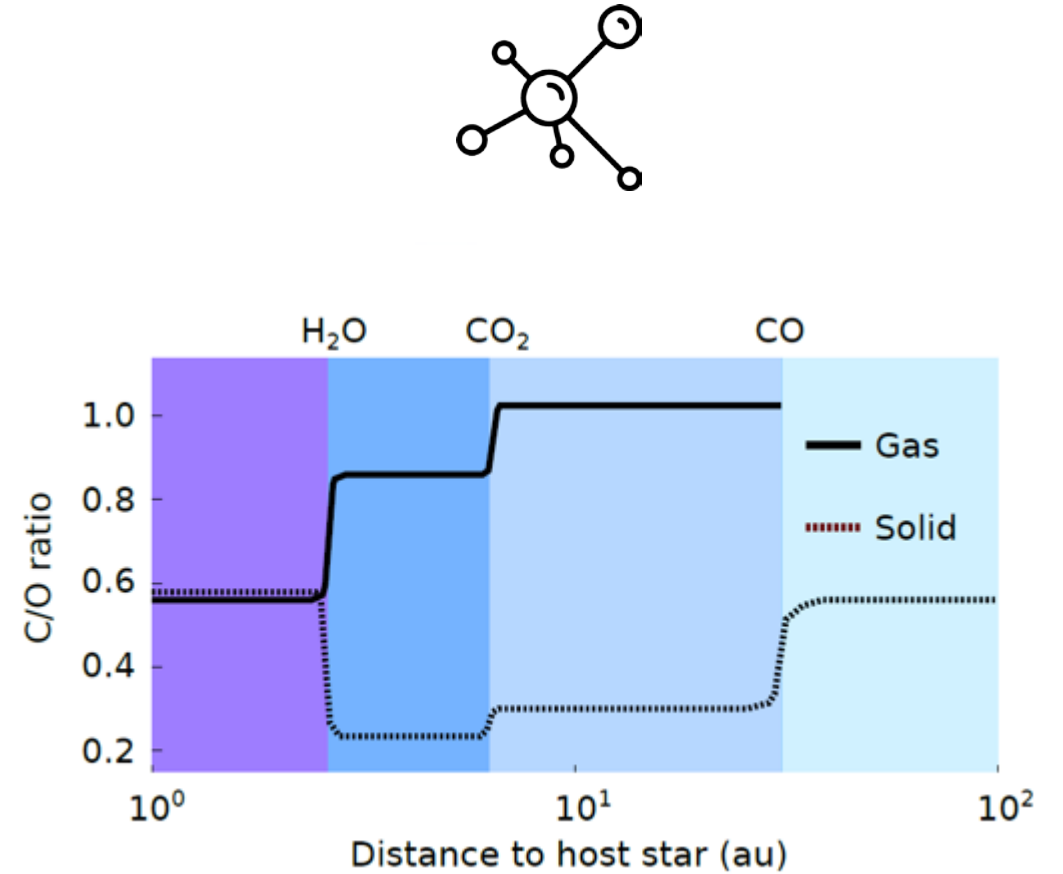
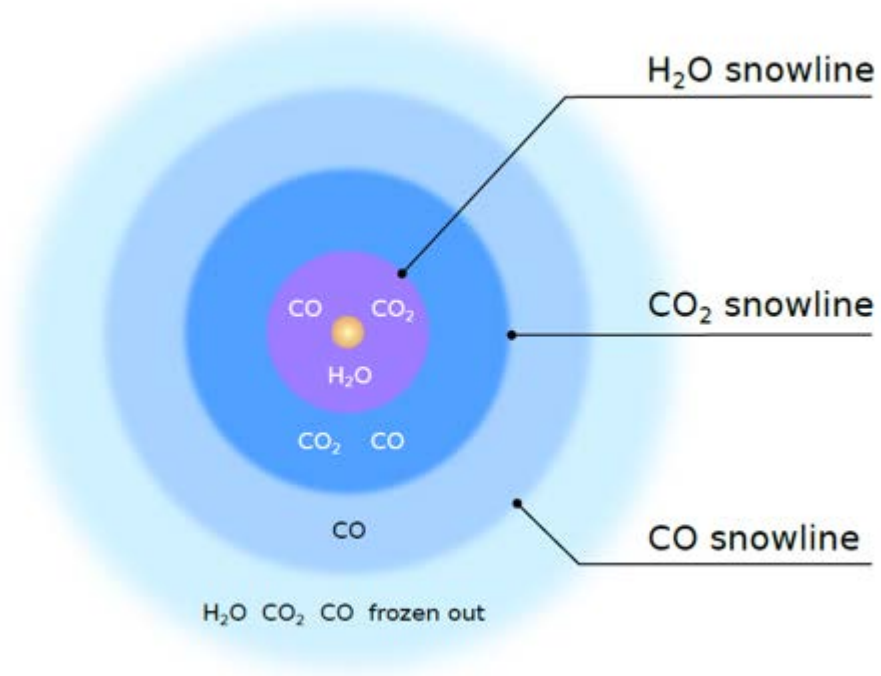
Kempton & Knutson  
2024; left: adapted  
from Sing et al 2010

# JWST vs. Spitzer - CO<sub>2</sub> and Sulfur dioxide in WASP-39b



CO<sub>2</sub> detection in WASP-39b  
The JWST Transiting Exoplanet  
Community Early Release Science  
Team  
2022

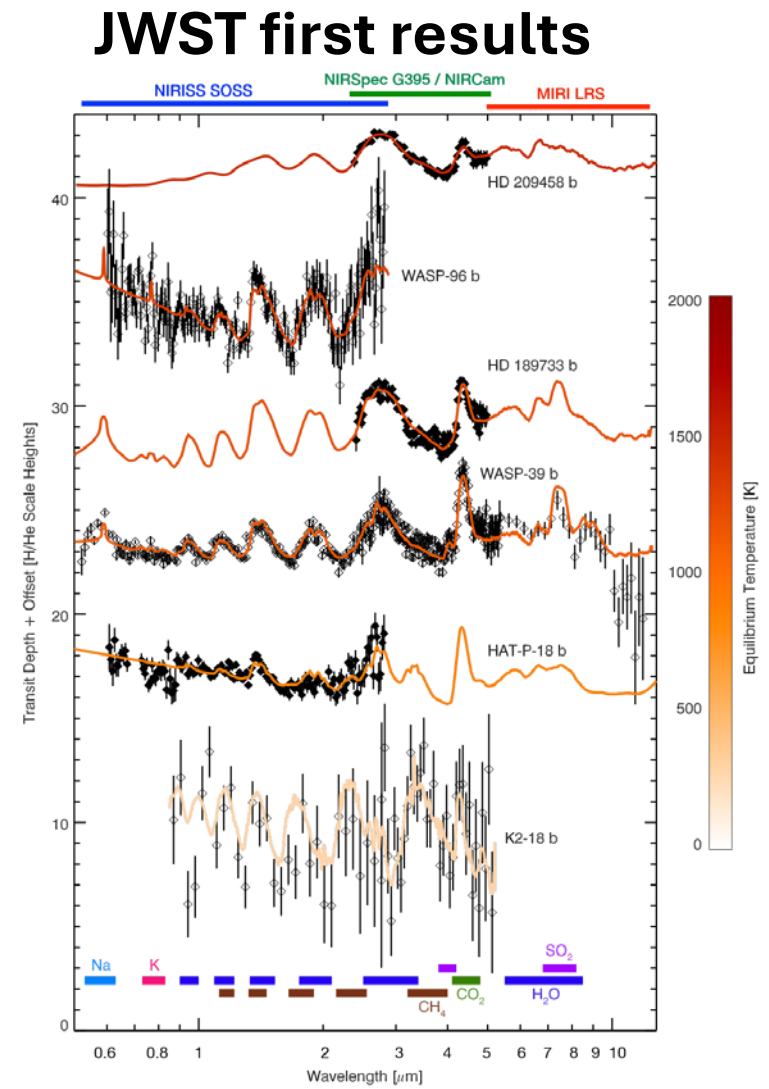
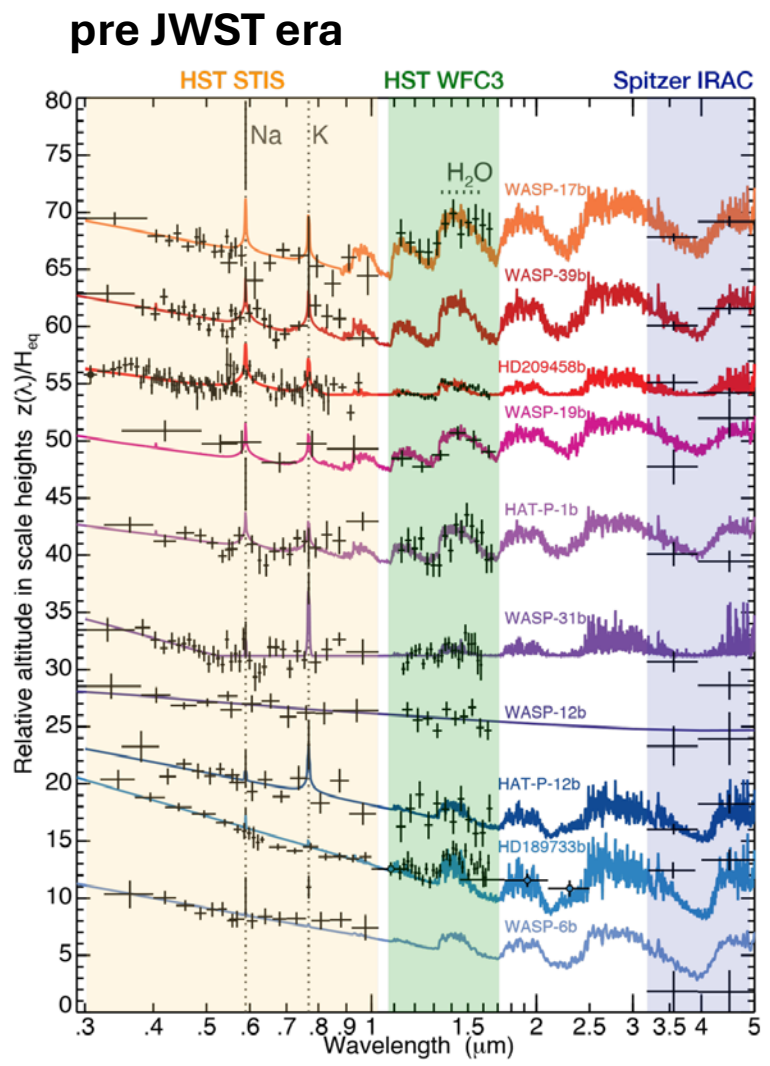
# C/O ratio and planet formation



Cont 2023,

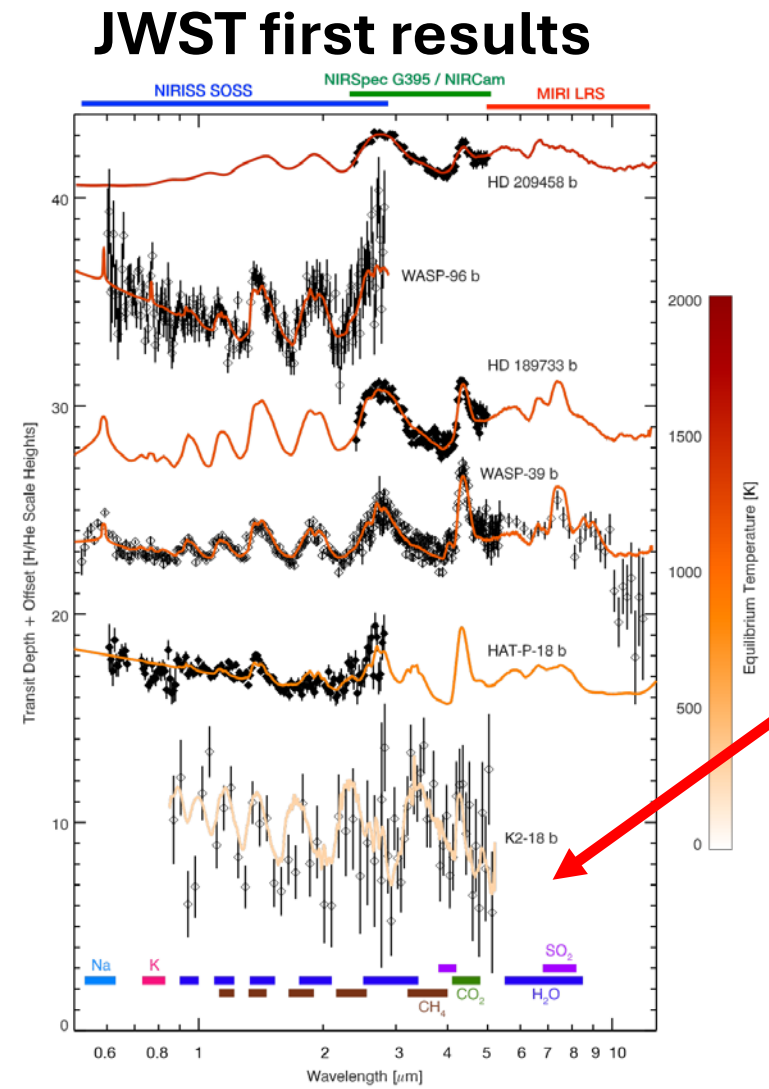
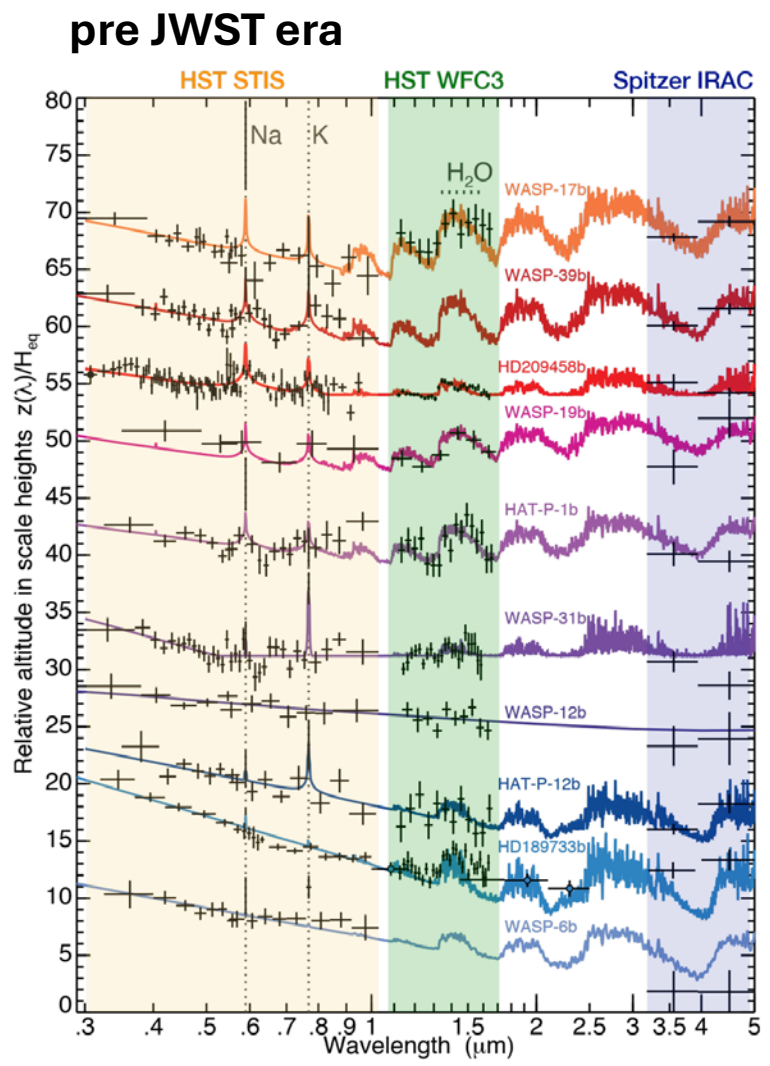
right panel adapted from Madhusudhan 2019, also see Odberg 2011

# Low resolution space based transmission spectra



Kempton & Knutson  
2024; left: adapted  
from Sing et al 2010

# Low resolution space based transmission spectra



Madhusudhan et al 2024

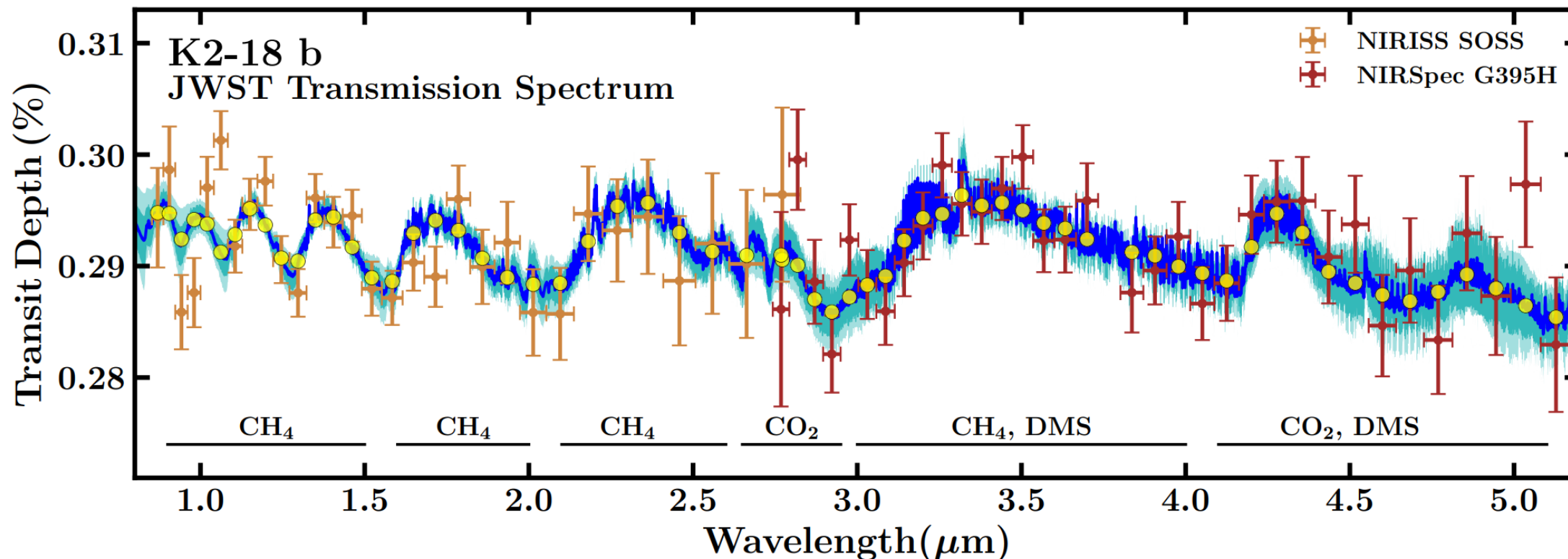
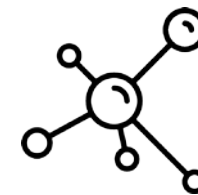
Kempton & Knutson  
2024; left: adapted  
from Sing et al 2010



# Low resolution space-based transmission spectra

## JWST results for K2-18b, a possible Hycean world

(Hycean: temperate ocean-covered worlds with H<sub>2</sub>-rich atmospheres)

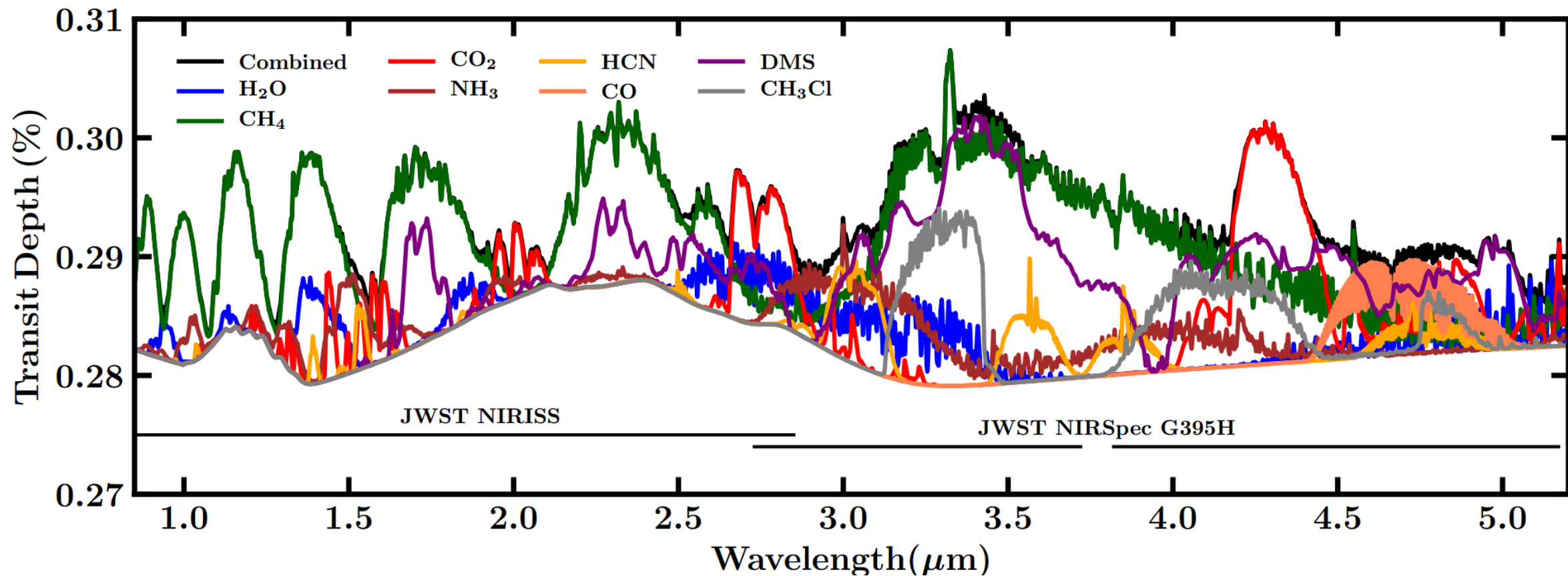
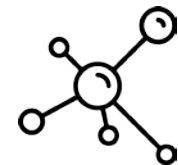


Madhusudhan et al 2024

Dimethyl sulfide (DMS) – a predicted biomarker for Hycean worlds

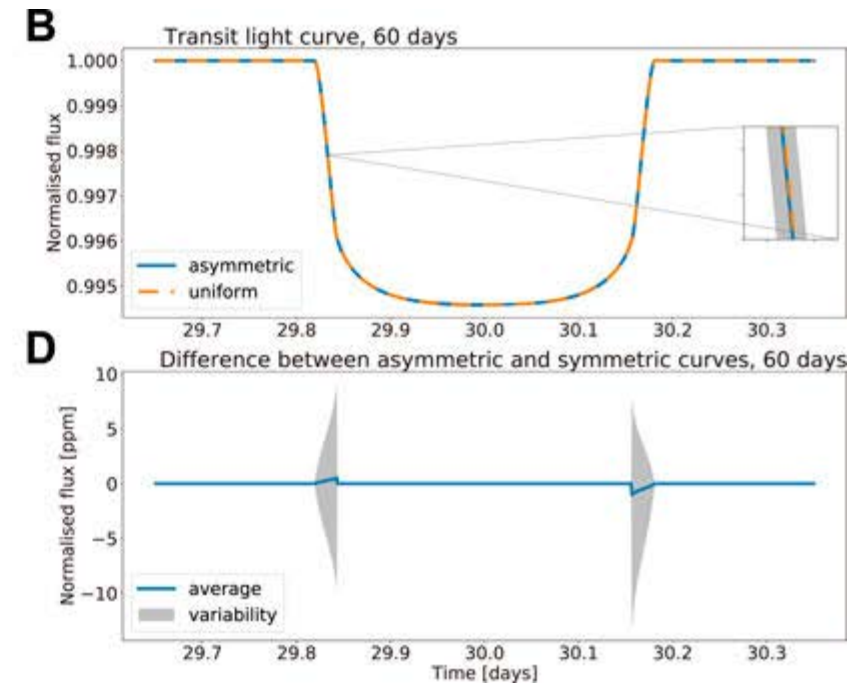
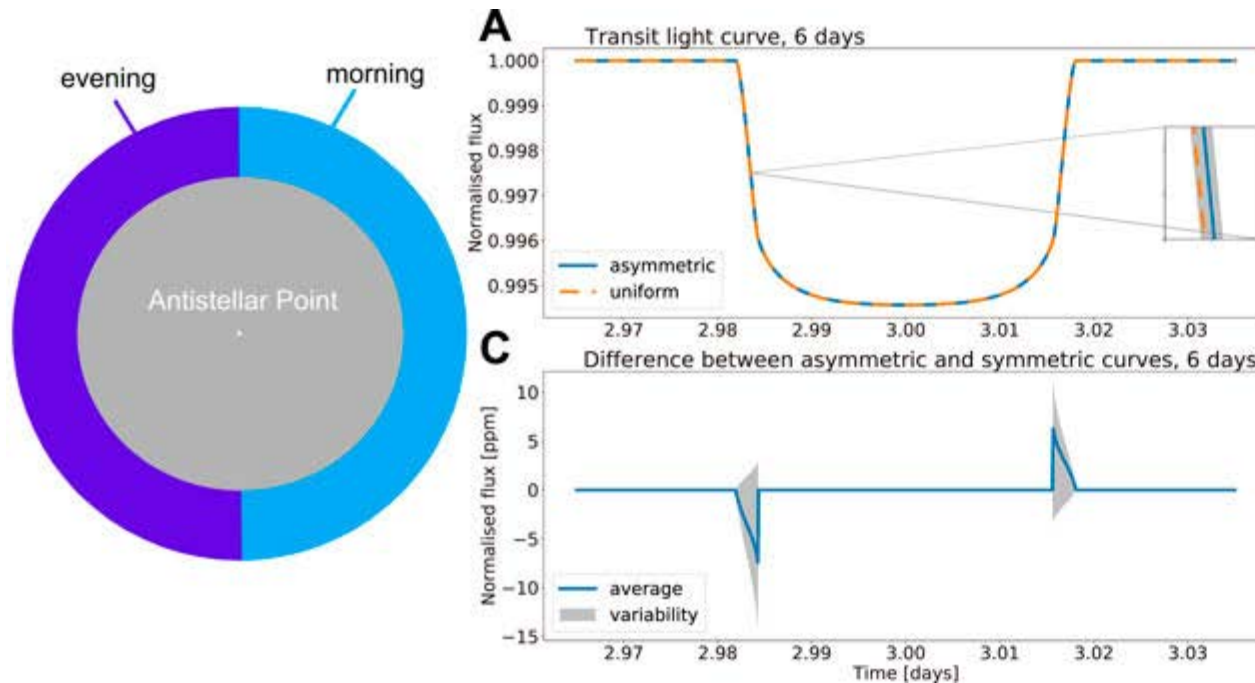
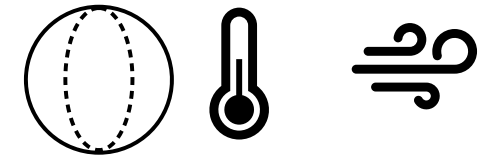
# Low resolution space-based transmission spectra

## The spectrum and its components from multiple absorbers



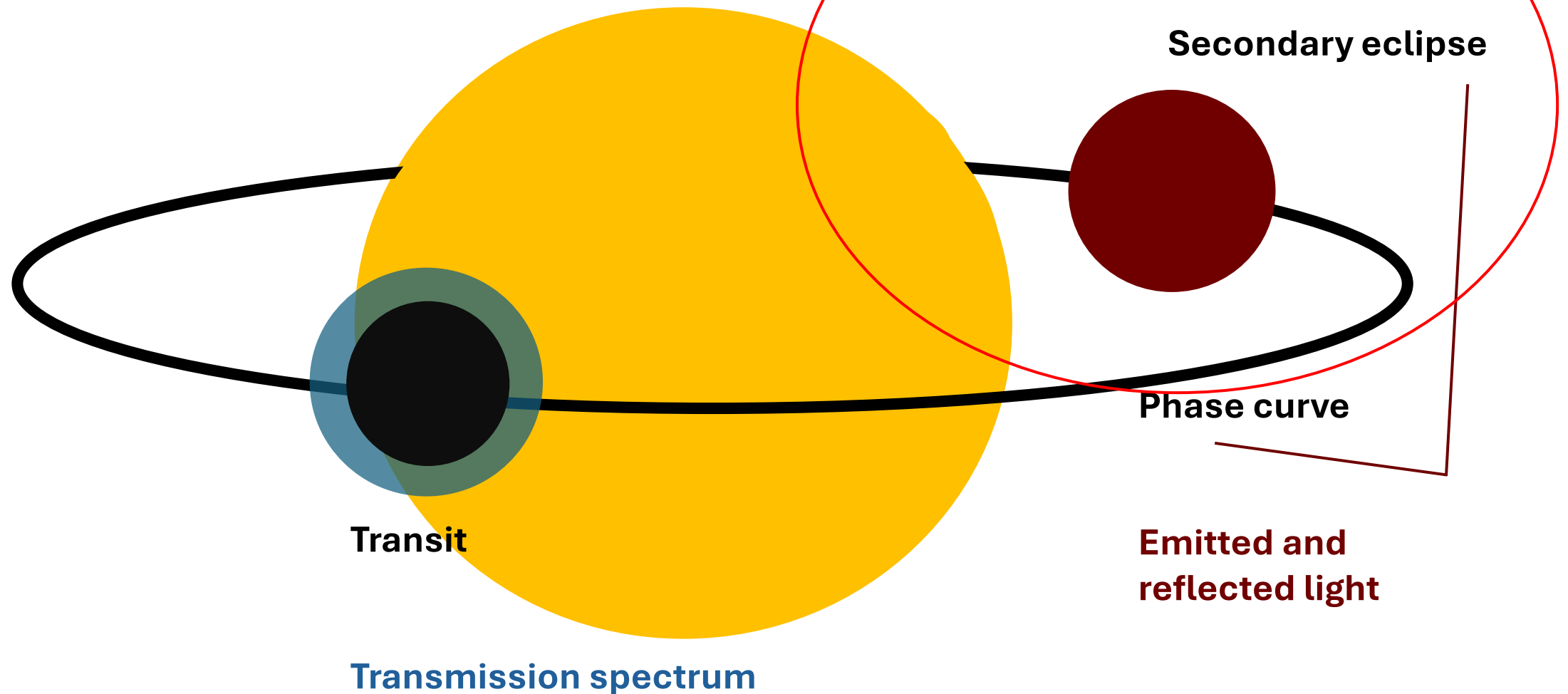
Madhusudhan et al 2024

# 3D effects during transit in low resolution



Song et al 2021  
Also Falco 2024

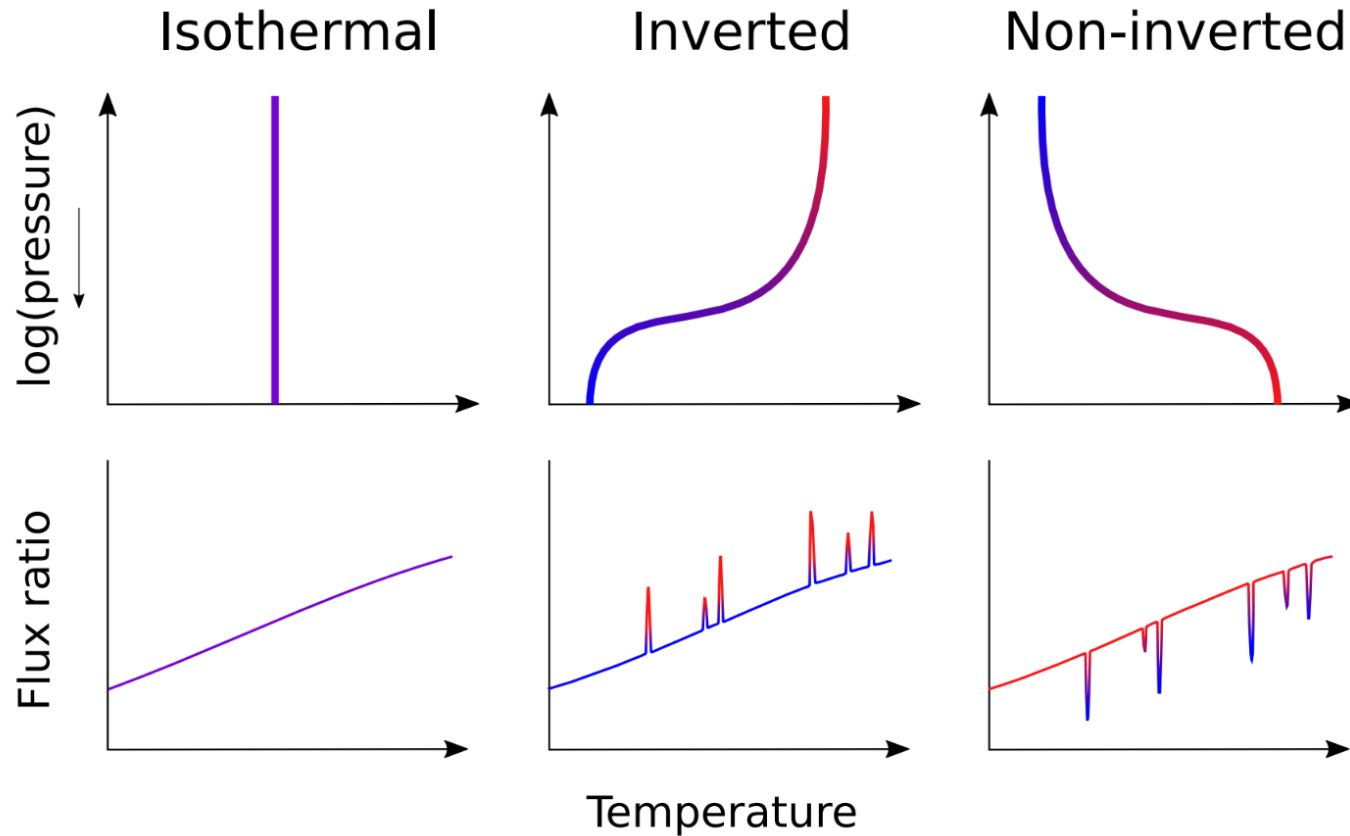
# How do we measure exoplanet atmospheres?



# Temperature – pressure profile



In the emission case:



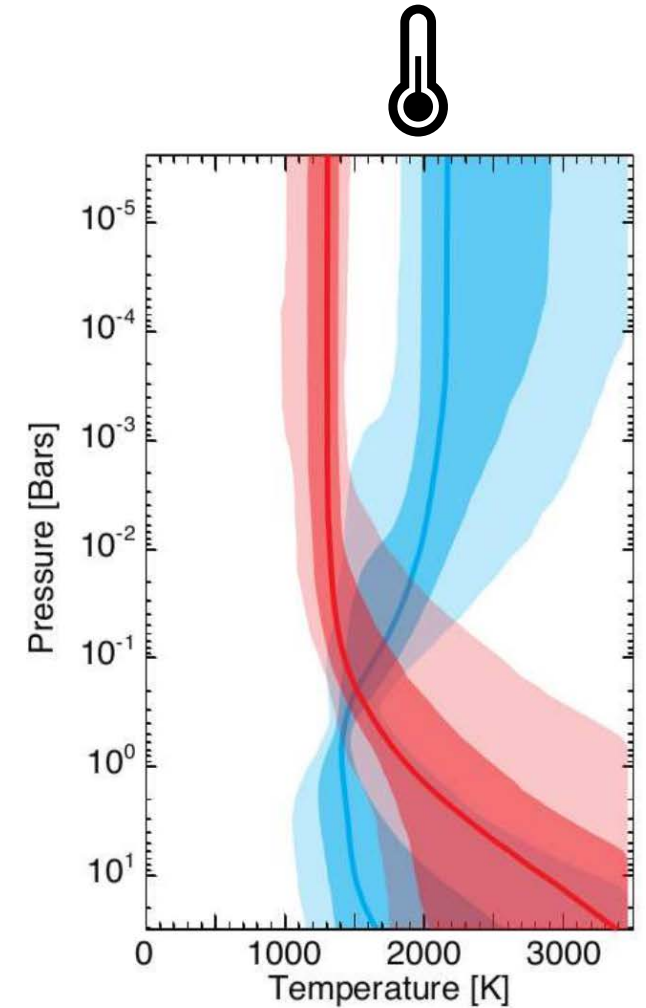
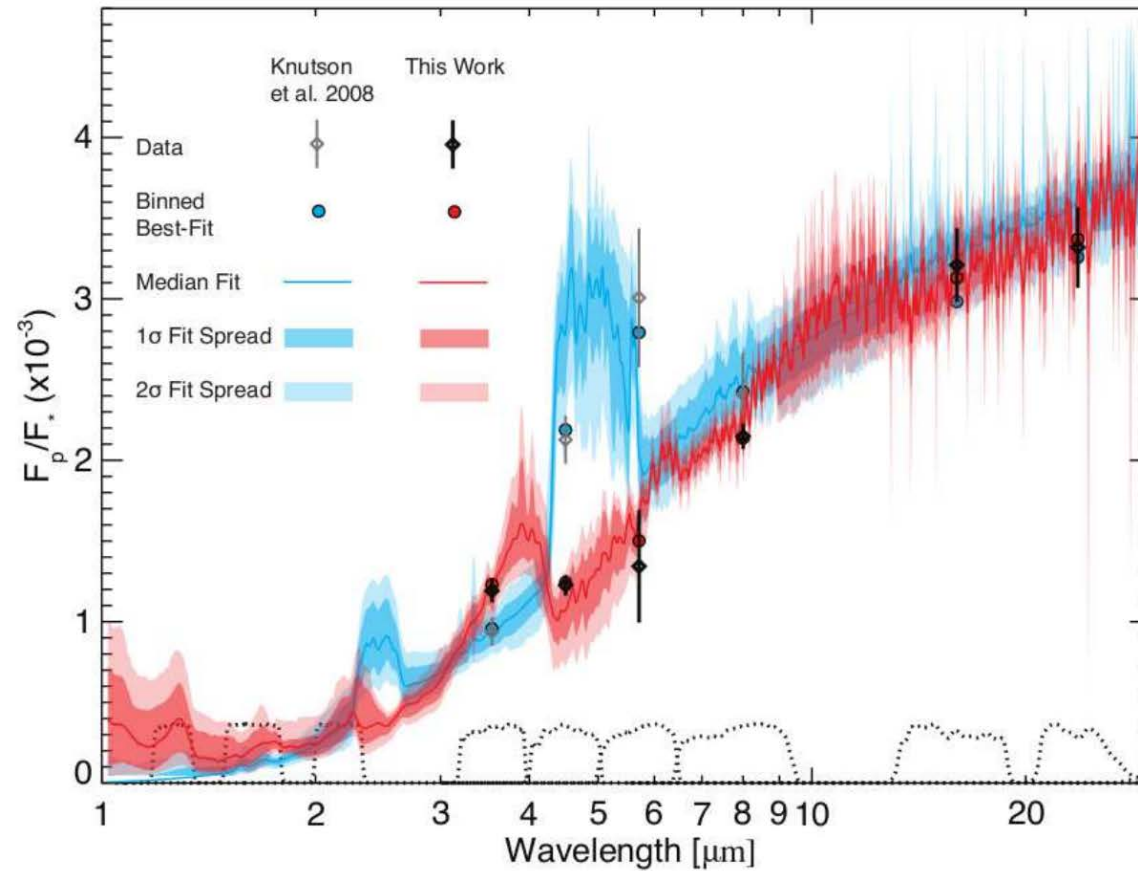
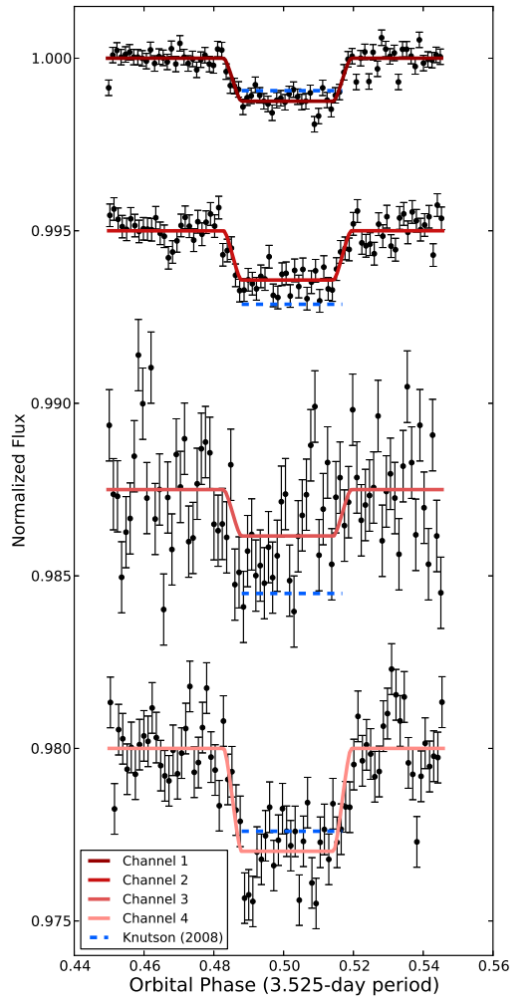
Blackbody spectra

Example Spitzer

Example high resolution

# Emitted light spectrum

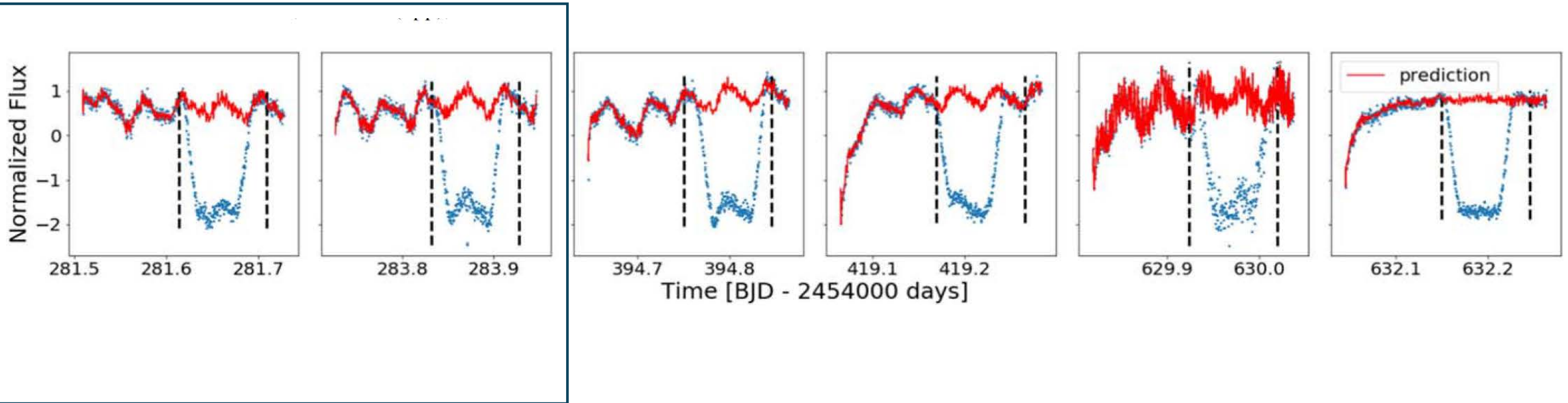
## HD 209458b with Spitzer



Diamond-Lowe et al 2014

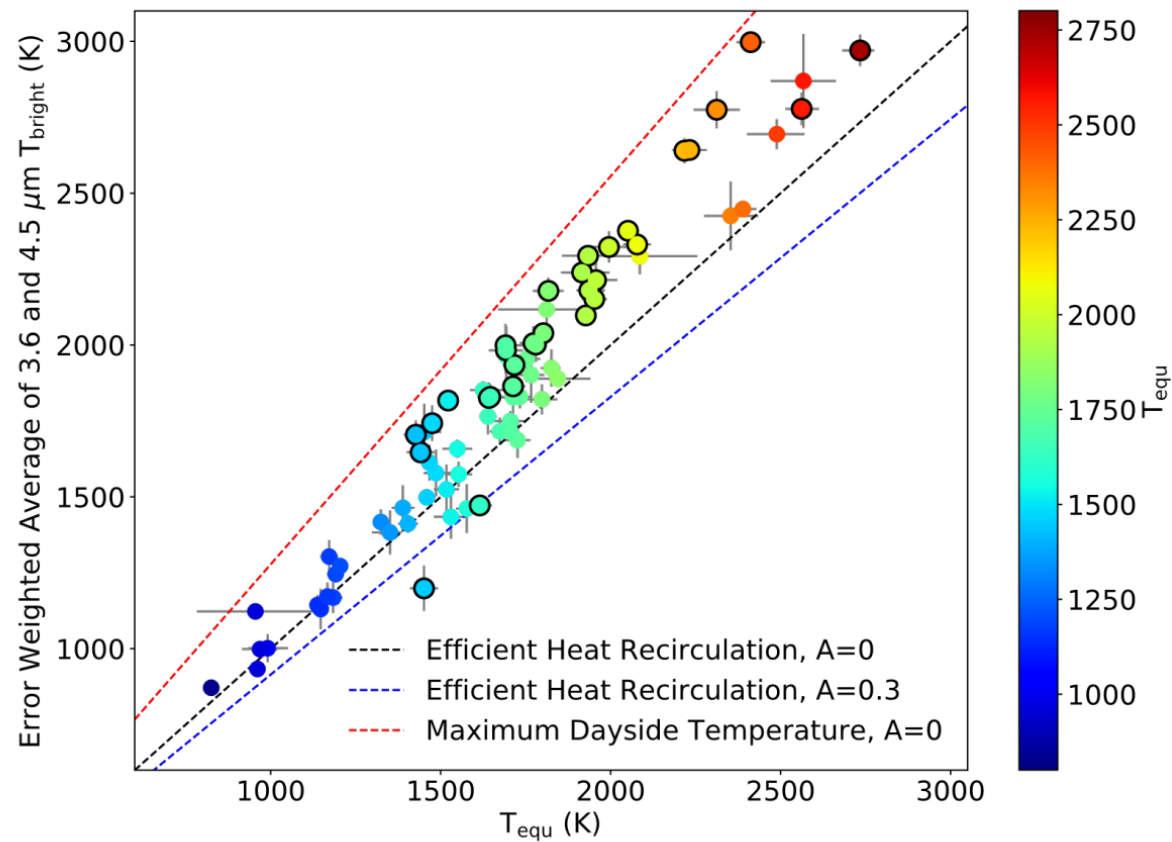
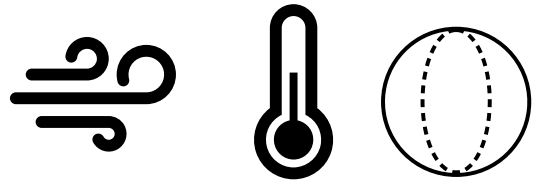
# Emitted light spectrum

Spitzer: (warm Spitzer: 3.6 $\mu$  and 4.5 $\mu$ ) photometry

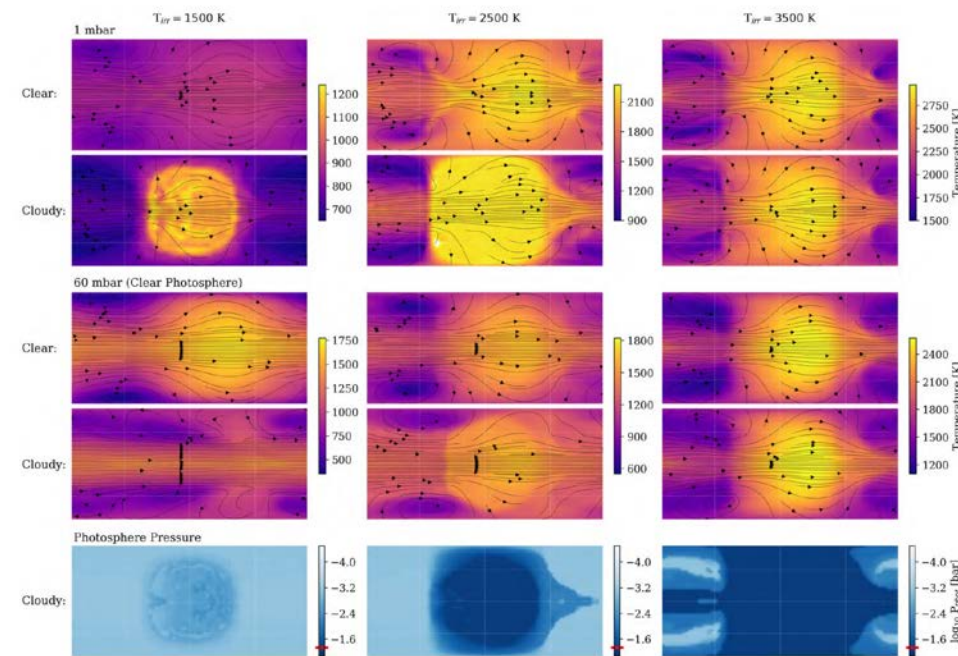


Morvan et al 2019

# Heat redistribution



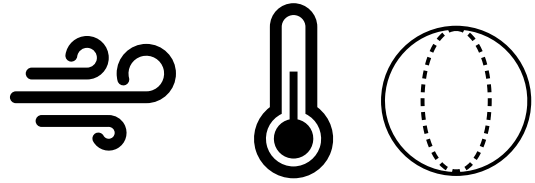
Wallack et al. (2021)



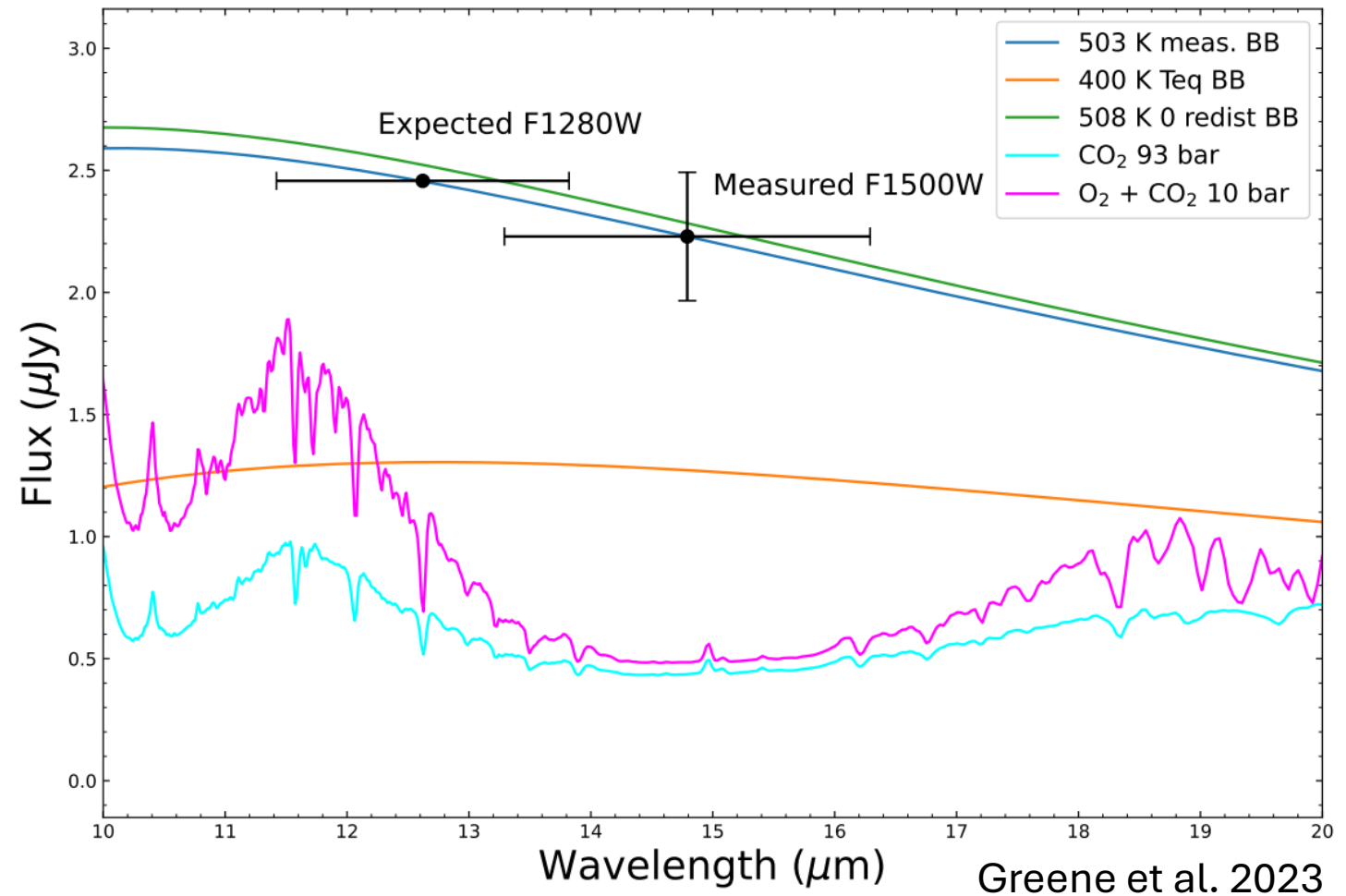
Roman et al. (2021)



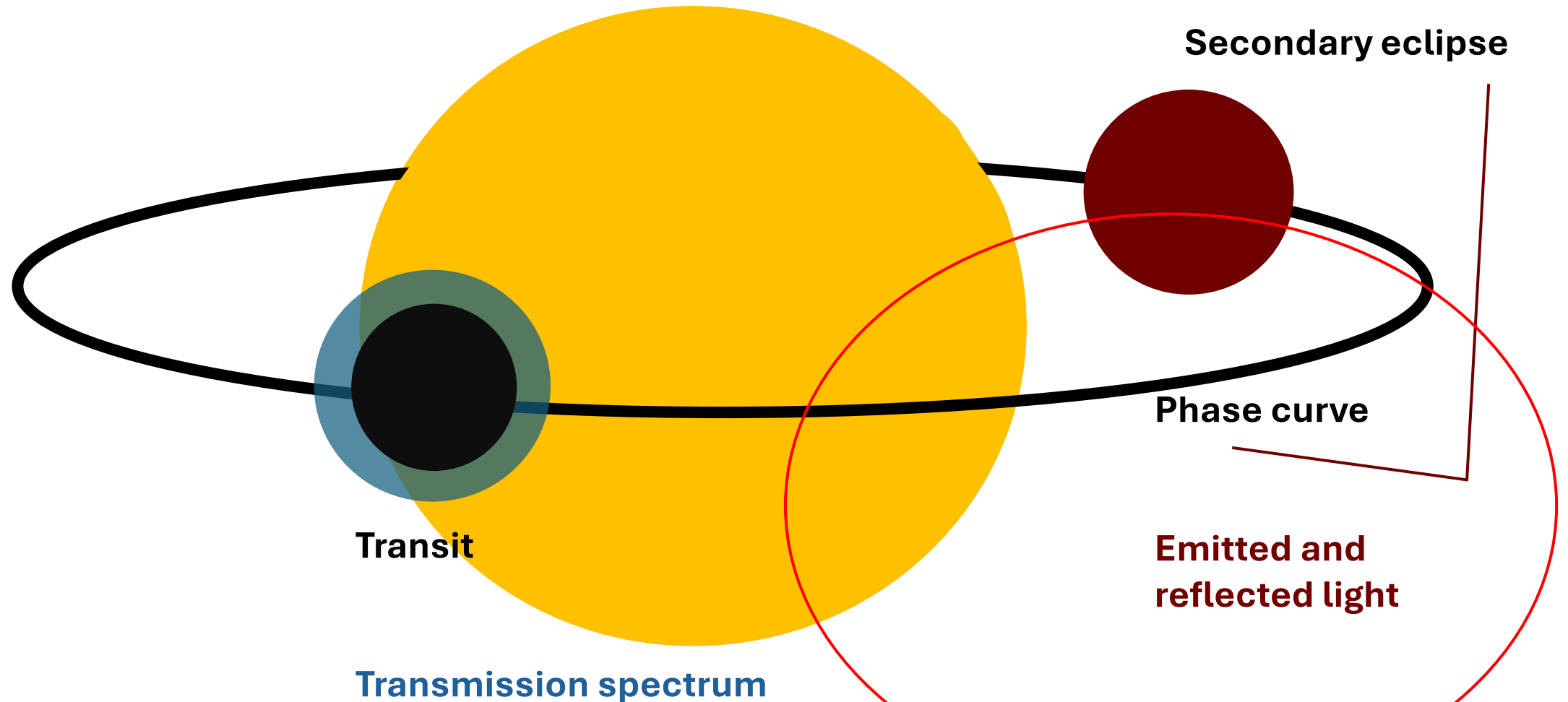
# (no) Heat redistribution



## Thermal emission spectrum of Trappist 1b



# How do we measure exoplanet atmospheres?

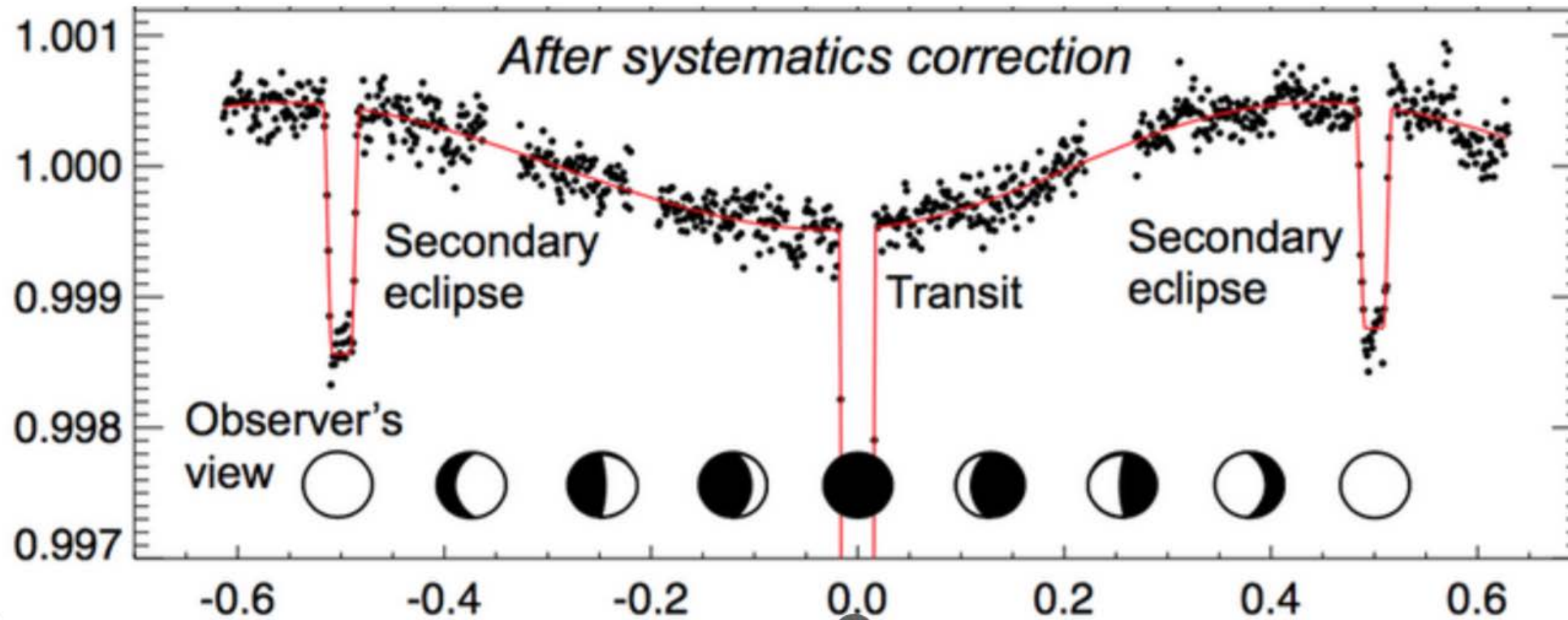


# How do we measure exoplanet atmospheres?



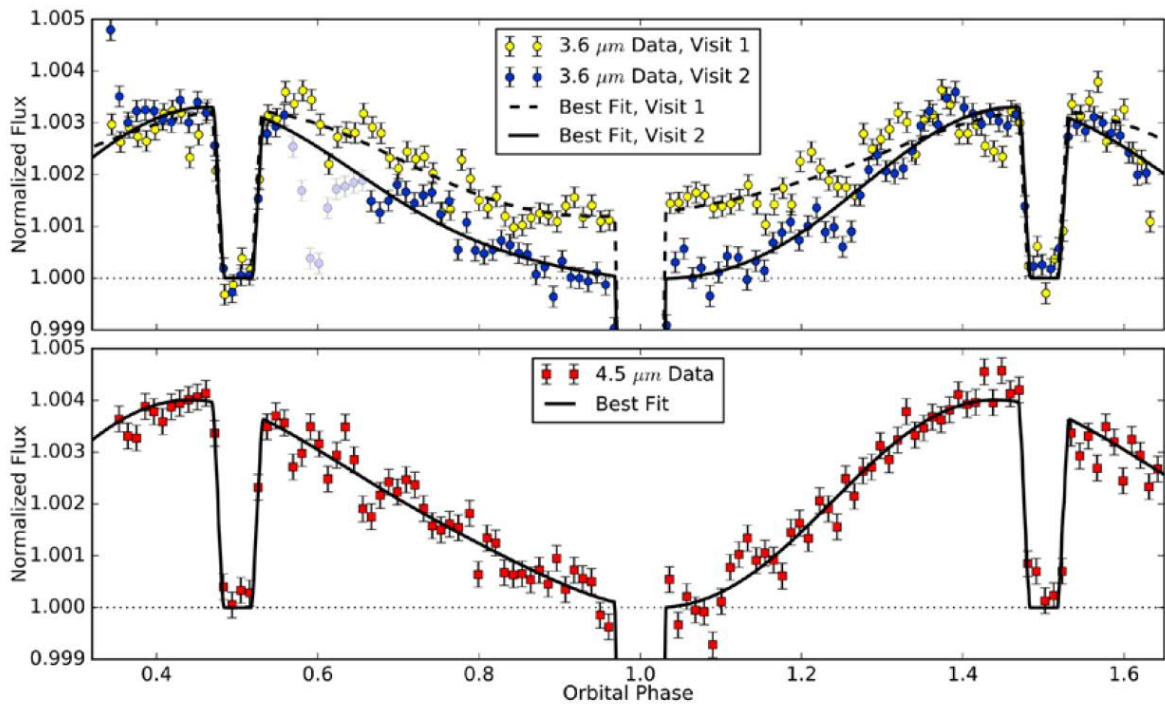
Phase curve  
Secondary eclipse

Emitted and reflected light

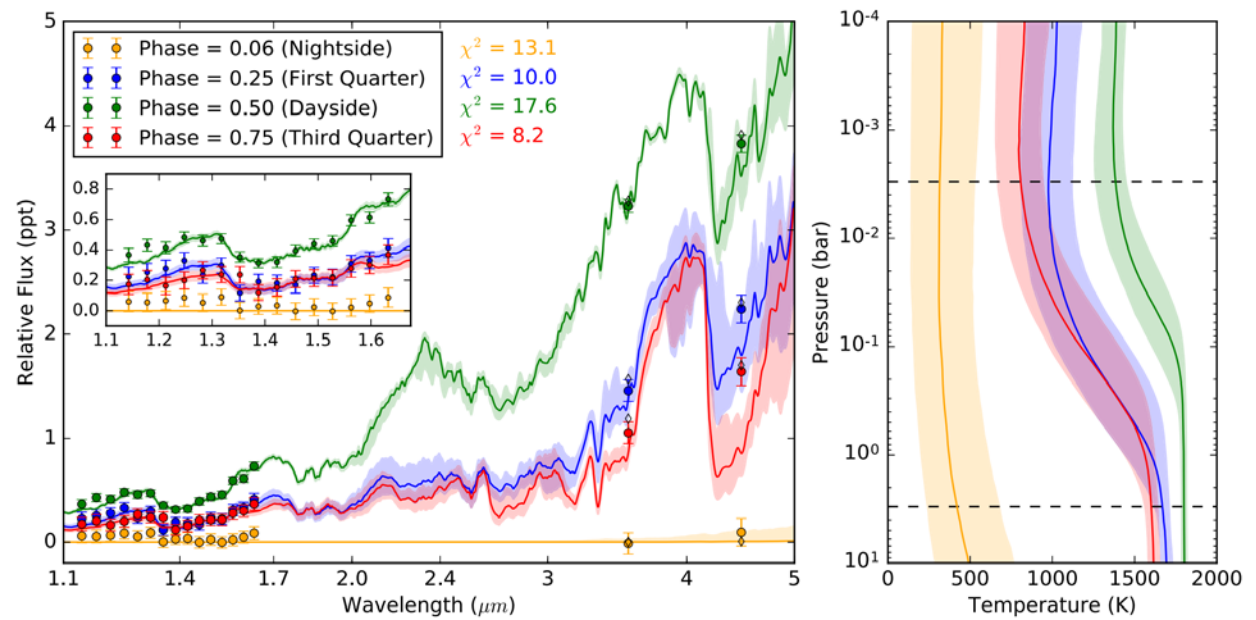
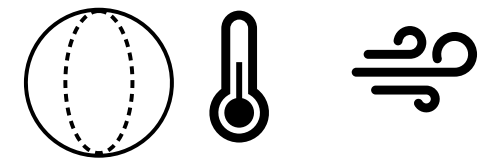


Pluriel 2023;  
adapted from  
Knutsen et al. 2012

# Phase Curves

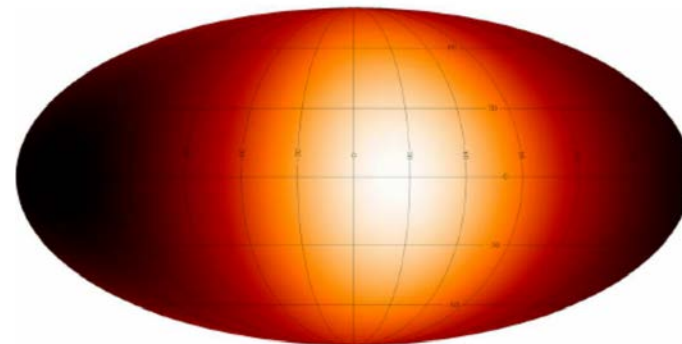
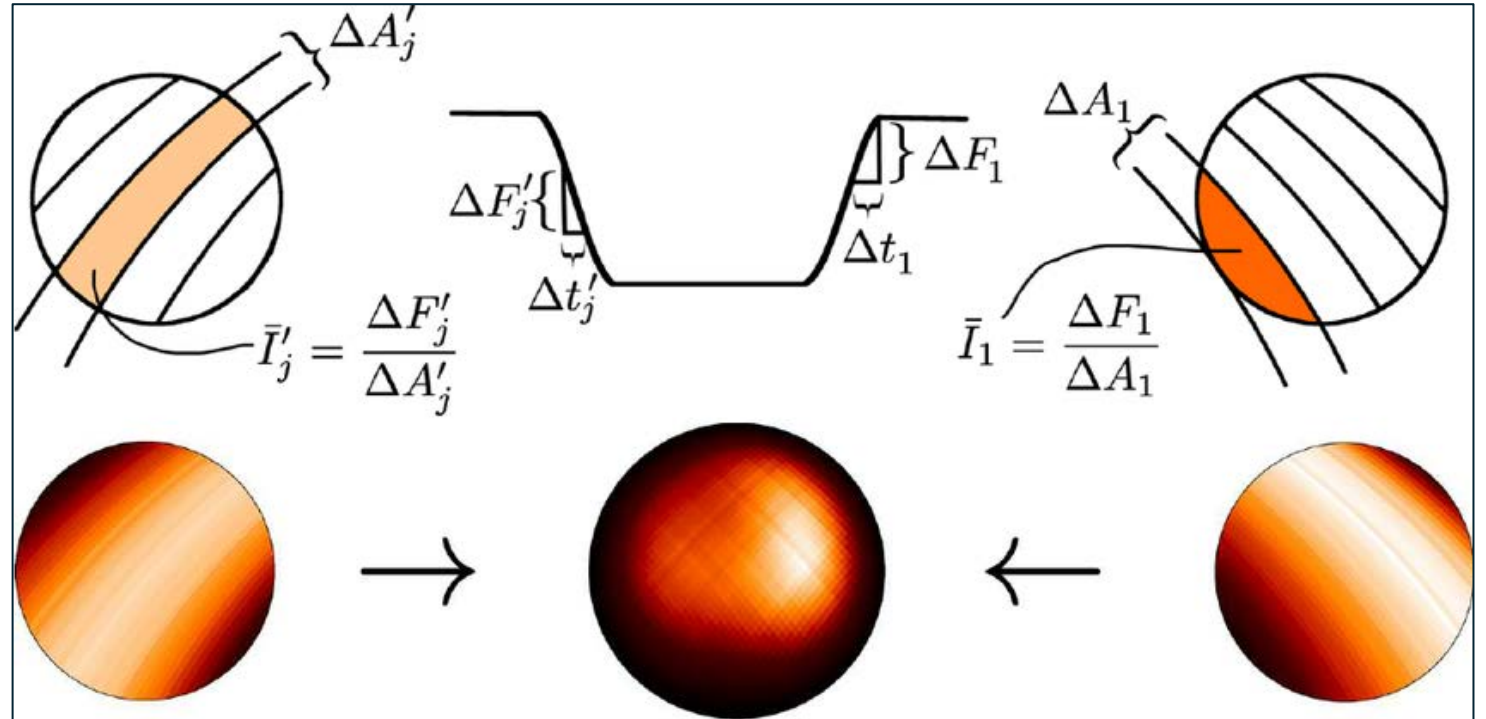
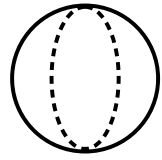
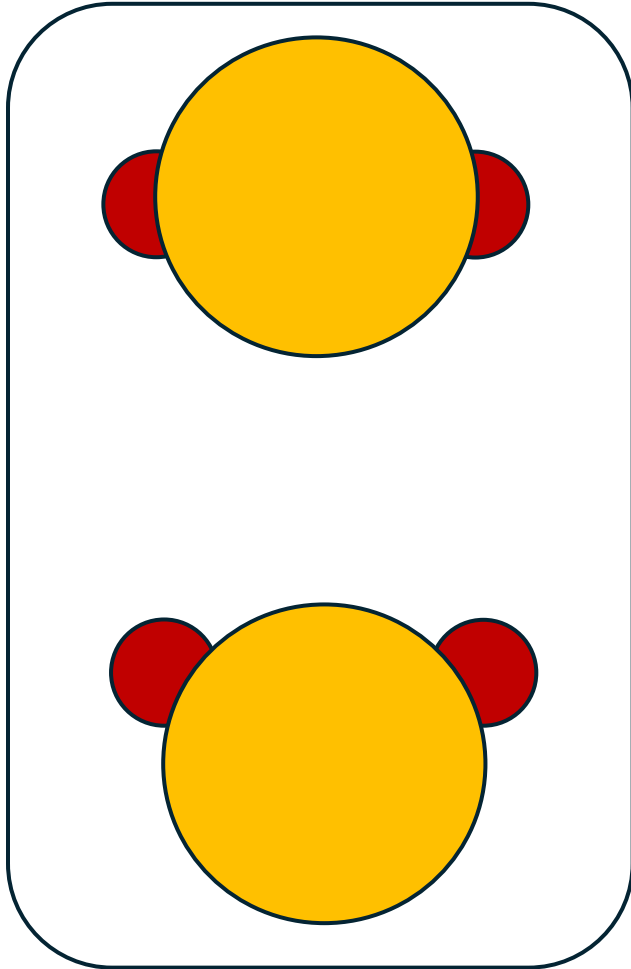


Stevenson *et al.*



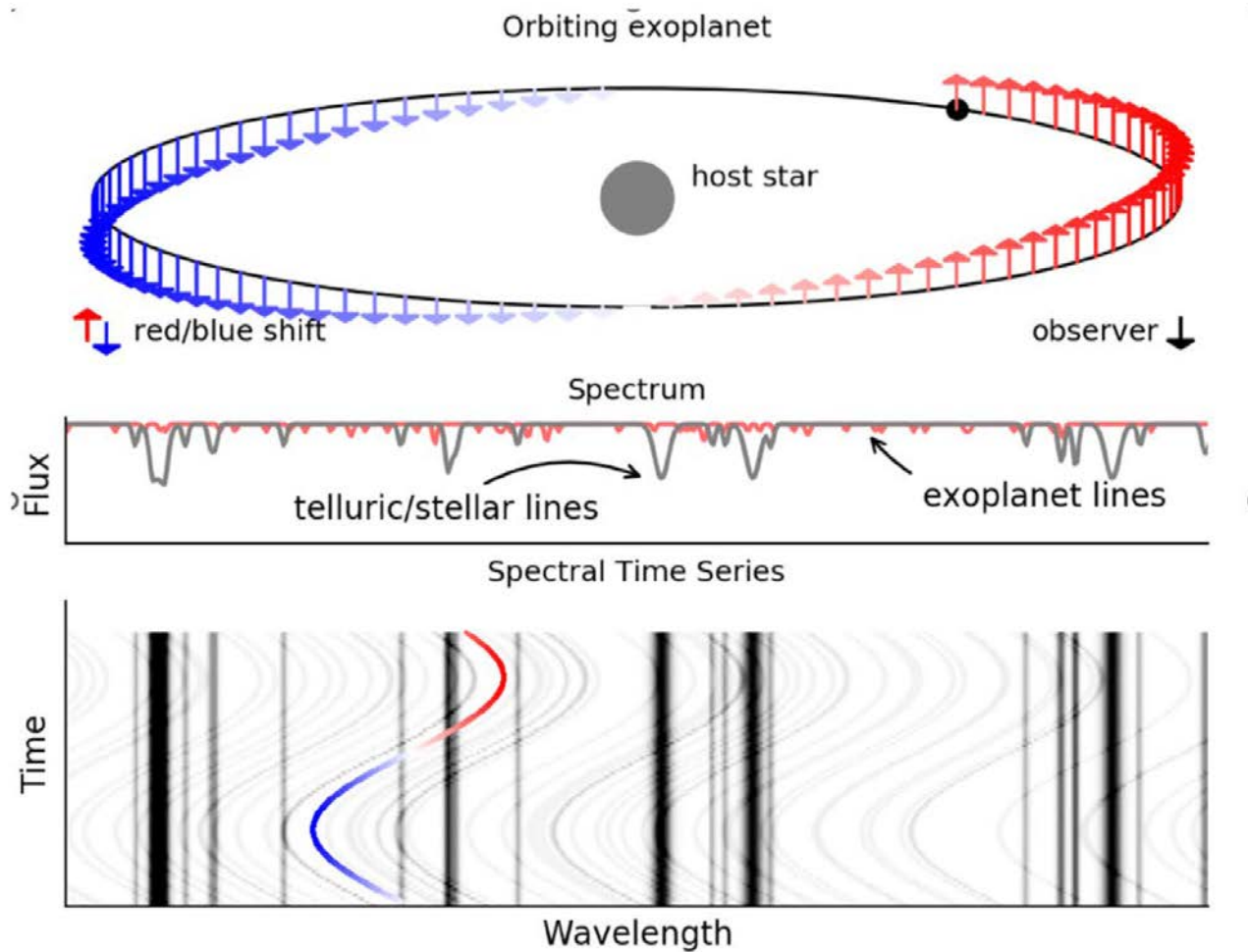
Stevenson *et al* 2017

# Secondary eclipse mapping

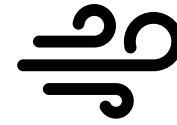


Majeau et al. 2012

# High-resolution spectroscopy

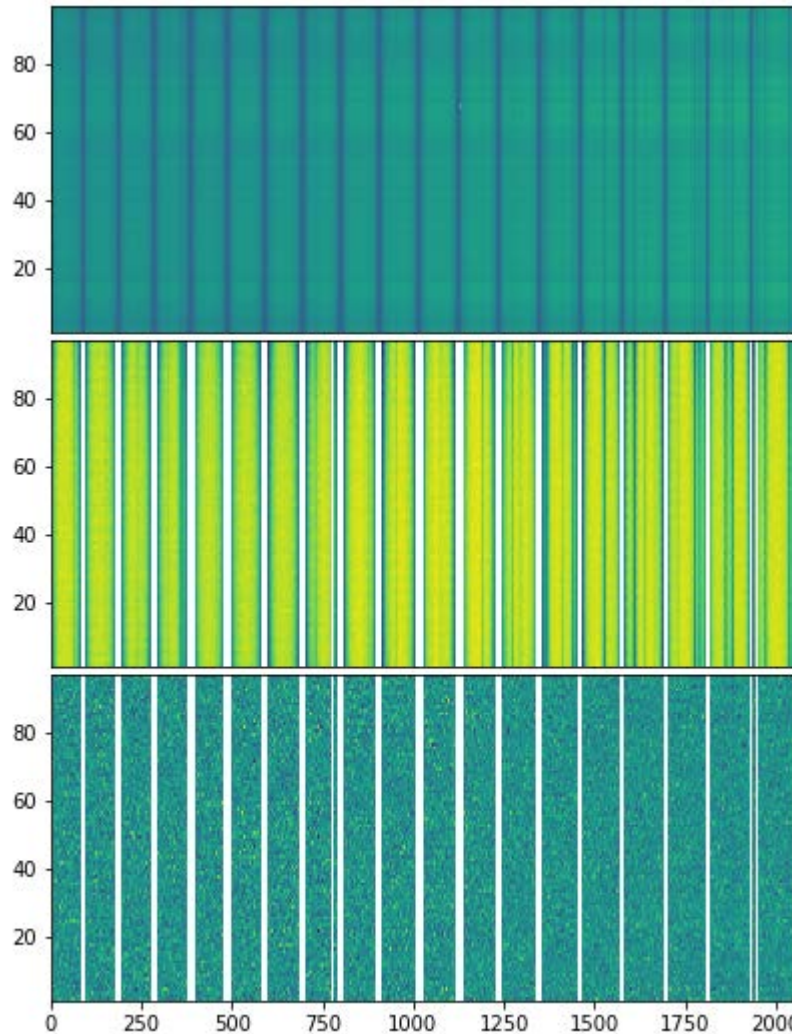


Animation by Lennart van Sluijs



Method pioneered by  
Snellen et al 2010

# High-resolution spectroscopy

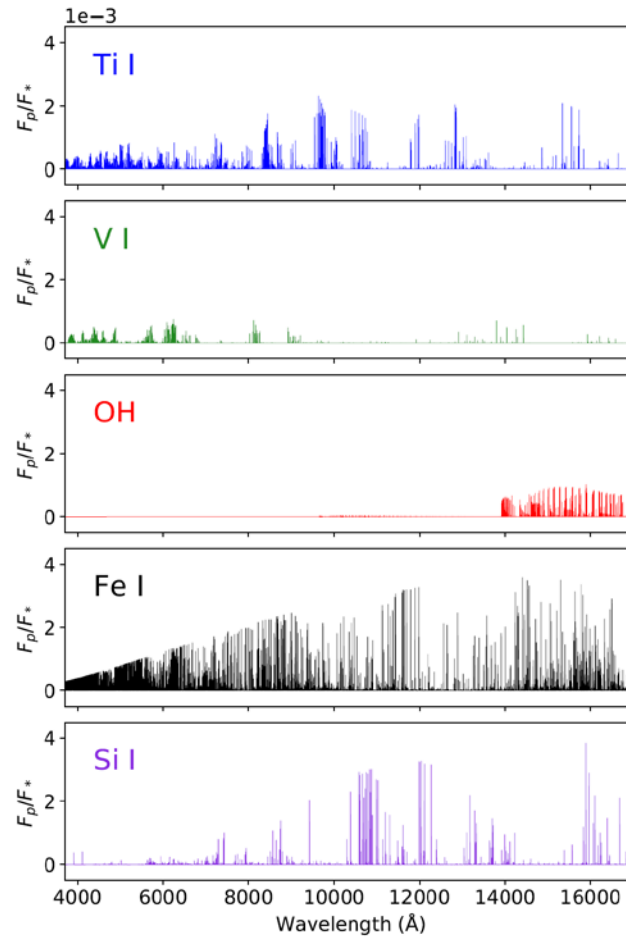
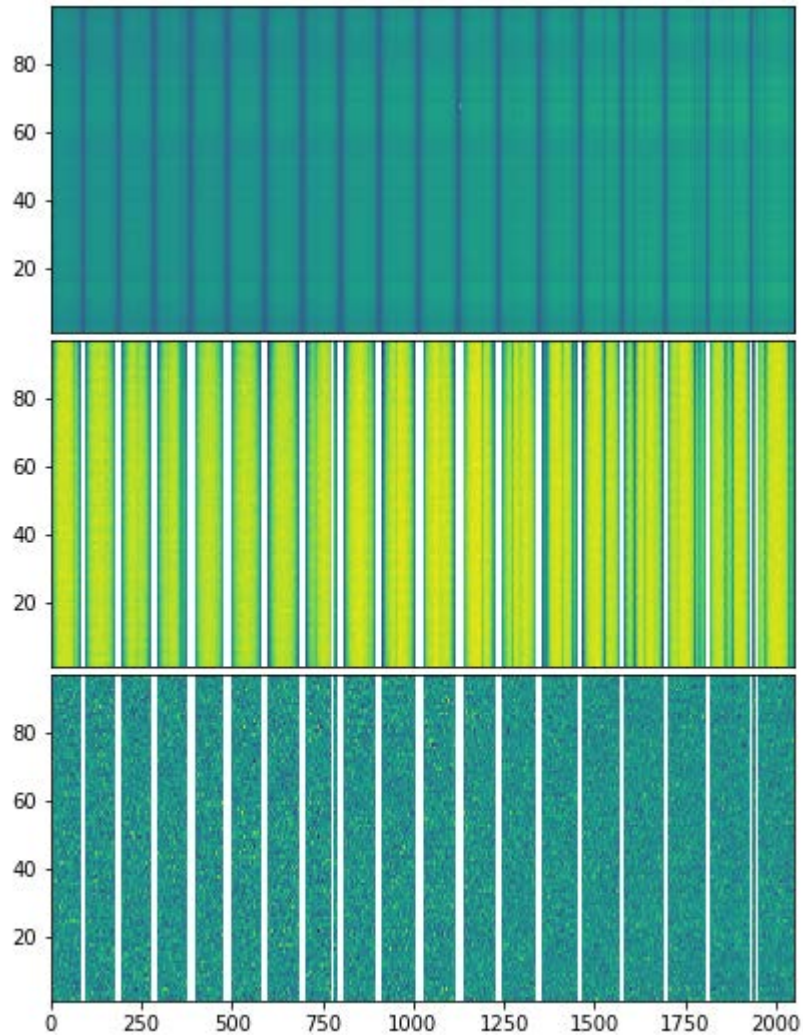


**Untreated spectra**

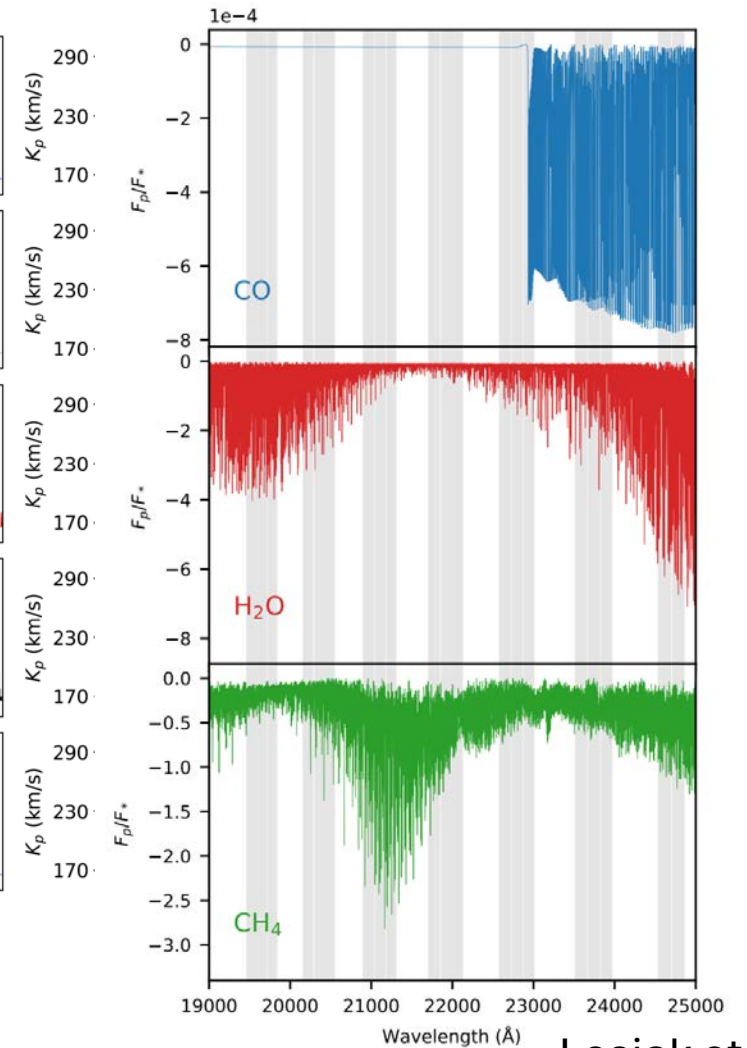
**Normalized and deep tellurics masked**

**After 4 SYSREM runs**

# High-resolution spectroscopy



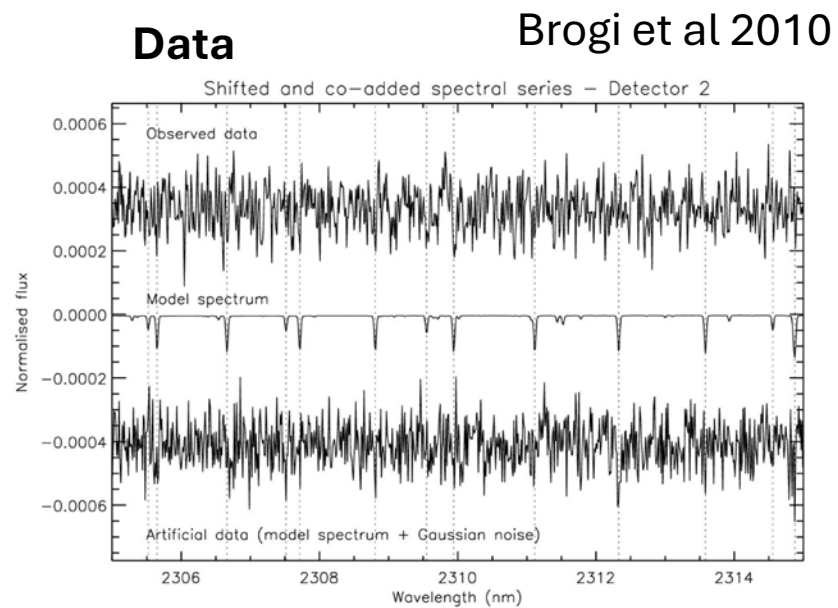
Cont et al. 2022



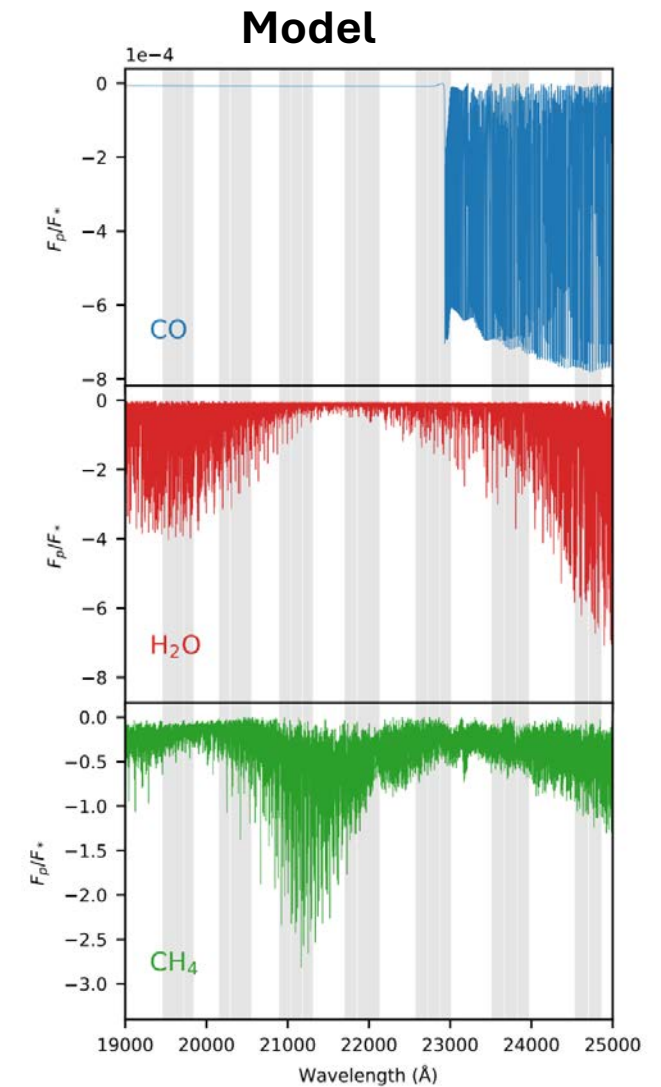
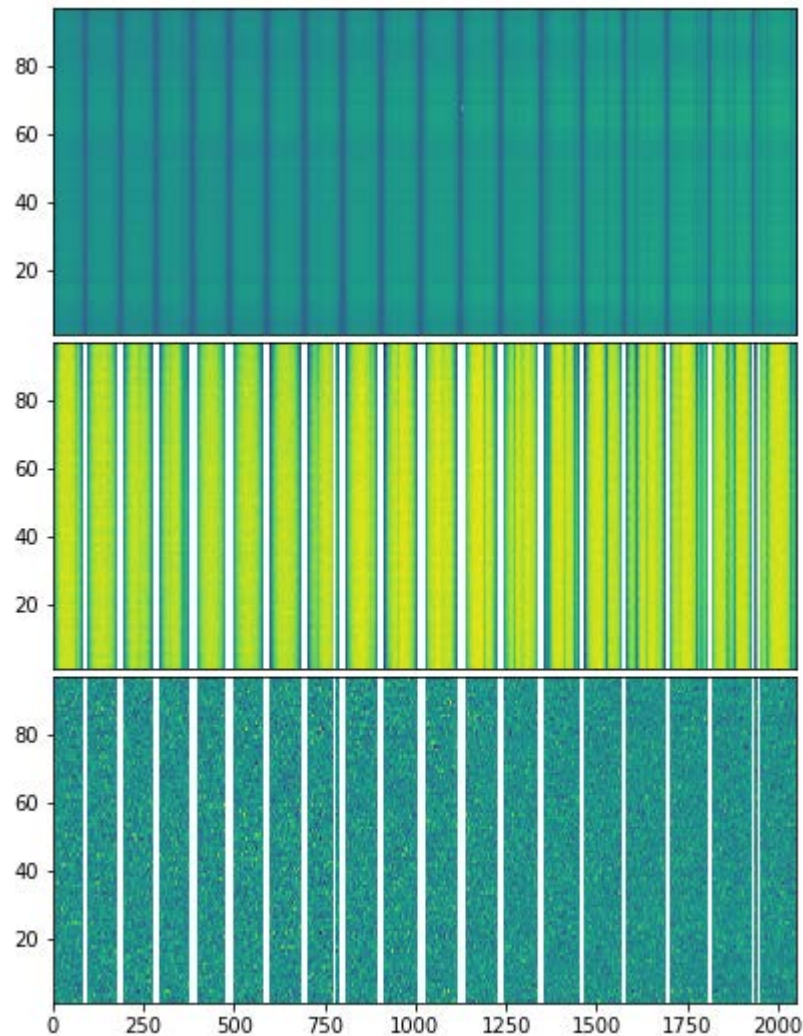
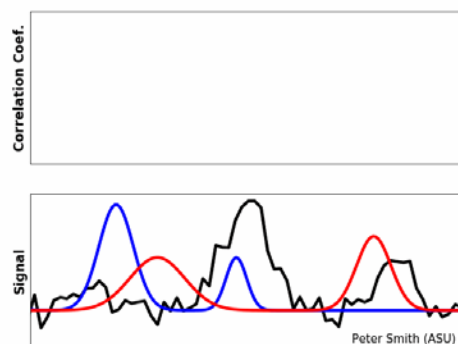
Lesjak et al. 2023



# High-resolution spectroscopy

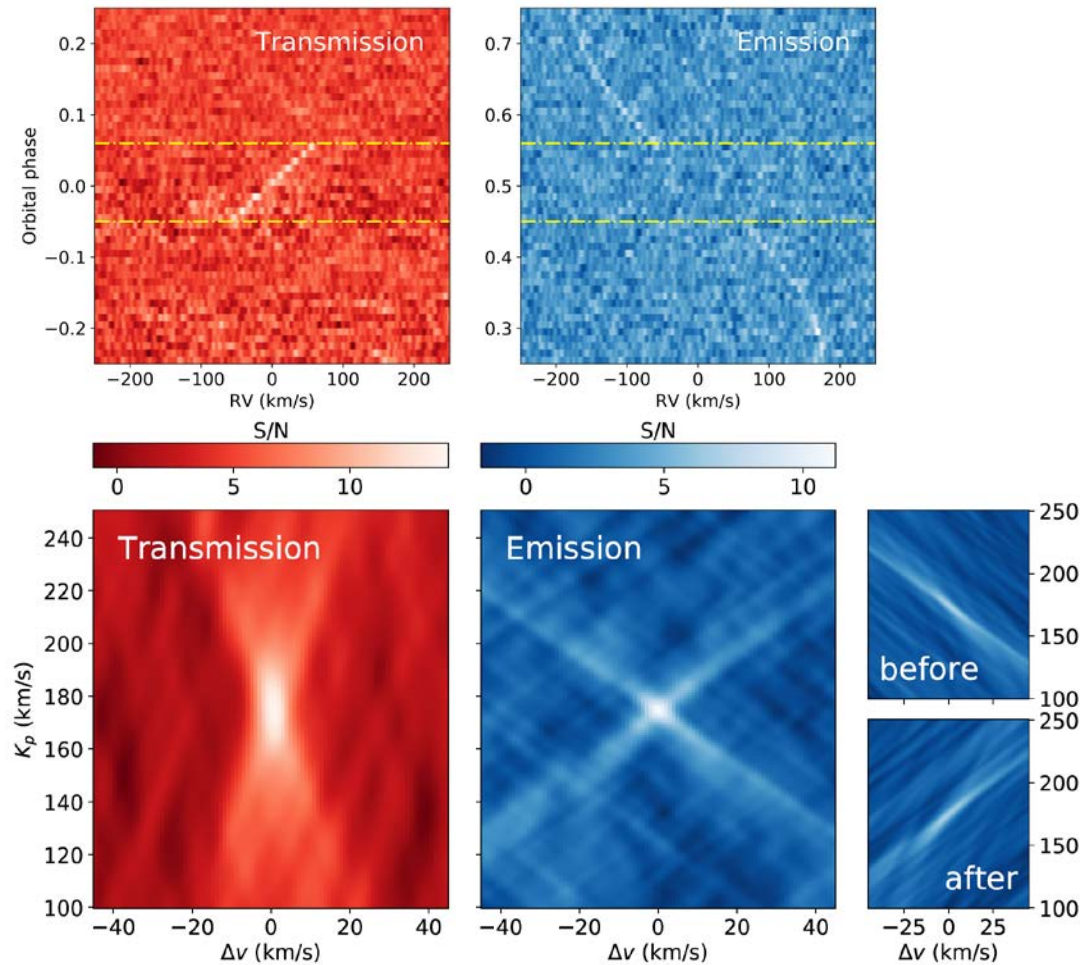


## Cross-correlation



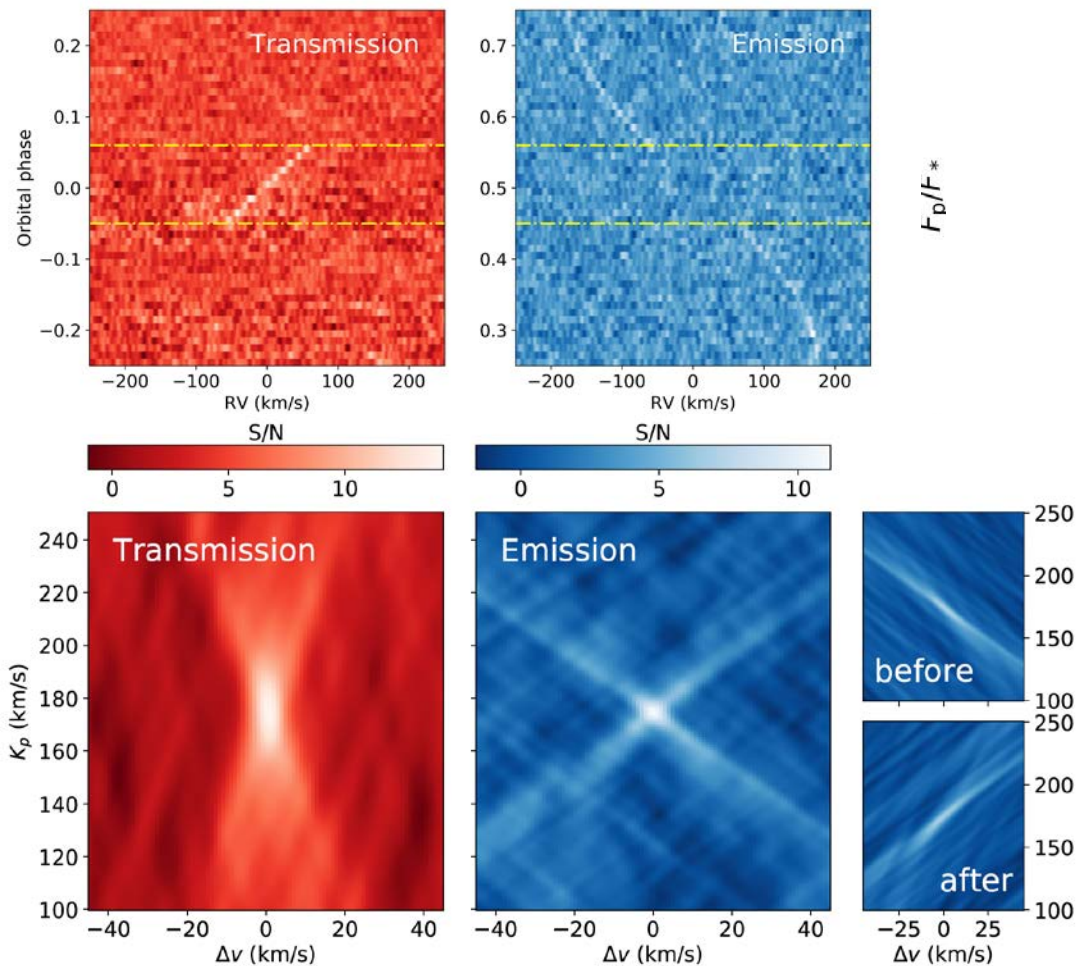
Lesjak et al. 2023

# Cross-correlation technique



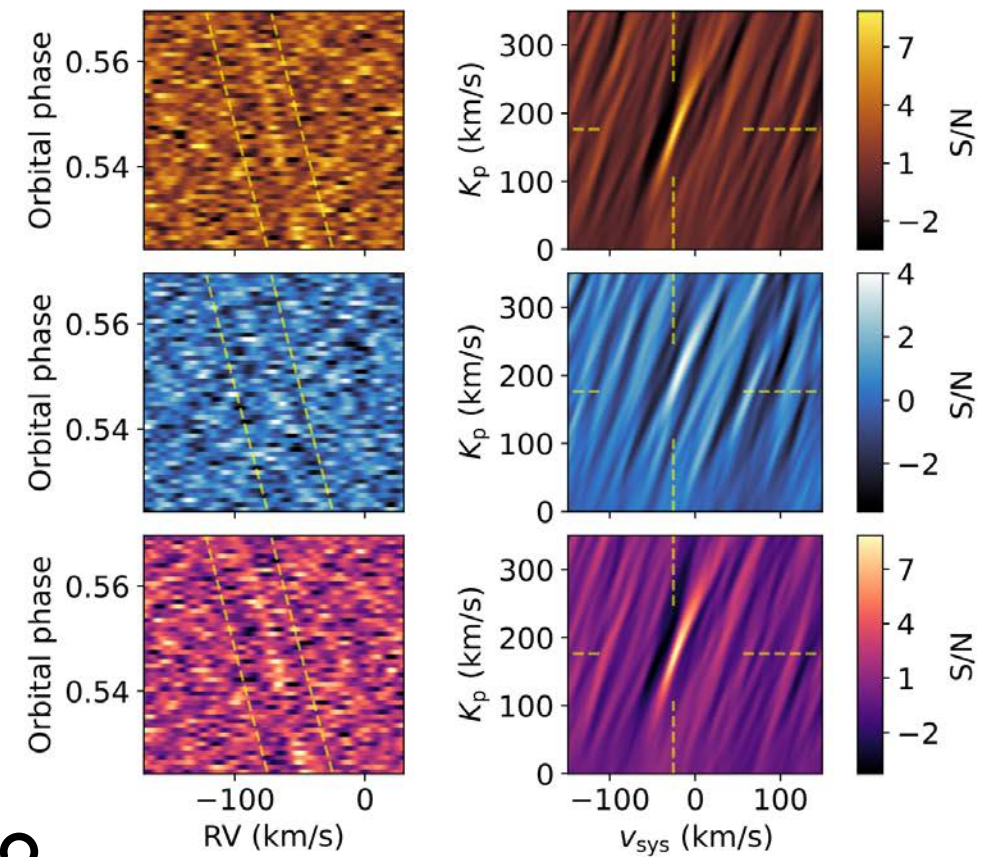
Cont, PhD thesis, 2023

# Cross-correlation technique



Cont, PhD thesis, 2023

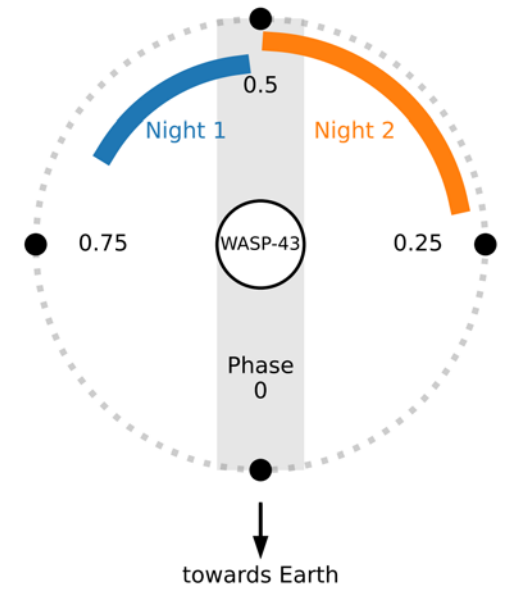
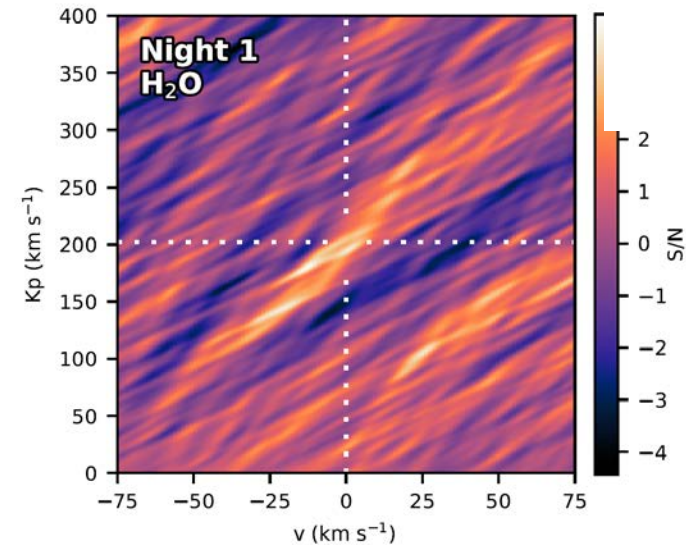
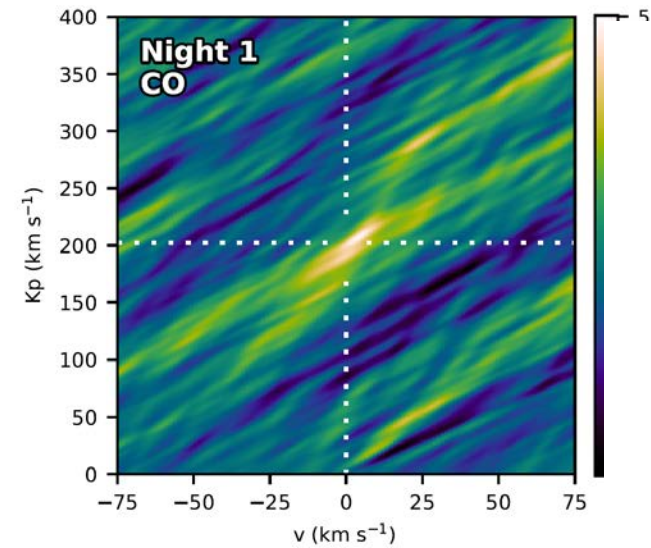
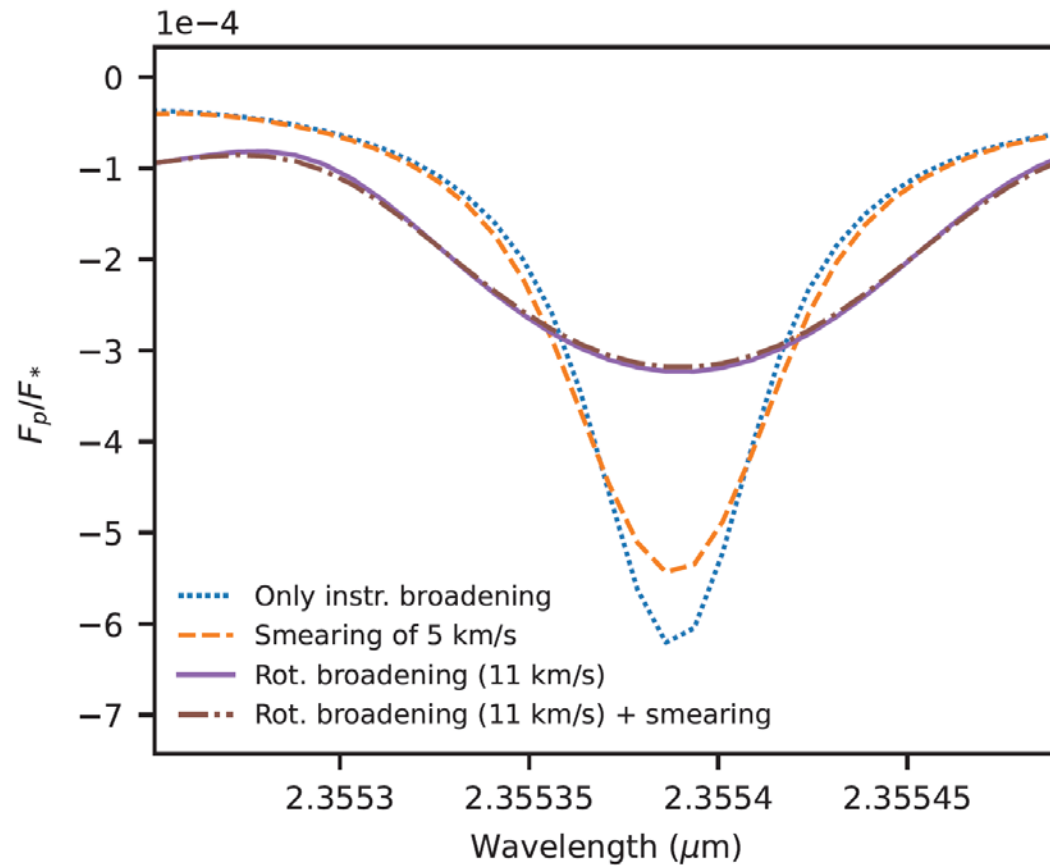
## CO and H2O in the emission spectrum of WASP-178b



Cont et al 2024



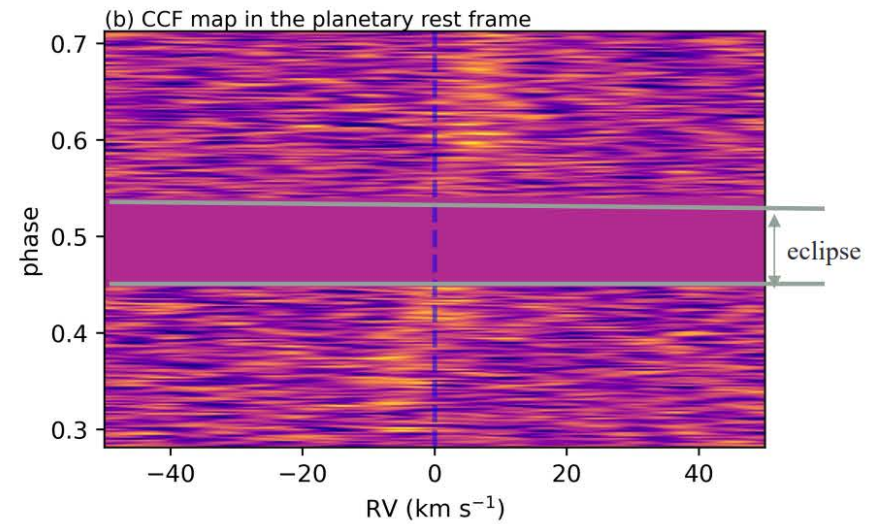
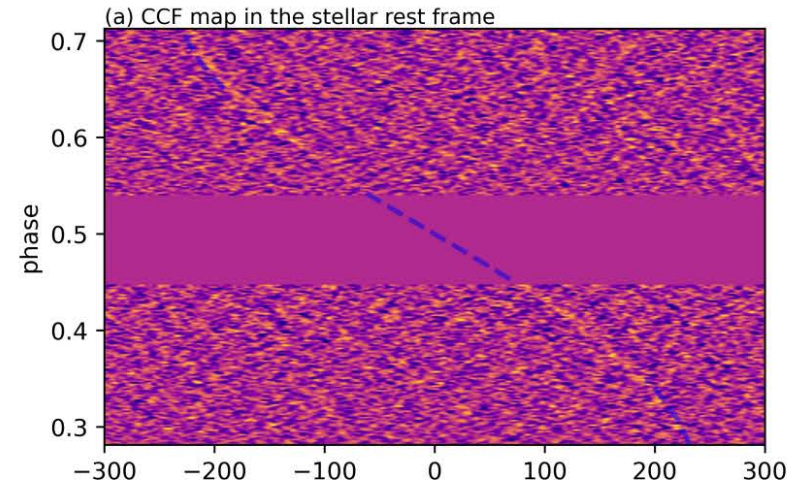
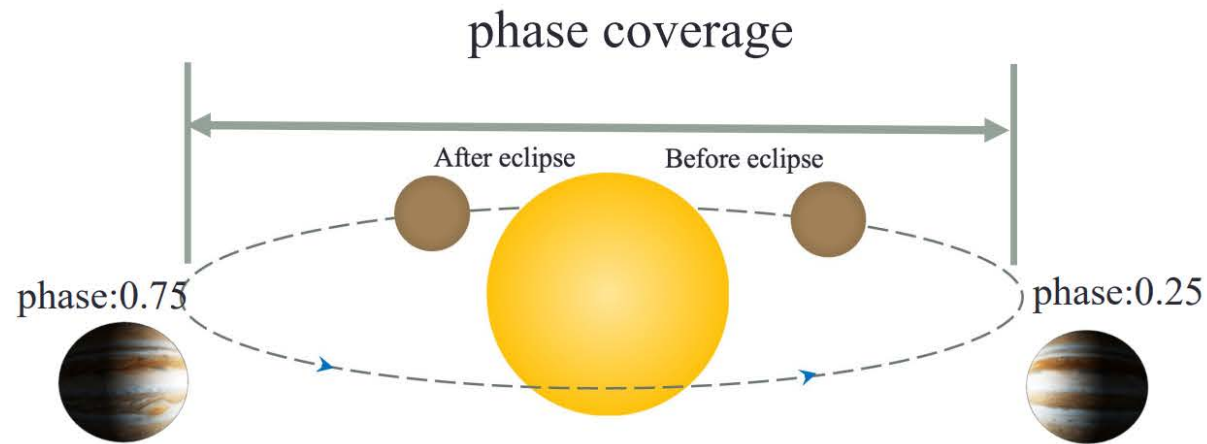
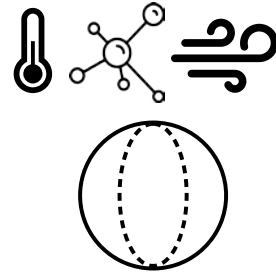
# Dynamics



Lesjak et al 2023

# Phase curves at high resolution

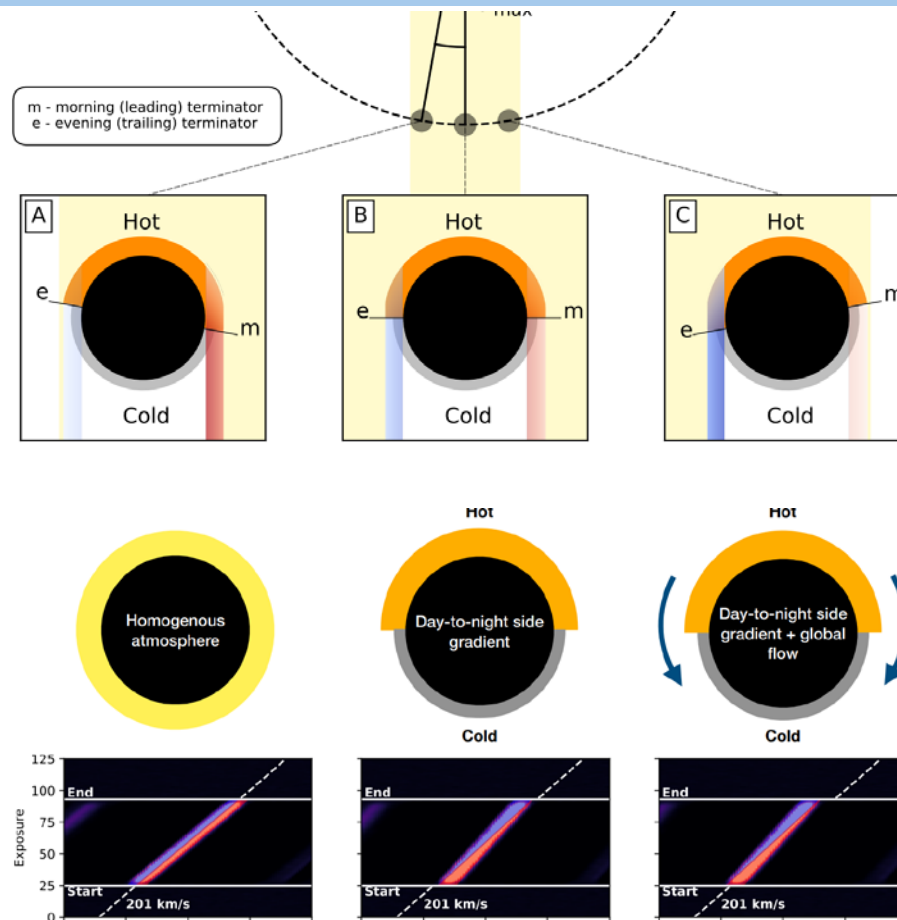
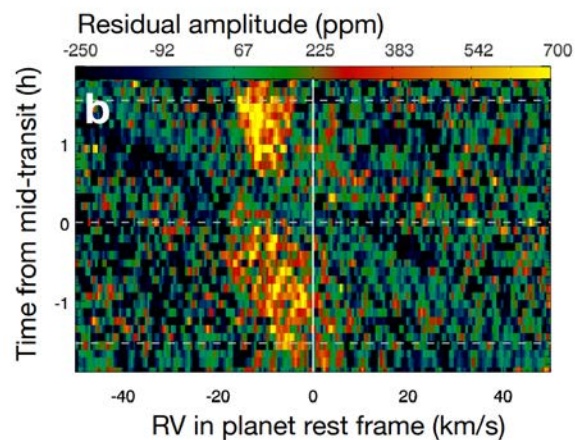
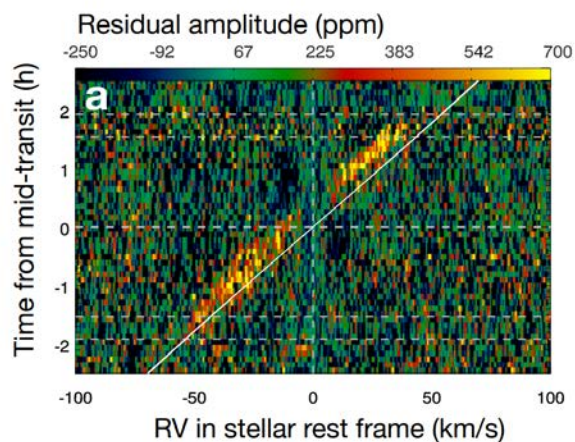
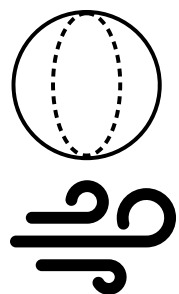
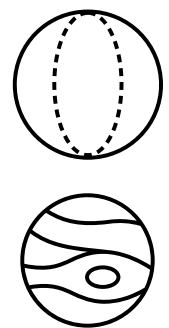
Phase curve of a hot Jupiter with  
CRIRES+ in the K band (1.9-2.5  $\mu\text{m}$ )  
CO+H<sub>2</sub>O



fixed K<sub>p</sub>=236 km/s

Yan et al. in prep.

# 3D structure in transmission spectroscopy

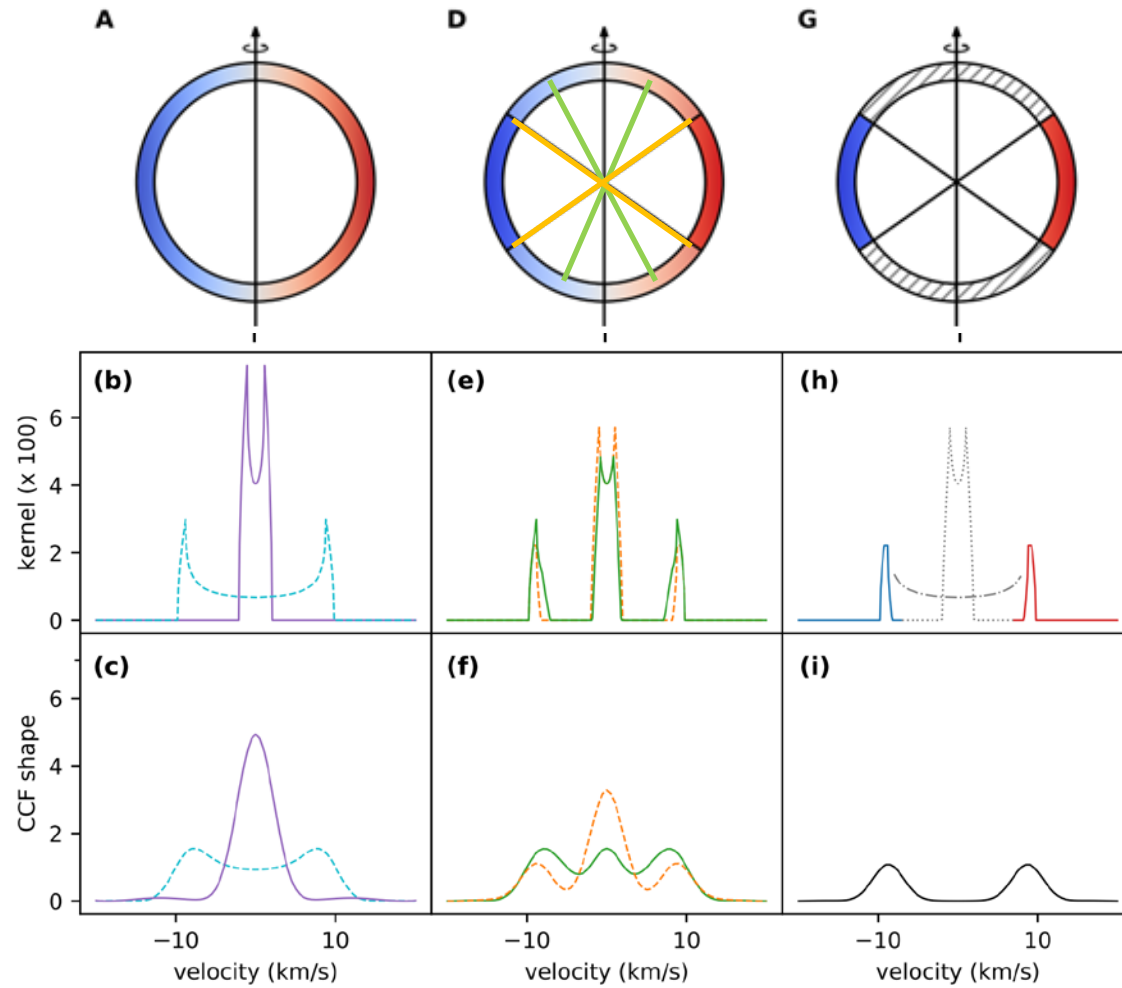
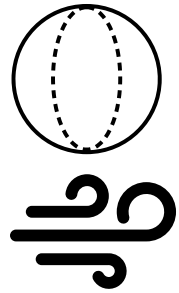
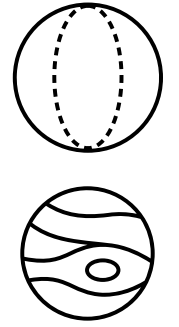


Ehrenreich et al 2020 (Fe in WASP-76b)

Also: Ghandi et al 2022

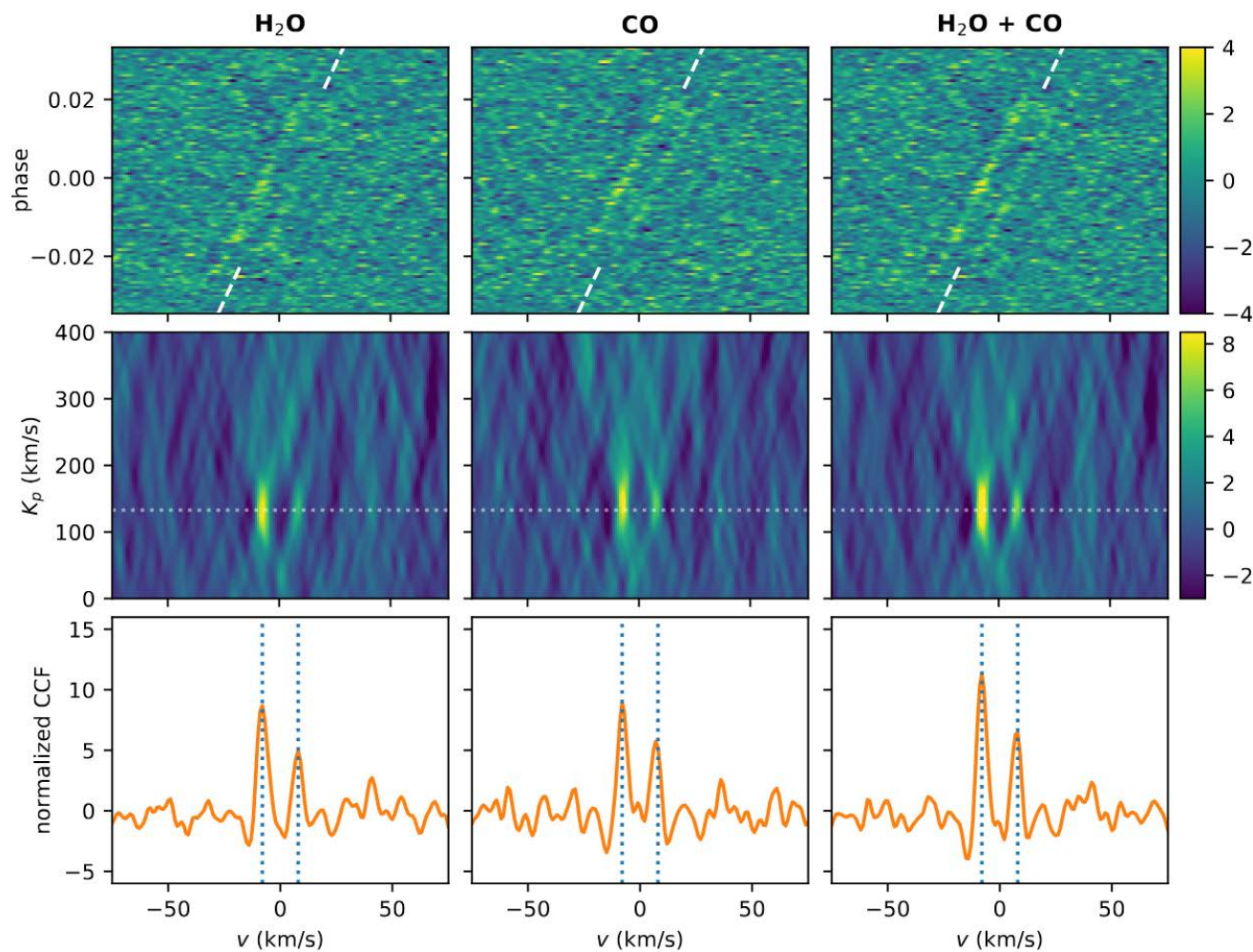
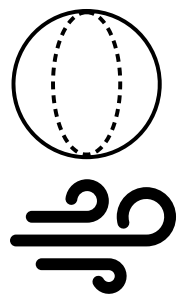
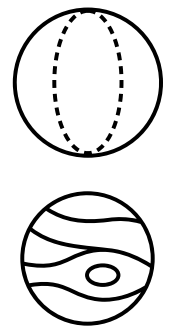
Prinoth et al 2022 (WASP-189b)

# 3D structure in transmission – WASP-127b



Nortmann et al. in ref at A&A  
arXiv:2404.12363

# 3D structure in transmission – WASP-127b

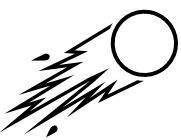


Morning and evening terminator and poles can be resolved and investigated

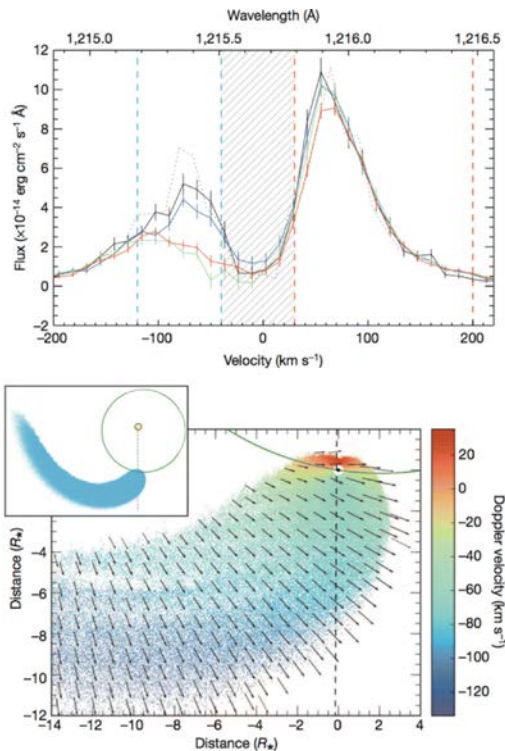
Nortmann et al. in ref at A&A  
arXiv:2404.12363



# Atmospheric escape - Evolution

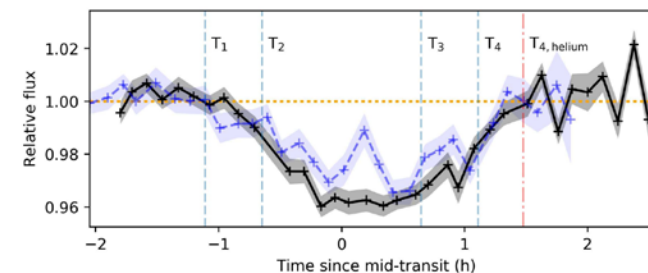
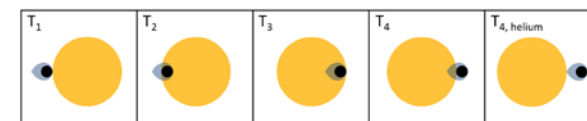
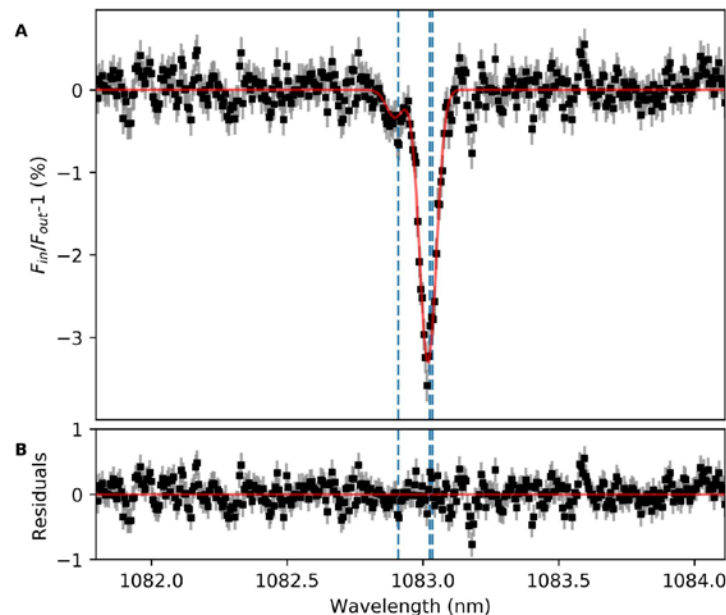


**Hydrogen: Lyman  $\alpha$**   
**GJ436b**  
**121.567 nm [UV]  $\rightarrow$  HST only**



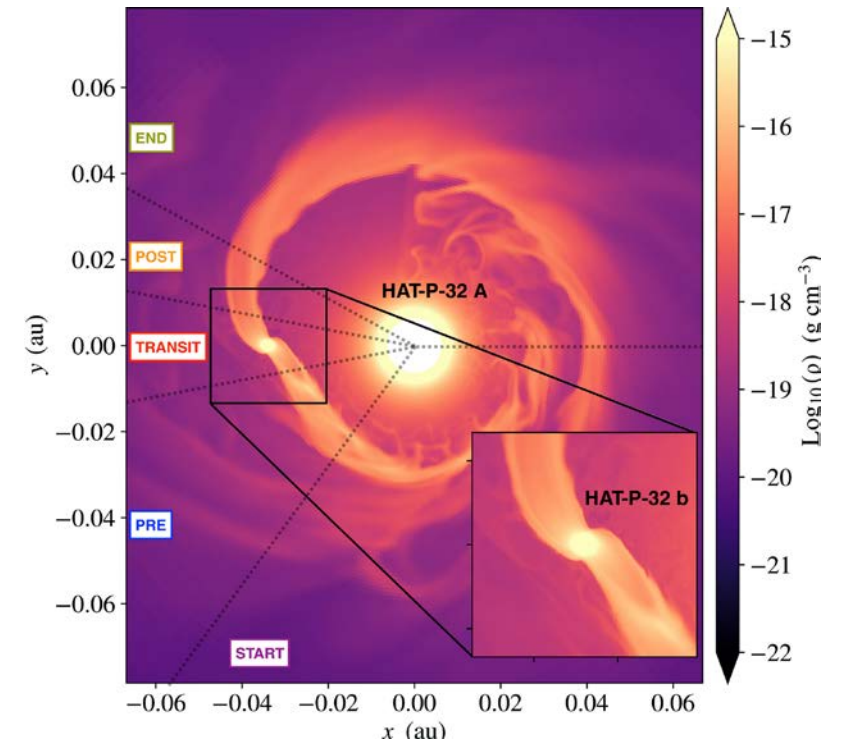
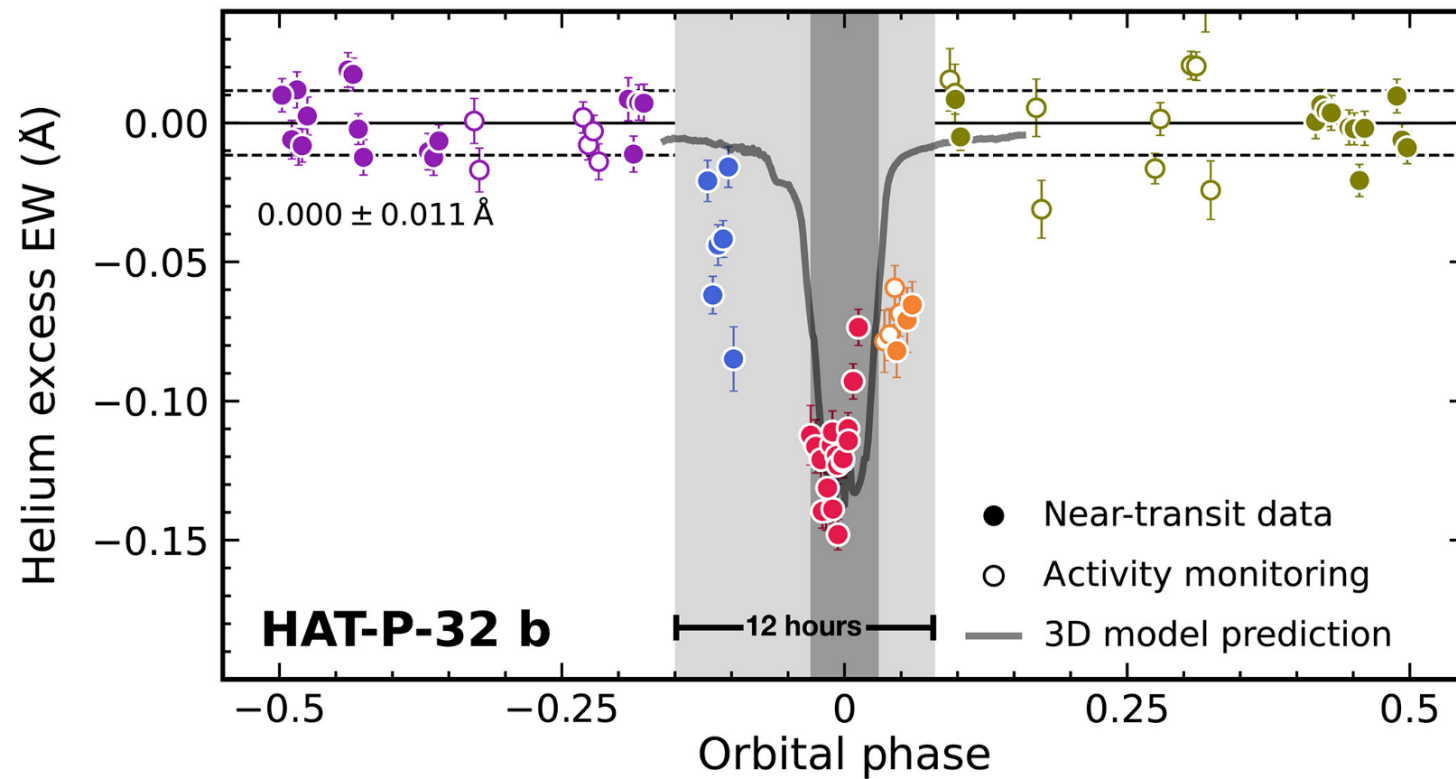
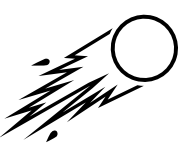
Ehrenreich et al. 2015  
 See also: Vidal-Madjar et al. 2003  
 for HD209458b

**Helium:**  
**WASP-69b**  
**10833 nm [ $\sim$  1  $\mu$ m NIR]  $\rightarrow$  many observatories**



Nortmann et al. 2018  
 See also Spake et al. 2018 WASP-107b with HST  
 Allart et al. 2018 HAT-P-11b

# Studying atmospheric escape using helium

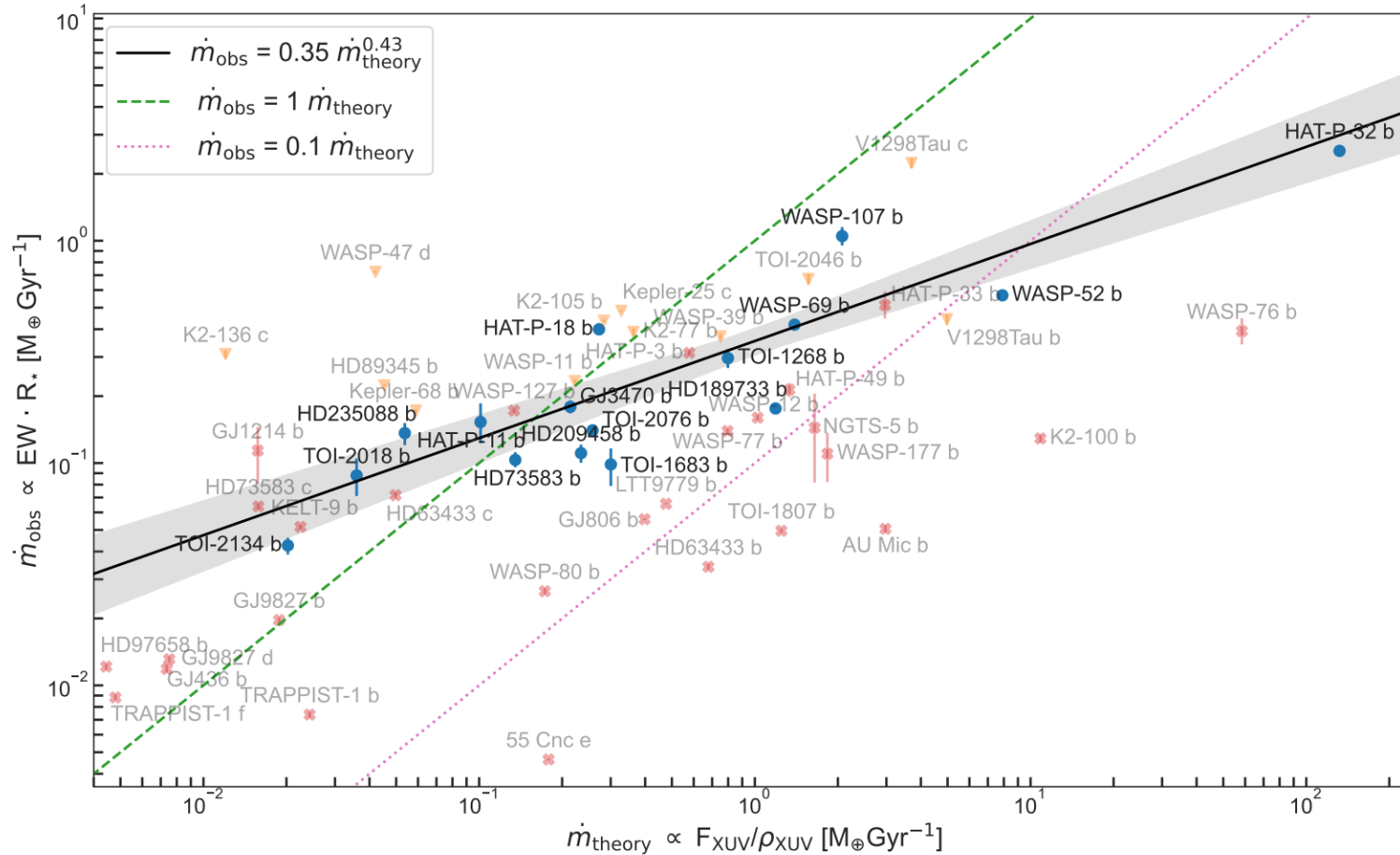
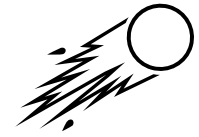


## HAT-P-32Ab

Zhang et al. 2023

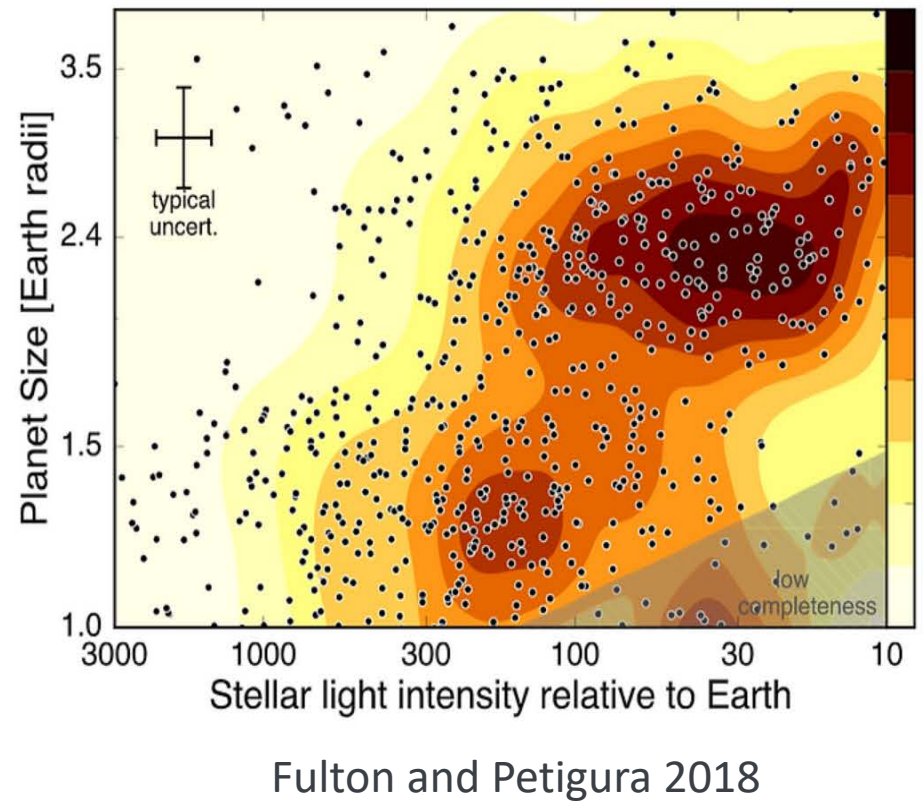
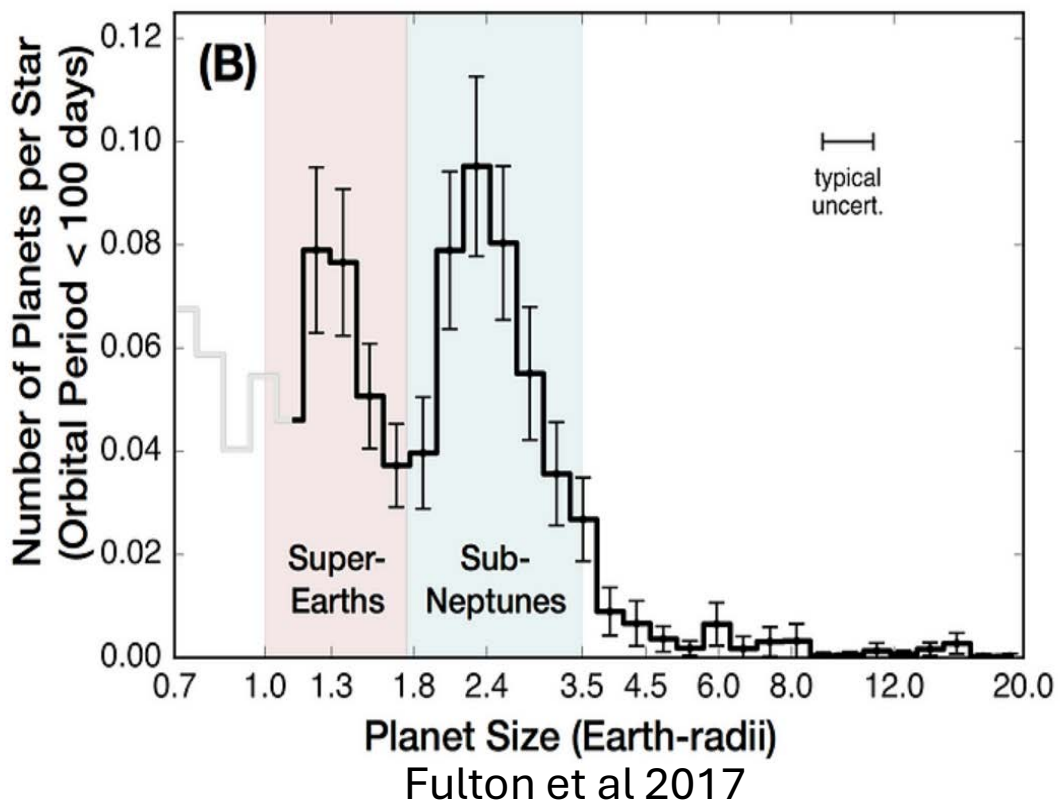
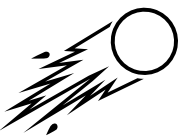
See also Czelsa et al. 2022

# Studying the Helium – XUV connection



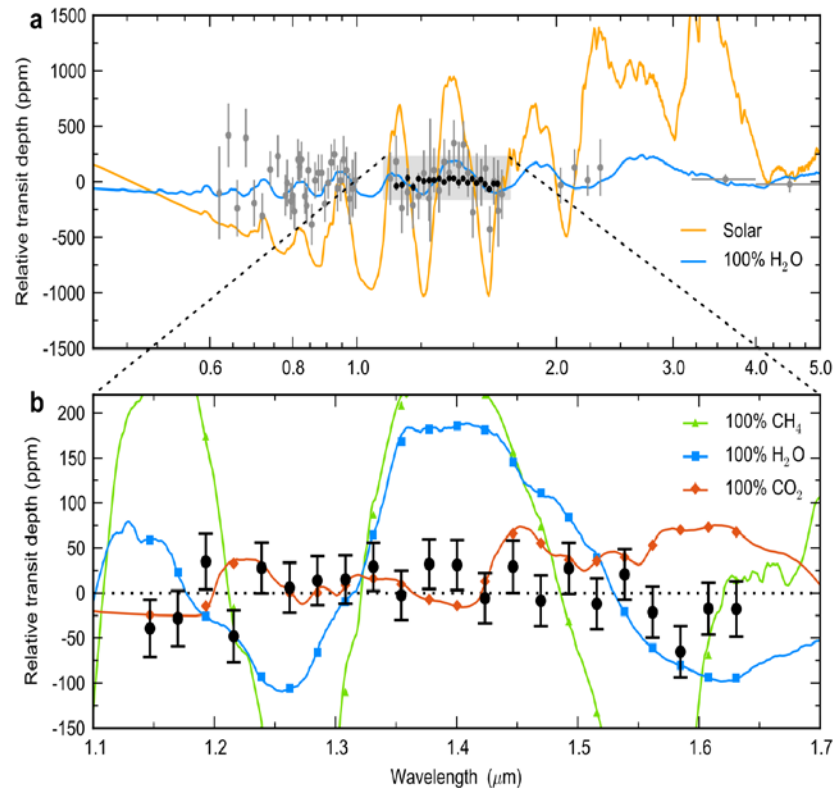
Orell-Miquel et al 2024  
See also Nortmann et al. 2018  
and many more

# Atmospheric escape - Evolution

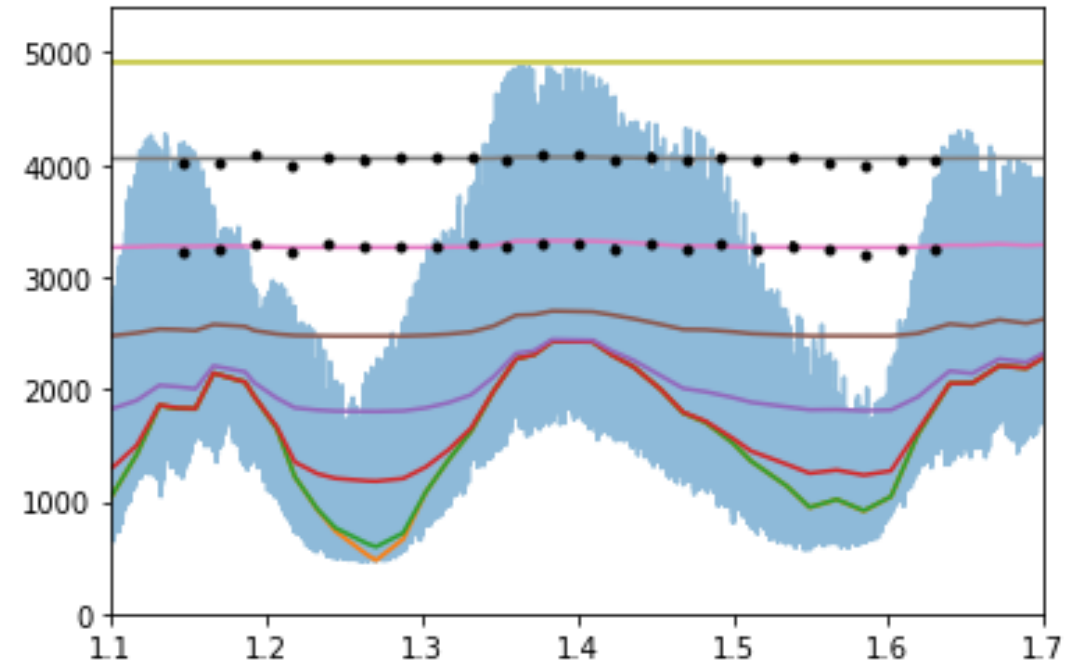


# Challenges - cloudy atmospheres

## HST WFC3 10 transits of GJ1214b

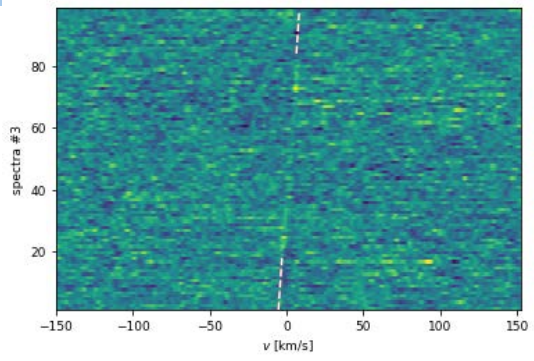


## Potential at high-res!



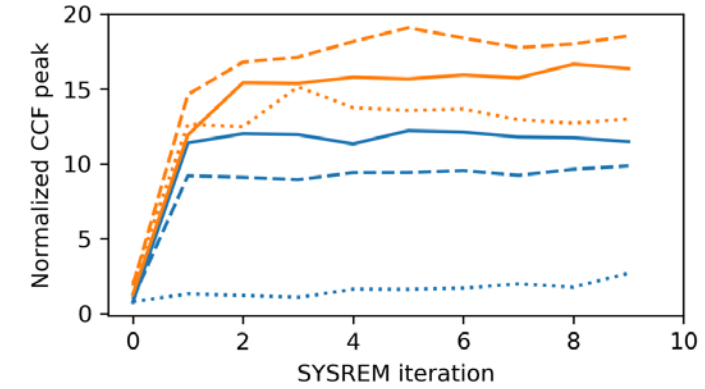
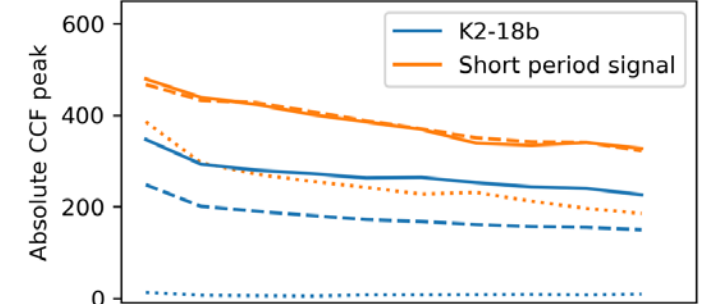
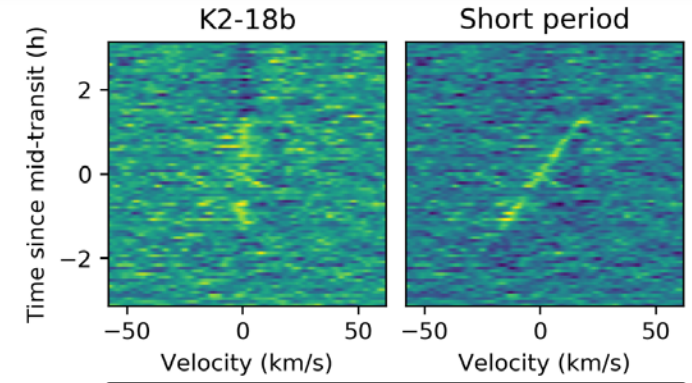
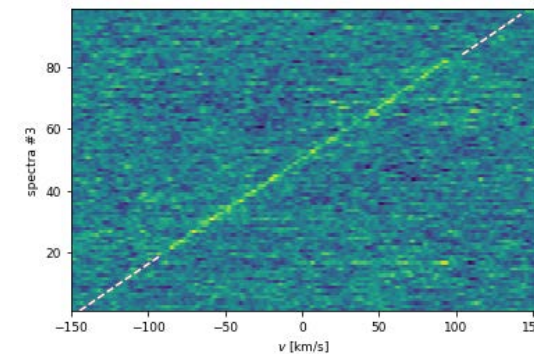
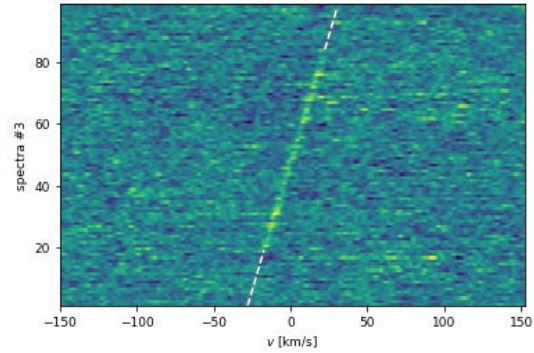
Kreidberg et al. 2014

# Challenges - Long period planets



$$t_{max} = \frac{S_{pixel} \cdot P}{2\pi K_p}$$

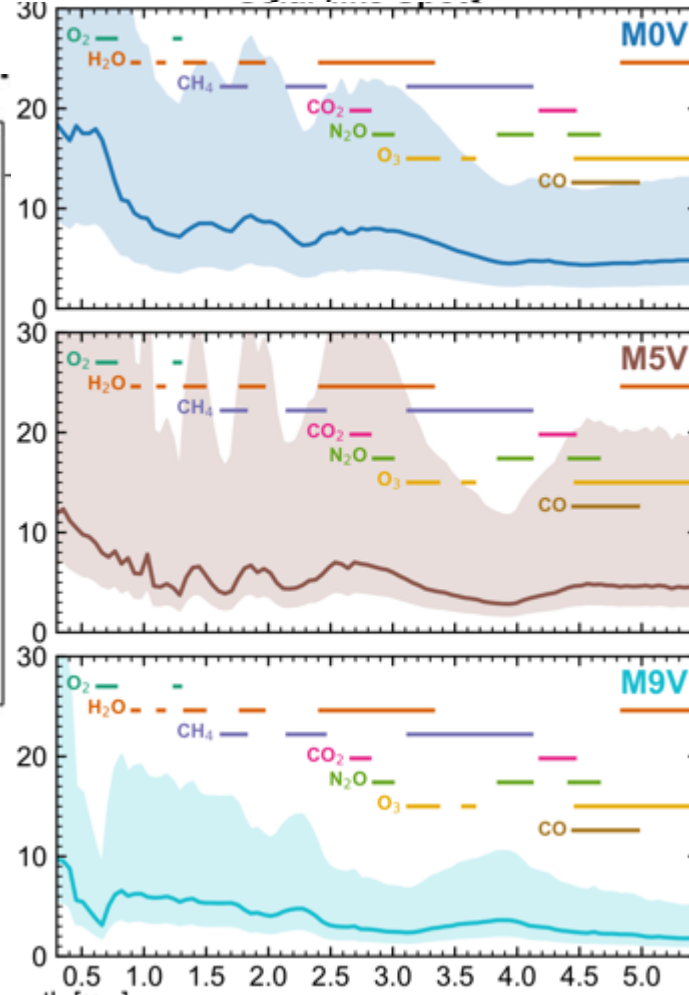
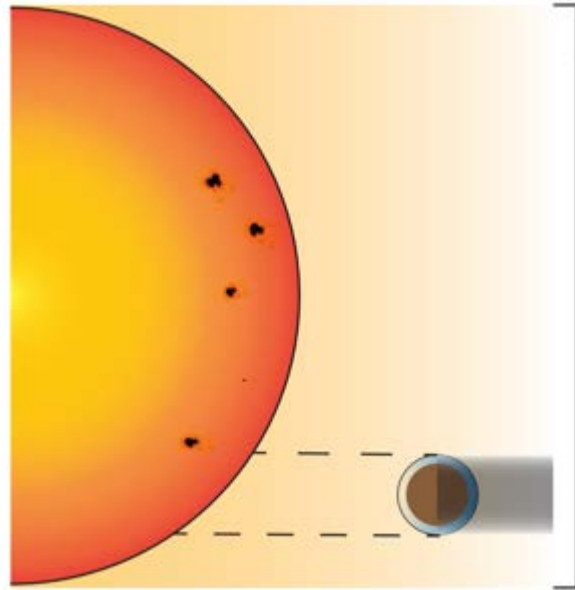
- $S_{pixel}$  = Size of detector pixel [km/s]
- $P$  = Orbital Period [s]
- $K_p$  = Radial velocity semi-amplitude [km/s]



Palle et al 2023 ANDES white paper

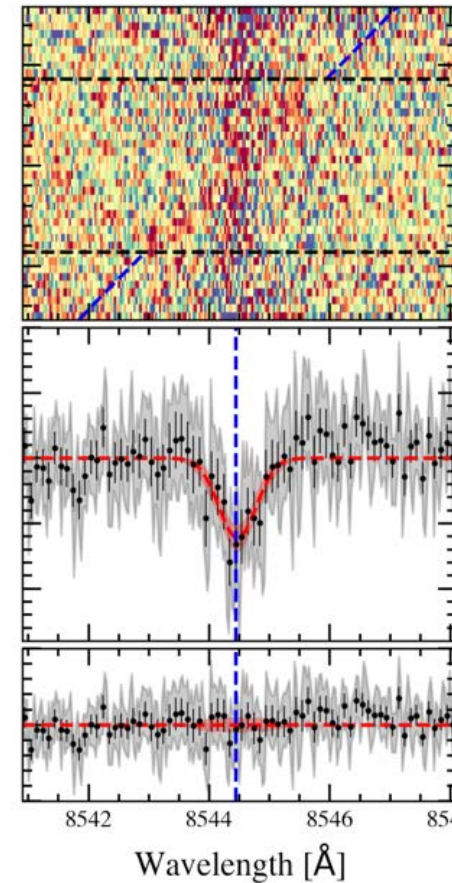
# Challenges – Stellar activity (also CLV+RME)

Stellar Contamination Spectra Produced by Spots-Only Models

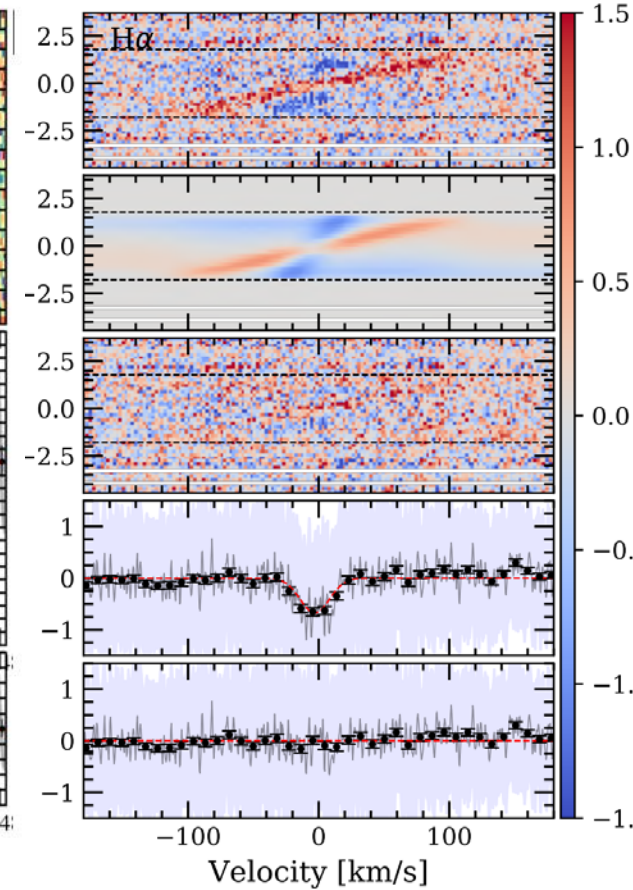


Rackham et al. 2018  
Apai et al.

CaII IRT  $\lambda 8544 \text{ \AA}$

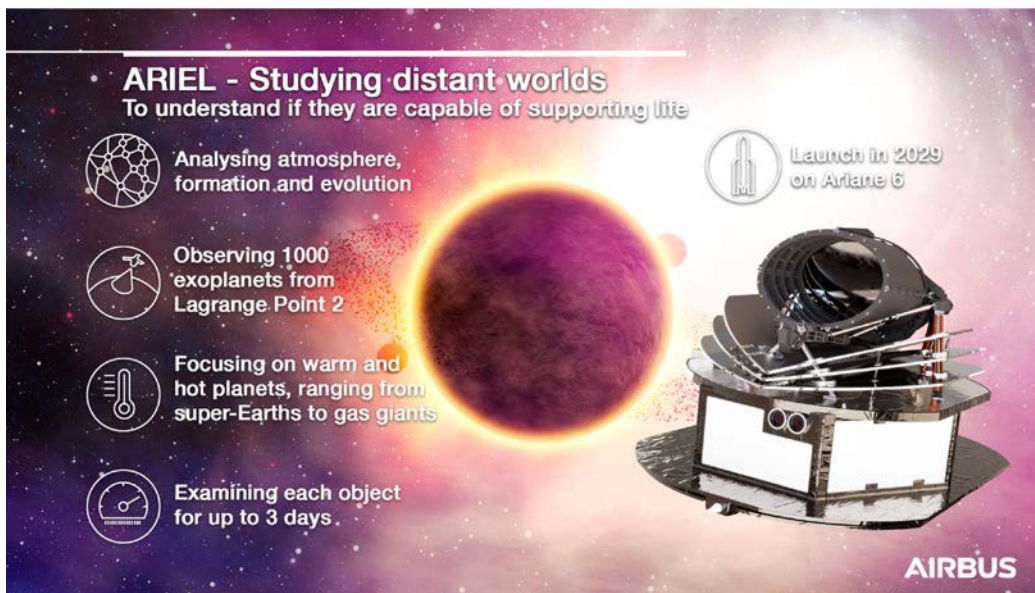


HARPS-N x 3



Casasayas-Barris et al. 2021

# The future:



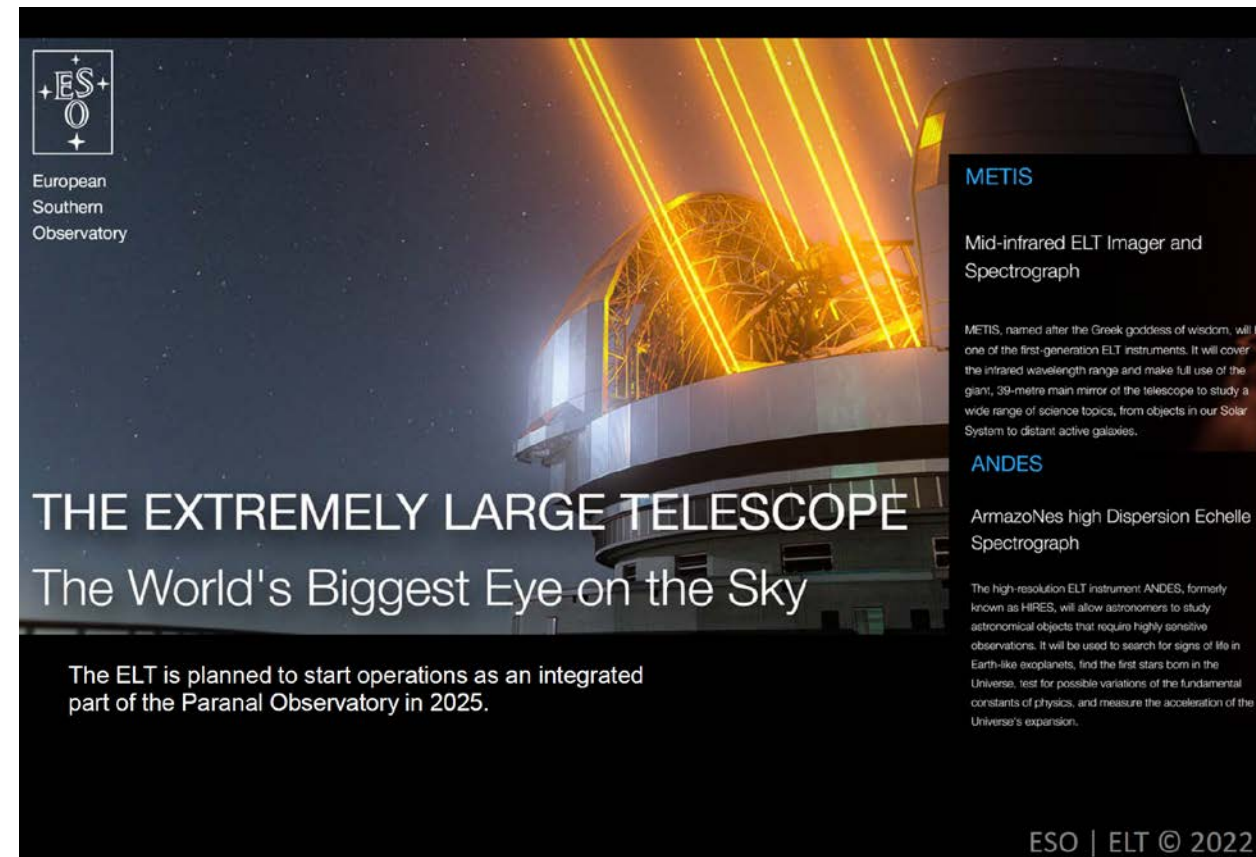
**ARIEL - Studying distant worlds**  
To understand if they are capable of supporting life

- Analysing atmosphere, formation and evolution
- Observing 1000 exoplanets from Lagrange Point 2
- Focusing on warm and hot planets, ranging from super-Earths to gas giants
- Examining each object for up to 3 days

Launch in 2029 on Ariane 6

**AIRBUS**

(Bild: Airbus)



**ESO**  
European Southern Observatory

**THE EXTREMELY LARGE TELESCOPE**  
The World's Biggest Eye on the Sky

The ELT is planned to start operations as an integrated part of the Paranal Observatory in 2025.

**METIS**  
Mid-infrared ELT Imager and Spectrograph

METIS, named after the Greek goddess of wisdom, will be one of the first-generation ELT instruments. It will cover the infrared wavelength range and make full use of the giant, 39-metre main mirror of the telescope to study a wide range of science topics, from objects in our Solar System to distant active galaxies.

**ANDES**  
ArmazoNes high Dispersion Echelle Spectrograph

The high-resolution ELT instrument ANDES, formerly known as HIRES, will allow astronomers to study astronomical objects that require highly sensitive observations. It will be used to search for signs of life in Earth-like exoplanets, find the first stars born in the Universe, test for possible variations of the fundamental constants of physics, and measure the acceleration of the Universe's expansion.

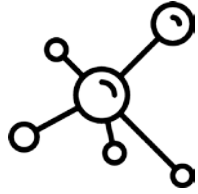
ESO | ELT © 2022



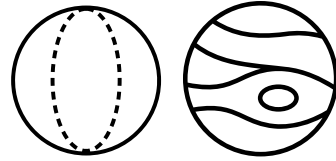
# What can we tell about a planet using its atmosphere?



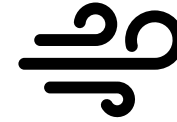
**Temperature**  
(-pressure profile)



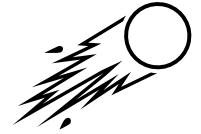
**Composition**  
C/O ratio  
Metallicity  
→ Formation  
→ and evolution



**3D structure**  
→ Day-to night side  
→ Hot spot-(offsets)  
→ Jets  
→ Cool poles



**Winds**  
→Supersonic  
Equatorial  
jets  
Day-to-  
nightside  
winds



**Atmospheric  
loss**  
  
**Evolution**