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.)

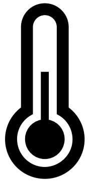
Planets that have **no counterpart in our Solar System**.

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

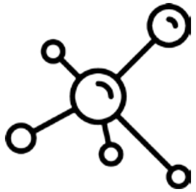
Super-Earths to mini Neptunes: may be gaseous, rocky or water worlds. Atmosphere is the only way to constrain the nature of these planets.

Habitability

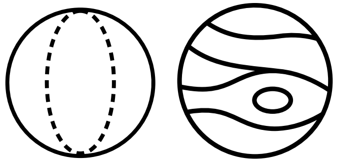
What can we tell about a planet using its atmosphere?



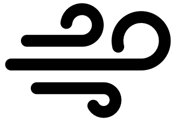
Temperature



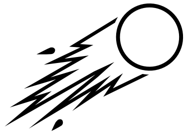
Composition



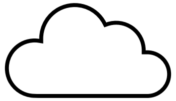
3D structure



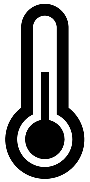
Winds



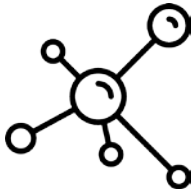
Mass loss



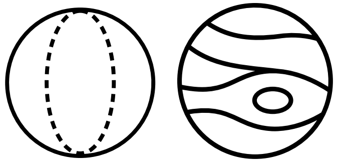
What can we tell about a planet using its atmosphere?



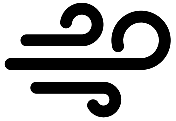
Temperature (-pressure profile)



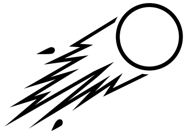
Composition
C/O ratio
Metallicity
→ Formation
→ and evolution



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



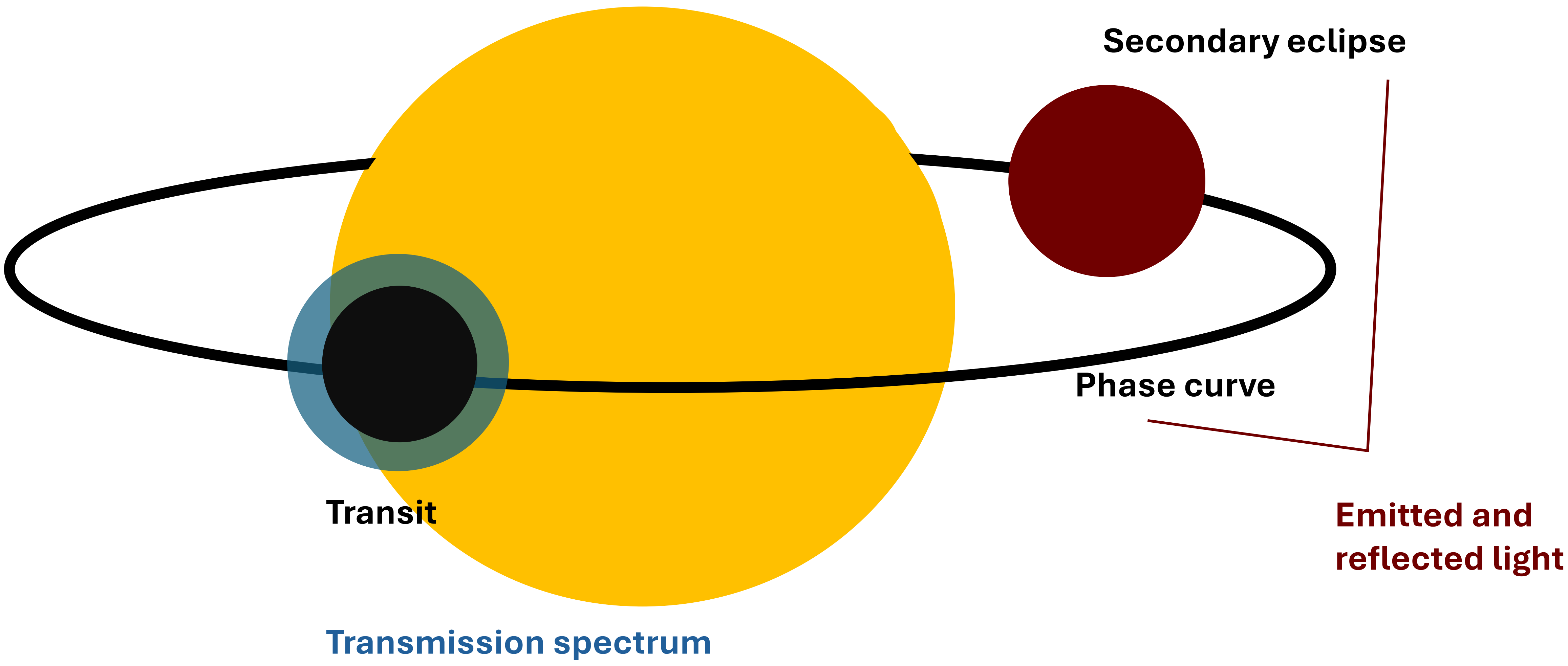
Winds
→Supersonic Equatorial jets
Day-to-nightside winds



Atmospheric loss

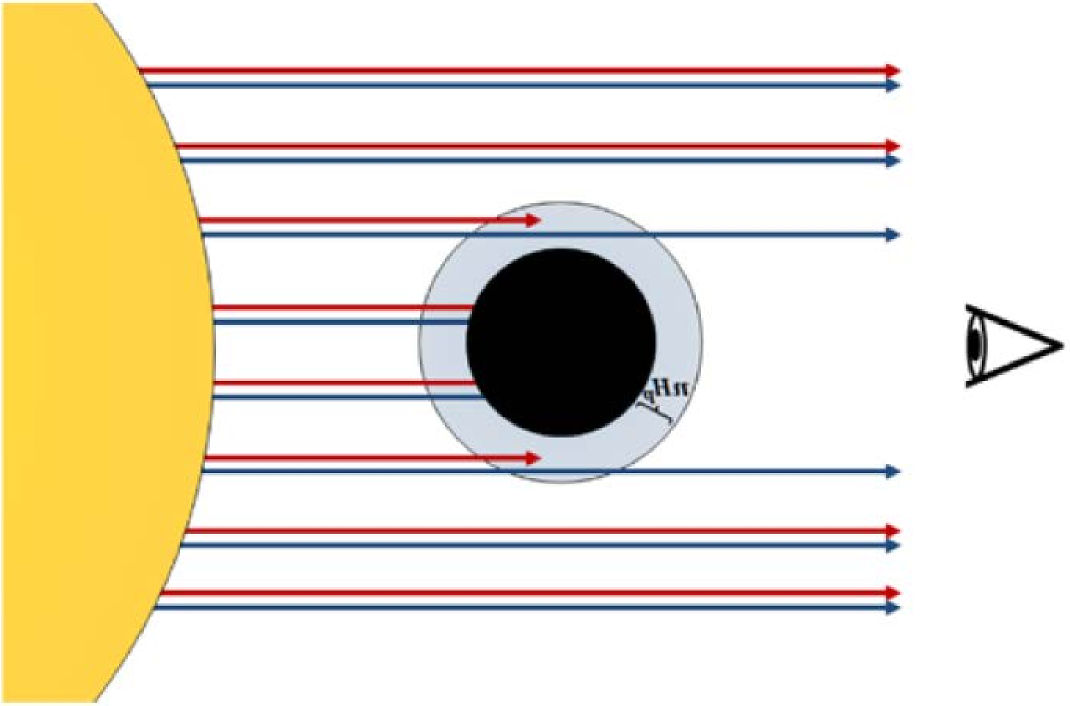
Evolution

How do we measure exoplanet atmospheres?



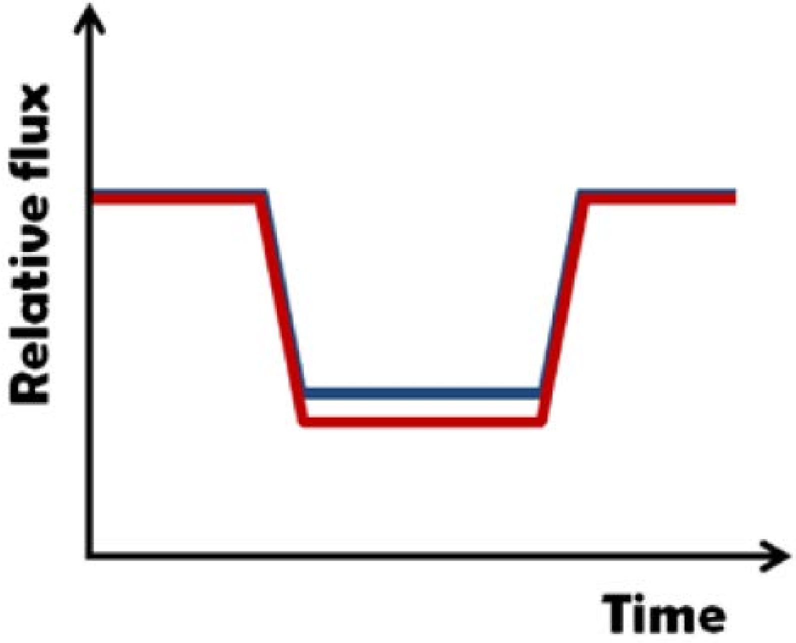
Transmission spectroscopy

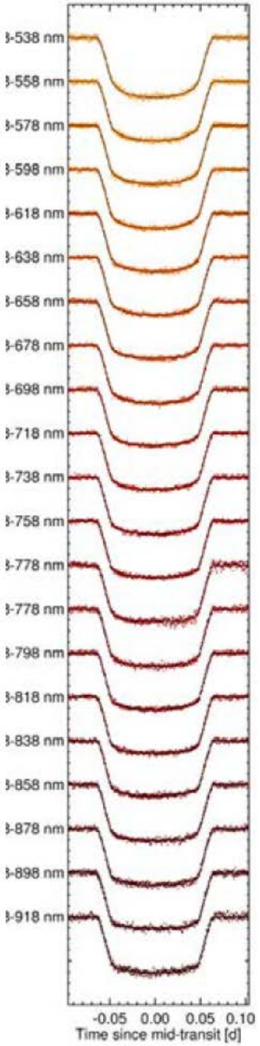
Transit



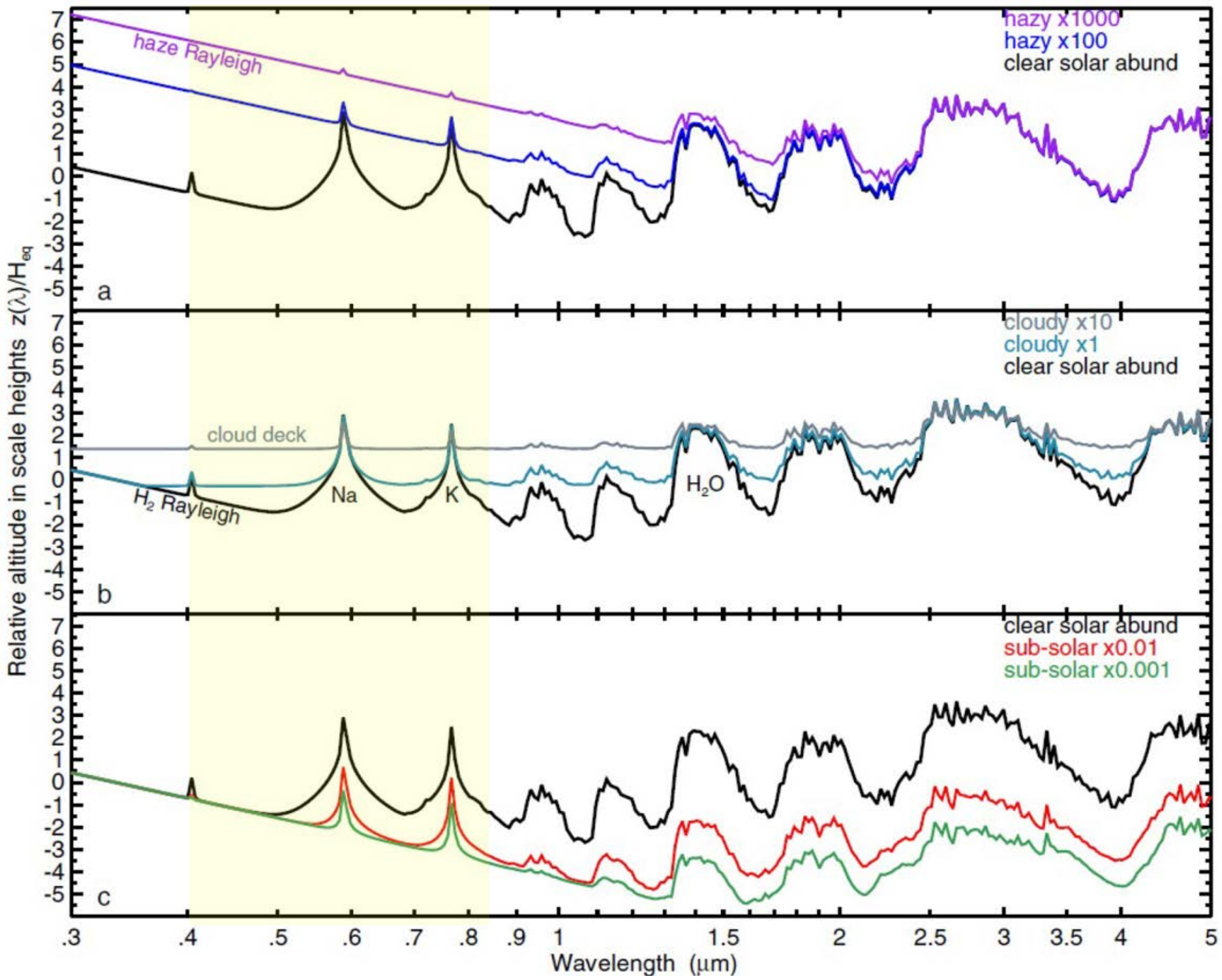
$$D = \frac{2R_p n H}{R_s^2}$$

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



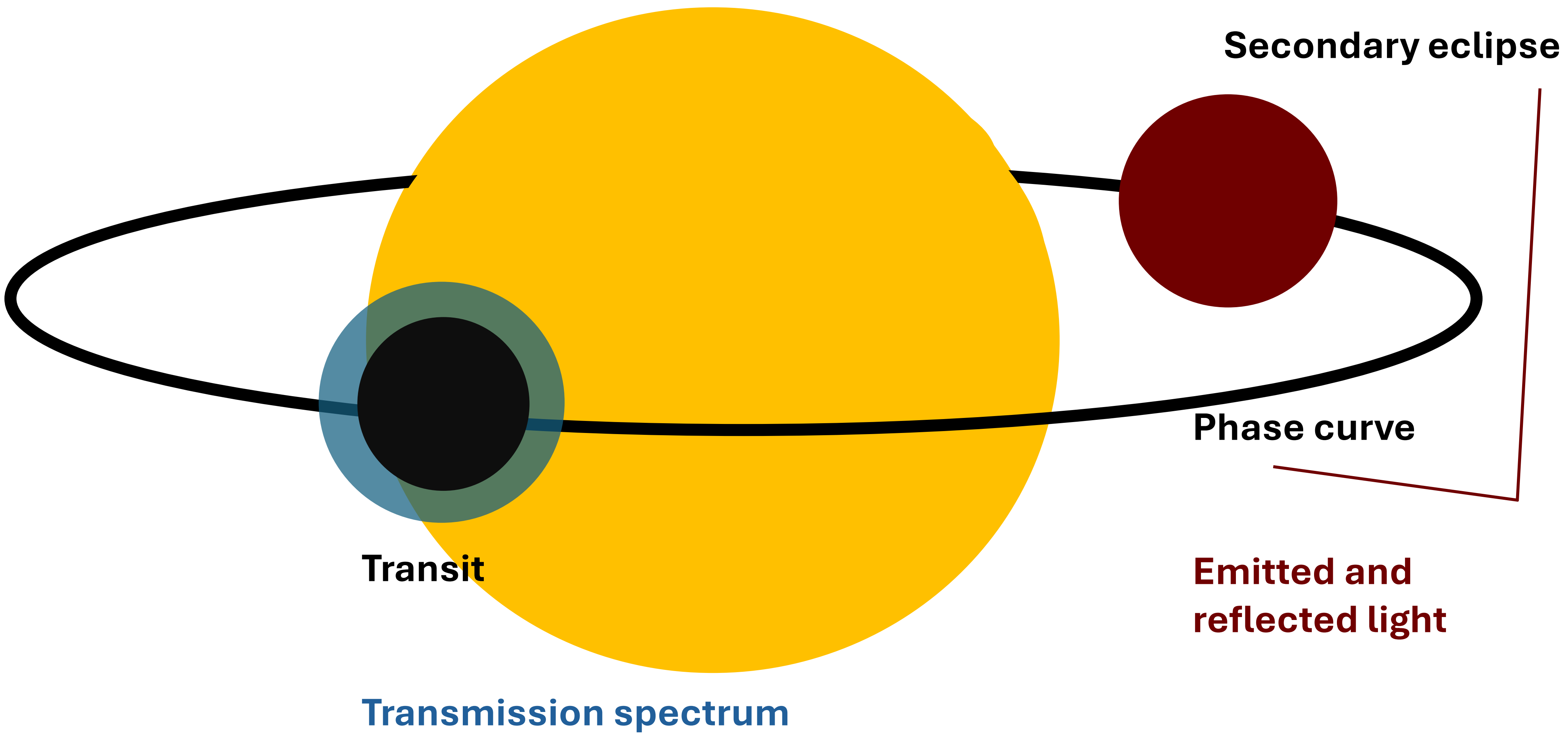


Transit – Transmission spectroscopy



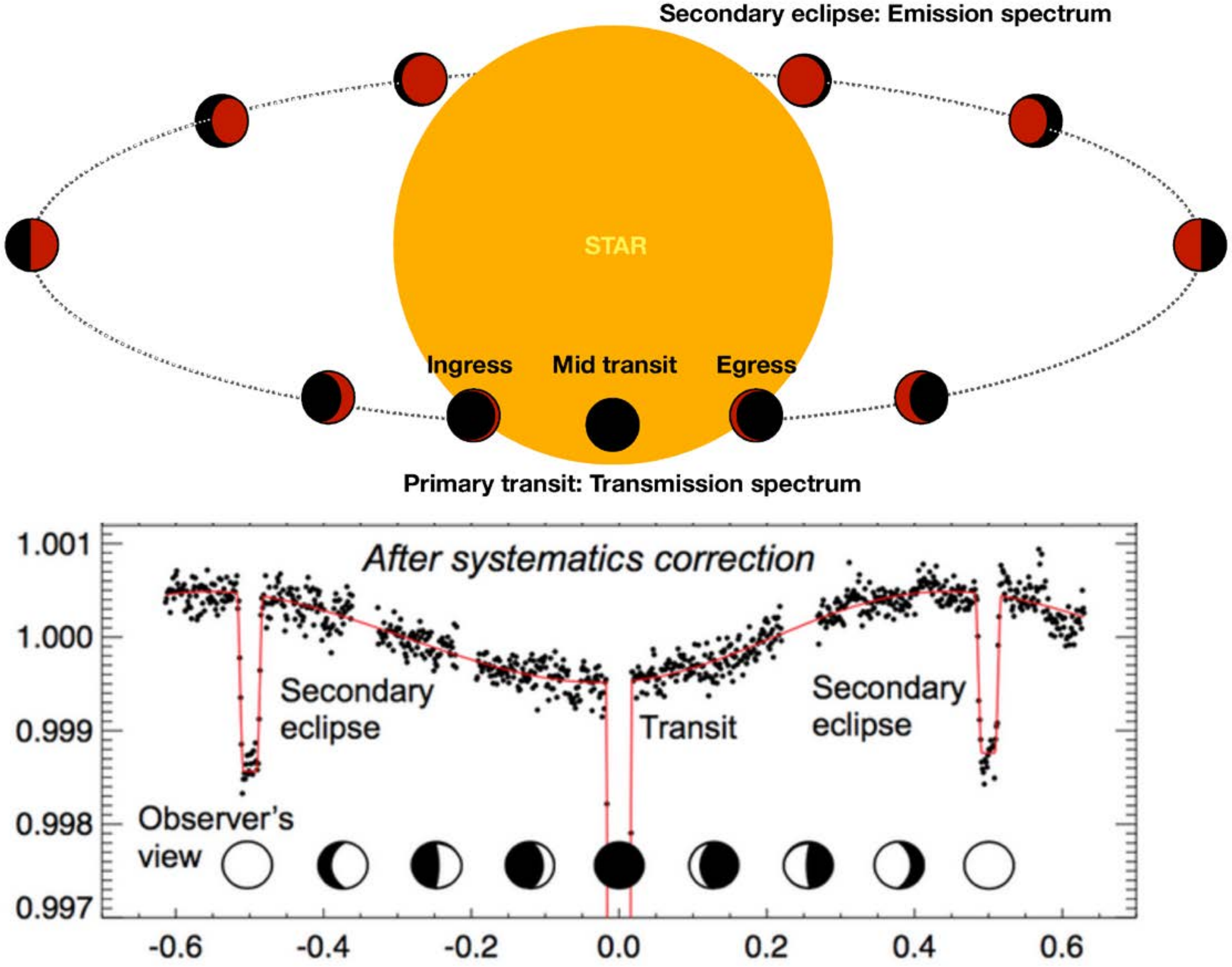
Sing et al. 2016

How do we measure exoplanet atmospheres?



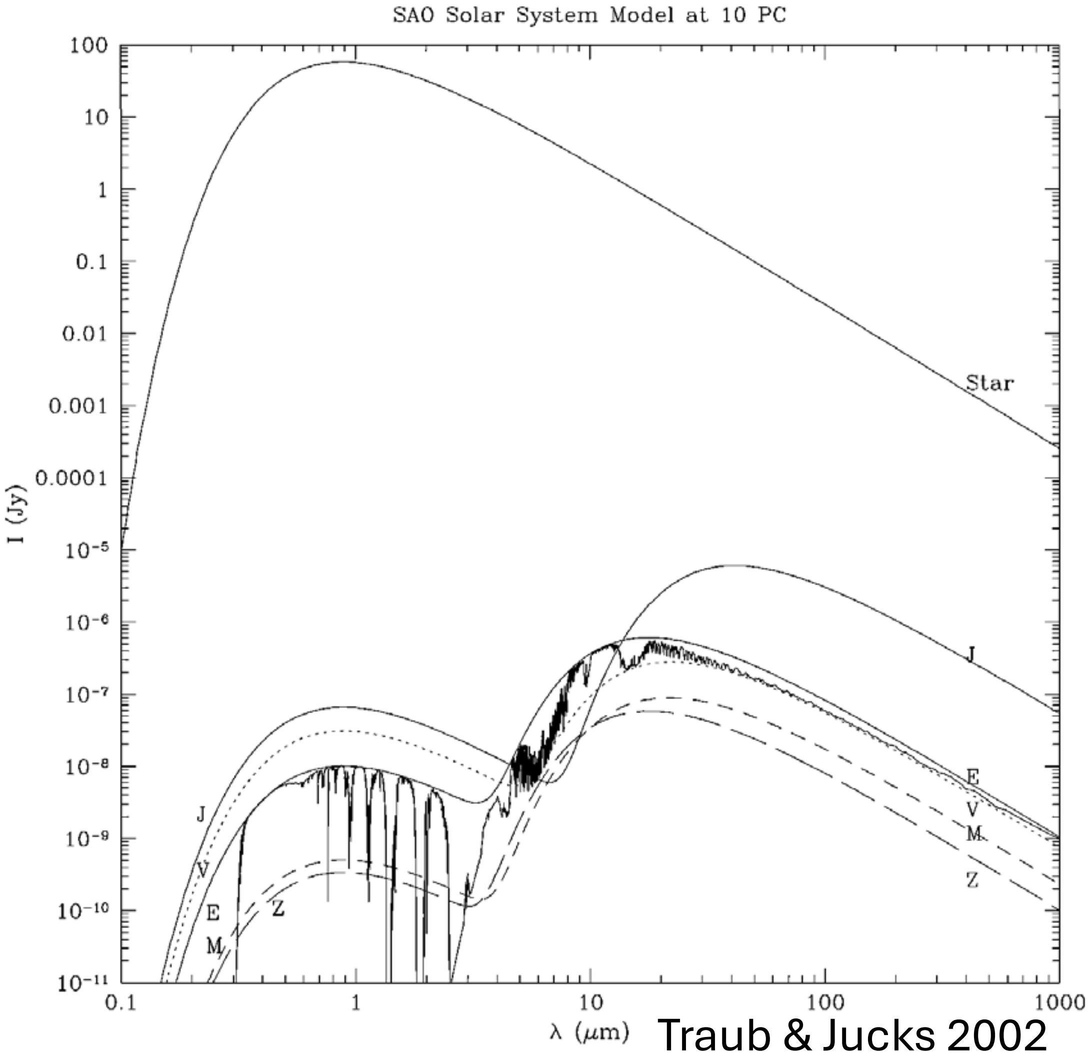
Emitted light / Reflected light

Phase curve
Secondary eclipse

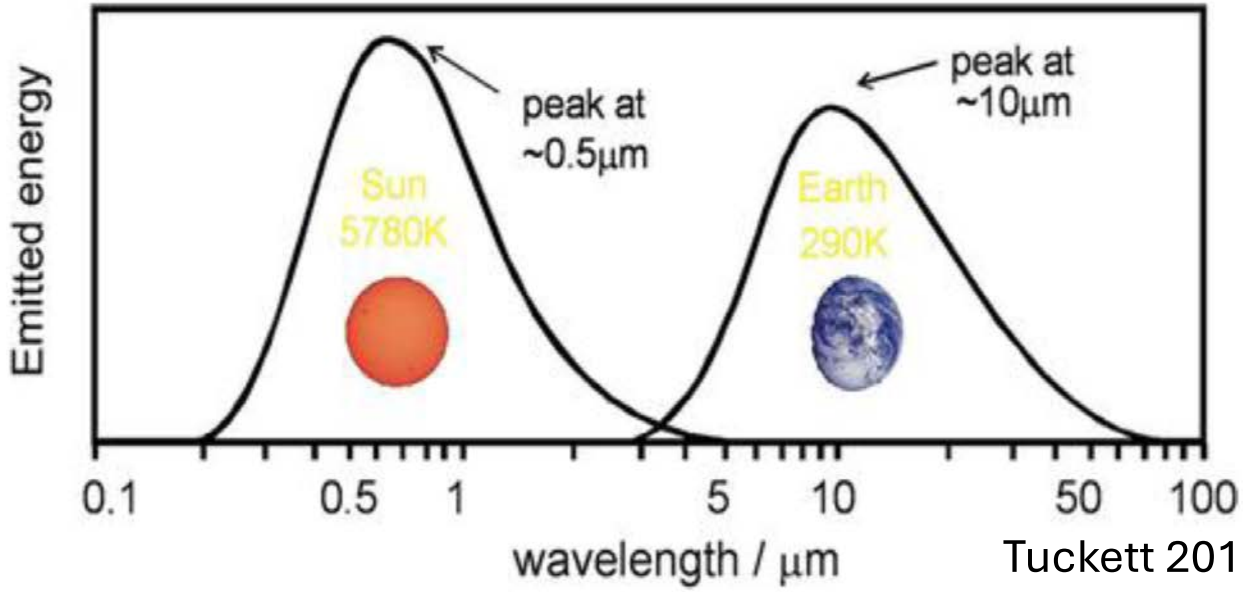


Pluriel 2023;
adapted from
Seager & Deming 2010
Knutsen et al. 2012

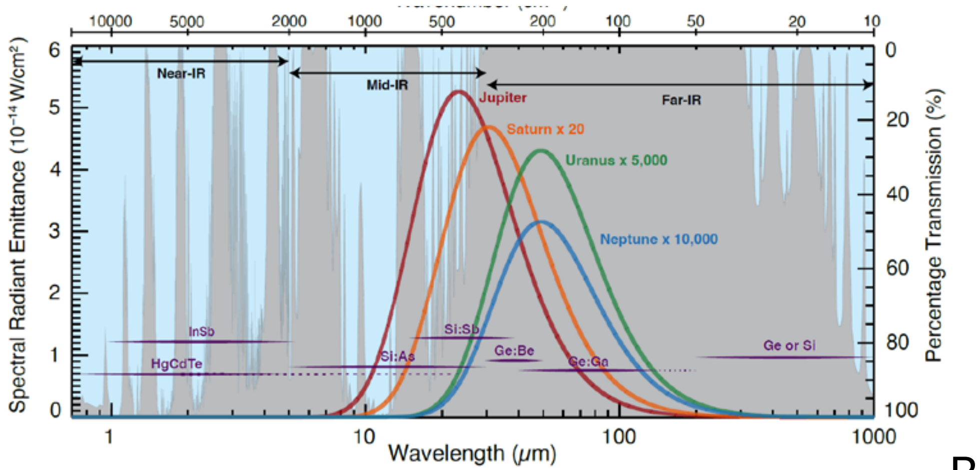
Emitted vs. Reflected light



Traub & Jucks 2002



Tuckett 2018



Roman 2023

How large are the signals?

$$\Delta\delta = \frac{(R_\mathrm{p} + n\,H_\mathrm{p})^2}{R_\star^2} - \frac{R_\mathrm{p}^2}{R_\star^2} = \frac{2\,R_\mathrm{p}\,n\,H_\mathrm{p} + (n\,H_\mathrm{p})^2}{R_\star^2}$$

~ n * 100-500 ppm

$$H_\mathrm{p} = \frac{k_b\,T_\mathrm{eq}}{\mu\,g_\mathrm{p}}$$

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

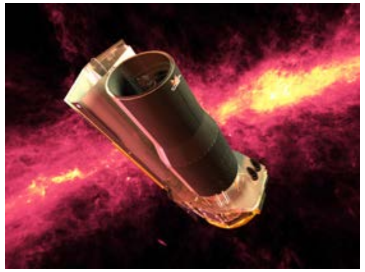
$$\mathrm{ESM} = 4.29 \times 10^6 \times \frac{B_{7.5}(T_{day})}{B_{7.5}(T_*)} \times \left(\frac{R_p}{R_*}\right)^2 \times 10^{-m_K/5}$$

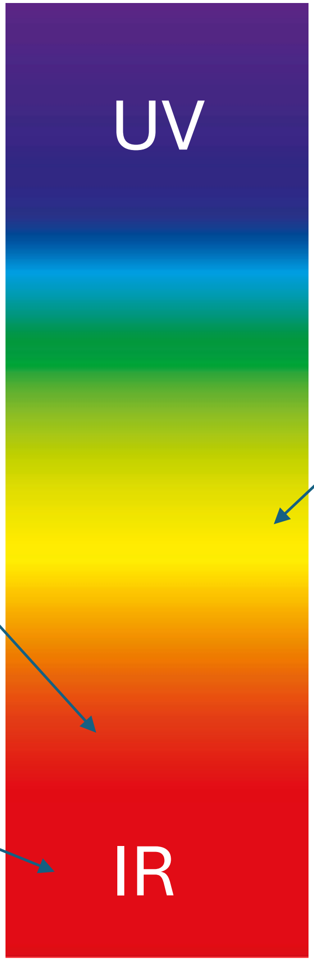
Kempton et al. 2018

Where does the data come from – Low resolution:

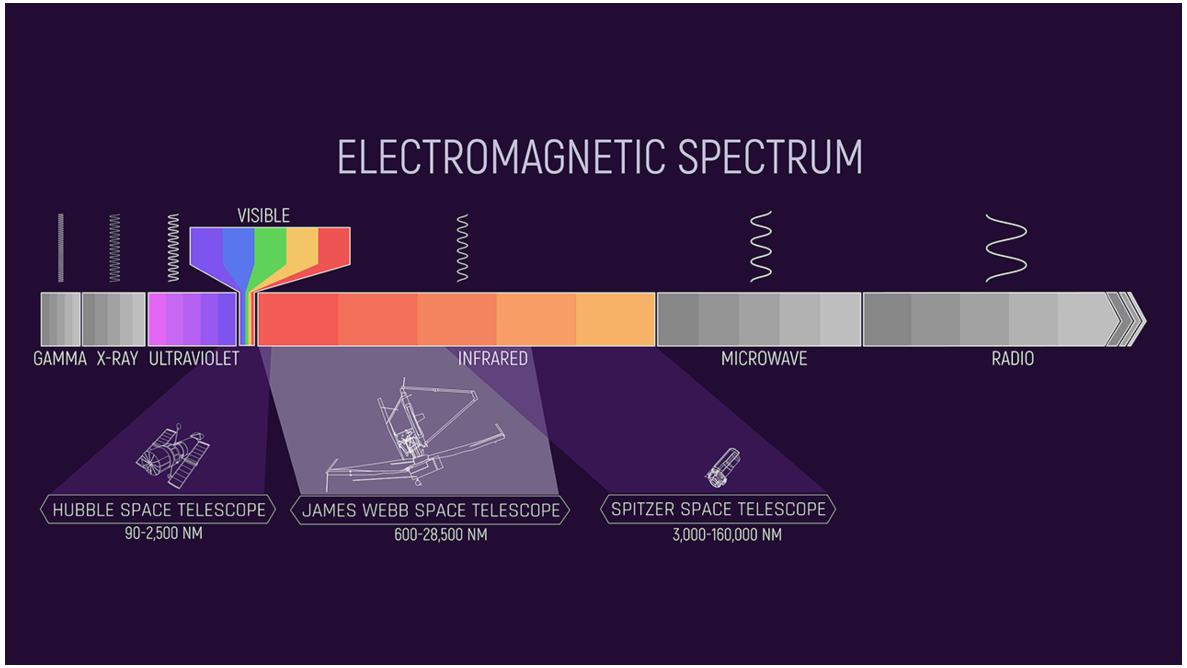
Space based:
HST (STIS,
WFC3)

Spitzer





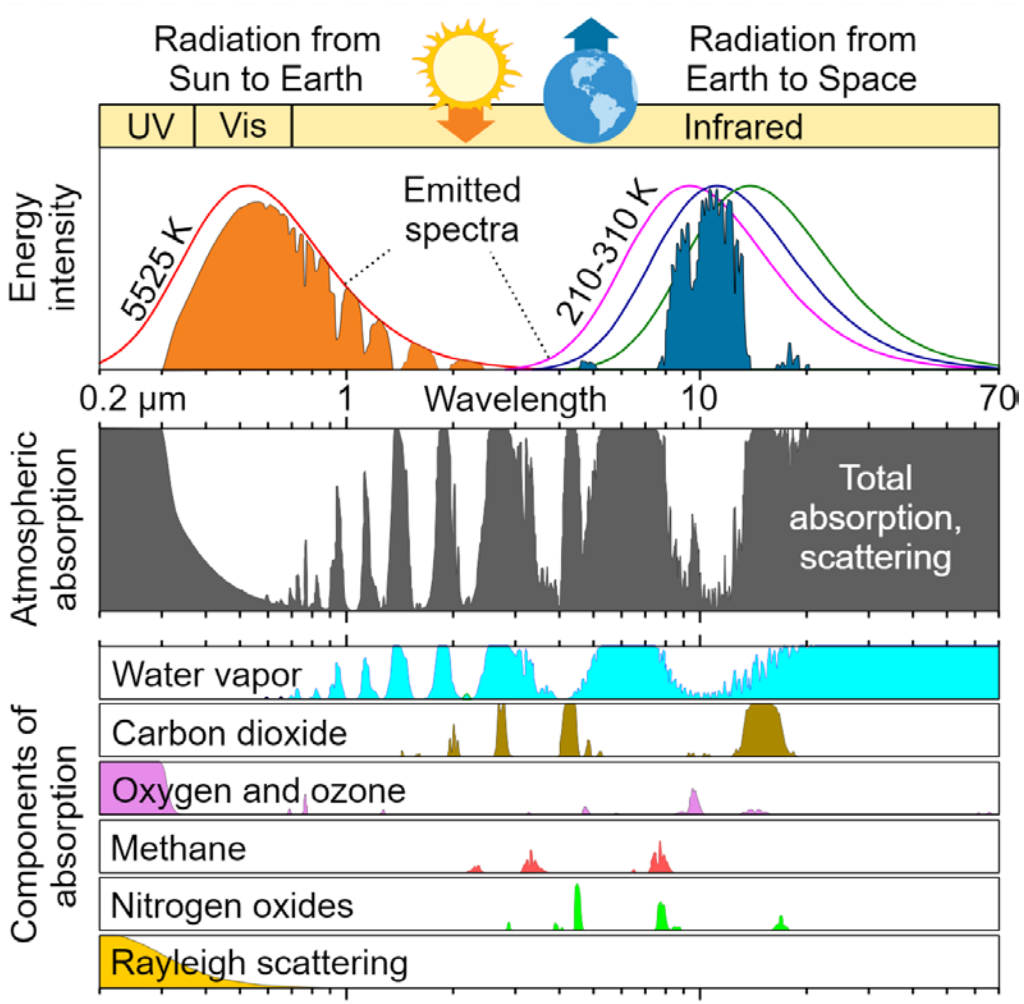
Ground-based:
FORS2/VLT, OSIRIS/GTC,
GMOS/GEMINI-South,
…



NASA, ESA, CSA, Joseph Olmsted (STScI)

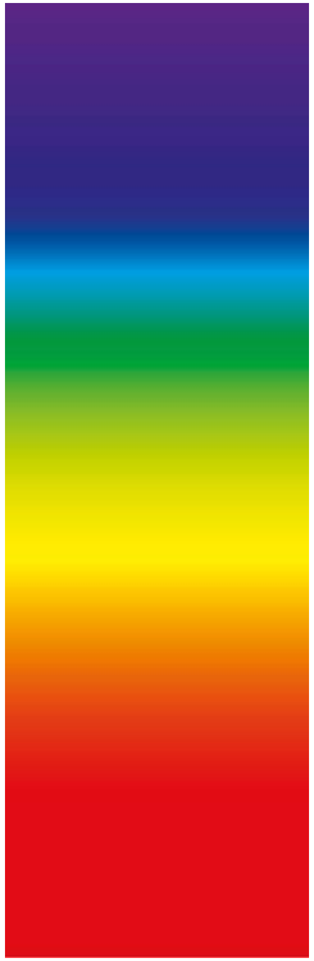
What can be measured at which wavelength?

Throughput Earth's atmosphere

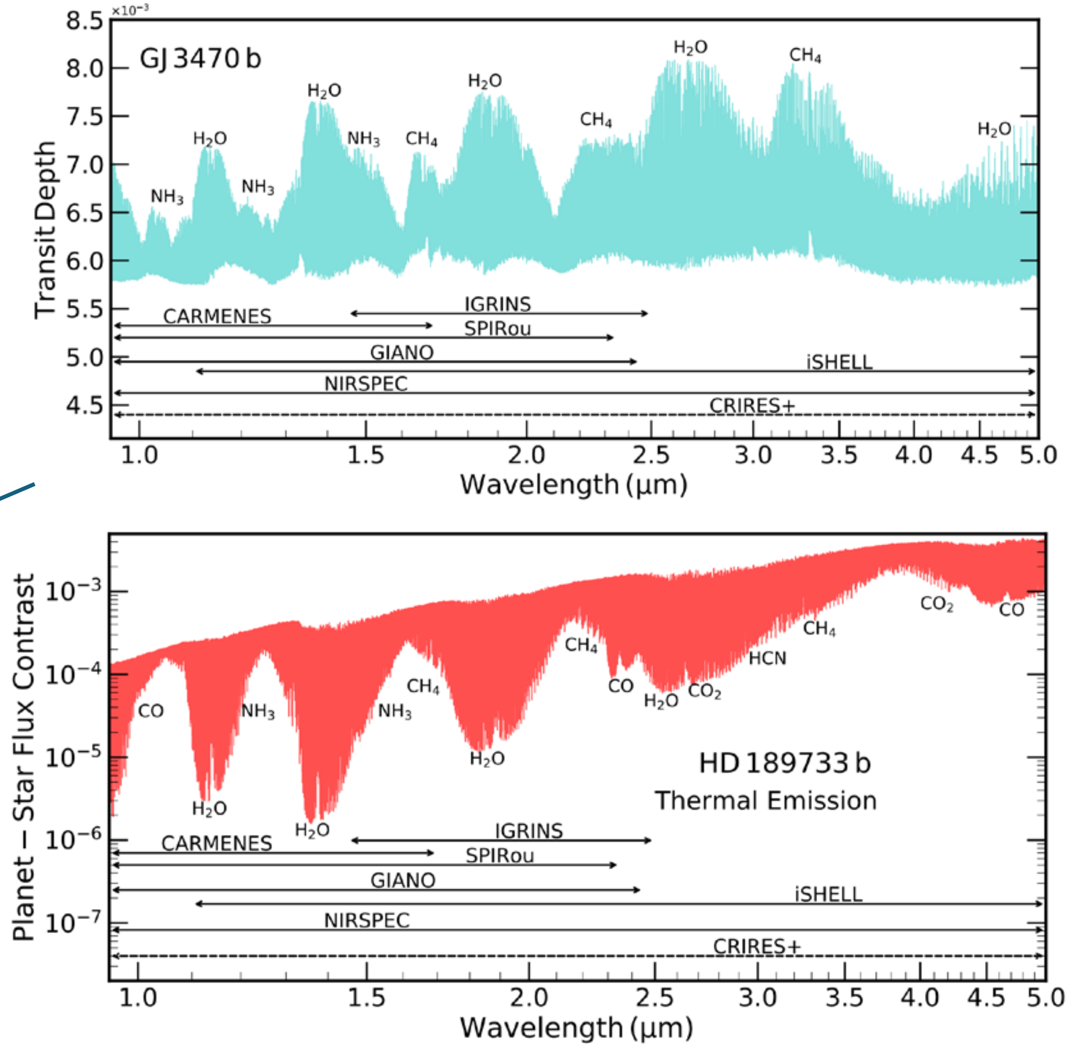


Credit: noaa.gov
The atmospheric window

Where does the data come from – High resolution:

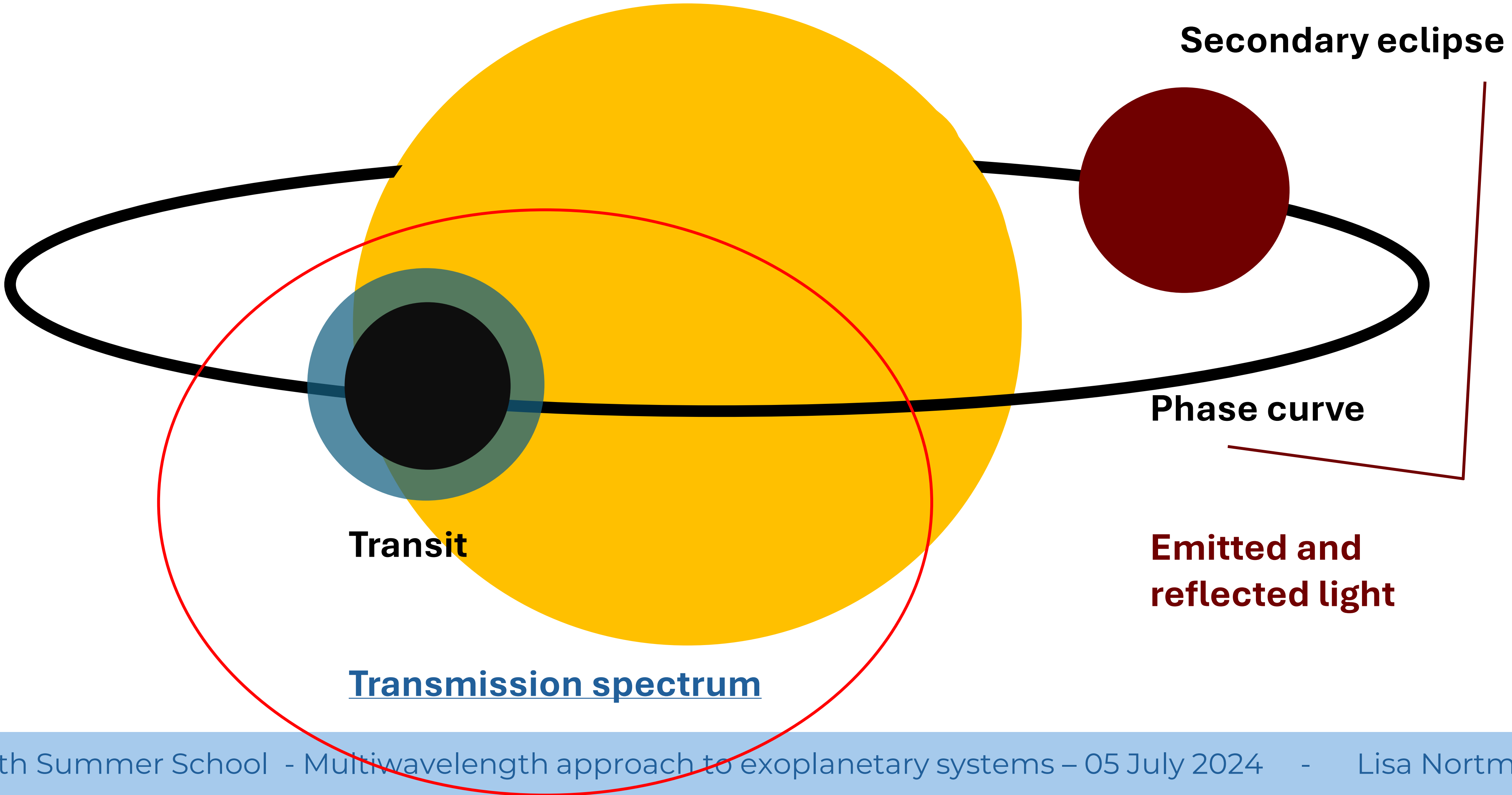


VLT/ESPRESSO
HARPS-N
CARMENES
...



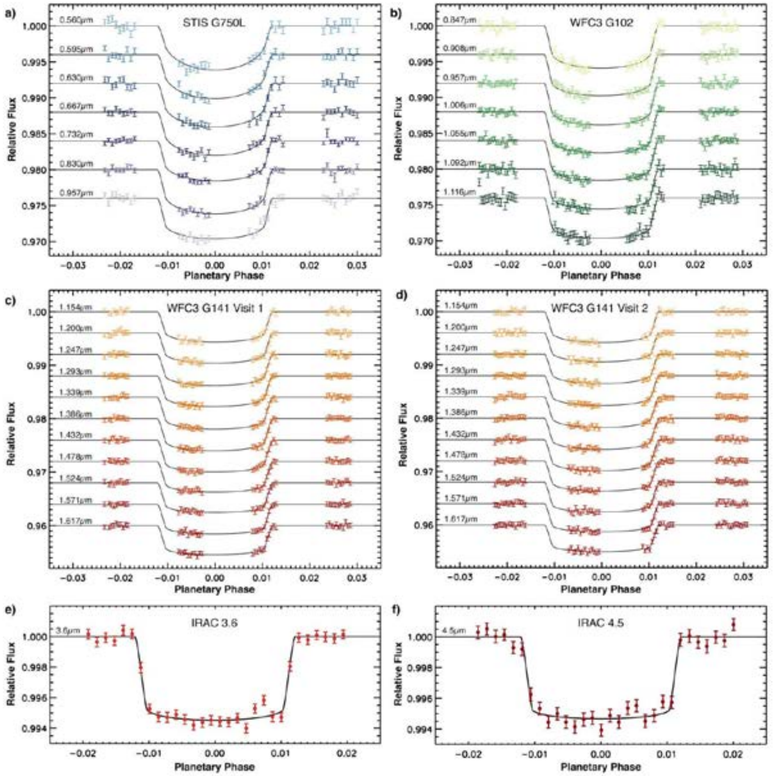
Ghandi et al 2020

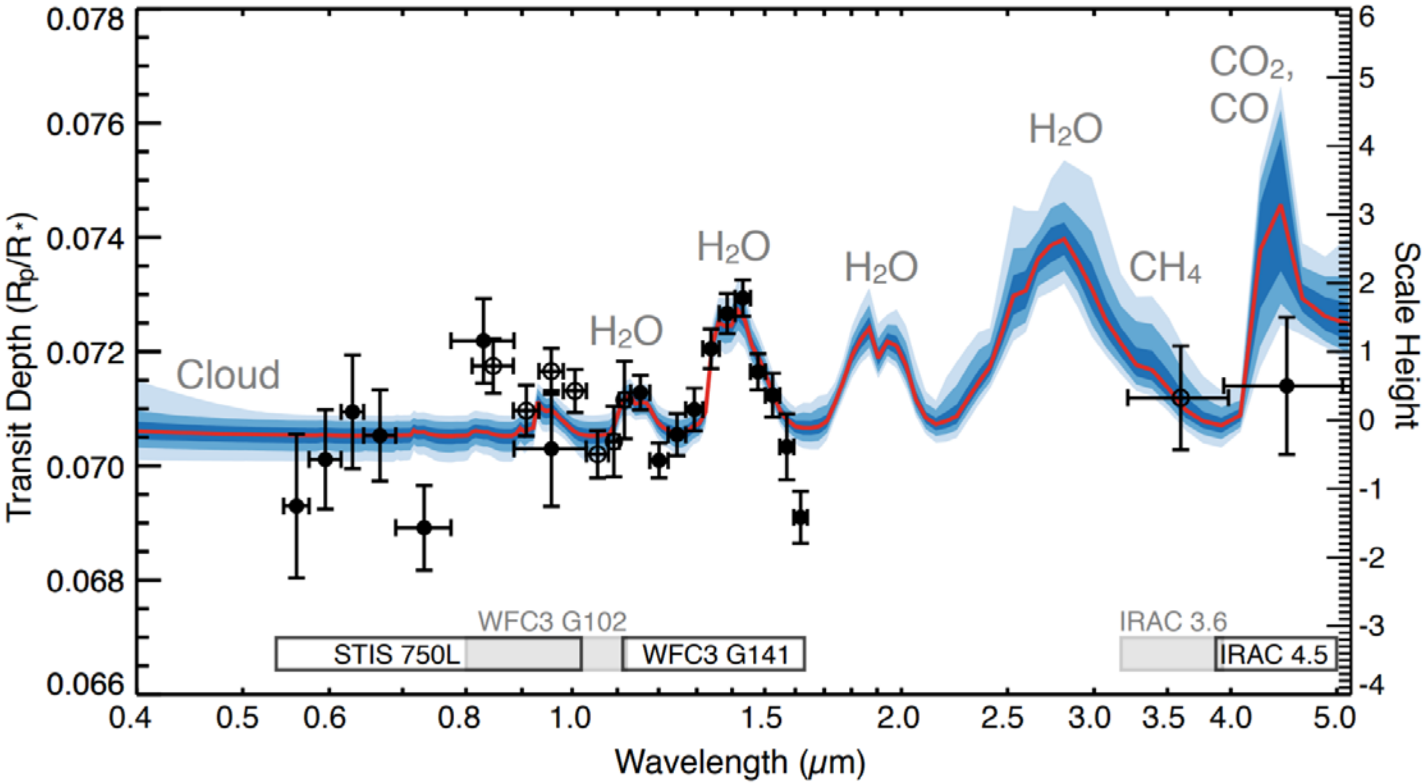
How do we measure exoplanet atmospheres?



Transit – Transmission spectroscopy

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

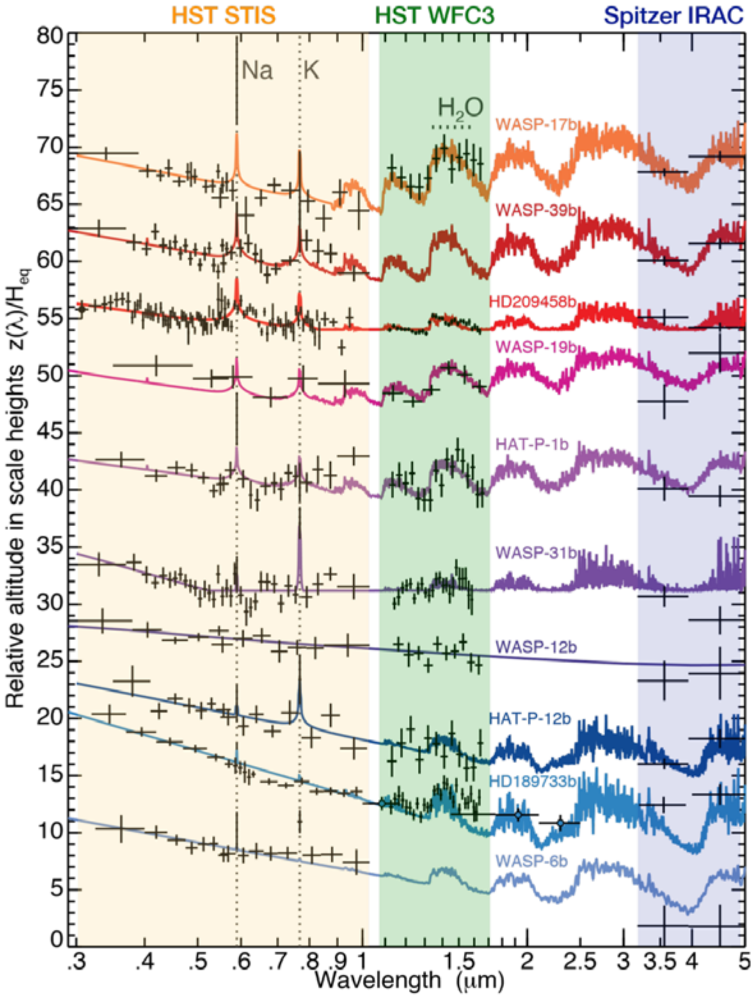


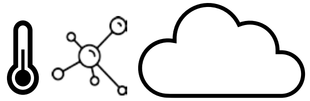


Wakeford et al. 2022

Low resolution space based transmission spectra

pre JWST era

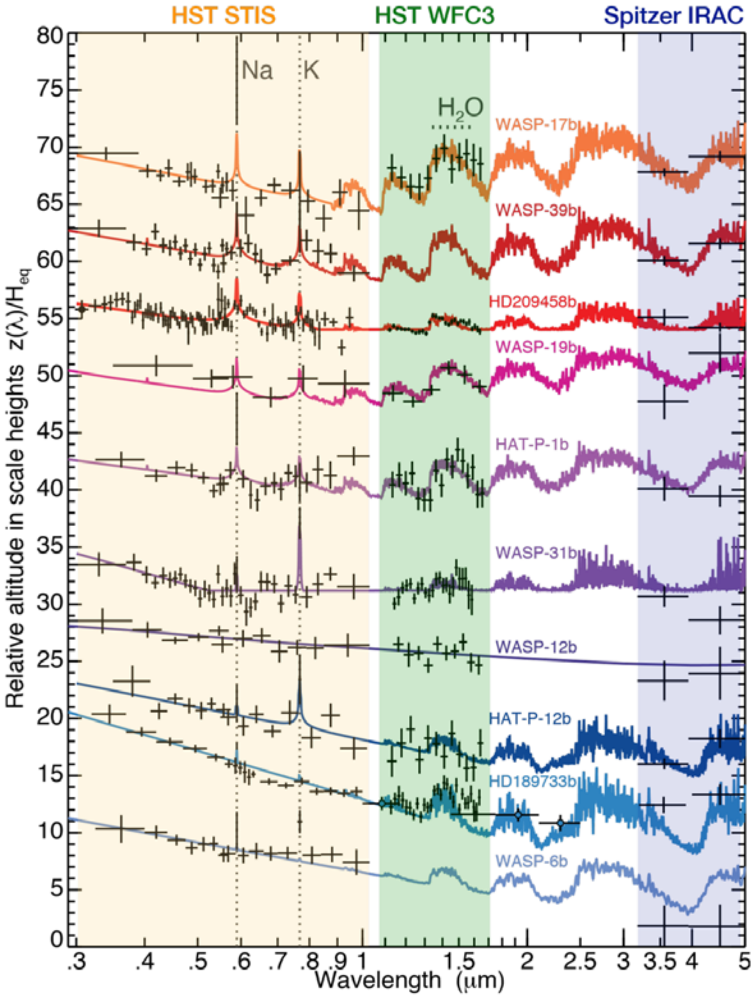




Kempton & Knutson 2024; adapted from Sing et al 2010

Low resolution space based transmission spectra

pre JWST era



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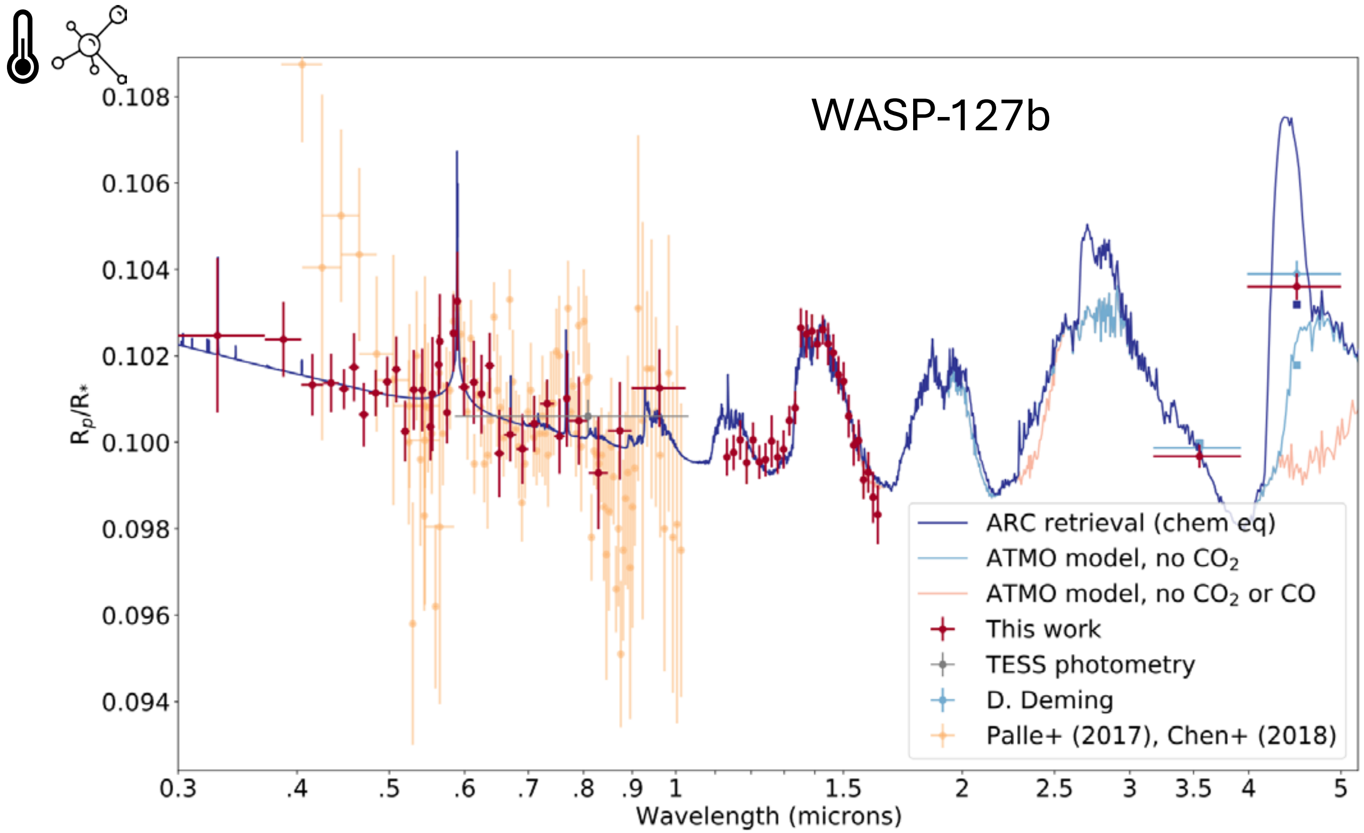
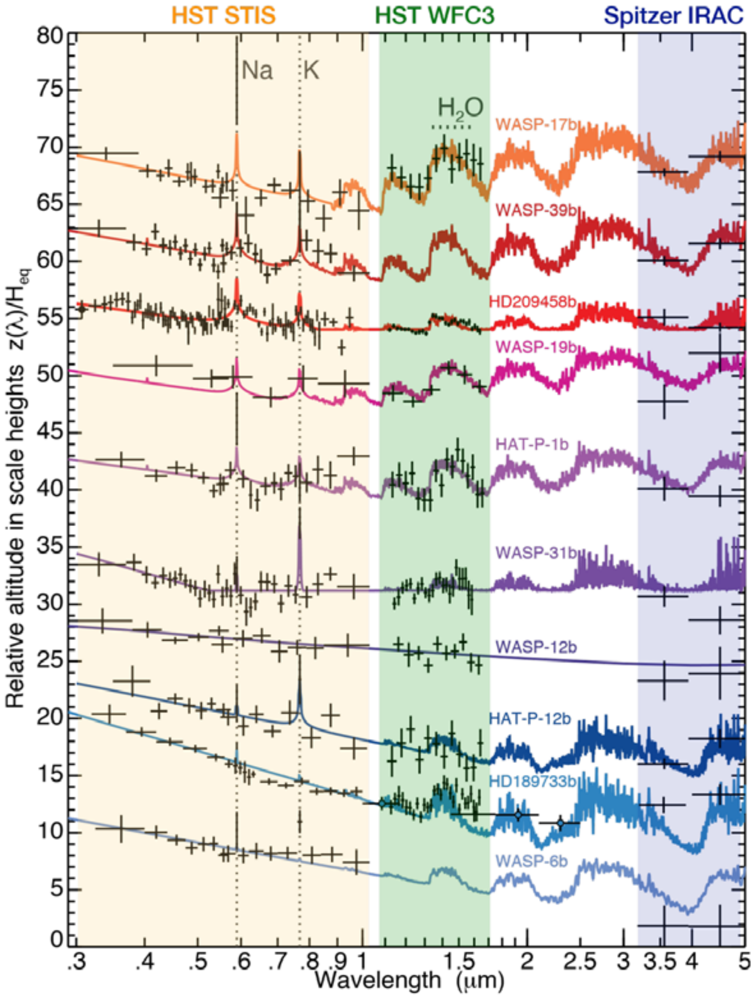


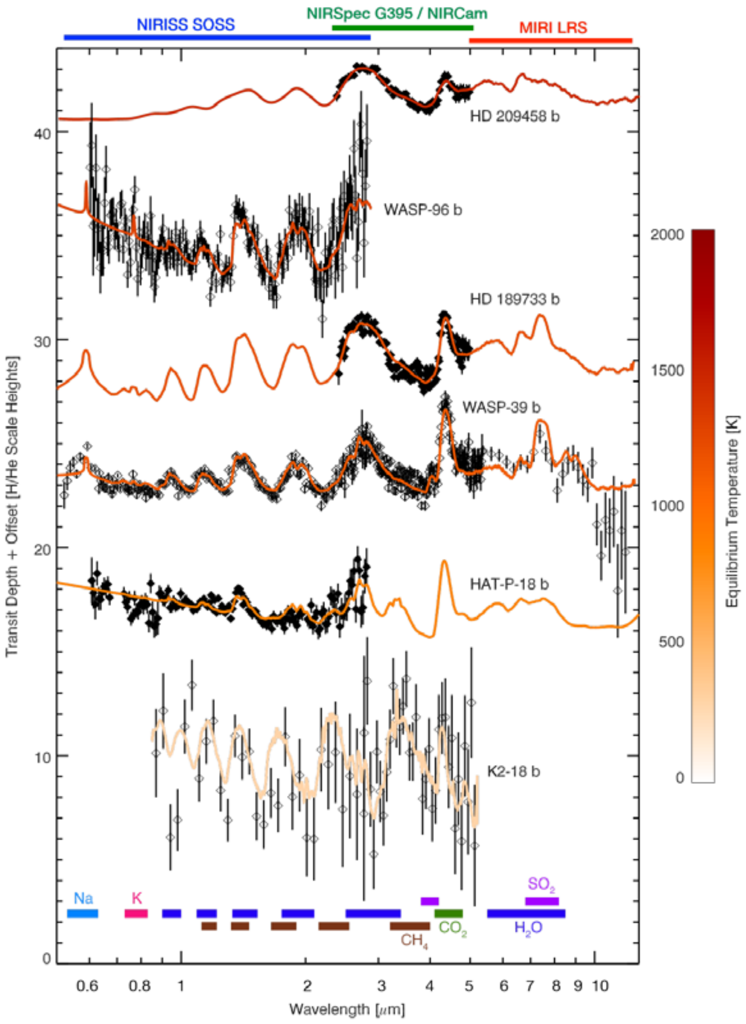
Spake et al 2019

Low resolution space based transmission spectra

pre JWST era



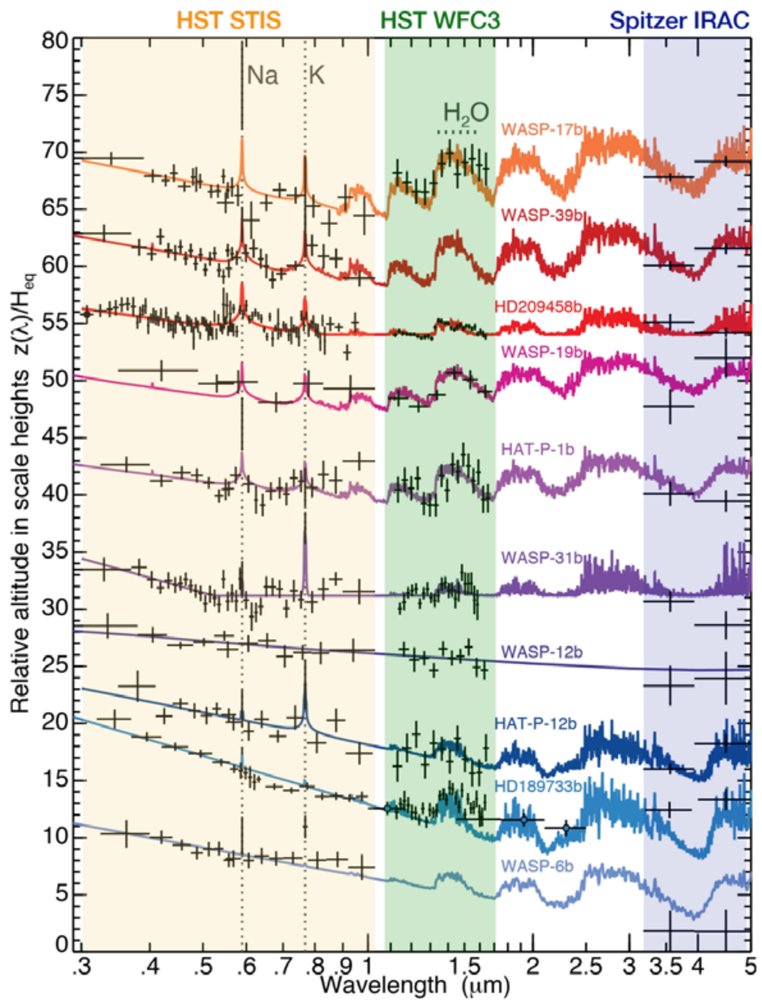
JWST first results



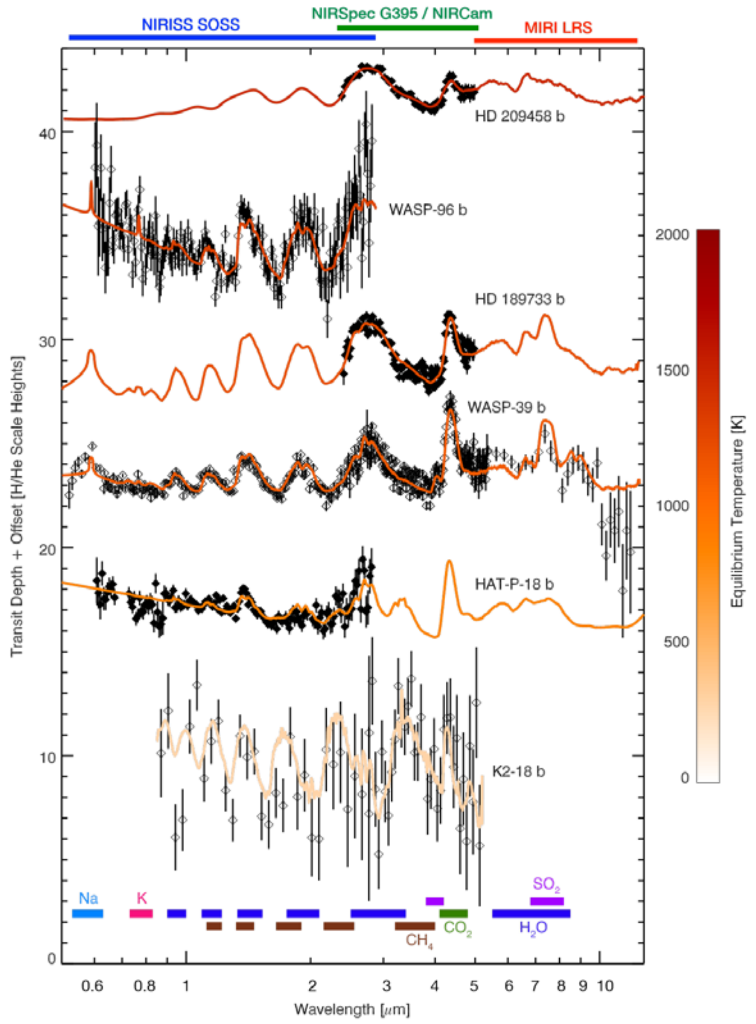
Kempton & Knutson 2024; left: adapted from Sing et al 2010

Low resolution space based transmission spectra

pre JWST era

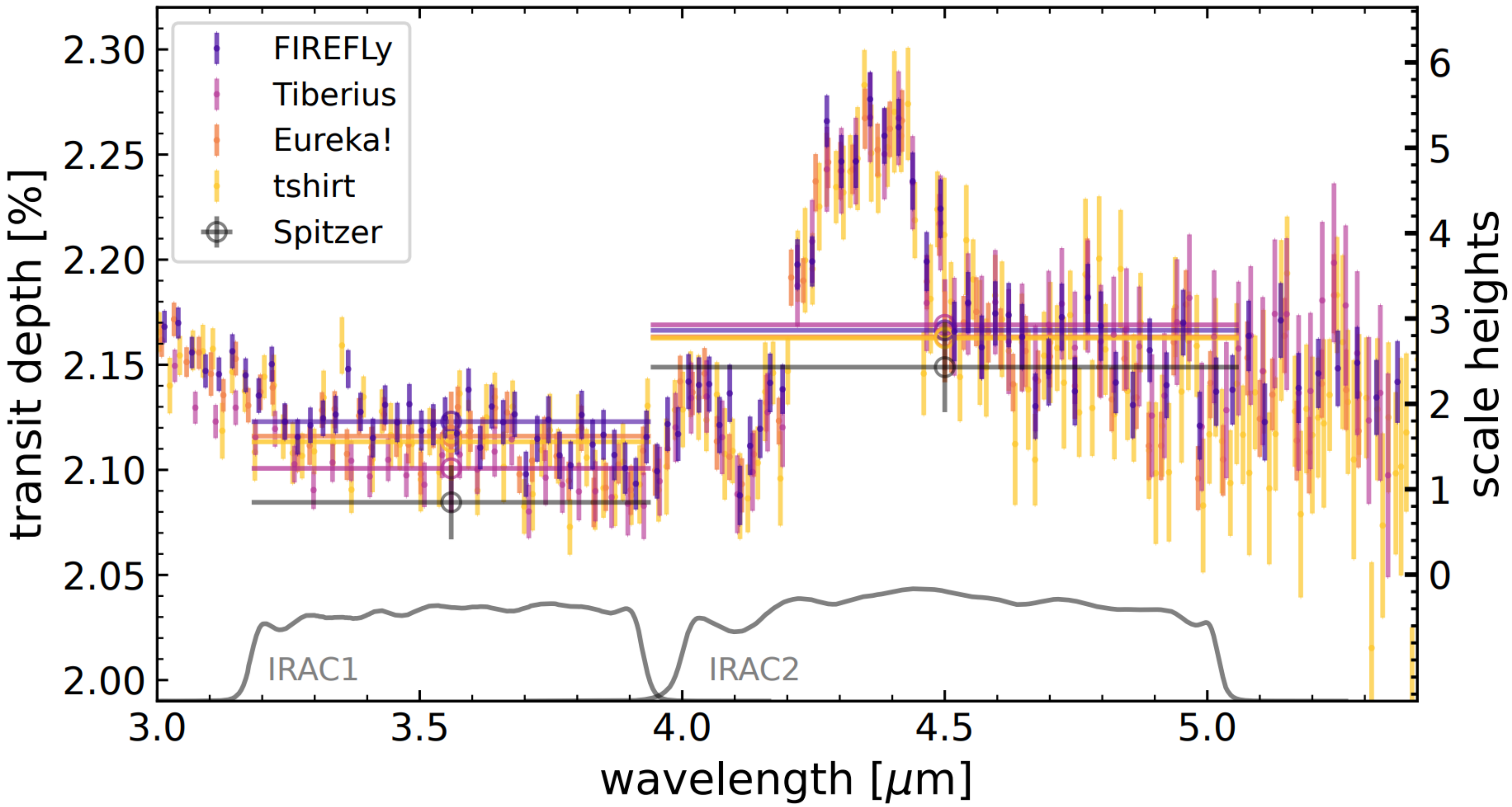


JWST first results



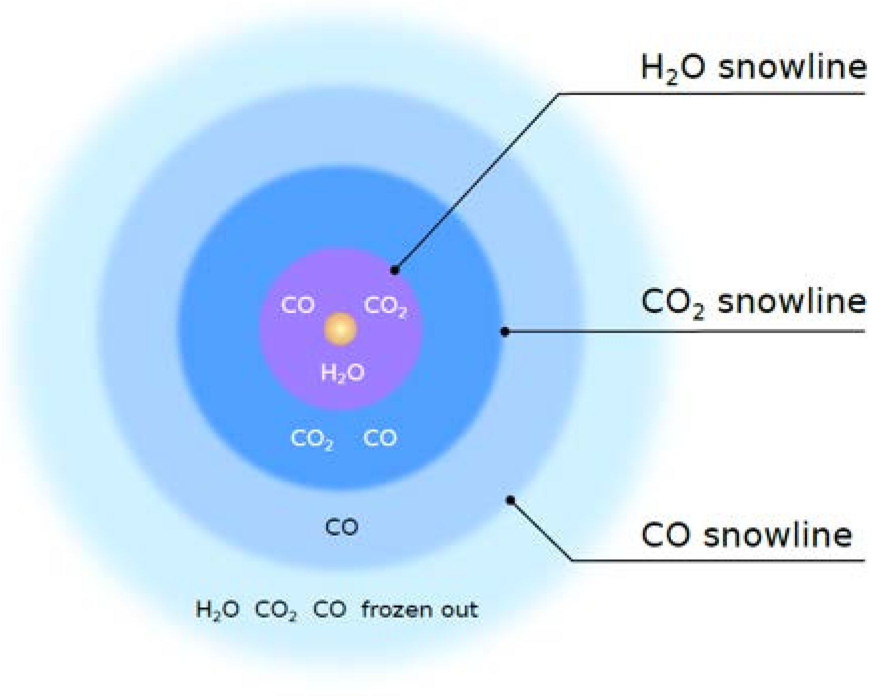
Kempton & Knutson 2024; left: adapted from Sing et al 2010

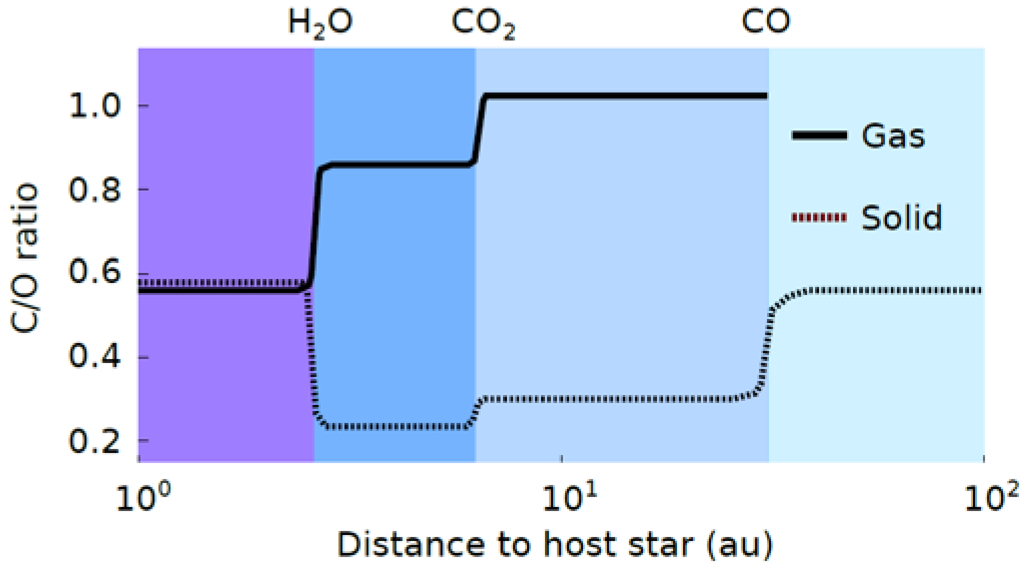
JWST vs. Spitzer - CO2 and Sulfur dioxide in WASP-39b



CO_2 detection in WASP-39b
The JWST Transiting Exoplanet Community Early Release Science Team
2022

C/O ratio and planet formation

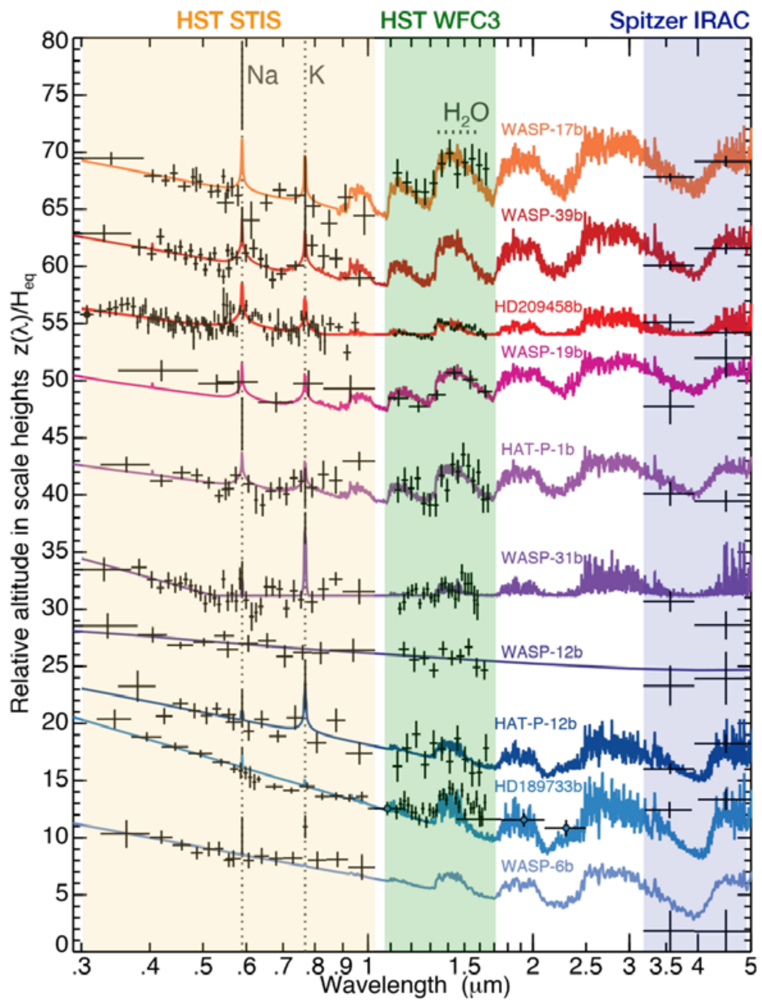




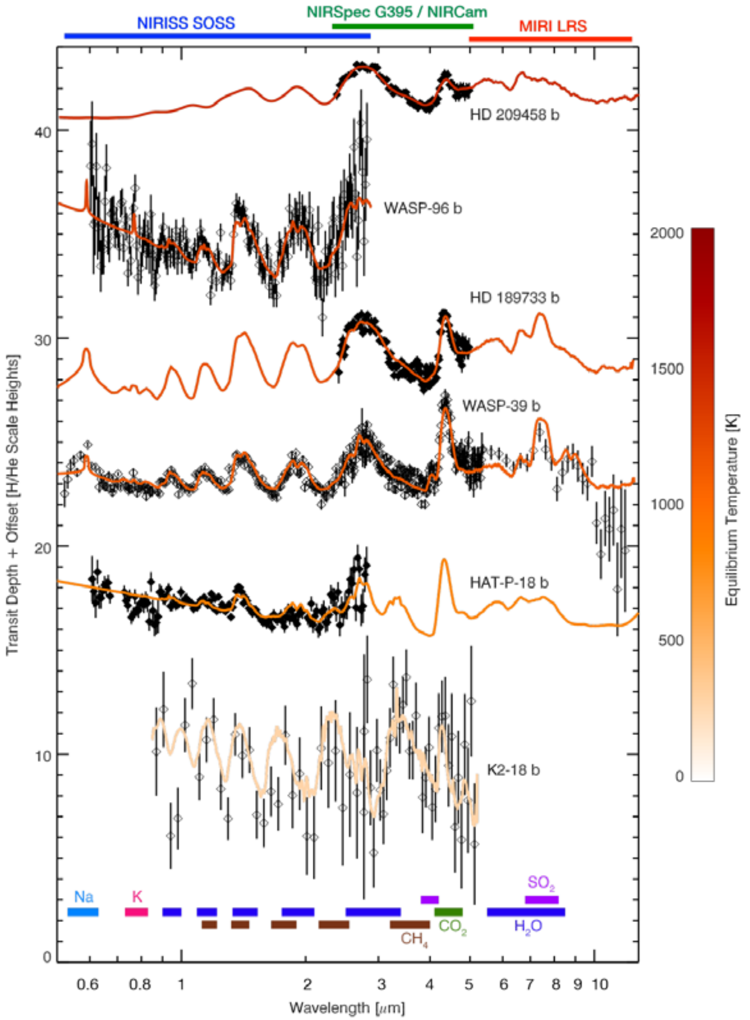
Cont 2023,
right panel adapted from Madhusudhan 2019, also see Odberg 2011

Low resolution space based transmission spectra

pre JWST era



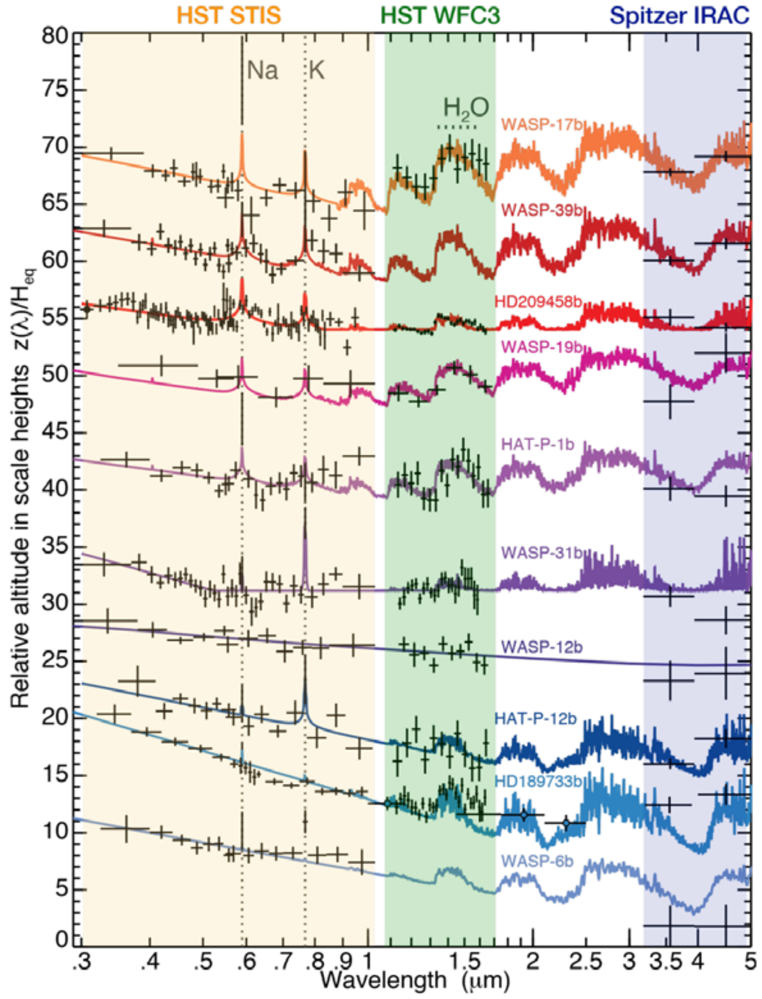
JWST first results



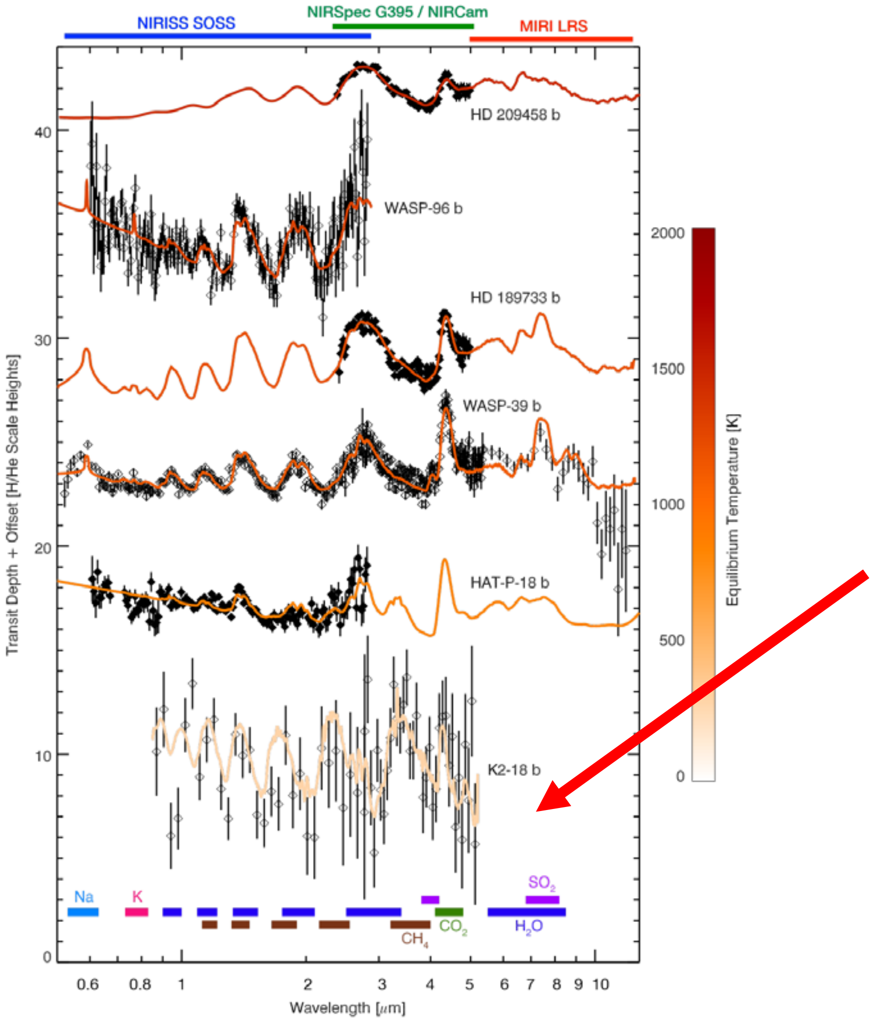
Kempton & Knutson 2024; left: adapted from Sing et al 2010

Low resolution space based transmission spectra

pre JWST era



JWST first results



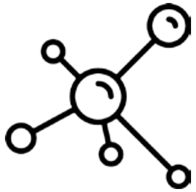
Madhusudhan et al 2024

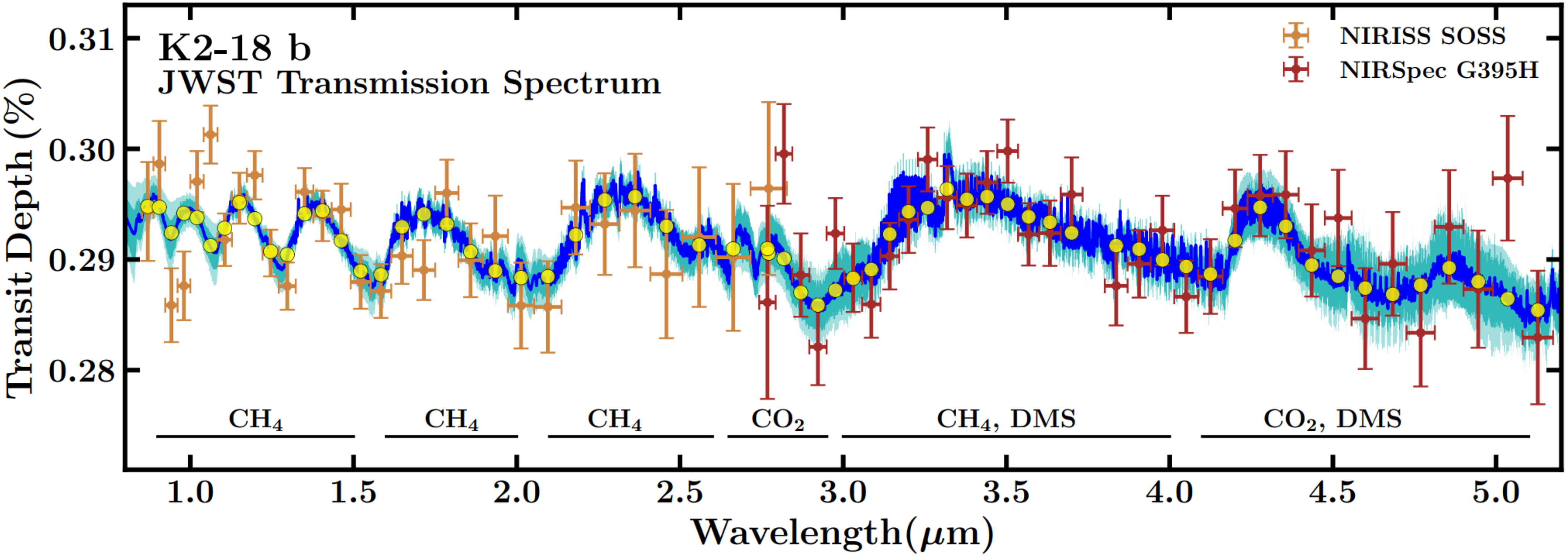
Kempton & Knutson 2024; left: adapted from Sing et al 2010

Low resolution space-based transmission spectra

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

(Hycean: temperate ocean-covered worlds with H2-rich atmospheres)



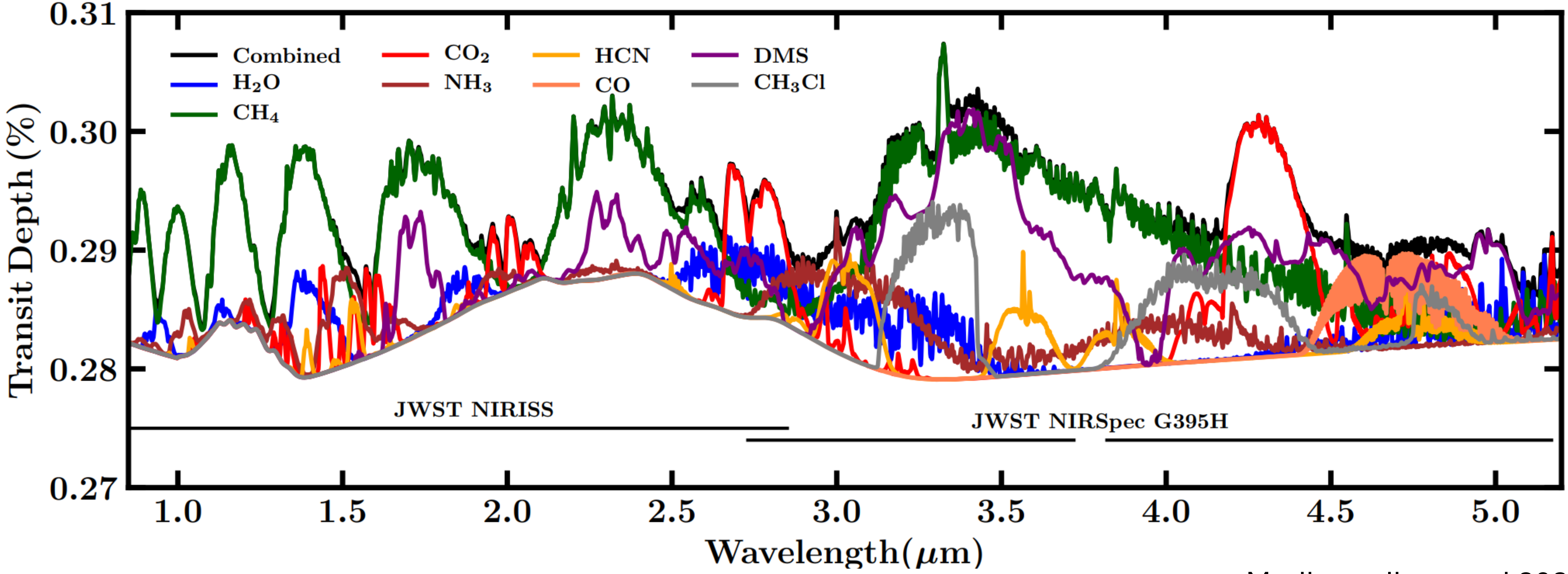


Madhusudhan et al 2024

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

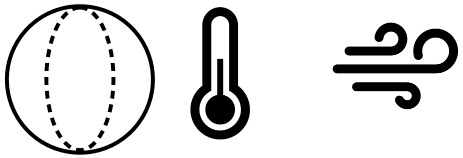
Low resolution space-based transmission spectra

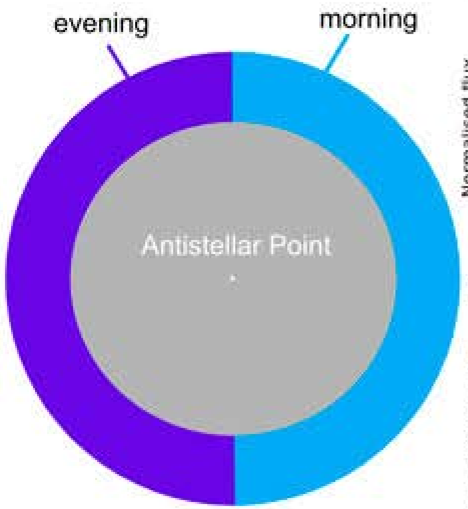
The spectrum and its components from multiple absorbers

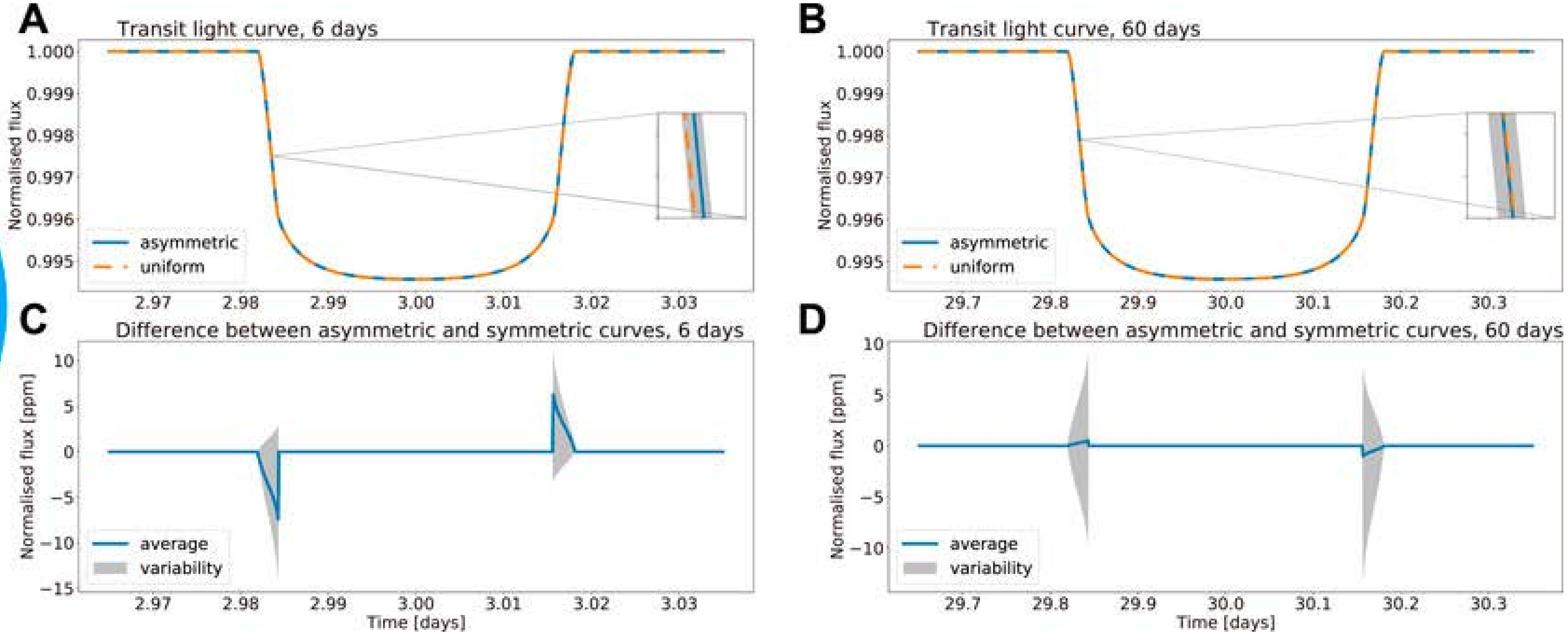


Madhusudhan et al 2024

3D effects during transit in low resolution

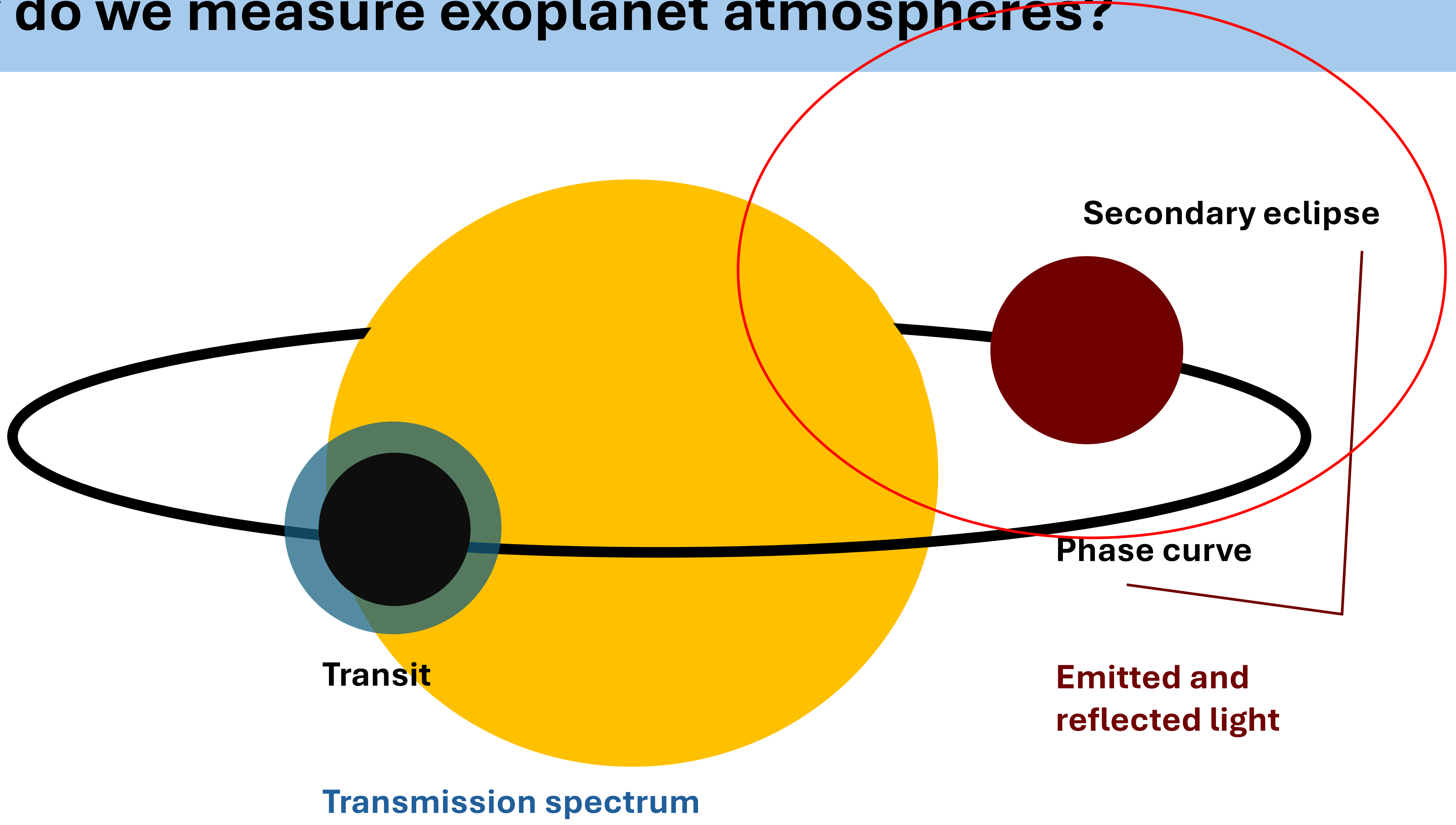






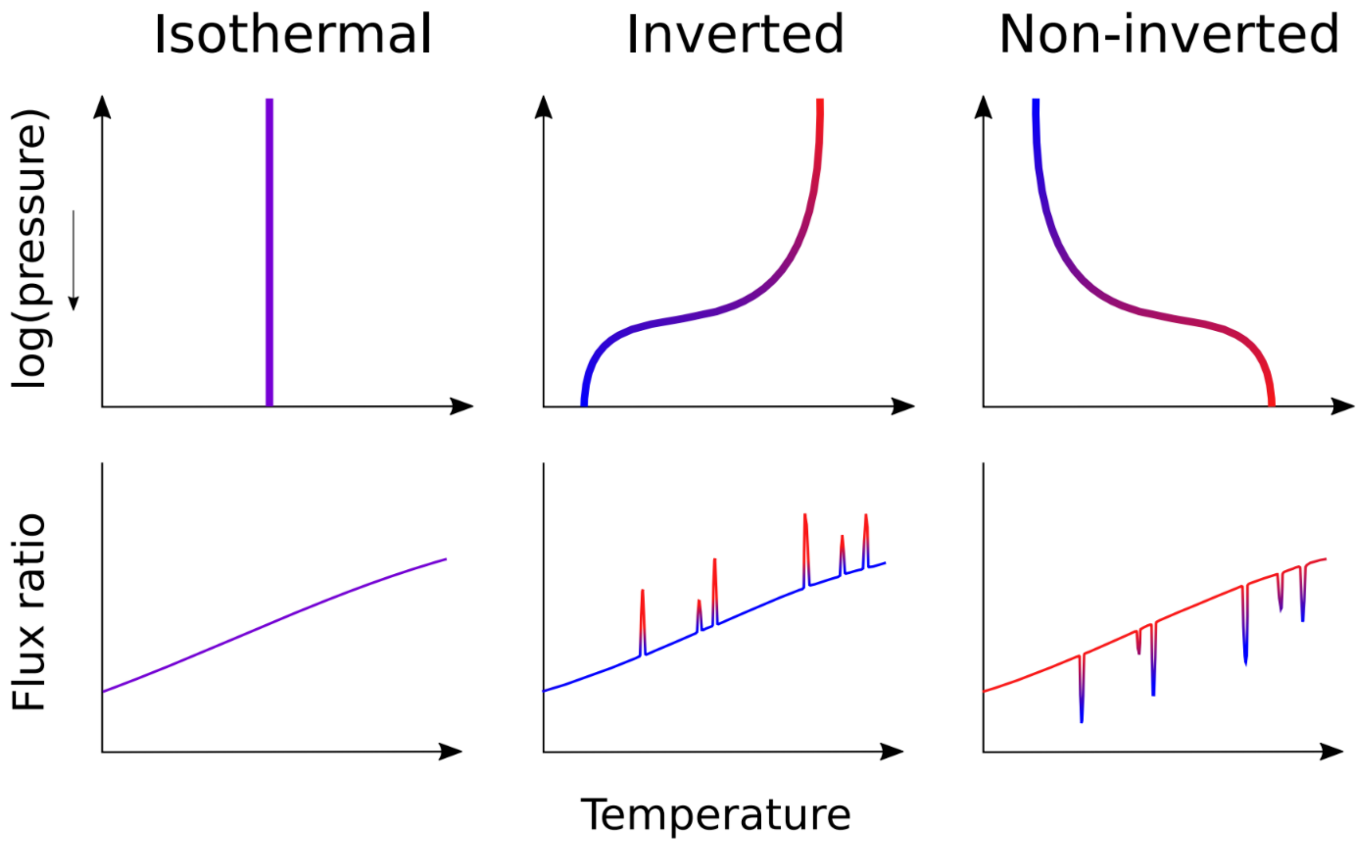
Song et al 2021
Also Falco 2024

How do we measure exoplanet atmospheres?



Temperature – pressure profile

In the emission case:

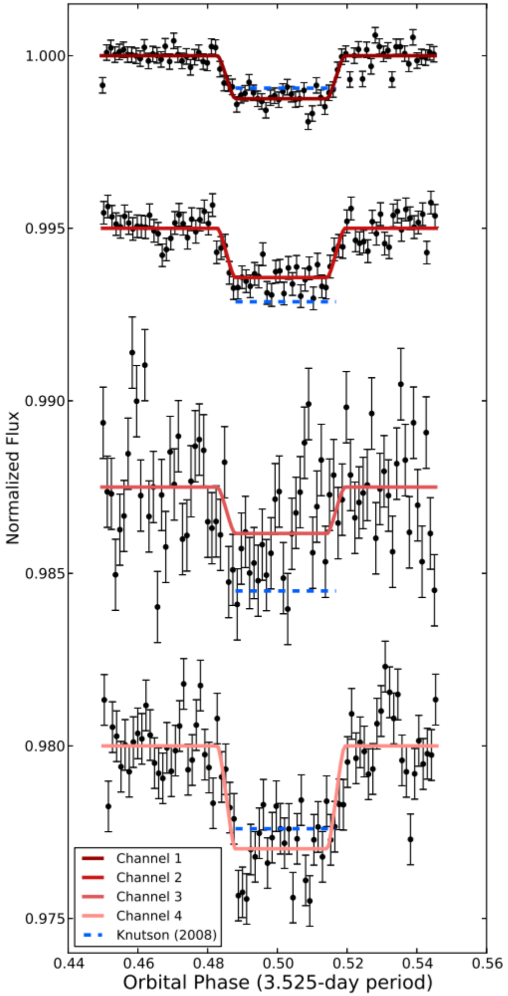


Blackbody spectra

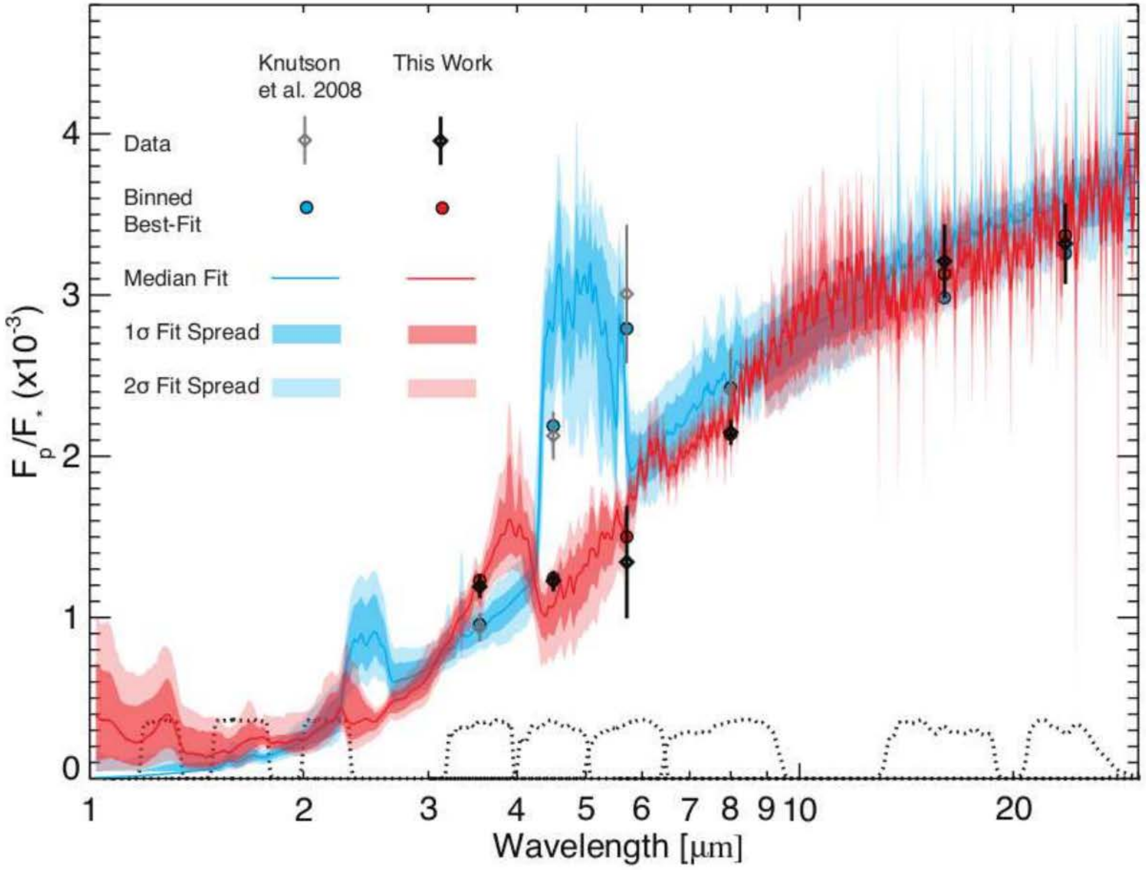
Example Spitzer

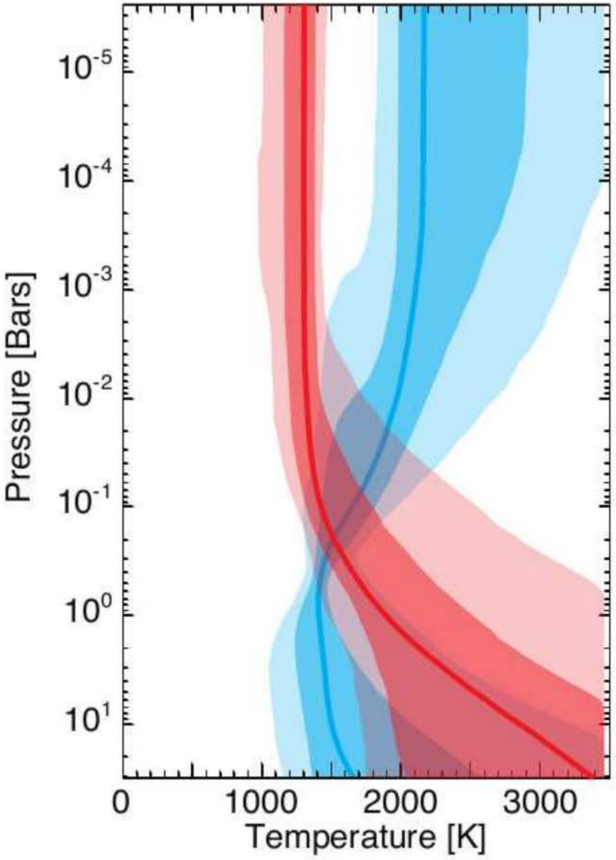
Example high resolution

Emitted light spectrum



HD 209458b with Spitzer

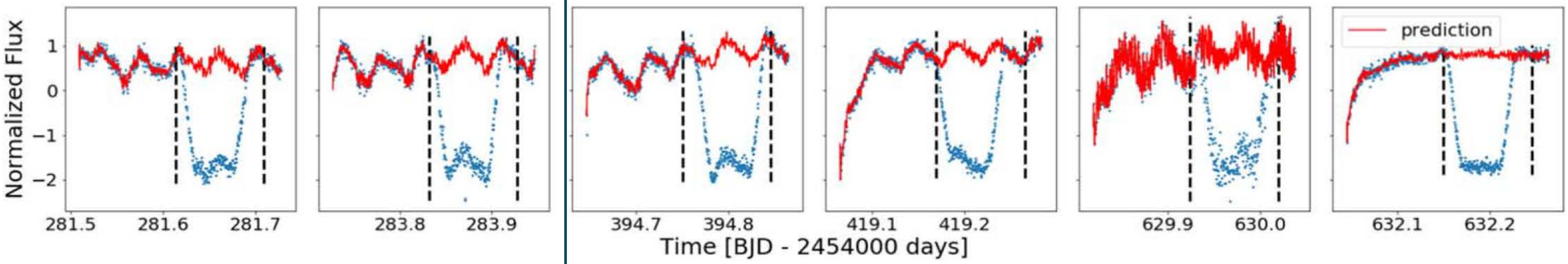




Diamond-Lowe et al 2014

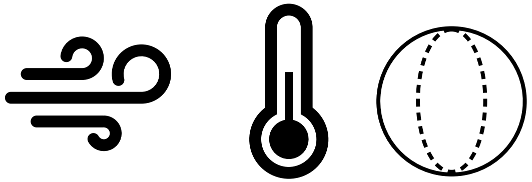
Emitted light spectrum

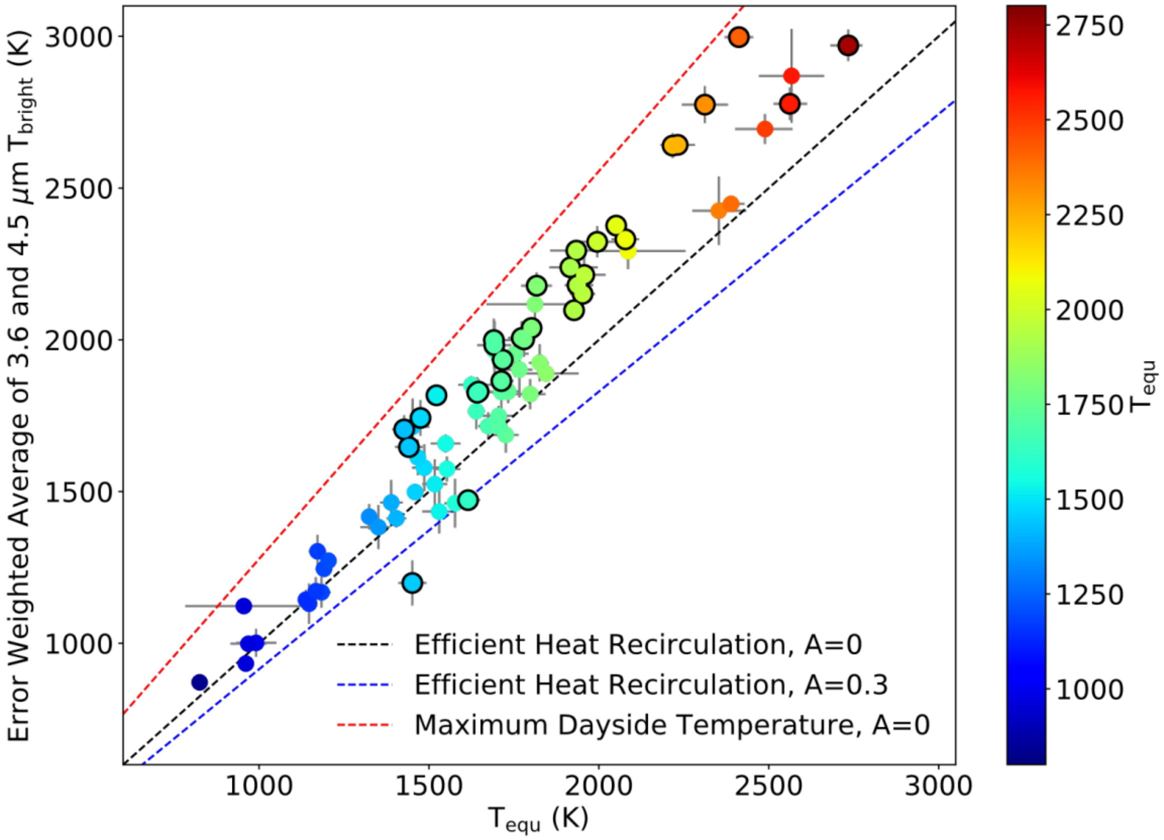
Spitzer: (warm Spitzer: 3.6μ and 4.5μ) photometry



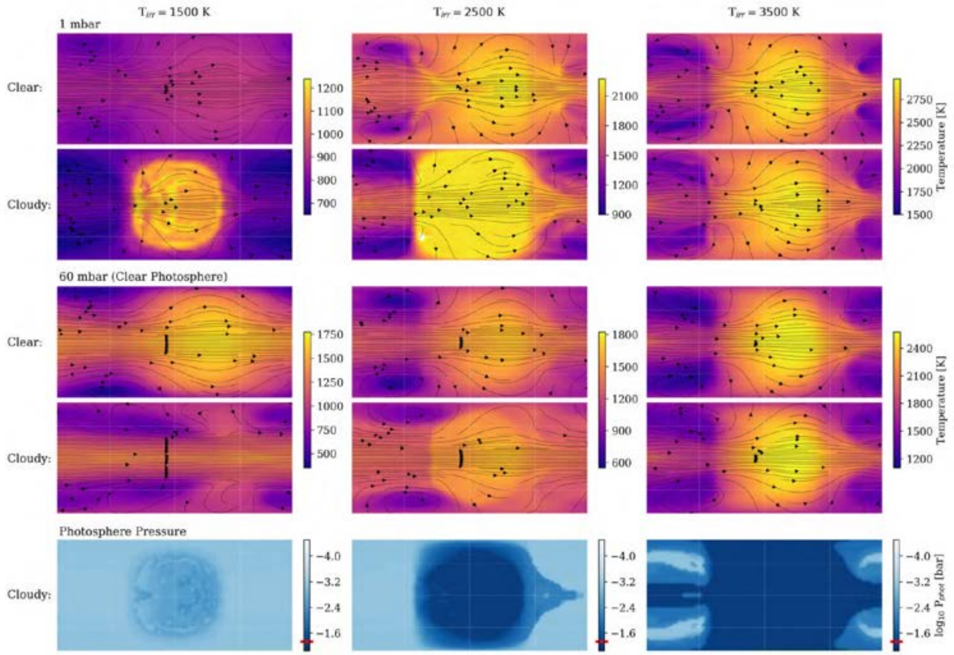
Morvan et a 2019

Heat redistribution



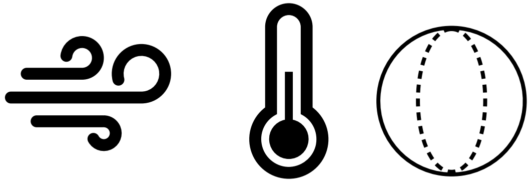


Wallack et al. (2021)

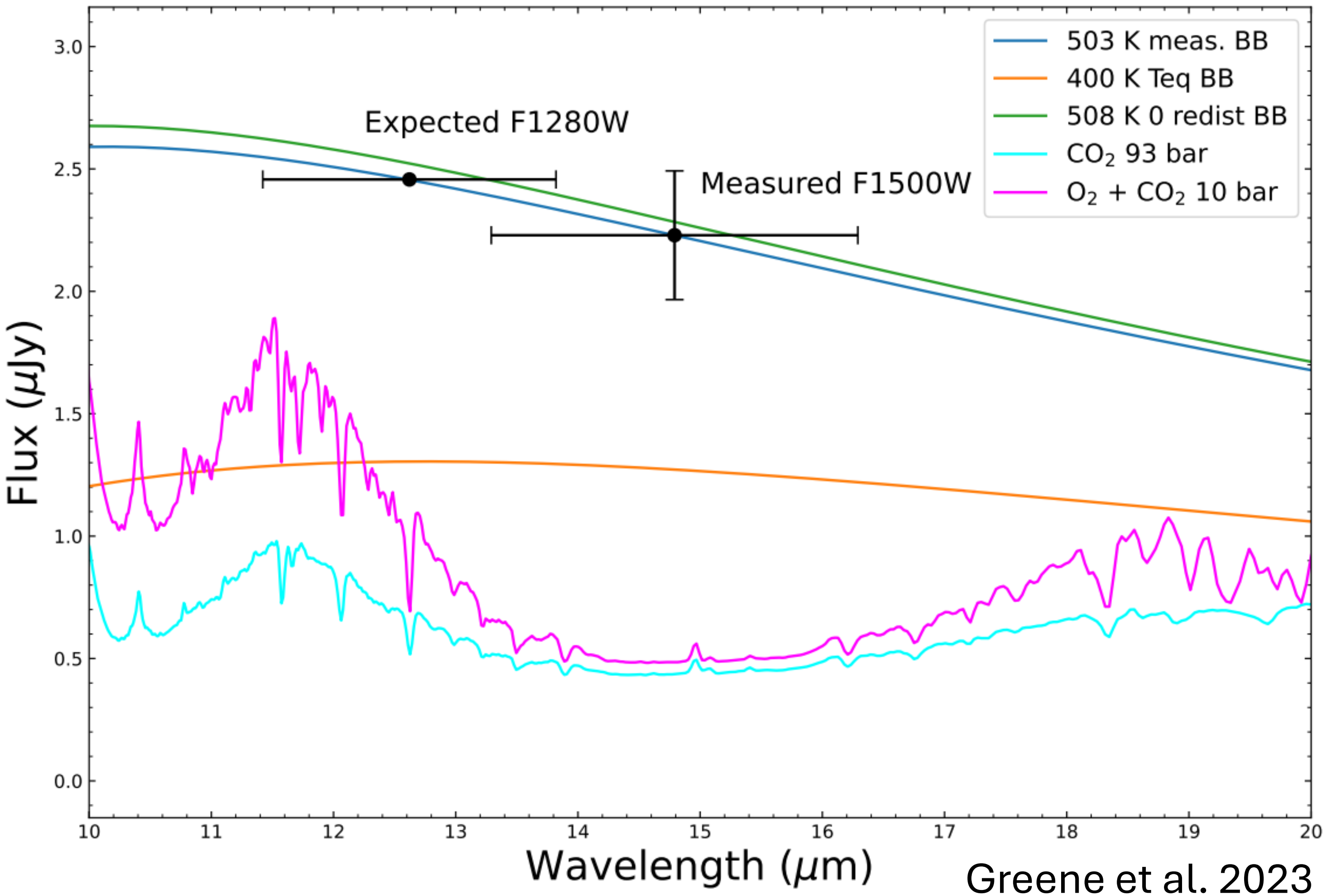


Roman et al. (2021)

(no) Heat redistribution

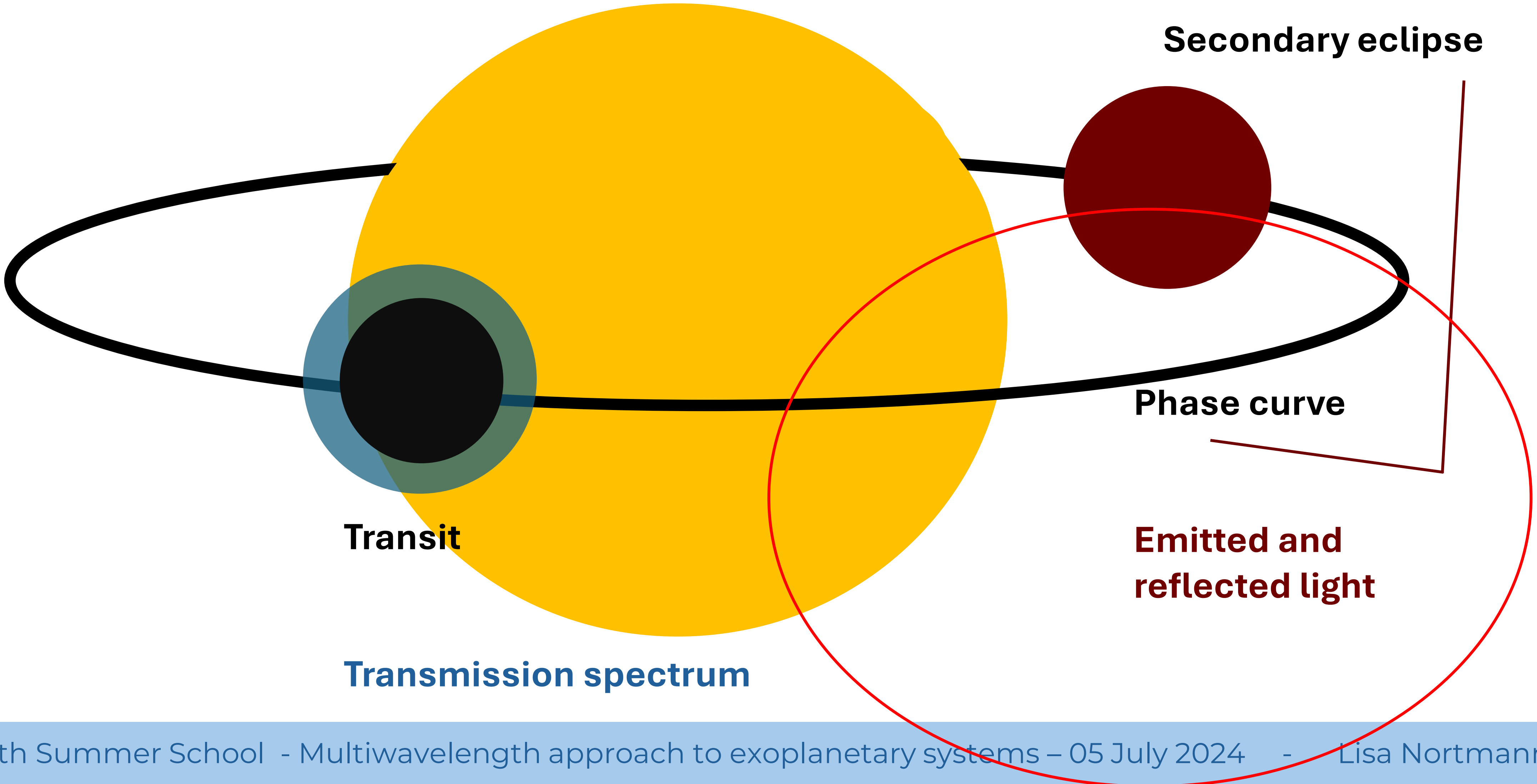


Thermal emission spectrum of Trappist 1b



Greene et al. 2023

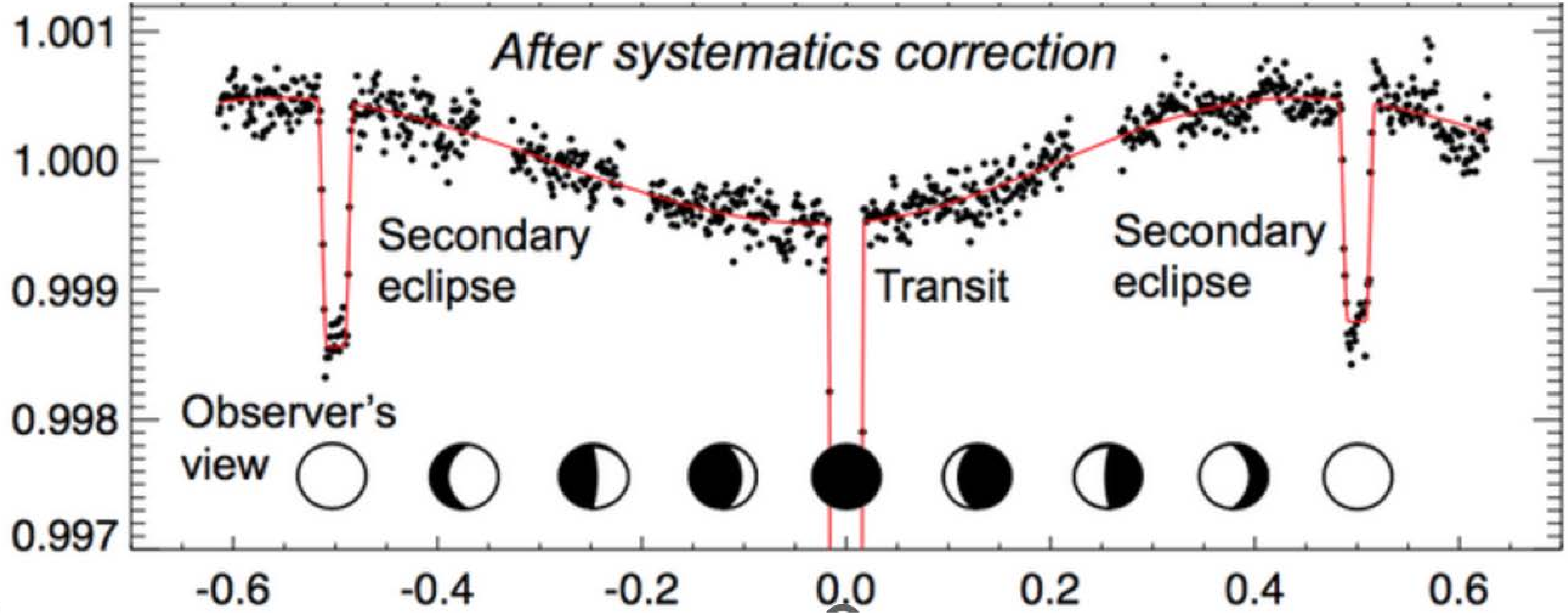
How do we measure exoplanet atmospheres?



How do we measure exoplanet atmospheres?

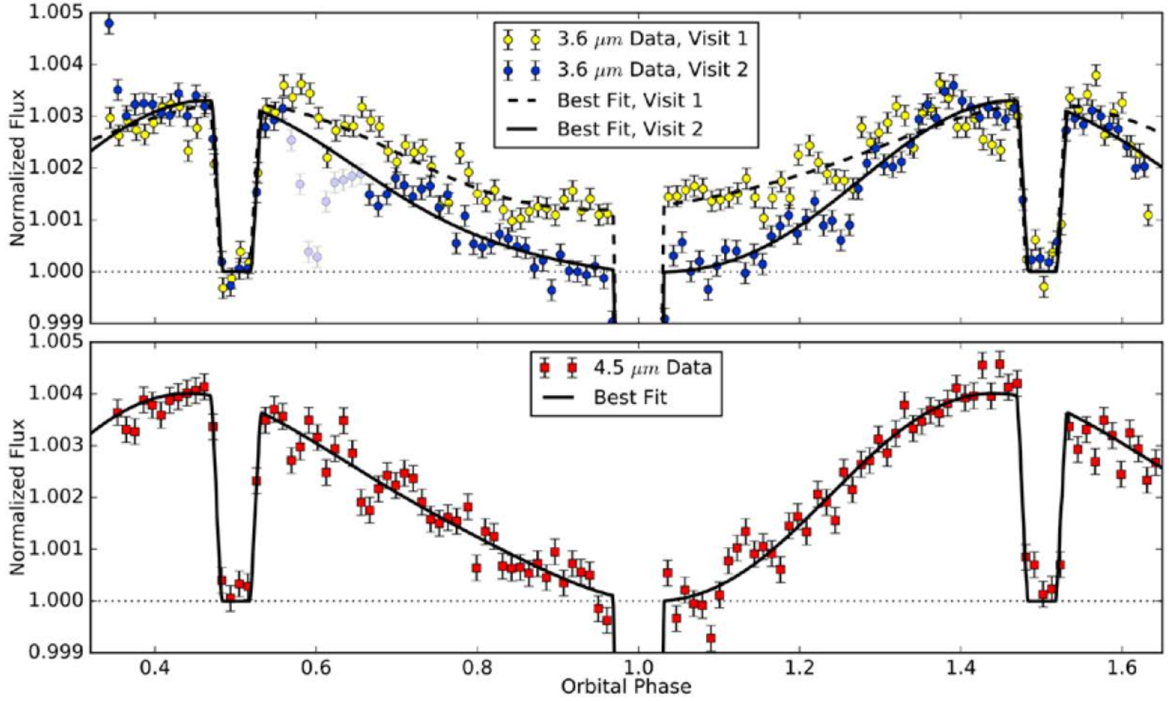
Phase curve
Secondary eclipse

Emitted and reflected light

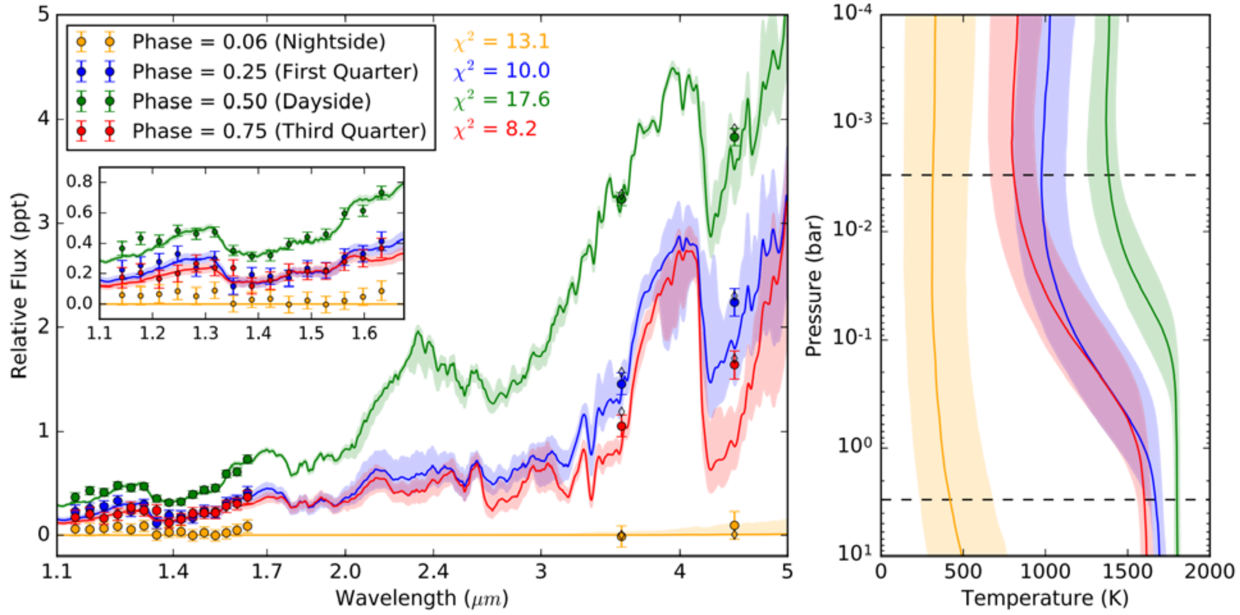


Pluriel 2023; adapted from Knutsen et al. 2012

Phase Curves

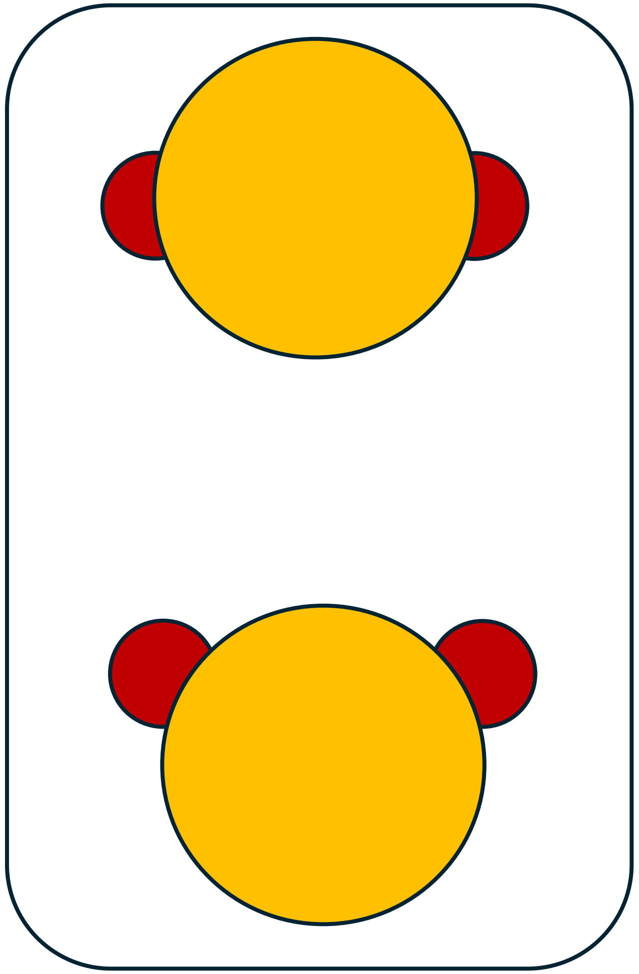


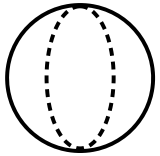
8 Stevenson *et al.*

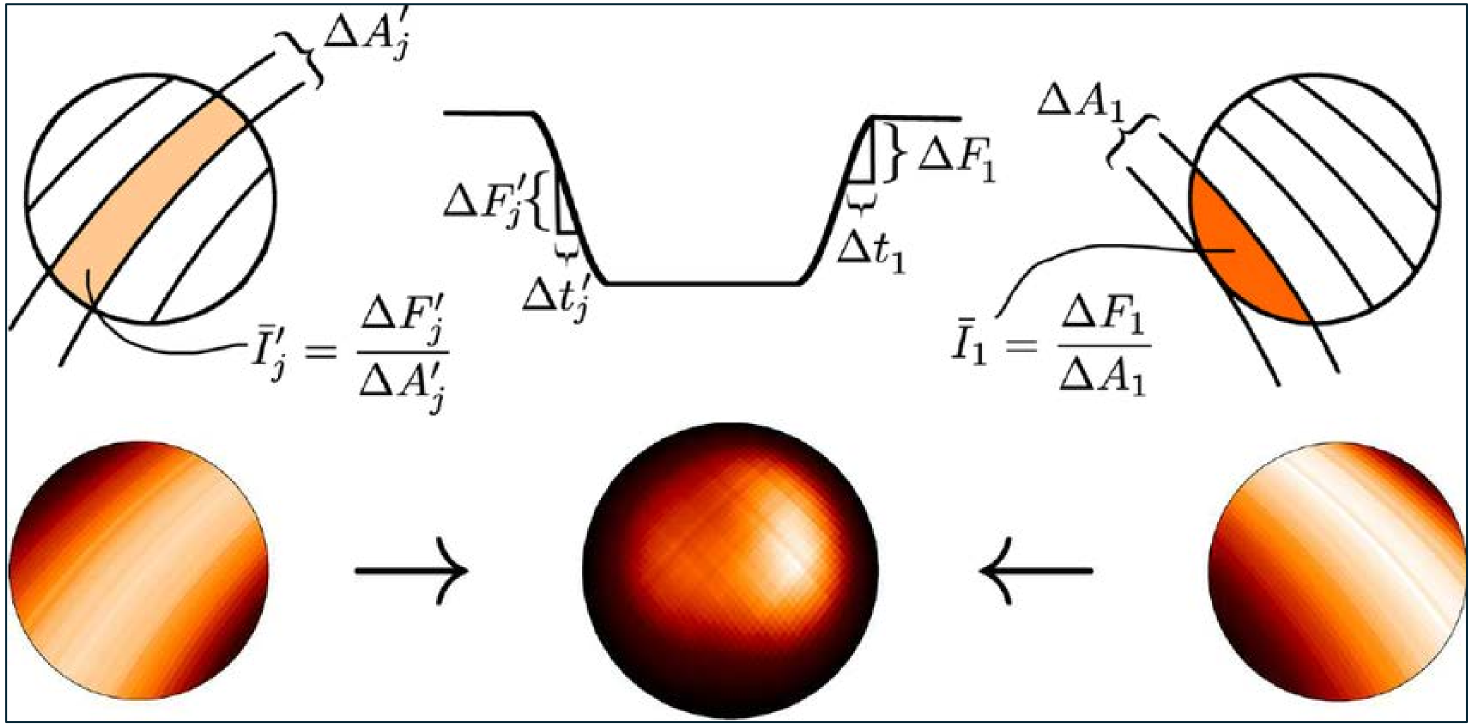


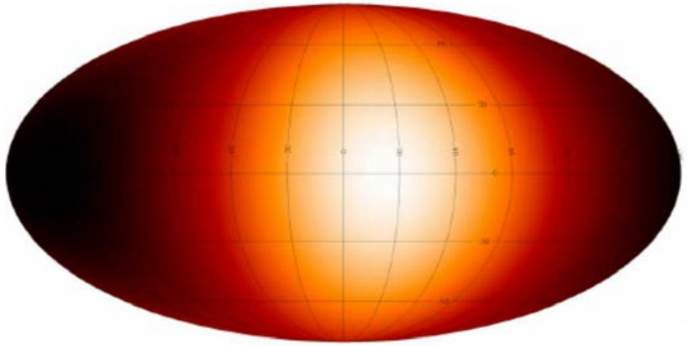
Stevenson et al 2017

Secondary eclipse mapping



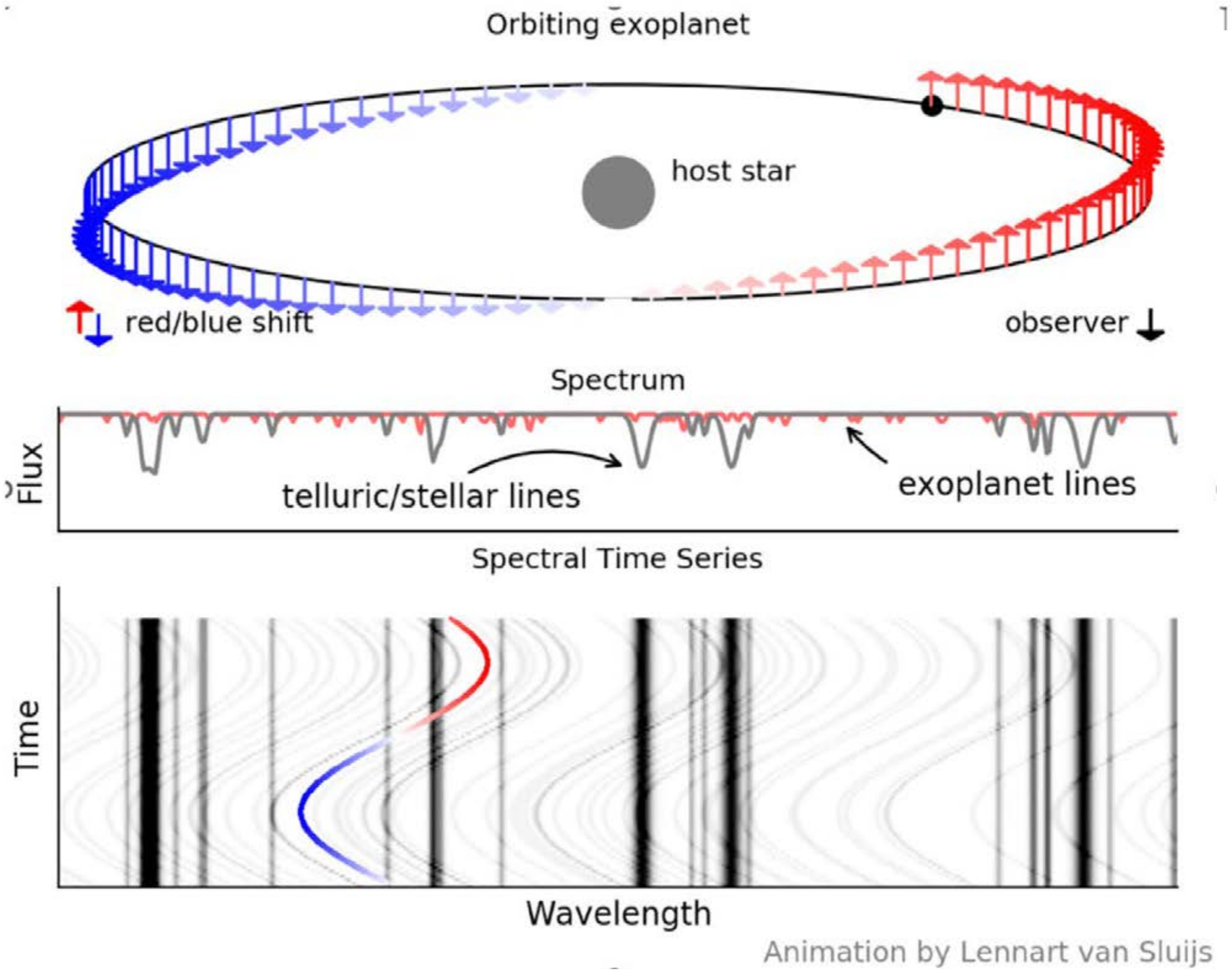






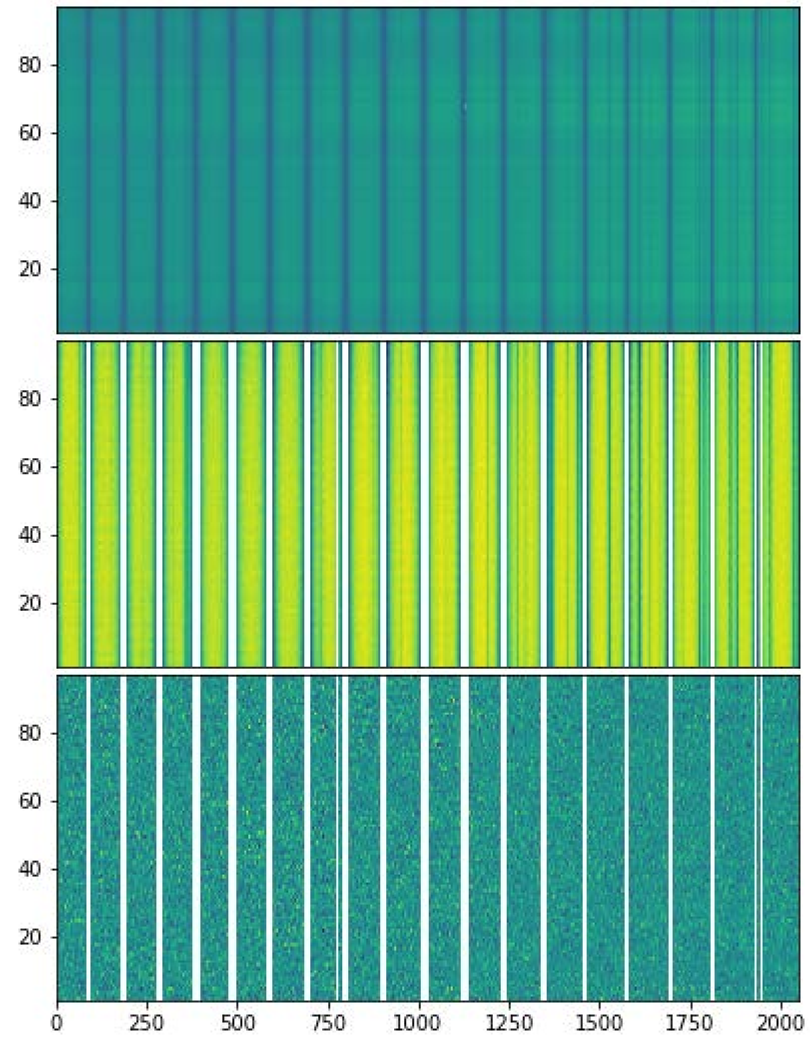
Majeau et al. 2012

High-resolution spectroscopy



Method pioneered by
Snellen et al 2010

High-resolution spectroscopy

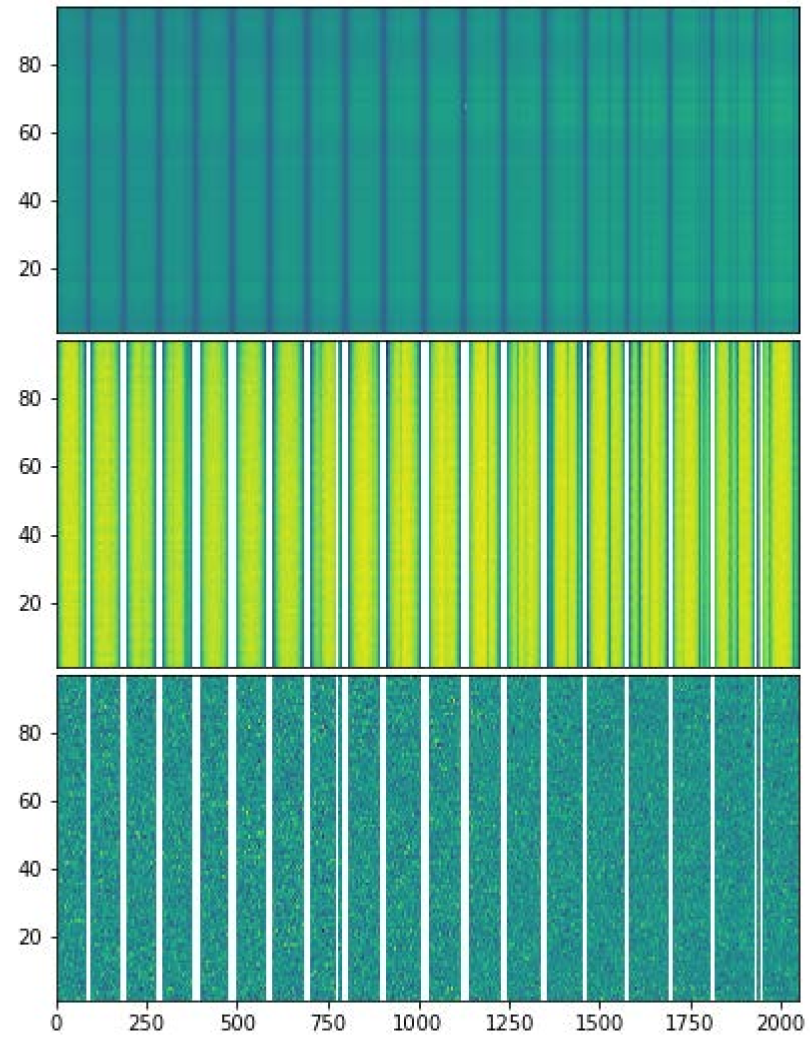


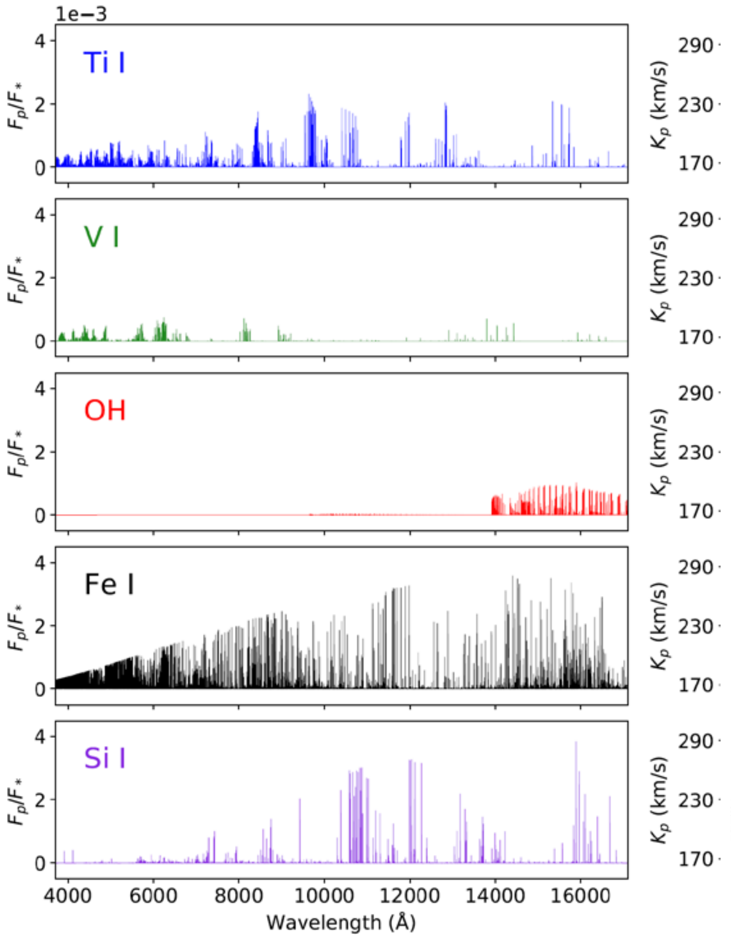
Untreated spectra

Normalized and deep tellruics masked

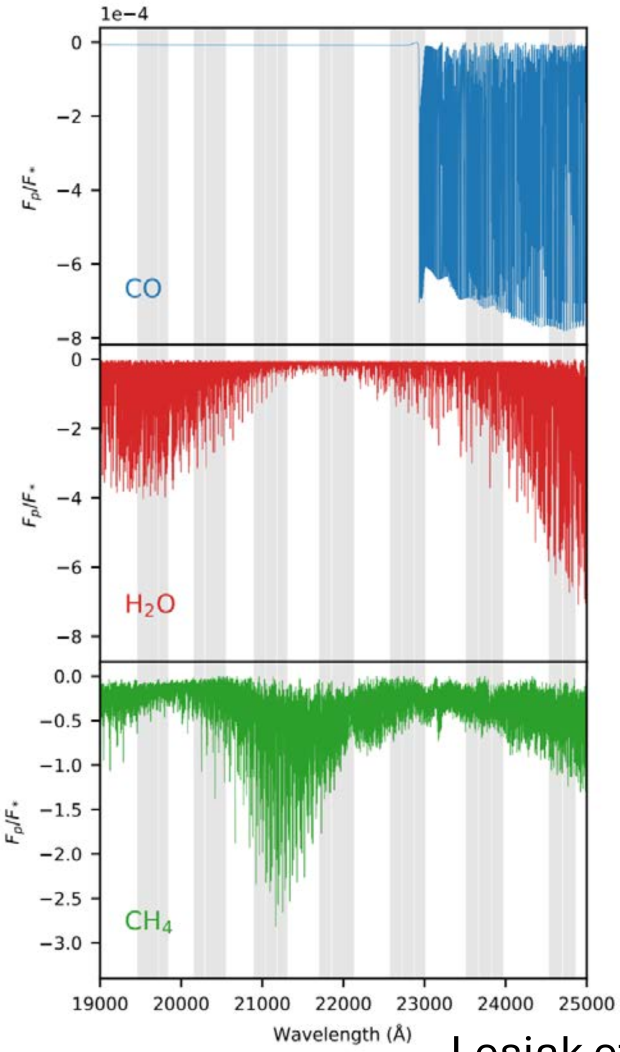
After 4 SYSREM runs

High-resolution spectroscopy





Cont et al. 2022

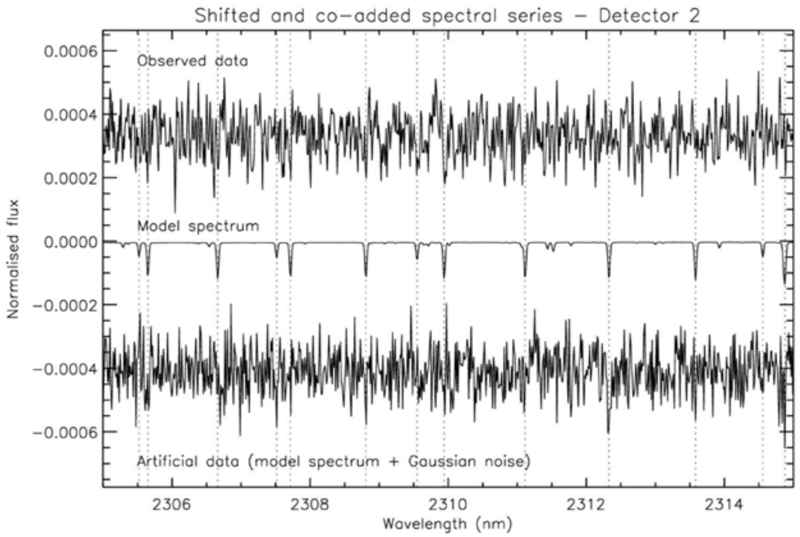


Lesjak et al. 2023

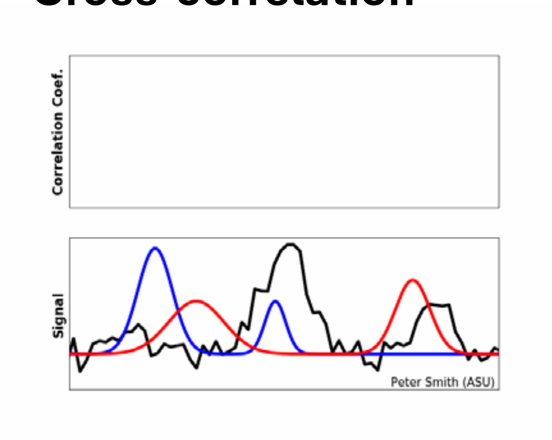
High-resolution spectroscopy

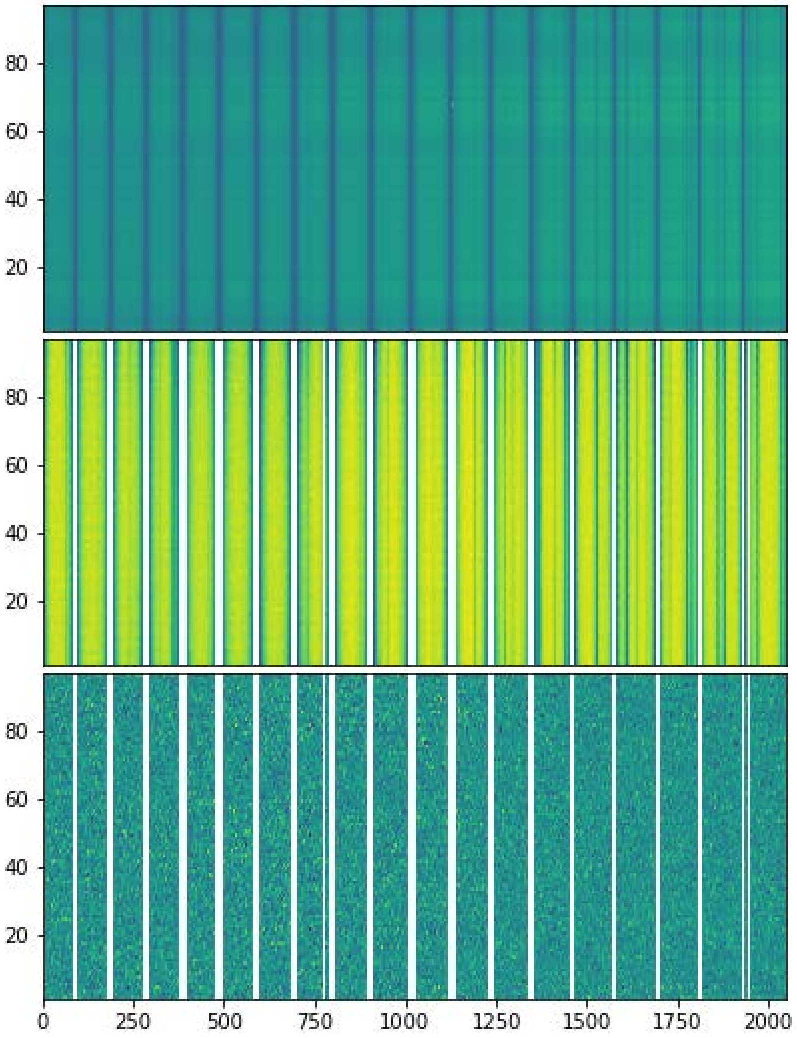
Data

Brogi et al 2010

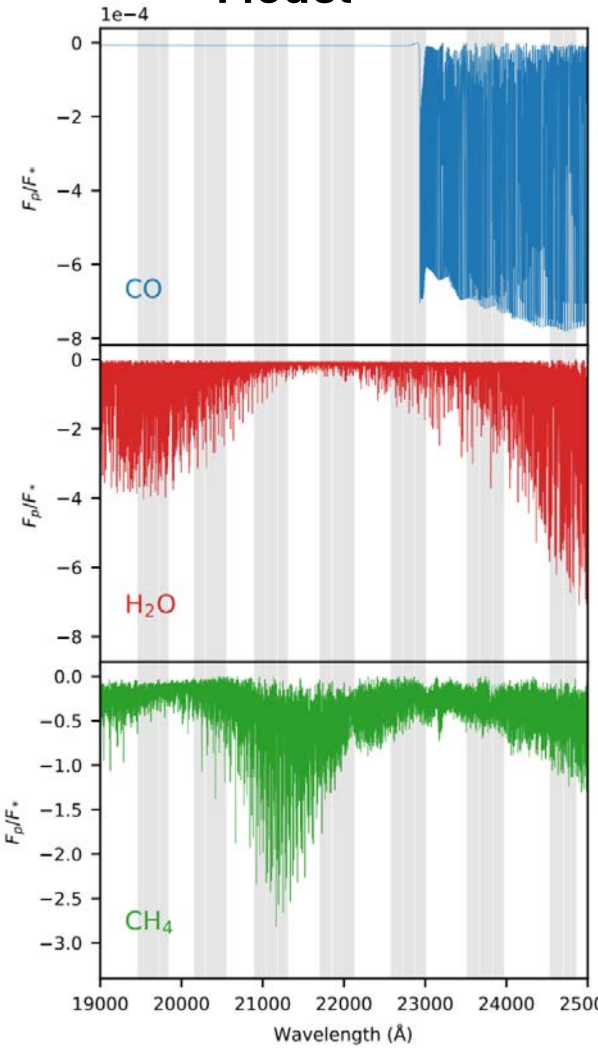


Cross-correlation



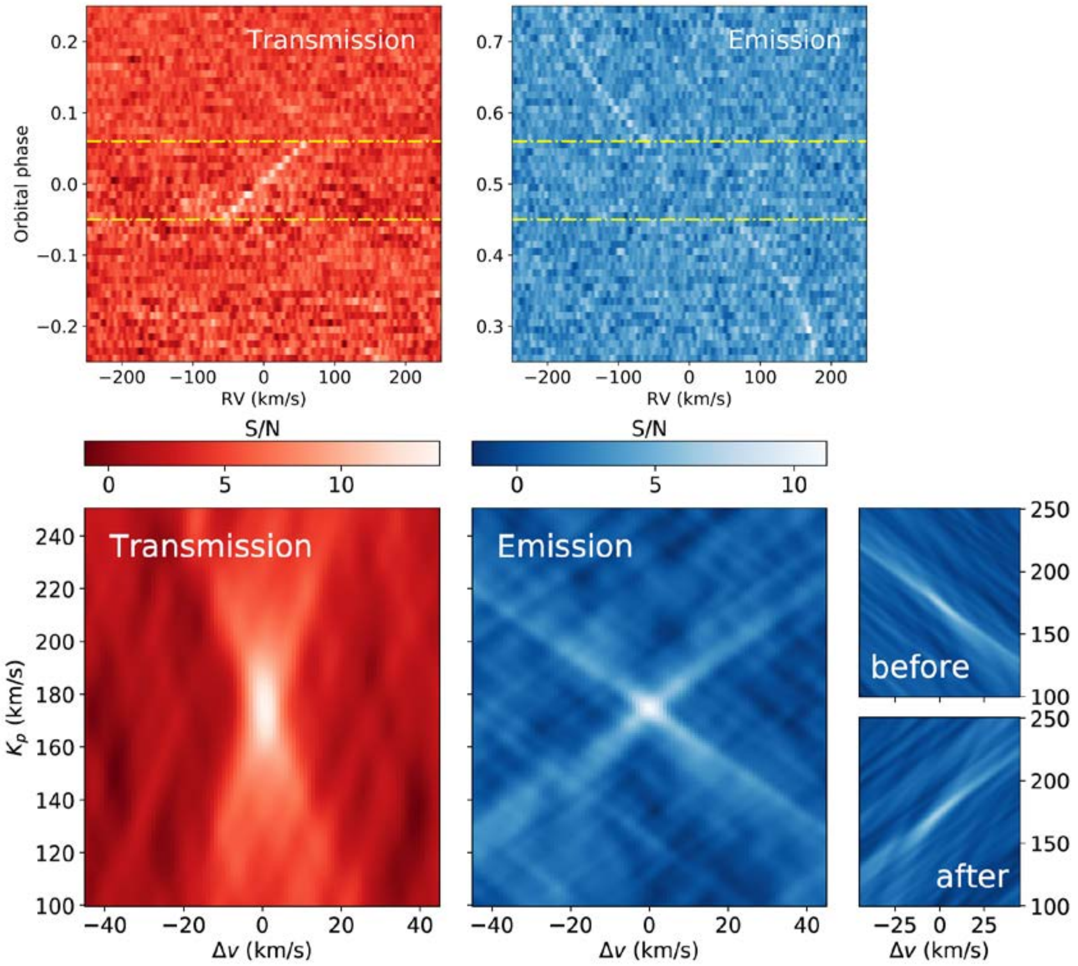


Model



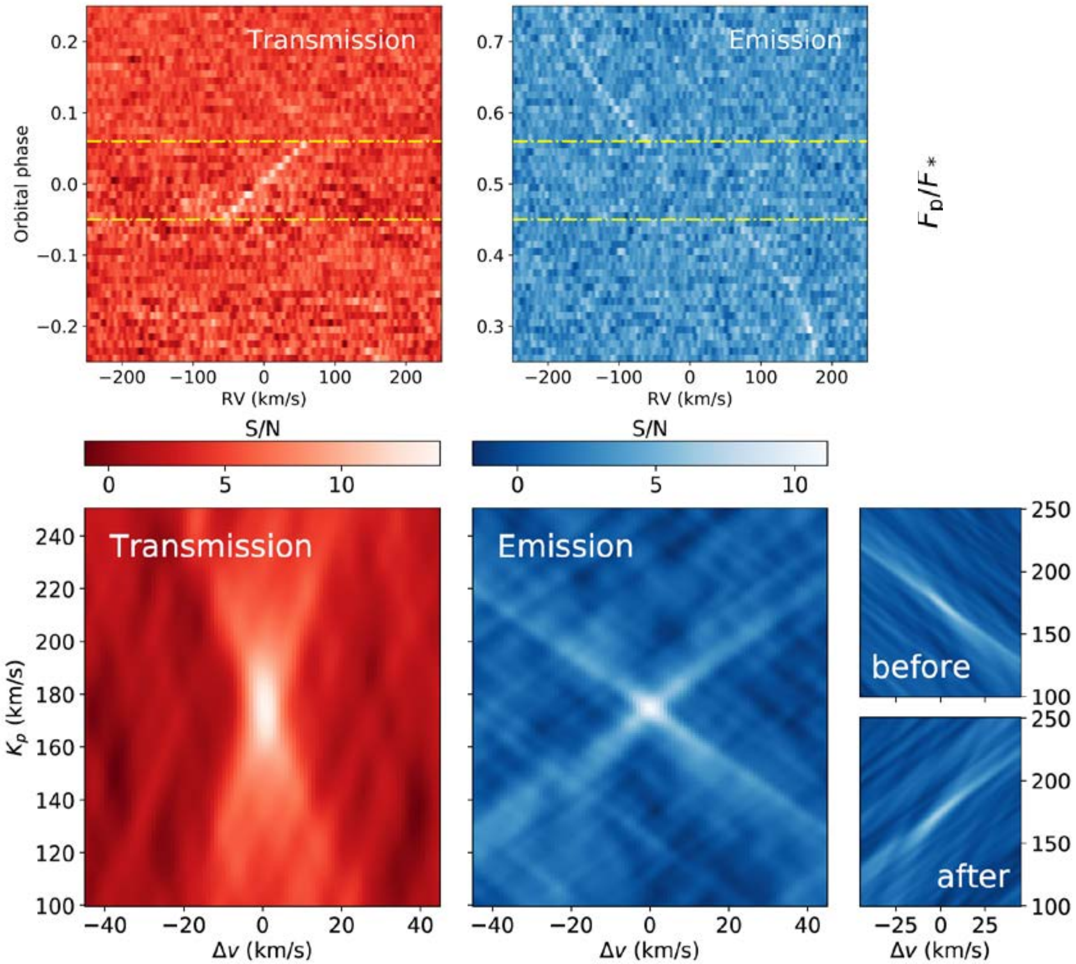
Lesjak et al. 2023

Cross-correlation technique



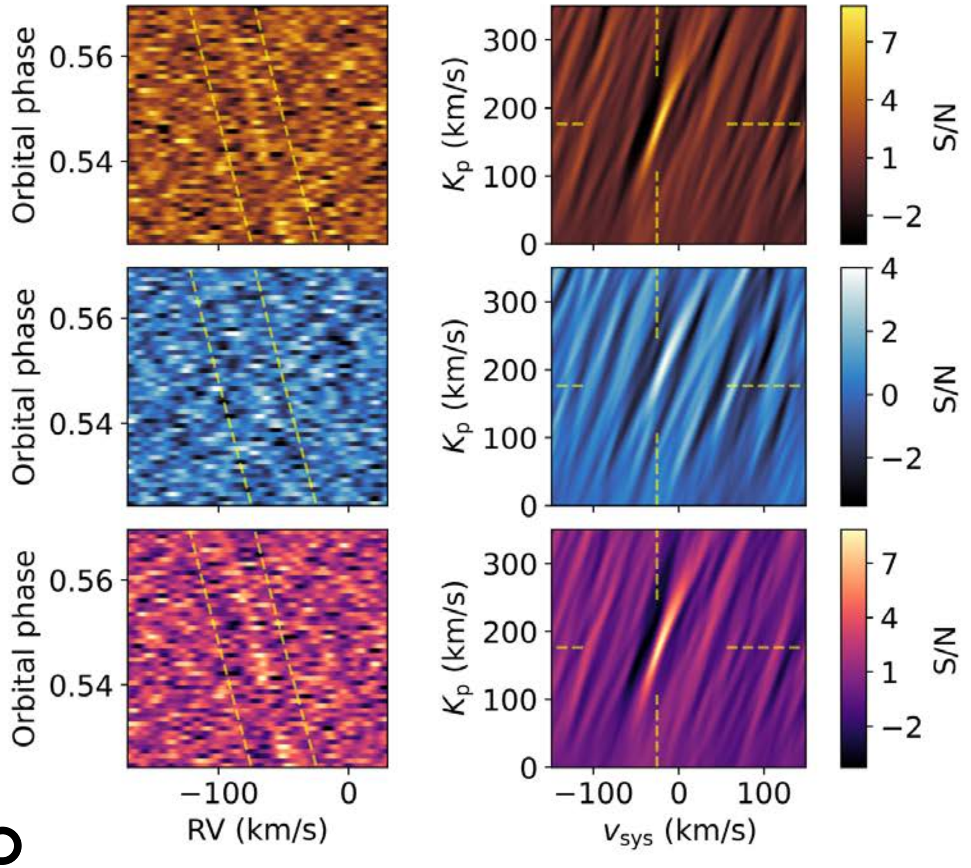
Cont, PhD thesis, 2023

Cross-correlation technique



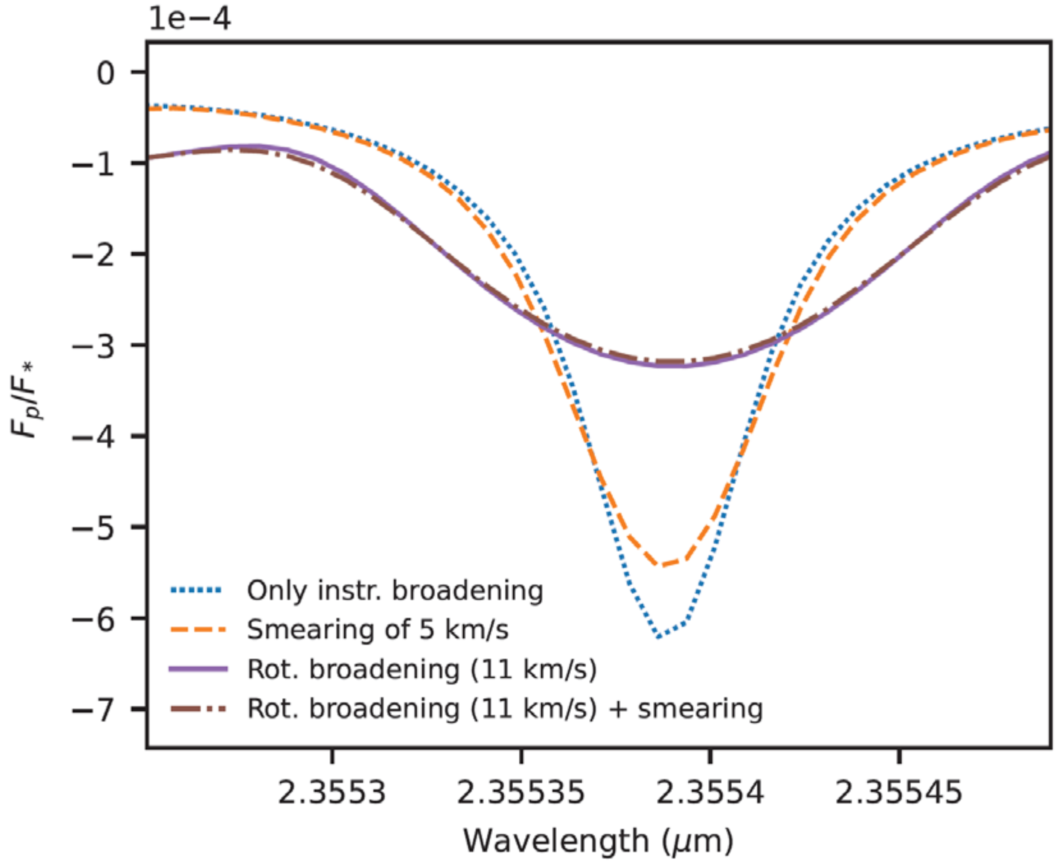
Cont, PhD thesis, 2023

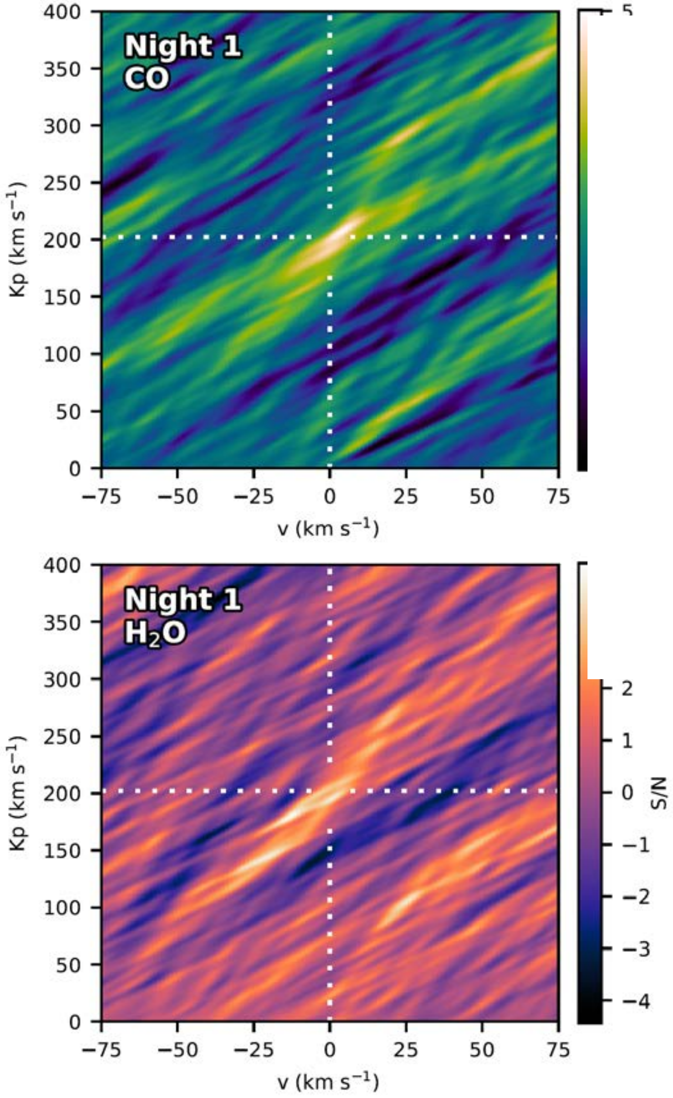
CO and H2O in the emission spectrum of WASP-178b

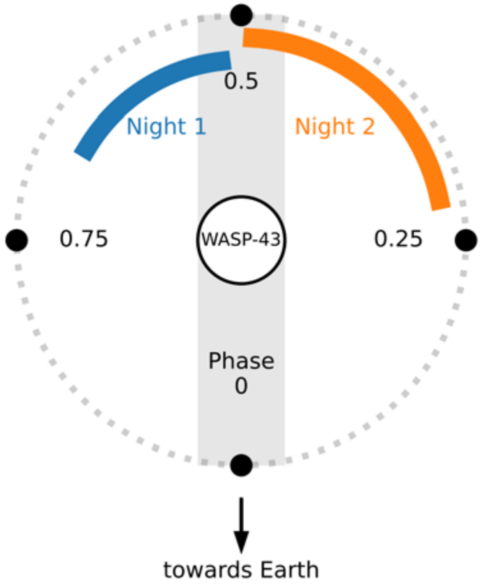


Cont et al 2024

Dynamics

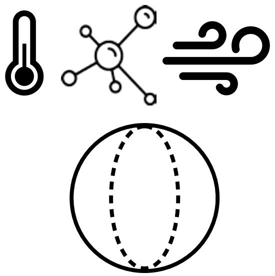




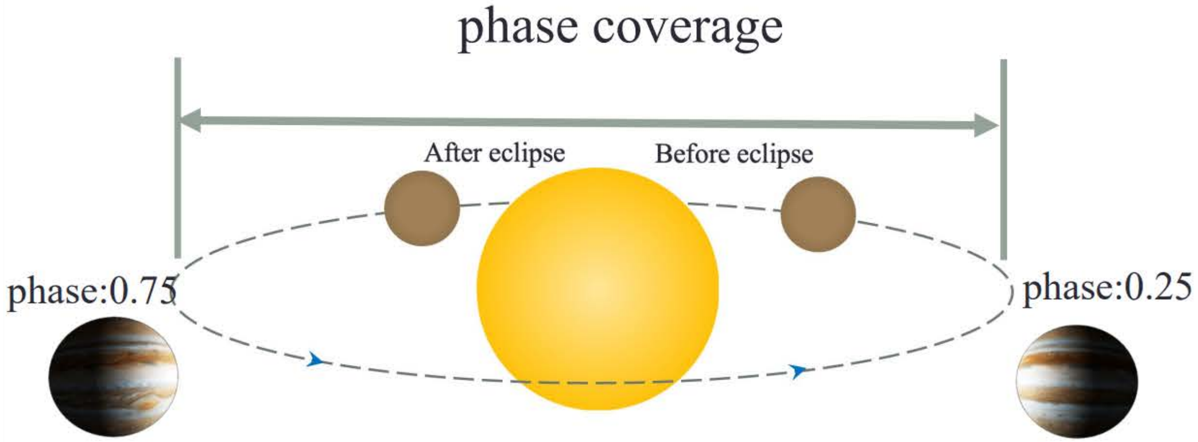


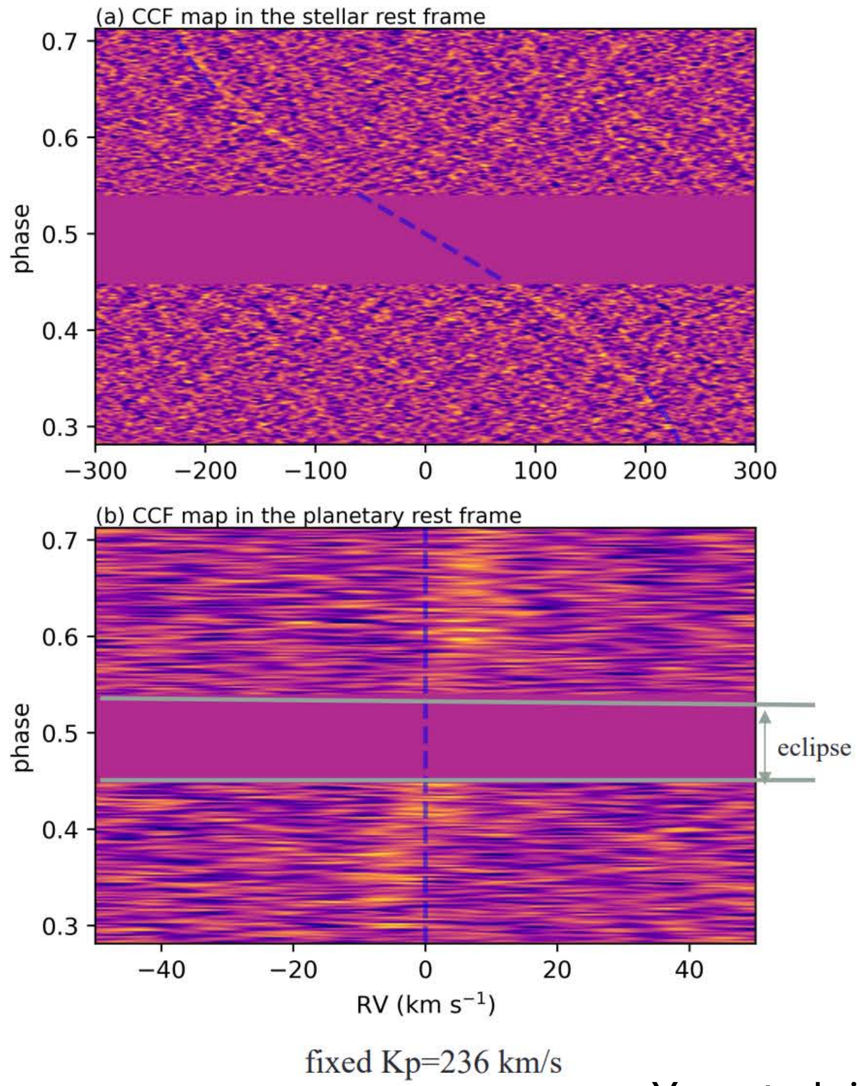
Lesjak et al 2023

Phase curves at high resolution



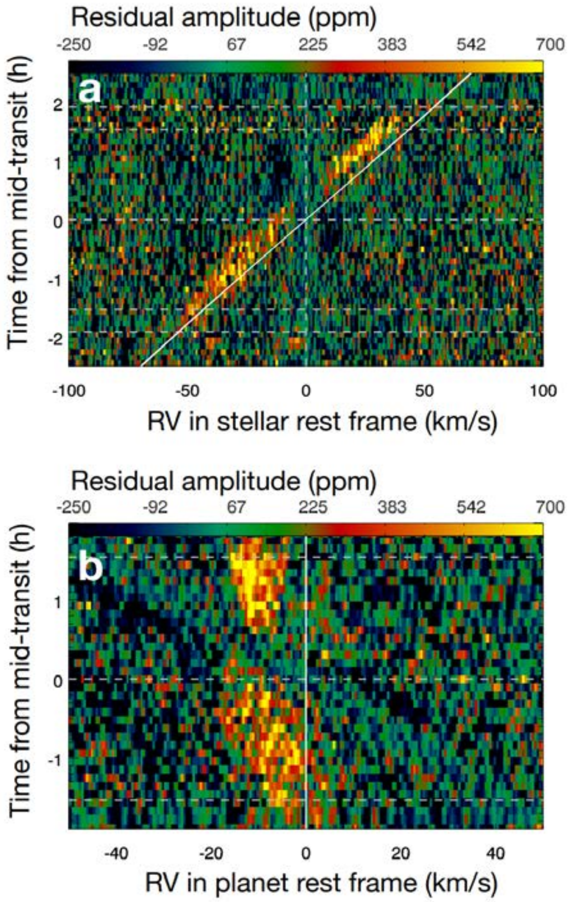
Phase curve of a hot Jupiter with CRIRES⁺ in the K band (1.9-2.5 μm)
CO+H_2O

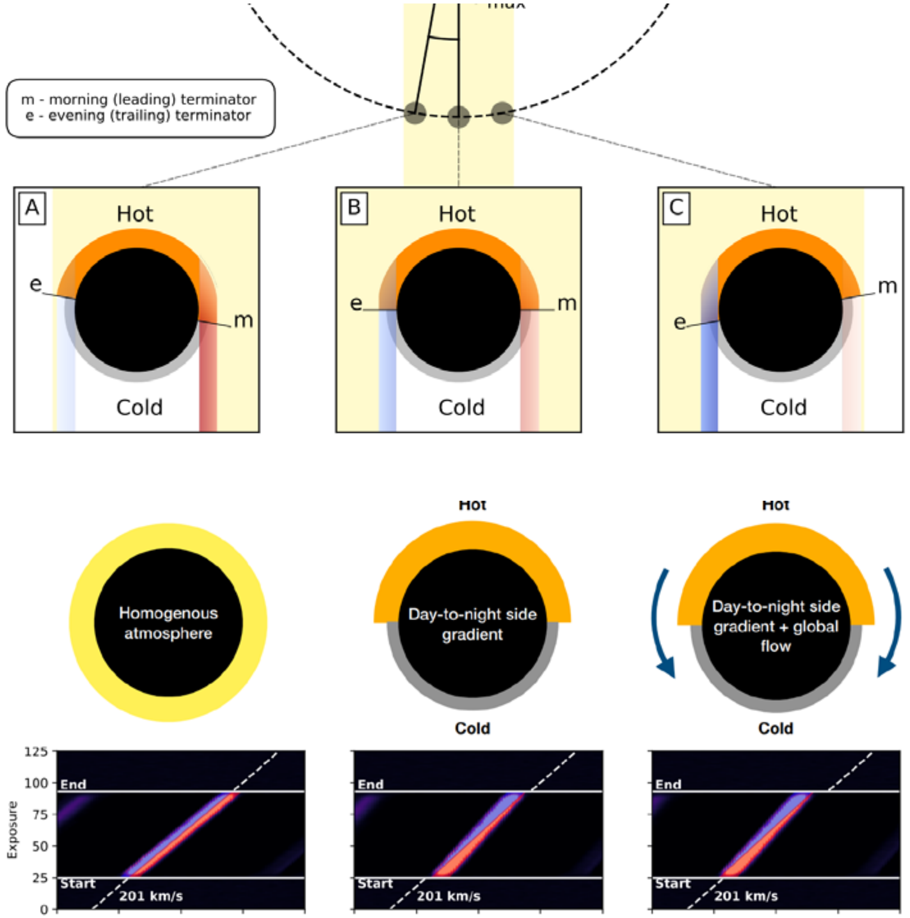




Yan et al. in prep.

3D structure in transmission spectroscopy



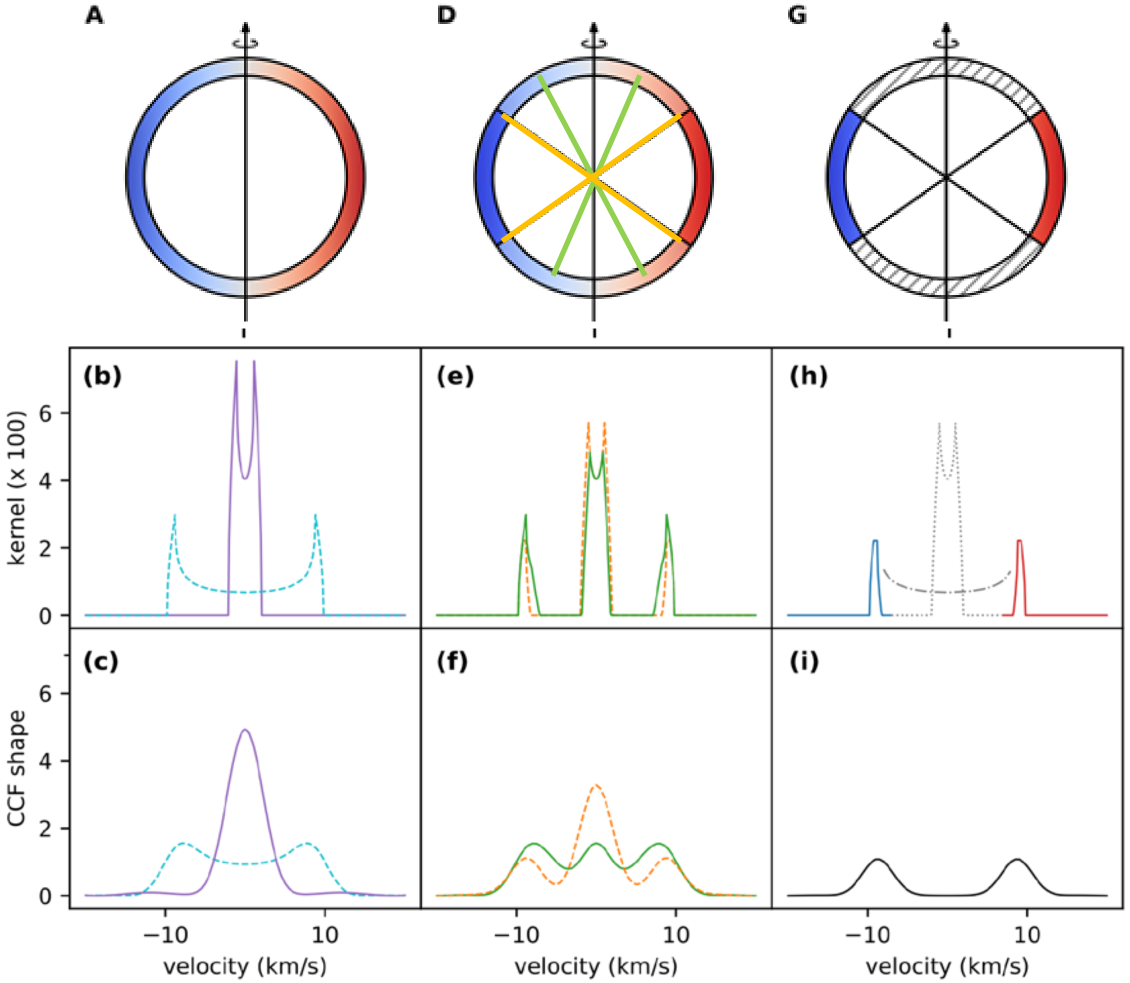


Ehrenreich et al 2020 (Fe in WASP-76b)

Also: Ghandi et al 2022

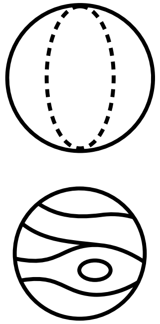
Prinoth et al 2022 (WASP-189b)

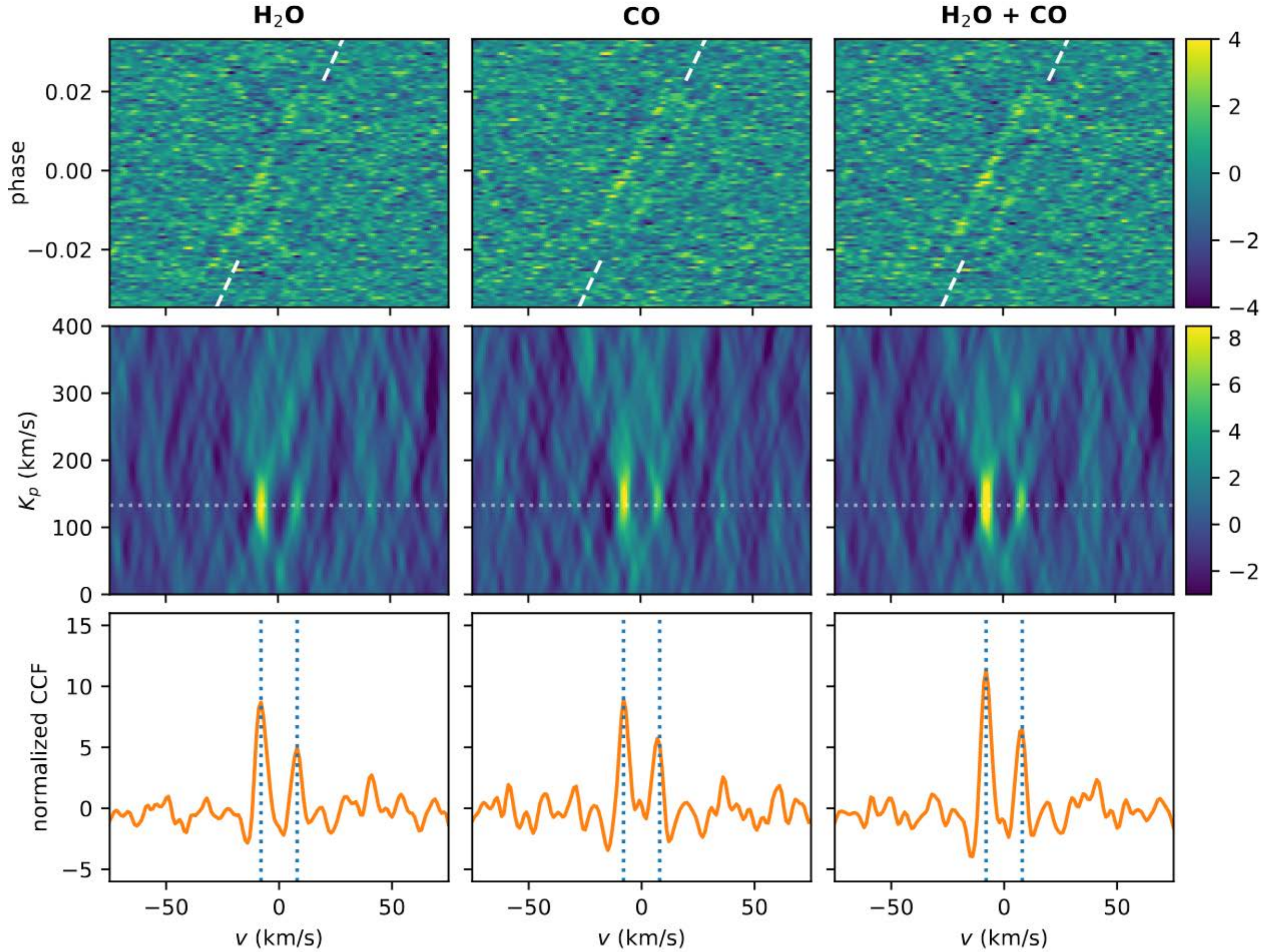
3D structure in transmission – WASP-127b



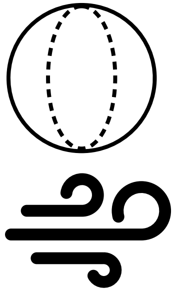
Nortmann et al. in ref at A&A
arXiv:2404.12363

3D structure in transmission – WASP-127b





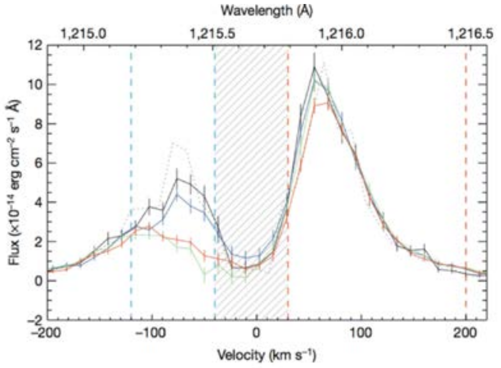
Morning and evening terminator and poles can be resolved and investigated

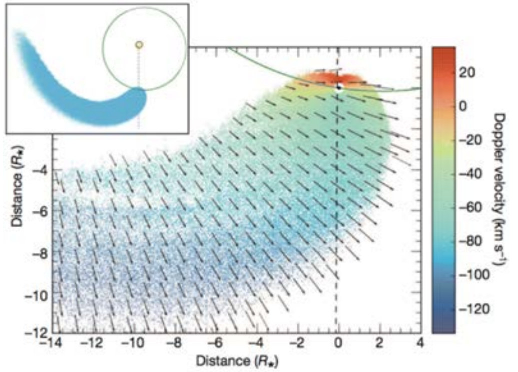


Nortmann et al. in ref at A&A
arXiv:2404.12363

Atmospheric escape - Evolution

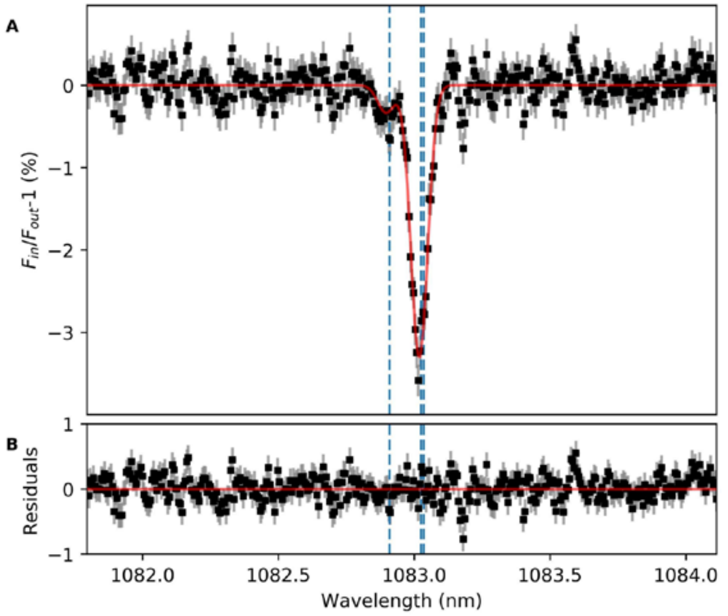
Hydrogen: Lyman α
GJ436b
121.567 nm [UV] → HST only

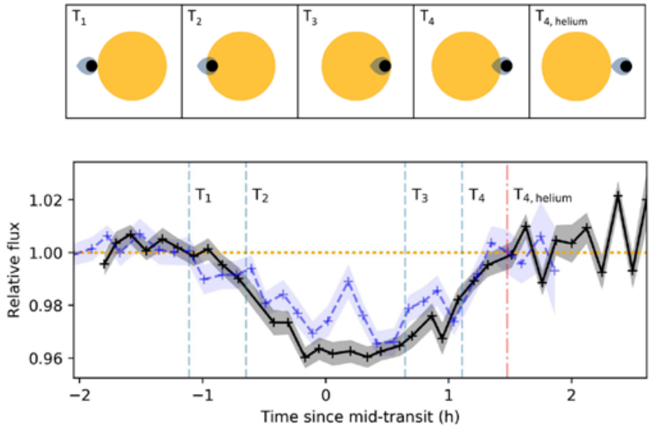




Ehrenreich et al. 2015
See also: Vidal-Madjar et al. 2003 for HD209458b

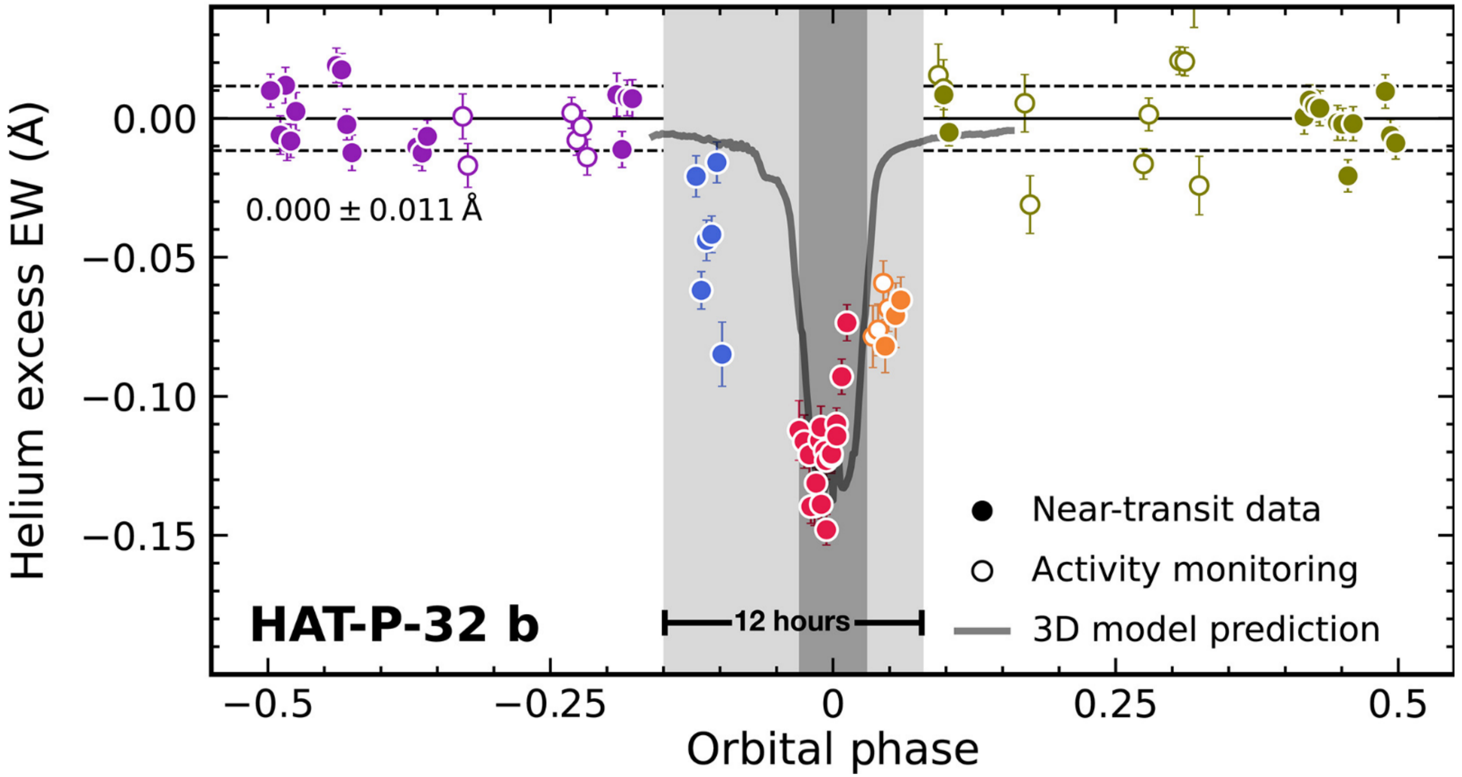
Helium:
WASP-69b
10833 nm [~ 1μm NIR] → many observatories

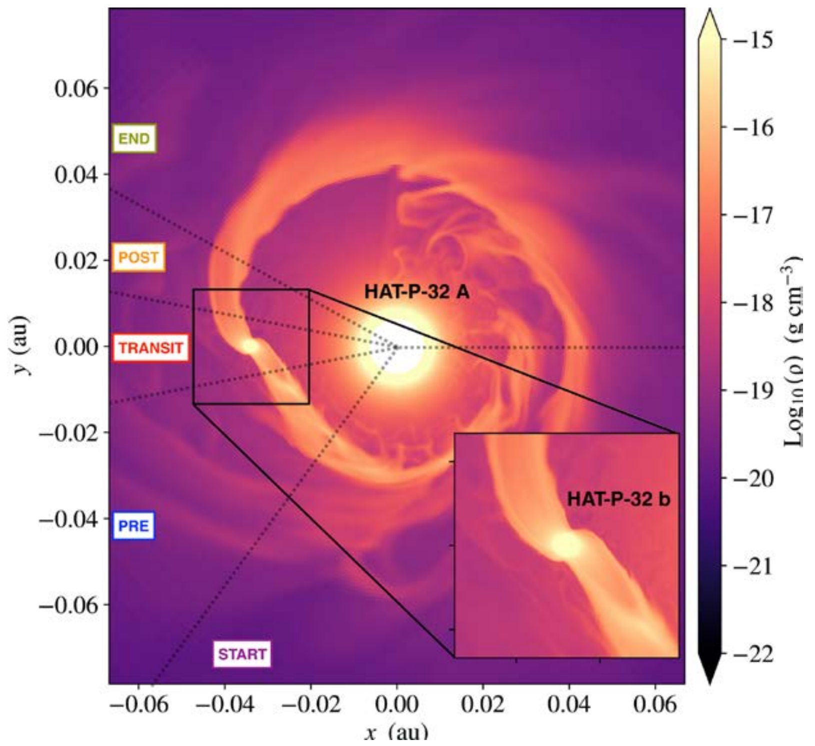




Nortmann et al. 2018
See also Spake et al. 2018 WASP-107b with HST
Allart et al. 2018 HAT-P-11b

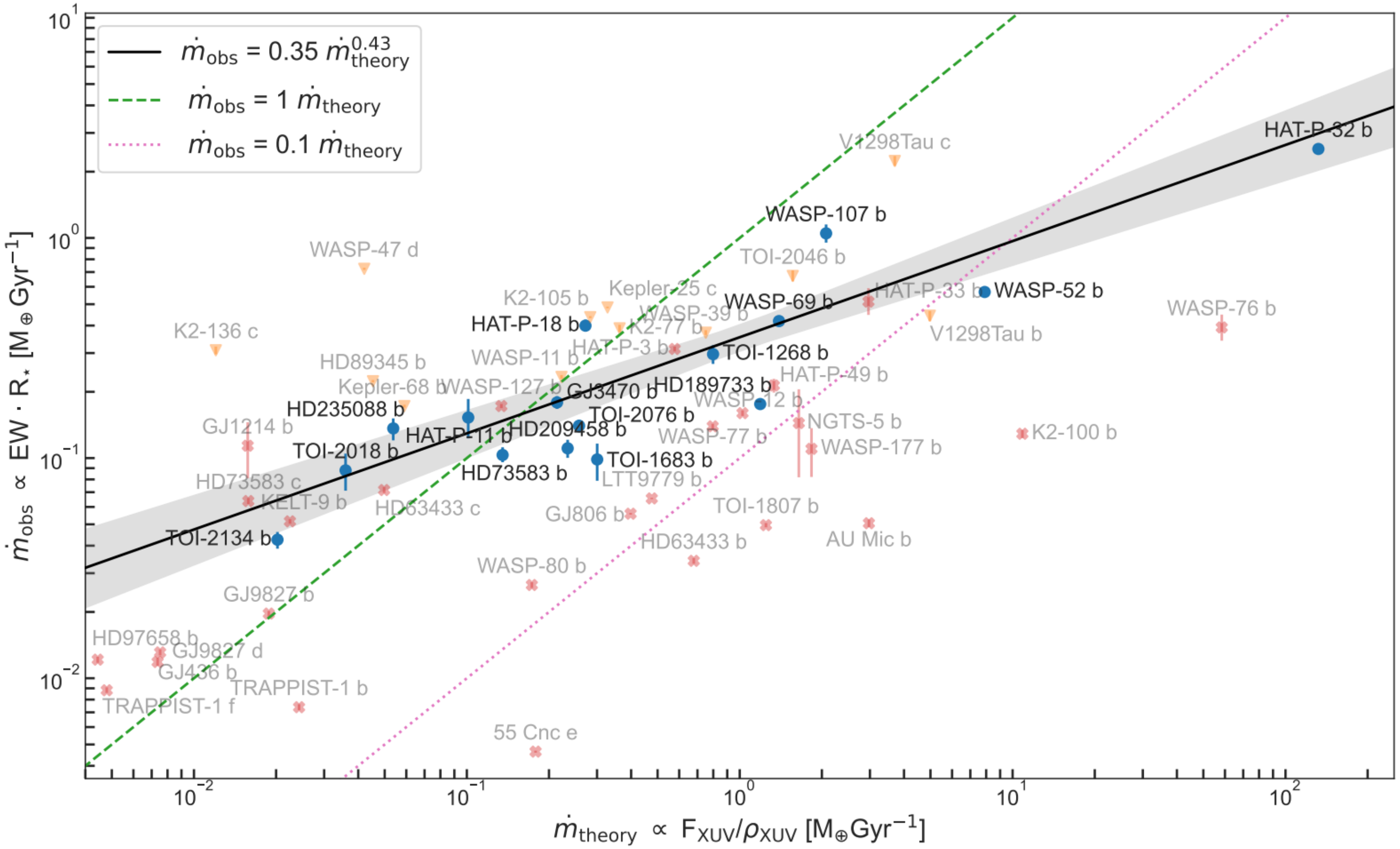
Studying atmospheric escape using helium





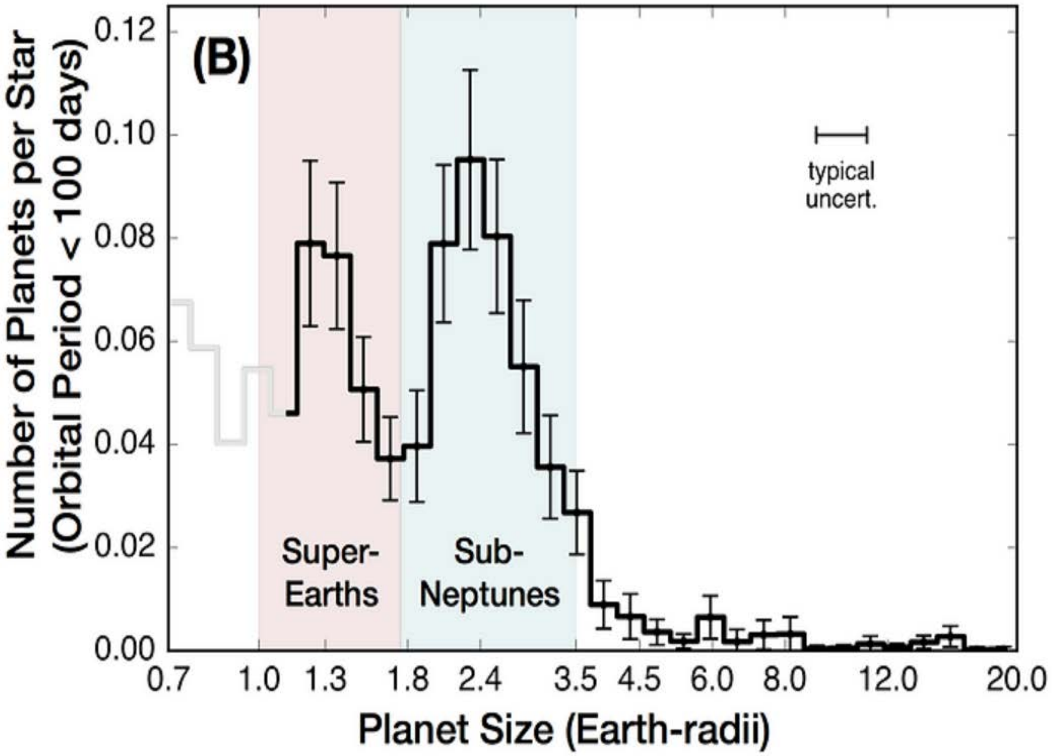
HAT-P-32Ab
Zhang et al. 2023
See also Czelsa et al. 2022

Studying the Helium – XUV connection

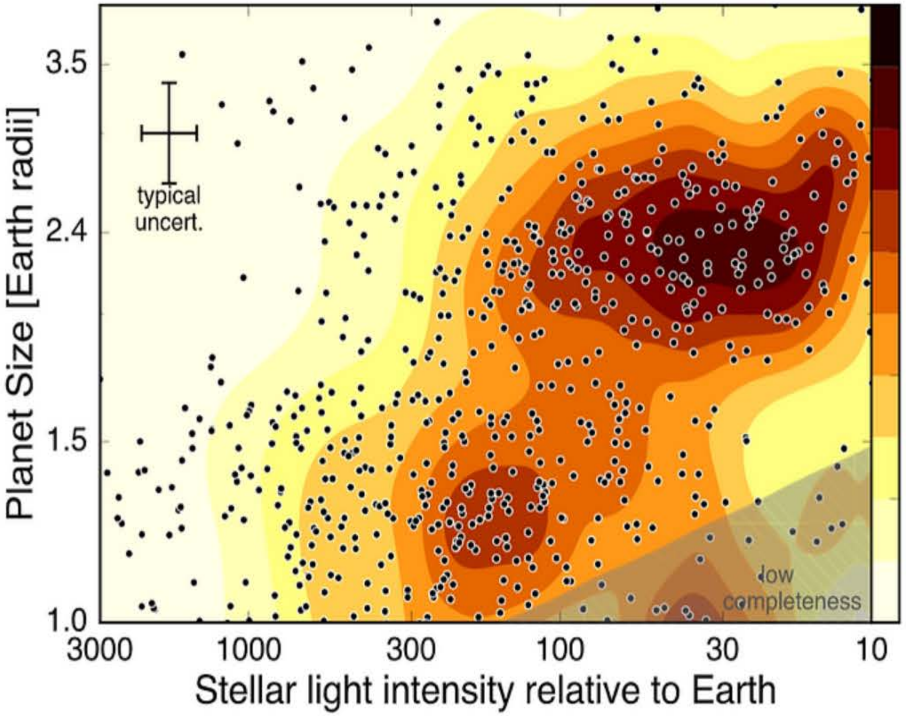


Orell-Miquel et al 2024
See also Nortmann et al. 2018
and many more

Atmospheric escape - Evolution



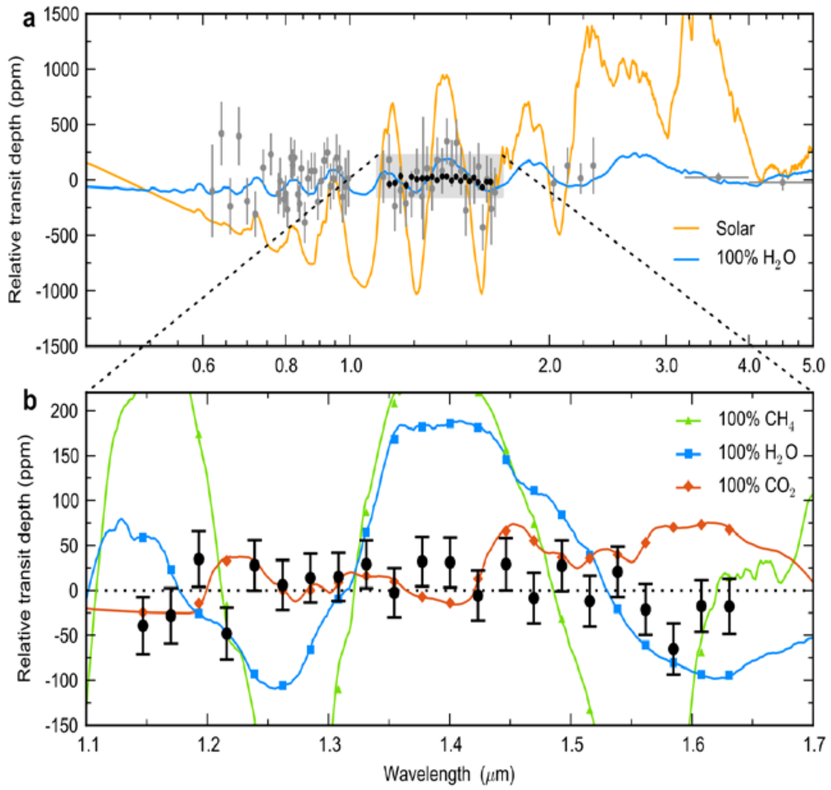
Fulton et al 2017



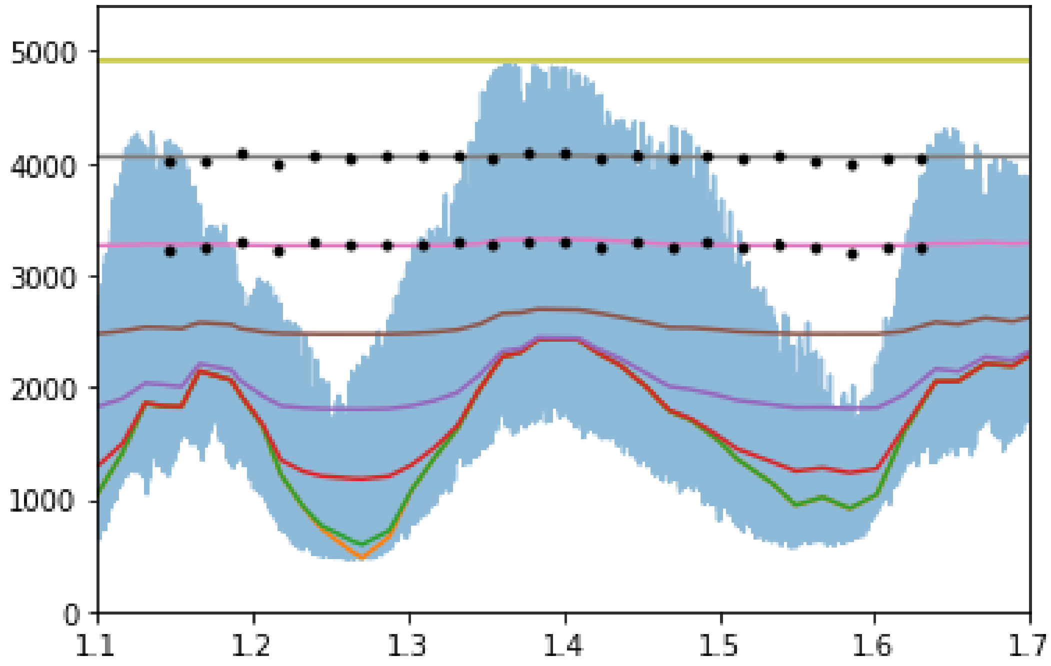
Fulton and Petigura 2018

Challenges - cloudy atmospheres

HST WFC3 10 transits of GJ1214b

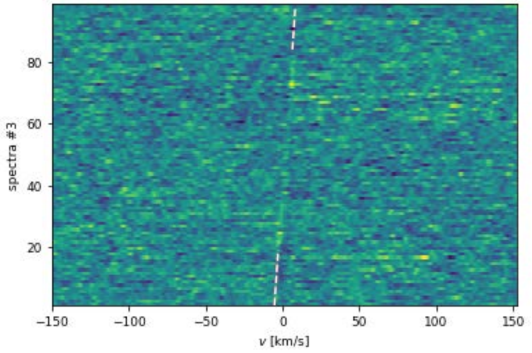


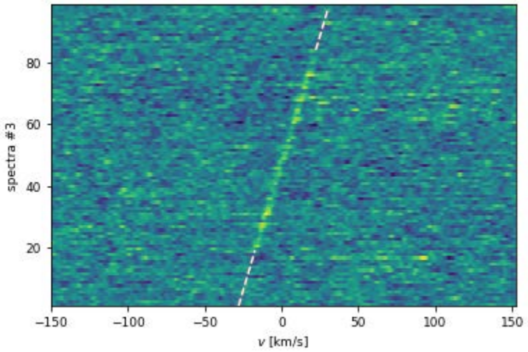
Potential at high-res!

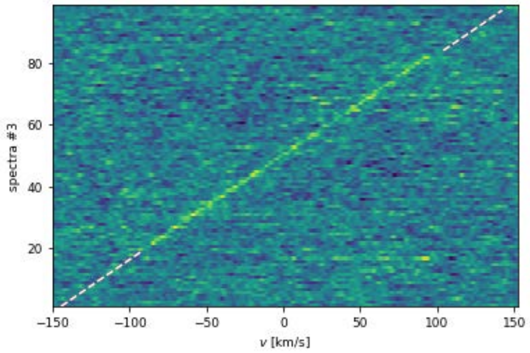


Kreidberg et al. 2014

Challenges - Long period planets





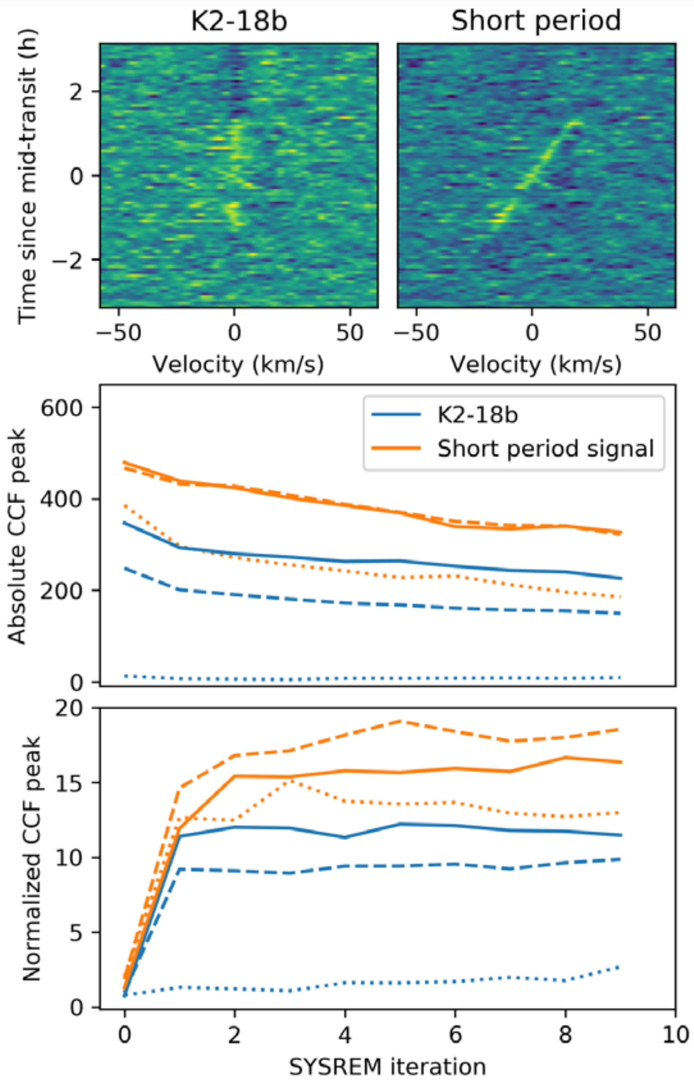


$$t_{max} = \frac{S_{pixel} \cdot P}{2\pi\, K_p}$$

S_{pixel} = Size of detector pixel [km/s]

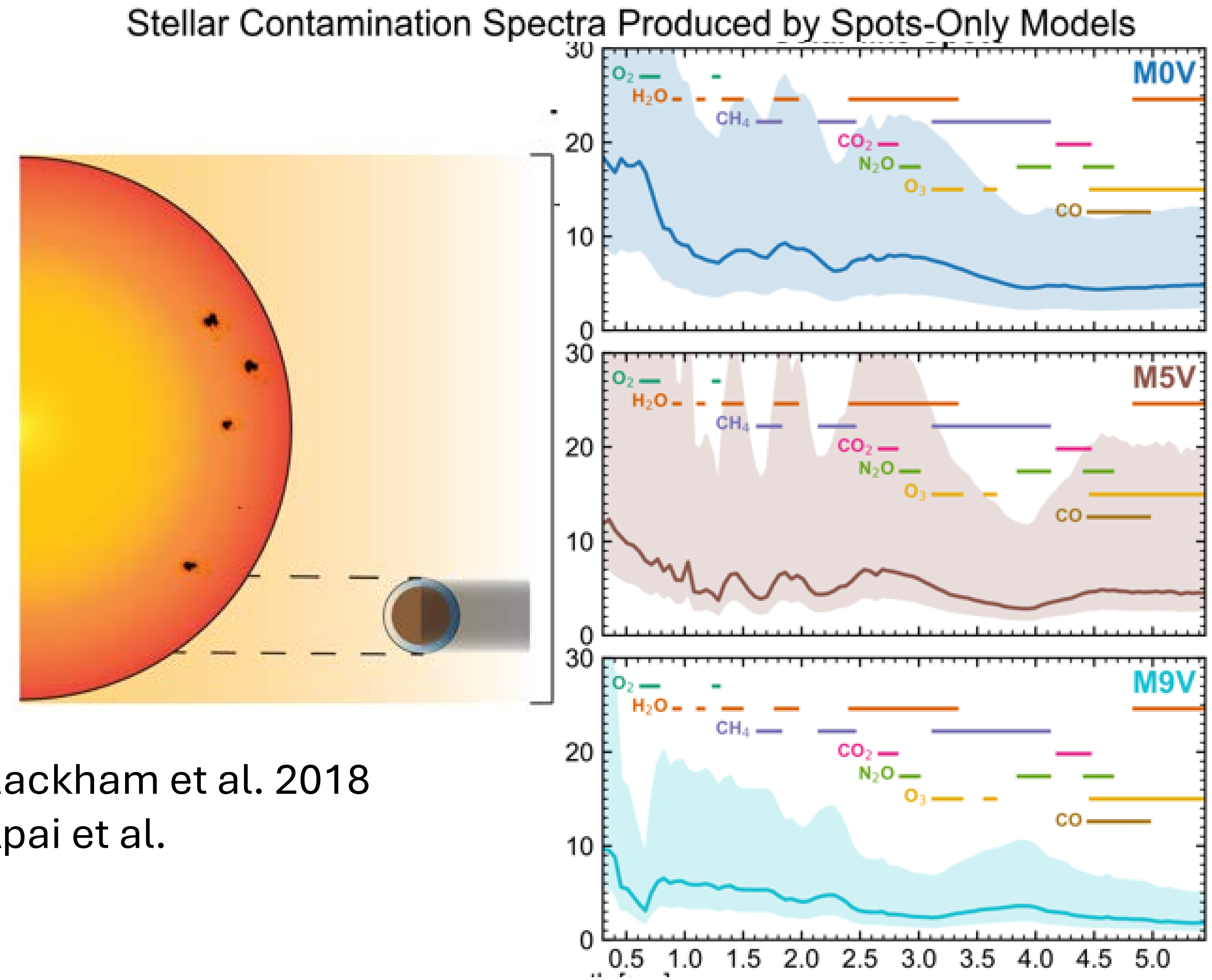
P = Orbital Period [s]

K_p = Radial velocity semi-amplitude [km/s]

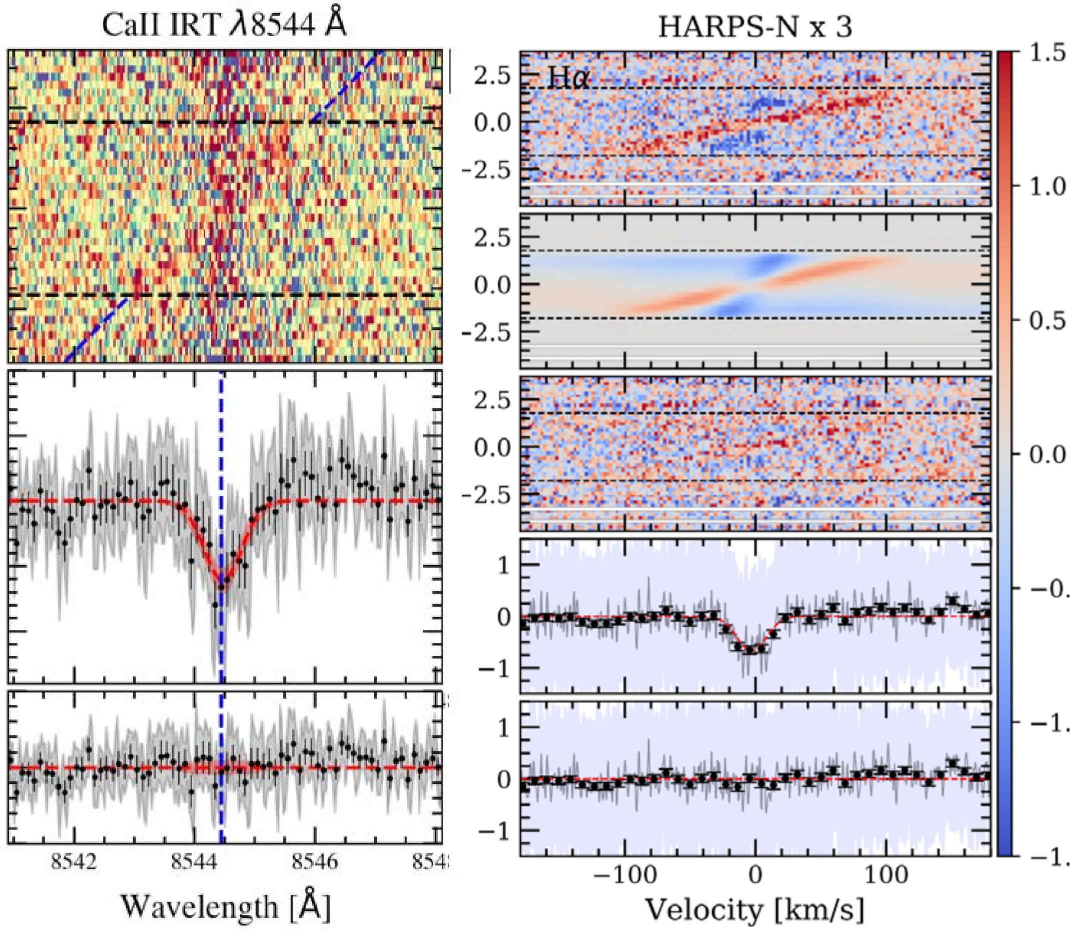


Palle et al 2023 ANDES white paper

Challenges – Stellar activity (also CLV+RME)



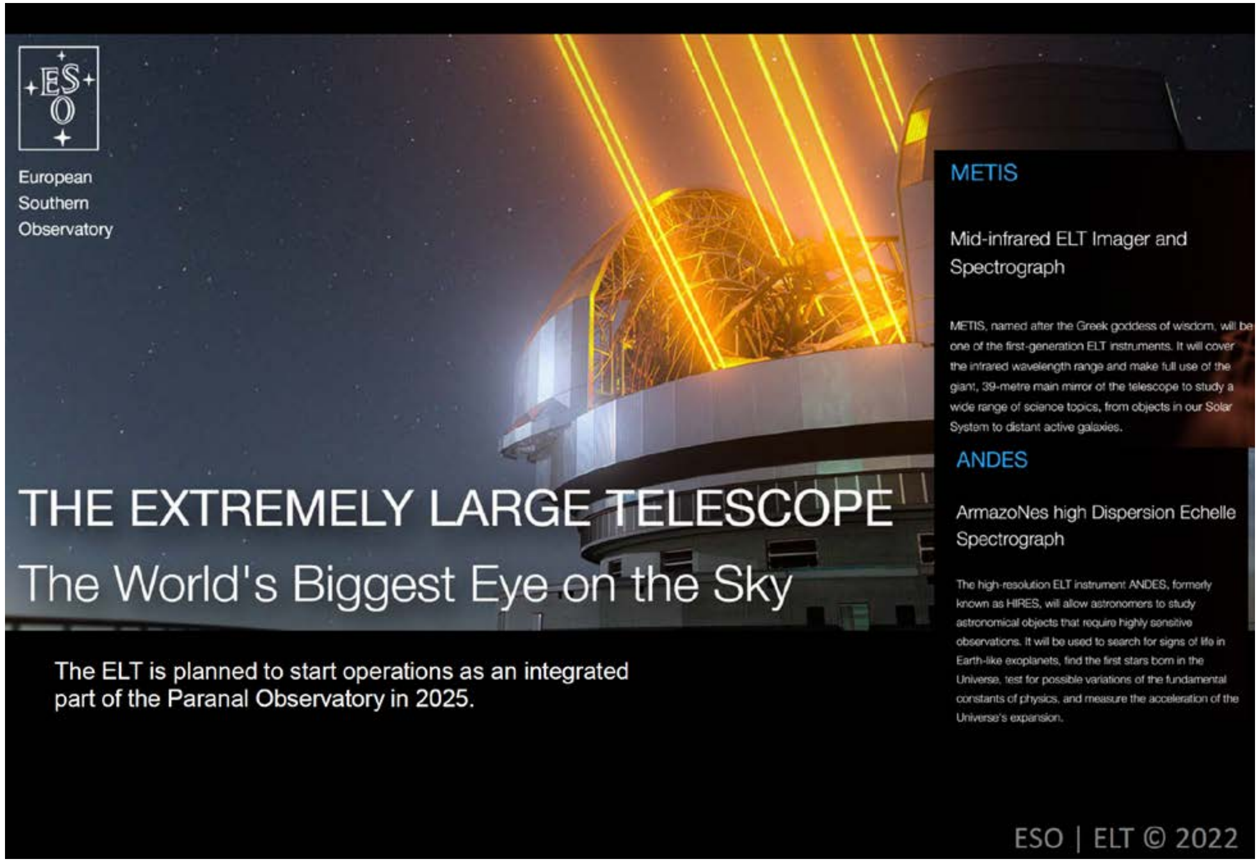
Rackham et al. 2018
Apai et al.



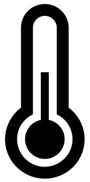
Casasayas-Barris et al. 2021

The future:

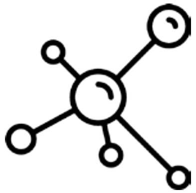
(Bild: Airbus)



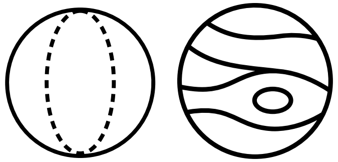
What can we tell about a planet using its atmosphere?



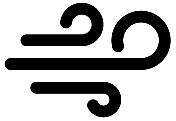
Temperature
(-pressure profile)



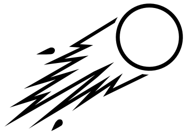
Composition
C/O ratio
Metallicity
→ Formation
→ and evolution



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



Winds
→Supersonic Equatorial jets
Day-to-nightside winds



Atmospheric loss

Evolution