

# Exoplanets

Lecture 9

13.11.2023

MFF UK

Winter semester 2023/2024

# A slide from the last lecture

- Rossiter - McLaughlin effect

$$A_{\text{RM}} \simeq \frac{2}{3} D v \sin i_{\star} \sqrt{1 - b^2}$$

$$D = (R_p/R_{\star})^2$$

- $b$  – impact param.,  $v \sin i_{\star}$  stellar rotational velocity
- <https://arxiv.org/pdf/1709.06376.pdf>

# Exoatmospheres

# Outline

- Recap exoatmospheres
- Detection methods
  - spectroscopic
  - spectrophotometric
- Weather on exoplanets
- Challenges of precise spectroscopy/photometry



# What do we know?

- Atmospheres of exoplanets do exist
- We know different types of atmospheres on exoplanets
  - H/He rich, heavy elements rich, water
  - the thinner the atmosphere is the more challenging is its detection
- Large telescopes with precise instruments needed, but....

# Scale height

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

k – Boltzmann constant

M – mean molecular weight

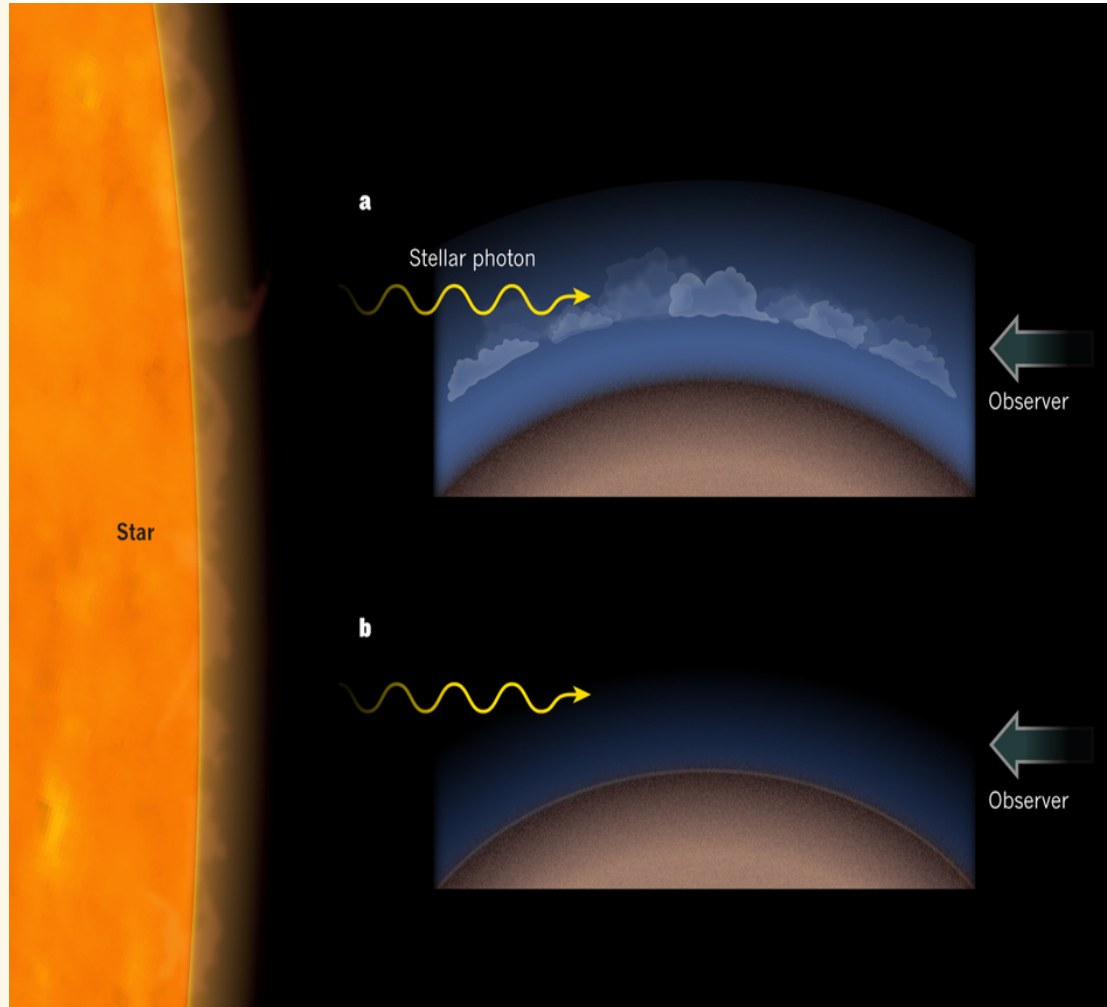
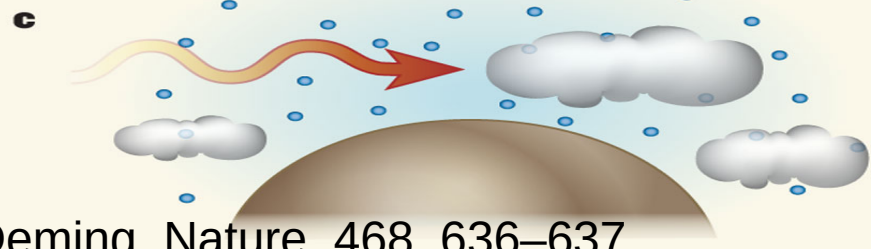
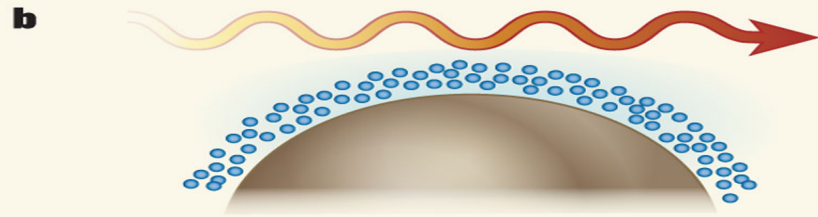
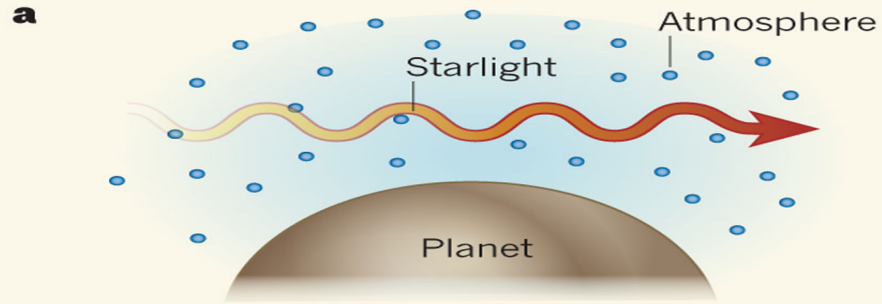
g – gravitational constant

T – mean atmospheric temperature

EARTH – about 8 km

TITAN - about 40 km

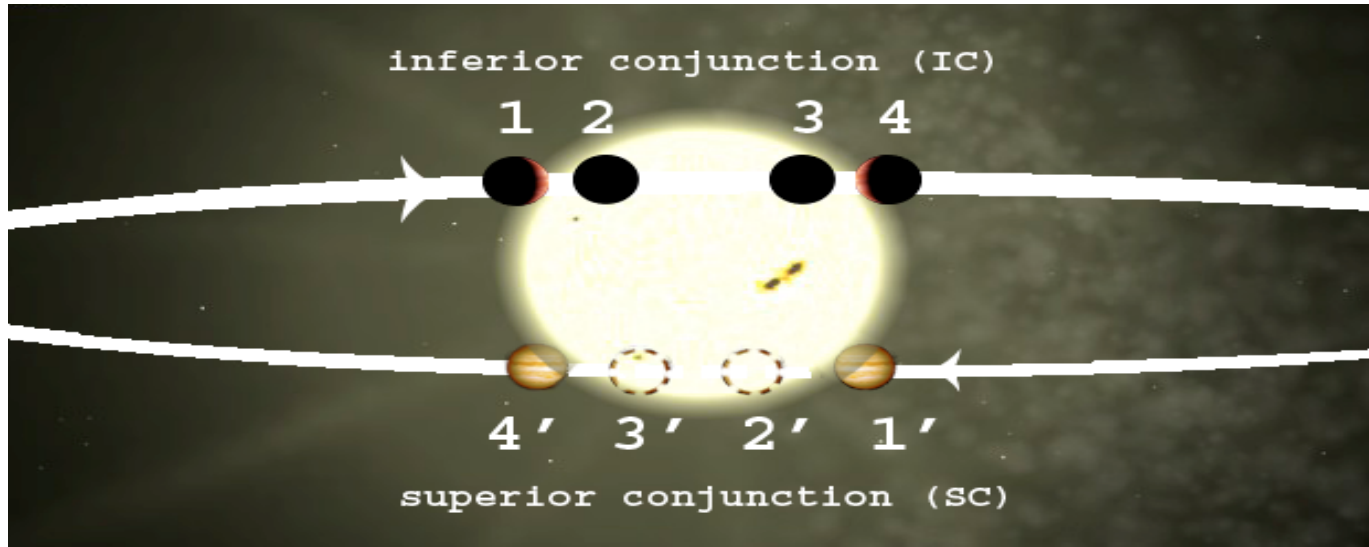
# Different types of atmospheres



## And how to detect the atmospheres?

- After new detections of exoplanets, also characterization attempts start in 2002
- Main goals are:
  - detection of atmosphere
  - physical conditions on the surface/in the atmosphere of the exoplanet
- Photometric and spectroscopic methods

# Transits and eclipses of exoplanets

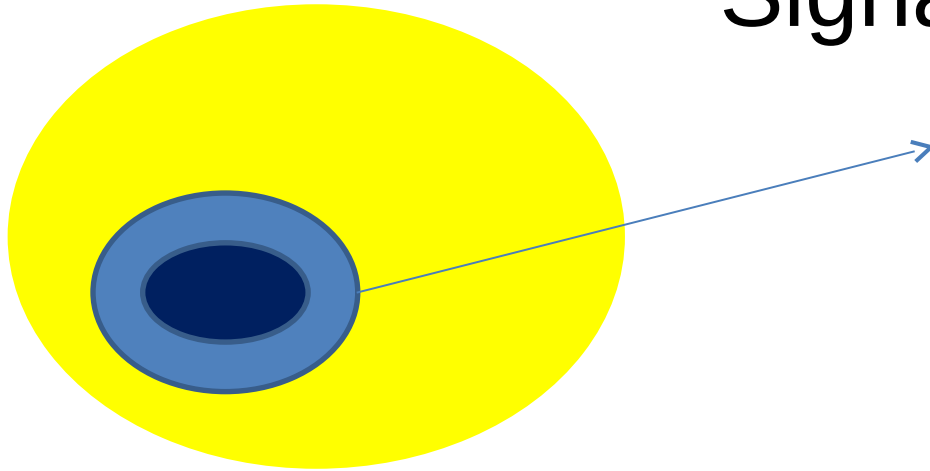


From Angerhausen et al. 2008

# Transit spectroscopy, the principle

Transit spectroscopy = transmission spectroscopy

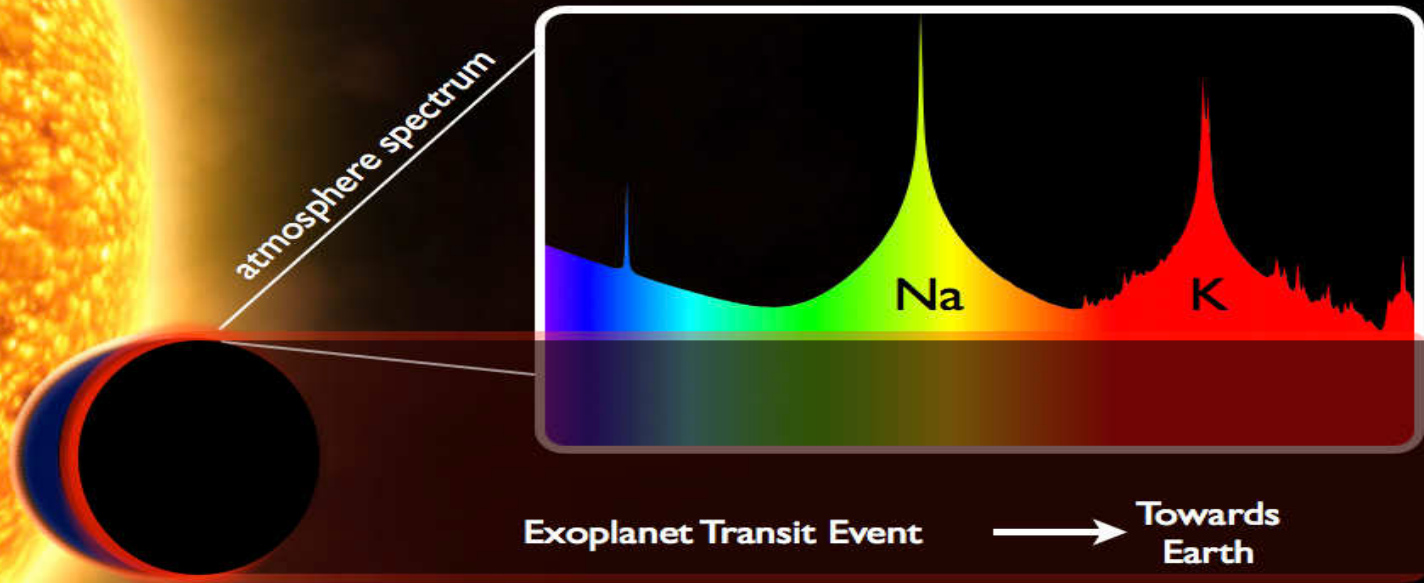
$$\text{Signal} = \text{Annulus} / R_{\text{star}}^2$$



Typical Signal of the planetary spectral lines  $< 10^{-4}$

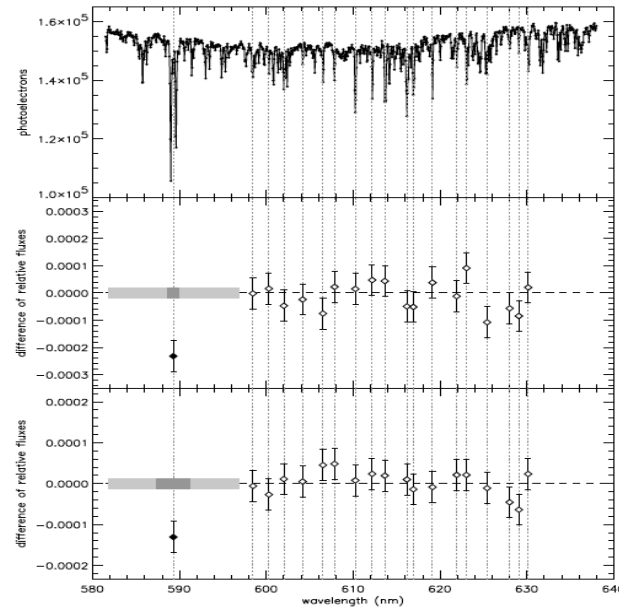
Smaller star & larger planet = better chance to see something

# Transmission spectroscopy high spectral resolution



# HD209458 b

- Charbonneau et al. 2002  
<https://arxiv.org/pdf/astro-ph/0111544.pdf>
- Detection with HST STIS





# What can we see?

- Absorption in stellar lines due to planetary atmosphere by atoms – high. resolution spectroscopy (Na, K)
- Absorption in stellar lines due to planetary atmosphere by molecules – low. resolution spectroscopy (H<sub>2</sub>O, CO<sub>2</sub>, TiO, CH<sub>4</sub>)
- First observations performed in 2002 with HST
  - HD209458b

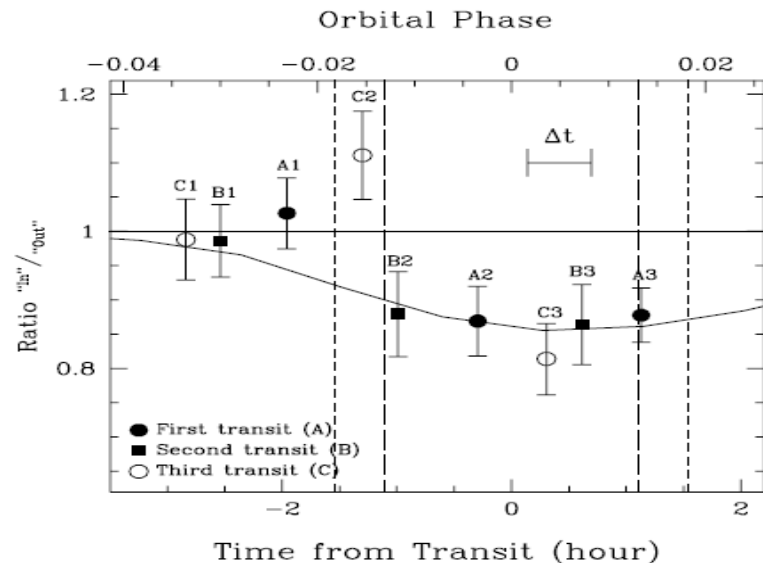
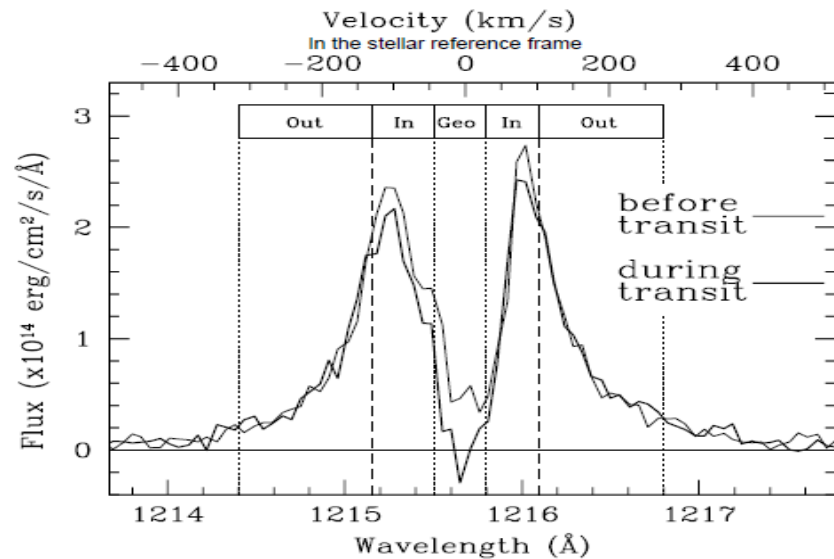
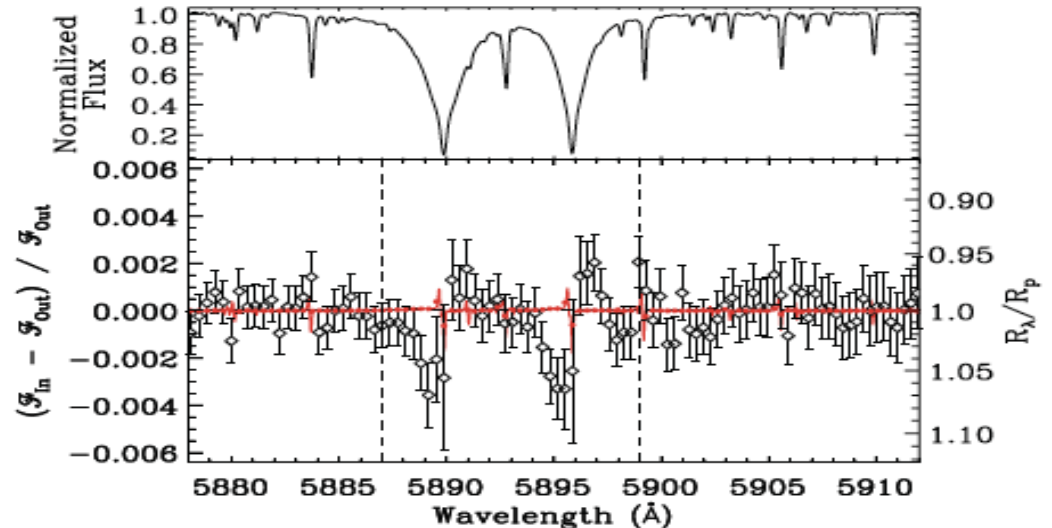


Figure 1. **Left:** The Lyman  $\alpha$  stellar line as observed by Vidal-Madjar et al. (2003). The averaged profile observed during transit (thick line) presents a reduced flux when compared to the pre-transit profile (thin line). The region named “Geo” corresponds to the region where the geocoronal Lyman  $\alpha$  correction was too important. In the “In” region absorption is observed while the “Out” region serves as a flux reference. **Right:** The averaged “In”/“Out” flux ratio in the individual exposures of the three observed transits (see text). Exposures A1, B1, and C1 were performed before and A2, B3, and C3 entirely during transits. Error bars are  $\pm 1\sigma$ . The “In”/“Out” ratio decreases by  $\sim 15\%$  during the transit. The thick line represents the absorption

# First ground based detection

- Redfield et al. 2008 - <https://iopscience.iop.org/article/10.1086/527475/pdf>
- Sodium doublet in HD189733b
- HET – 9.2-m telescope



# First ground-based detection with 4m class telescope

- Wyttenbach et al 2015 - <https://arxiv.org/abs/1503.05581>
- HD187933b with HARPS

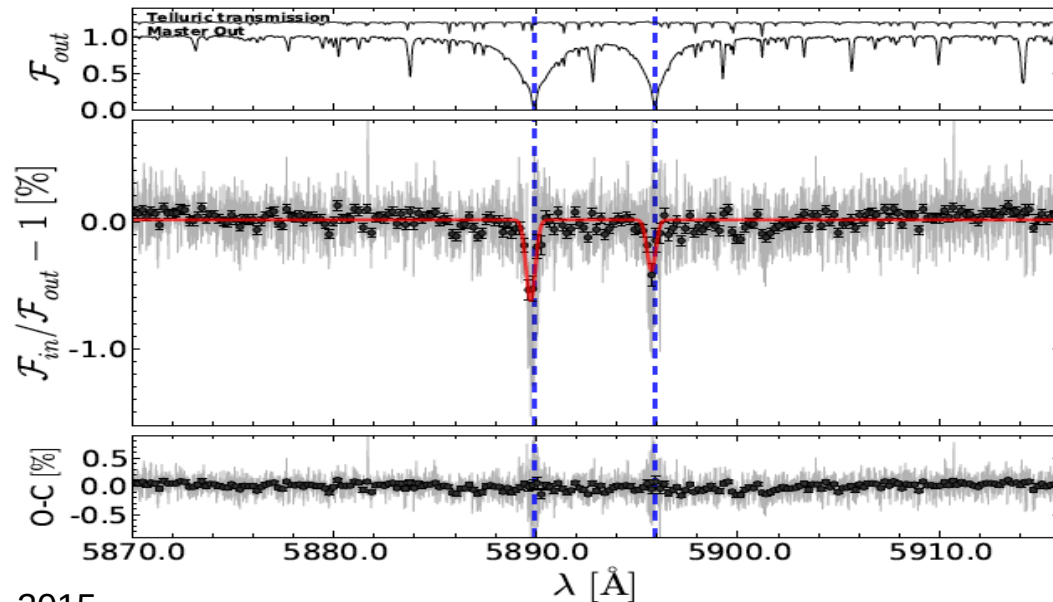
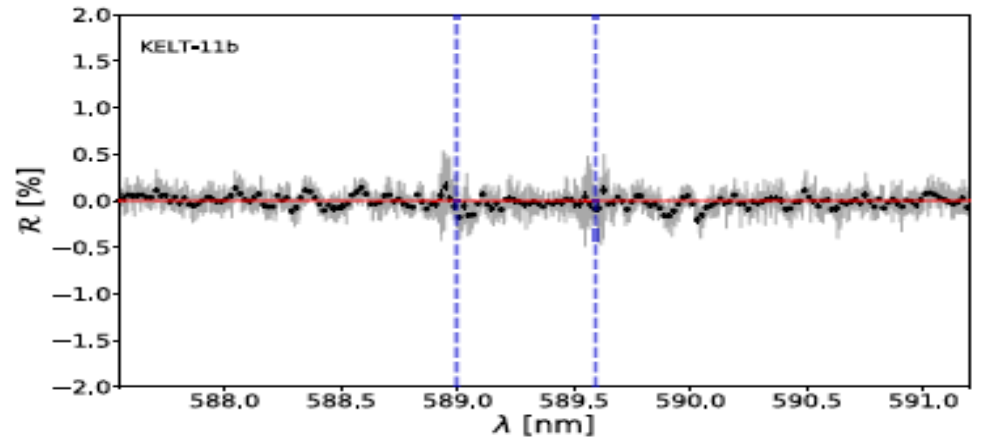
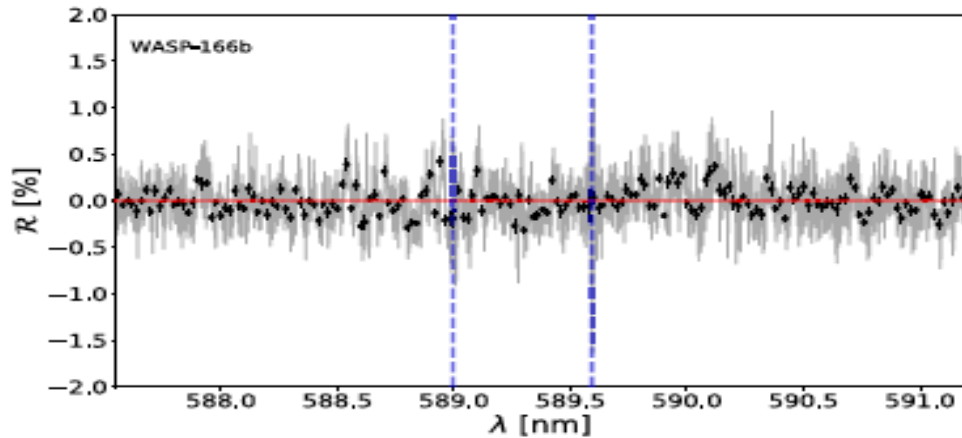
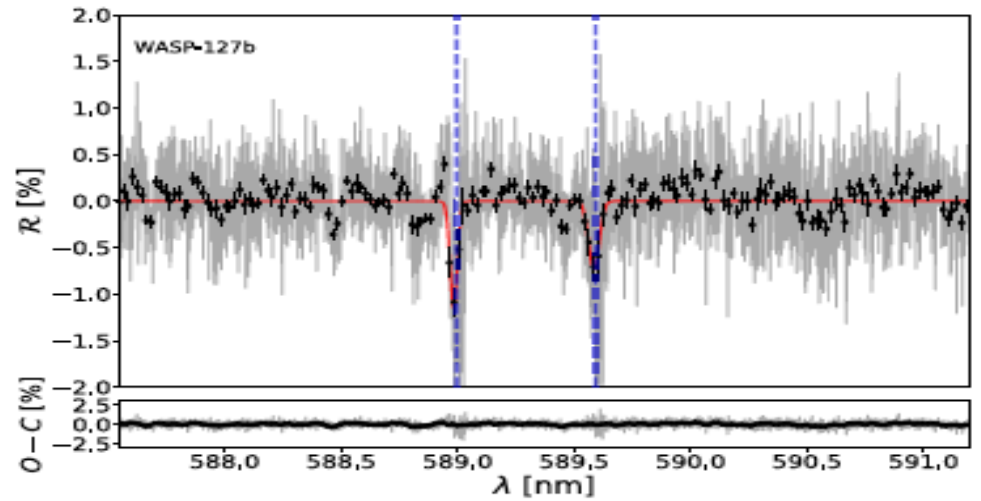
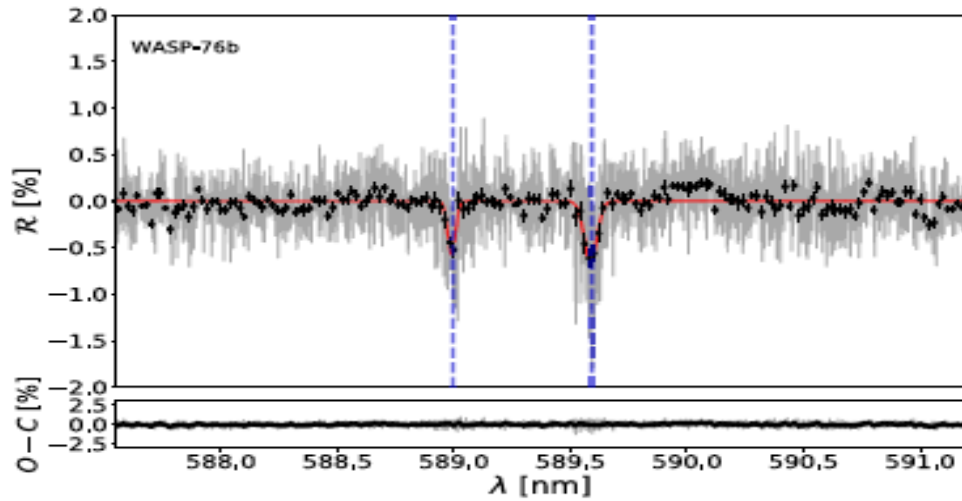
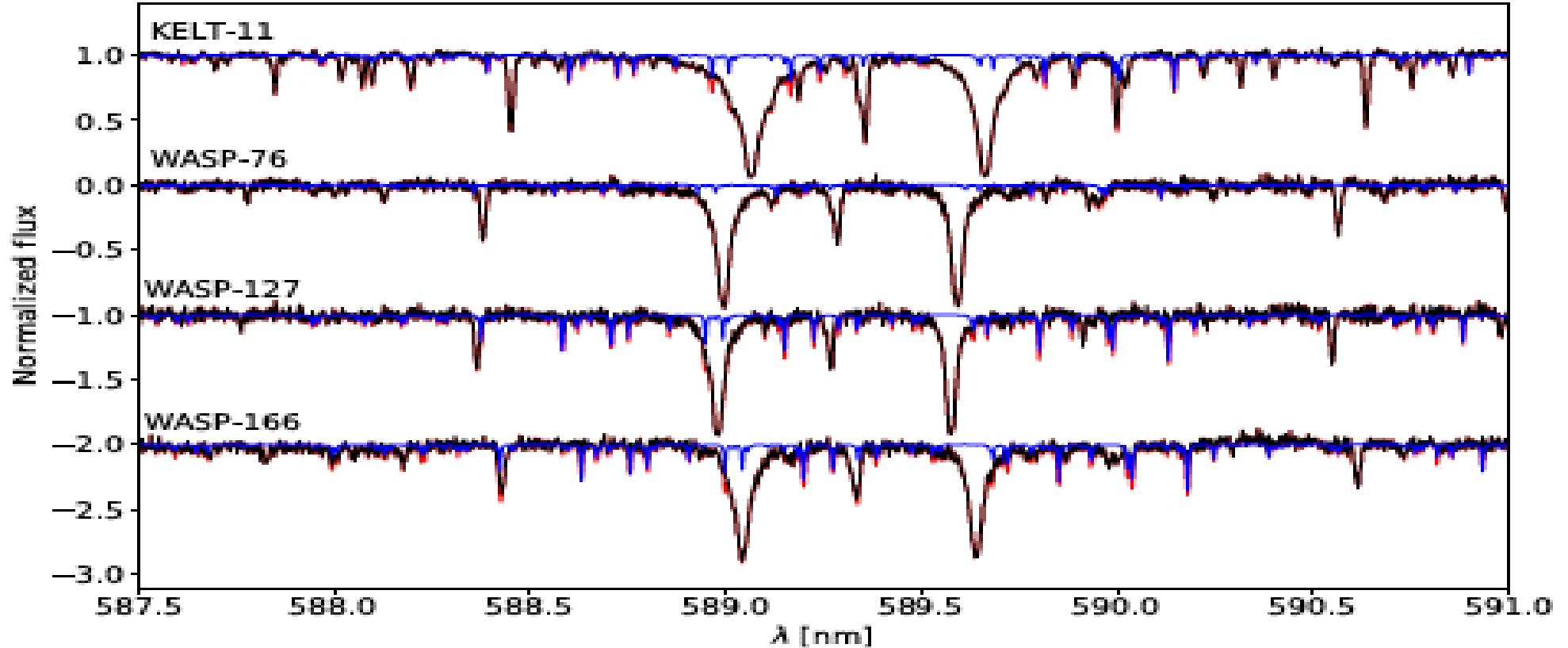


Image from Wyttenbach et al. 2015

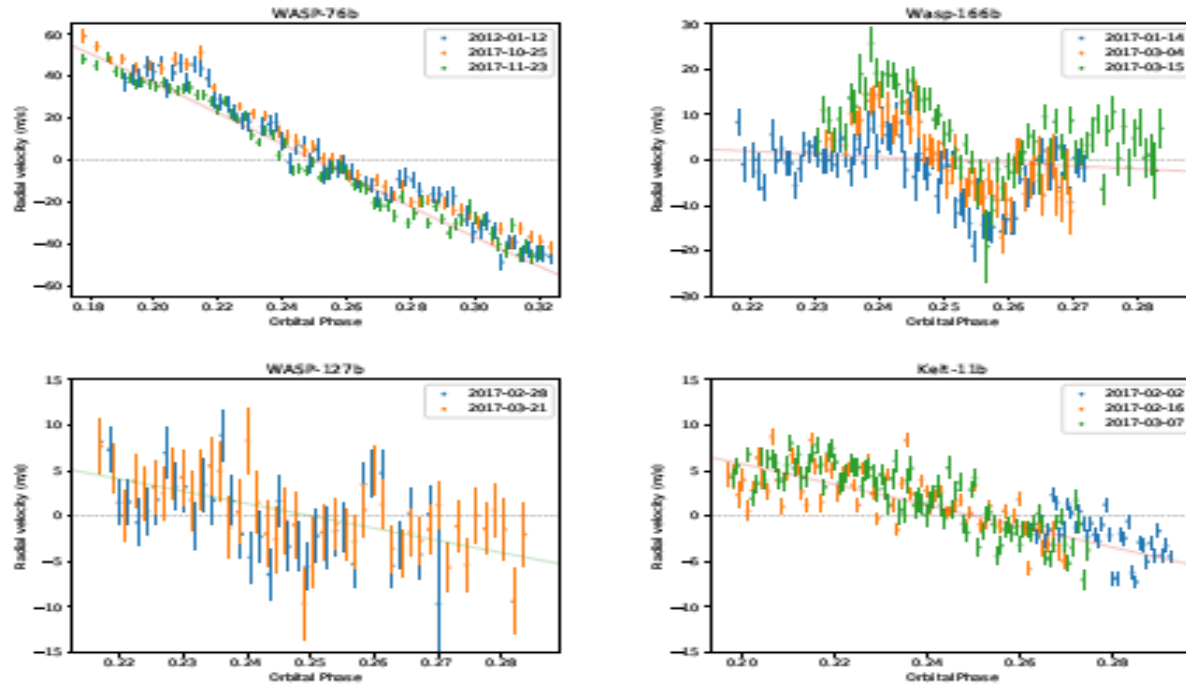
# Another Sodium Detection with HARPS



# Another Sodium Detection with HARPS

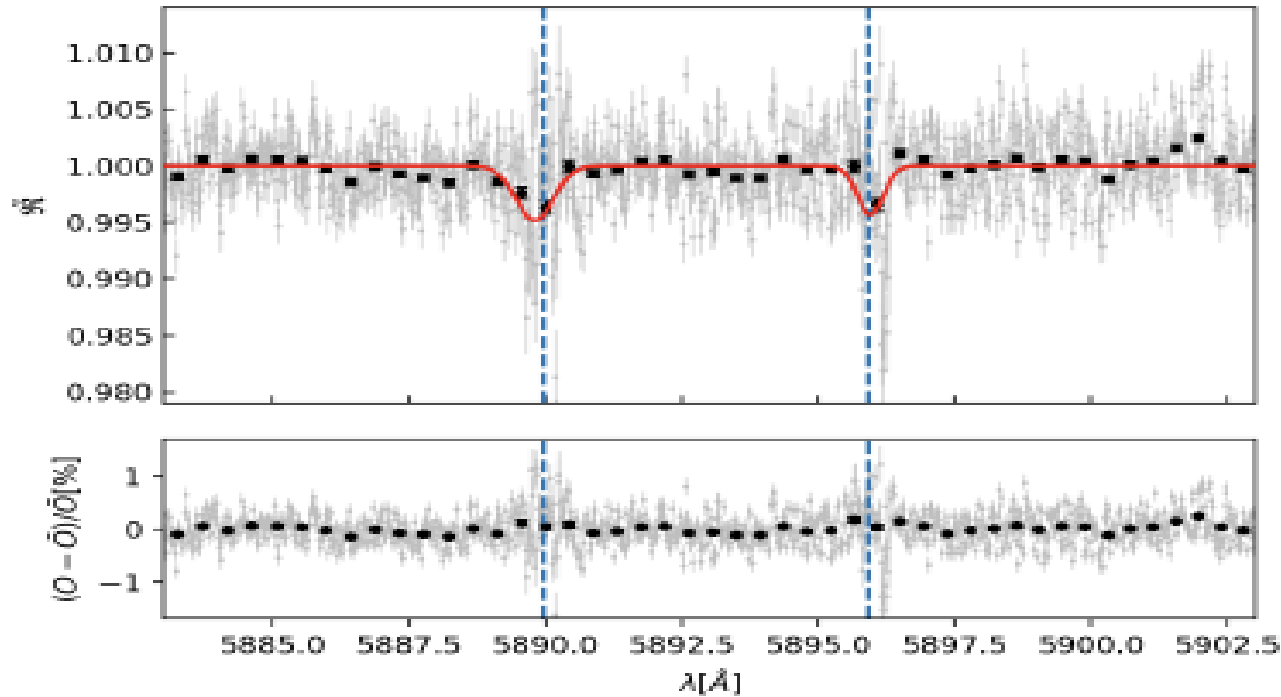


# Another Sodium Detection with HARPS



**Figure 4.** The radial velocities of our targets have been measured with HARPS: WASP-76 (top left), WASP-166 (top right), WASP-127 (bottom left) and KELT-11 (bottom right). There is some apparent offset between various epochs for the same target, which may be due to some instrumental shift or could be caused by the planet crossing star spots or faculae regions. In each case, the orbital motion is also indicated with the dashed line. Any deviation from this is due to the Rossiter–McLaughlin effect, which is clearly in all but one of our targets.

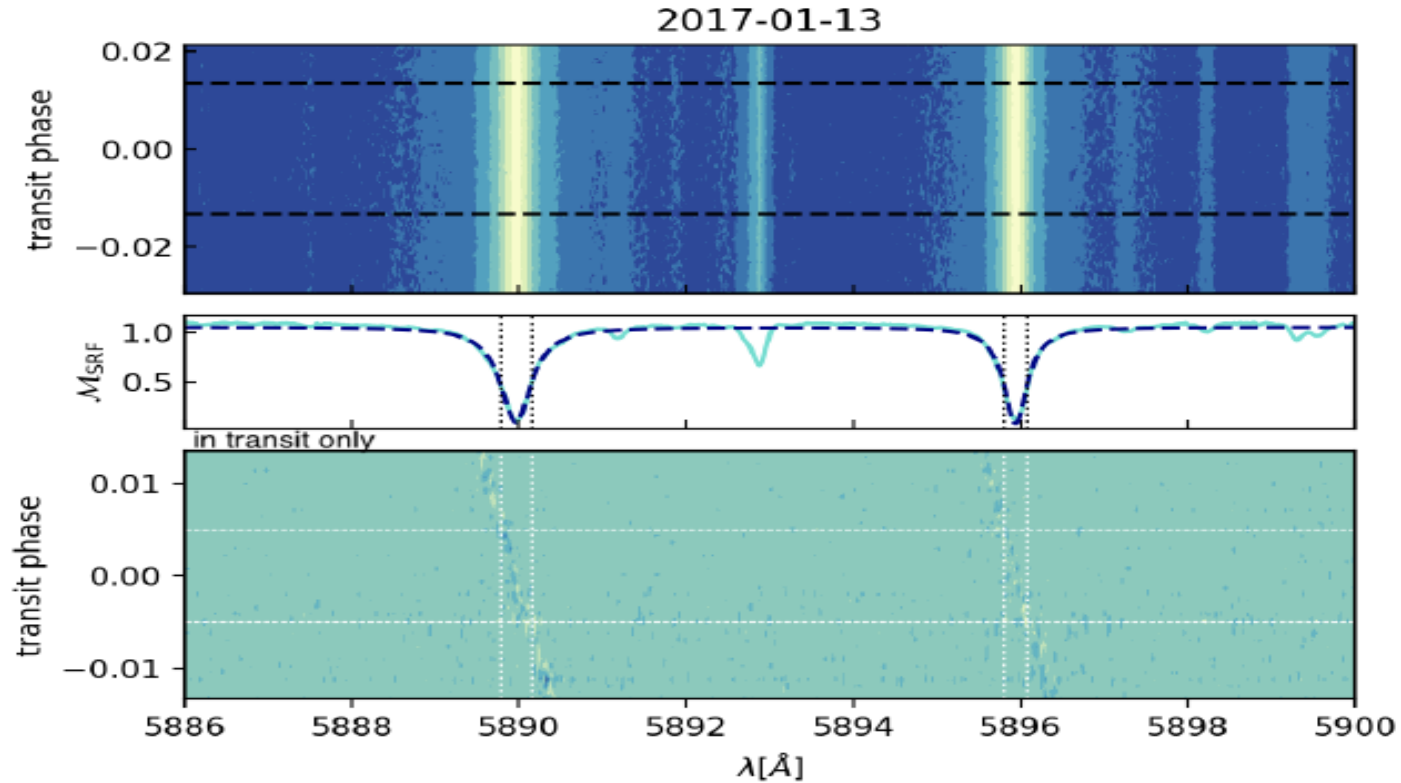
# Wasp-166b revisited



**Fig. 4.** HARPS sodium doublet transmission spectrum of WASP-166b for all nights combined shown in the PRF. Upper panel: In grey, data points at full HARPS resolution. In black, grey data points binned by  $\times 25$  for visibility. The theoretical line centres for the sodium doublets are shown as vertical blue dashed lines, a Gaussian fit to the unbinned data is shown in red. The sodium absorption is visible for both lines of the doublet. The combined line contrast is measured at  $0.455 \pm 0.135\%$ , resulting in a  $3.4\sigma$  detection, see Sec. 4.3. Lower panel: Residuals of the Gaussian fit in %.



# Wasp-166 revisited



**Fig. A.1.** The upper panel shows all spectra in the SRF as a 2D map of wavelength and transit phase for the first transit. The stellar sodium doublet is visible as two horizontal light yellow bands. Transit ingress and egress are marked with black dashed lines. The central plot shows the normalised sum of all spectra with a fit to each line in dashed blue. The FWHM is indicated as dotted vertical lines. The lower panel shows the same data, but corrected for the stellar spectrum by the master-out, in the PRF. The dotted lines propagate the position of the FWHM from the central panel. The low-SNR remnants are clearly visible, but the SNR is too low to see the planetary trace.

# Wasp-127 revisited (with ESPRESSO)

R. Allart, L. Pino, C. Lovis et al.: WASP-127b seen by ESPRESSO

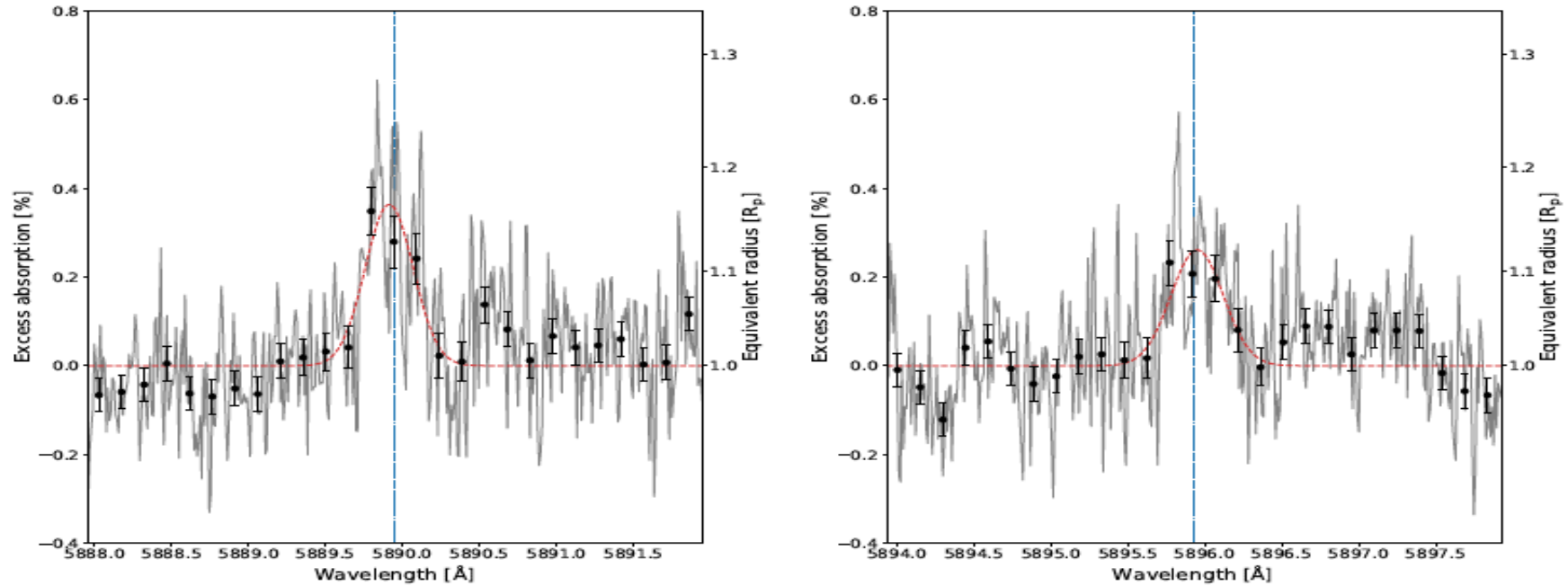
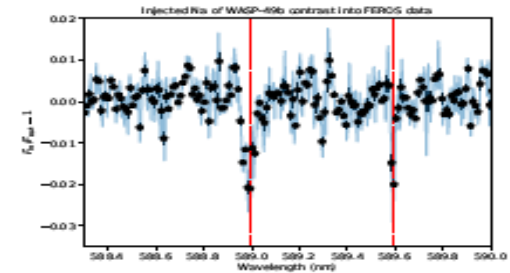
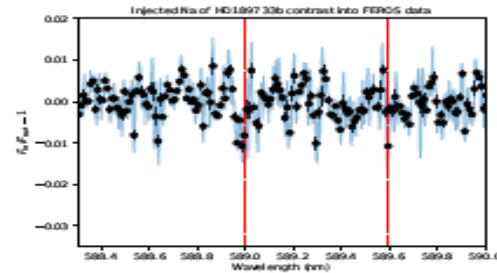
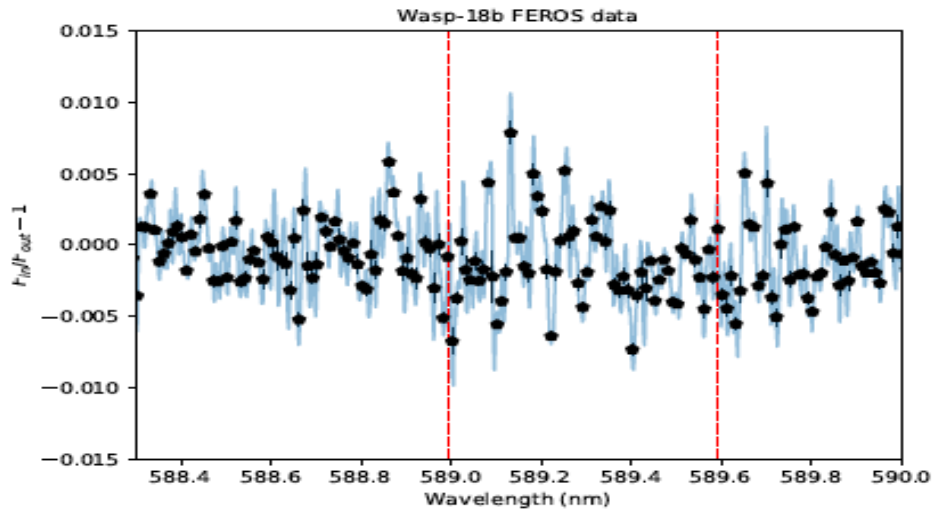


Fig. 8: Transmission spectrum around the NaD2 (*left*) and NaD1 (*right*) line averaged across the two transits in grey and binned by fifteen elements in black. The vertical blue dash dotted line represents the expected position of planetary sodium lines.

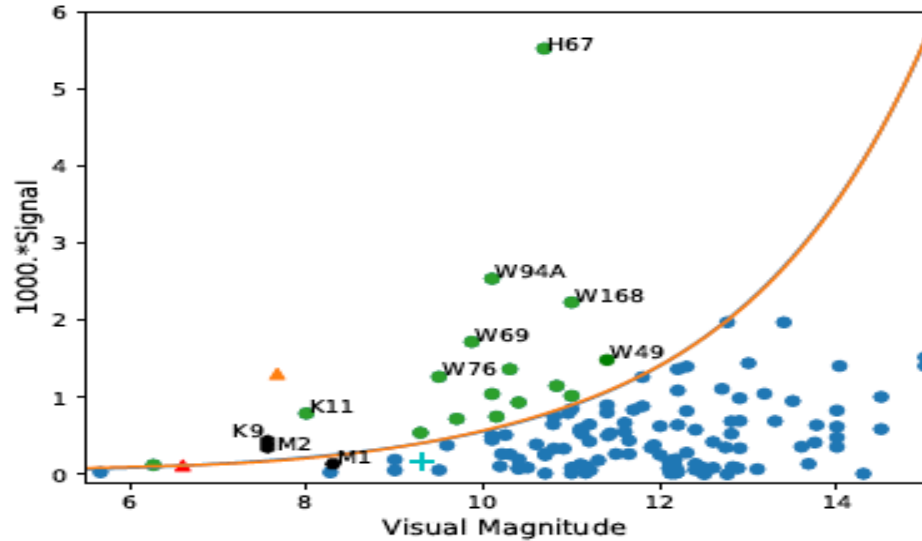
# But... small telescopes?

- Kabath et al. 2019
- FEROS at 2-m telescope real data and injected sodium –  
DETECTION POSSIBLE!

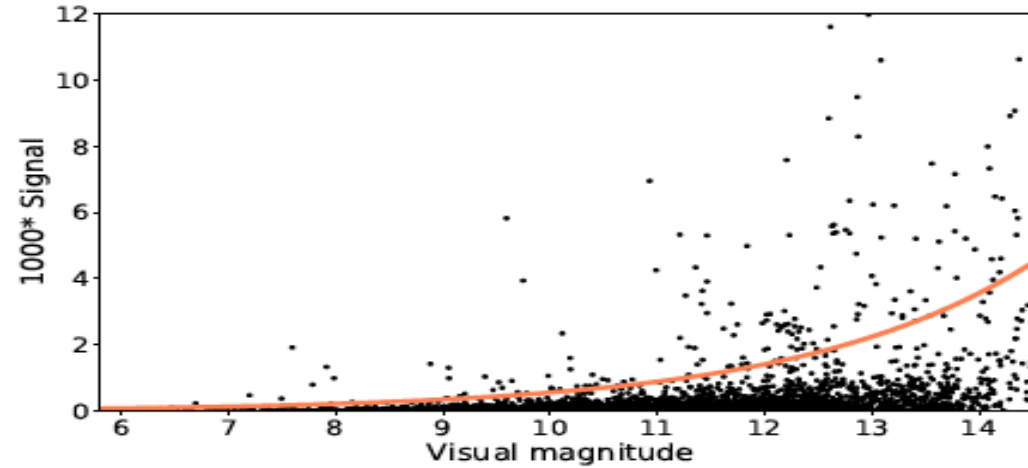


**Figure 4.** Sanity test with injected signal: (left) the signature of sodium absorption in the planetary atmosphere was injected into the FEROS WASP-18b data set. The strength of the sodium signal was set to be equal to that detected from HD189733b by Wyttenbach et al. (2015). (right) Injected sodium signal of the equivalent strength to the WASP-49b detection by Wyttenbach et al. (2017). Black points in both panels correspond to binning by a factor 10. The red dashed lines indicate the position of the NaD lines.

# Prospects for small telescopes



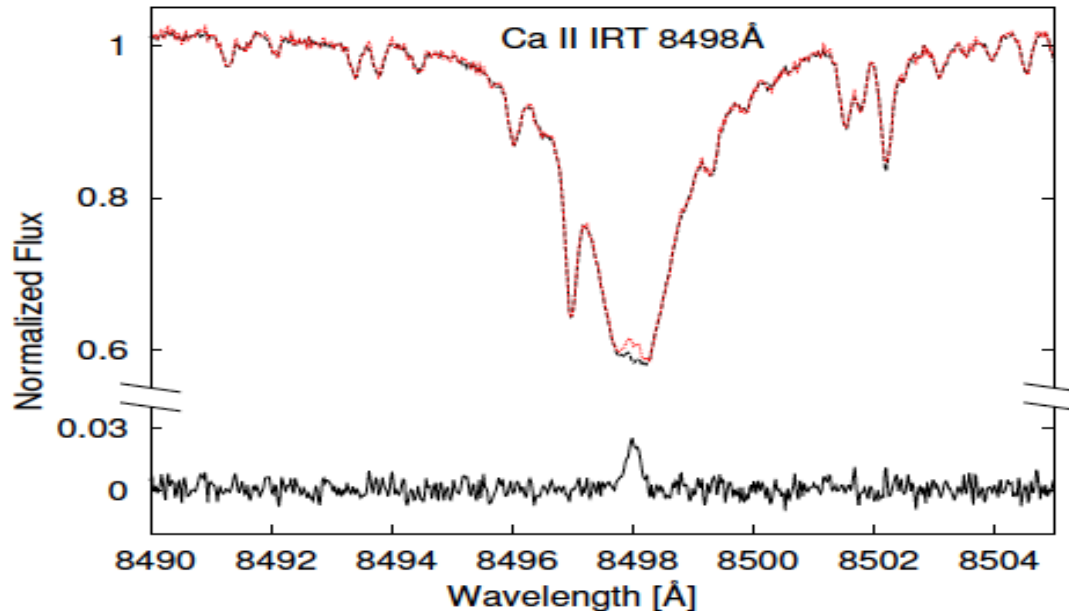
**Figure 5.** The expected atmospheric signal for well-characterised transiting planets as a function of the visual magnitude of the host star. The orange triangle shows the position of HD 189733, while the red triangle is the rescaled value, assuming a 2-m-class telescope (see text). All the points above the solid line are suitable candidates to perform transmission spectroscopy with a 2-m-class telescope.



**Figure 6.** Expected signal as in previous Fig. 5 but from TESS planets which are depicted as black dots. The orange line is the detection limit for 2-m telescopes and good candidates for further follow-up will be above the line (see text for more detail).

# What happens if the star is flaring?

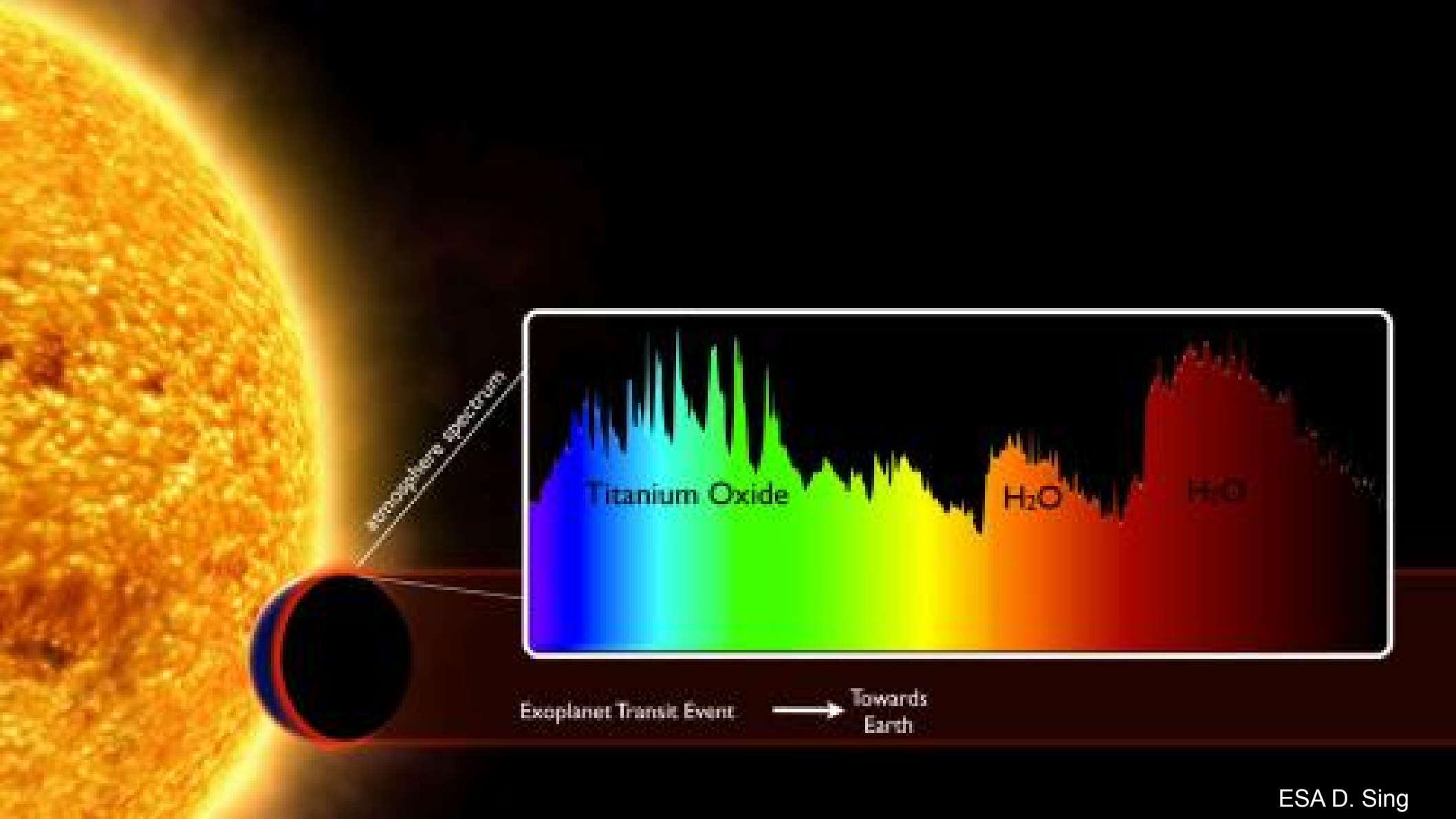
- Klocova 2017 et al. - <https://arxiv.org/pdf/1707.09831.pdf>
- What happens if during the transit a flare occurs?



Other methods

# Spectrophotometry

- Spectroscopy during the transit/eclipse
- Usually, low spectral resolution
- Spectral bins are selected to obtain spectrophotometric light curve (by integrating of the flux)
- Resulting light curve is fitted and transit parameters are obtained
- Depth of transit varies with wavelength  
= TRANSMISSION SPECTRUM



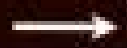
atmosphere spectrum

Titanium Oxide

H<sub>2</sub>O

H<sub>2</sub>O

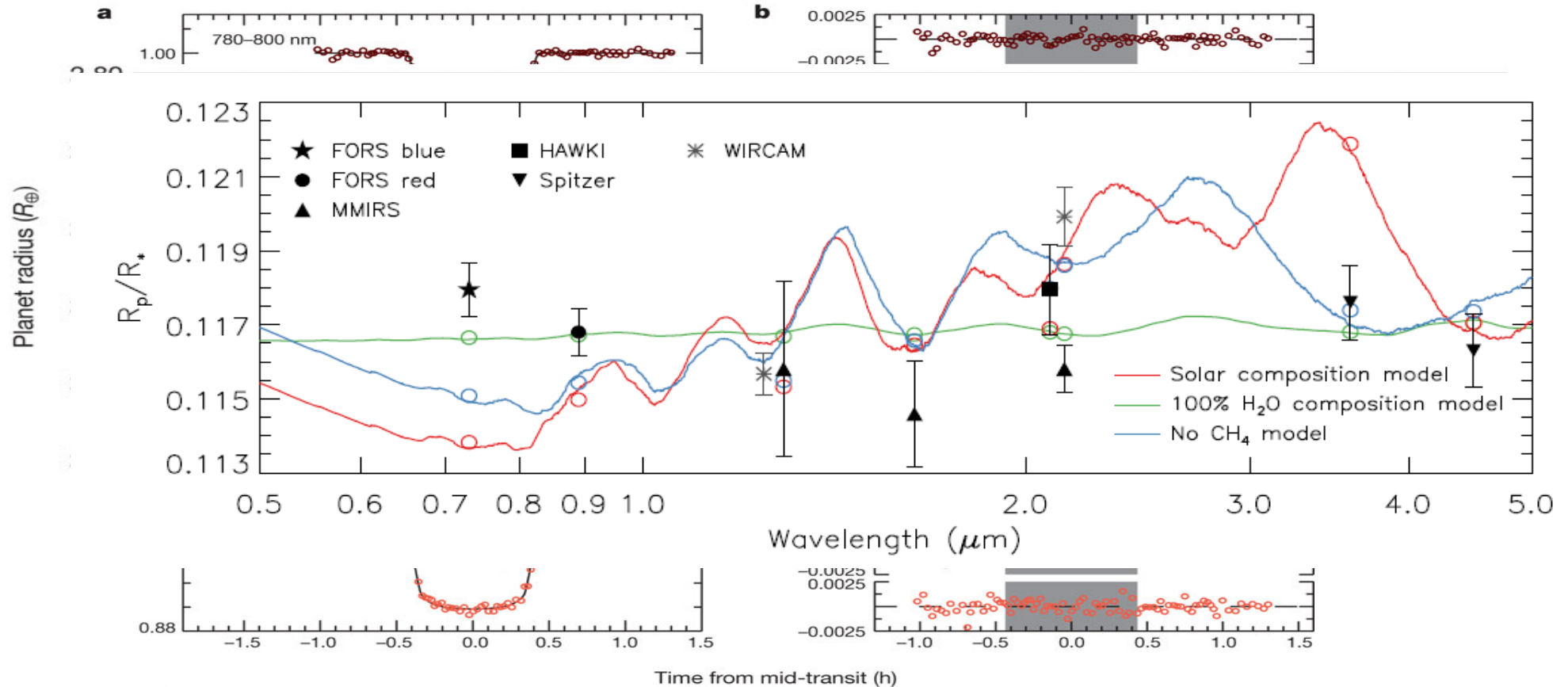
Exoplanet Transit Event



Towards Earth



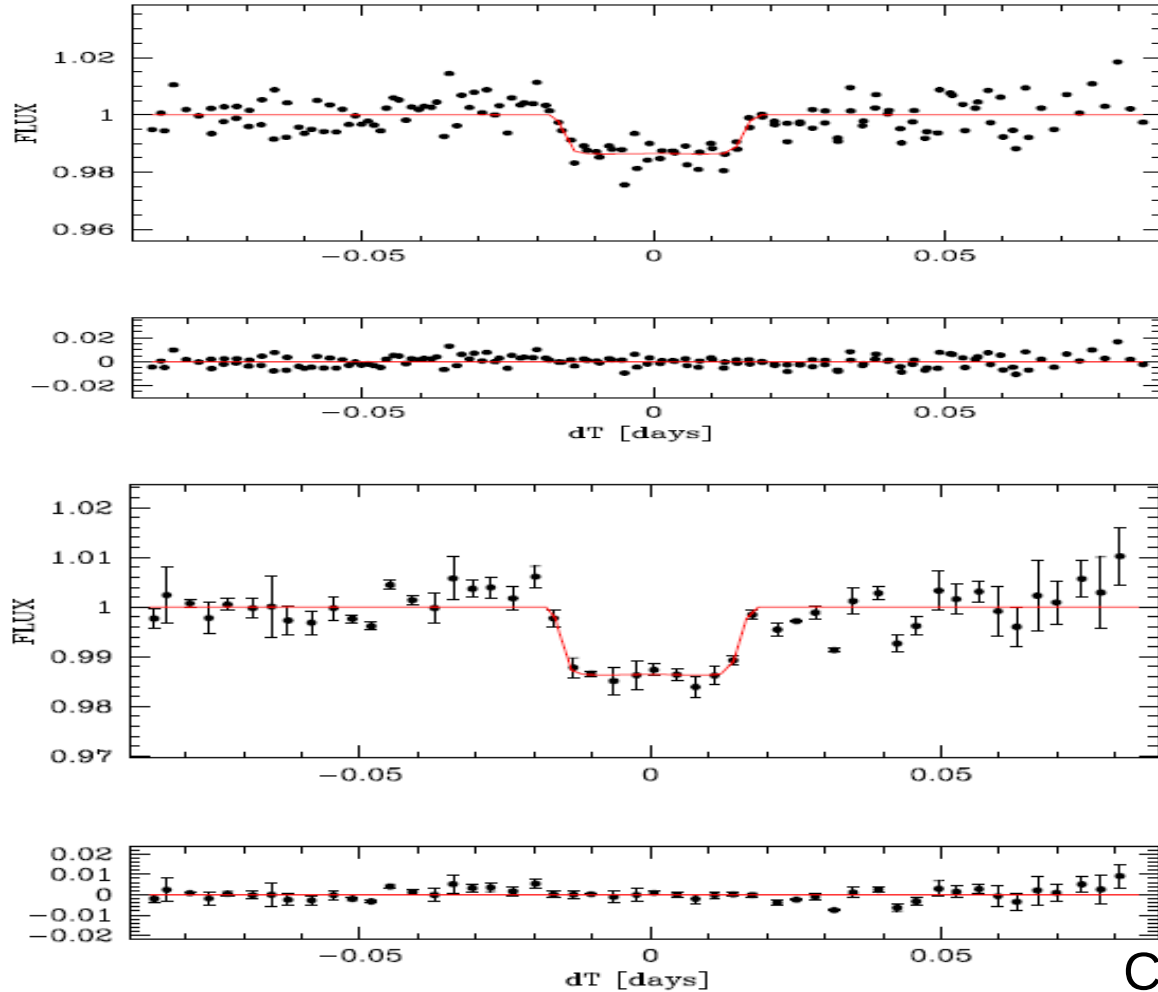
# FORS2 2010, 2011



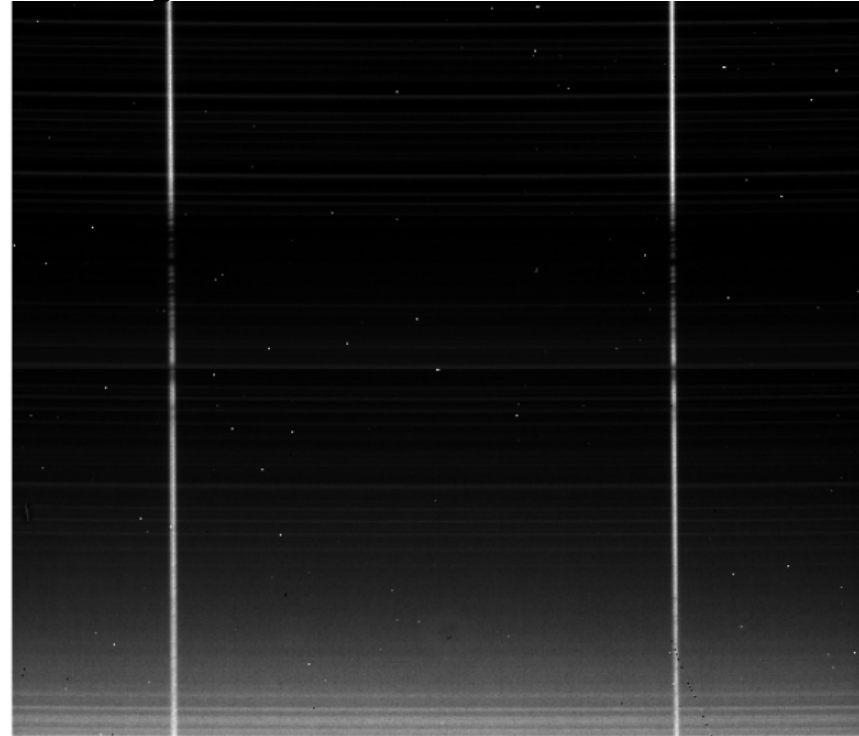
Bean et al. 2010, Nature

Bean, Desert, Kabath et al. 2011, AandA

# SOFI NIR transmission spectroscopy



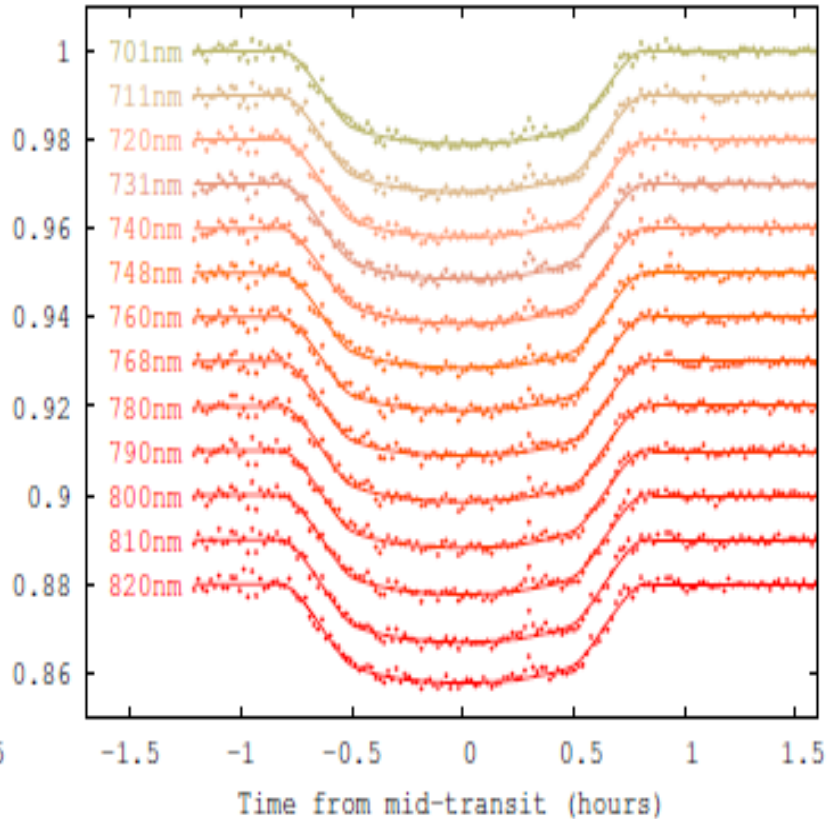
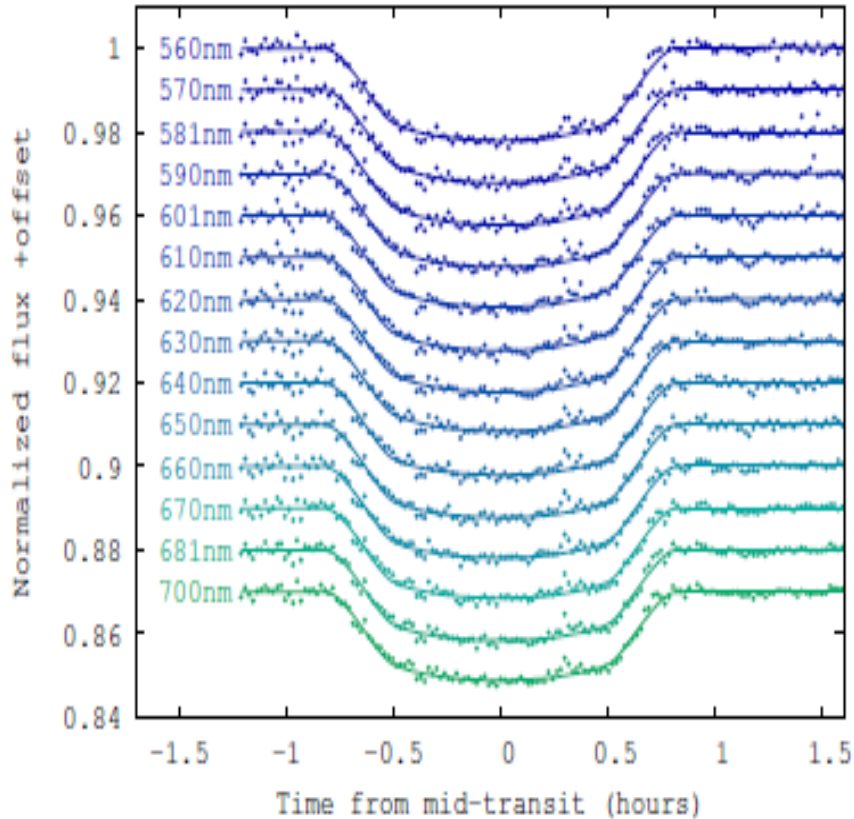
1.5 – 2.3 micron low res.  
3 nights in 2011

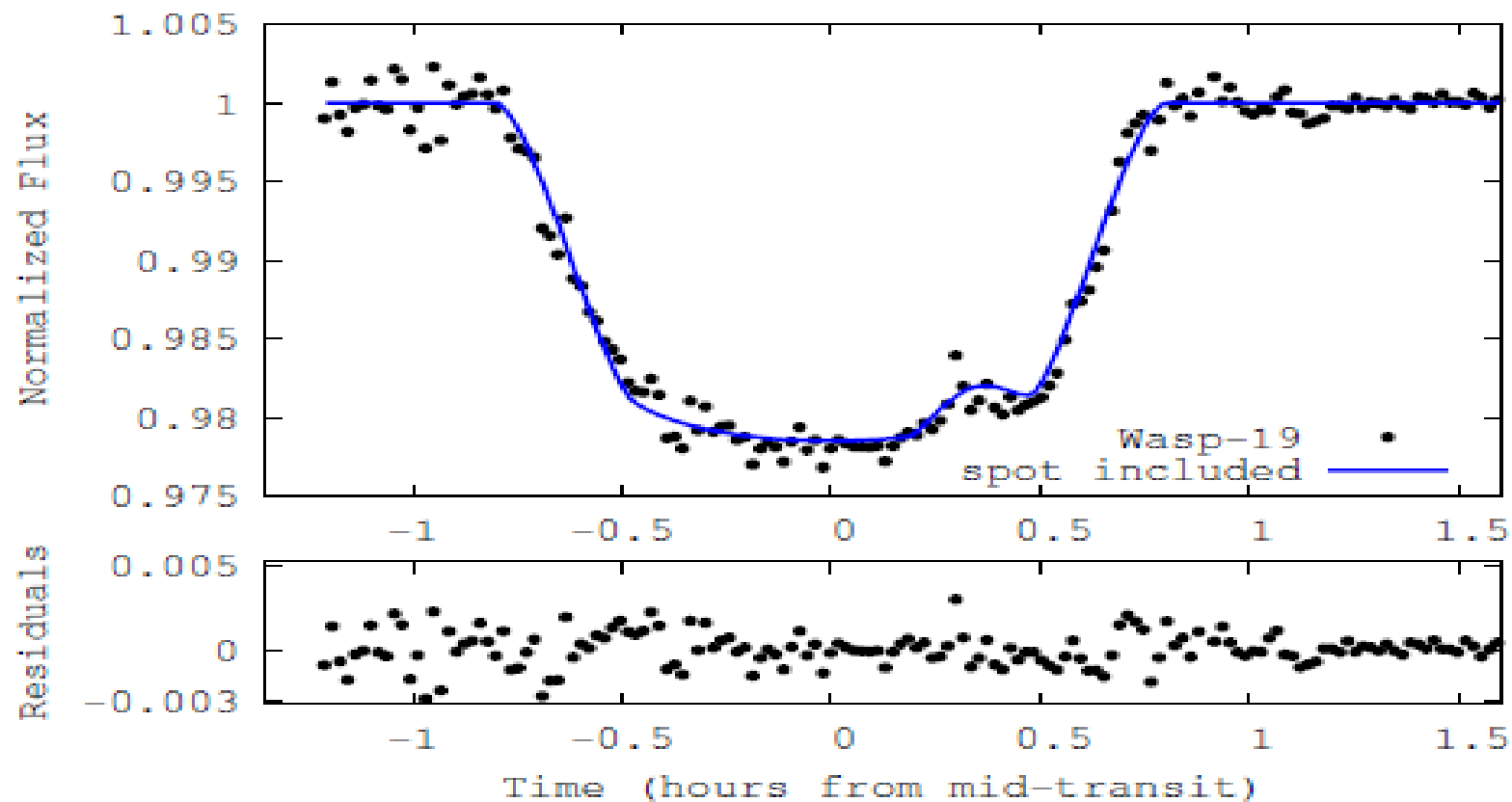


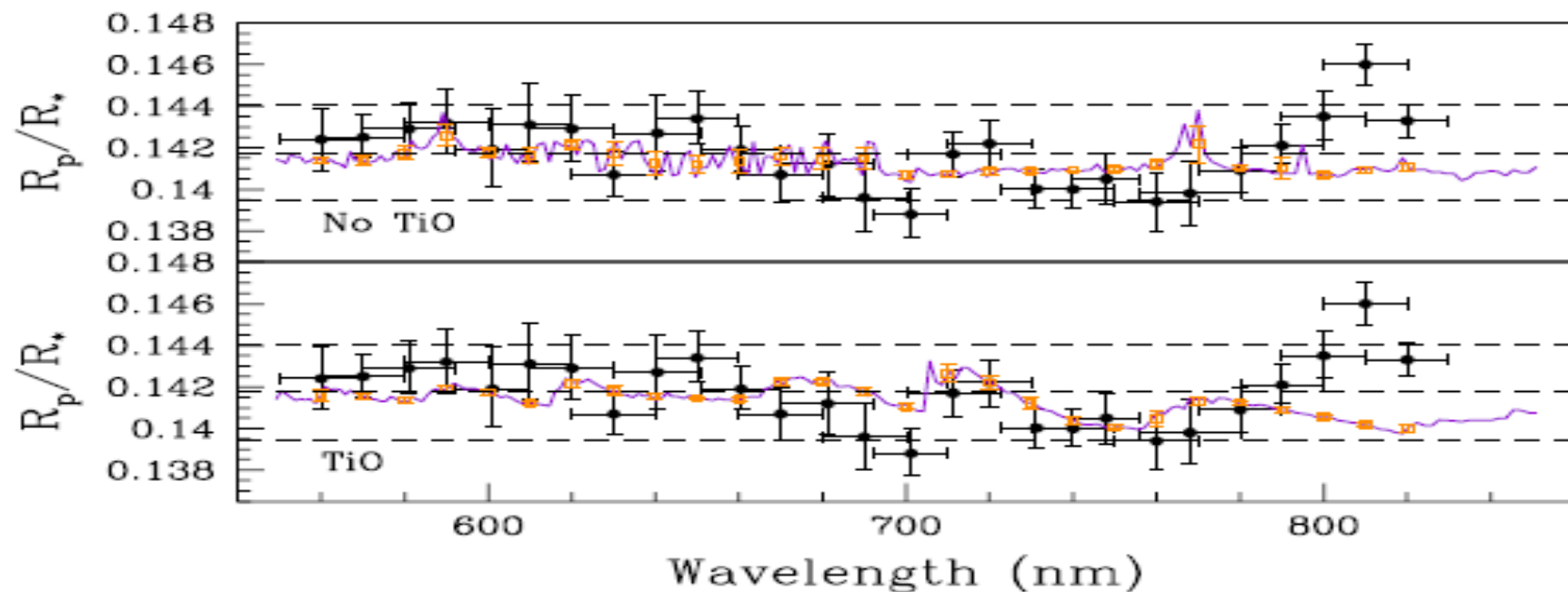
Caceres, Kabath et al., 2014, A&A

# WASP-19b – better resolution

- Sedaghati et al. 2015, A&A



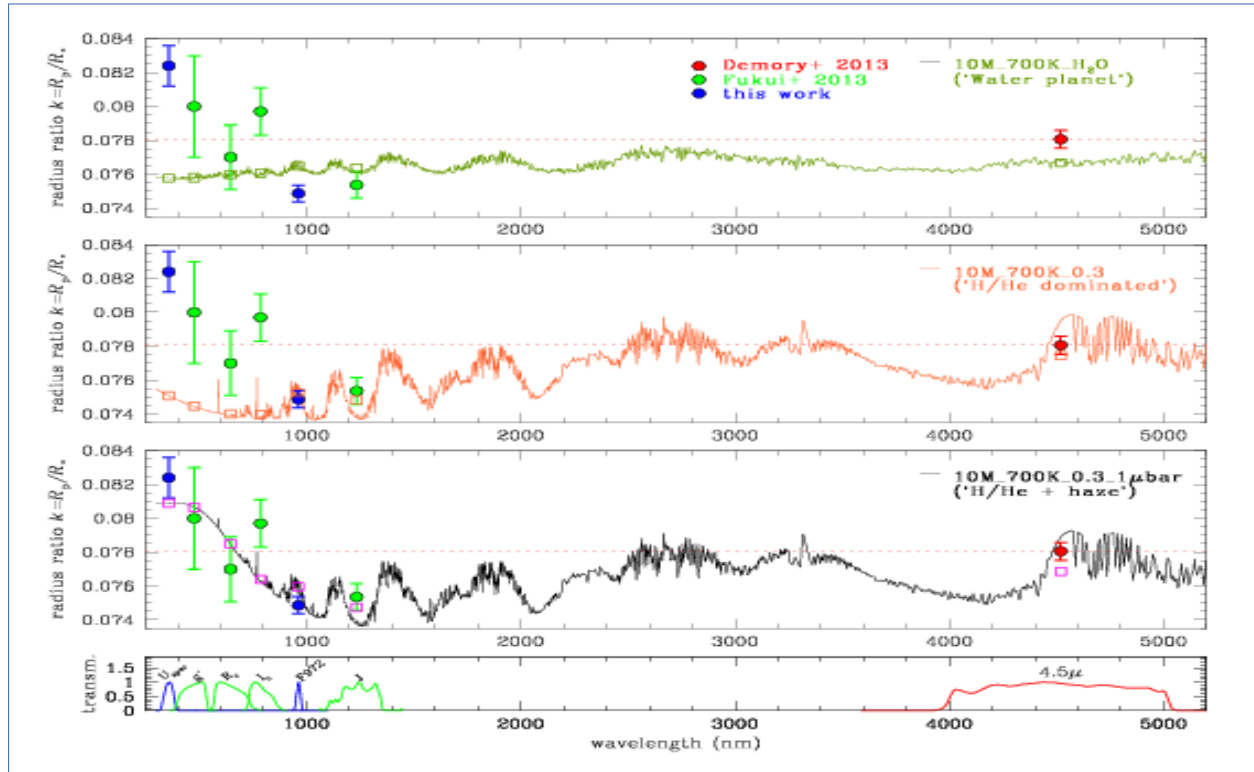


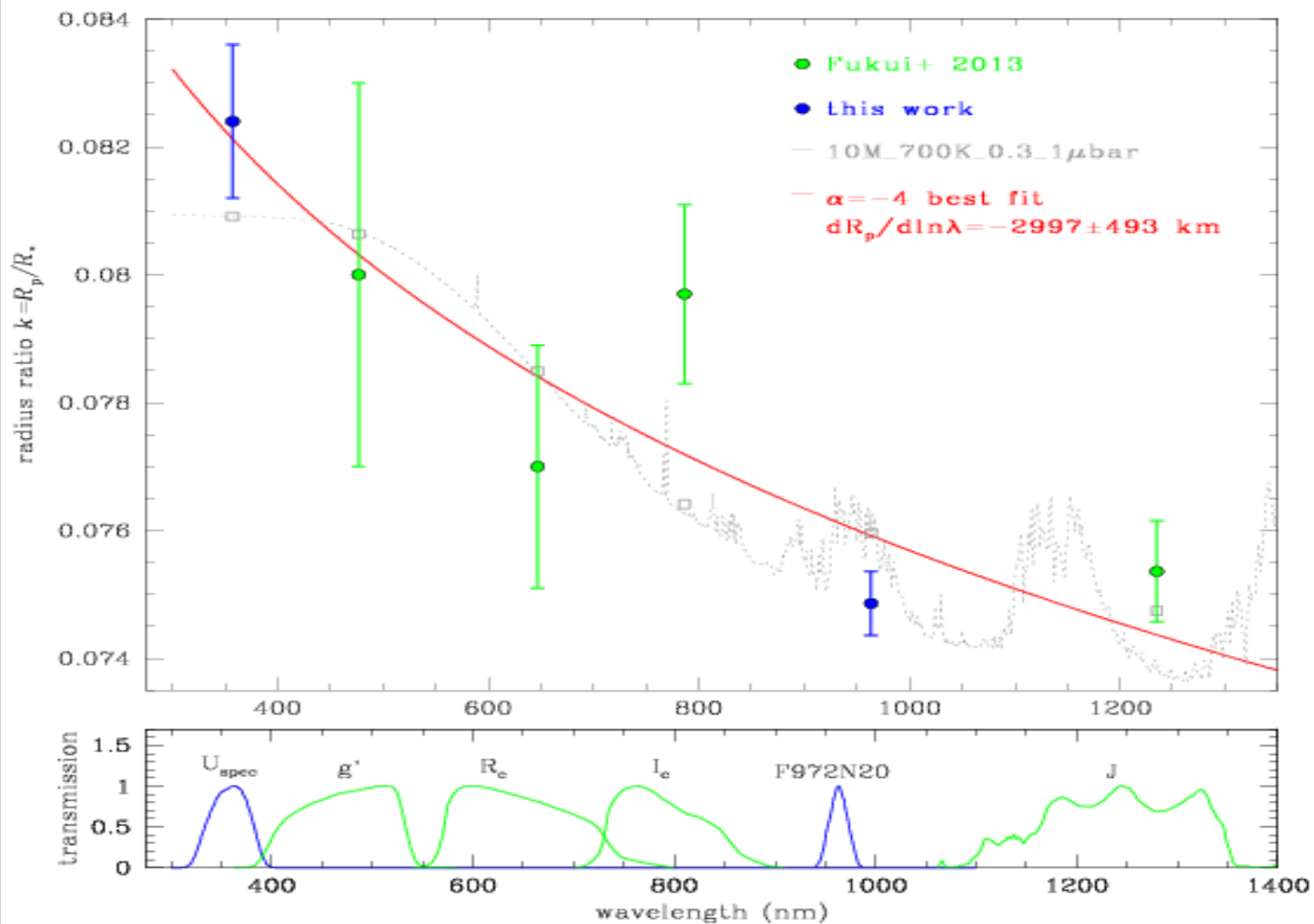


**Fig. 2.** Transmission spectrum of WASP-19b as measured with FORS2 (black dots, with error bars) compared to two models of planetary atmospheres, one with no TiO (top panel) and one with a solar abundance of TiO (bottom panel), from Burrows et al. (2010) and Howe & Burrows (2012). We have also estimated the mean value of the models in bin sizes of 20 nm (orange open squares). The dashed lines represent the weighted mean and plus or minus three scale heights.

# Can we determine the colour of skies on exoplanets?

- Rayleigh scattering - GJ3470b?





Very accurate photometry



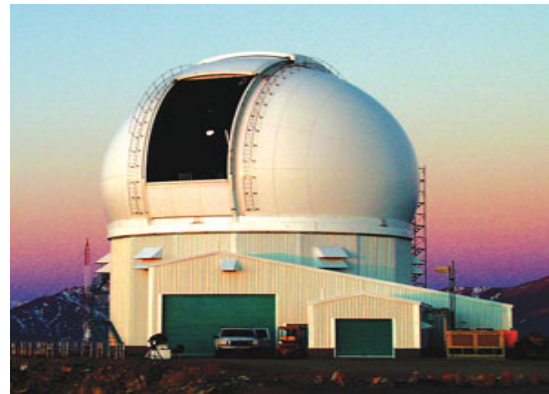
# Our observations with 4m class

- SOFI @ NTT – La Silla 3 nights
- OSIRIS @ SOAR - Cerro Pachon 1 night
- SOI @ SOAR - Cerro Pachon 1 night

Both telescopes are 4-m class!!!

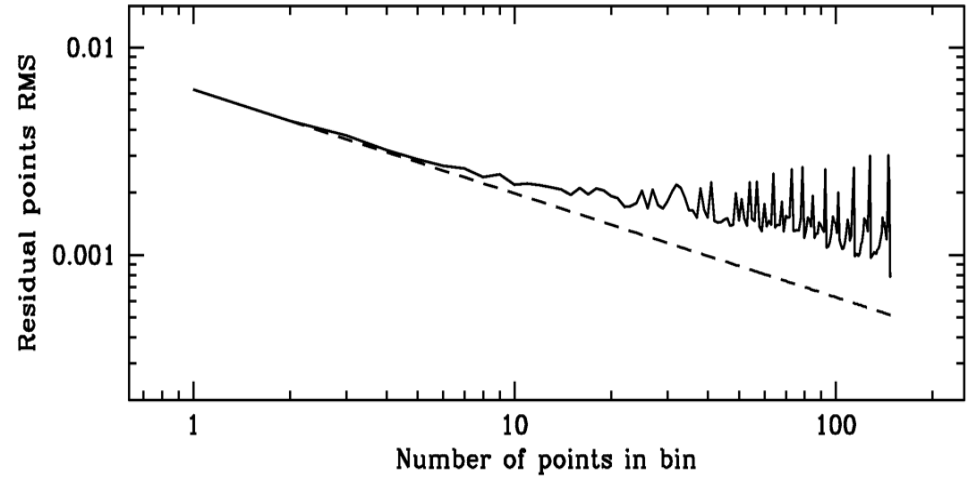
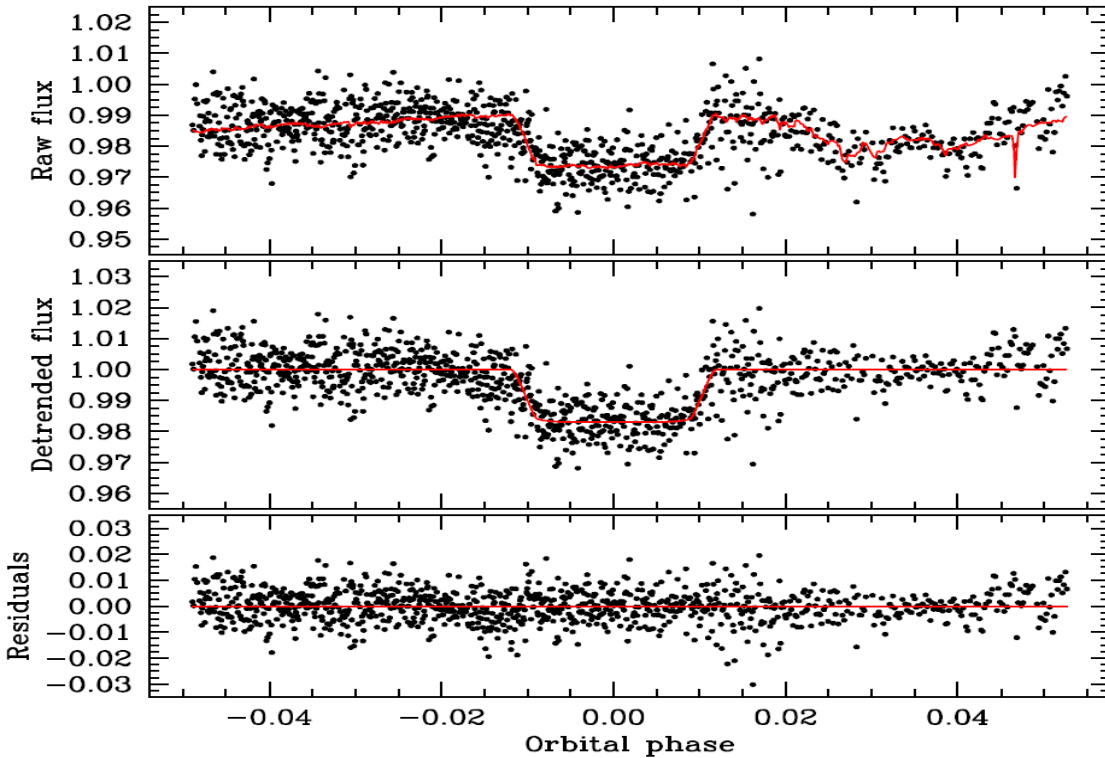


ESO



SOAR

# Our measurements - OSIRIS

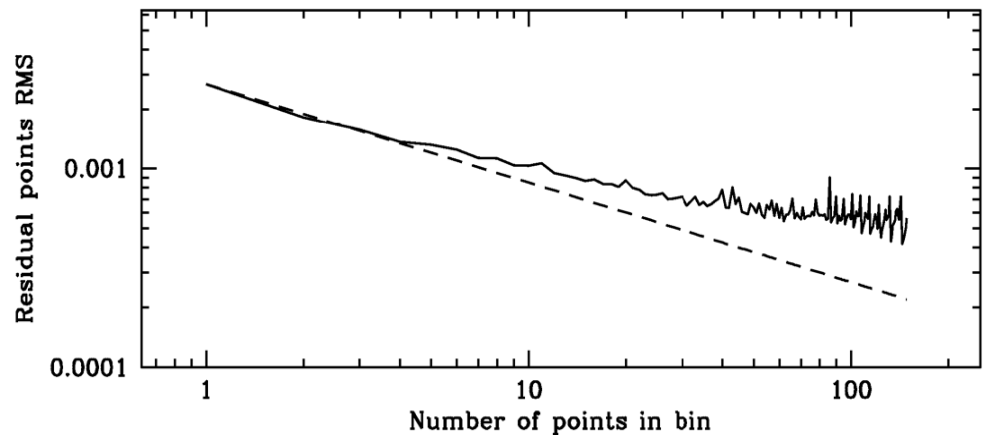
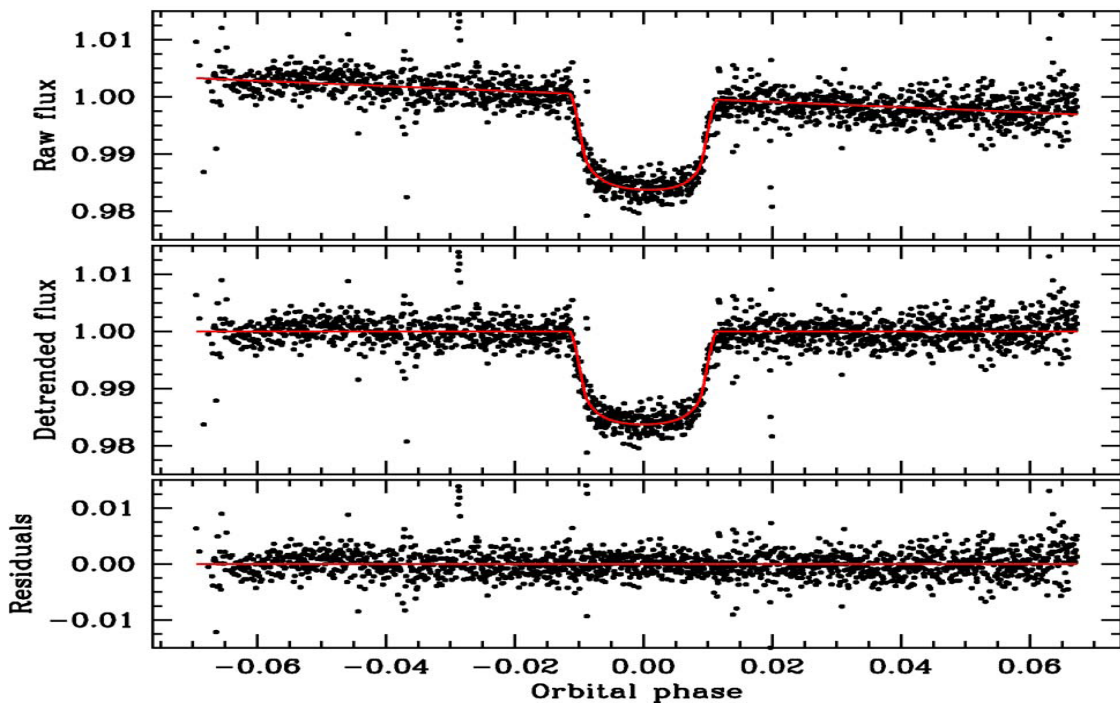


$$R_p/R_s = 0.118101 (-)0.002766(+)0.002562$$

Caceres et al. 2012, in prep.

MCMC code by M. Gillon and C. Caceres  
(e.g. Gillon et al. 2012; Caceres et al. 2011)

# Our measurements - SOI

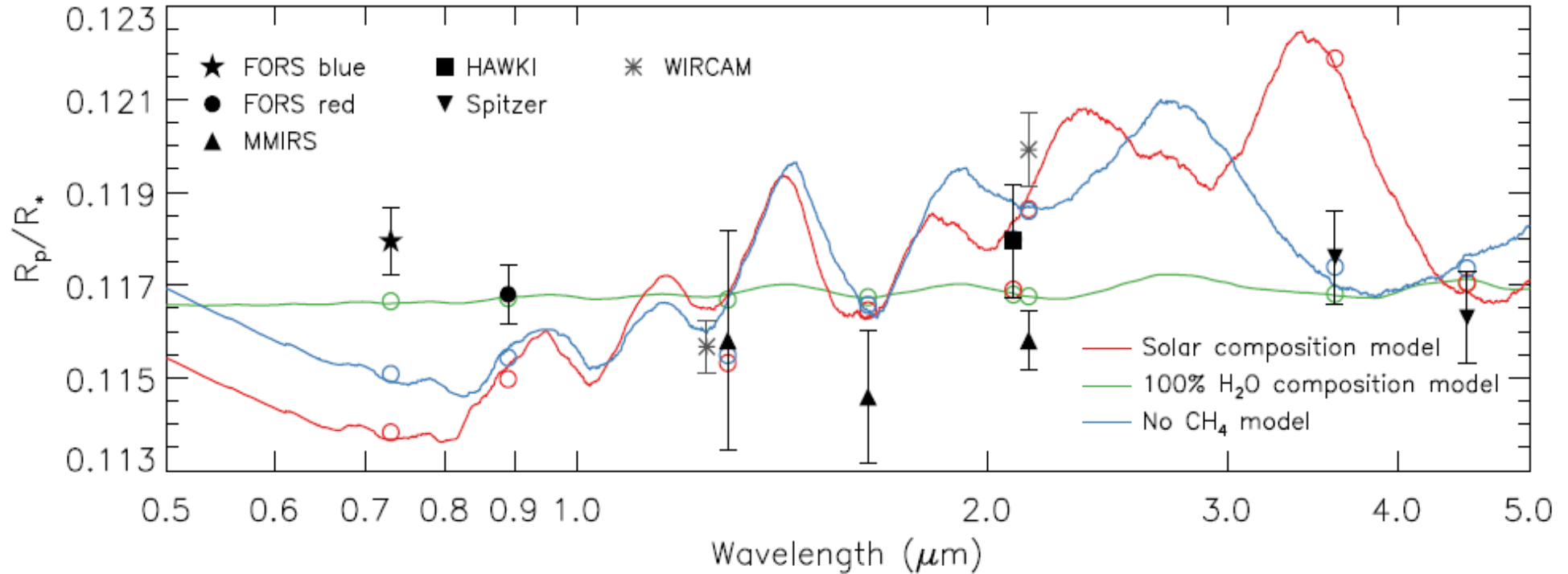


Observations performed by S. Hoyer

SOAR I-BESSEL:

$R_p/R_s = 0.117151 (-)0.001173$   
 $(+)0.001182$

# 4-m class telescopes good?



# Our results compared (photometry)

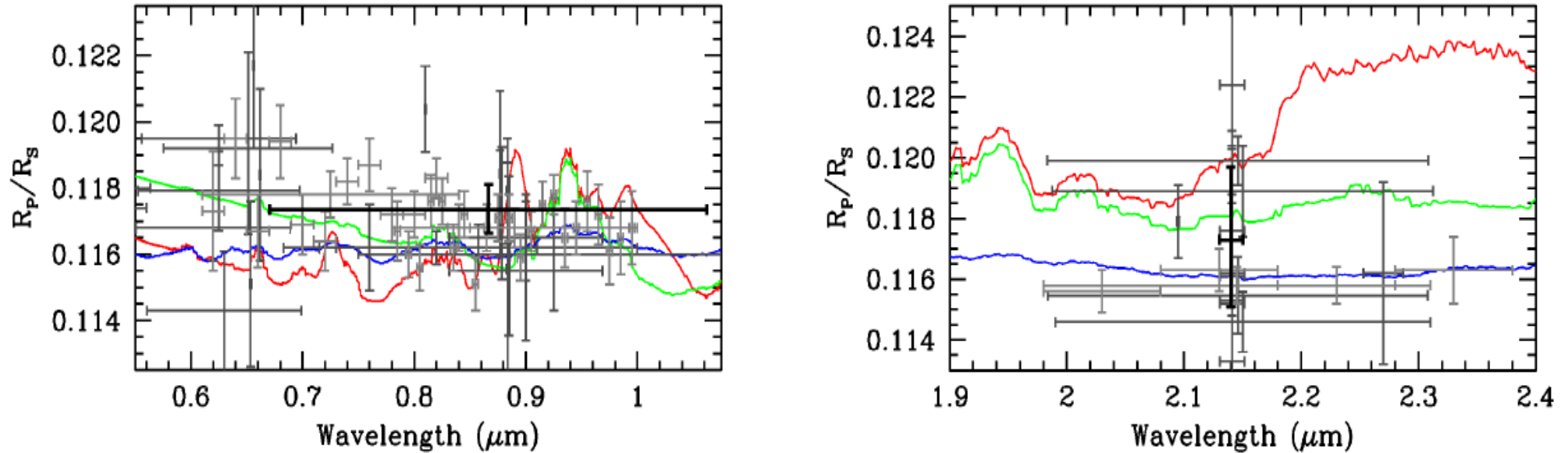
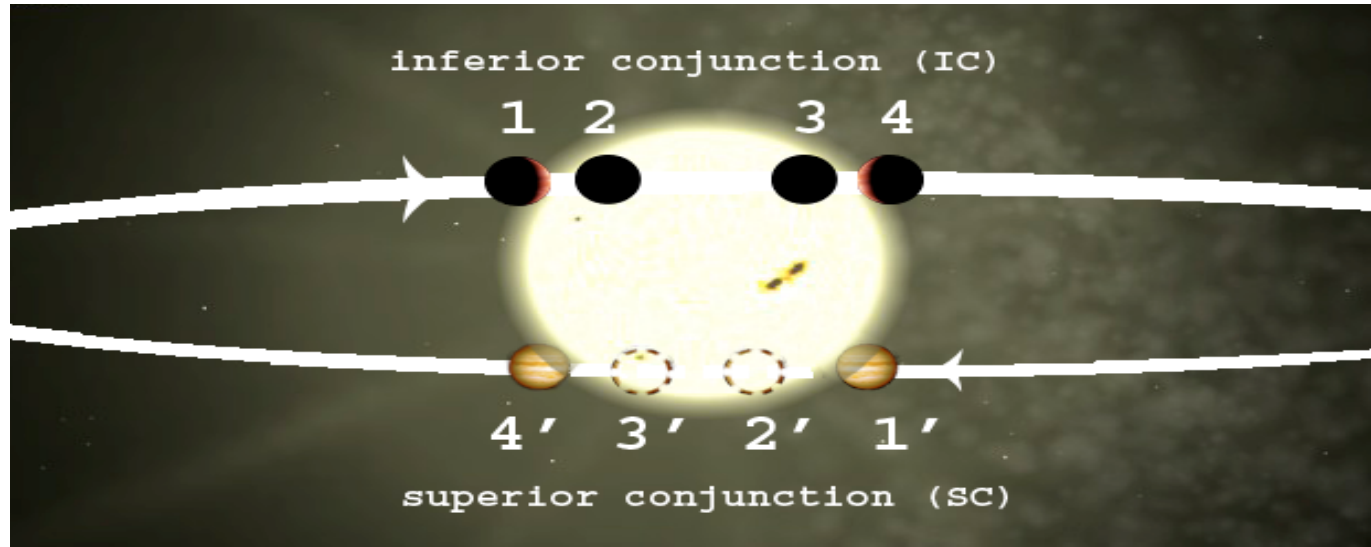


Fig. 11. *Left:* A zoom-in from Fig. 10 for the optical region around our *I*-Bessel measurements. *Right:* The *K*-band region of spectra around our 2.14  $\mu\text{m}$  observation. Our measurement points are represented by dark circles, while gray points follow the description in Fig. 10. A color version of this plot can be found in the electronic version of the paper.

# Transits and eclipses of exoplanets



From Angerhausen et al. 2008

## Emission from the planet

- Thermal radiation from the planet in IR

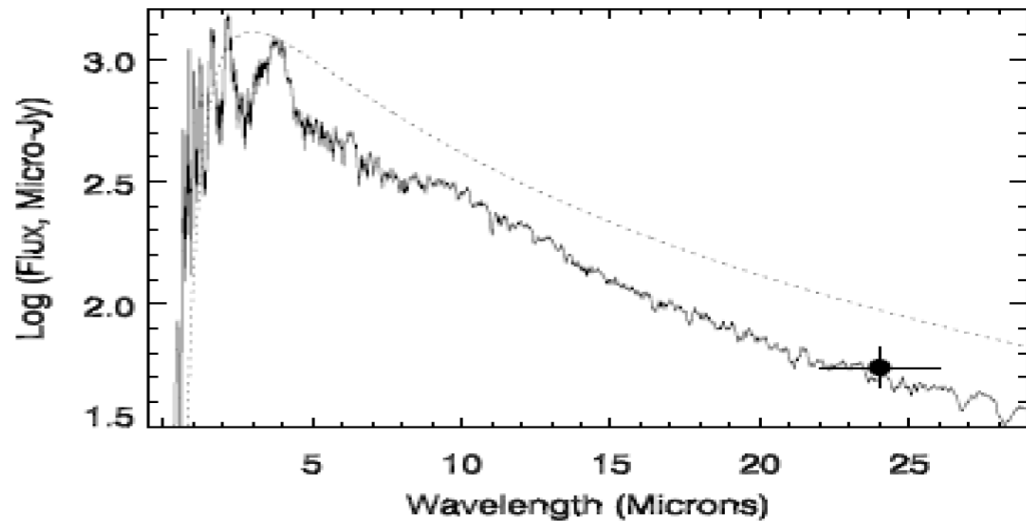
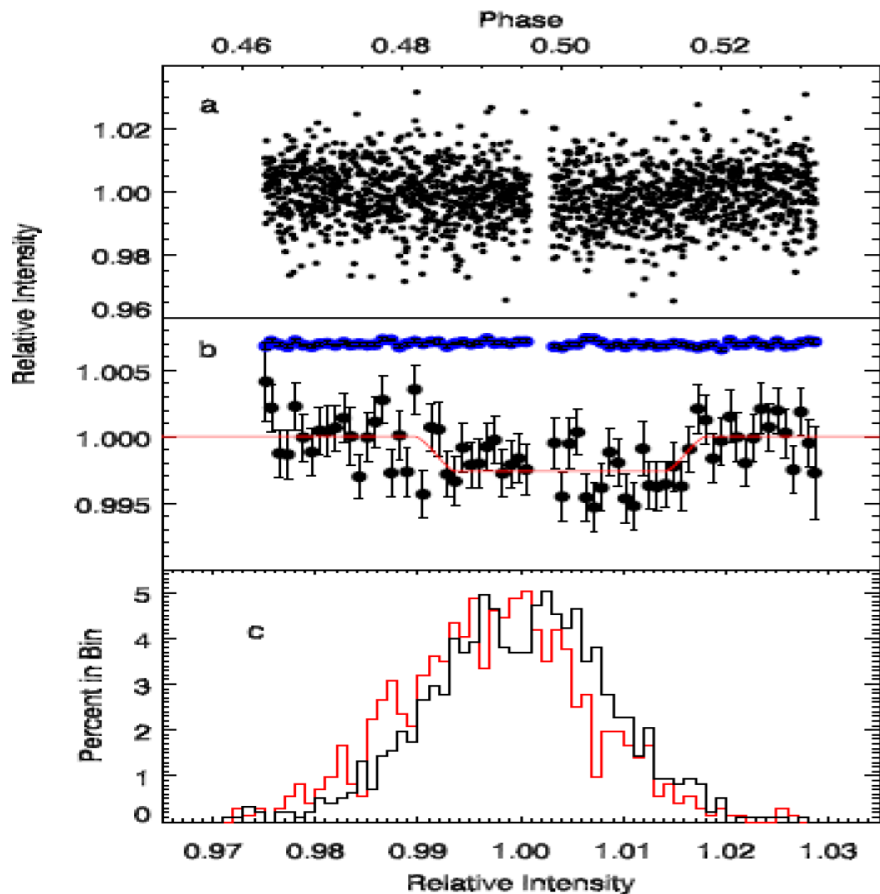
$$\text{Signal} = T_{\text{planet}}/T_{\text{star}}(R_{\text{planet}}/R_{\text{star}})^2$$

- Very shallow signals – few mmags
- Measuring directly the (missing) emission of the reflected light from the planet
- Result is an emission spectrum
- Due to geometry, not all planets hide behind the host star

# Secondary eclipse photometry HD209458b

Měření: Spitzer 24 $\mu$ m

$T_{\text{pl}}$ : ca 1130K



Deming et al. 2005 Nature

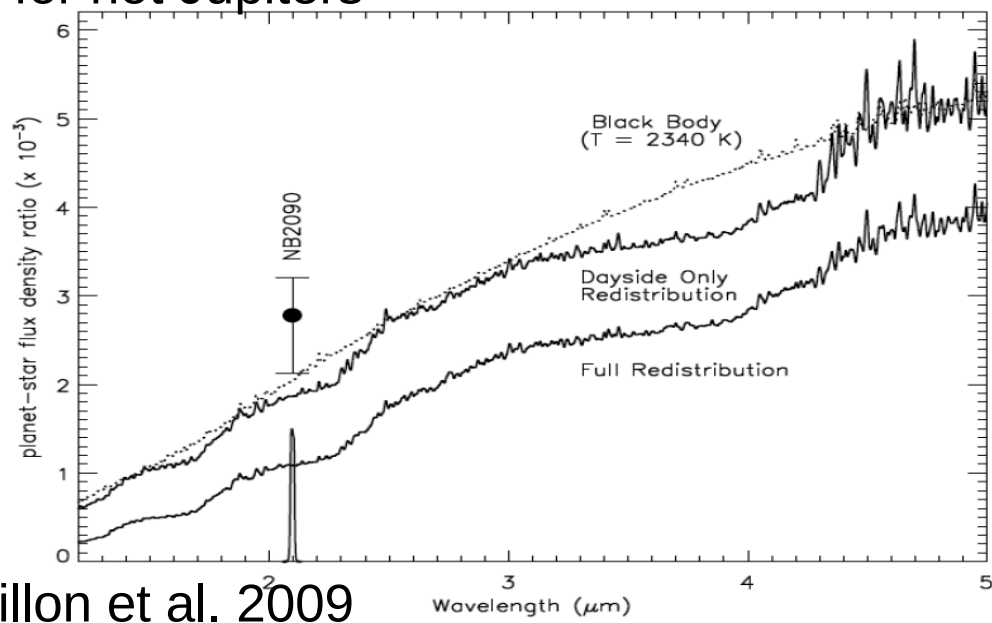
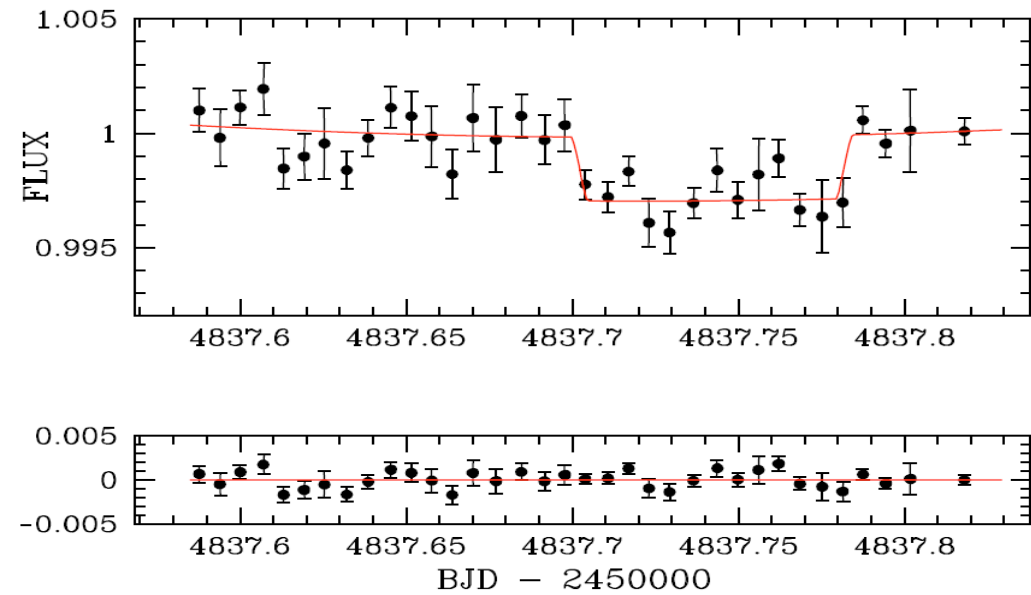


# Secondary eclipse photometry from the ground

- Thermal radiation from the planet in IR

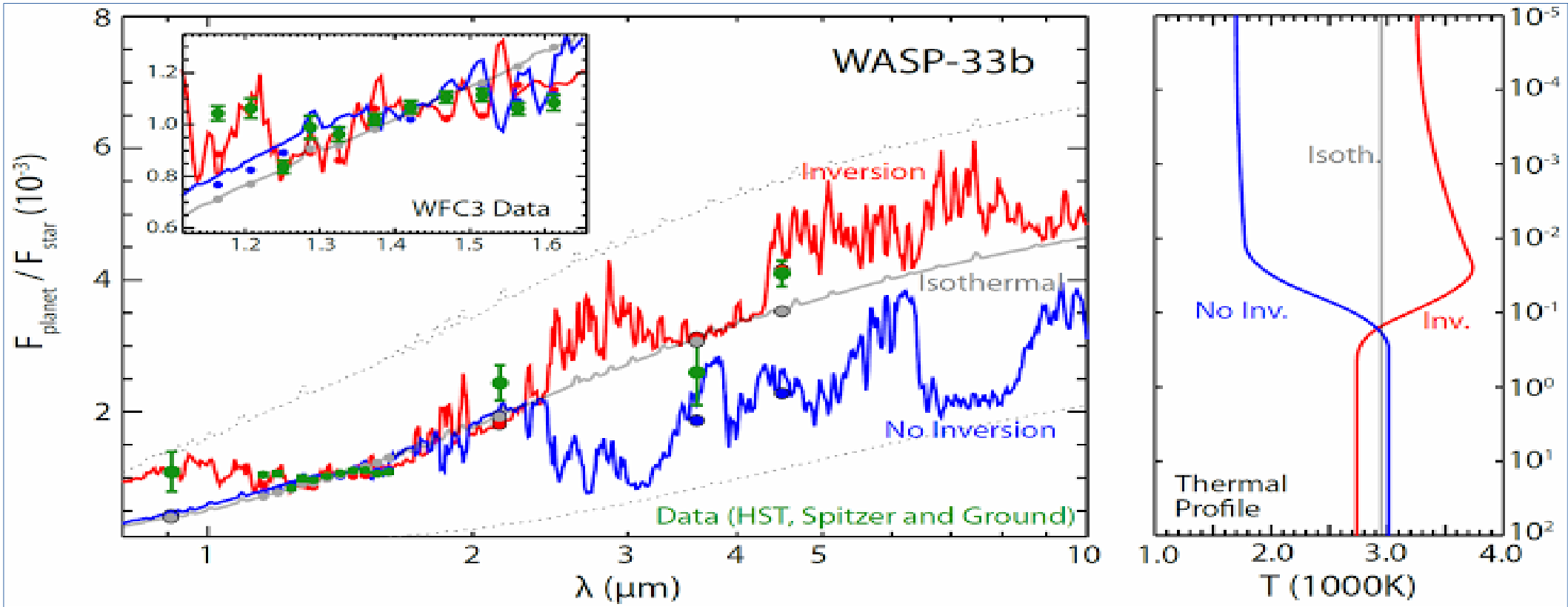
$$\text{Signal} = T_{\text{planet}}/T_{\text{star}} (R_{\text{planet}}/R_{\text{star}})^2$$

Typically few mmags for hot Jupiters



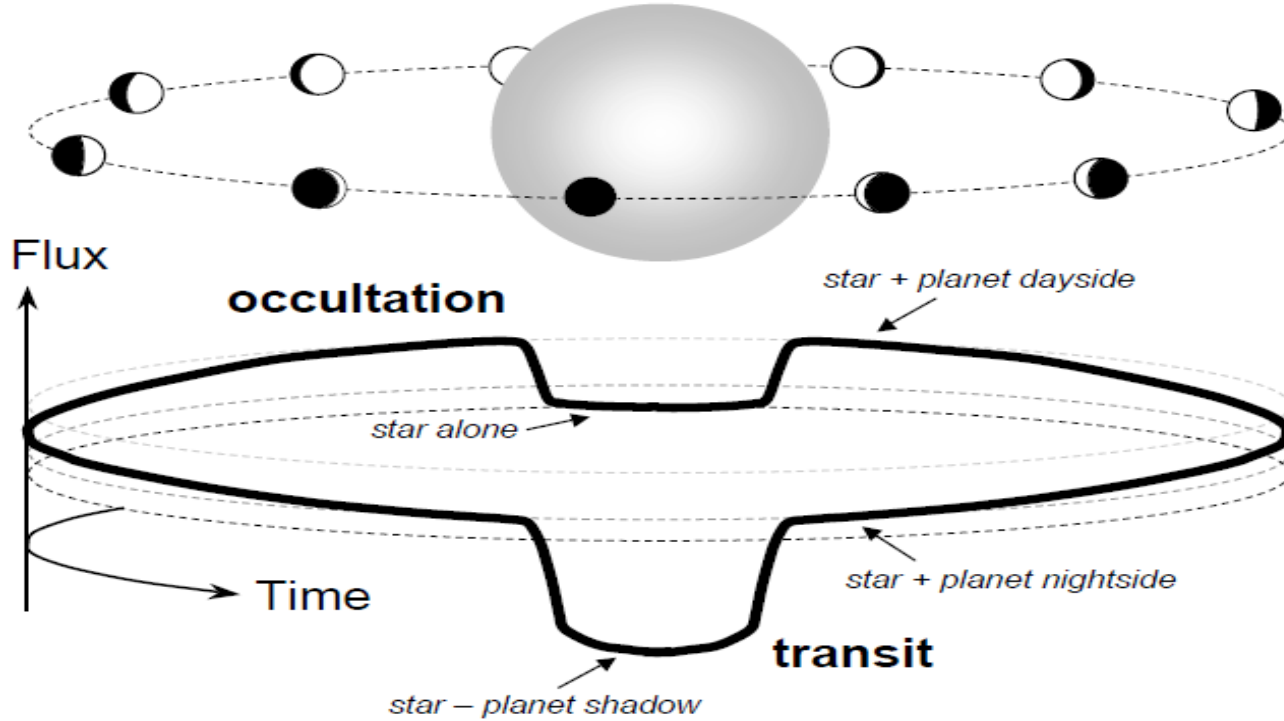
Gillon et al. 2009

# TiO species absorbing the stellar heat?



# Weather on exoplanets

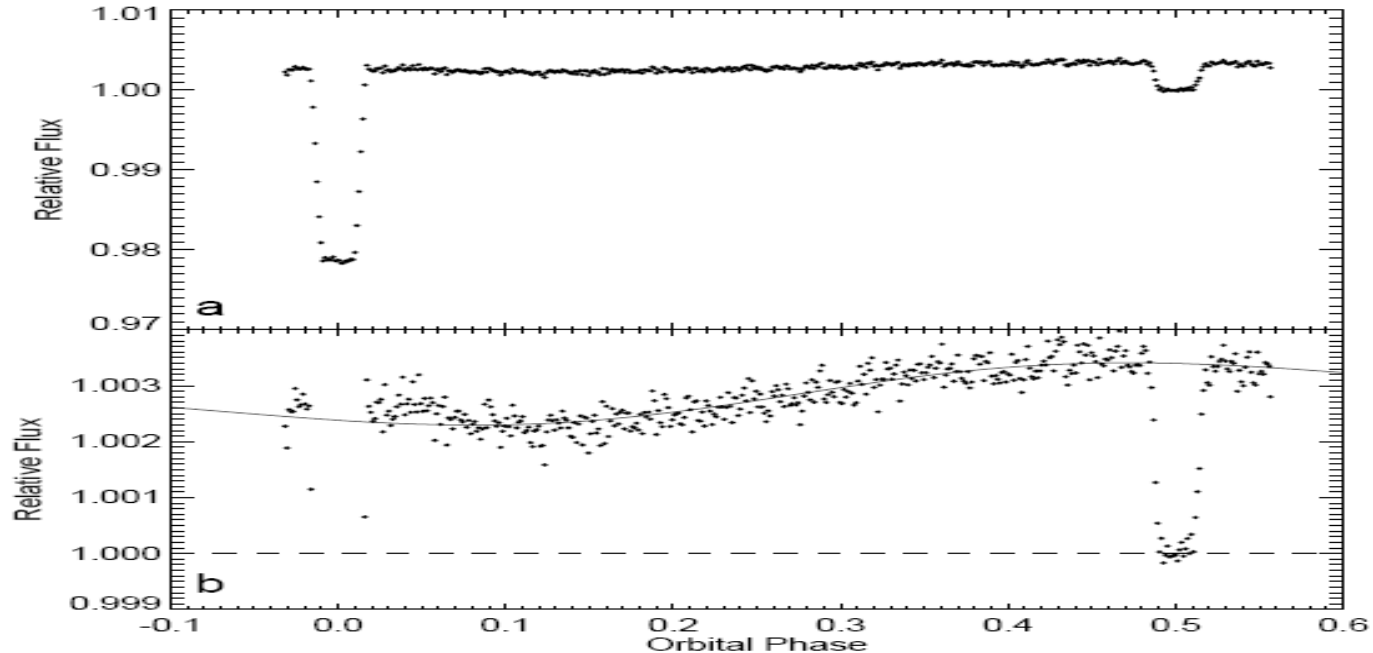
# Eclipses/transits



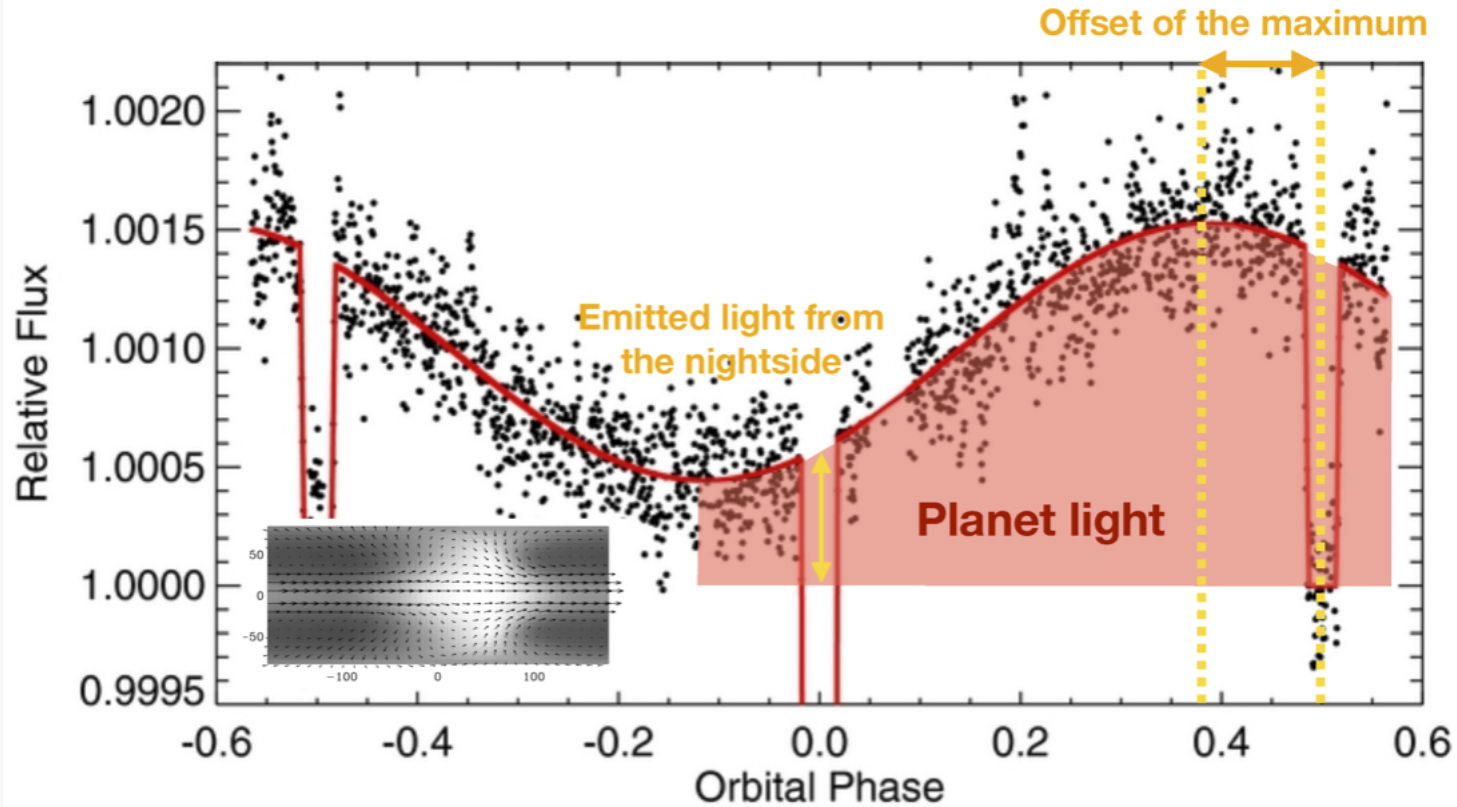
From Winn, 2010, <http://arxiv.org/pdf/1001.2010v5.pdf>

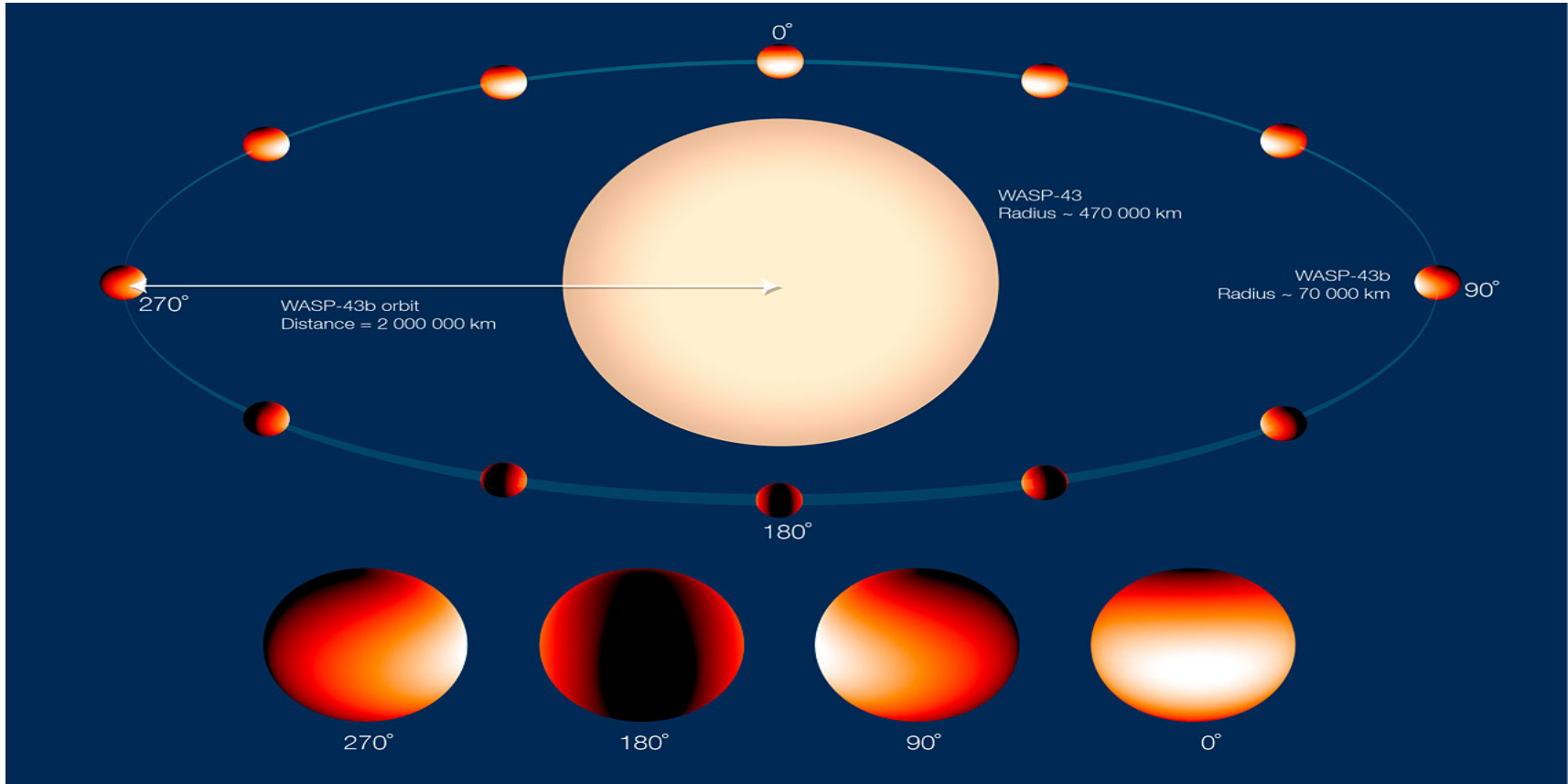
# Variation due to day/night cycle

- Near to mid IR with SPITZER (now no more possible)

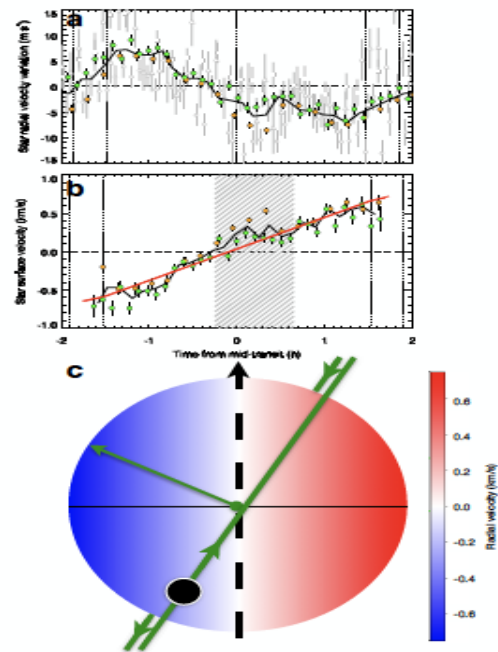
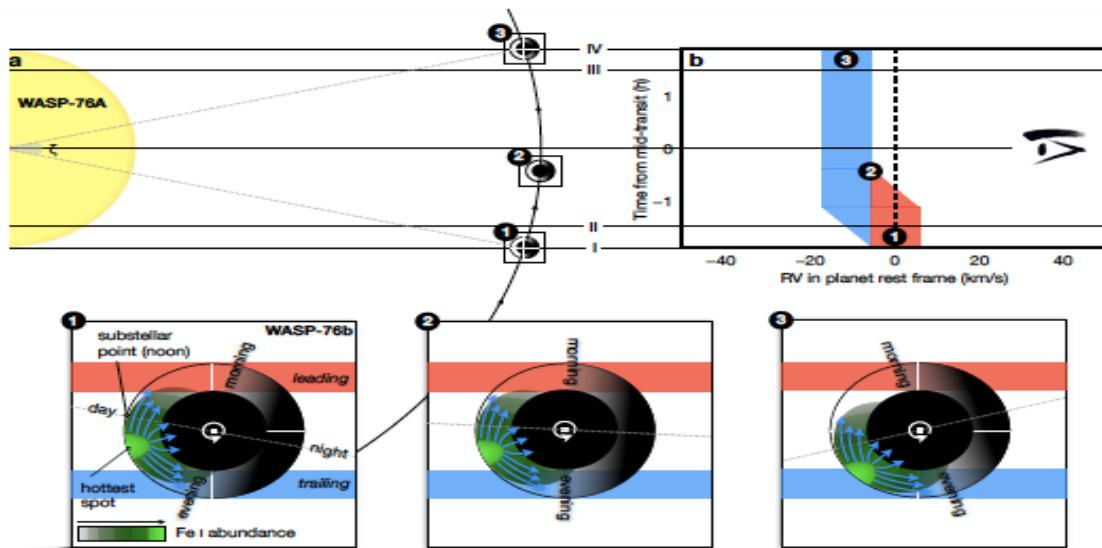


# Strong winds on HD209458b



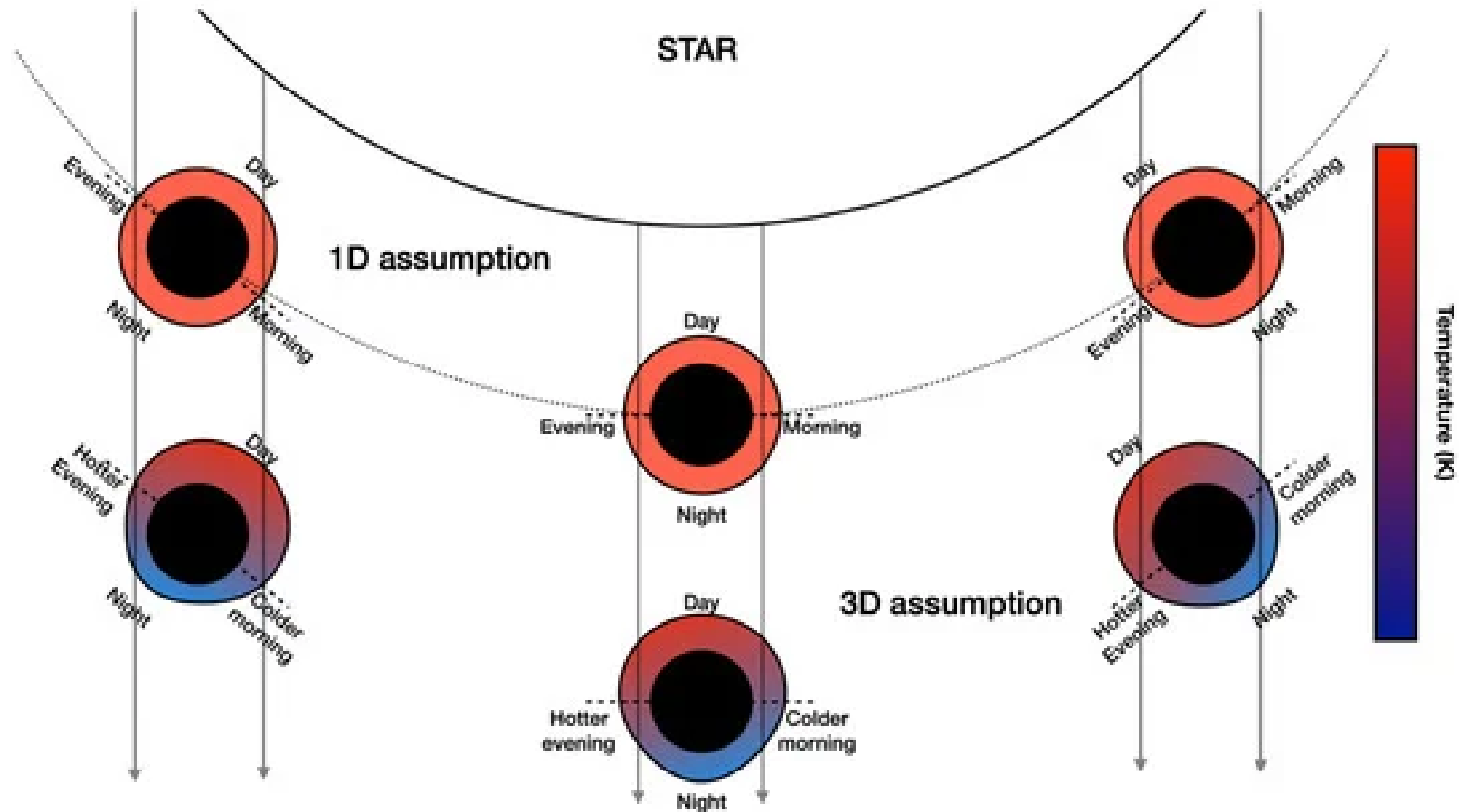


# Raining iron?





# 1D or 3D model?



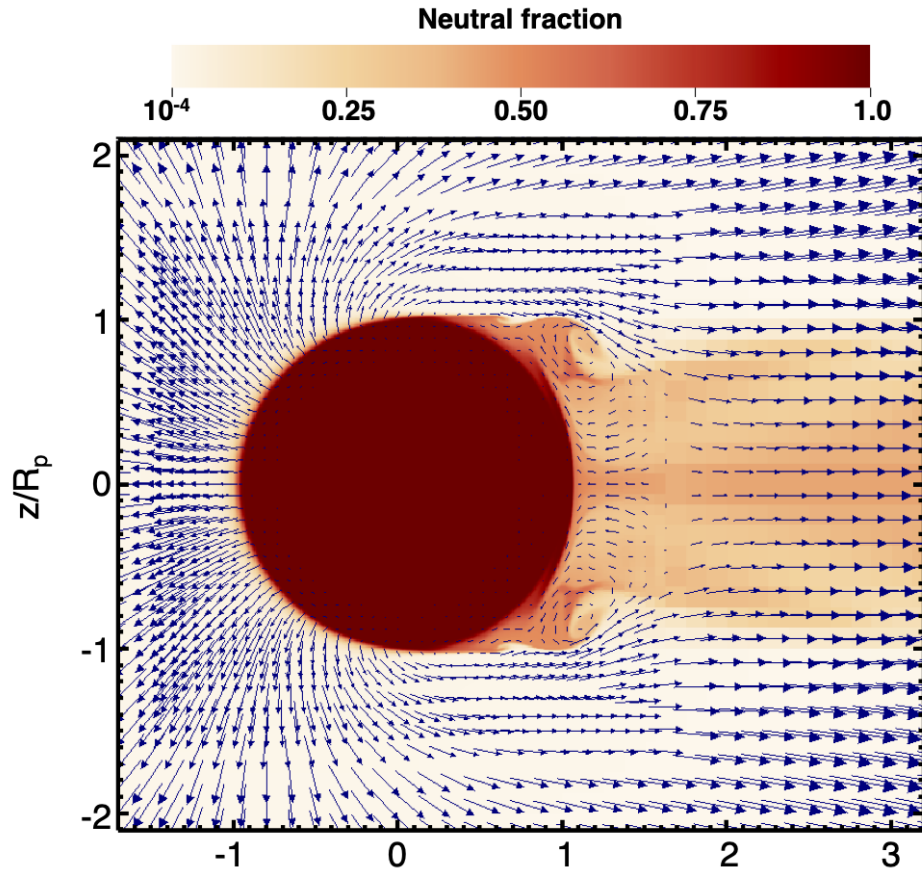
Various regions probed considering 1D or 3D assumption for the atmosphere, with large temperature and scale height differences

# Probed atmospheres

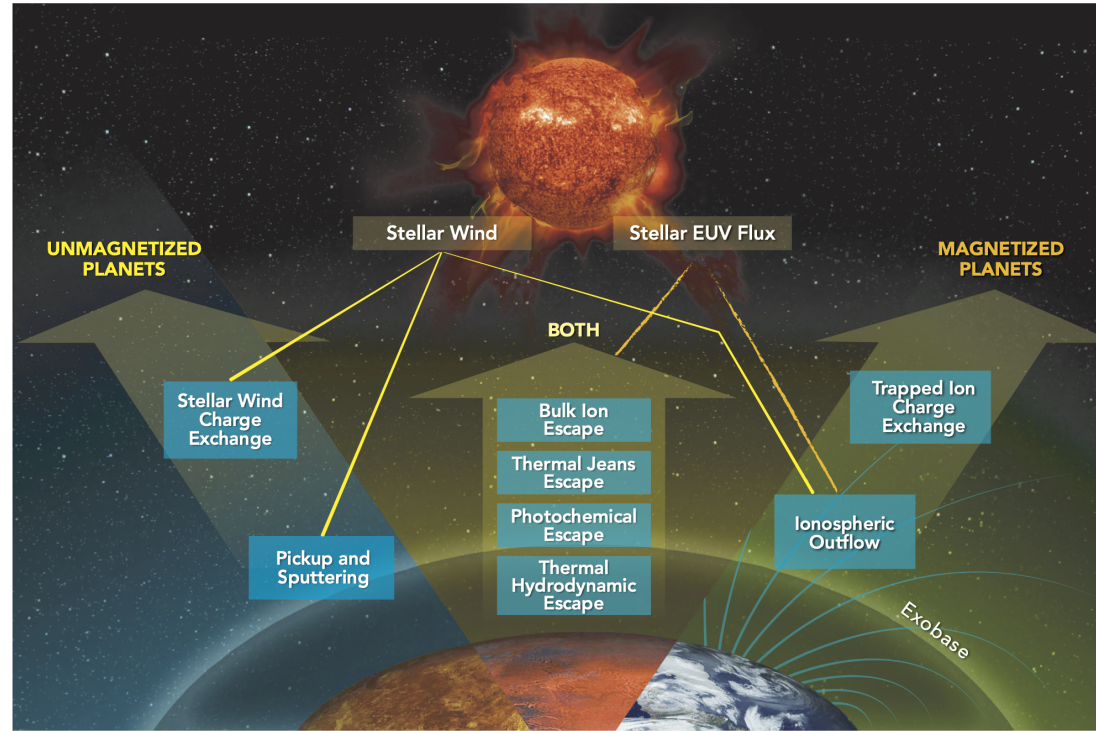
<https://arxiv.org/pdf/2205.04100.pdf>

Guilliot et al. 2022

# Evaporating atmospheres



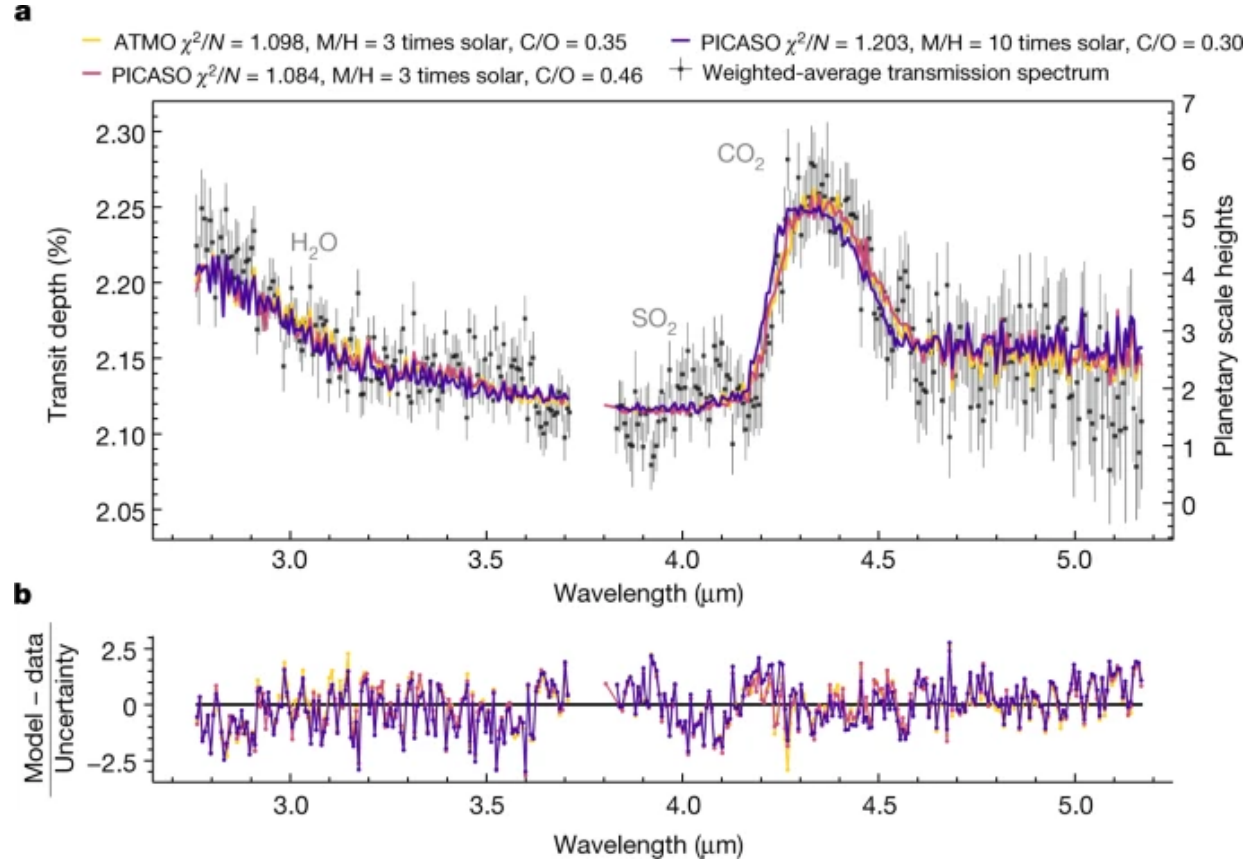
<https://arxiv.org/pdf/2003.03231.pdf>



Owen J. E. - <https://arxiv.org/pdf/1807.07609.pdf>

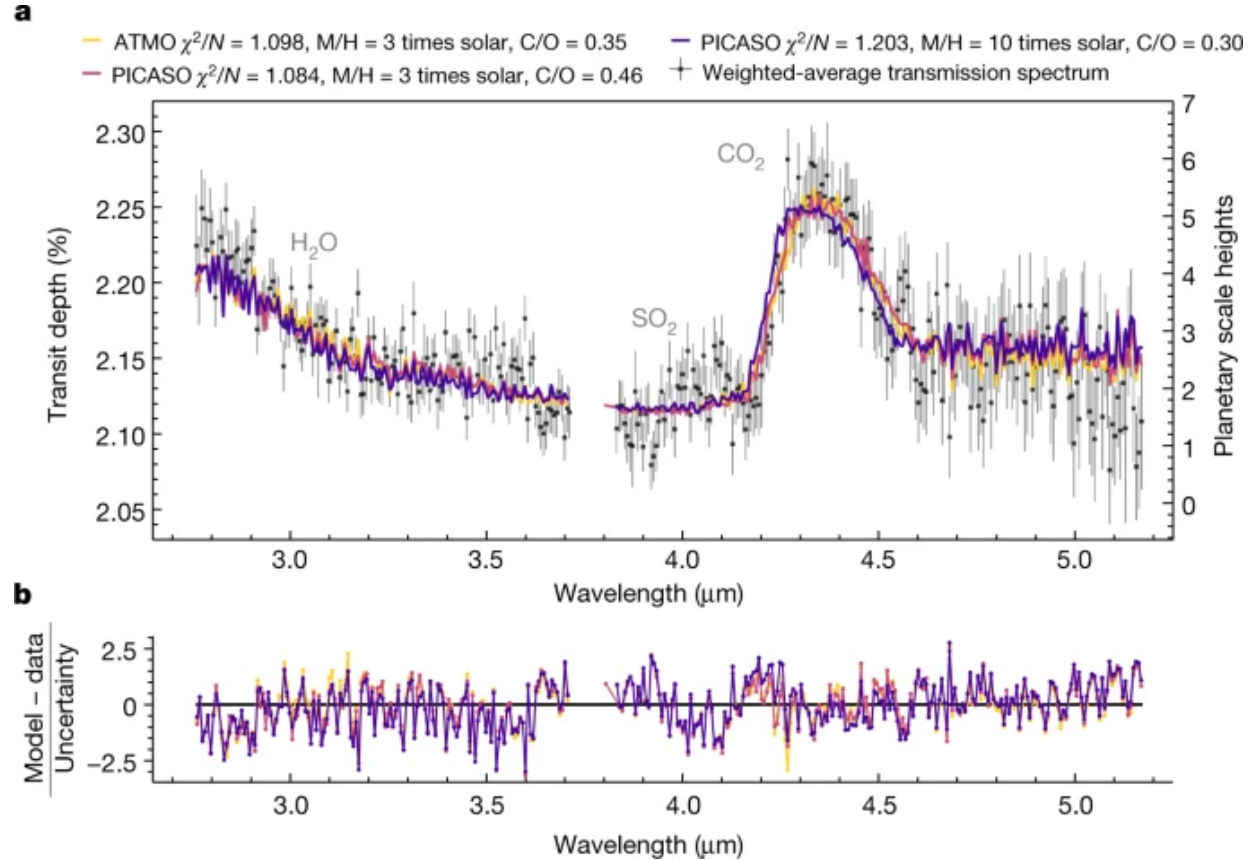
# What do we have now?

- JWST – WASP-39b
- NIRSpec G395H
- Transmission spectroscopy

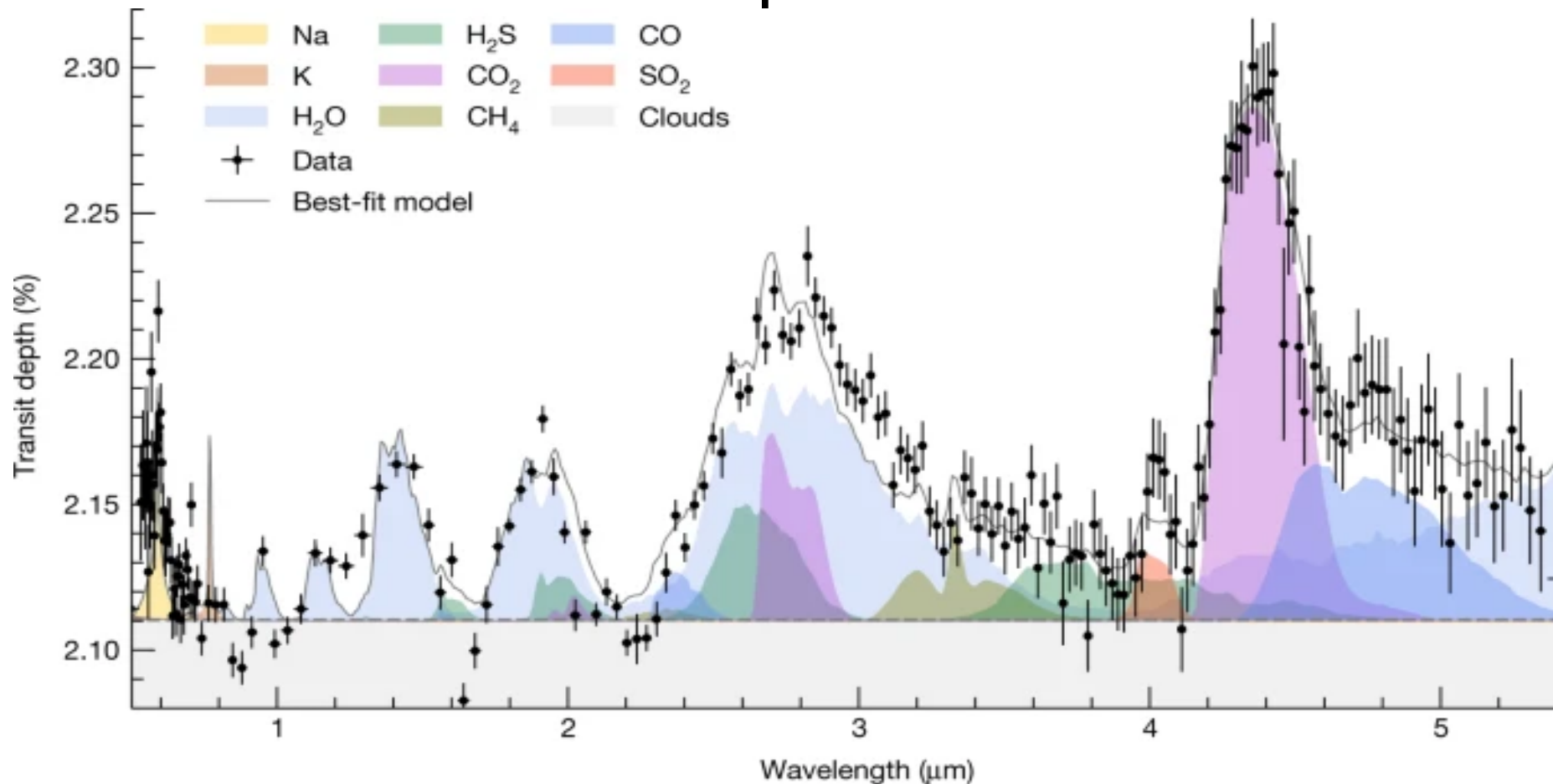


# What do we have now?

- JWST – WASP-39b
- NIRSpec G395H
- Transmission spectroscopy



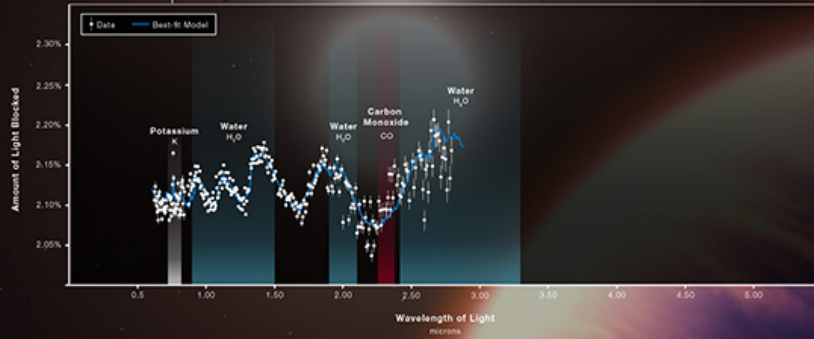
# Wasp-39b



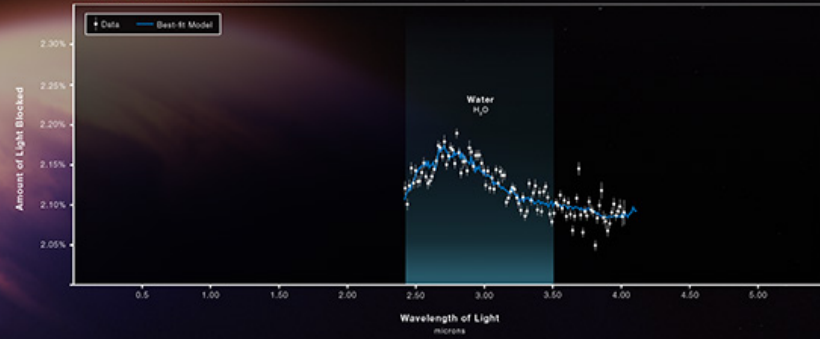


# HOT GAS GIANT EXOPLANET WASP-39 b ATMOSPHERE COMPOSITION

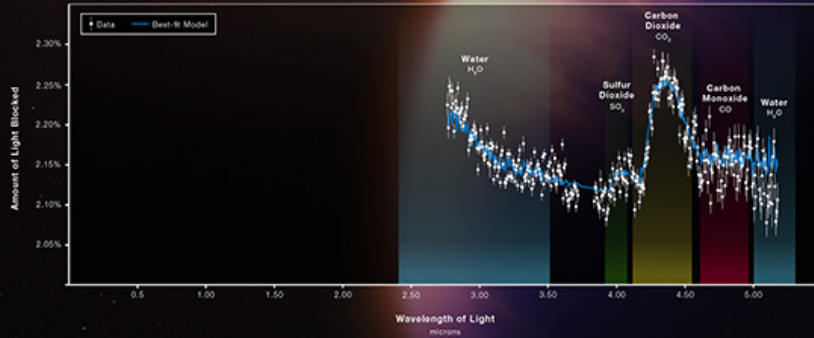
NIRISS | Single Object Slitless Spectroscopy



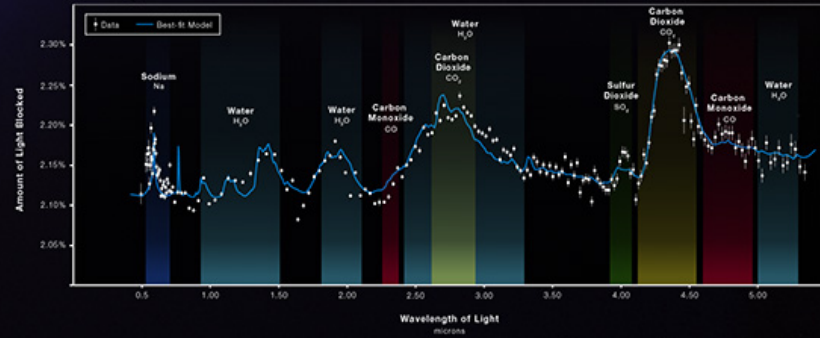
NIRCam F322W2



NIRSpec G395H



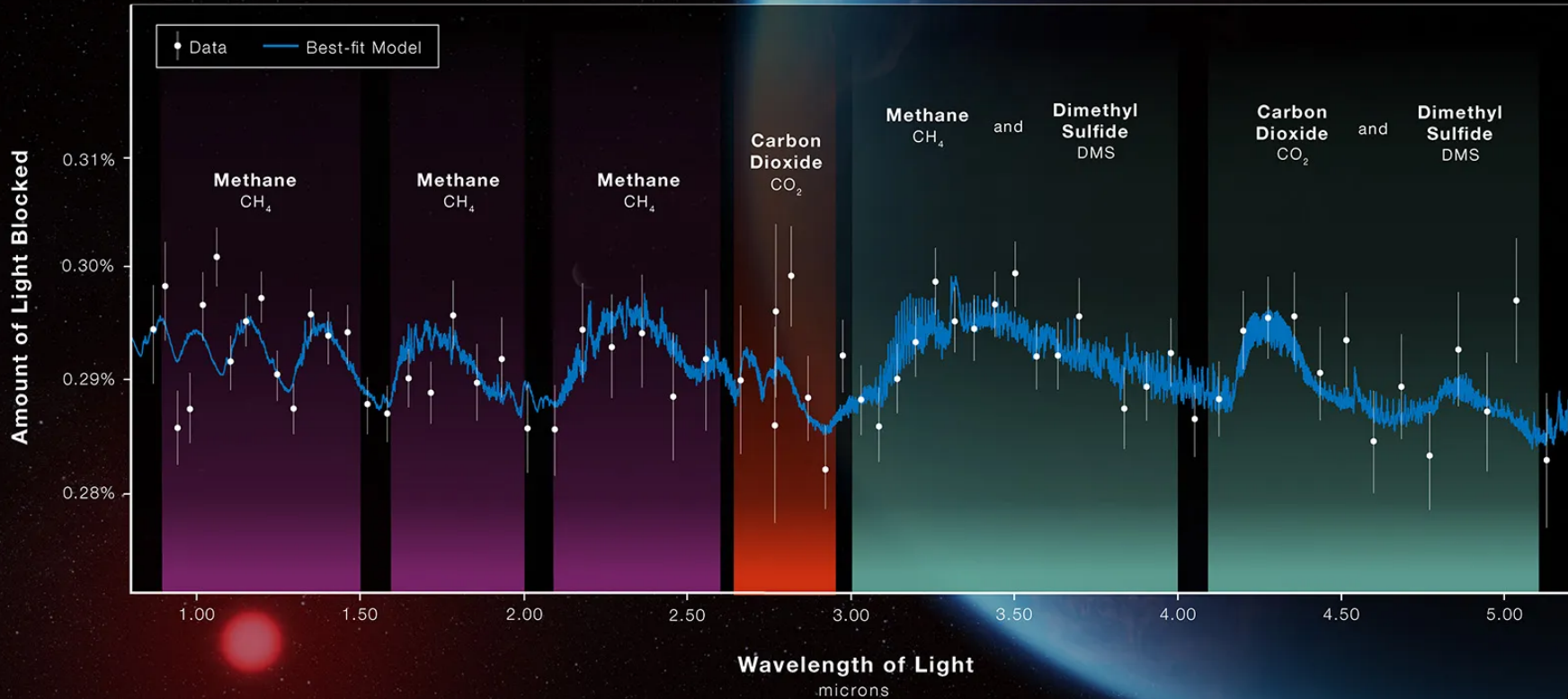
NIRSpec PRISM



**WEBB**  
SPACE TELESCOPE

# ATMOSPHERE COMPOSITION

NIRISS and NIRSpec (G395H)





# ARIEL

**Elliptical primary mirror:** 1.1 x 0.7 metres

**Mission lifetime:** at least 4 years in orbit

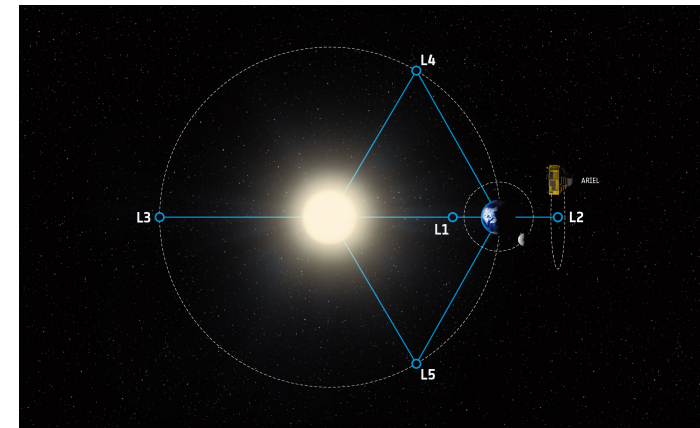
**Payload mass / launch mass:** ~500 kg / ~ 1500kg

**Instrumentation:** 3 photometric channels and 3 spectrometers covering continuously from 0.5 to 7.8 microns in wavelength

**Launch date:** 2029

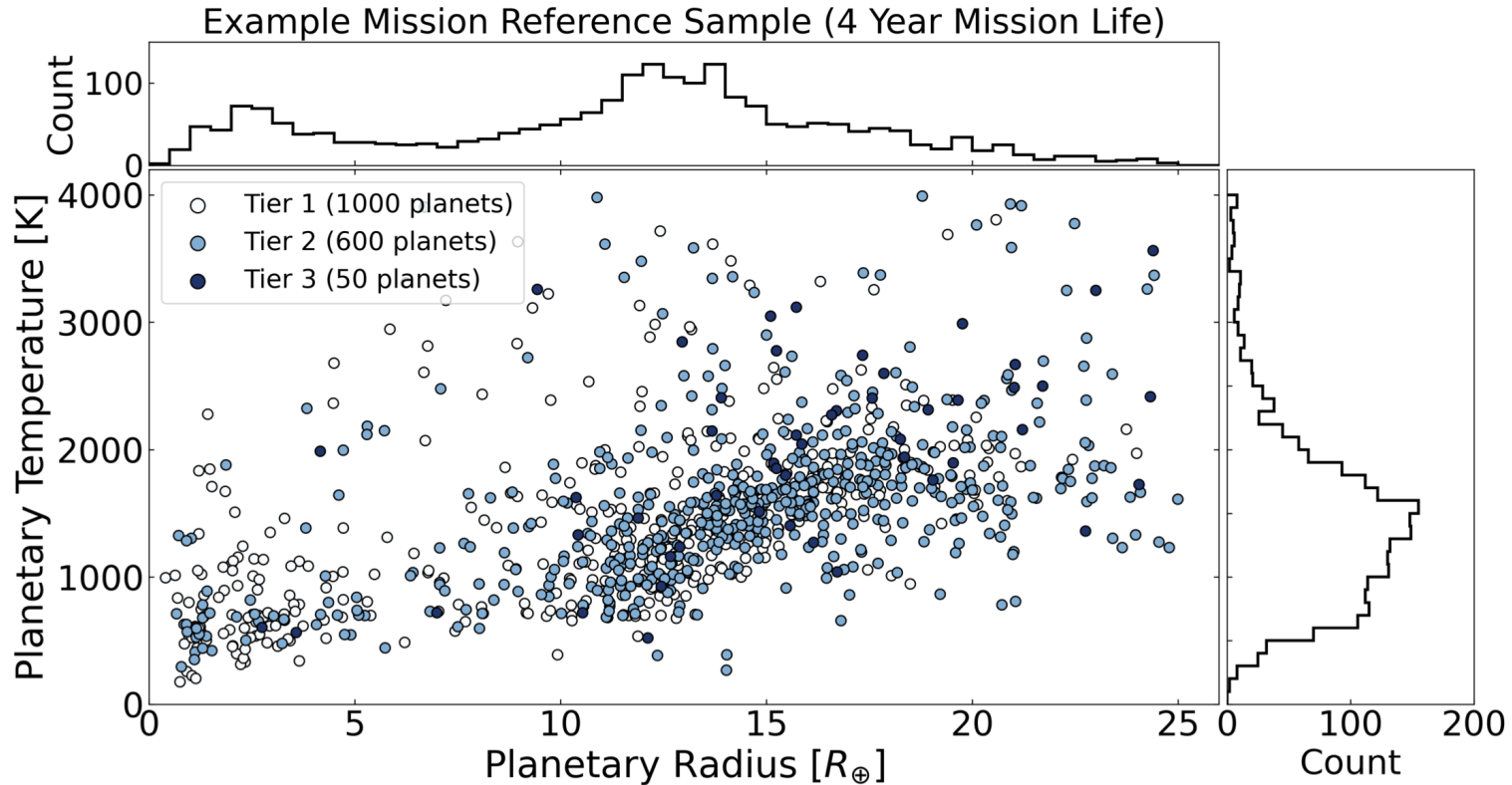
**Destination:** Sun – Earth Lagrange Point 2 (L2)

**Launch vehicle:** Ariane 6-2. Launch shared with Comet Interceptor.



# ARIEL sample and goals

- 1000 atmospheres characterisation target



Thank you