Exoplanets

Lecture 12
MFF UK
10.12.2021
(from Chile, La Silla)

Exoatmospheres

Outline

- Recap exoatmospheres
- Detection methods
  - spectroscopic
  - spectrophotometric
- Weather on exoplanets
- Challenges of precise spectroscopy/photometry (J. Subjak input)

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….

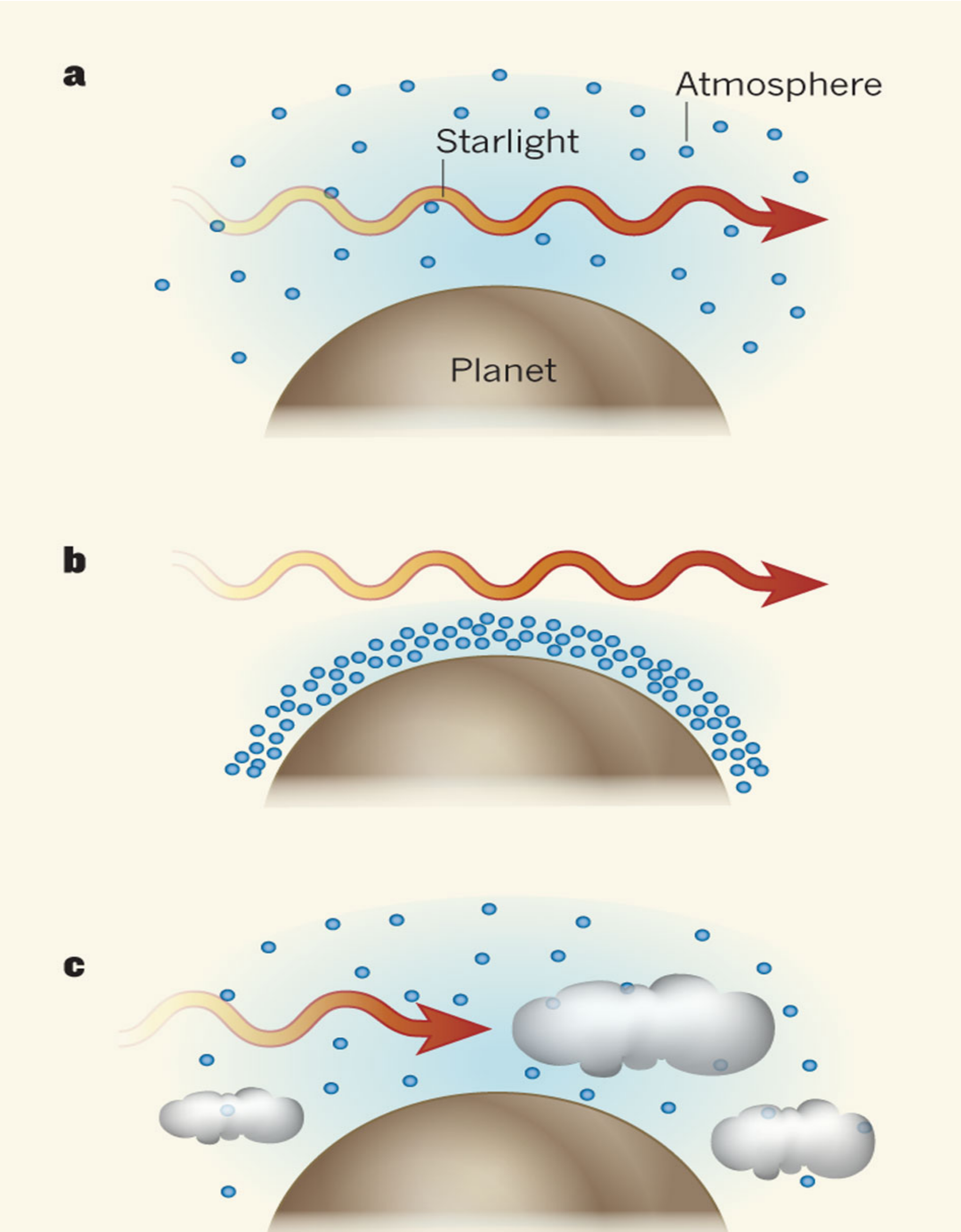
Scale height

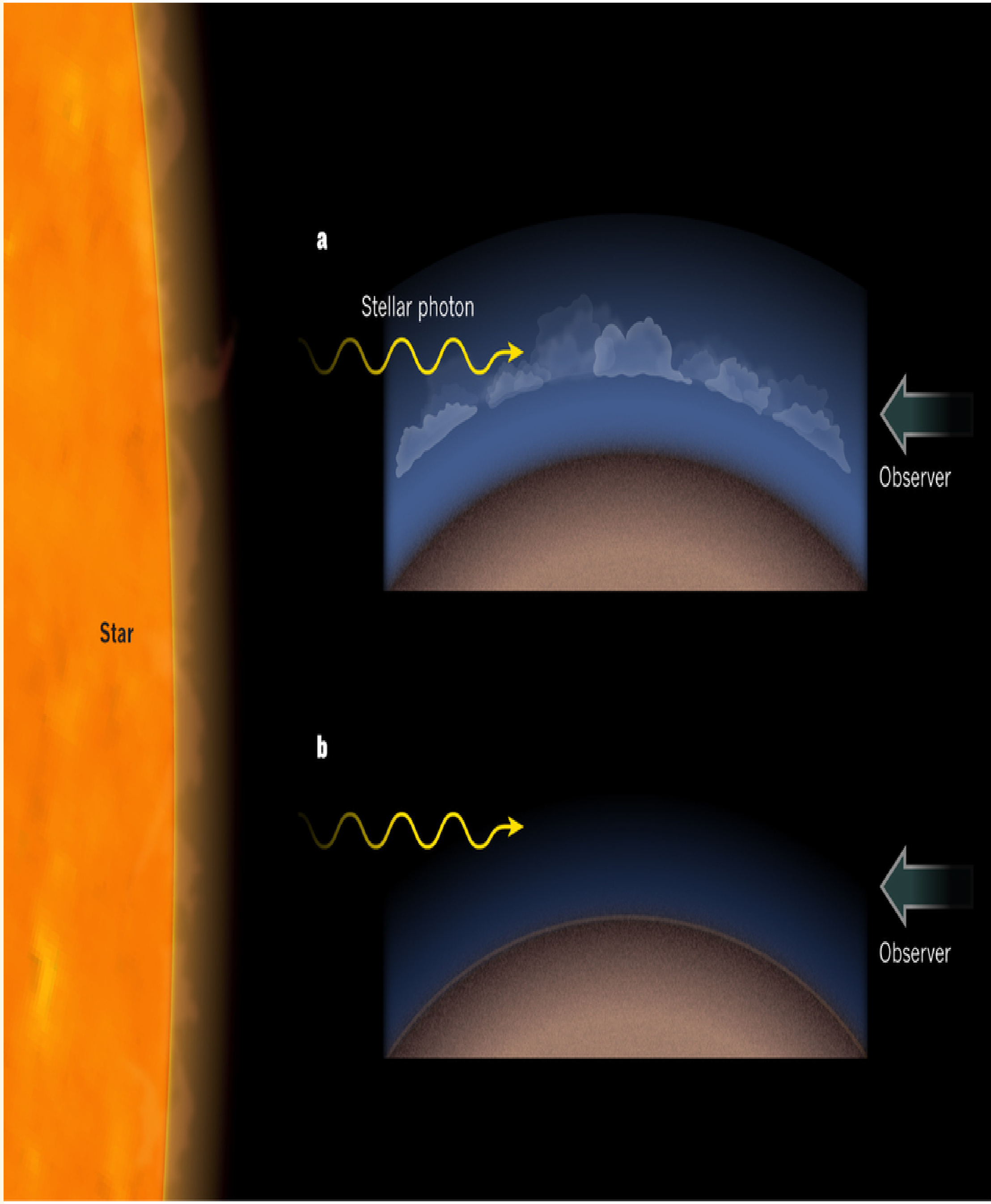
$$H = \frac{kT}{Mg}$$

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



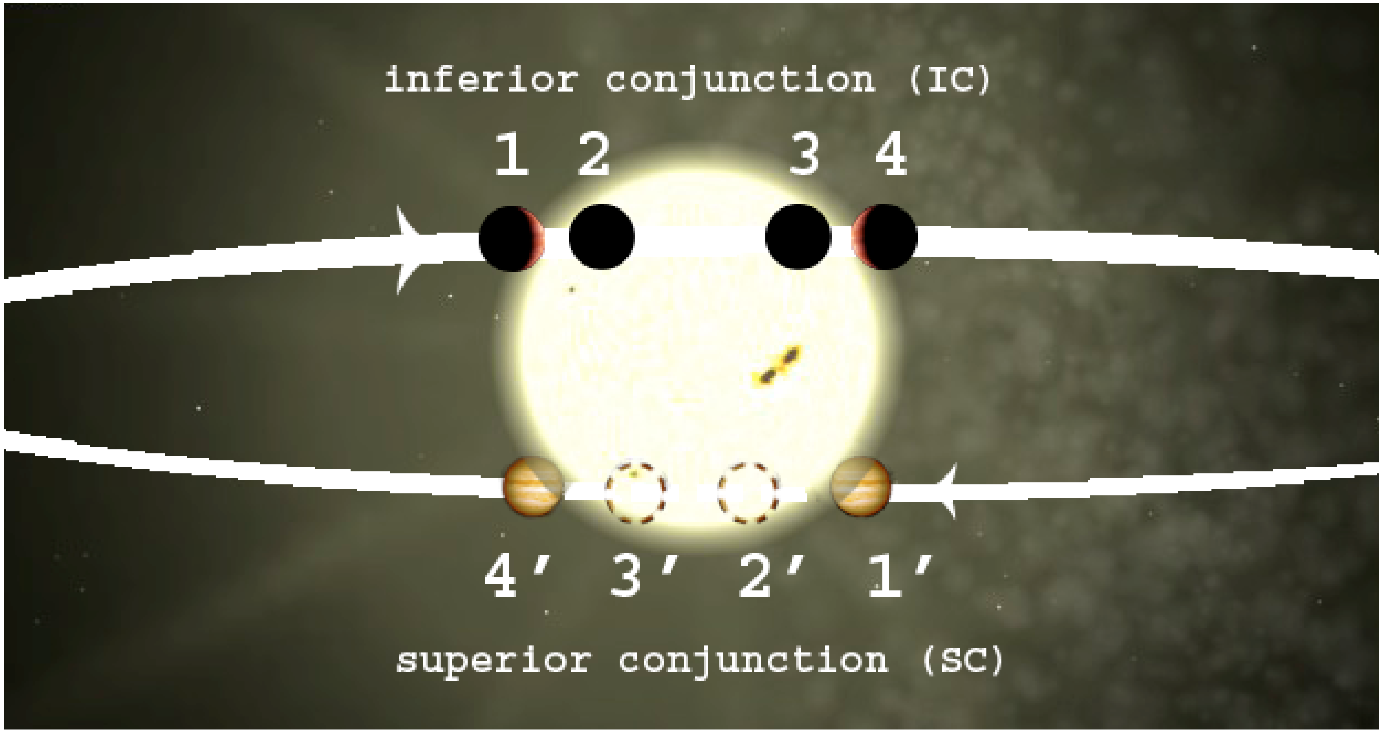


Deming, Nature, 468, 636–637

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

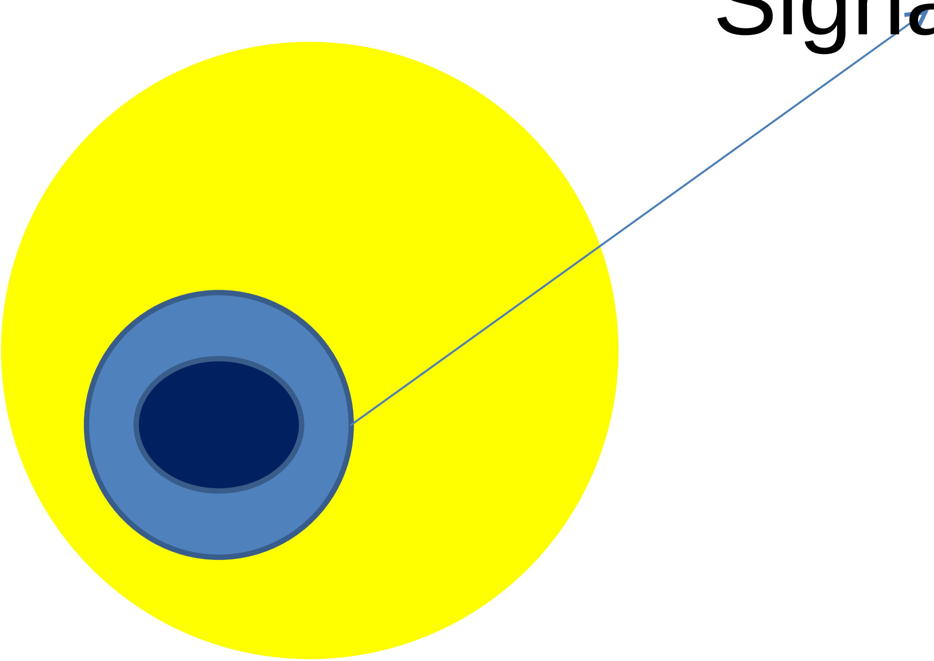


From Angerhausen et al. 2008

Transit spectroscopy, the principle

Transit spectroscopy = transmission spectroscopy

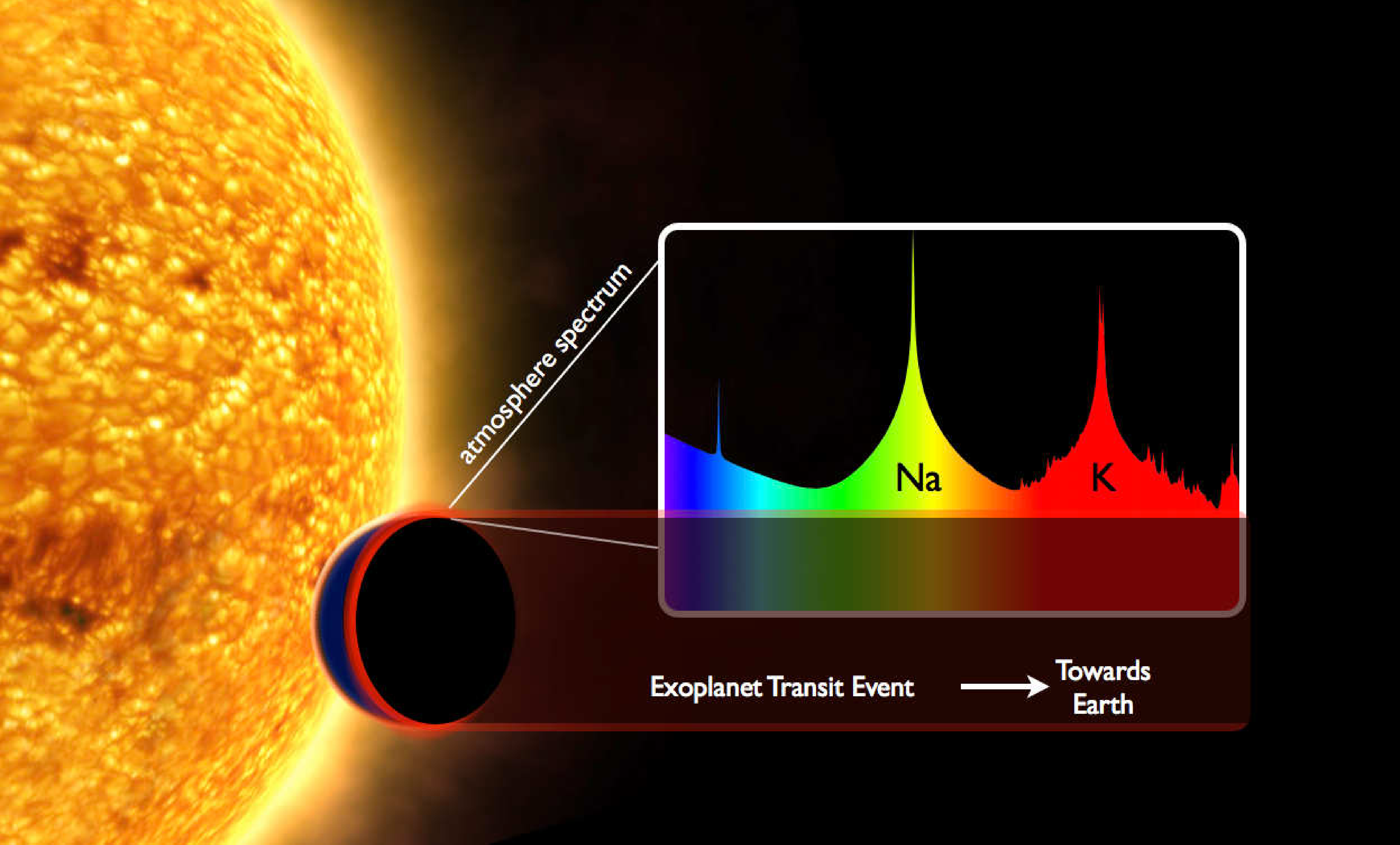
$$\text{Signal} = \text{Annulus}/R^2_{star}$$



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

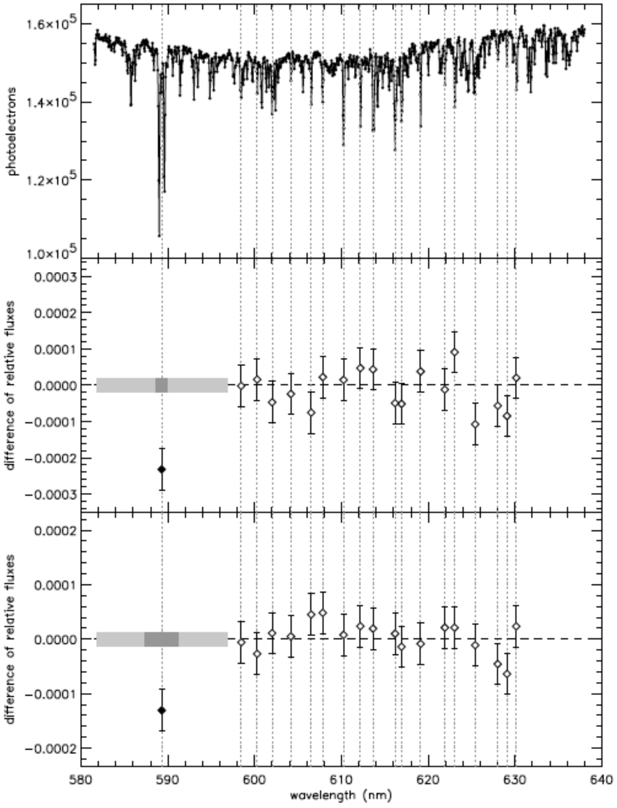
Smaller star & larger planet = better chance to see something

Transmission spectroscopy high spectral resolution



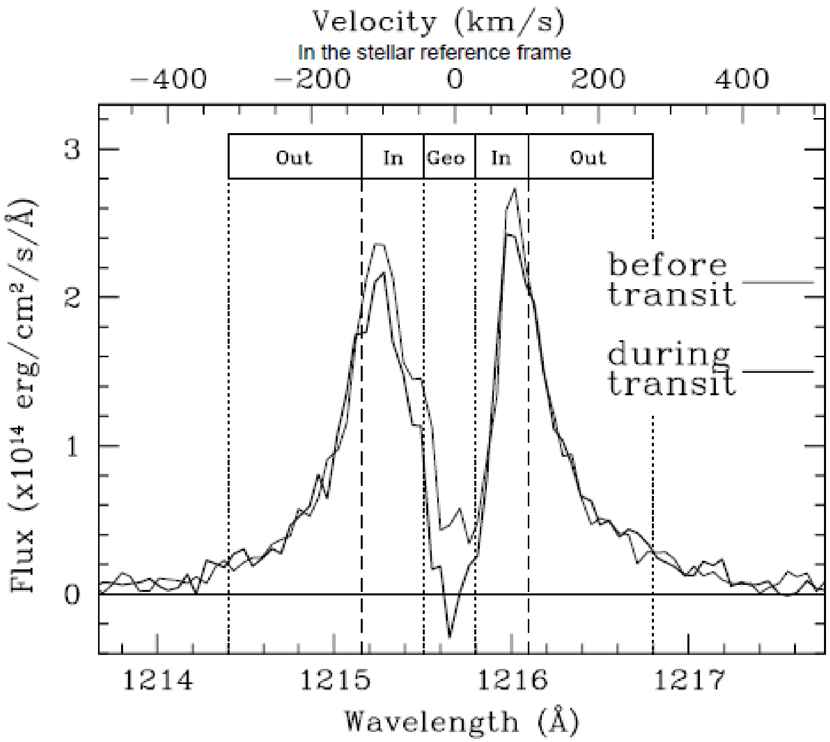
HD209458 b

- 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 (H20, CO2, TiO, CH4)
- First observations performed in 2002 with HST
  - HD209458b



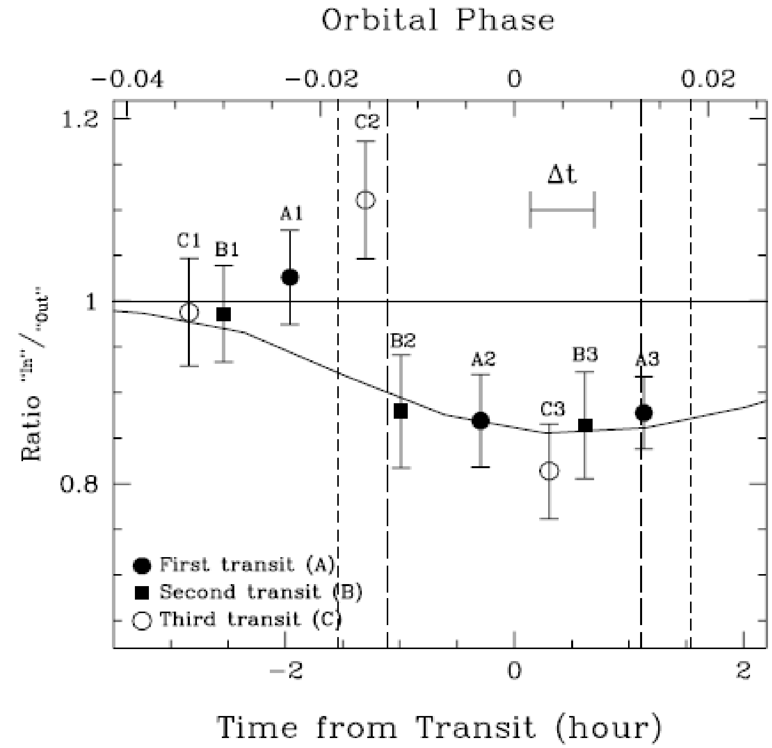


Figure 1. **Left:** The Lyman α stellar line as observed by Vidal–Madjar et al. (2003). The averaged profile observed during transit (thick line) presents a reduced flux when compared to the pre–transit profile (thin line). The region named "Geo" corresponds to the region where the geocoronal Lyman α 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 ratio modeled through a particle simulation (see Fig. 3).

Vidal-Madjar et al. http://arxiv.org/pdf/astro-ph/0312382v1.pdf

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

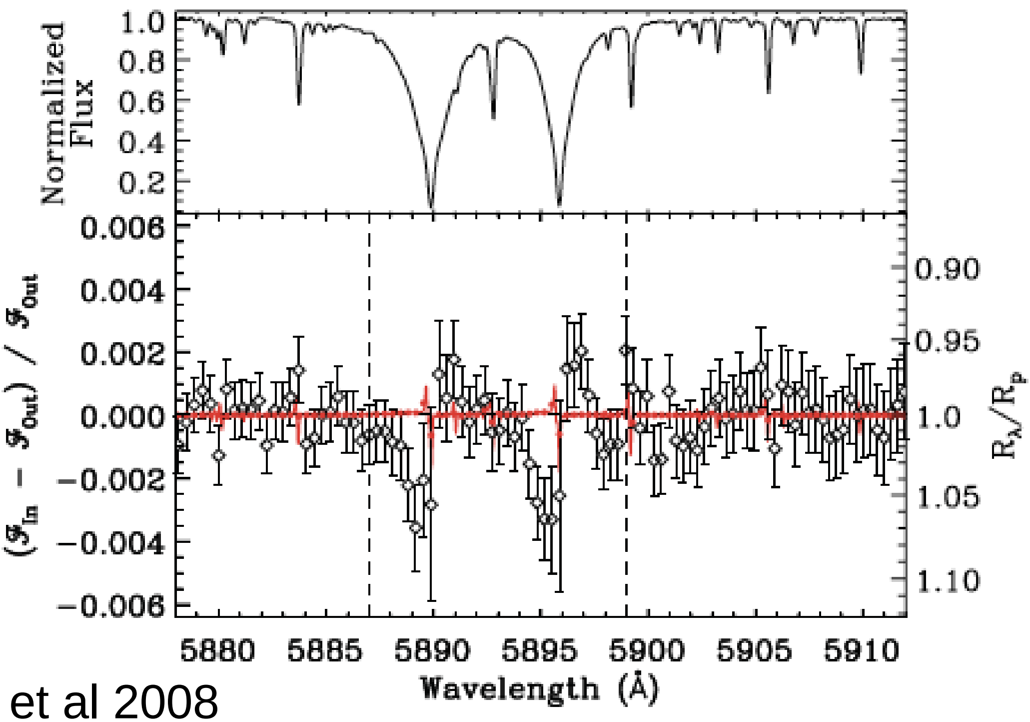


Image from Redfield et al 2008

First ground-based detection with 4m class telescope

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

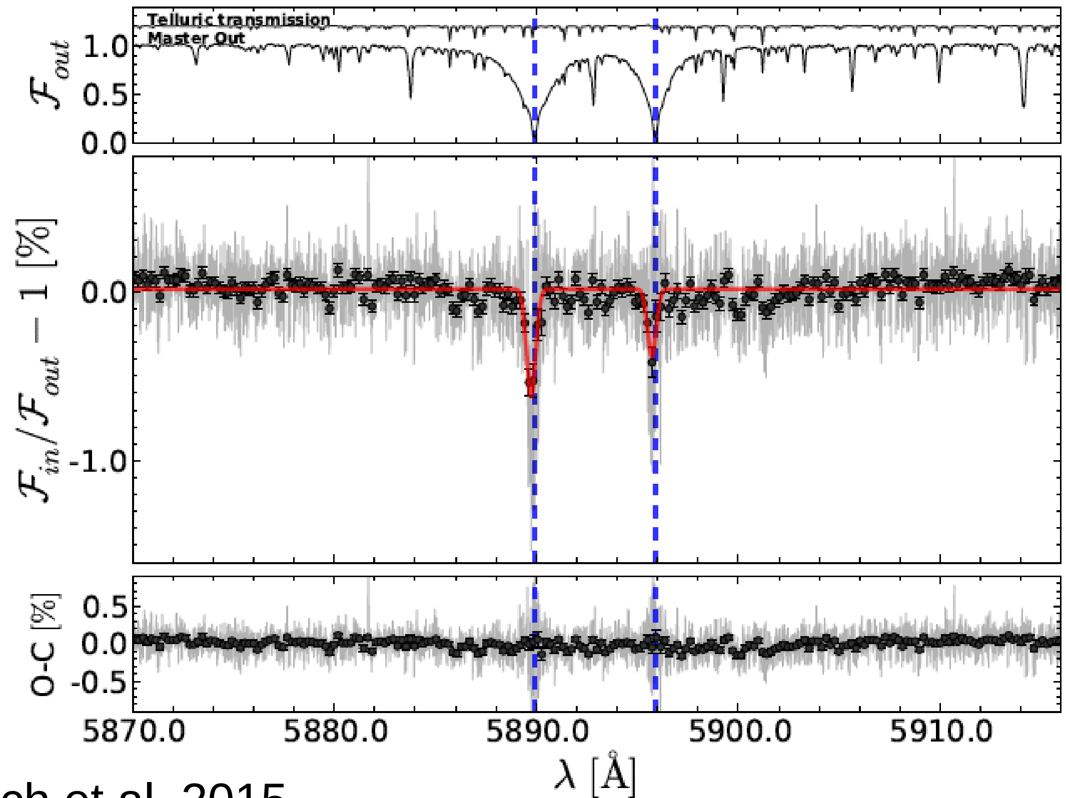
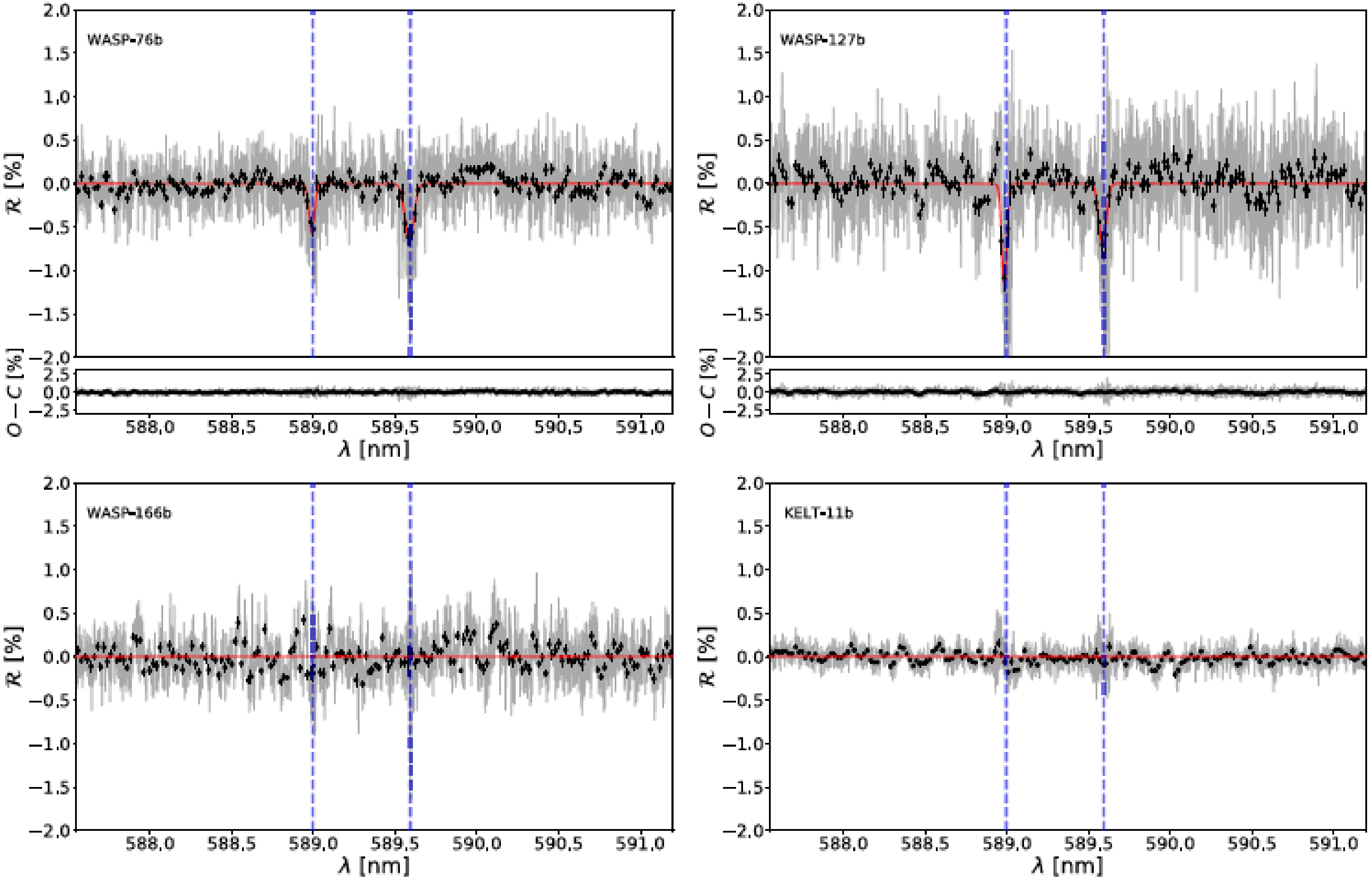


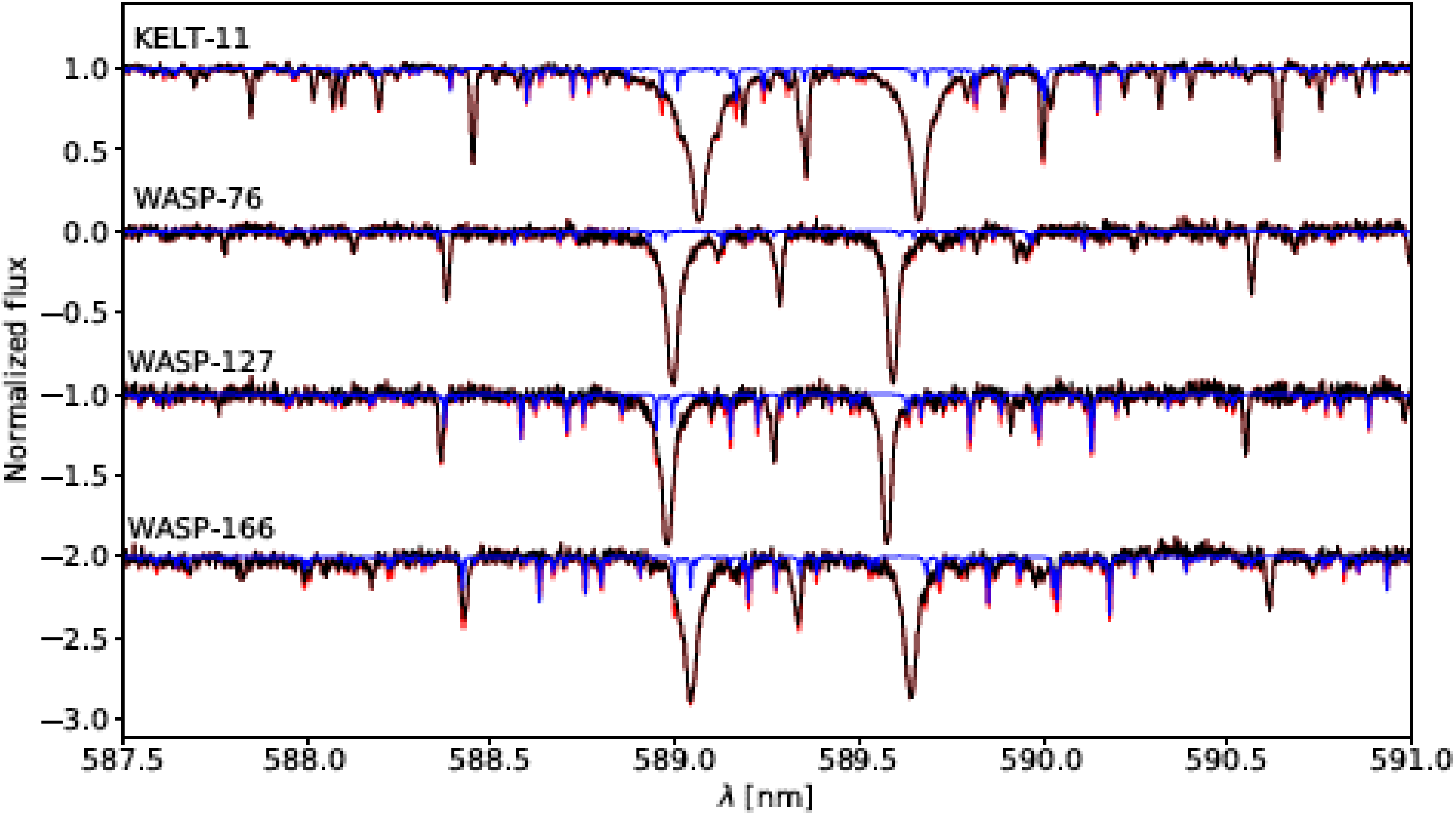
Image from Wyttenbach et al. 2015

Another Sodium Detection with HARPS



Zak, Kabath et al. 2019, AJ

Another Sodium Detection with HARPS



Zak, Kabath et al. 2019, AJ

Another Sodium Detection with HARPS

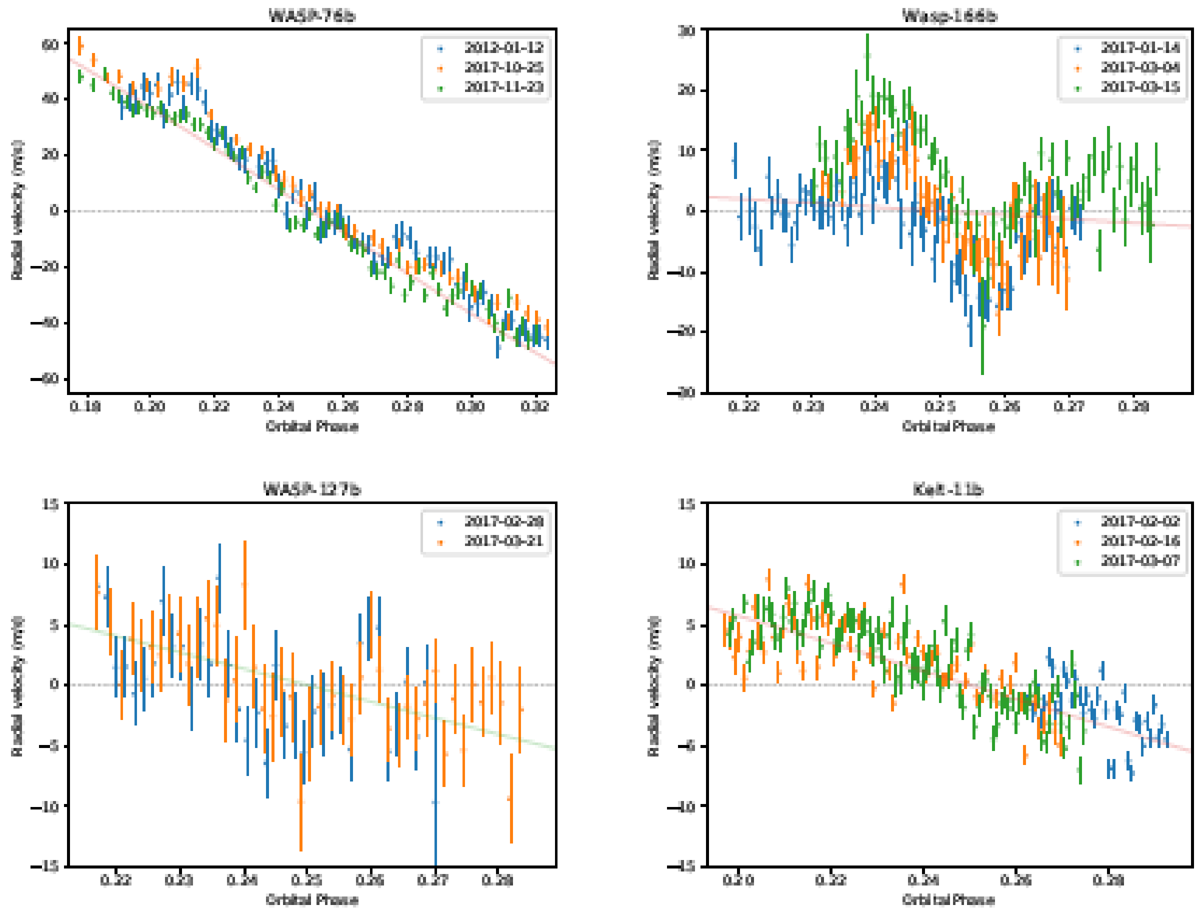


Figure 4. The radial velocities of our targets have been measured with HARPS: WASP-76 (top left), WASP-166 (top right), WASP-127 (bottom left) and KELT-11 (bottom right). There is some apparent offset between various epochs for the same target, which may be due to some instrumental shift or could be 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.

Zak, Kabath et al. 2019, AJ

Wasp-166b revisited

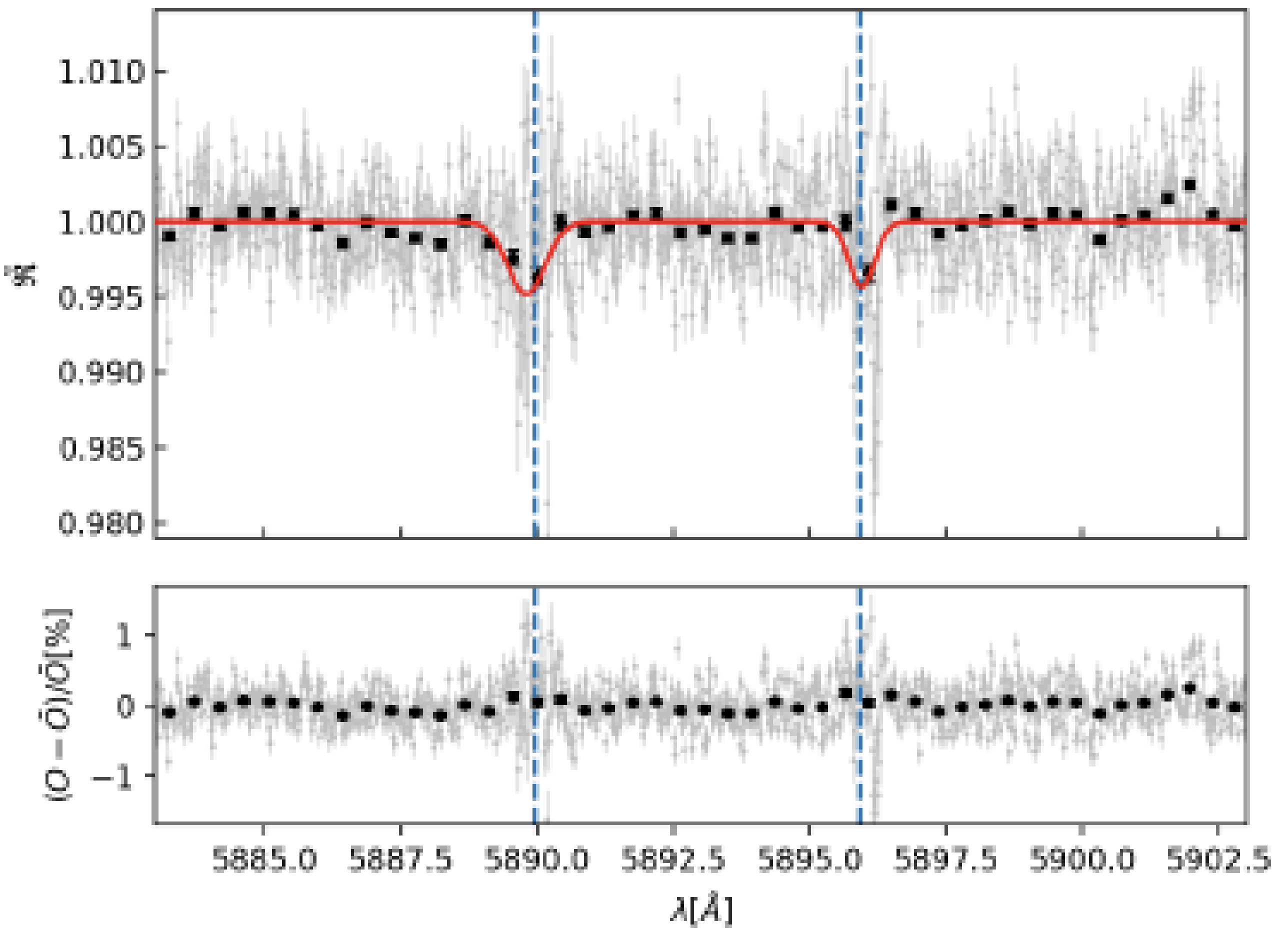


Fig. 4. HARPS sodium doublet transmission spectrum of WASP-166b for all nights combined shown in the PRF. Upper panel: In grey, data points at full HARPS resolution. In black, grey data points binned by x25 for visibility. The theoretical line centres for the sodium doublets are shown as vertical blue 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 ± 0.135 %, resulting in a 3.4 σ detection, see Sec. 4.3. Lower panel: Residuals of the Gaussian fit in %.

Wasp-166 revisited

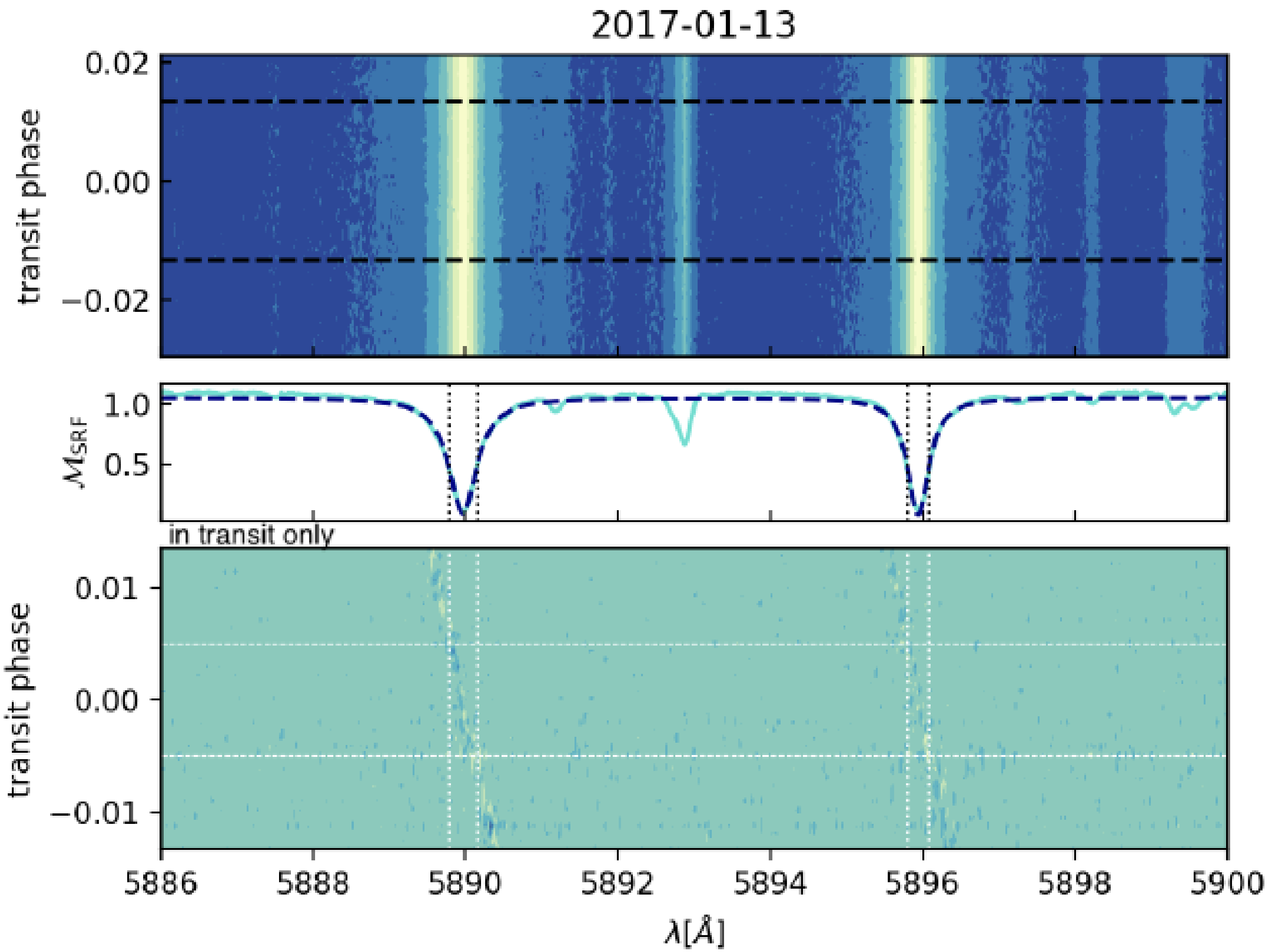


Fig. A.1. The upper panel shows all spectra in the SRF as a 2D map of wavelength and transit phase for the first transit. The stellar sodium doublet is visible as two horizontal light yellow bands. Transit ingress and egress are marked with black dashed lines. The central plot shows the normalised sum 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.

Credit: Seidel at al. https://arxiv.org/abs/2007.01783

Wasp-127 revisited (with ESPRESSO)

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

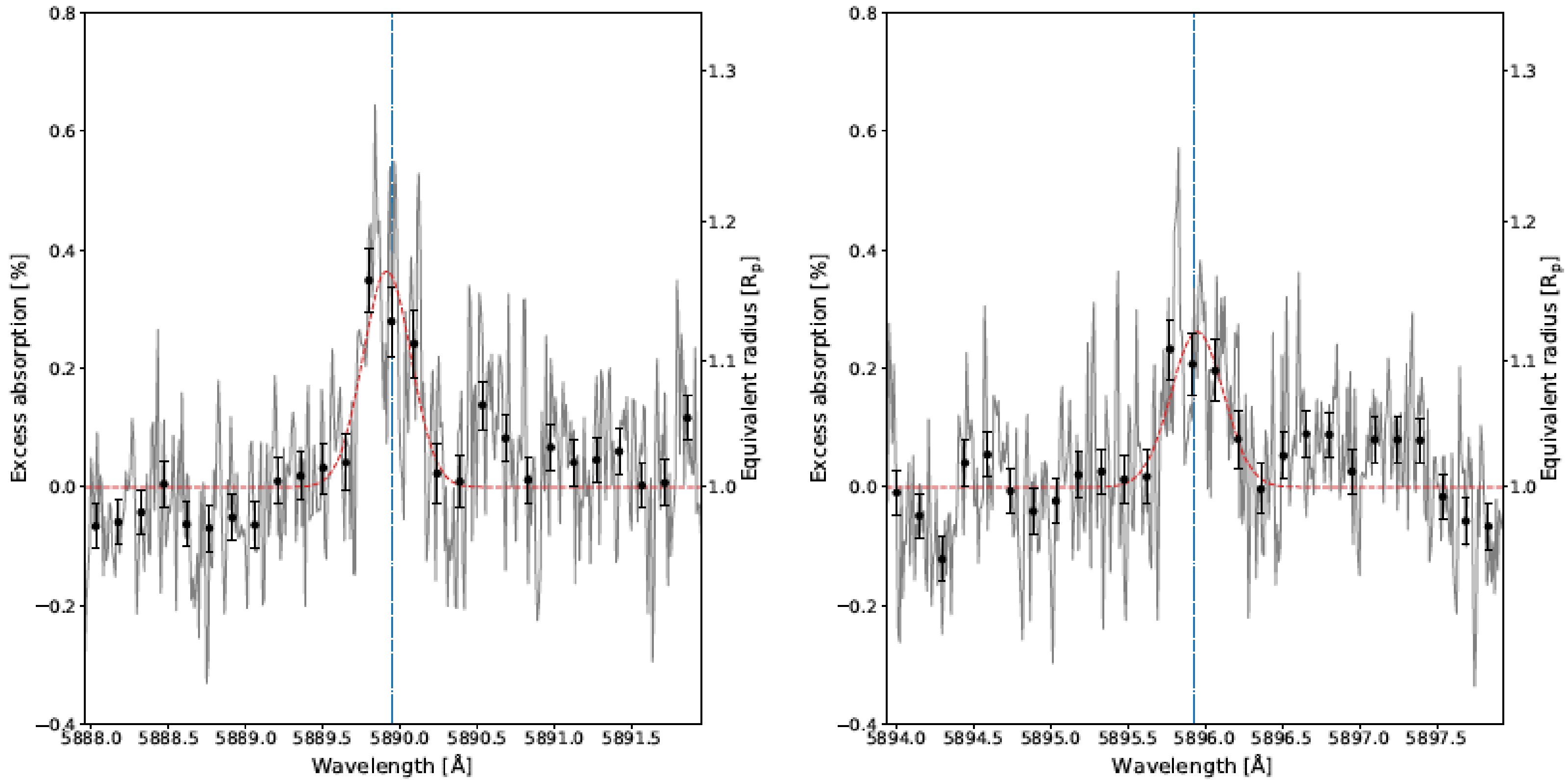
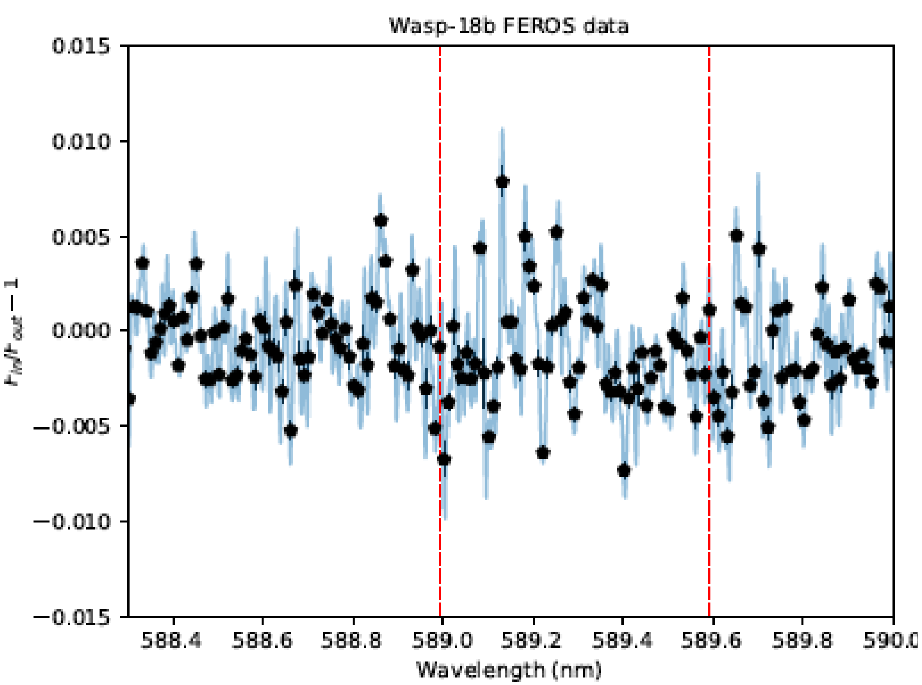


Fig. 8: Transmission spectrum around the Na D2 (*left*) and Na D1 (*right*) line averaged across the two transits in grey and binned by fifteen elements in black. The vertical blue dash dotted line represents the expected position of planetary sodium lines.

Credit: Allart et al. https://arxiv.org/abs/2010.15143

But… small telescopes?

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



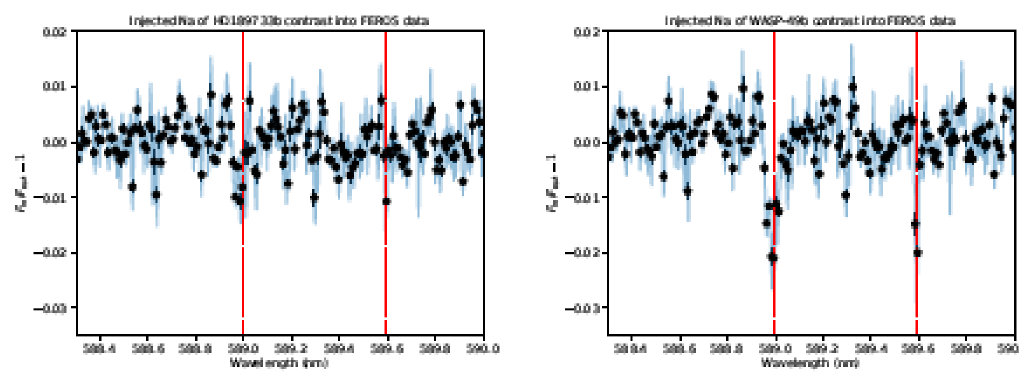


Figure 4. Sanity test with injected signal: (left) the signature of sodium absorption in the planetary atmosphere was injected into the FEROS WASP-18b data set. The strength of the sodium signal was set to be equal to that detected from HD189733b by Wyttenbach et al. (2015). (right) Injected sodium signal 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.

Kabath et al. 2019 - https://arxiv.org/pdf/1905.04665.pdf

Prospects for small telescopes

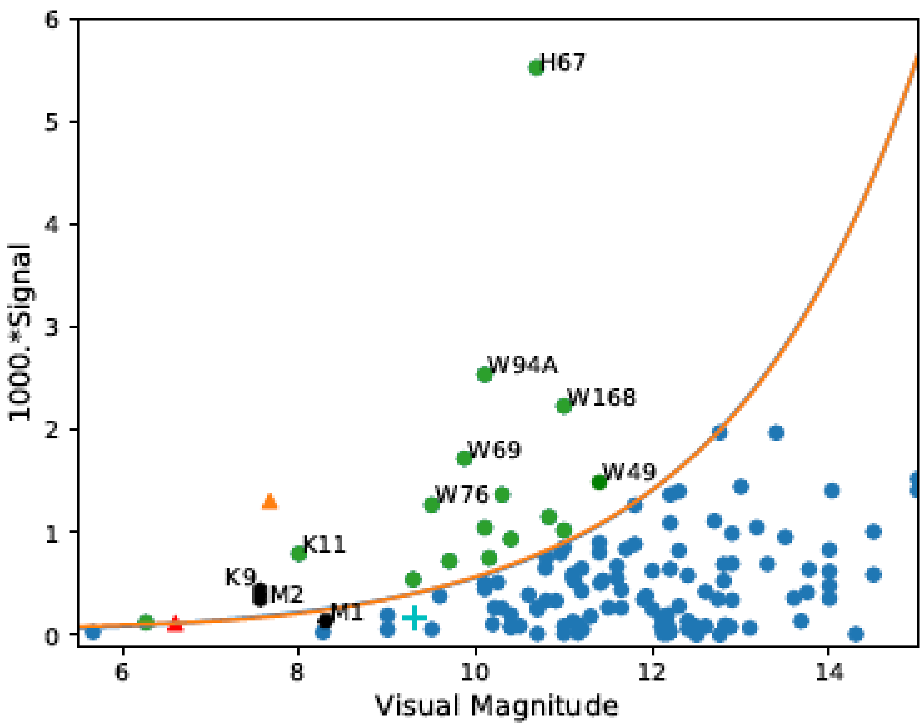


Figure 5. The expected atmospheric signal for well-characterised transiting plan as a function of the visual magnitude of the host star. The orange triangle shows the position of HD 189733, while the red triangle is the rescaled value, assuming a 2m-class telescope (see text). All the points above the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

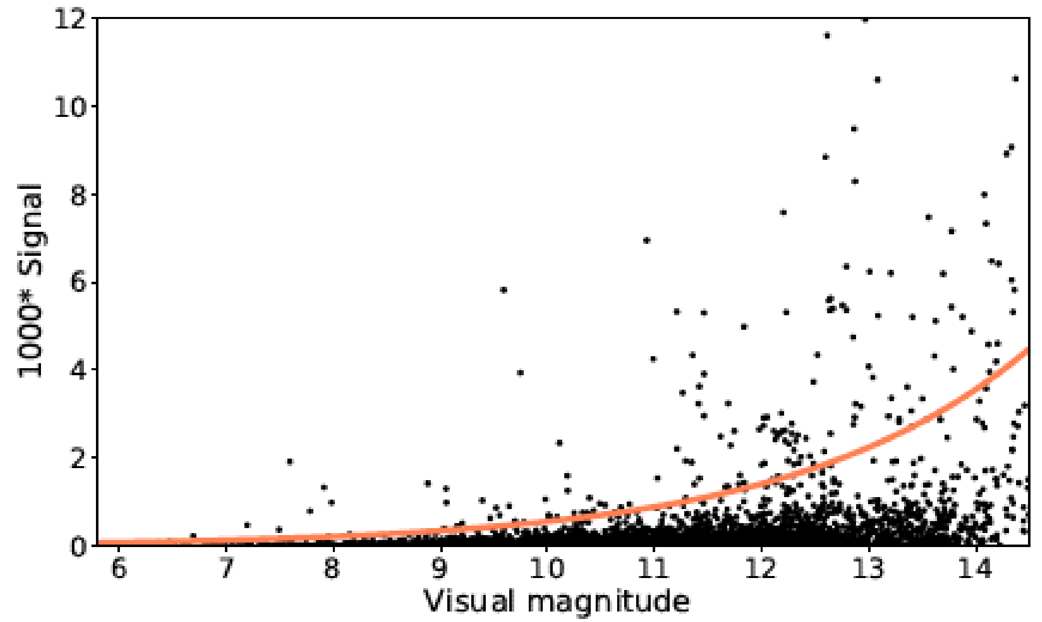
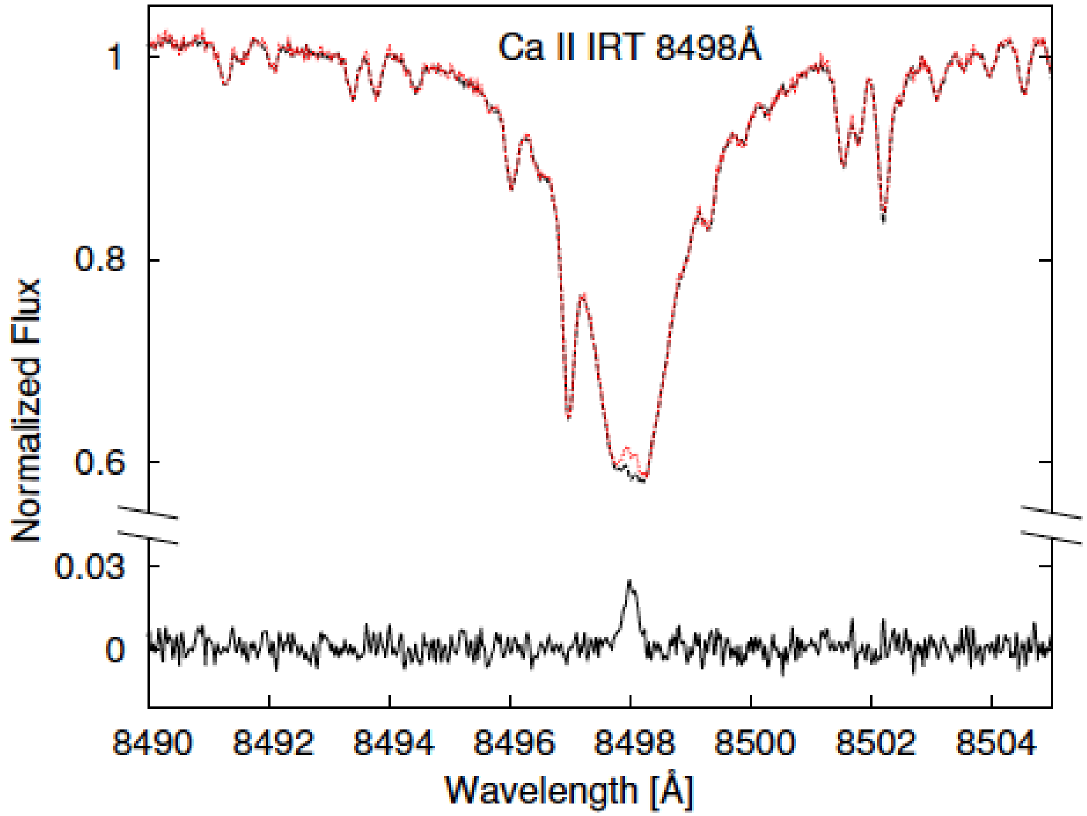


Figure 6. Expected signal as in previous Fig. 5 but from TESS planets which are depicted as black dots. The orange line is the detection limit for 2-m telescopes and good candidates for further follow-up will be above the line (see text for more detail).

Kabath et al. 2019 - https://arxiv.org/pdf/1905.04665.pdf

What happens if the star is flaring?

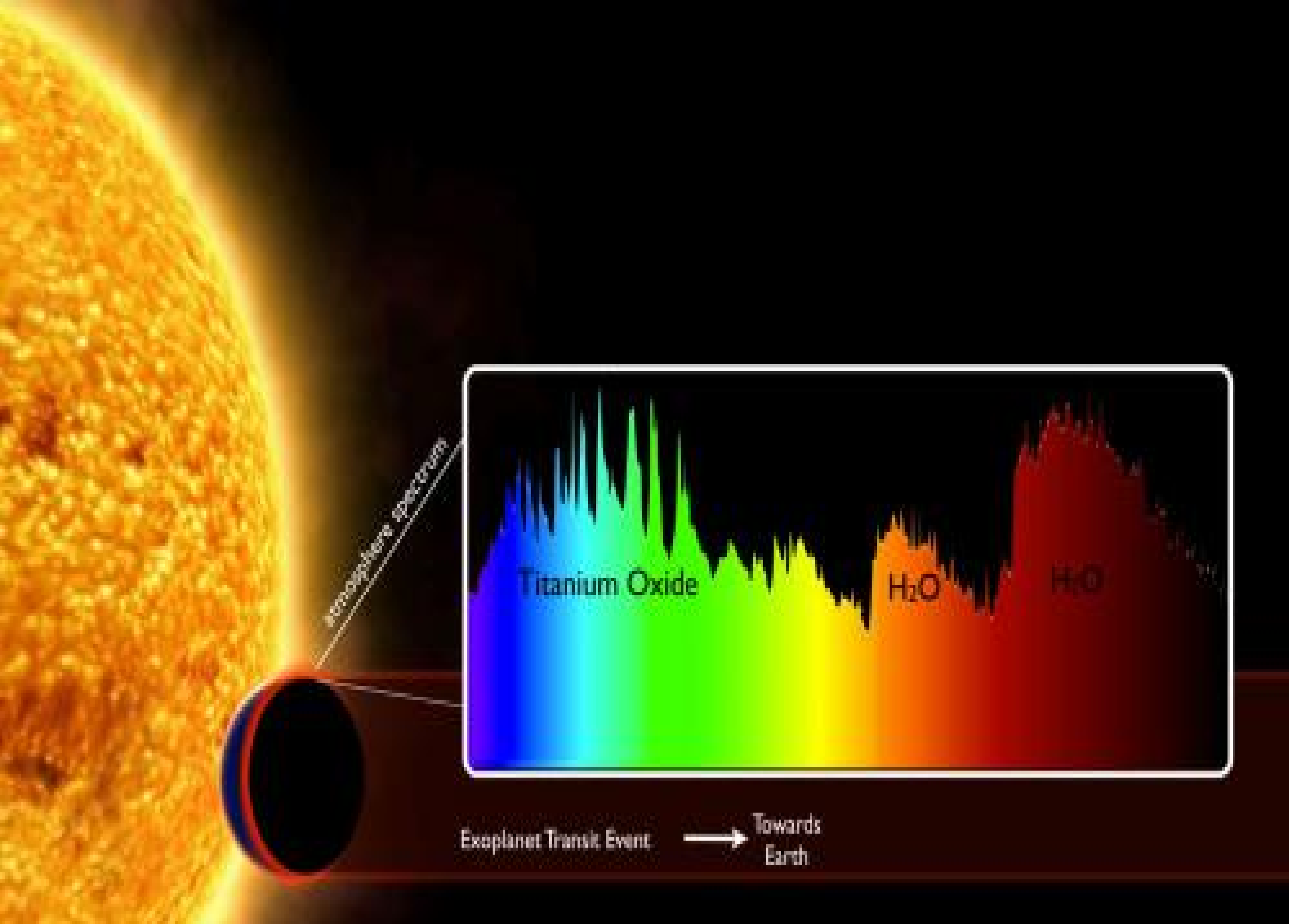
- Klocova 2017 et al. - https://arxiv.org/pdf/1707.09831.pdf
- What happens if during the transit a flare occurs



Other methods

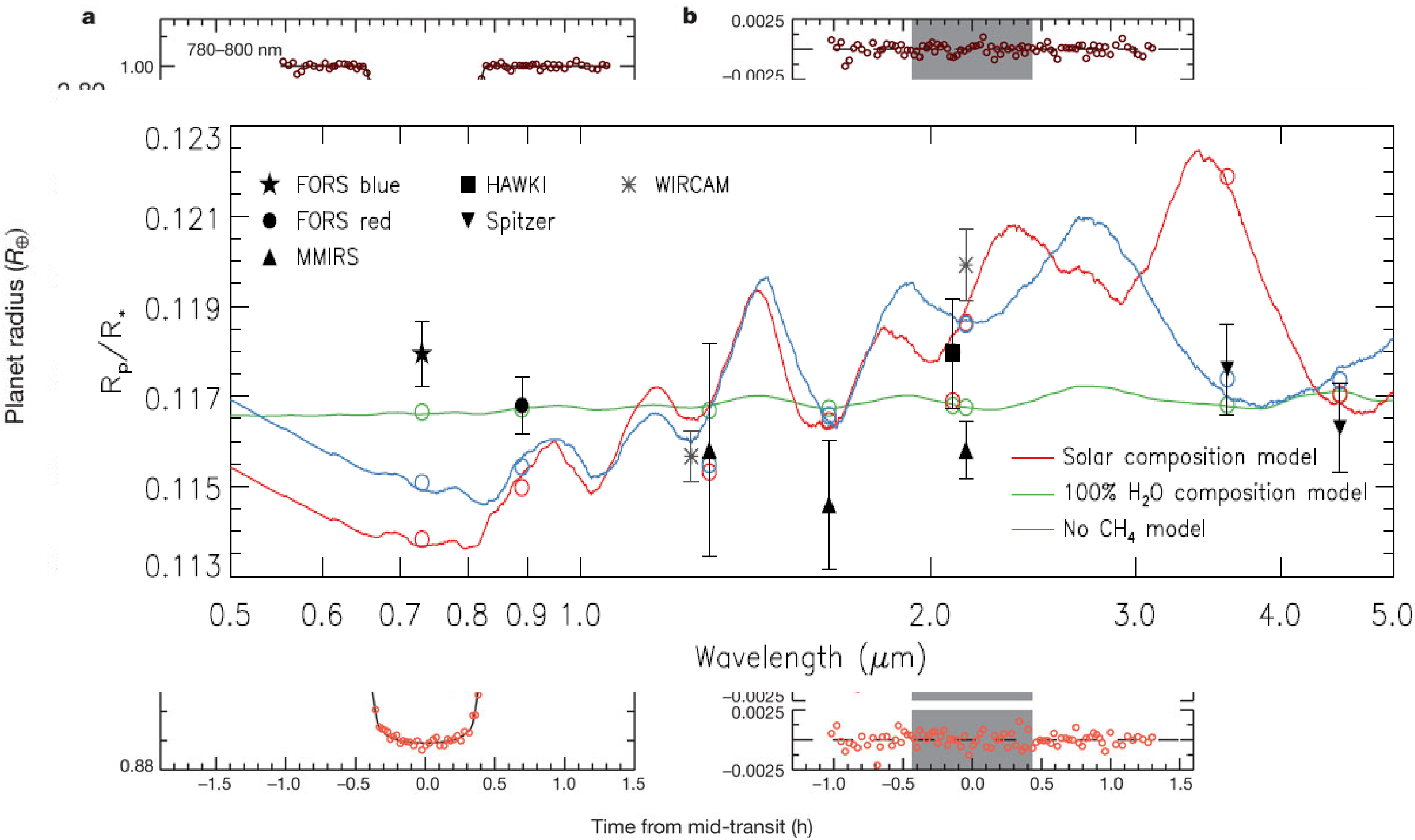
Spectrophotometry

- 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_2O
H_2O
Exoplanet Transit Event
Towards Earth

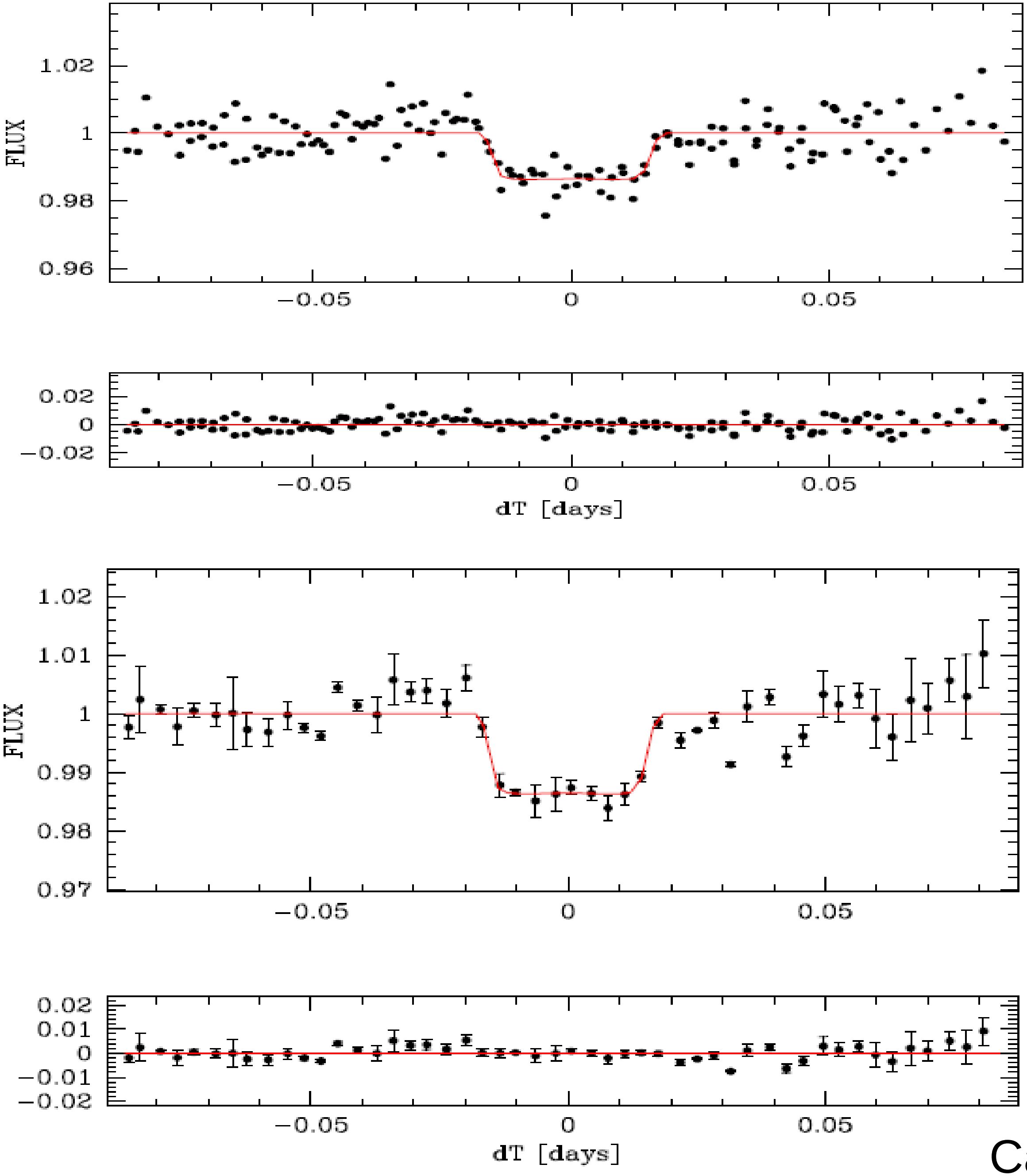
ESA D. Sing

FORS2 2010, 2011

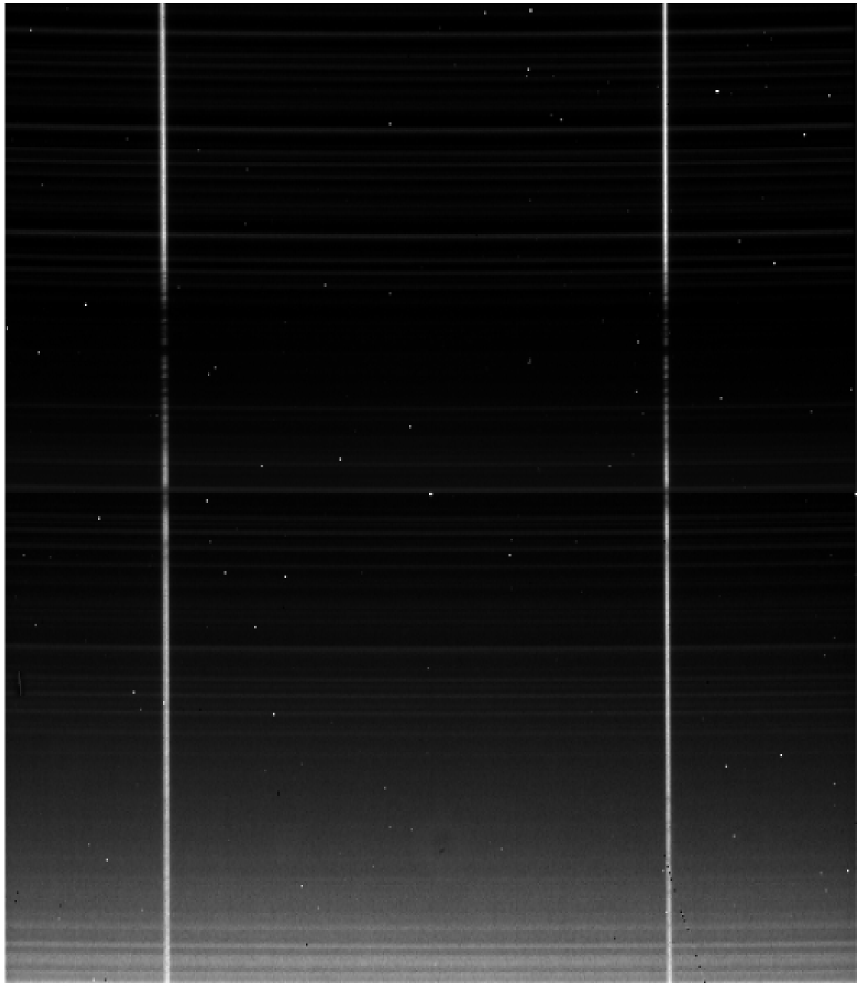


Bean et al. 2010, Nature
Bean, Desert, Kabath et al. 2011, AandA

SOFI NIR transmission spectroscopy



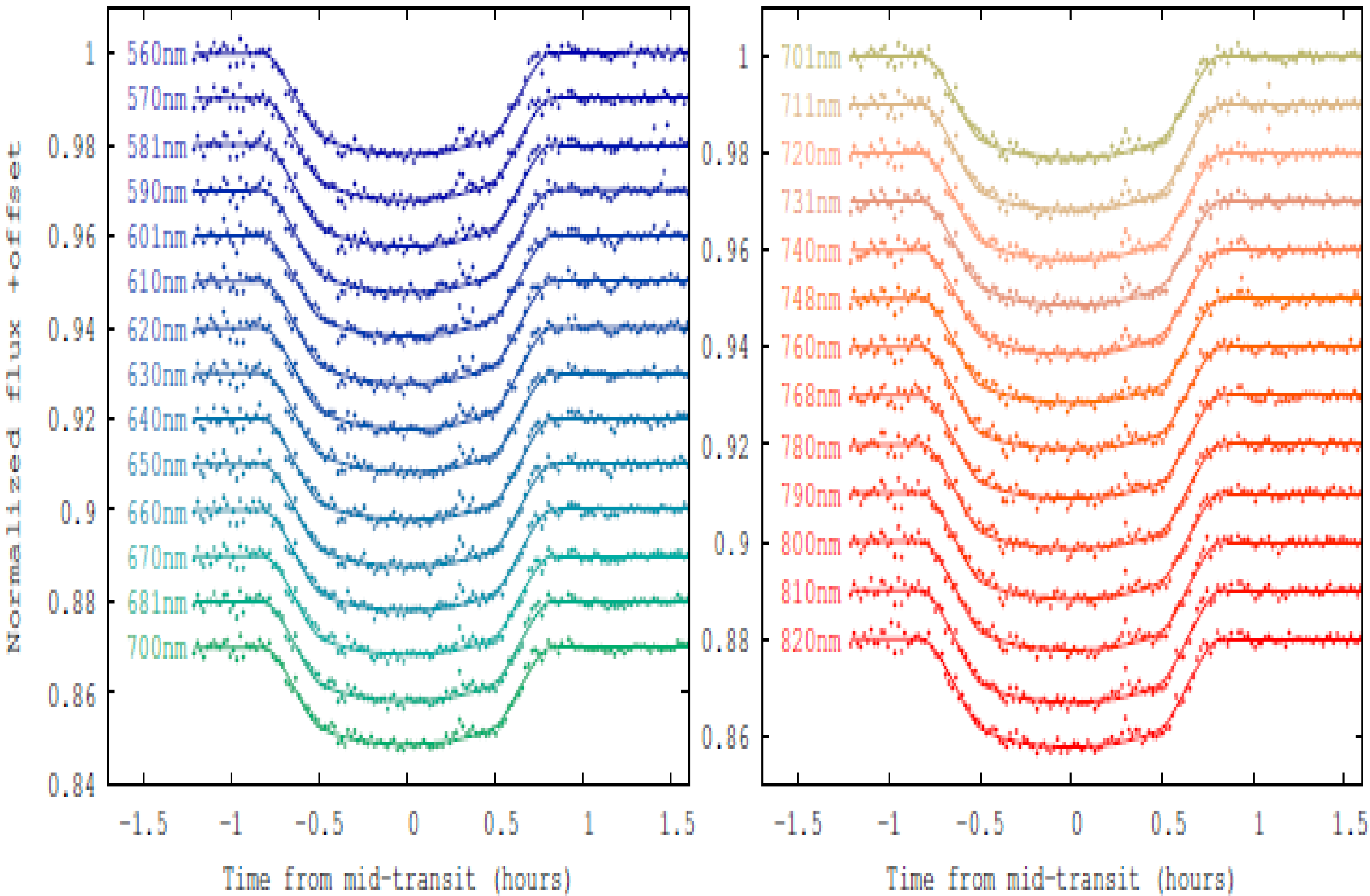
1.5 – 2.3 micron low res.
3 nights in 2011

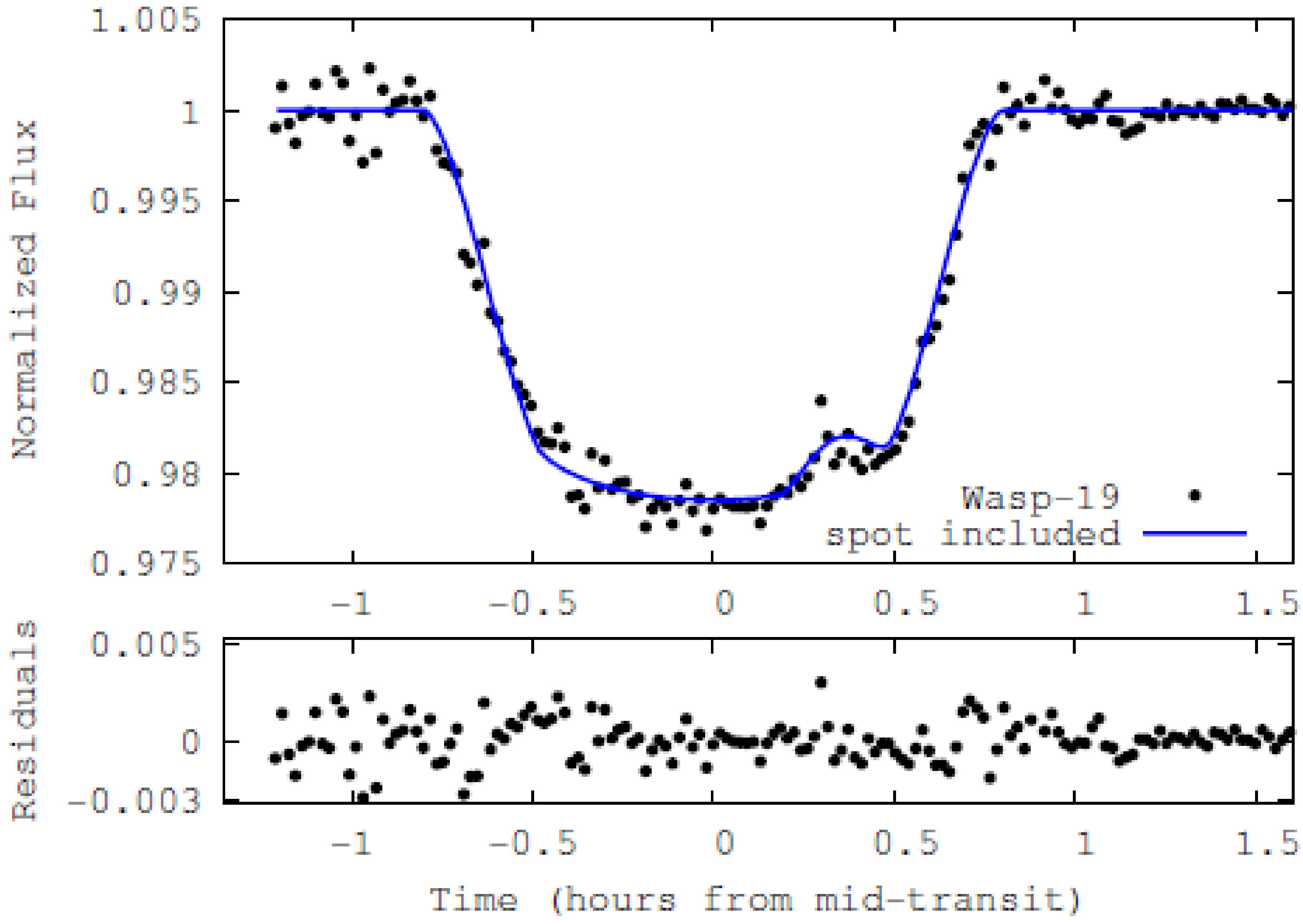


Caceres, Kabath et al., 2014, A and A

WASP-19b – better resolution

- Sedaghati et al. 2015, A&A




1.005
1
0.995
0.99
0.985
0.98
0.975
Normalized Flux
Wasp-19
spot included
-1
-0.5
0
0.5
1
1.5
0.005
0
-0.003
Residuals
Time (hours from mid-transit)

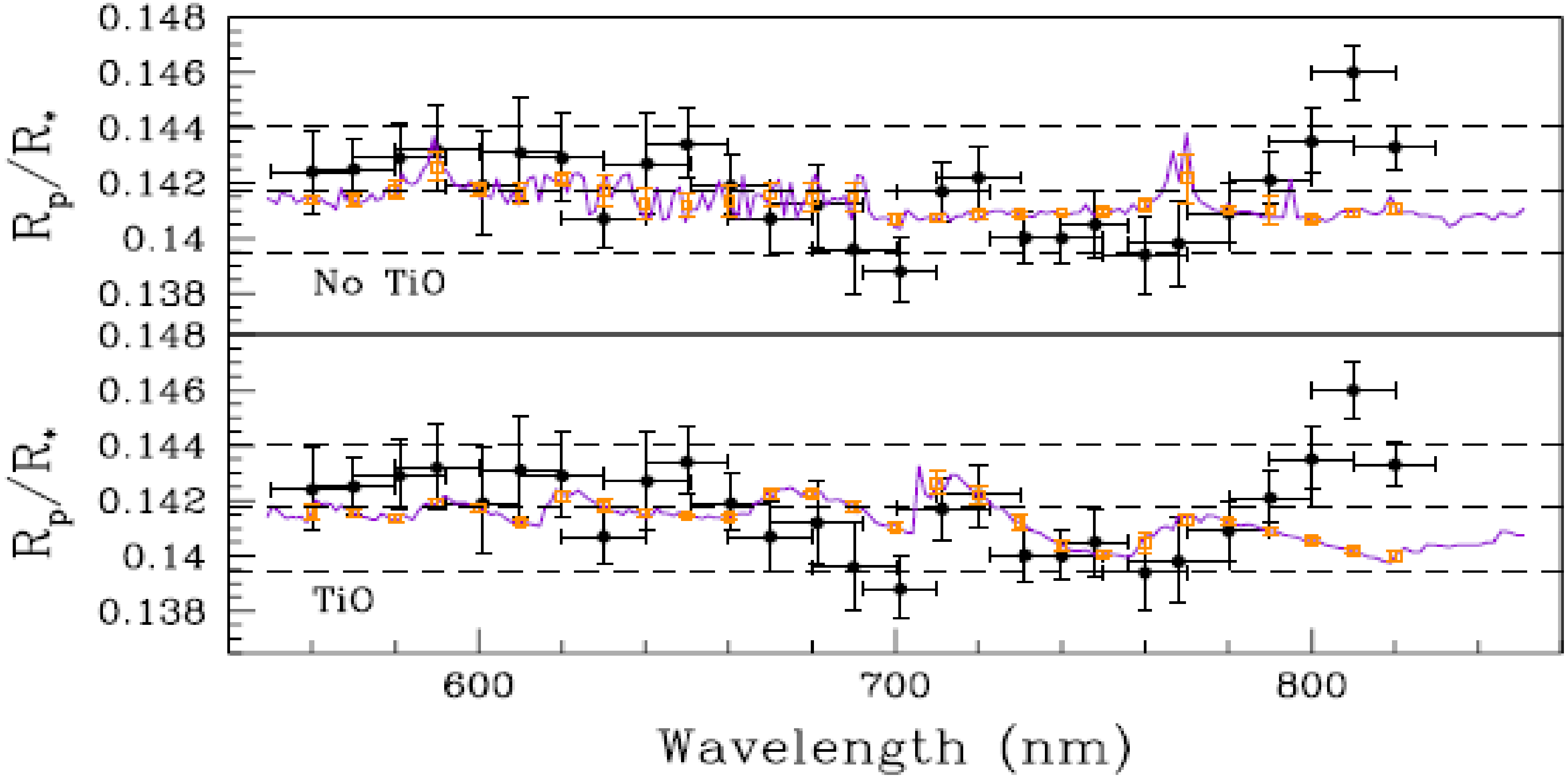
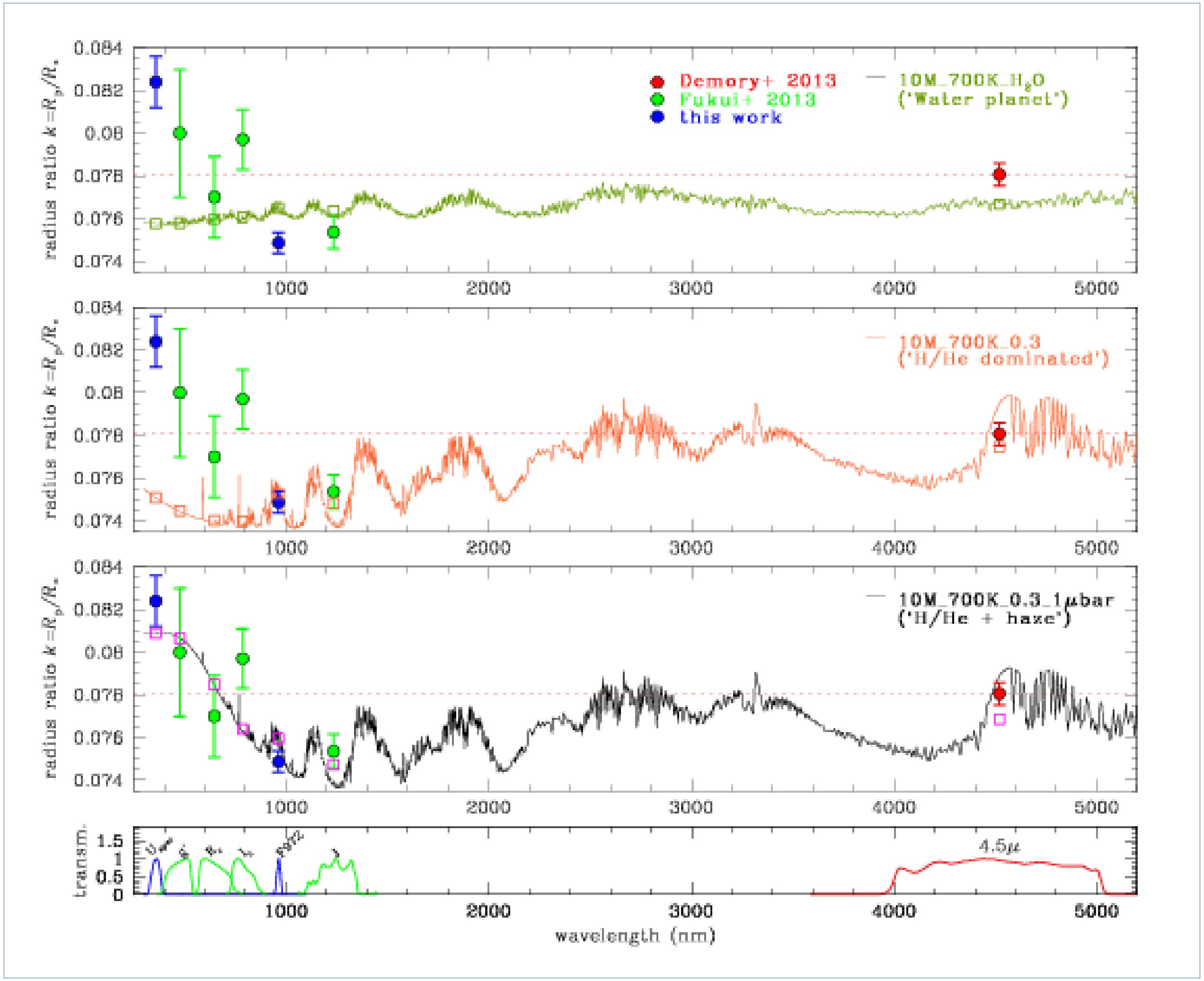


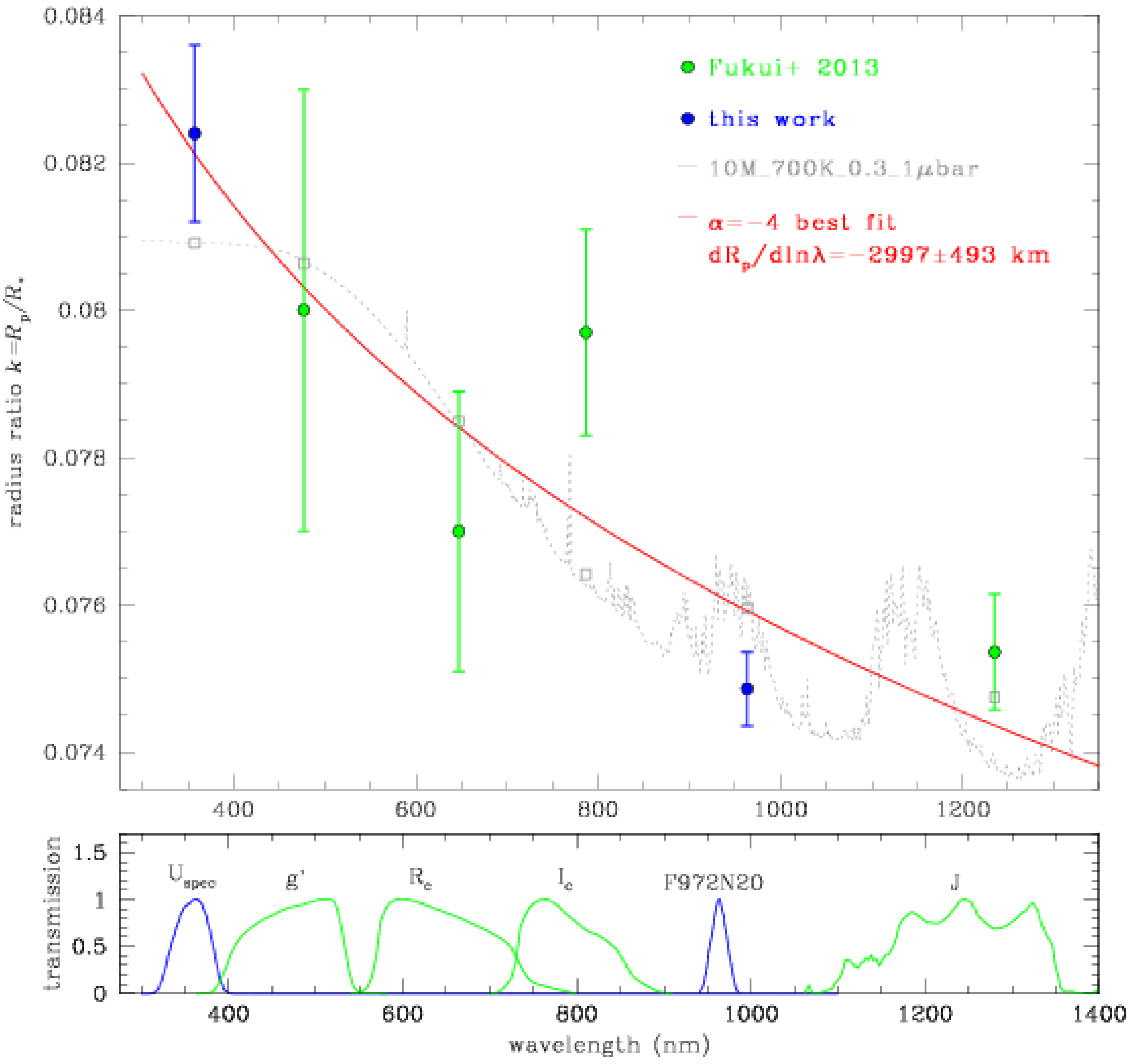
Fig. 2. Transmission spectrum of WASP-19b as measured with FORS2 (black dots, with error bars) compared to two models of planetary atmospheres, one with no TiO (top panel) and one with a solar abundance of TiO (bottom panel), from Burrows et al. (2010) and Howe & Burrows (2012). We have also estimated 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?



Nascimbeni et al. 2013, AandA



Nascimbeni et al. 2013, AandA

Very accurate photometry

Our observations with 4m class

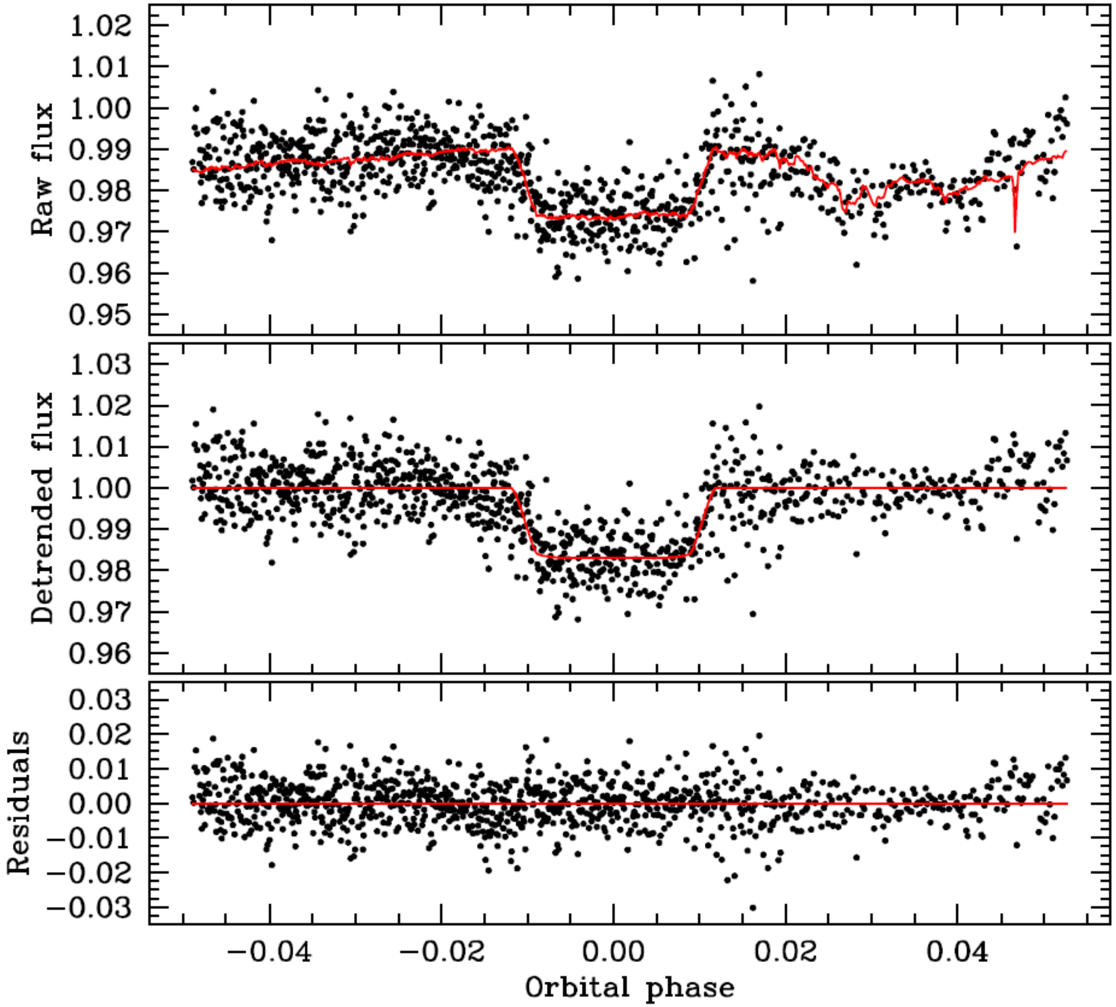
- SOFI @ NTT – La Silla 3 nights
- OSIRIS @ SOAR - Cerro Pachon 1 night
- SOI @ SOAR - Cerro Pachon 1 night

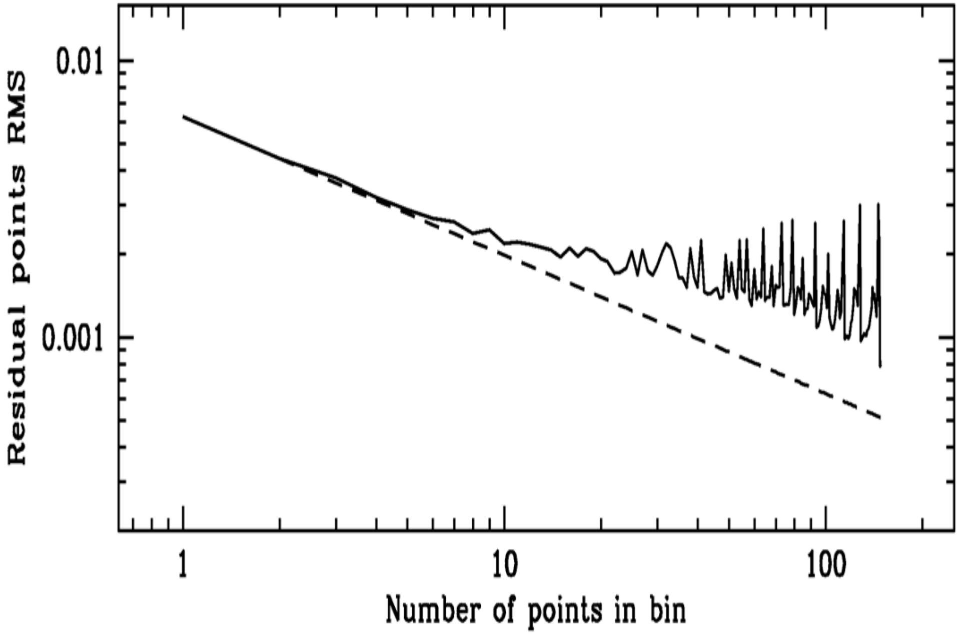
Both telescopes are 4-m class!!!

ESO

SOAR

Our measurements - OSIRIS



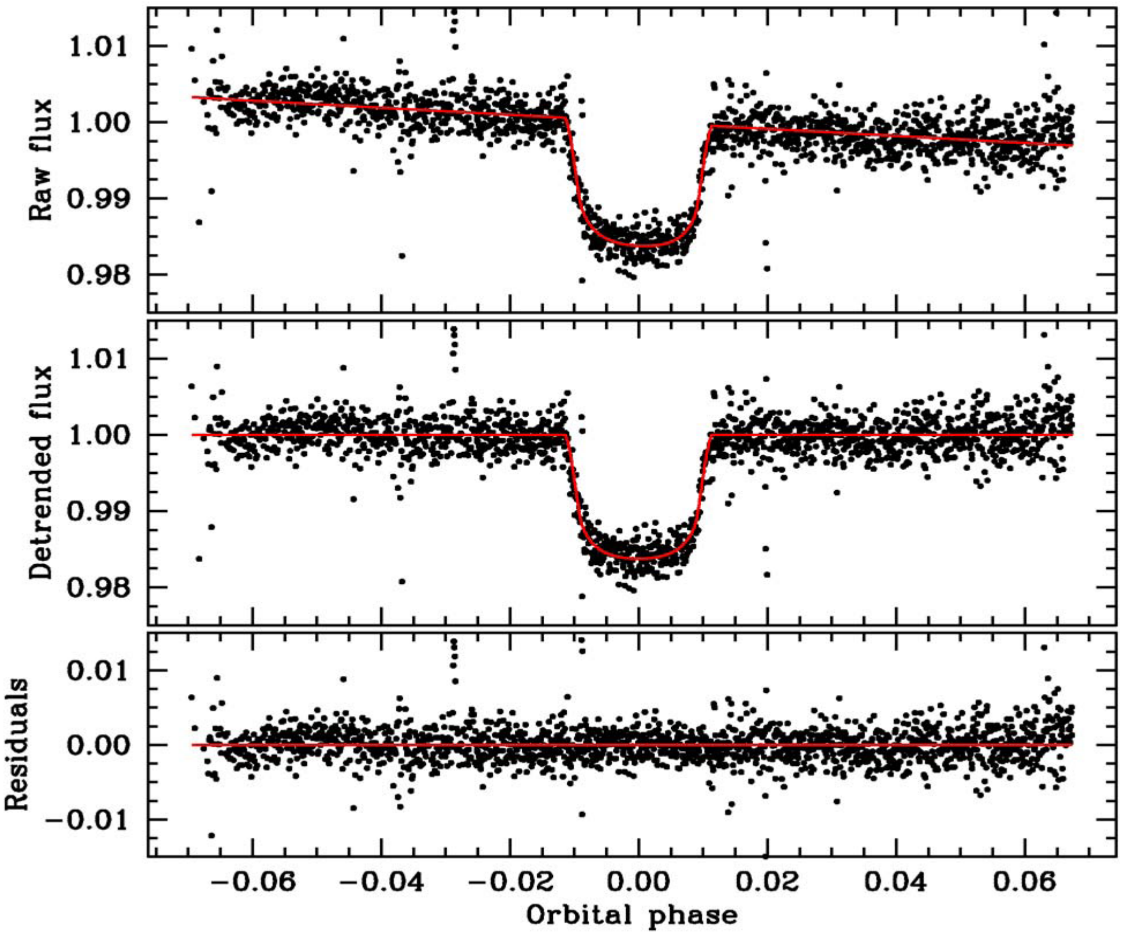


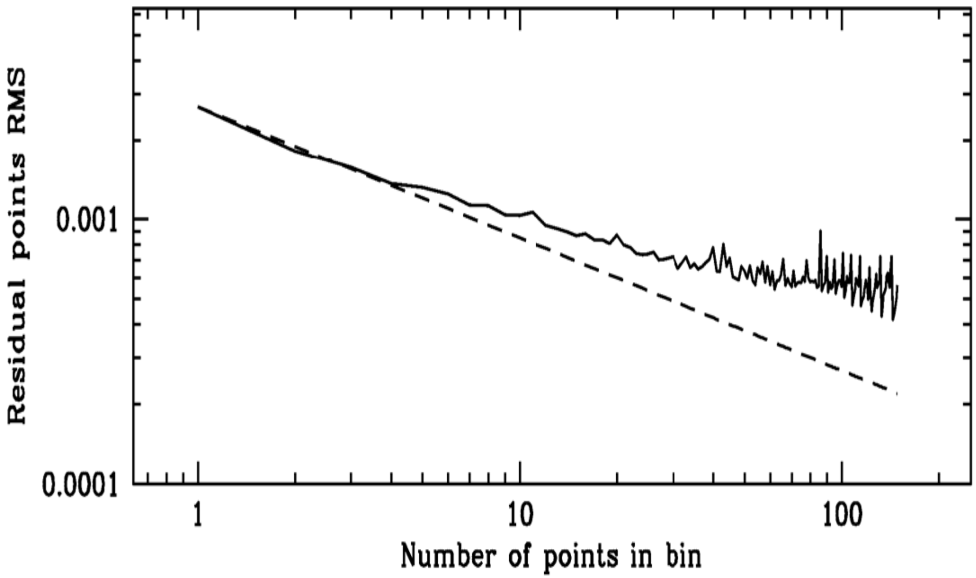
Rp/Rs = 0.118101 (-)0.002766(+)0.00256

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

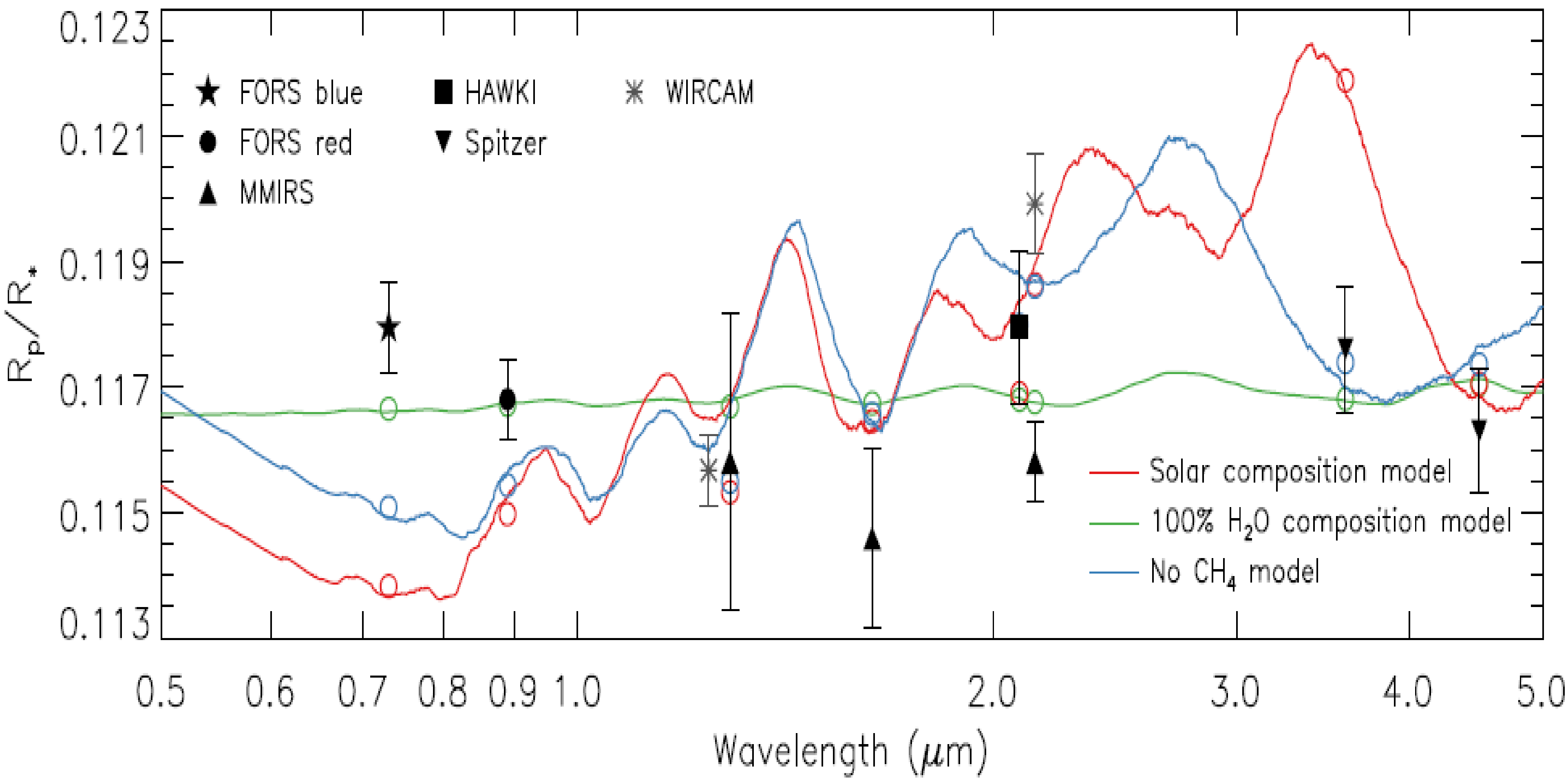




SOAR I-BESSEL:
Rp/Rs = 0.117151 (-)0.001173 (+)0.001182

Observations performed by S. Hoyer

4-m class telescopes good?



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

Our results compared (photometry)

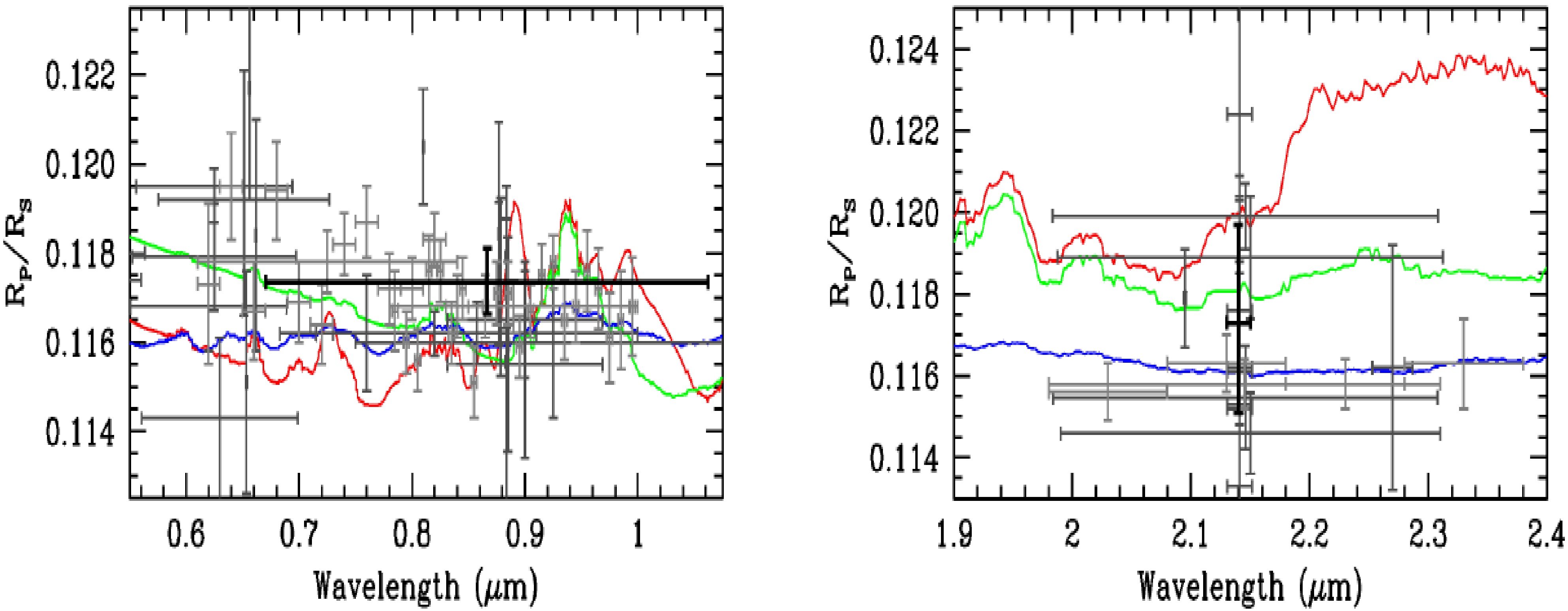
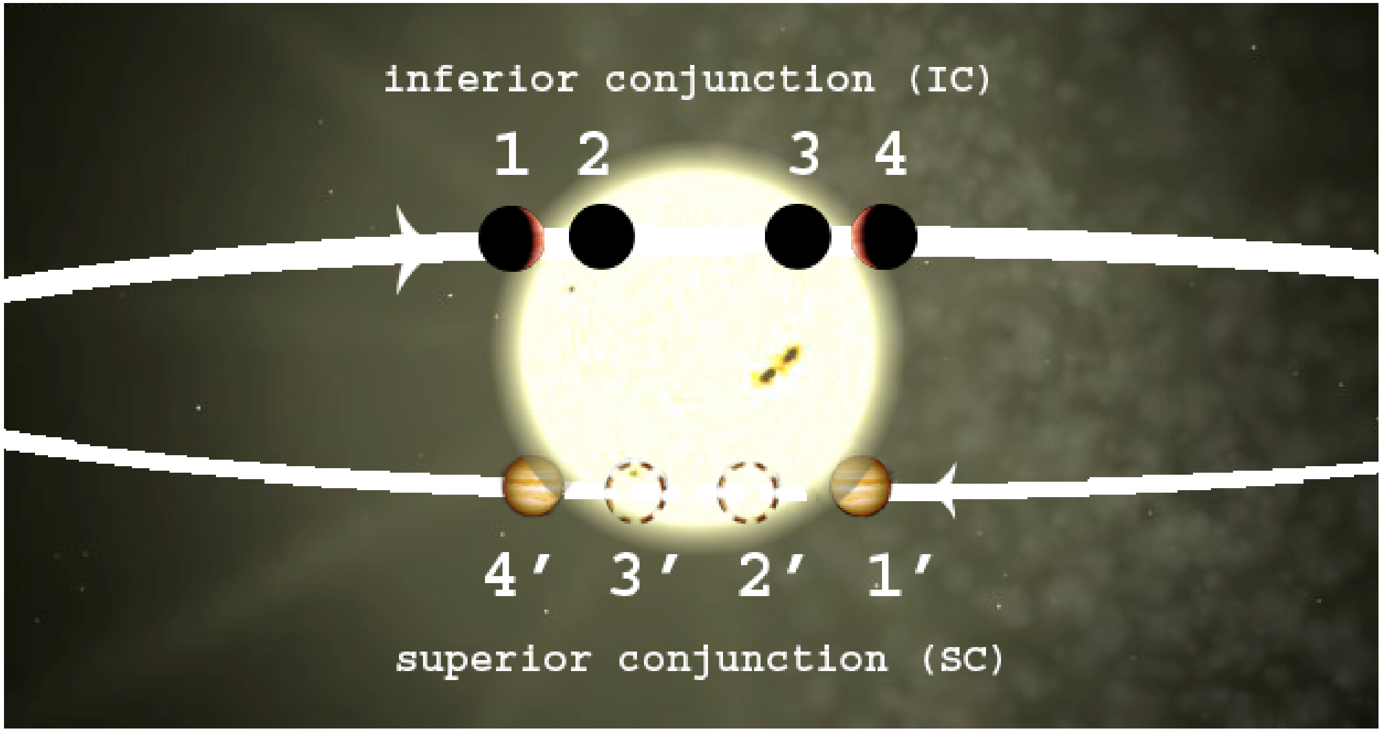


Fig. 11. *Left:* A zoom-in from Fig. 10 for the optical region around our *I*-Bessel measurements. *Right:* The *K*-band region of spectra around our 2.14 μm observation. Our measurement points are represented by dark circles, while gray points follow the description in Fig. 10. A color version of this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

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

Transits and eclipses of exoplanets



From Angerhausen et al. 2008

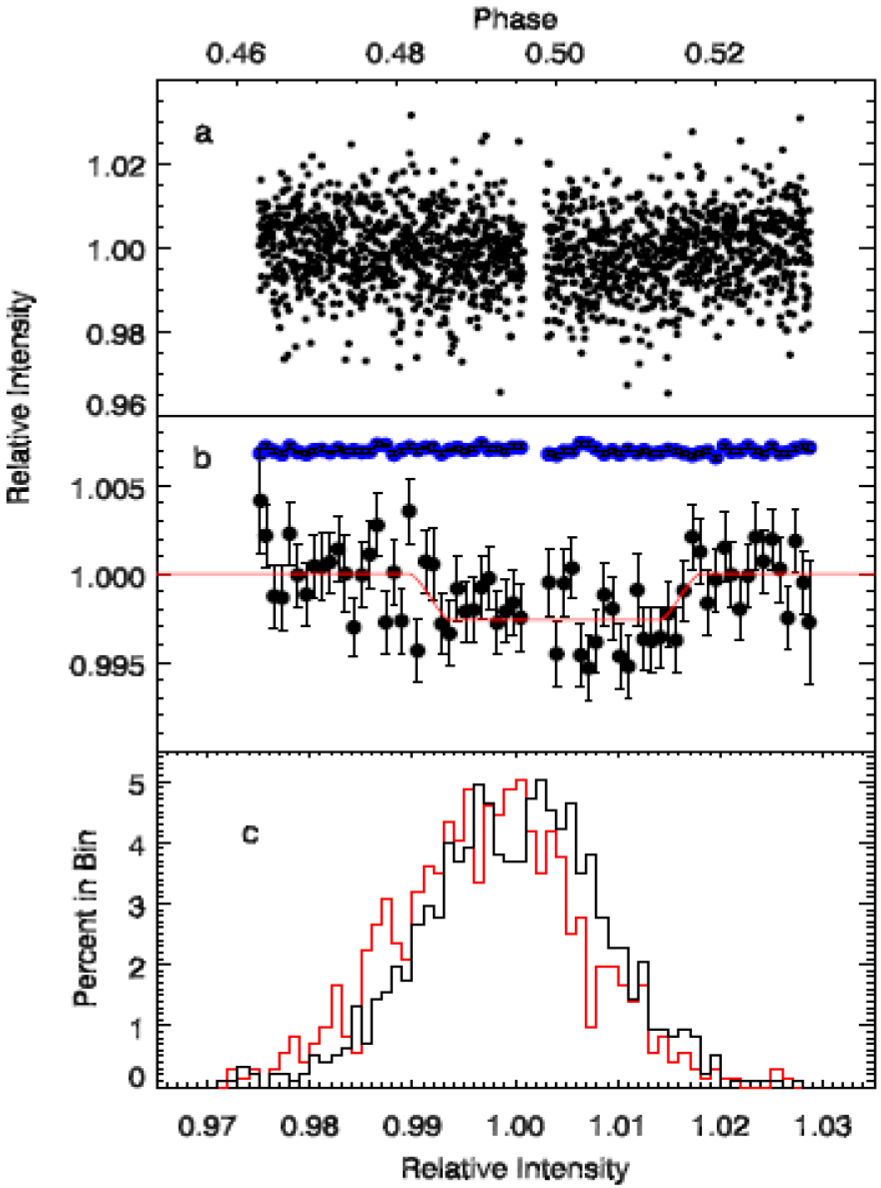
Emission from the planet

- Thermal radiation from the planet in IR

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

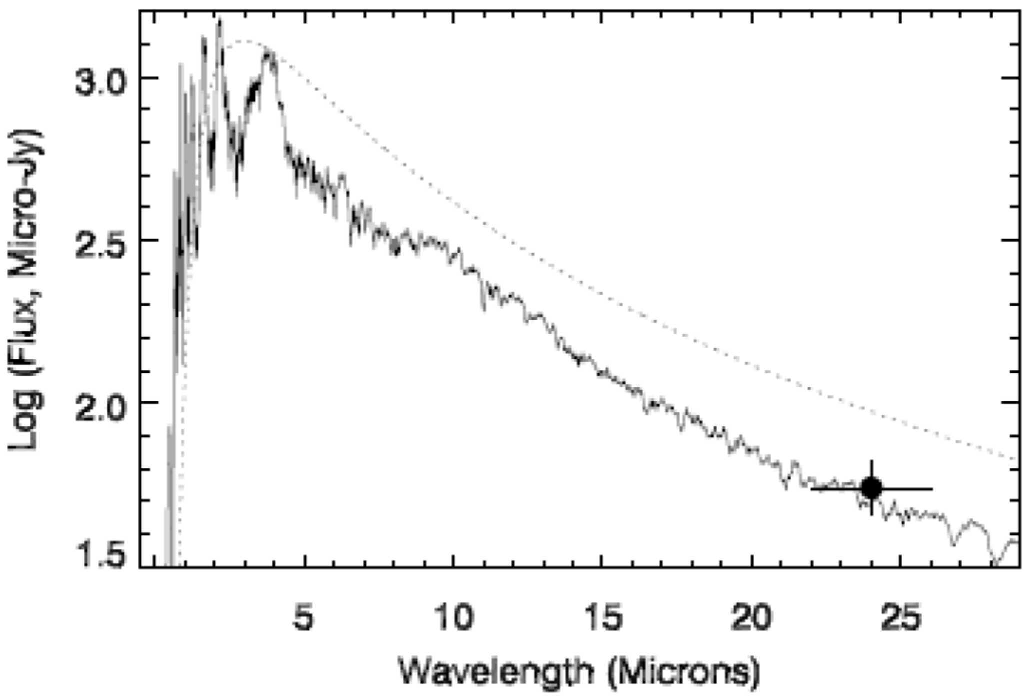
- Very shallow signals – few mmags
- Measuring directly the (missing) emission of the reflected light from the planet
- Result is an emission spectrum
- Due to geometry, not all planets hide behind the host star

Secondary eclipse photometry HD209458b



Měření: Spitzer 24μm

T_{pl}: ca 1130K



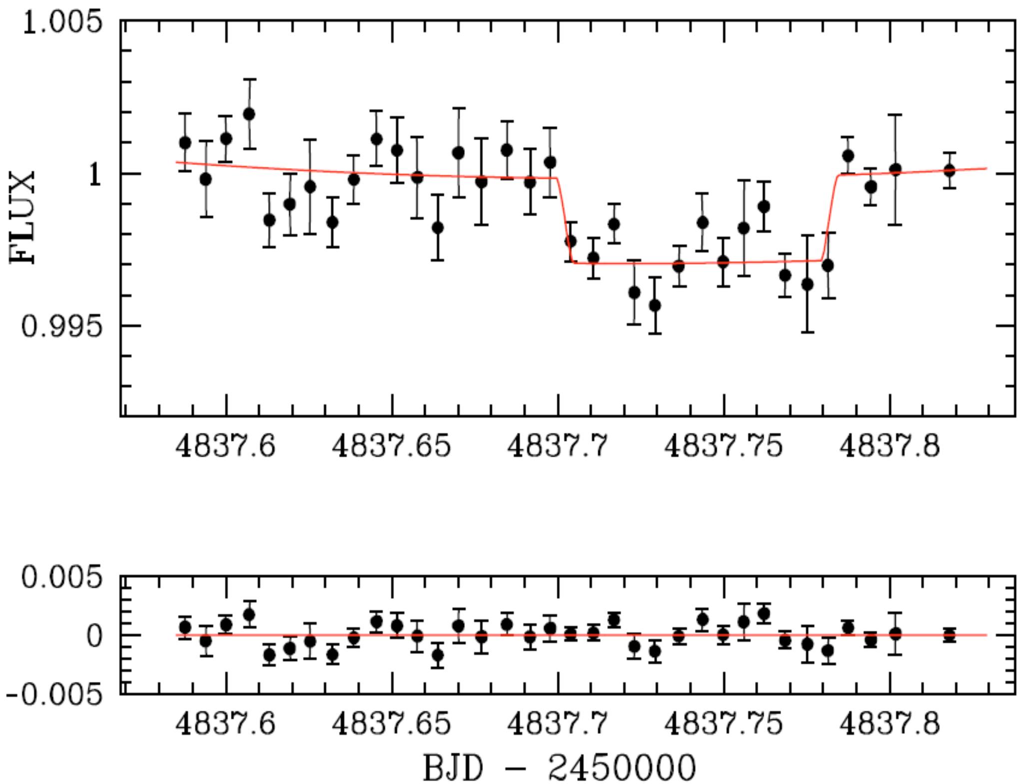
Deming et al. 2005 Nature

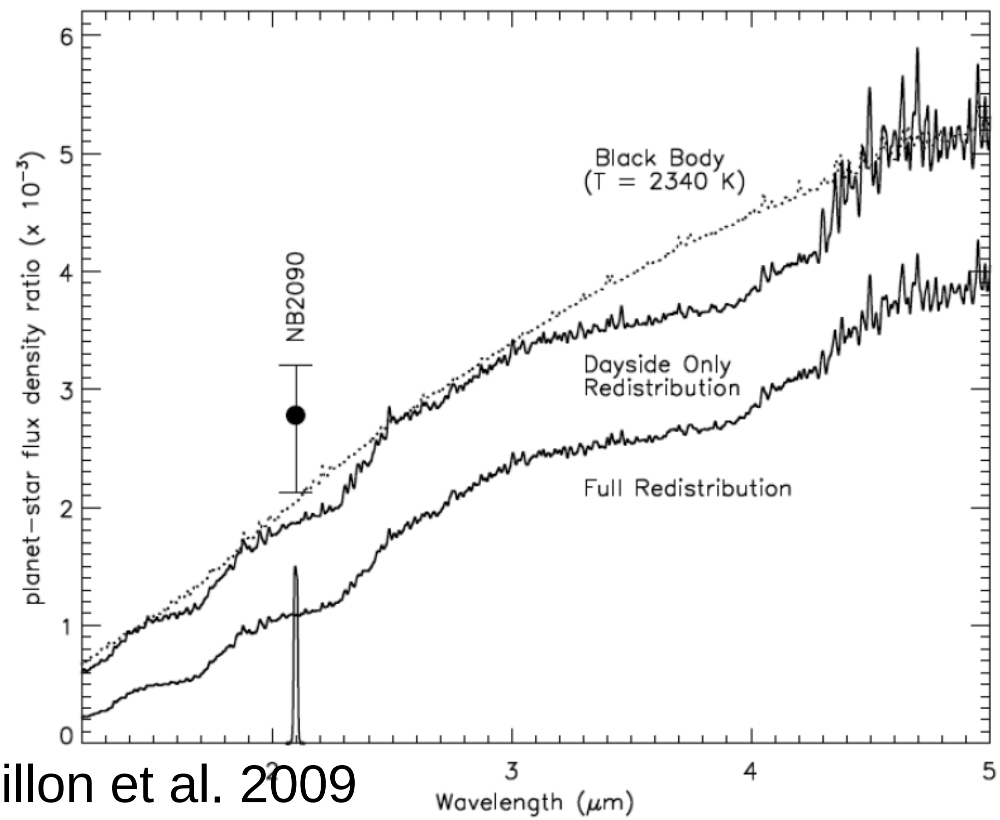
Secondary eclipse photometry from the ground

- Thermal radiation from the planet in IR

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

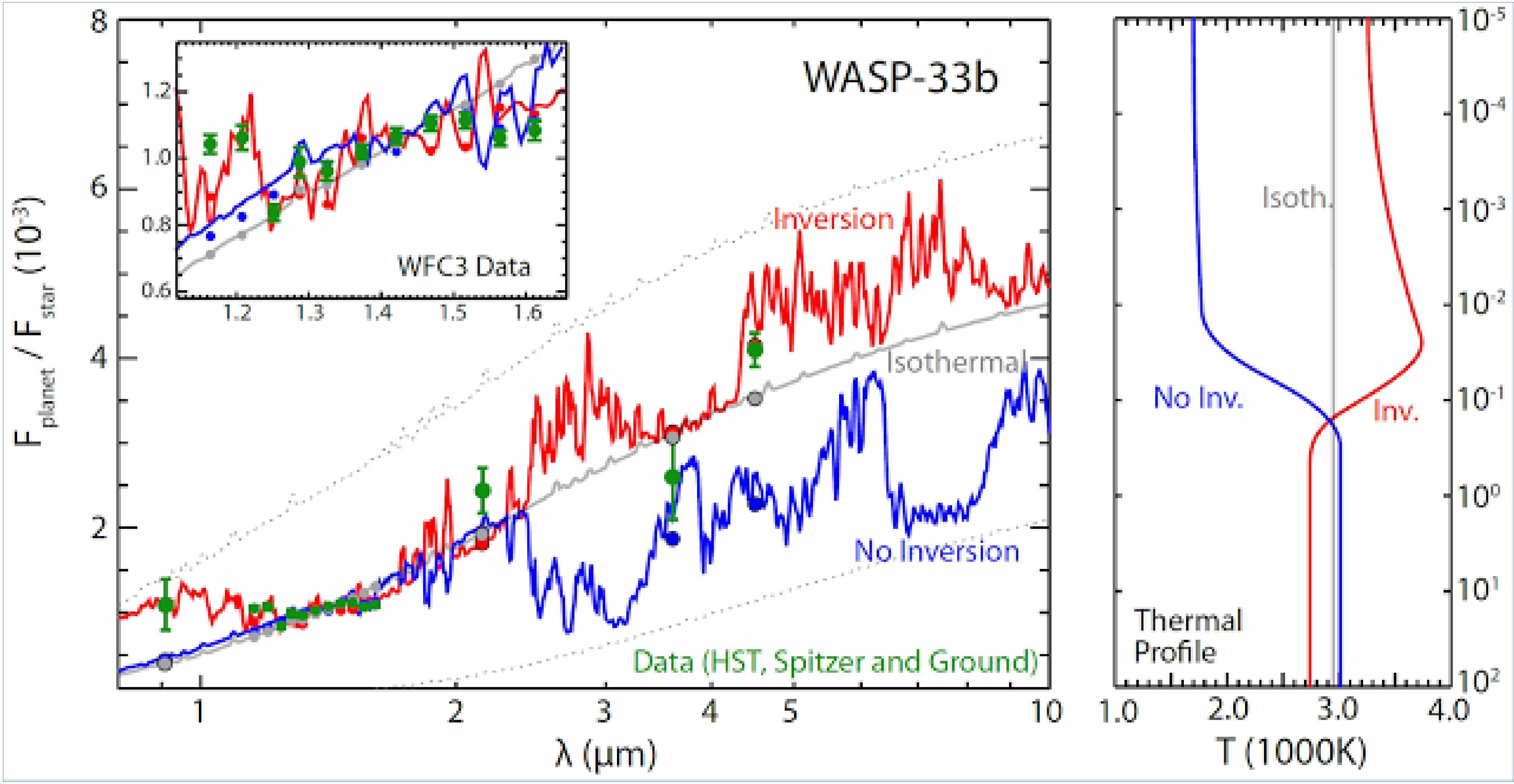
Typically few mmags for hot Jupiters





Gillon et al. 2009

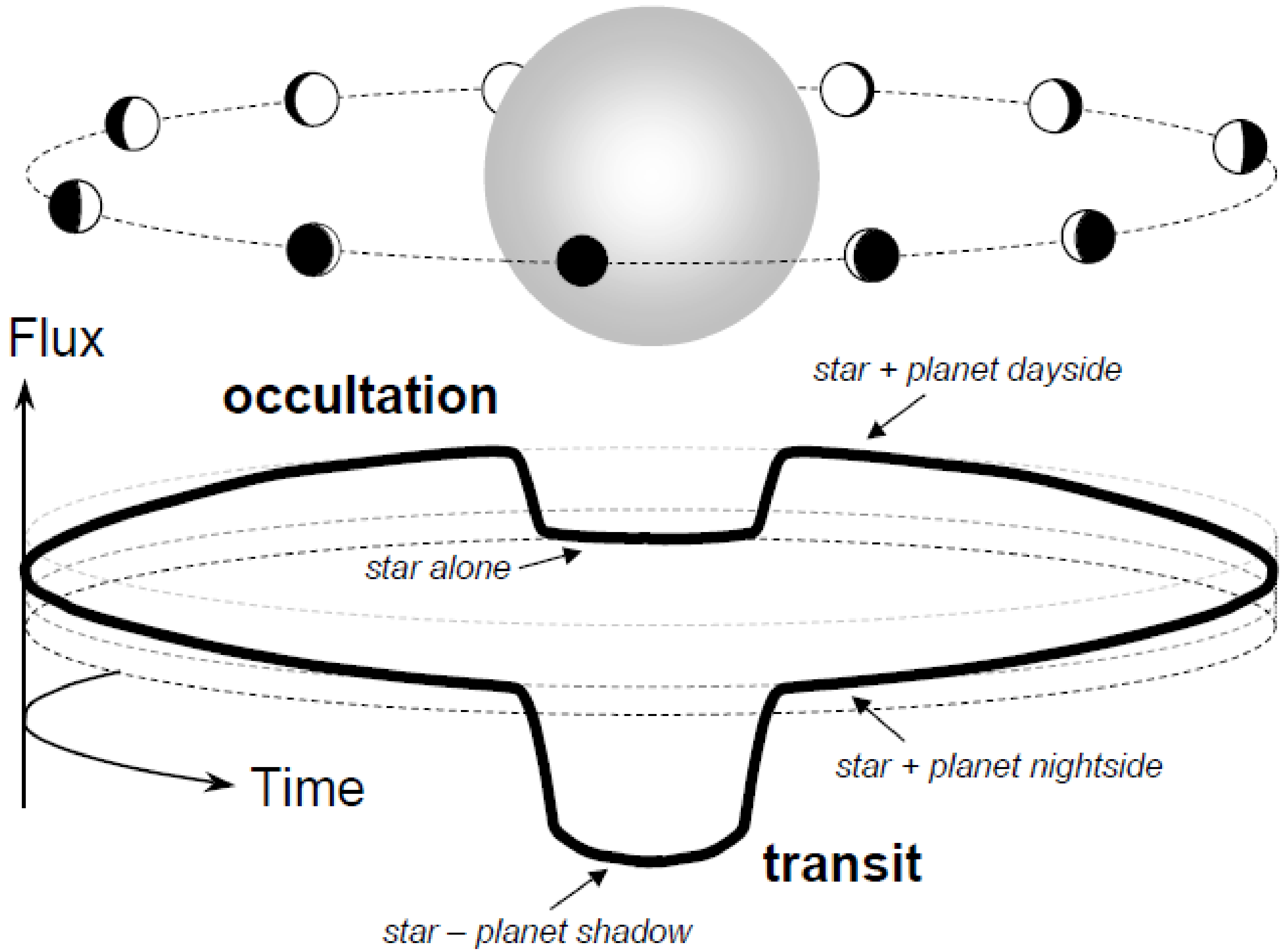
TiO species absorbing the stellar heat?



Mandell et al. (2015), "Spectroscopic Evidence for a Temperature Inversion in the Dayside Atmosphere of the Hot Jupiter WASP-33b", arXiv:1505.01490

Weather on exoplanets

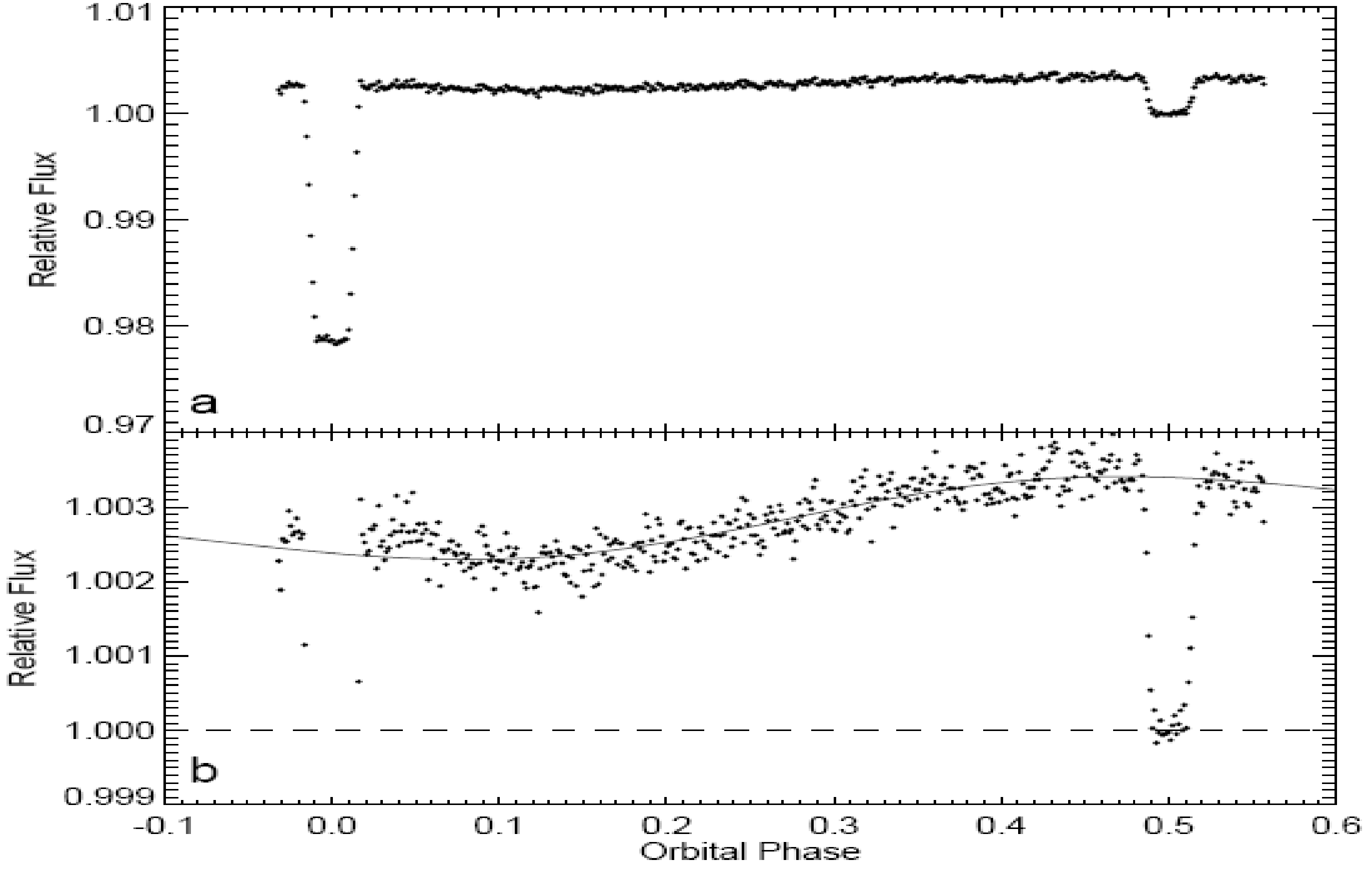
Eclipses/transits



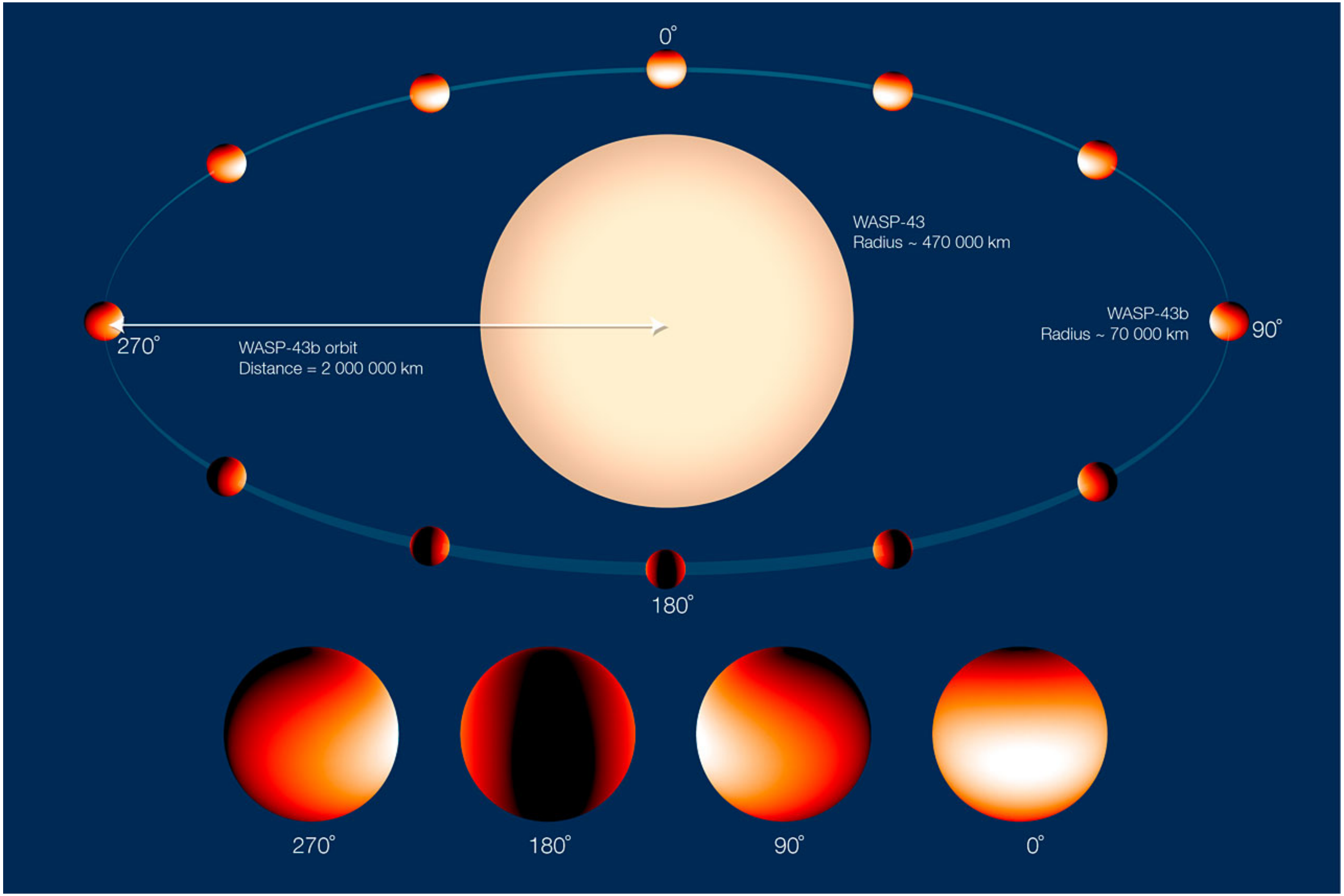
From Winn, 2010, http://arxiv.org/pdf/1001.2010v5.pdf

Variation due to day/night cycle

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

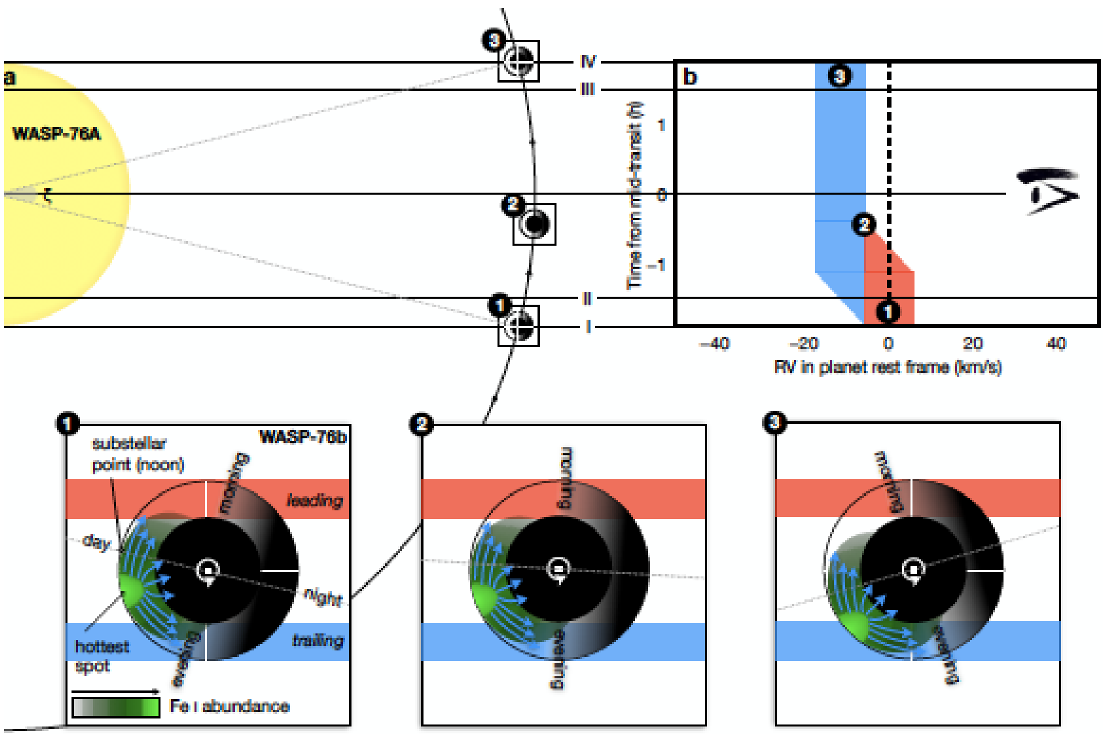


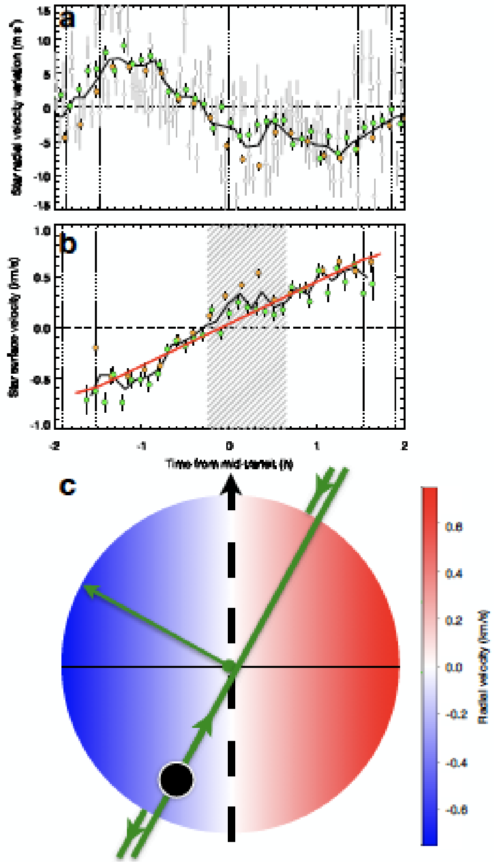
Knutson et al. 2007, Nature



https://www.spacetelescope.org/news/heic1422/

Raining iron?





Ehrenreich et al. 2020, https://arxiv.org/abs/2003.05528

TOI-700 example models

#	Archetype	Surface type	Surface pressure (bar)	Primary atmospheric constituent	Minor constituents, partial pressures (bar)	Rotation	Surface temperature (K)	TOA albedo	Sea ice fraction (%)	Stratospheric water vapor (kg/kg)
1	Plain	aqua	1	N_2	H_2O	synchronous	236.7	0.3968	76.2%	6.5014e−8
2	Modern Earth	aqua	1	N_2	H_2O CO_2 (4e-4) CH_4 (1.7e-6)	synchronous	246.7	0.3893	71.2%	3.605e−7
3	Modern Earth	land	1	N_2	H_2O CO_2 (4e-4) CH_4 (1.7e-6)	synchronous	232.7	0.2840	N/A	N/A
4	Archean Earth	aqua	1	N_2	H_2O CO_2 (0.01) CH_4 (1.0e-4)	synchronous	258.4	0.3594	66.3%	7.316e−7
5	Archean Earth	aqua	1	N_2	H_2O CO_2 (0.1) CH_4 (1.0e-3)	synchronous	263.2	0.3988	62.3%	2.644e−5
6	Archean Earth	aqua	1	N_2	H_2O CO_2 (0.1) CH_4 (2.0e-3)	synchronous	263.7	0.3998	61.6%	3.645e−5
7	Archean Earth	land	1	N_2	H_2O CO_2 (0.1) CH_4 (1.0e-3)	synchronous	251.5	0.2455	N/A	N/A
8	Archean Earth	aqua	0.5	N_2	H_2O CO_2 (0.1) CH_4 (1.0e-3)	synchronous	256.8	0.3906	67.3%	5.615e−5
9	Archean Earth	aqua	4	N_2	H_2O CO_2 (0.1) CH_4 (1.0e-3)	synchronous	307.2	0.317	0	6.406e−6
10	Archean Earth	aqua	10	N_2	H_2O CO_2 (0.1) CH_4 (1.0e-3)	synchronous	360.8	0.2452	0	2.203e−6
11	Archean Earth	aqua	1	N_2	H_2O CO_2 (0.1) CH_4 (1.0e-3)	2:1 resonant	325.7	0.131	0	6.095e−6
12	Archean Earth	land	1	N_2	H_2O CO_2 (0.1) CH_4 (1.0e-3)	2:1 resonant	257.0	0.2547	N/A	N/A
13	H_2-supporting	aqua	1	N_2	H_2O CO_2 (0.1) CH_4 (1.0e-3) H_2 (0.1)	synchronous	267.6	0.394	60.3%	2.669e−5
14	Early Mars	aqua	0.5	CO_2	H_2O	synchronous	266.2	0.3572	62.6%	2.802e−5
15	Early Mars	aqua	1	CO_2	H_2O	synchronous	284.4	0.3775	0.05%	2.520e−5
16	Early Mars	aqua	2	CO_2	H_2O	synchronous	324.3	0.2771	0%	3.027e−5
17	Early Mars	aqua	4	CO_2	H_2O	synchronous	364.2	0.2214	0%	2.857e−4
18	Early Mars	land	1	CO_2	none	synchronous	258.9	0.2304	N/A	N/A
19	Early Mars	land	4	CO_2	none	synchronous	302.3	0.2165	N/A	N/A
20	Early Mars	land	10	CO_2	none	synchronous	353.5	0.2310	N/A	N/A

Table 3. Global mean climatological properties for each of our simulations. By definition, sea ice fraction and stratospheric water vapor or not applicable for desiccated land planet cases. The stratospheric water vapor is taken at the model top, 0.01 mbar. All quantities given are the global and temporal mean.

Suissa et al 2020- https://arxiv.org/abs/2001.00955

TOI-700 example models

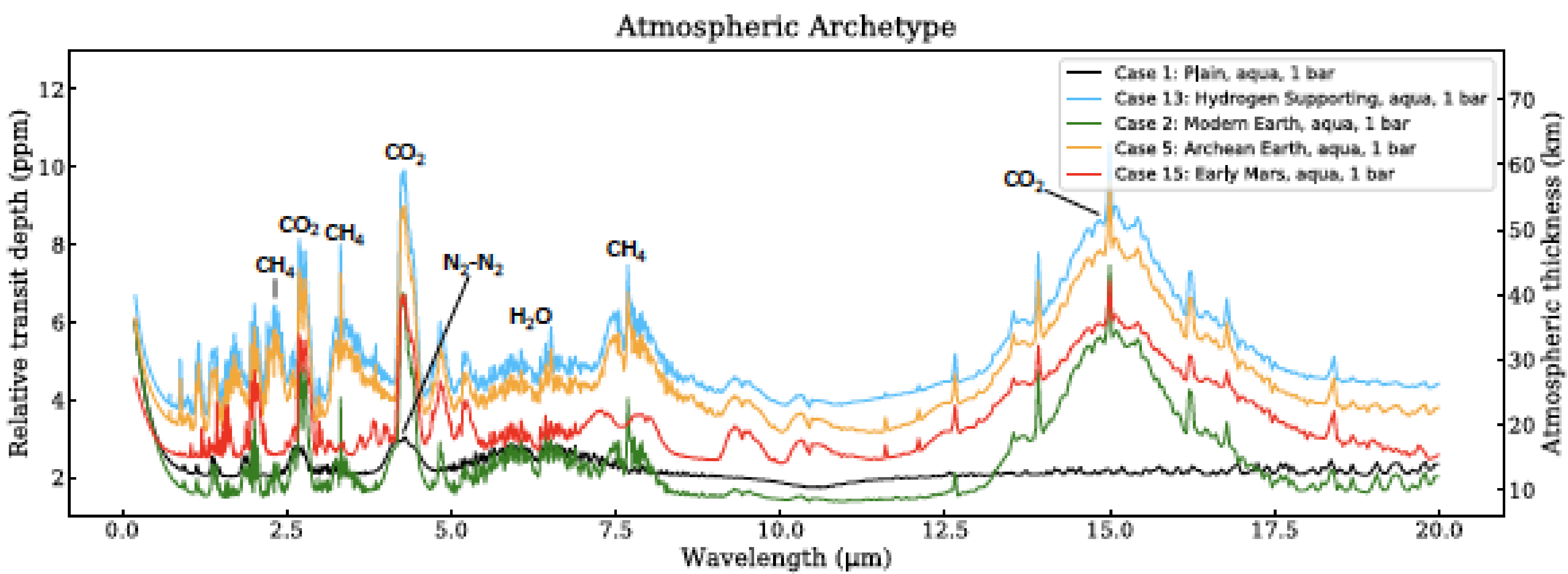


Figure 4. Comparison of transmission spectra for different atmospheric archetypes. All simulations shown here are ocean-covered and have a surface pressure of 1 bar. Prominent features are labeled. The spectrum for the "hydrogen-supporting" atmosphere (10% H_2) has both the highest continuum and the largest 15 μm CO_2 feature.

Suissa et al. 2020 - https://arxiv.org/abs/2001.00955

TOI-700 example phase curves

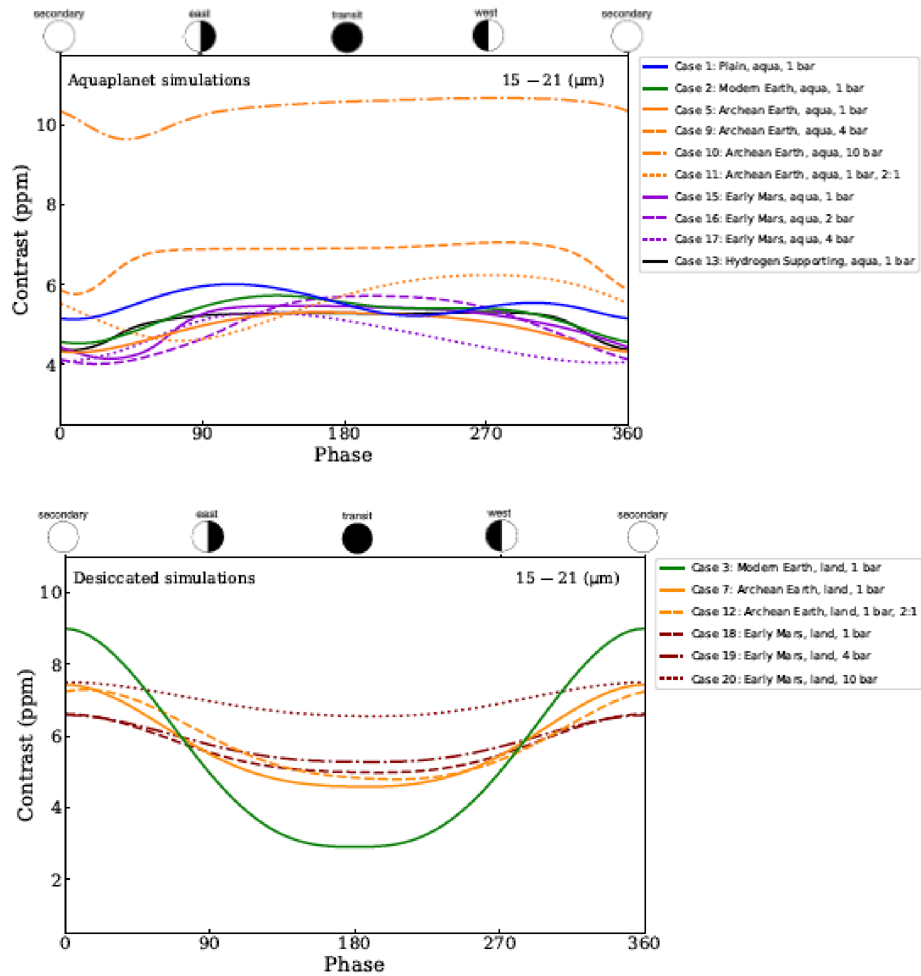
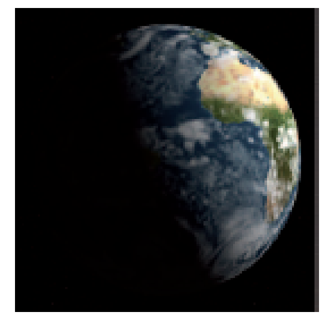
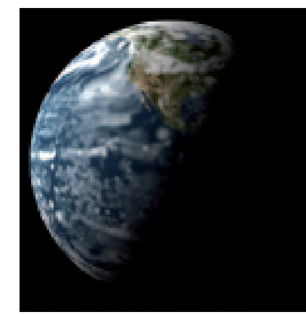


Figure 10. Phase curves for the majority of our simulations in this work. Aquaplanets are shown in the top panel; desiccated planets are shown in the bottom panel. Transit occurs at 180°. In the left panel, the contribution of reflected light dominates at wavelengths <∼4.3μm, while thermally emitted light dominates at wavelengths >∼4.3μm. In the right panel, the integrated fluxes for the phase curves are 15−21 μm.

Suissa et al. 2020 - https://arxiv.org/abs/2001.00955

The Earthshine

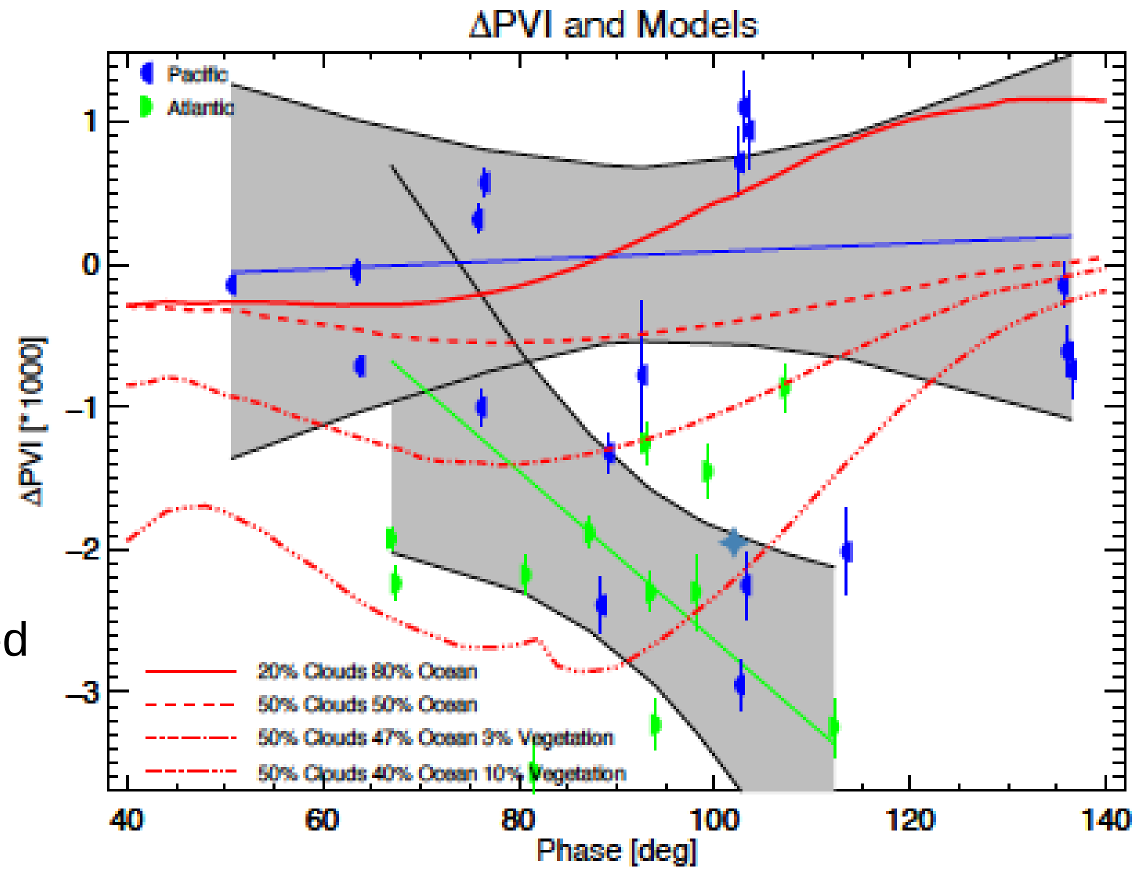
- Sterzik et al. 2012, Nature
- Observing of the Earthsine reflected by the Moon
- FORS at VLT
- Polarization can help to describe the surface features

	Observing date	
Observations	25 April 2011, 09:00 UT	10 June 2011, 01:00 UT
View of Earth as seen from the Moon		
Sun–Earth–Moon phase (degrees)	87	102
Ocean fraction in Earthshine (%)	18	46
Vegetation fraction in Earthshine (%)	7	3
Tundra, shrub, ice and desert fraction in Earthshine (%)	3	1
Total cloud fraction in Earthshine (%)	72	50
Cloud fraction $\tau > 6$ (%)	42	27

Credits: http://research.iac.es/proyecto/earthshine//media/publications/nature10778.pdf

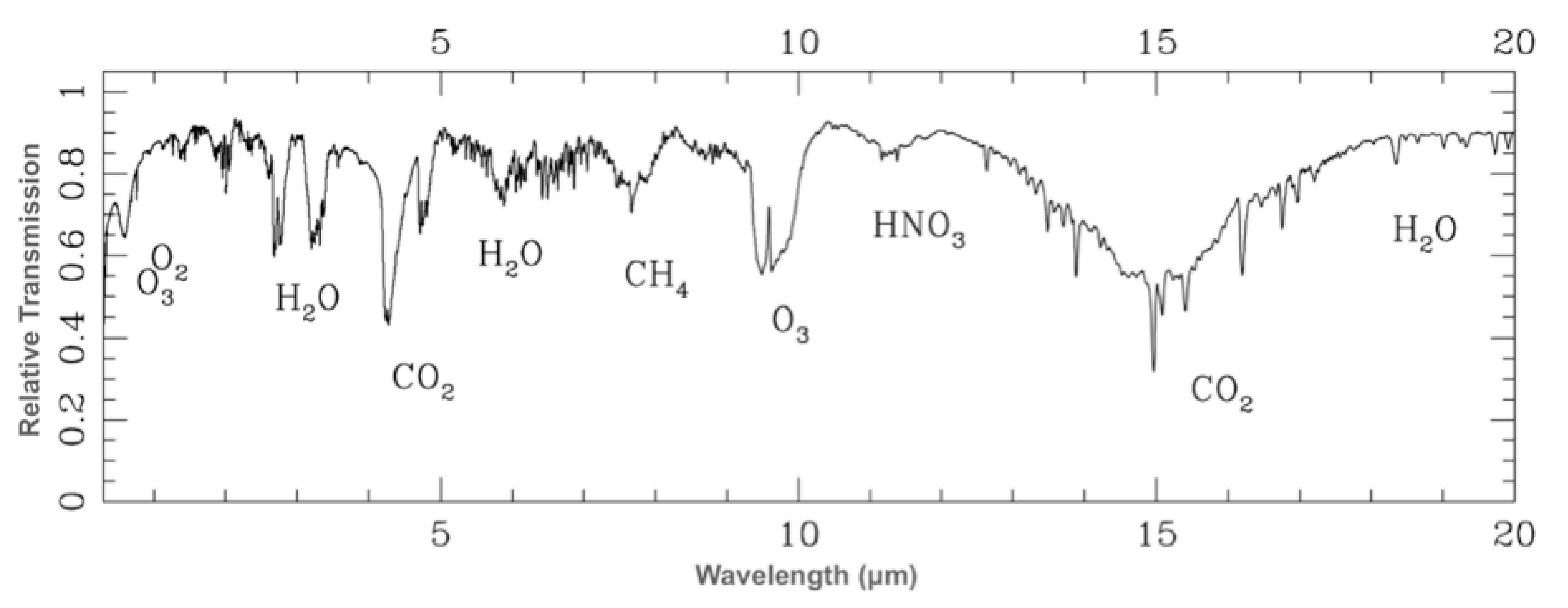
The Earthshine

- The Atlantic side hints at decreasing PVI
- The Pacific side shows no correlation with PVI
- PVI is a Polarization Vegatation Index
- PVI reflects the difference of polarization between vegetated and not vegetated surfaces

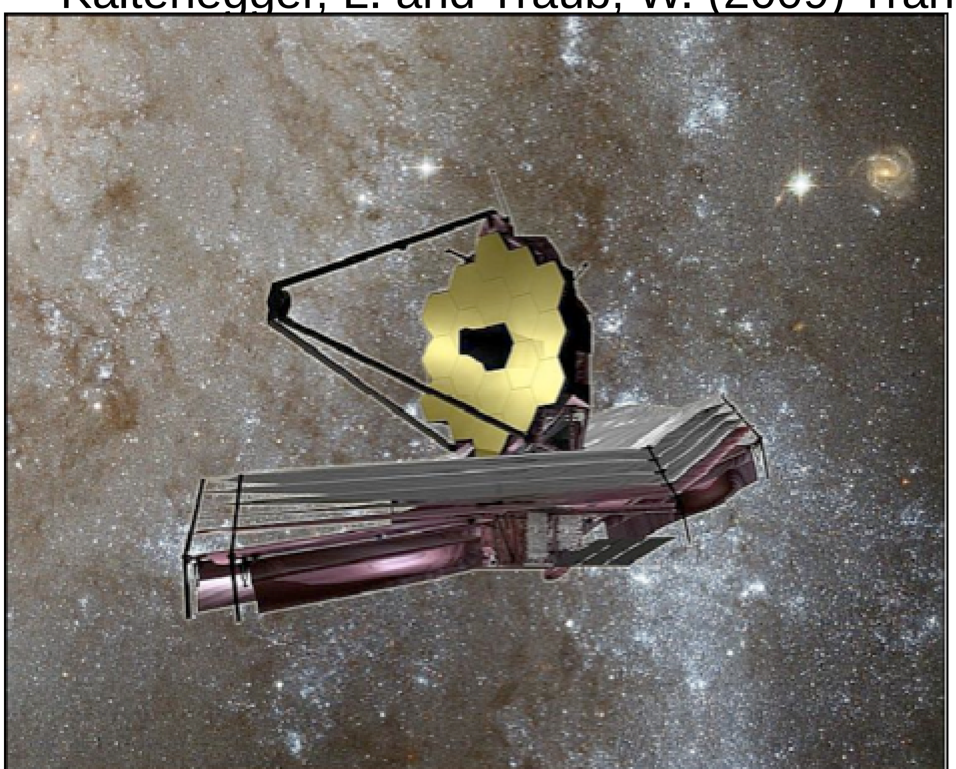


Credit: Sterzik et al. 2018, A&A, https://arxiv.org/pdf/1811.12079.pdf

Next week (Xmass session)
Life in the Universe
Habitable zones
Discussions (papers)



Kaltenegger, L. and Traub, W. (2009) Transits of Earth-Like Planets. Astrophysical Journal



JWST
Launch 2018
Ideal for characterization of small planets in infrared
Image NASA