Exoplanets

Lecture 10
12.12.2025
MFF UK
Winter semester 2025/2026

Exoatmospheres

Outline

- Recap exoatmospheres
- Detection methods

  - spectroscopic

  - spectrophotometric
- Weather on exoplanets
- Challenges of precise spectroscopy/photometry

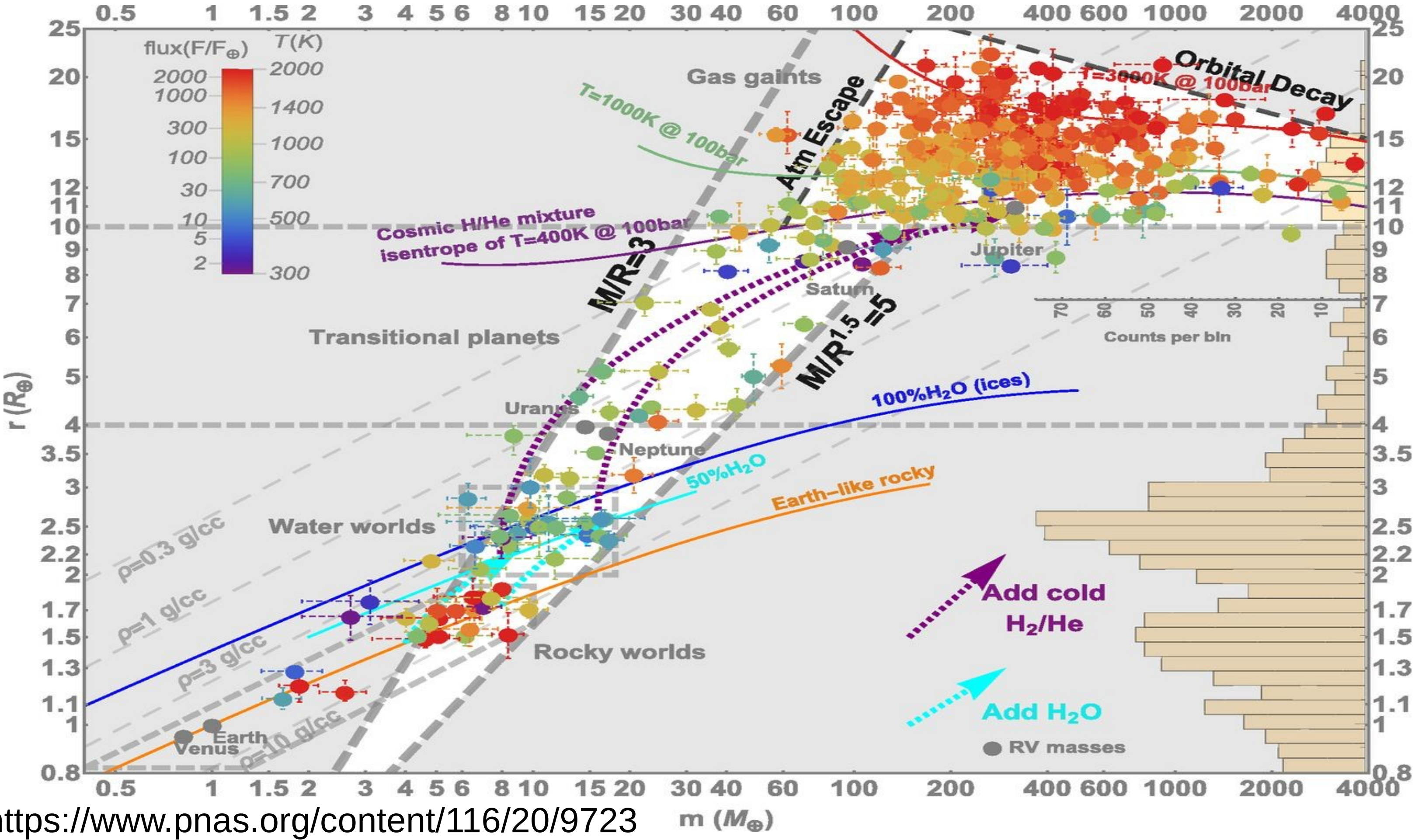
What do we know?

- Atmospheres of exoplanets do exist
- We know different types of atmospheres on exoplanets

  - H/He rich, heavy elements rich, water

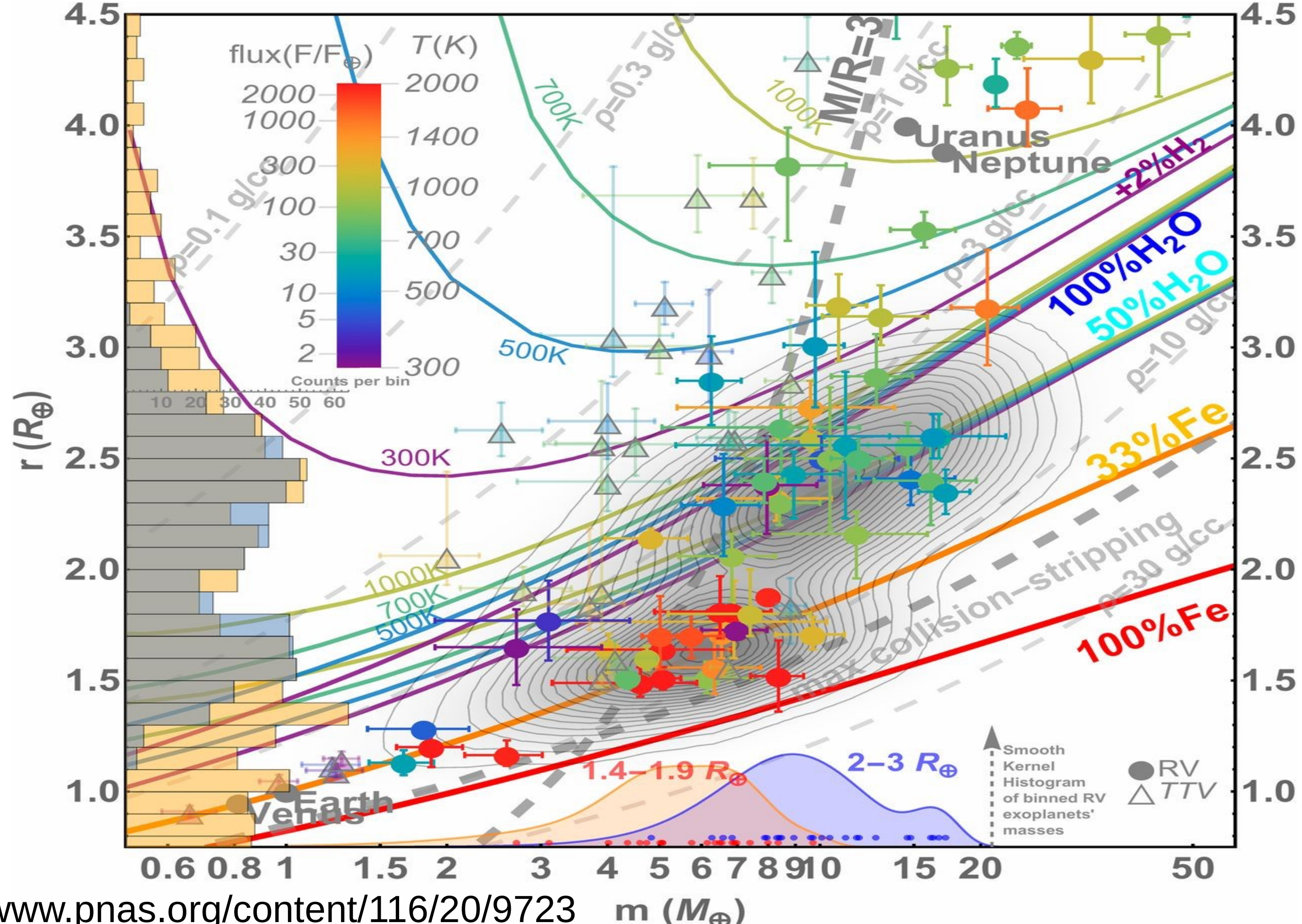
  - the thinner the atmosphere is the more challenging is its detection
- Large telescopes with precise instruments needed, but….

Mass-radius



Zeng et al. https://www.pnas.org/content/116/20/9723

Missing small planets?



Zeng et al. https://www.pnas.org/content/116/20/9723

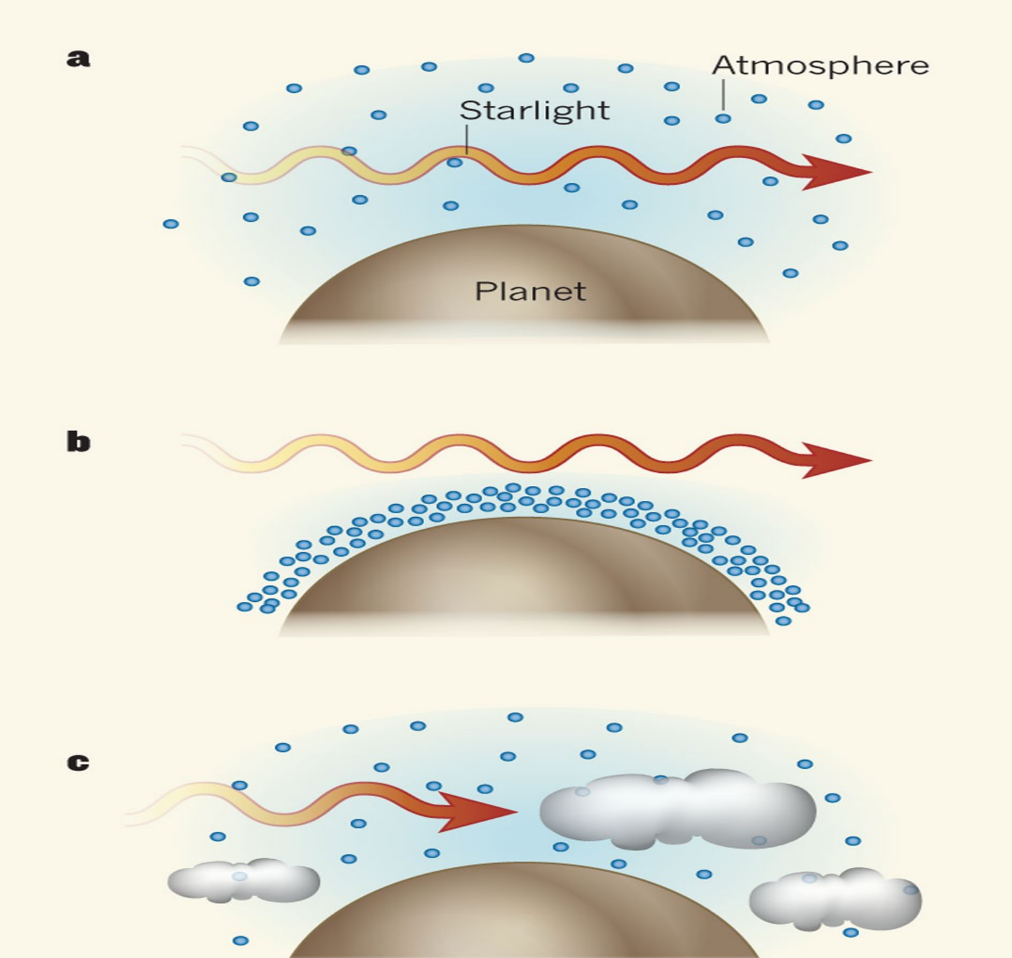
Scale height

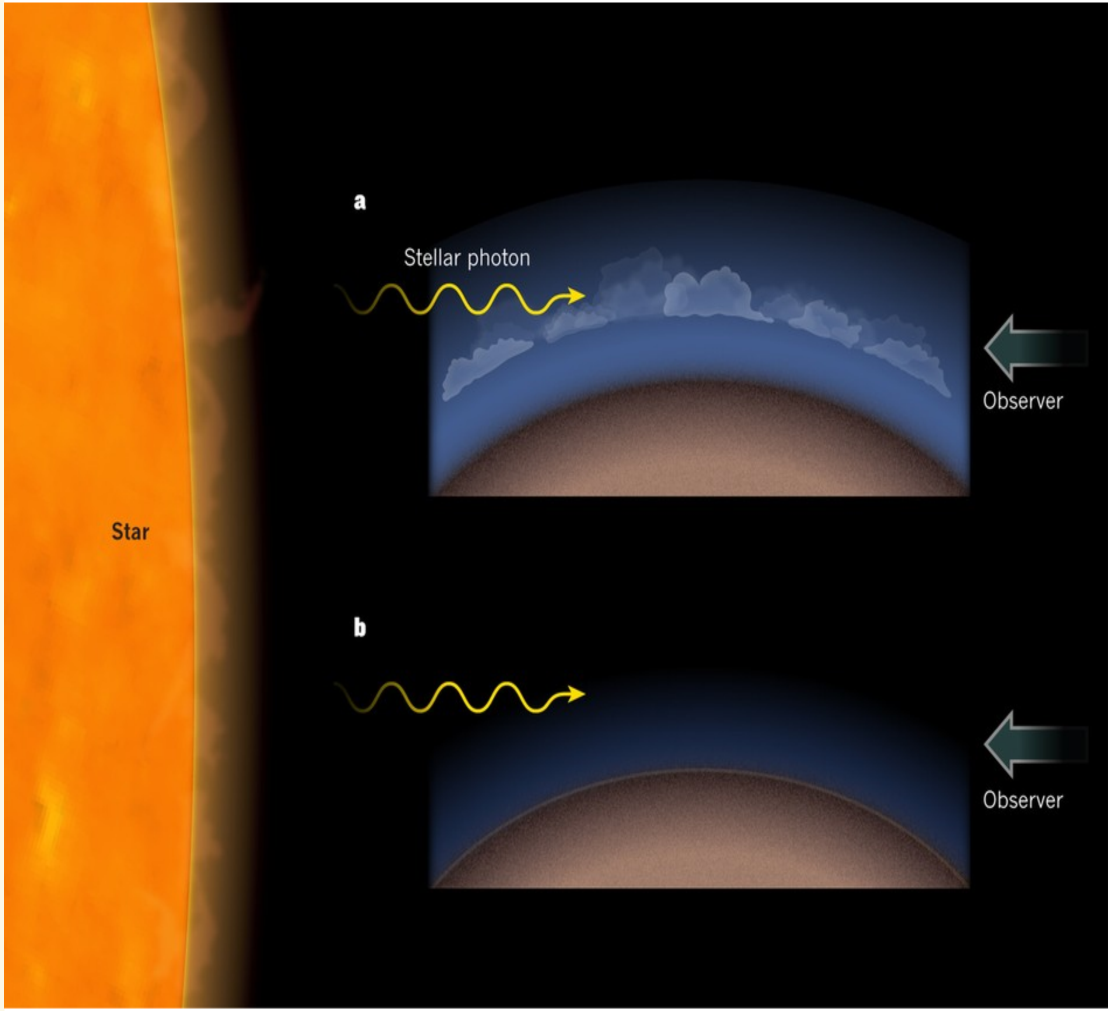
$$H = \frac{kT}{Mg}$$

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

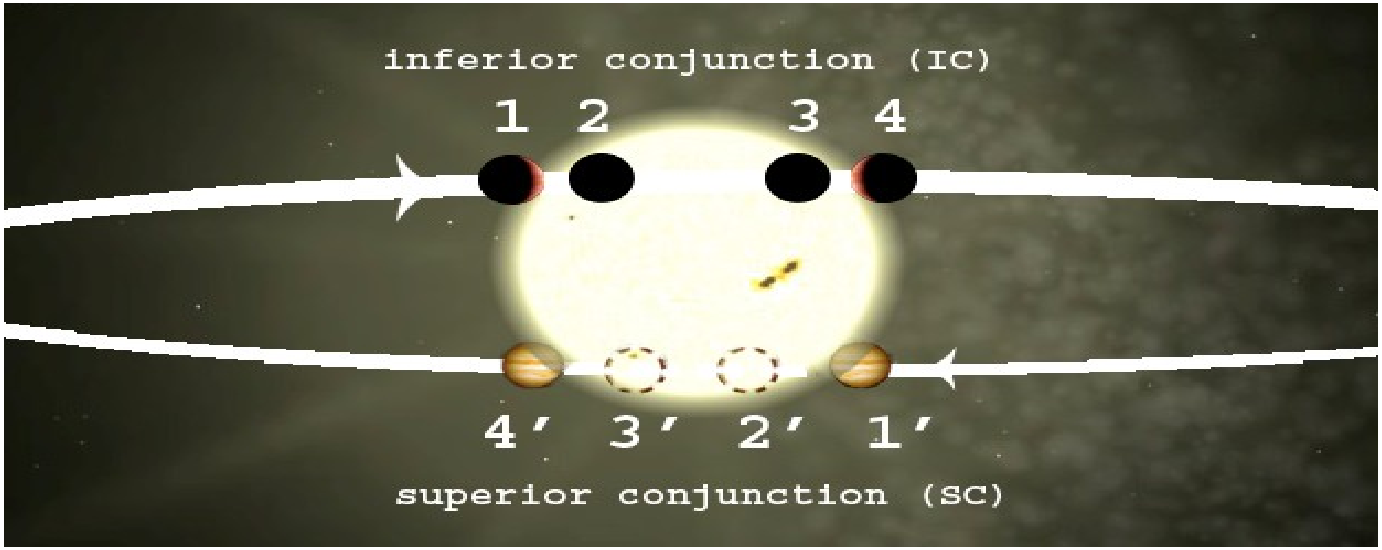
And how to detect the atmospheres?

- 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

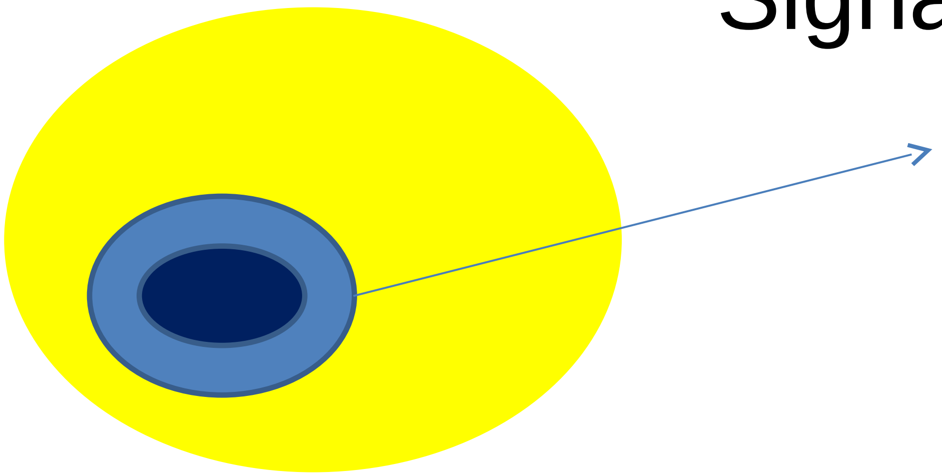


From Angerhausen et al. 2008

Transit spectroscopy, the principle

Transit spectroscopy = transmission spectroscopy

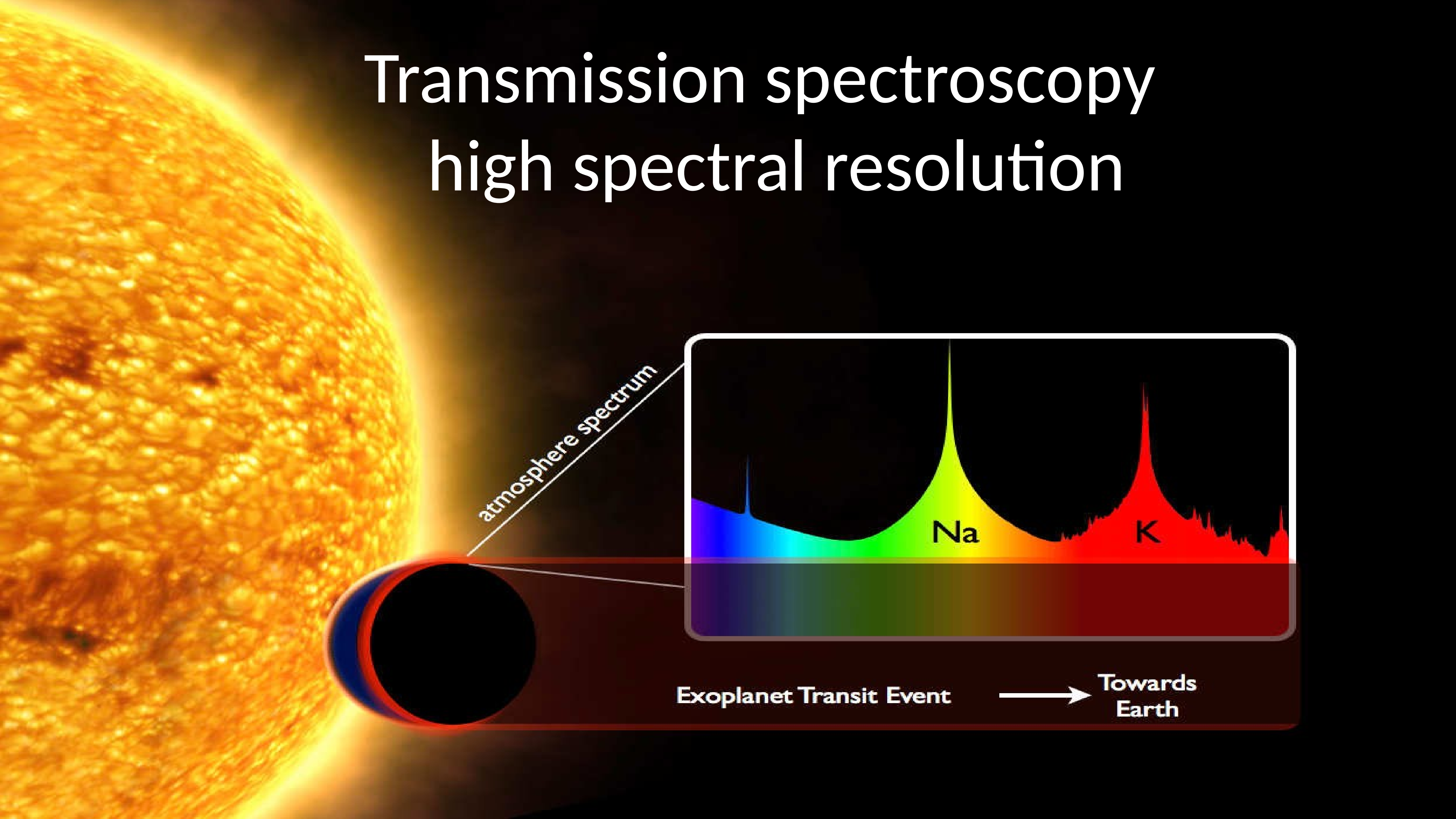
$$Signal = Annulus/R^2_{star}$$



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

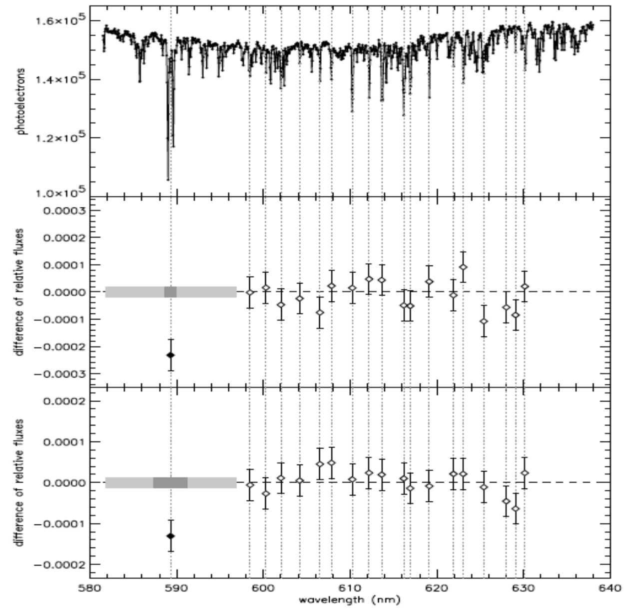
Smaller star & larger planet = better chance to see something

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

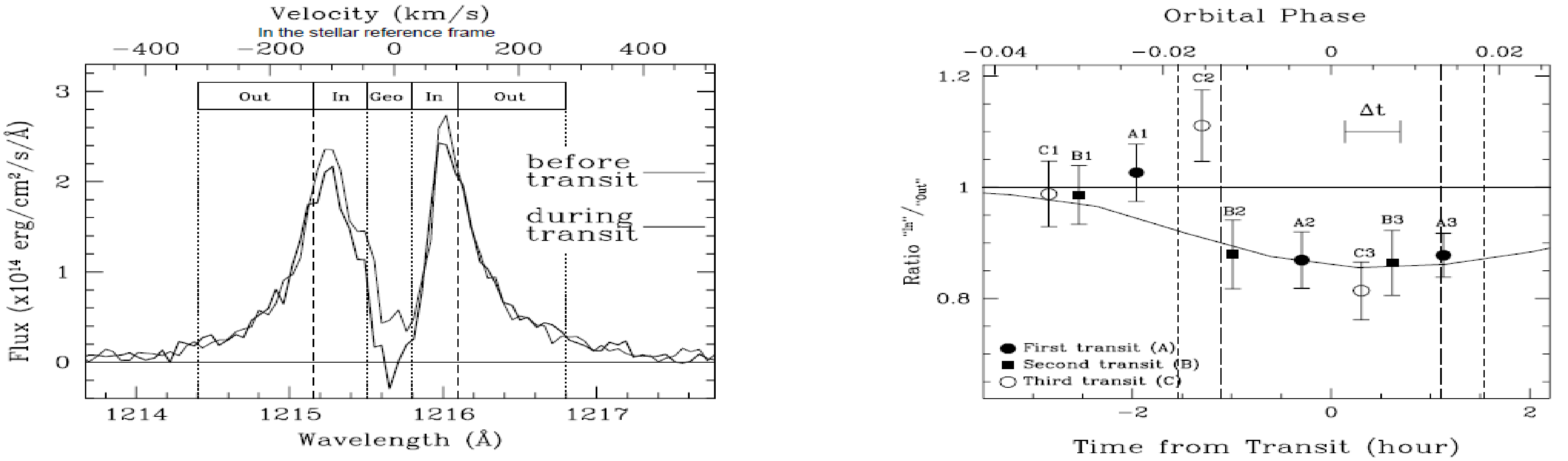


Figure 1. **Left:** The Lyman α stellar line as observed by Vidal–Madjar et al. (2003). The averaged profile observed during transit (thick line) presents a reduced flux when compared to the pre–transit profile (thin line). The region named "Geo" corresponds to the region where the geocoronal Lyman α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

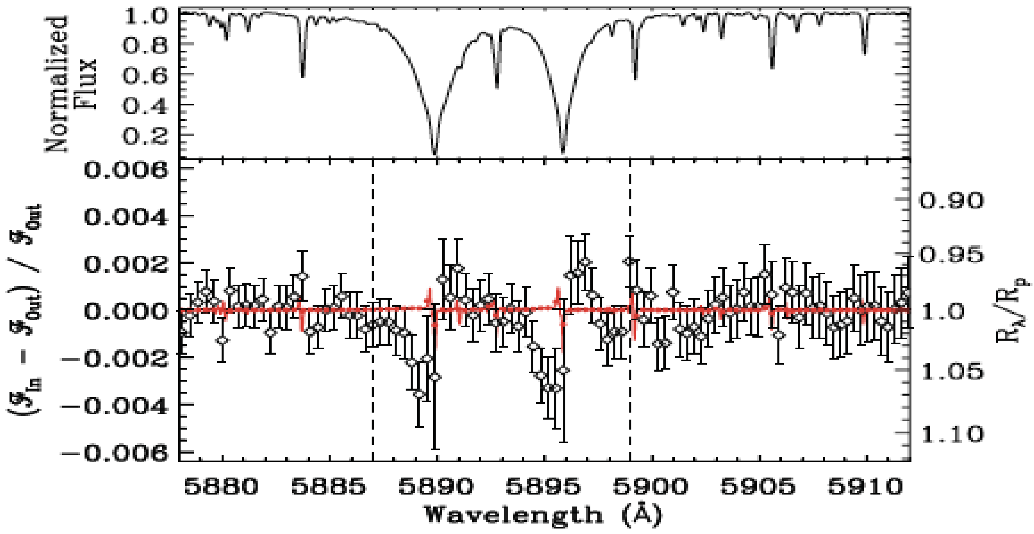


Image from Redfield et al 2008

First ground-based detection with 4m class telescope

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

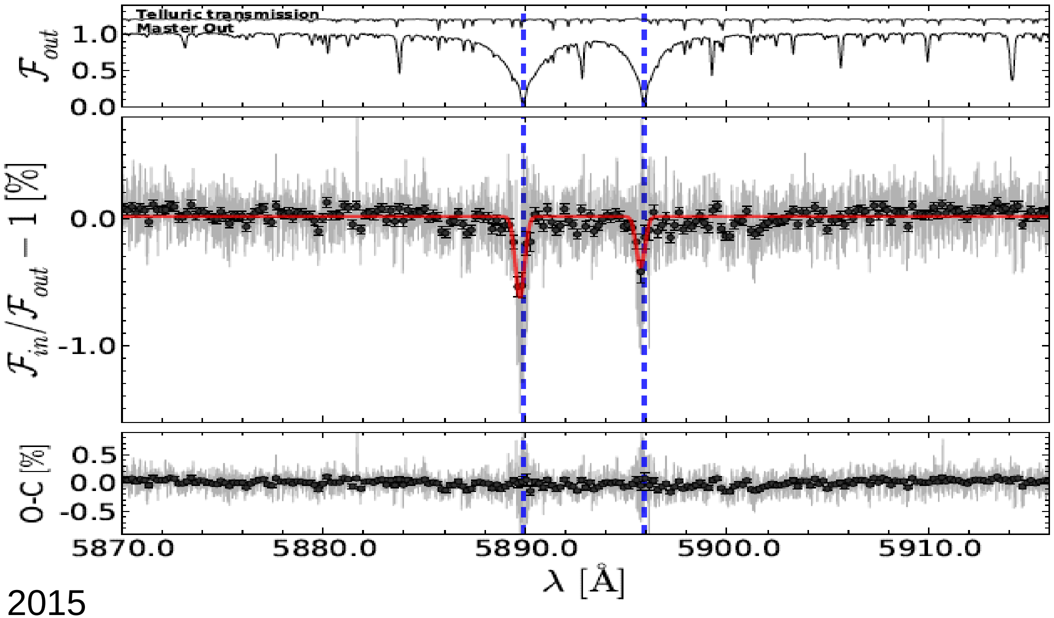
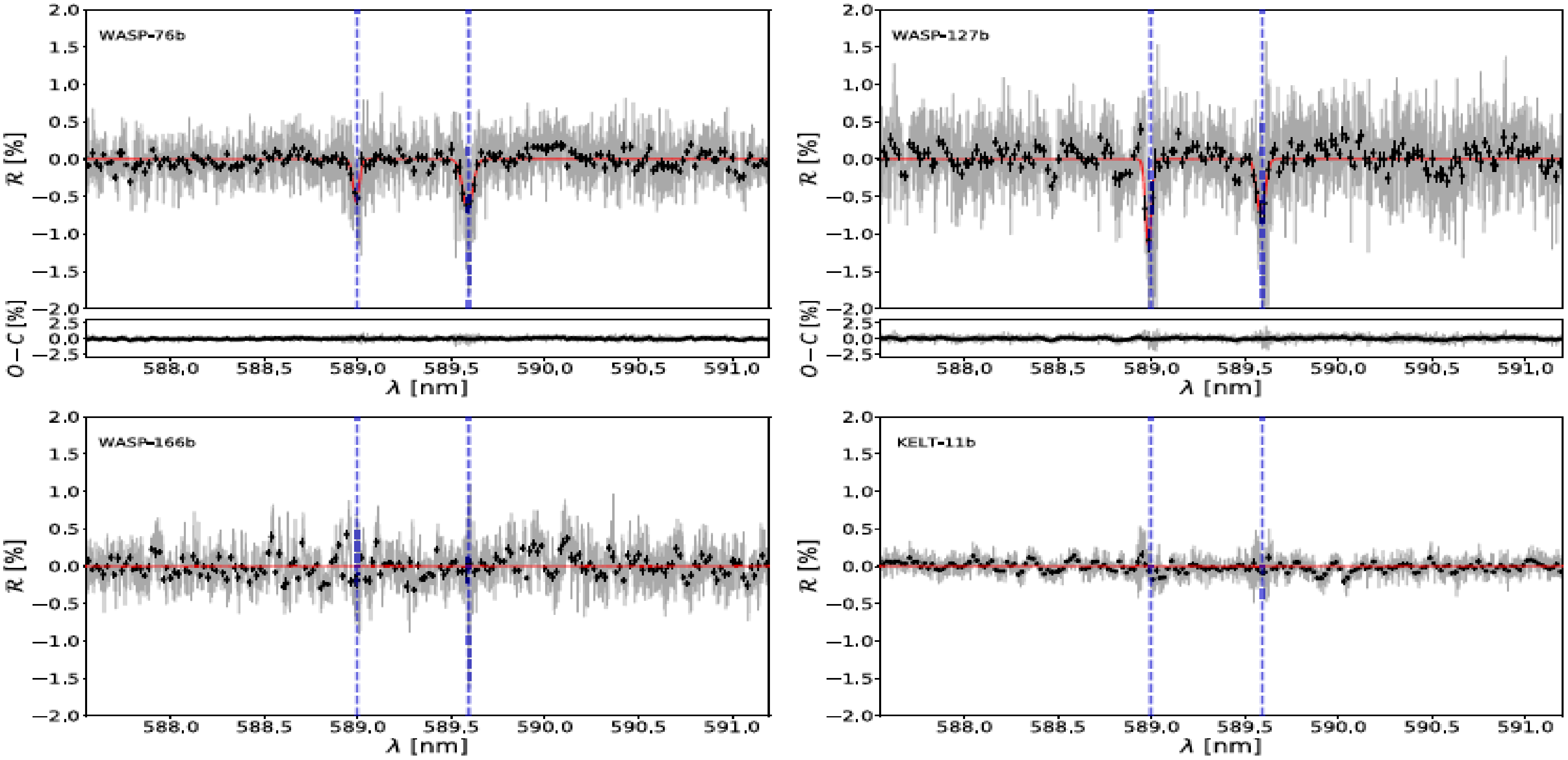


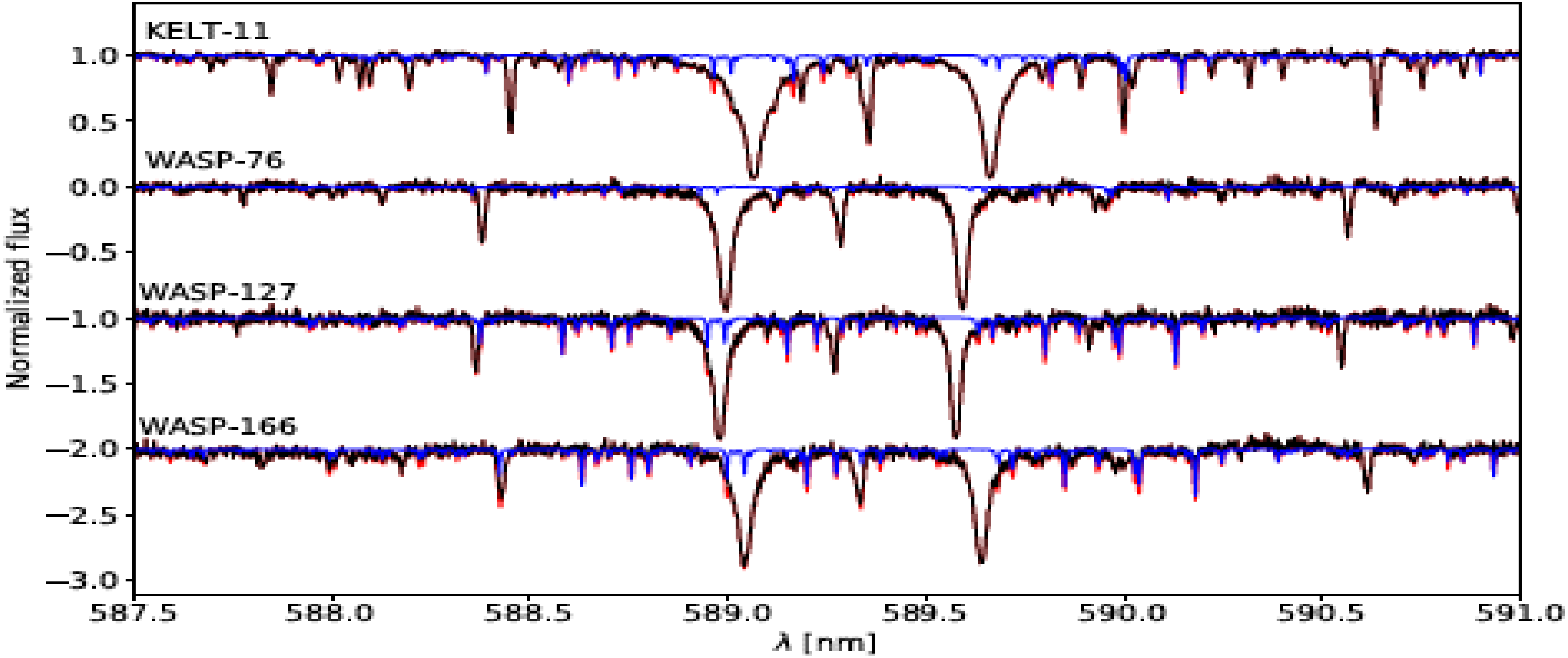
Image from Wyttenbach et al. 2015

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

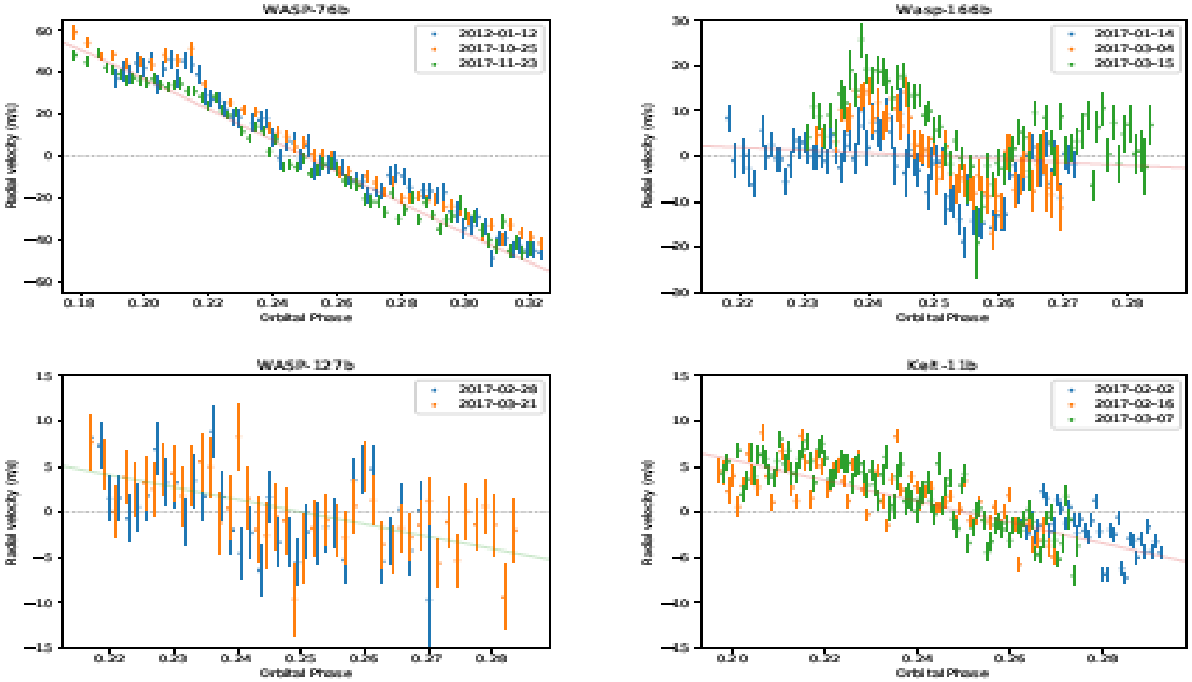


Figure 4. The radial velocities of our targets have been measured with HARPS: WASP-76 (top left), WASP-166 (top right), WASP-127 (bottom left) and KELT-11 (bottom right). There is some apparent offset between various epochs for the same target, which may be due to some instrumental shift or could be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

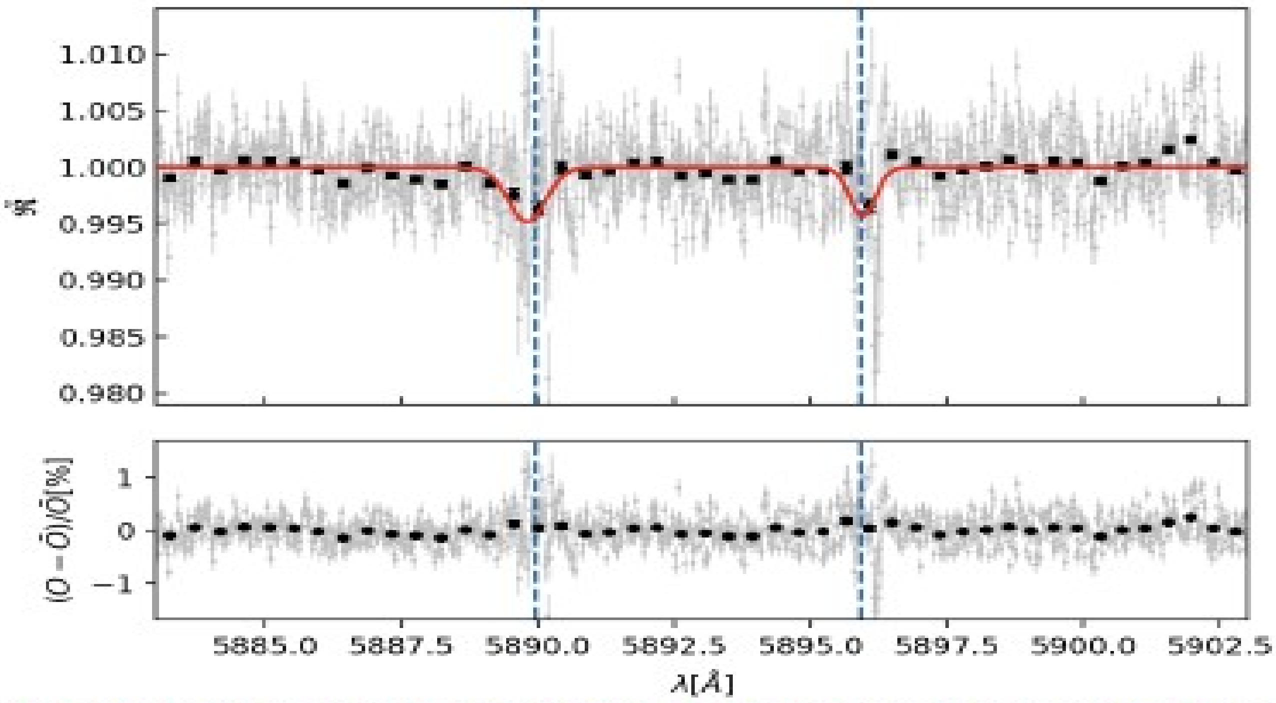


Fig. 4. HARPS sodium doublet transmission spectrum of WASP-166b for all nights combined shown in the PRF. Upper panel: In grey, data points at full HARPS resolution. In black, grey data points binned by x25 for visibility. The theoretical line centres for the sodium doublets are shown as vertical blue 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

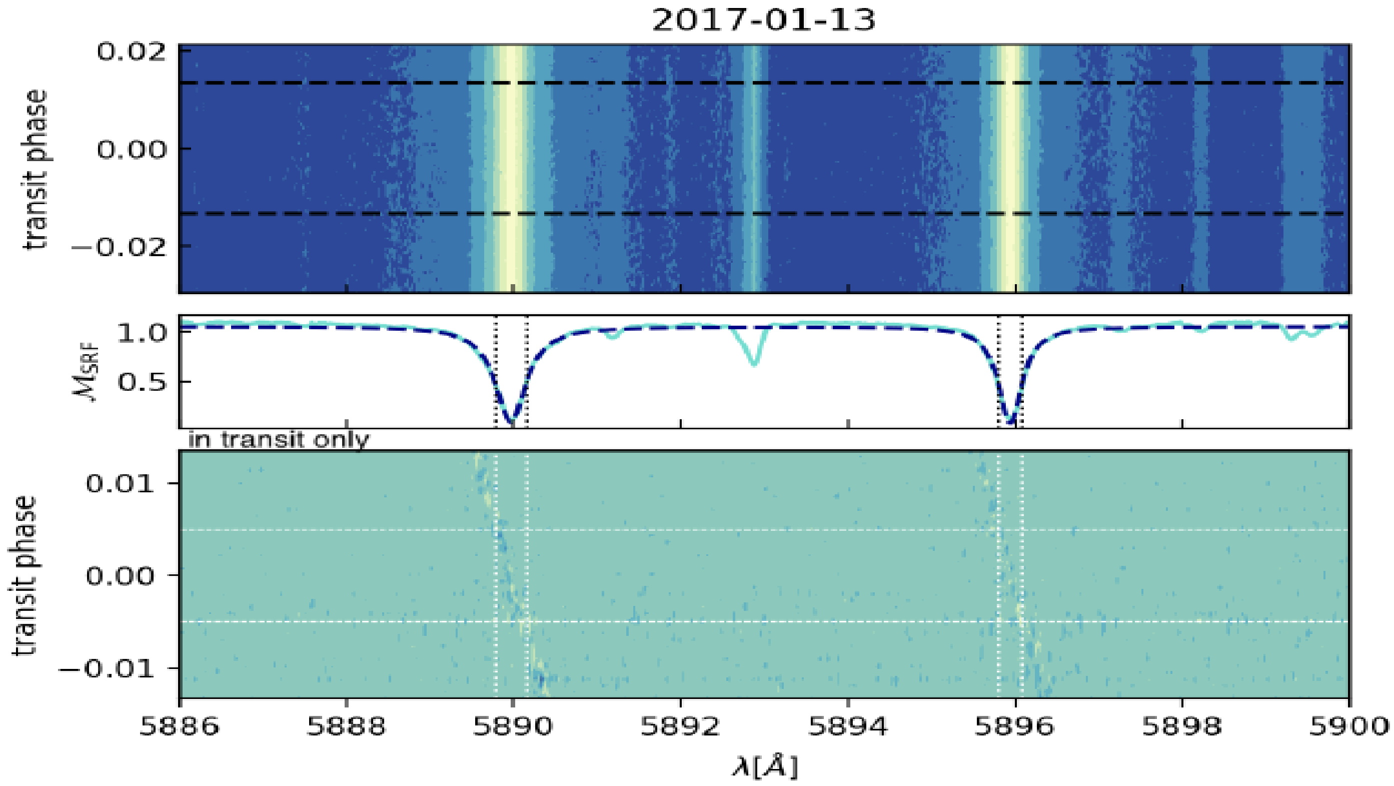


Fig. A.1. The upper panel shows all spectra in the SRF as a 2D map of wavelength and transit phase for the first transit. The stellar sodium doublet is visible as two horizontal light yellow bands. Transit ingress and egress are marked with black dashed lines. The central plot shows the normalised sum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

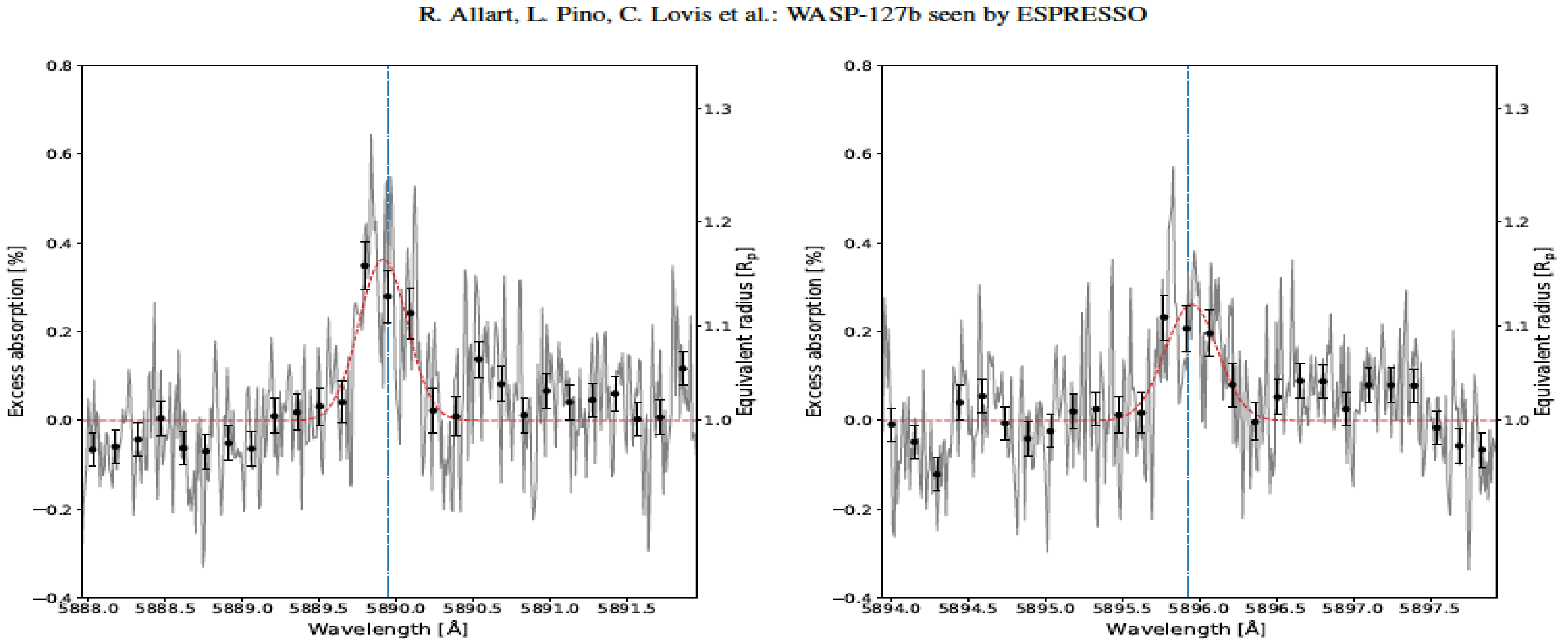
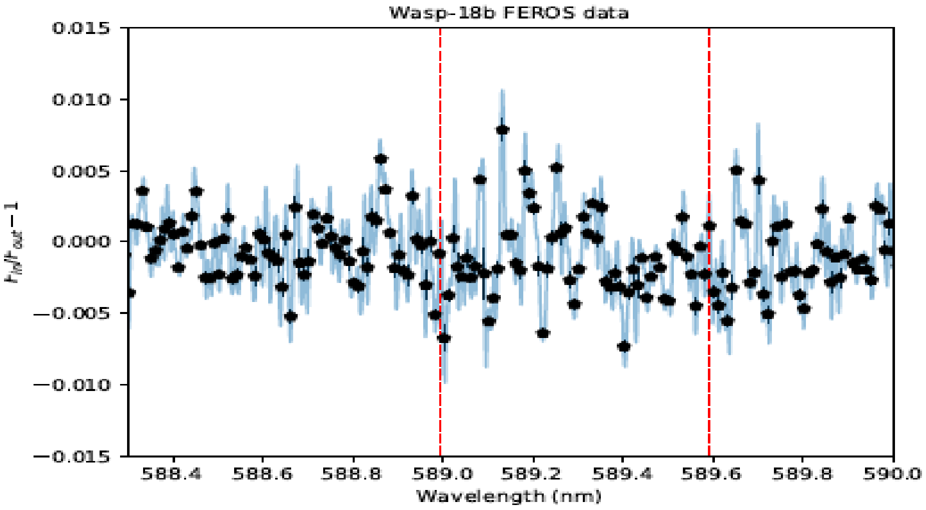


Fig. 8: Transmission spectrum around the Na D2 (*left*) and Na D1 (*right*) line averaged across the two transits in grey and binned by fifteen elements in black. The vertical blue dash dotted line represents the expected position of planetary sodium lines.

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!



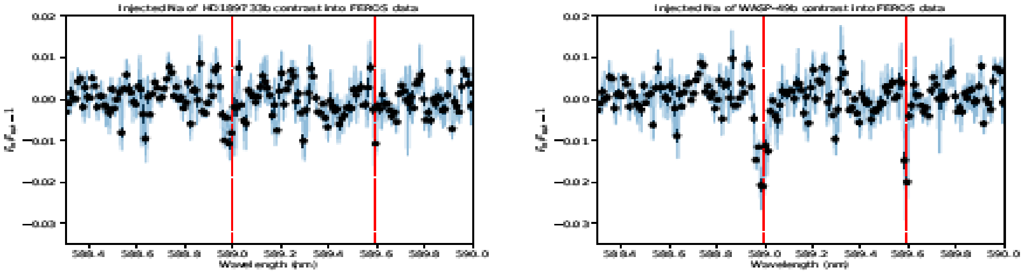


Figure 4. Sanity test with injected signal: (left) the signature of sodium absorption in the planetary atmosphere was injected into the FEROS WASP-18b data set. The strength of the sodium signal was set to be equal to that detected from HD189733b by Wyttenbach et al. (2015). (right) Injected sodium signal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

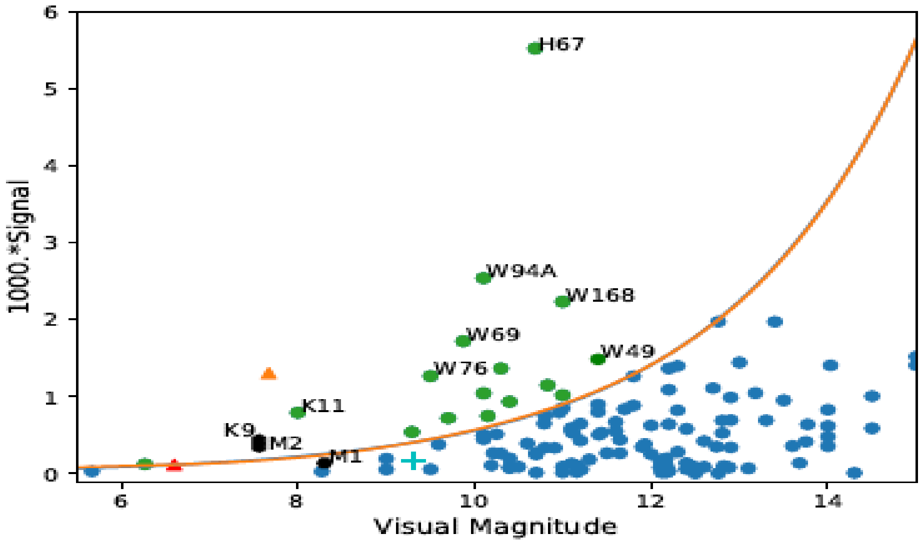


Figure 5. The expected atmospheric signal for well-characterised transiting plan as a function of the visual magnitude of the host star. The orange triangle shows the position of HD 189733, while the red triangle is the rescaled value, assuming a 2m-class telescope (see text). All the points above the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

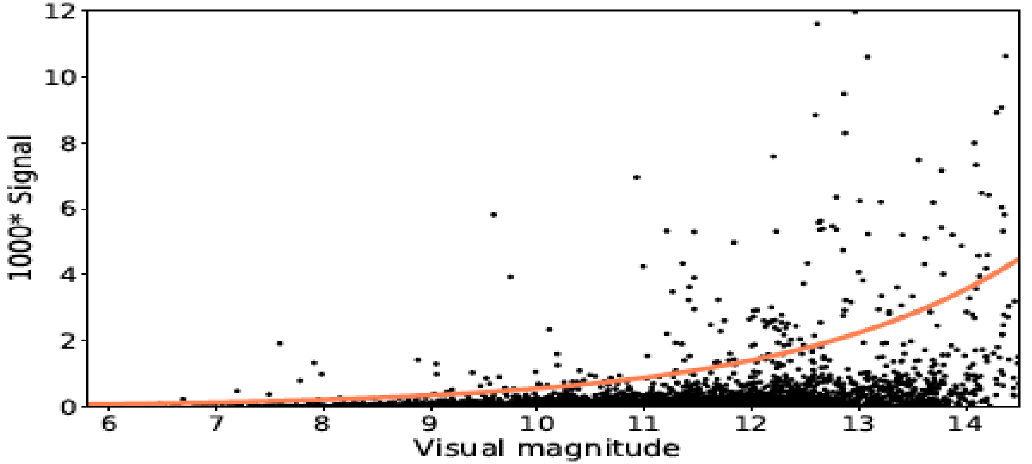
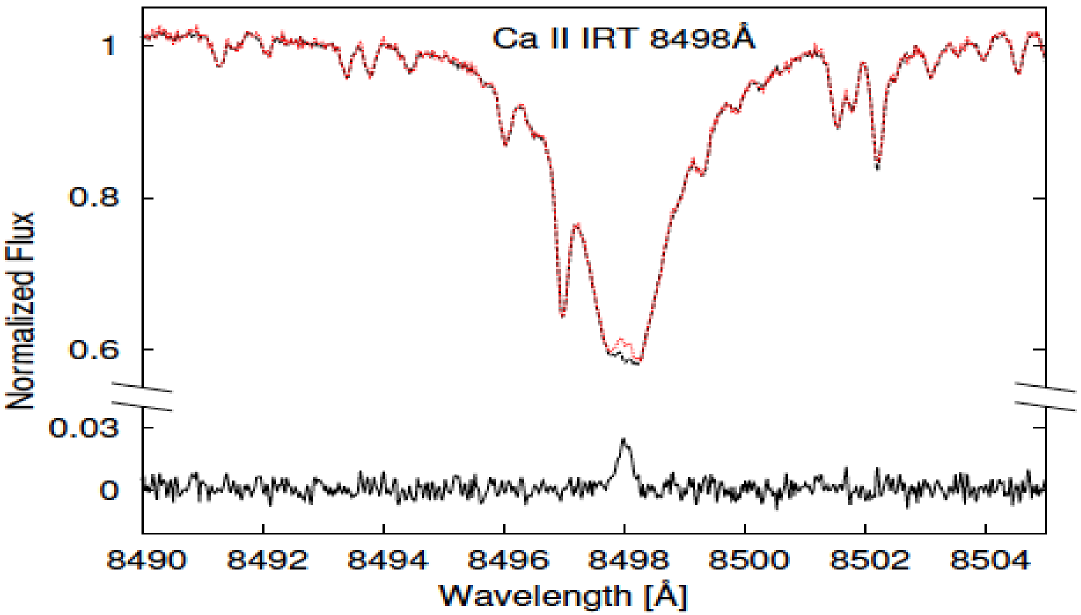


Figure 6. Expected signal as in previous Fig. 5 but from TESS planets which are depicted as black dots. The orange line is the detection limit for 2-m telescopes and good candidates for further follow-up will be above the line (see text for more detail).

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

What happens if the star is flaring?

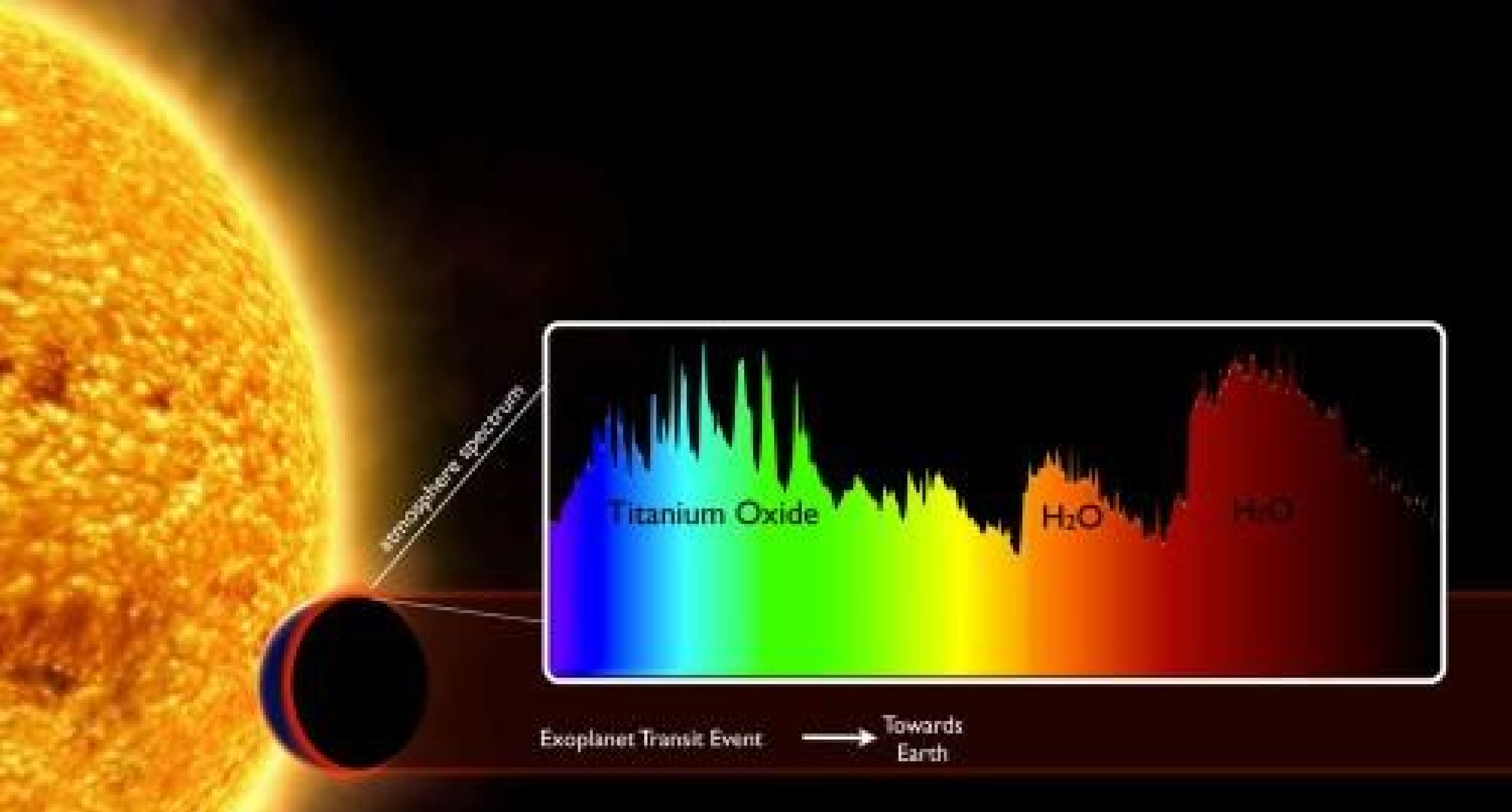
- Klocova 2017 et al. - https://arxiv.org/pdf/1707.09831.pdf
- What happens if during the transit a flare occurs?



Other methods

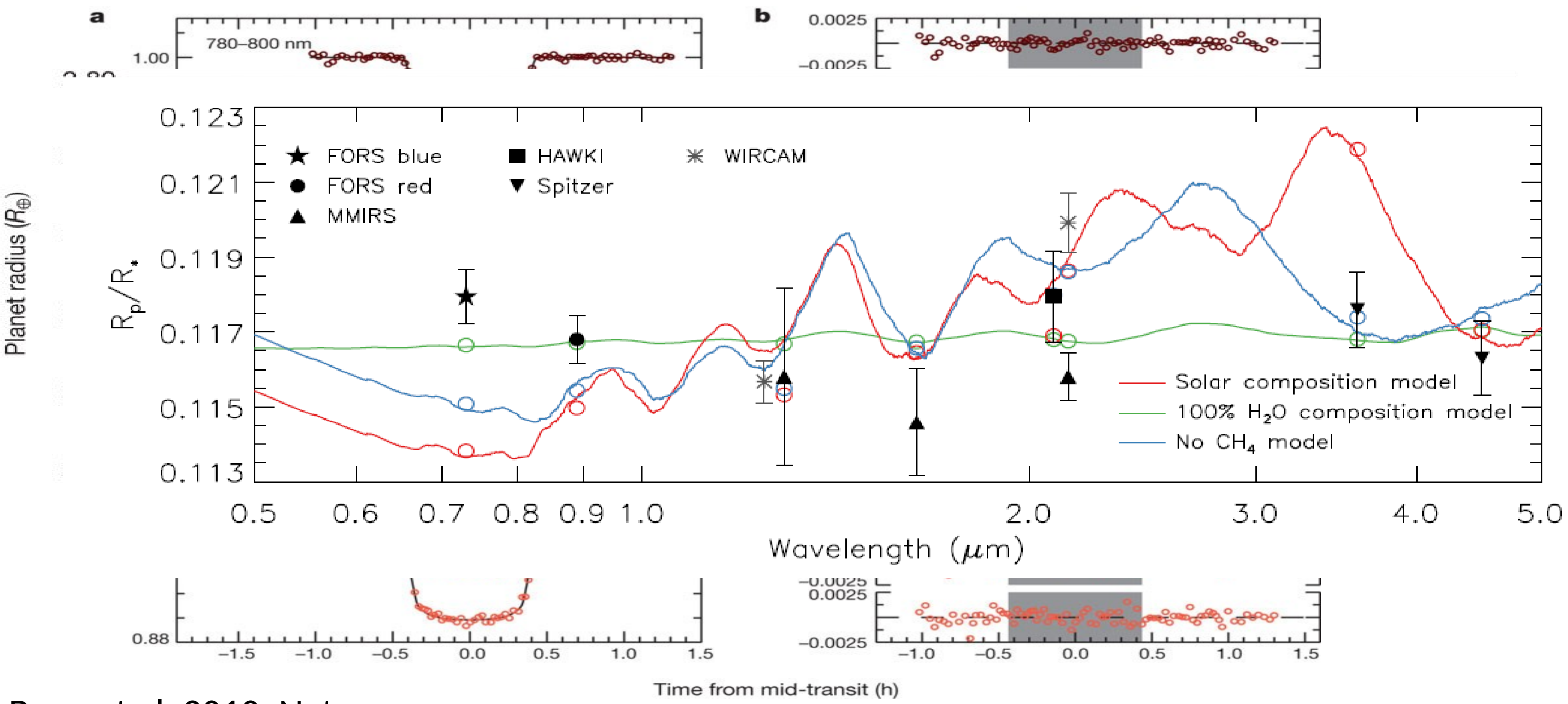
Spectrophotometry

- 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
Exoplanet Transit Event
Towards Earth

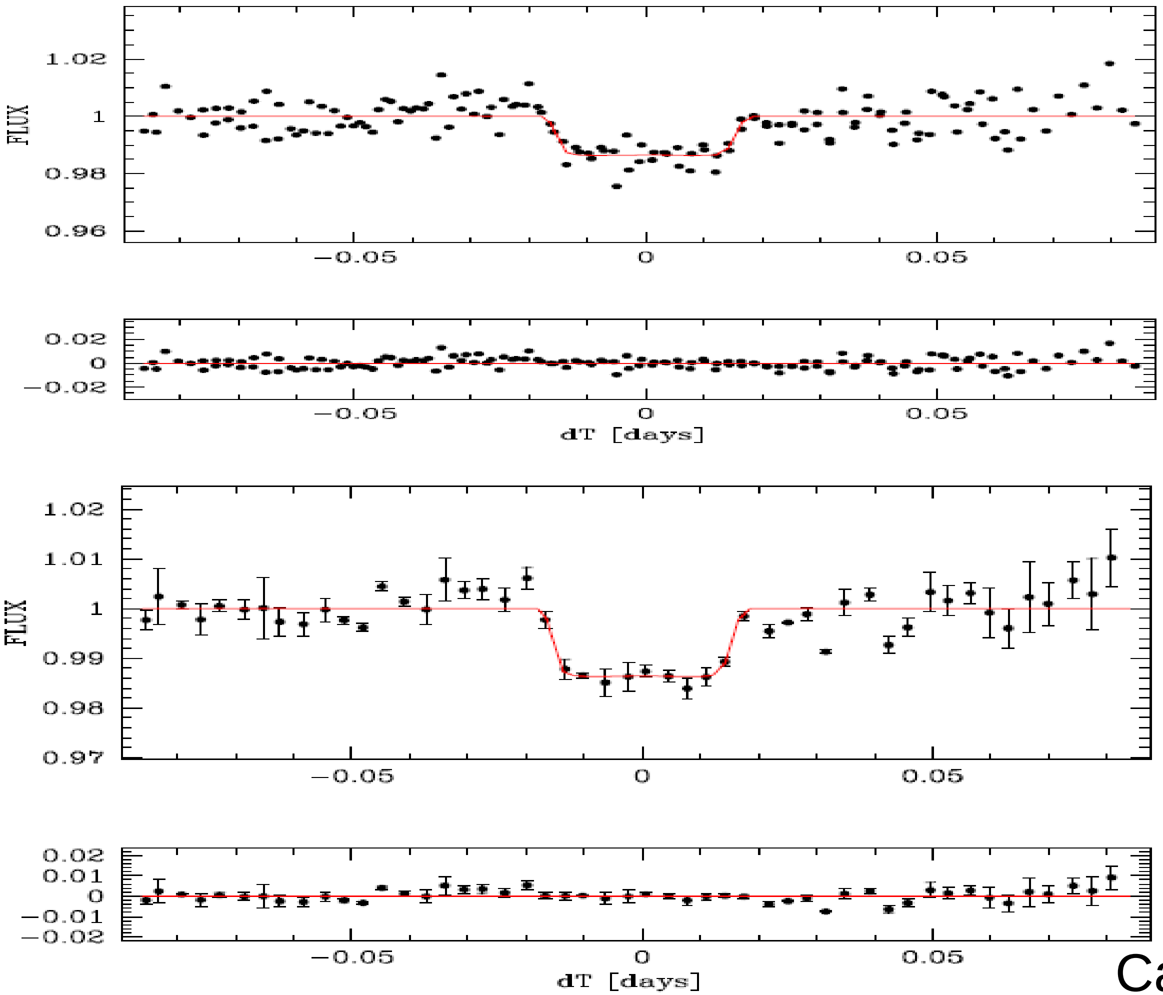
ESA D. Sing

FORS2 2010, 2011



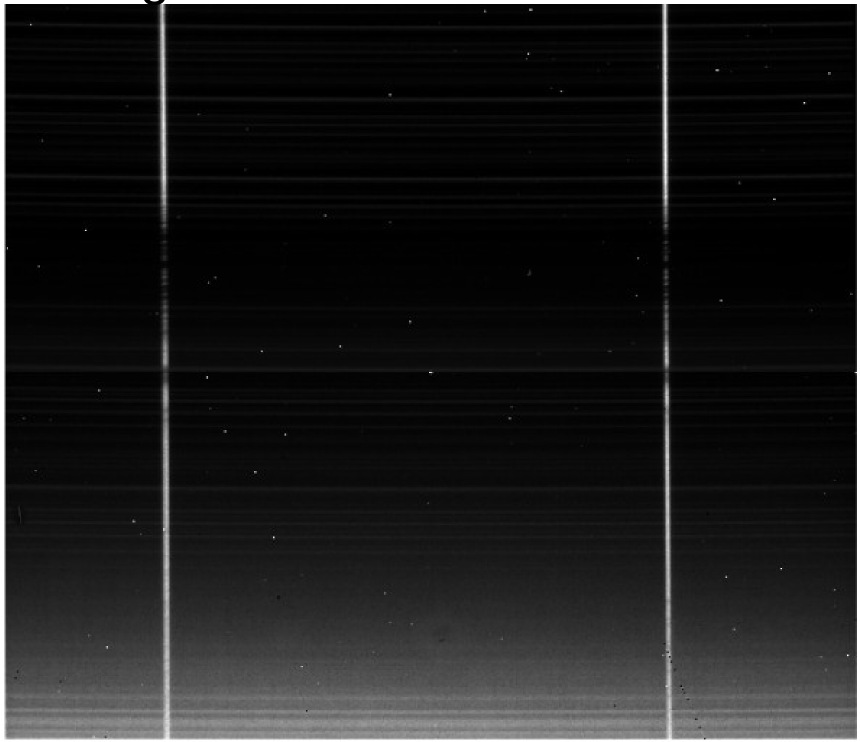
Bean et al. 2010, Nature
Bean, Desert, Kabath et al. 2011, AandA

SOFI NIR transmission spectroscopy



1.5 – 2.3 micron low res.

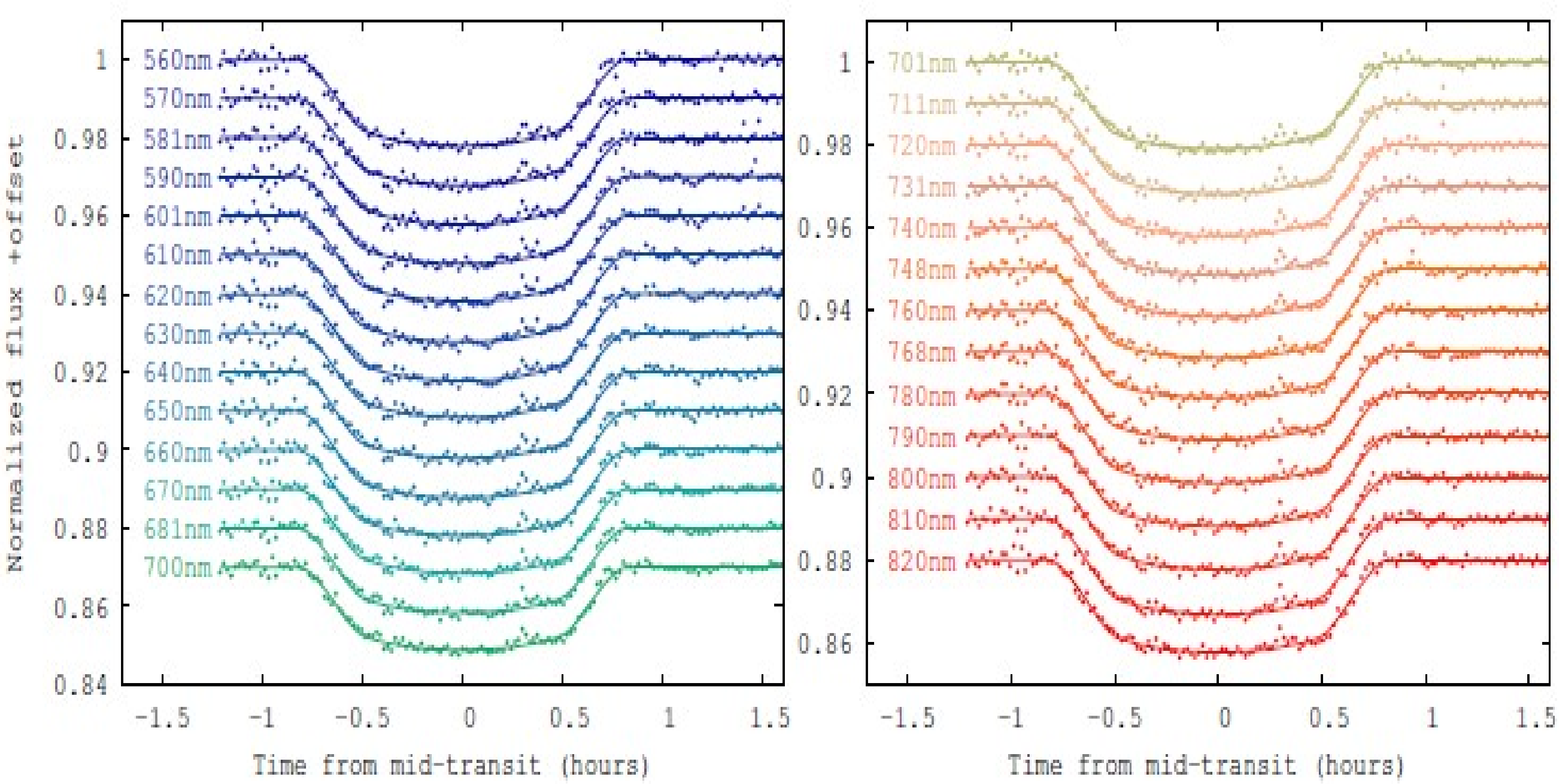
3 nights in 2011

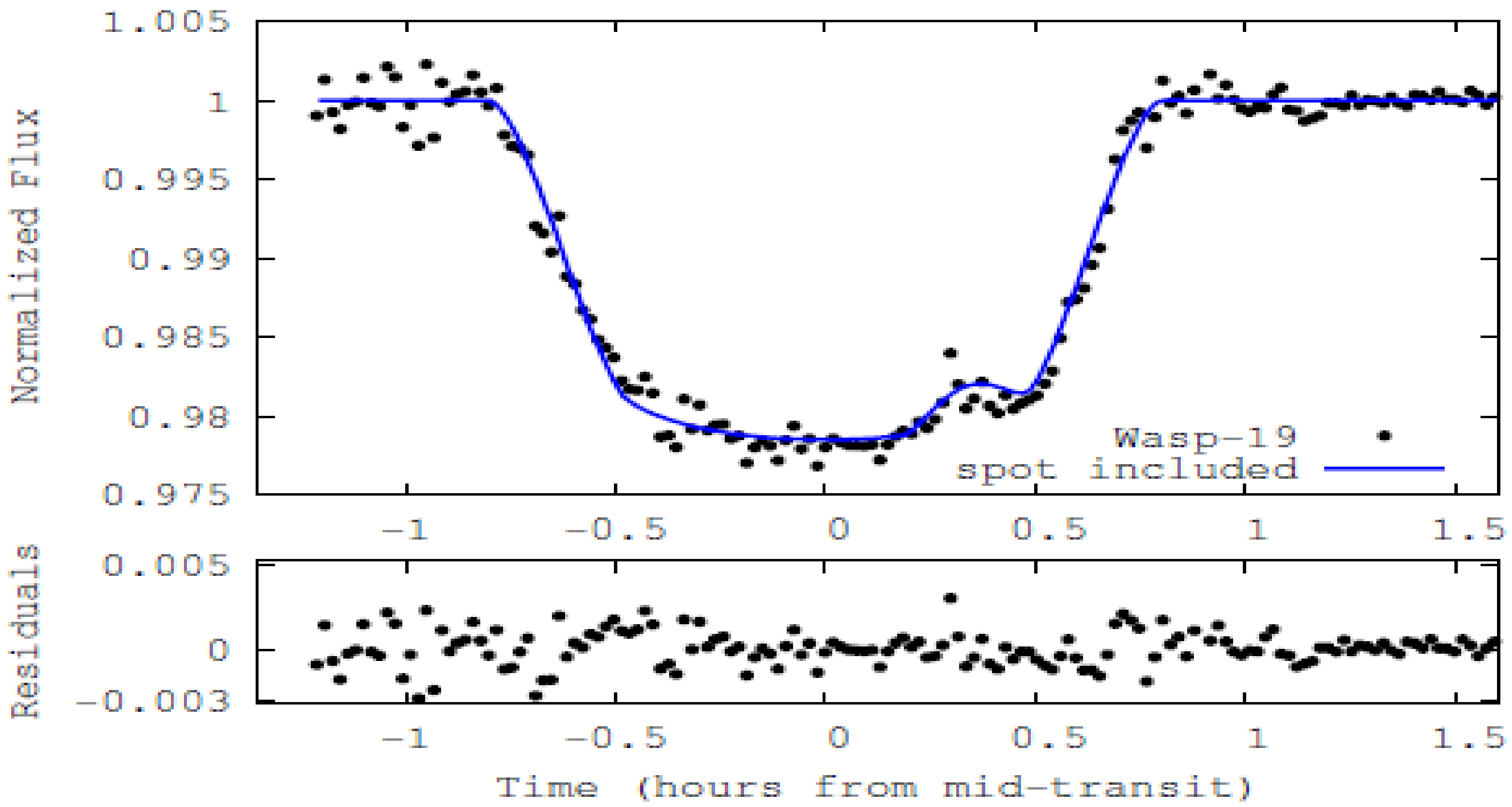


Caceres, Kabath et al., 2014, A&A

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)

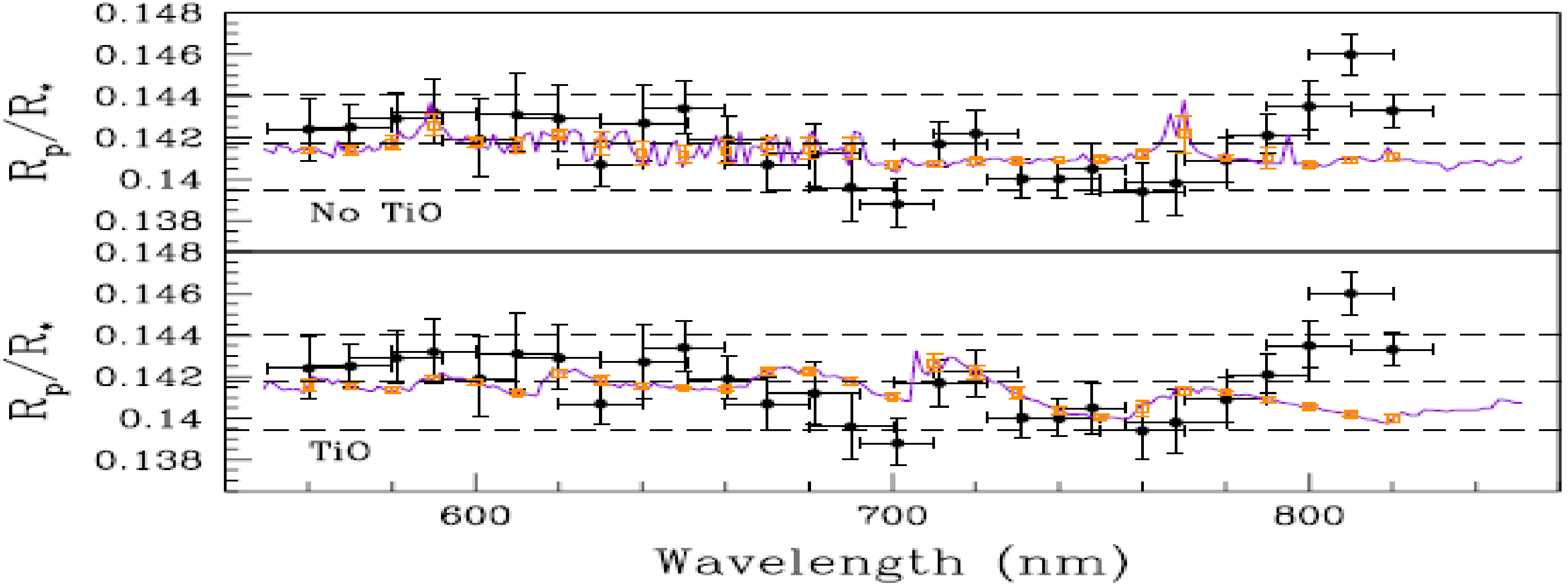
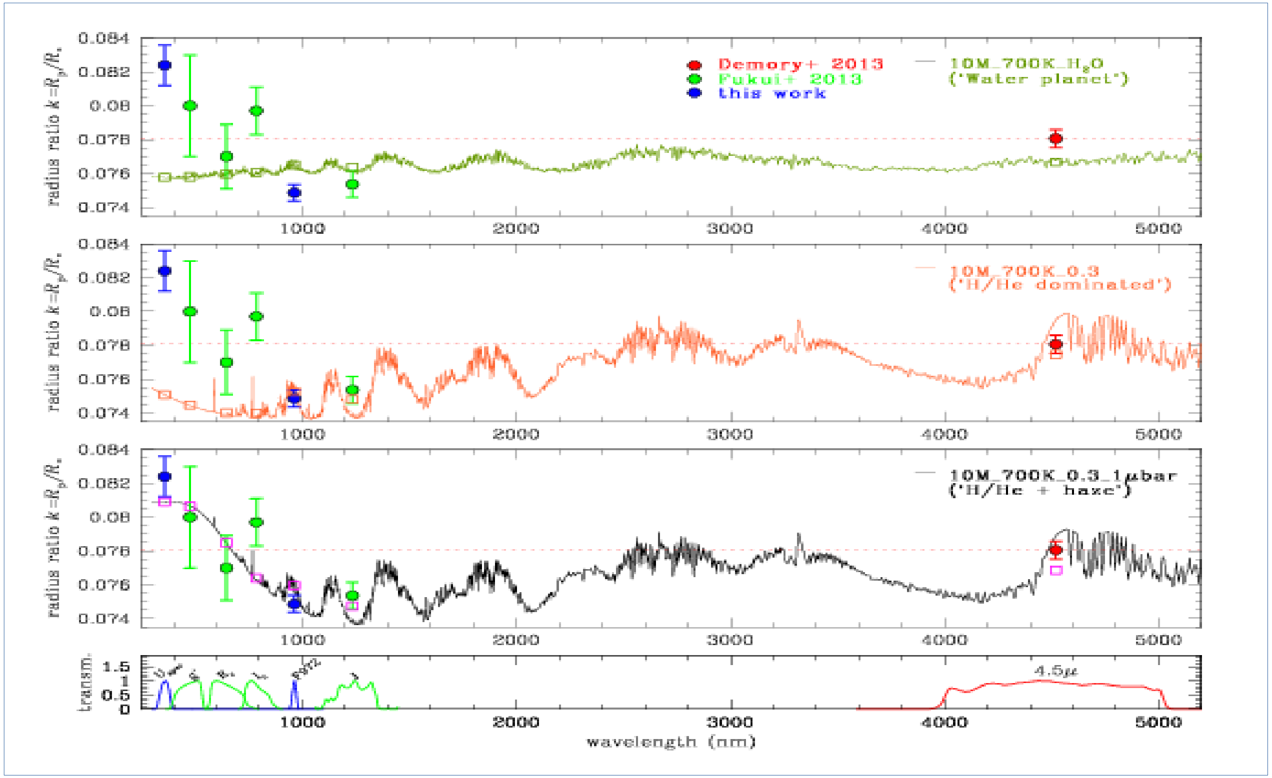


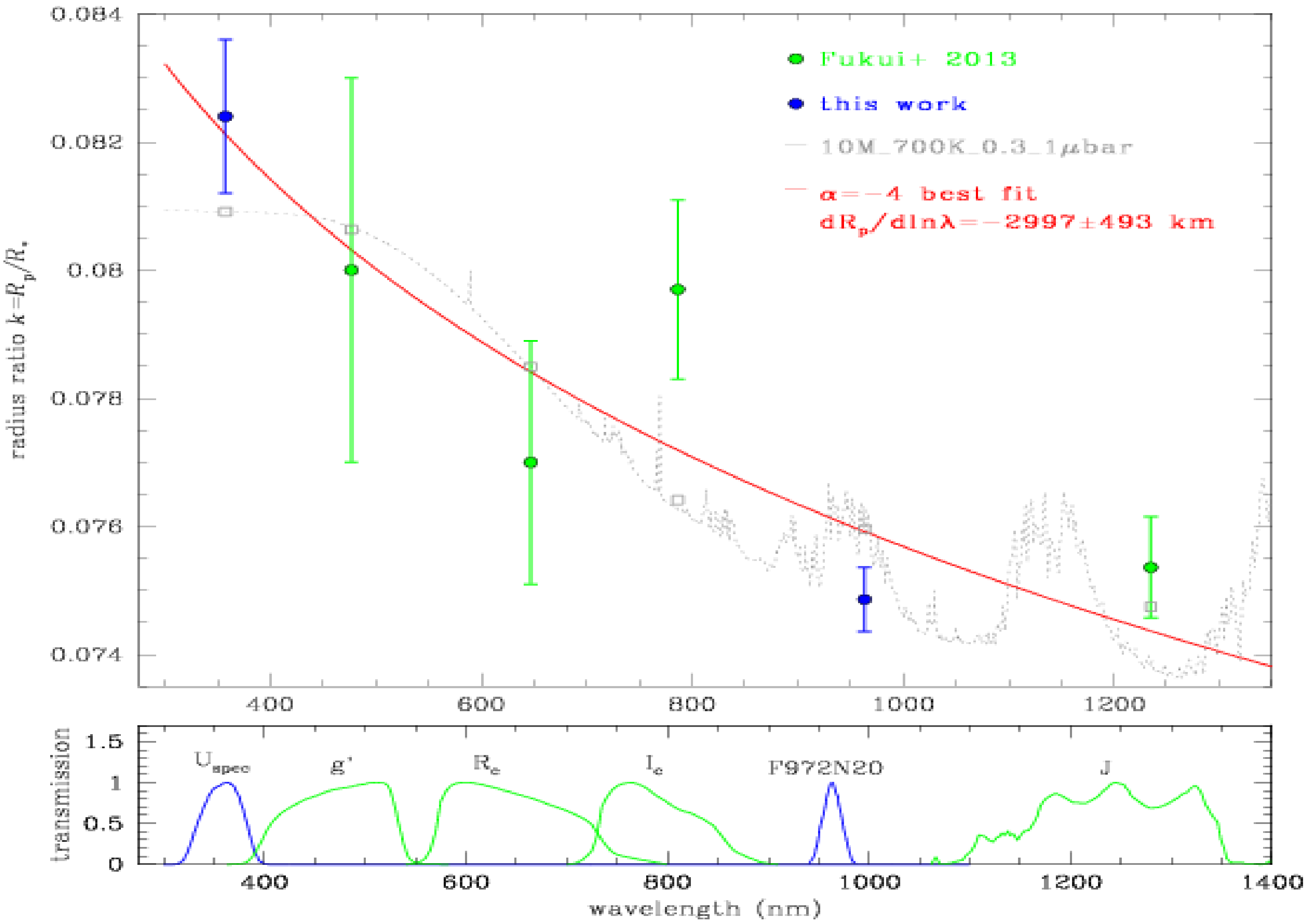
Fig. 2. Transmission spectrum of WASP-19b as measured with FORS2 (black dots, with error bars) compared to two models of planetary atmospheres, one with no TiO (top panel) and one with a solar abundance of TiO (bottom panel), from Burrows et al. (2010) and Howe & Burrows (2012). We have also estimated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



Nascimbeni et al. 2013, A&A

Very accurate photometry

Our observations with 4m class

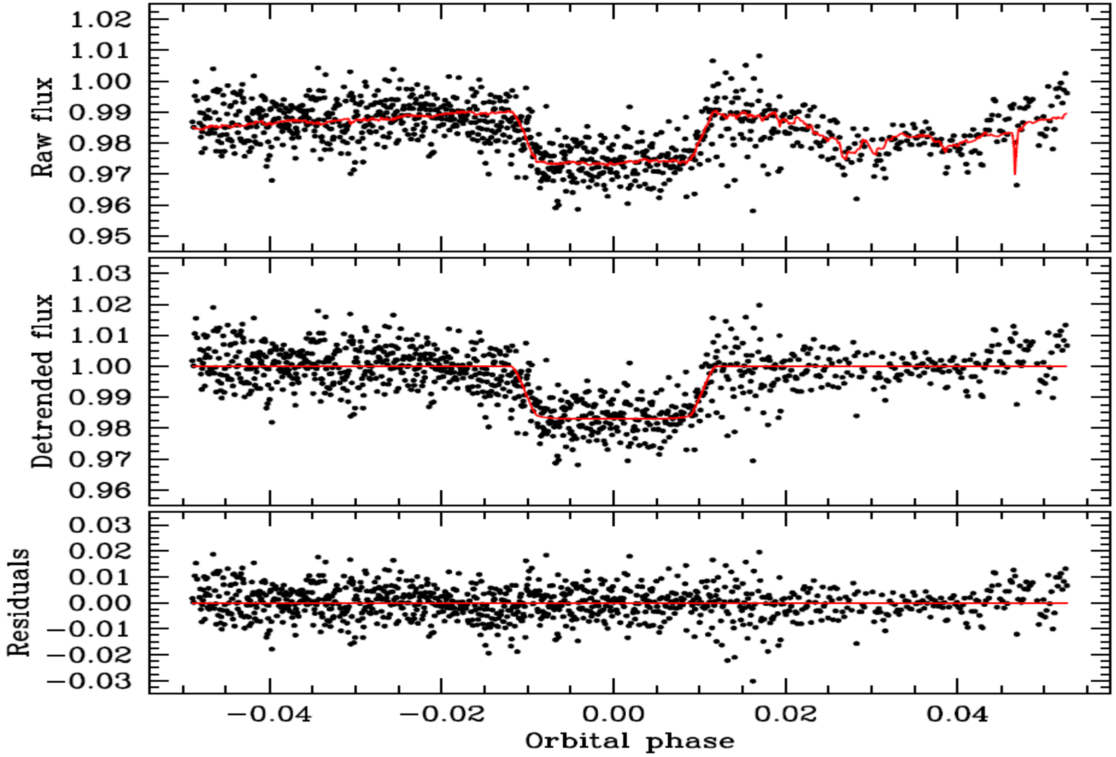
- SOFI @ NTT – La Silla 3 nights
- OSIRIS @ SOAR - Cerro Pachon 1 night
- SOI @ SOAR - Cerro Pachon 1 night

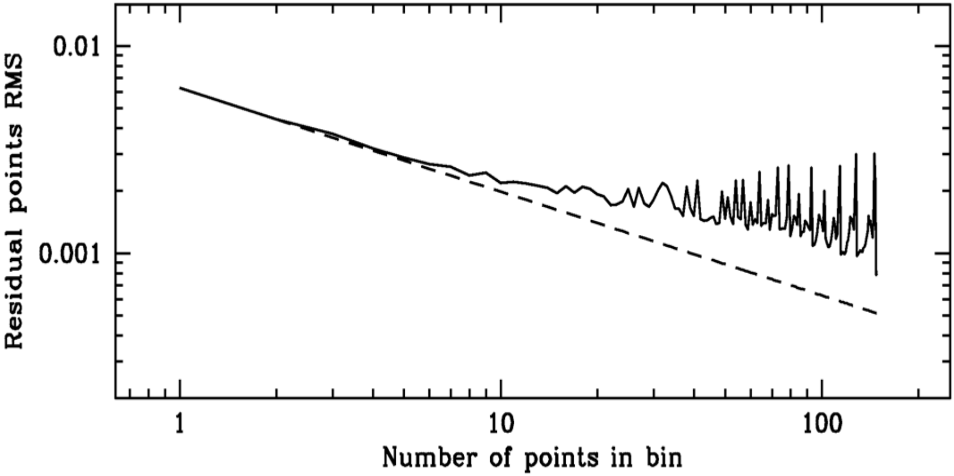
Both telescopes are 4-m class!!!

ESO

SOAR

Our measurements - OSIRIS



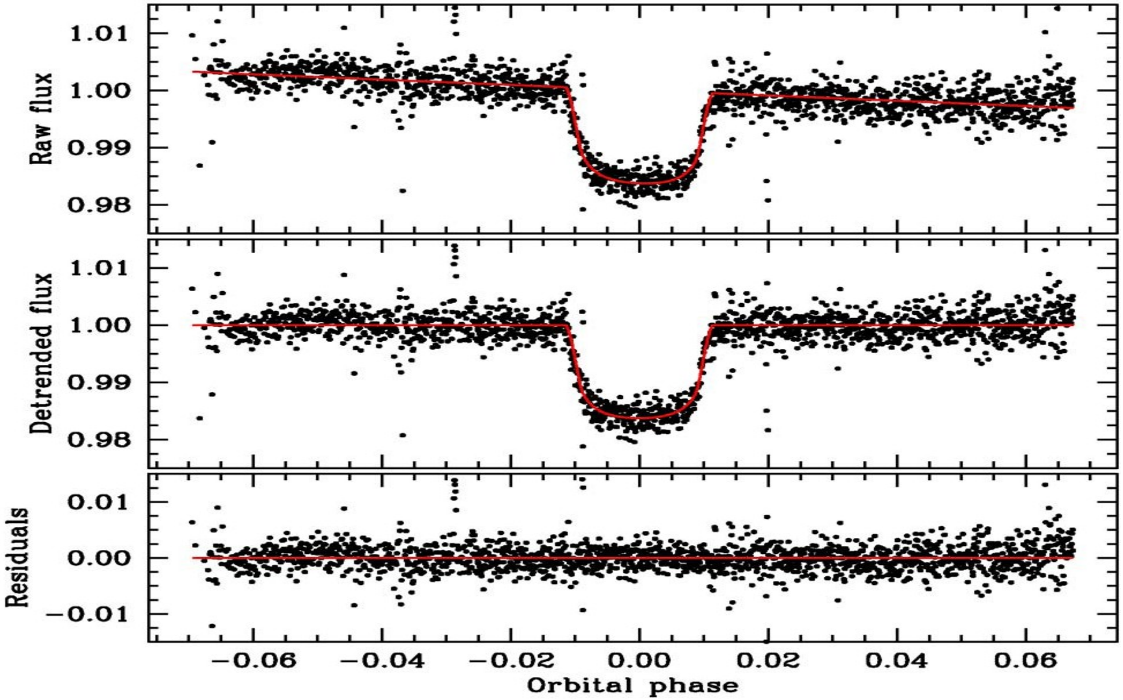


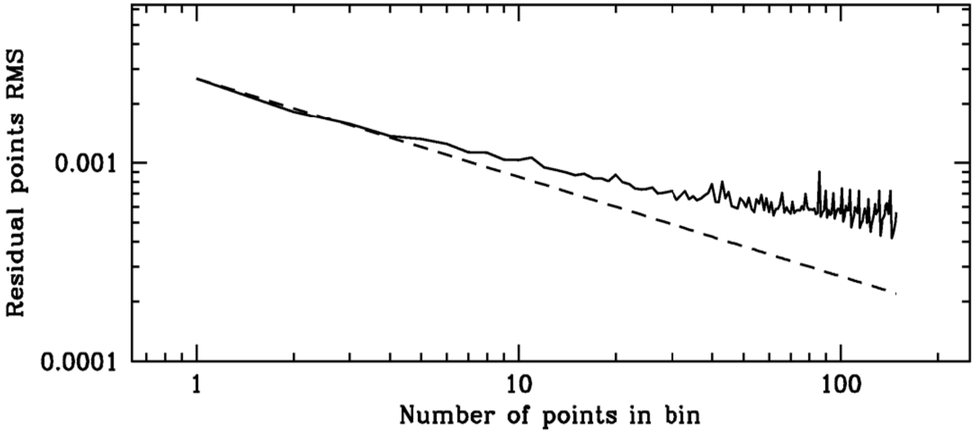
Rp/Rs = 0.118101 (-)0.002766(+)0.00256

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

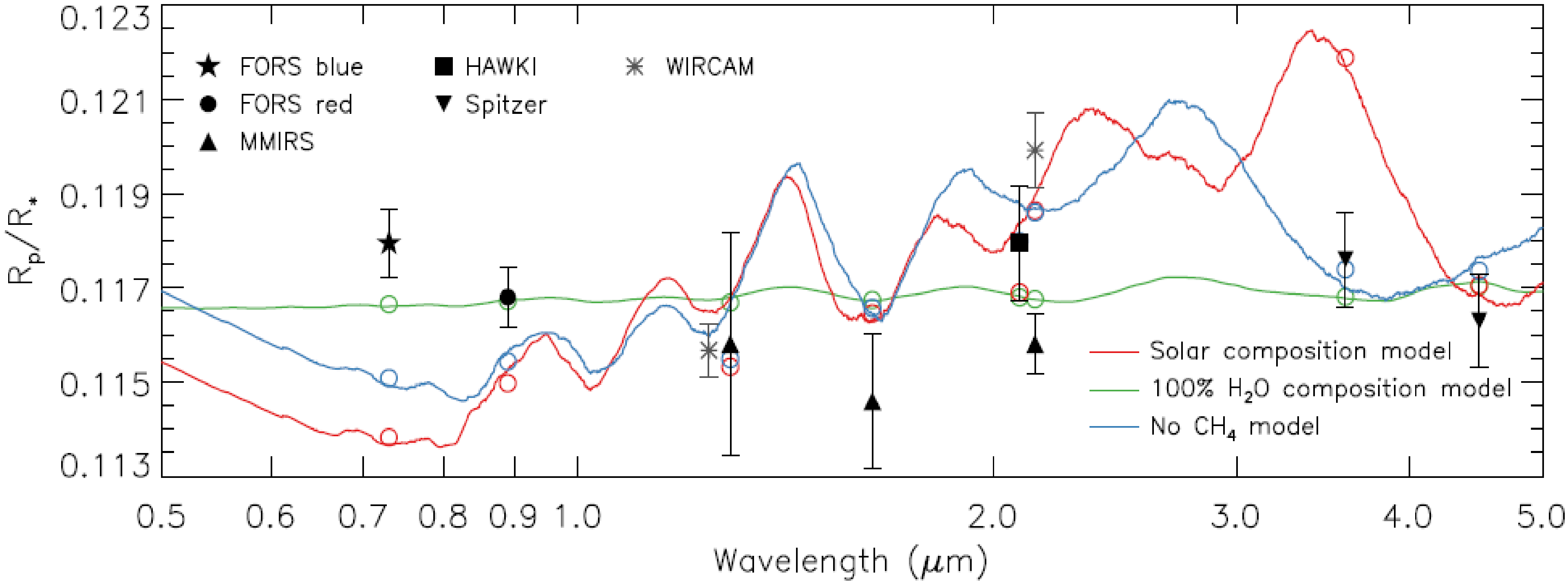




Observations performed by S. Hoyer

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

4-m class telescopes good?



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

Our results compared (photometry)

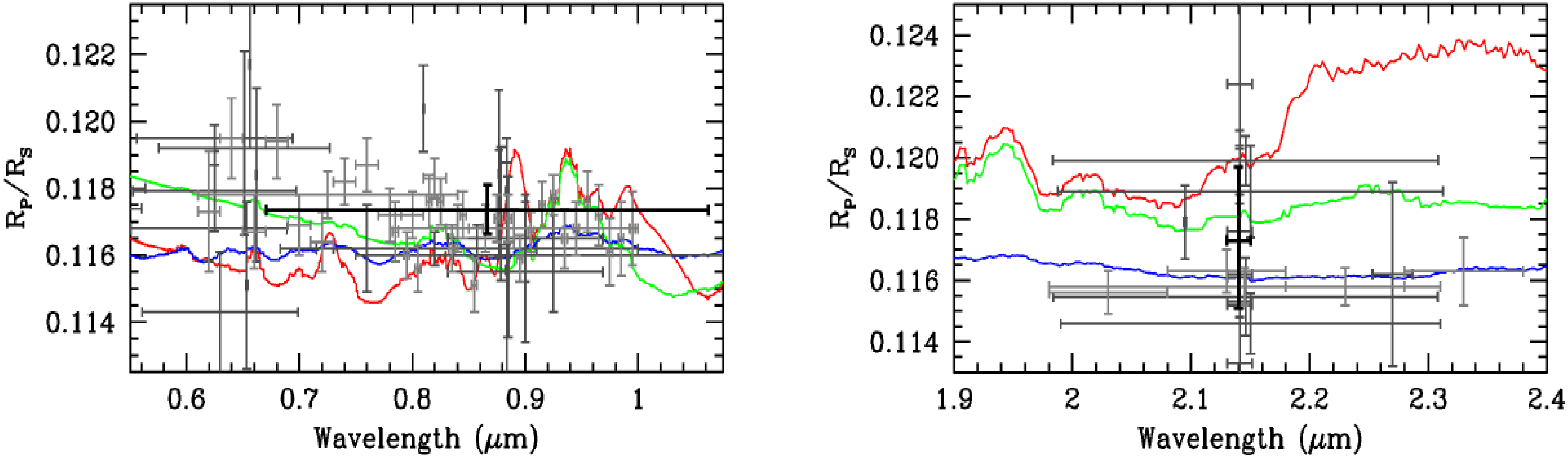
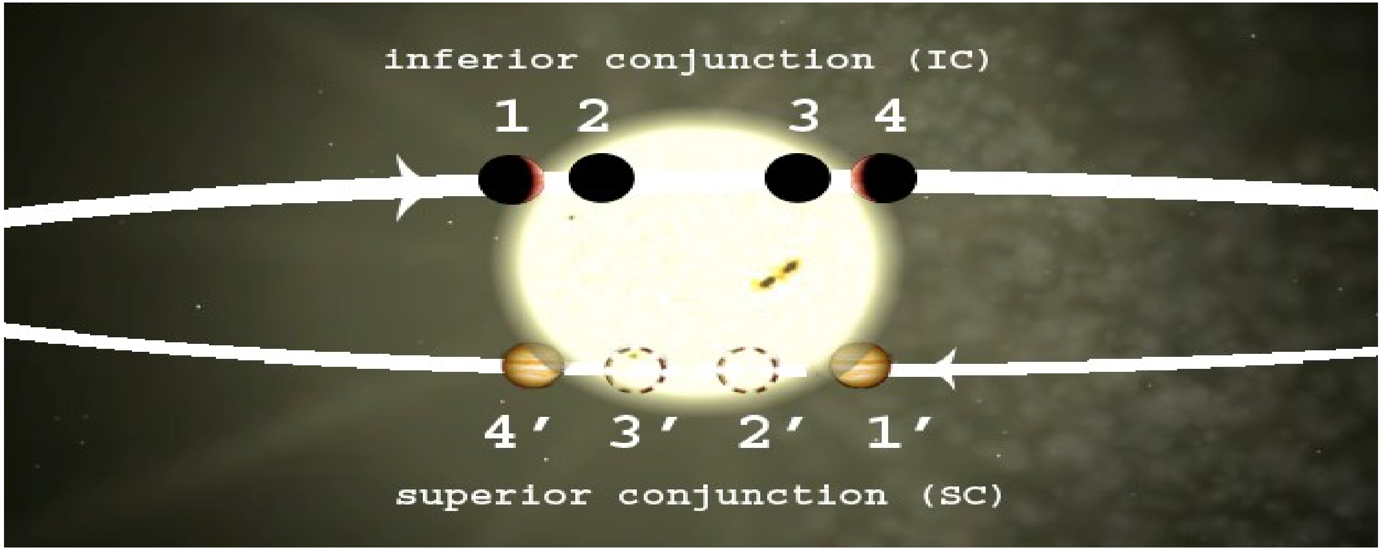


Fig. 11. *Left:* A zoom-in from Fig. 10 for the optical region around our *I*-Bessel measurements. *Right:* The *K*-band region of spectra around our 2.14 μm observation. Our measurement points are represented by dark circles, while gray points follow the description in Fig. 10. A color version of this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

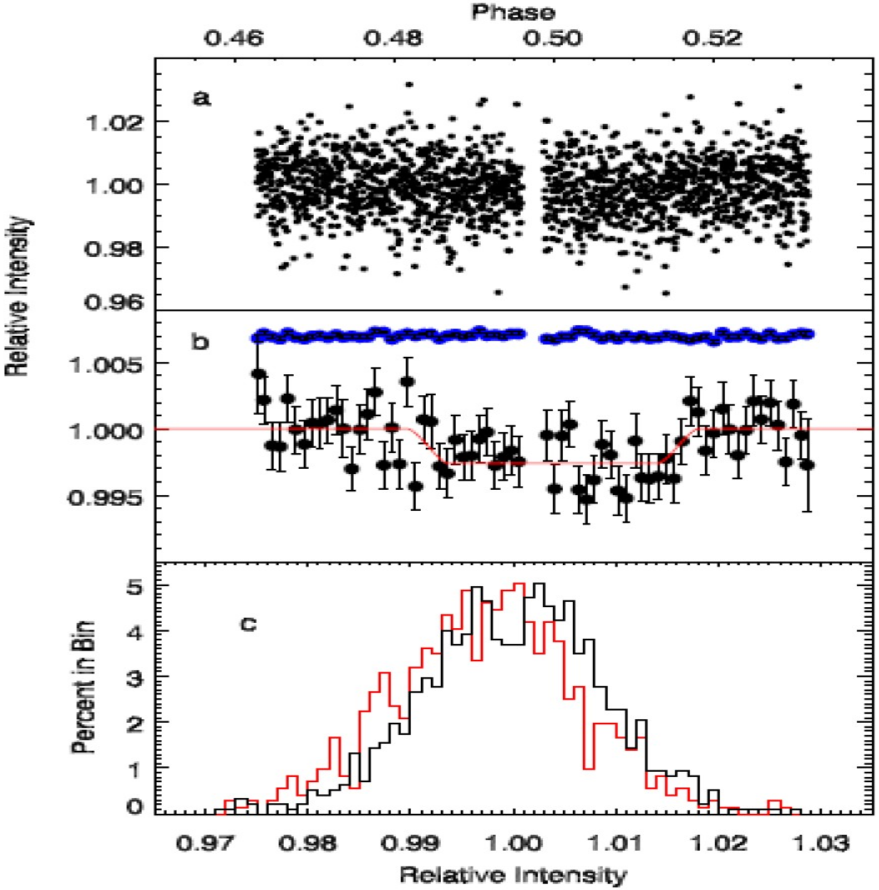
Emission from the planet

- Thermal radiation from the planet in IR

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

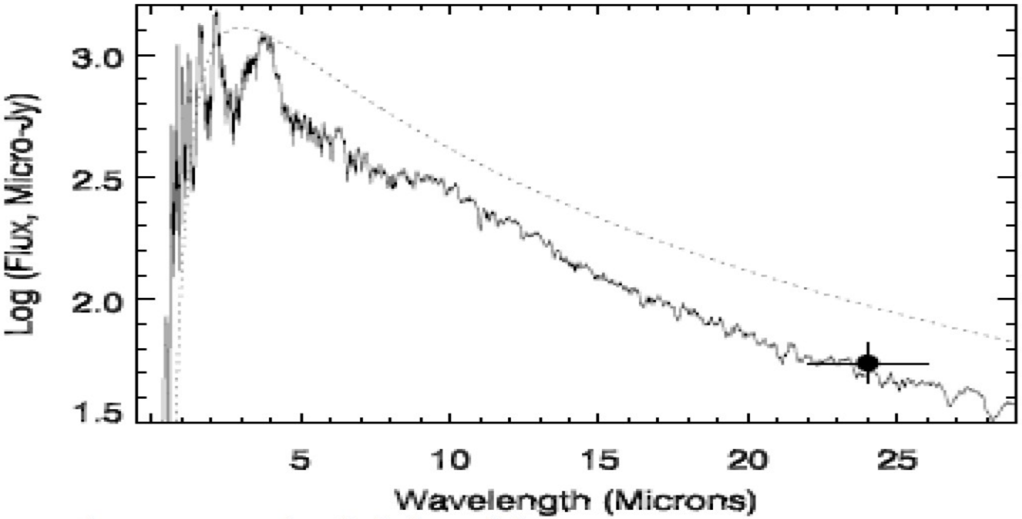
- Very shallow signals – few mmags
- Measuring directly the (missing) emission of the reflected light from the planet
- Result is an emission spectrum
- Due to geometry, not all planets hide behind the host star

Secondary eclipse photometry HD209458b



Měření: Spitzer 24μm

T_{pl}: ca 1130K



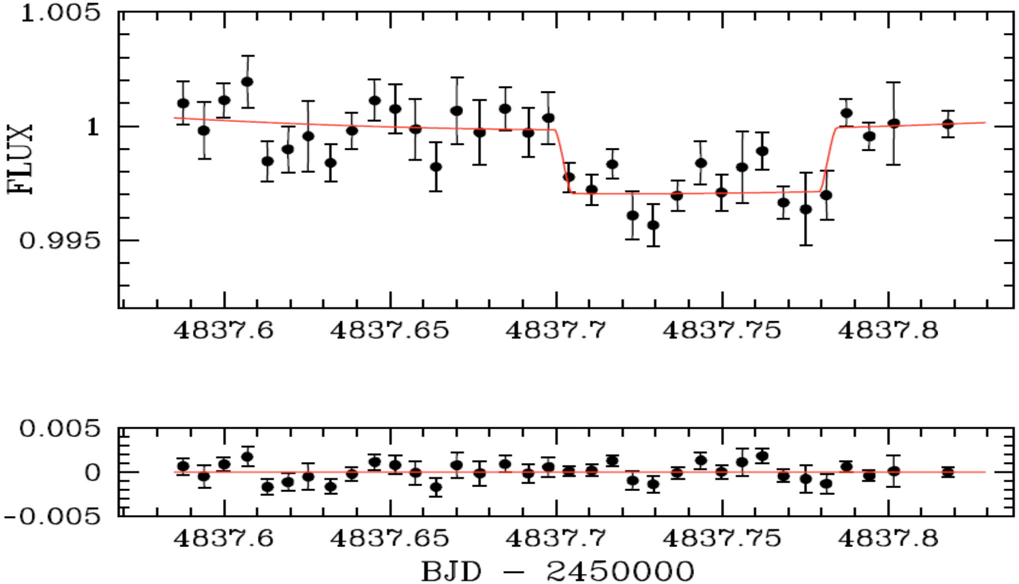
Deming et al. 2005 Nature

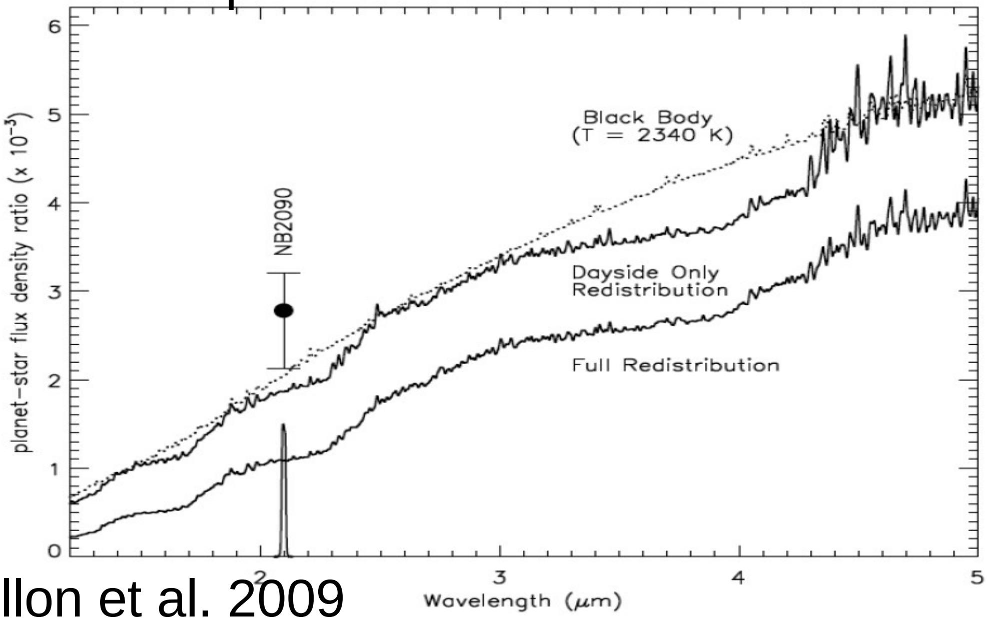
Secondary eclipse photometry from the ground

- Thermal radiation from the planet in IR

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

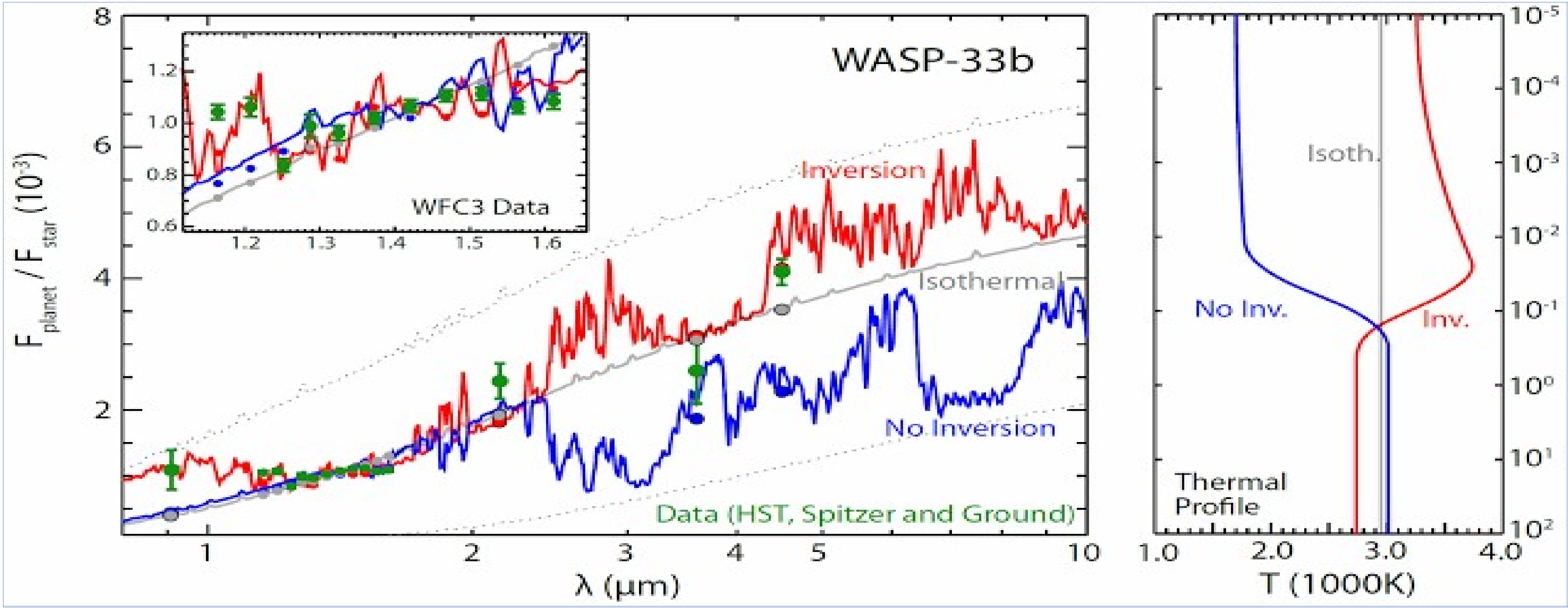
Typically few mmags for hot Jupiters





Gillon et al. 2009

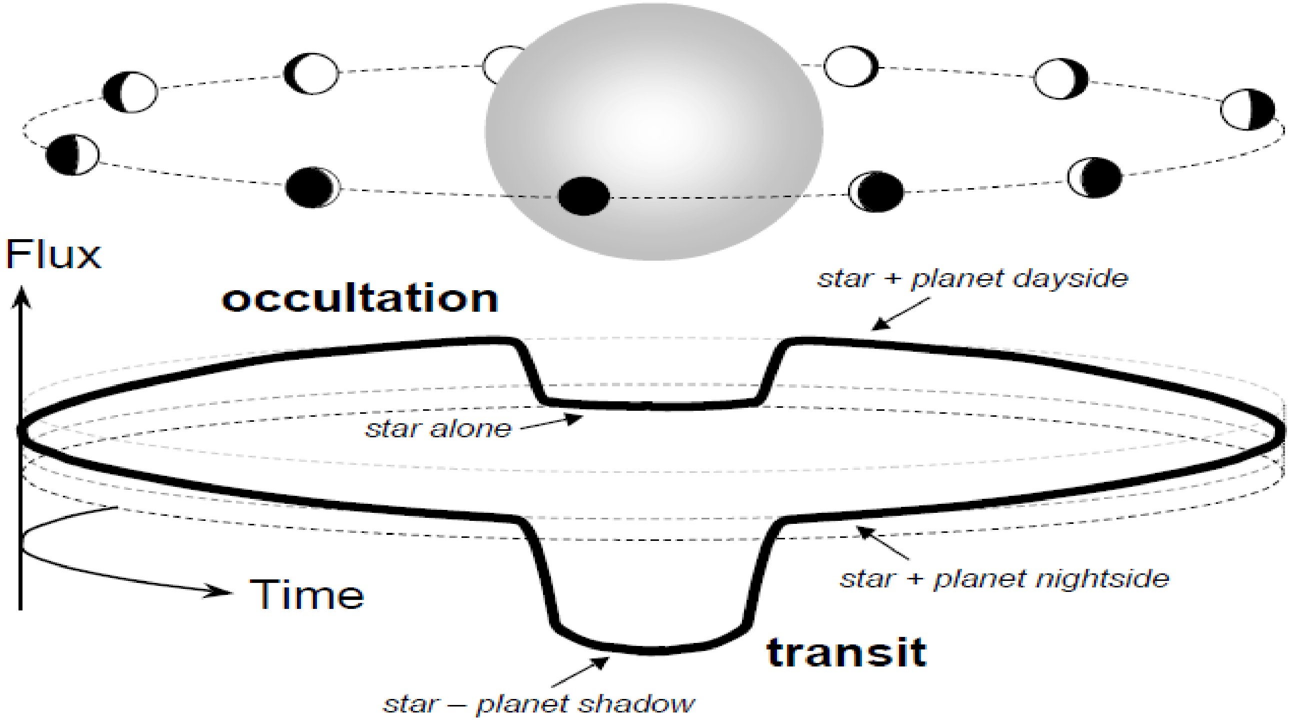
TiO species absorbing the stellar heat?



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

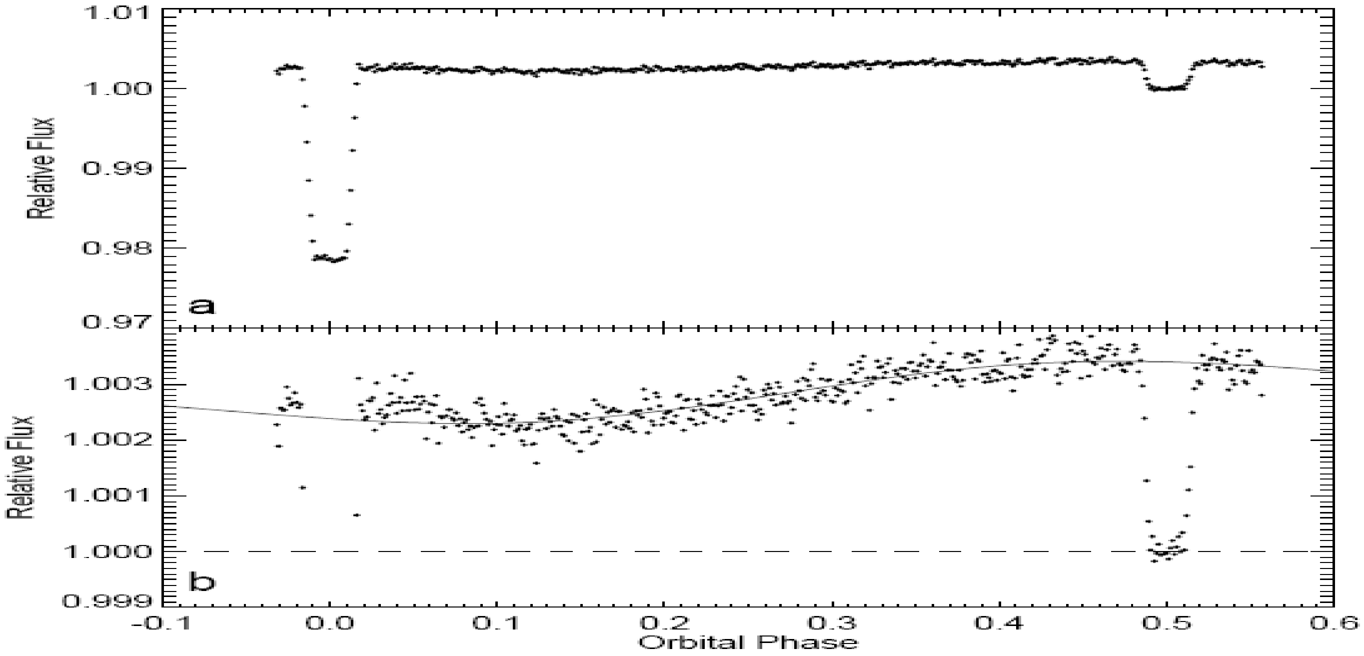
Eclipses/transits



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

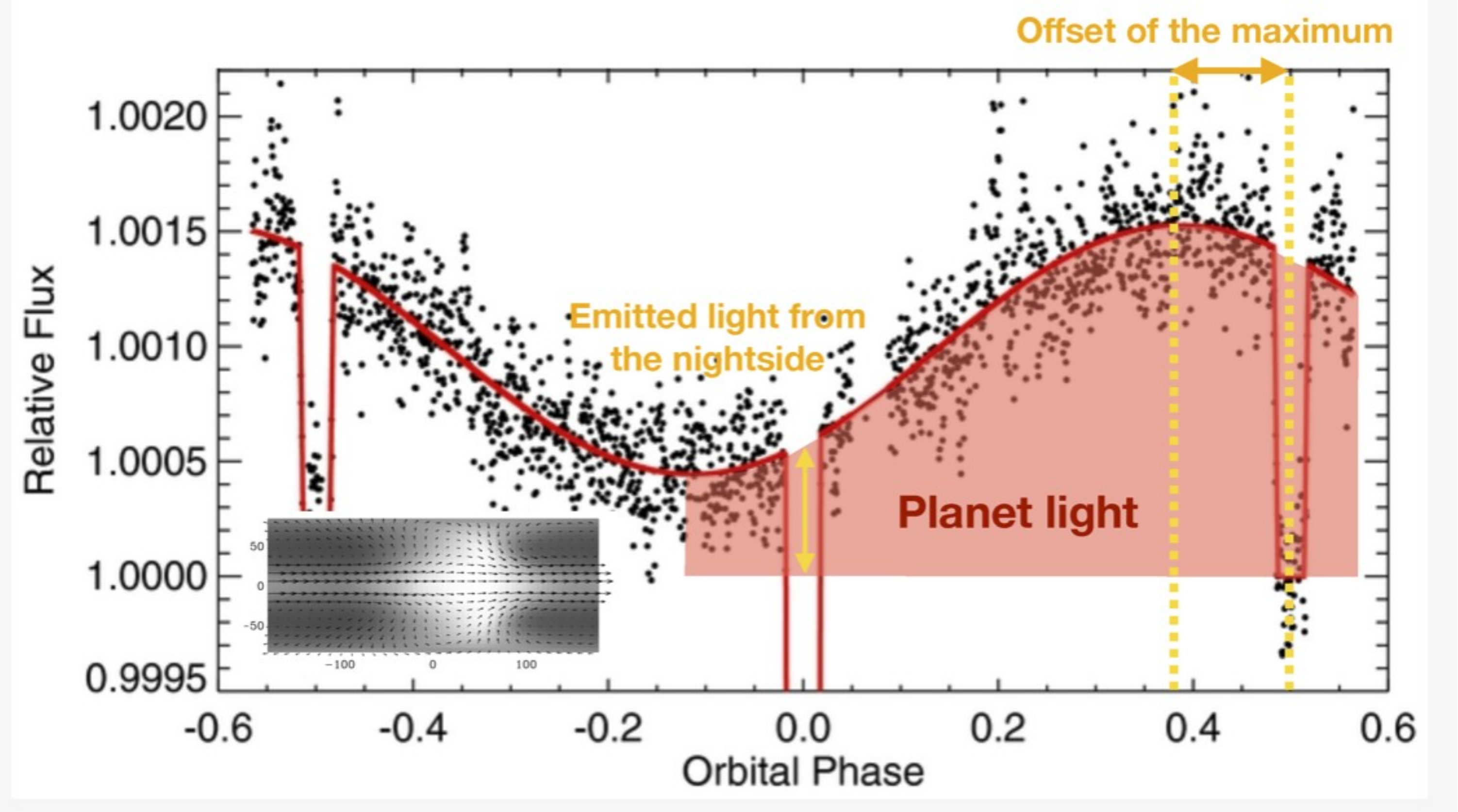
Variation due to day/night cycle

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

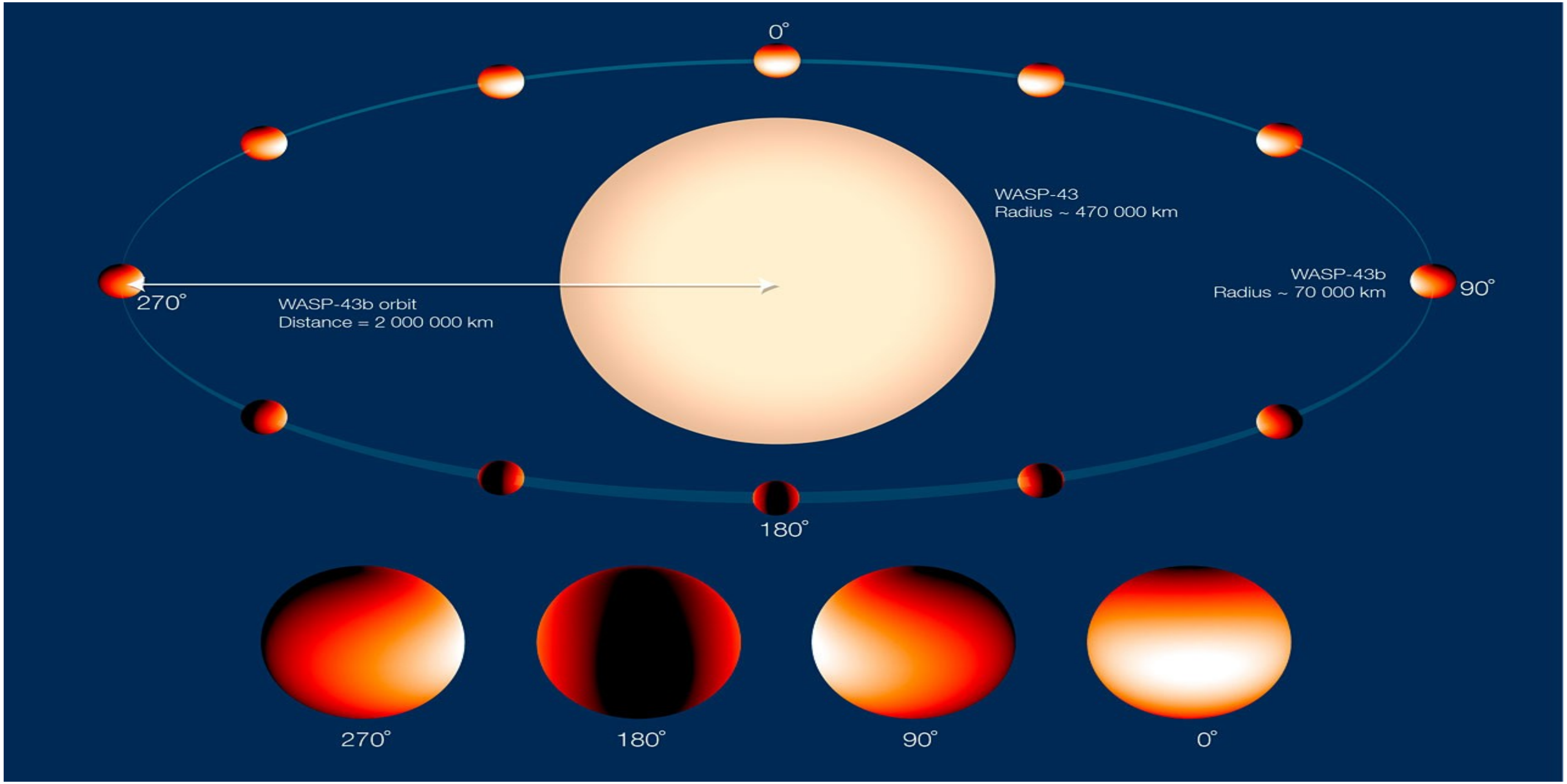


Knutson et al. 2007, Nature

Strong winds on HD209458b

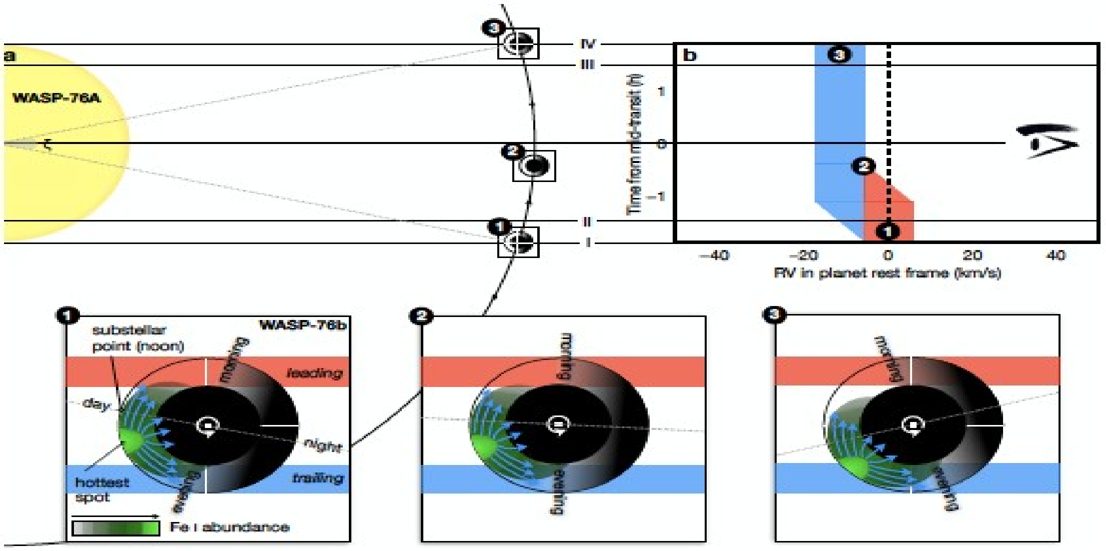


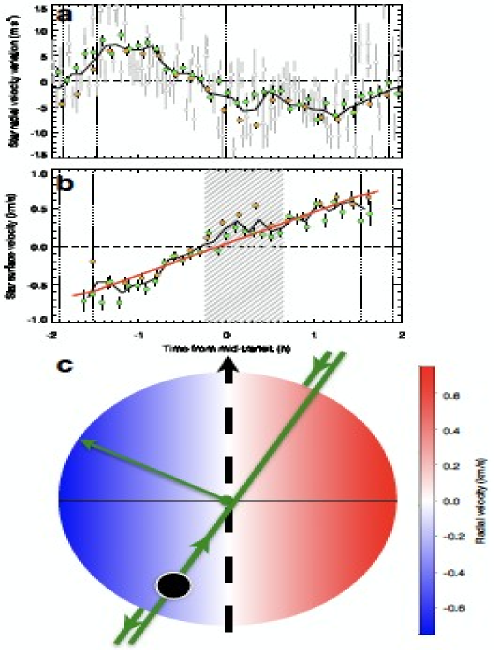
https://www.mdpi.com/2072-4292/15/3/635



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

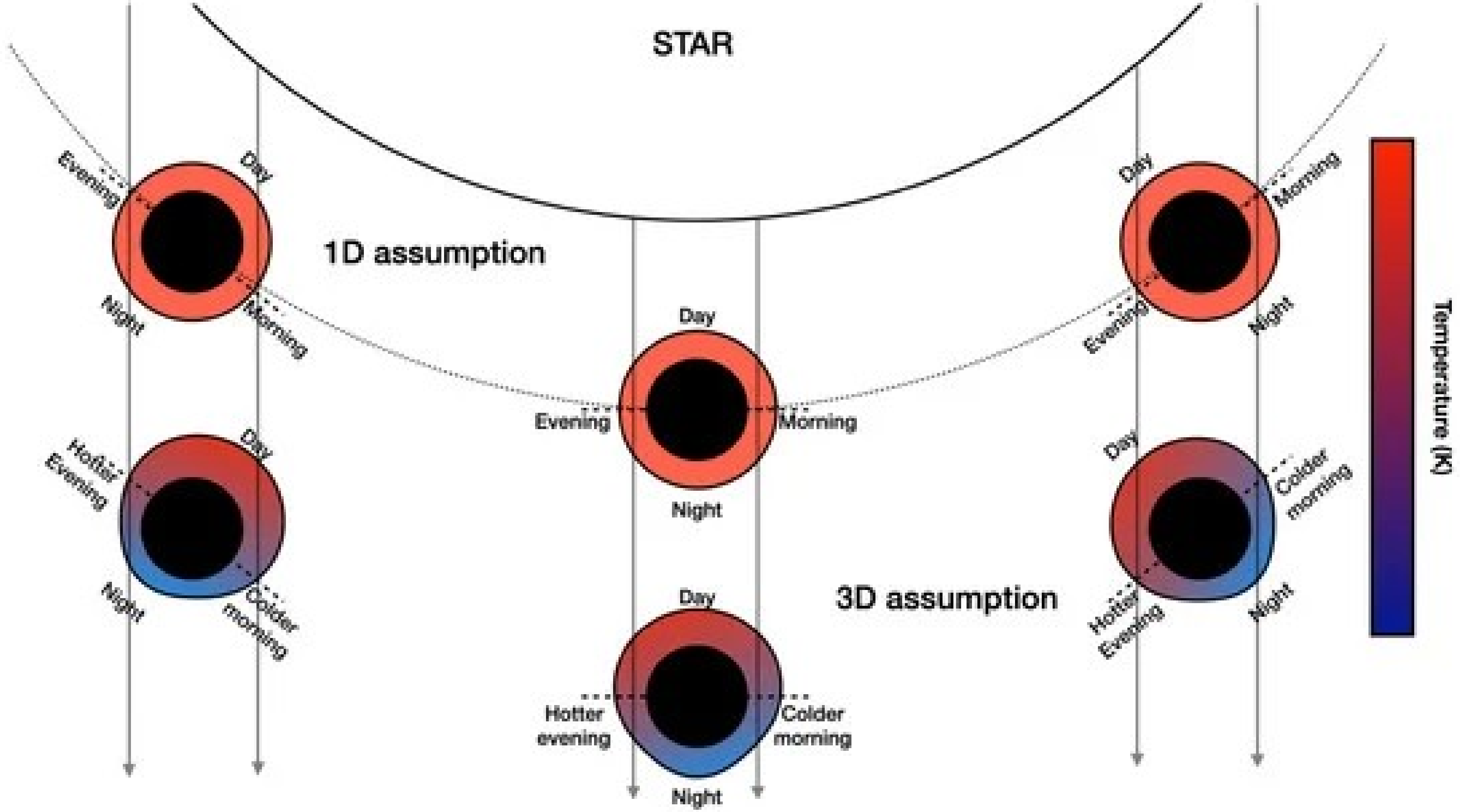
Raining iron?





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

1D or 3D model?



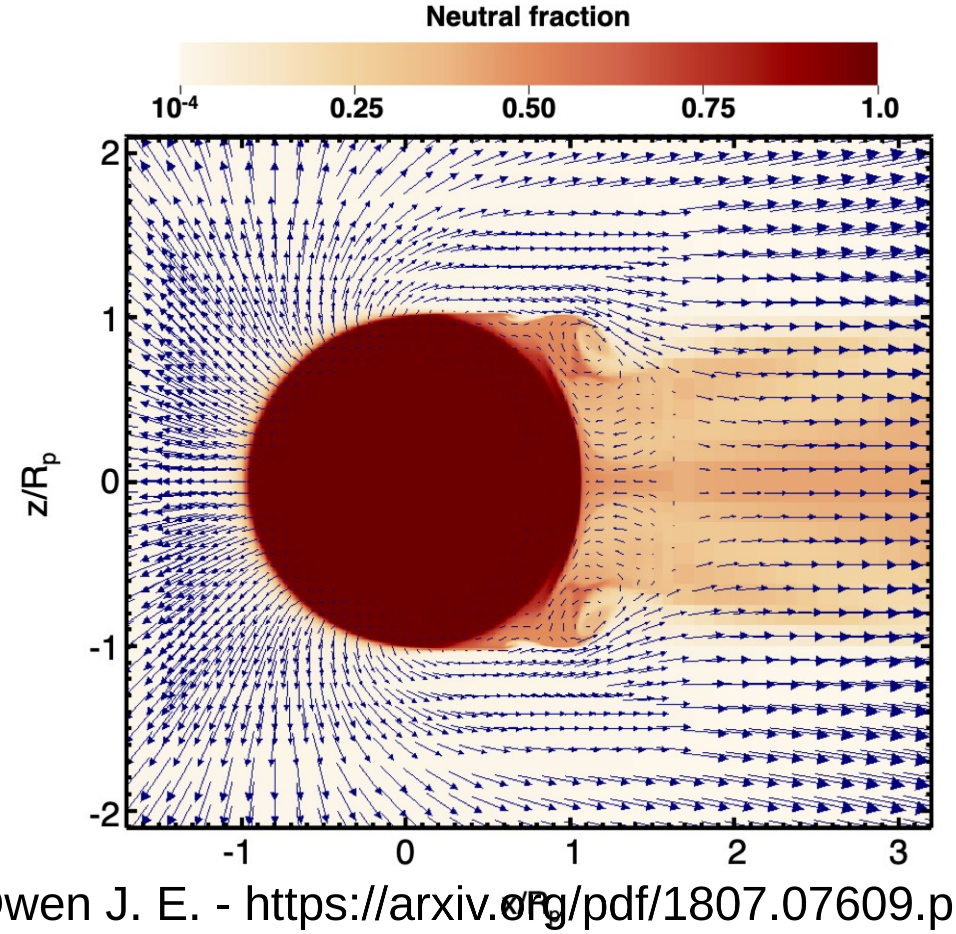
Varius regions probed considering 1D or 3D assumption for the atmosphere, with large temperature and scale height differences

https://www.mdpi.com/2072-4292/15/3/635

Probed atmospheres

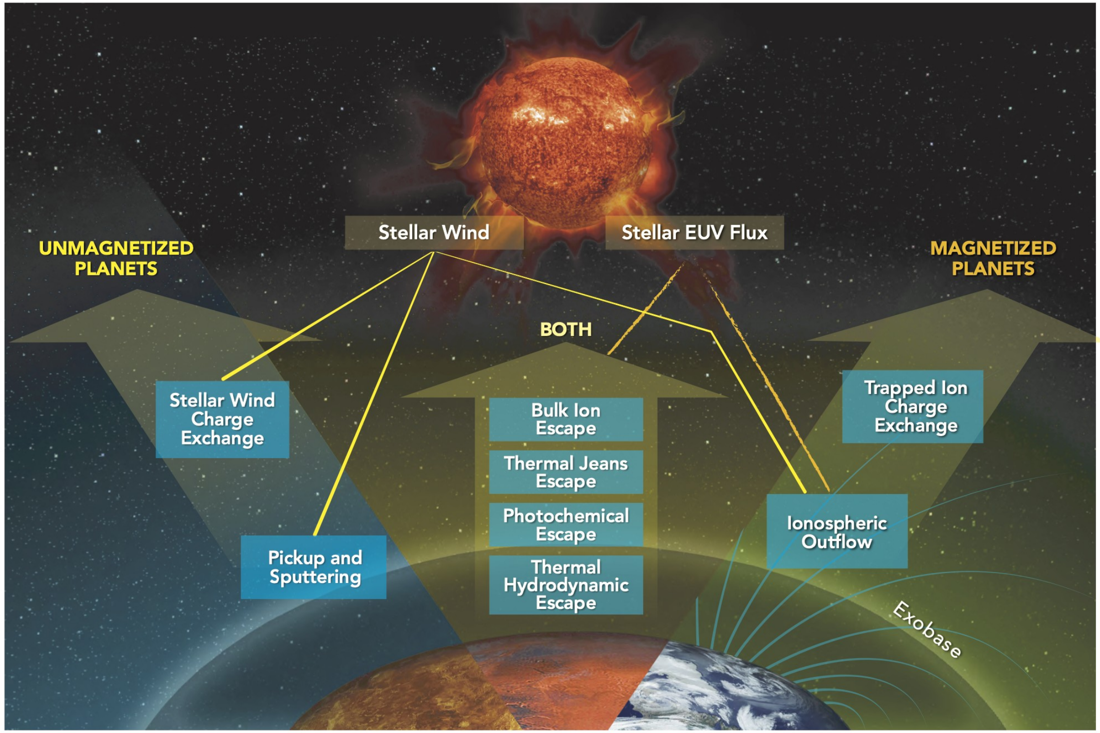
https://arxiv.org/pdf/2205.04100.pdf
Guilliot et al. 2022

Evaporating atmospheres



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

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



TMS/EMS

- Metrics for selection of suitable candidates for the follow-up
- The higher the TMS/EMS the better detectability of the atmosphere is expected (prioritisation of candidates)
- Scaling factors chosen to be c requirements

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

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

planets that should be advanced expeditiously for RV follow-up and subsequent atmospheric investigations. For the purpose of selecting easy-to-remember round numbers for the threshold transmission spectroscopy metric, based on the values in Table 1, we recommend that planets with TSM >10 for $R_p < 1.5\, R_\oplus$ and TSM >90 for $1.5 < R_p < 10\, R_\oplus$ be selected as high-quality atmospheric characterization targets among the *TESS* planetary candidates. We also recommend a threshold of TSM = 10 for putative habitable zone planets. For emission spectroscopy of terrestrial planets, we recommend a threshold of ESM = 7.5. Applying these cuts should result in ~300 new ideal targets for transmission spectroscopy investigations from the *TESS* mission.

https://iopscience.iop.org/article/10.1088/1538-38

TSM/ESM

- Metrics for selection of suitable candidates for the follow-up
- The higher the TMS/EMS the better detectability of the atmosphere is expected (prioritisation of candidates)
- Scaling factors chosen to be consistent with SNR of JWST requirements

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

$$T_{\mathrm{eq}} = T_* \sqrt{\frac{R_*}{a}} \left(\frac{1}{4}\right)^{1/4},$$

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

https://iopscience.iop.org/article/10.1088/1538-3873/aadf6f/pdf

What are the best TSM/ESM values?

planets that should be advanced expeditiously for RV follow-up and subsequent atmospheric investigations. For the purpose of selecting easy-to-remember round numbers for the threshold transmission spectroscopy metric, based on the values in Table 1, we recommend that planets with TSM >10 for $R_p < 1.5\,R_\oplus$ and TSM >90 for $1.5 < R_p < 10\,R_\oplus$ be selected as high-quality atmospheric characterization targets among the *TESS* planetary candidates. We also recommend a threshold of TSM = 10 for putative habitable zone planets. For emission spectroscopy of terrestrial planets, we recommend a threshold of ESM = 7.5. Applying these cuts should result in ~300 new ideal targets for transmission spectroscopy investigations from the *TESS* mission.

https://iopscience.iop.org/article/10.1088/1538-3873/aadf6f/pdf

What are the best TSM/ESM values?

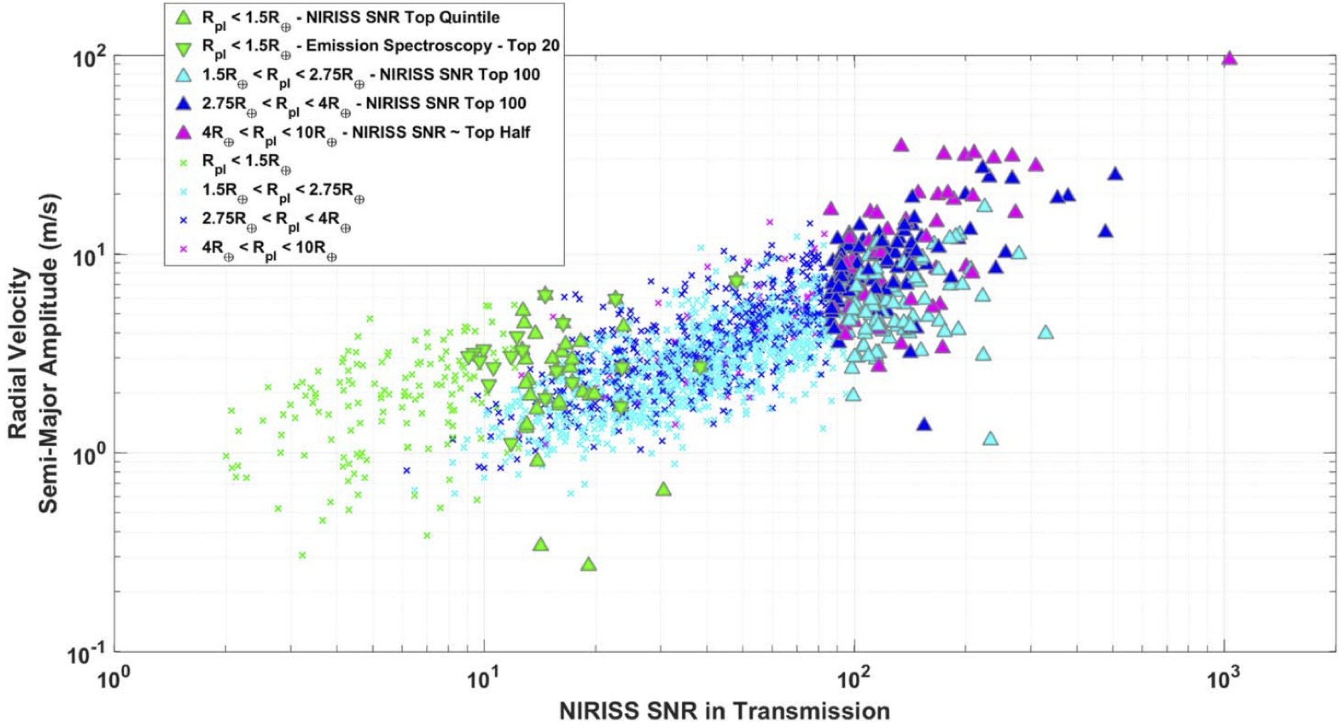
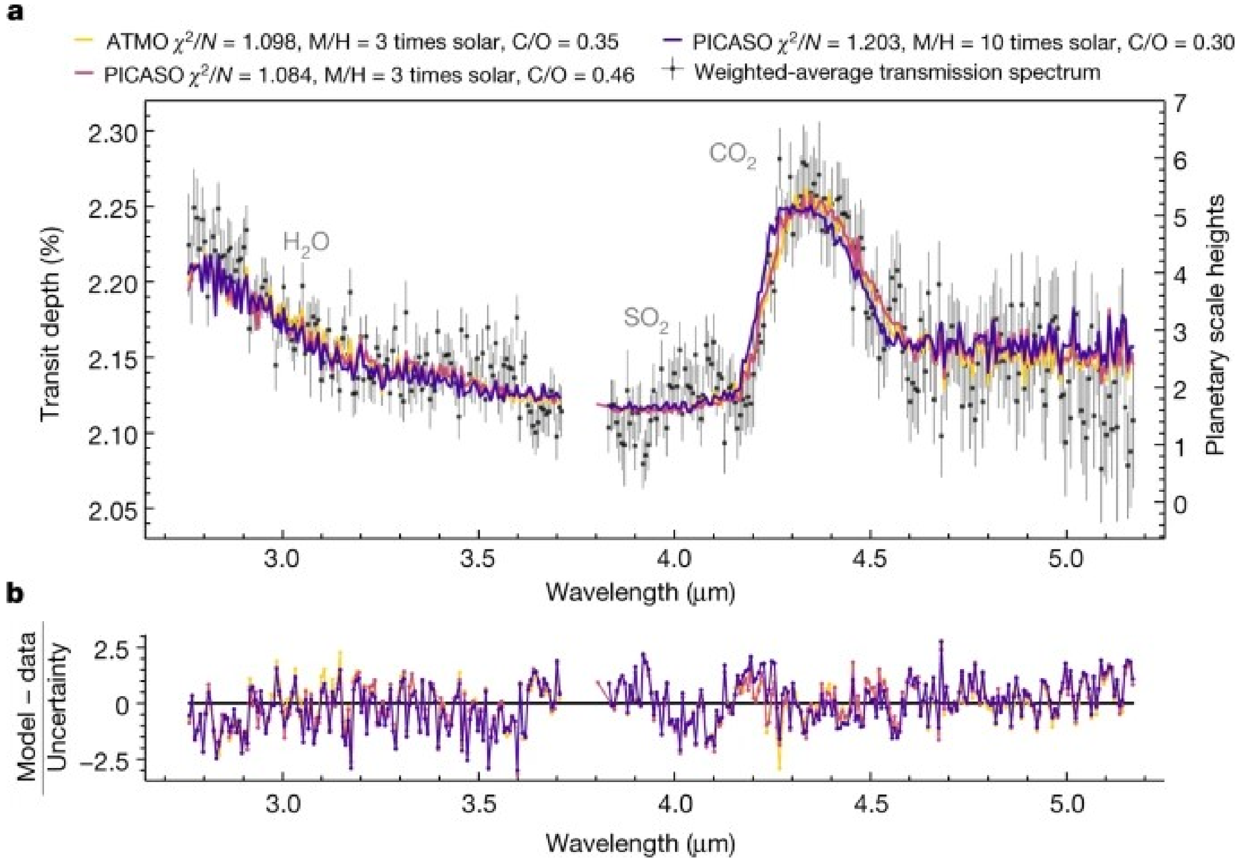


Figure 6. RV semi-amplitude vs. NIRISS S/N for the planets in the simulated Sullivan et al. (2015) *TESS* catalog and the Louie et al. (2018) 10 hr S/N predictions. Filled triangles denote the planets included in our transmission statistical sample using the threshold criteria from Table 1, upside down triangles indicate the planets included in our emission sample, and small x's denote targets that are disfavored for atmospheric characterization based on low expected S/N. (Note that the S/N values were calculated for a high-μ water-rich atmosphere for planets with $R_p < 1.5\ R_\oplus$ and a low-μ hydrogen-rich atmosphere for $R_p > 1.5\ R_\oplus$.)
(A color version of this figure is available in the online journal.)

https://iopscience.iop.org/article/10.1088/1538-3873/aadf6f/pdf

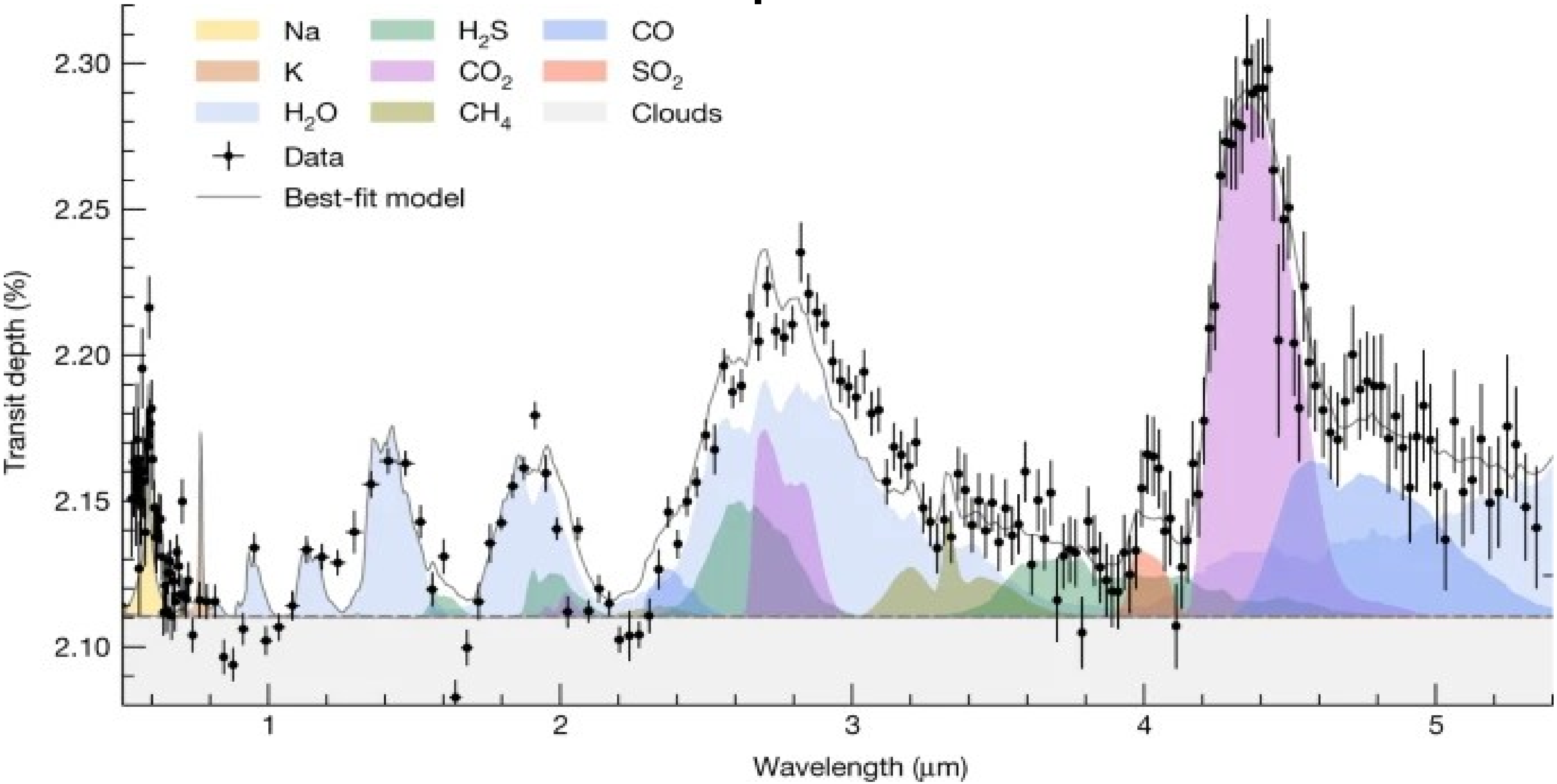
What do we have now?

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

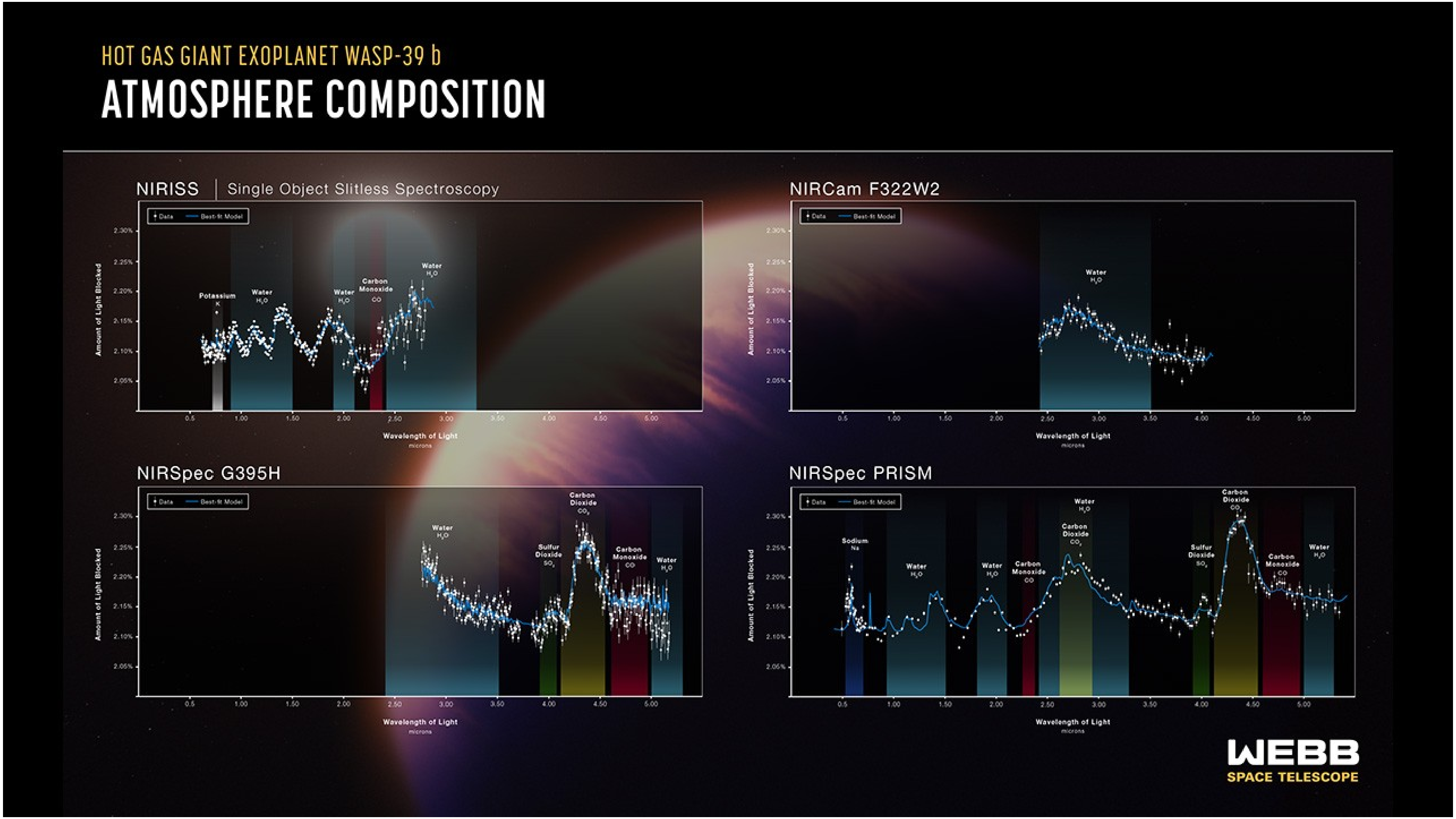


https://www.nature.com/articles/s41586-022-05591-3

Wasp-39b



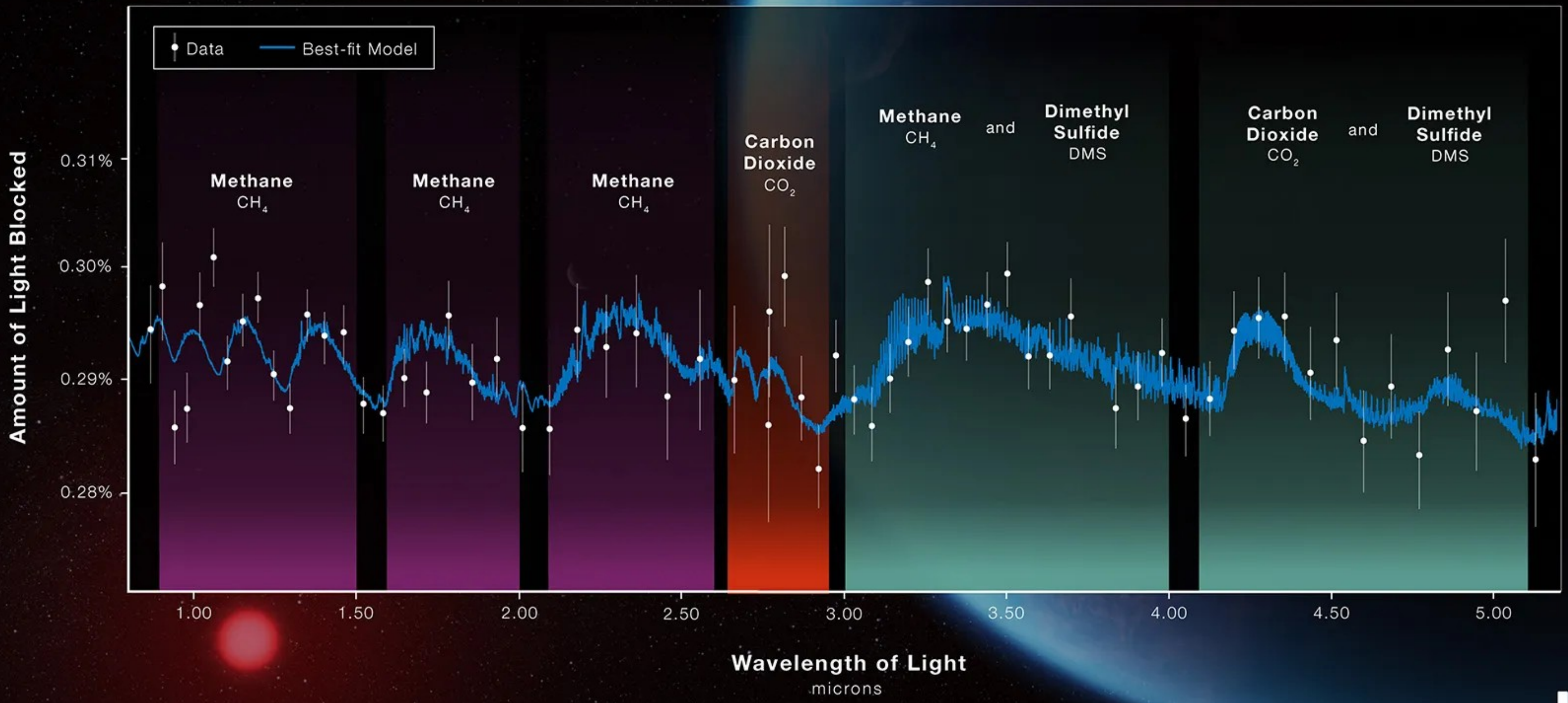
https://www.nature.com/articles/s41586-022-05677-y



https://webbtelescope.org/contents/media/images/2022/060/01GJ3Q66DTT4HPMDCVNC9GXH5Y?news=true

EXOPLANET K2-18 b
ATMOSPHERE COMPOSITION

NIRISS and NIRSpec (G395H)



WEBB
SPACE TELESCOPE

ARIEL

Elliptical primary mirror: 1.1 x 0.7 metres

Mission lifetime: at least 4 years in orbit

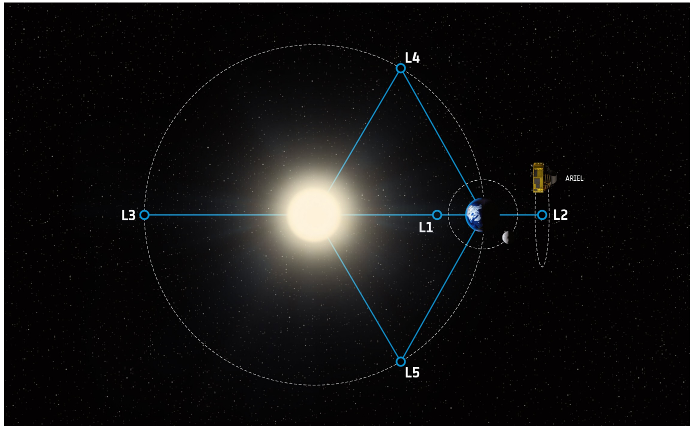
Payload mass / launch mass: ~500 kg / ~ 1500kg

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)

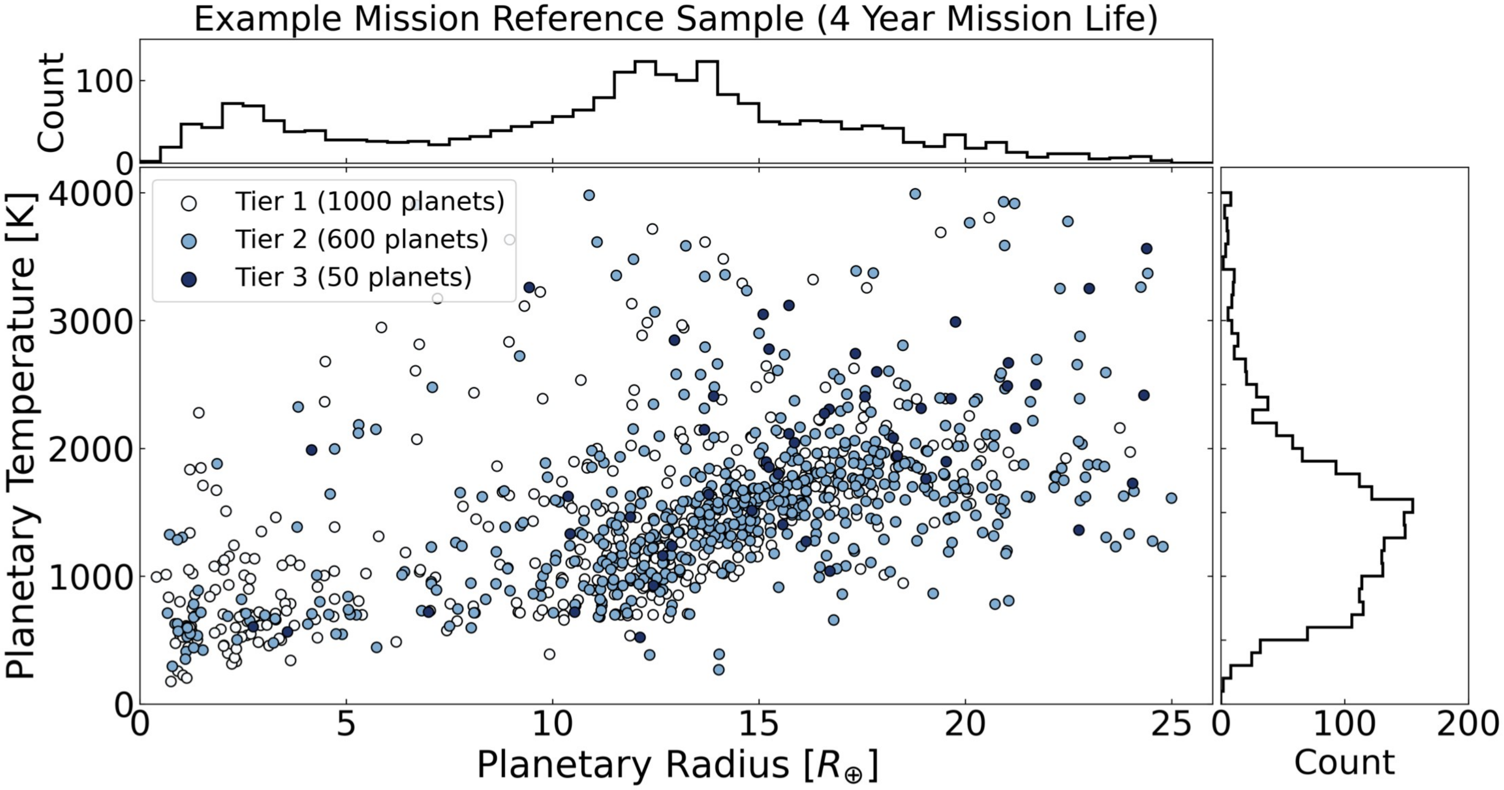
Launch vehicle: Ariane 6-2. Launch shared with Comet Interceptor.



https://arielmission.space/index.php/press-releases/

ARIEL sample and goals

- 1000 atmospheres characterisation target



https://arxiv.org/pdf/2205.05073.pdf

Exam

- Please choose 1 from the topics below and prepare a 5 minutes presentation which will be followed by a discussion of about 10-15 minutes

  Format of the presentation is free but the idea is to wrap-up the chosen topic and present to other colleagues

- Please look for an interesting paper from your topic (of your choice) and you will present it as in a journal club

  (10-15 minutes presentation on screen with discussion)

Exam topics

- 1 Spectroscopic characterization of exoplanets
- 2 Photometric characterization of exoplanets
- 3 Exoplanetary atmospheres
- 4 Statistics of exoplanets (occurance rates, etc.)
- 5 Statistics of exoplanets (types of exoplanets, etc.)
- 6 Instrumentation for exoplanetary research
- 7 Evolution of exoplanetary systems
- 8 Life in the Universe
- 9 Architecture of exoplanetary systems (interesting systems)

- Requirements:
  Please choose 1 topic from above
  Presentation 10 minutes + 2 papers of your choice related to chosen topic presentation

Thank you