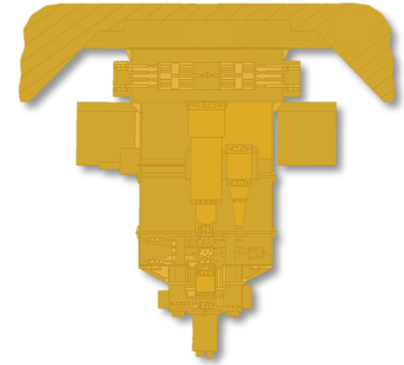


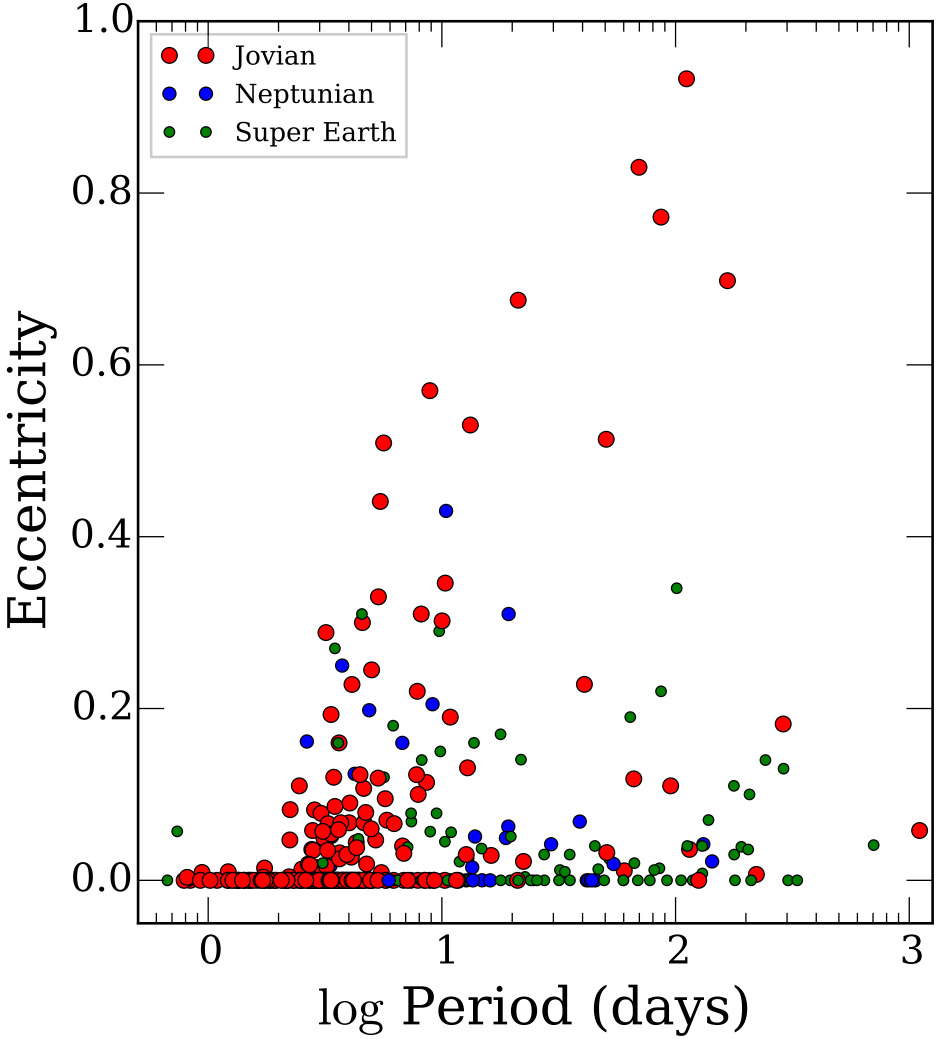
Regaining the FORS

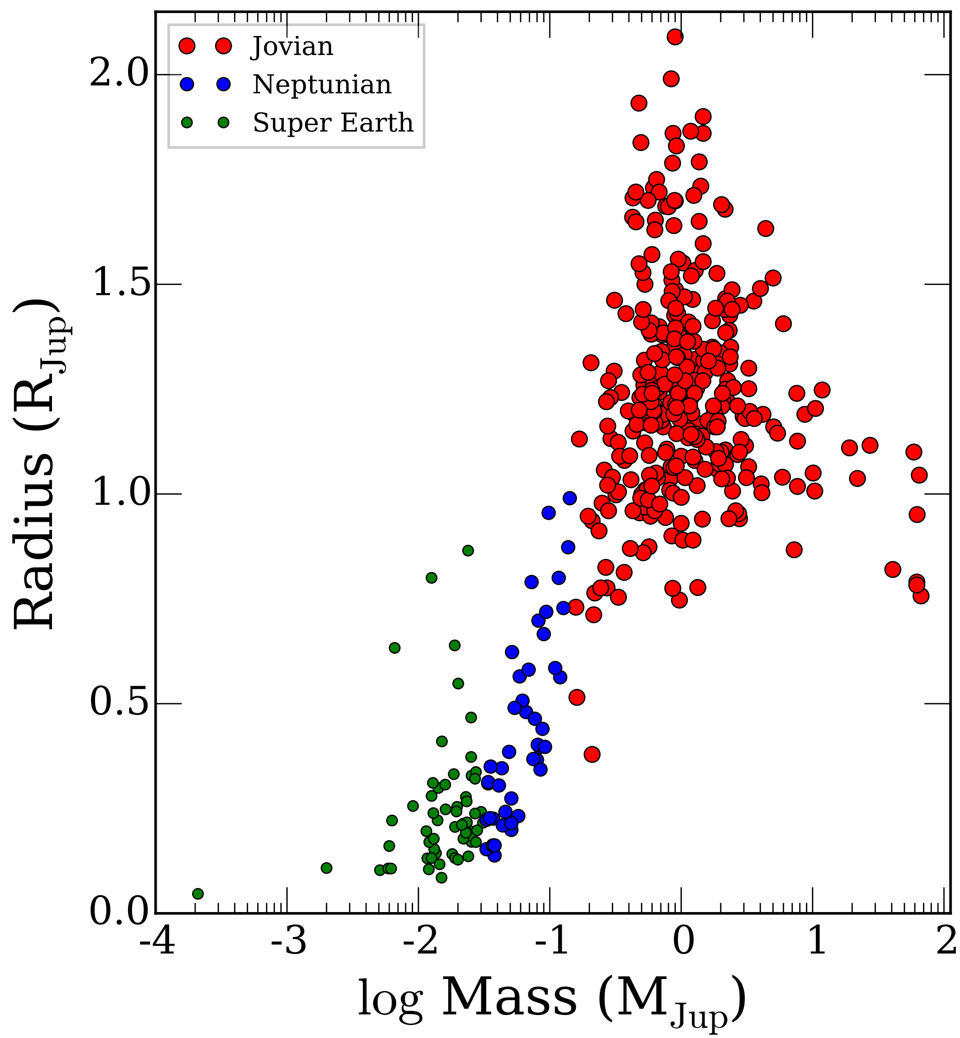
Optical ground-based transmission spectroscopy of exoplanets with VLT+FORS2

Henri Boffin

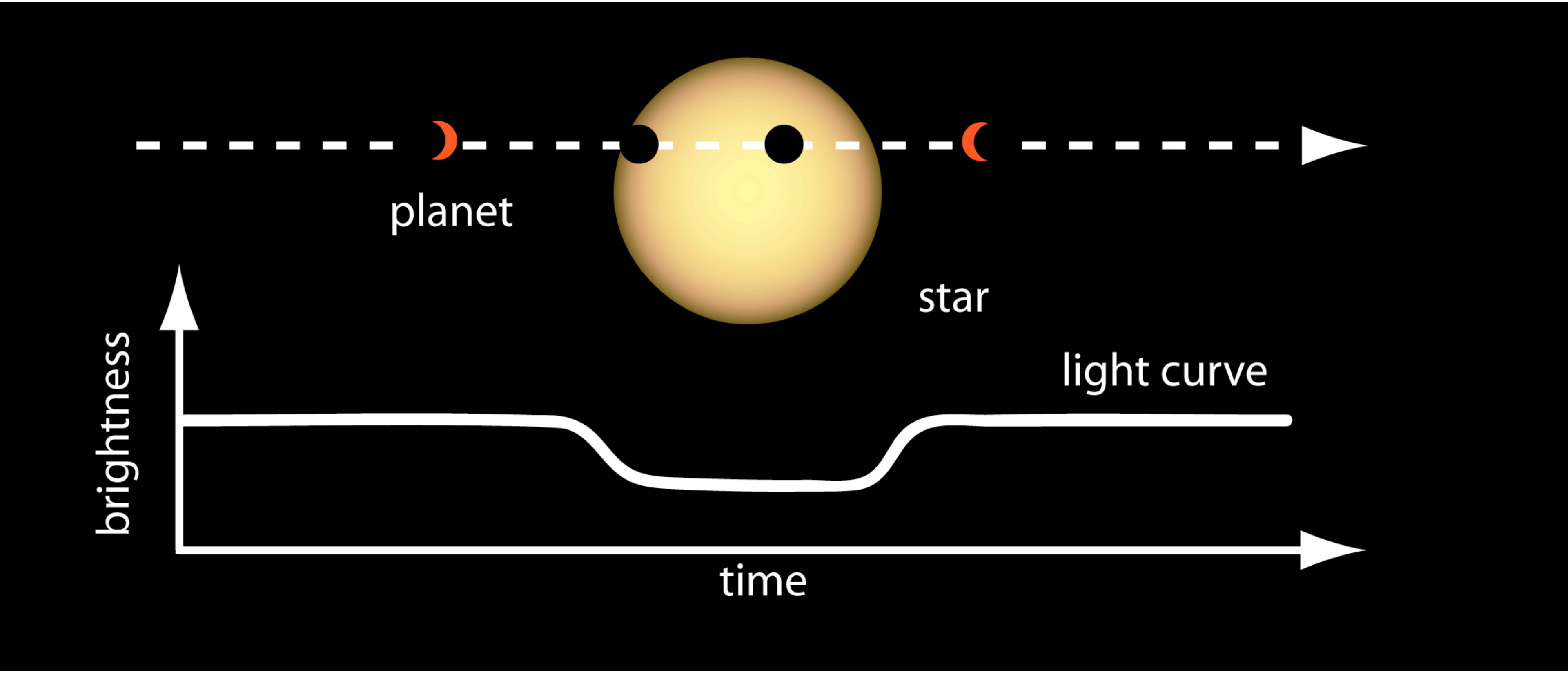
E. Sedaghati, G. Blanchard, Sz. Csizmadia, N. Gibson, P. Kabath, M. Mallonn, and M.E. Van den Ancker

Transiting planets

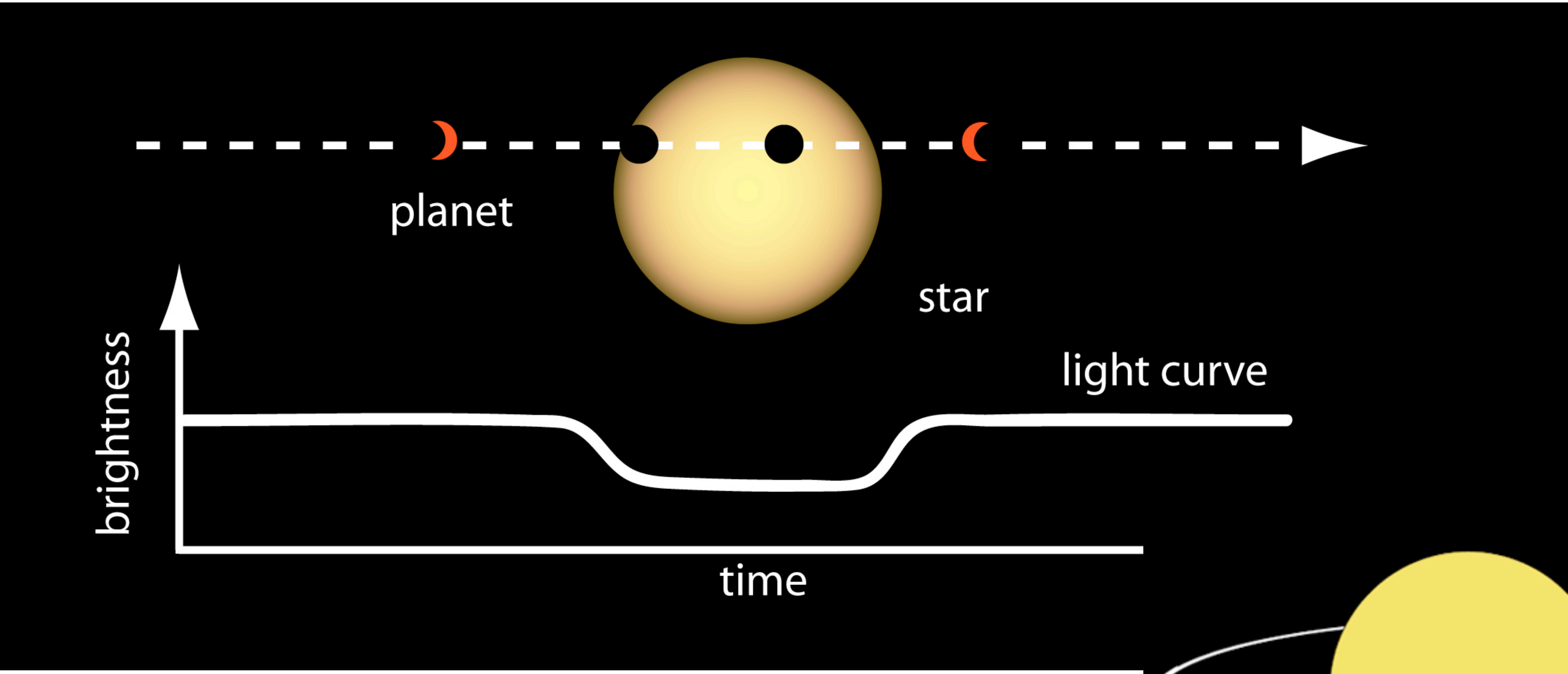


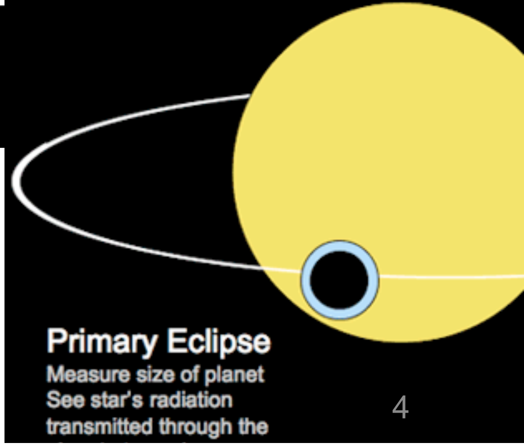


Transiting planets

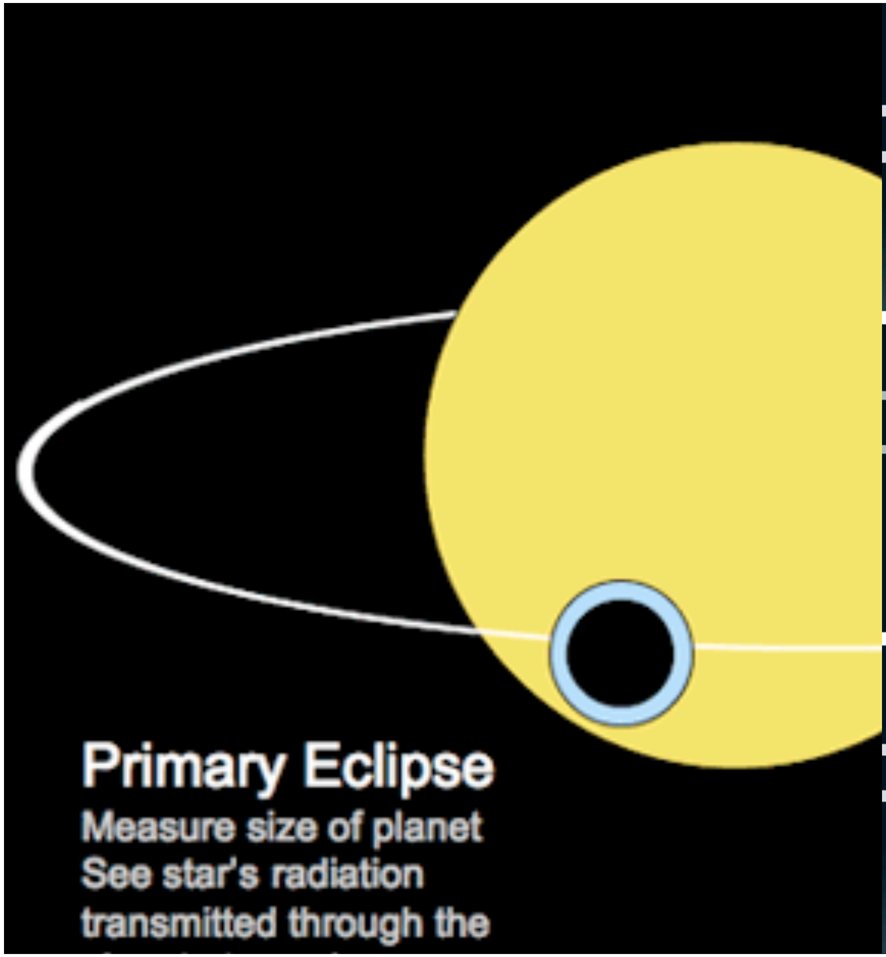


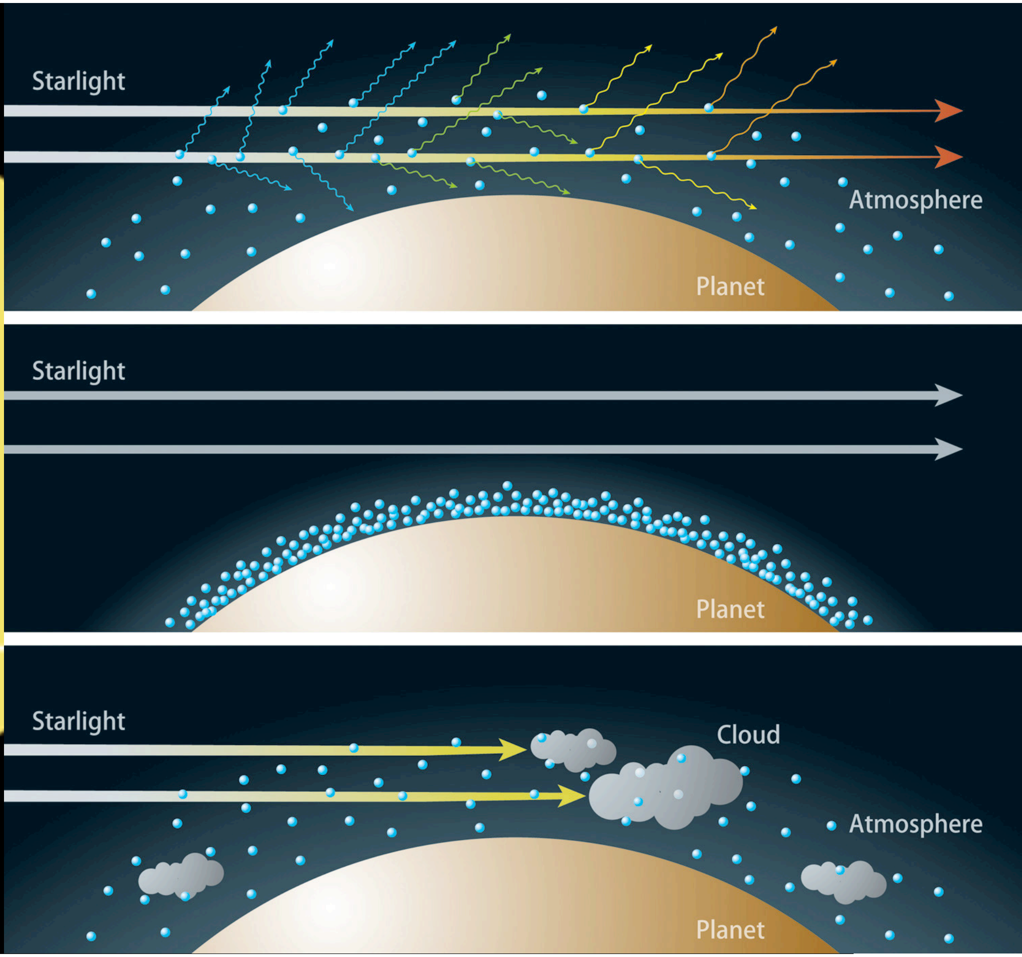
Transiting planets





Transiting planets

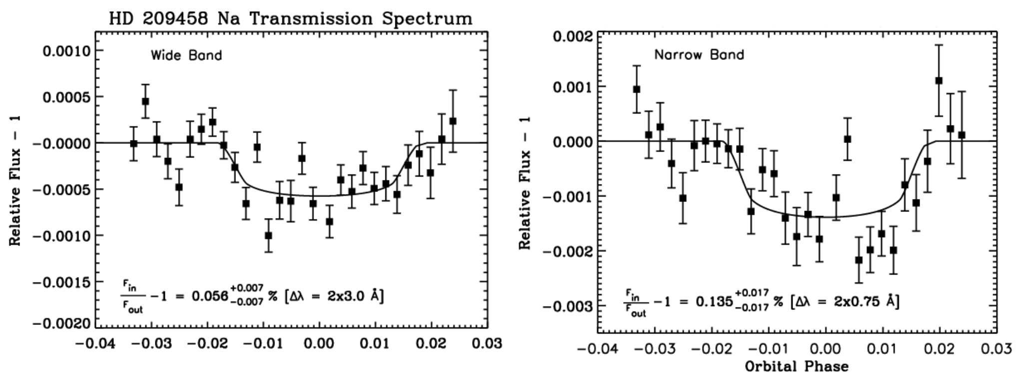




The depth of the transit will thus be wavelength dependent

A tricky business

Ground-based detection of **Sodium** in HD 209458b (Snellen et al. 2008)



Δλ = 3.0 Å Depth = 0.056%

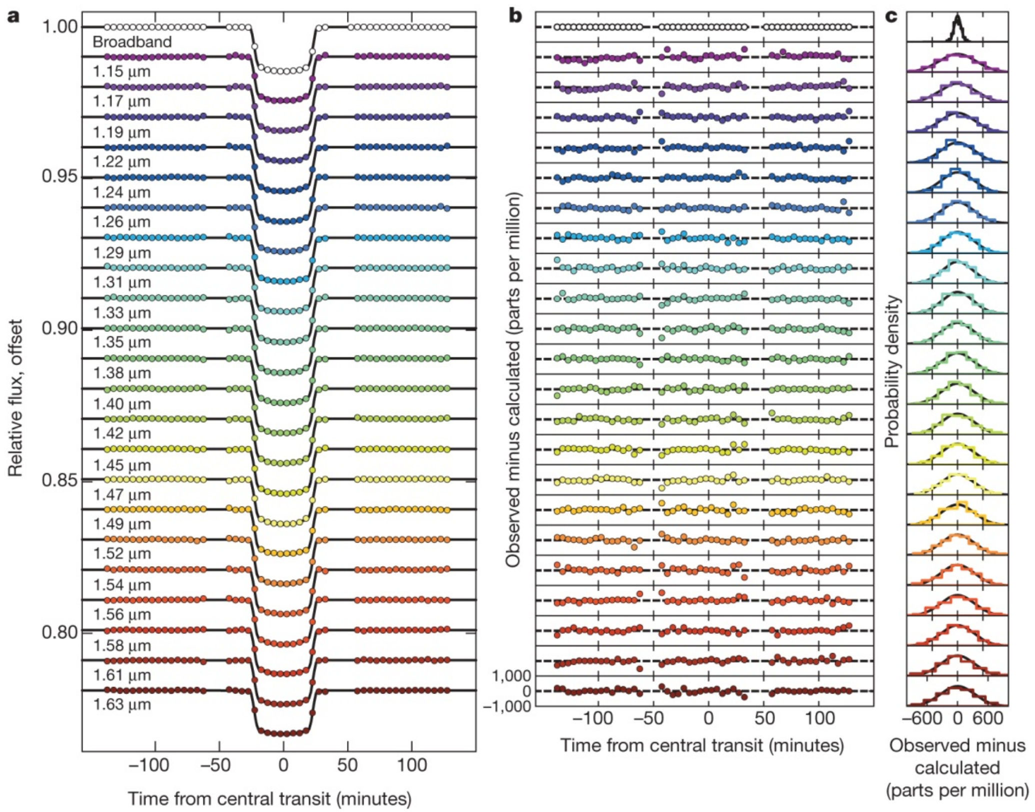
Δλ = 0.75 Å Depth = 0.135%

> 5σ detection With HDS@Subaru

López-Morales 14

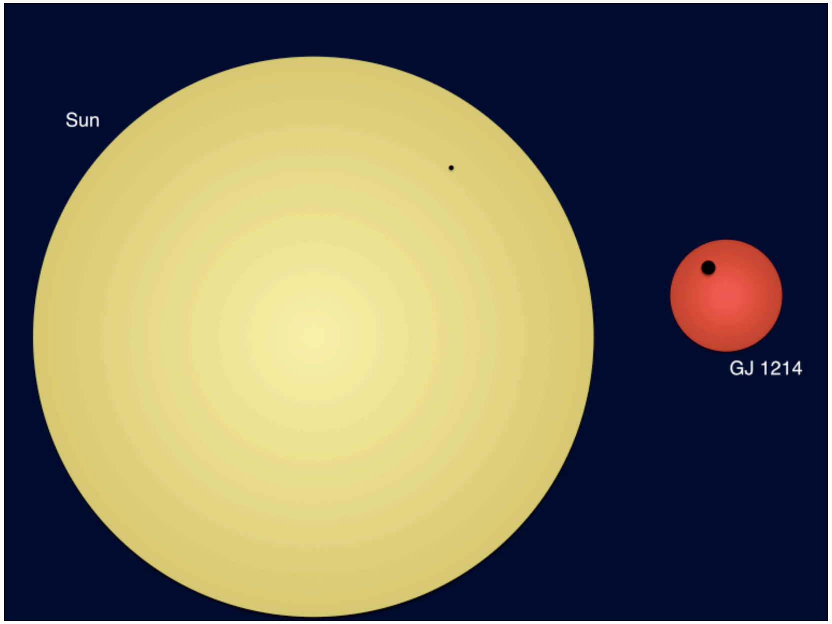
This is better done from space

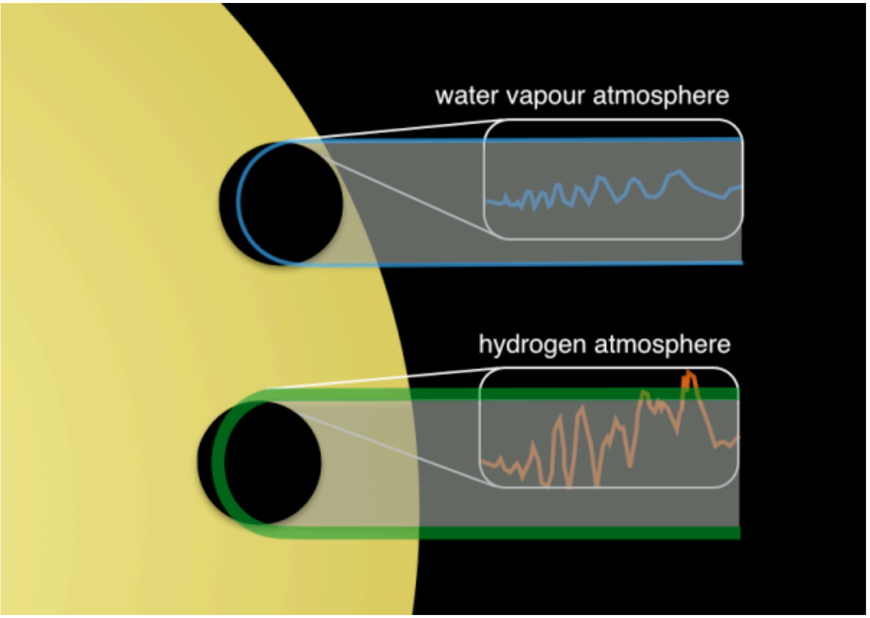
Spectrophotometric data for transit observations of GJ 1214b.



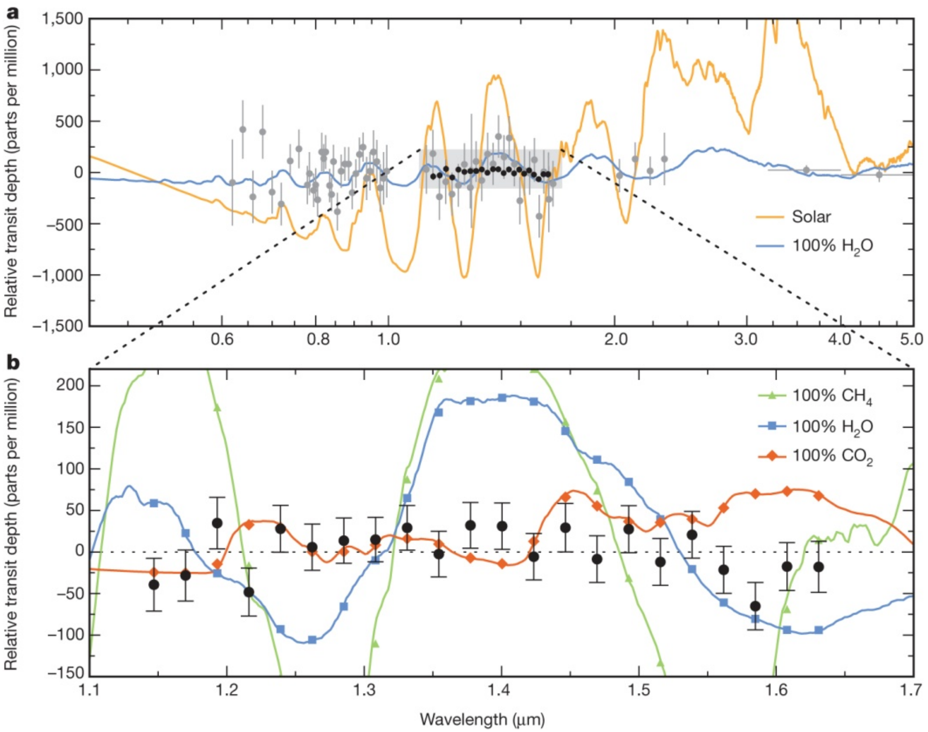
L Kreidberg *et al. Nature* **505**, 69-72 (2014) doi:10.1038/nature12888

Super-Earth GJ 1214b





The transmission spectrum of GJ 1214b.

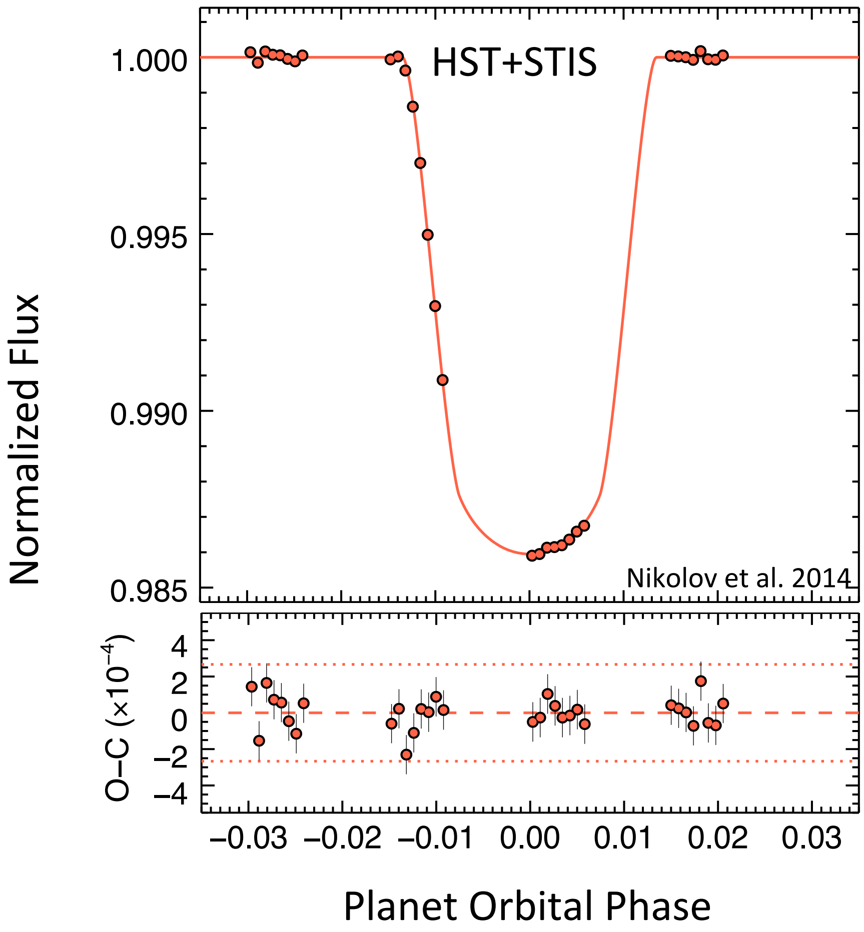


A flat spectrum!
Cloudy!

L Kreidberg *et al. Nature* **505**, 69-72 (2014) doi:10.1038/nature12888

So, why on ground?

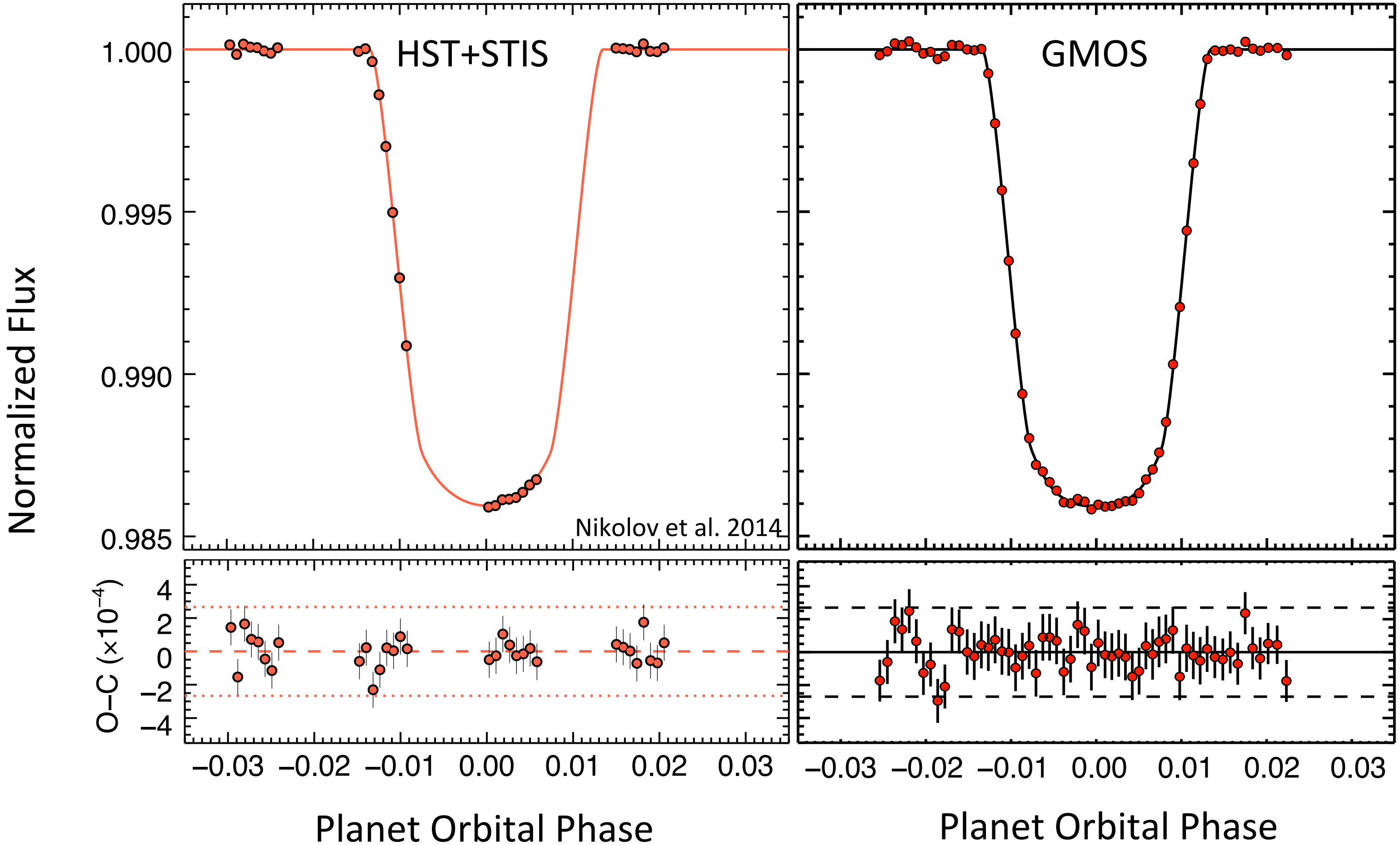
The case of HAT-P-1b: 6-hour observaJon



C. Huitson 15

Why on ground?

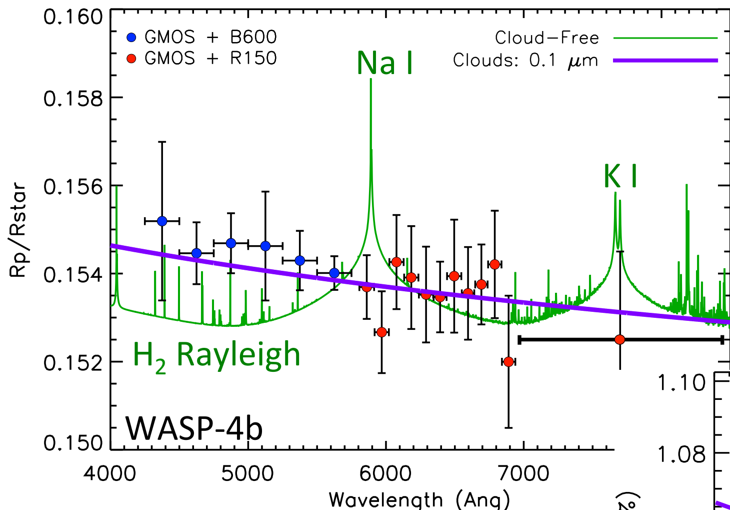
The case of HAT-P-1b: 6-hour observaJon



C. Huitson 15

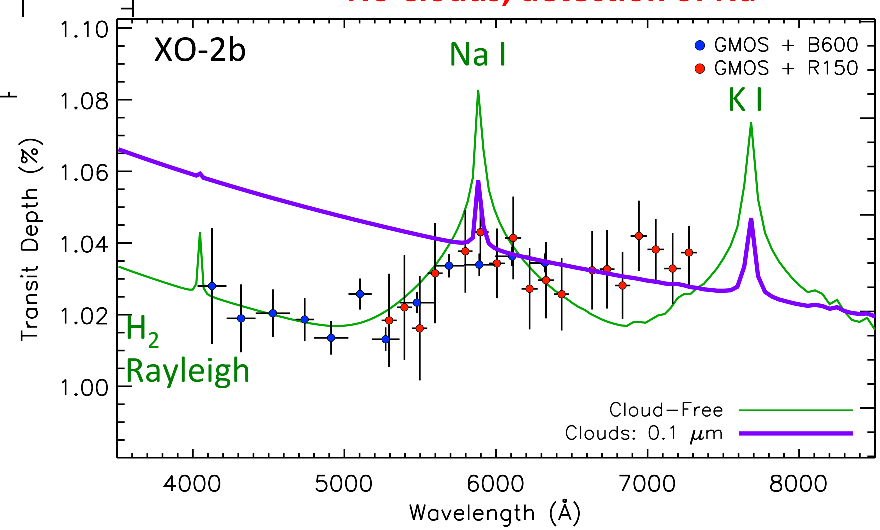
GMOS Results

Clouds detected



<u>First Important Result</u>
Two planets similar, yet two different signatures => diversity

No Clouds, detection of Na



C. Huitson 15

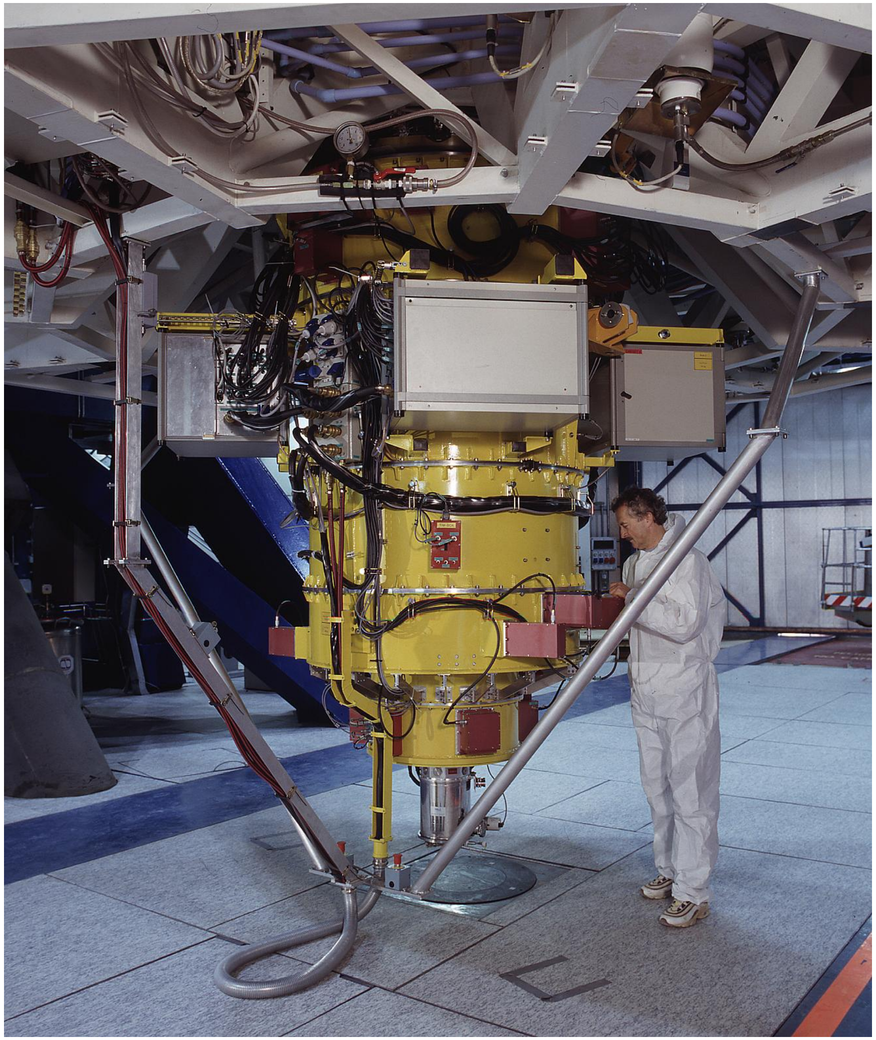
Transmission Spectroscopy

Boffin+ 16

Table 1. Ground-based transmission spectroscopic studies as of now.

Instrument	**Telescope**	**Target**	**λ-range** (nm)	**Bin size** (nm)	**Reference**
DOLORES	TNG	HAT-P-1	525–760	60	Montalto et al. 2015 [20]
FORS2	VLT	GJ 1214	780–1 000	20	Bean et al. 2010 [3]
		GJ 1214	610–850	10,20	Bean et al. 2011 [4]
		WASP-19	560–820	16–22.5	Sedaghati et al. 2015 [25]
		WASP-17	570–825	5–20	Sedaghati et al. 2016a [26]
		WASP-19	400–1 000	5–20	Sedaghati et al. 2016b [27]
		WASP-49	730–1 000	10	Lendl et al. 2016 [16]
GMOS (N/S)	Gemini	HAT-P-32	520–930	14	Gibson et al. 2013a [11]
		WASP-29	515–720	15	Gibson et al. 2013b [12]
		WASP-12	720–1 010	15	Stevenson et al. 2014 [29]
IMACS	Magellan	WASP-6	480–860	20	Jordàn et al. 2013 [14]
LDSS-3C	Magellan	HAT-P-26	720–1 000	12.5	Stevenson et al. 2016 [30]
MMIRS	Magellan	WASP-19	1 250–2 350	100	Bean et al. 2013 [5]
MODS	LBT	HAT-P-32	330–1 000	11	Mallonn & Strassmeier 2016 [18]
MOSFIRE	Keck	GJ3470	1 960–2 390	40	Crossfield et al. 2013 [10]
OSIRIS	GTC	HAT-P-19	560–770	5–20	Mallonn et al. 2015 [17]
		WASP-43	540–920	10,25	Murgas et al. 2014 [21]
		HAT-P-32	518–918	20	Nortmann et al. 2016 [22]
		TrES-3	530–930	25	Parviainen et al. 2016 [23]

And at the VLT? FORS2



- FOcal Reducer and low dispersion Spectrograph
- At the Cassegrain focus of UT1
- FoV of 6.8'×6.8'
- Offers: imaging, polarimetry, long slit and multi-object spectroscopy
- Spectral coverage of 330-1100nm
- Mosaic of two 2k×4k MIT(red) or E2V(blue) available

FORS2

FOcal Reducer
low dispersion Spectrograph

A wonderful German understatement!

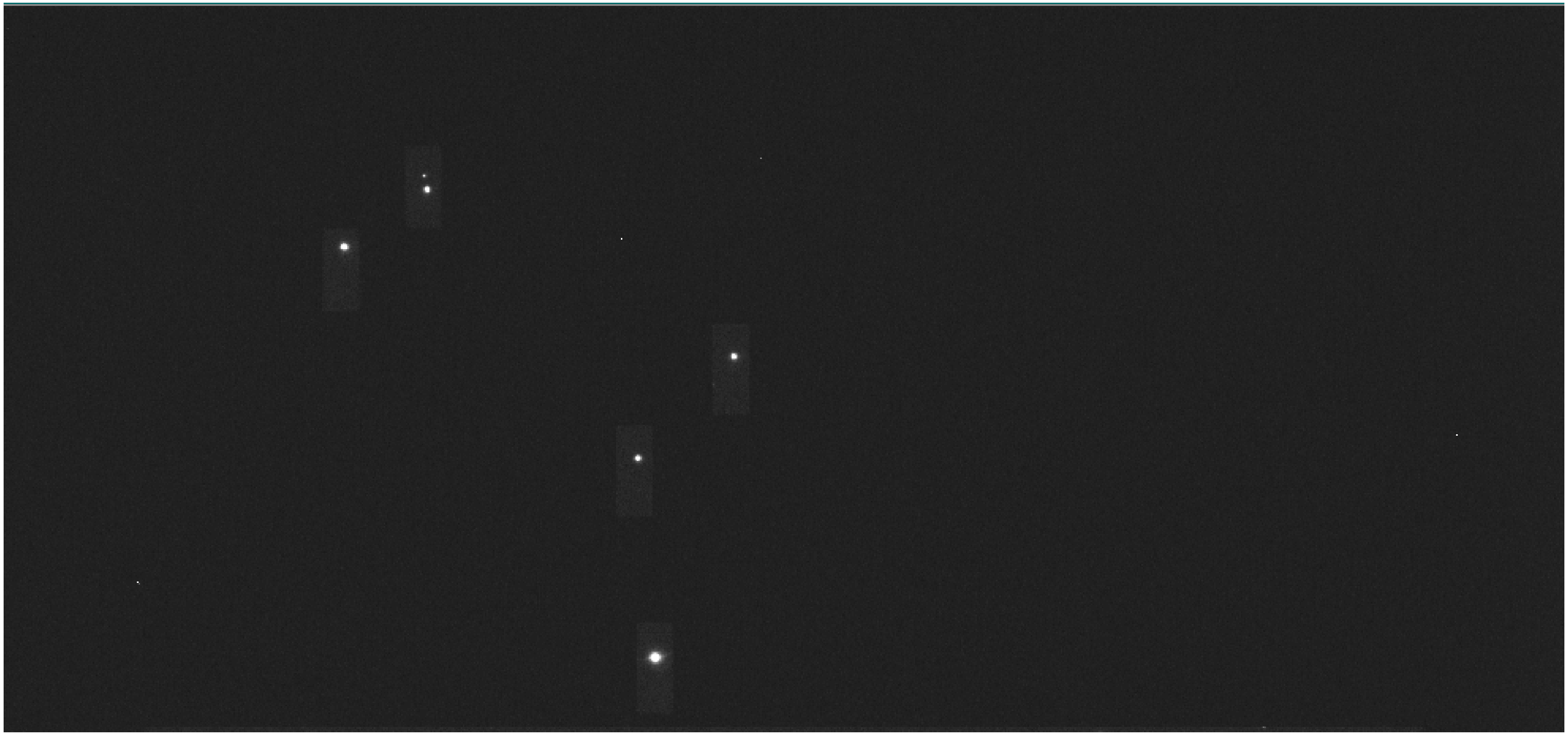
It should be called

FOcal Reducer **Fast Imager and low dispersion Single and Multi-Object Spectropolarimeter**

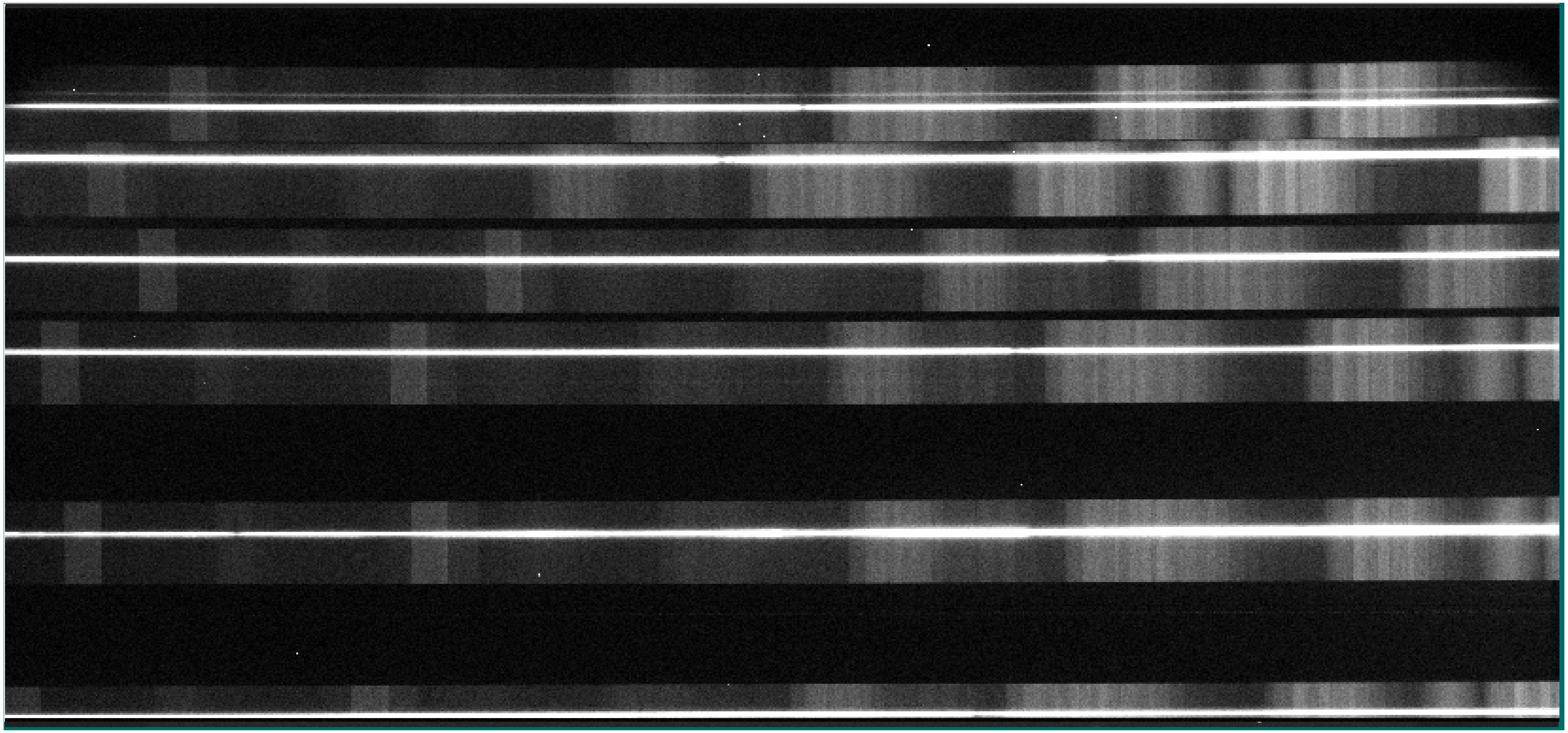
FORFISMOS

Multi-Object Spectroscopy

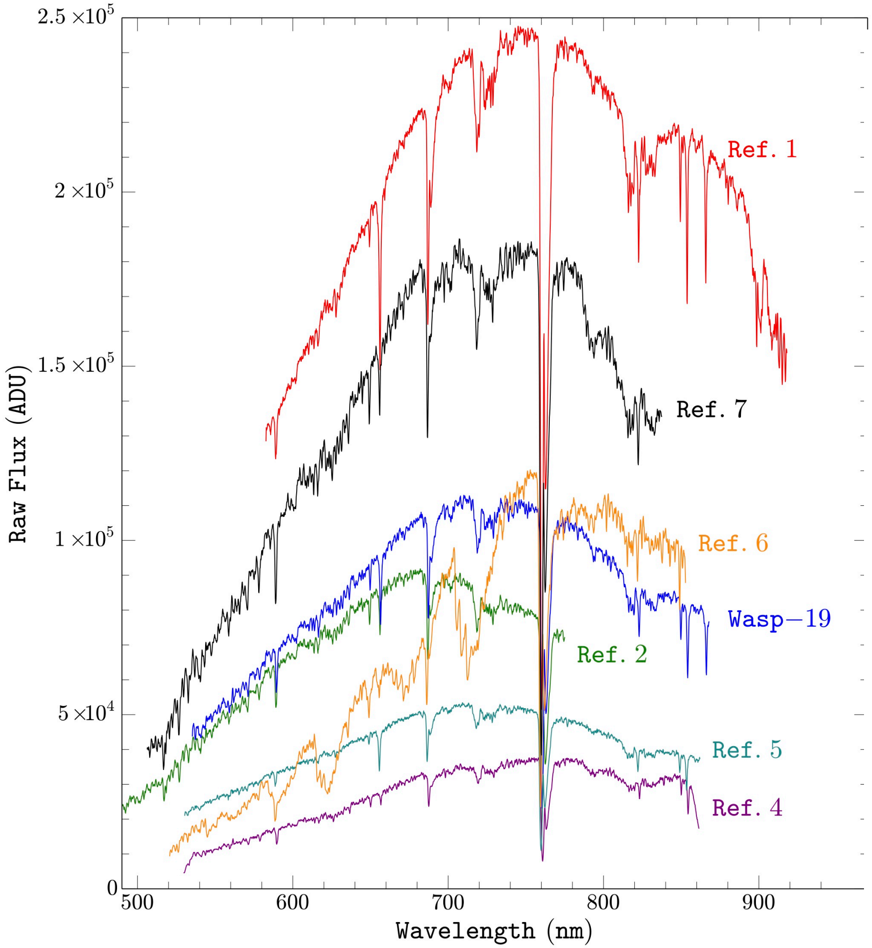
Multi-Object Spectroscopy

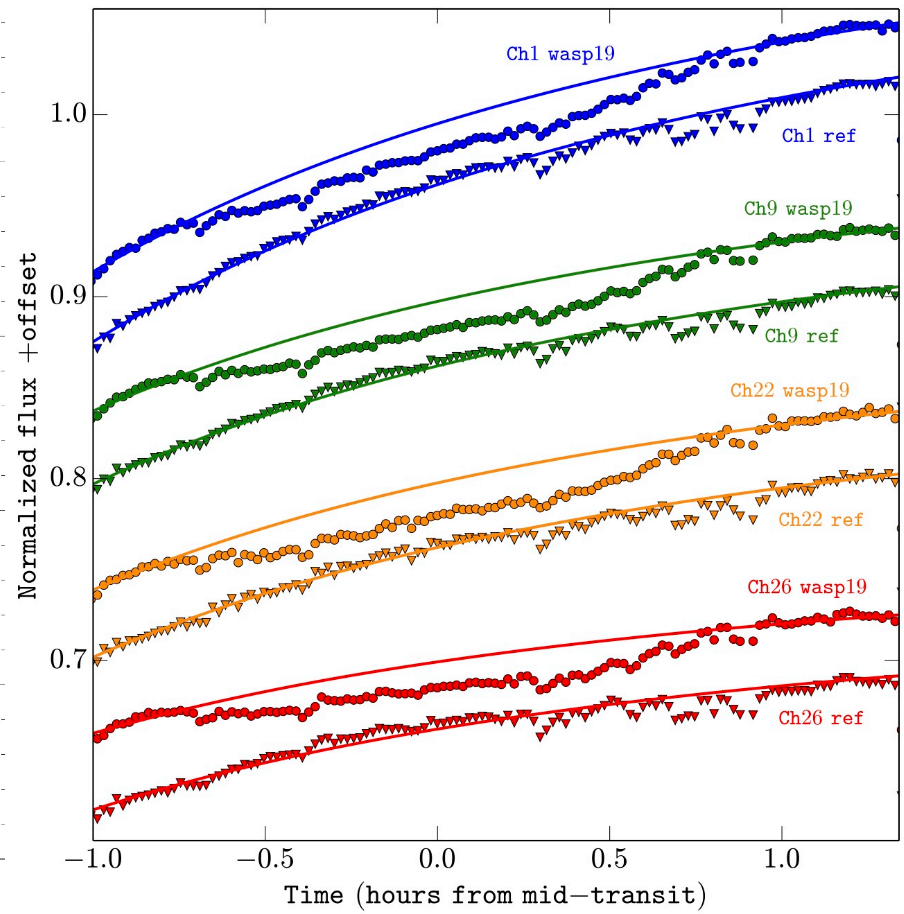


Multi-Object Spectroscopy

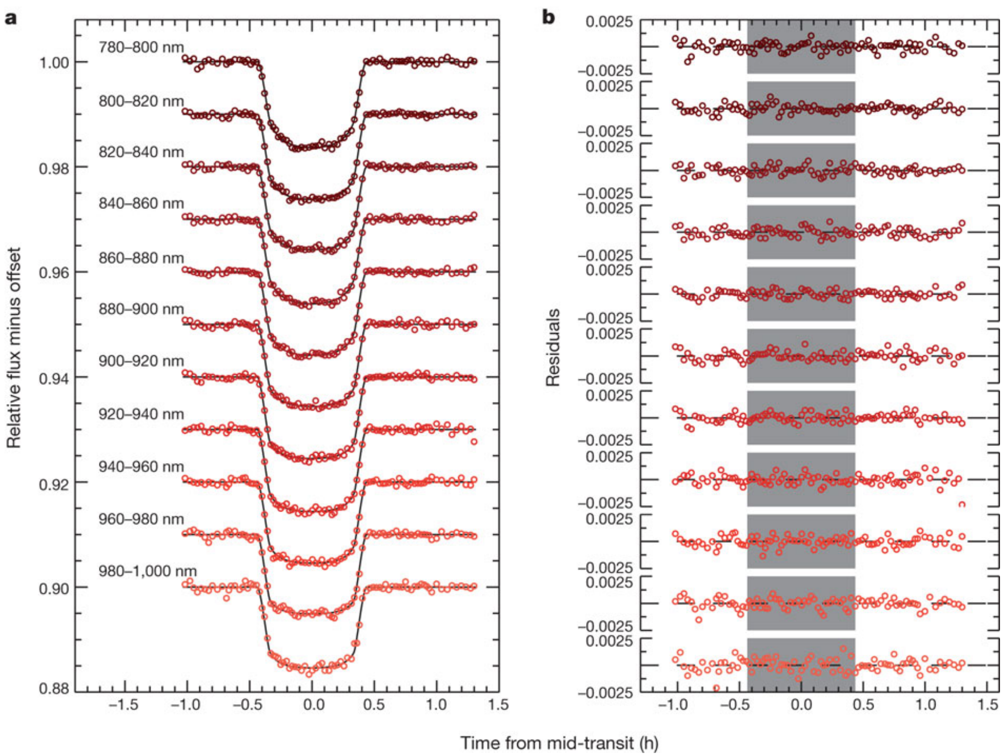


Multi-Object Spectroscopy



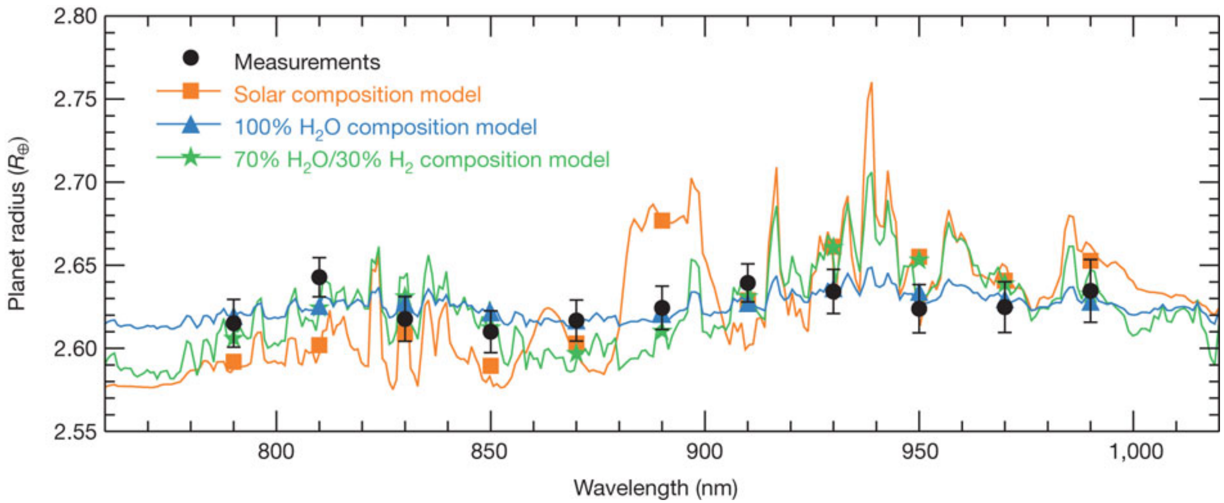


Promising result



- Bean et al. (2010, Nature 468, 669): Lightcurve of transit of exo-planet GJ 1214b with FORS2.

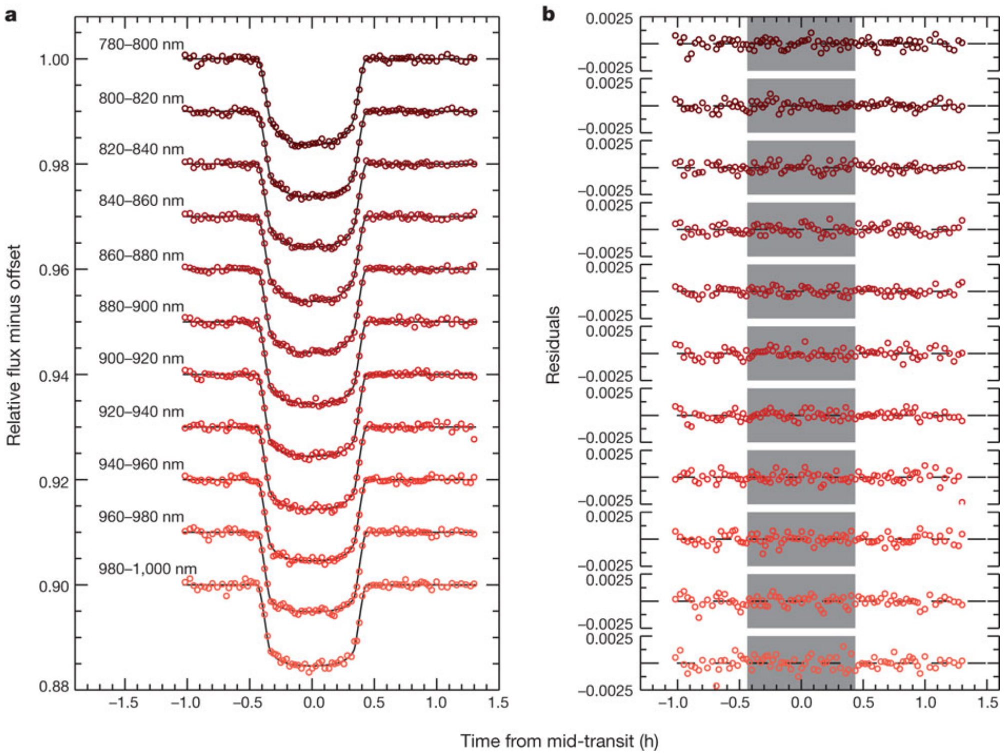
The transmission spectrum of GJ 1214b compared to models.



Lack of spectral features rules out cloud-free Hydrogen atmosphere.

JL Bean *et al.* *Nature* **468**, 669-672 (2010) doi:10.1038/nature09596

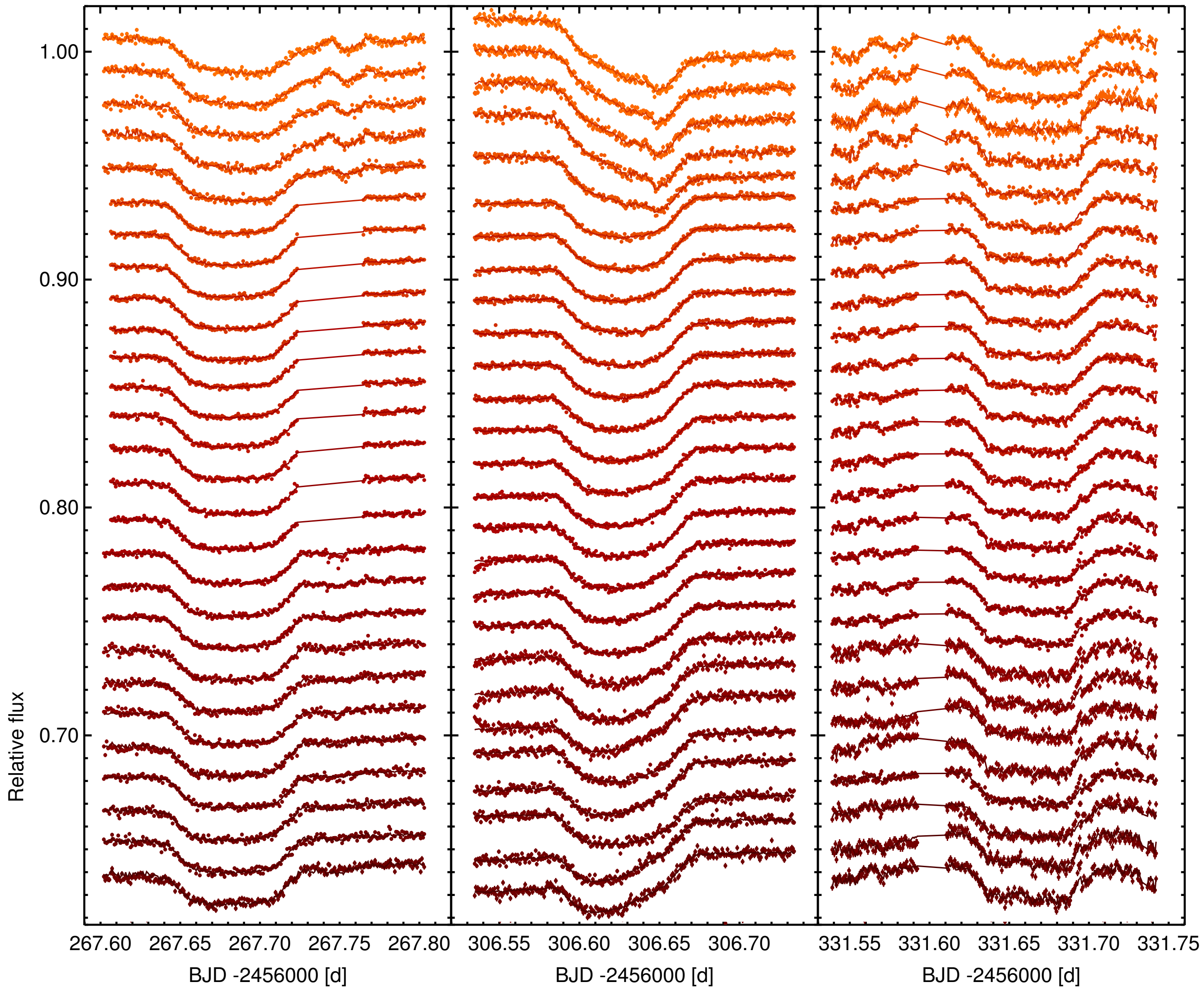
Promising result



- Bean et al. (2010, Nature 468, 669): Lightcurve of transit of exo-planet GJ 1214b with FORS2.
- Lack of spectral features rules out cloud-free Hydrogen atmosphere.

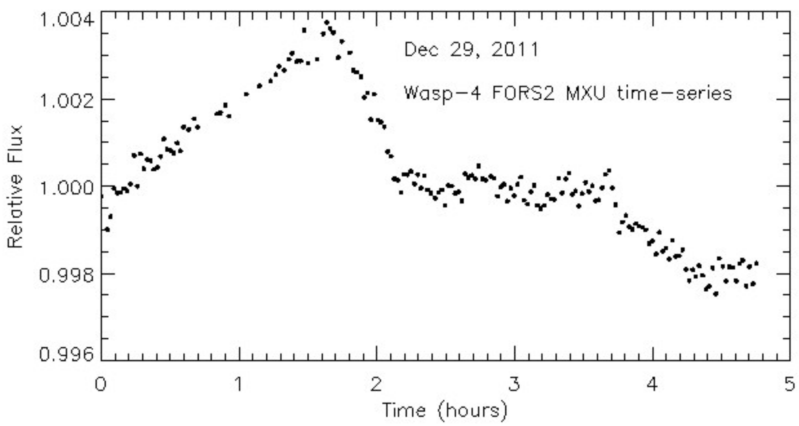
- **Since then**: Many exo-planet transit programmes executed with FORS2, but no papers!
- User questionnaire: Data suffers from unexpected high level of systematics which did not allow the PIs to reach their science goals.

Systematic problems with FORS2



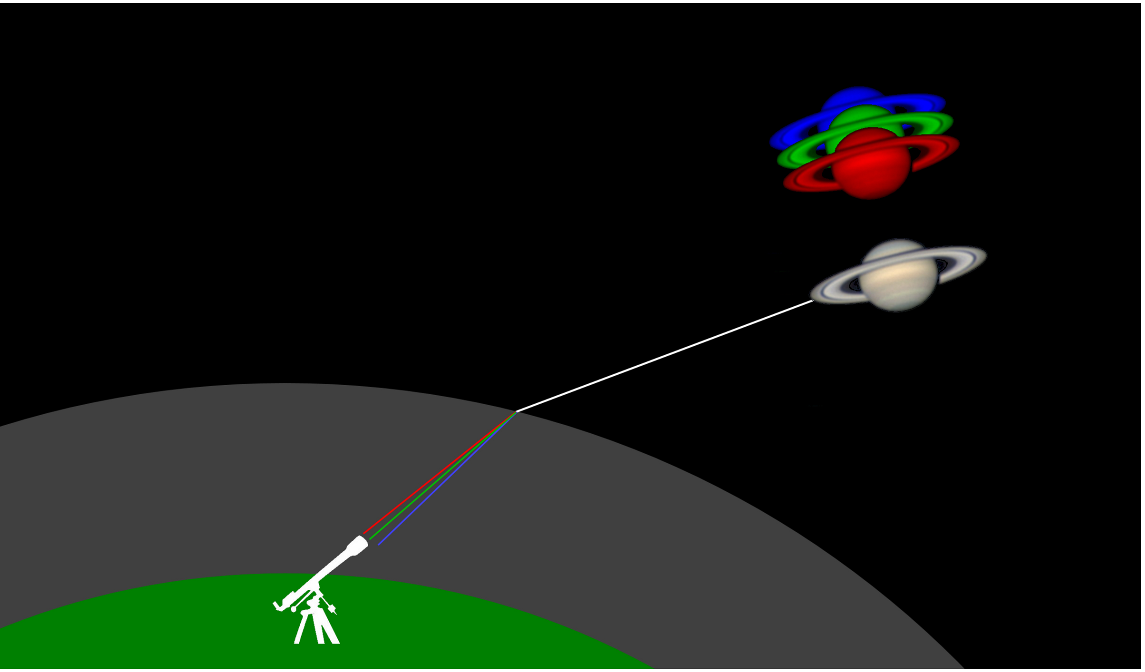
WASP49-b transmission spectroscopy Lendl et al. (2016)

FORS2 MXU Spectro-Photometry of an Exoplanet Transit

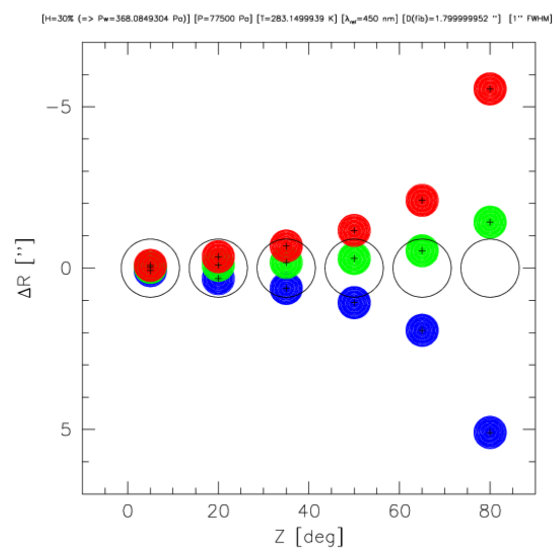


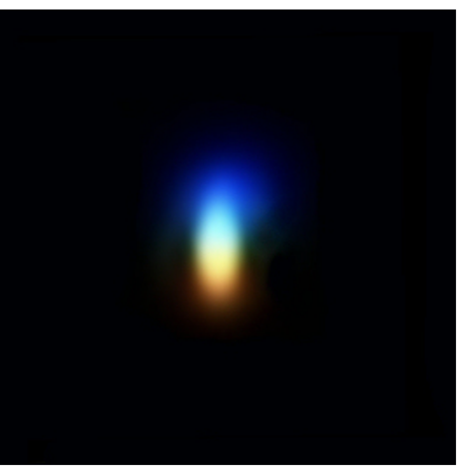
- Systematics ~6 x 10^{-3} on timescales of 0.5-5 hours.
- Time scales and amplitude consistent with hypothesis that systematics are dominated by non-uniform throughput of LADC.

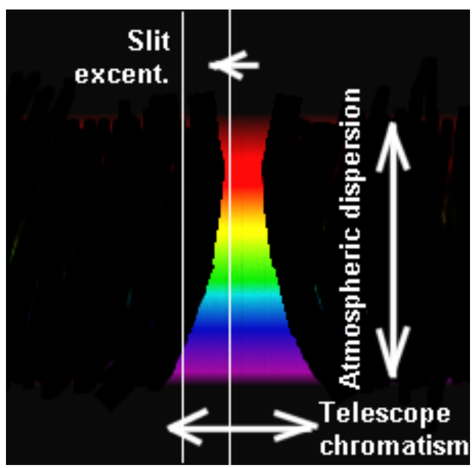
Atmospheric Dispersion



- Refraction
- Dispersion







This will spread light

- **imaging: degrade image quality**
- **spectroscopy: loose light from slit**

FORS2 **Linear Atmospheric Dispersion Corrector**

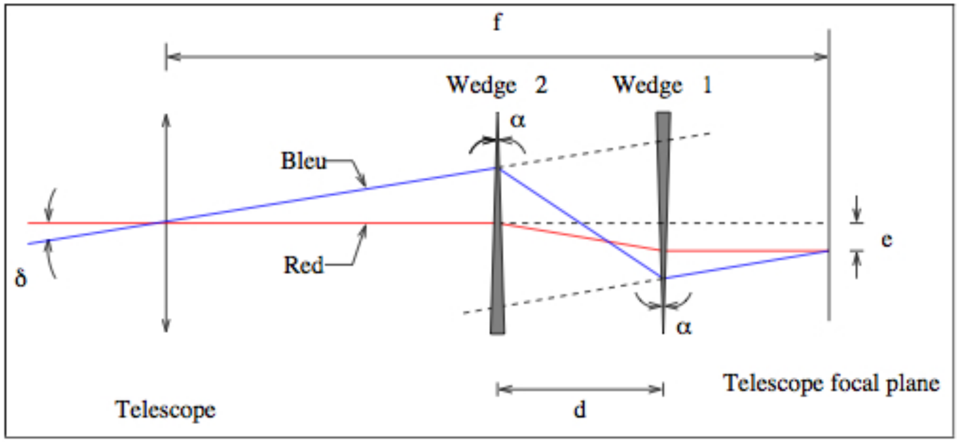
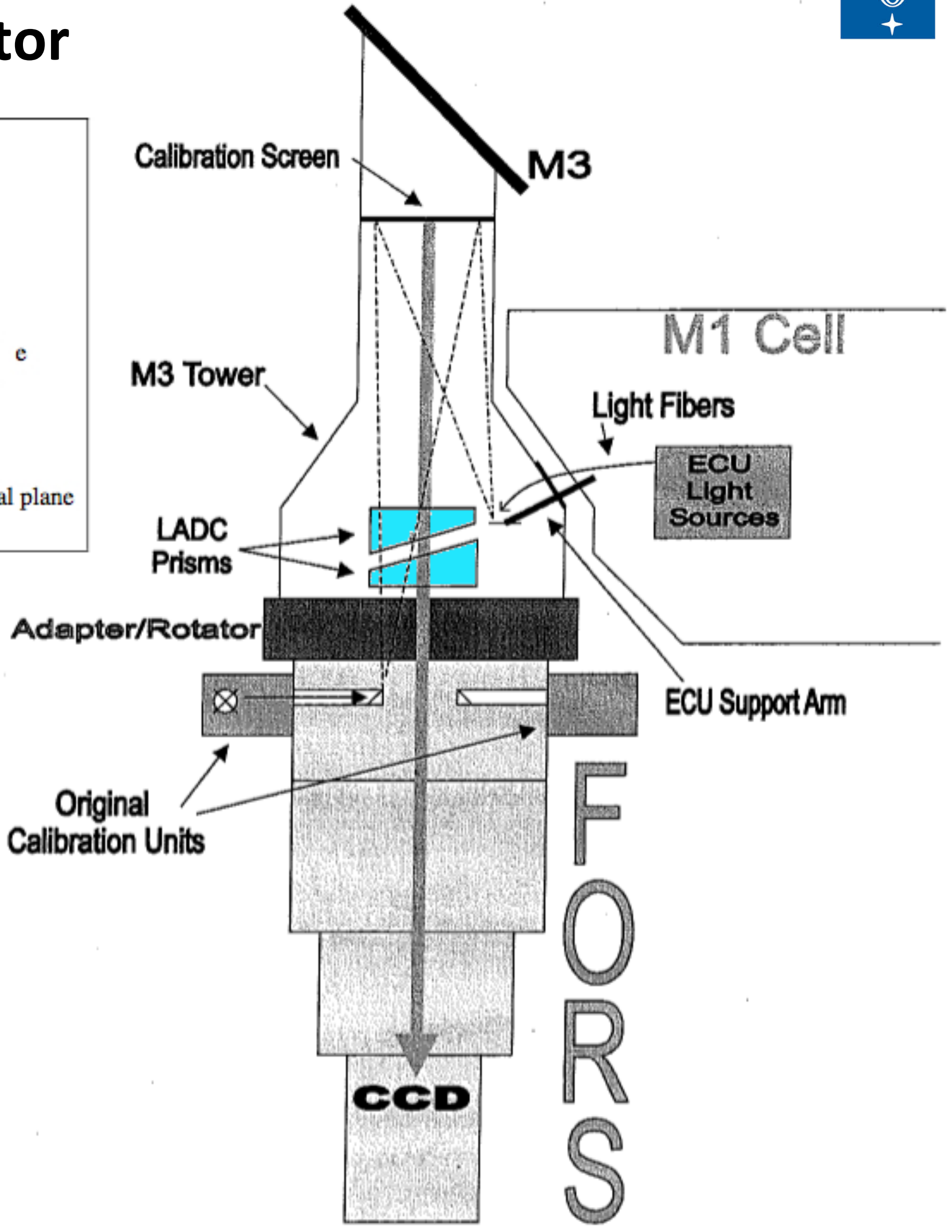


Figure 5: Optical design of the LADC

Distance between prism is linearly adjusted → LADC

30 → 1100 mm

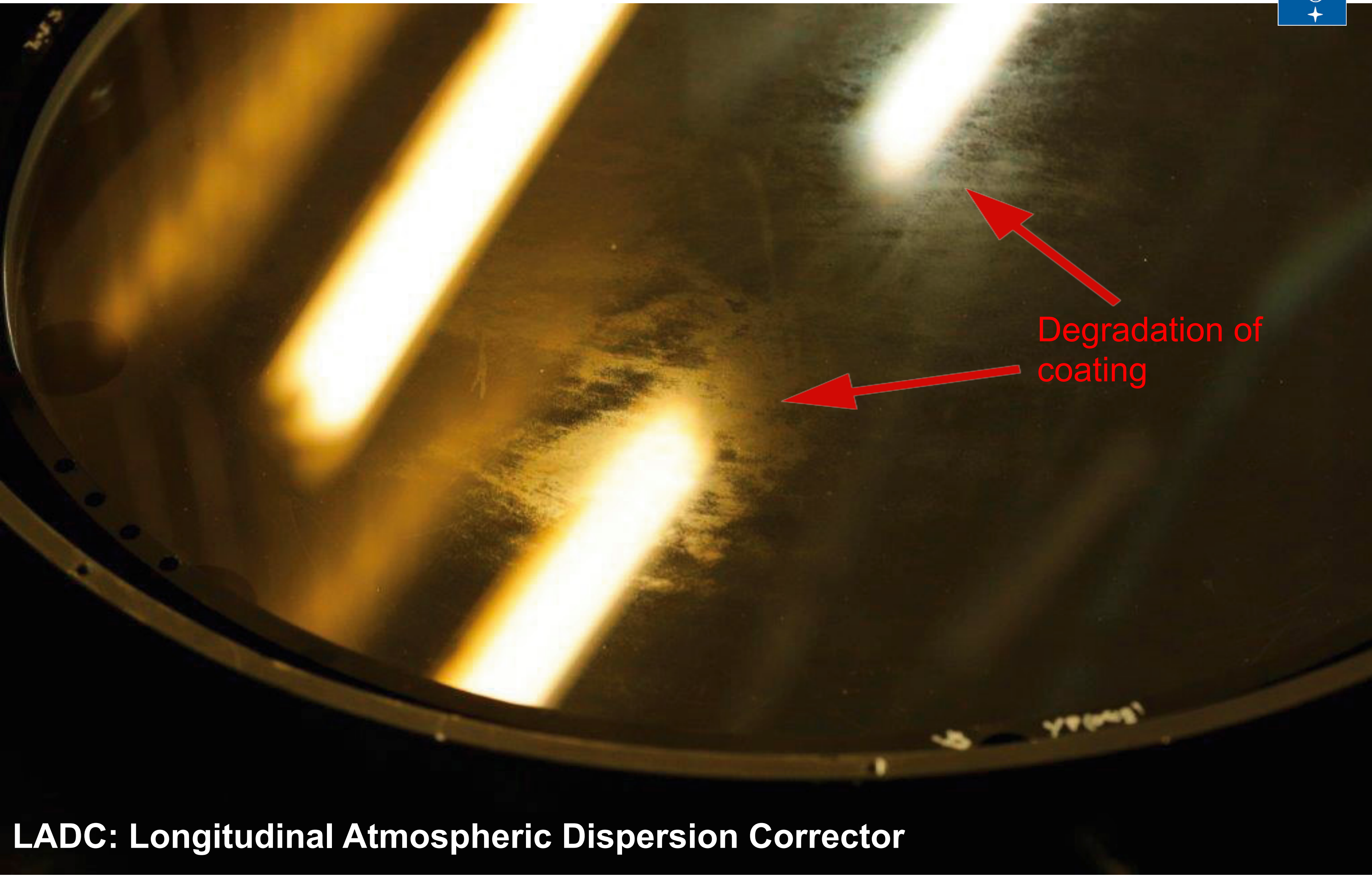
Distance depends on altitude, wavelength range, Temp. and pressure: calculated at each exposure



LADC coating initially

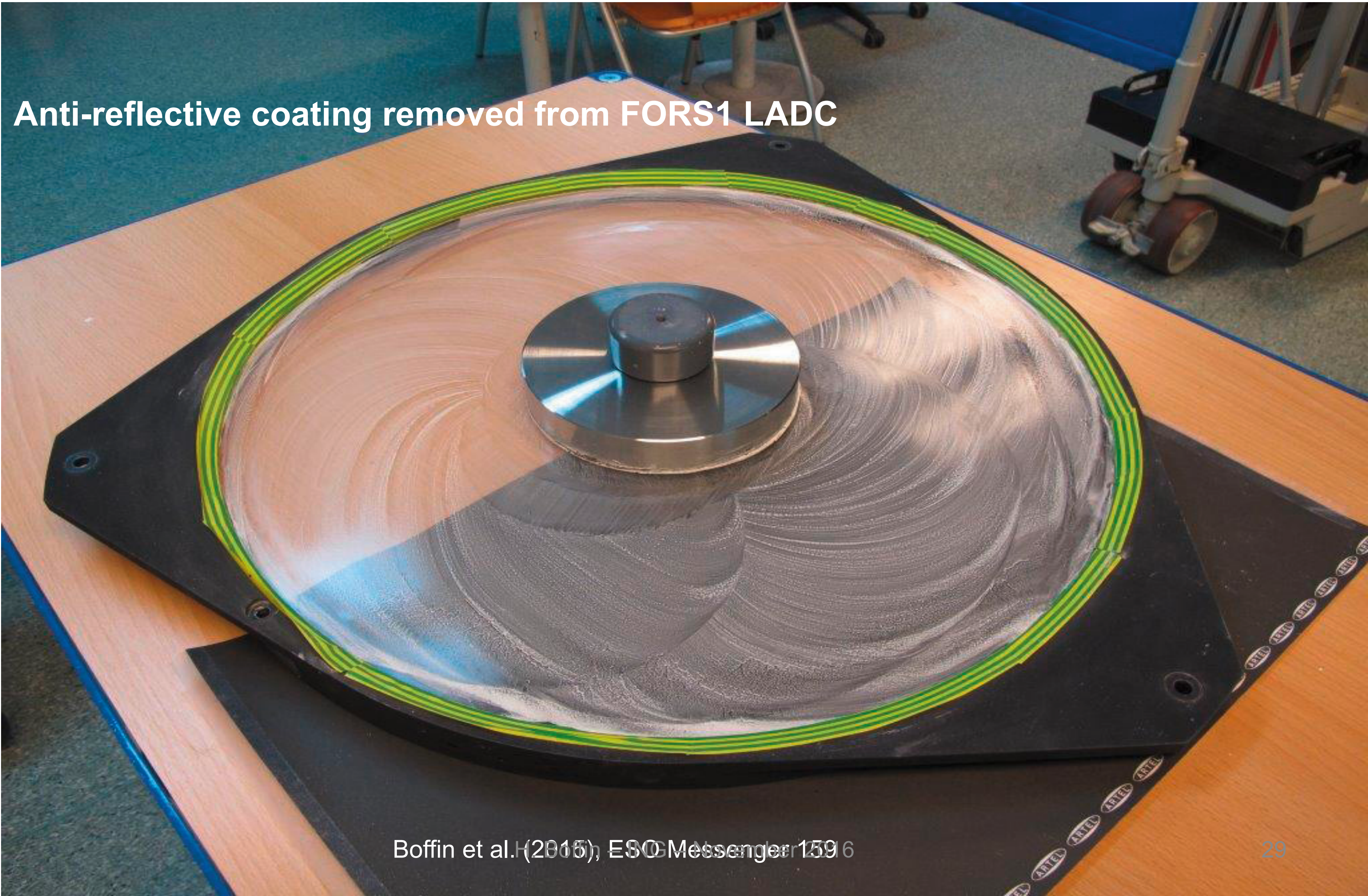
LADC at origin

Systematic problems with FORS2



LADC: Longitudinal Atmospheric Dispersion Corrector

Addressing the Problem

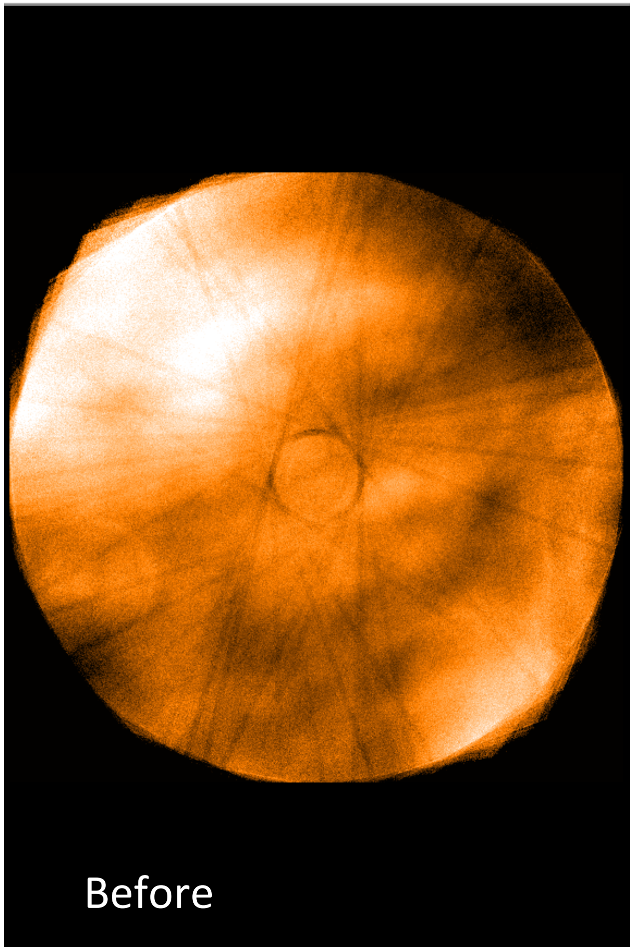


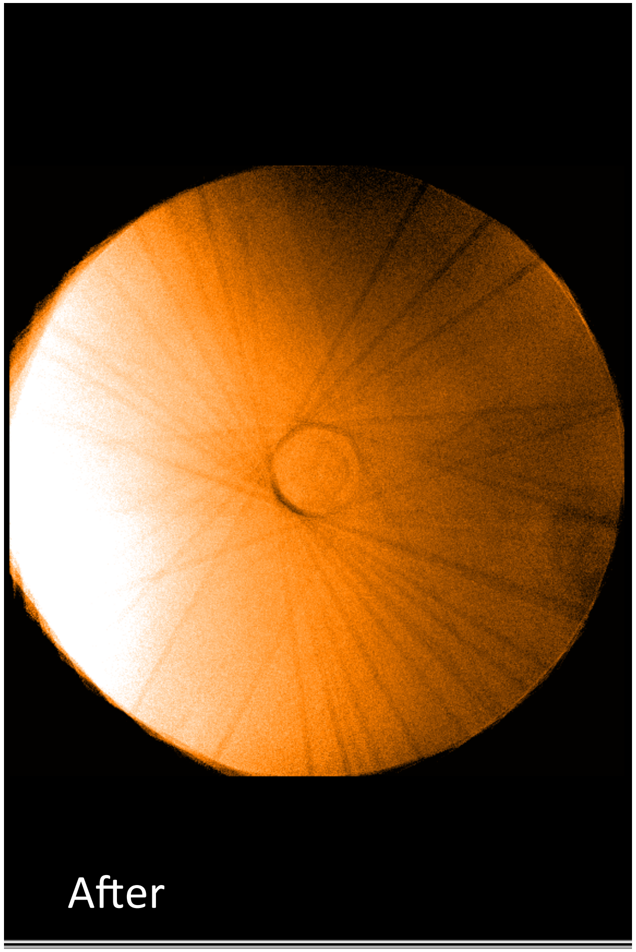
Anti-reflective coating removed from FORS1 LADC

Boffin et al. (2015), ESO Messenger 159

Sky flats

Boffin+ 16

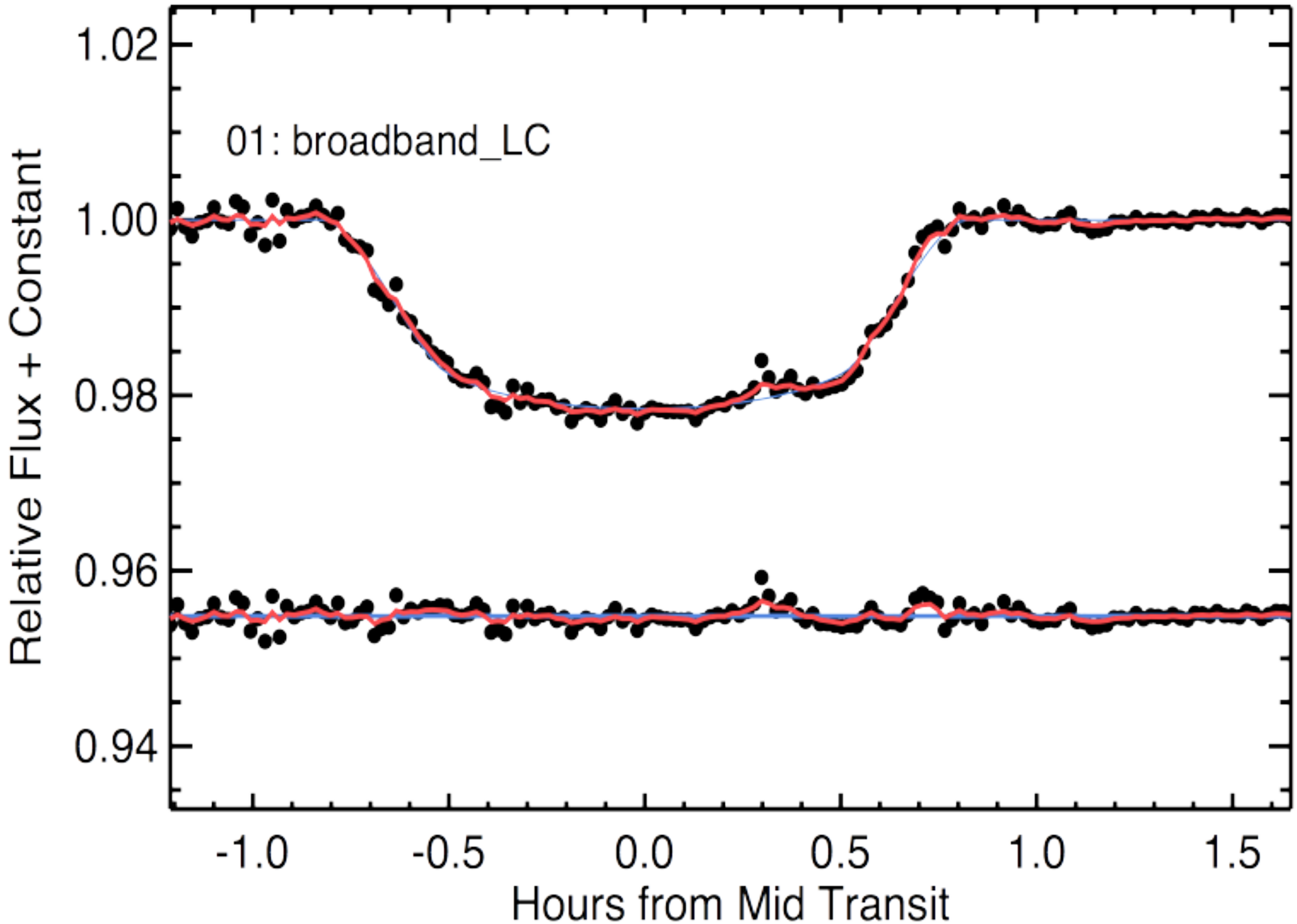




FORS2 is back!

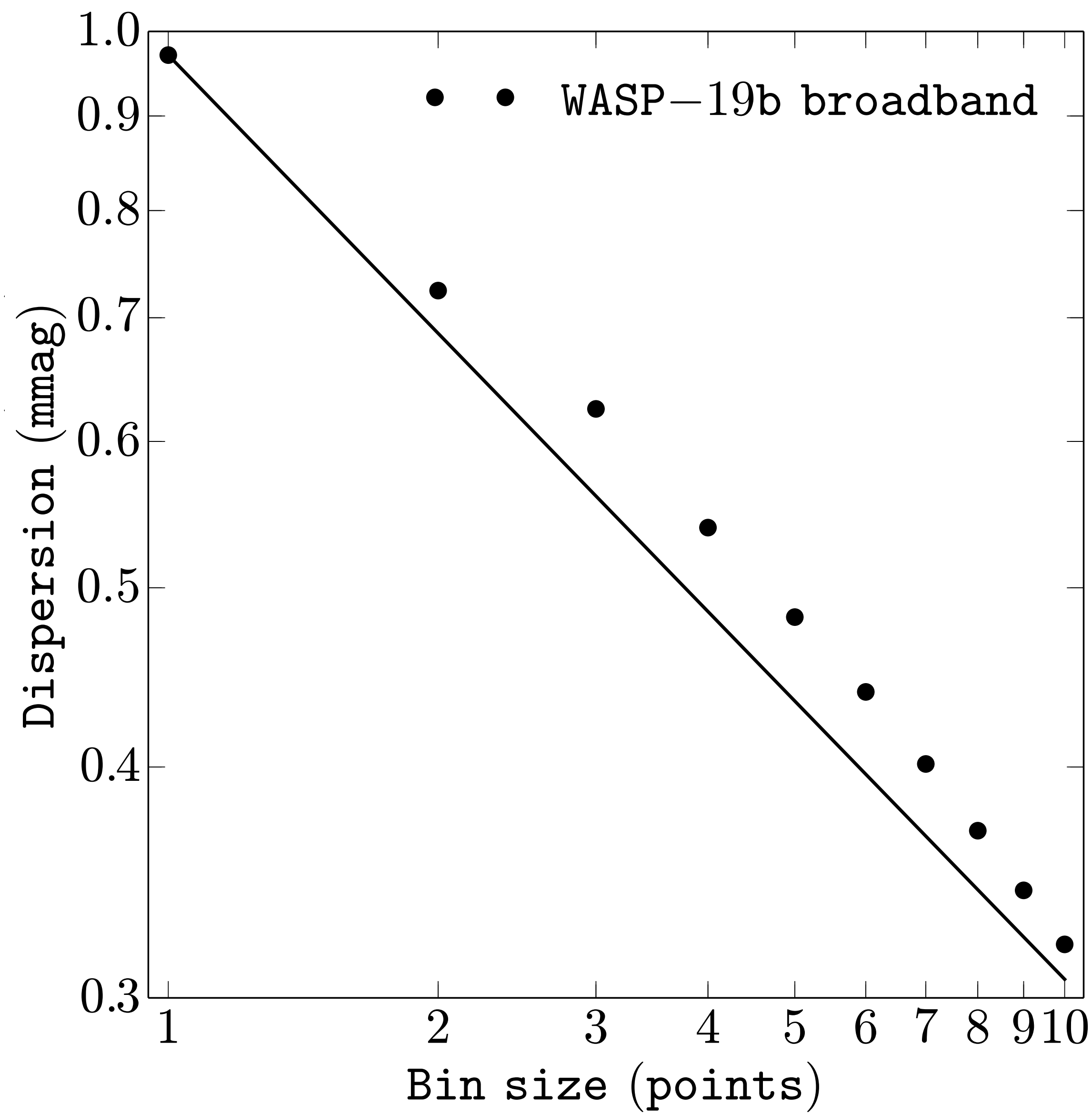
Broadband (white) light curve model

Wasp-19
November 2014



Sedaghati et al. (2015)

A closer look at the systematics



From:

$$\sigma_1^2 = \sigma_w^2 + \sigma_r^2$$

$$\sigma_{10}^2 = \frac{\sigma_w^2}{10} + \sigma_r^2$$

(Gillon et al. 2006),

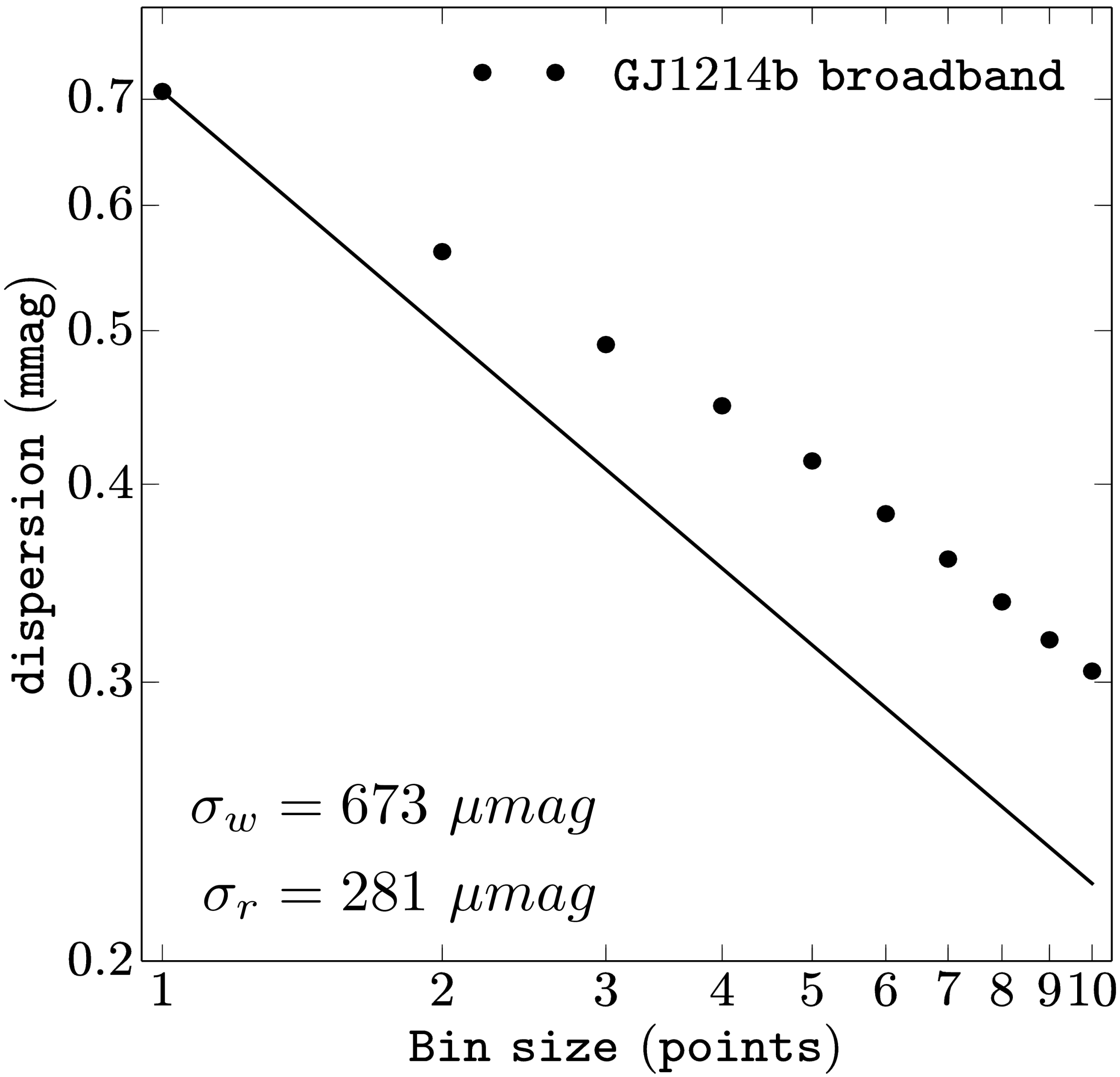
we estimate:

$$\sigma_w = 579\ \mu mag$$

$$\sigma_r = 169\ \mu mag$$

for the broadband LC.

A closer look at the systematics



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(Gillon et al. 2006),

we estimate:

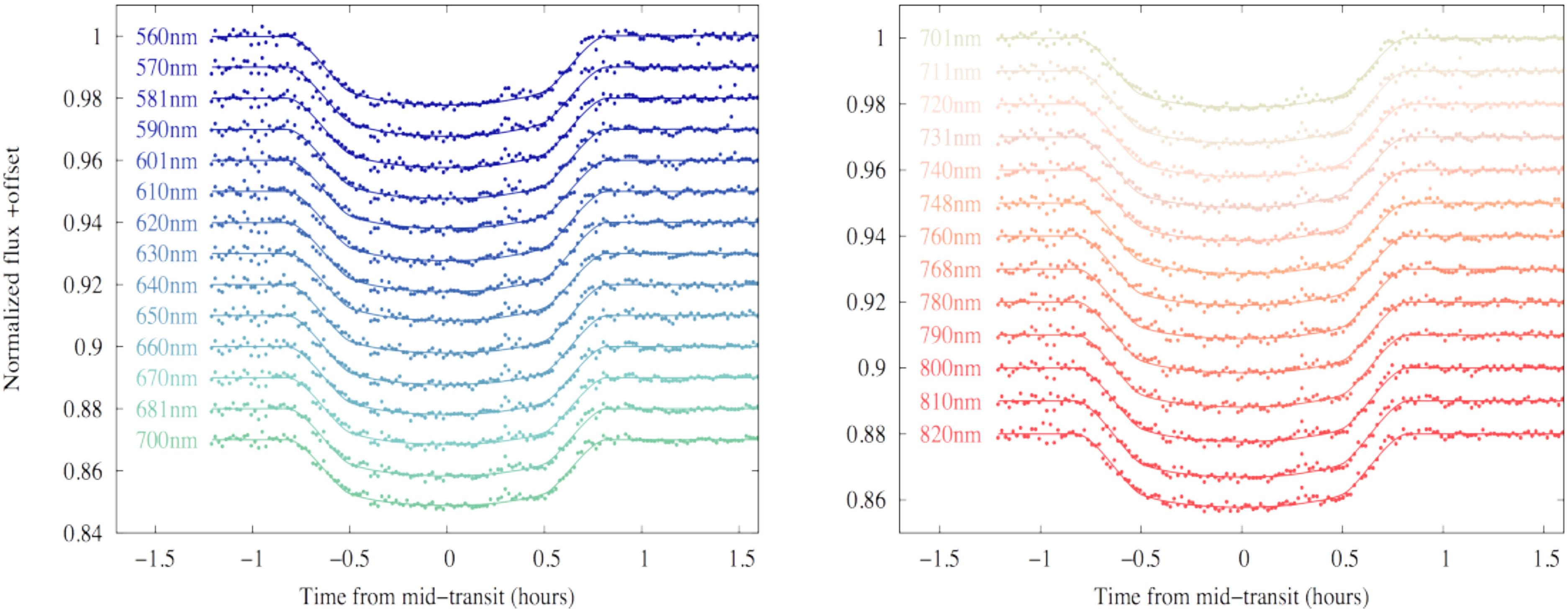
$$\sigma_w = 579\ \mu mag$$

$$\sigma_r = 169\ \mu mag$$

for the broadband LC.

Doing better than Bean+ 10 result!

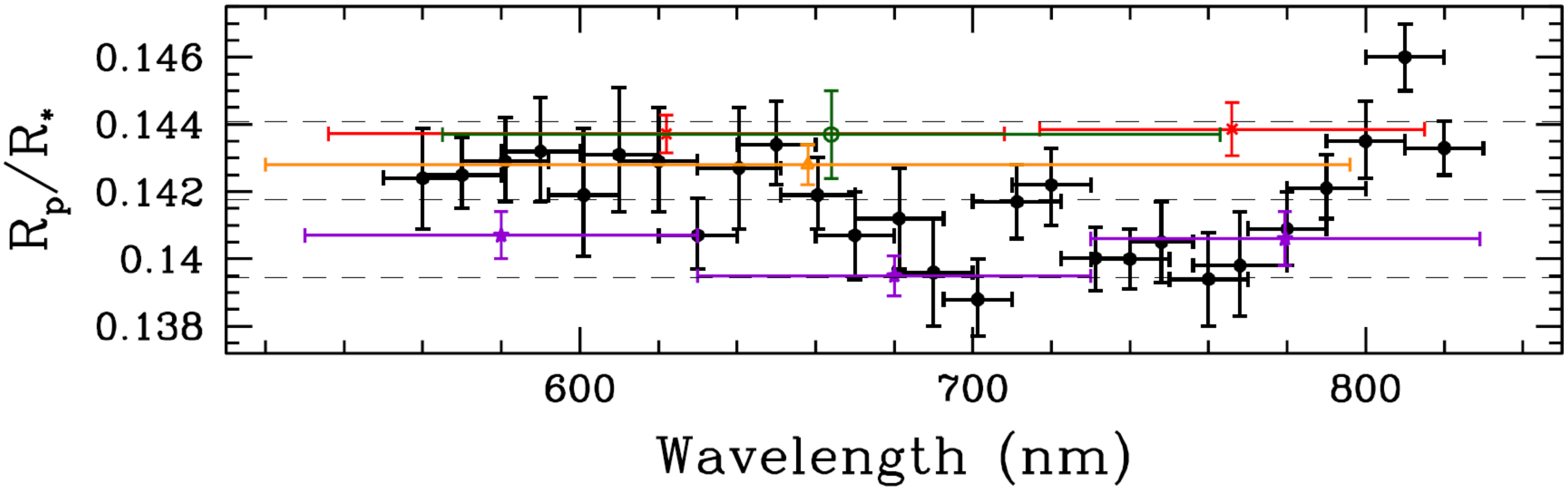
Spectrophotometric light curves



All non-wavelength dependent parameters fixed to the white LC solution
Only scaled planetary radius, Limb darkening coefficients* & noise model parameters free

Transmission spectrum

Literature comparison → highest spectral resolution!



Black filled circles: Sedaghati et al. (2015), FORS2+VLT spec.

Purple filled stars: Huitson et al. (2013), STIS+HST spec.

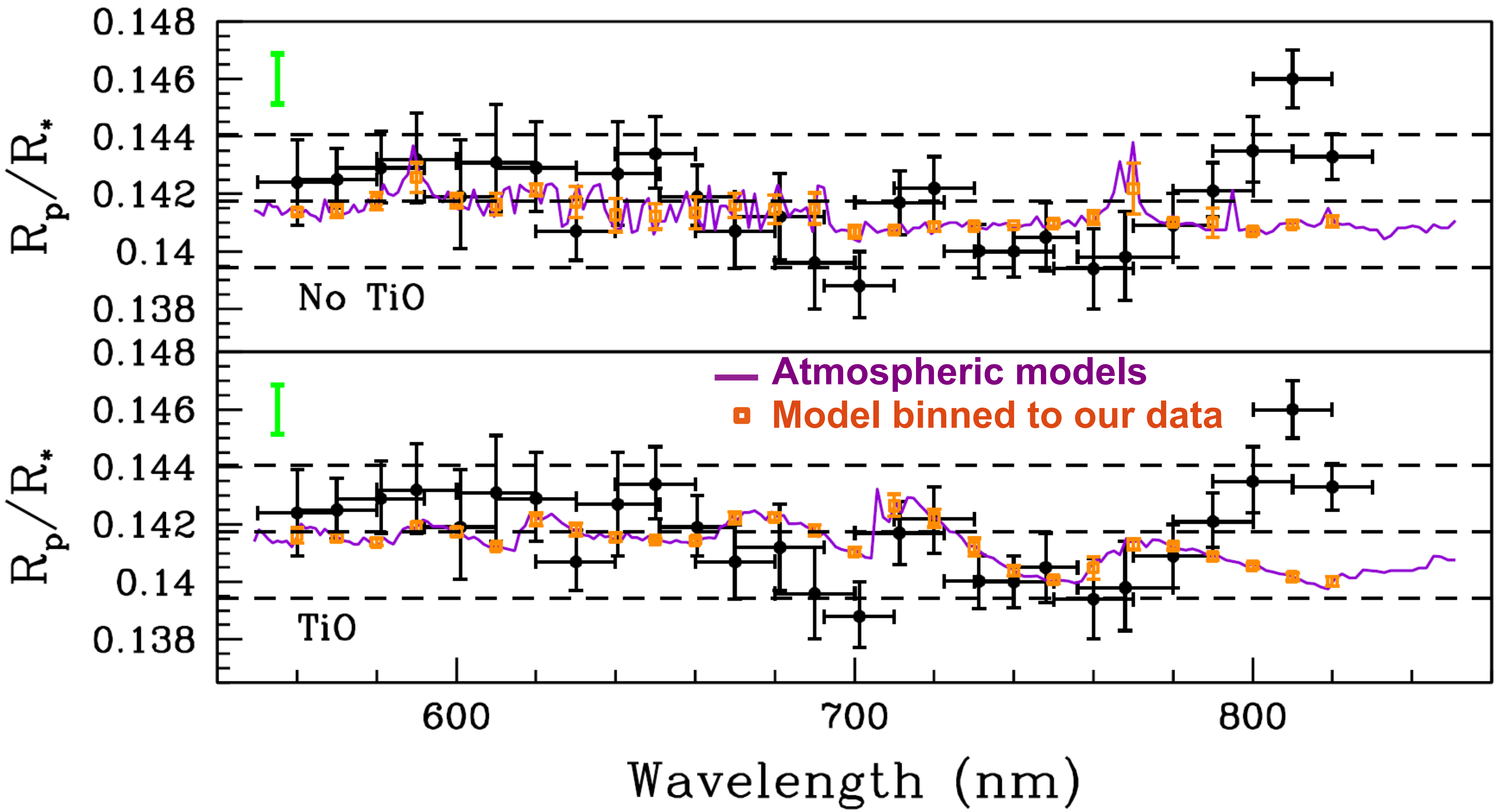
Red crosses: Mancini et al. (2013), 1.54 Danish, PEST, GROND phot.

Green cricle: Lendl et al. (2013), HAWK-I/VLT, EulerCam phot.

Orange triangle: Tregloan-Reed (2013), EFOSC2/NTT phot.

Transmission spectrum

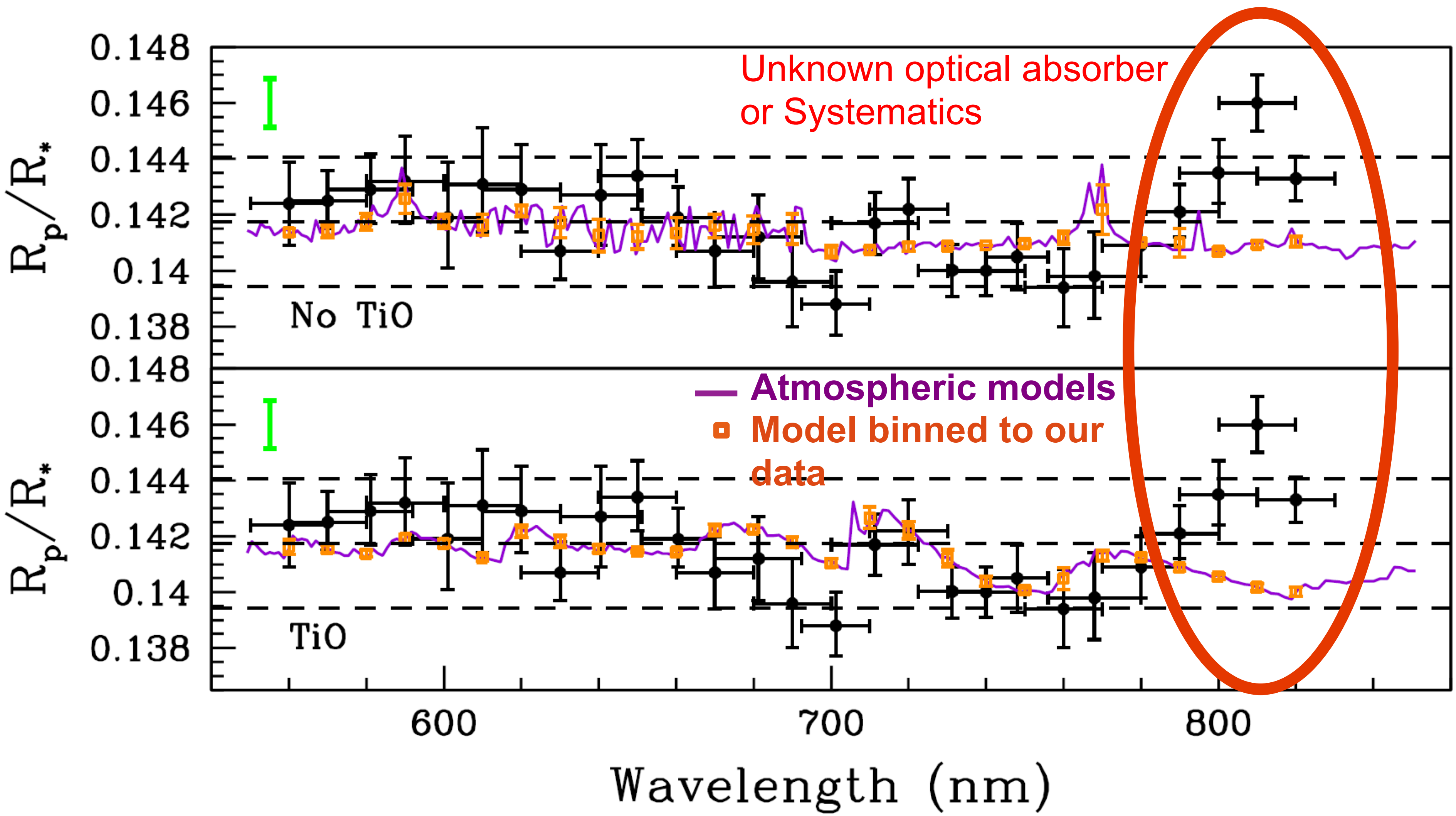
Atmospheric model comparison



Sedaghati et al. (2015)
Atmospheric models from Burrows et al. (2010) ApJ, 791, 341

Transmission spectrum

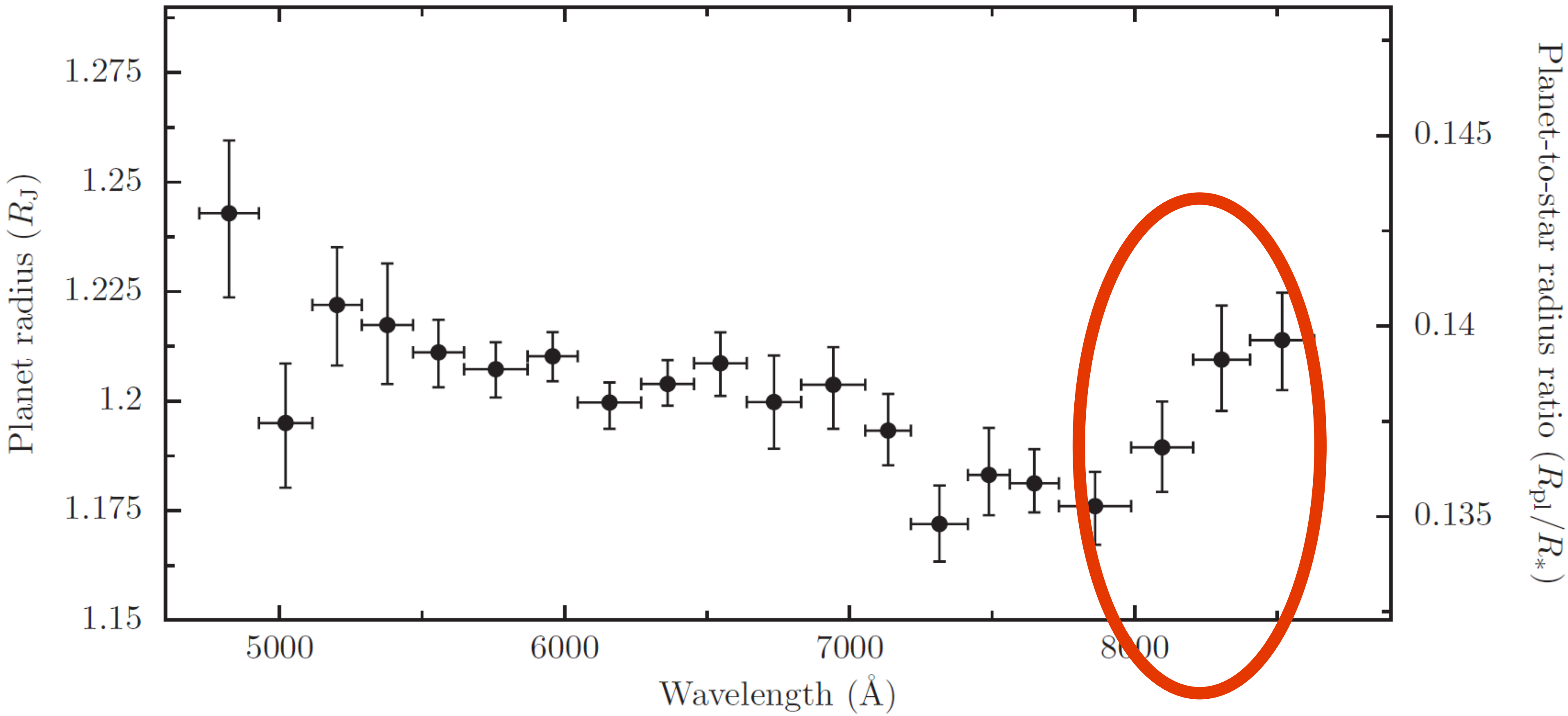
Atmospheric model comparison



Sedaghati et al. (2015)
Atmospheric models from Burrows et al. (2010) ApJ, 791, 341

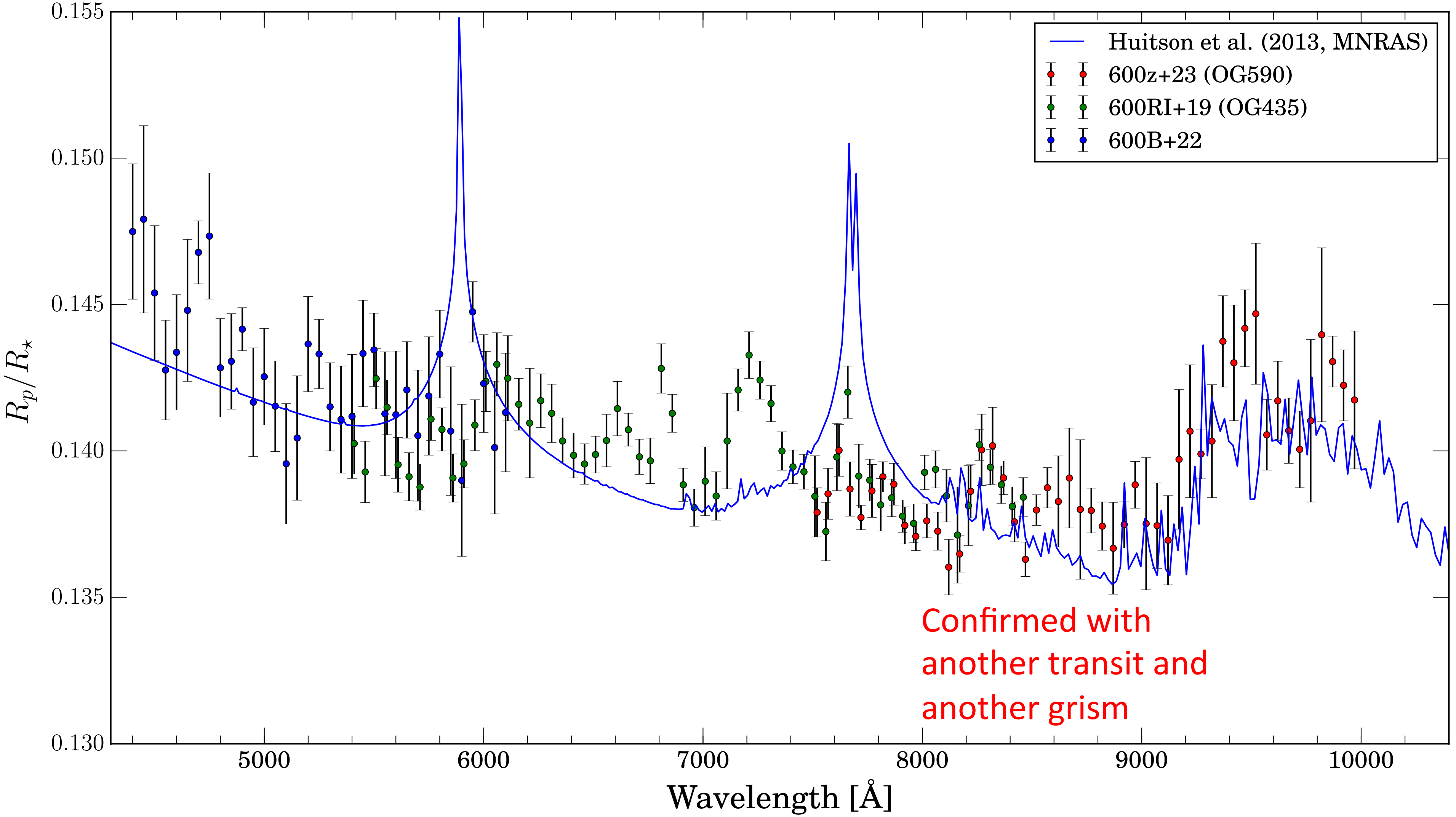
Transmission spectrum

Coincidence??

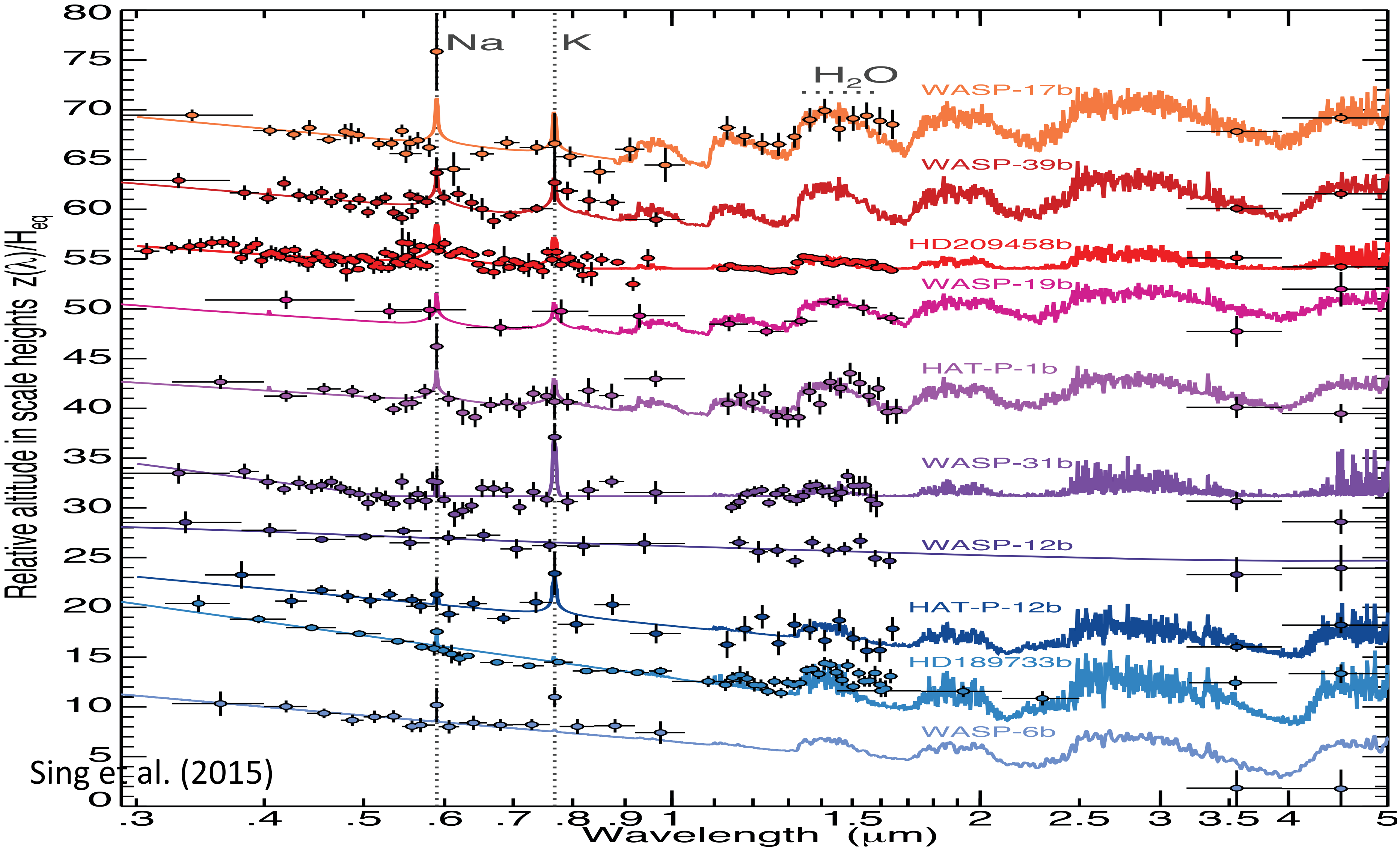


Transmission spectrum of WASP-6b with IMACS/Magellan
Jordán et al. (2013) ApJ, 778, 184

WASP-19b – FORS2 – 3 grisms

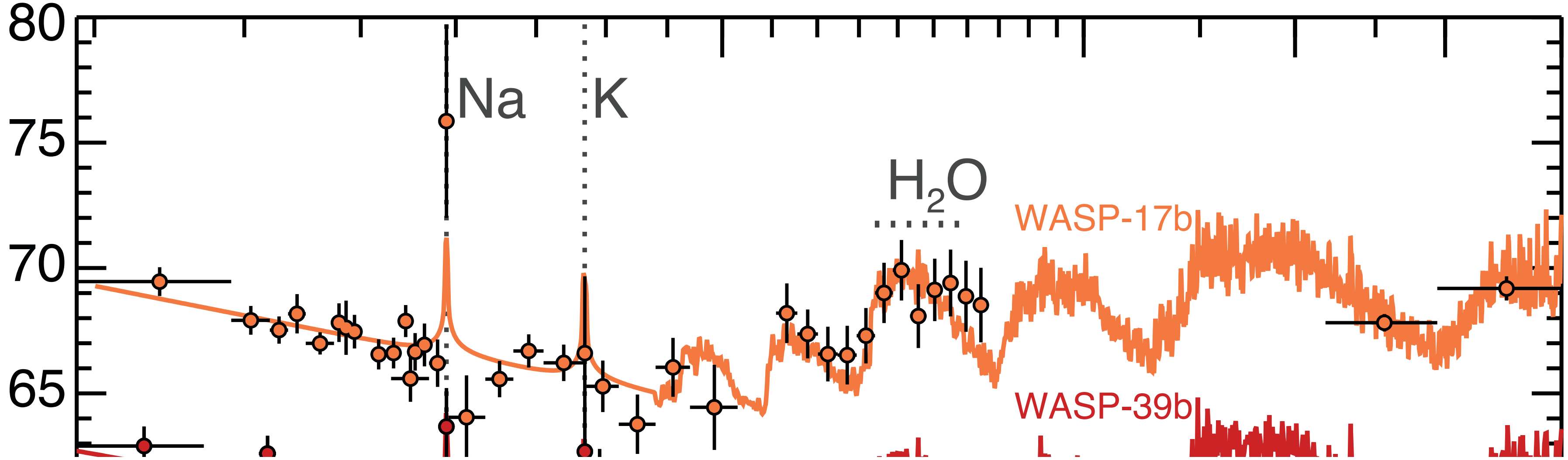


Transmission spectrum from space



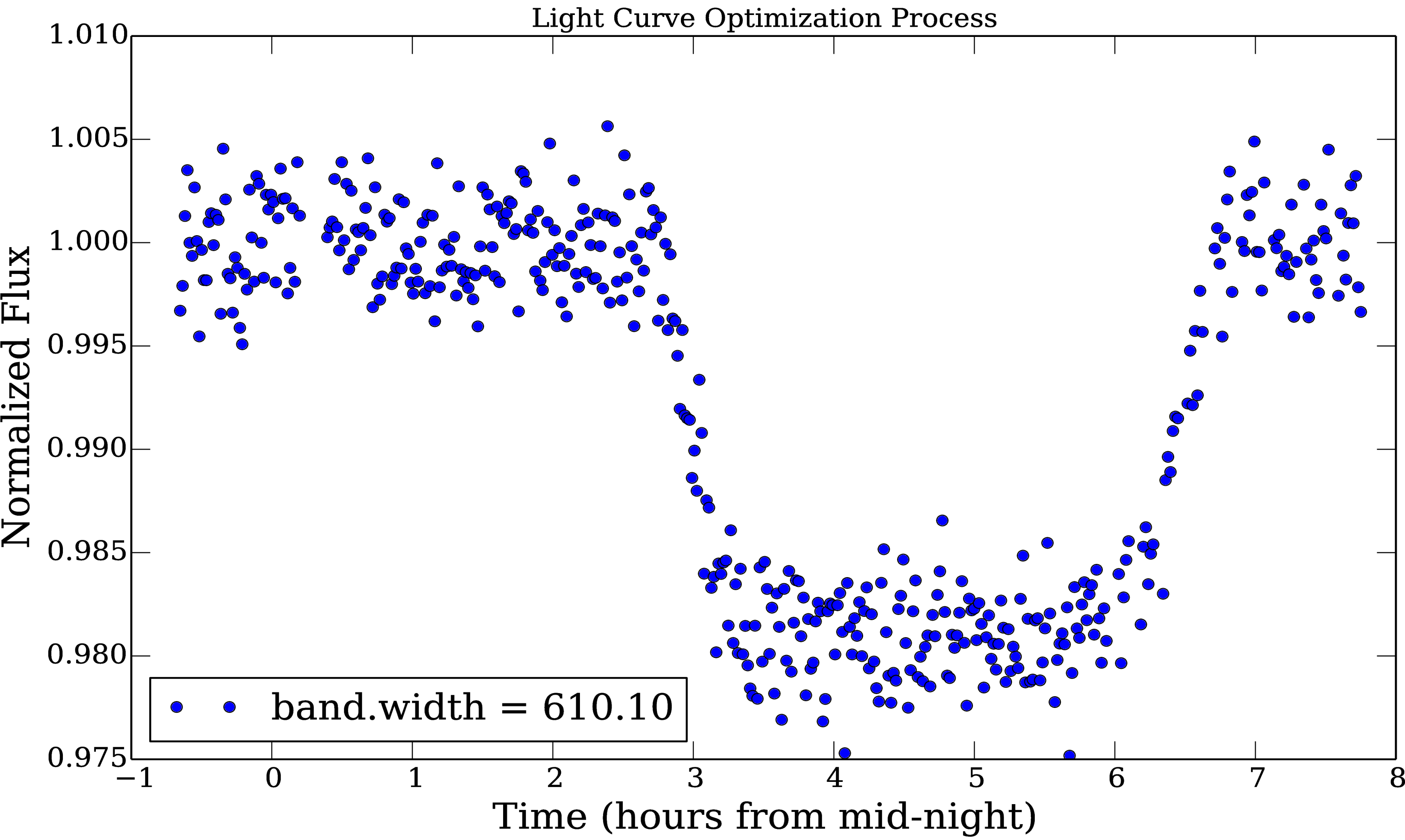
Sing et al. (2015)

Transmission spectrum from space



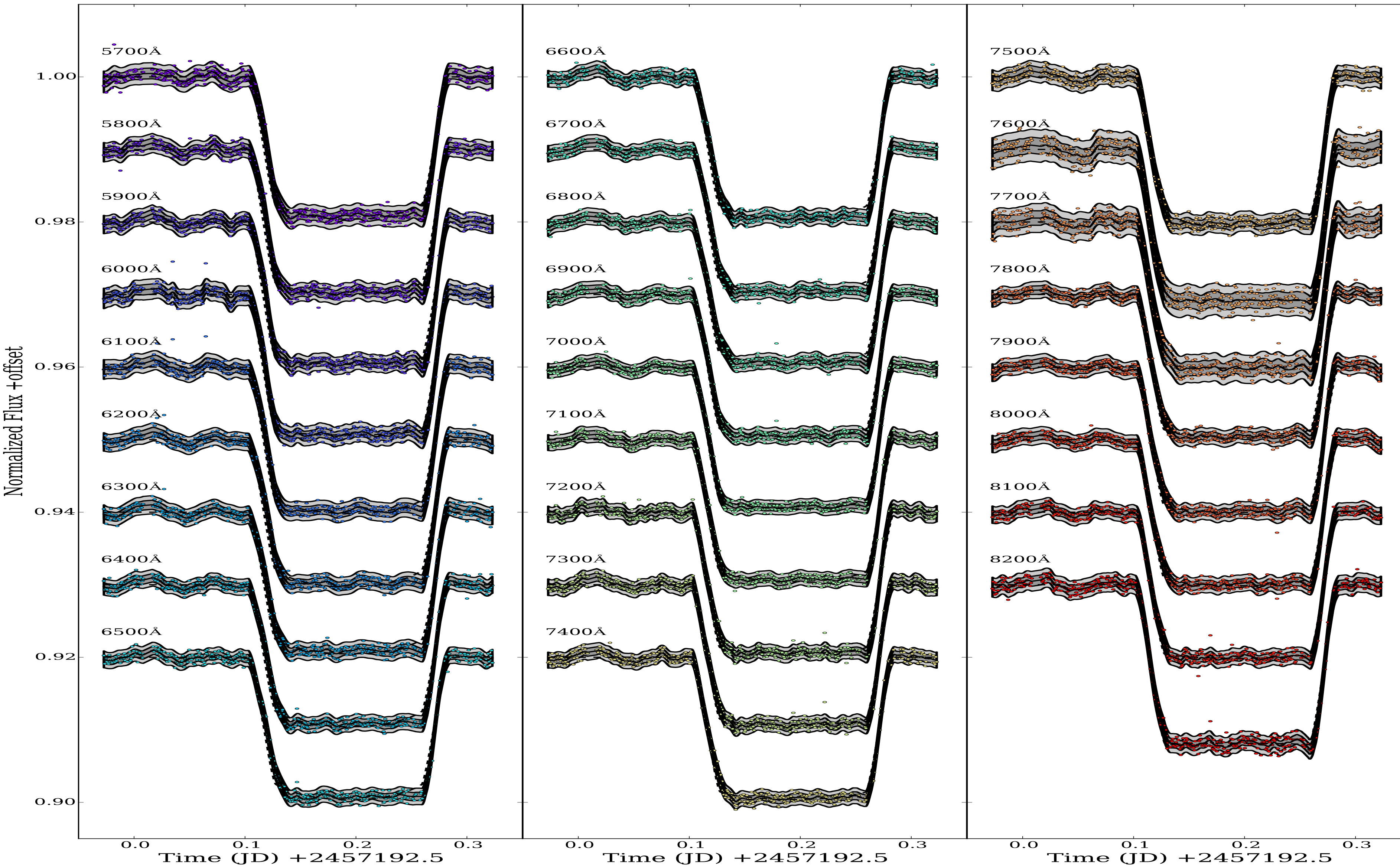
Sing et al. (2015)

WASP-17b

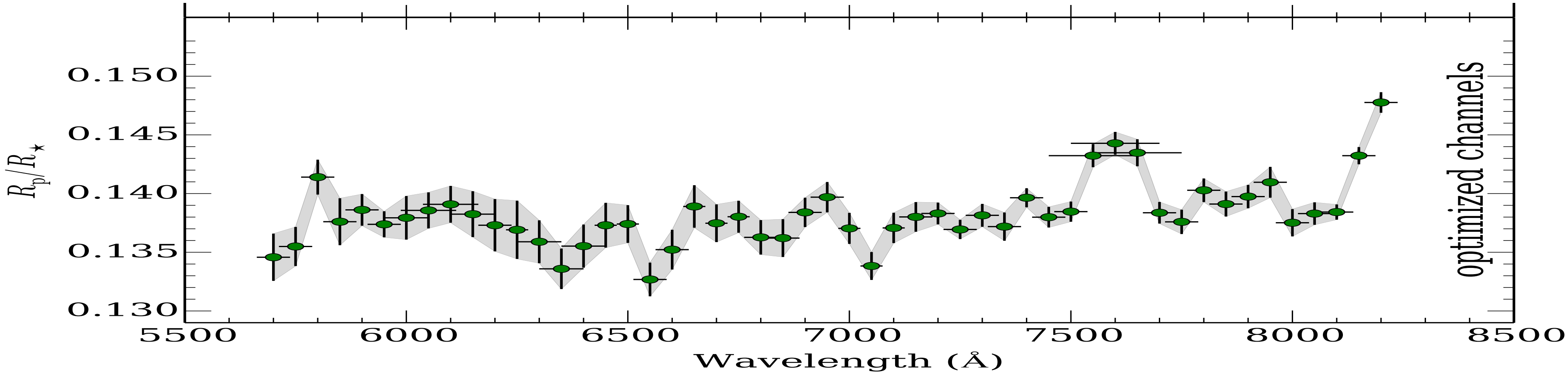


Light Curve Optimization Process
Normalized Flux
1.010
1.005
1.000
0.995
0.990
0.985
0.980
0.975
−1
0
1
2
3
4
5
6
7
8
Time (hours from mid-night)
band.width = 610.10

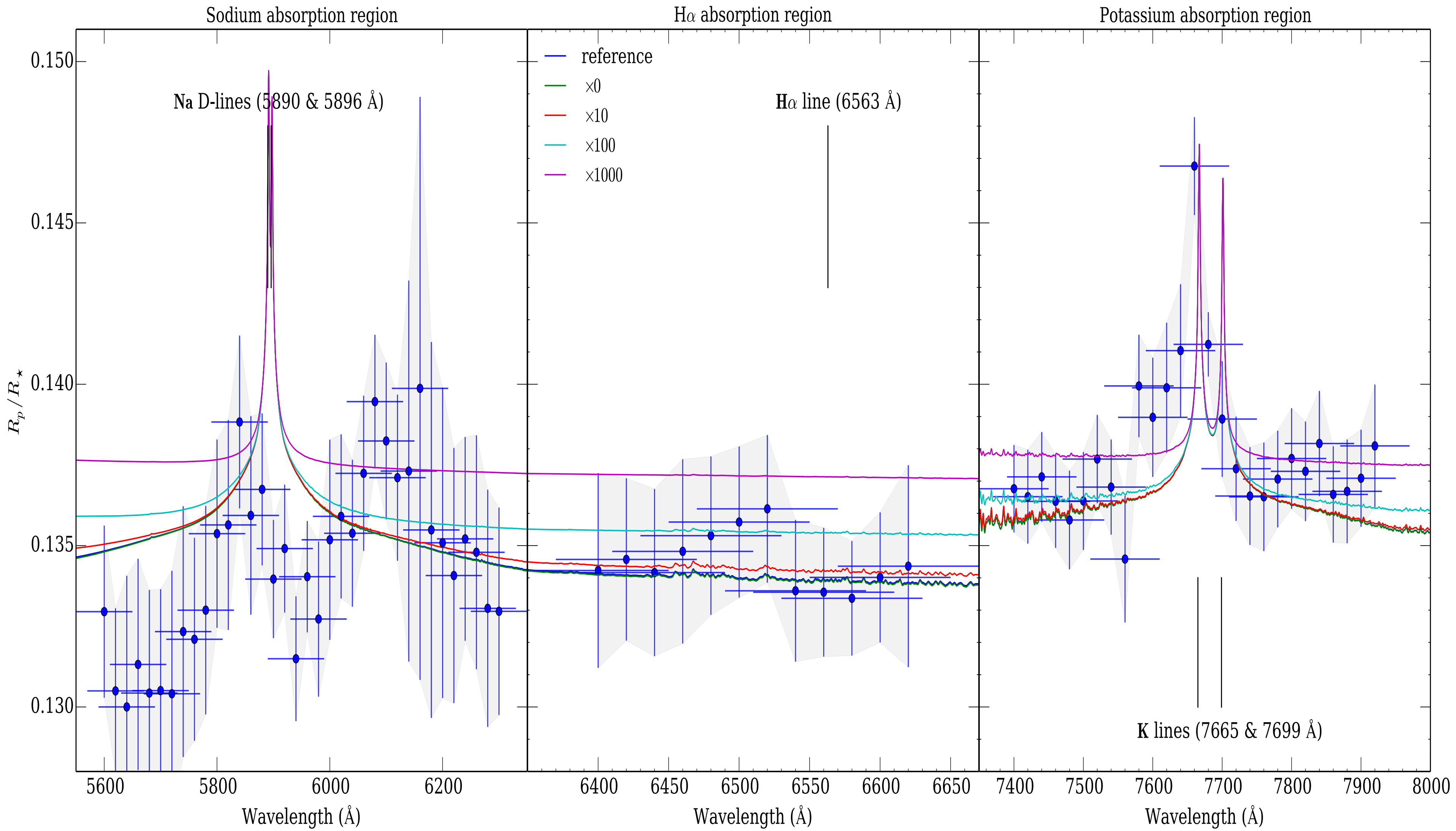
Spectrophotometric light curves



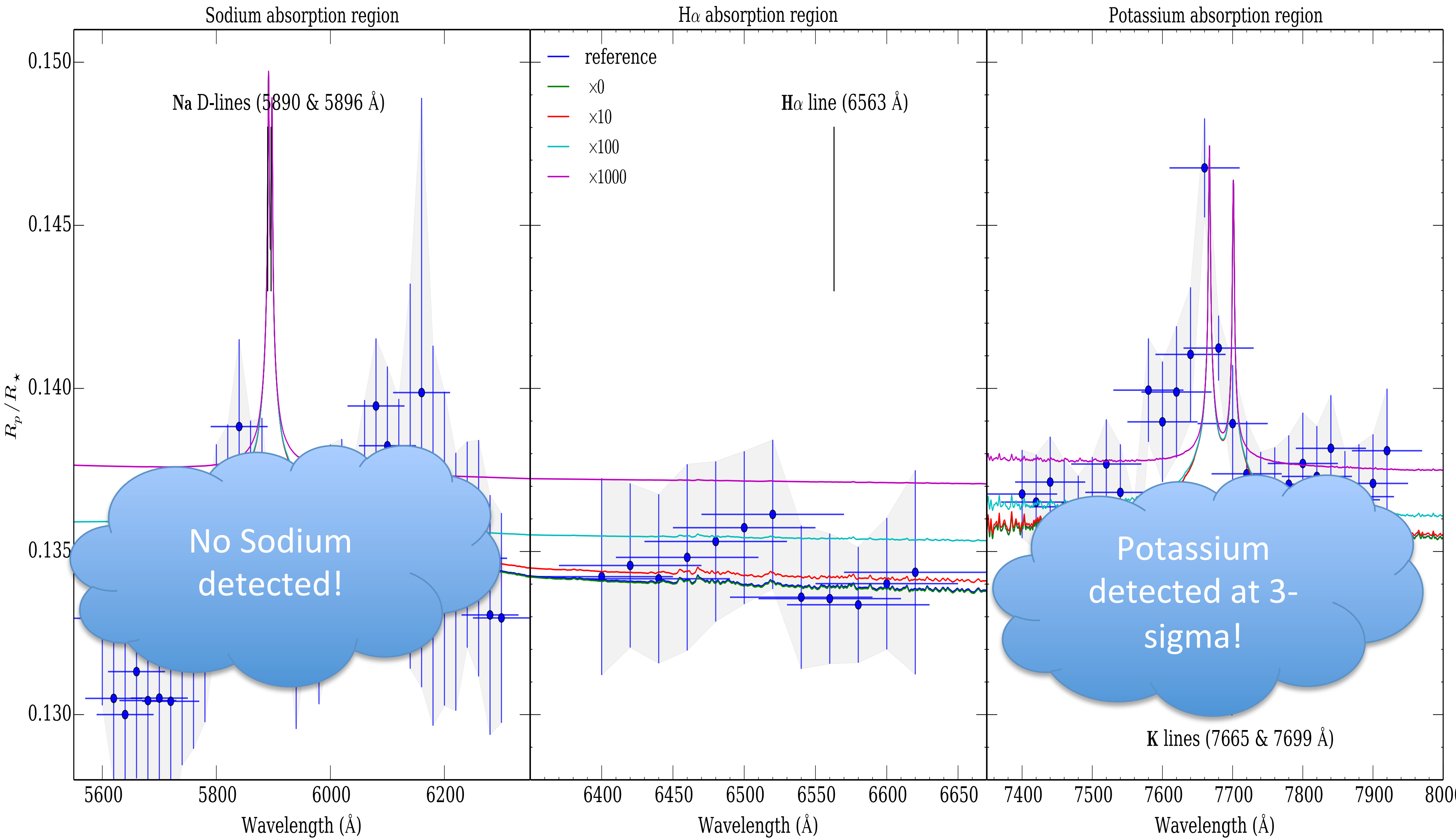
Transmission spectra



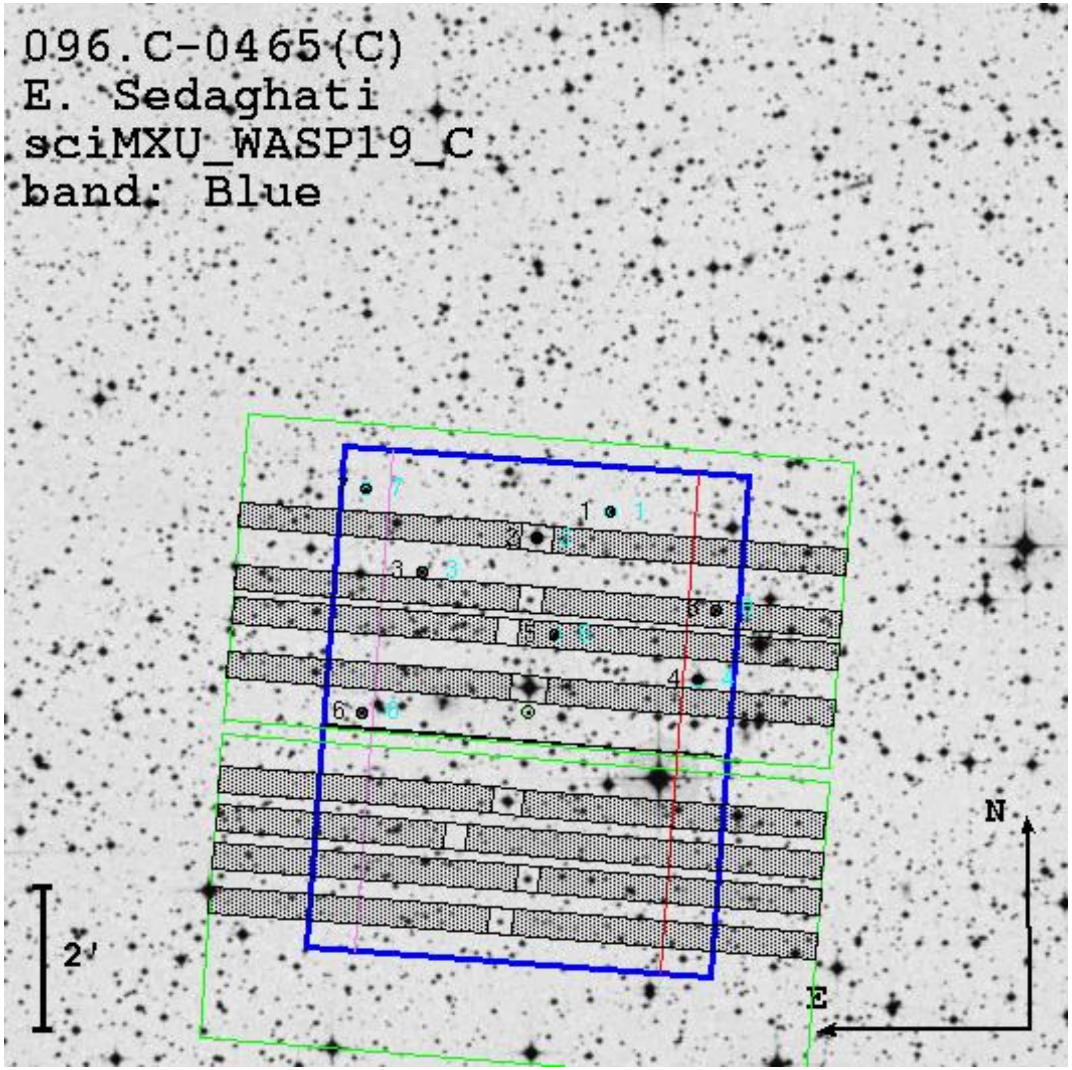
Searching for optical absorbers



Searching for optical absorbers



The importance of setting things up right



- Targets in the middle
- Similar magnitudes
- Wide slits
- Include sky slits for each detector
- Check proper motion for fine placement
- Adjust exposure time to get as close as possible to saturation
- Check counts *in-situ*
- Consider non-standard readout
- Avoid observing through meridian if possible since telescope rotation can have adverse effects

See Boffin+ 16, SPIE, for hints on the best strategy

Still many planets reachable

Boffin+ 16

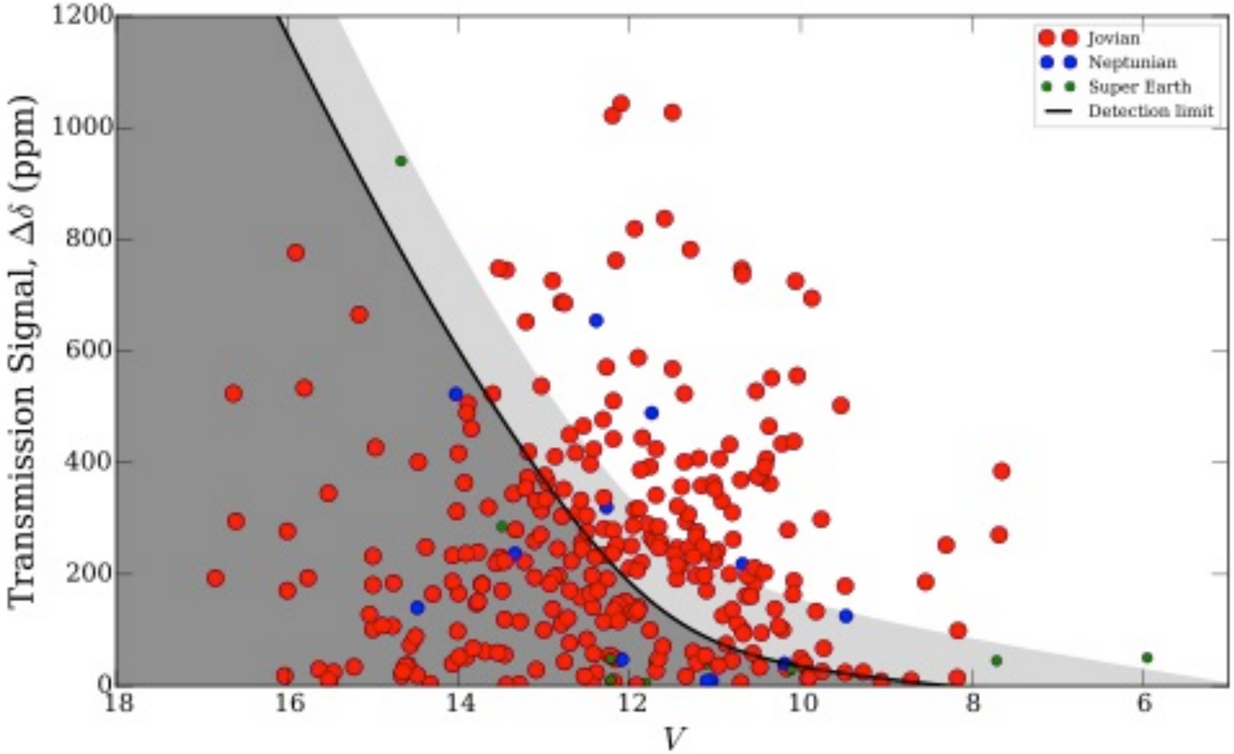
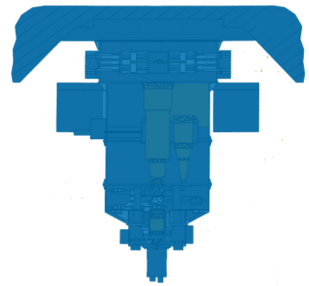


Figure 2. The transmission signal ($\Delta\delta$) of known transiting exoplanets versus the V magnitude of the host star. The line represents the detection limit of FORS2, estimated from previous transmission spectroscopy observations with this instrument. Atmospheric signals of planets in the dark grey region are beyond the reach of the instrument, whereas those in the white area should be detectable with FORS2. Light grey represents an area where the detection would be tentative.

Conclusions & Outlook

- FORS2 appears now ready again for multi-object spec. obs.
- Transmission spectrum of WASP-19b with feature due to unknown optical absorbers
- WASP-17 shows no Na but clear K
- Global effort required to obtain a statistically large sample of atmospheric spectra
  → FORS2 will hopefully be key to this effort



KEEP

CALM

MAY THE

FORS BE

WITH YOU