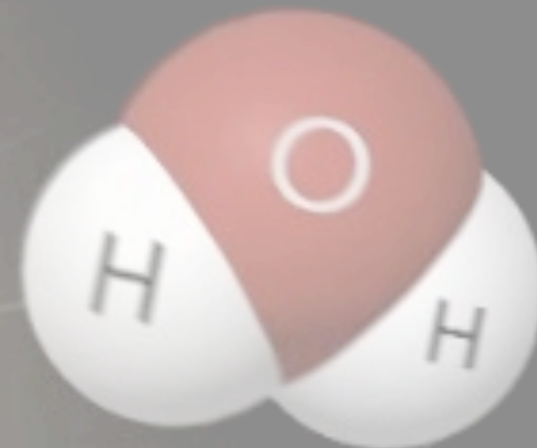
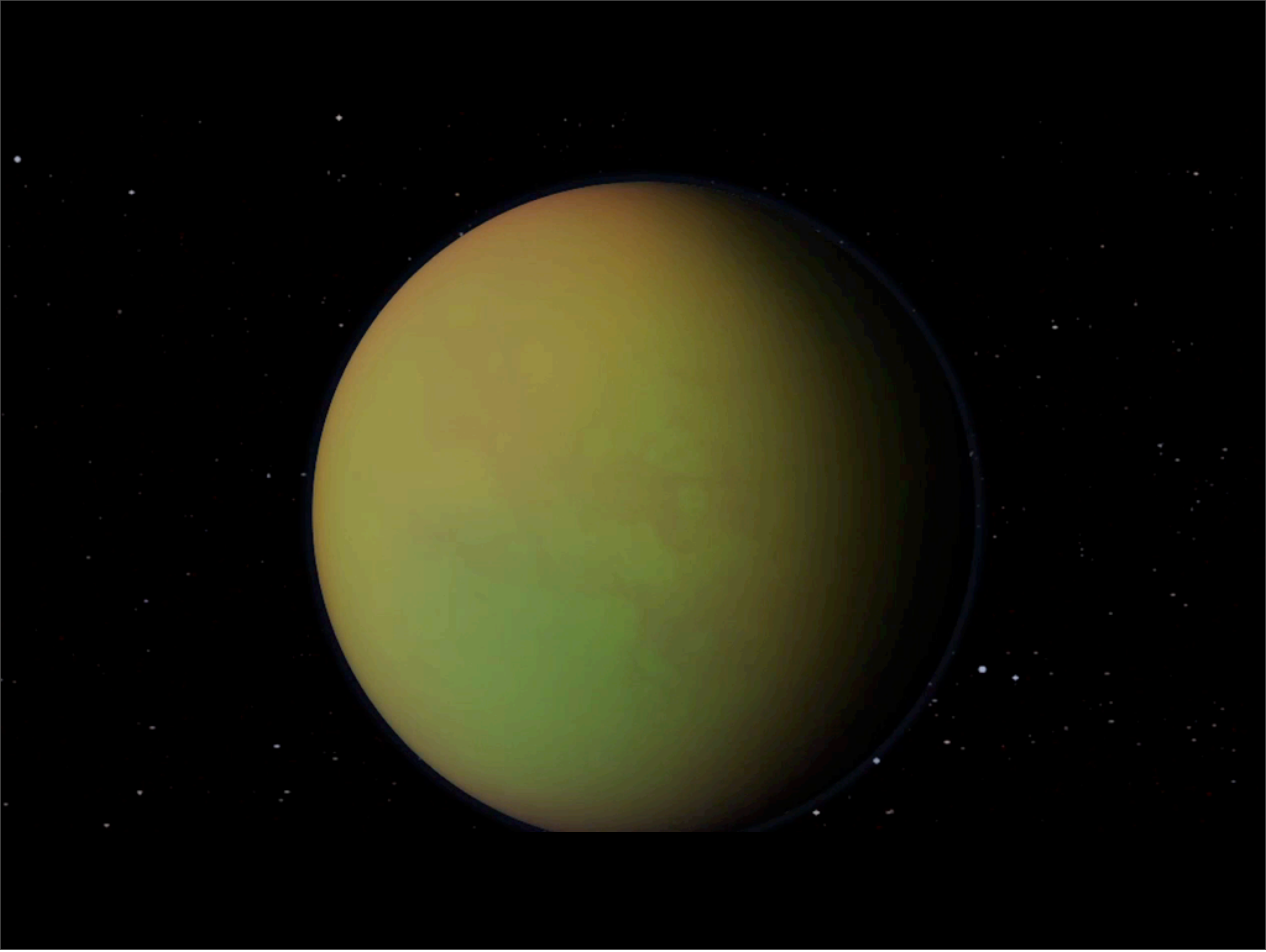


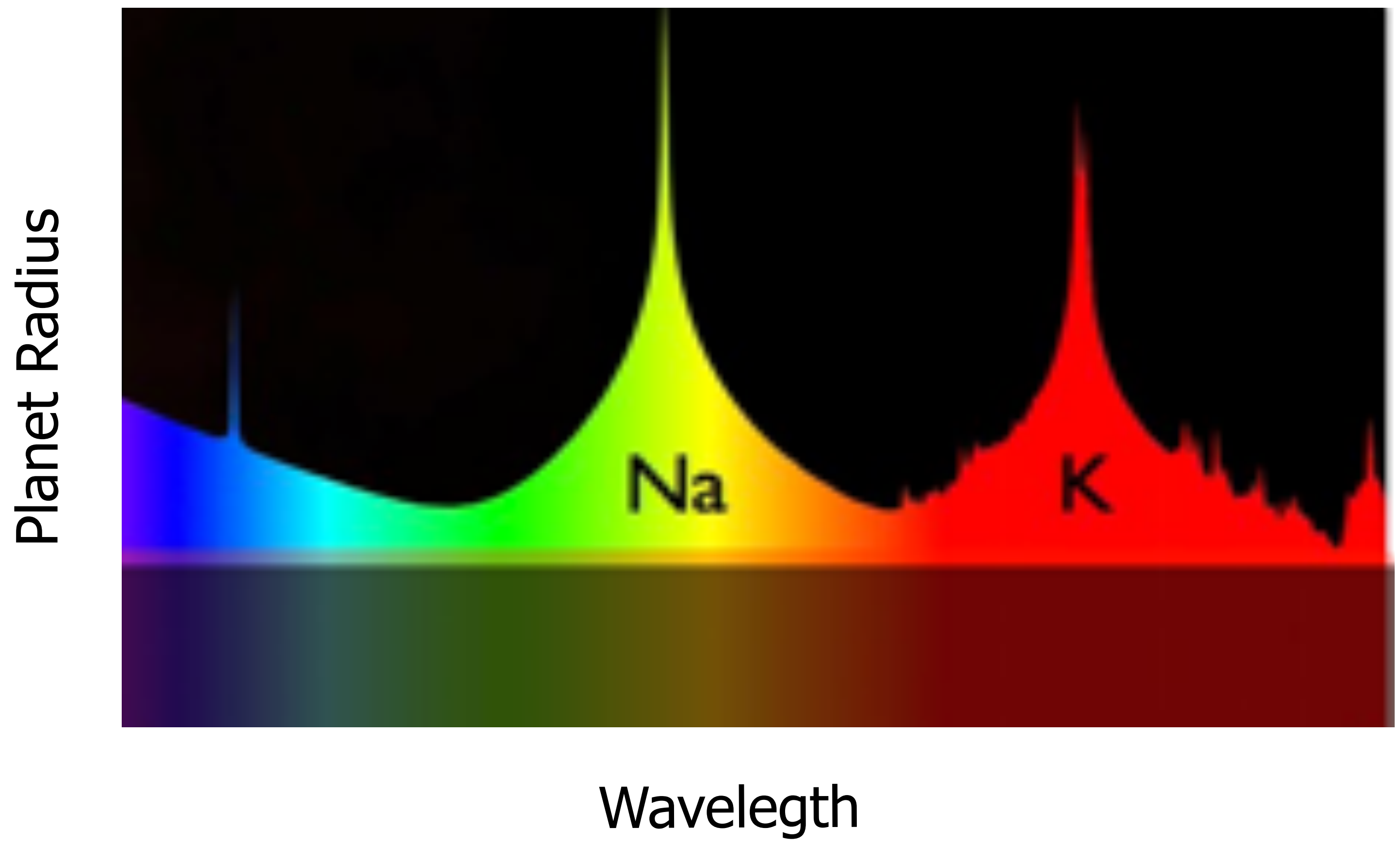
Exoplanet Characterisation through Transit Spectroscopy

(from the ground)

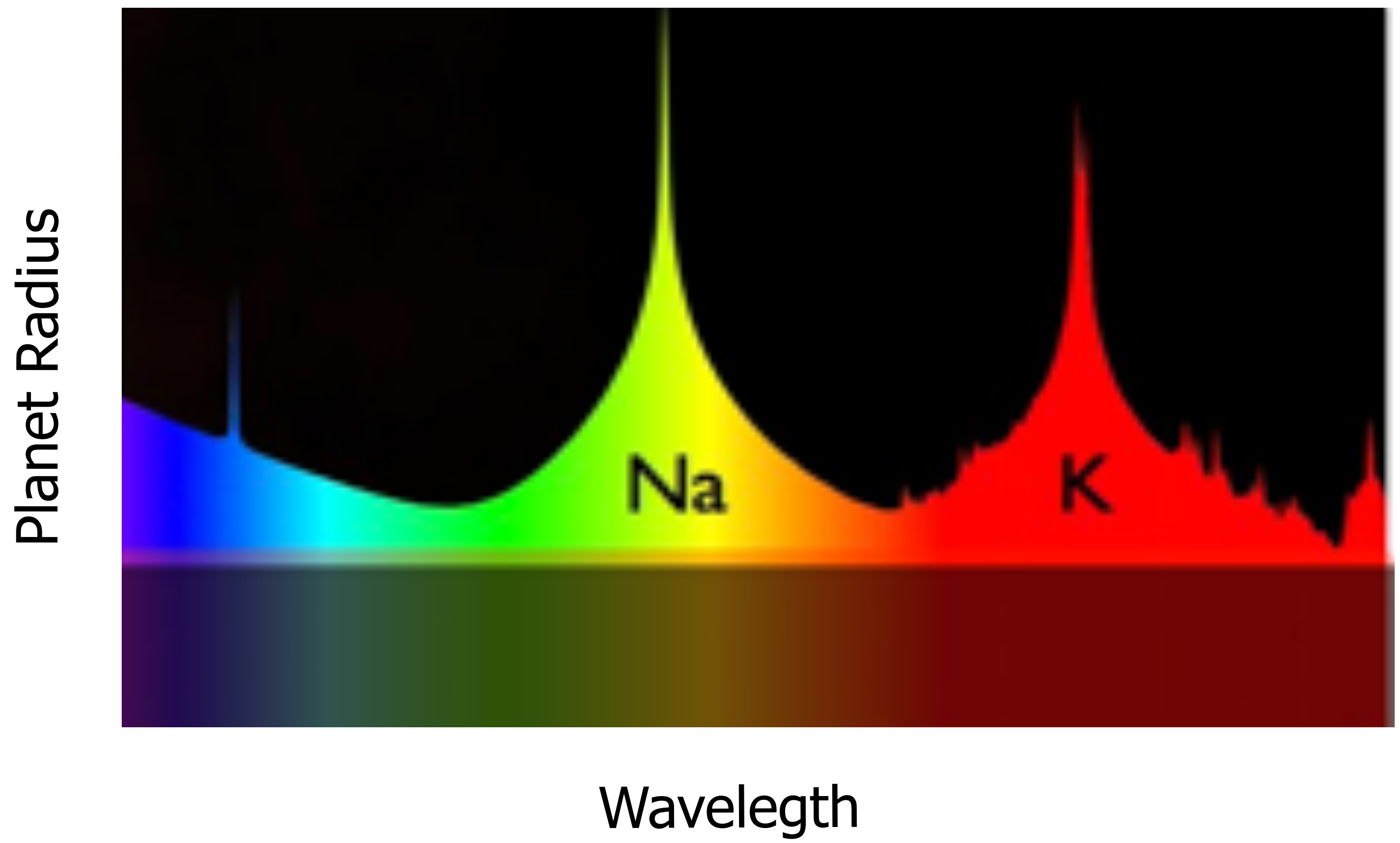
Mercedes López-Morales
Harvard-Smithsonian Center for Astrophysics



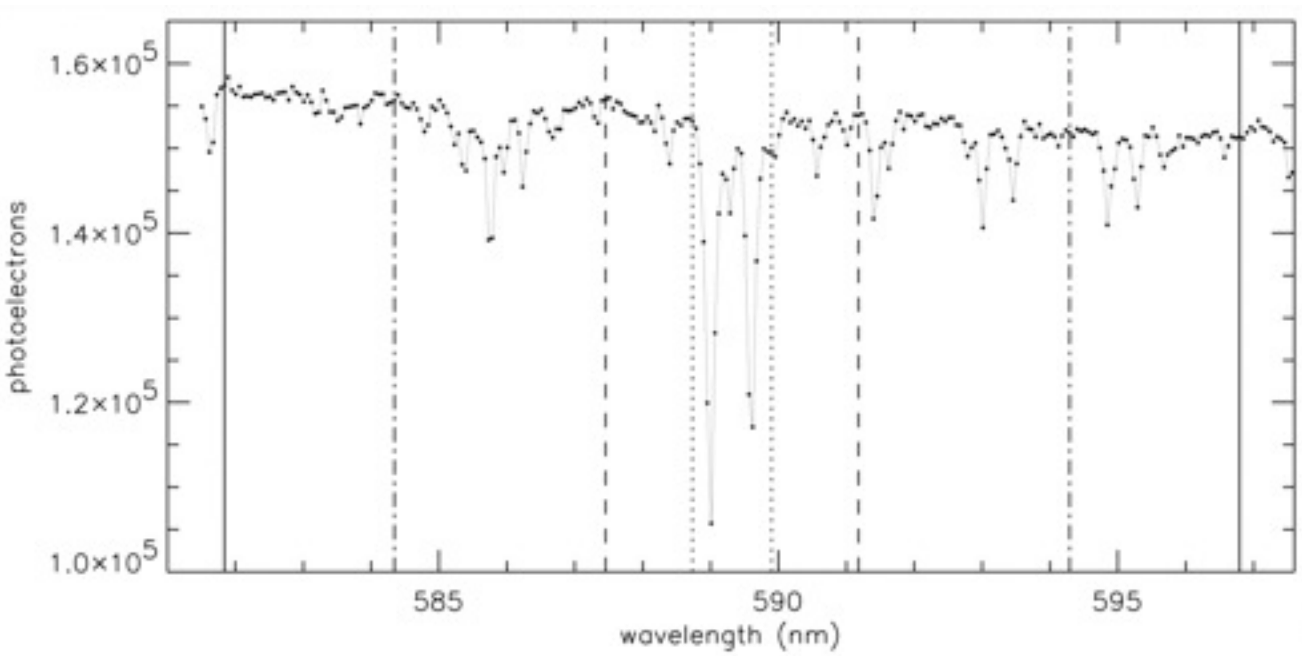
Proposed by Seager & Sasselov (2000)



Proposed by Seager & Sasselov (2000)



First detected by Charbonneau et al. (2002)



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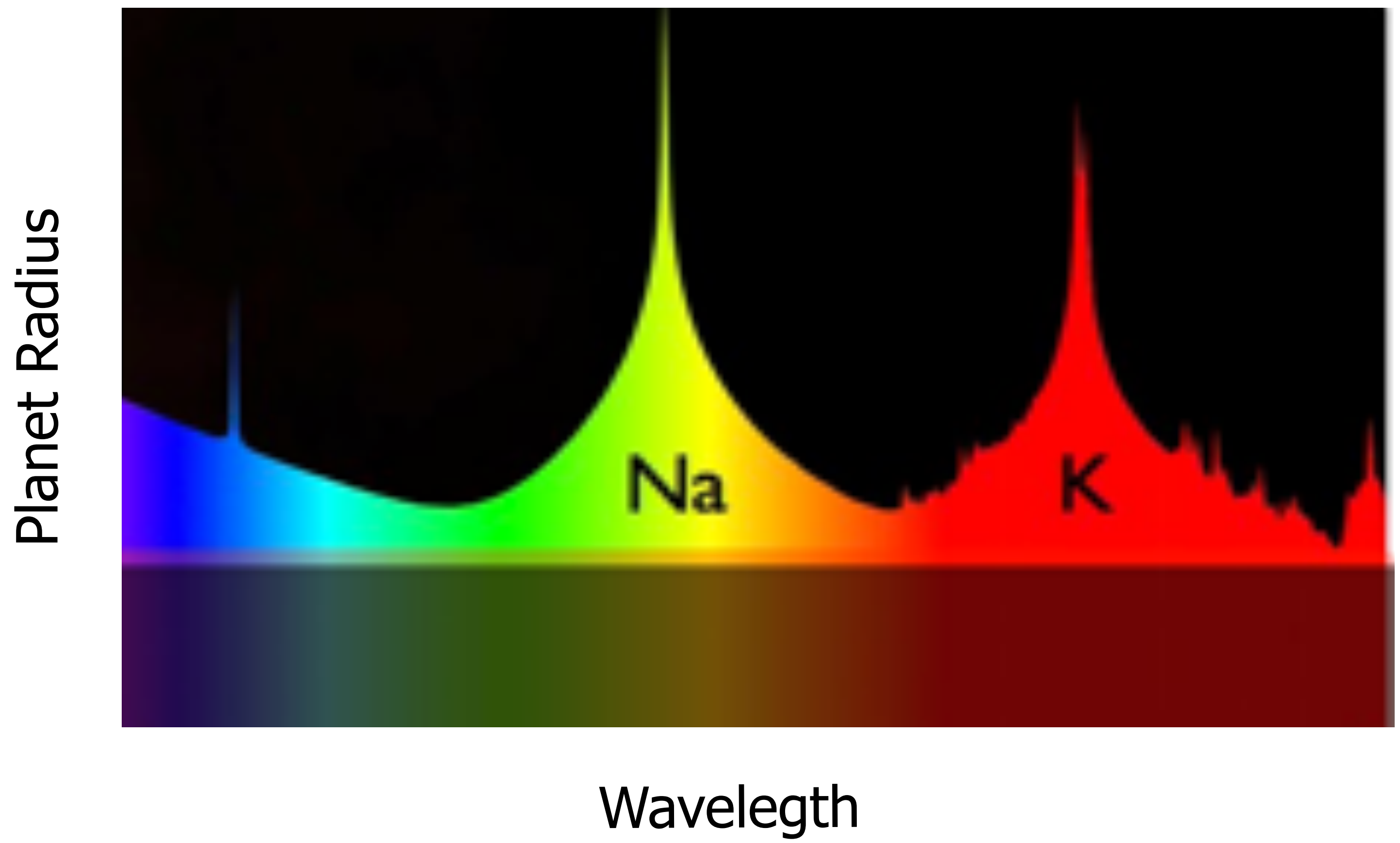

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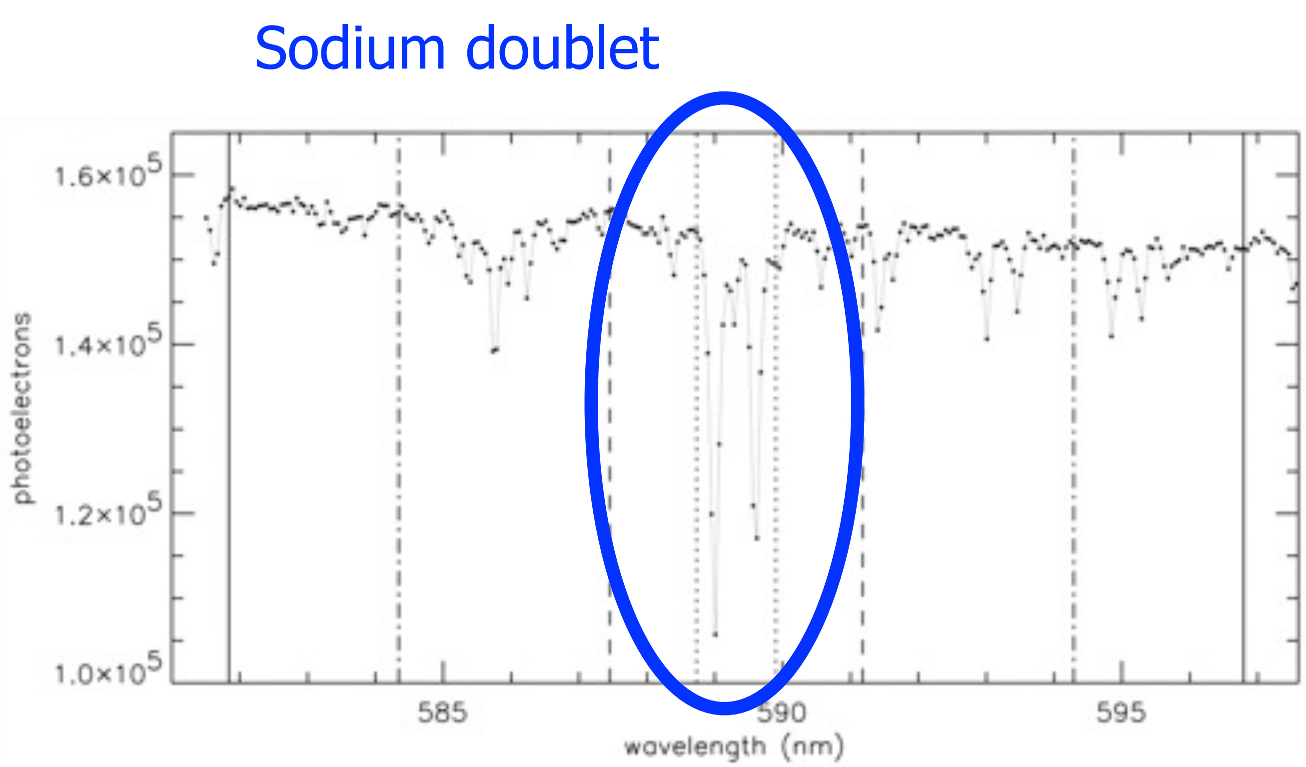

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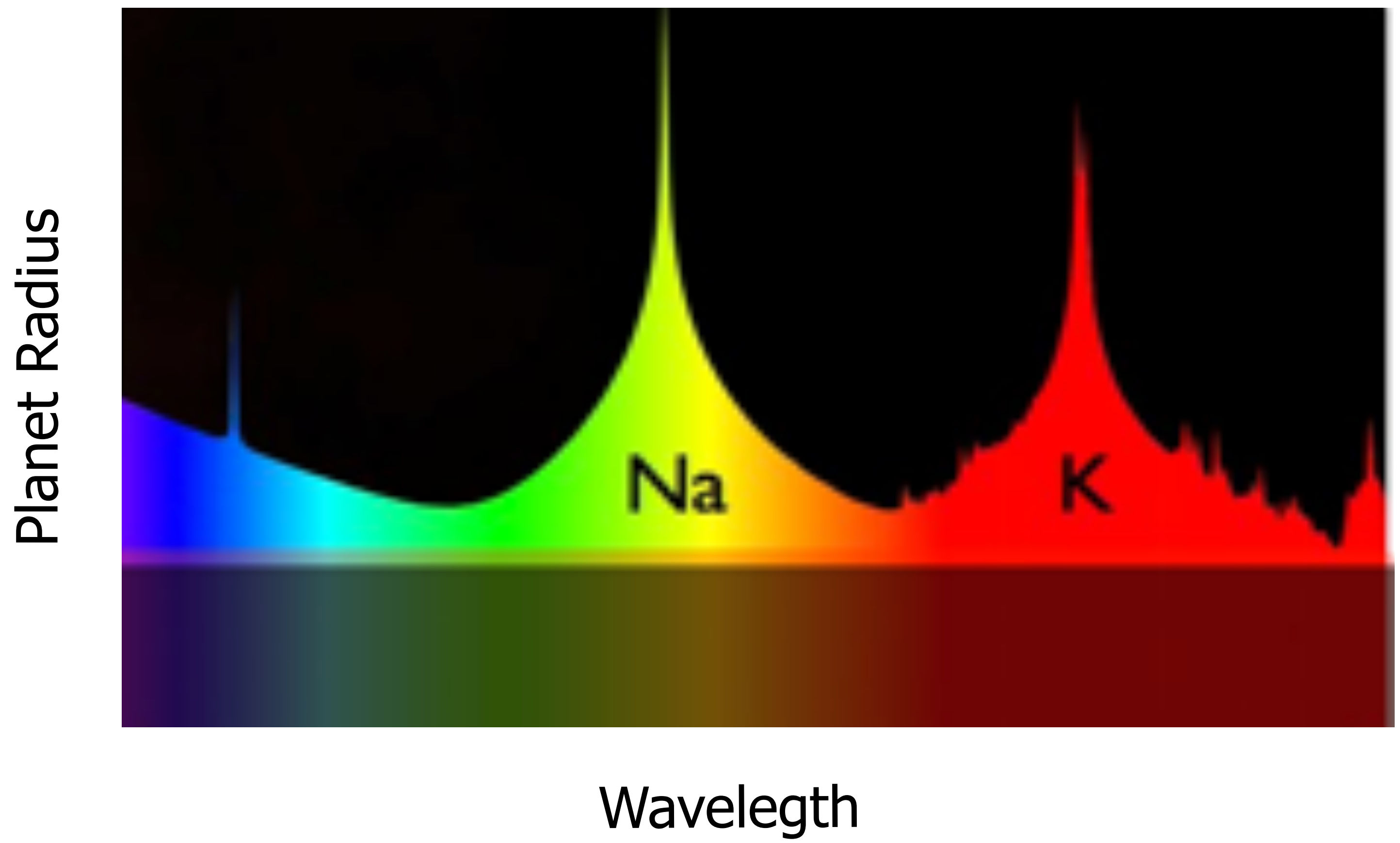

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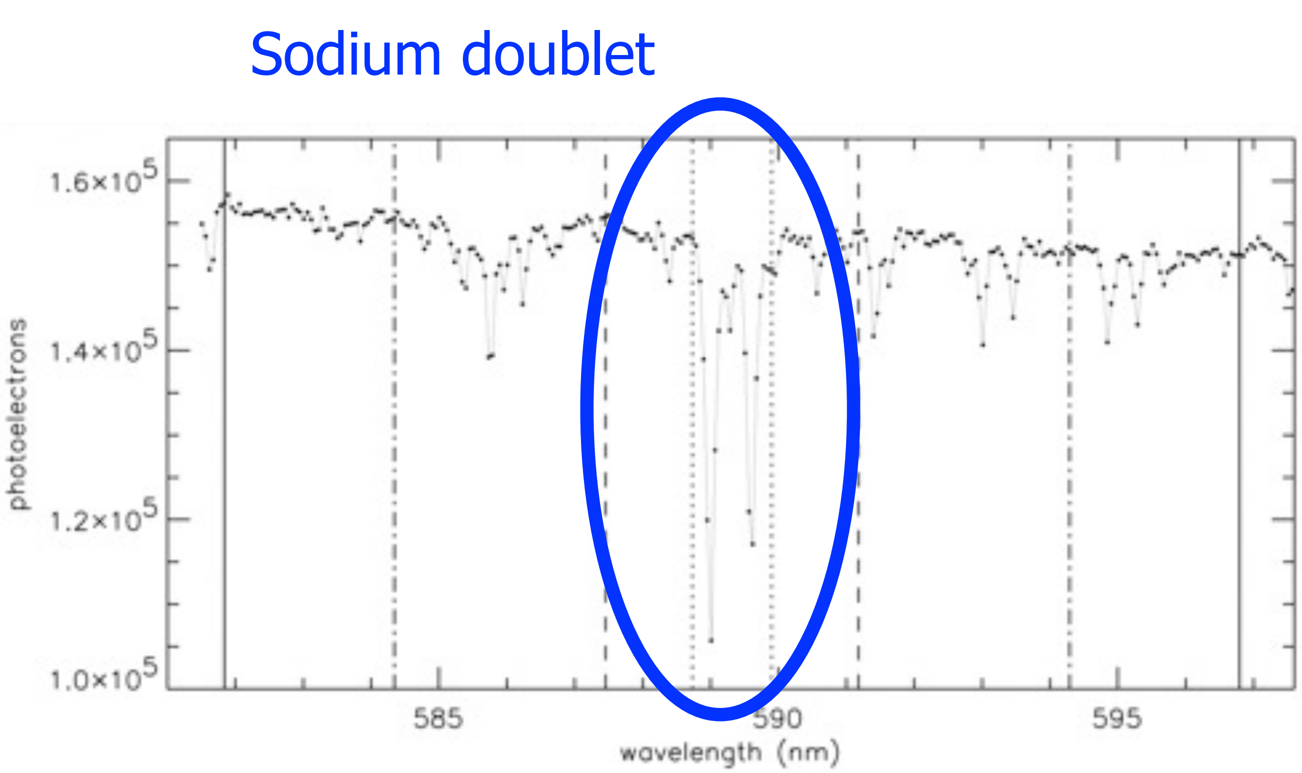
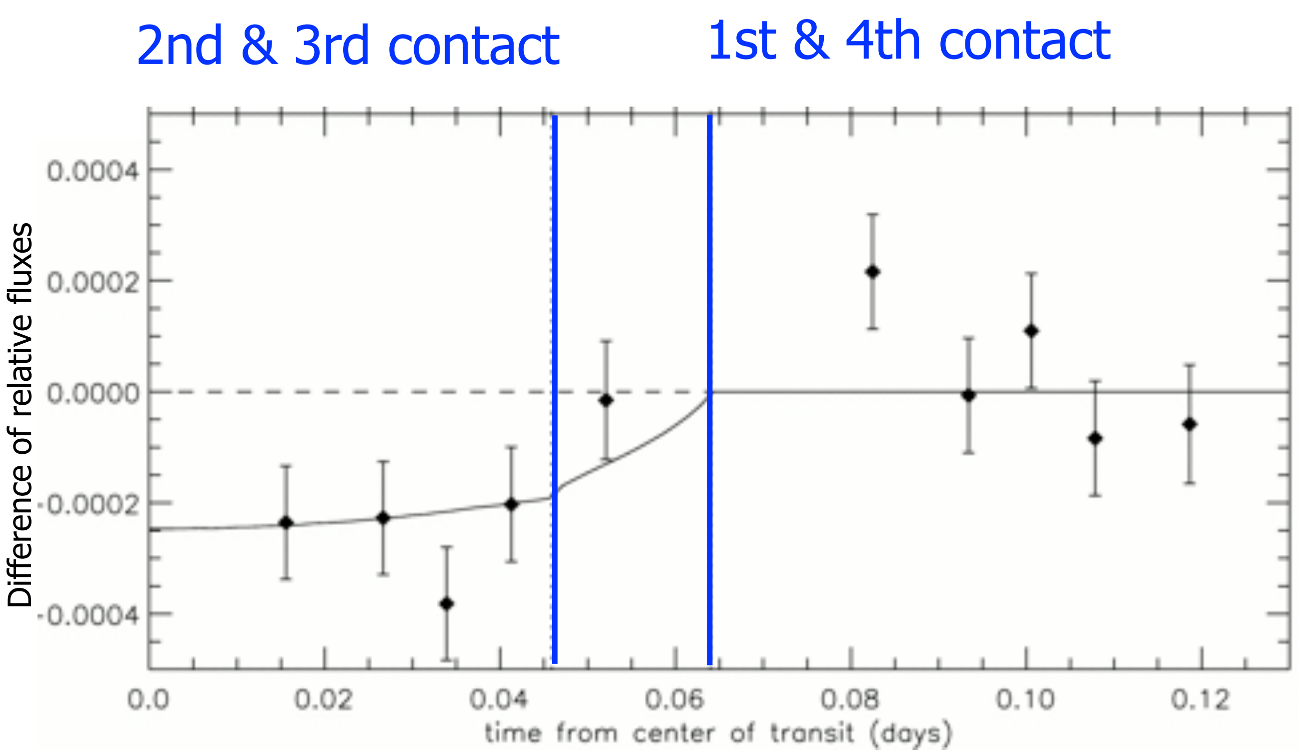


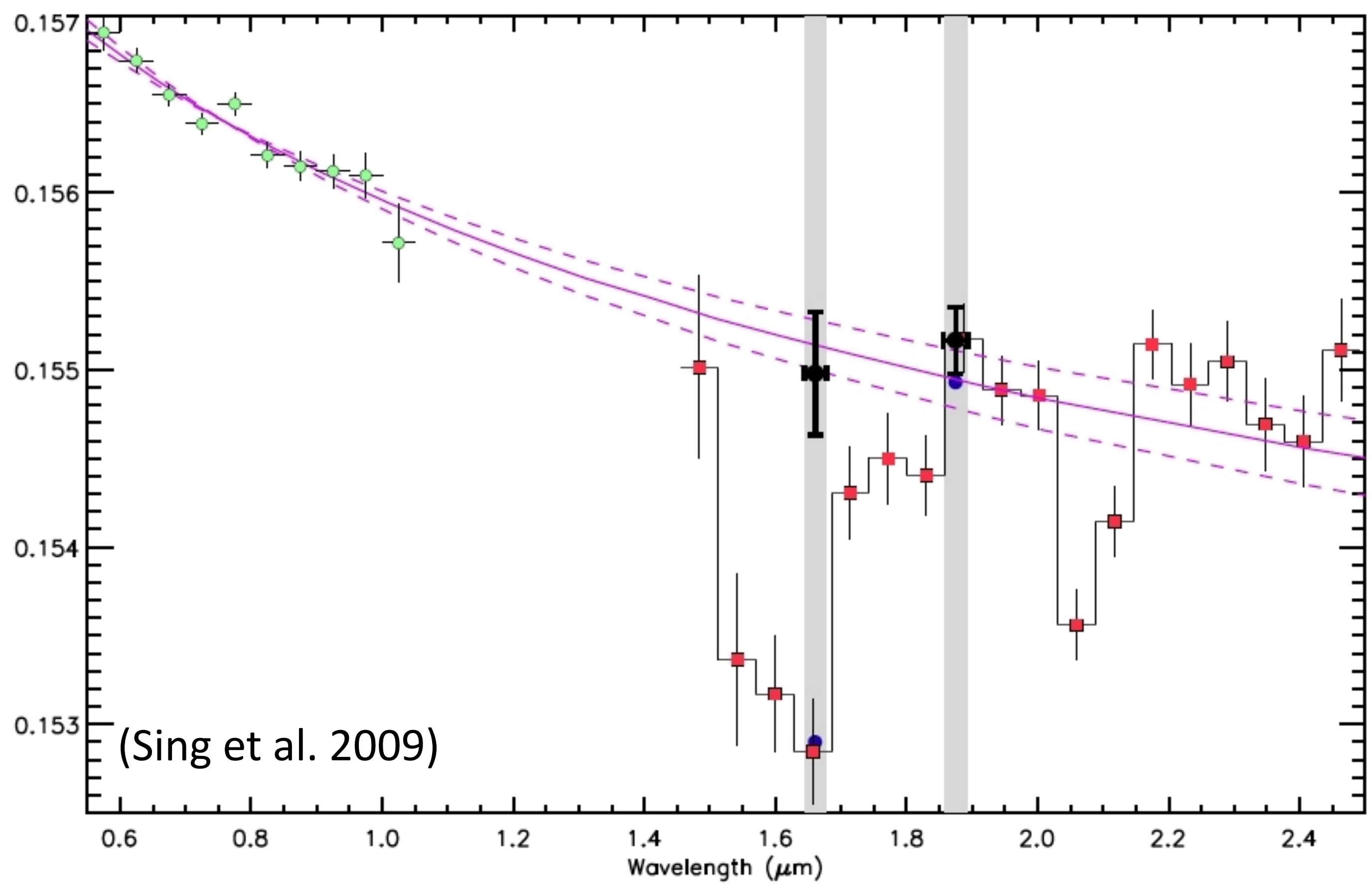


Summary of main detections from space between 2002 and 2008.

- Escaping H atmosphere in HD 209458b (Vidal-Madjar et al. 2003, 2004). See also Ben-Jaffel 2007, 2008)

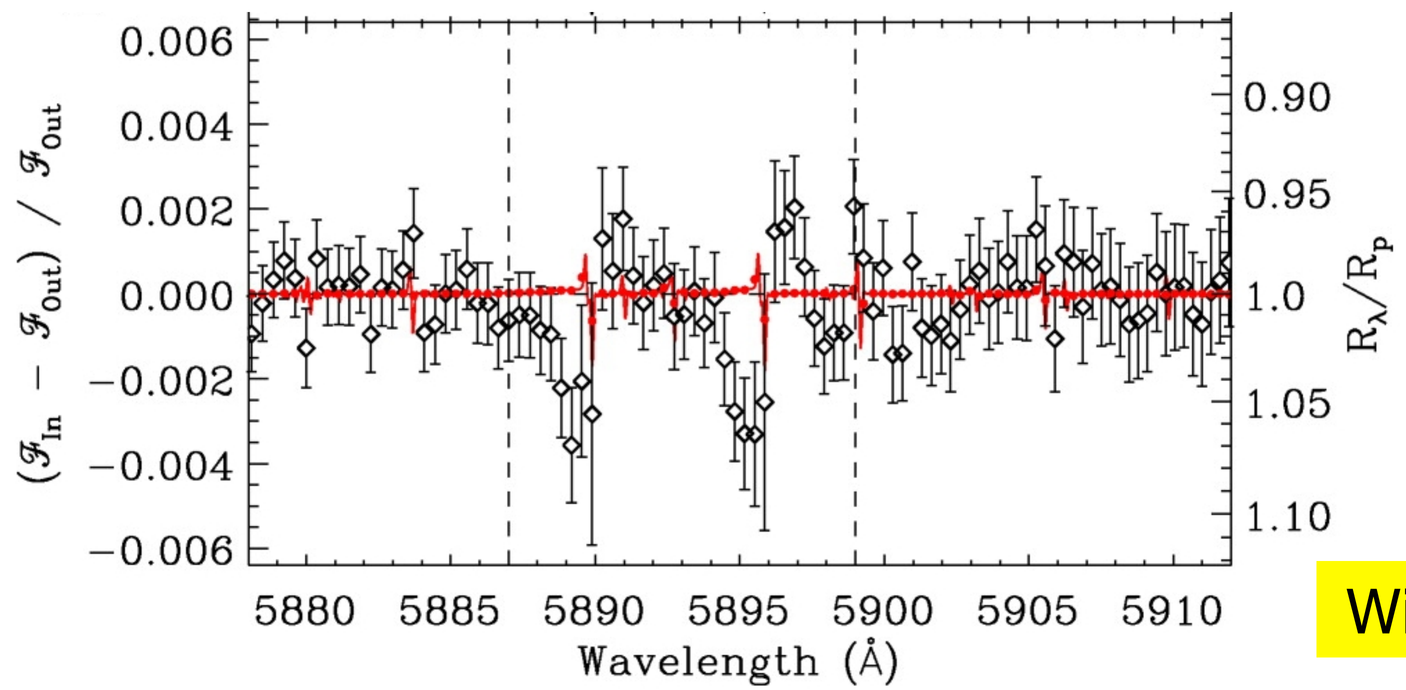
- Detection of H_2O and CH_4 in HD 189733b:

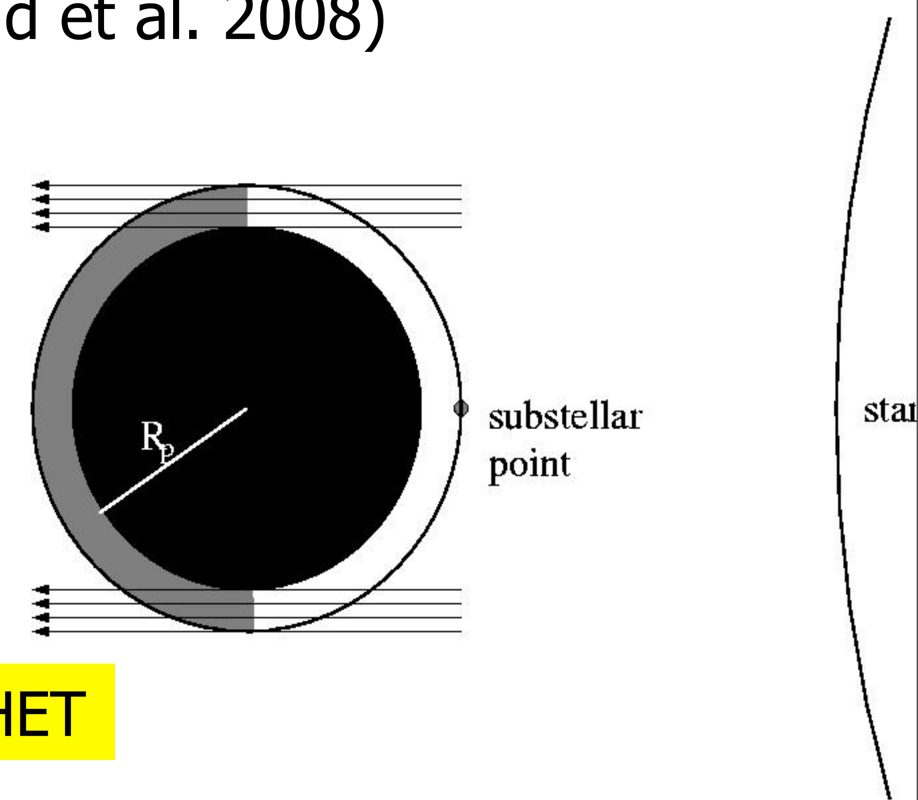
Tinetti et al. 2007 → Water in transmission spectrum
Grillmair et al. 2007 → No water in emission spectrum
■ Swain et al. 2008 → Water
● Pont et al. 2008 → No water features, but haze
Grillmair et al. 2008 → Water
● Sing et al. 2009 → No water, but haze



The First Ground-based Detections

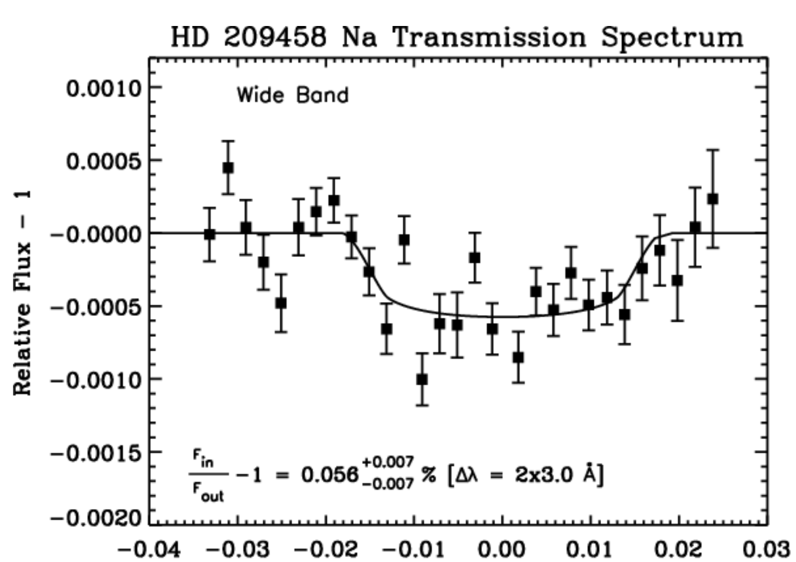
Ground-based detection of **Sodium** in HD 189733b (Redfield et al. 2008)

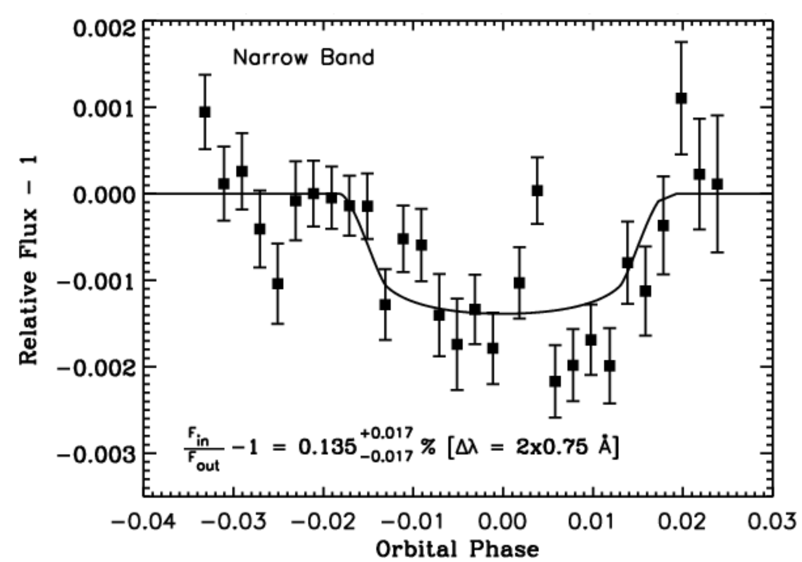




With HRS@HET

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





$\Delta\lambda$ = 3.0 Å Depth = 0.056%

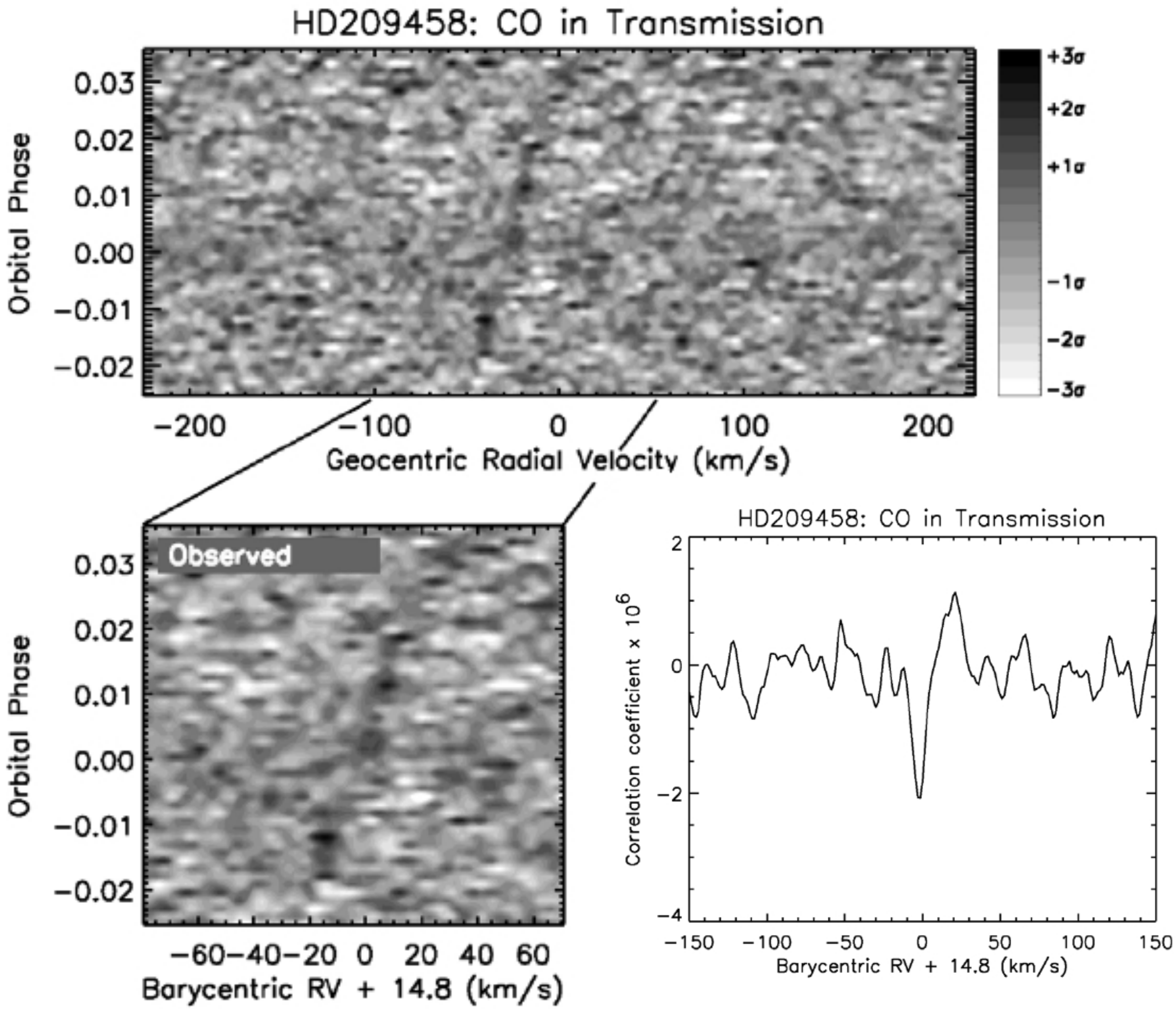
$\Delta\lambda$ = 0.75 Å Depth = 0.135%

> 5σ detection

With HDS@Subaru

** More recently, detection of Na I in WASP-17b (Wood et al. 2011; Zhou & Bayliss 2012).

CO and orbital motion detection of HD 209458b



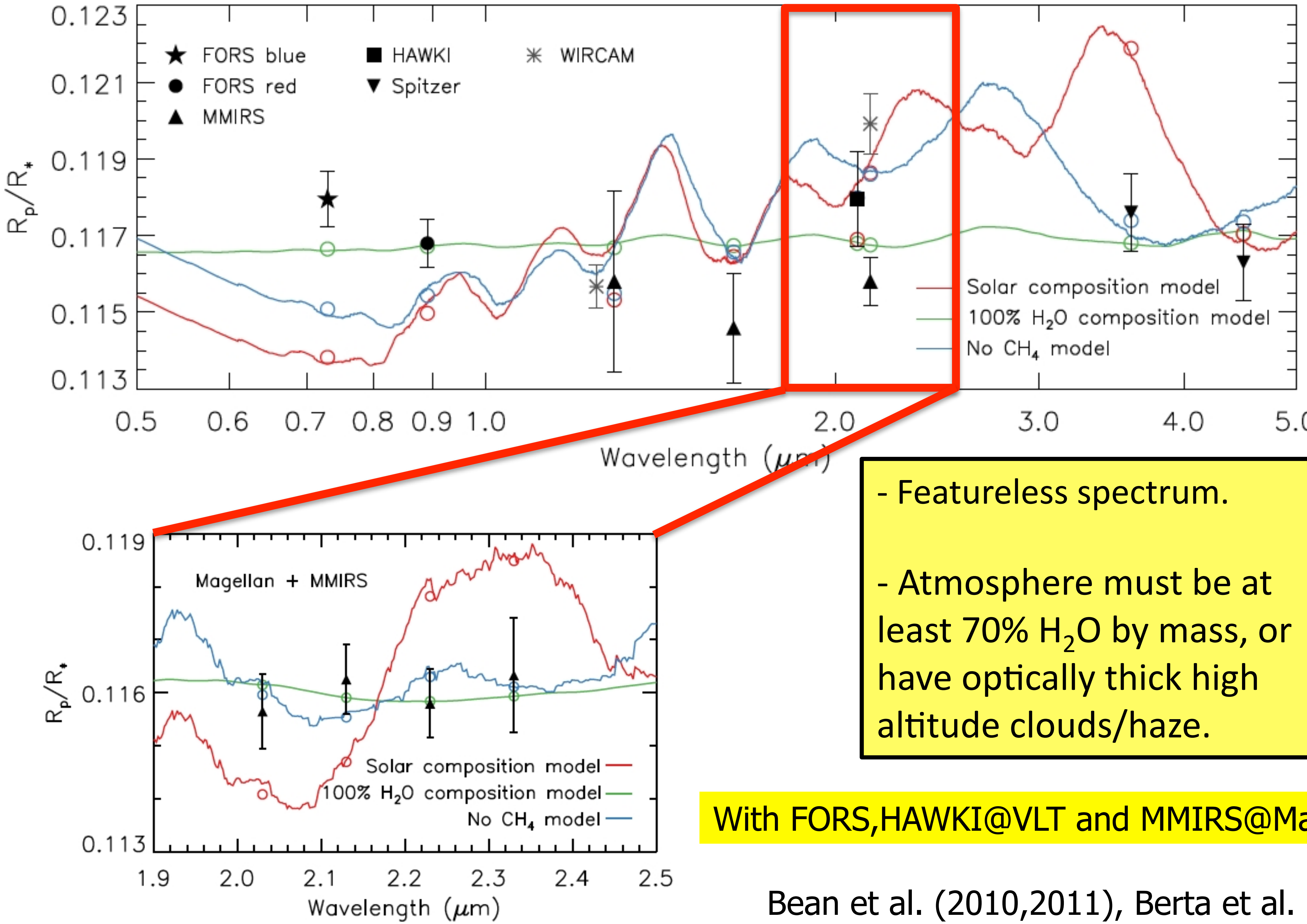
- Detection of CO.
  Mixing ratio = 1 – 3 x 10^{-3}.
- Non-detection of H_2O.
  Mixing ratio < 3 x 10^{-3} (3σ).
- Non-detection of CH_4.
  Mixing ratio < 8 x 10^{-4} (3σ).

With CRIRES@VLT

Snellen et al. (2010)

** H2O and CO have been now also detected in HD189733b using this techniques (Birkby et al. 2013; de Kok et al. 2013).

A flat transmission spectrum for GJ1214b



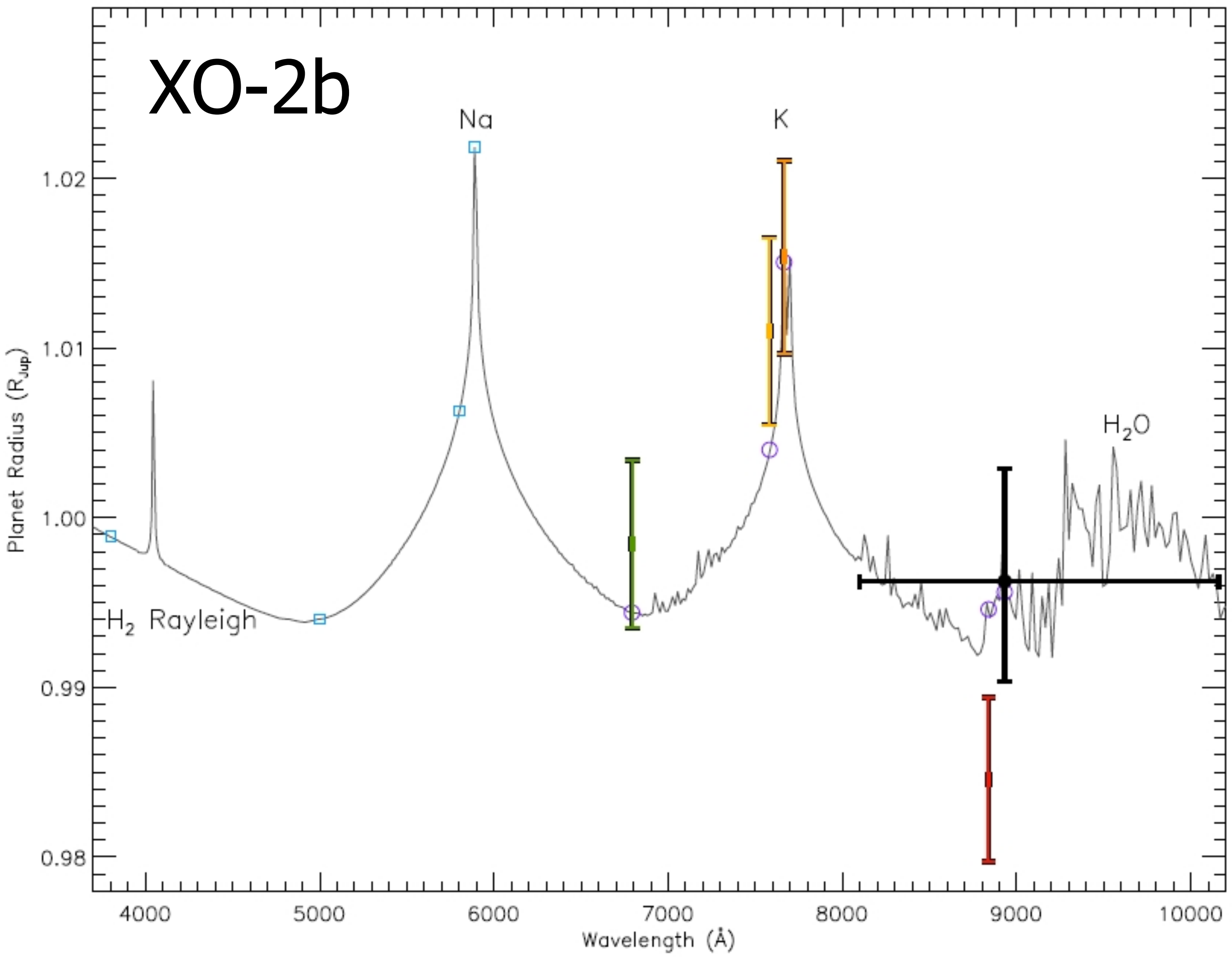
- Featureless spectrum.

- Atmosphere must be at least 70% H_2O by mass, or have optically thick high altitude clouds/haze.

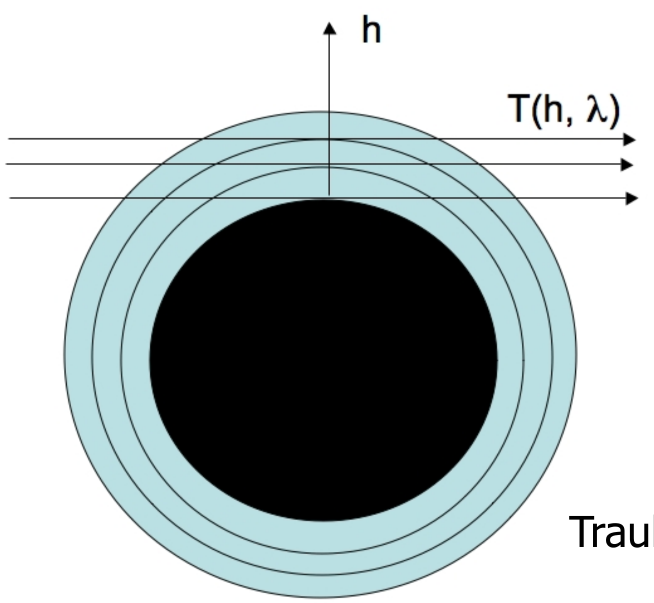
With FORS,HAWKI@VLT and MMIRS@Magellan

Bean et al. (2010,2011), Berta et al. (2011), Croll et al. (2010), Fraine et al. (2011)

Potassium detection in XO-2b and HD 80606 b

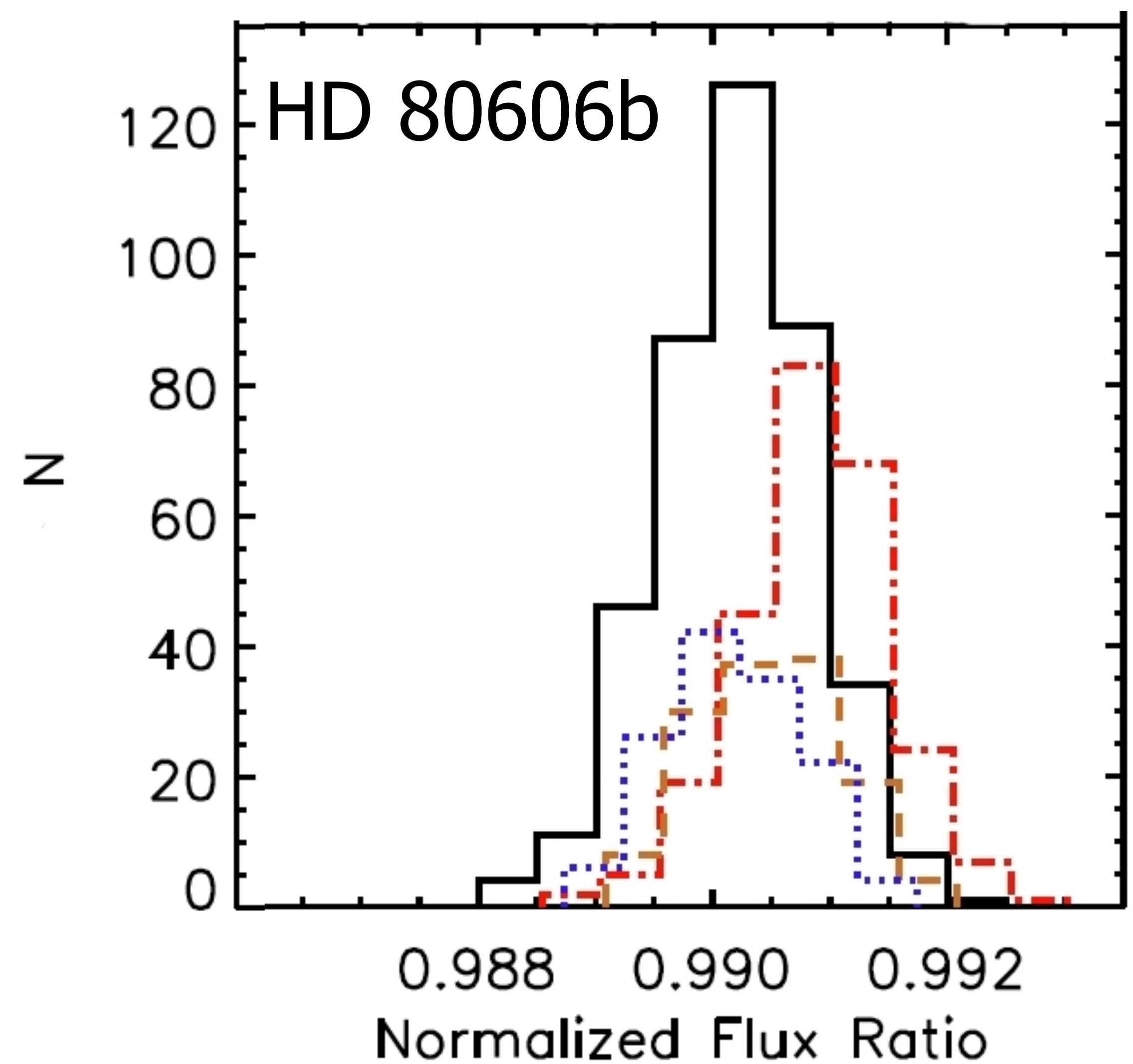


Sing et al. 2010



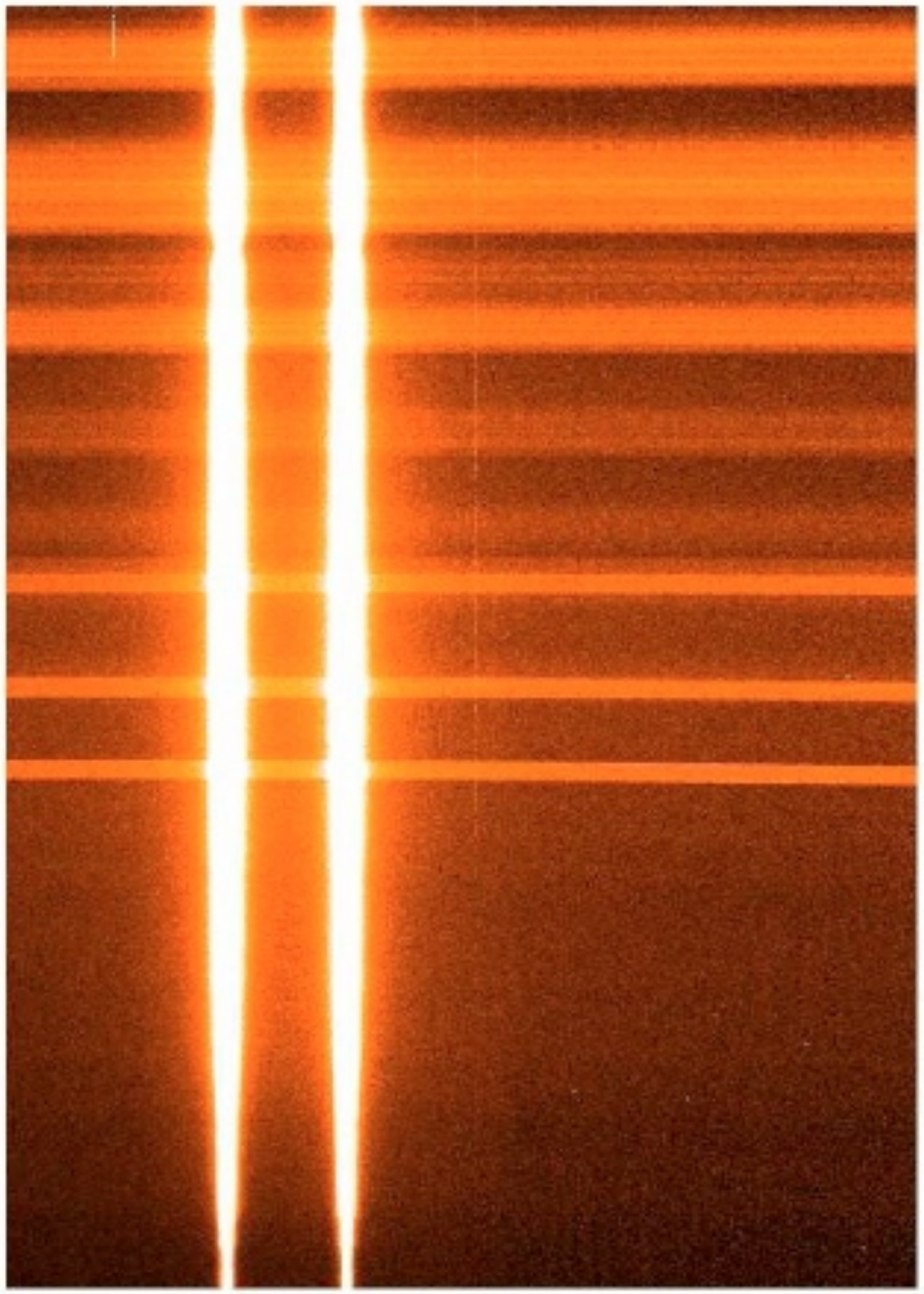
Traub 2009

Colón et al. 2010

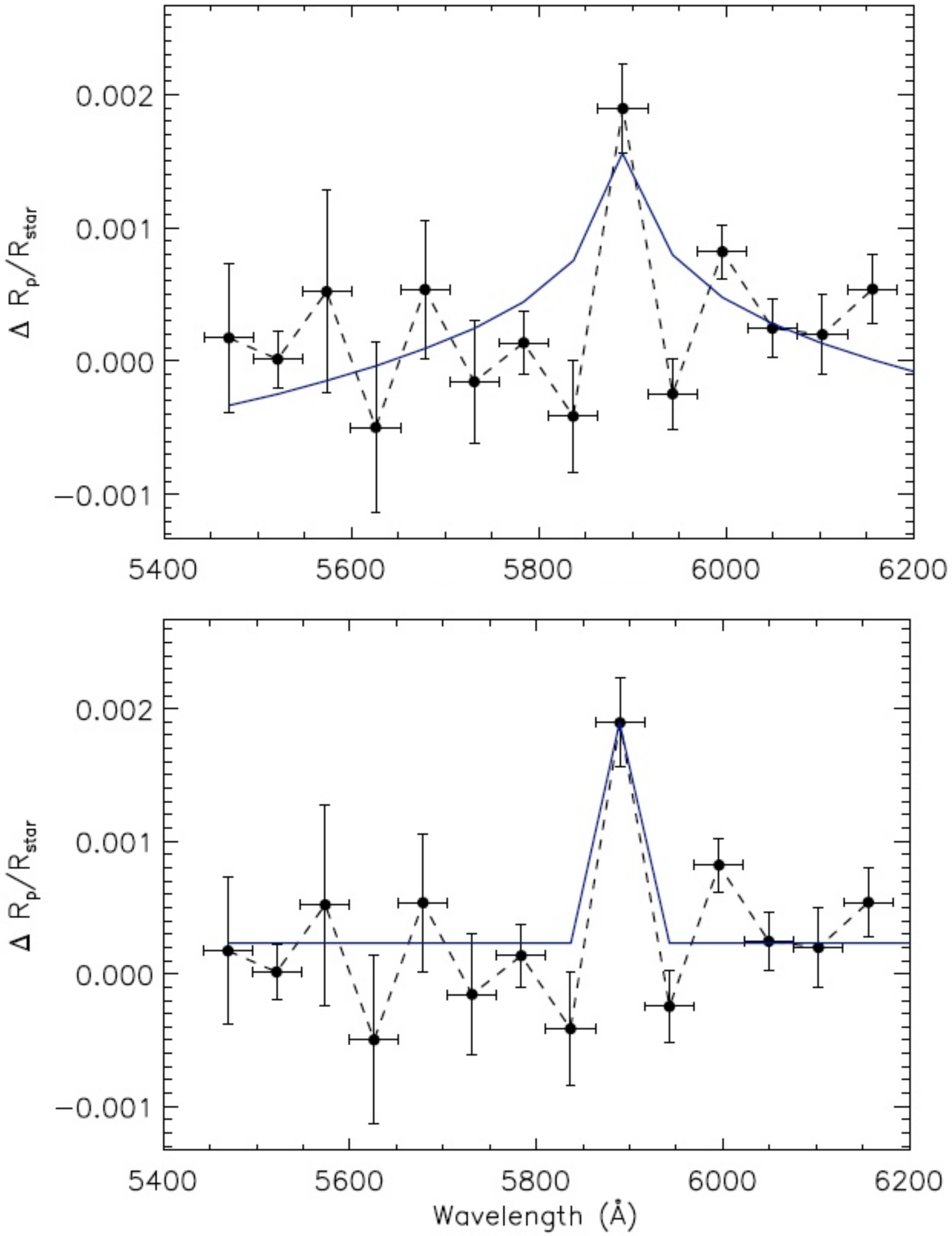


Both detections with OSIRIS@GTC's Tunable Filters

Tentative Sodium detection in XO-2b



CCD spectrum of XO-2 A and XO-2 B observed simultaneously with OSIRIS@GTC with R500B grism and 5" wide slit.



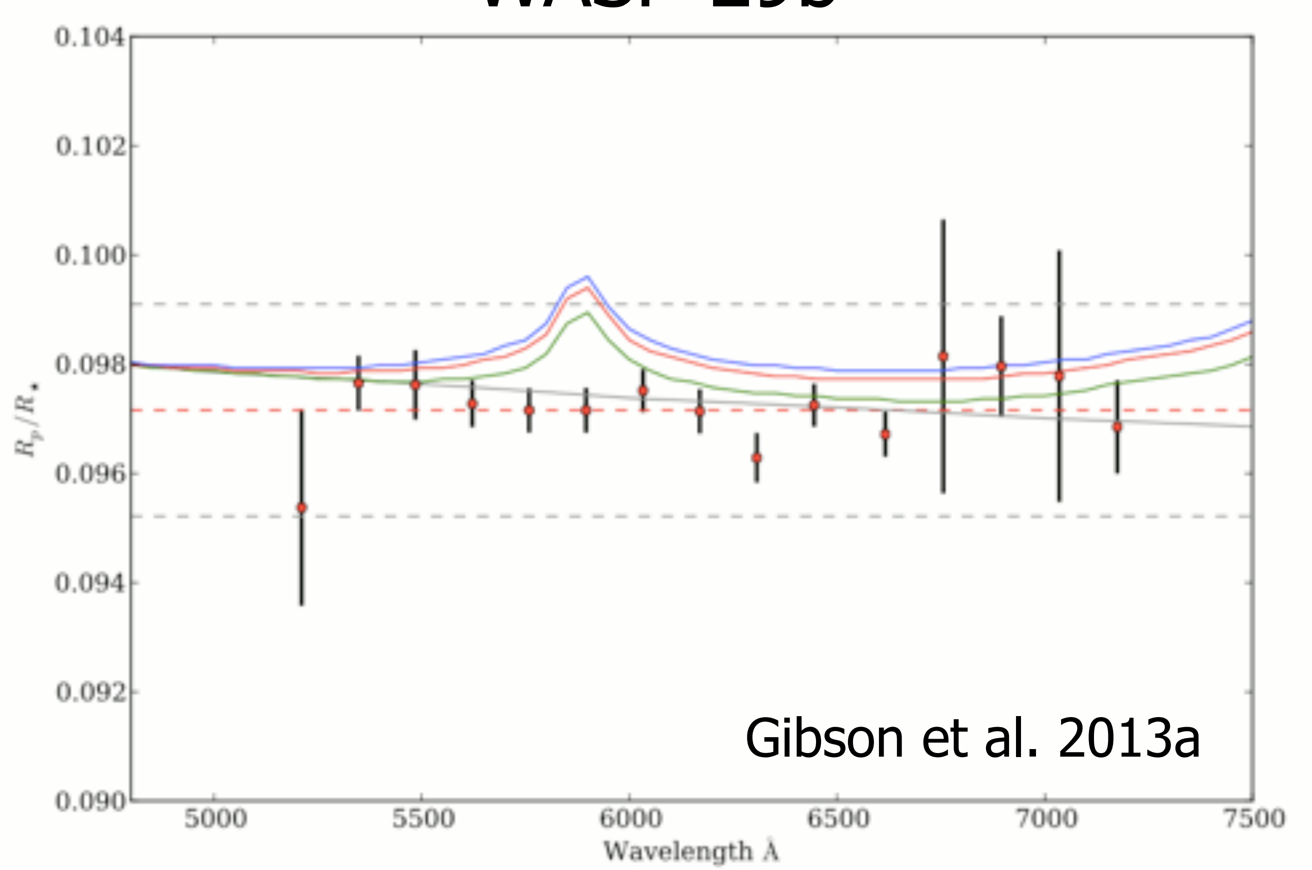
Haze/Cloud free atmosphere.

Atmosphere with Haze/clouds obscuring the Na line wings.

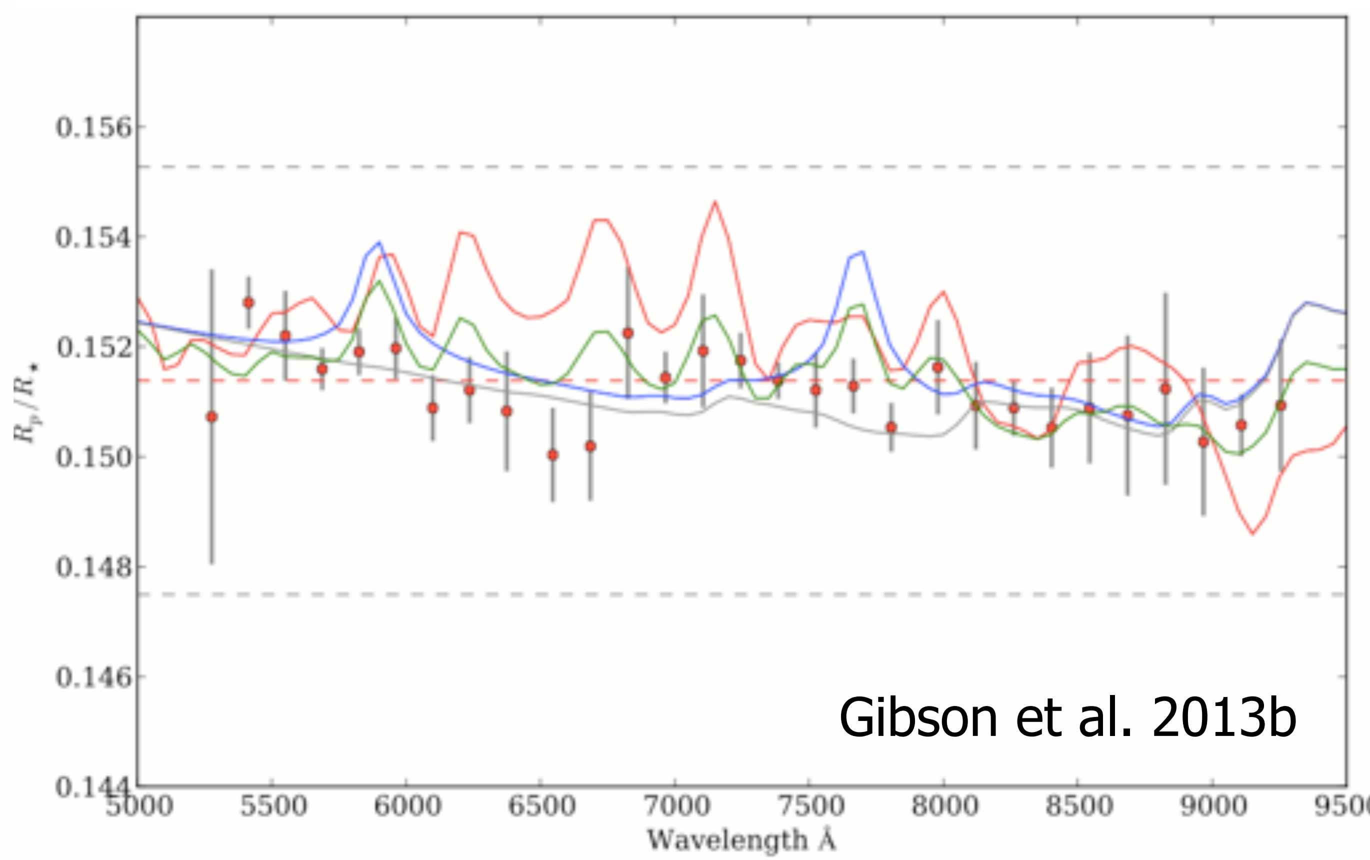
Sing et al. 2012

Results in the past year: Multi-object Spectroscopy

WASP-29b



HAT-P-32b

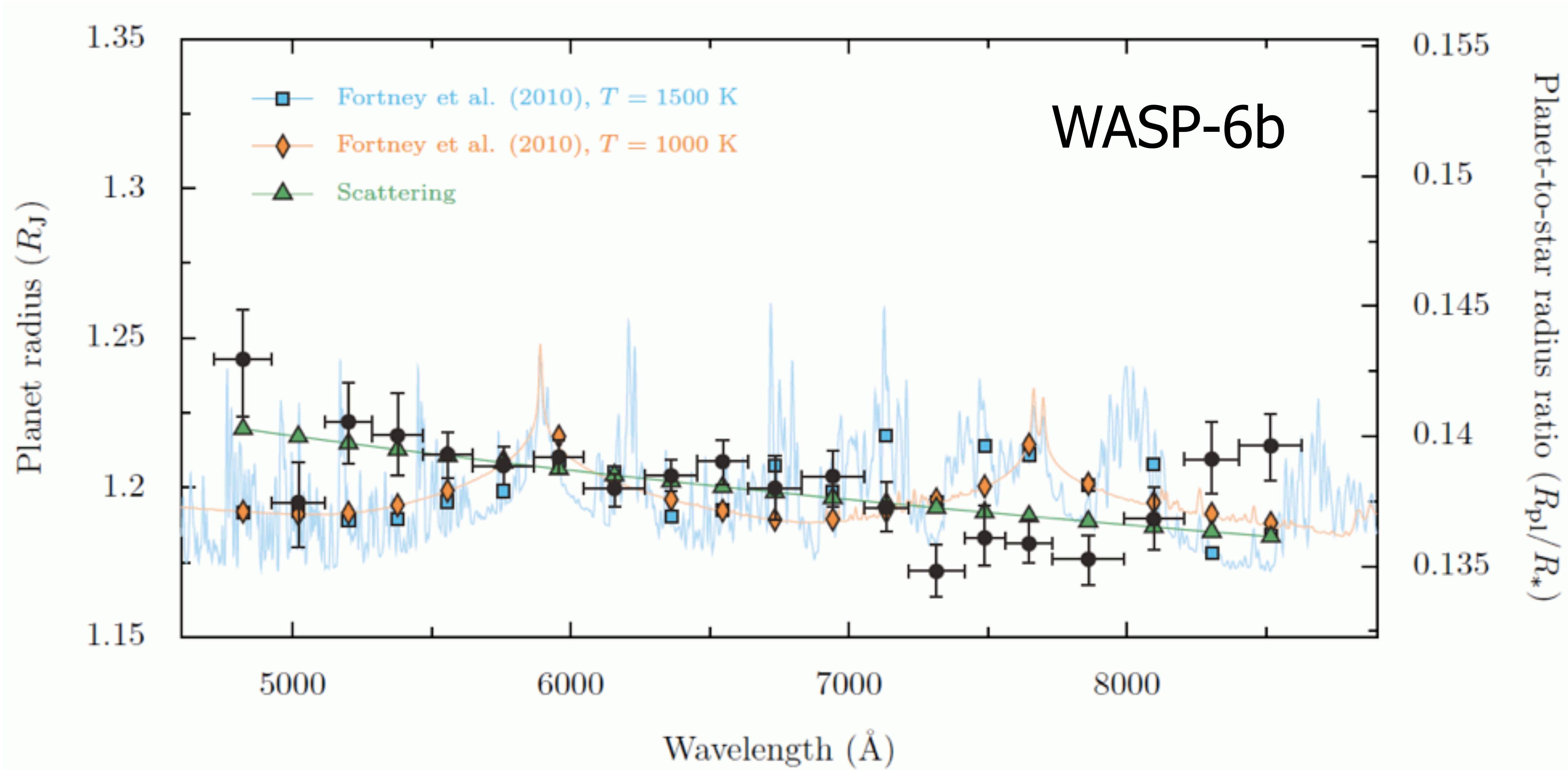


Detections with GMOS@Gemini-N & Gemini-S. Both planets show featureless spectra.

- No Na I rich, free of clouds atmosphere
- Clouds of haze present
- No Na I rich atmosphere is the most likely case, given Tp ~ 970K.

- No Na I or K I wings or prominent TiO/VO features.
- Grey absorption clouds in upper atmosphere likely
- Cannot rule out clear atmosphere models with low abundances.

Results in the past year: Multi-object Spectroscopy



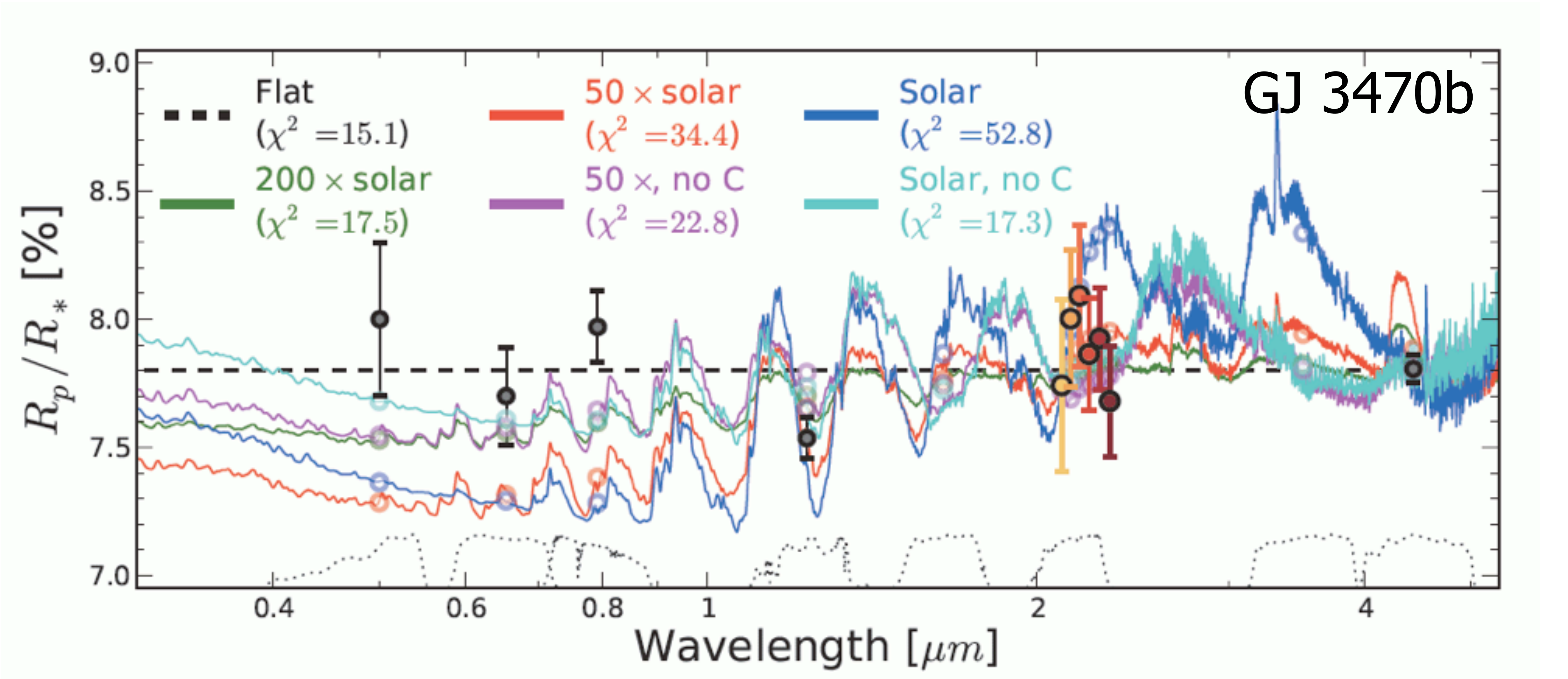
- No sign of akali metals.

- Slope consistent with scattering by hazes or condensates.

With IMACS@Magellan

Jordan et al. 2013

Results in the past year: Multi-object Spectroscopy



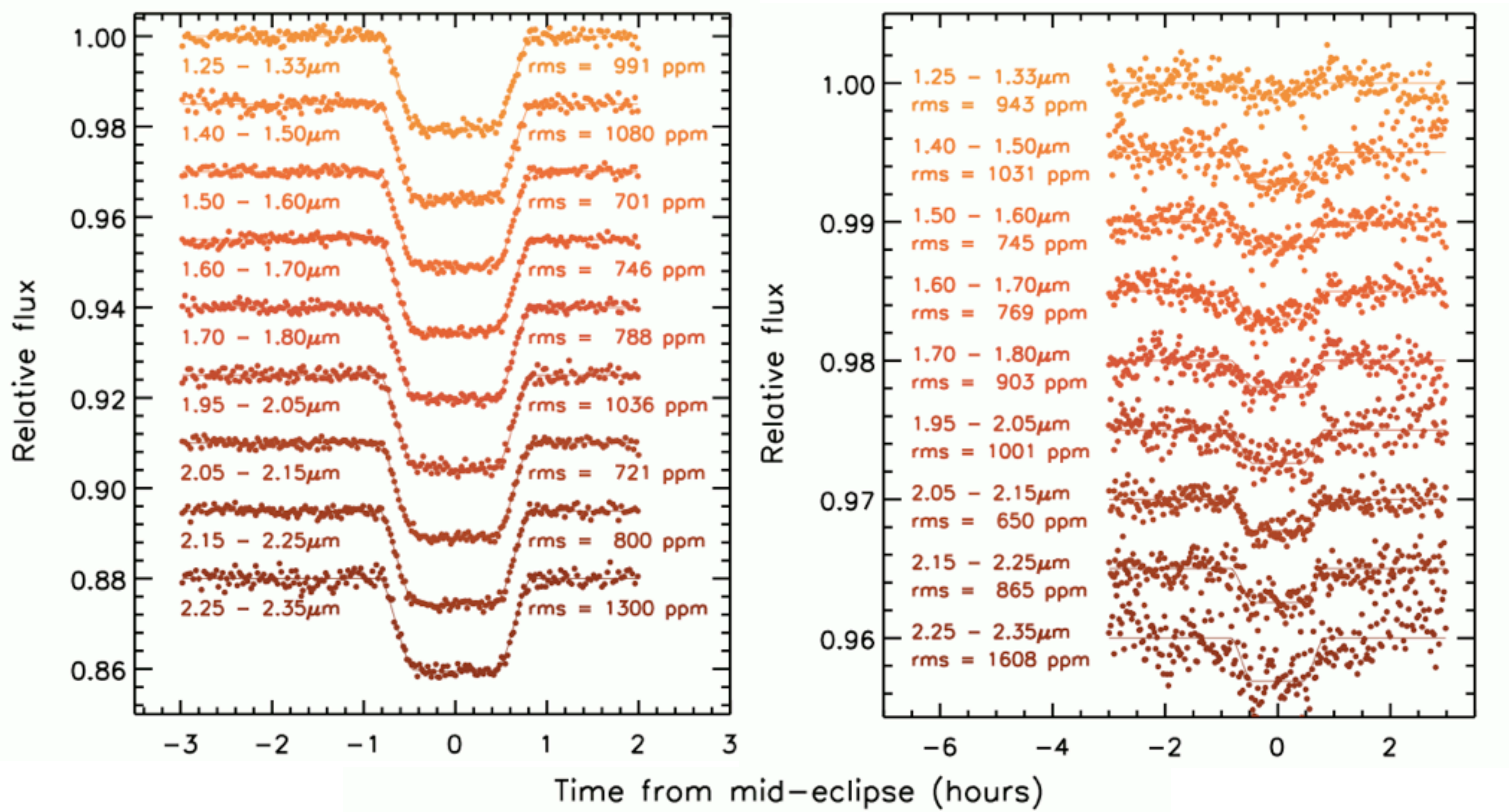
- can rule out models with solar composition and 50x solar.

- cannot rule out methane depleted models, highly enriched models, or a flat spectrum.

With MOSFIRE@Keck

Crossfield et al. 2013, Fukui et al. 2013, Demory et al. 2013

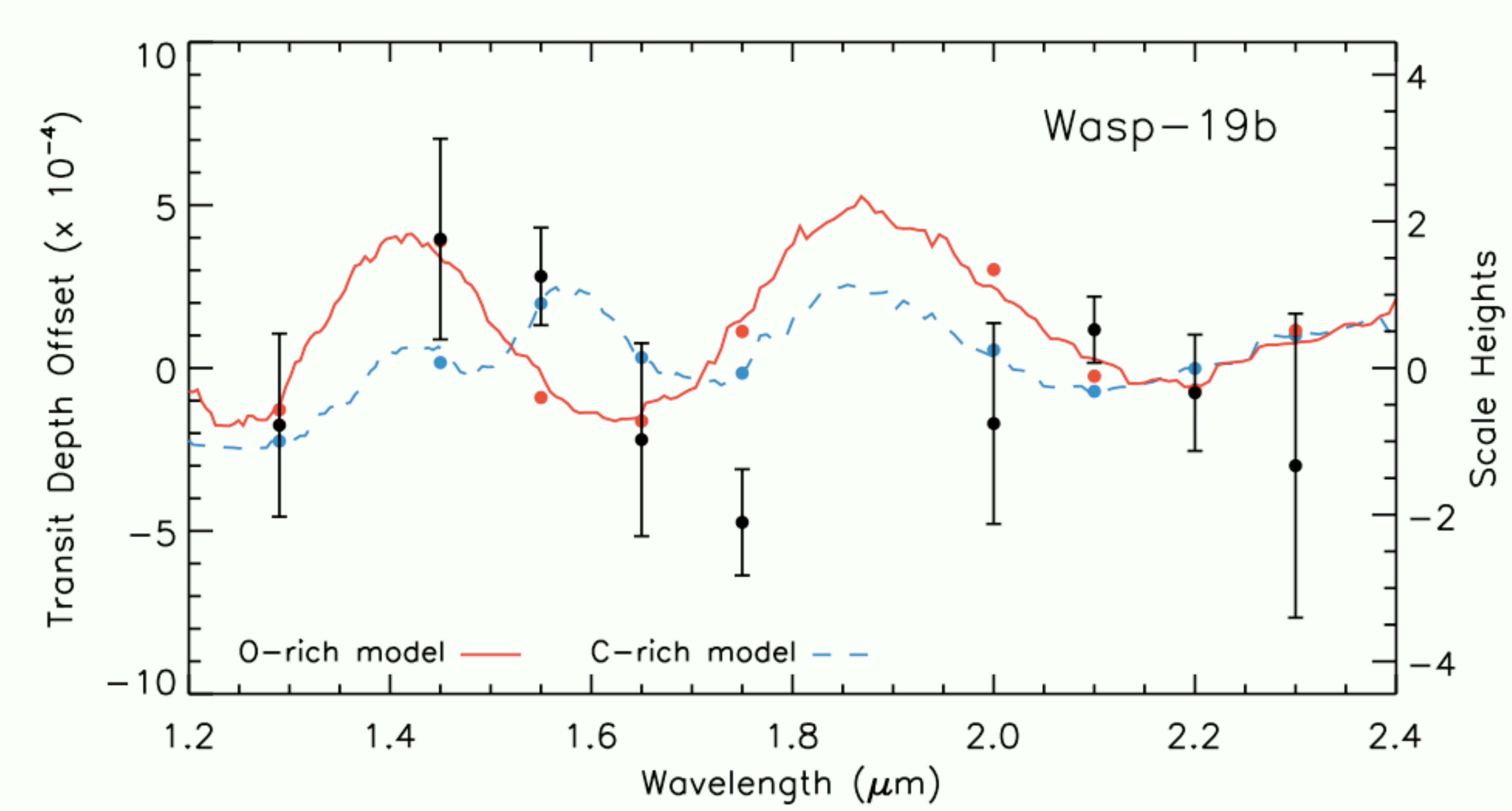
Transmission and **emission** spectroscopy of WASP-19b



Both detections with MMIRS@Magellan MOS

Bean et al. 2013

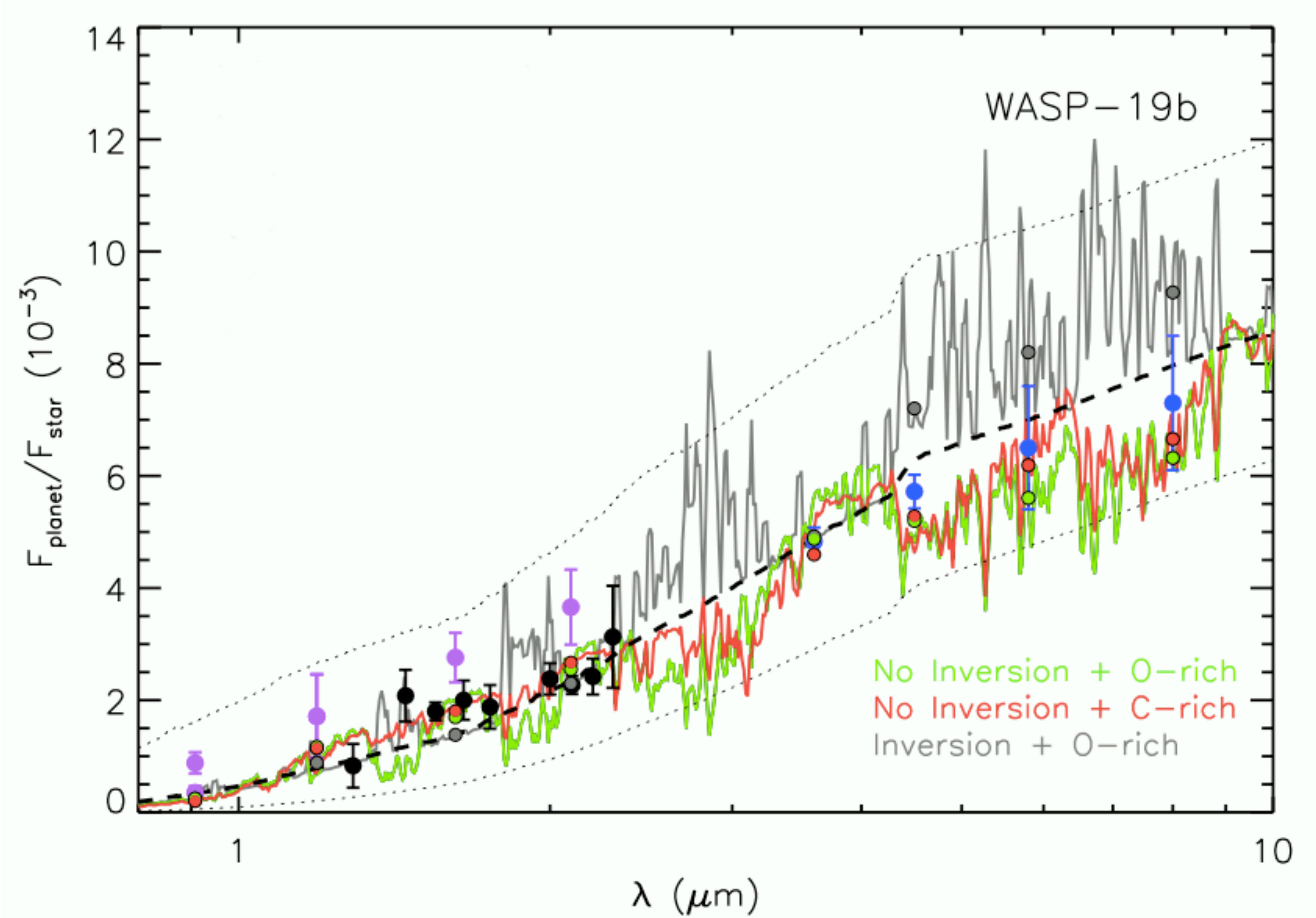
Transmission and emission spectroscopy of WASP-19b



- No evidence of strong absorbers
- Observations do not match either a C-rich or O-rich model

Bean et al. 2013

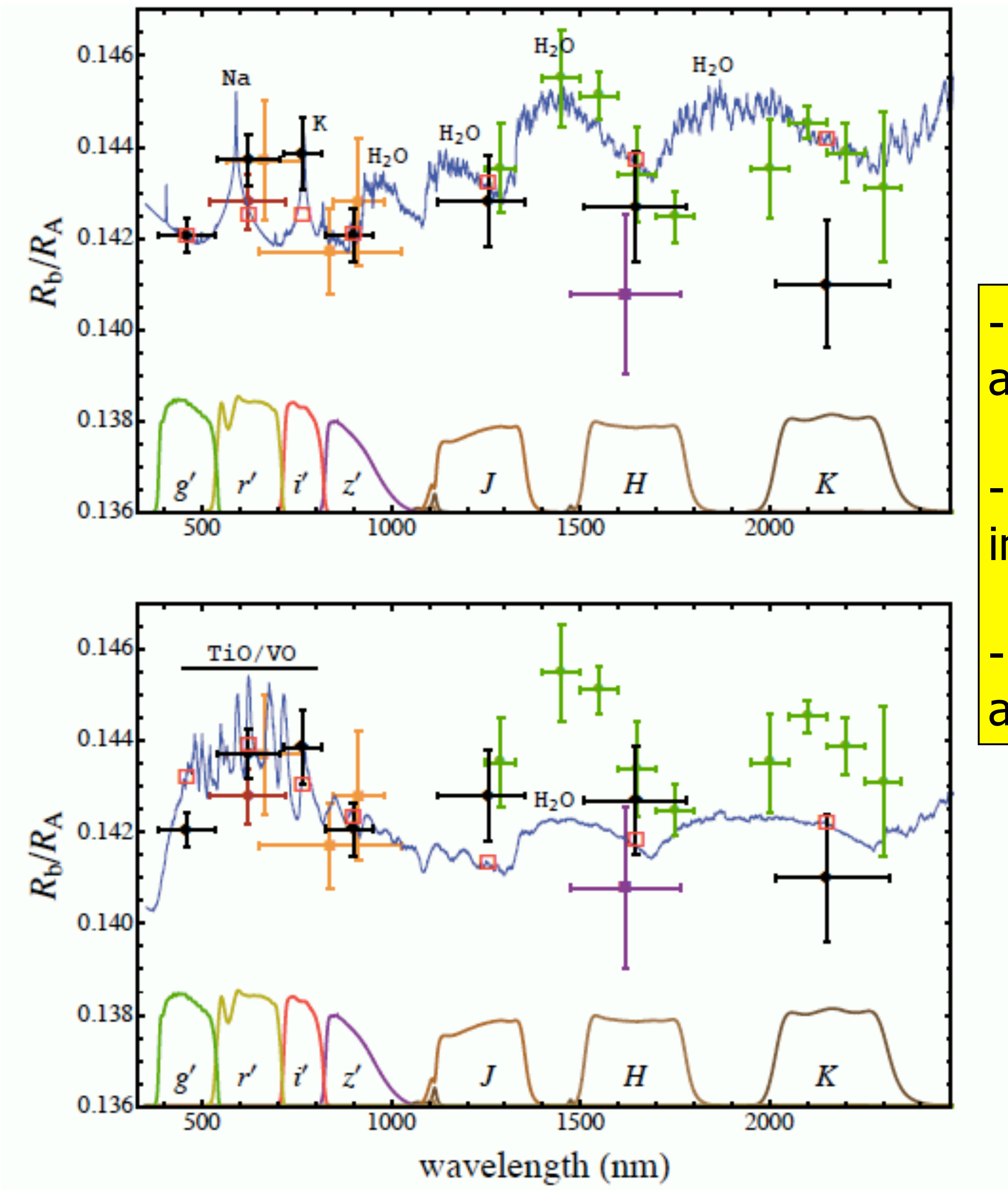
Transmission and emission spectroscopy of WASP-19b



- No thermal inversion
- No extra flux observed by individual photometric observations

Bean et al. 2013

Transmission and emission spectroscopy of WASP-19b



- Observations compared to models with and without TiO/VO (or thermal inversion)

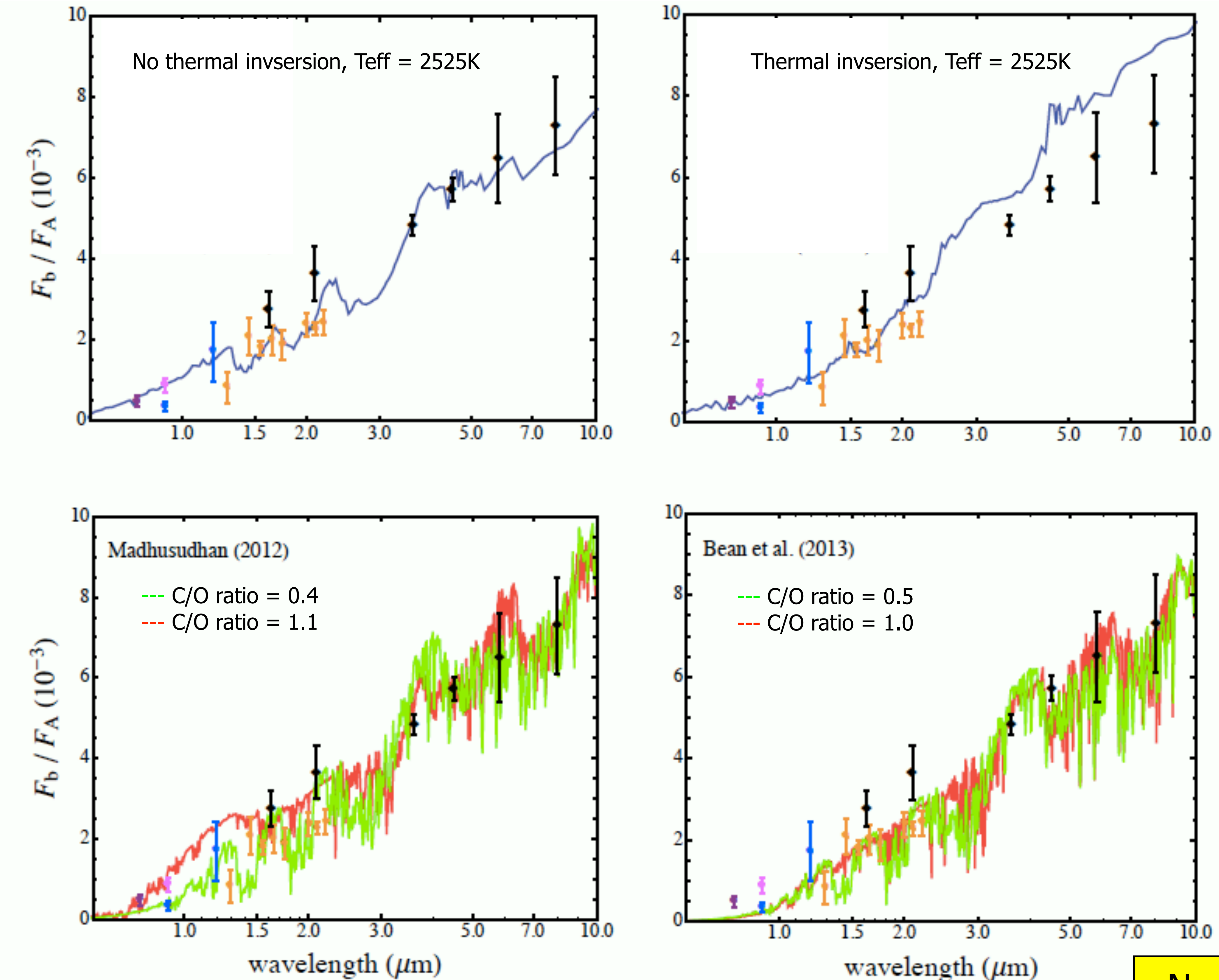
- They seem to favor the non-thermal inversion model.

- Atmosphere most likely dominated by absorption of H2O, Na and K.

With GROND@MPG/ESO 2.2m

Mancini et al. 2013

Transmission and emission spectroscopy of WASP-19b



- No thermal inversion
- C/O ratio of ~ 0.4

Techniques used to detect exoplanet atmospheres from the ground

Technique	**Pros** ✓	**Cons** ✗
Broad-band photometry	• Easier to reduce. • Can use small telescopes.	• Hard to resolve features. • Non-simultaneous observations*.
Narrow-band photometry (Tunable Filters)	• Ideal to search for specific features, e.g. Na or K.	• Wastes light.
Low resolution, long-slit spectroscopy	• Simultaneous coverage of wide range of wavelengths.	• Limited to one comparison star.
Low resolution, MOS	• Simultaneous coverage of wide range of wavelengths. • Several comparison stars.	• Limited to moderately crowded fields.
High Resolution Spectroscopy	• Ideal to search specific features in the spectrum. • Ideal to search for Doppler shift.	• Limited to very bright stars.

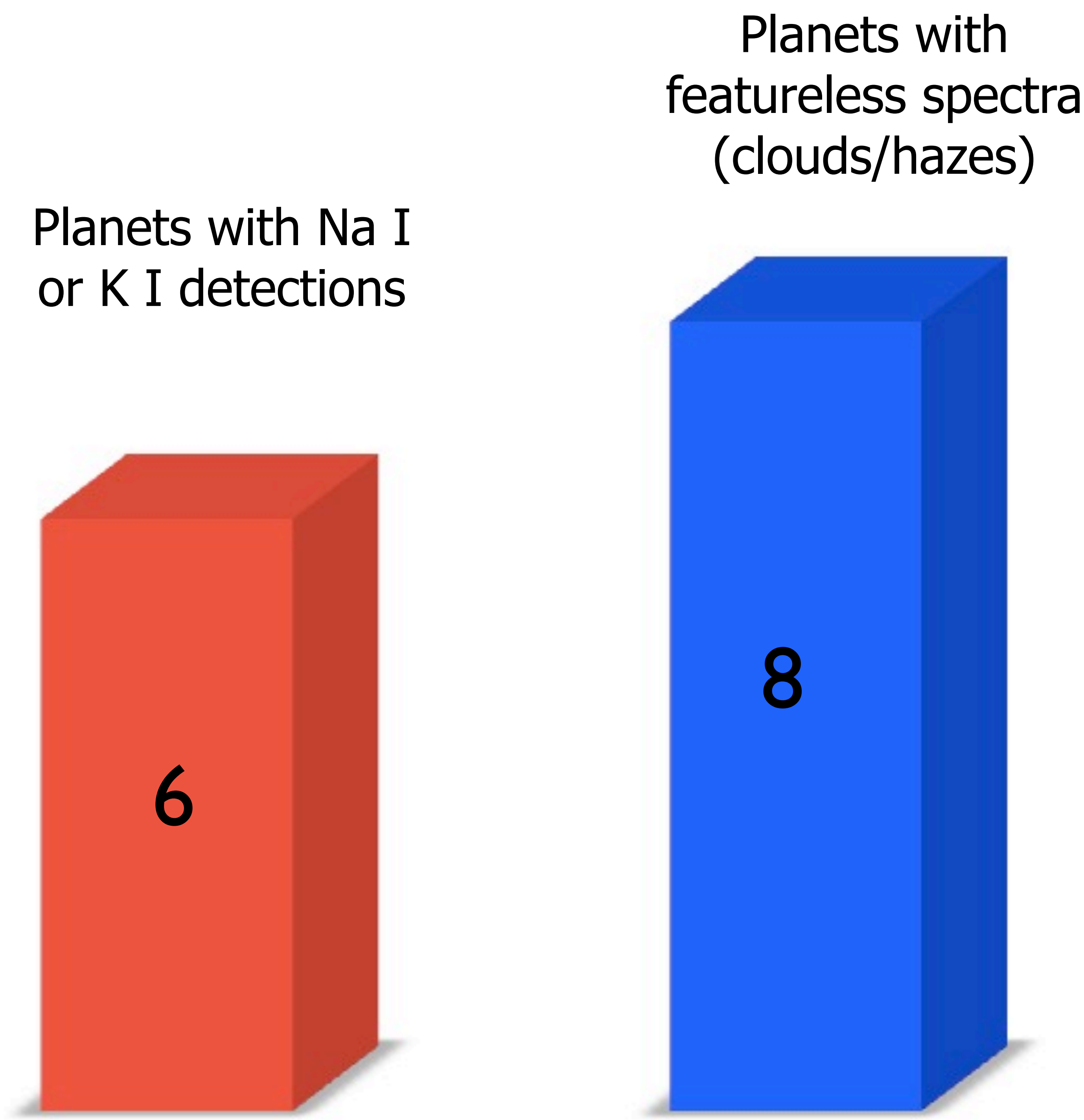
* except for simultaneous multi-wavelength observations, e.g. GROND.

Telescopes/Instruments used to perform spectroscopy of exoplanet atmospheres from the ground **

Telescope	Instrument	Wavelength	Technique
6.5m Magellan	IMACS →	Optical →	Low-Res MOS
	MMRIS →	Near-IR →	Low-Res MOS
8.1m Gemini	GMOS →	Optical →	Low-Res MOS
8.2m Subaru	HDS →	Optical →	High-Res Spectroscopy
8.2m VLT	CRIRES →	Near-IR →	High-Res Spectroscopy
9.2m HET	HRS →	Optical →	High-Res Spectroscopy
10m GTC	OSIRIS →	Optical →	Tunable filters
		→	Low-Res, Long Slit Spec.
10m Keck	MOSFIRE →	Near-IR →	Low-Res MOS

** List includes only the instruments for the results mentioned in the talk, which are examples of the most successful.

Some facts are getting unveiling ...



Charbonneay et al. 2002; Colon et al. 2010; Crossfield et al. 2013; Gibson et al. 2013; Jordan et al. 2013; Knutson et al. 2014; Kreidberg et al. 2014; Mancini et al. 2013; Murgas et al. 2013; Snellen et al. 2008; Sing et al. 2010, 2012, 2013; Zhou & Bayliss 2012.

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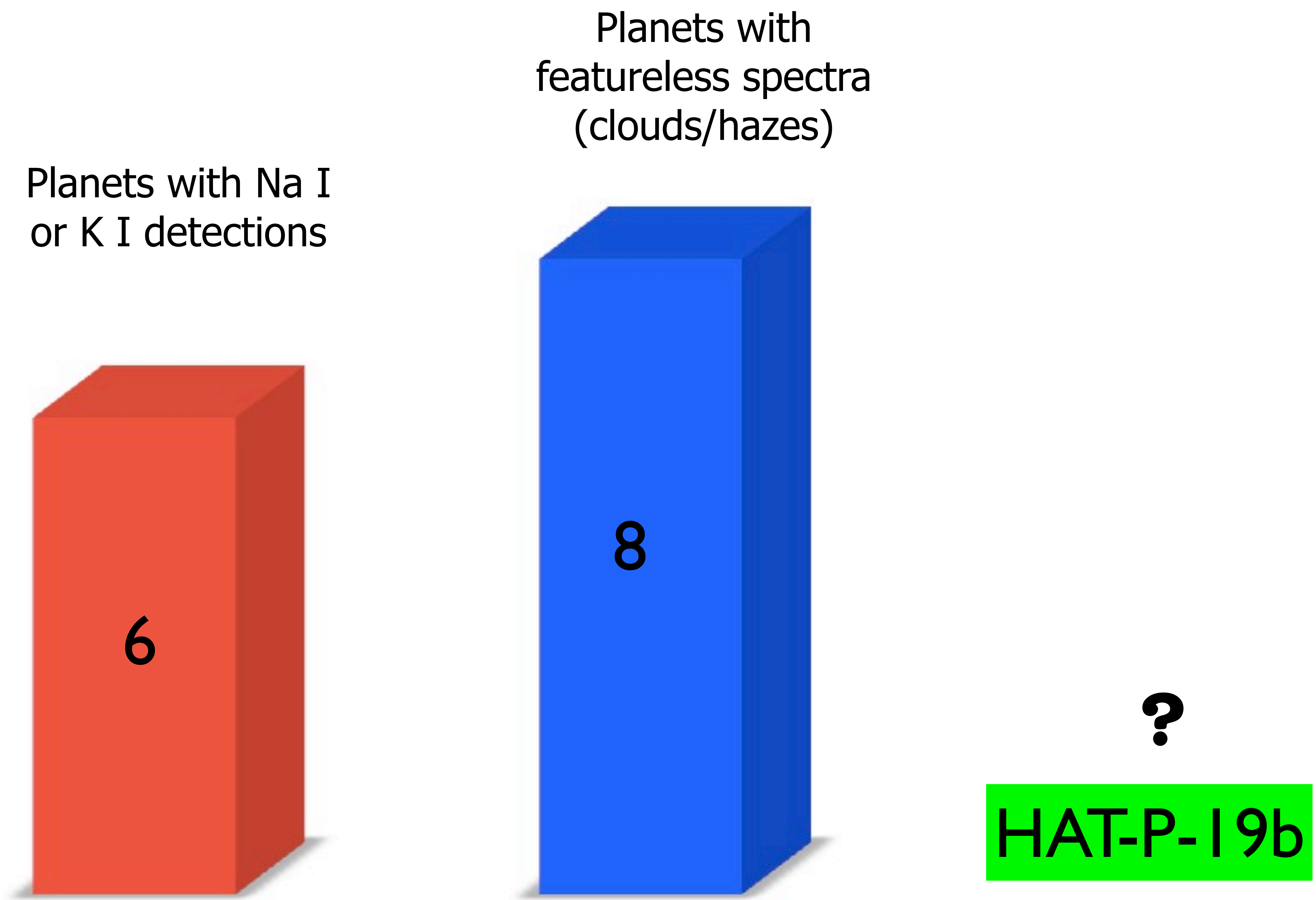

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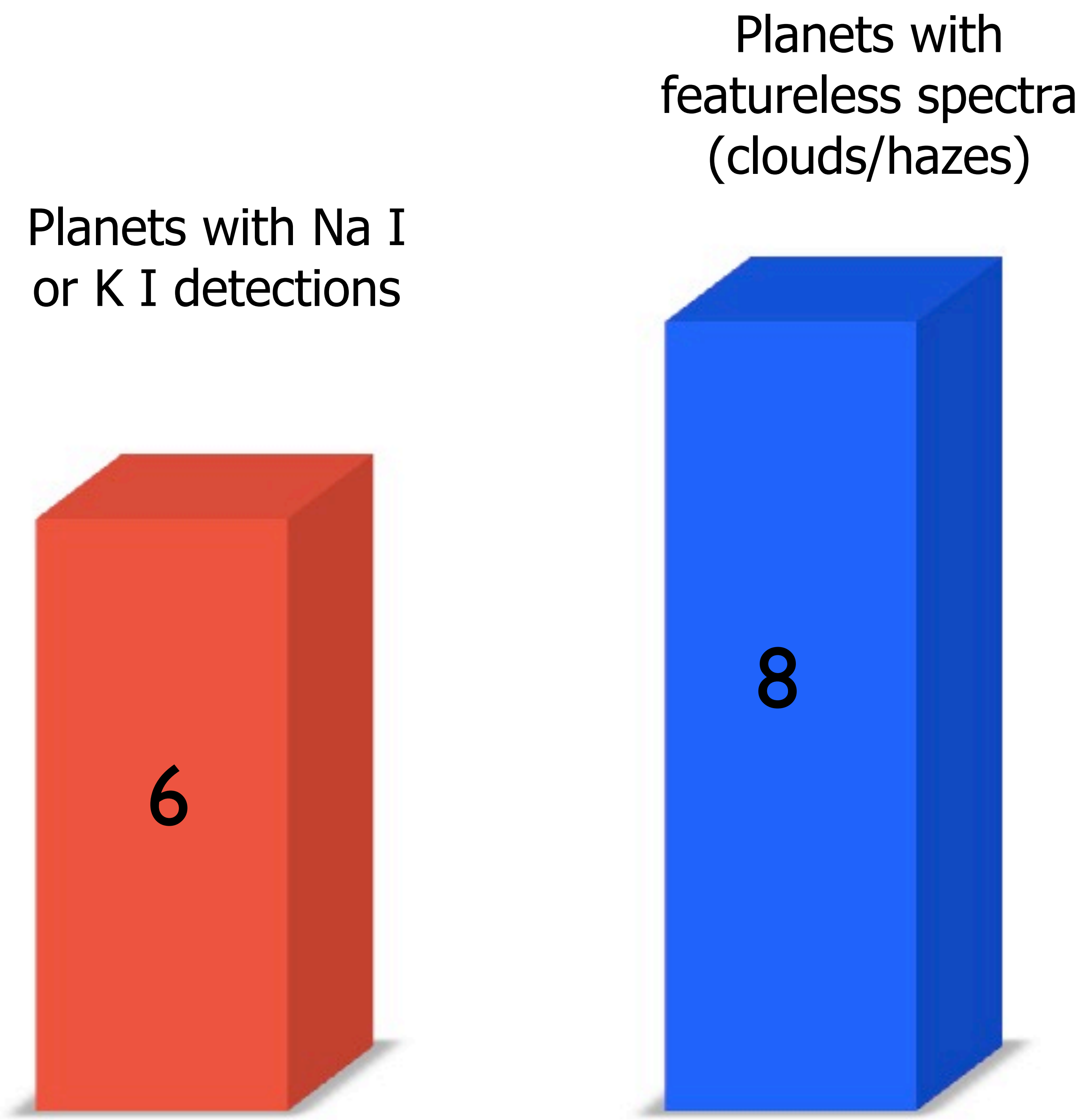

Charbonneay et al. 2002; Colon et al. 2010; Crossfield et al. 2013; Gibson et al. 2013; Jordan et al. 2013; Knutson et al. 2014; Kreidberg et al. 2014; Mancini et al. 2013; Murgas et al. 2013; Snellen et al. 2008; Sing et al. 2010, 2012, 2013; Zhou & Bayliss 2012.