Observations of Exoplanet Atmospheres

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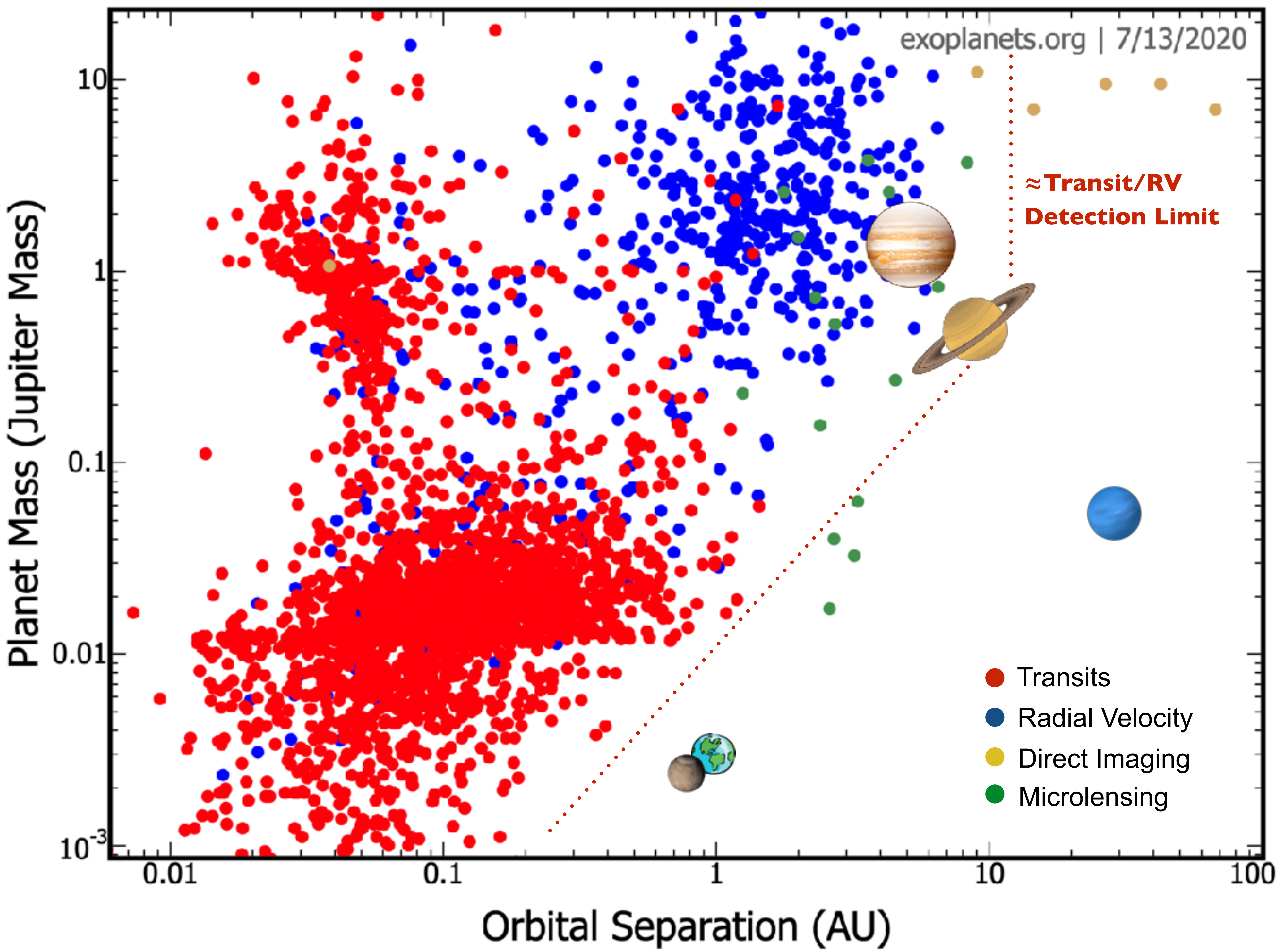
Image Credit: ESO / Y. Beletsky

More than 4,000 exoplanets have been detected



Exoplanet demographics tells us:

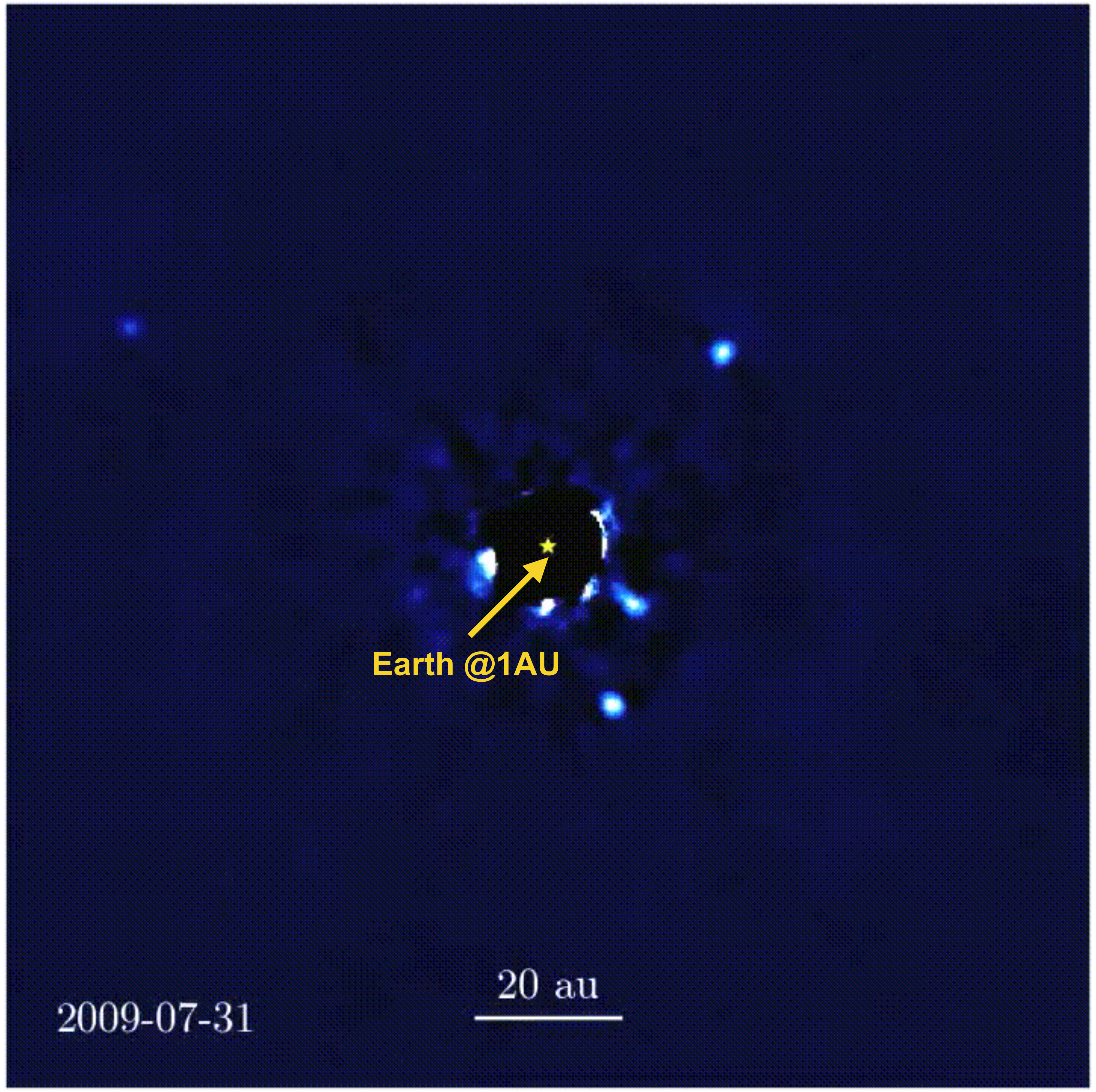
- Planets are more common that stars
- Planetary systems are incredibly diverse

Spectroscopic observations are required to fully understand the population of exoplanets

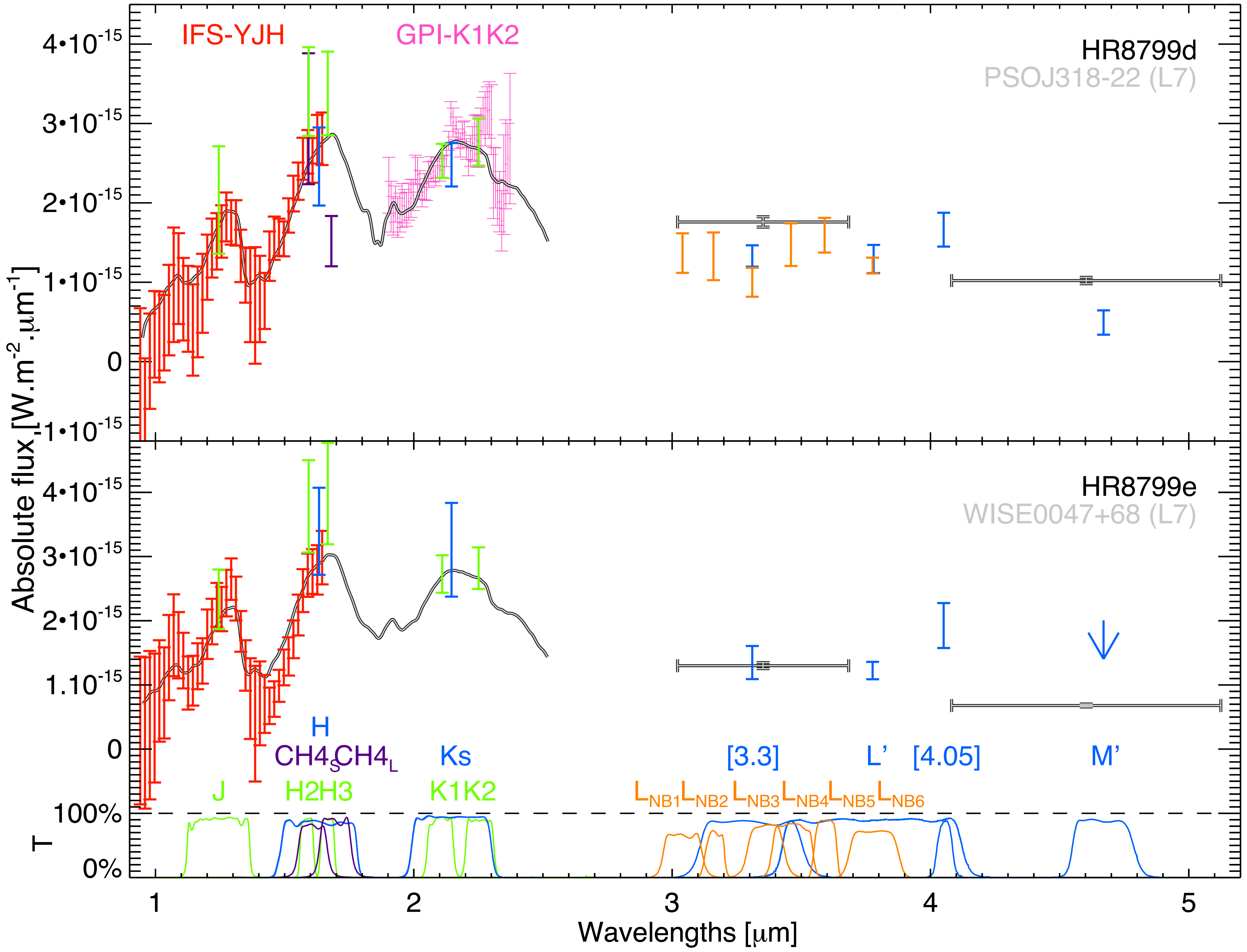
Talk Outline:

- How do we probe the atmospheres of exoplanets?

Direct Imaging/Spectroscopy is (conceptually) the "easiest" way to get a planet's spectrum

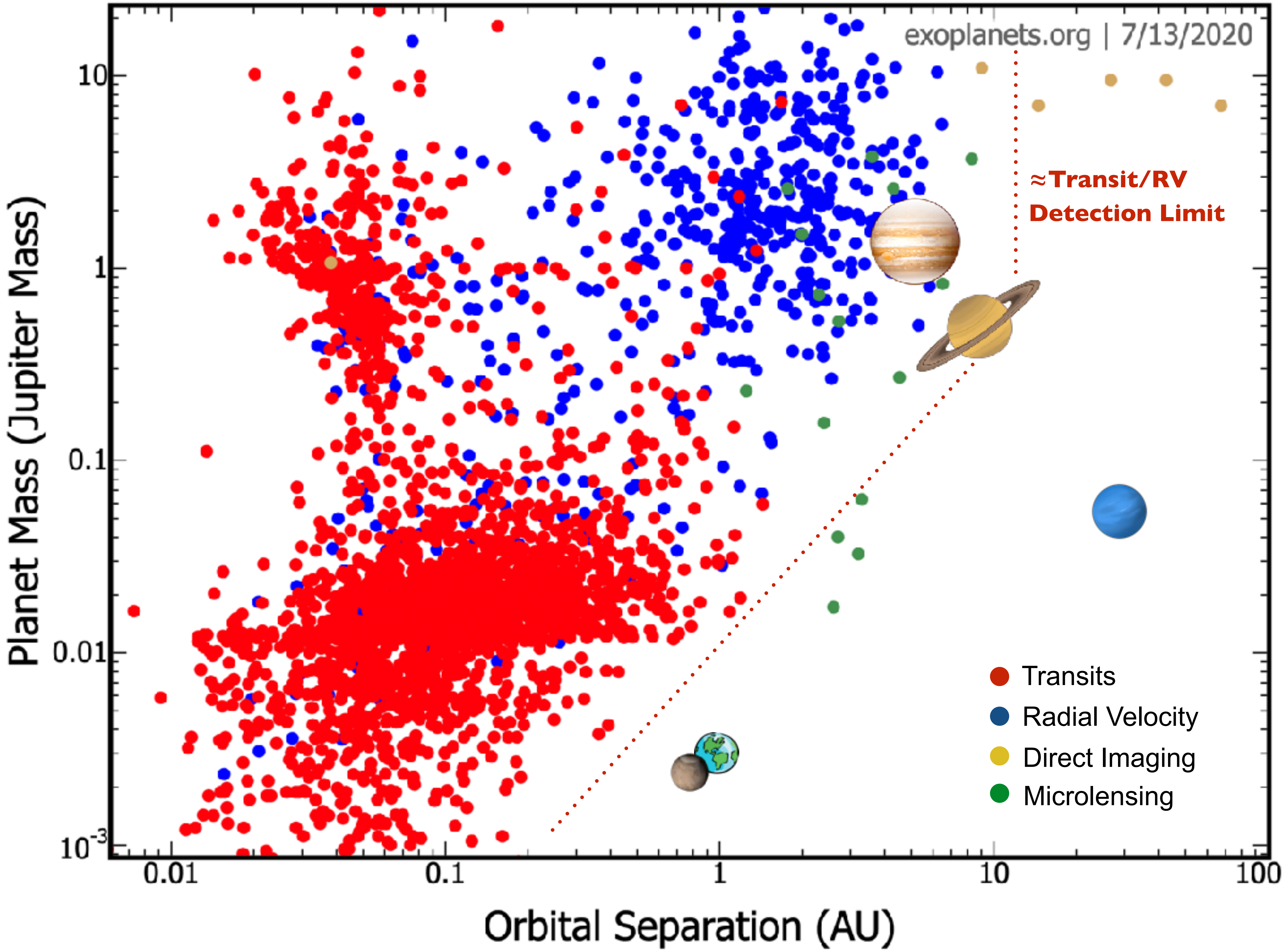


HR 8799: Marois et al. (2010) Image credit: J. Wang/ C. Marois



Biller & Bonnefoy (2018); data from Oppenheimer et al (2013); Skemer et al (2012, 2014); Ingraham et al (2014); Bonnefoy et al (2016); Zurlo et al (2016).

For now, direct imaging can only access a subset of known planets…



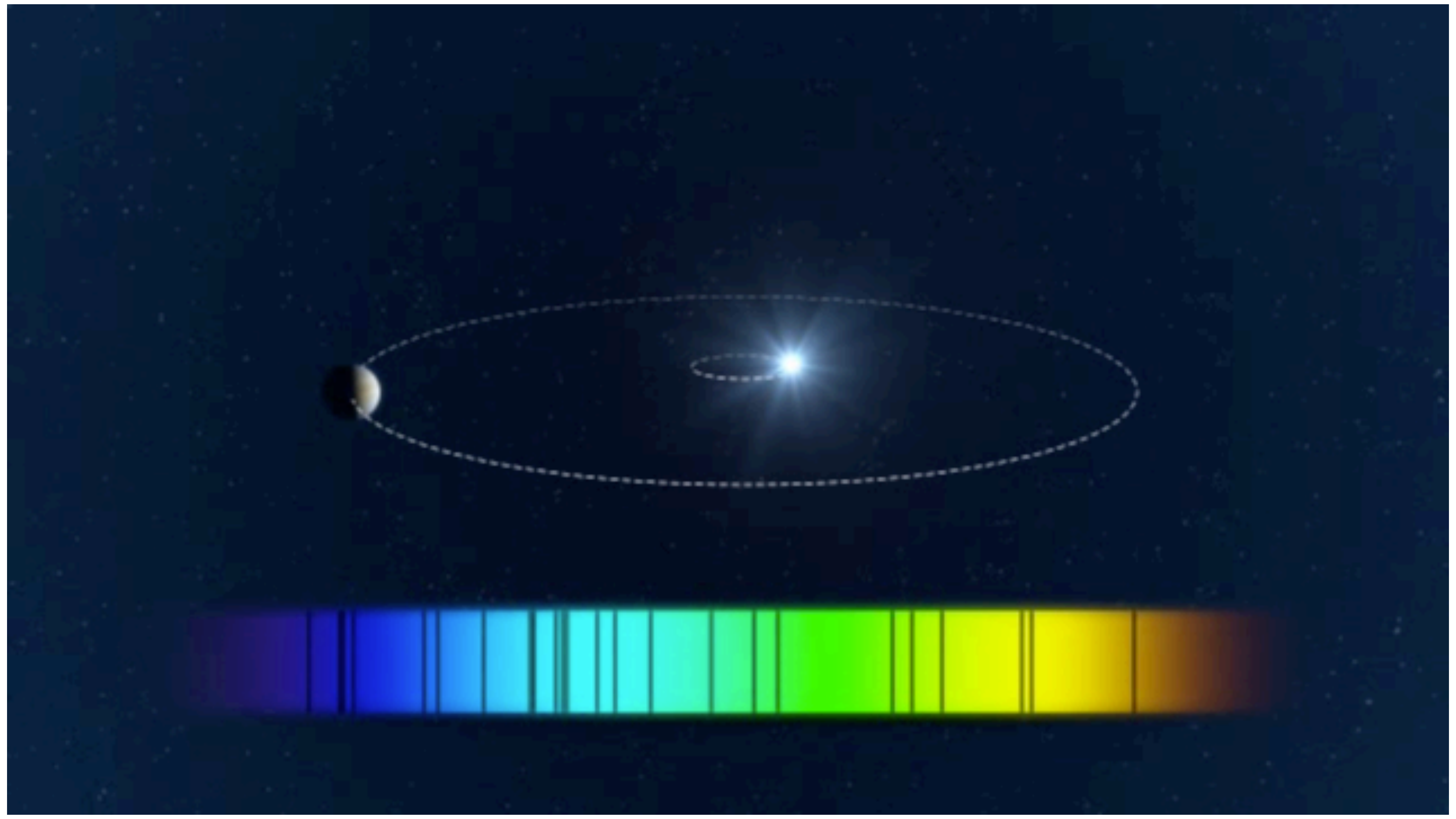
- Directly imaged planets are typically:
  - Massive (i.e. gas-giants)
  - Far from their host stars
  - Young (hence self-luminous)

Majority of planet population are discovered + characterised via indirect methods

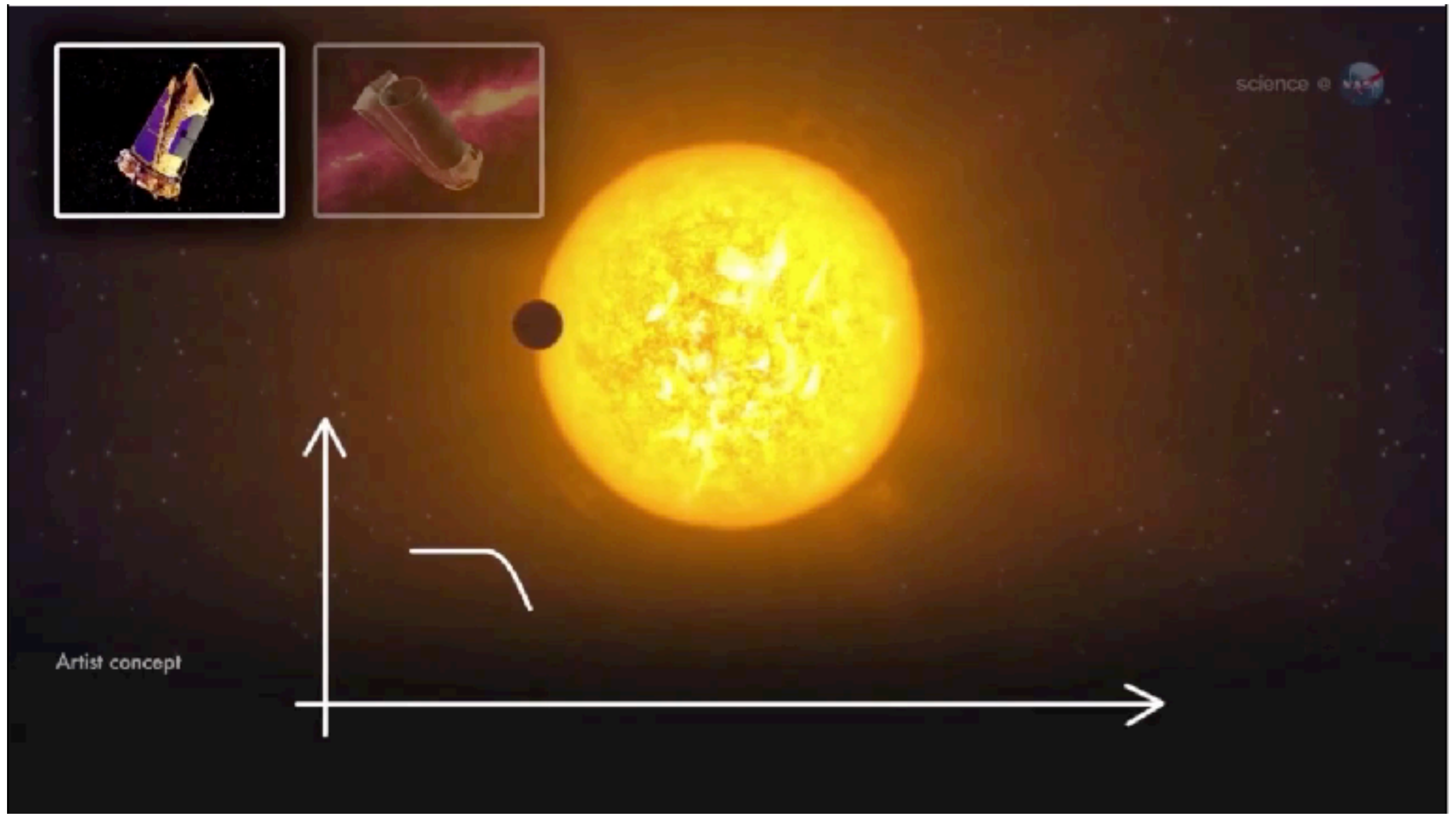
(how long will this remain the case?)

Majority of planets are discovered using indirect techniques

Credit: ESO

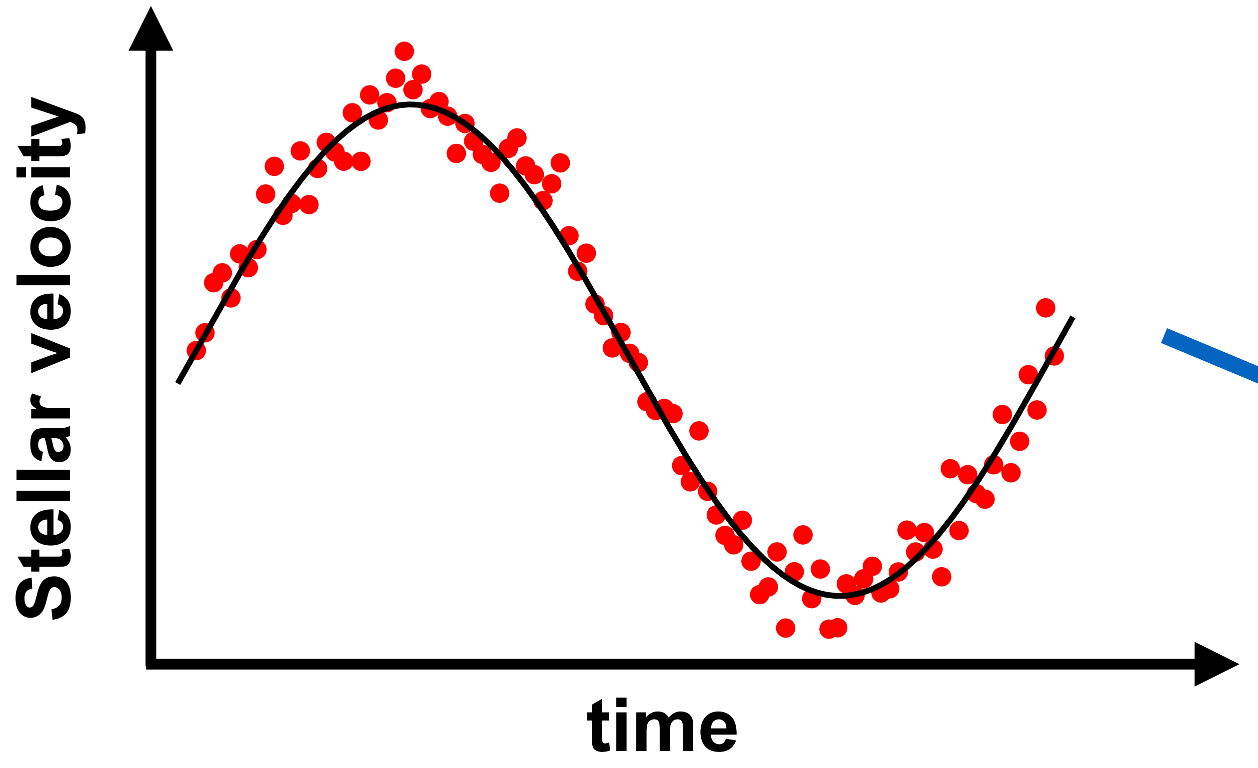


Credit: NASA

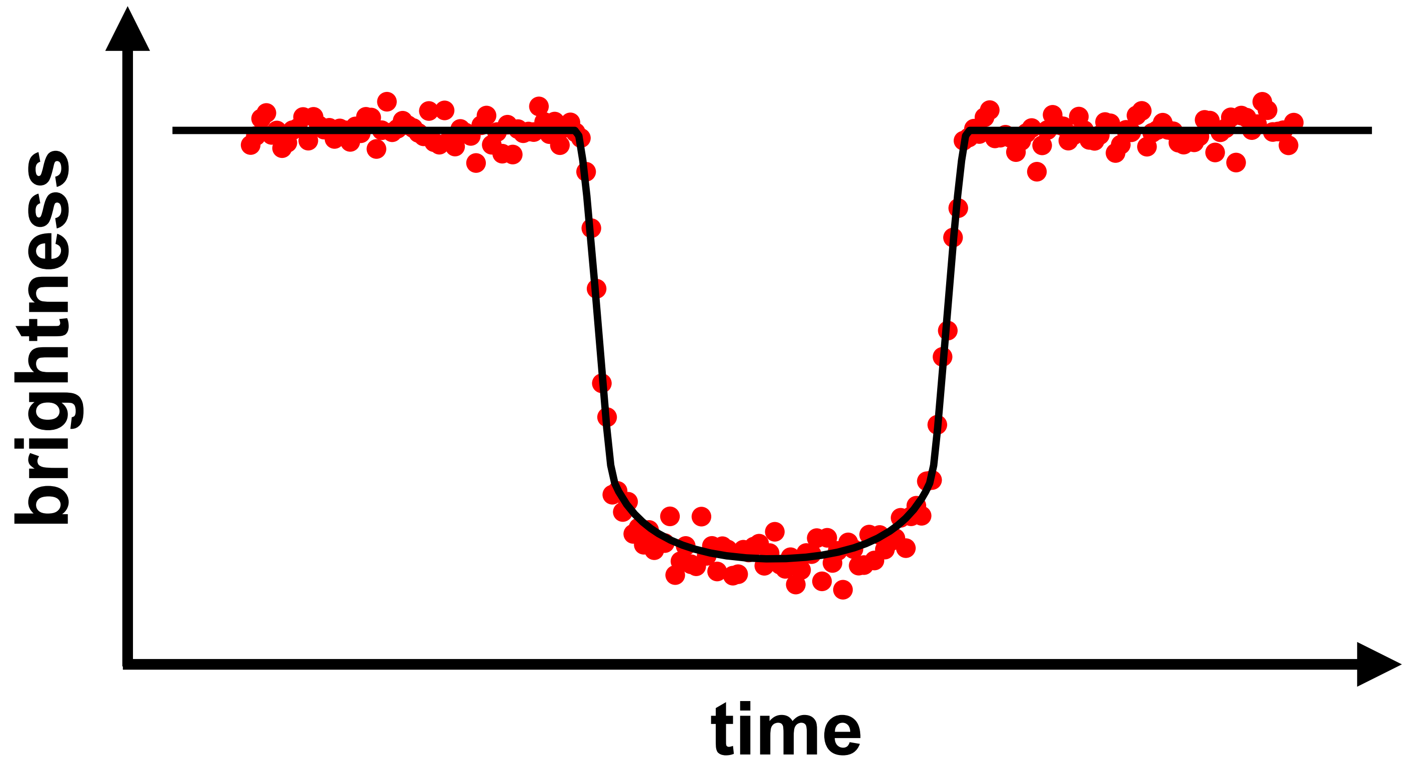


• The Radial Velocity technique measures the planet mass (degenerate with inclination)

• The Transit technique measures the planet radius (+ inclination)



Mass, Radius ➡ Density
+ Bulk composition
+ Orbital parameters



Planetary transits also enable atmospheric characterisation…

- **composition**
- **atmospheric chemistry**
- **scattering properties**
- **temperature structure**
- **line shapes/shifts ➡ dynamics**
- **biomarkers?**

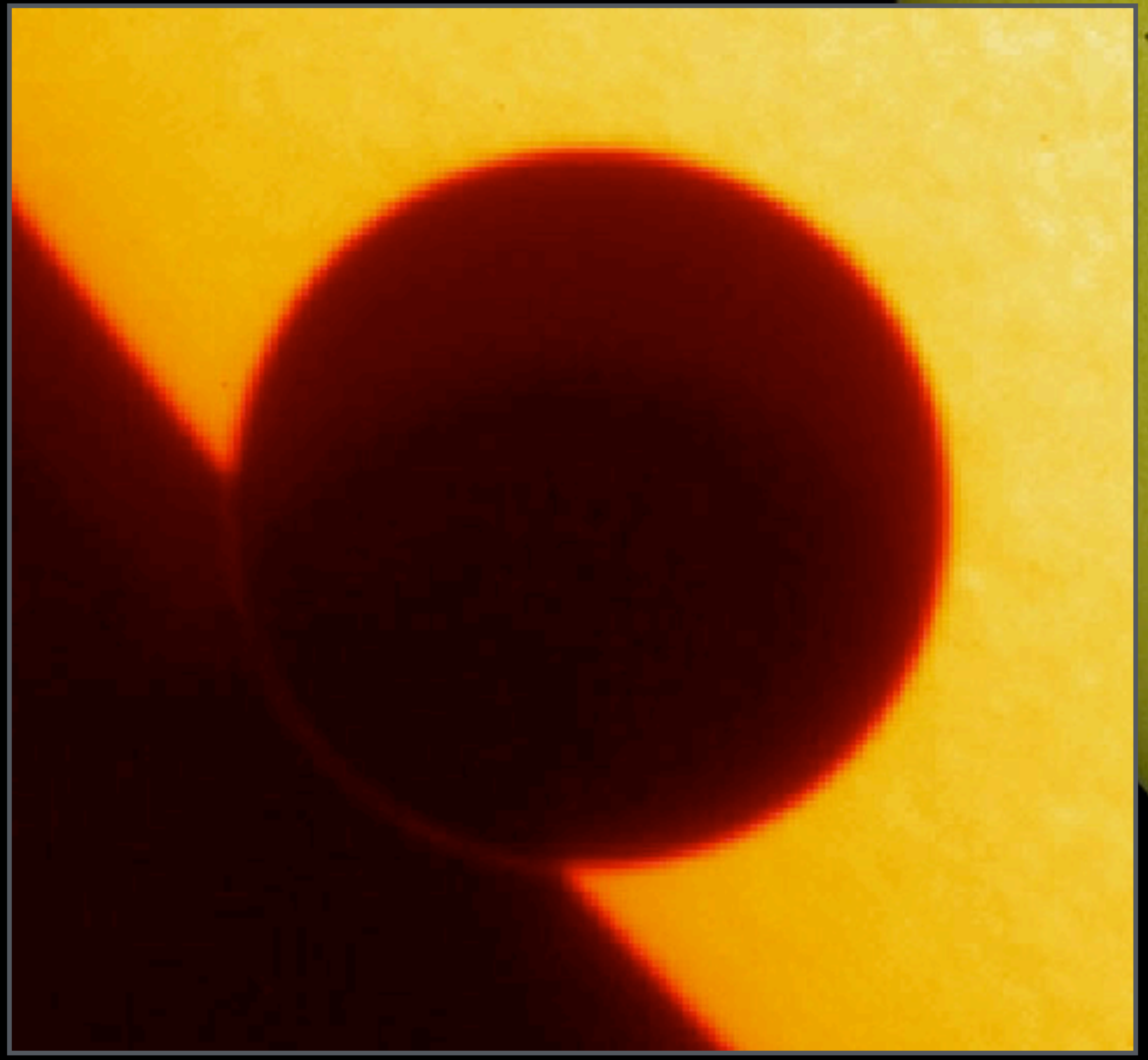


Image credit: NASA/LMSAL

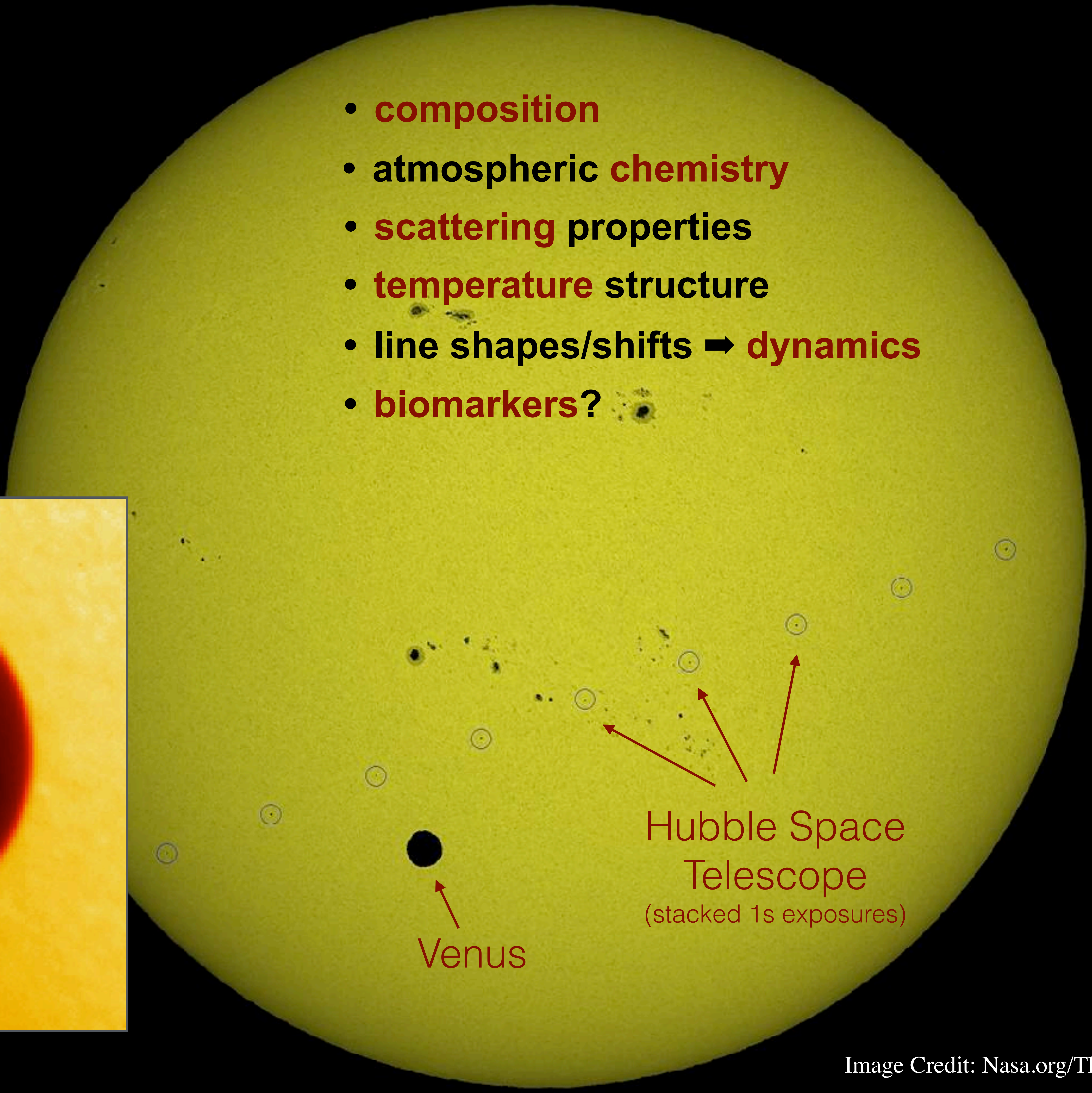
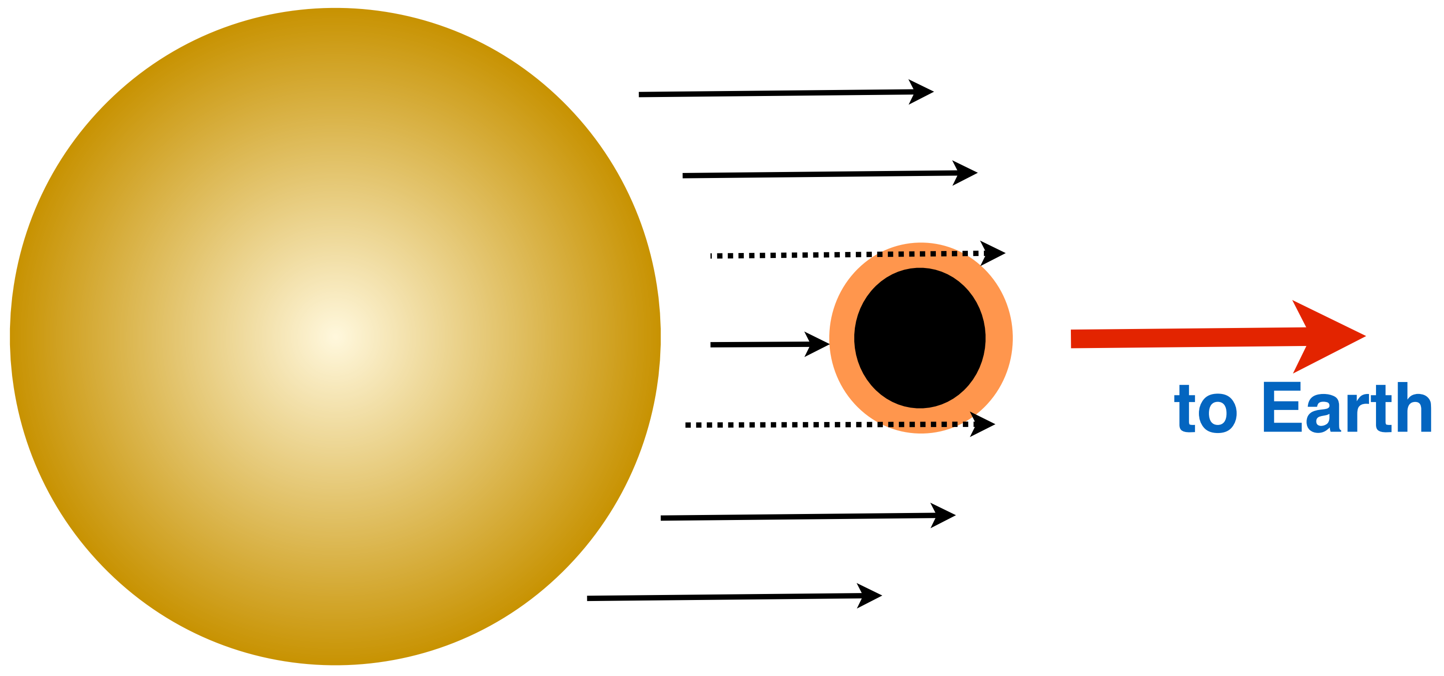
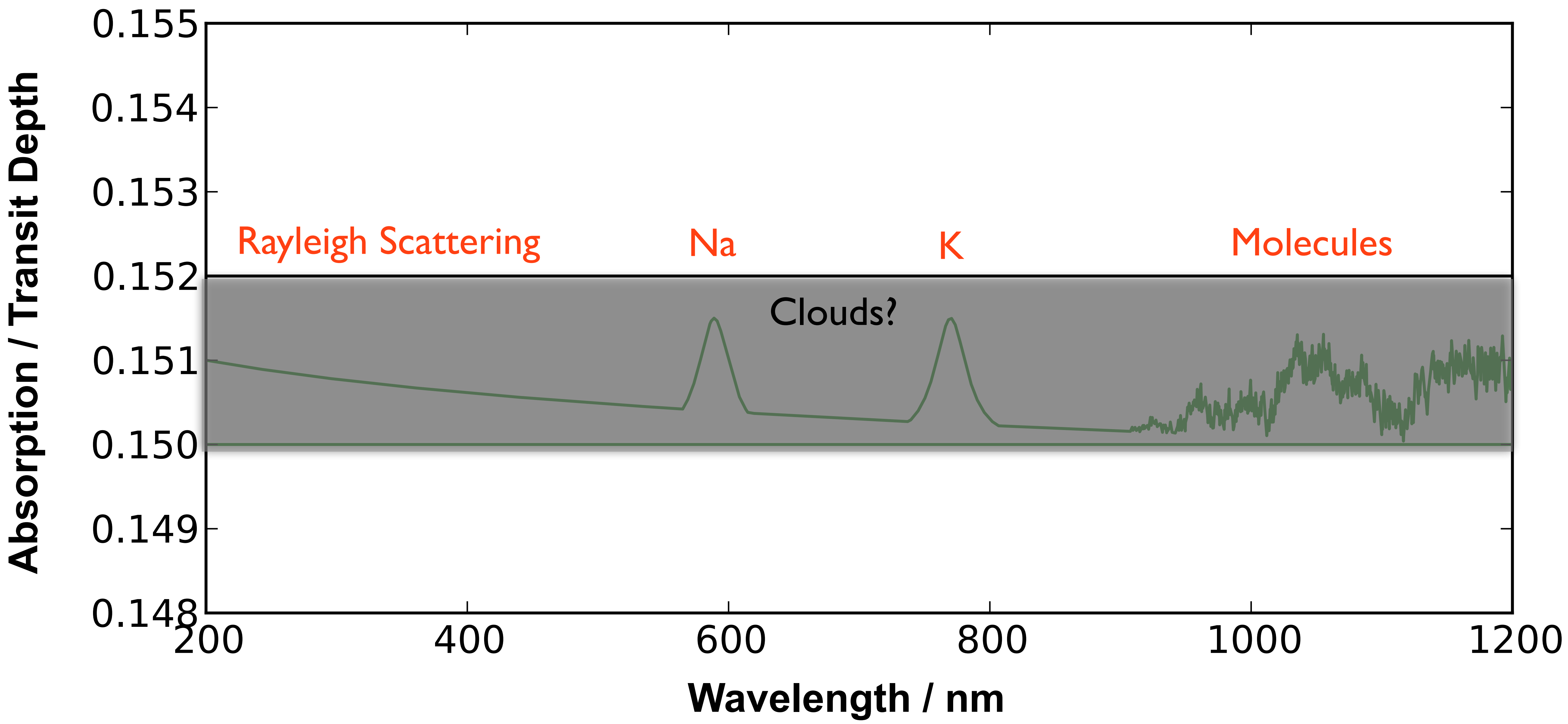
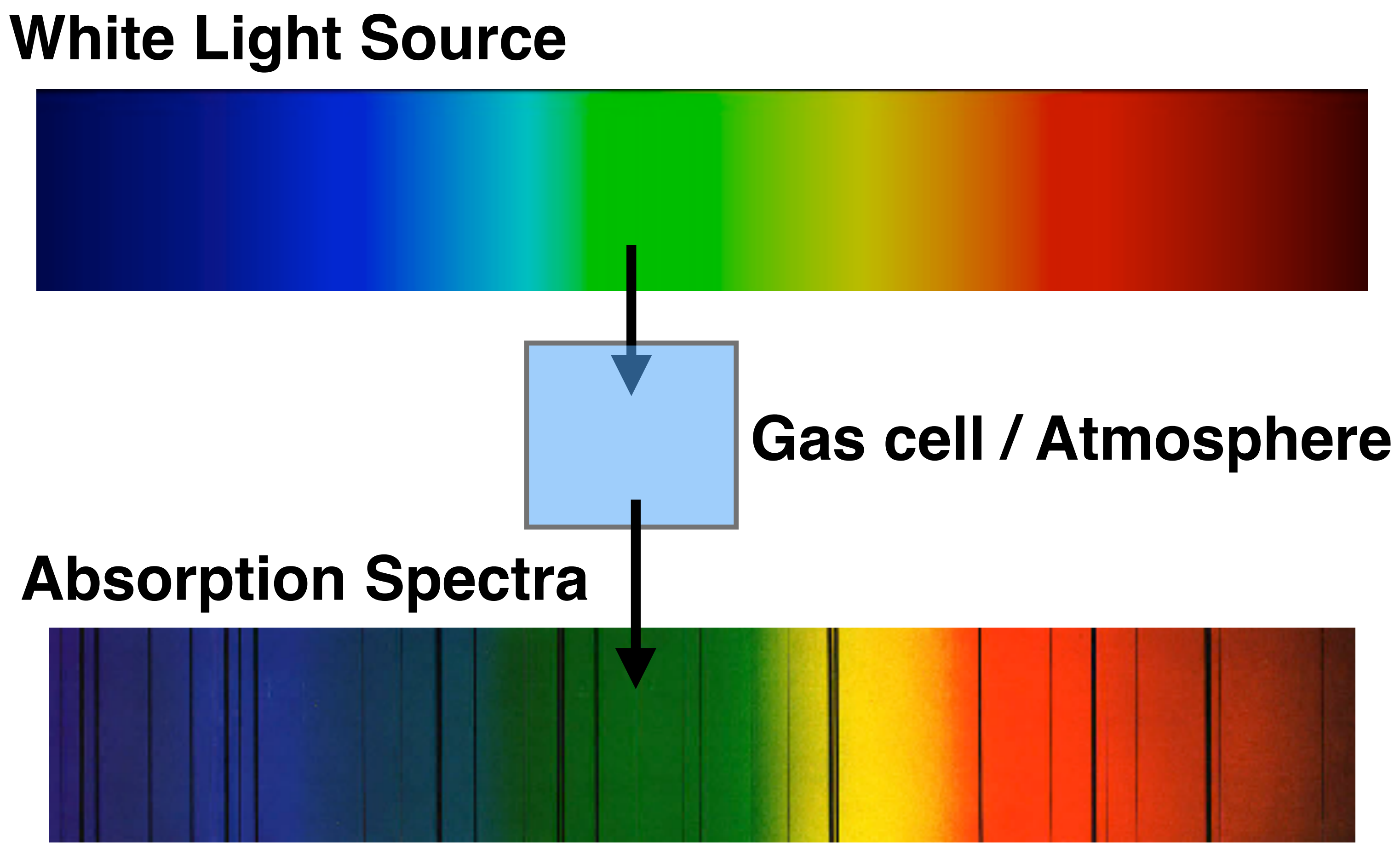


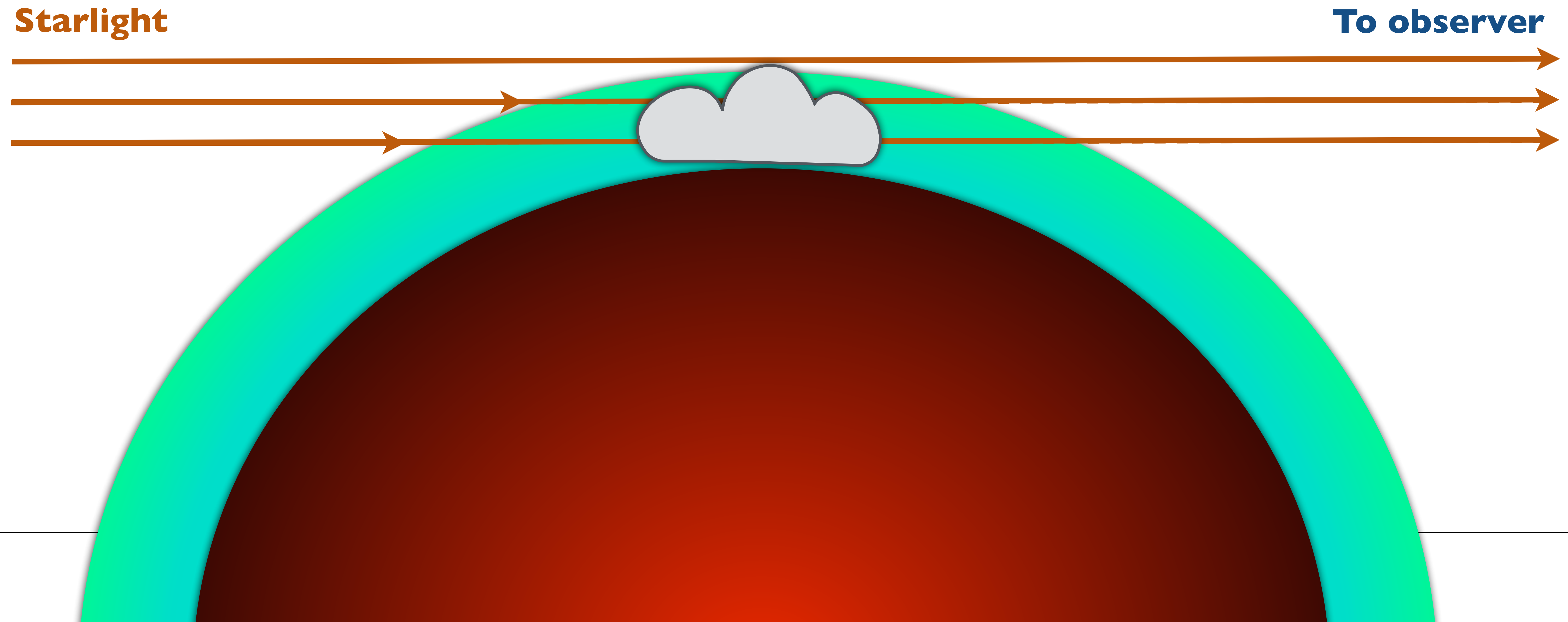
Image Credit: Nasa.org/Thierry Lagault

Transmission spectroscopy uses absorption of starlight through a planet's atmosphere

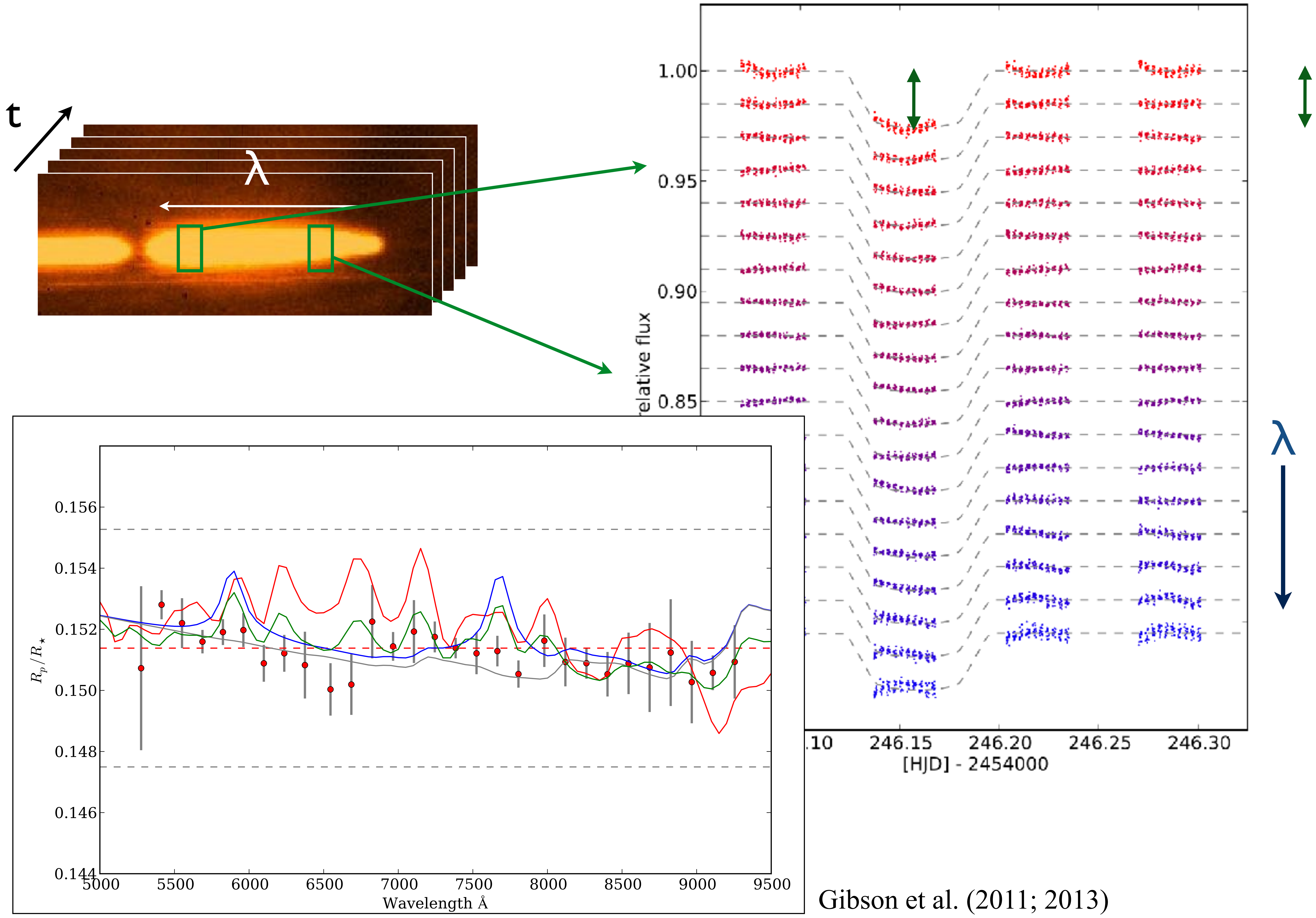








Transmission spectroscopy in practice



Gibson et al. (2011; 2013)

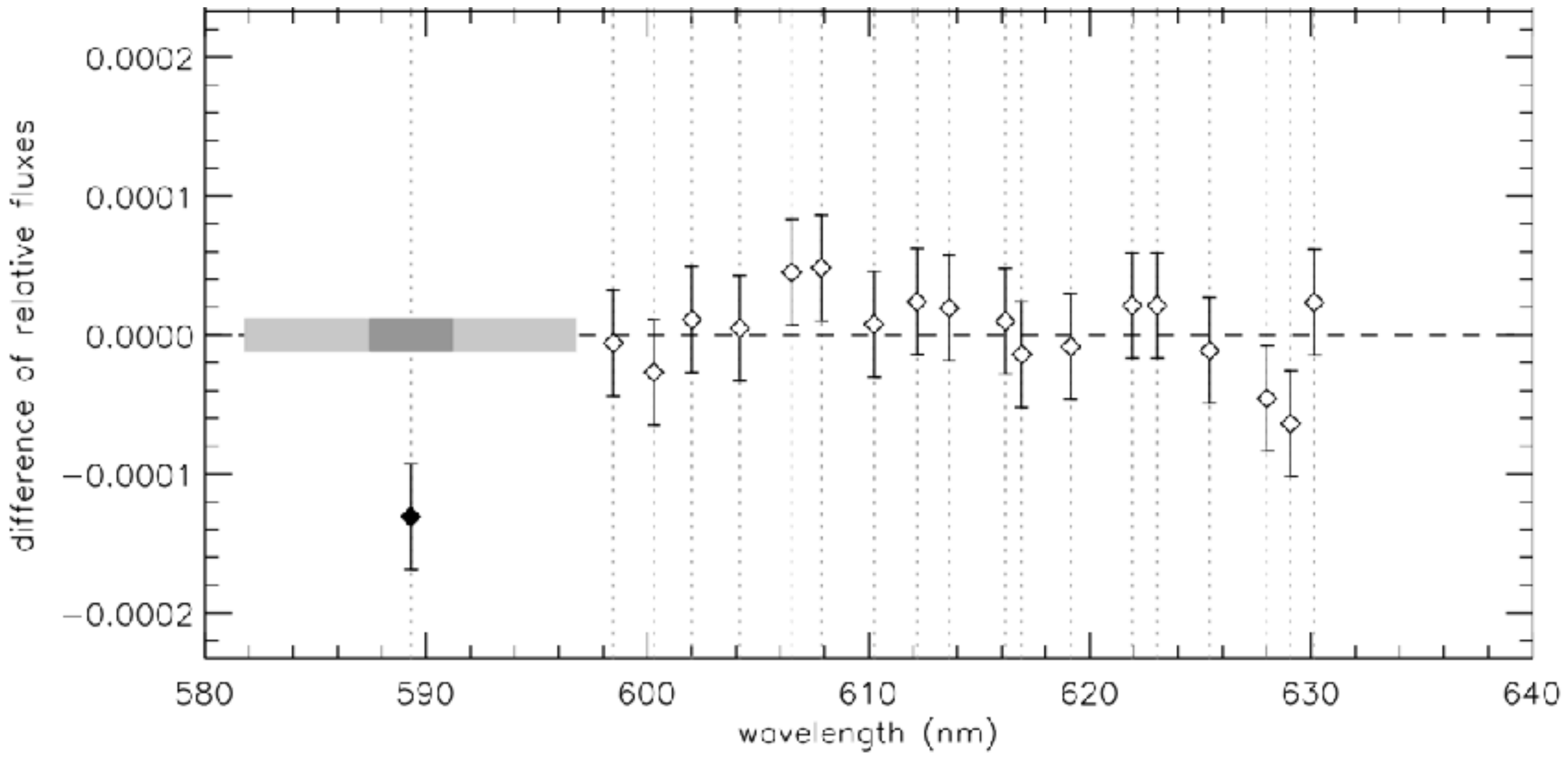
Transit Depth ~1%
(for Sun-Jupiter)

Variations due to atmosphere
~1x10^{-4} (for hot-Jupiter)

Instrumental systematics + stellar activity remain a huge unsolved problem

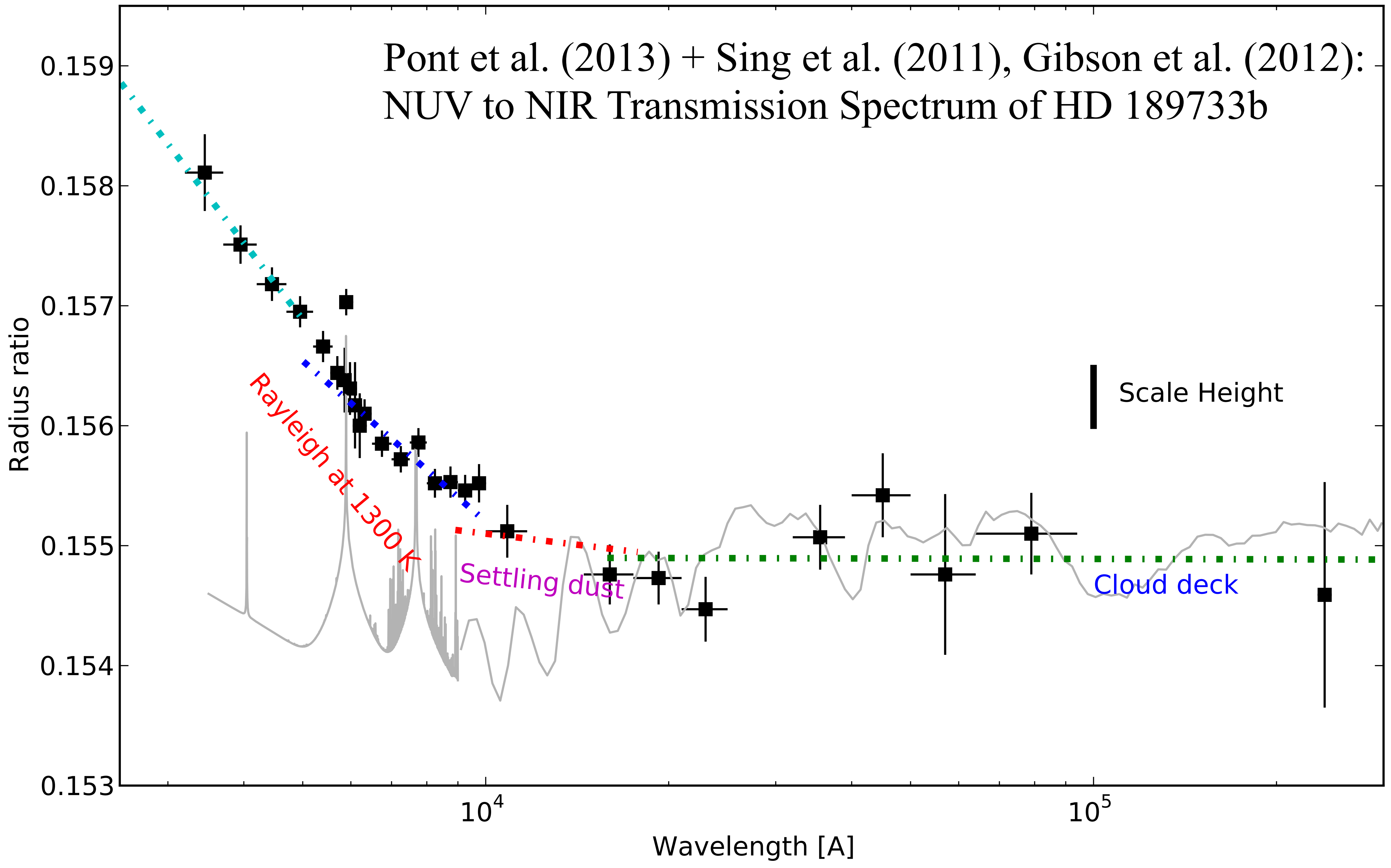
Transmission spectroscopy provided the first glimpse at exoplanet atmospheres

Charbonneau et al. (2002): Detection of excess Na absorption in HD 209458b

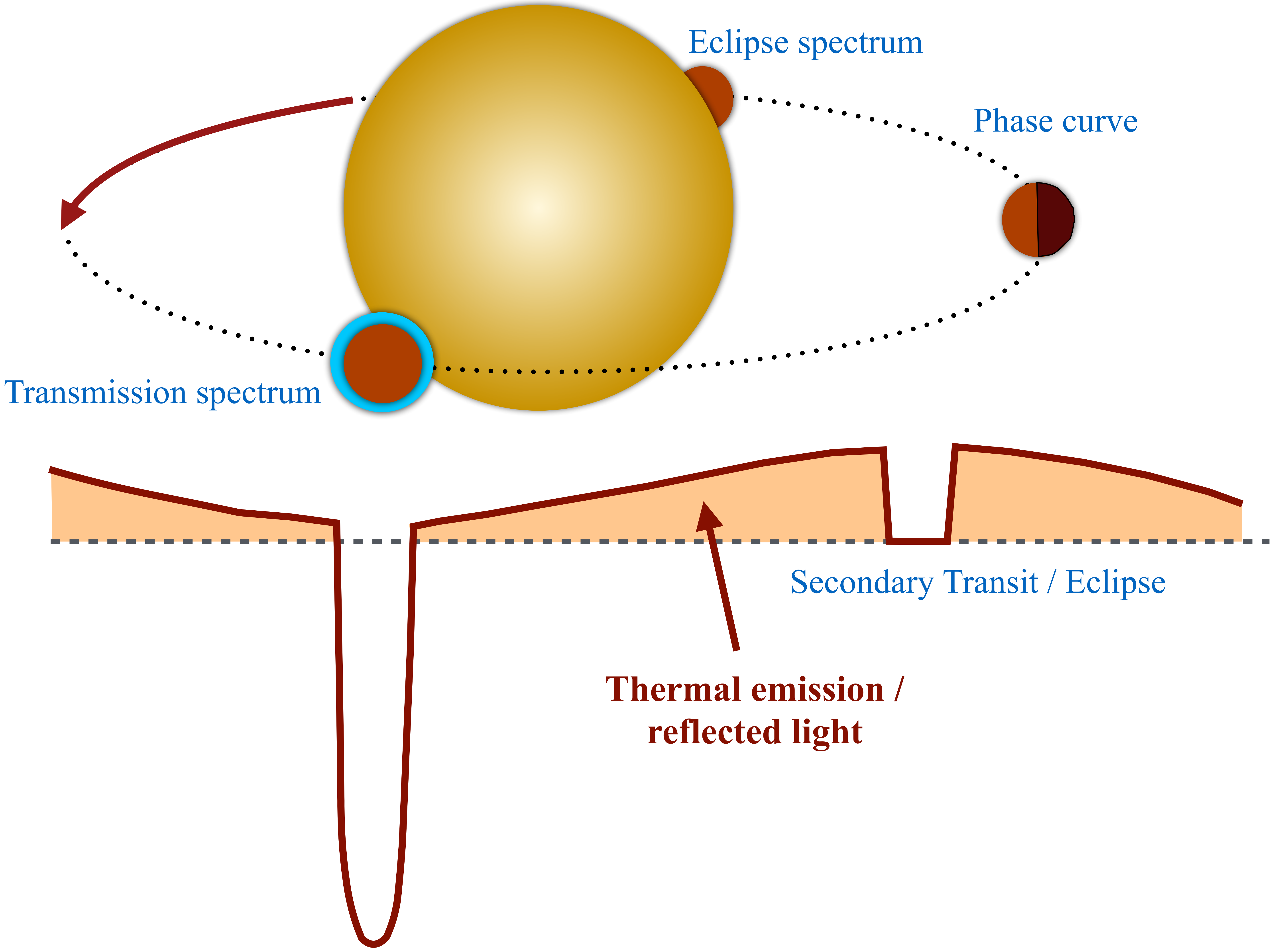


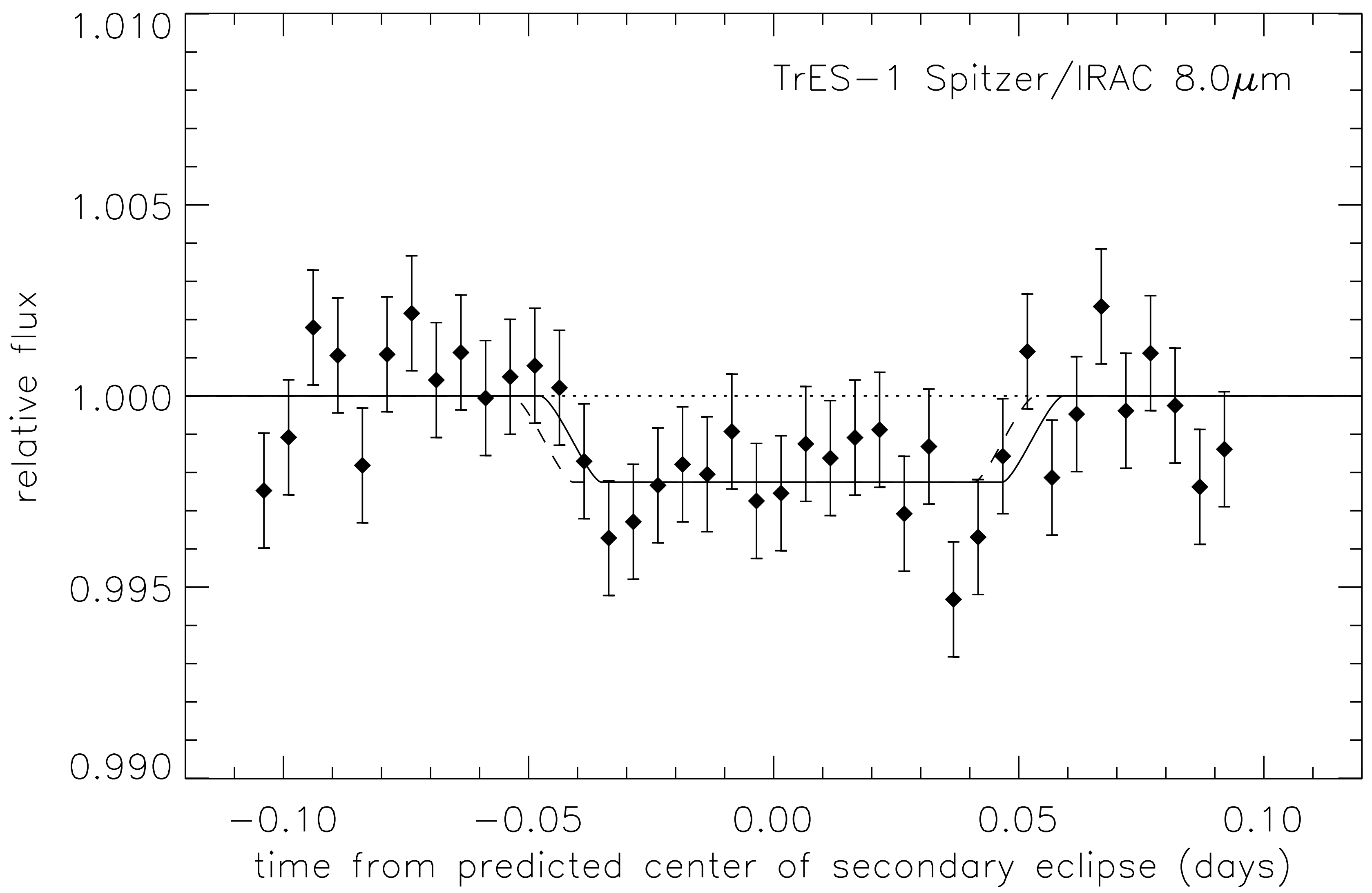
- Excess Na absorption in HD 209458b first sign of an exoplanet atmosphere in 2002

- Many years after before the first reliable, broadband spectra were observed

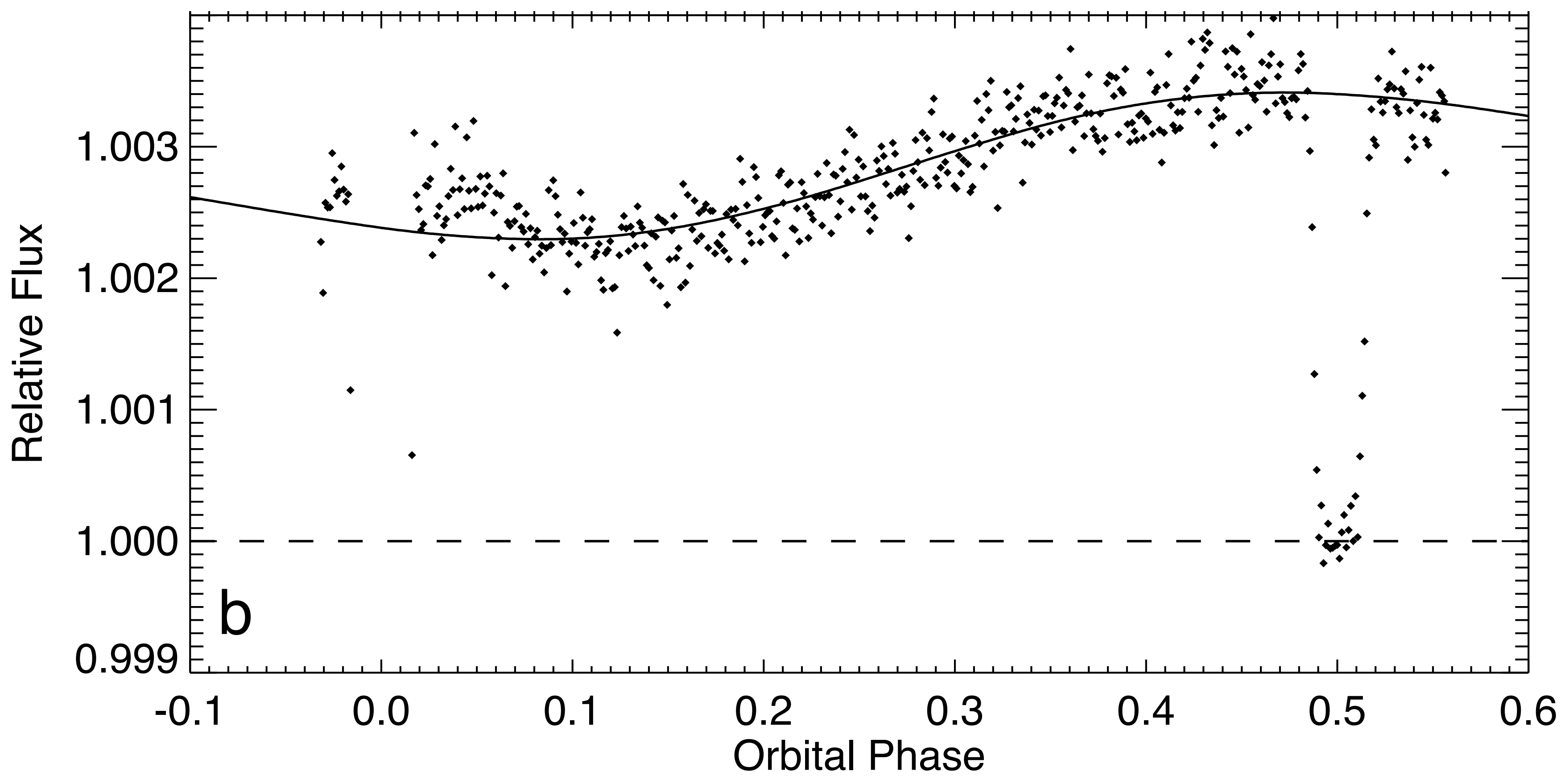


Planets can also be observed using emission spectra



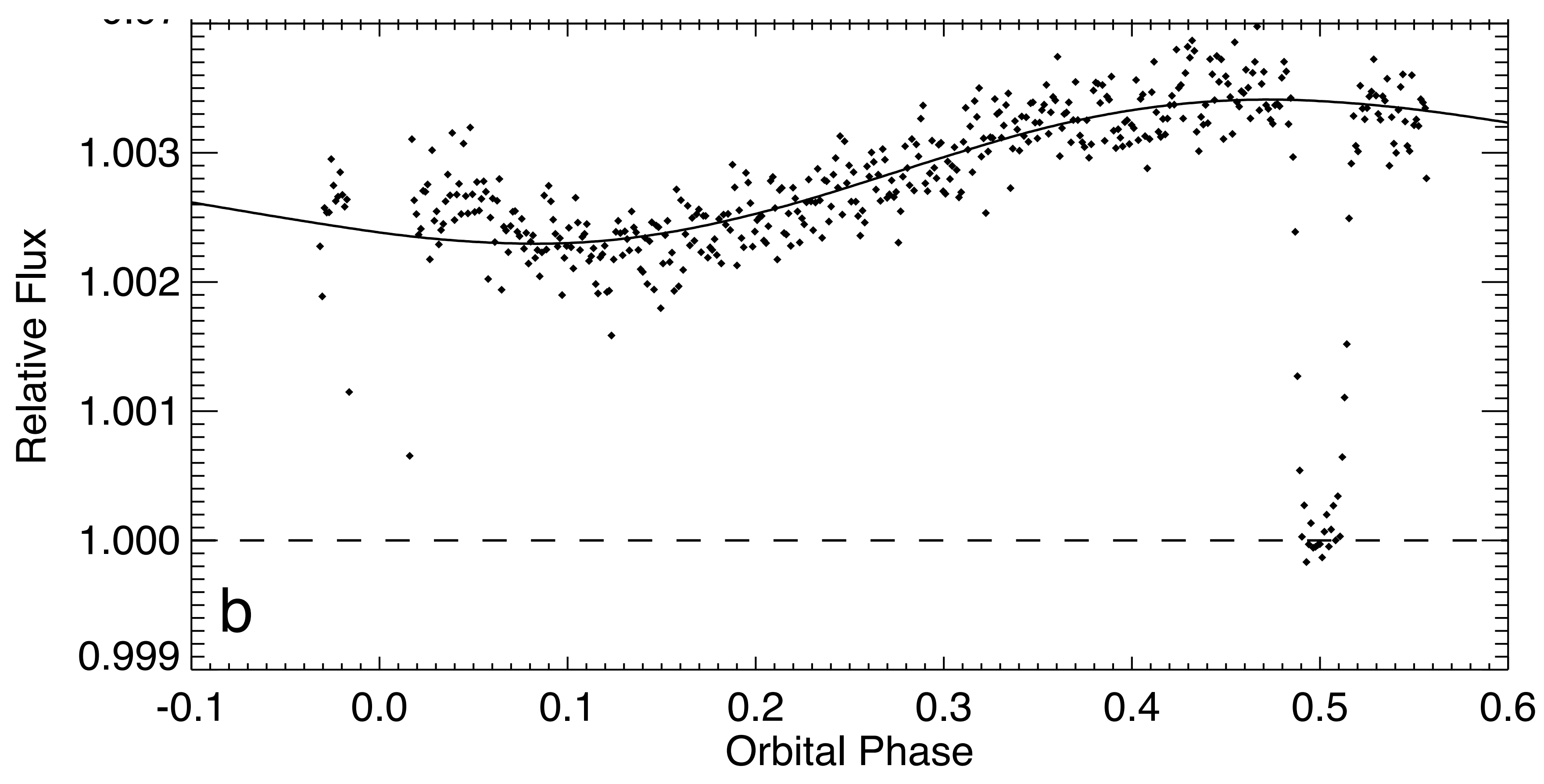


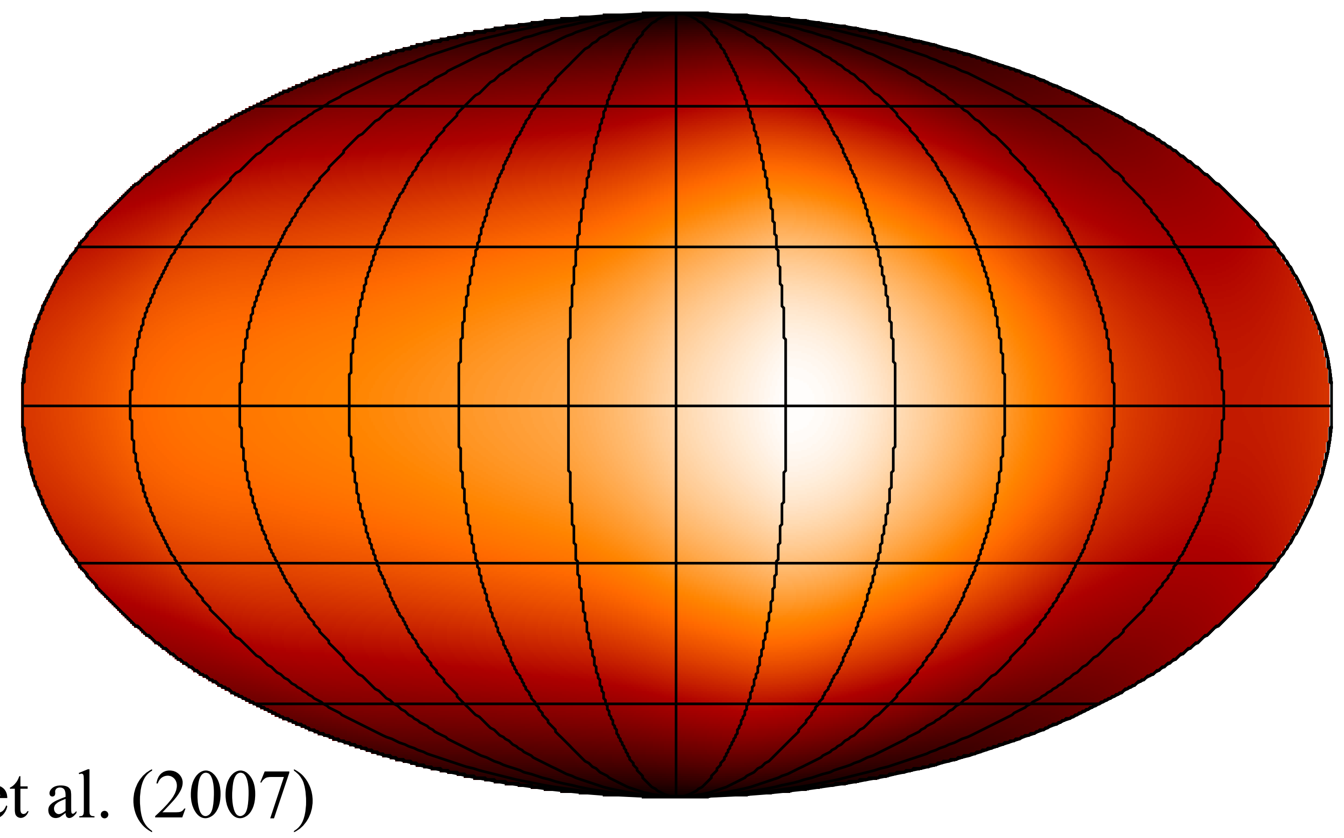
Charbonneau et al (2005); Deming et al. (2005)



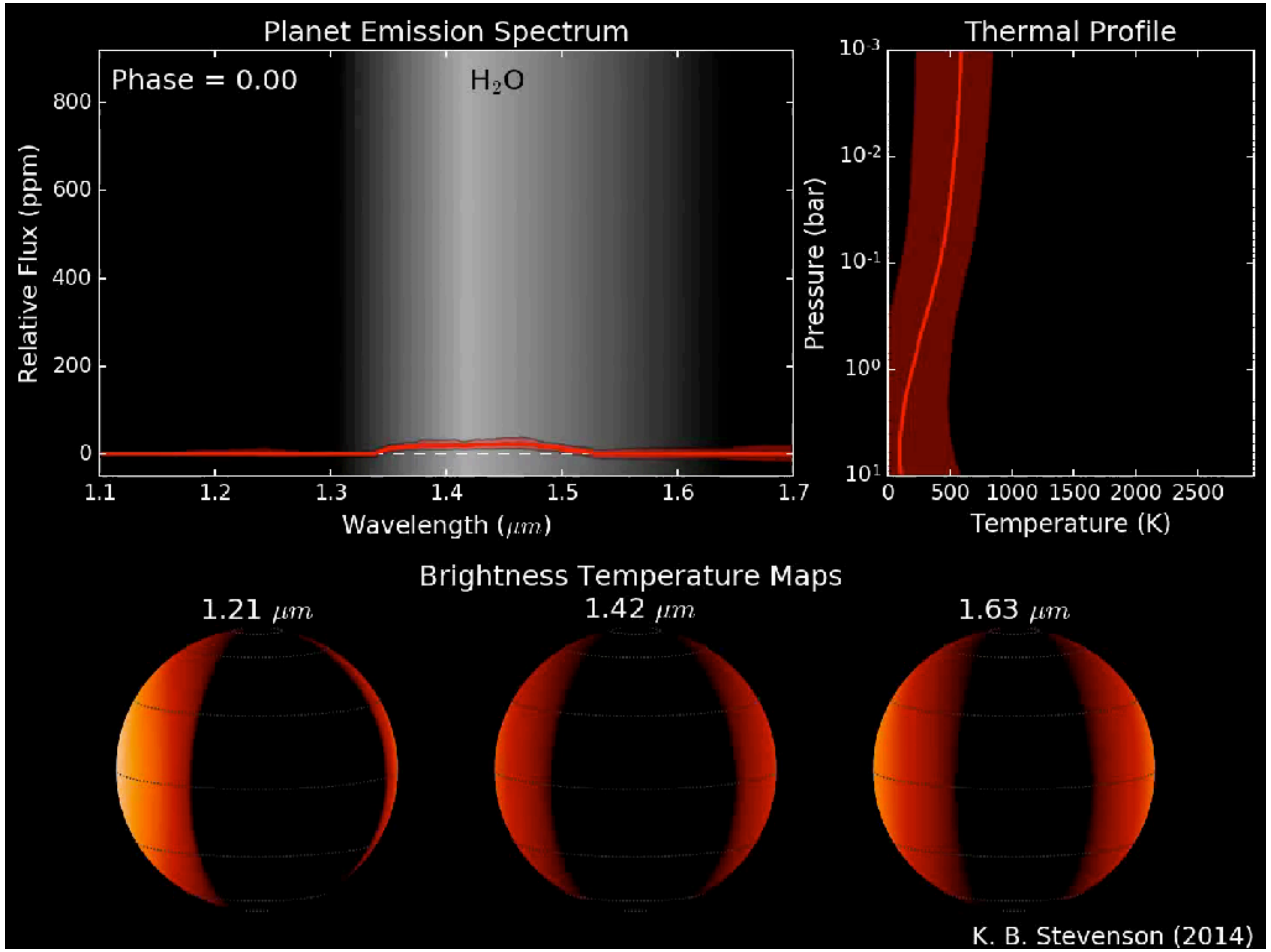
Knutson et al. (2007); see also Harrington et al. (2006)

Phase curves map the surfaces of planets





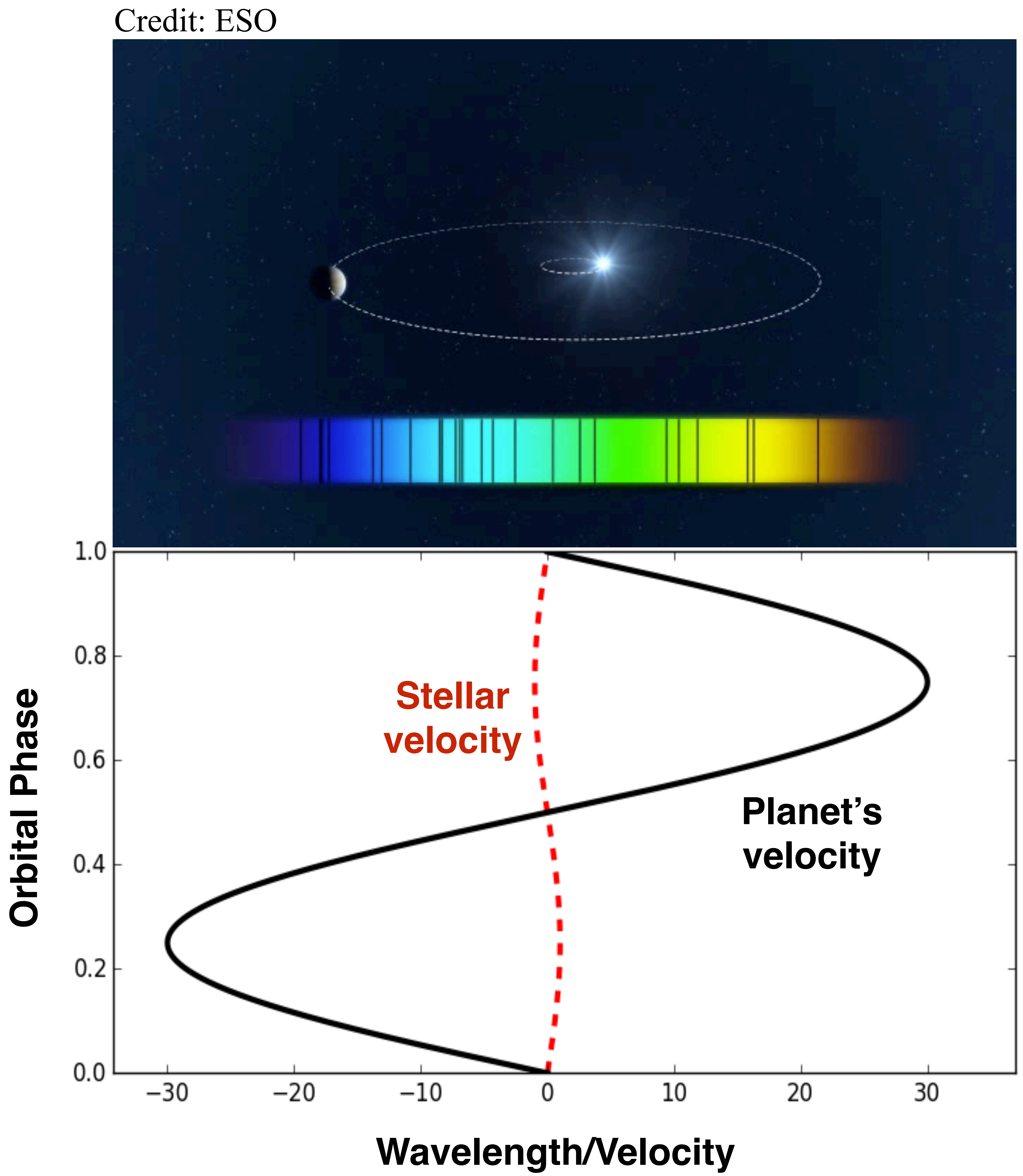
Knutson et al. (2007)

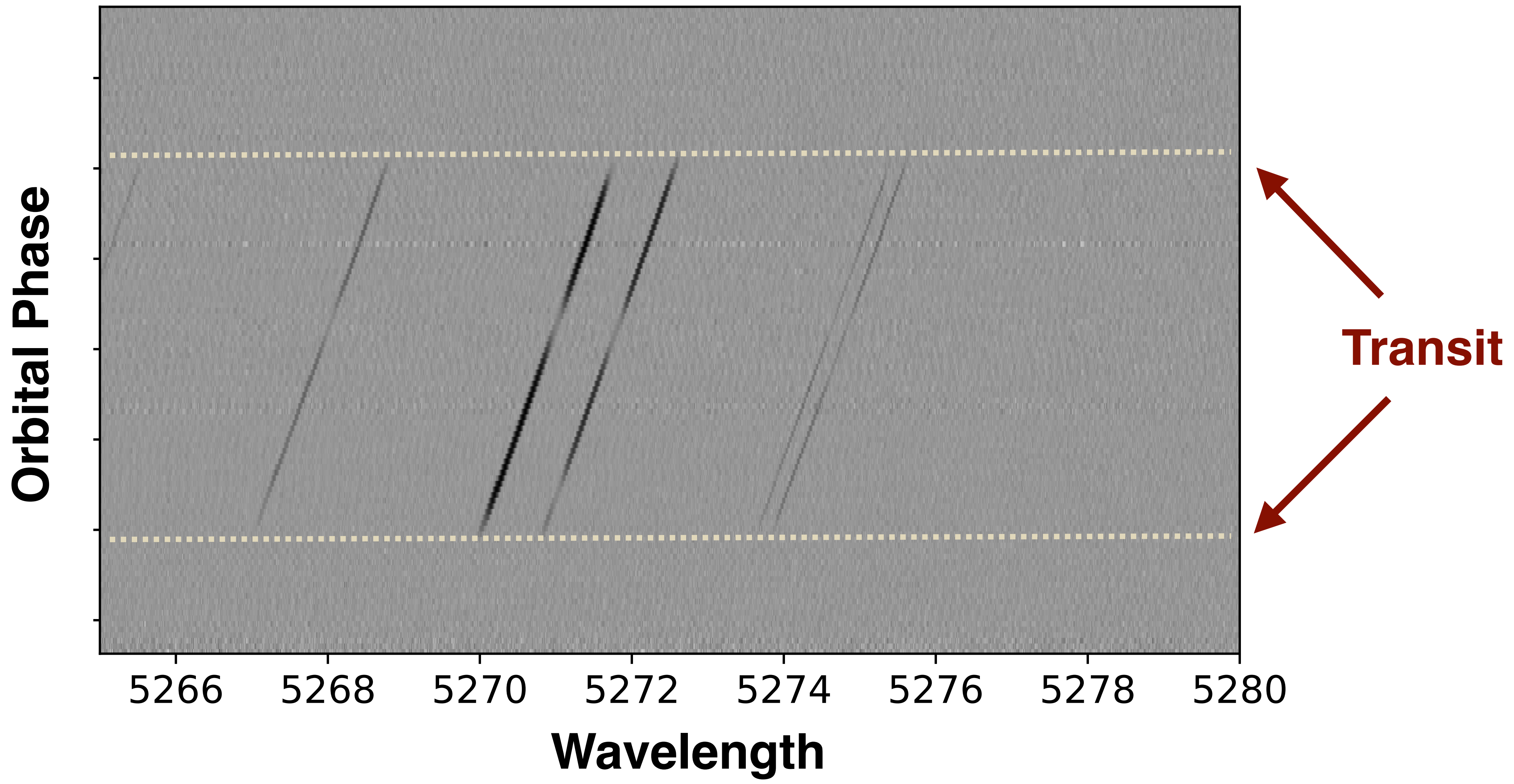


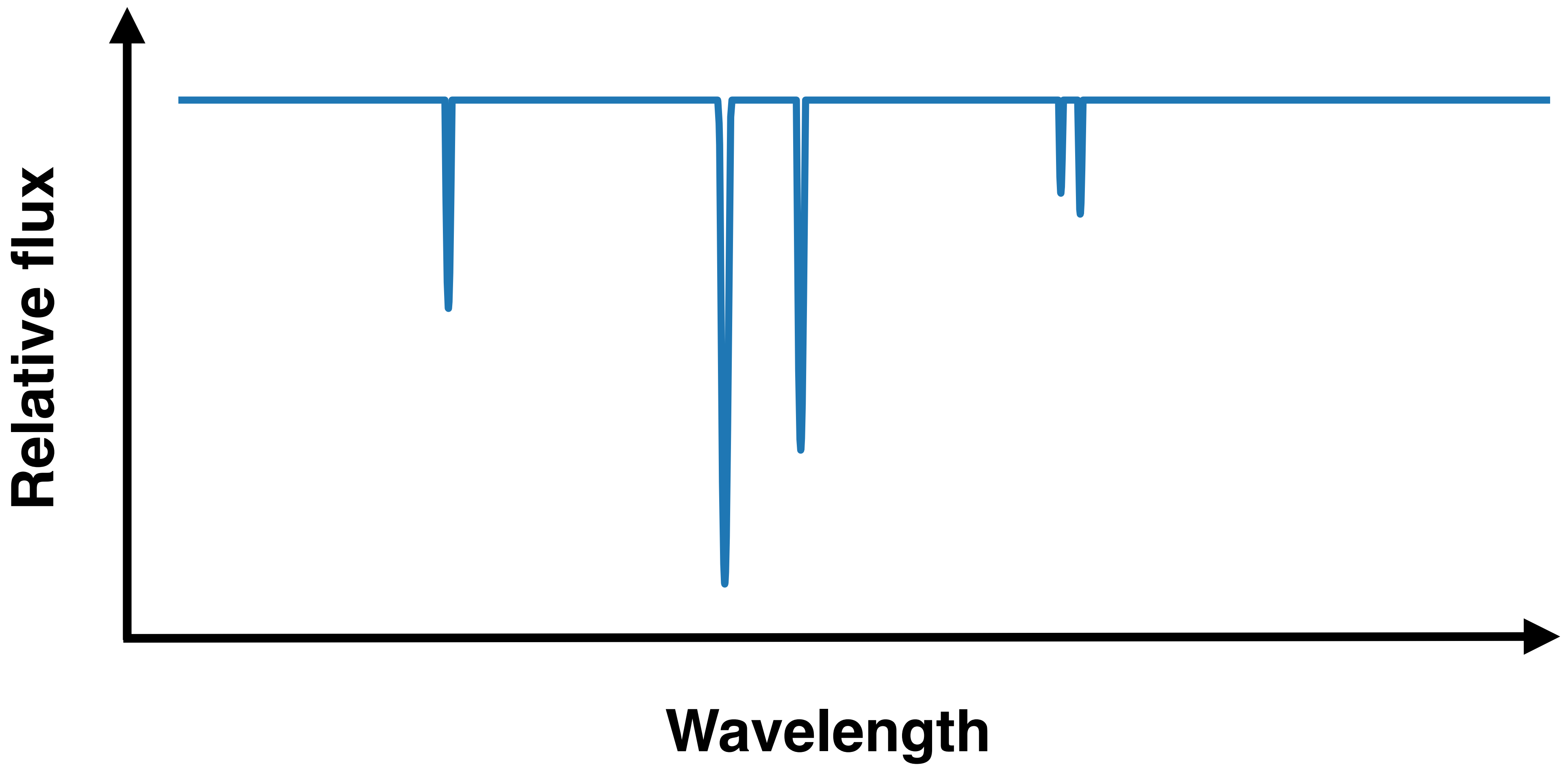
Stevenson et al. (2014)

- The phase curve allows us to map the locations of “hot spots” on planets’ “surfaces”

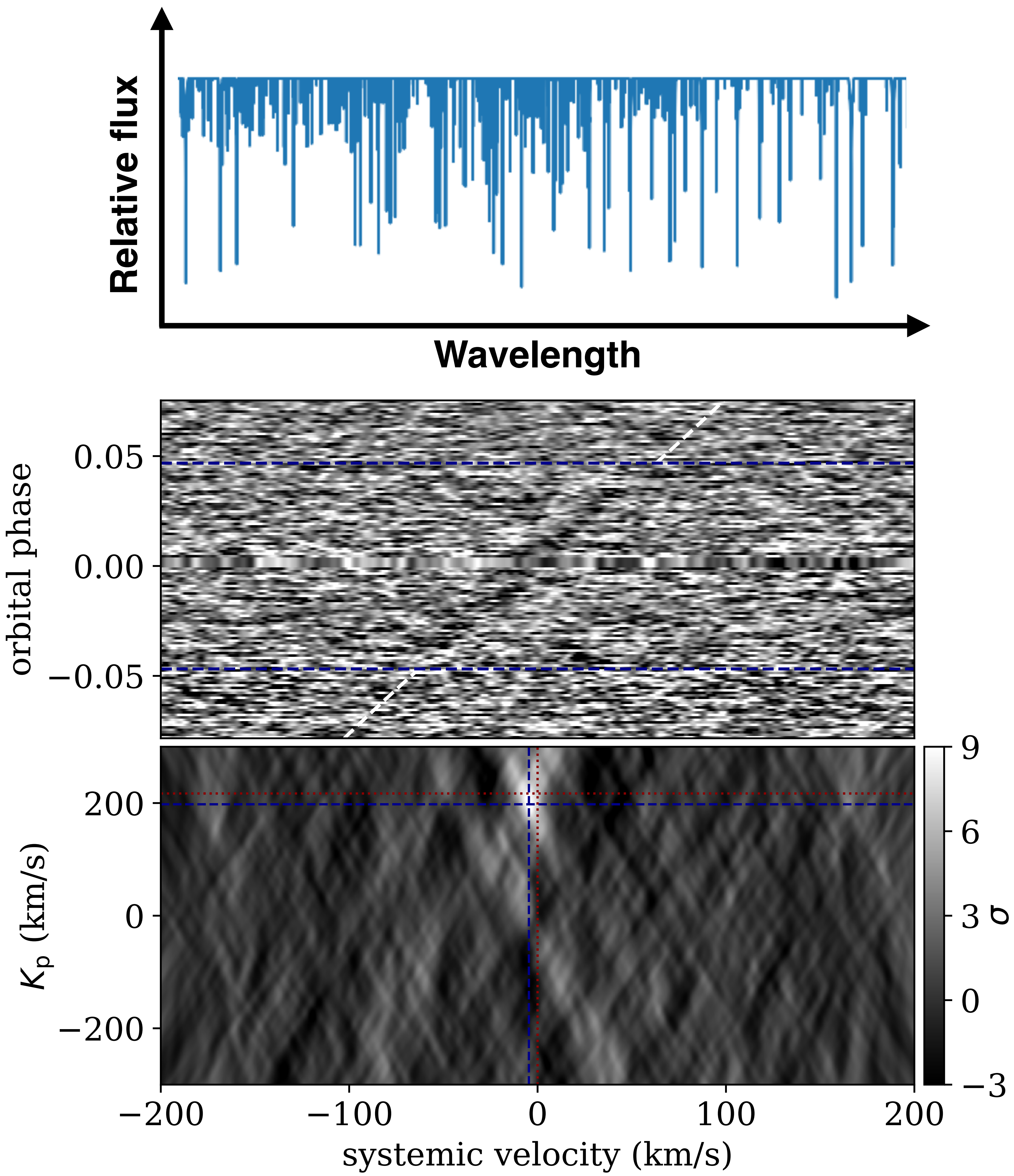
High-resolution Doppler-resolved Spectroscopy



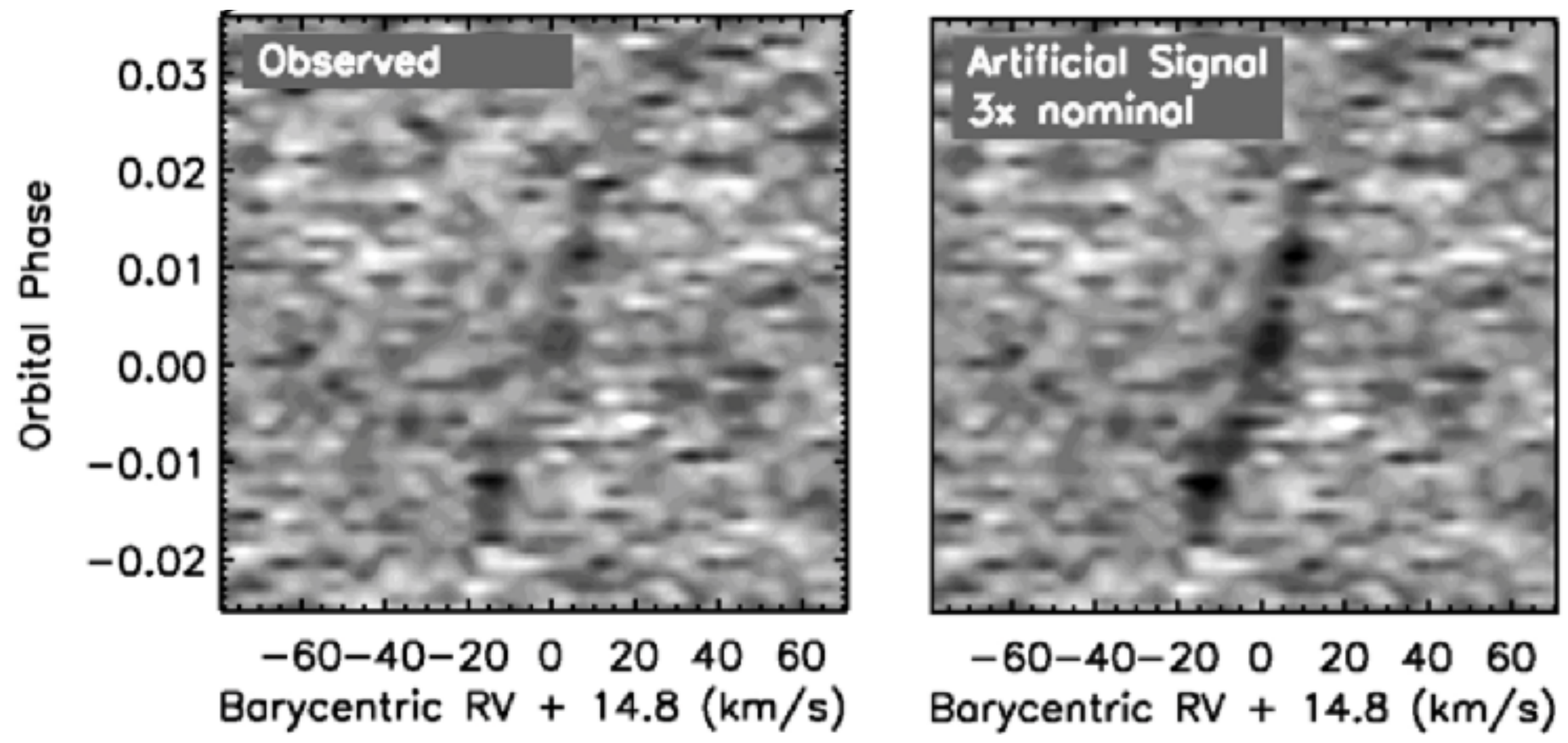




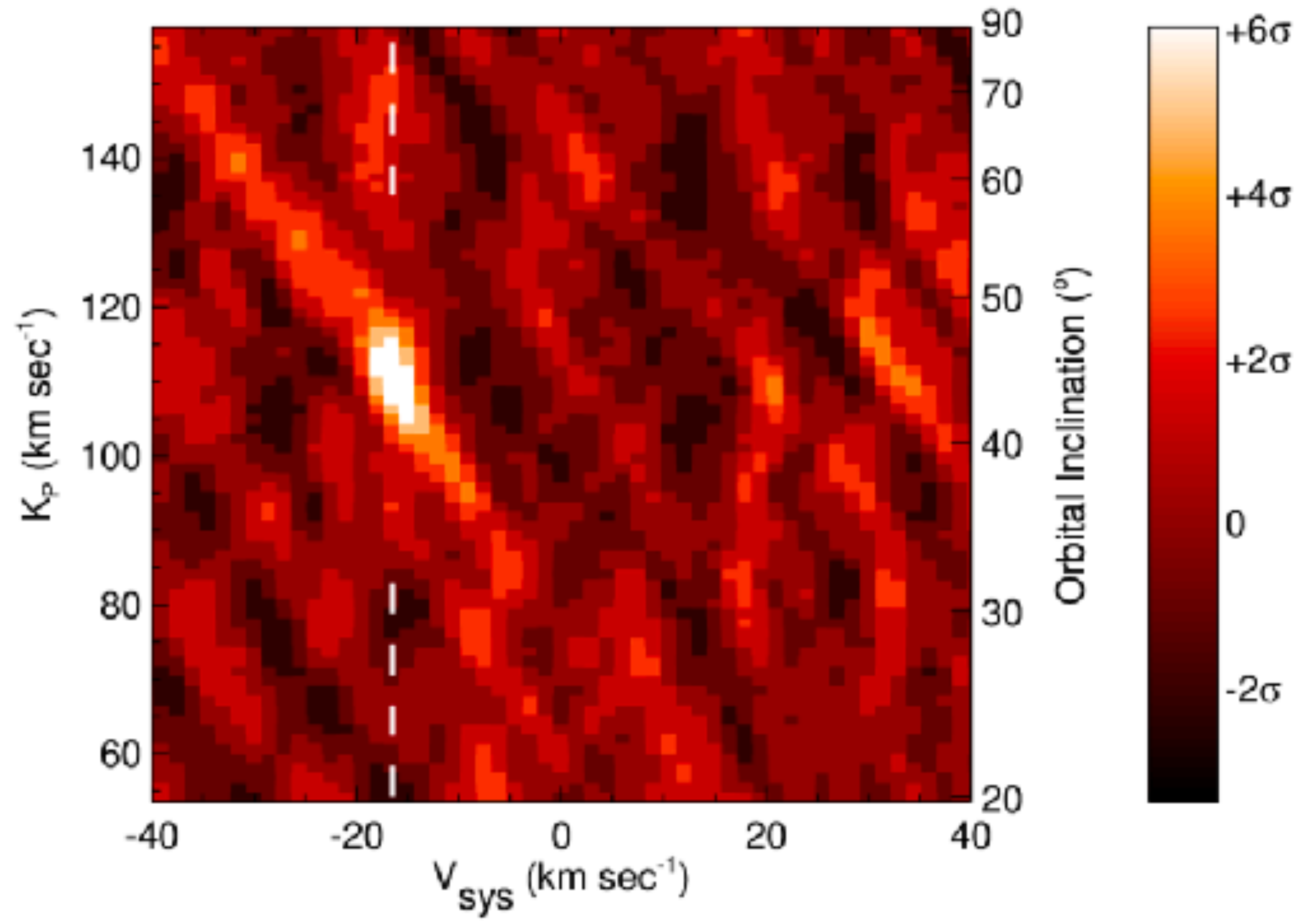
High-resolution Doppler-resolved Spectroscopy



Gibson et al. (2020)

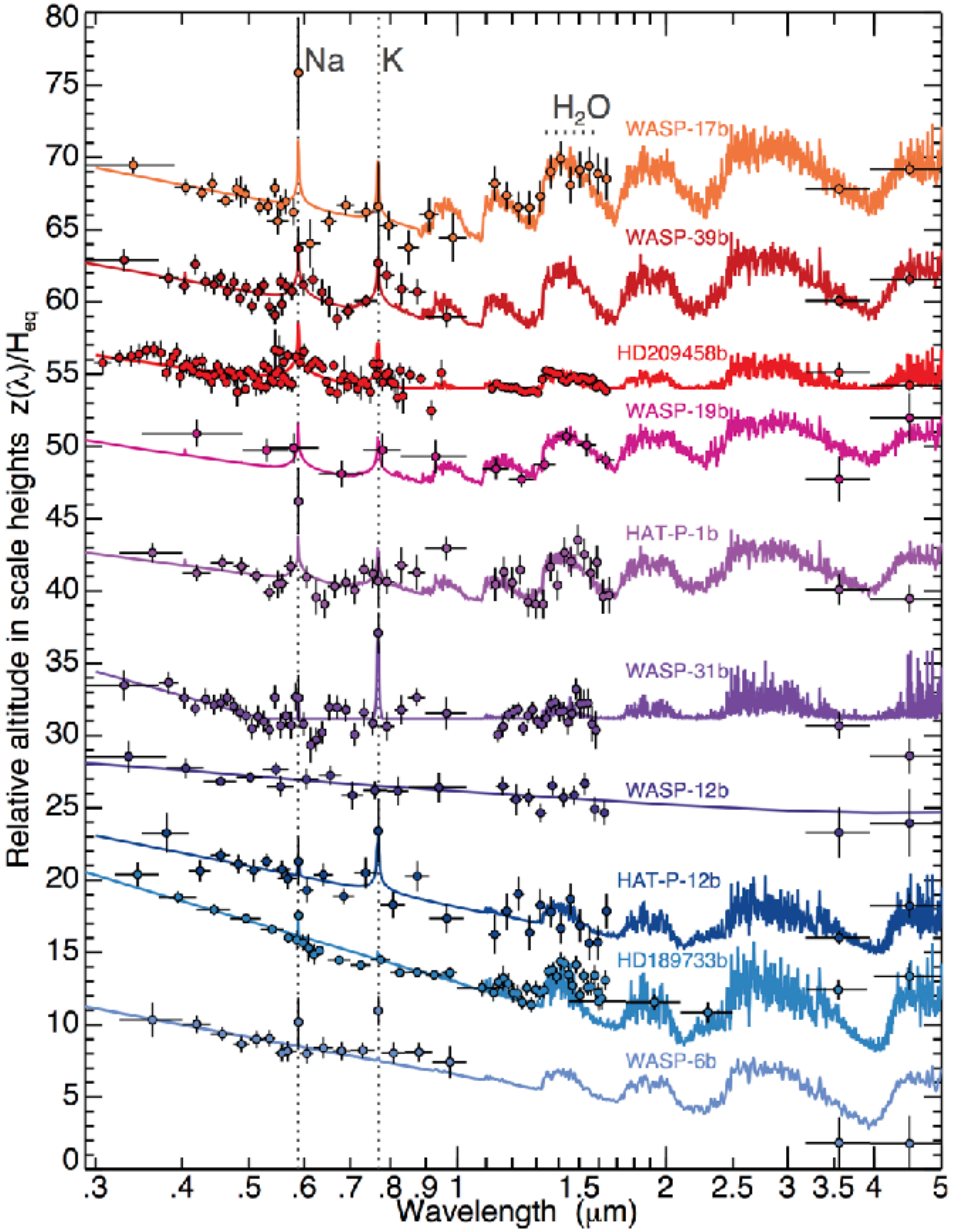


- Snellen et al. (2010): Detection of CO in HD 189733b



- Brogi et al. (2012): Detection of CO in τ Boo b
  - a *non-transiting* planet

We are finally entering the era of comparative studies…



Sing et al. (2015)

Transmission Spectroscopy:

Na, K, Fe, Li , Mg, Mn, O, C, Ca, H, He, Sc, Si, V, Ti…
H_2O, CO, HCN, TiO, AlO, VO
+ ions (of Fe, Mg, Ca, Ti,…)

Emission Spectroscopy:

H_2O, CO, VO, TiO, HCN

Direct Imaging:

H_2O, CH_4, NH_3, CO

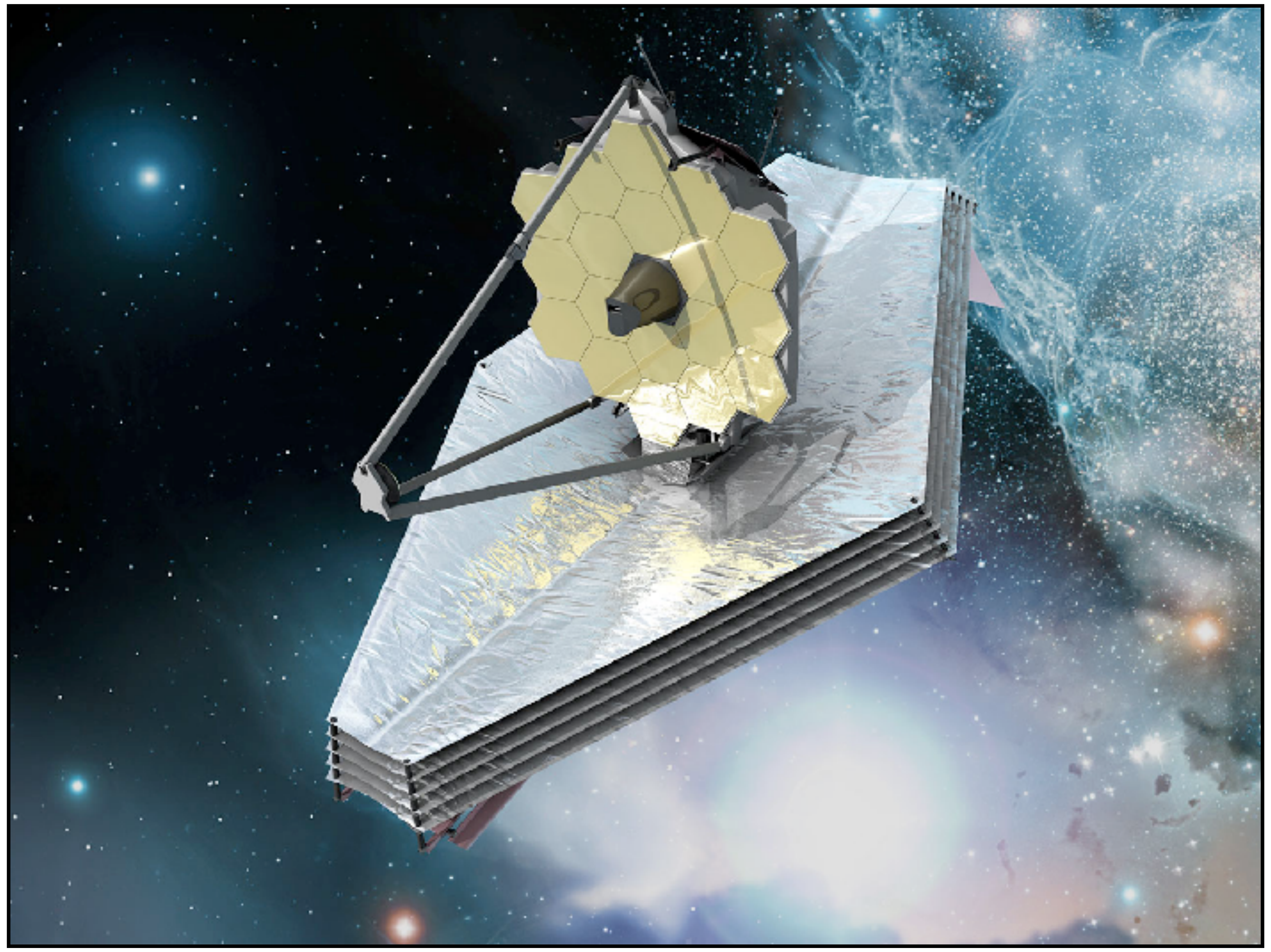
(collected from Madhusudhan 2019 review)

Plus:

- *Abundance measurements*
- *Atmospheric escape*
- *'Surface' mapping*
- *Detection of winds, planet rotation*
- *Lower mass planets*

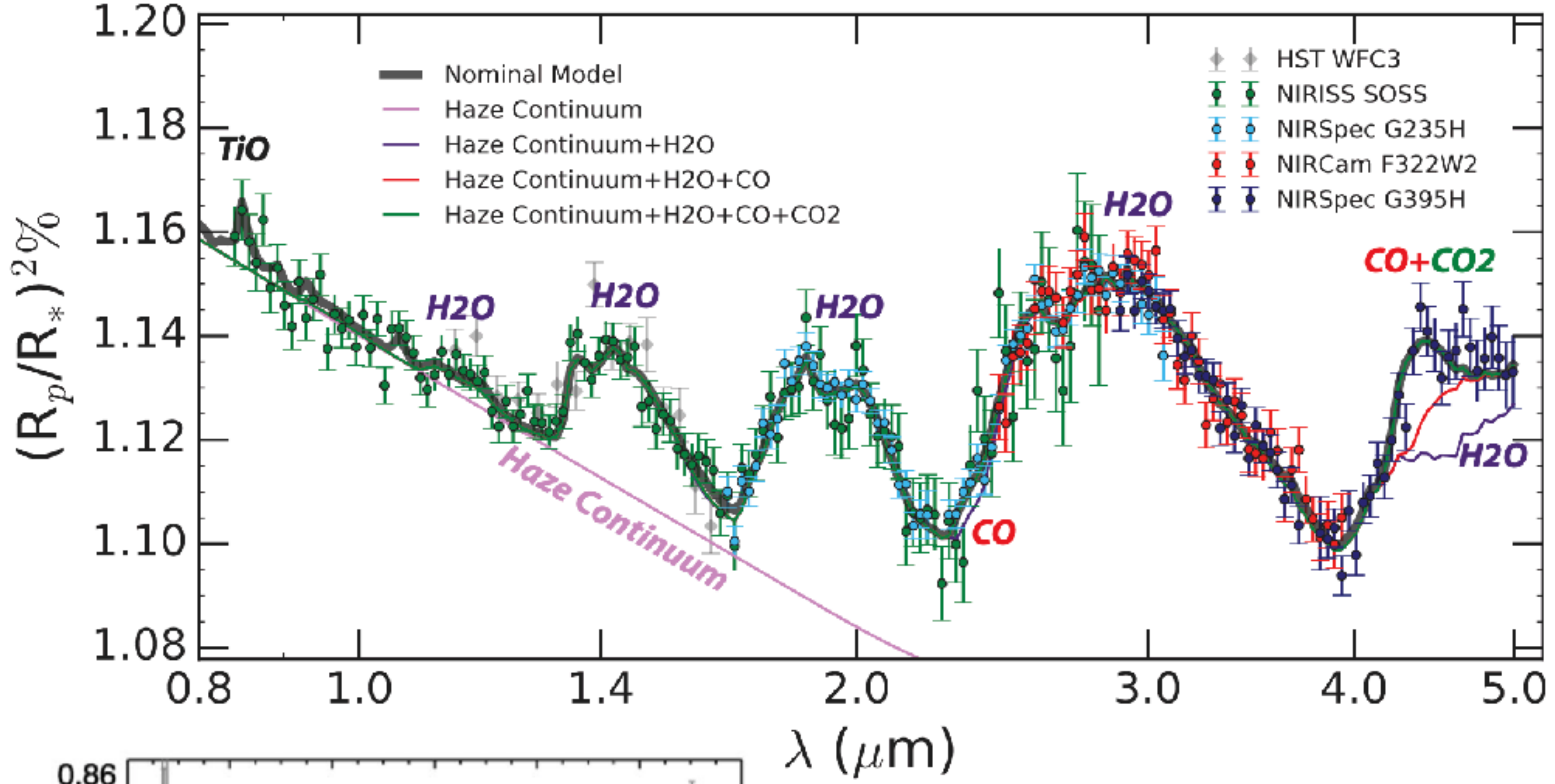
(all without dedicated instrumentation!)

What's Next? The James Webb Space Telescope

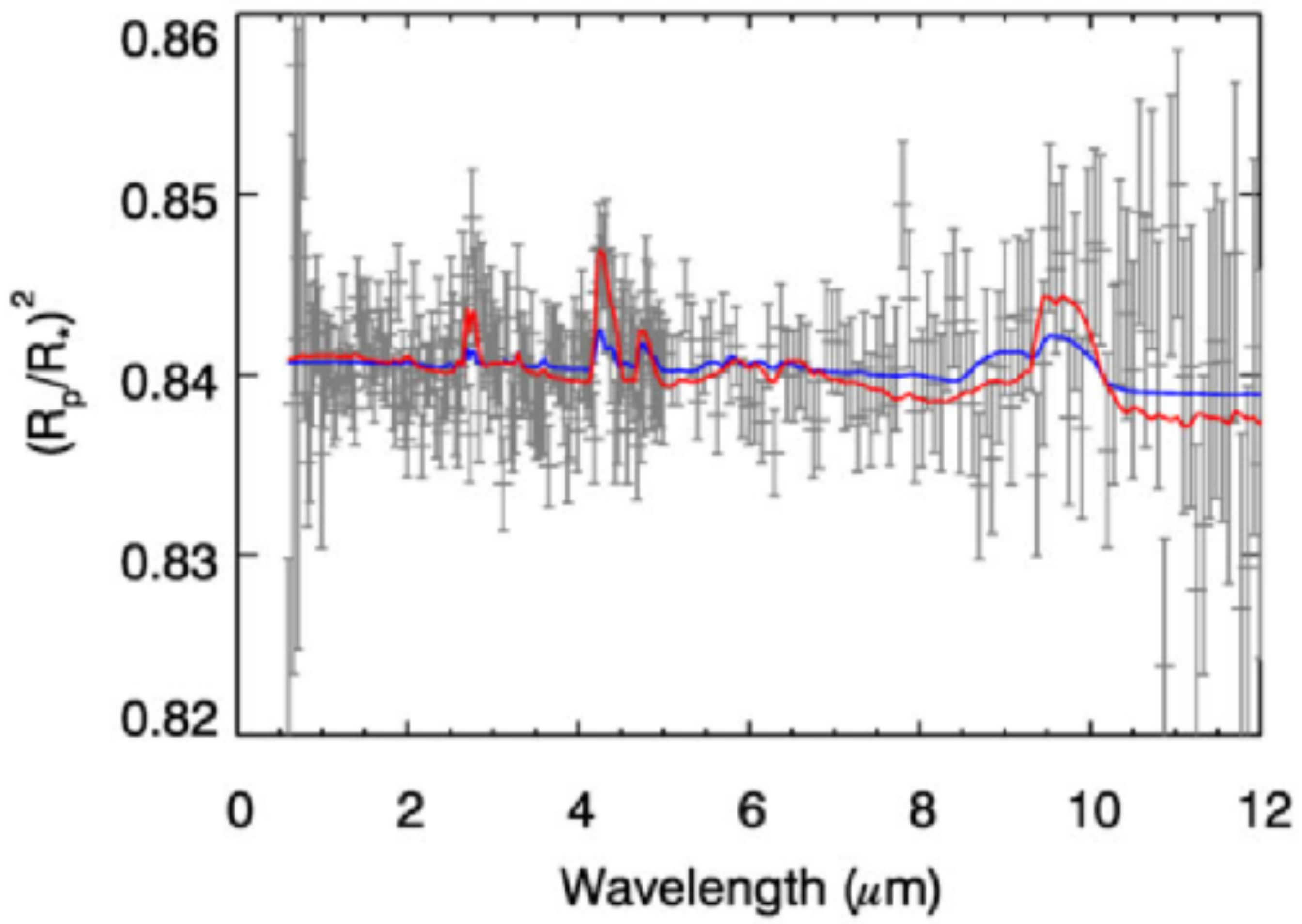


JWST (Launch Oct 2021?)

Simulated transmission spectrum of WASP-79b (Bean et al. 2018)

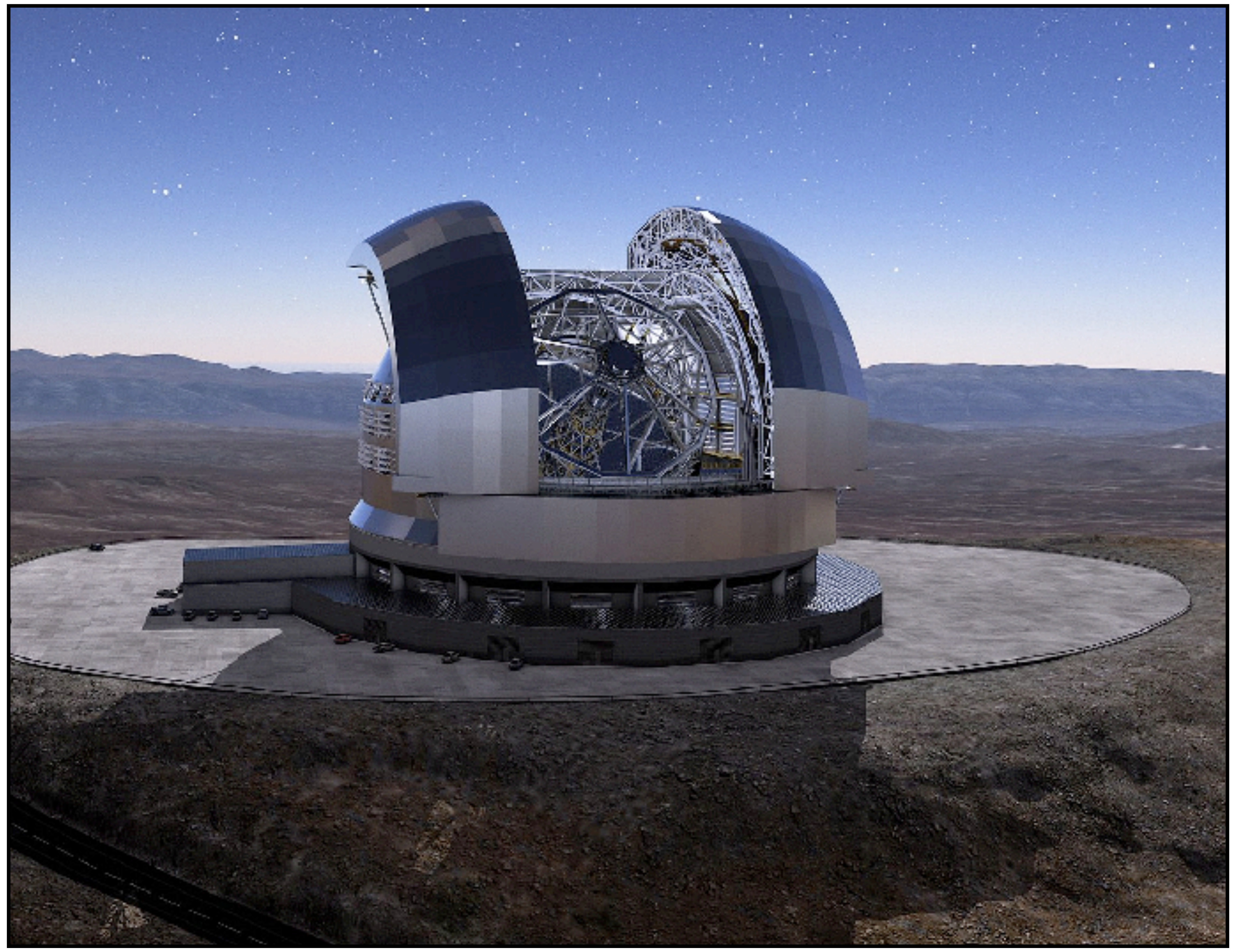


ERS programs already accepted for both transiting planets (N. Batalha et al.) + direct imaging (S. Hinkley et al.)



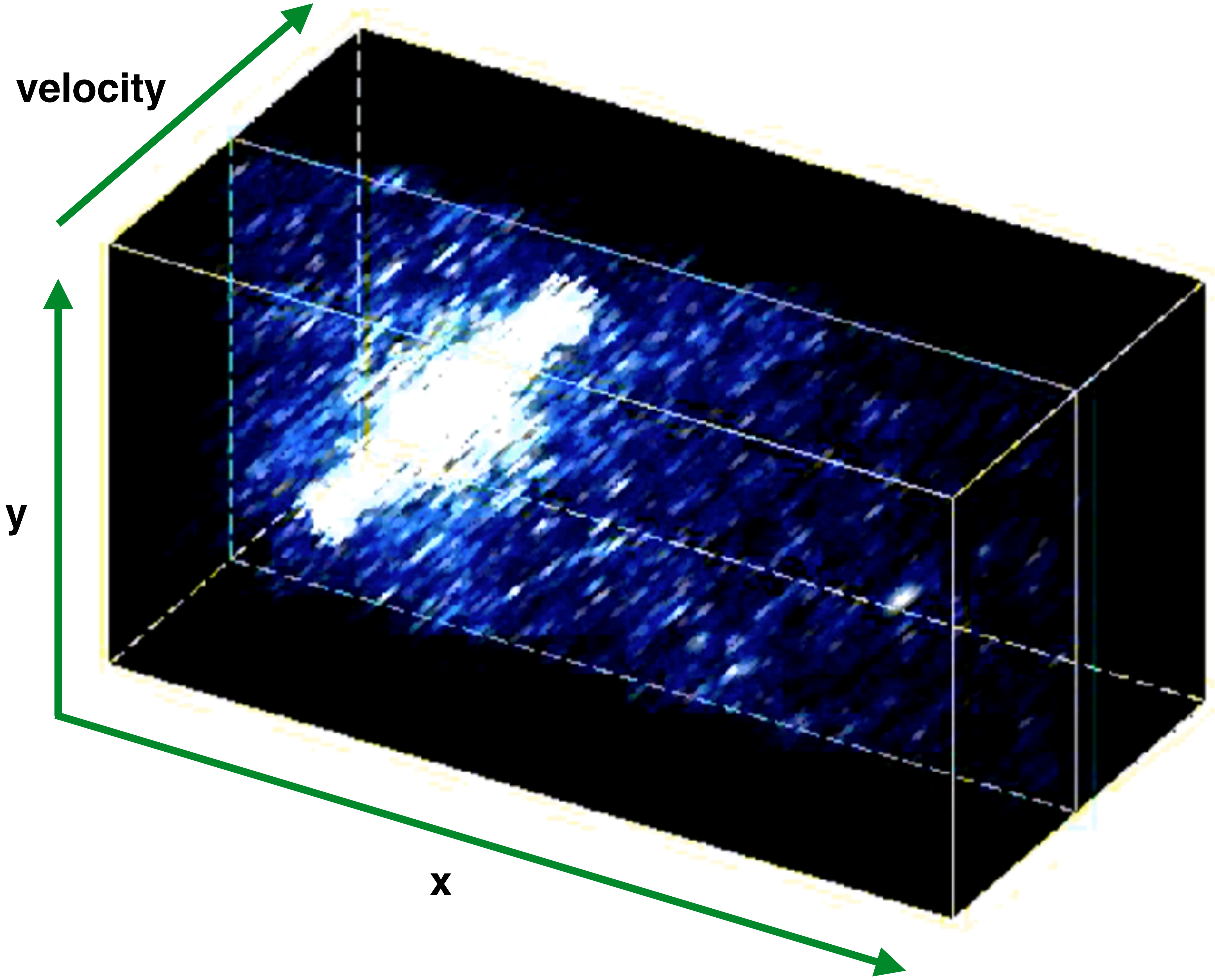
Simulated spectrum of TRAPPIST-1d (Barstow et al. 2016): Detection of O_3 by combining many transits?

What's Next? The ELT(s)



E-ELT (~2025)

- Will revolutionise direct imaging and high-resolution Doppler-resolved spectroscopy

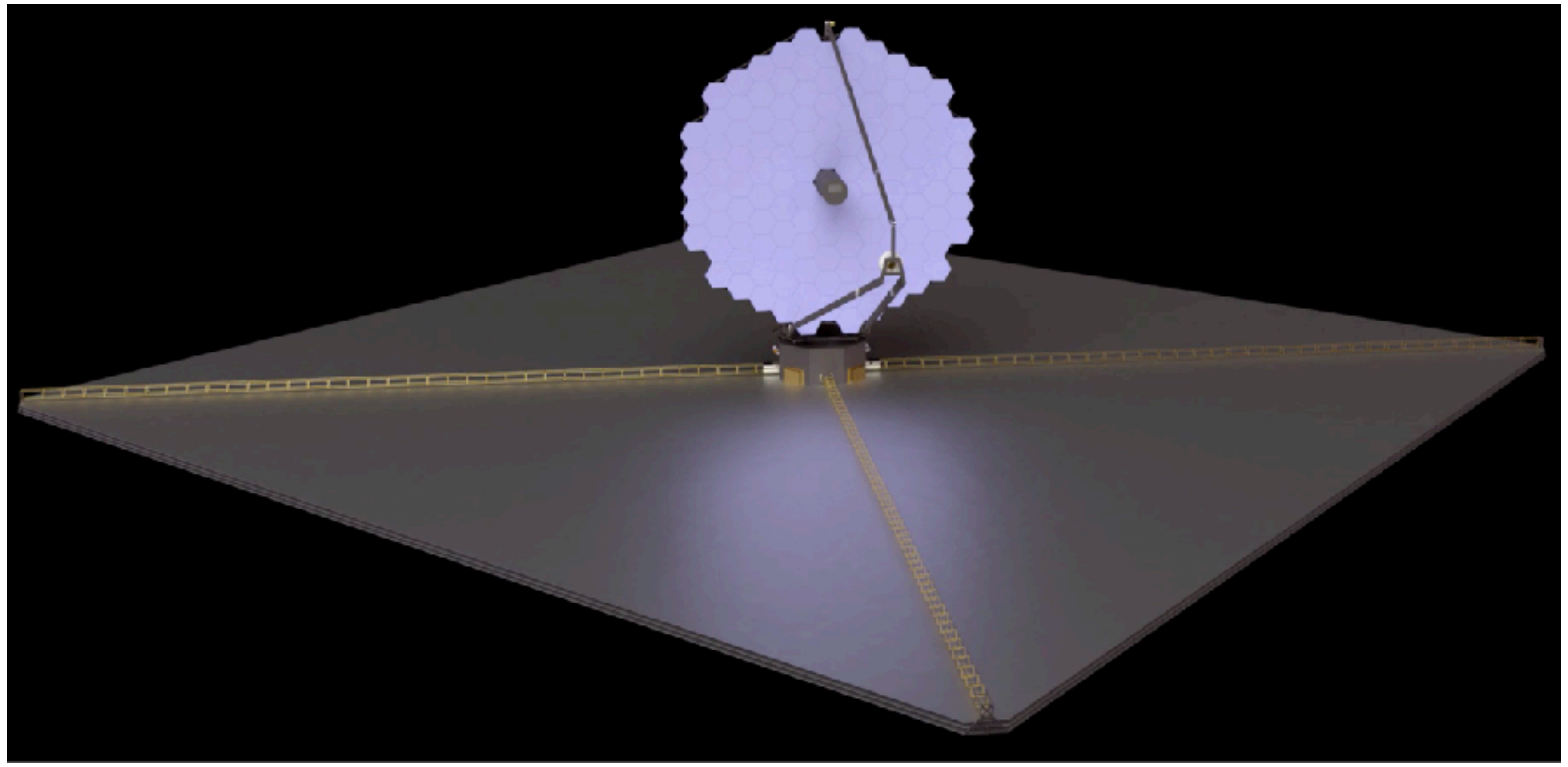


Can these techniques be combined? (Snellen et al. 2015)

What's Next? Future Instrumentation

ARIEL 2028?

Sample of ~1000 atmospheres?



LUVOIR/HABEX? Mid/late 2030s

Direct imaging of habitable zone planets?

Conclusions

- Remarkable progress has been made in observing exoplanet atmospheres in the last decades
- Enormous challenges still remain with instrumental systematics and stellar activity
- Next-generation instrumentation such as JWST and ELT promise to revolutionise exoplanet spectroscopy
- Statistical studies of gas giants, first look at terrestrial planets will be possible (+precise abundances, broad spectral coverage, spatially resolved spectra)

Image Credit: ESO / Y. Beletsky