State of the Art in Exoplanet Atmosphere Observations

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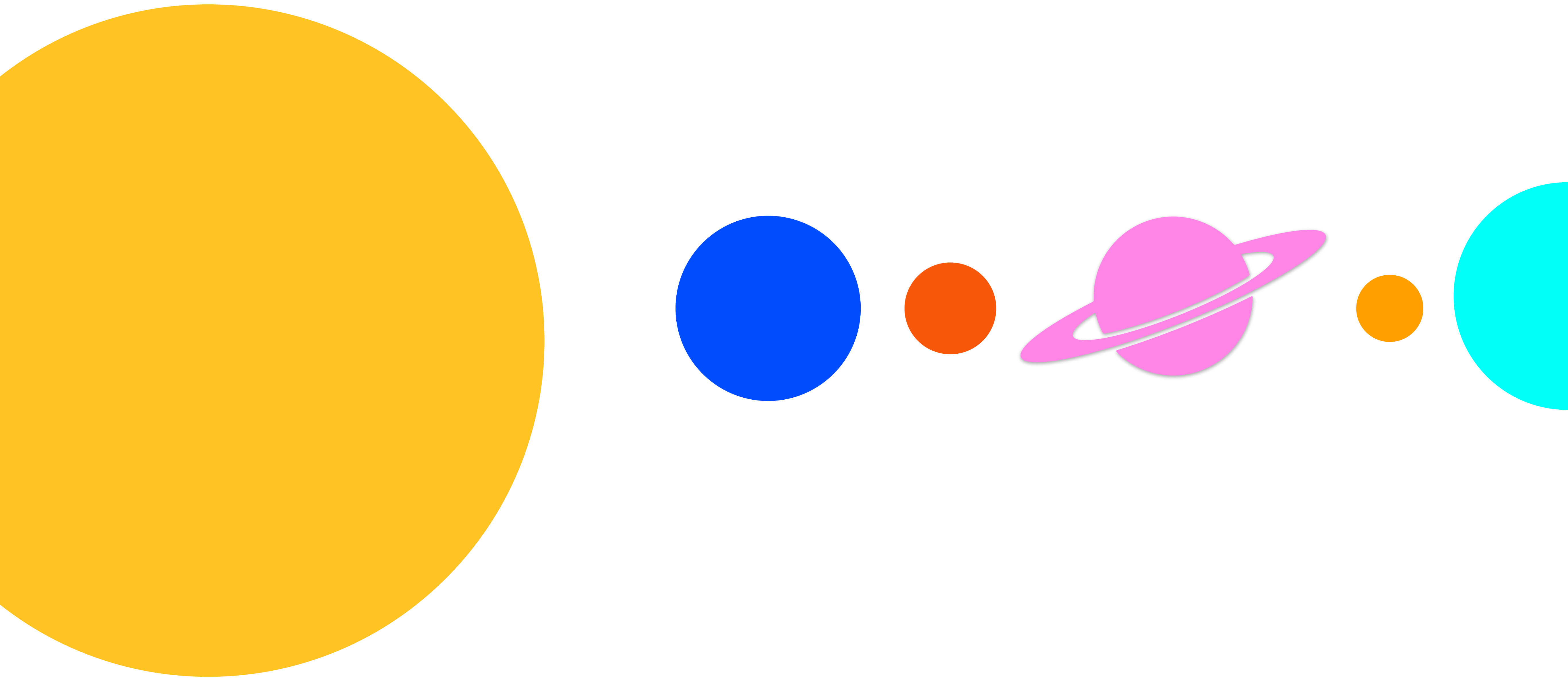
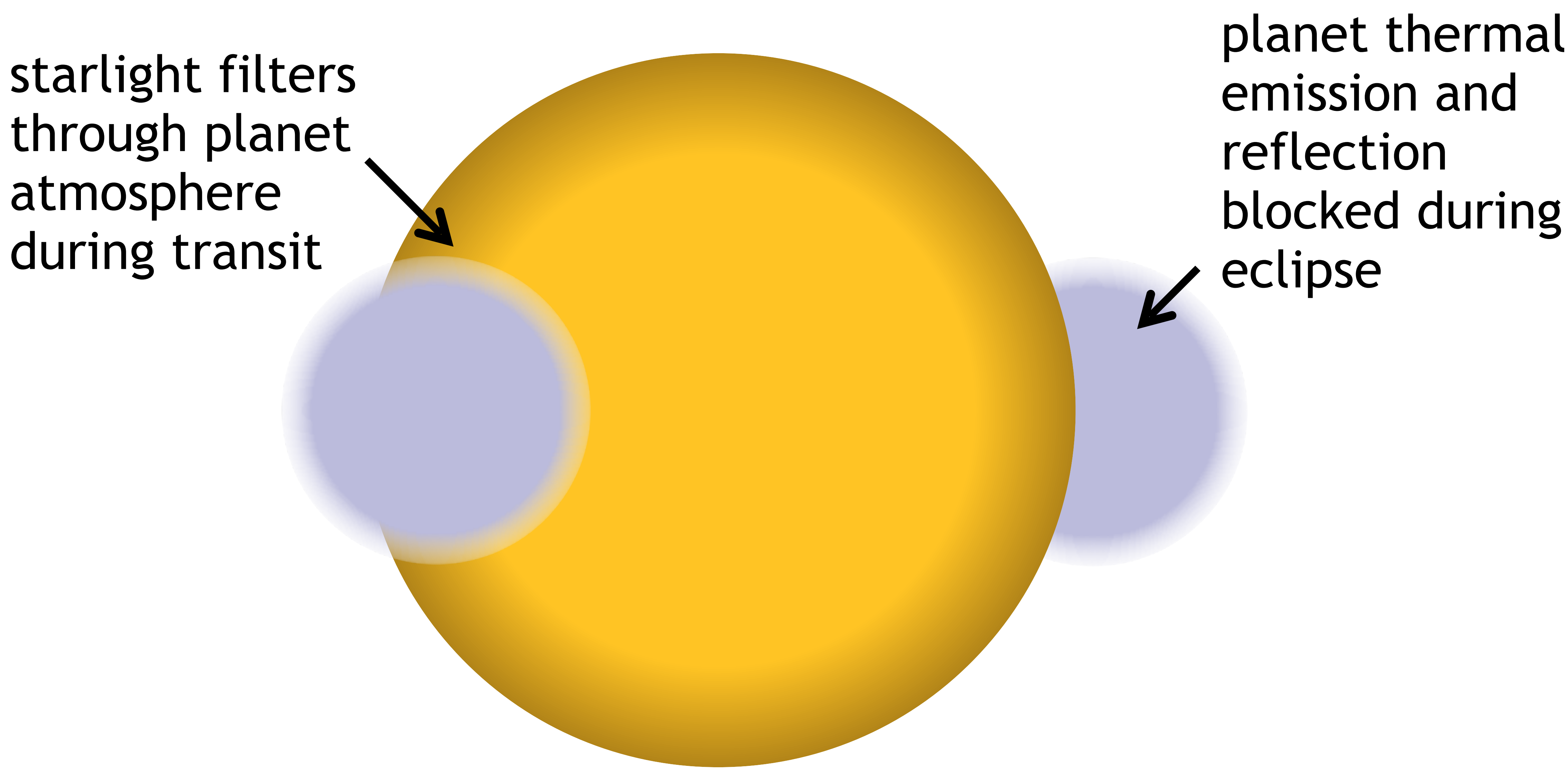


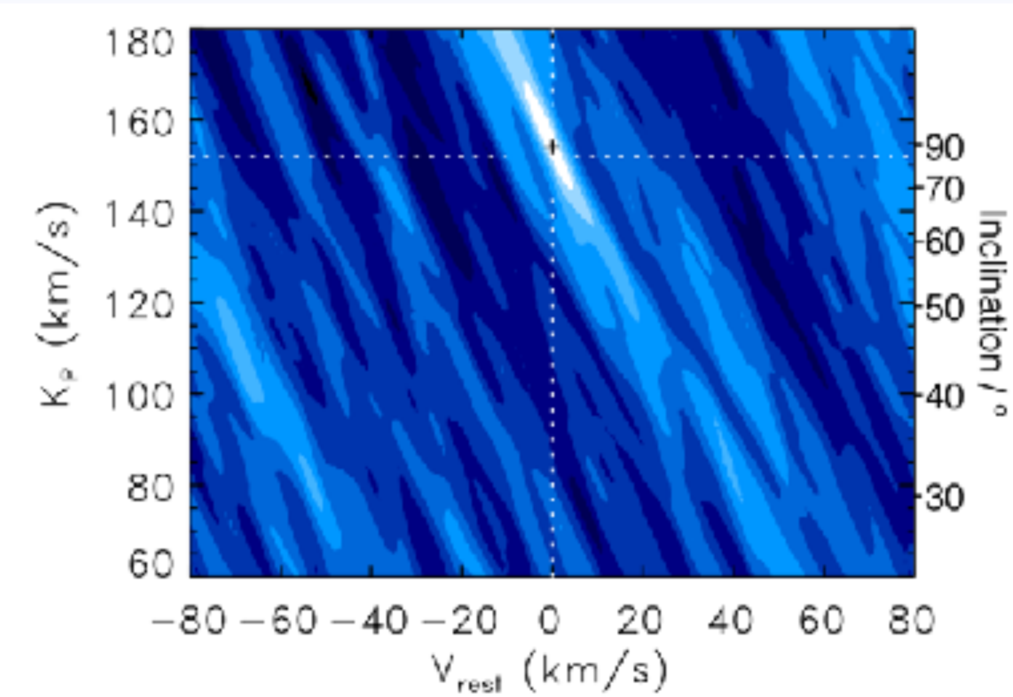
Atmosphere Characterization I:
Transmission and Emission Spectroscopy

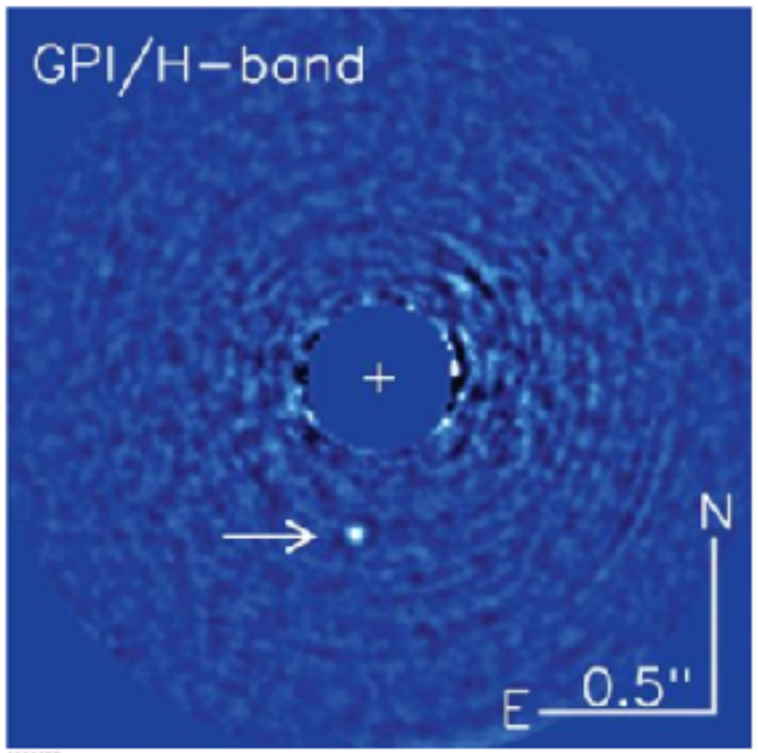


- At wavelengths where the atmosphere is opaque, more starlight is blocked
- Sensitive to chemical composition, temperature, clouds/haze

Atmosphere Characterization II:
Ground-Based Techniques

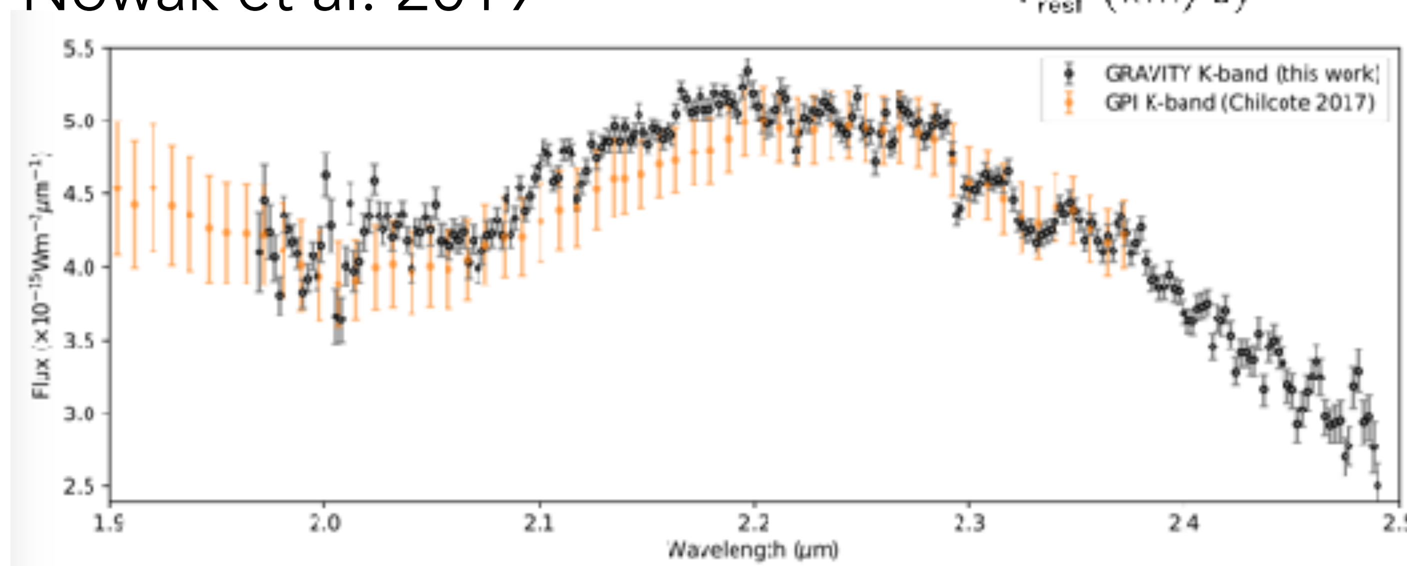
Birkby et al. 2018





Macintosh et al. 2015

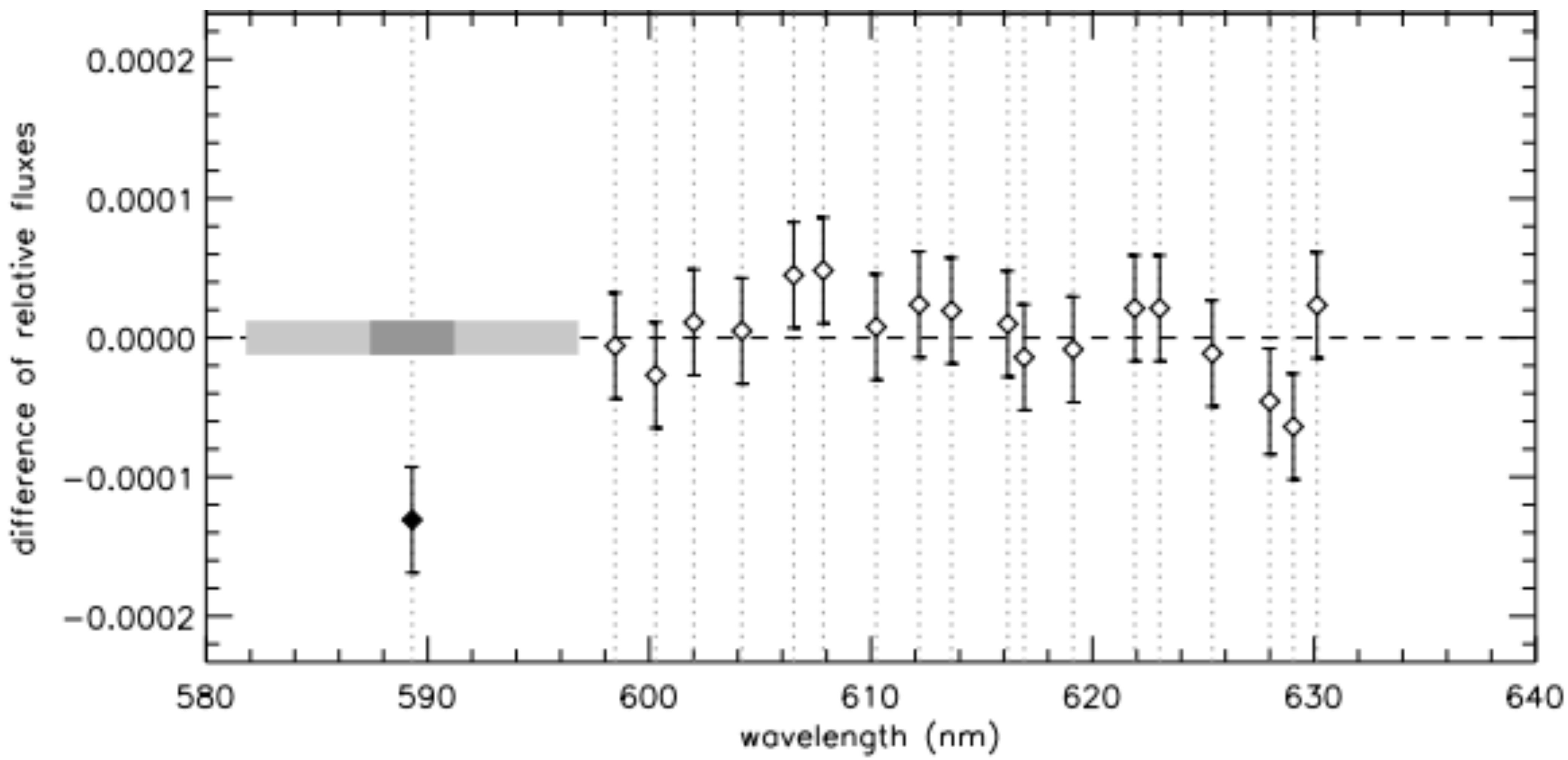
Nowak et al. 2019



- High spectral resolution — planet's spectrum is Doppler shifted
- Low spectral resolution — correct for Earth's atmo with companion stars
- Direct imaging — mask stellar flux
- Interferometry — superb angular resolution separates planet from star

18 years of exoplanet atmosphere characterization

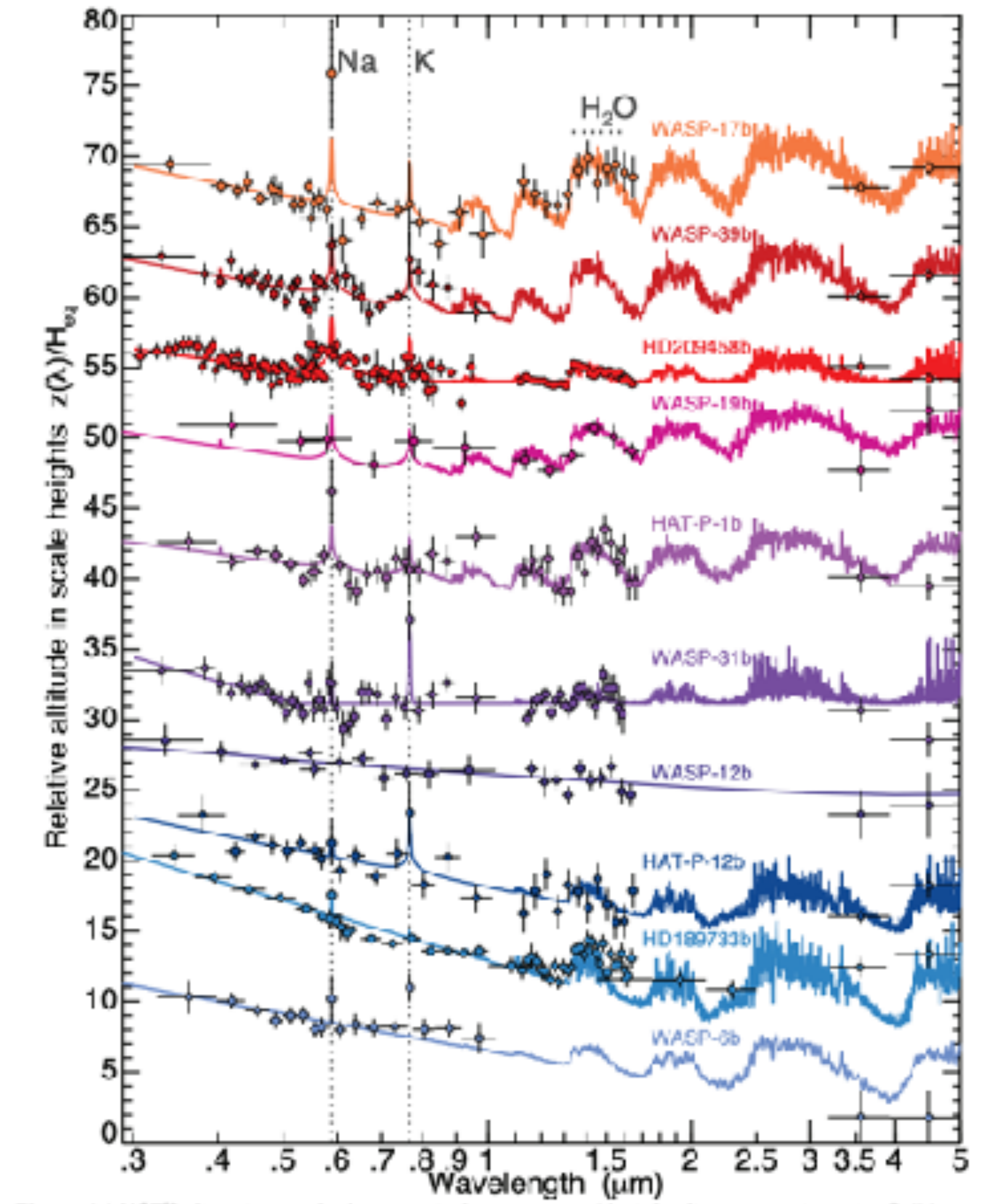
Charbonneau et al. 2002



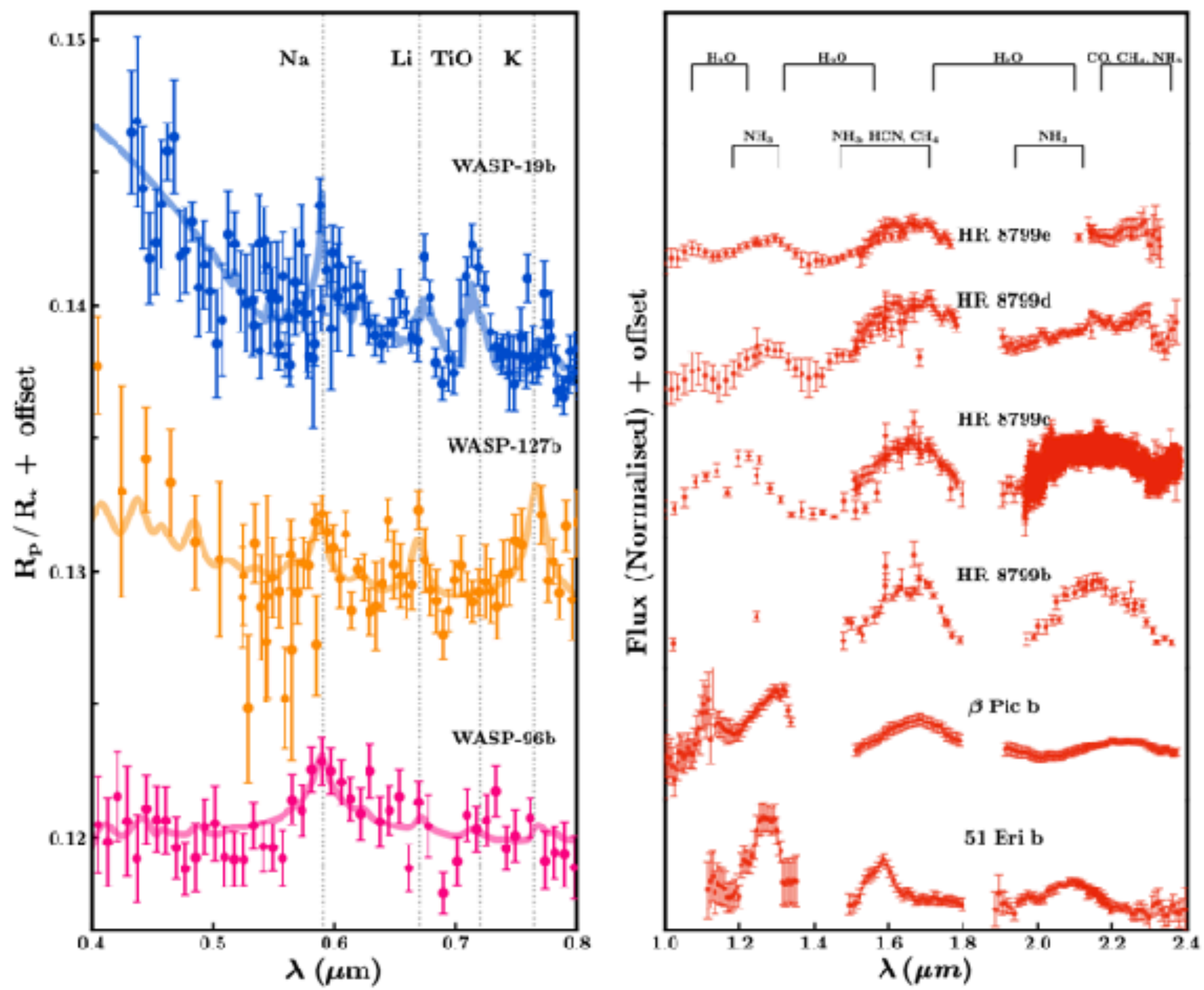
First exoplanet atmosphere detected : sodium absorption in HD 209458b

18 years of exoplanet atmosphere characterization

Sing et al. 2016



Madhusudhan et al. 2019

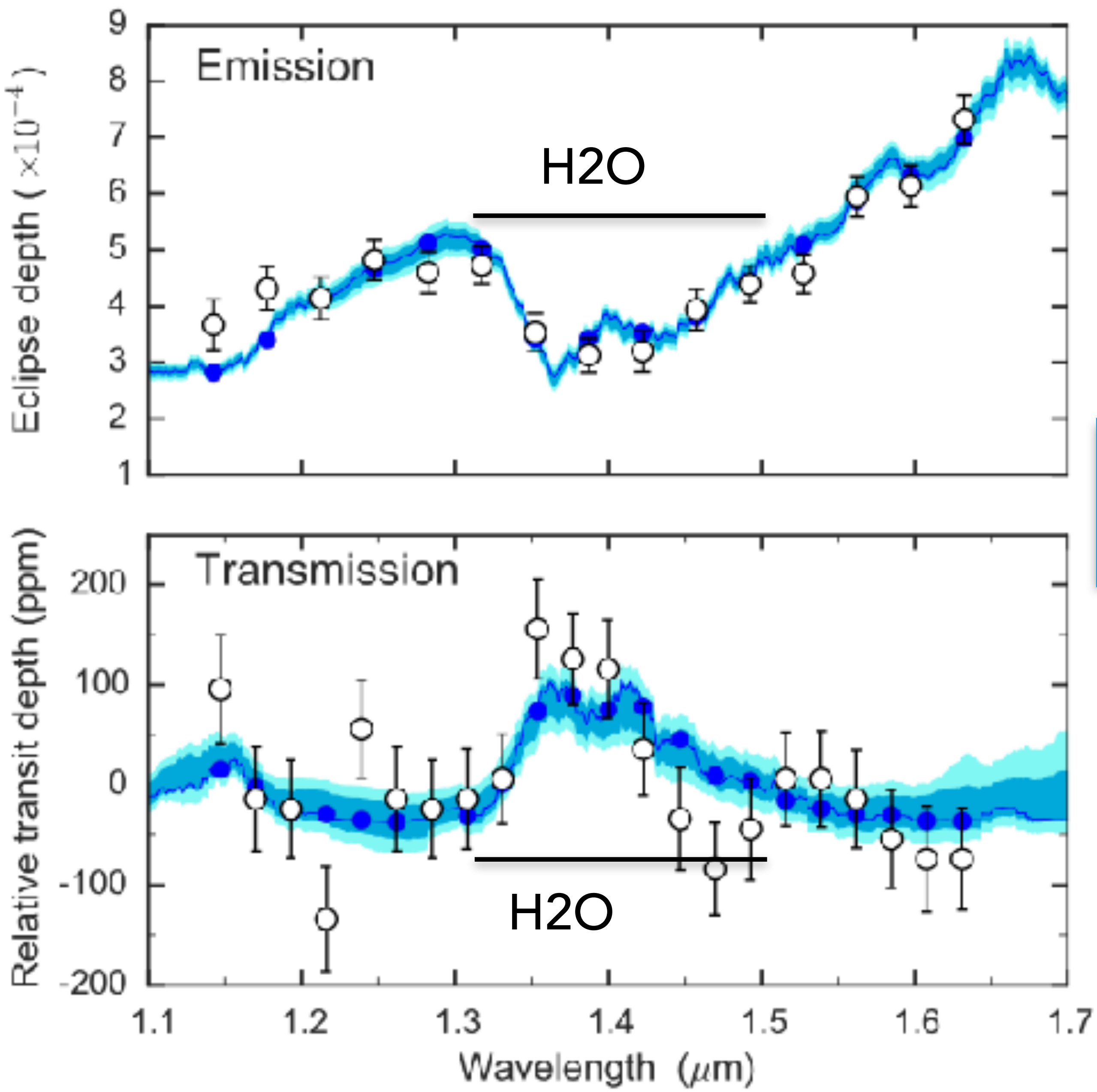


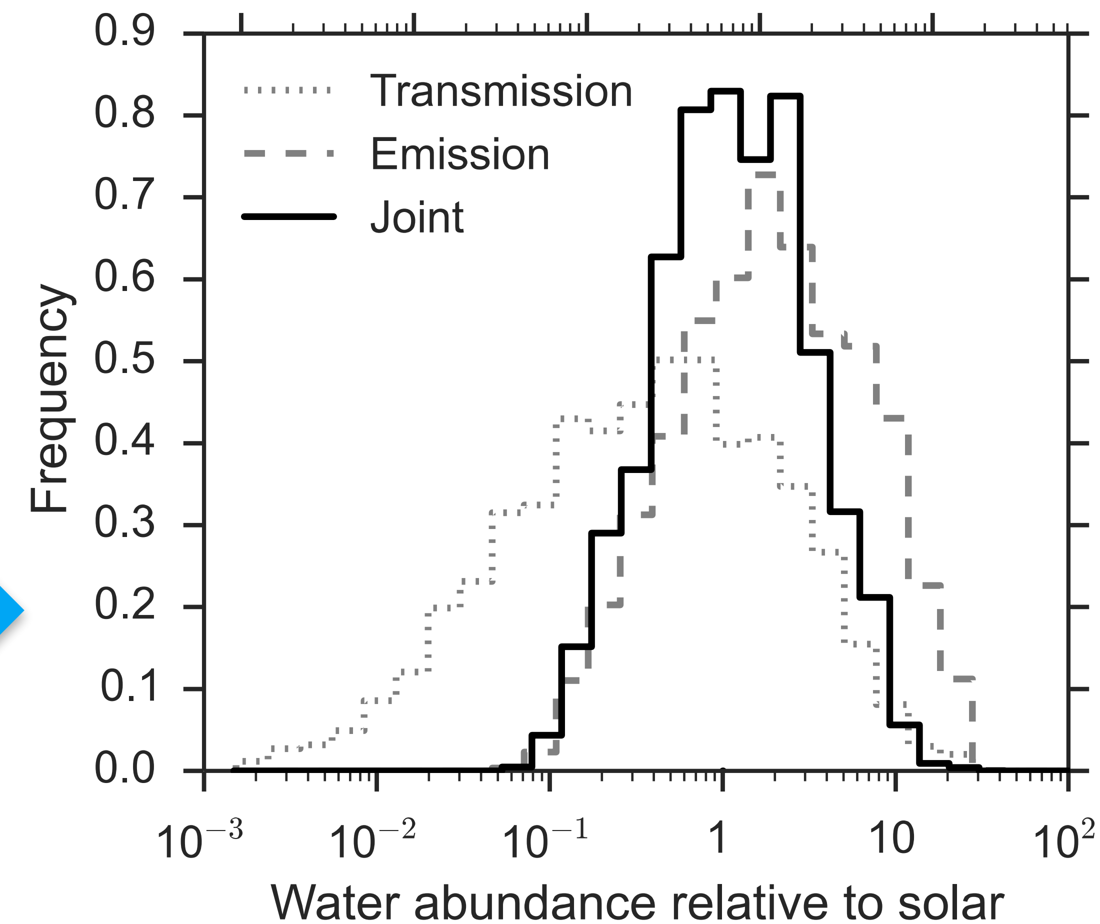
Atmosphere studies are now routine!

Frontiers in Exoplanet Atmosphere Characterization

I. Moving from detection to precise abundances

Hubble/Wide Field Camera 3



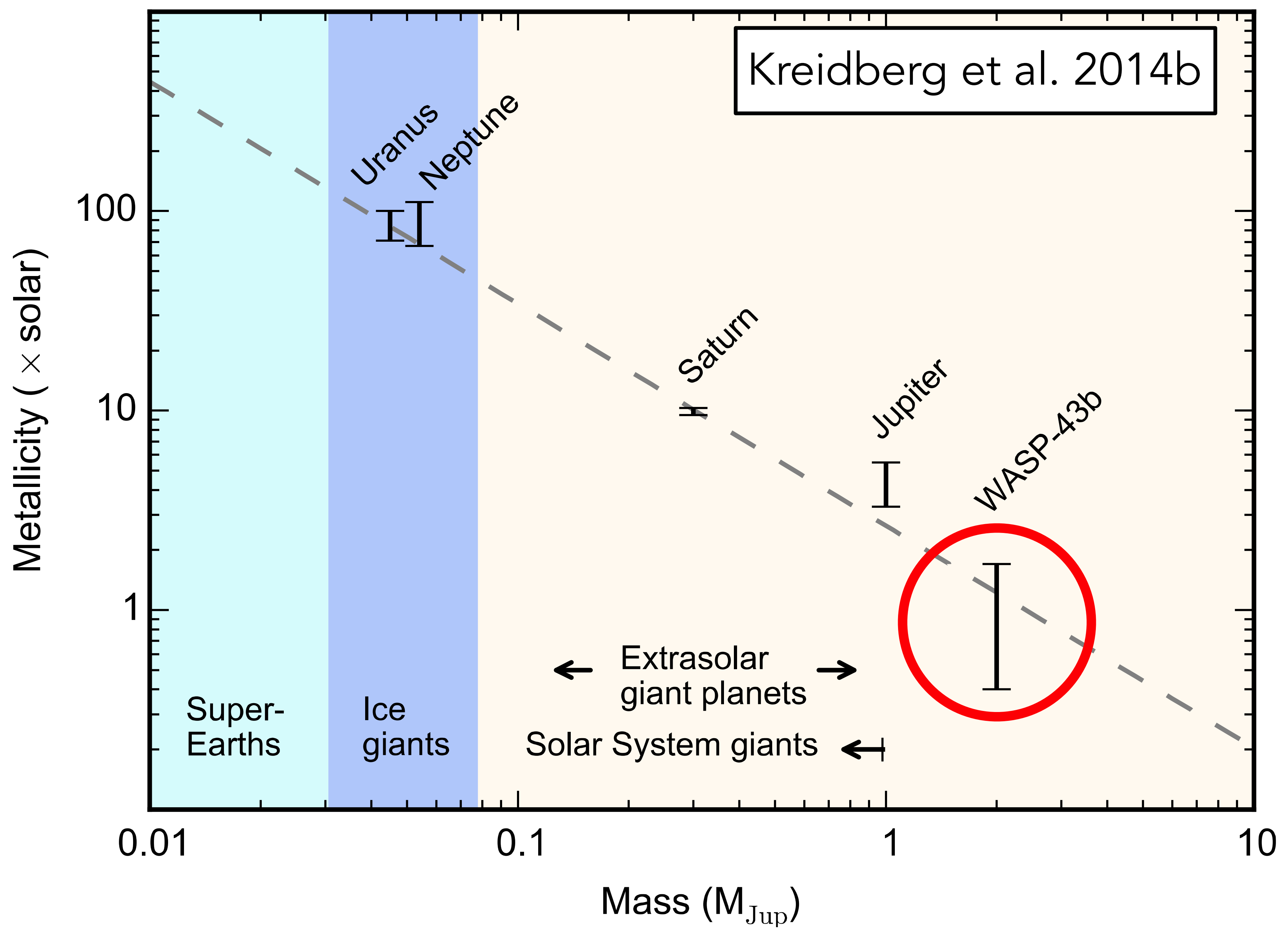


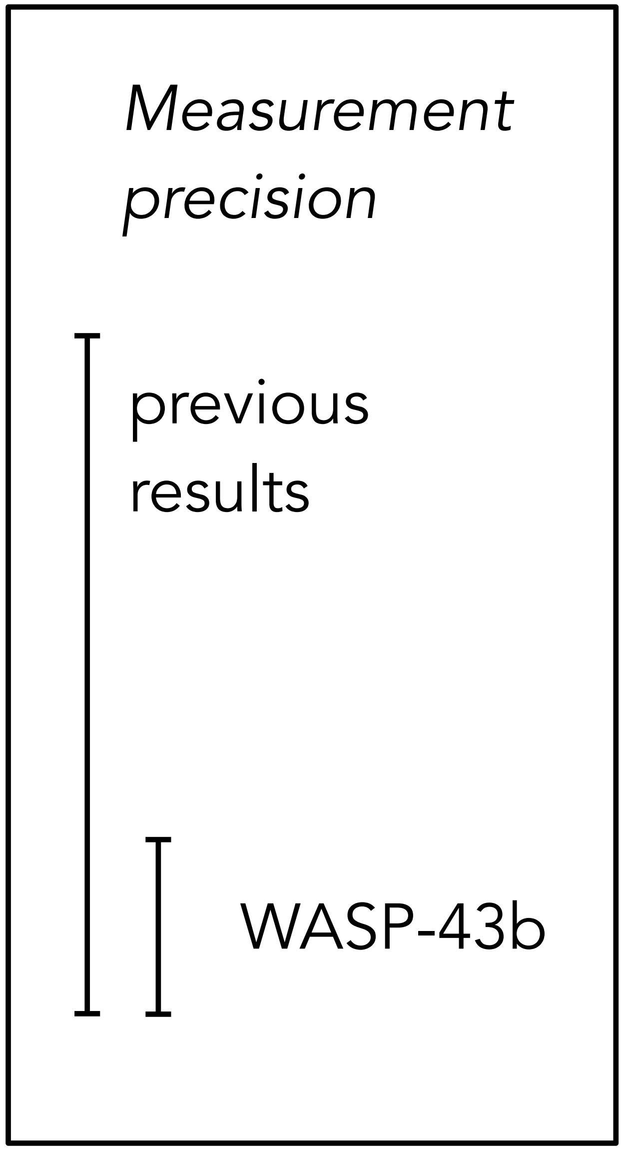
H2O mixing ratio = 240 - 3100 ppm

Kreidberg et al. 2014b

Frontiers in Exoplanet Atmosphere Characterization

I. Moving from detection to precise abundances



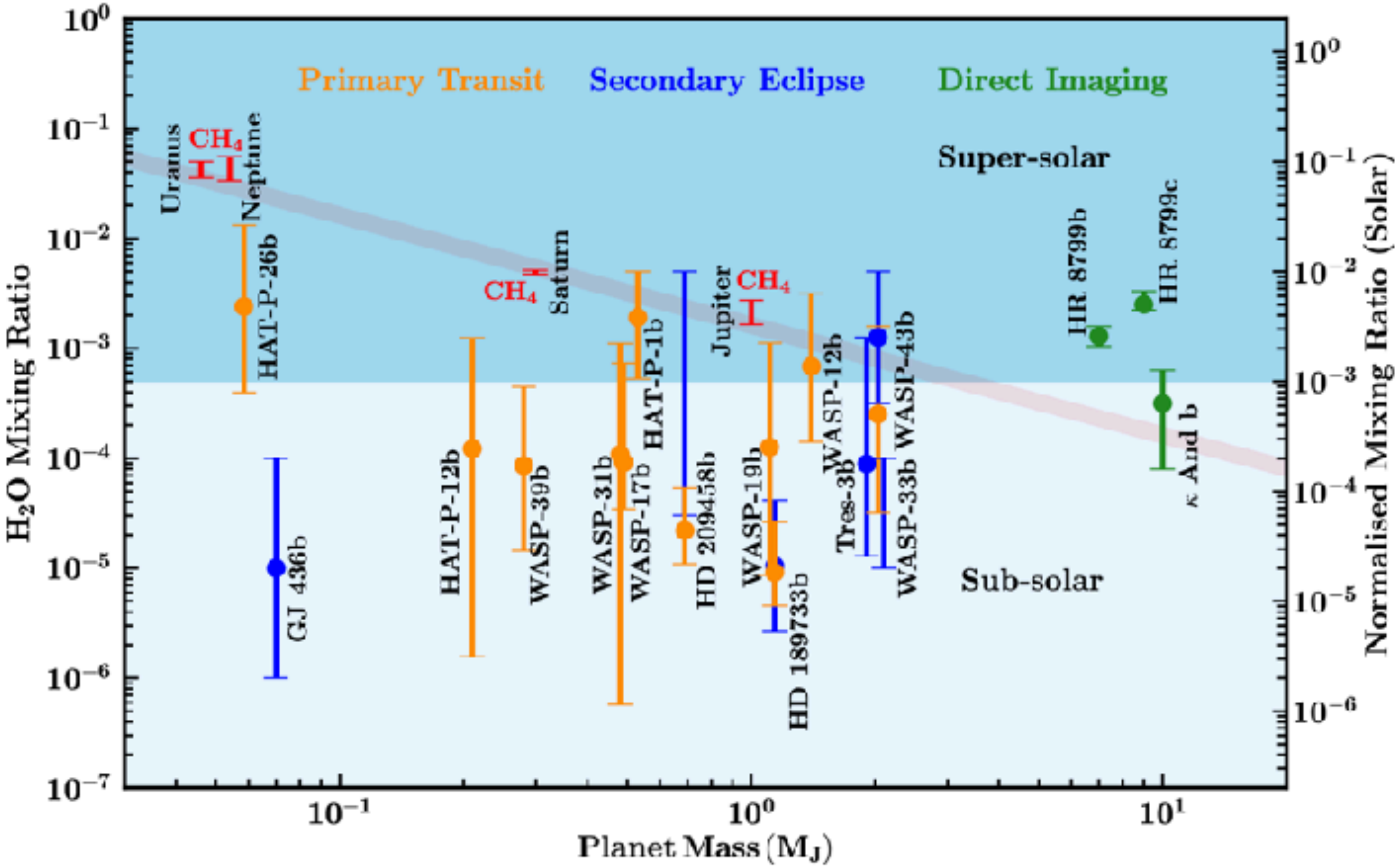


Proof of concept that **precise abundance measurements are possible** for exoplanets

Frontiers in Exoplanet Atmosphere Characterization

I. Moving from detection to precise abundances

Madhusudhan et al. 2019

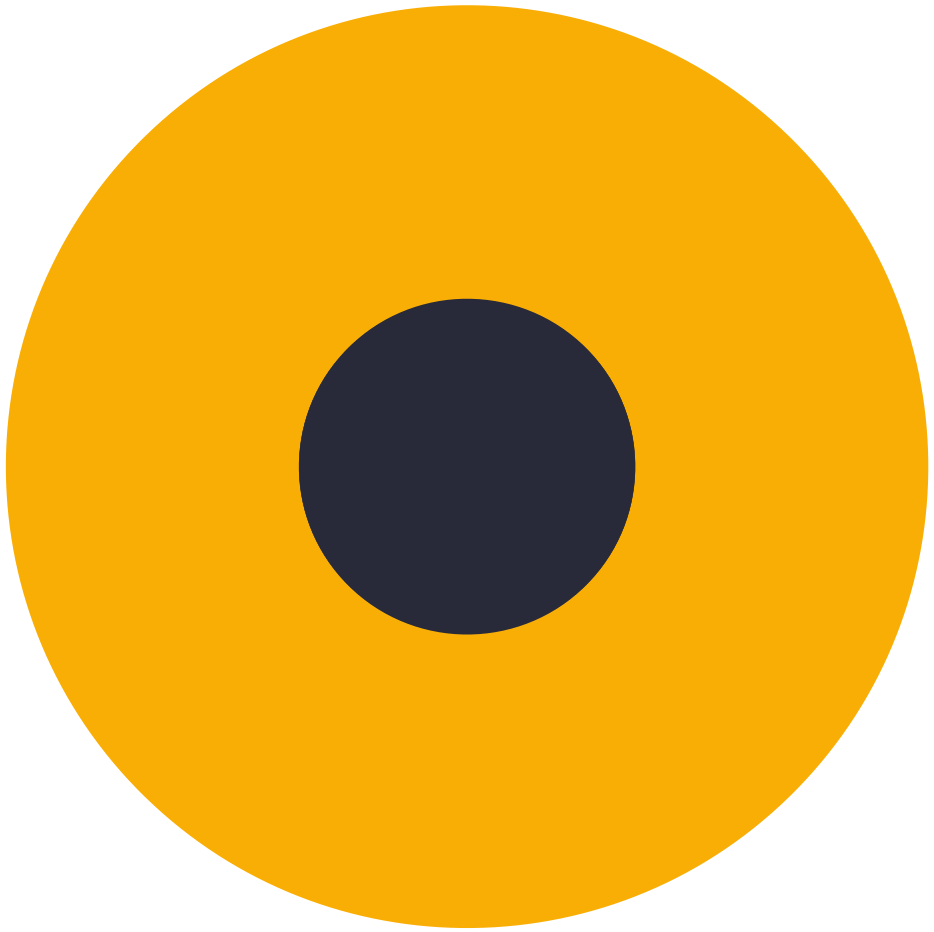


Unsurprisingly, exoplanets already show a more complicated trend than the SS

Planets are complicated

A simple planet model:

- rock/iron core
- Solar composition, chemical equilibrium envelope
- 1D
- Static in time



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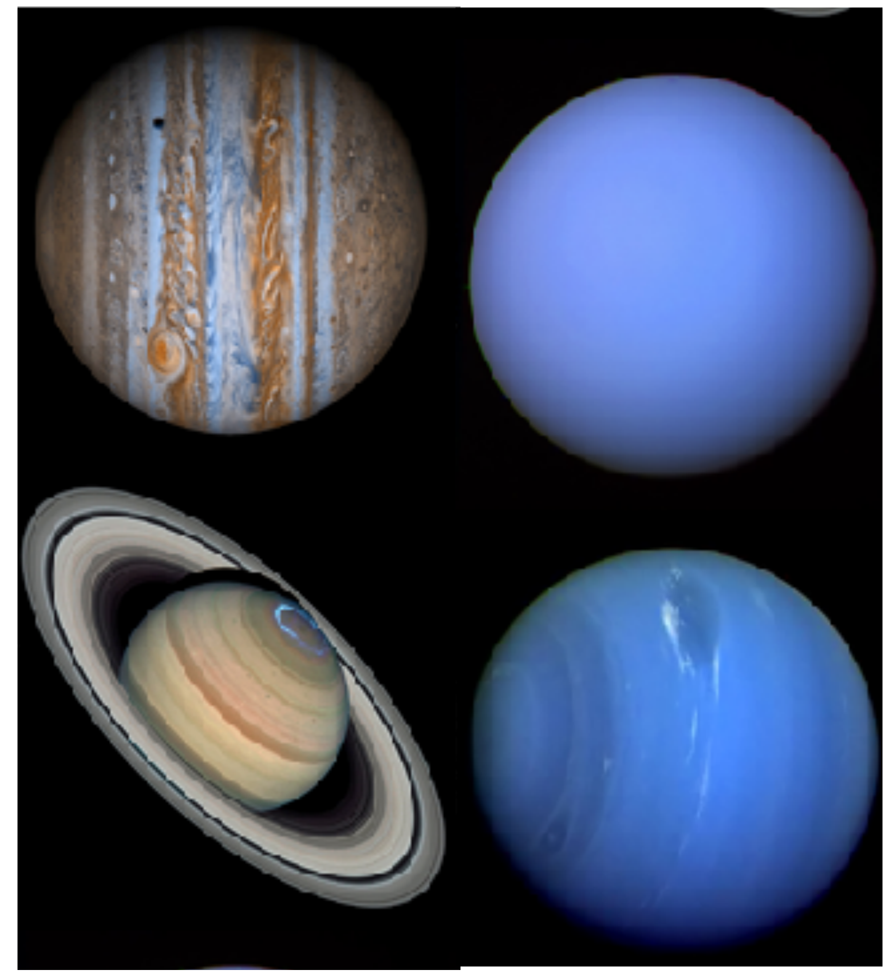
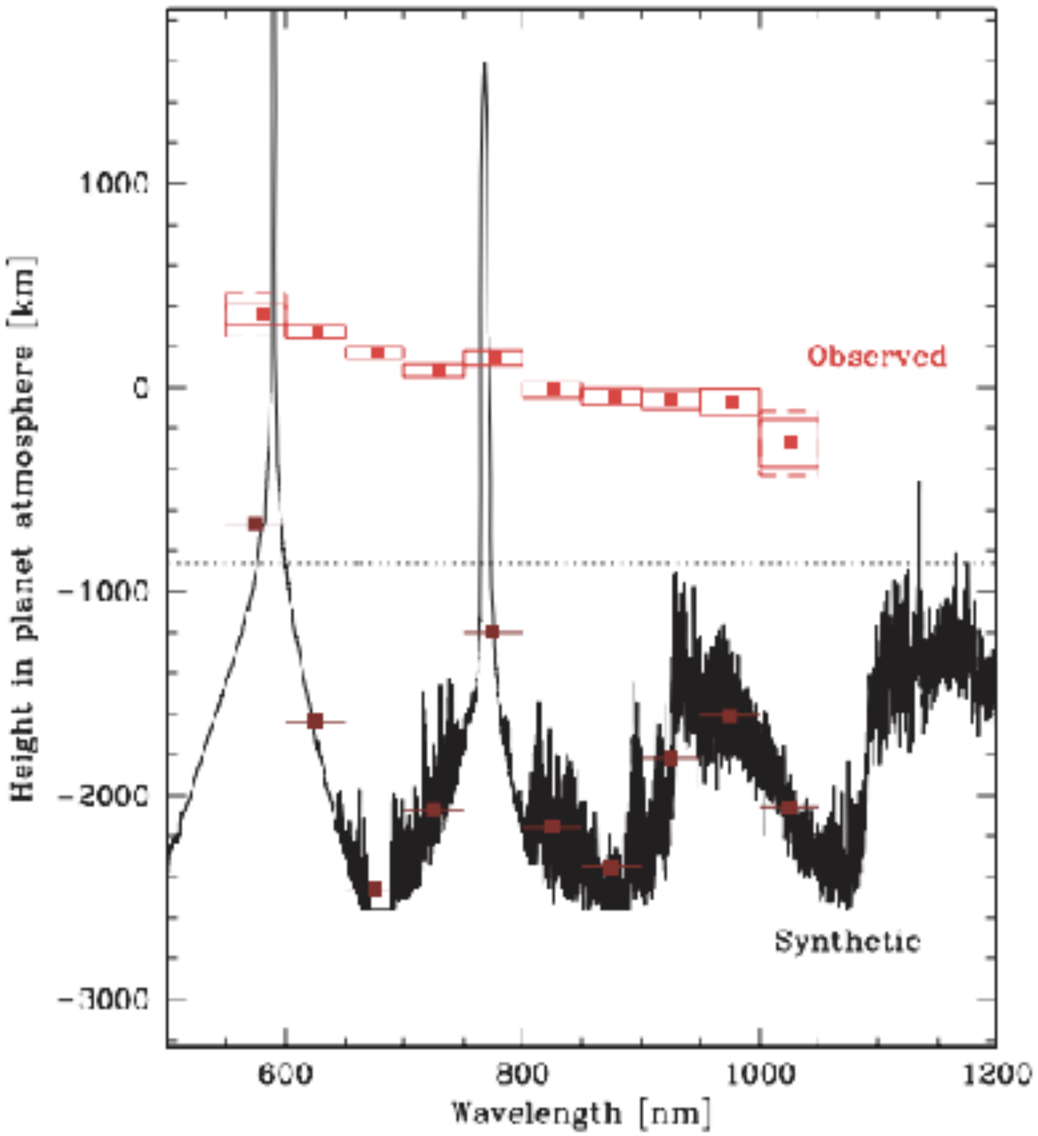


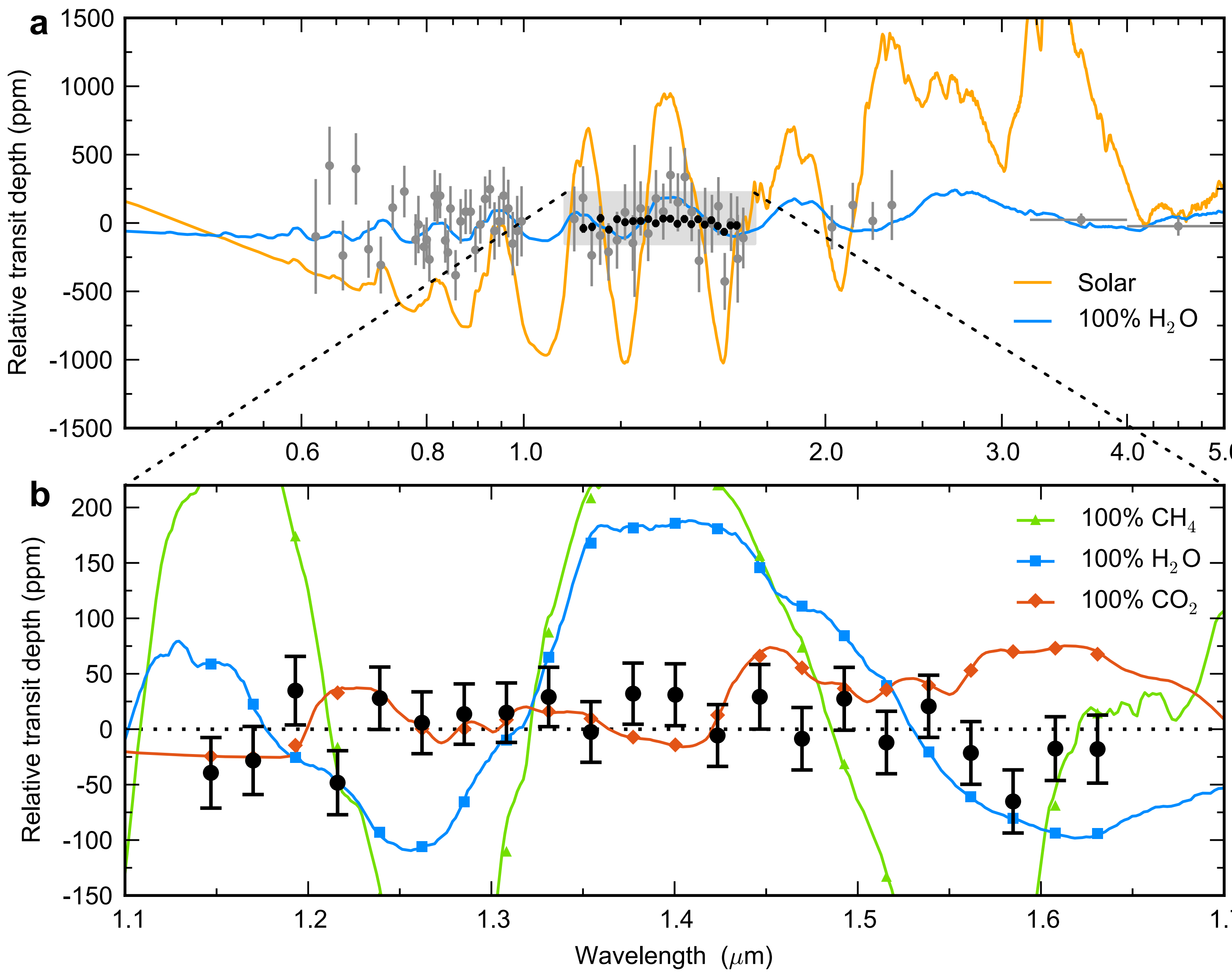
Planets are complicated

I. Clouds + haze

HD 189733b, Pont et al. 2008



GJ 1214b, Kreidberg et al. 2014

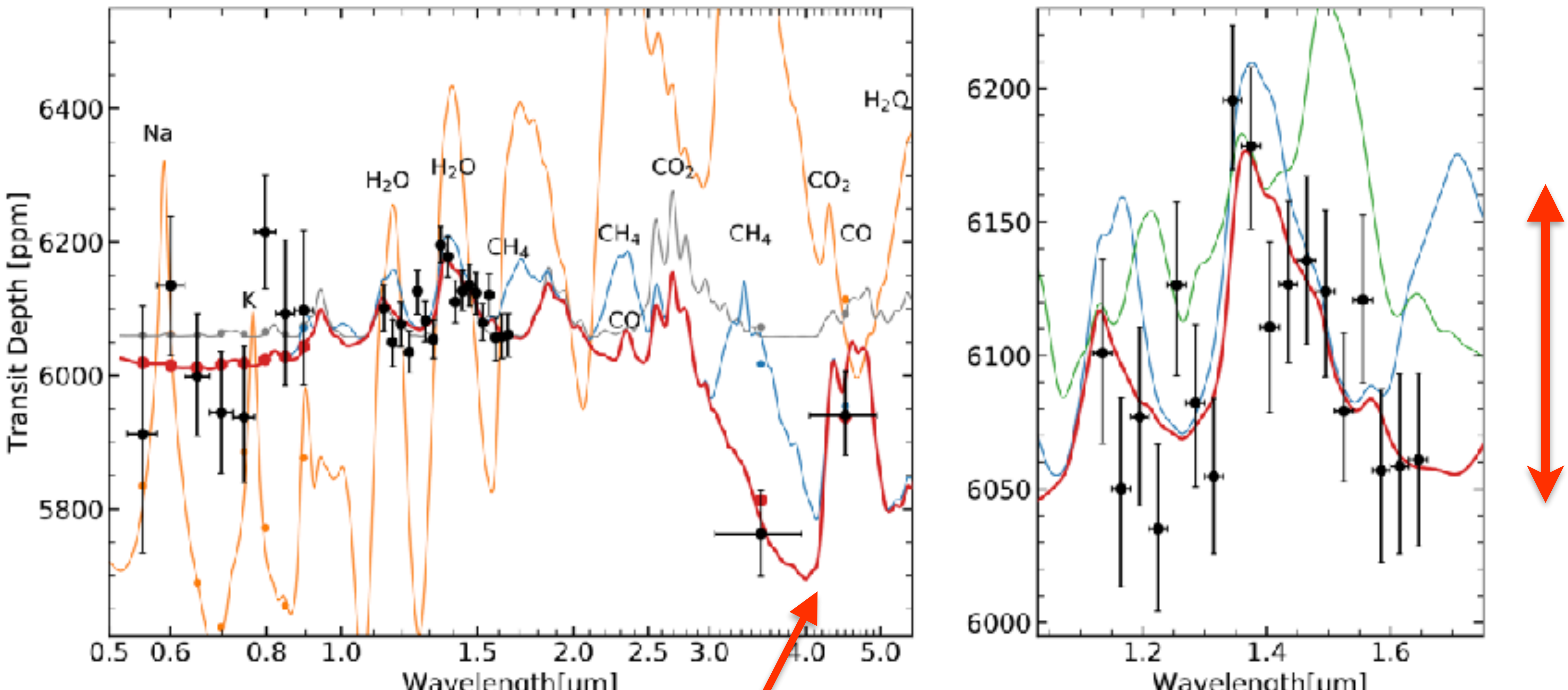


Condensates are common in hot Jupiters and sub-Neptunes

Planets are complicated

I. Clouds + haze

GJ 3470b (12 M_E) transmission spectrum (Benneke et al. 2019)

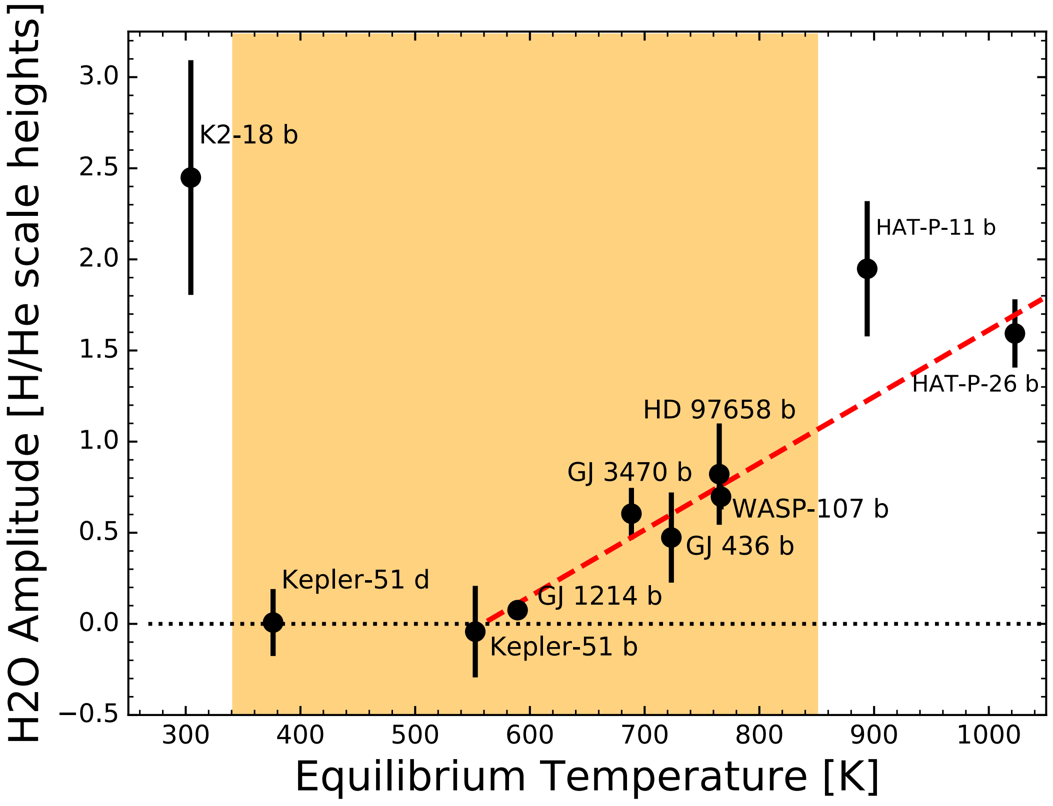


Small infrared transit depth —>
Mie scattering, 0.3 - 0.5 micron particles

Muted water feature

Planets are complicated

I. Clouds + haze



Gao et al. submitted
(see also Fu et al. 2017, Tsiaras et al.2017)

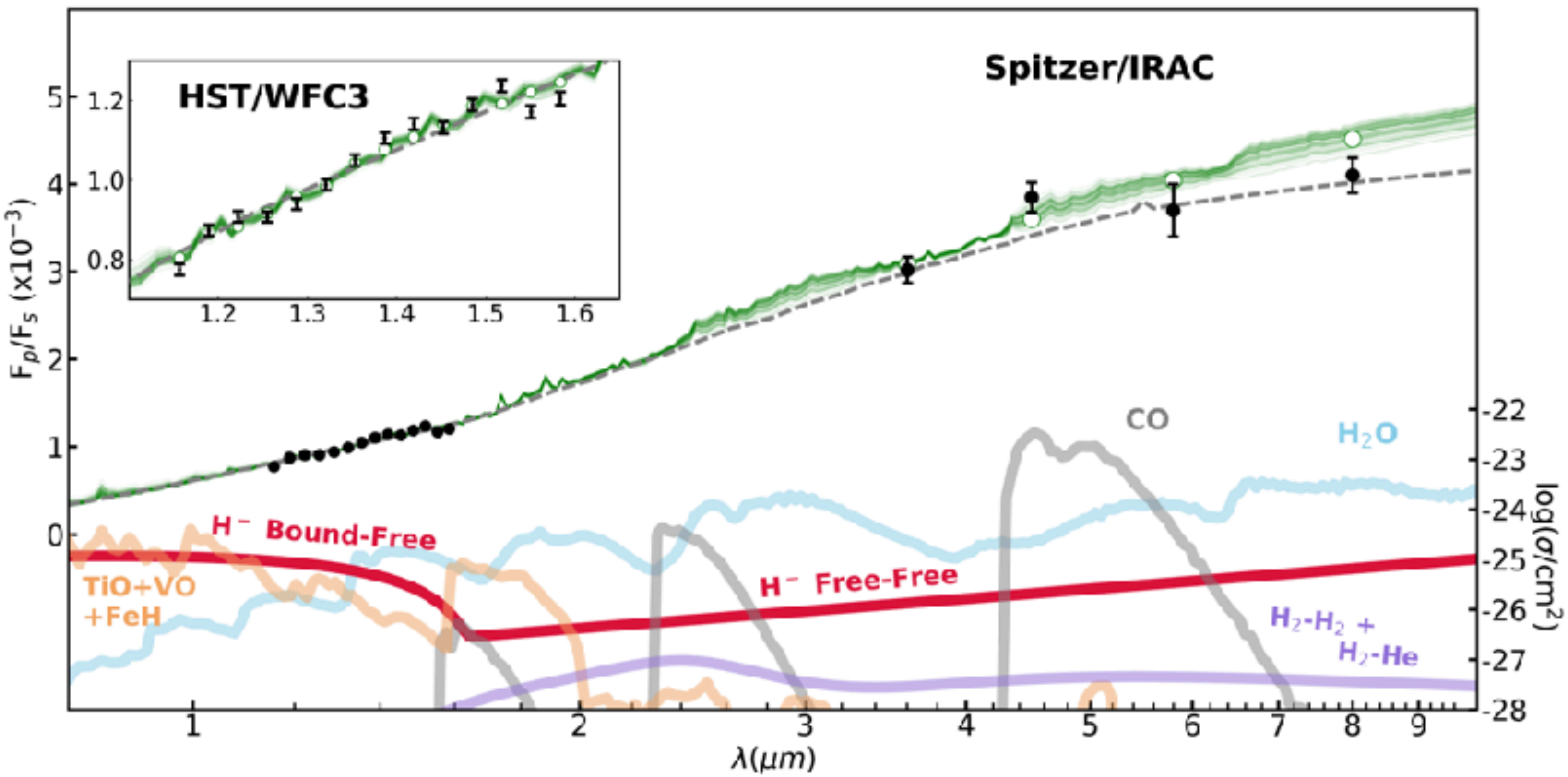
Adapted from Crossfield & Kreidberg 2017

Possible trends in H2O feature size with planet temperature

Planets are complicated

II. 3D effects

Arcangeli et al. 2018



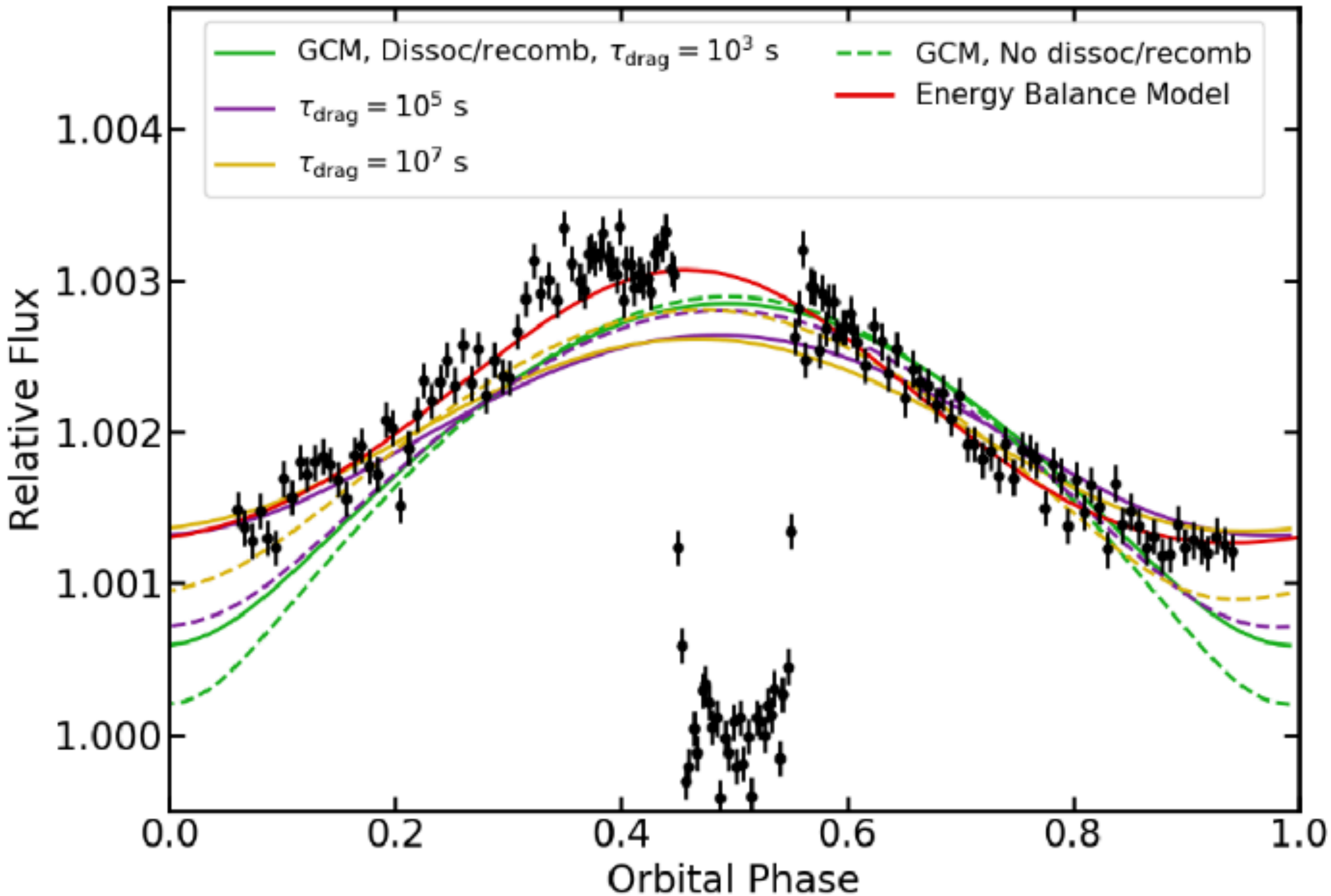
H2O dissociates on the dayside of the ultra-hot Jupiter WASP-18b

See also Parmentier et al. 2018, Mansfield et al. 2018, Kreidberg et al. 2018b, Bell & Cowan 2018, Komacek & Tan 2018

Planets are complicated

II. 3D effects

Mansfield et al. 2019, also Wong et al. 2019

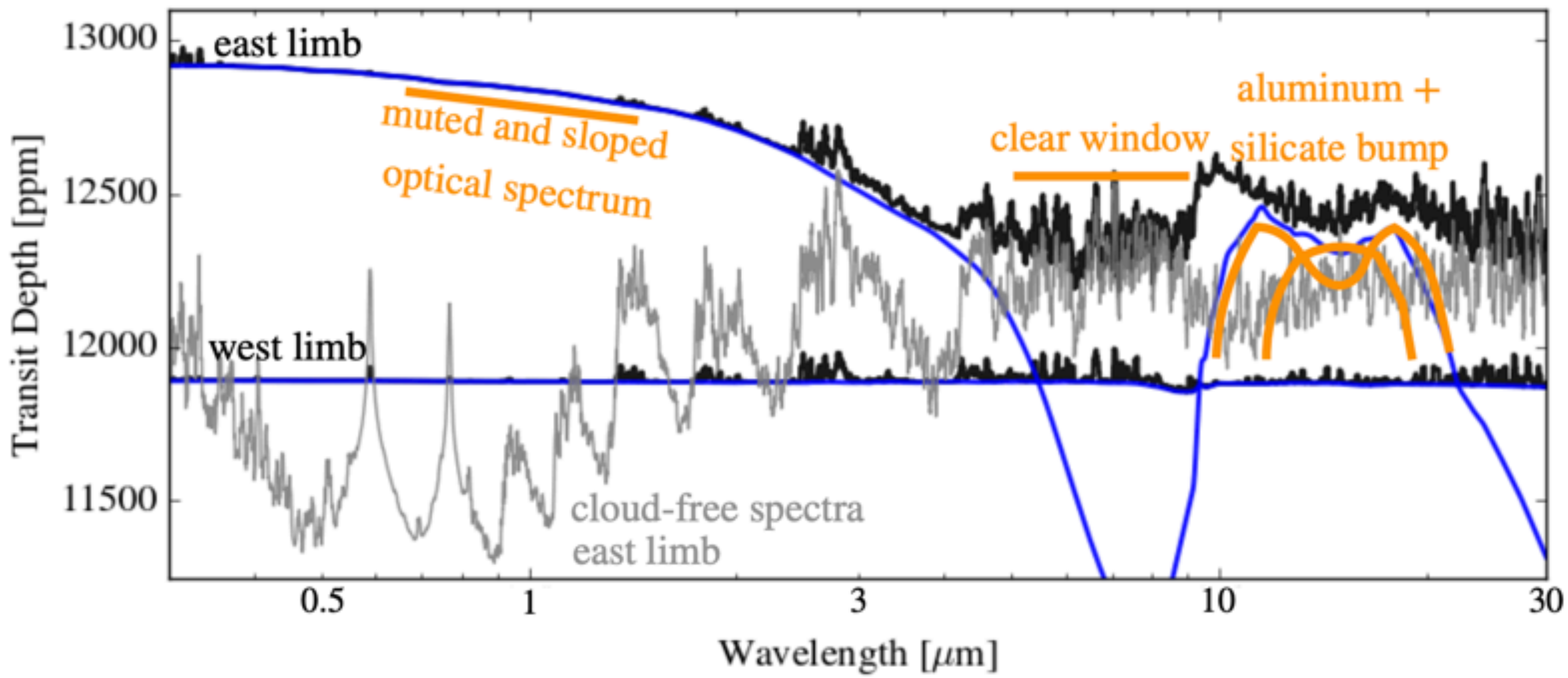


H2 recombination heats the nightside of the ultra-hot Jupiter KELT-9b

Planets are complicated

II. 3D effects

Powell et al. 2019 (see also Kempton et al. 2017)

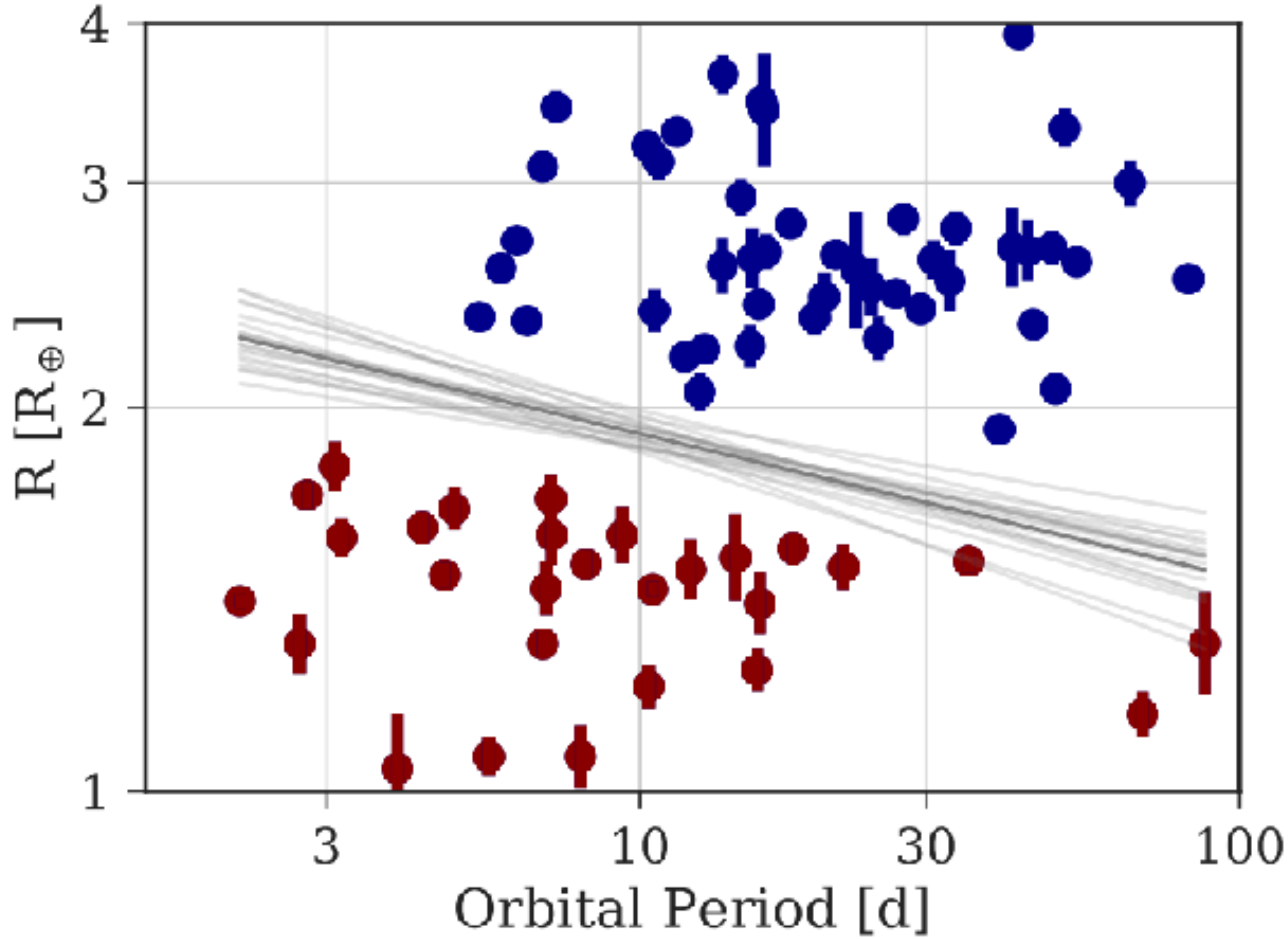


Planet's eastern and western limbs may have different spectra (not yet observed)

Planets are complicated

III. Time evolution

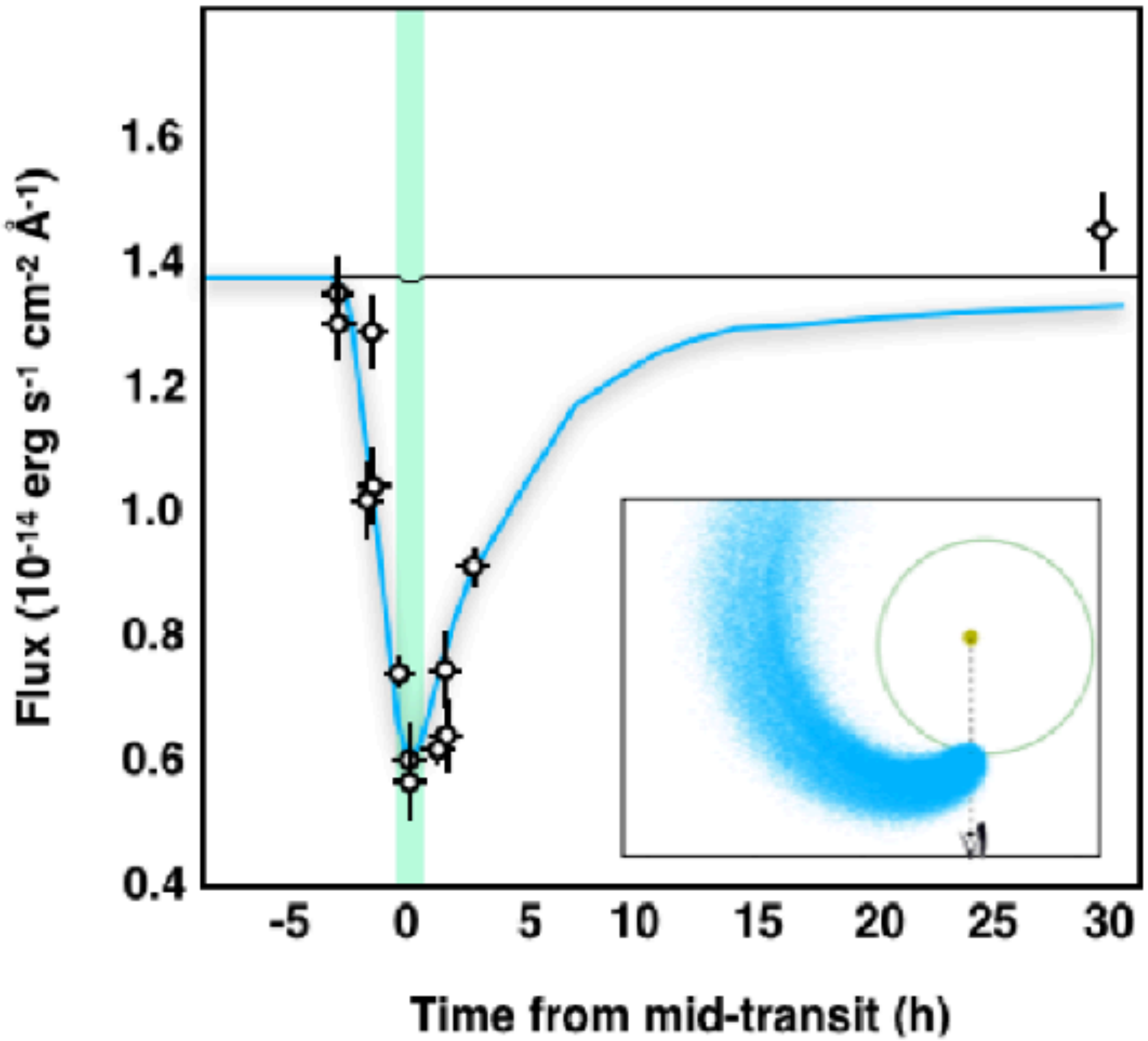
Van Eylen et al. 2017



Photoevaporation can entirely strip atmospheres

Planets are complicated

III. Escaping atmospheres have been caught in the act



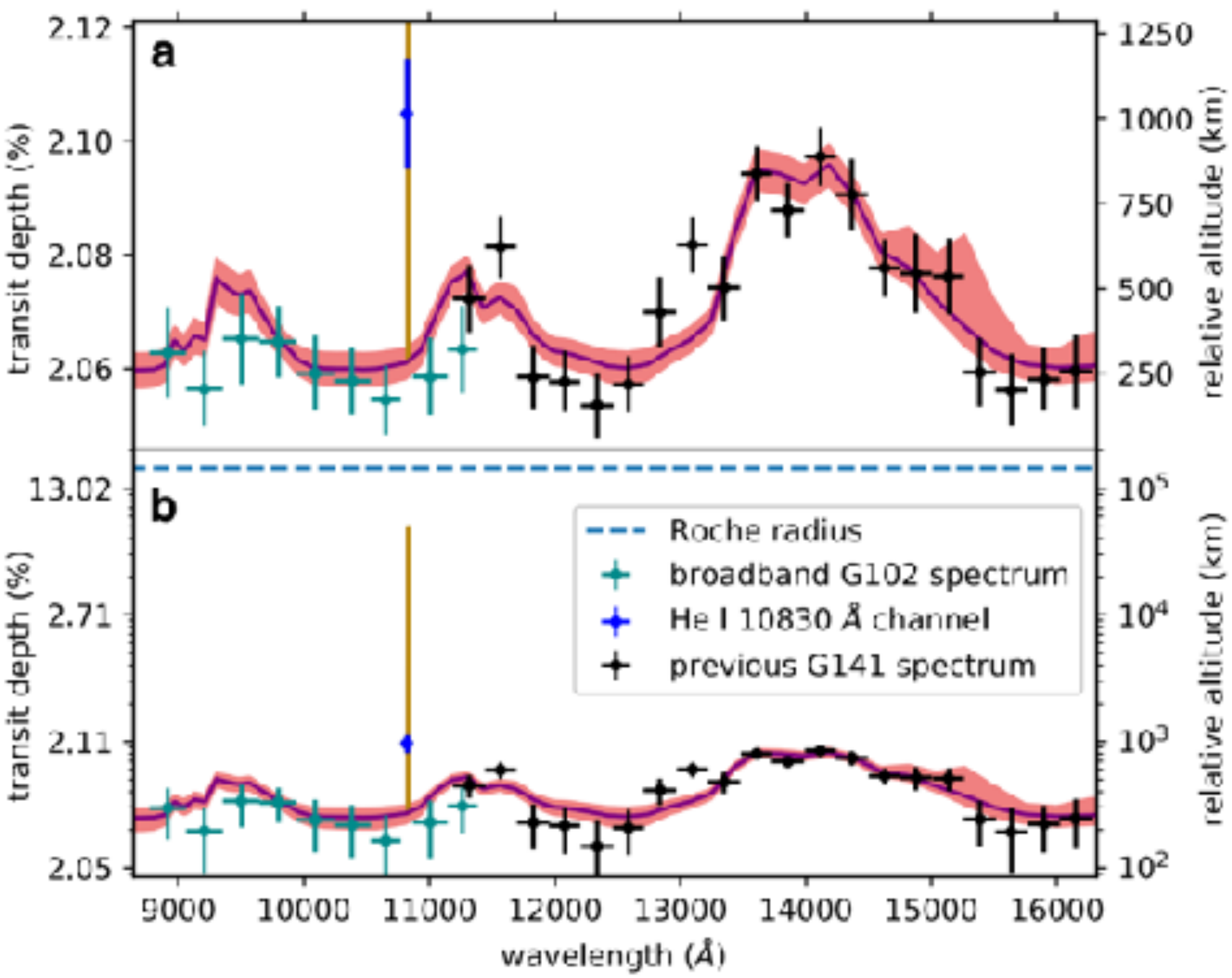
Lyman-alpha transit of GJ 436b

Adapted from Ehrenreich et al. 2015, Nature

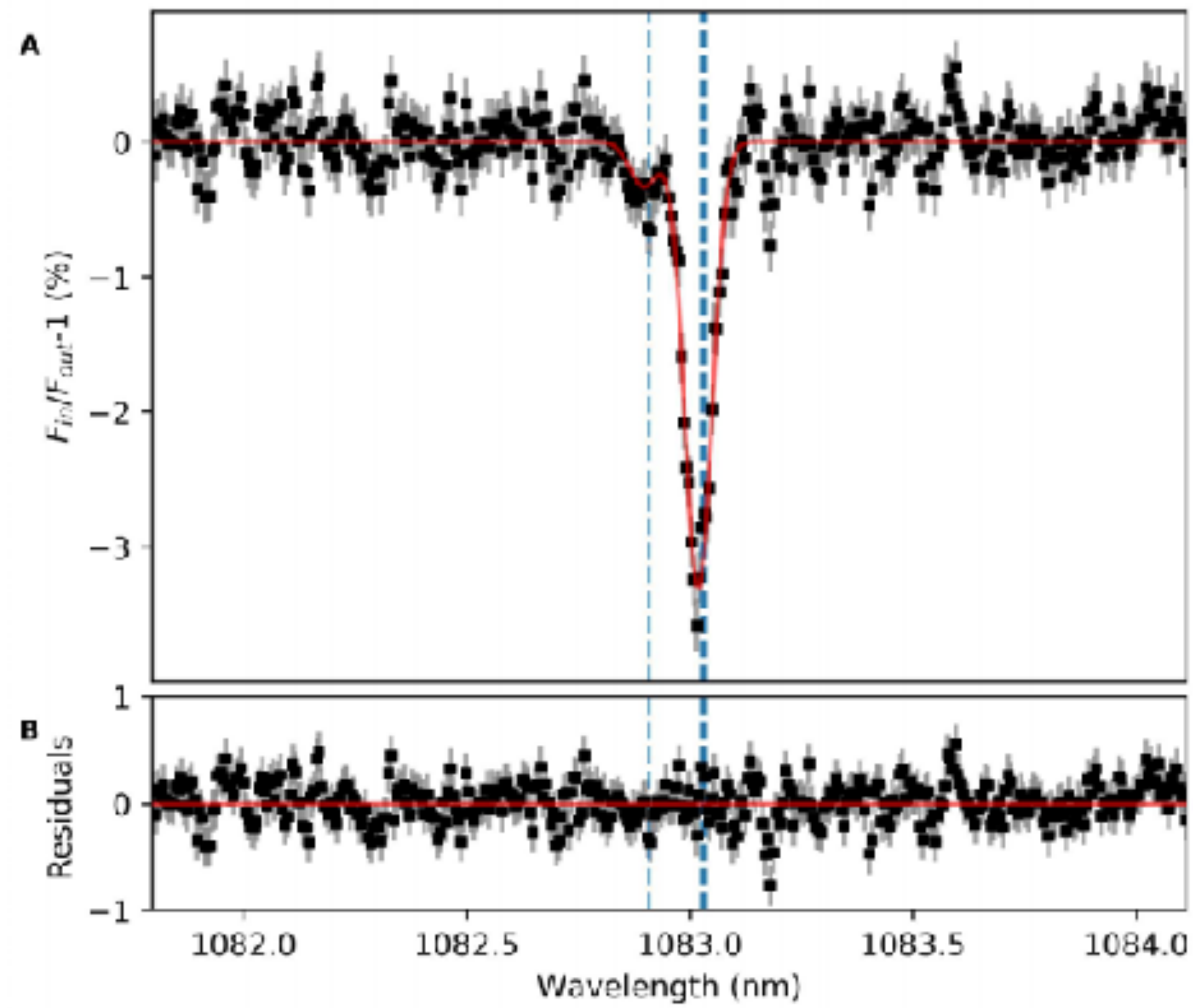
Planets are complicated

III. He 10830 Å is a powerful new probe of atmosphere loss

Spake et al. 2018, Nature



Nortmann et al. 2018, Science



+ Allart et al. 2018, Salz et al. 2018, Mansfield et al. 2018, Alonso-Floriano et al. 2019…

Frontiers in Exoplanet Atmosphere Characterization

II. First thermal phase curves for small exoplanets

Mercury ✗
(1e-15 bar)

Venus ✓
(100 bar)

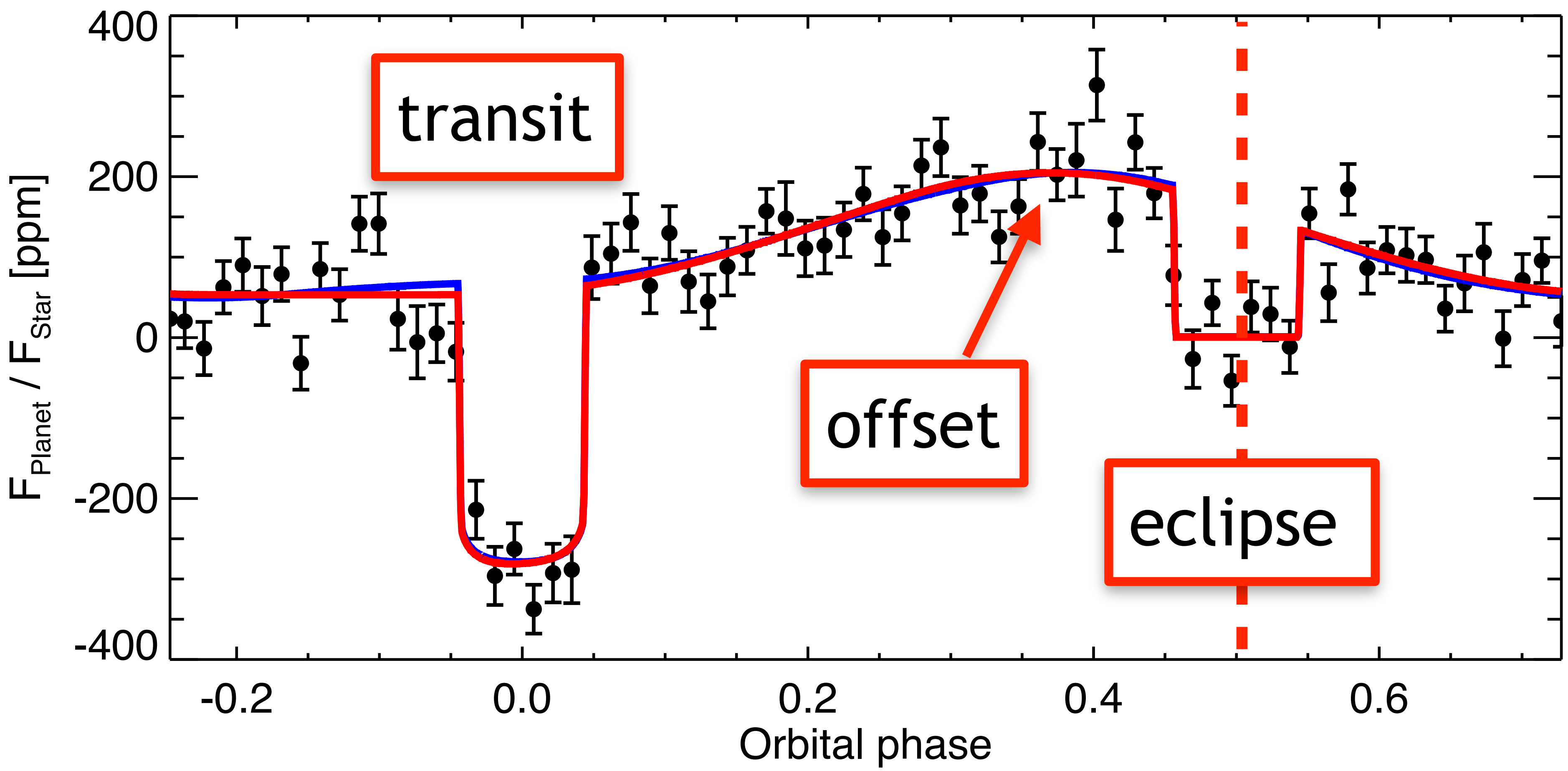
Earth ✓
(1 bar)

Mars ✗
(0.1 bar)

Frontiers in Exoplanet Atmosphere Characterization

II. First thermal phase curves for small exoplanets

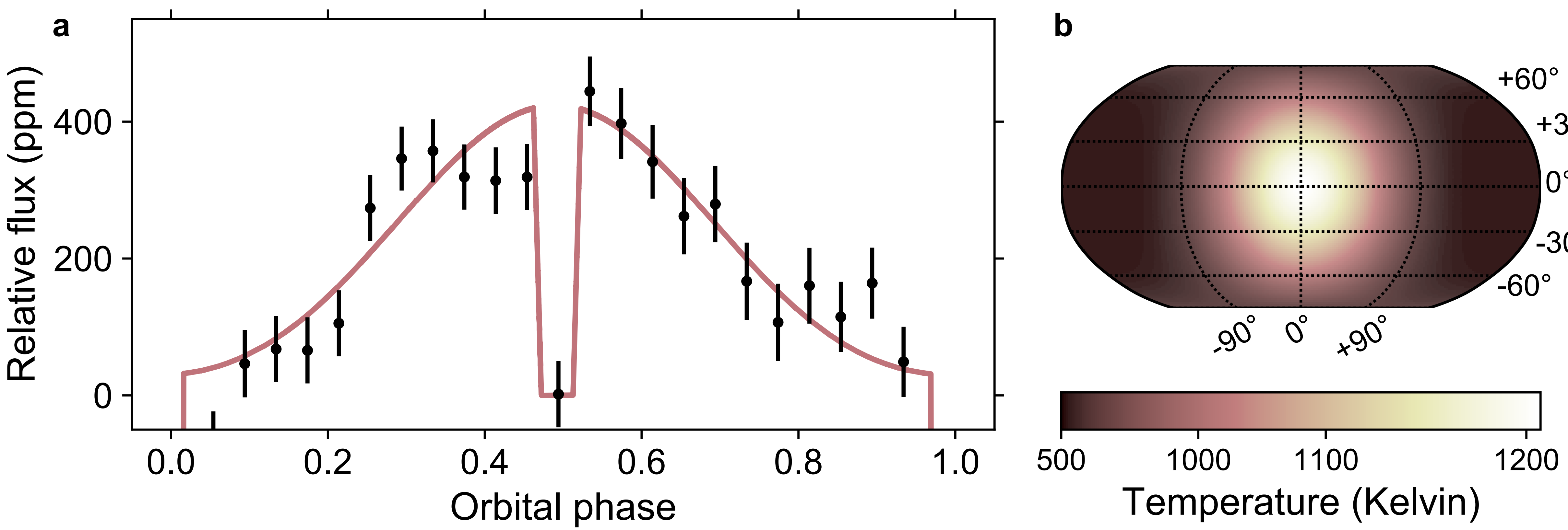
Demory et al. 2016, Nature



Offset hotspot hints at atmospheric circulation

Frontiers in Exoplanet Atmosphere Characterization

II. First thermal phase curves for small exoplanets



- Lack of heat circulation for LHS 3844b rules out surface pressures >10 bar
- Thinner atmospheres are unstable

Kreidberg et al. 2019, Nature

+gargantuan modeling effort from Koll, Morley, Hu, & Schaefer, et al.

Lots to look forward to in coming decades

Planet are complicated!

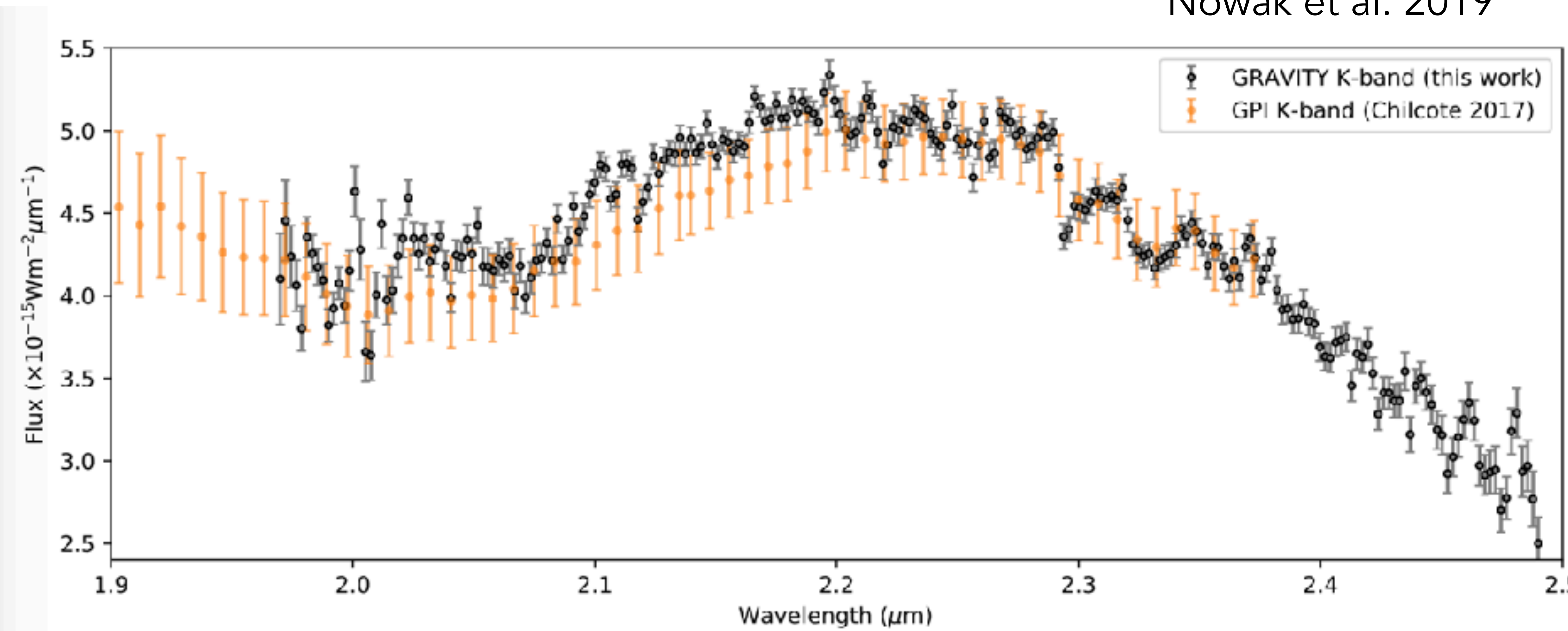
- Their chemistry is likely out of equilibrium
  - Cloud formation
  - Mixing
- They are 3D
  - Chemistry, climate, clouds all change with position
- They are dynamic over a wide range of timescales
  - Weather (short-term)
  - Accretion / evaporation (long-term)

Need a large sample of high quality spectra and sophisticated theory to disentangle all these effects

A new era of ground-based facilities

K-band interferometry with VLTI/GRAVITY

Nowak et al. 2019



Atmospheric C/O of Beta Pic b is 0.43 +/- 0.5

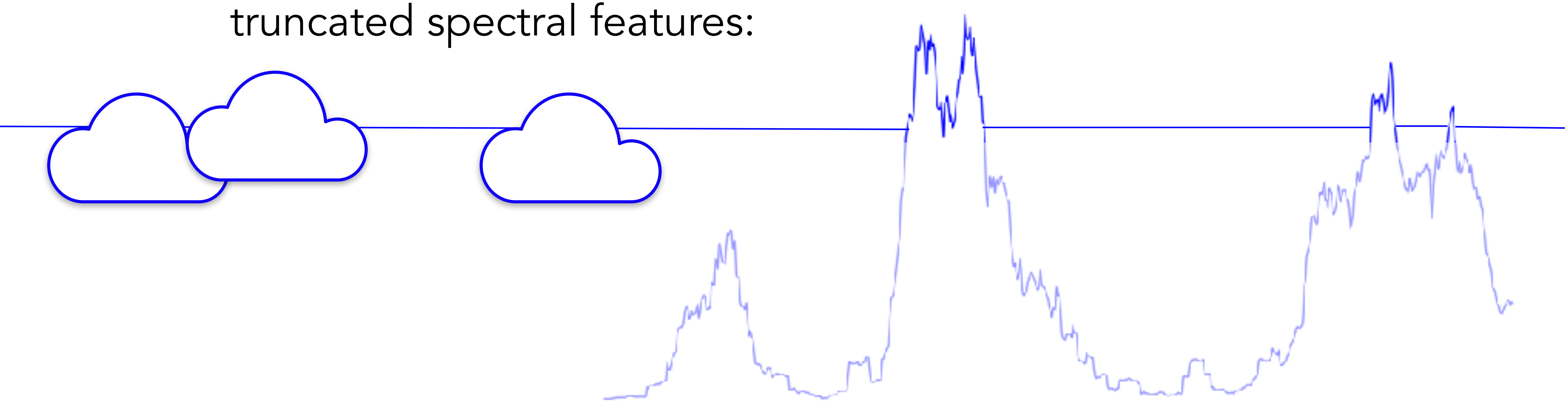
Suggests core accretion and lots of planetesimal enrichment

Planets are complicated

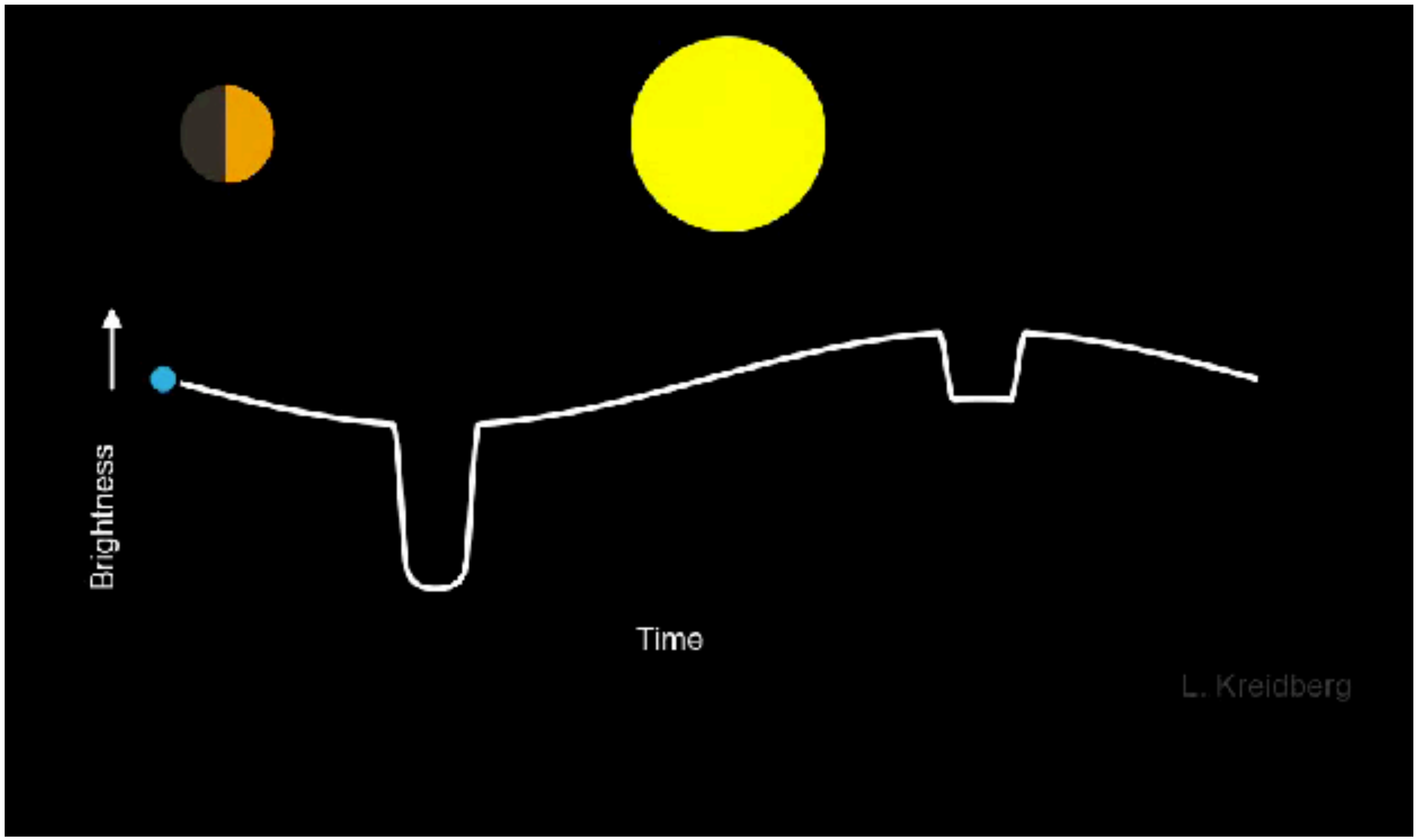
I. Clouds + haze

- All solar system planets with substantial atmospheres have clouds
- Are they also present in exoplanets? (hint: yes)

Tell-tale signature of clouds is truncated spectral features:



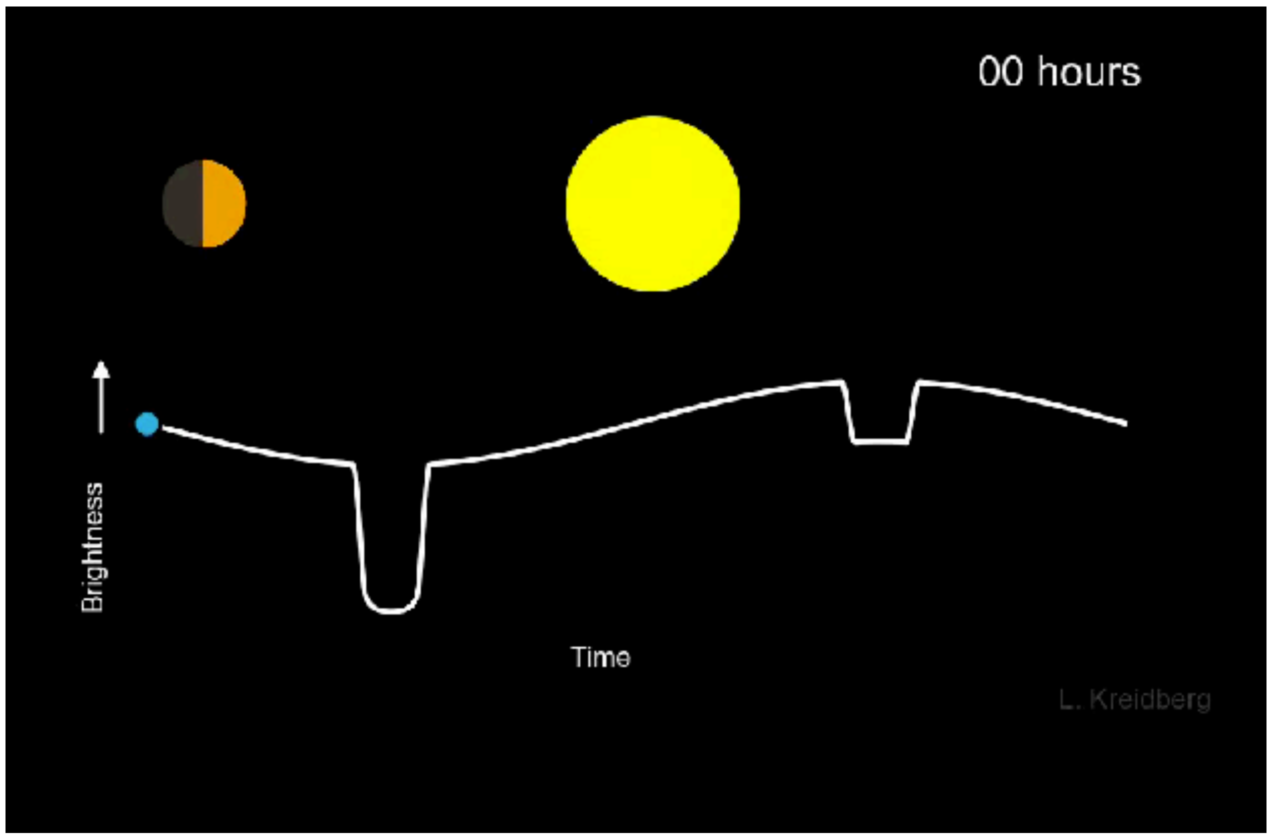
Atmosphere Characterization II:
Thermal Phase Curves

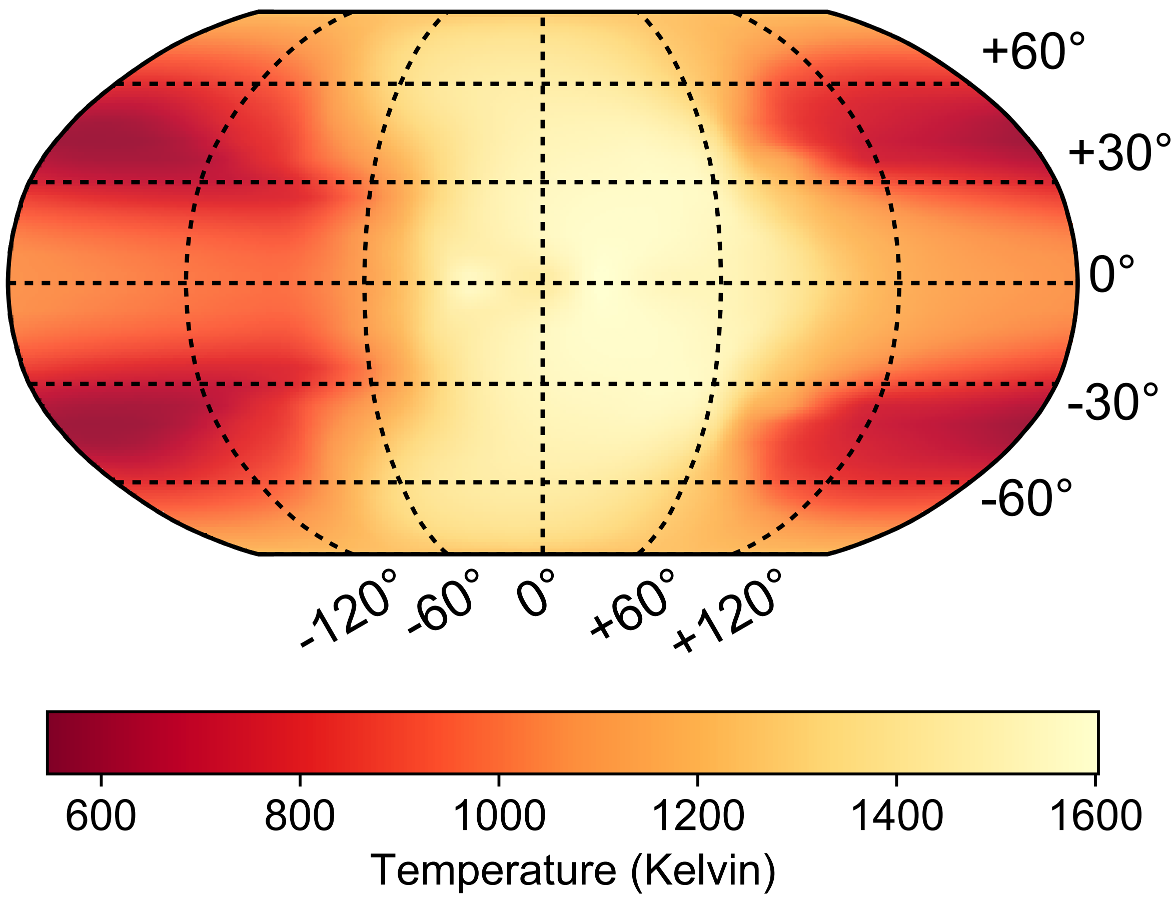


- Sensitive to temperature structure, chemical composition
- NOT spatially resolved — planet separated from star by ~nanoradians

Frontier #2:

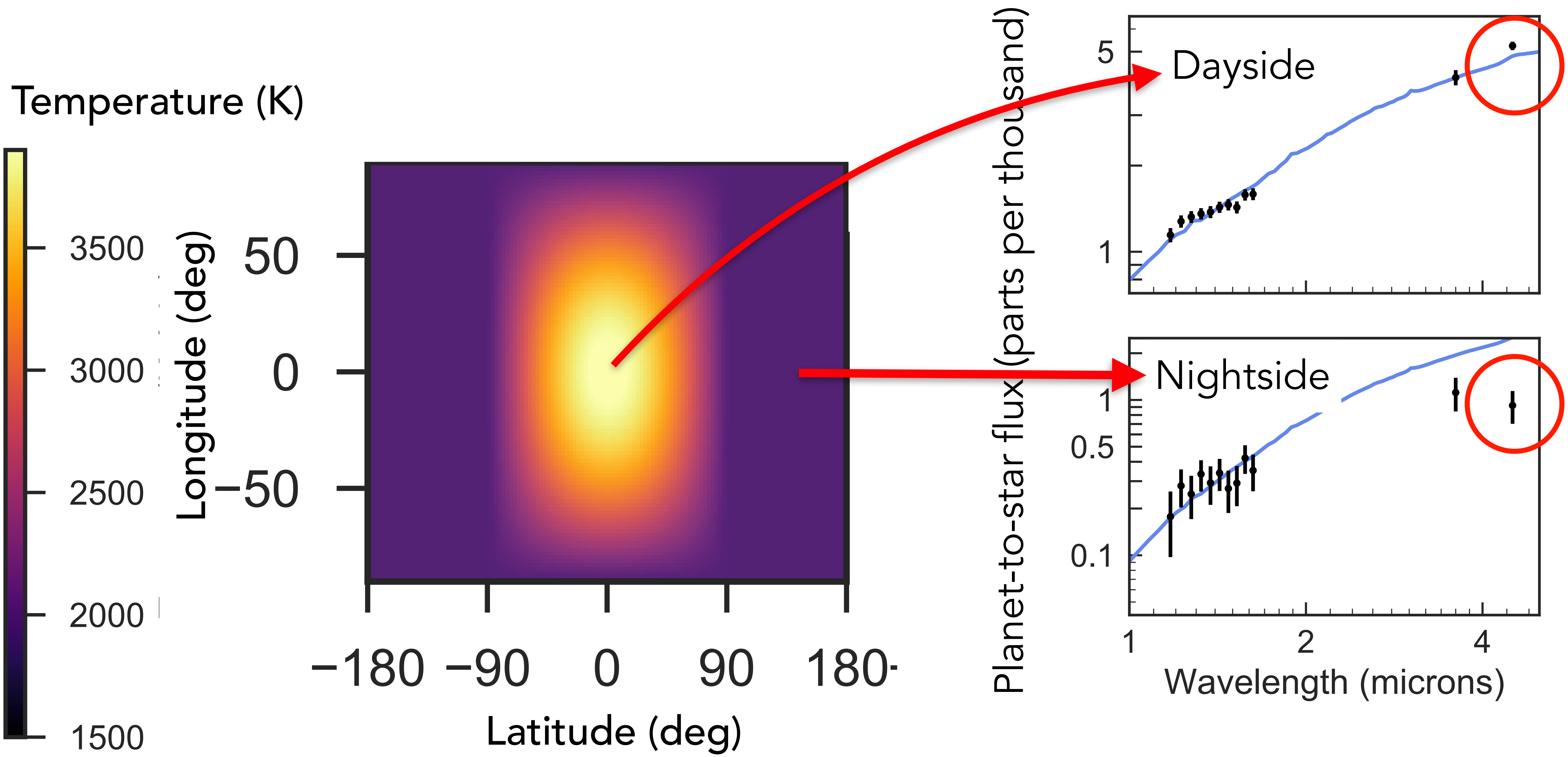
Exploring exoplanet atmospheres in 3D





What is the temperature/chemistry at a given latitude, longitude, and altitude?

A climate map for the ultra-hot Jupiter WASP-103b from Hubble + Spitzer phase curves



- Large day-to-night temperature contrast of 2000 K
- Dayside inversion (stratosphere) caused by stellar heating
- No heat source on nightside —> no inversion

Cloud deck pressure is 0.1 mbar or lower

Possibly made of salts/sulfides, photochemical soots