The Pursuit of A Meticulous Chemical Survey of Exoplanet Atmospheres

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Expectation

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Reality

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Reality

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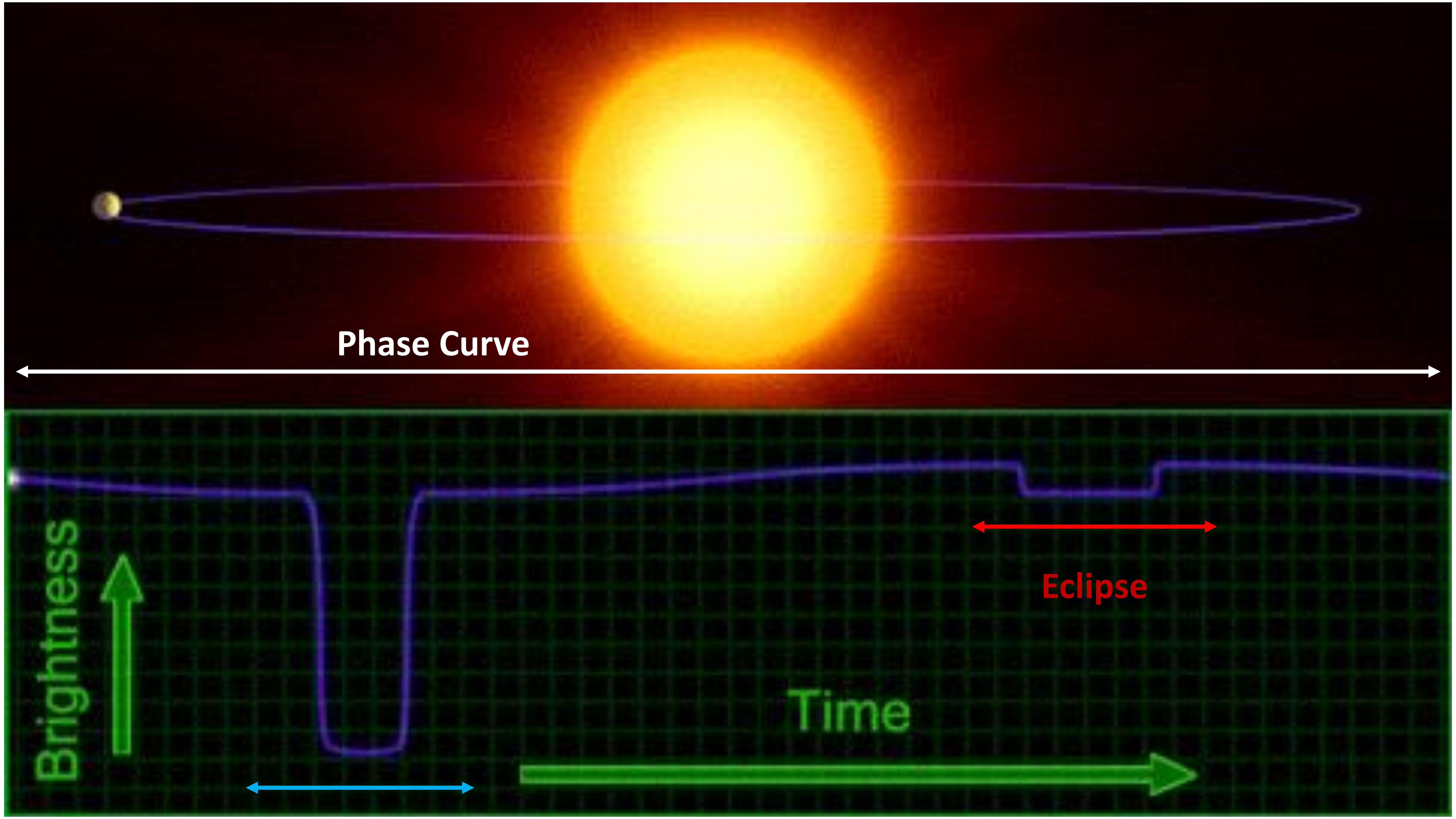
Summary of Topics

- Introduction to current space-based datasets
- Potential issues with combining data from different instruments
- Importance of target selection
- Biases in current retrieval methods
- Opportunities offered by phase-curves

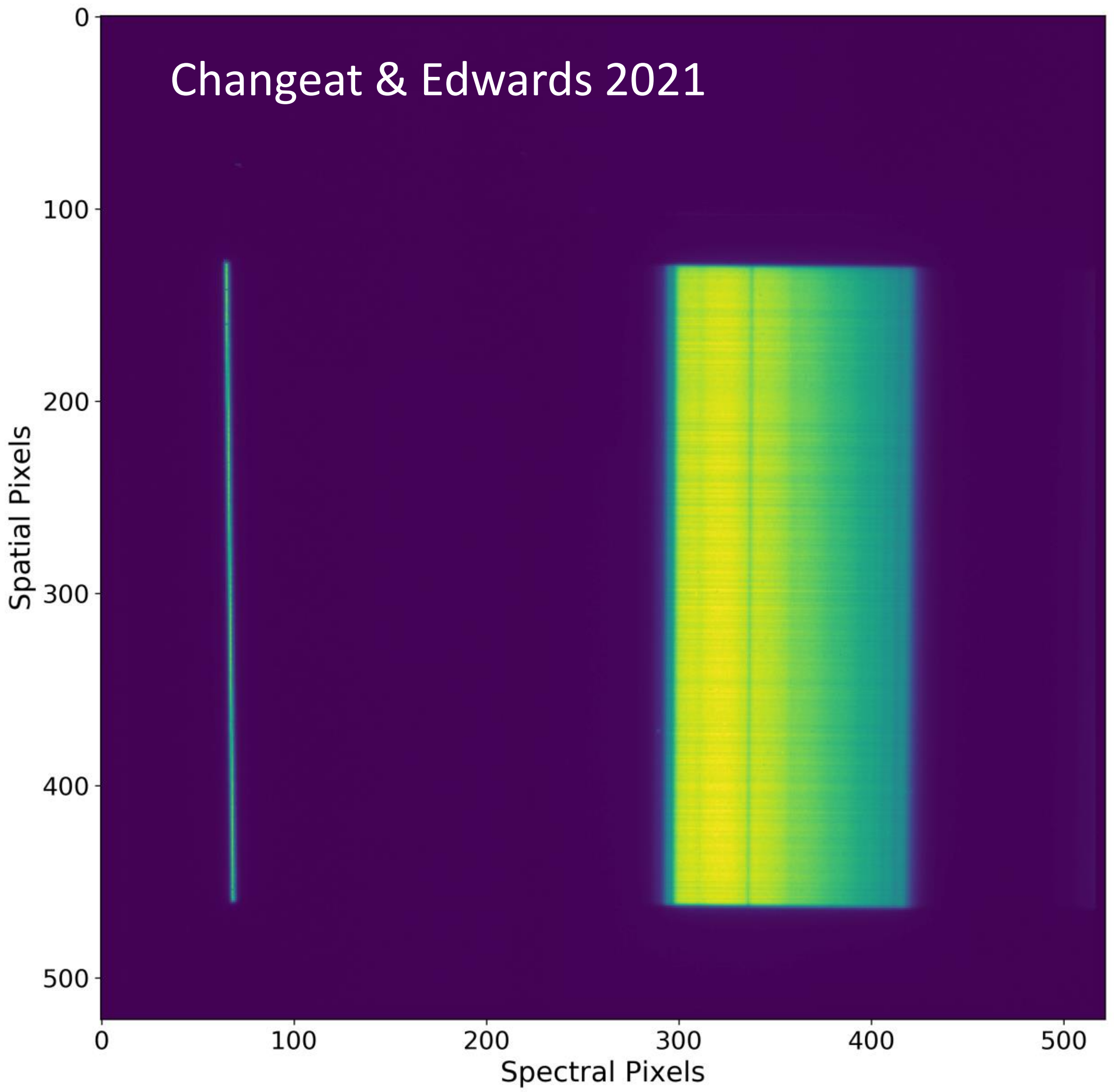
Observing Methods

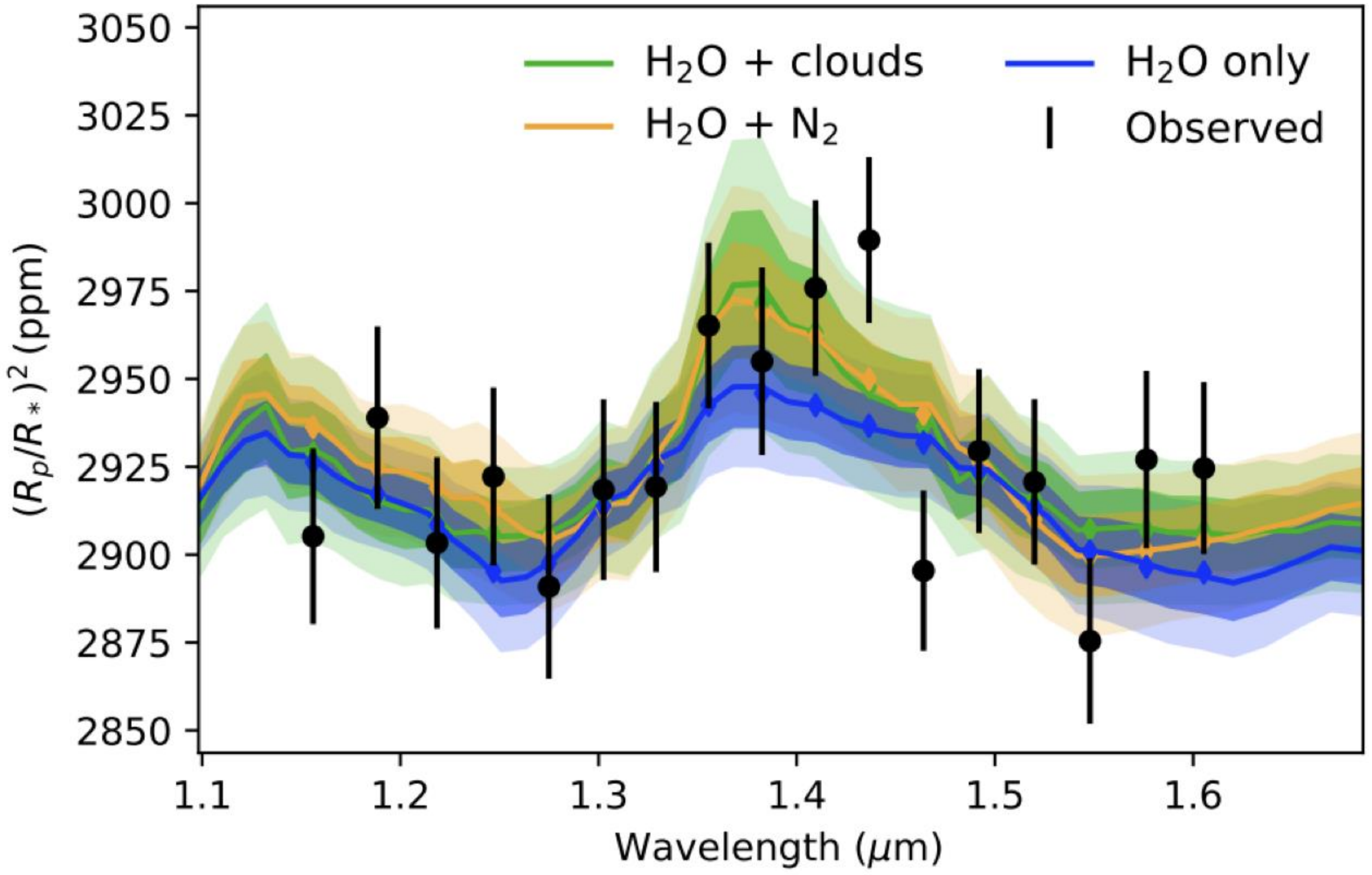


Transit

Observing Atmospheres with HST WFC3

- Not designed to observe exoplanet atmospheres
- Yet spatial scan technique widely used to do so
- ~60 planets in transit, ~25 in eclipse

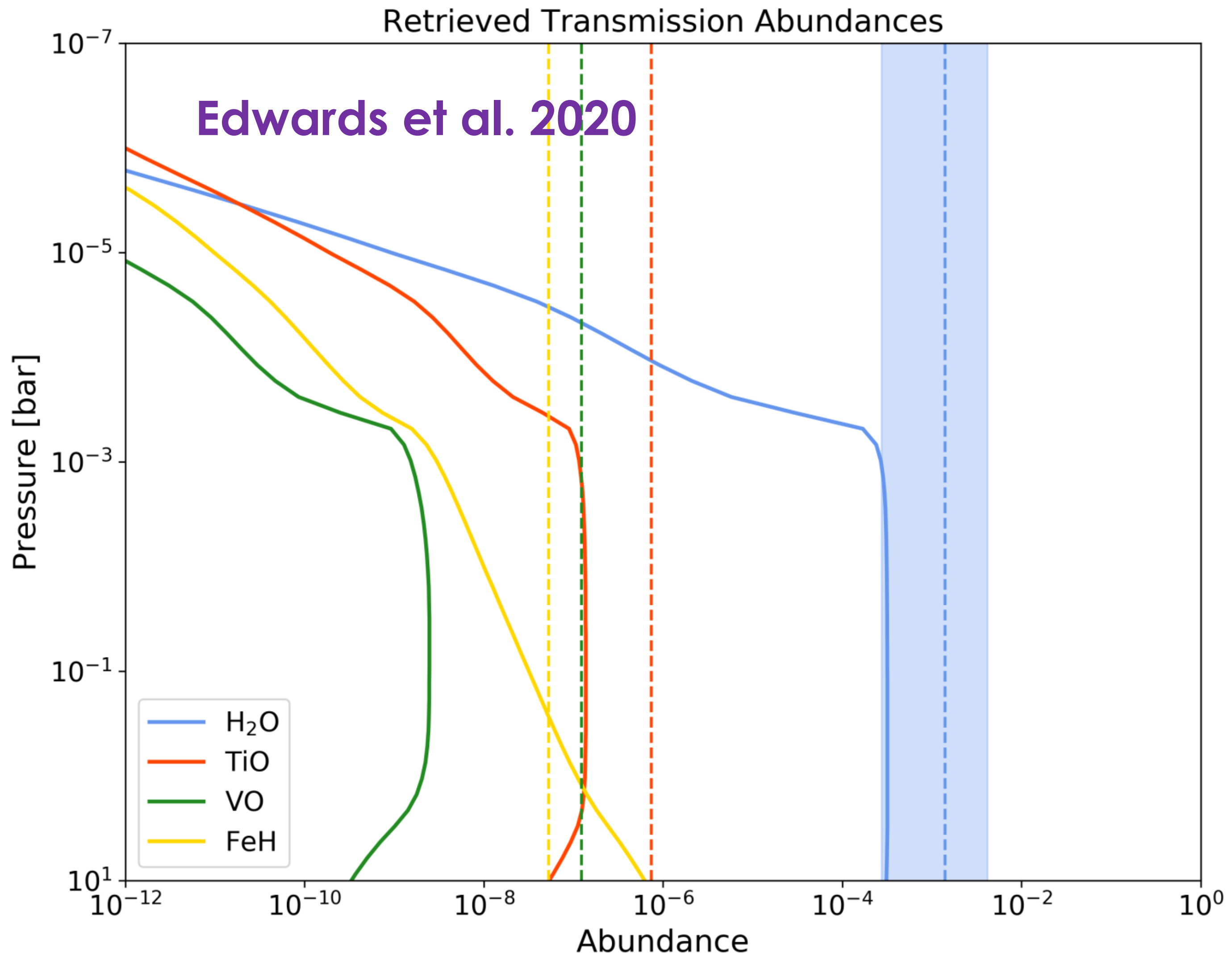


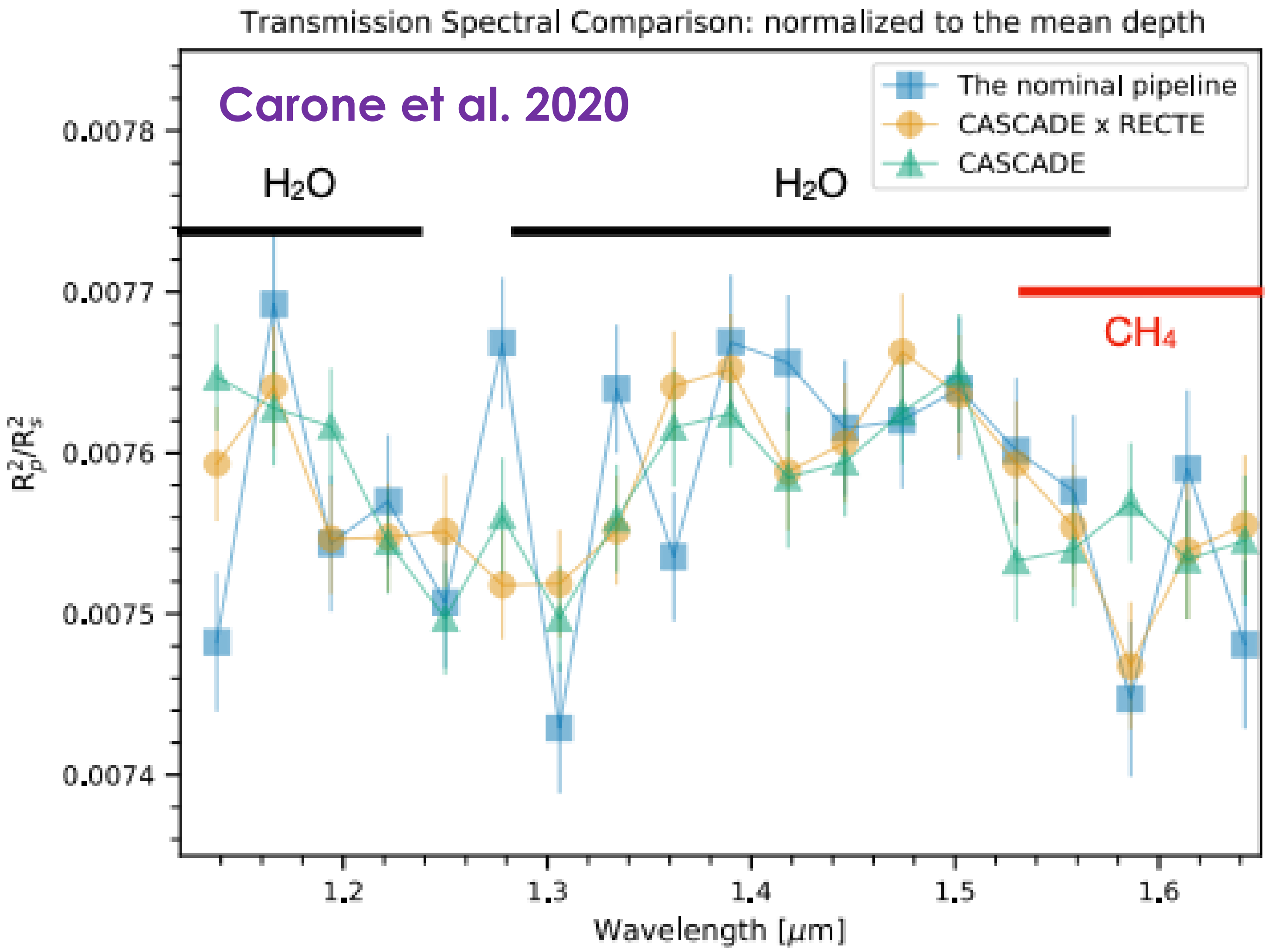


Tsiaras et al. 2019

Observing Atmospheres with HST WFC3

- Difficult to measure abundances of species other than H_2O
- Some indications of TiO/VO/FeH (e.g. Evans et al. 2018, Skaf et al. 2020)
- CH_4 not detected in cooler planets (e.g. Anisman+ 2020, Carone+ 2020)

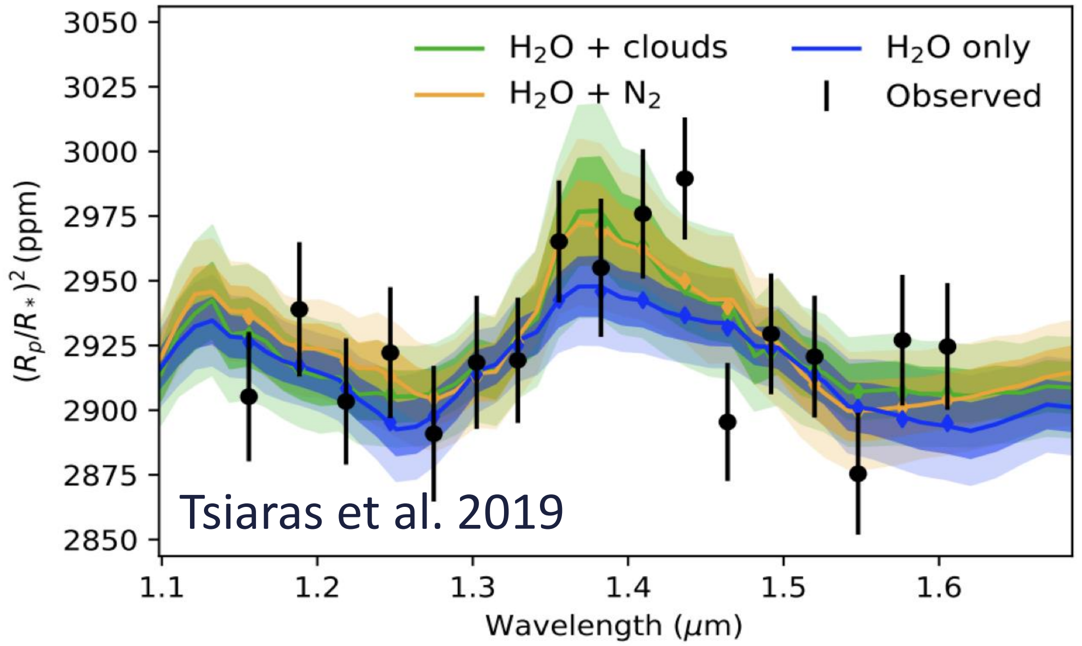




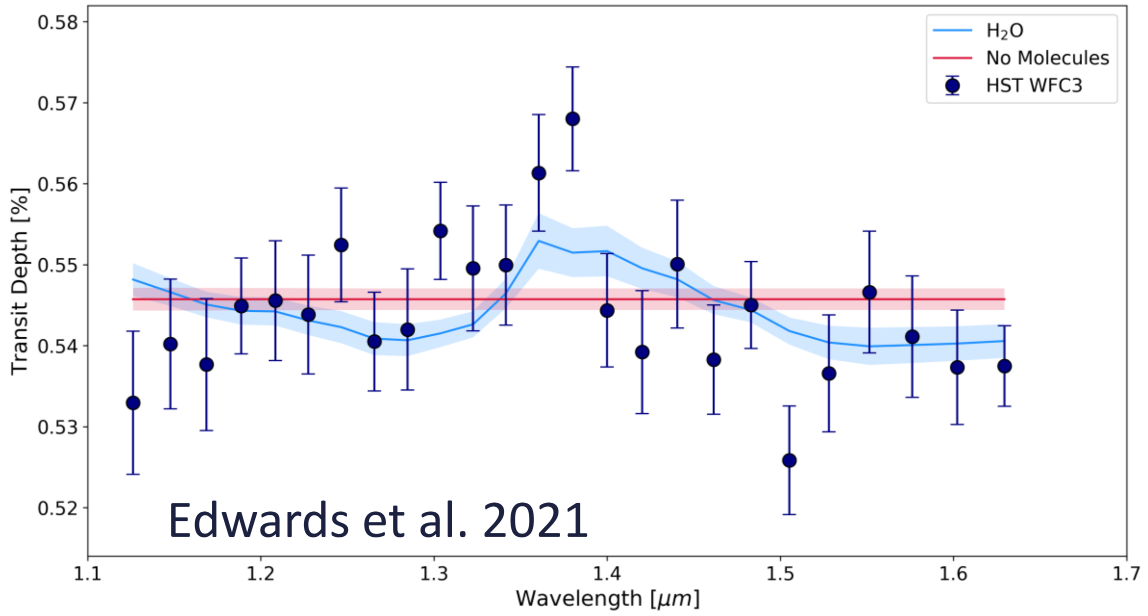
Observing Atmospheres with HST WFC3

- Recently, large number of observations of smaller worlds

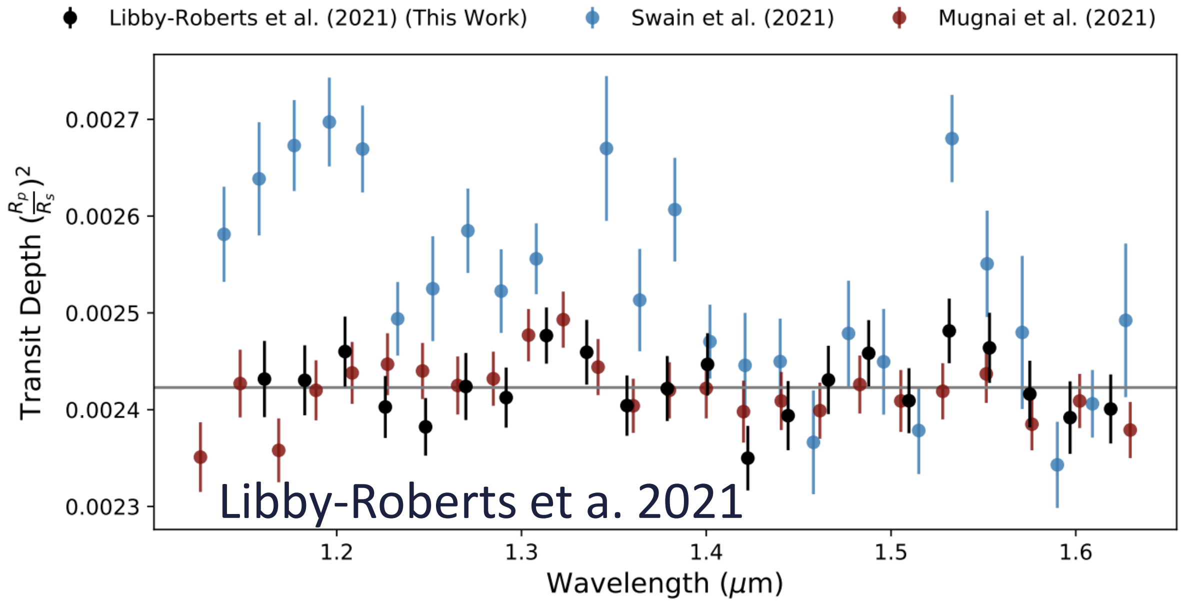
K2-18 b



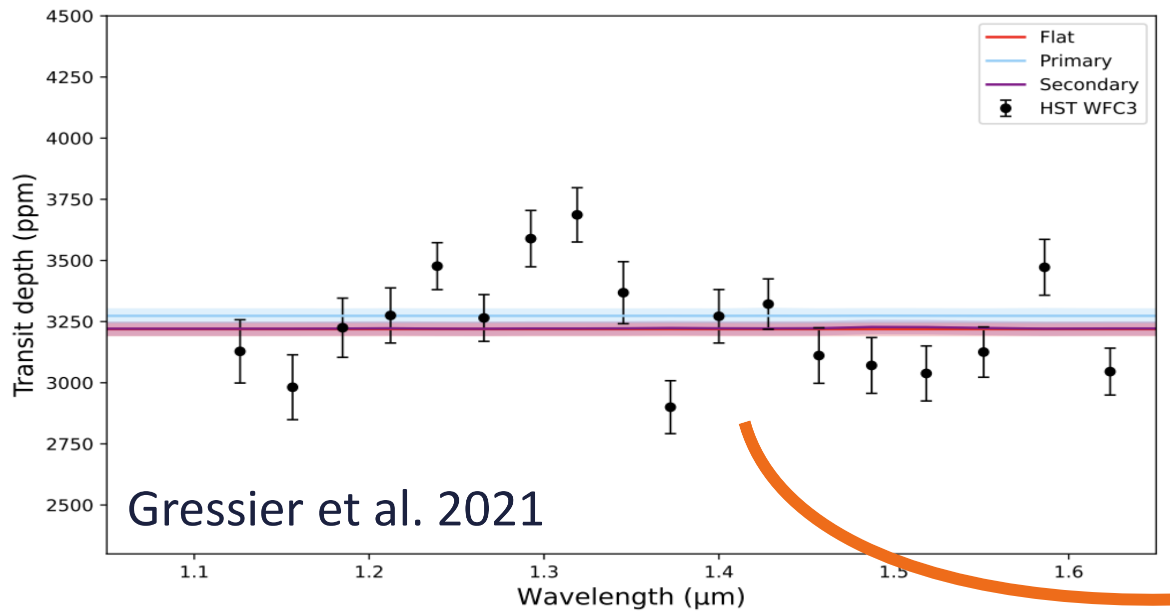
LHS 1140 b



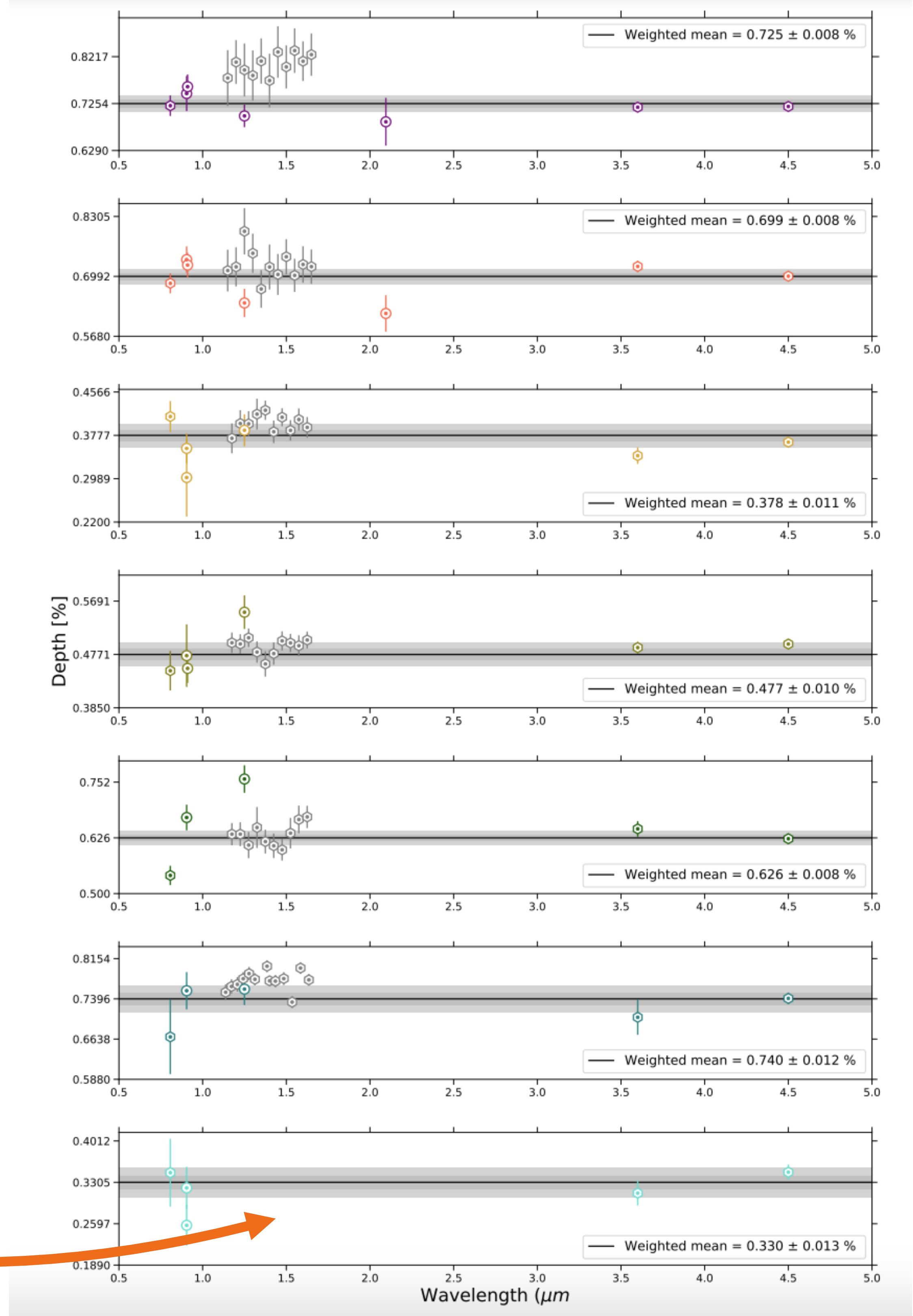
GJ 1132 b



TRAPPIST-1 h



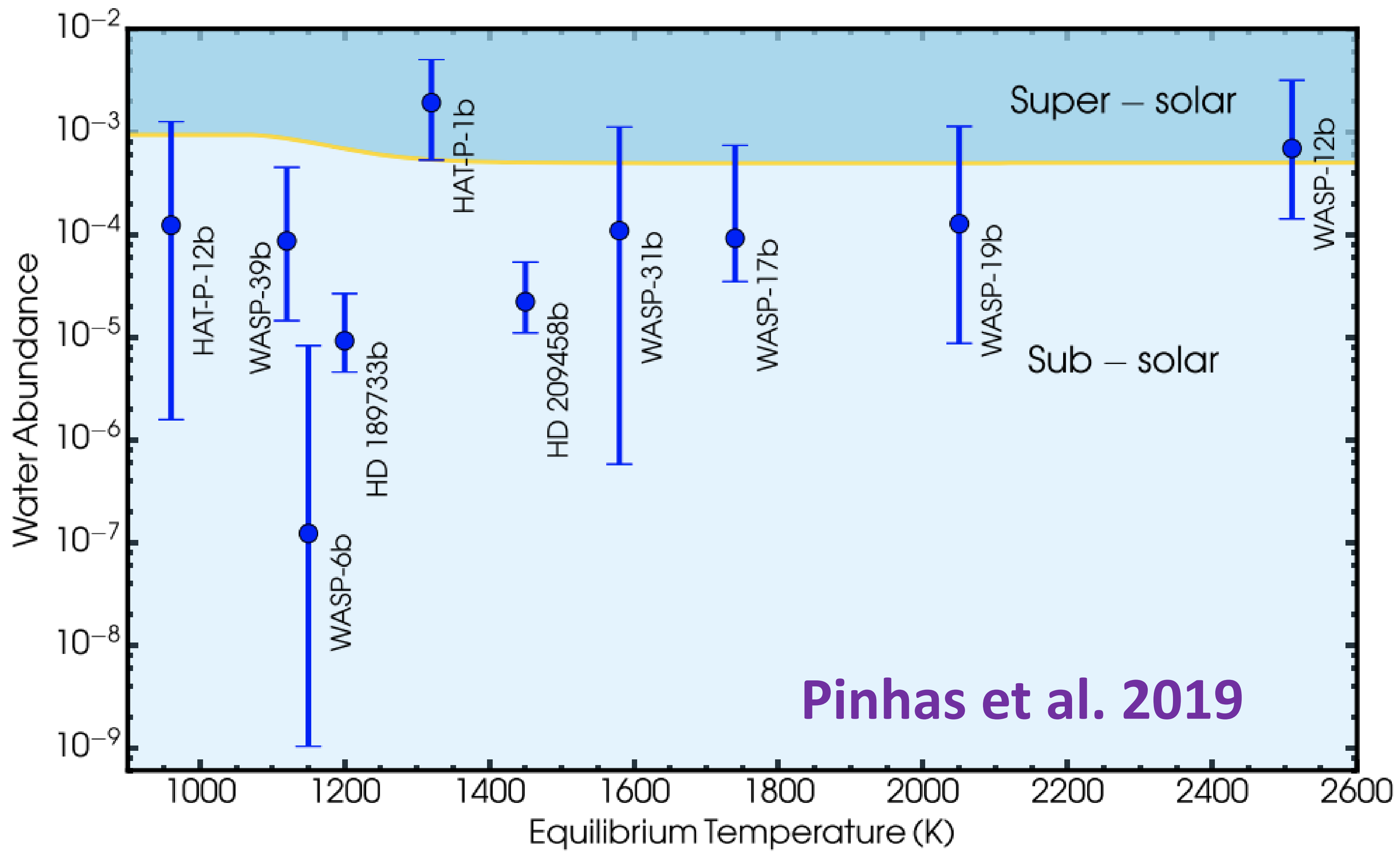
TRAPPIST-1 b-h

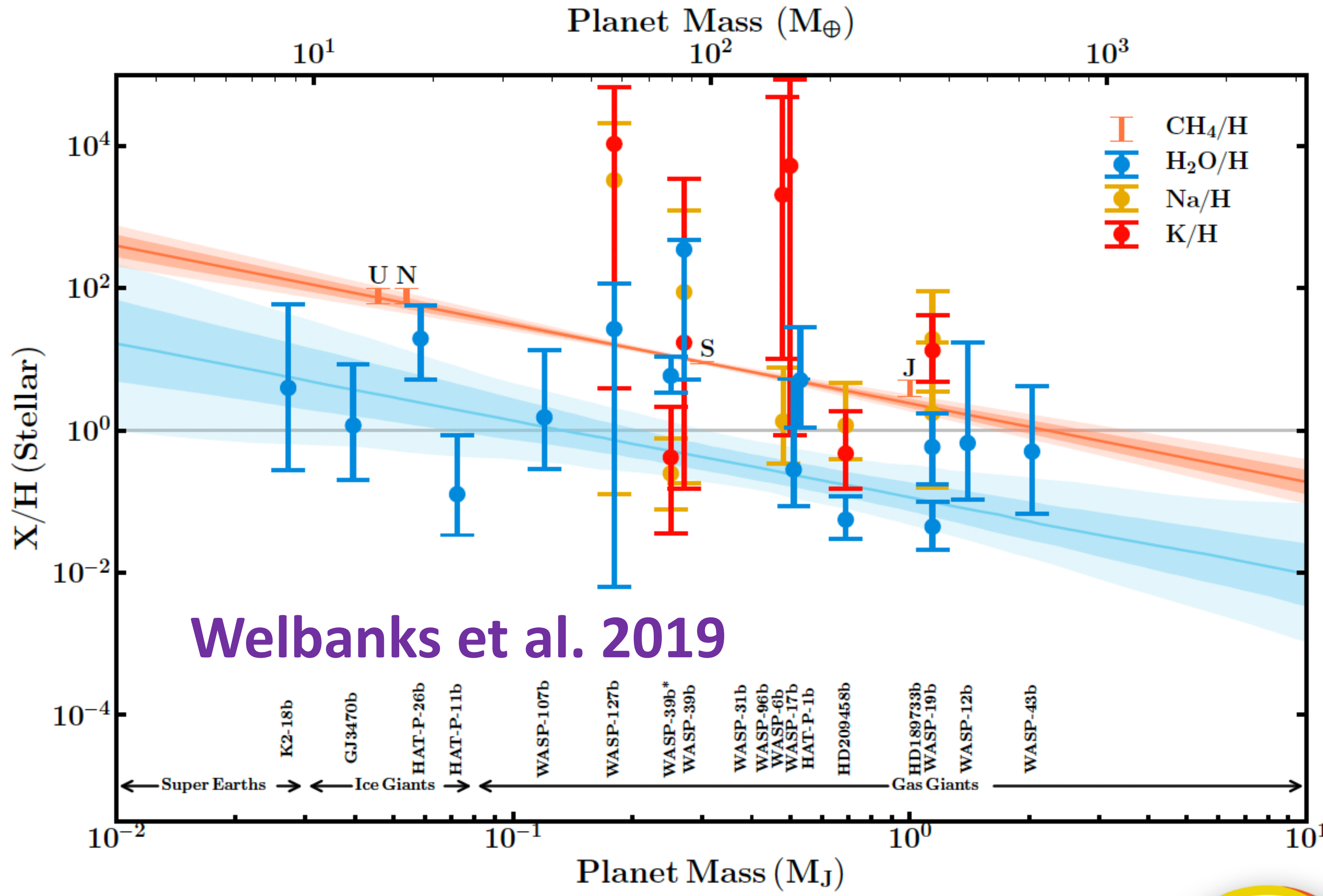


See Amelie's talk for more!

Outcomes of Studying Exoplanet Atmospheres

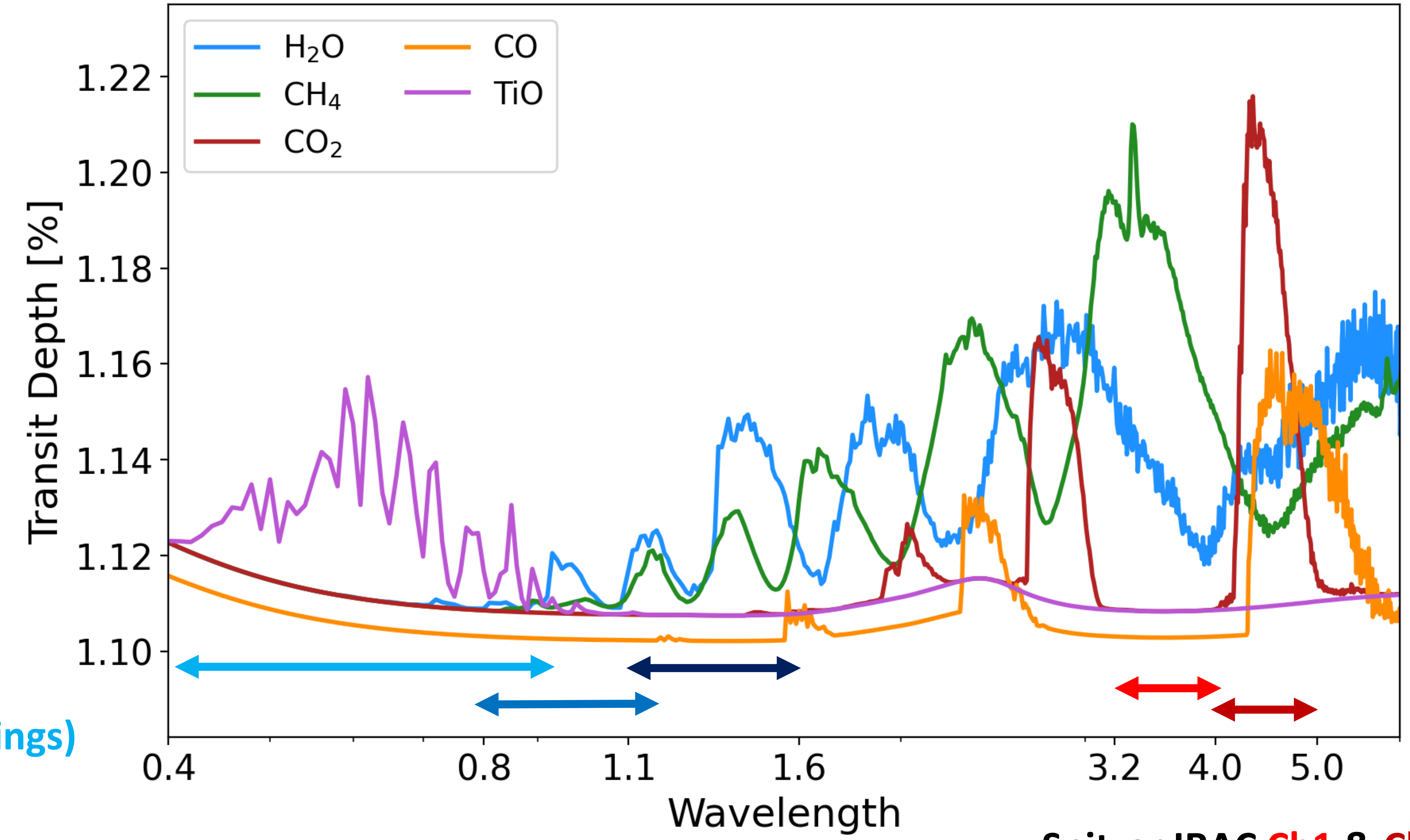
- Constrain chemistry and elemental ratios (e.g. C/O), temperature-profile
- Look for chemical trends with bulk parameters (e.g. mass-metallicity)
- Some population studies attempted (e.g. Sing+2016, Tsiaras+2018)
- Results can be limited by narrow wavelength coverage





Need for a Wide Wavelength Coverage

- Molecules absorb at different wavelengths
  - Pre-JWST space-based instruments only cover narrow range



HST STIS (various gratings)

HST WFC3 G102 and G141

Spitzer IRAC Ch1 & Ch2 (photometric)

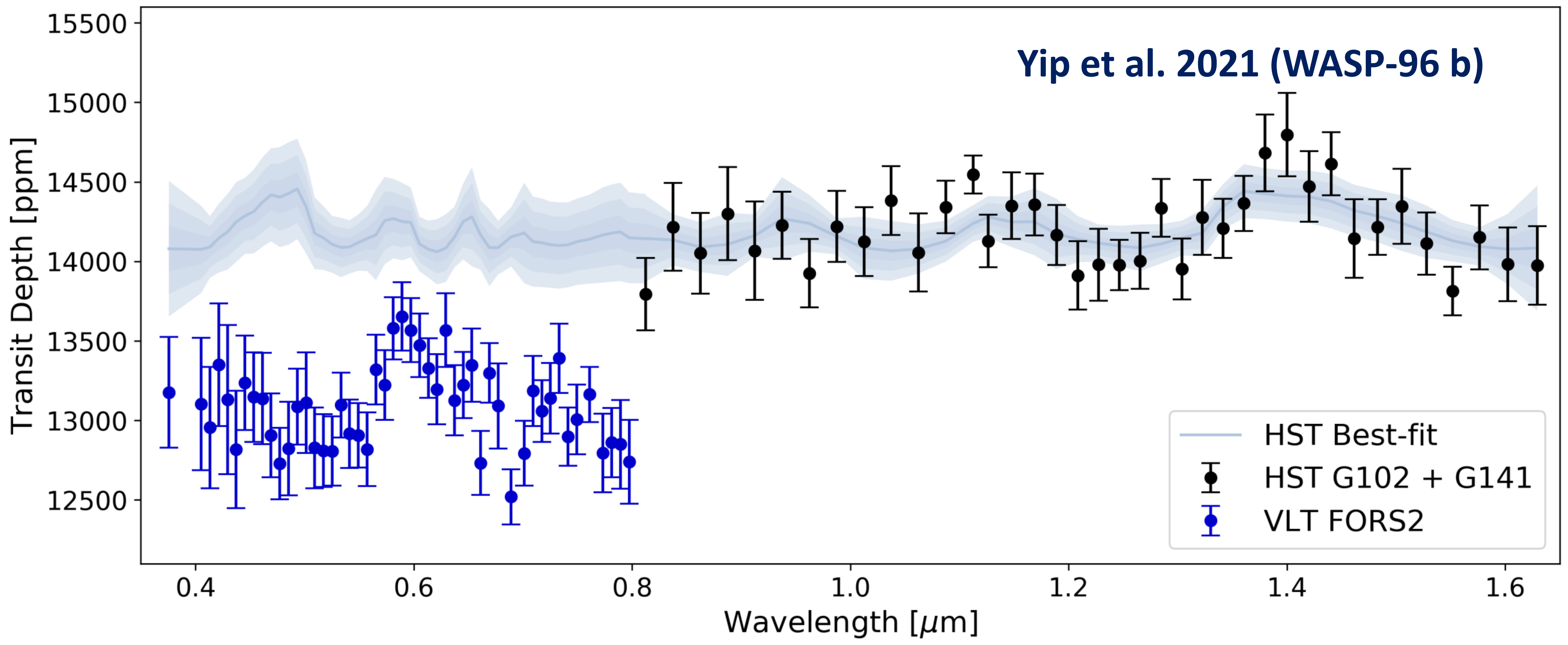
Common solution:

Combine data from different instruments...

(e.g. the majority of low resolution studies of exoplanet atmospheres)

Combining Instrument: Potential Offsets

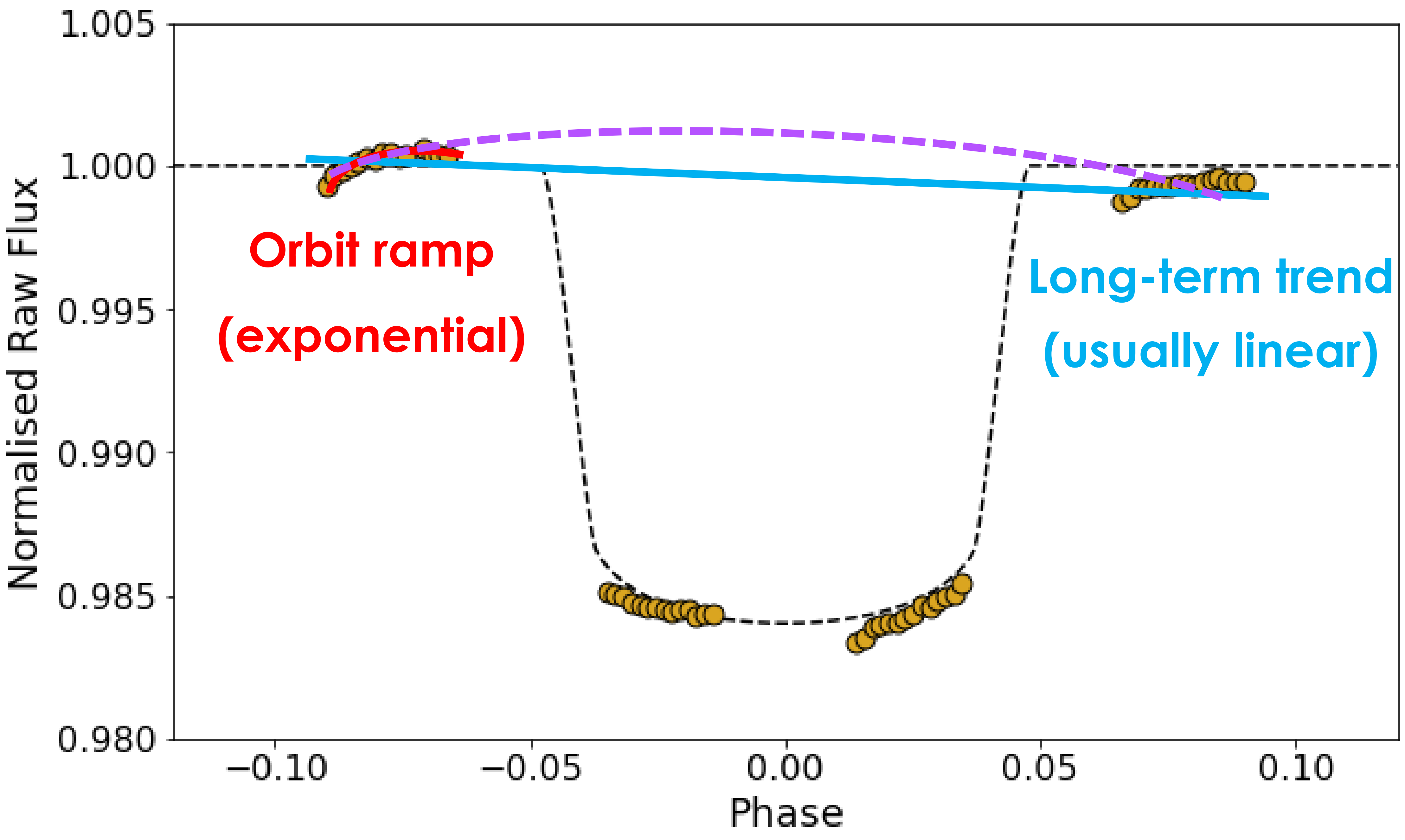
- Datasets are not guaranteed to be compatible



Why might offsets in mean transit depth occur?

Combining Instrument: Potential Offsets

- Datasets are not guaranteed to be compatible
  - Choice of long-term WFC3 trend can change white light-curve depth

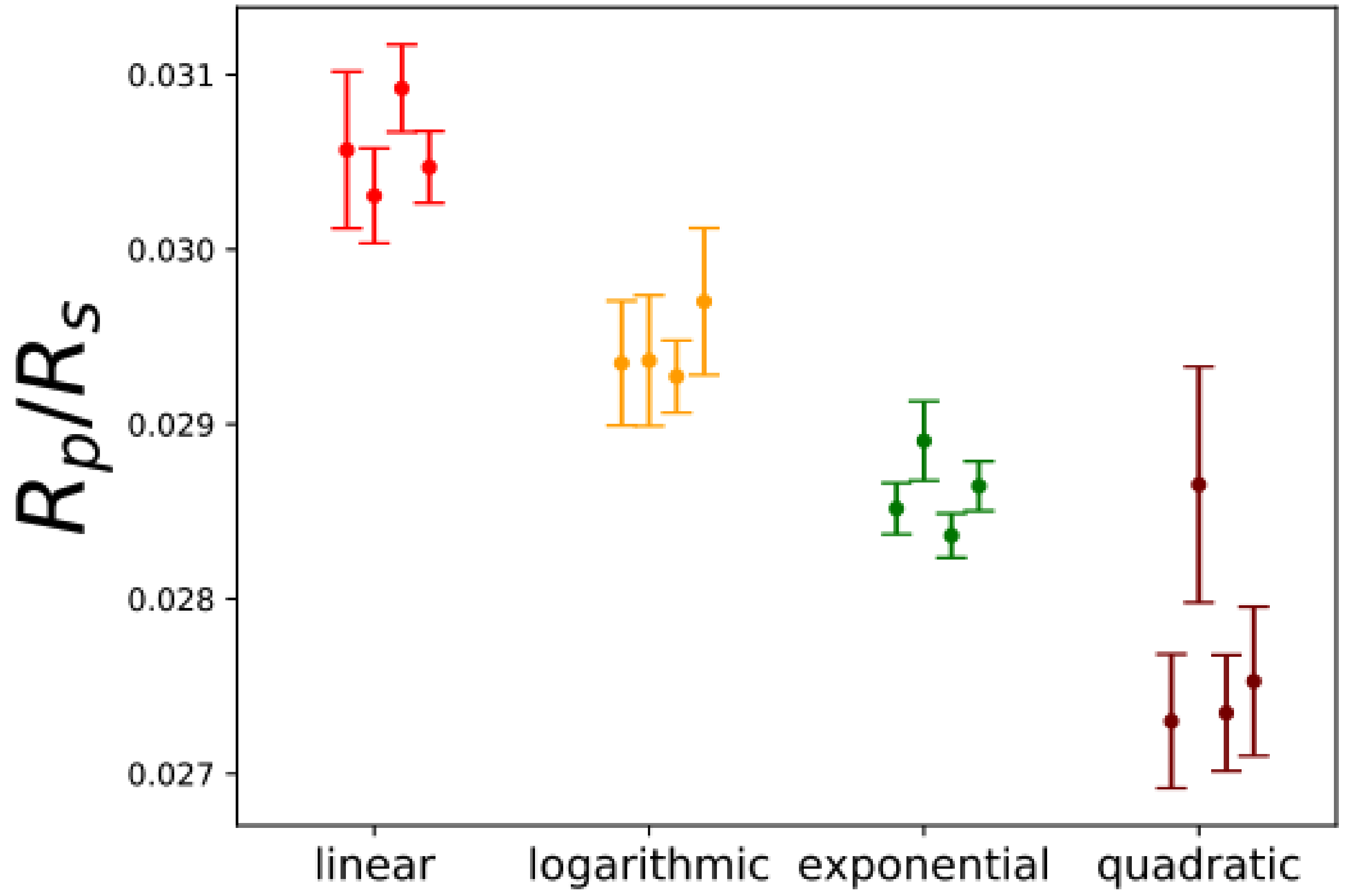


Sometimes other long-term trends are used (e.g. quadratic)

Combining Instrument: Potential Offsets

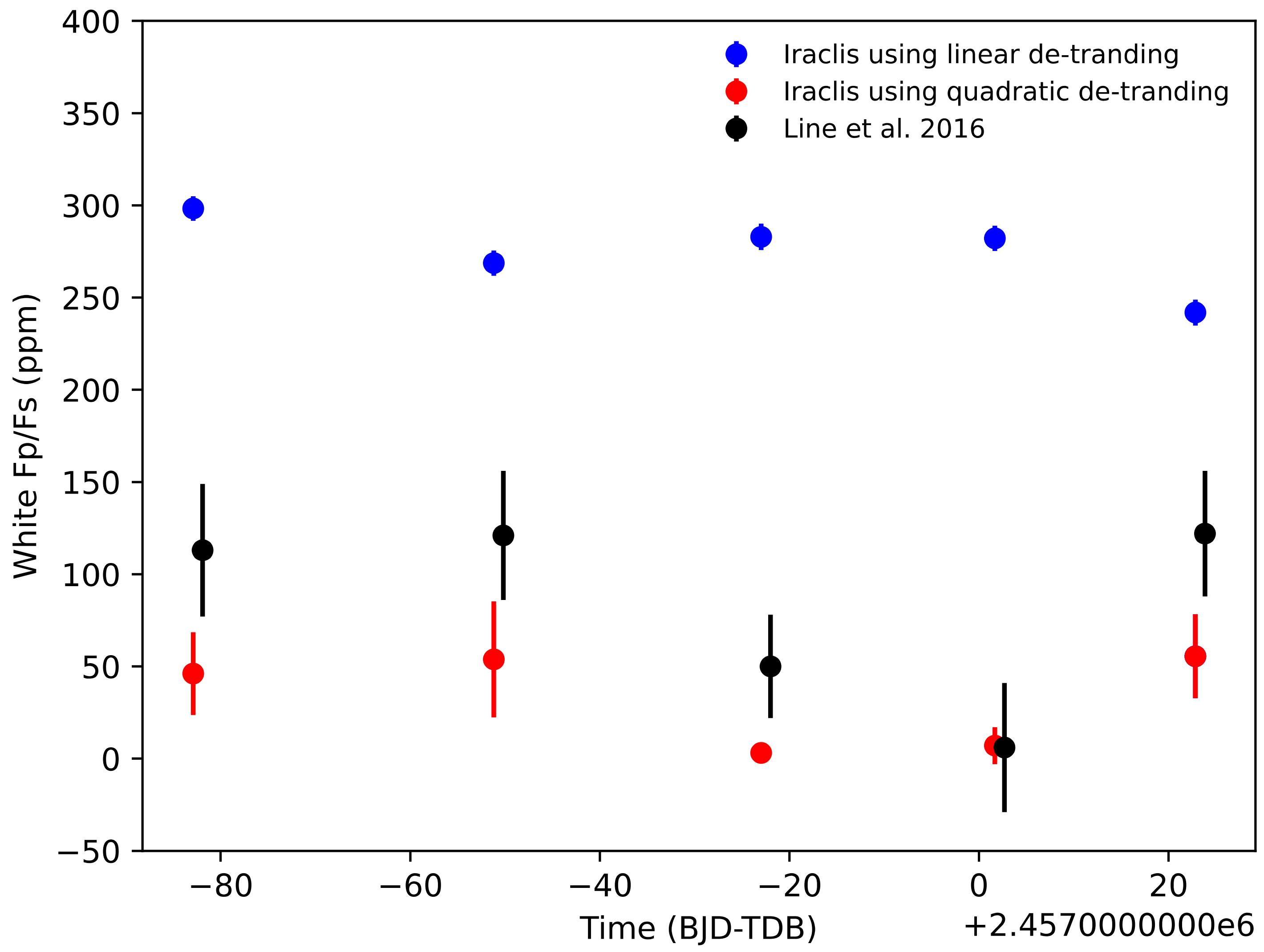
- Datasets are not guaranteed to be compatible
  - Choice of long-term WFC3 trend can change white light-curve depth

Guo et al. 2020 (HD 97658 b, HST WFC3 G141)



Long-term trend

A. Tsiaras, priv. com (HD 209458 b, HST WFC3 G141)

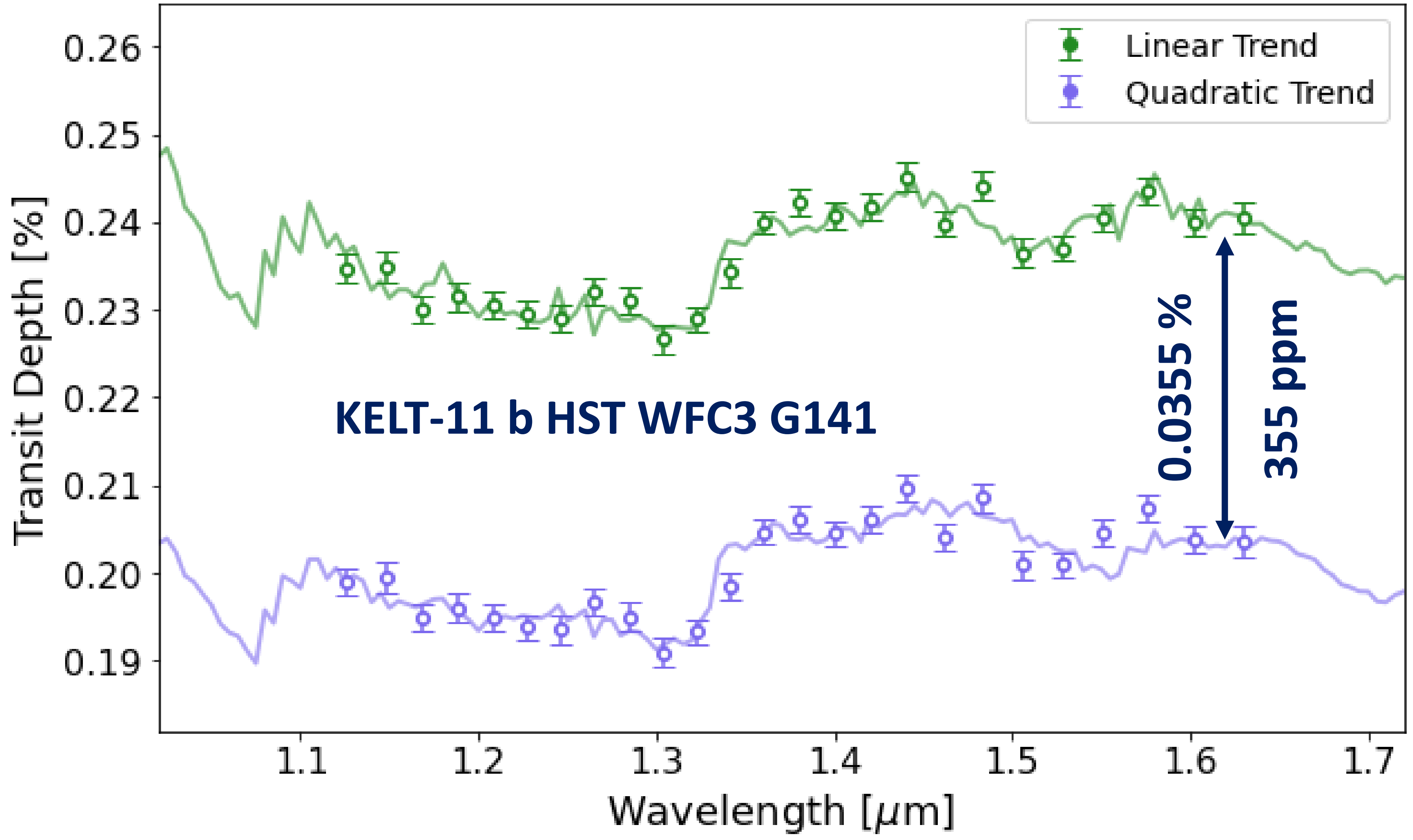


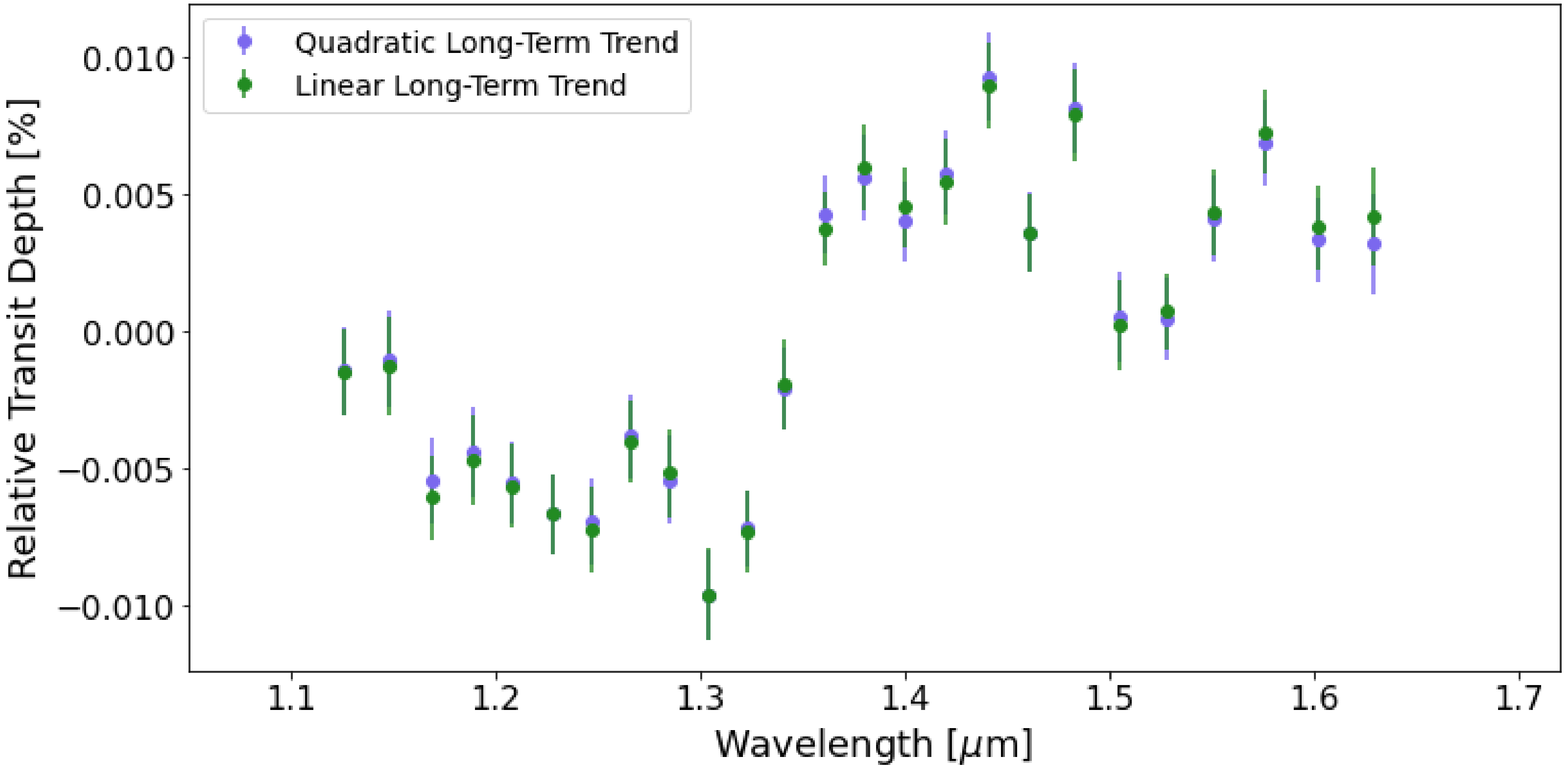
Pipeline used can also change mean depth (e.g. Colon et al. 2021, Mugnai et al. 2021, Mansfield et al. 2022)

Combining Instrument: Potential Offsets

- Datasets are not guaranteed to be compatible
  - Choice of long-term WFC3 trend can change white light-curve depth

Fit using Iraclis!





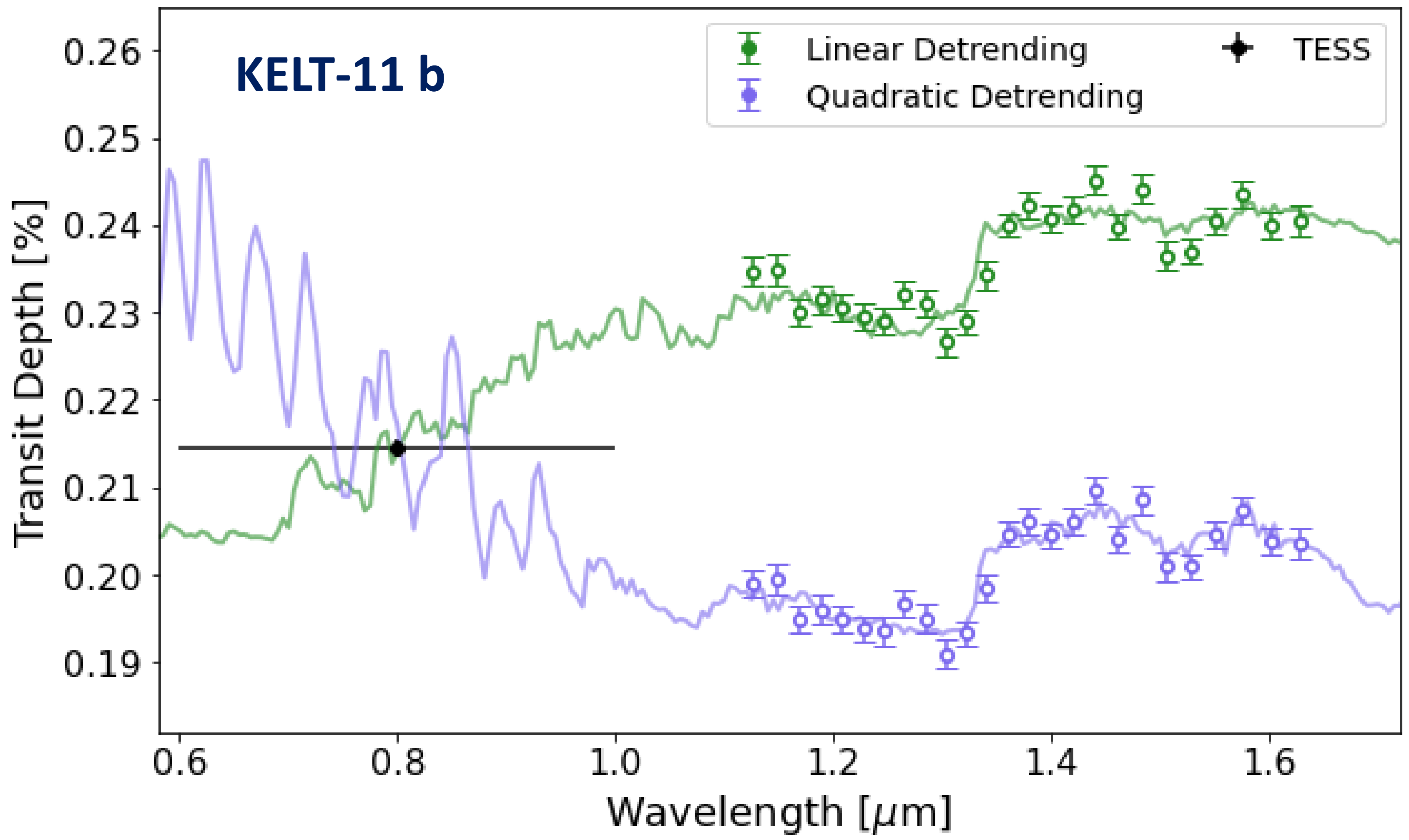
But spectral features are very similar…

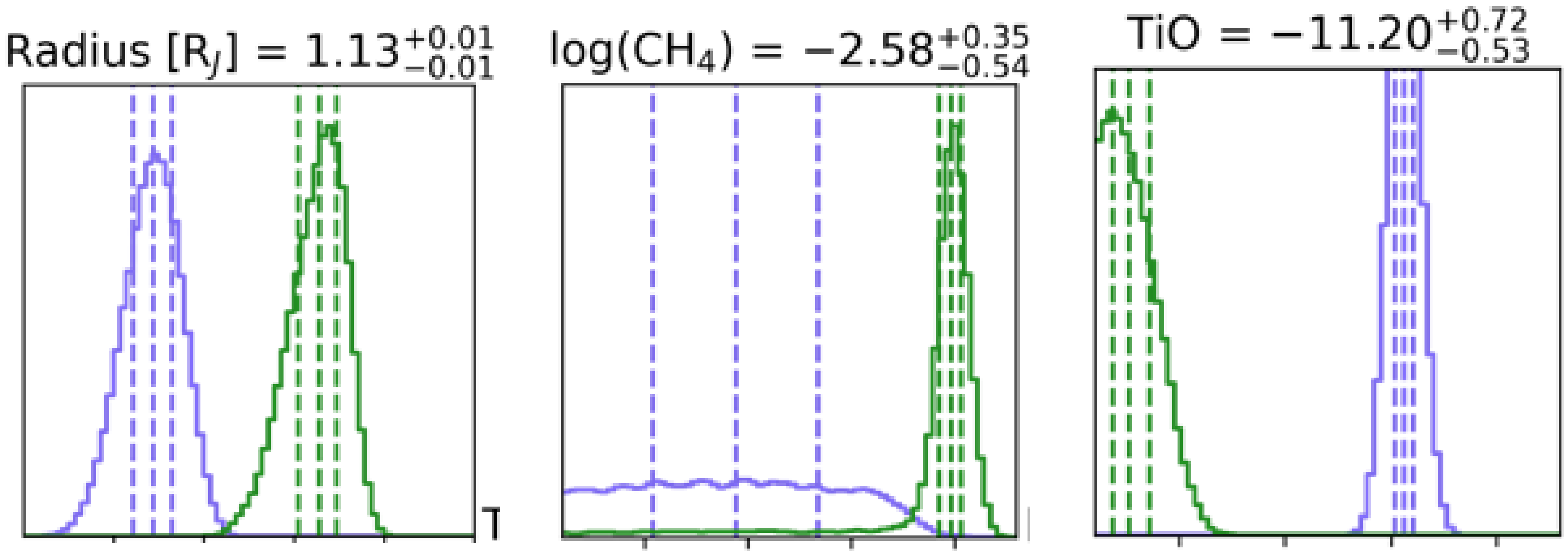
Colon et al. 2021 also found offsets of 0.036 % (360 ppm) between reductions with different pipelines

Combining Instrument: Potential Offsets

- Datasets are not guaranteed to be compatible
  - Choice of long-term WFC3 trend can change white light-curve depth

Fit using Iraclis!



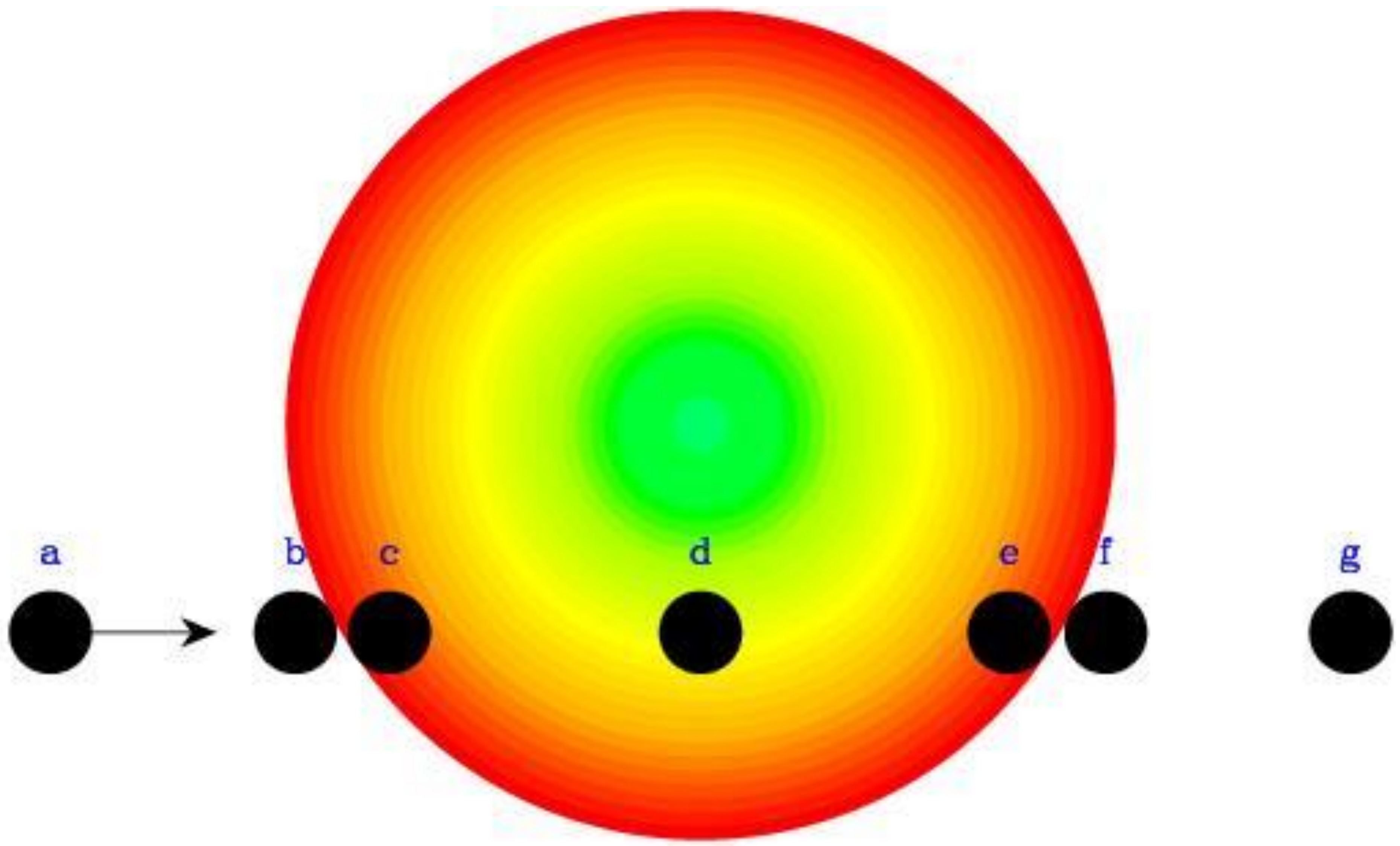


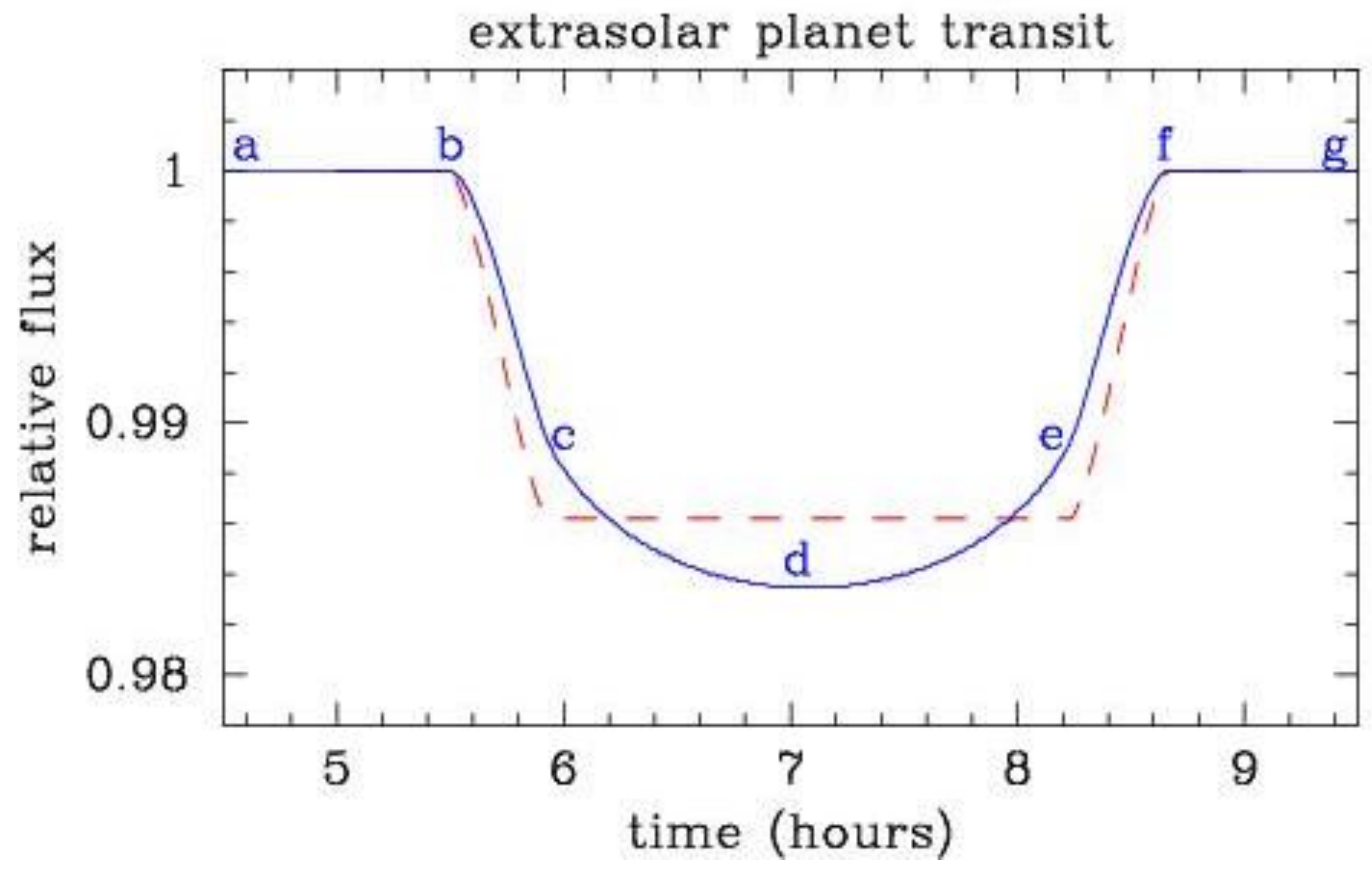
Disparate solutions when combining datasets

Which is correct?!

Combining Instrument: Potential Offsets

- Datasets are not guaranteed to be compatible
  - Choice of limb-darkening coefficients

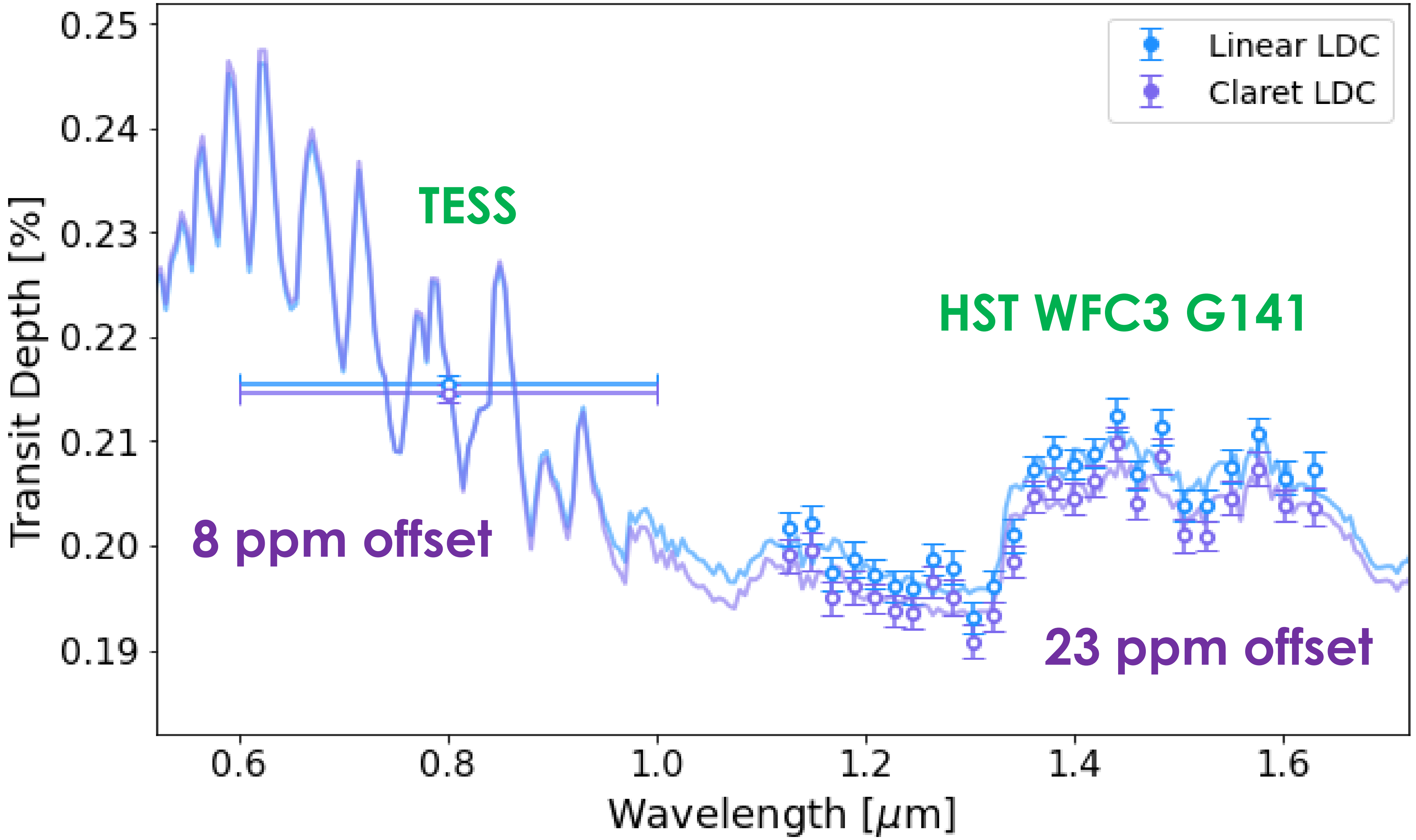


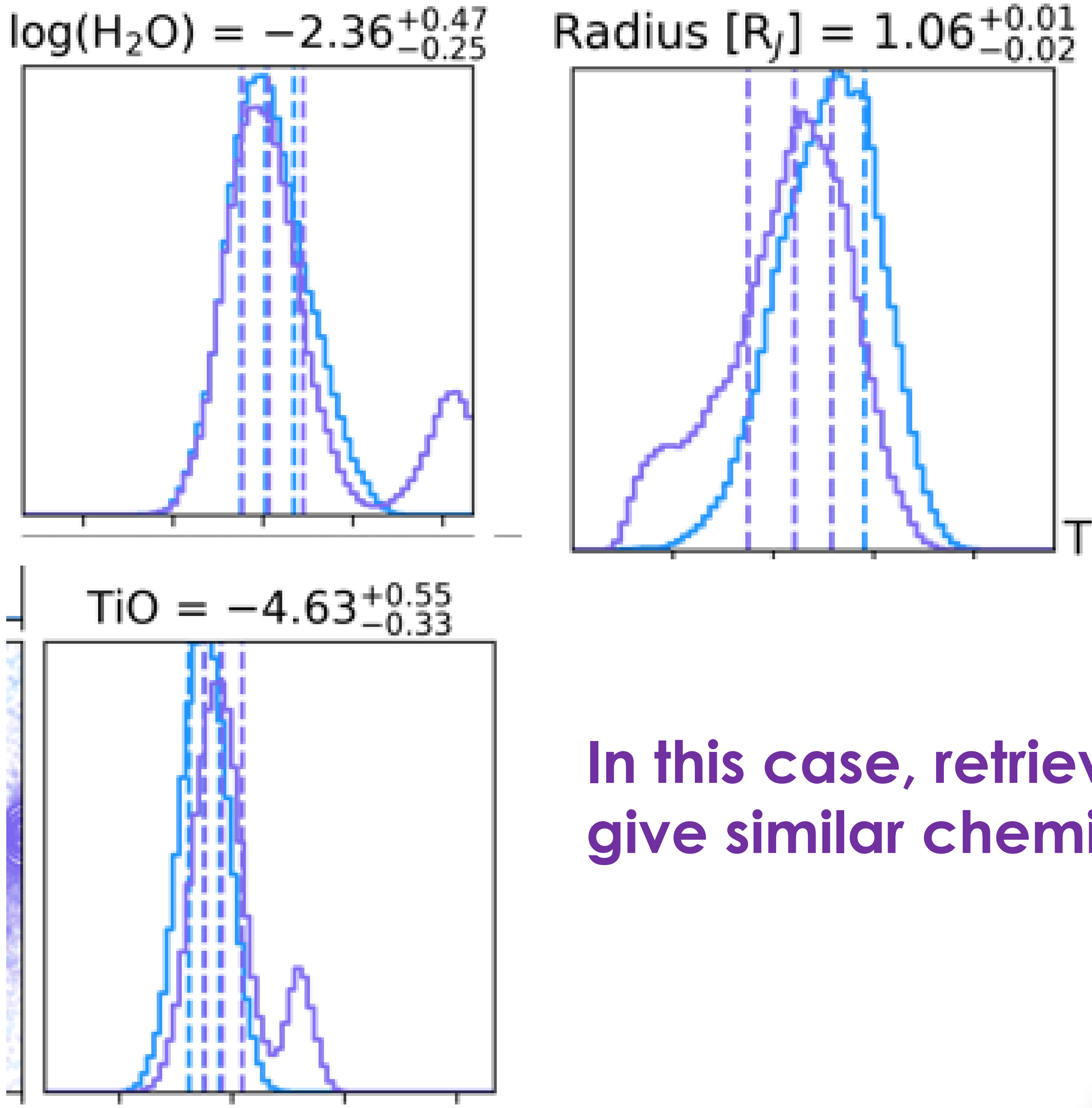


Combining Instrument: Potential Offsets

- Datasets are not guaranteed to be compatible
  - Choice of limb-darkening coefficients

Fit using Iraclis!





In this case, retrievals give similar chemistries

See also Tsiaras et al. 2018

Combining Instrument: Potential Offsets

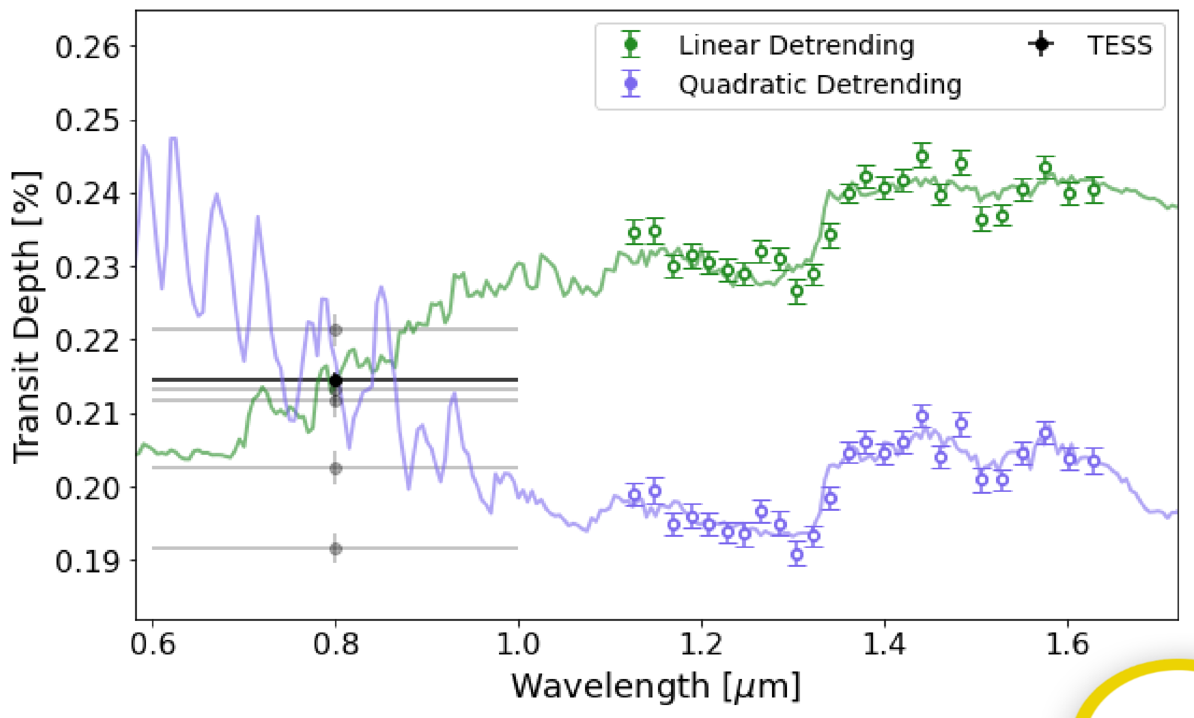
- Potential sources of offsets:
  - Choice of limb-darkening coefficients
  - Choice of orbital parameters (e.g. a/Rs, inclination)
  - Choice of detrending model (and pipeline used)
  - Imperfect removal of systematics
  - Amount of out-of-transit baseline used
  - Stellar variability

The example shown,
see also e.g. Tsiaras et al. 2018

e.g. Yip et al. 2020
Can also change optical slope
(Alexoudi et al. 2018)

Example shown, see also e.g. Guo et al. 2021, Colon et al. 2021, Mugnai et al. 2021, Mansfield et al. 2022, plus many CASCADE/Iraclis comparisons

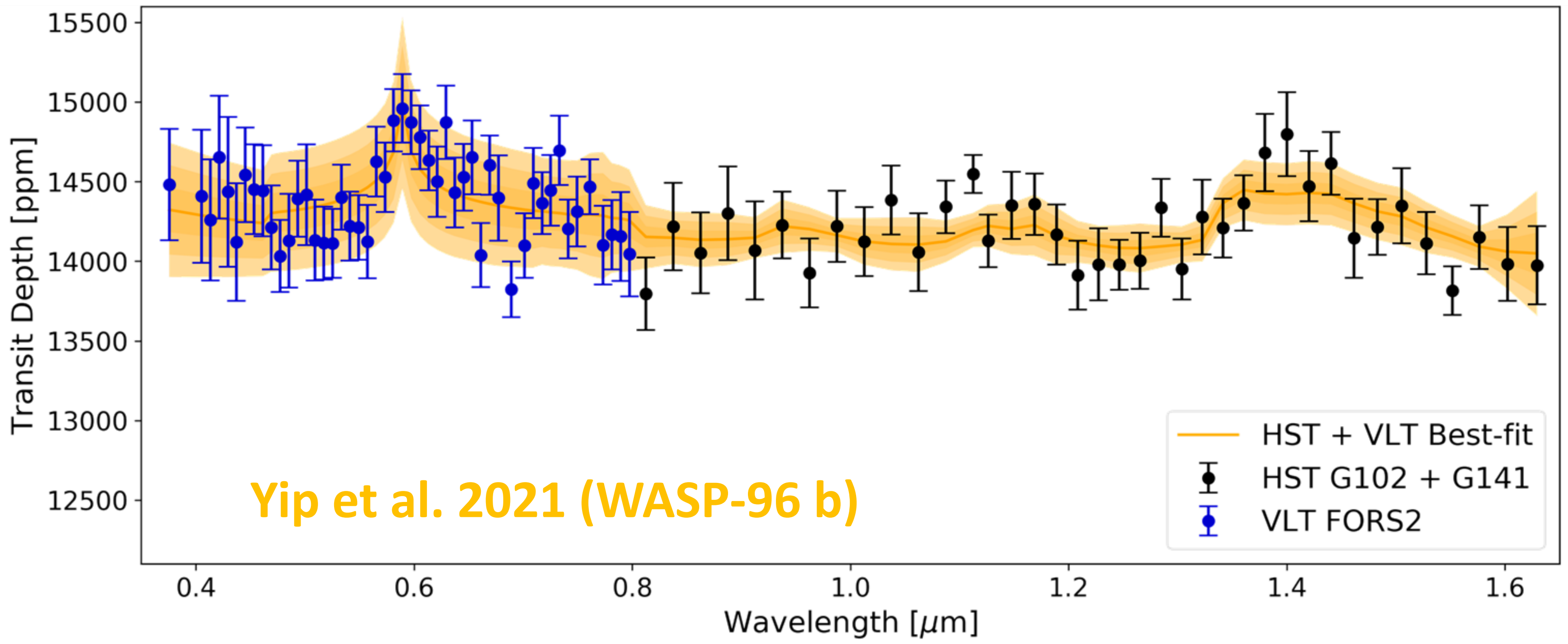
Possibly every dataset ever analysed?



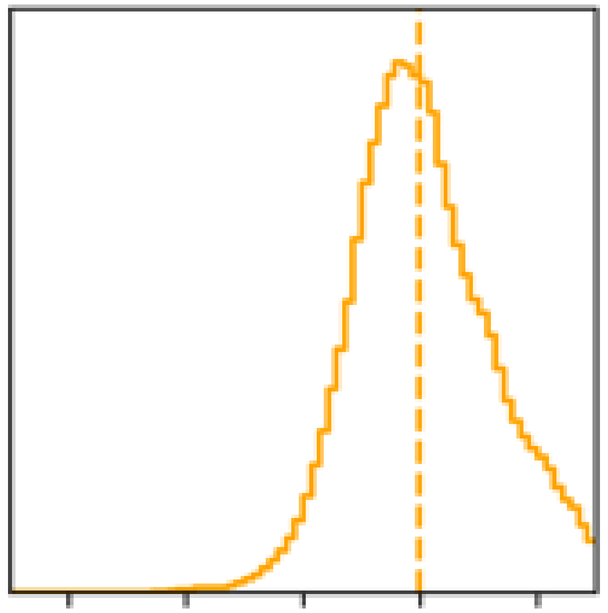
Potentially the example shown (TESS depths are highly variable)
Can also change spectral features (e.g. Espinoza et al. 2019, Saba et al. 2021)

Combining Instrument: Potential Offsets

- Potential solutions:
  - Wavelength overlap to be sure there's no offset
  - Fit for offset in retrievals* (e.g. Luque et al. 2021, Murgas et al. 2021, Yip et al. 2021)
  - Explore how the extra data affects the retrieval
  - Only use data from a single instrument



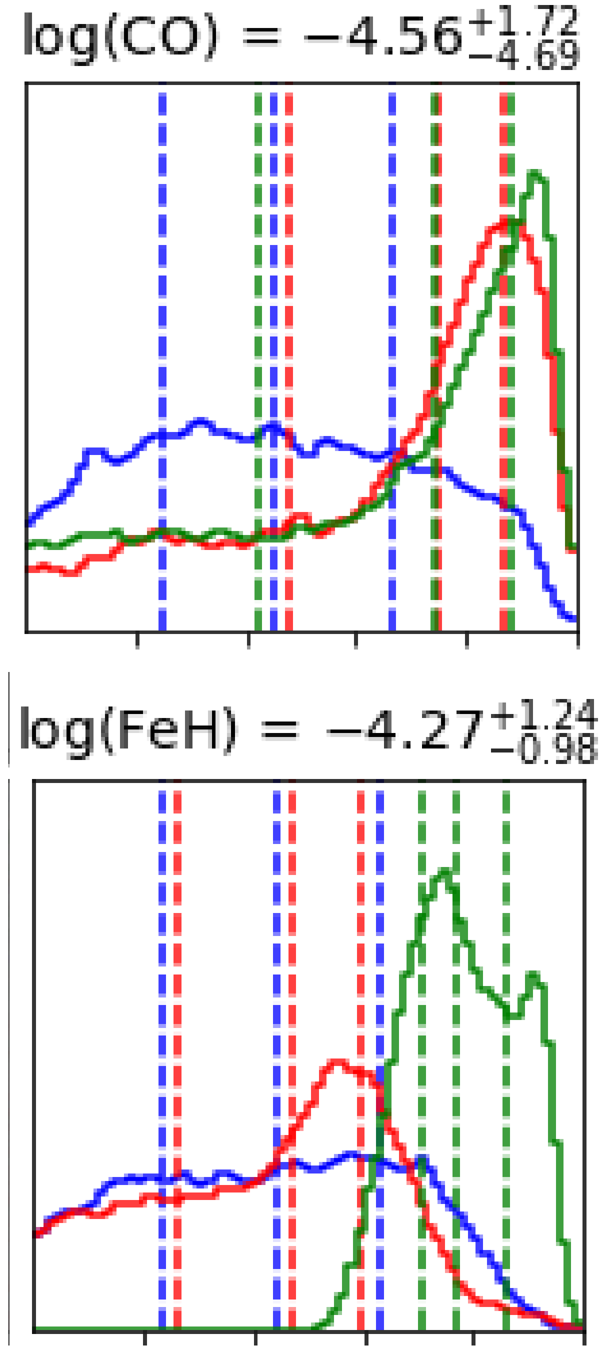
$Offset = 1197^{+135}_{-102}\ ppm$



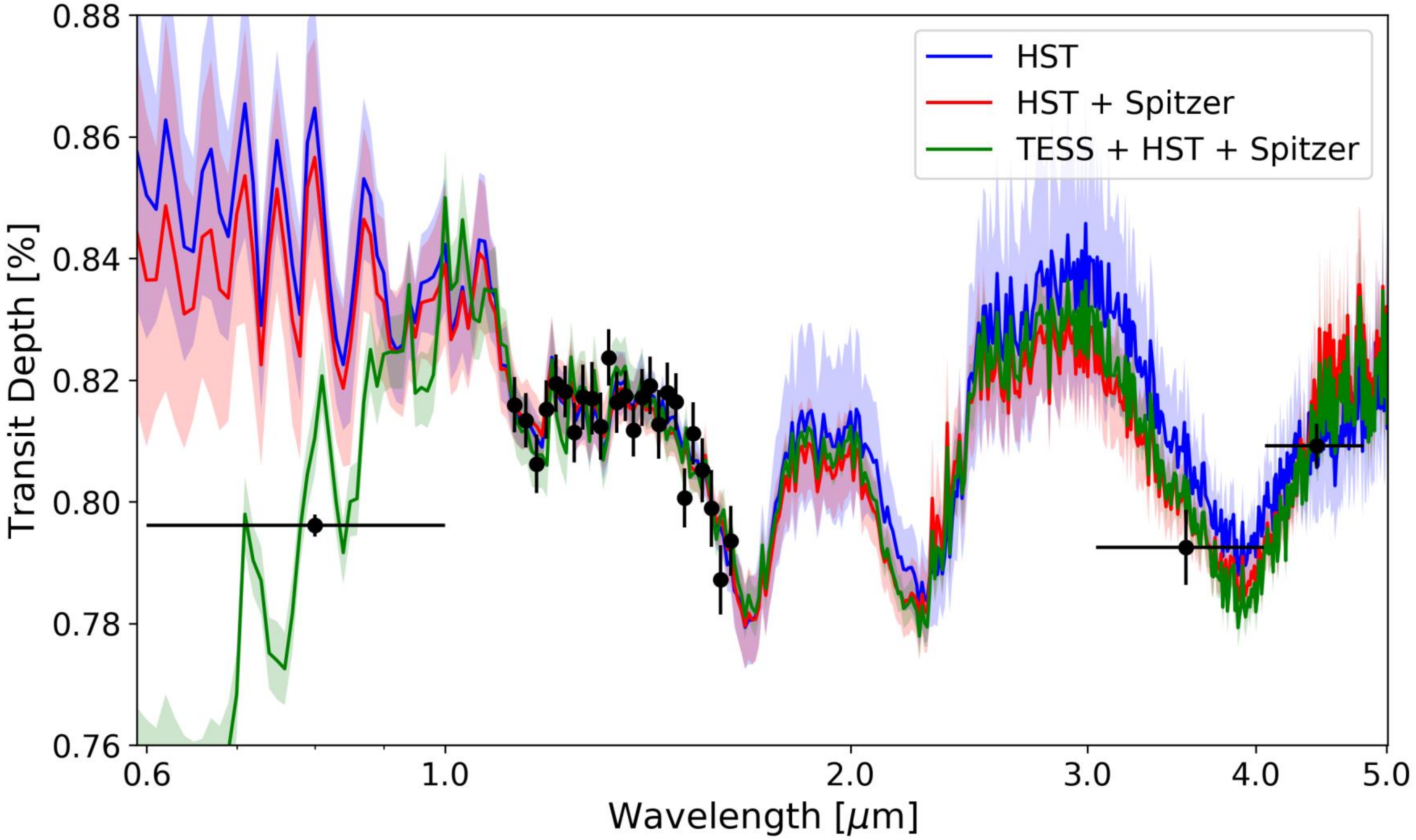
*only confidently works if there is wavelength overlap

Combining Instrument: Changes In Sensitivity

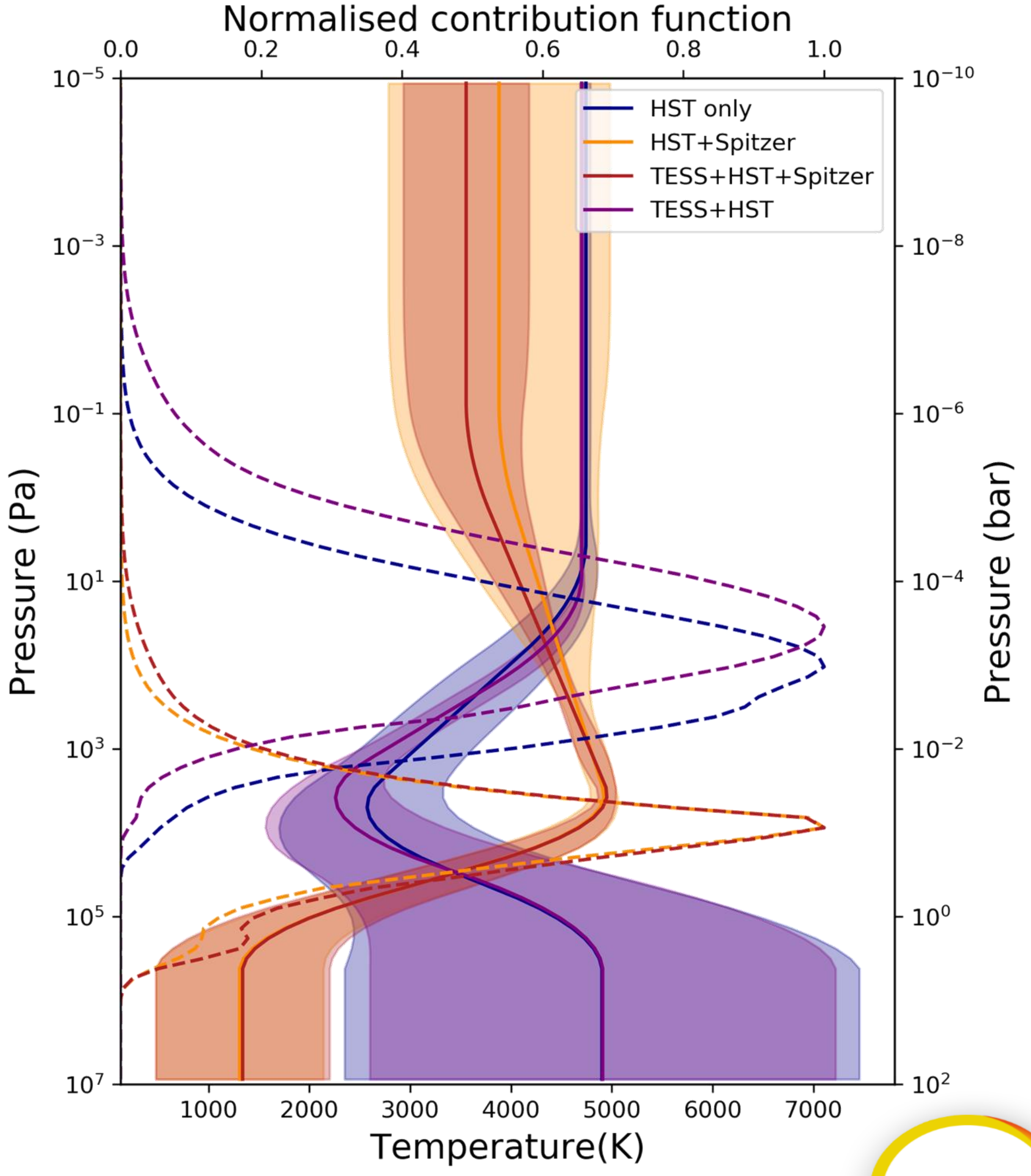
- Adding additional datasets often changes the retrieval result
  - Wider spectral coverage gives access to new molecular features
  - Can also help constrain T-P profile



Pluriel et al. 2021 (KELT-7 b)

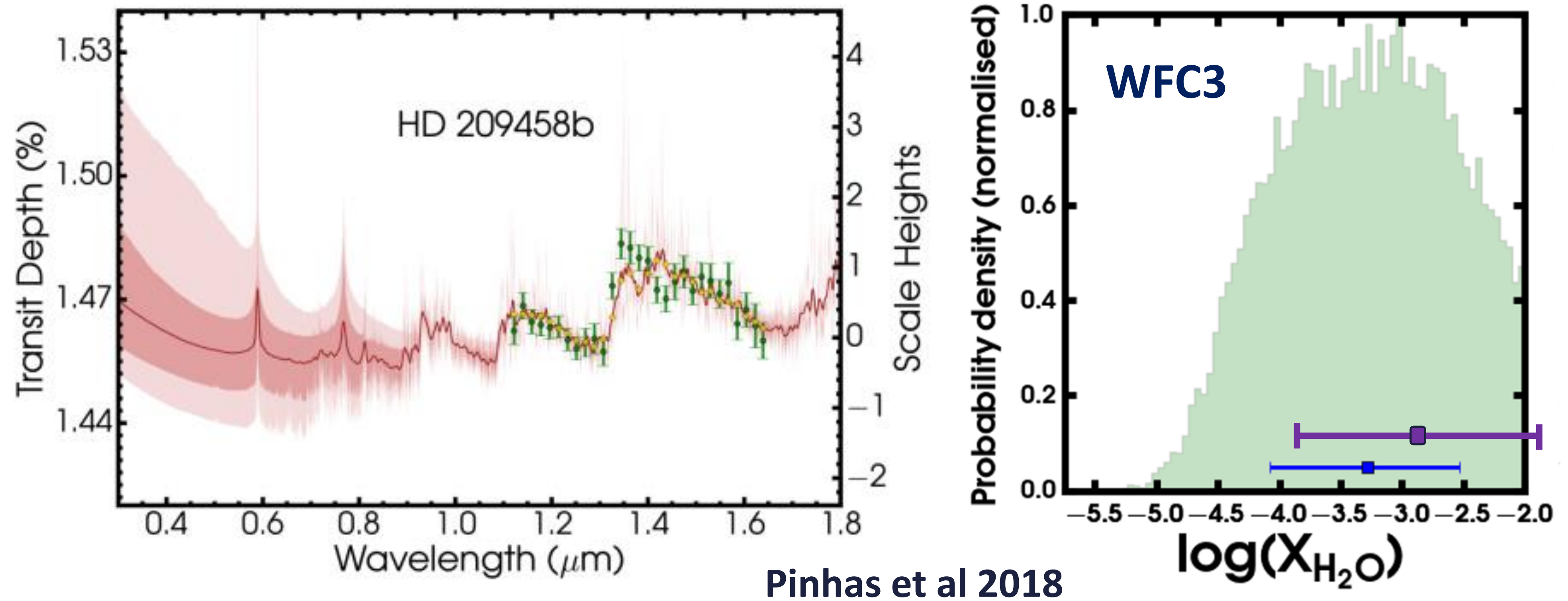


Changeat & Edwards 2021 (KELT-9 b)



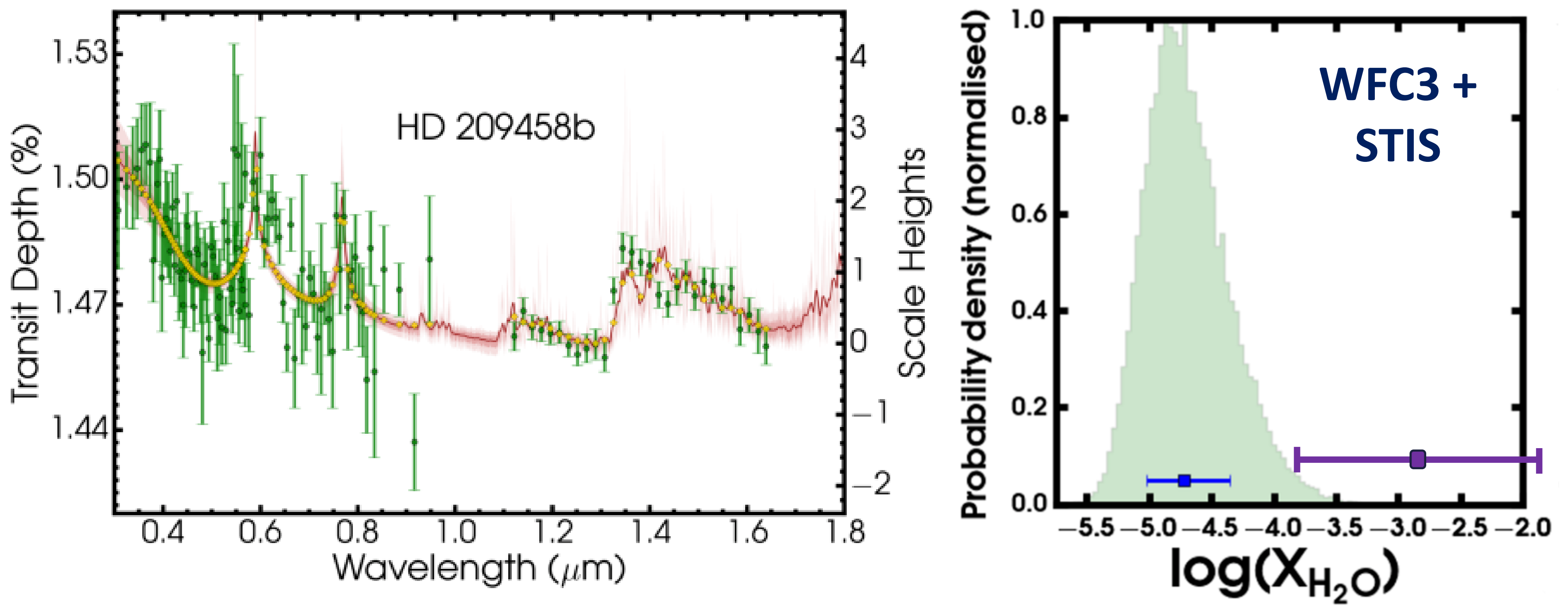
Combining Instrument: Changes In Sensitivity

- Adding additional datasets often changes the retrieval result

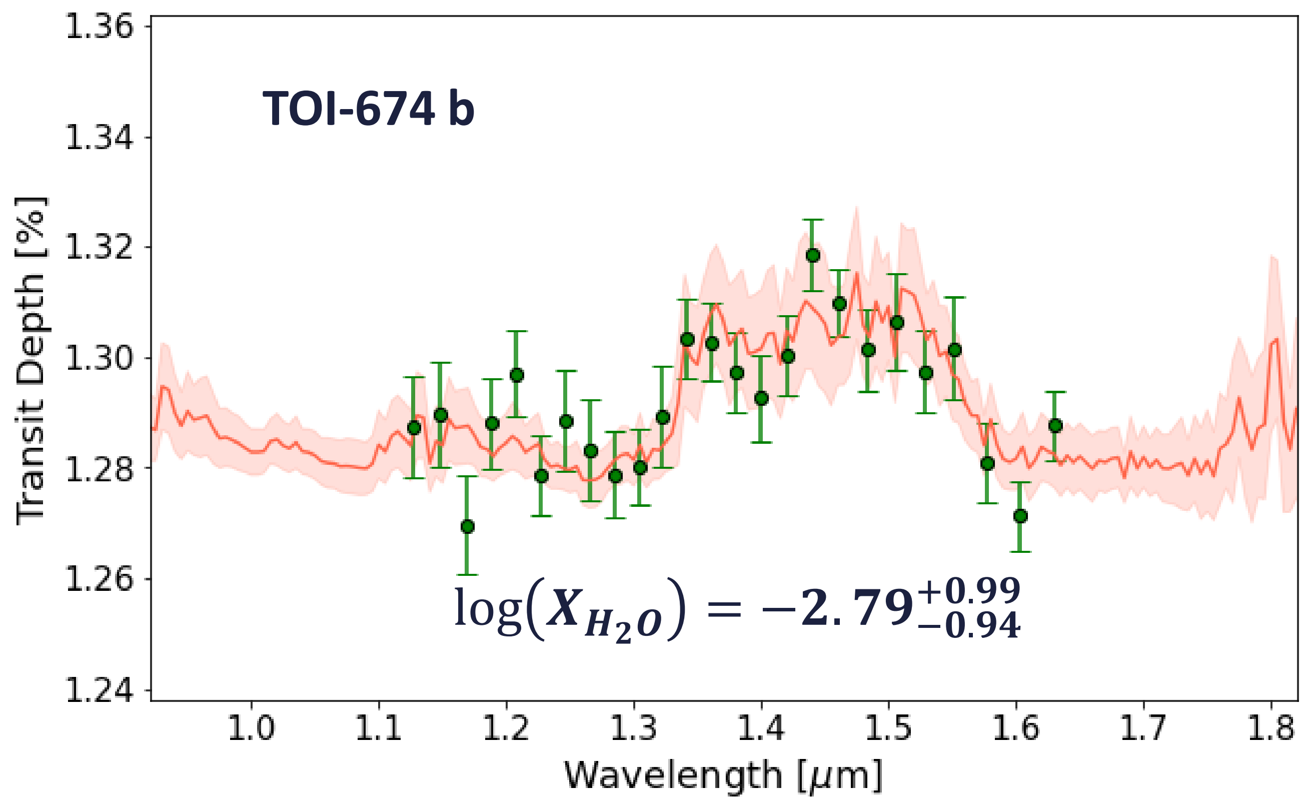


Yes

Pinhas et al 2018



No

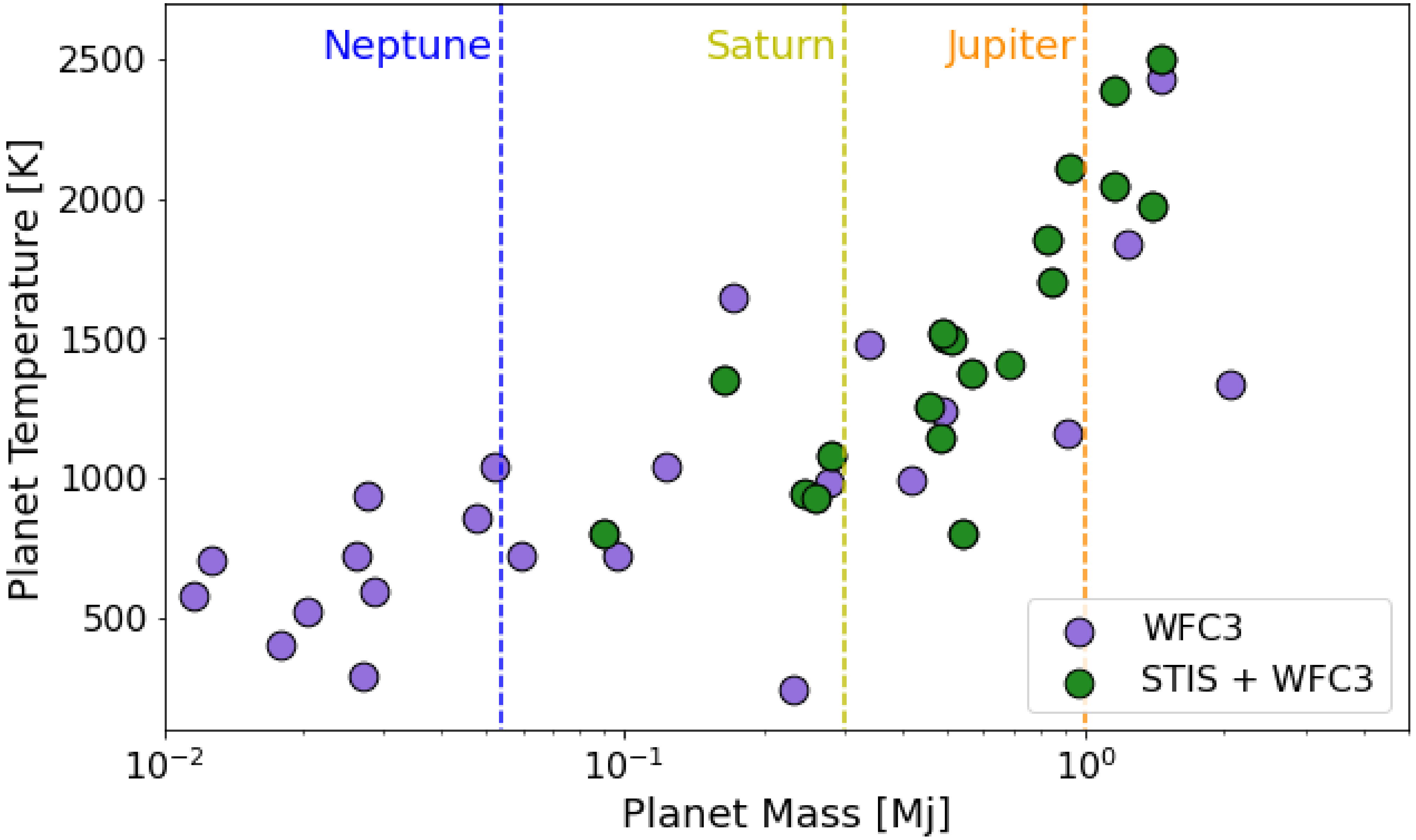


No HST STIS data for TOI-674 b

Do TOI-674 b and HD 209458 b have similar water abundances?

Combining Instrument: Changes In Sensitivity

- Adding additional datasets often changes the retrieval result
  - Not all planets have been studied with the same instruments



Studies have often looked for mass-metallicity trend in exoplanet atmospheres

↓

Studies use inhomogeneous datasets and H_2O abundance is used to infer metallicity of the atmosphere

↓

High mass planets have often been studied with STIS, lower mass planets generally haven't

↓

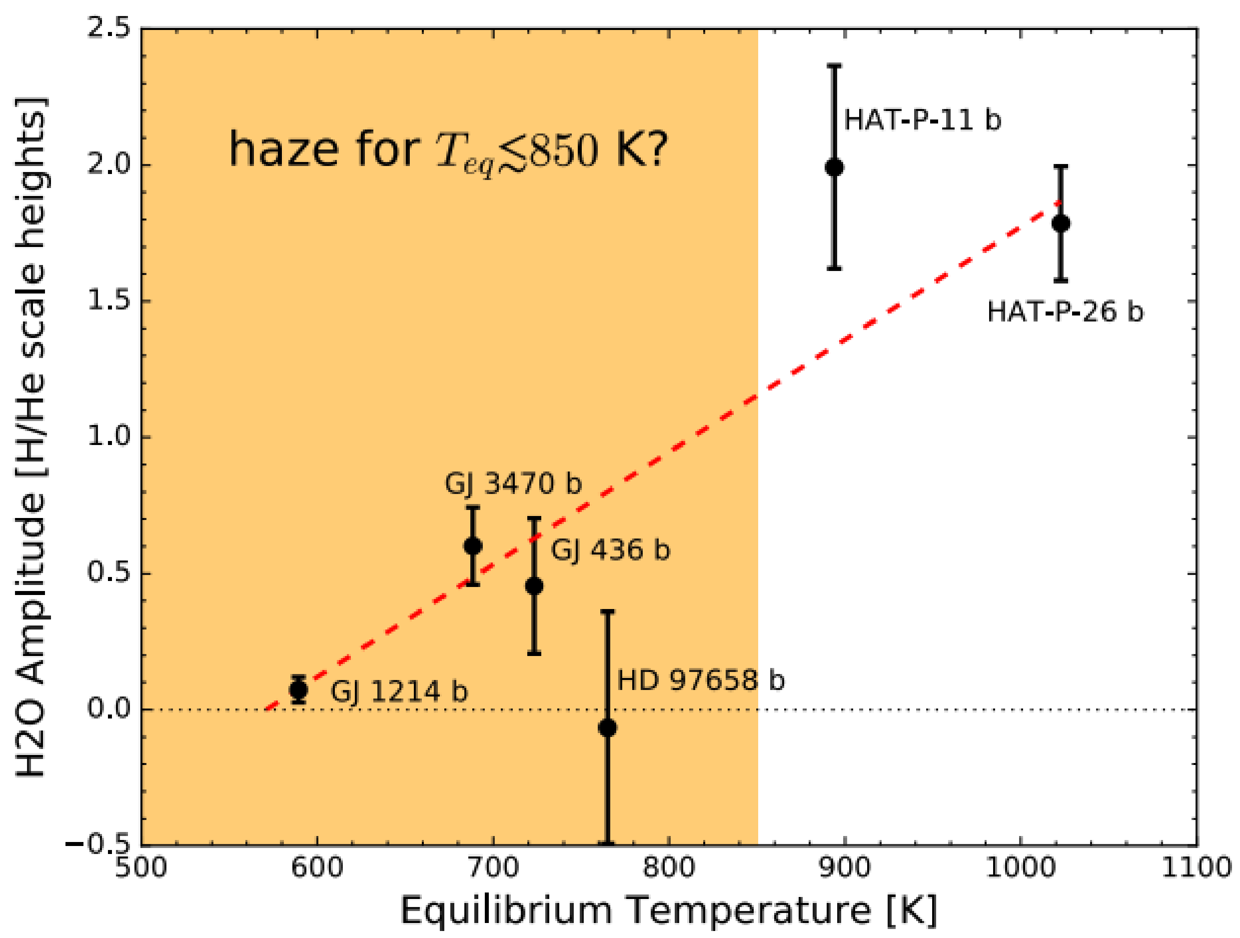
You may retrieve lower H_2O abundances for these STIS + WFC3 datasets

↓

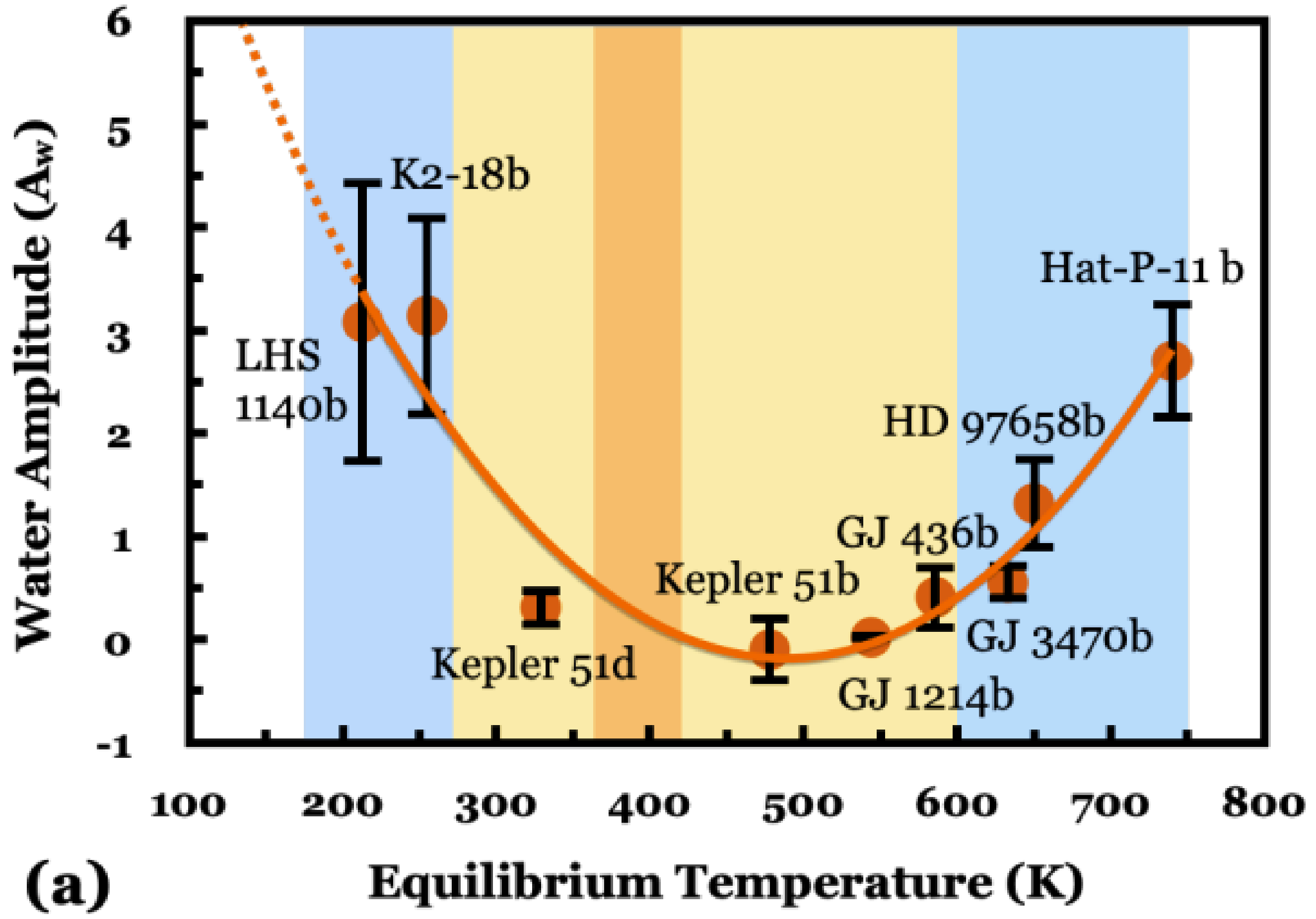
Could artificially create a trend of decreasing H_2O abundance with increasing mass

Population Studies: Importance of Target Selection

- Current population studies acquire data from multiple proposals
  - No consistent selection criterion
- Hard to divide-up planets by more than one parameter
- Apparent trends can be largely based on a single planet



Crossfield & Kreidberg 2017



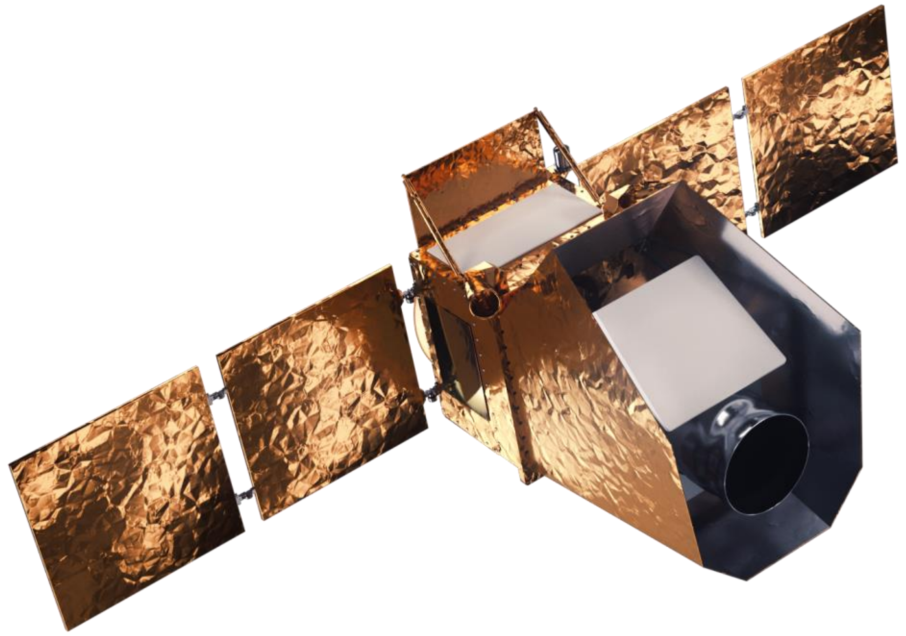
Yu et al. 2021

Analysis of JWST Data Will Face These Issues

- JWST has four instruments
  - NIRCam and NIRSpec have many different operating modes
  - Only NIRSpec PRISM entirely covers crucial 0.5 - 5 micron range
  - Planets will not be studied over same wavelengths or at same resolution
  - Confidently comparing planets will be difficult
- Many proposals plan to combine JWST instruments (or HST + JWST)
  - Systematics or non-linearities can cause offsets (e.g. Schlawin et al. 2021)
- Proposals are largely stand-alone
  - Same issue of target-selection

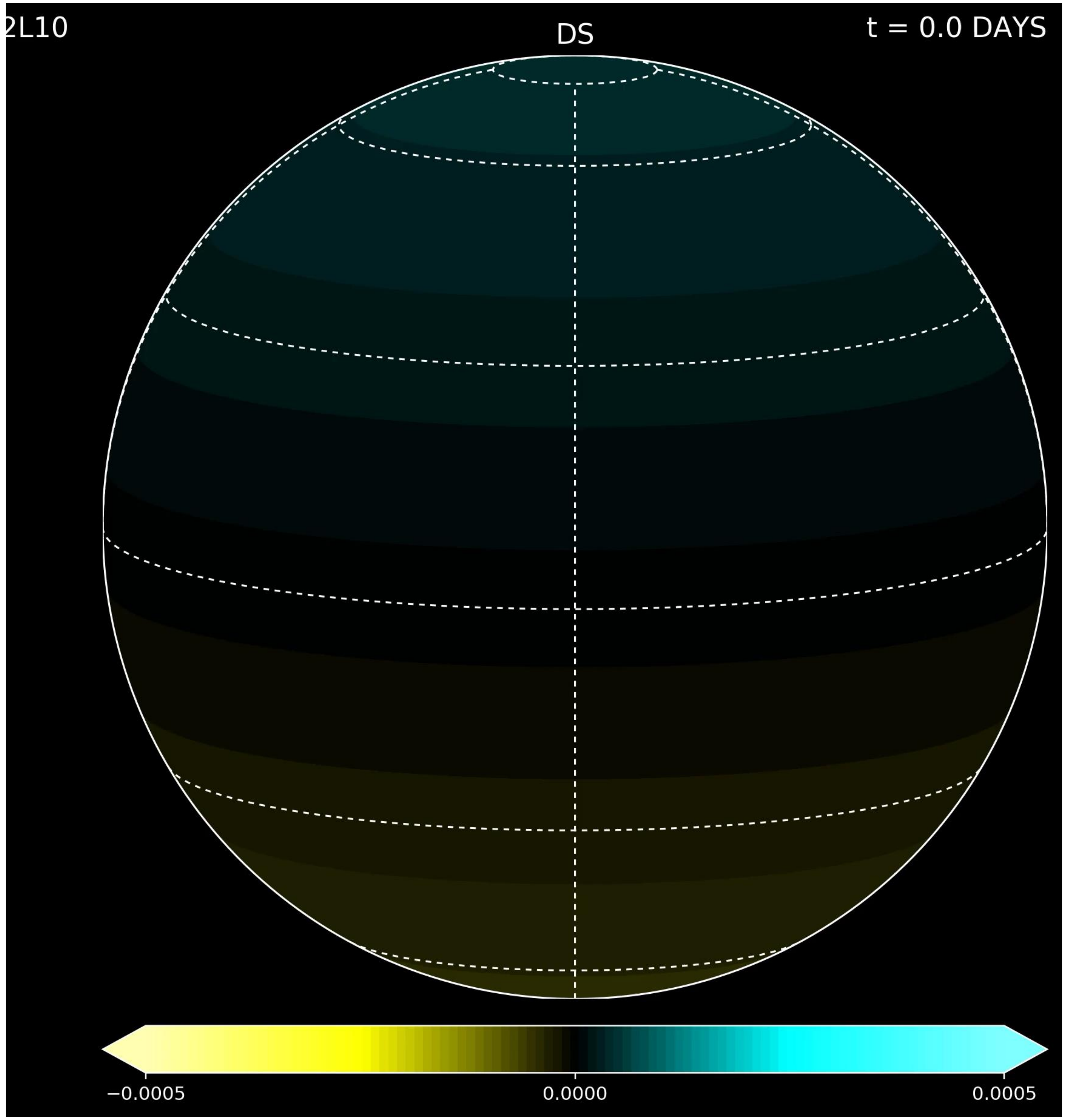
Ariel and Twinkle Aim To Avoid These Issues

- Only one operating mode
- Wide, simultaneous coverage
  - Ariel: 0.5-7.8 micron
  - Twinkle: 0.5-4.5 micron
- Dedicated exoplanet surveys
- Structured approach to target selection
- Aim to deliver uniform catalogue of spectral data

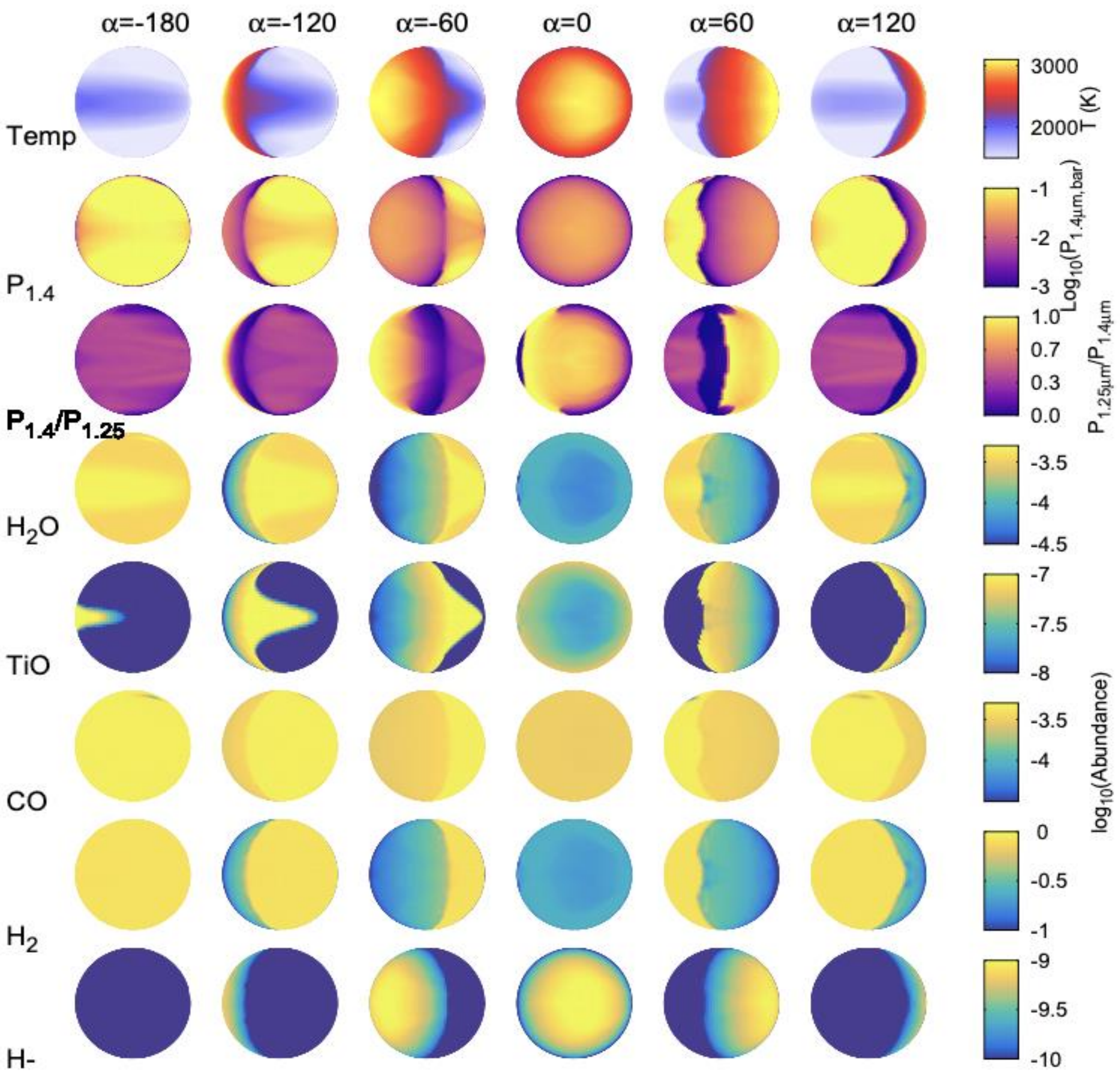


More info in Giovanna's talk

Exoplanets are not 1D



Skinner+ 2021, Cho+ 2021

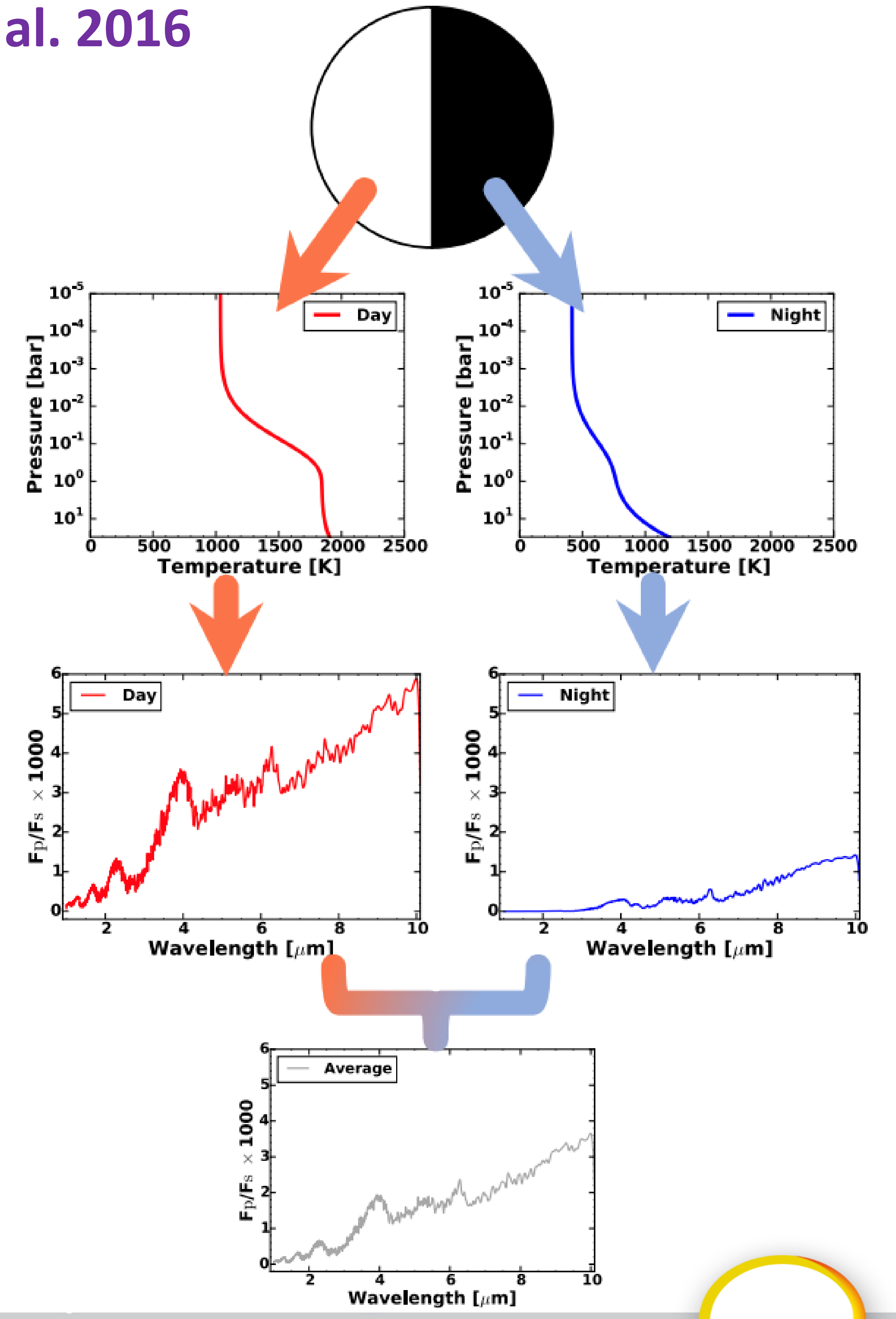


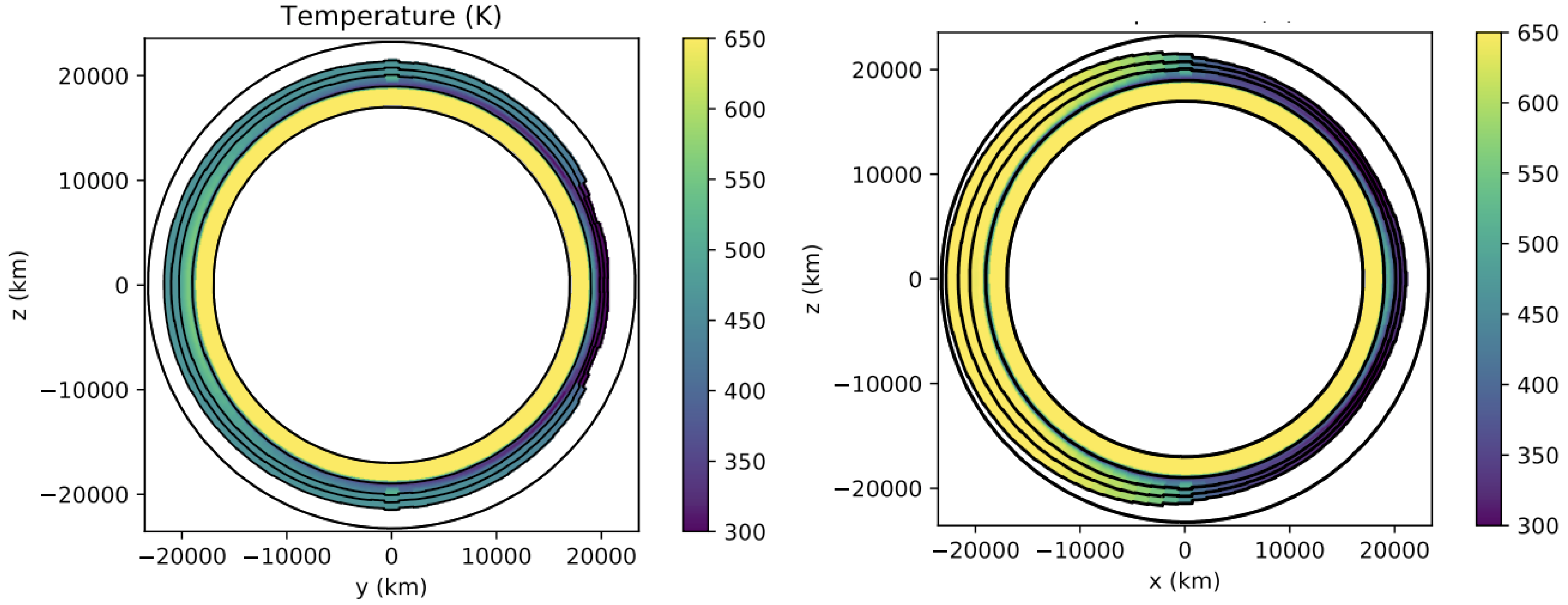
WASP-121b: Parmentier et al (2018)

What's the problem with 3D planets?

- Current retrieval methods use 1D models
- 3D effects can bias your results
- 3D models of transmission/emission are complex
- Some current data sensitive enough ton be affected
- Future data definitely is

Feng et al. 2016



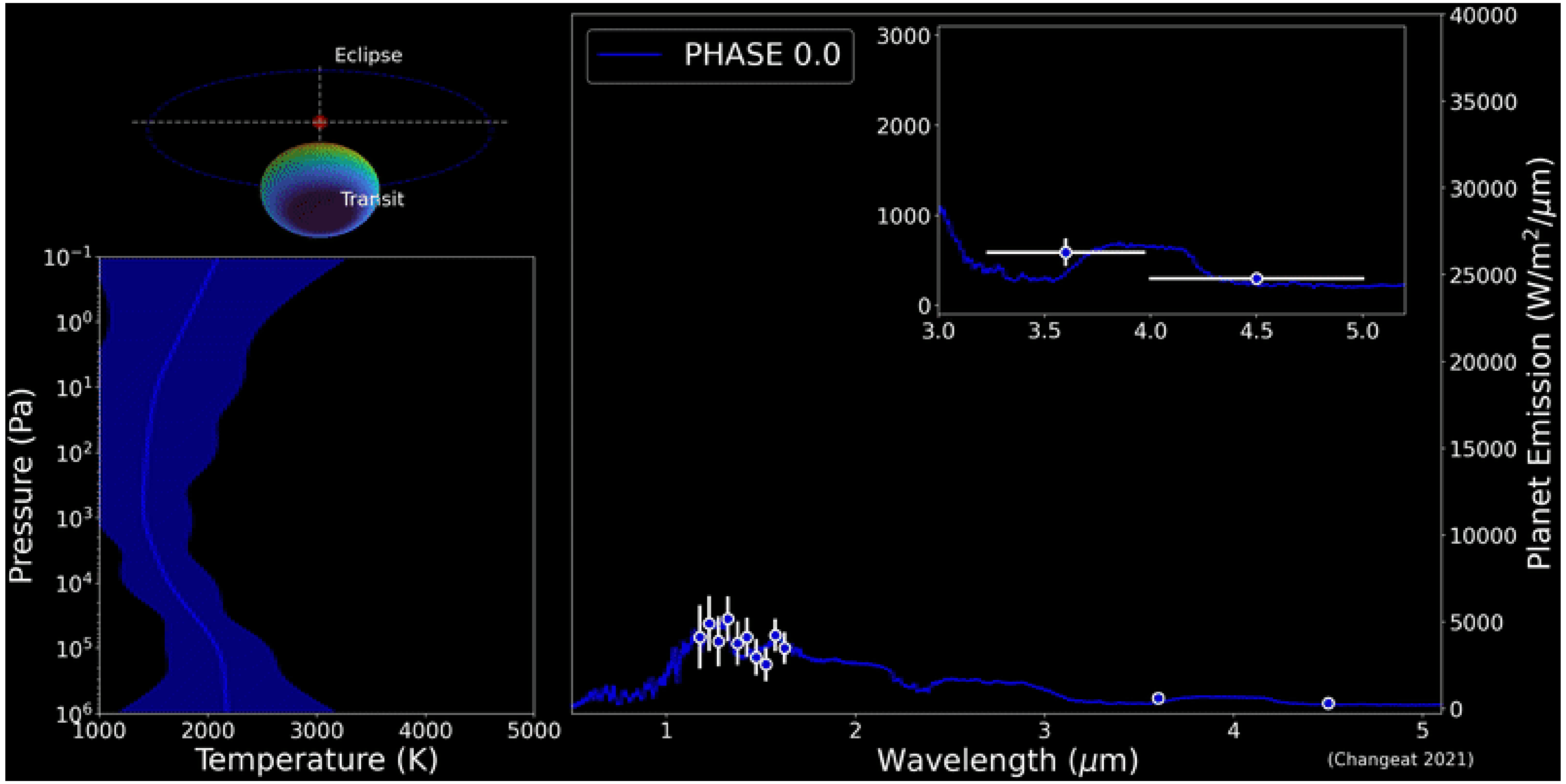


Caldas et al. 2019

Phase-Curves

- Planets observed throughout their entire orbit
- Chance to study all sides of a planet

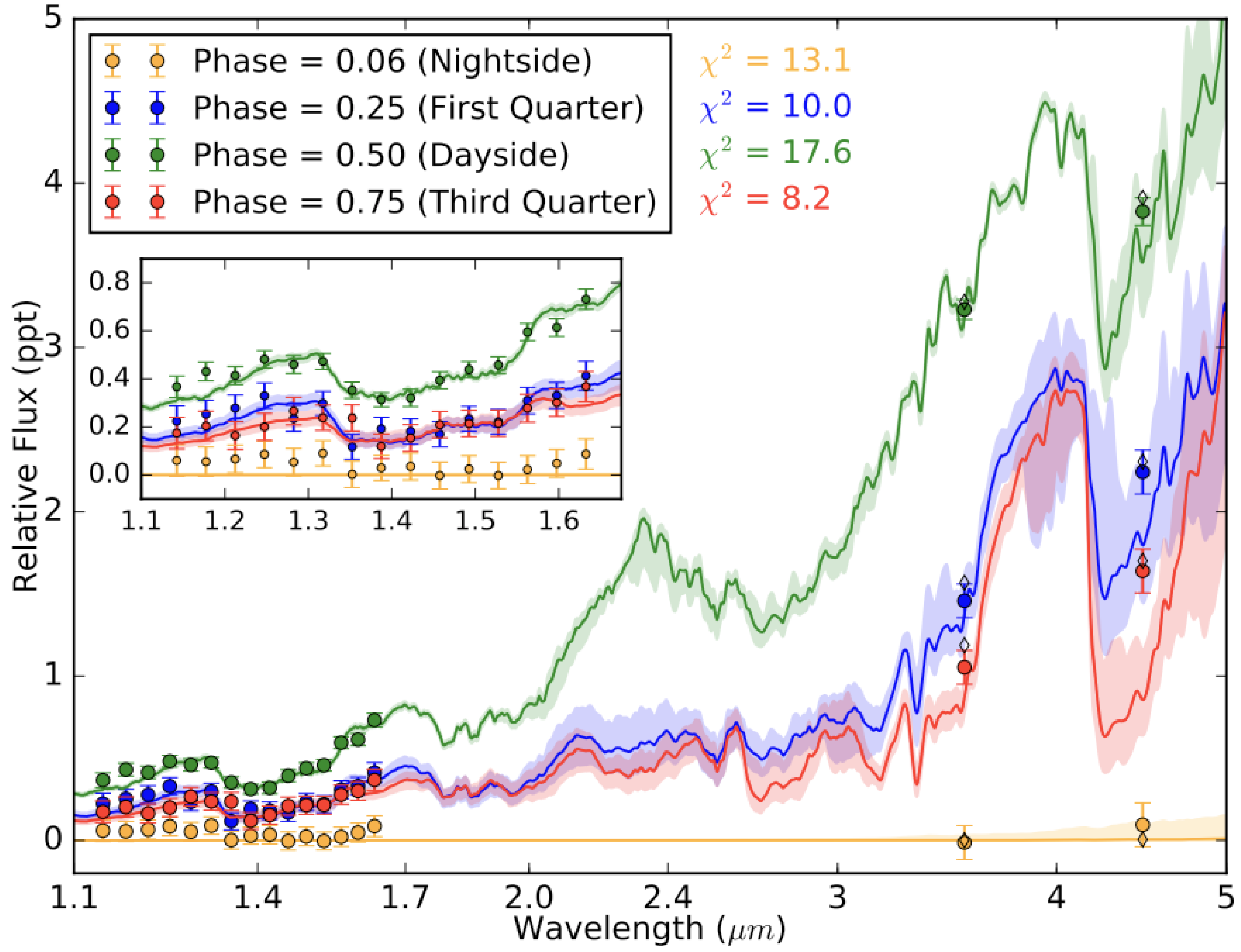
See also Tom's talk later!

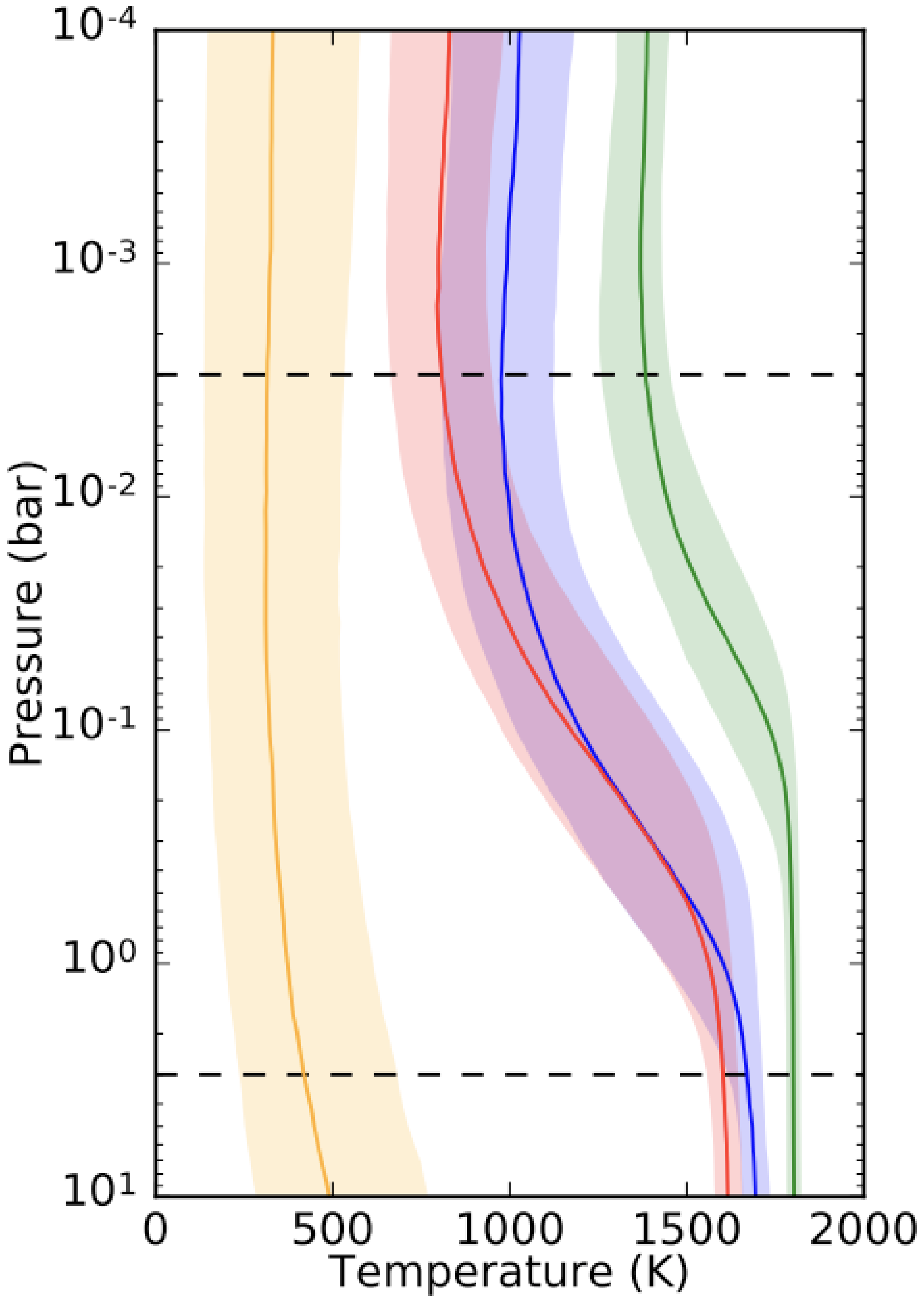


Full Exploitation of Phase-Curve Data is Rare

- HST WFC3 + Spitzer phase curves of WASP-43b
- 15 spectra,15 separate retrievals
- Information redundancy?

Stevenson et al. (2016)





Recent unified retrieval attempts by **Irwin et al. (2019)** and **Feng et al. (2020).**

TauREx 3.1

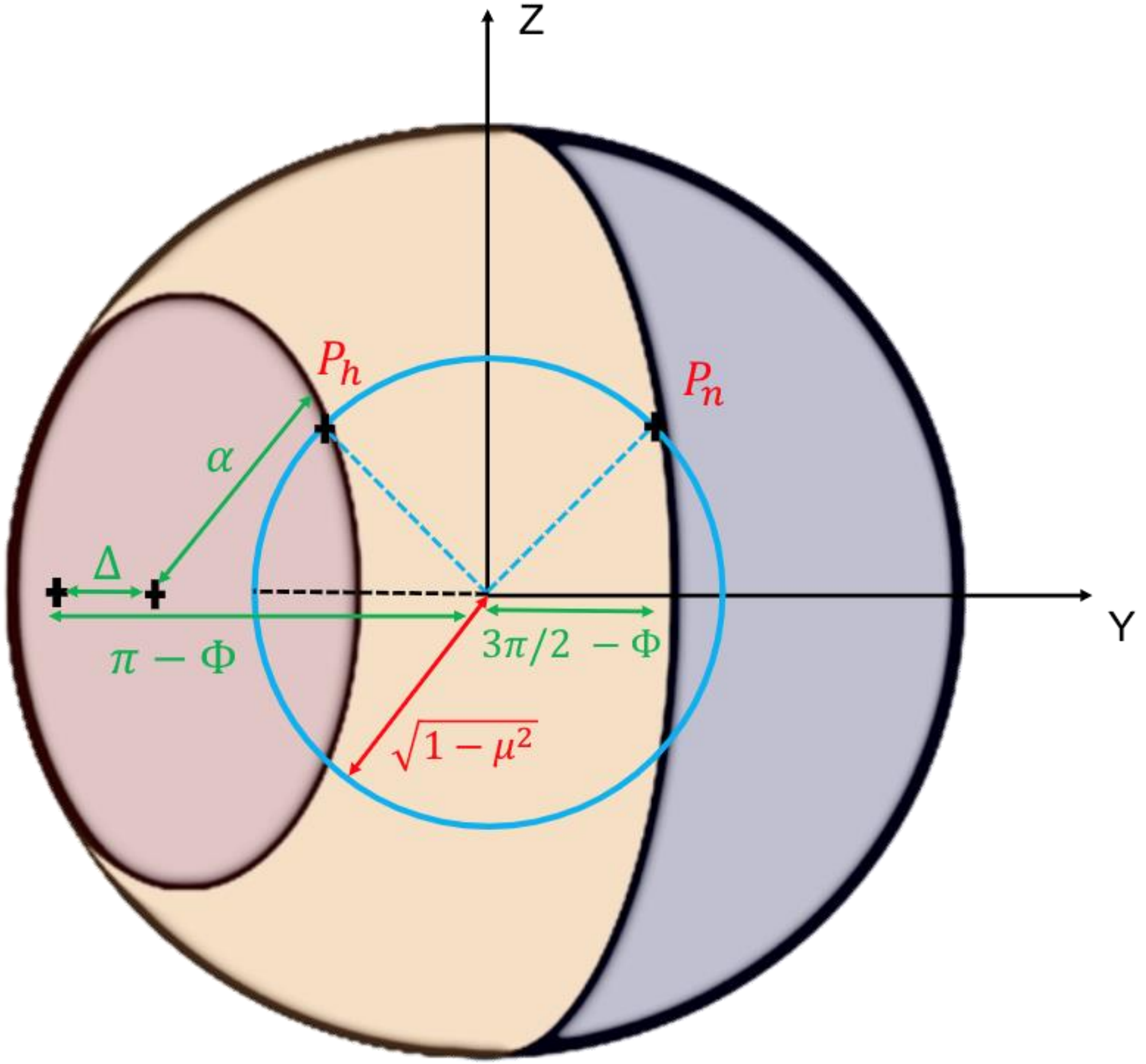
- New version of TauREx
- Open-source: https://github.com/ucl-exoplanets/TauREx3_public

Plugin	Description	Availability
`taurex_cuda`	CUDA-acceleration of forward models	PyPI
`taurex_hip`	HIP-acceleration of forward models	PyPI
`taurex_ace`	Equilbrium Chemistry using ACE	PyPI
`taurex_ggchem`	Equilbrium Chemistry using GGChem	PyPI
`taurex_fastchem`	Equilbrium Chemistry using FastChem	PyPI
`taurex_pychegp`	Chemical Kinetic Solver based on code by Venot et al. (2012)	PyPI
`taurex_dynesty`	Dynesty optimizer	PyPI
`taurex_scipypriors`	`scipy.stat` continuous functions as priors	PyPI
`taurex_petitrad`	petitRADTRANS forward models and opacity formats	PyPi
`taurex_catalogue`	Set planetary and stellar parameters from name	PyPi
`taurex_uv`	UV stellar spectra slicing	PyPi
`taurex_phasecurve`	1.5D phasecurve forward models	On publication
`taurex_jwst`	JWST instrument noise simulator	On publication
`taurex_ariel`	Ariel instrument noise simulator	On publication

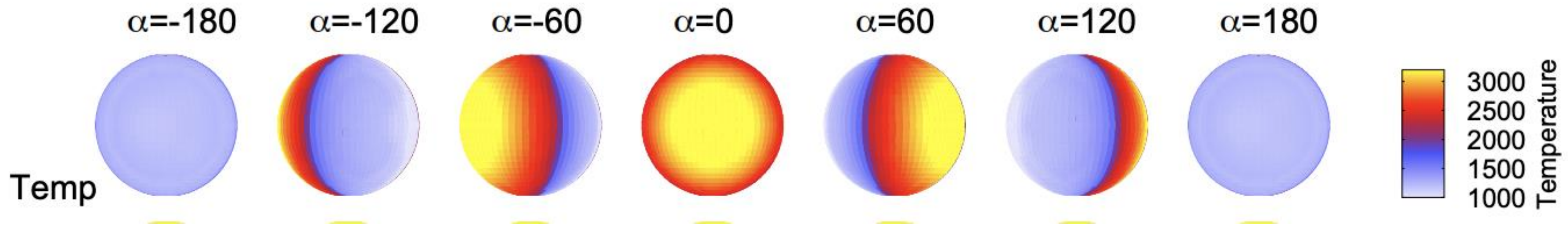
See posters by Lorenzo Mugnai!

TauREx Phase-Curve

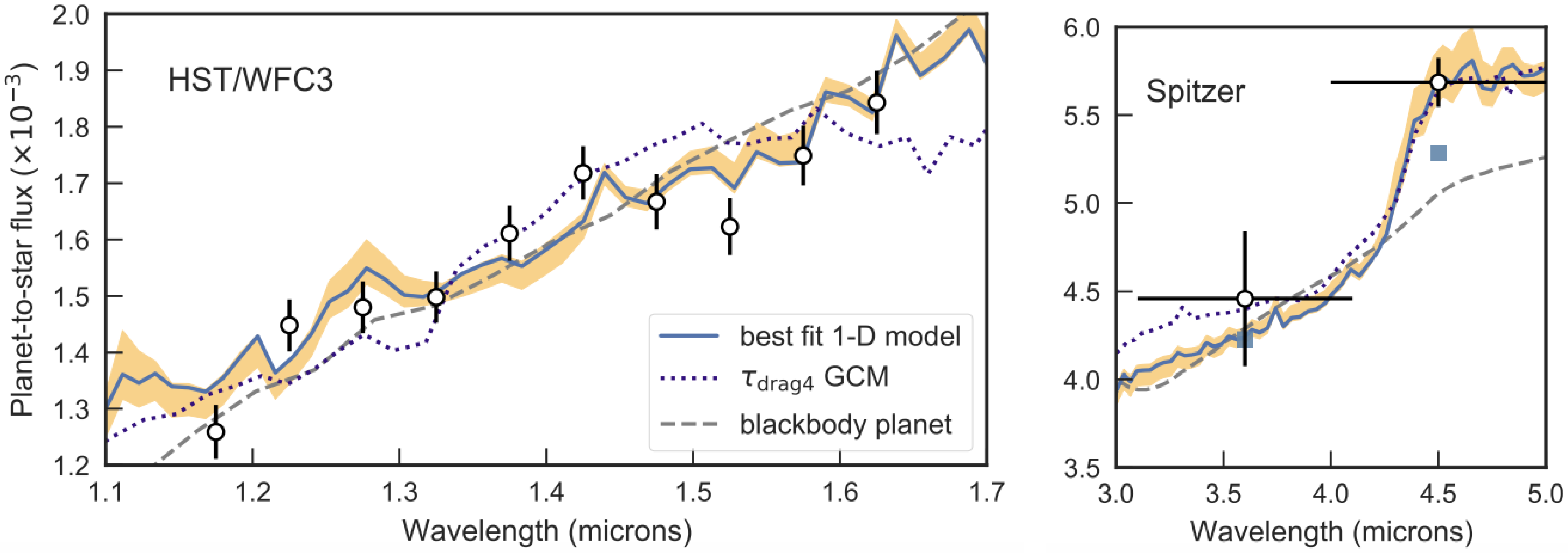
- Plugin of TauREx 3
- Planet separated into regions
  - E.g. hot-spot, day-side, night-side
- Regions have homogeneous properties
- Computes all phases at once



TauREx Phase-Curve: WASP-103 b



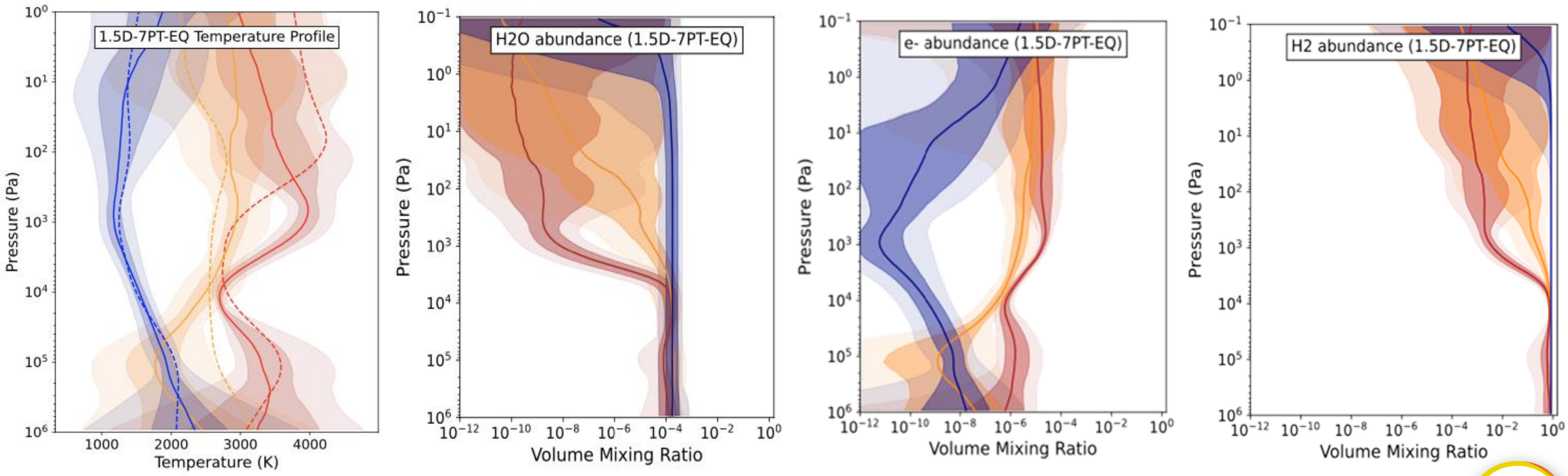
- Ultra-hot Jupiter (2500 K)
- HST and Spitzer phase-curves (Kreidberg et al. 2018)
- HST WFC3 consistent with blackbody, Spitzer data suggests thermal inversion



TauREx Phase-Curve: WASP-103 b

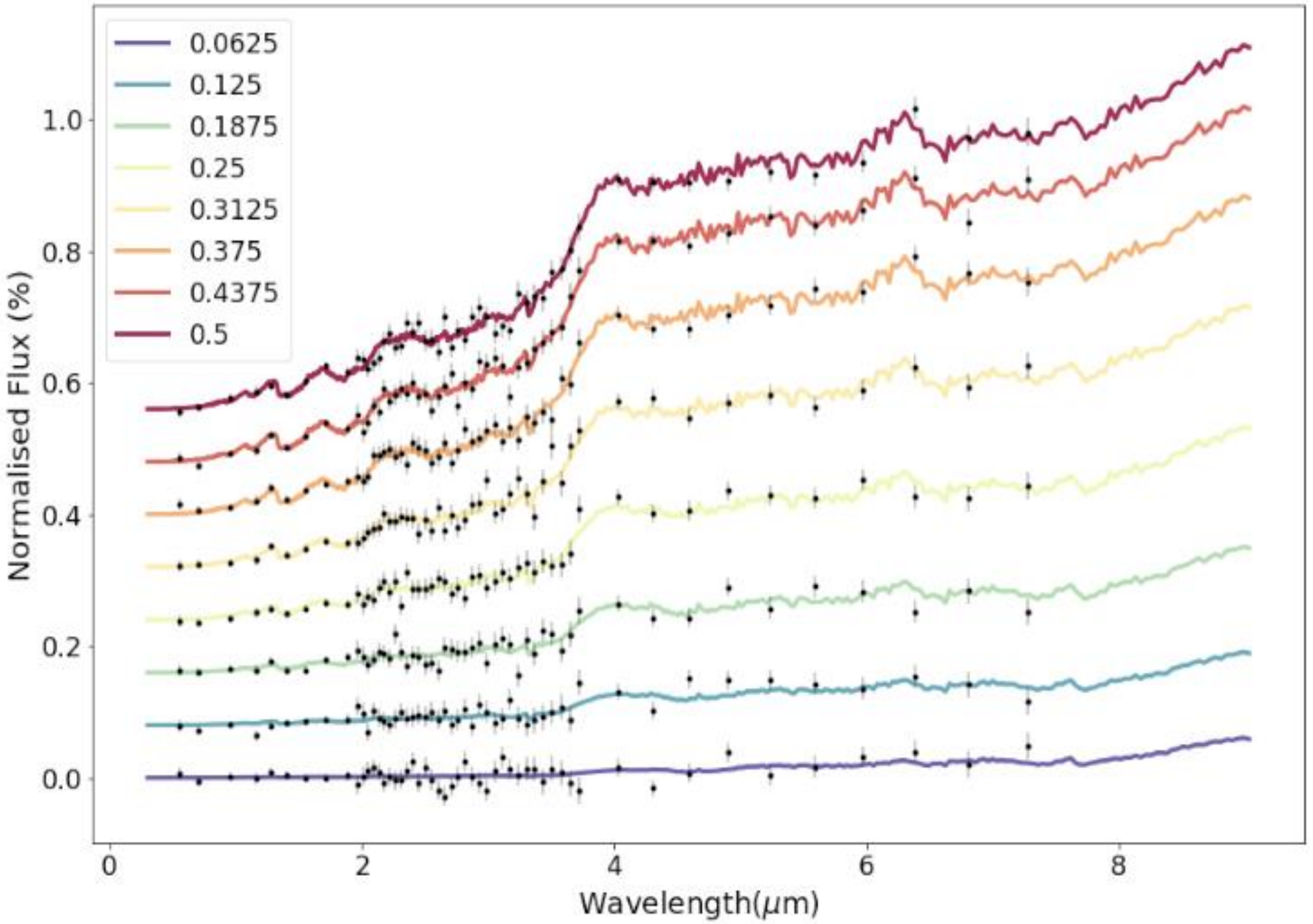
- Retrieve chemistry and temperature-pressure profile for each region
- See changes with regions, e.g. dissociation of H_2O on the day-side

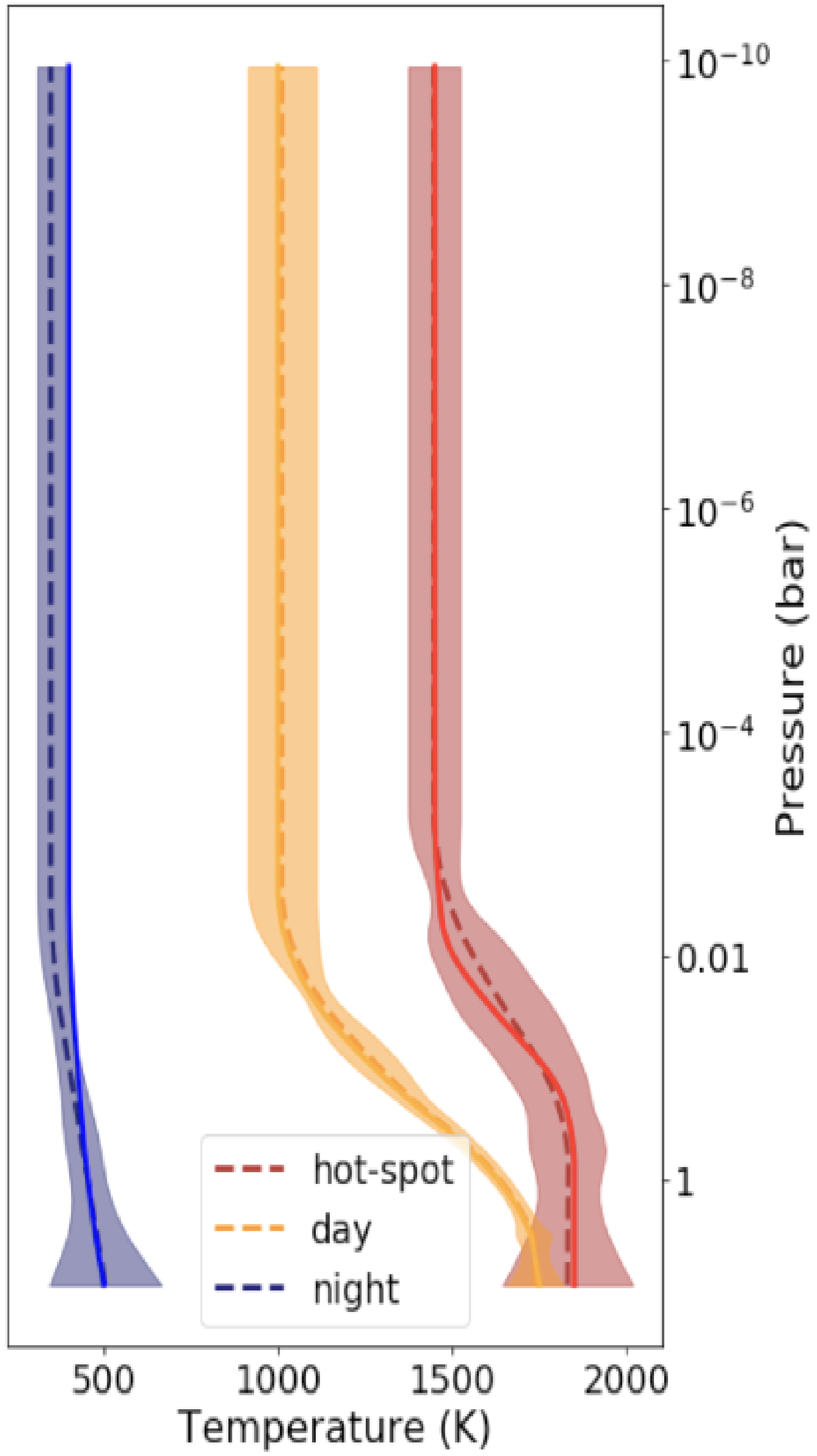
Night-side
Day-side
Hot-spot



Phase-Curves In The Future

- Higher data quality (SNR and wavelength coverage)
- Better constraints on chemistry and thermal structure





Key Takeaways

- Datasets can easily be incompatible
- Different instruments provide different sensitivities (and biases)
- Meticulous target selection is vital when searching for trends
- Biases exist in retrieval methods
- Different observation methods offer unique perspectives of the planet

Questions?