The New Landscape of Exoplanet Atmospheres as Revealed by JWST

Johanna Teske
Carnegie Earth & Planets Lab
Carnegie Observatories

Photo credit HikingGuy
Gabrielino Trail Guide

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If you are on the postdoc job market, please consider applying to Carnegie!

Carnegie Fellowship
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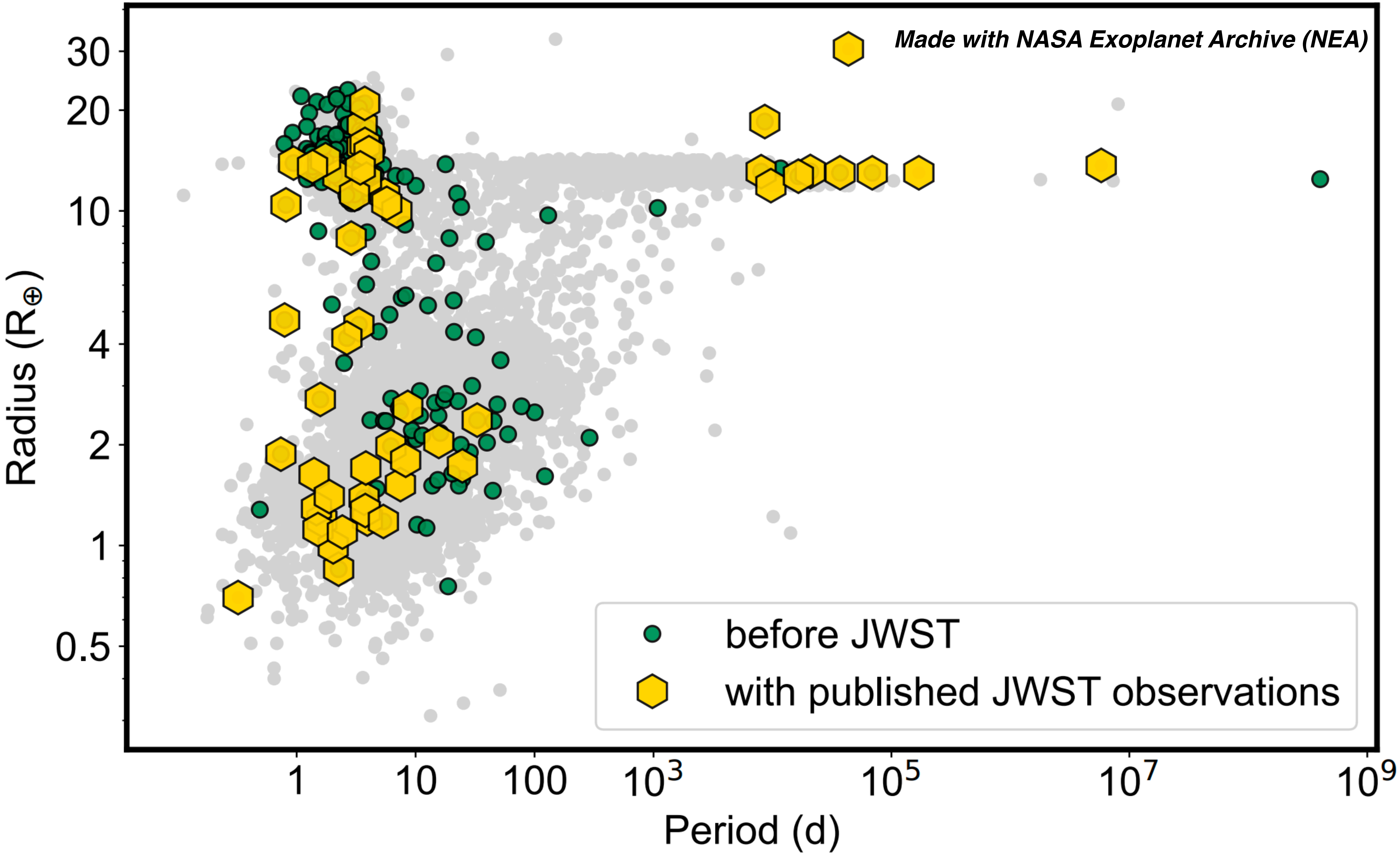
This is not a technique talk.

SSW 2023 was Characterizing Exoplanet Atmospheres — wonderful resources there with more details!

https://nexsci.caltech.edu/workshop/2023/agenda.shtml

It is still early in the exploration of exoplanet atmospheres with JWST, but the landscape is clearly different.



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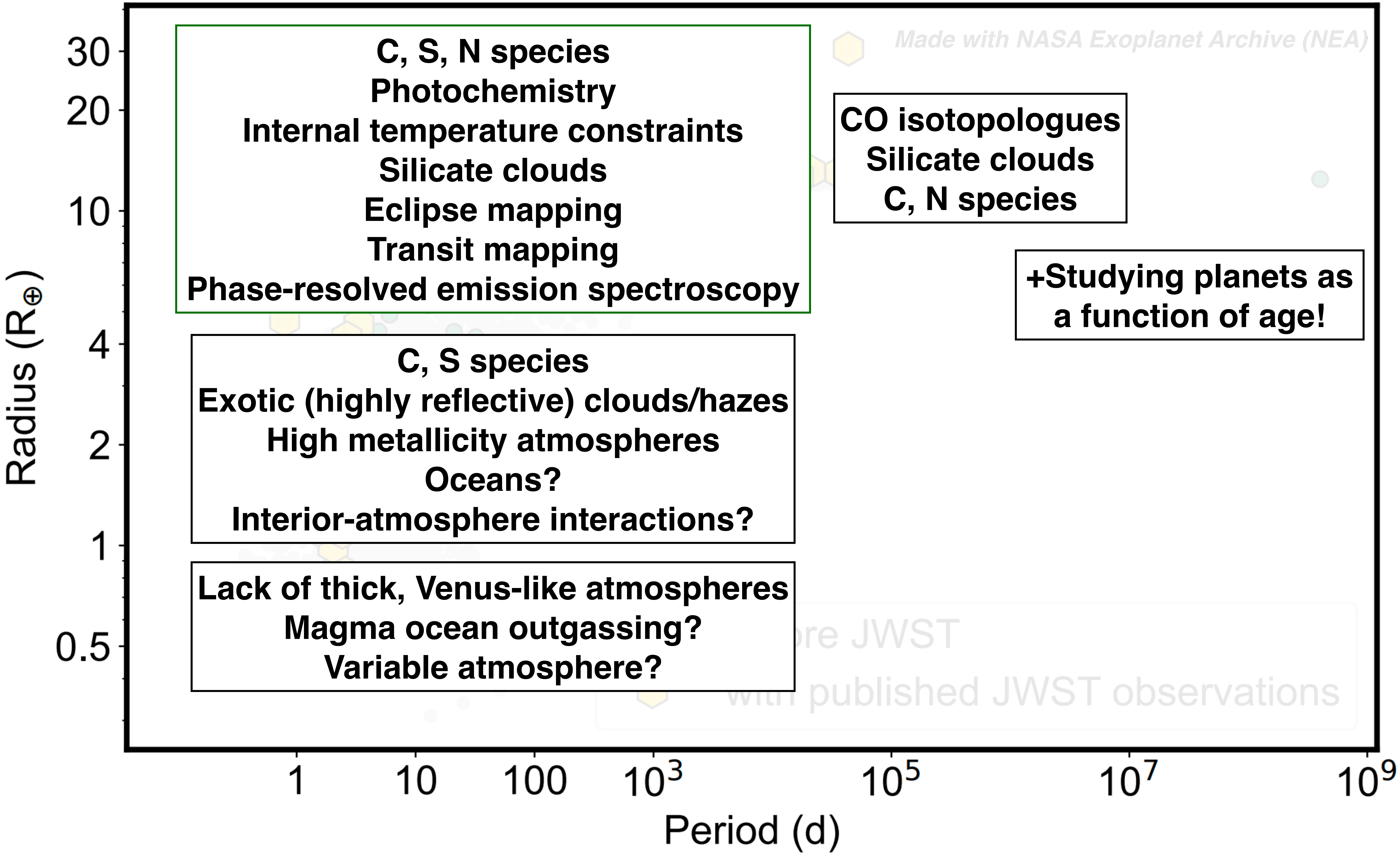

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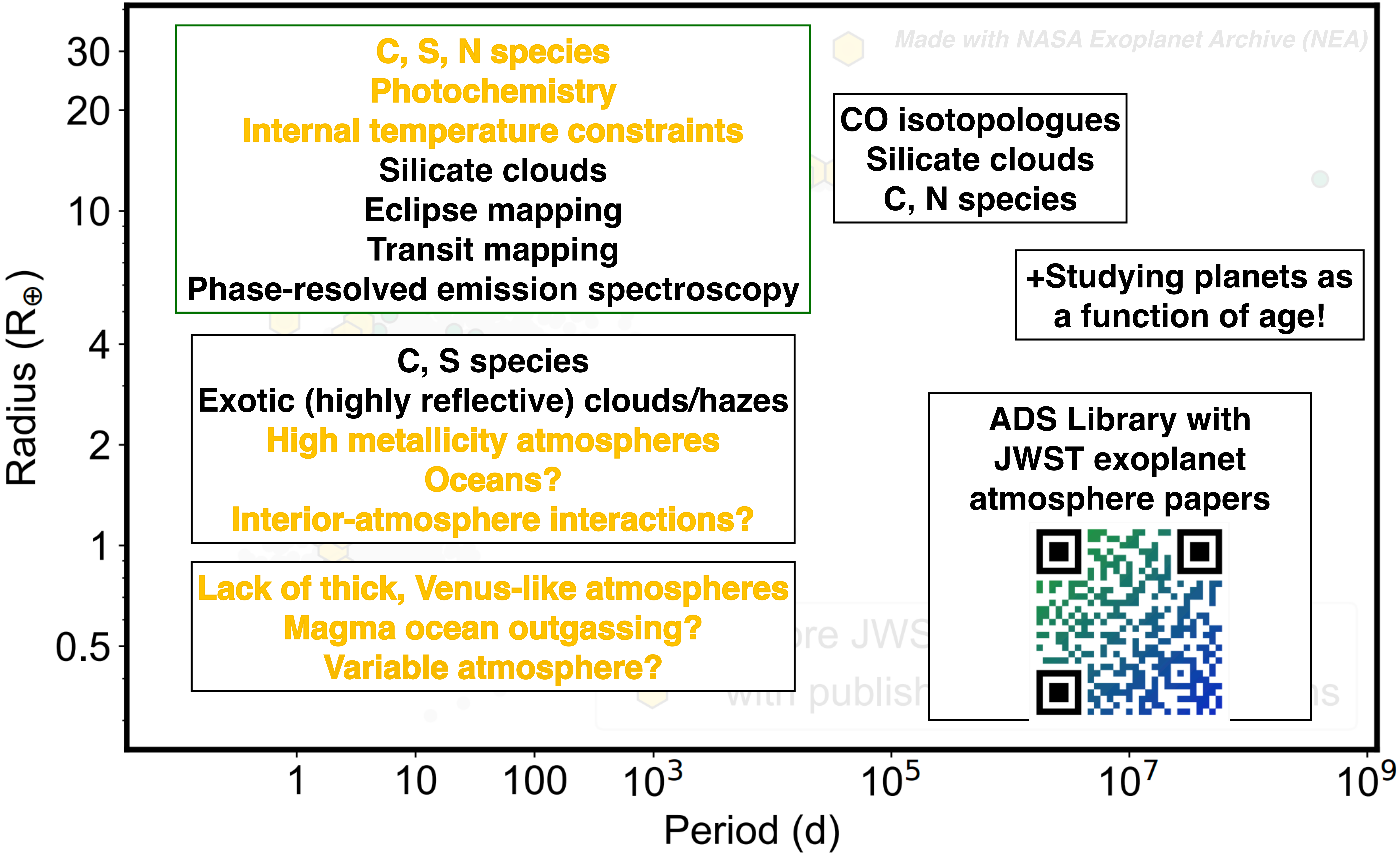
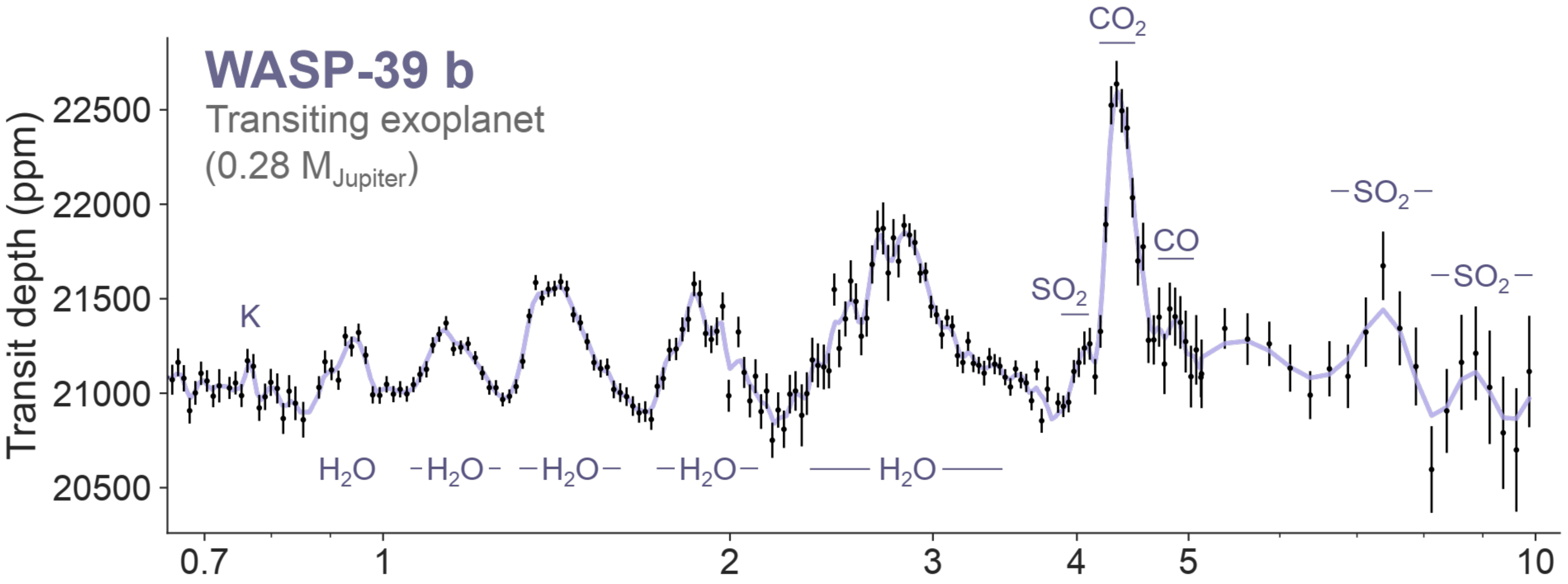


The extended wavelength coverage of JWST is providing a closer look at short period giant planet atmospheres.

The accessibility of sulfur species in exoplanet atmospheres through the aid of photochemistry allows for a new window into planet



Espinoza & Perrin 2025
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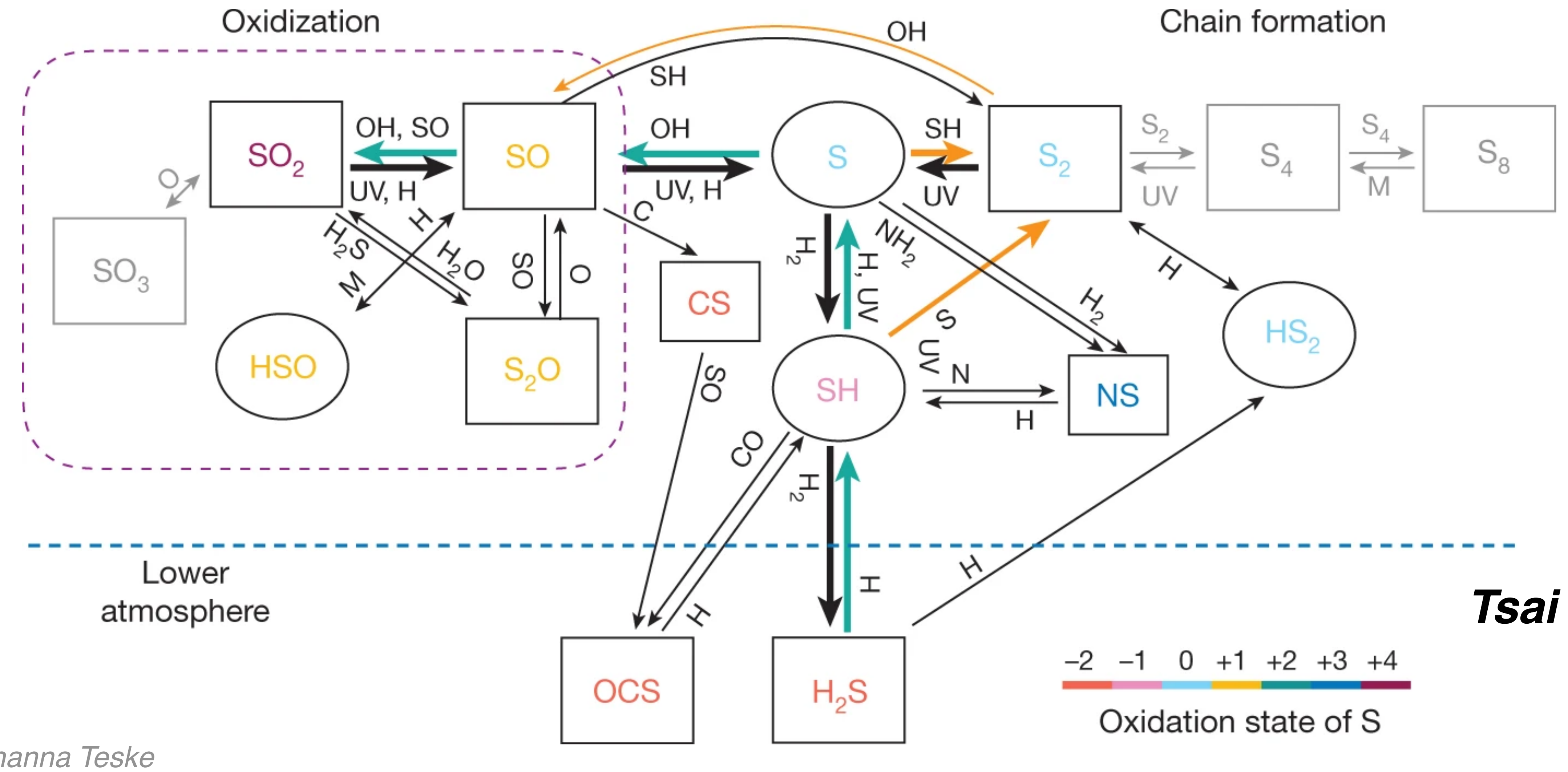

Tsai et al. 2023

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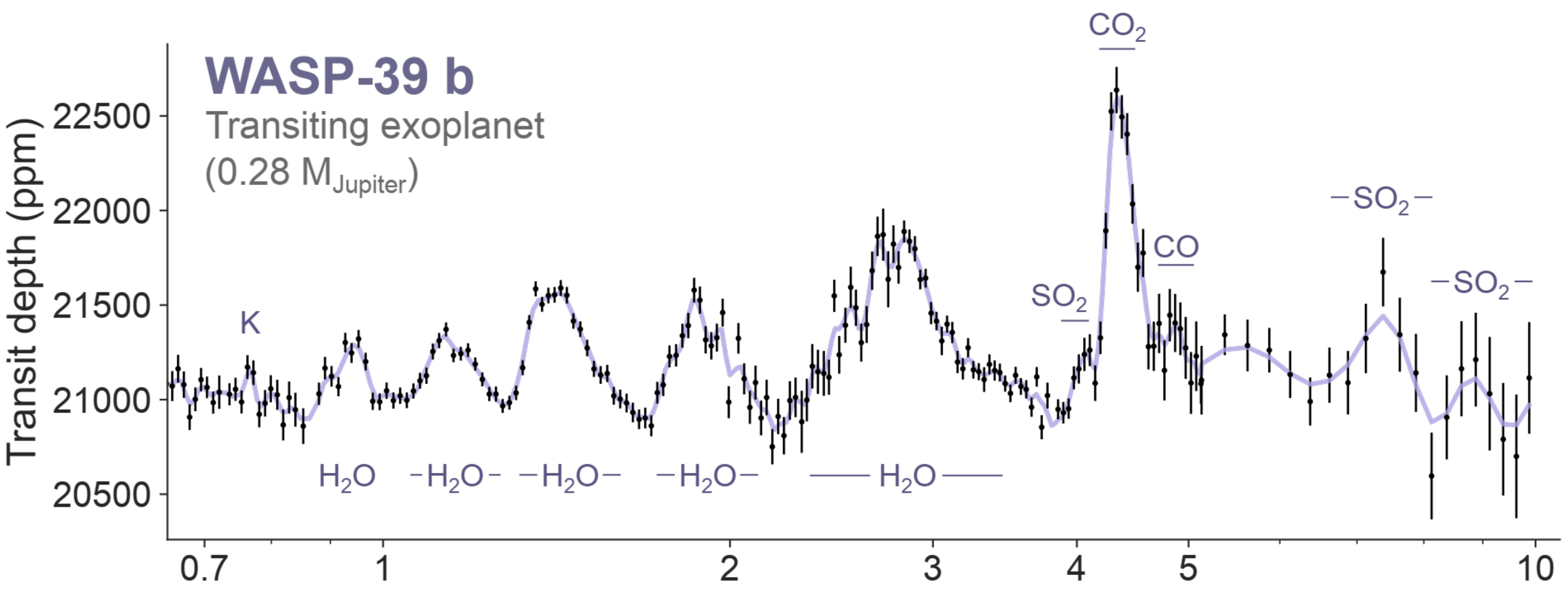

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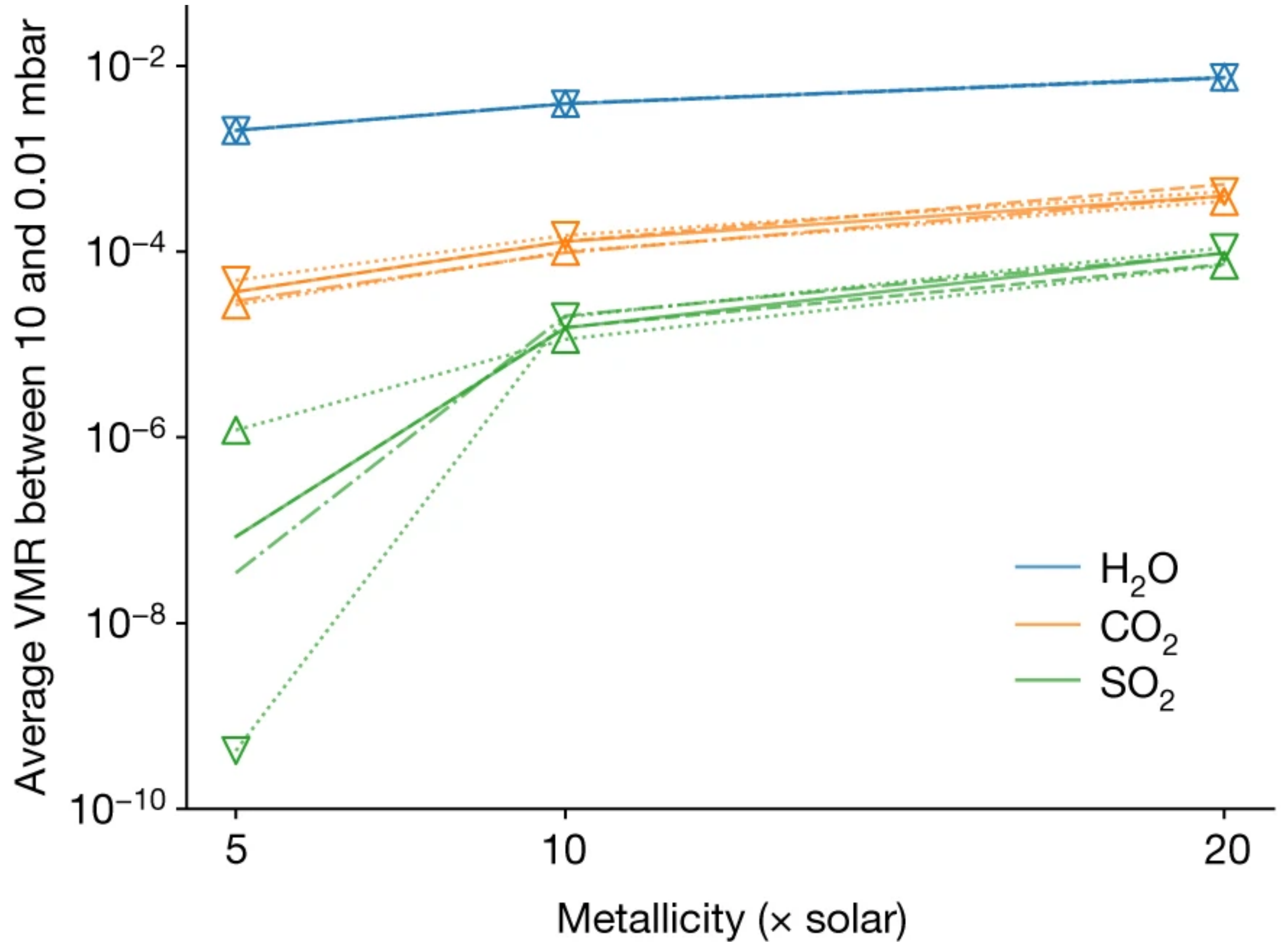

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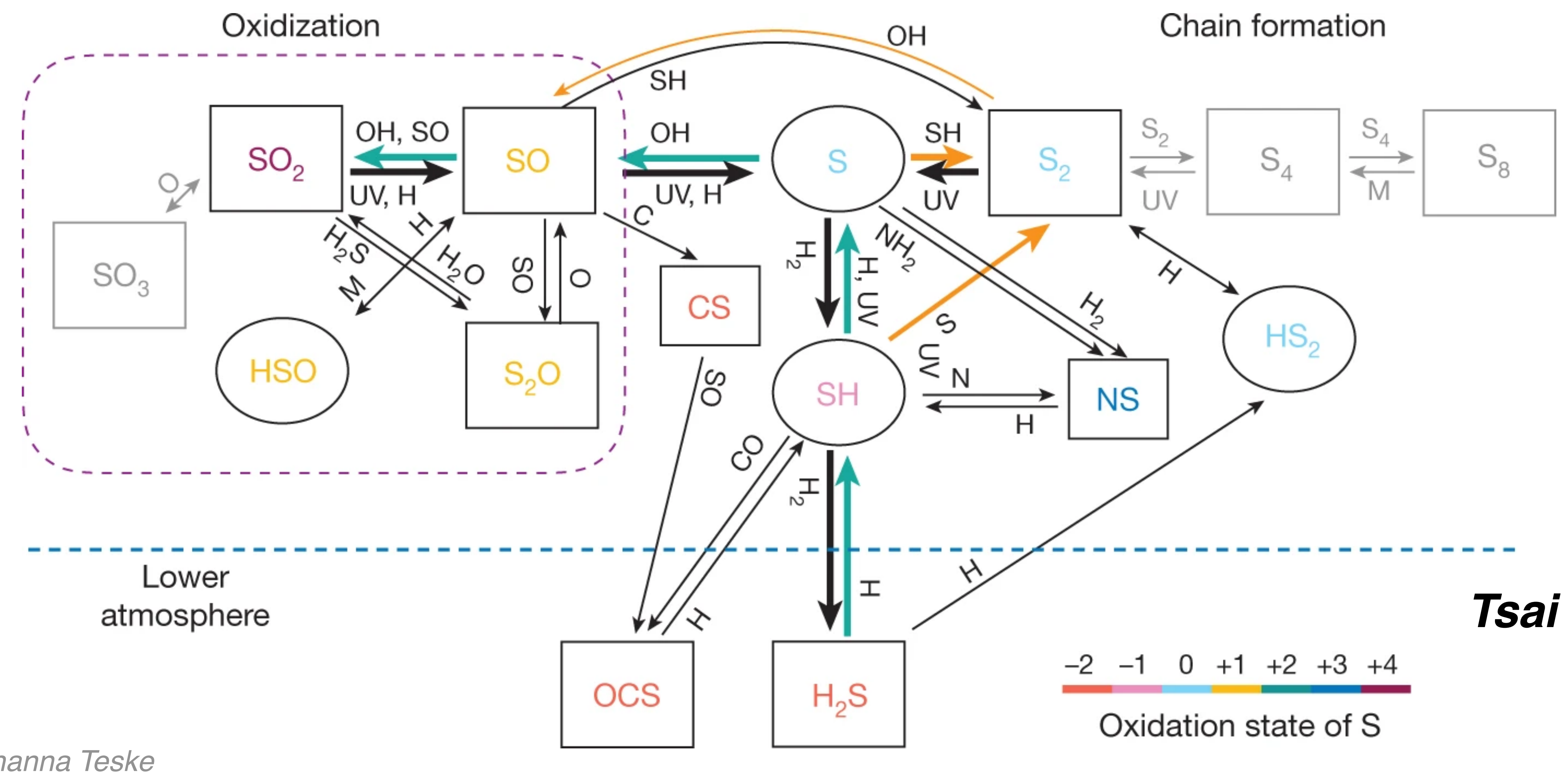

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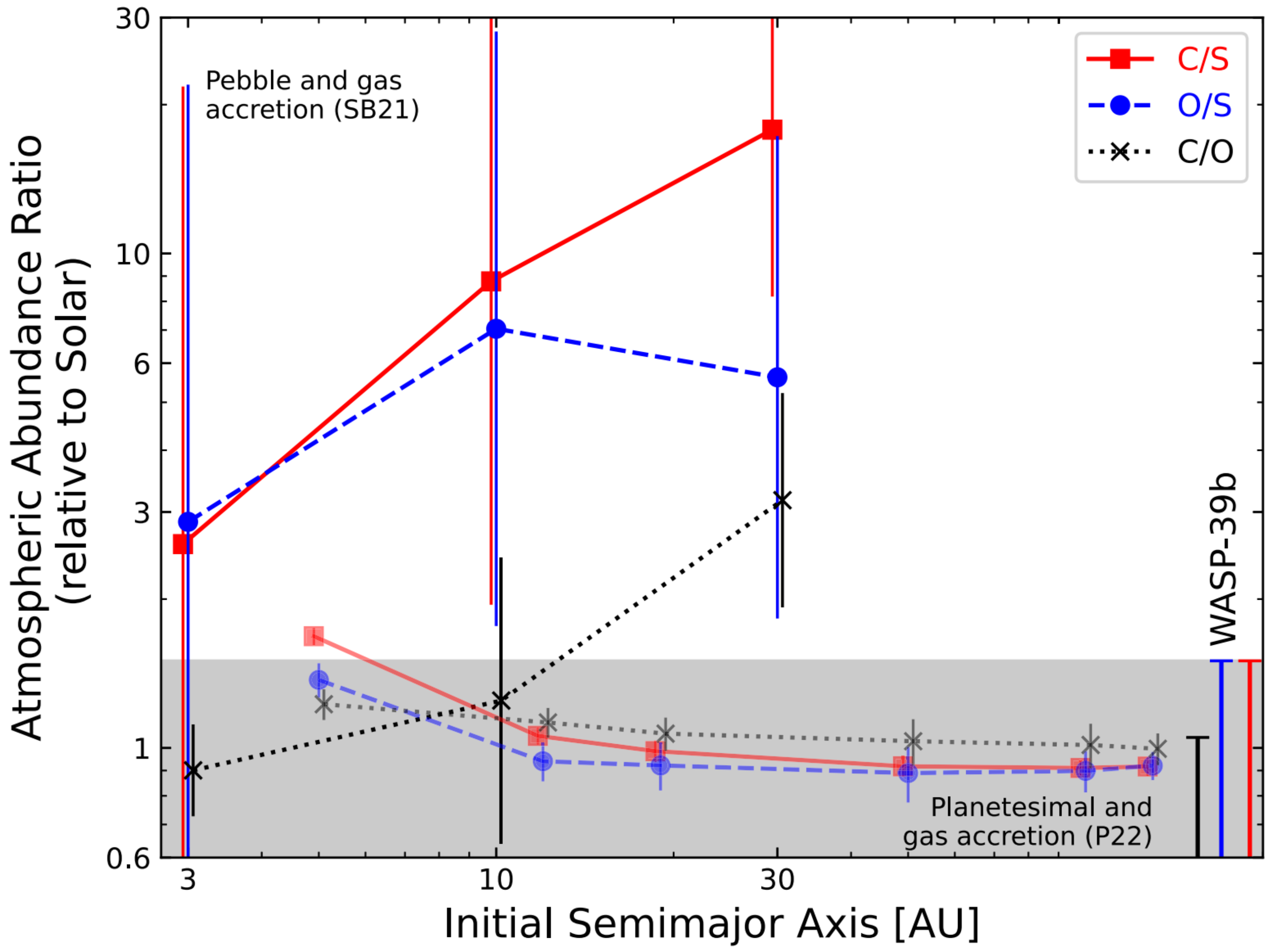
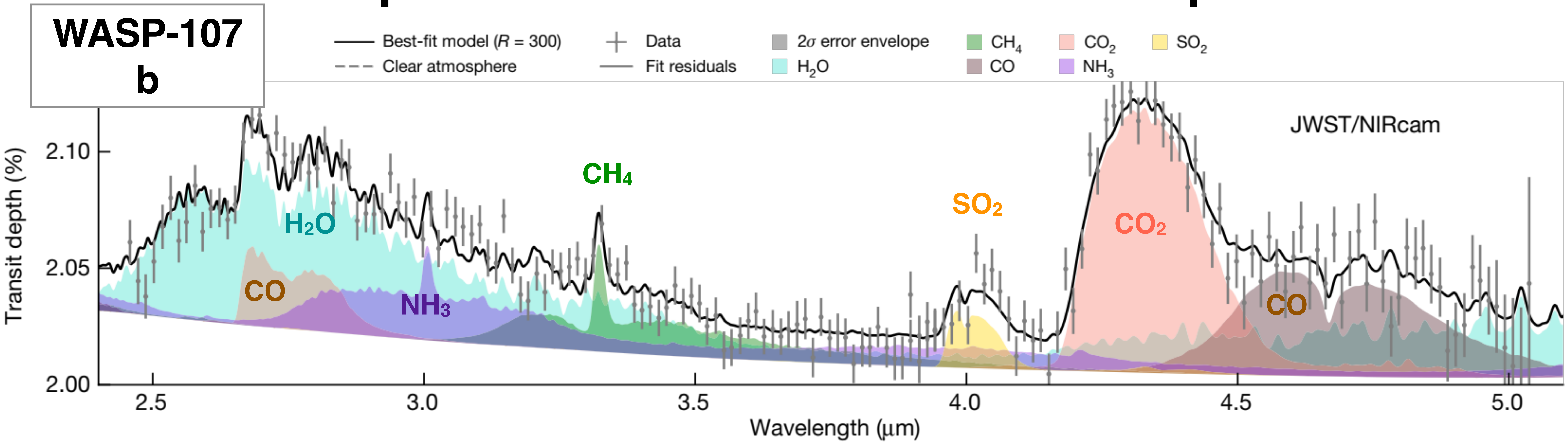


Crossfield et al. 2023

modeling results from Schneider & Bitsch 2021 and Pacetti et al. 2022

Access to carbon species like CH_4 improves constrains on the atmospheric as well as the interior composition.



Welbanks et al. 2024
see also Sing et al. 2024

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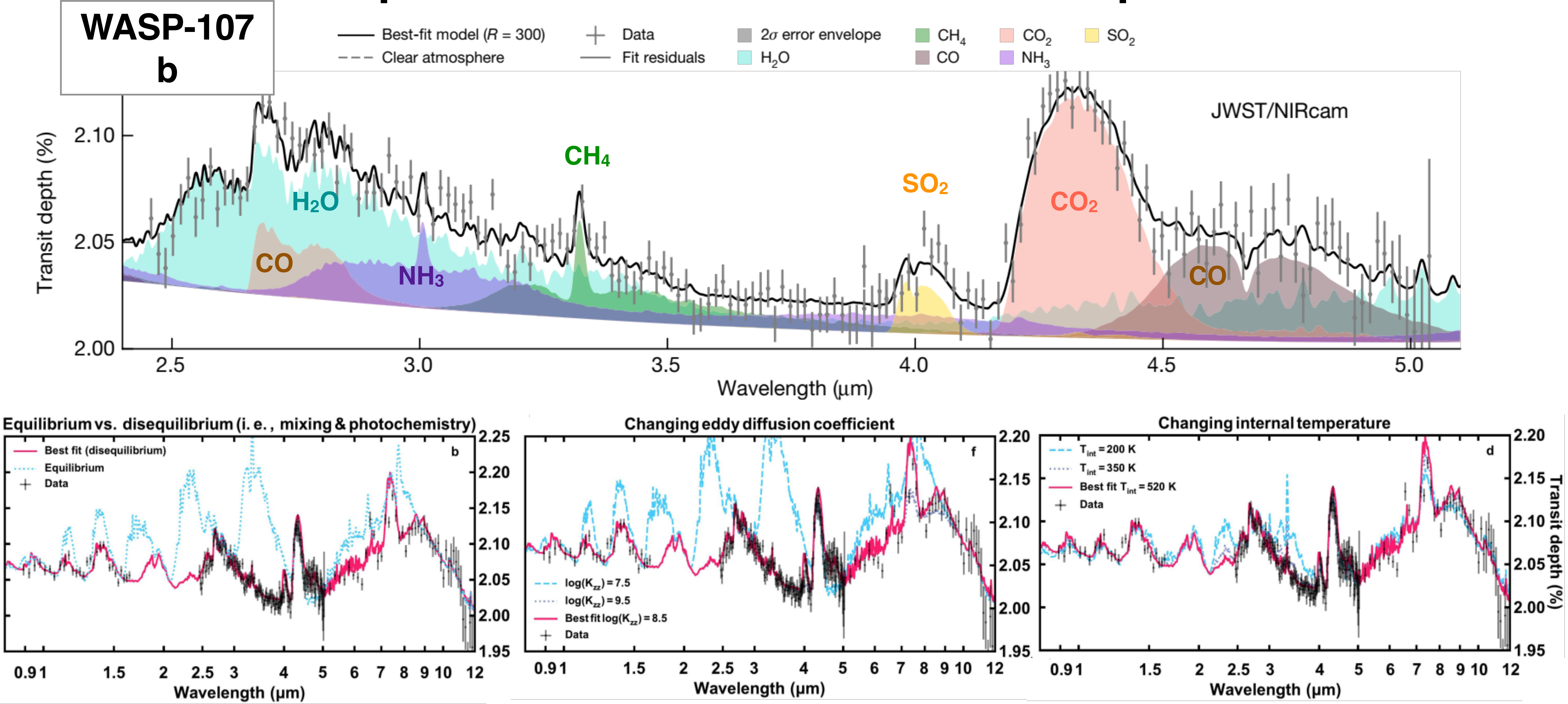
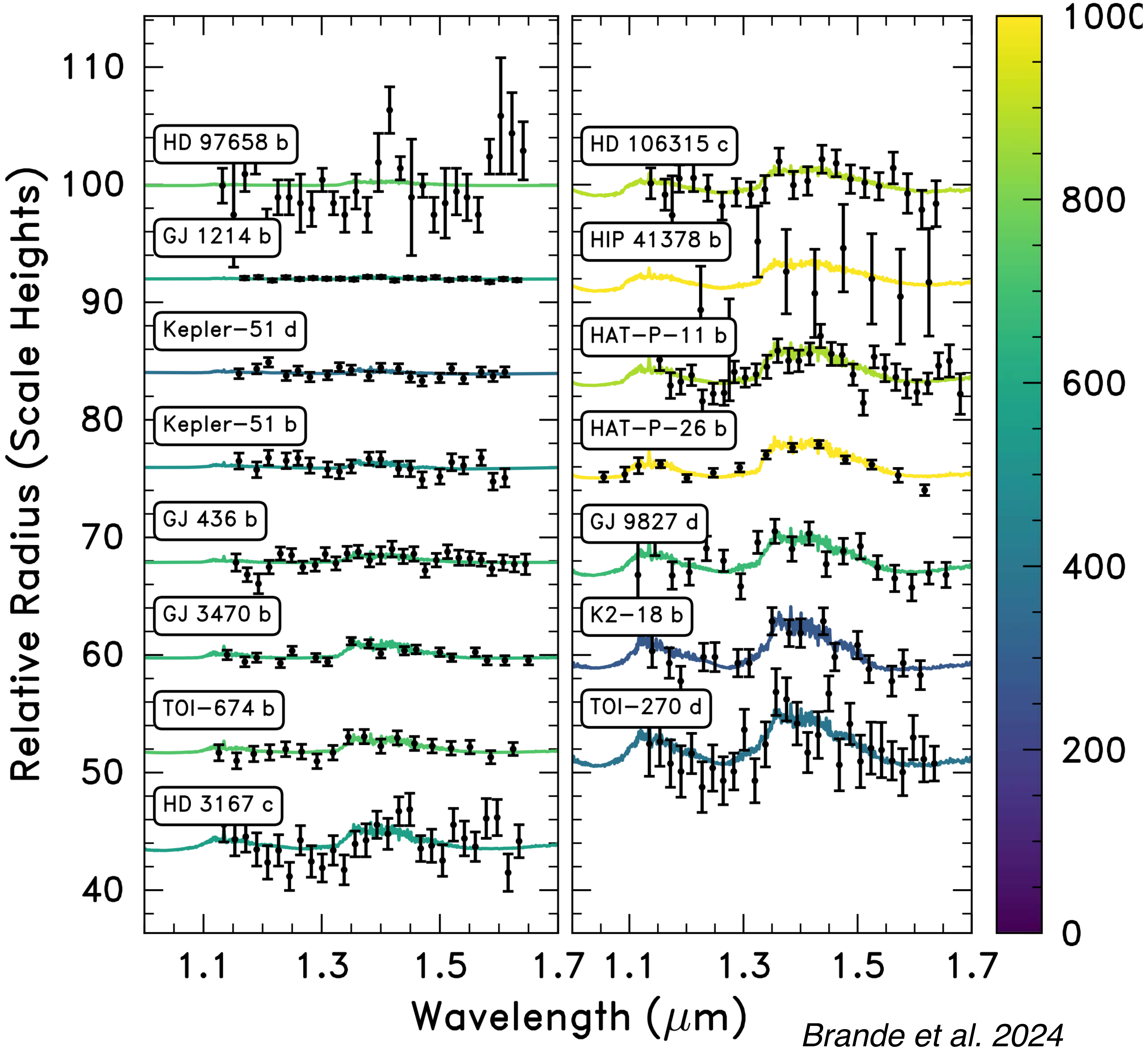


Welbanks et al. 2024
see also Sing et al. 2024

Is JWST helping solve the mystery of sub-Neptune planets…?

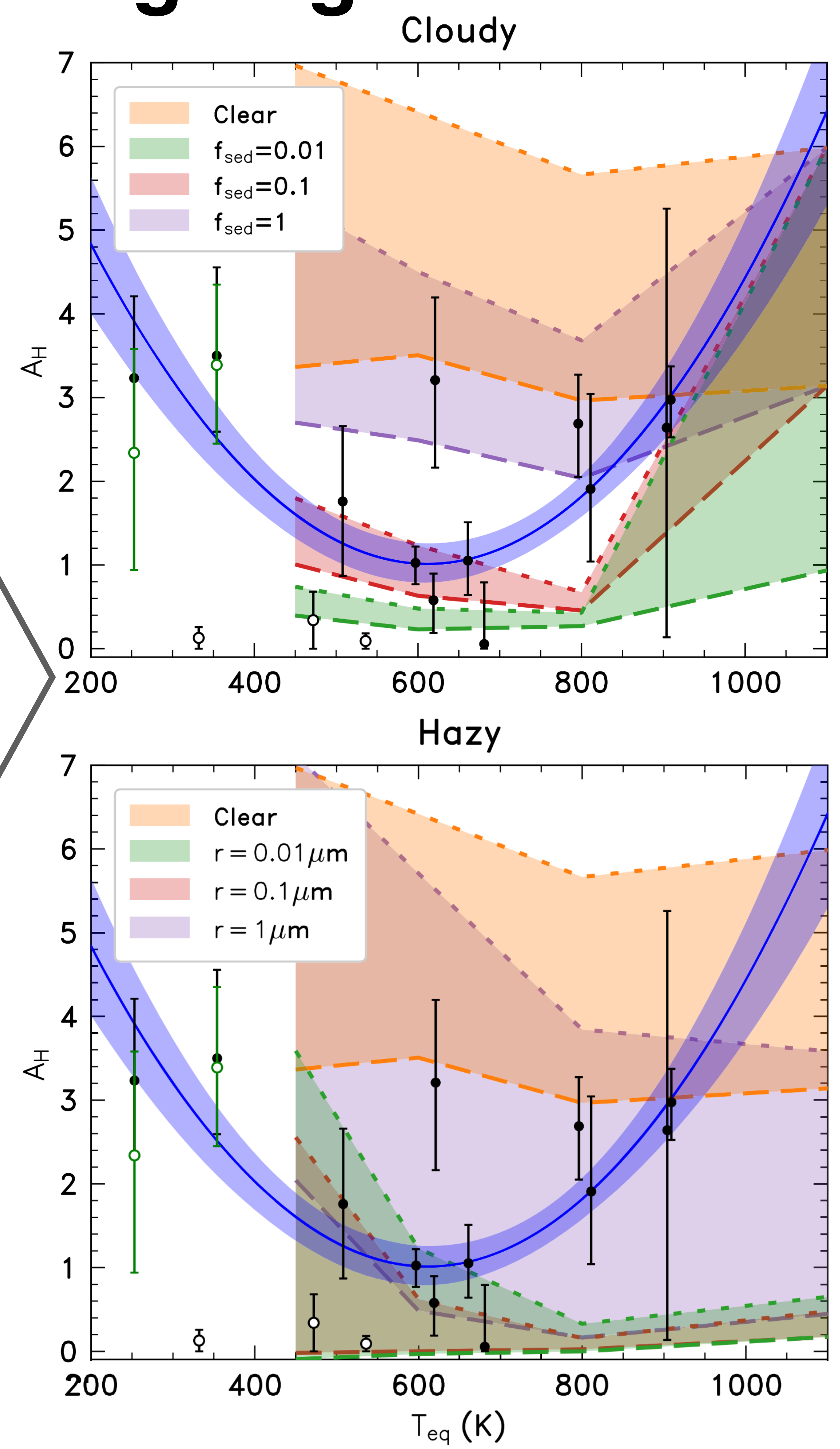
Actually, first, what hypothesis did we have going in?



Data suggest parabolic trend between clarity and T_{eq}

However, still intrinsic scatter in water feature size, and limited sample

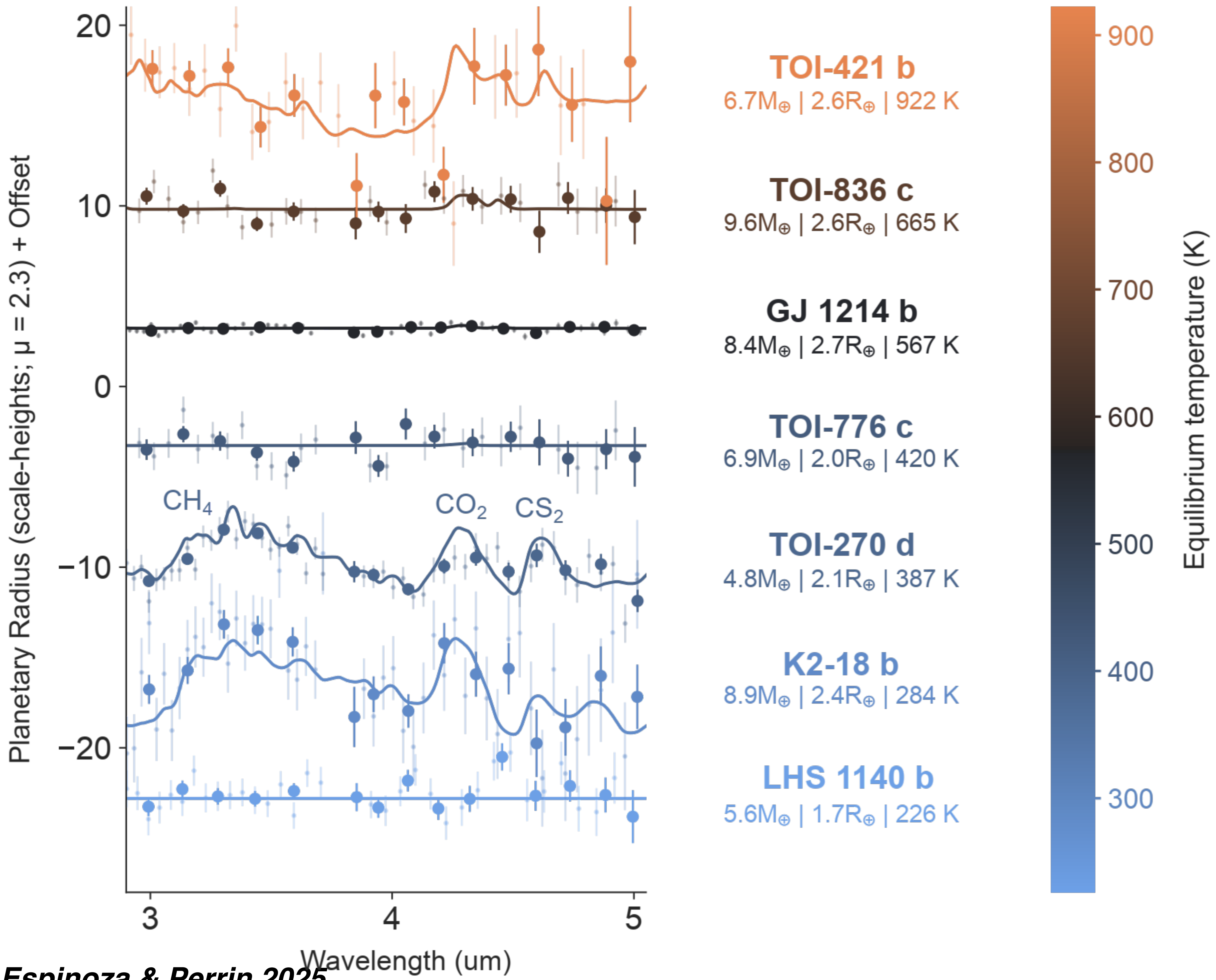
Also need to extend/ expand modeling efforts for clouds and hazes



Brande et al. 2024
See also Yu et al. 2021; Edwards et al. 2023

A small sample from JWST already shows diversity in feature strengths.

$$H = \frac{K_b T_{eq}}{\mu g}$$



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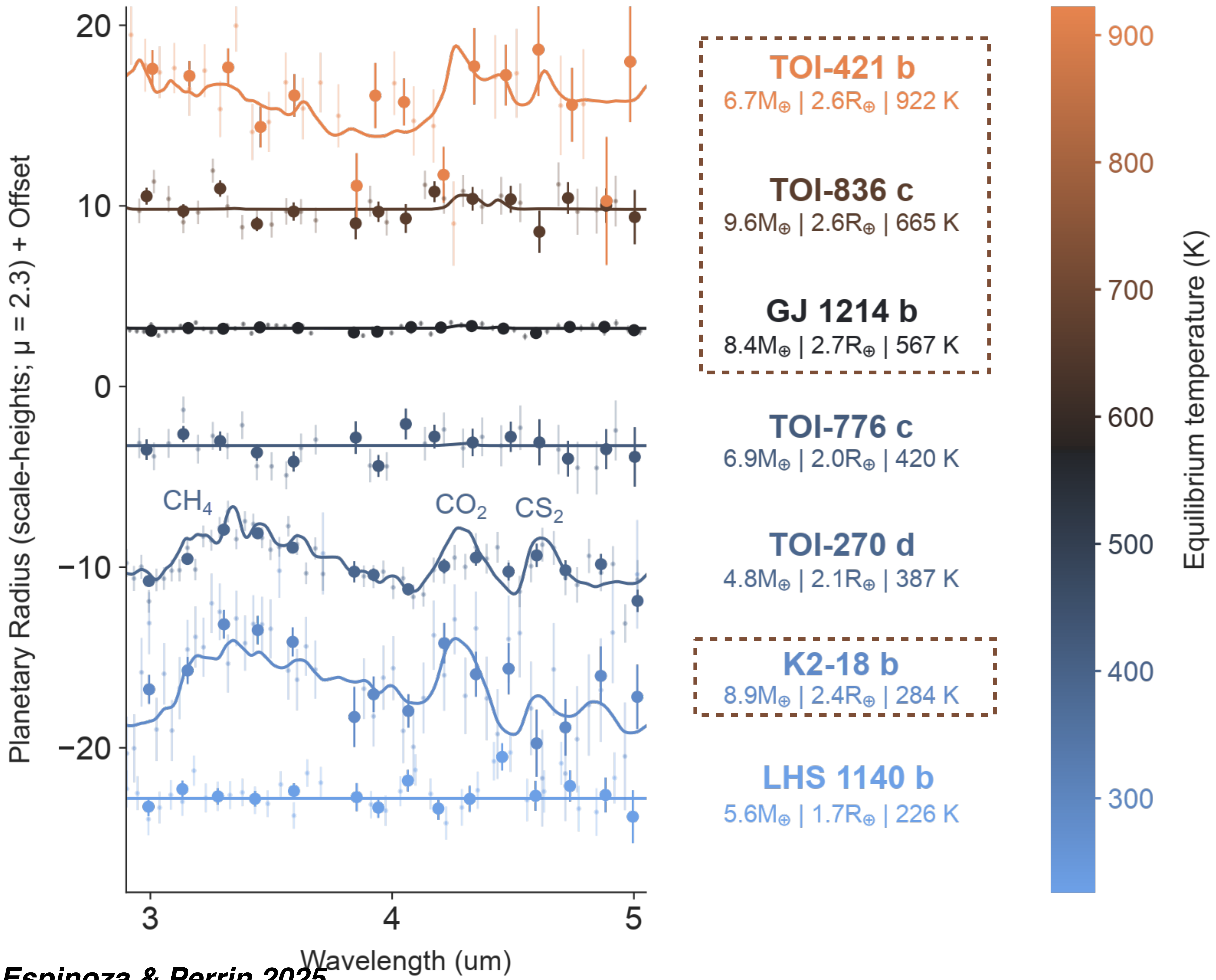
Is diversity in spectral features due to temperature (aerosols), surface gravity?



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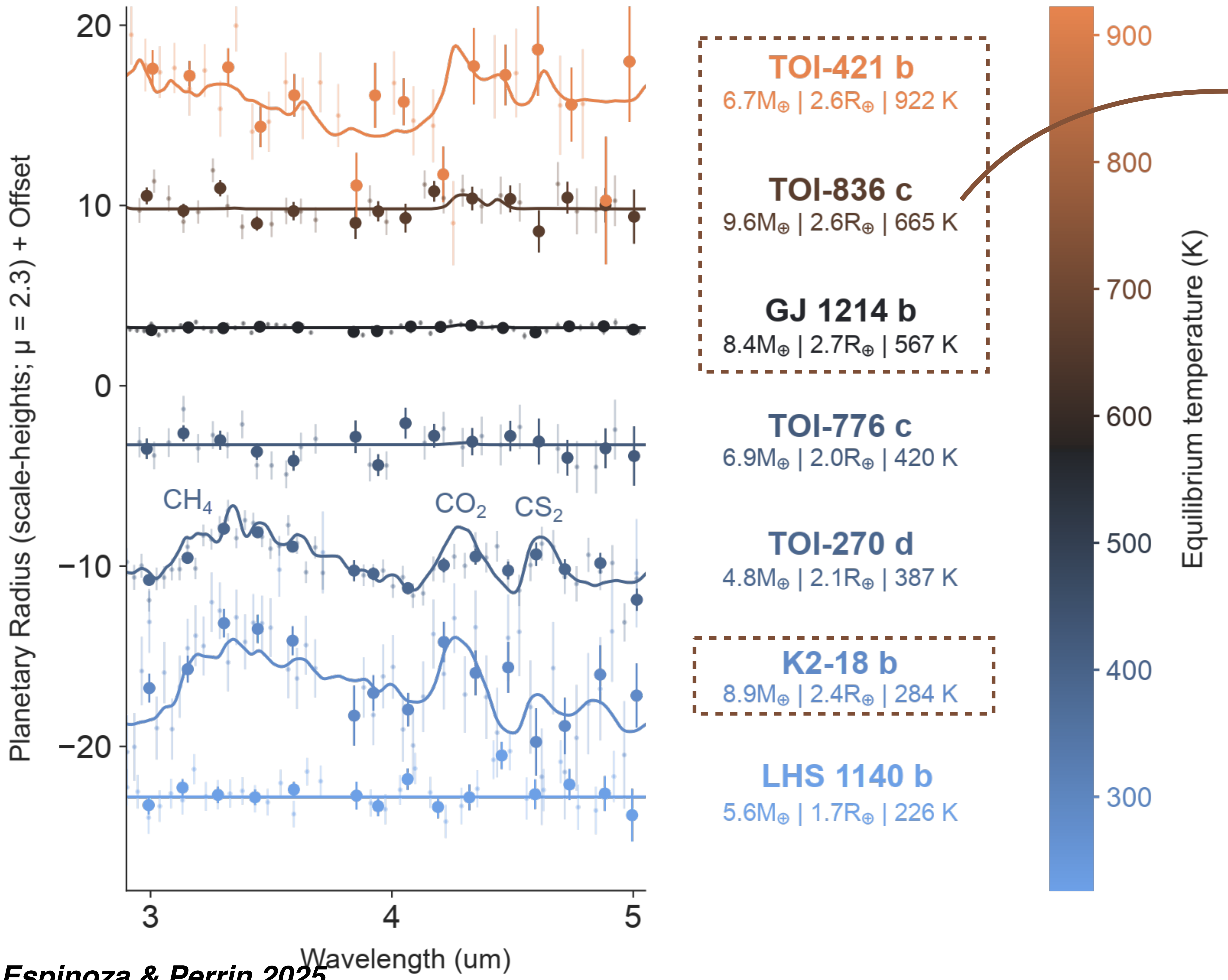

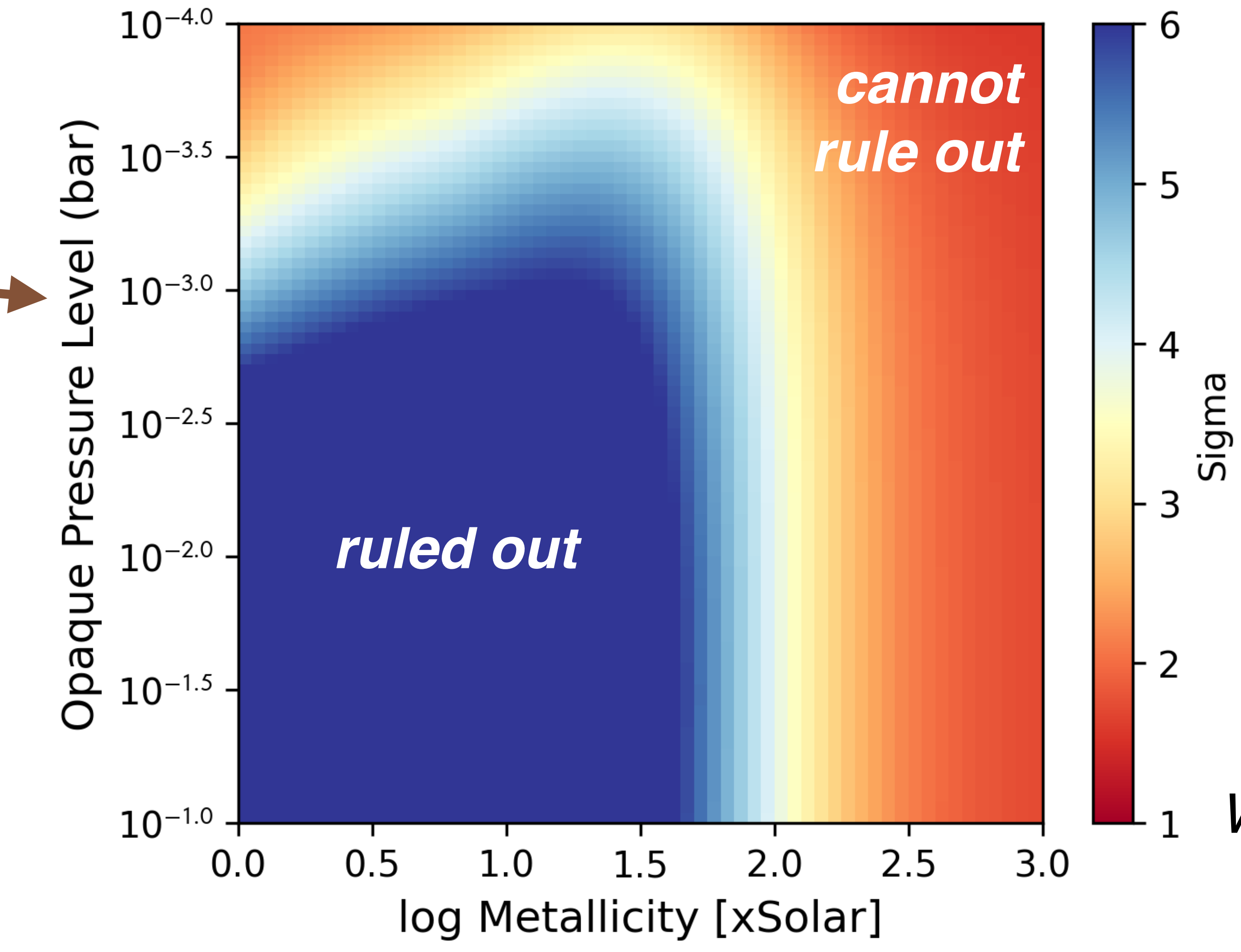

Wallack et al. 2024

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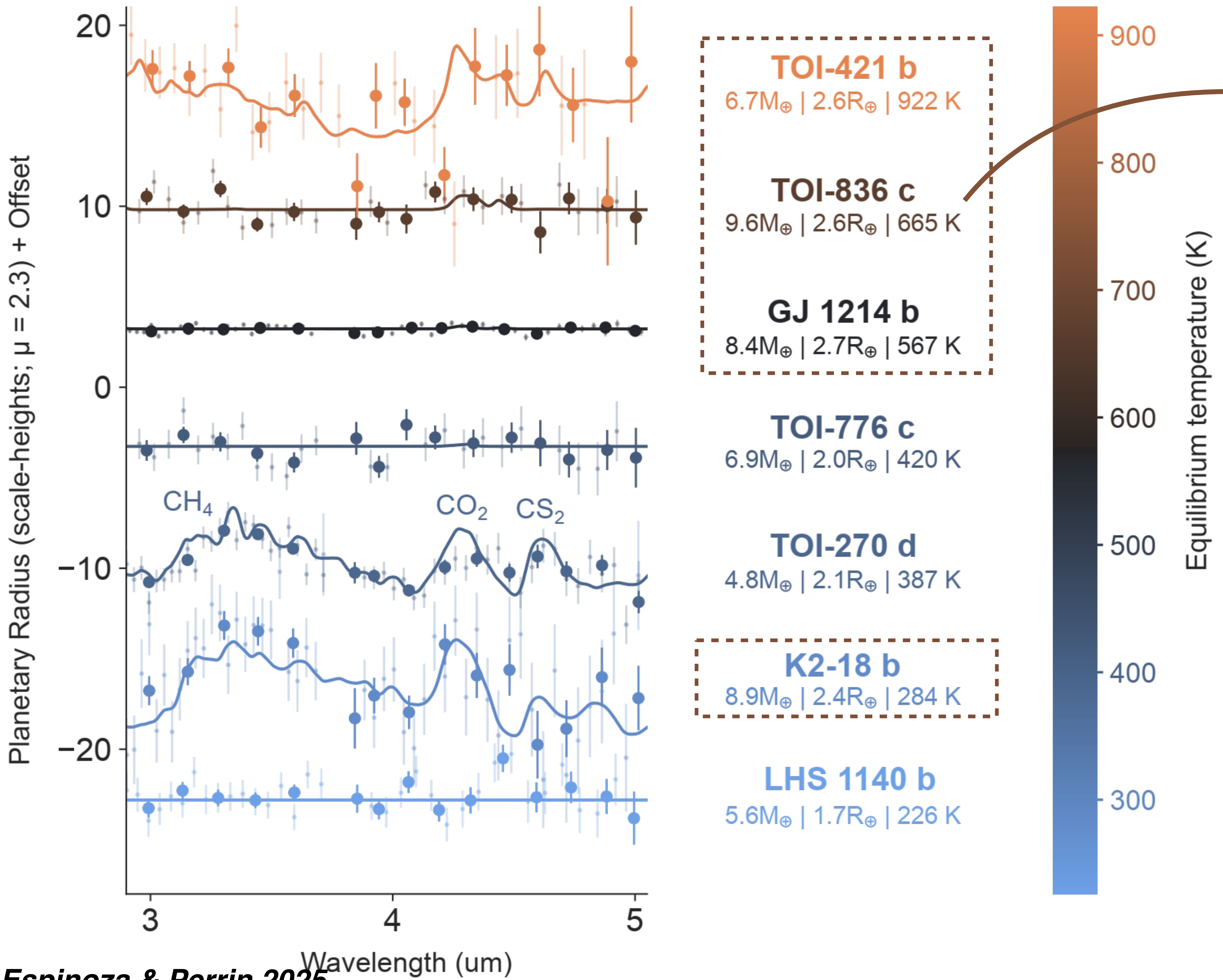
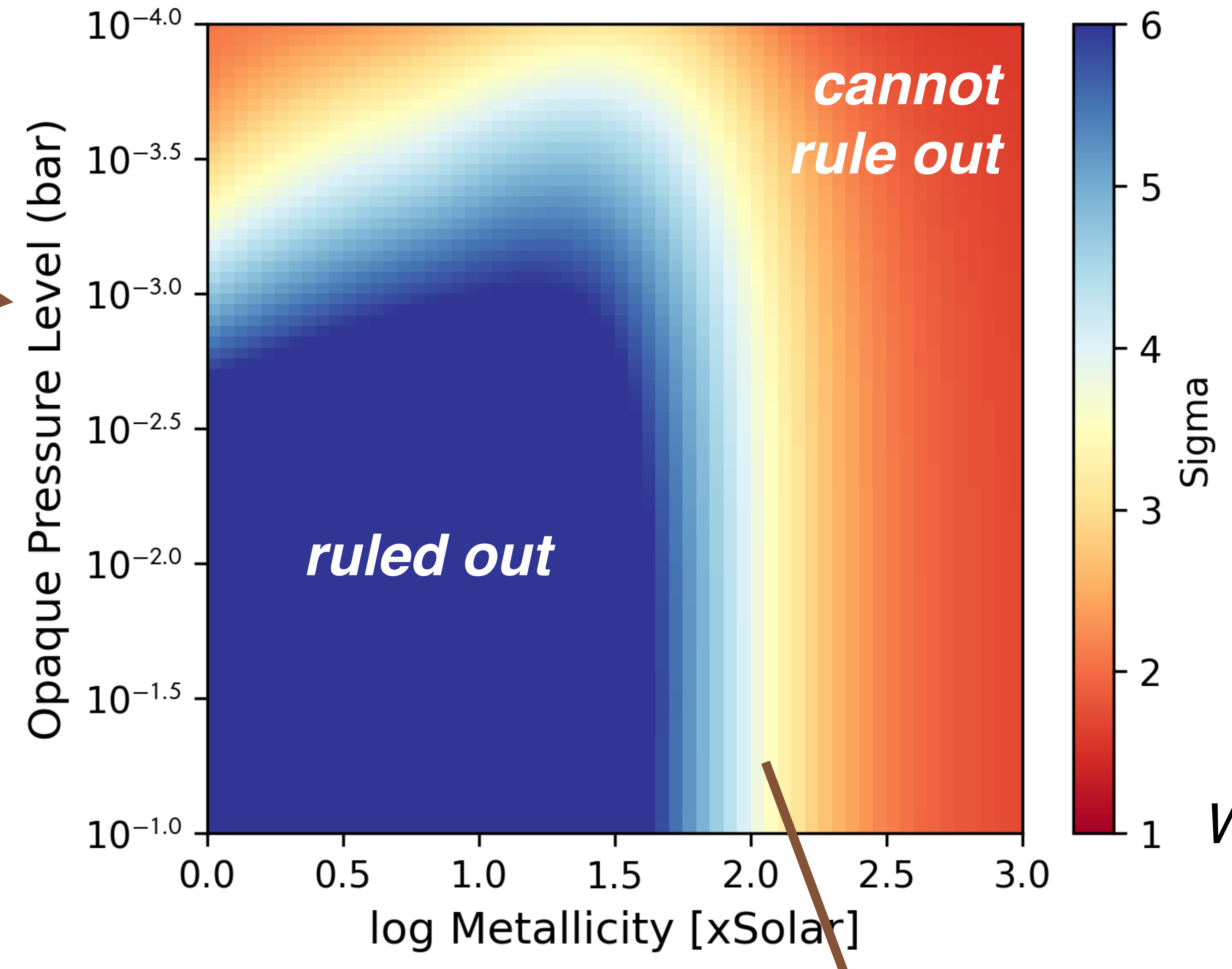
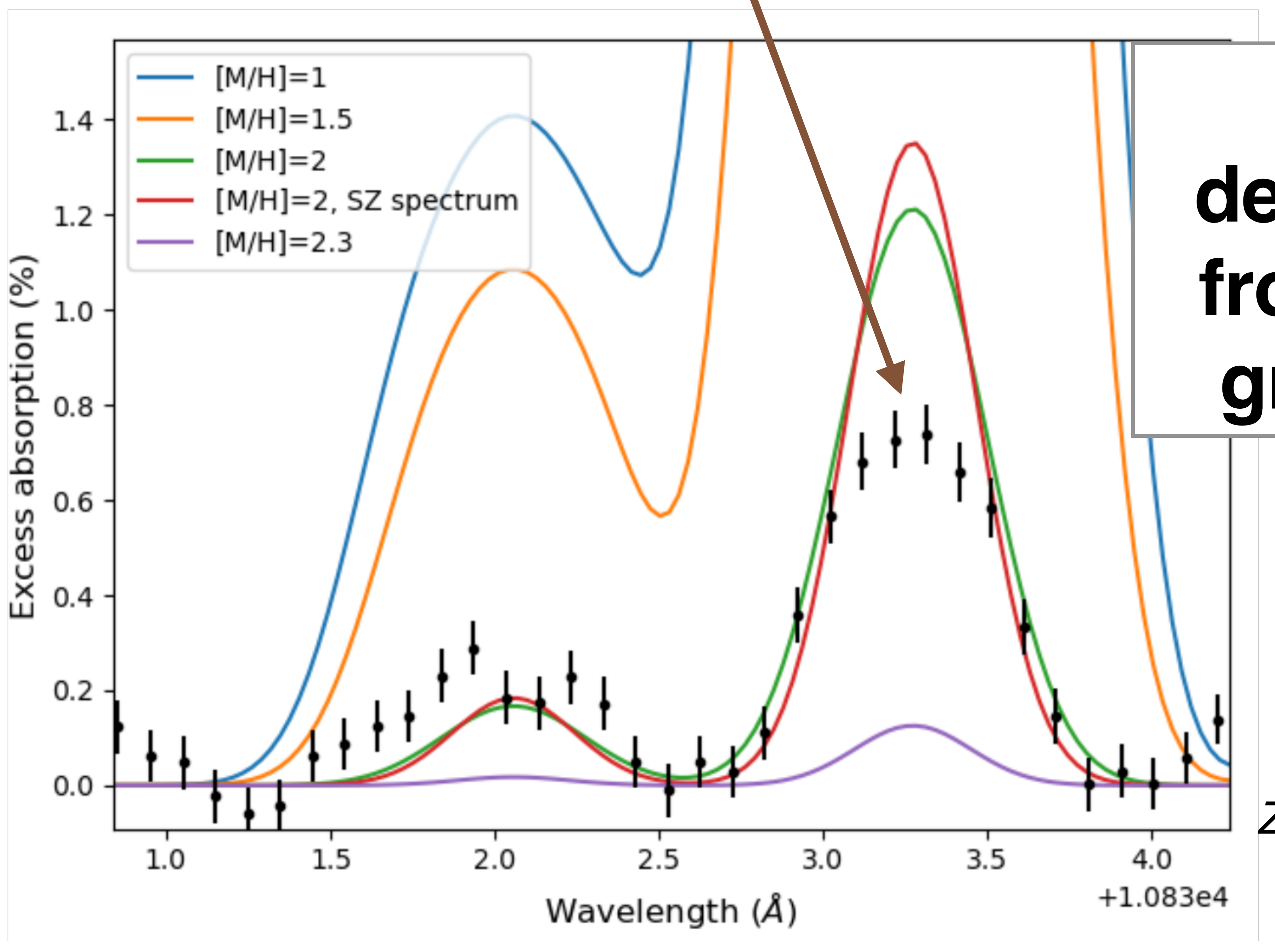




Wallack et al. 2024

see also GJ 3090 b in Ahrer et al. 2025



He detected from the ground

Zhang et al. 2024

Espinoza & Perrin 2025
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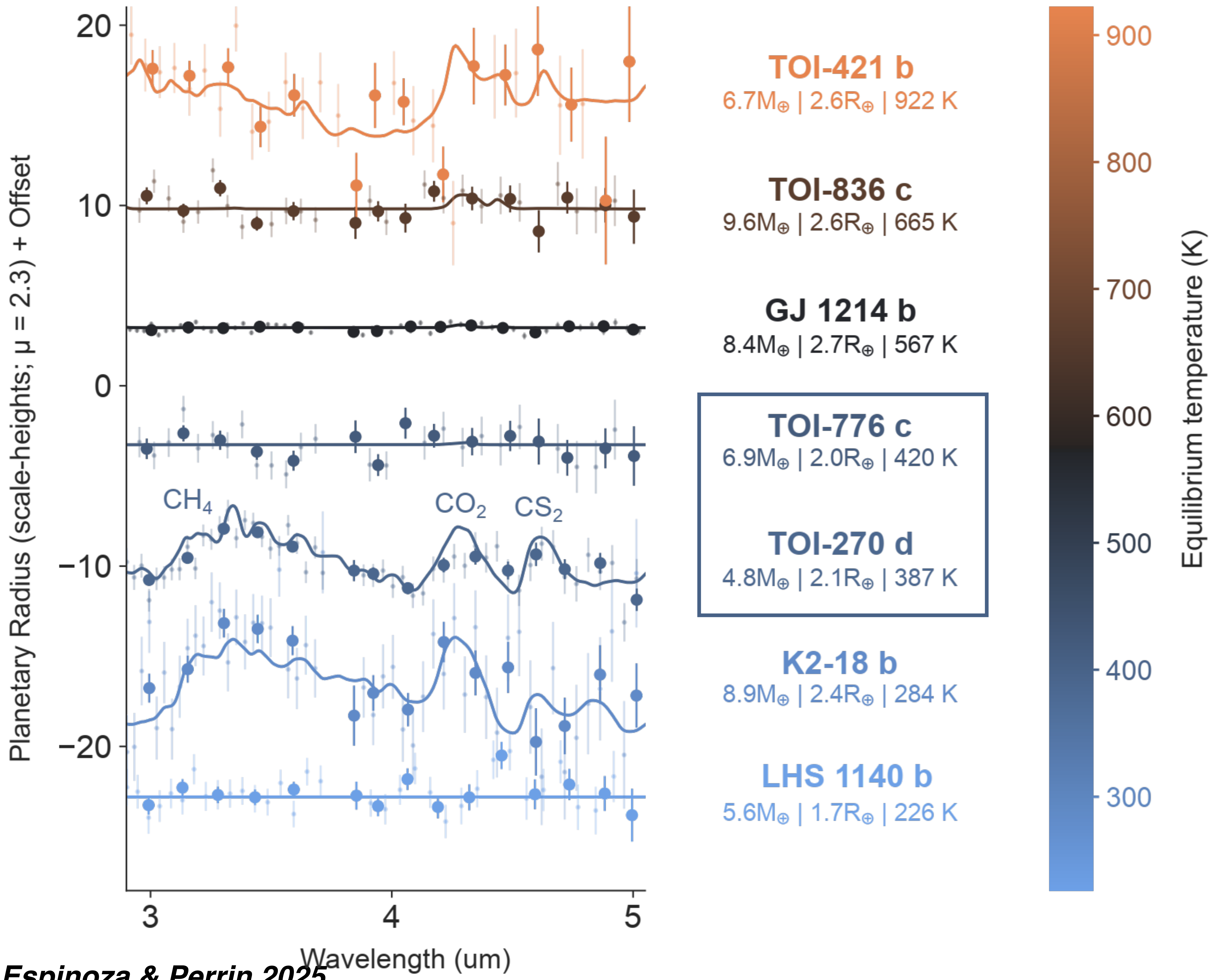

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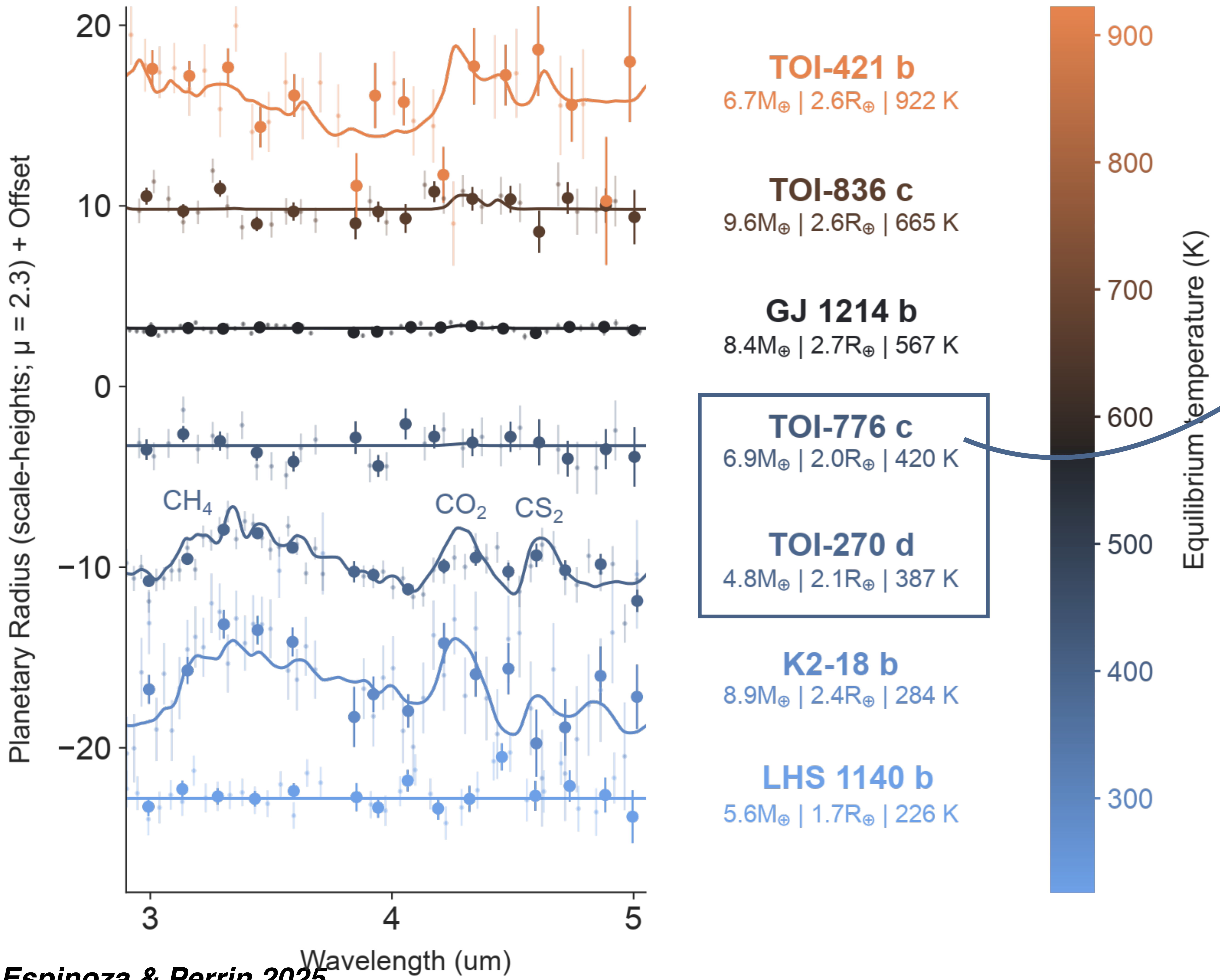

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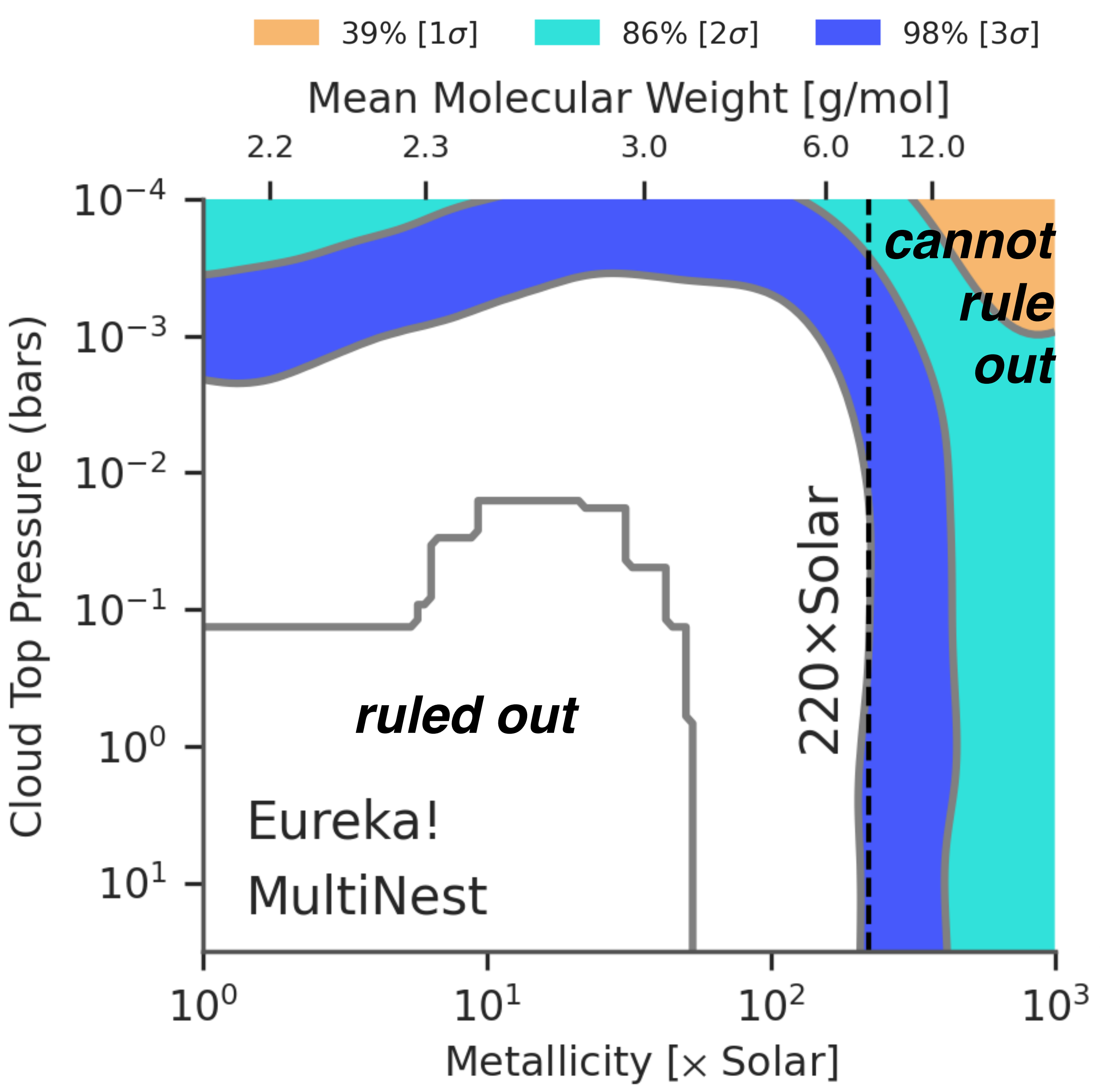

Atmospheric metallicity likely ≳200x solar

Very similar to measured TOI-270 d metallicity —> may be brushing up against what makes detectable features

Teske, Batalha et al. 2025

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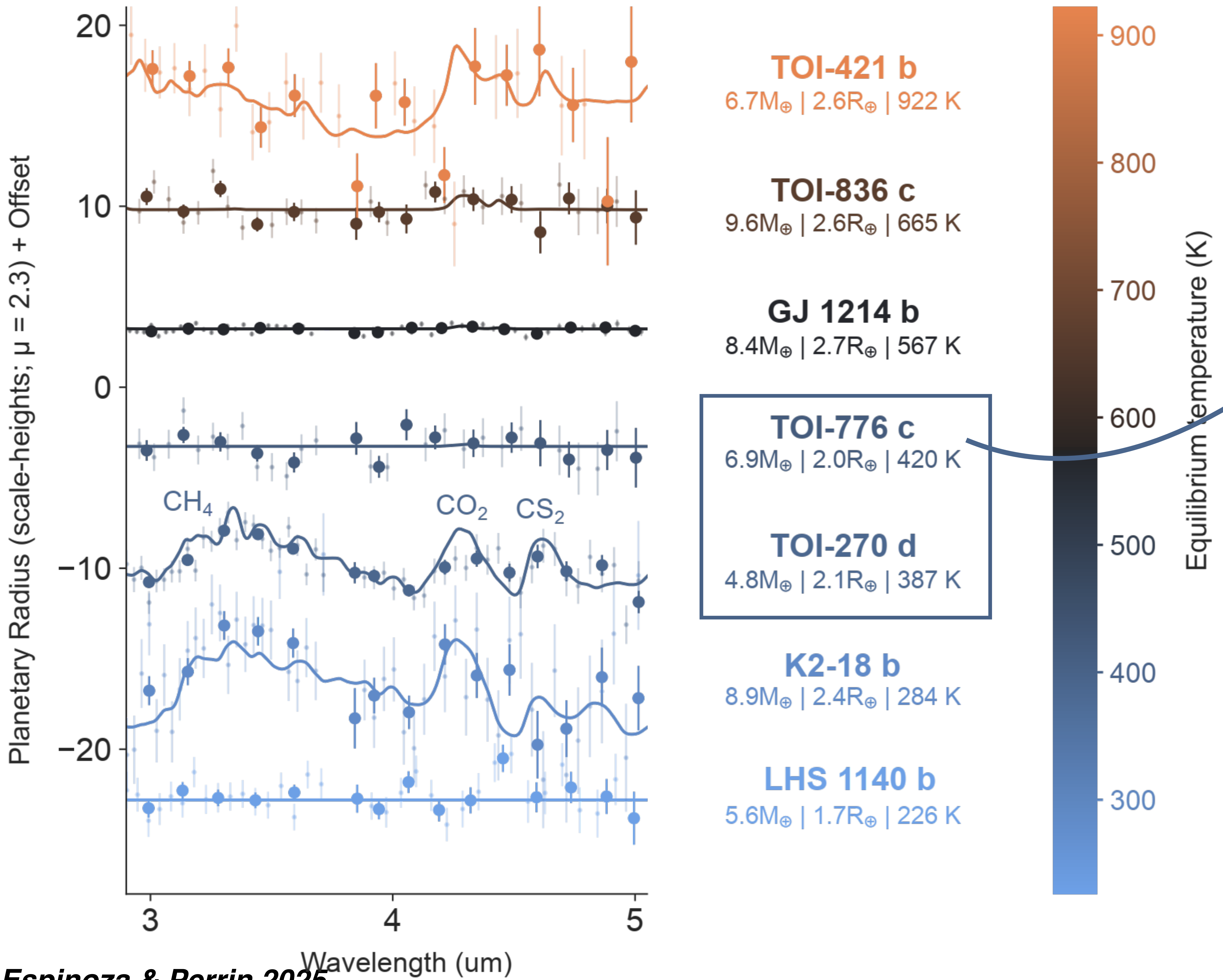

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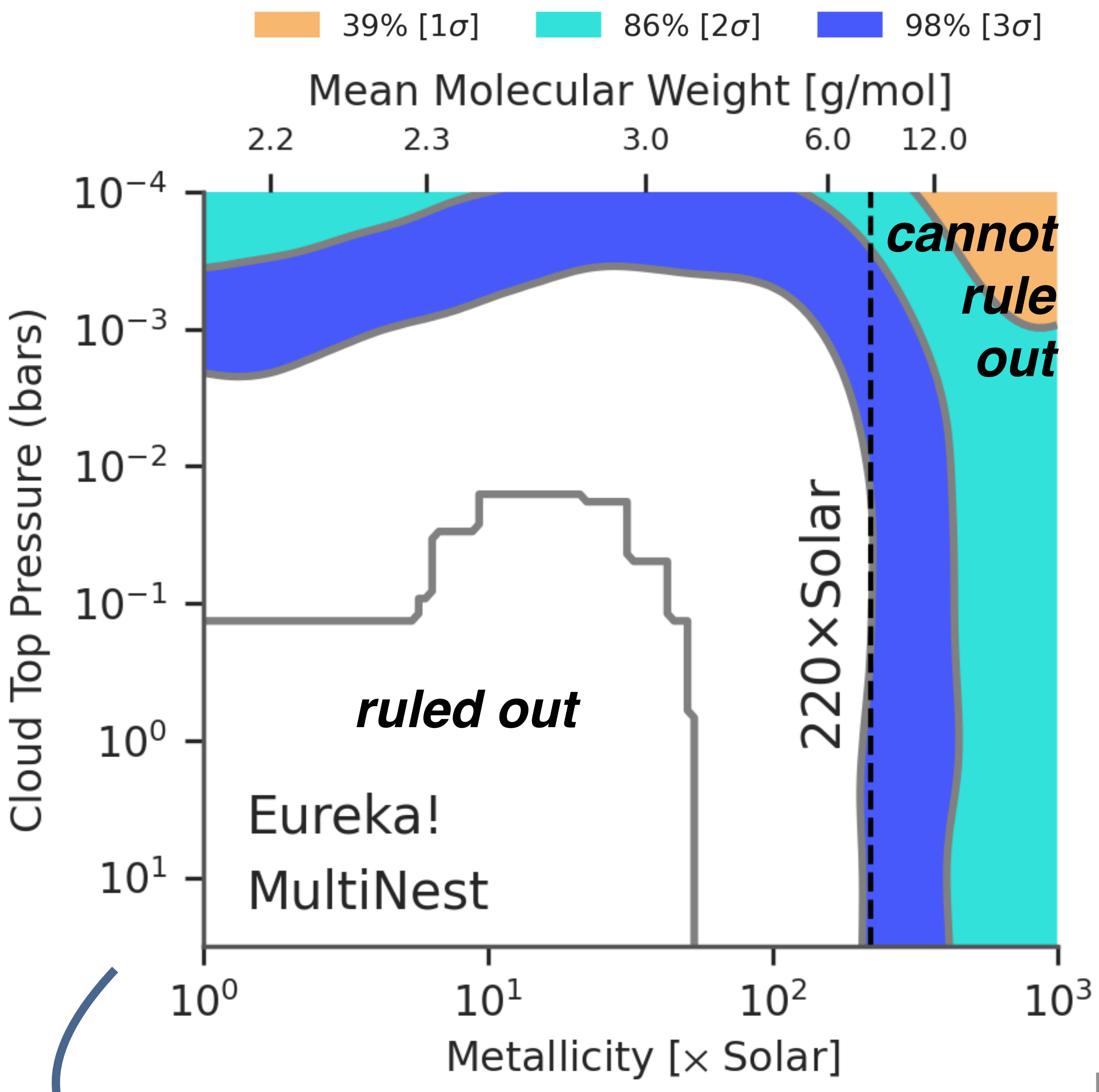

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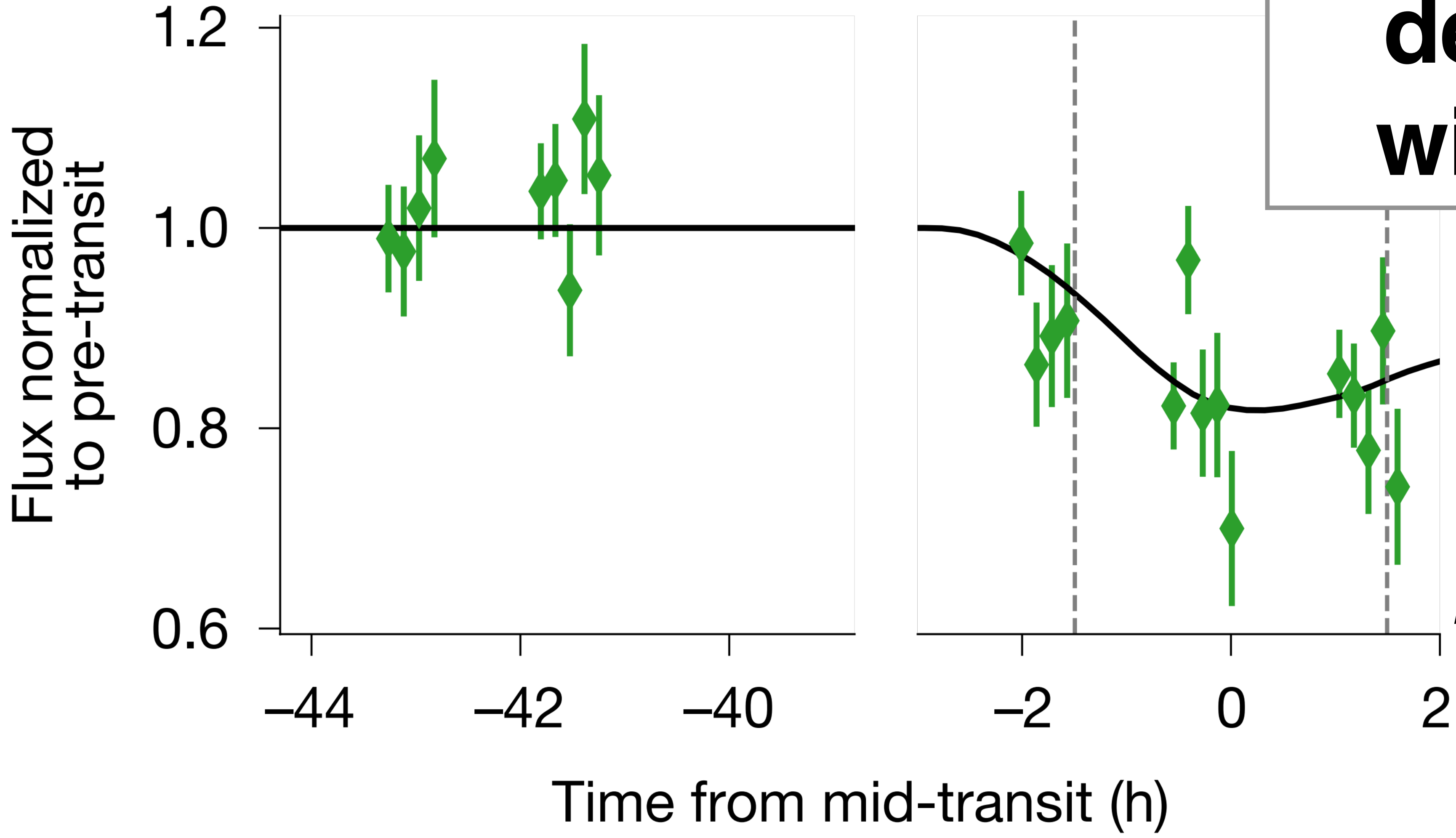
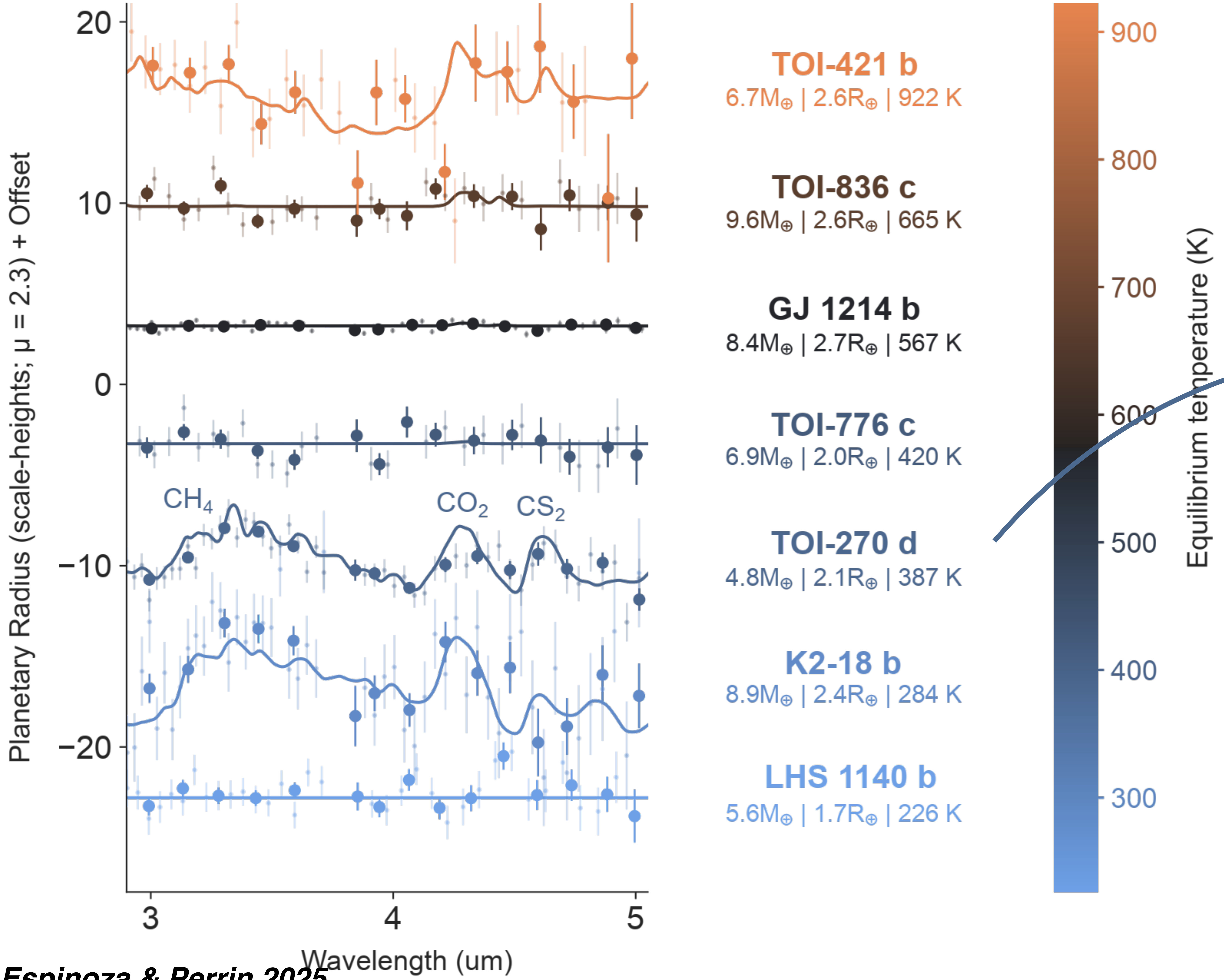
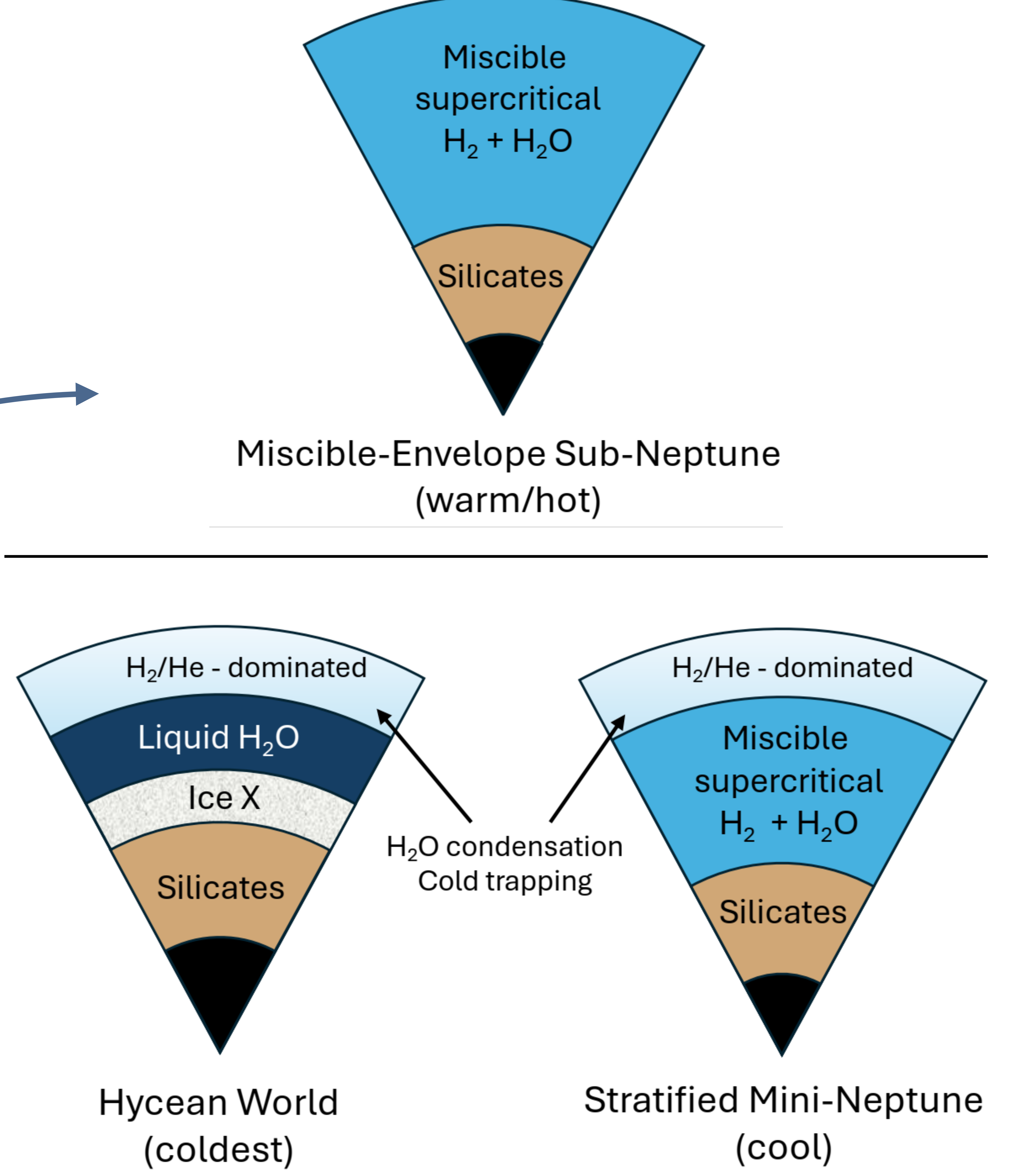


Loyd et al. 2025

Ly-α detected with HST

For many sub-Neptunes, H_2 and heavier volatiles will be miscible in the gas and supercritical phases.





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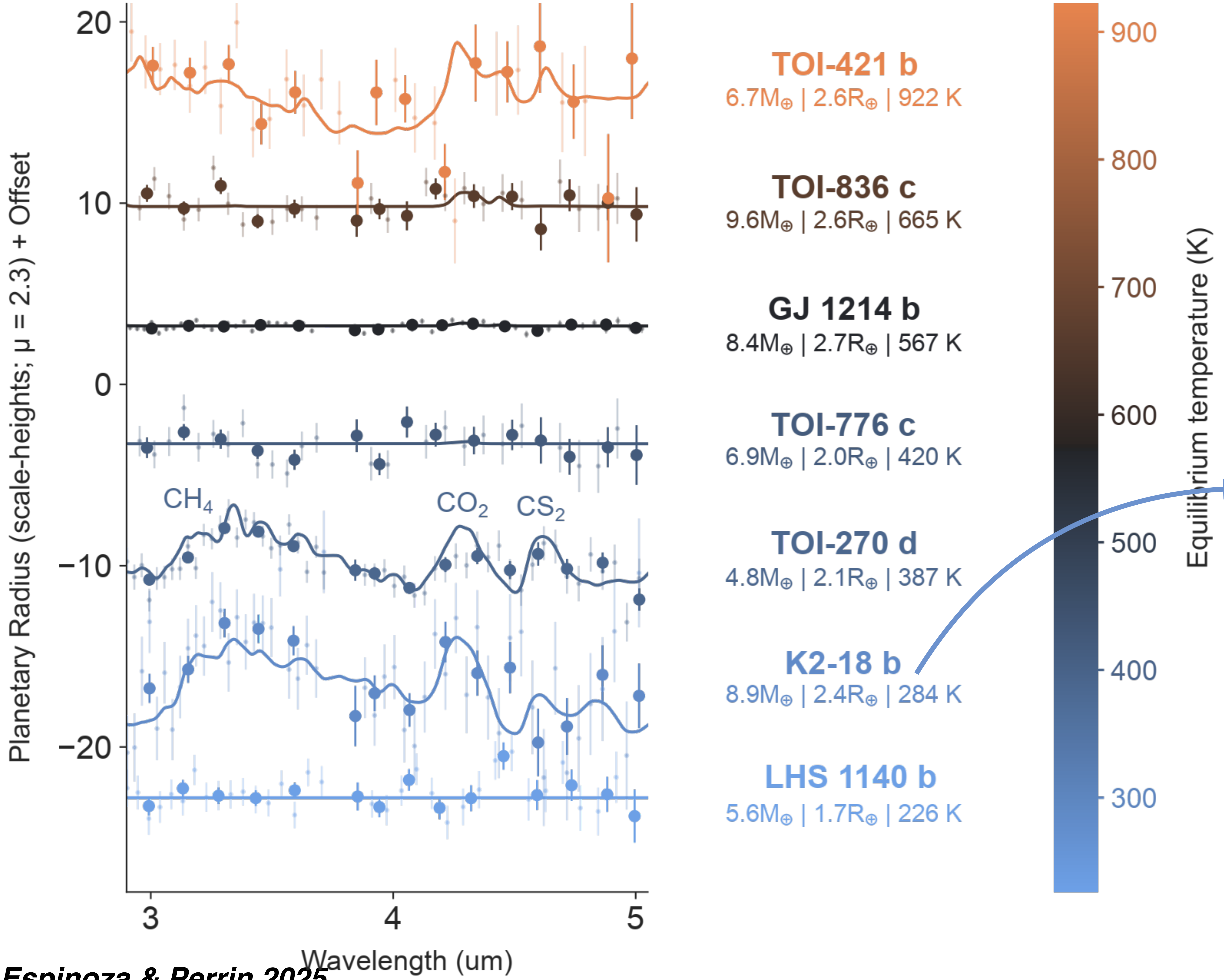
Benneke et al. 2024, submitted

Coldest sub-Neptunes like K2-18 b may host liquid-water oceans, but may require indirect inference.



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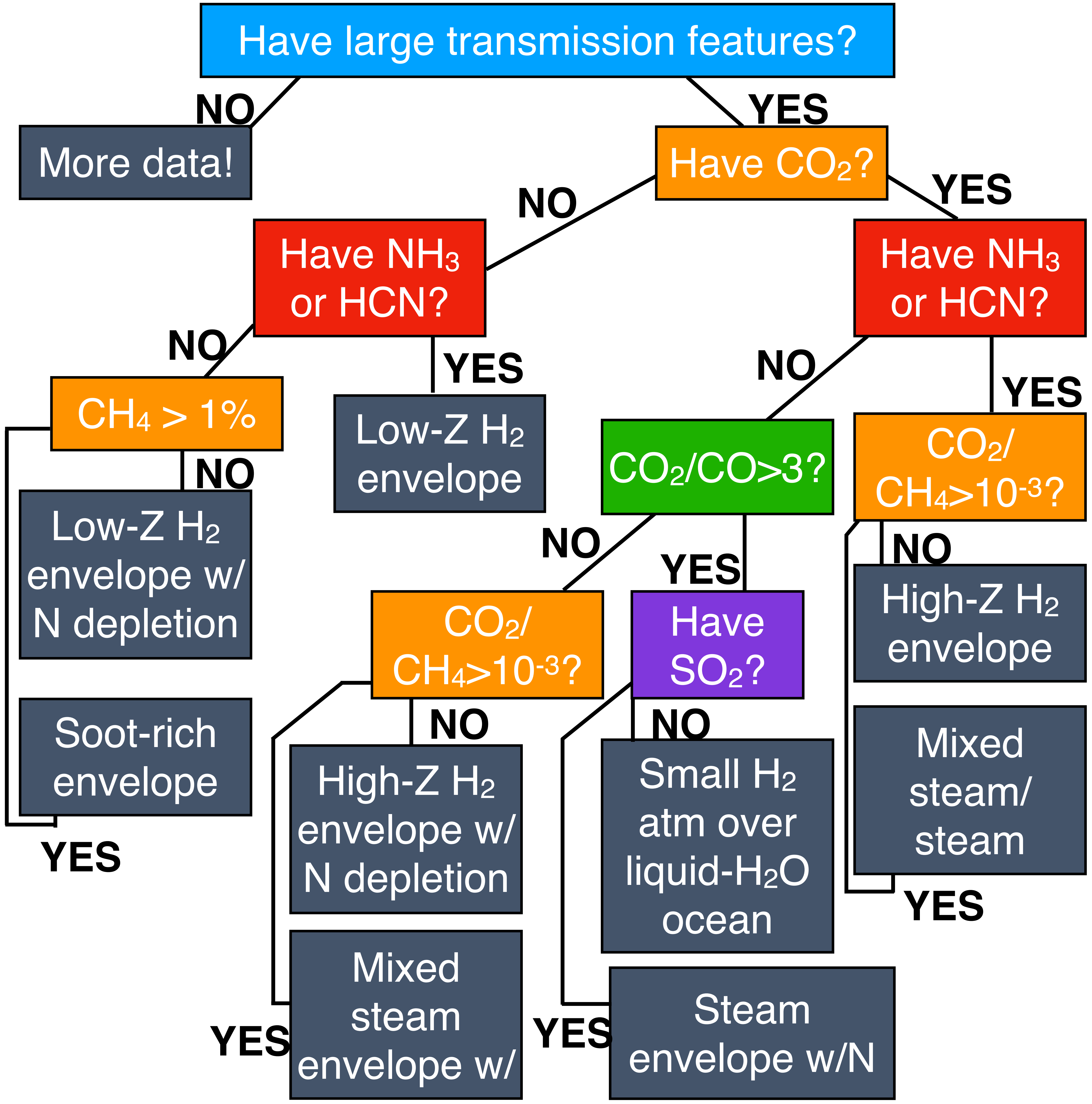

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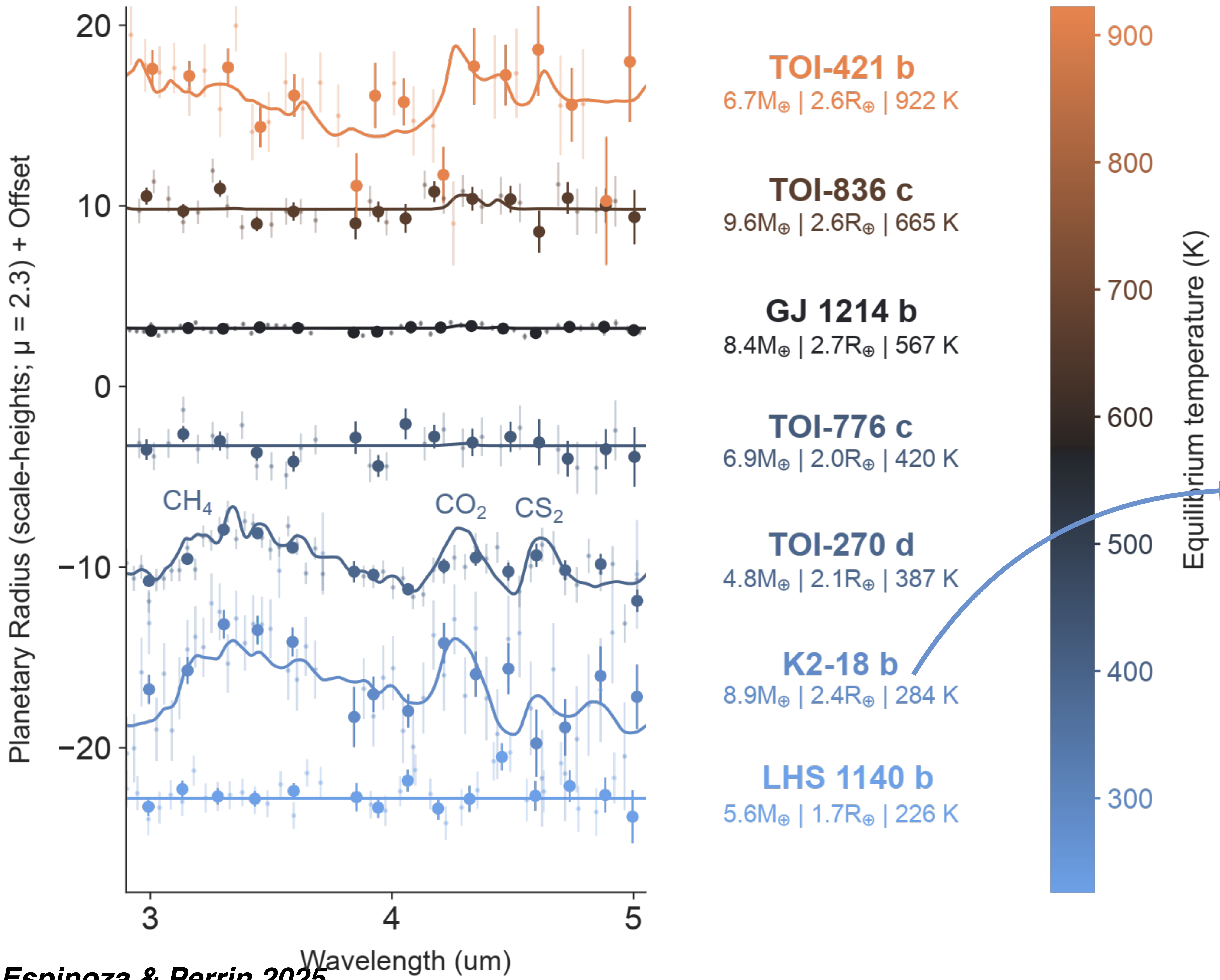

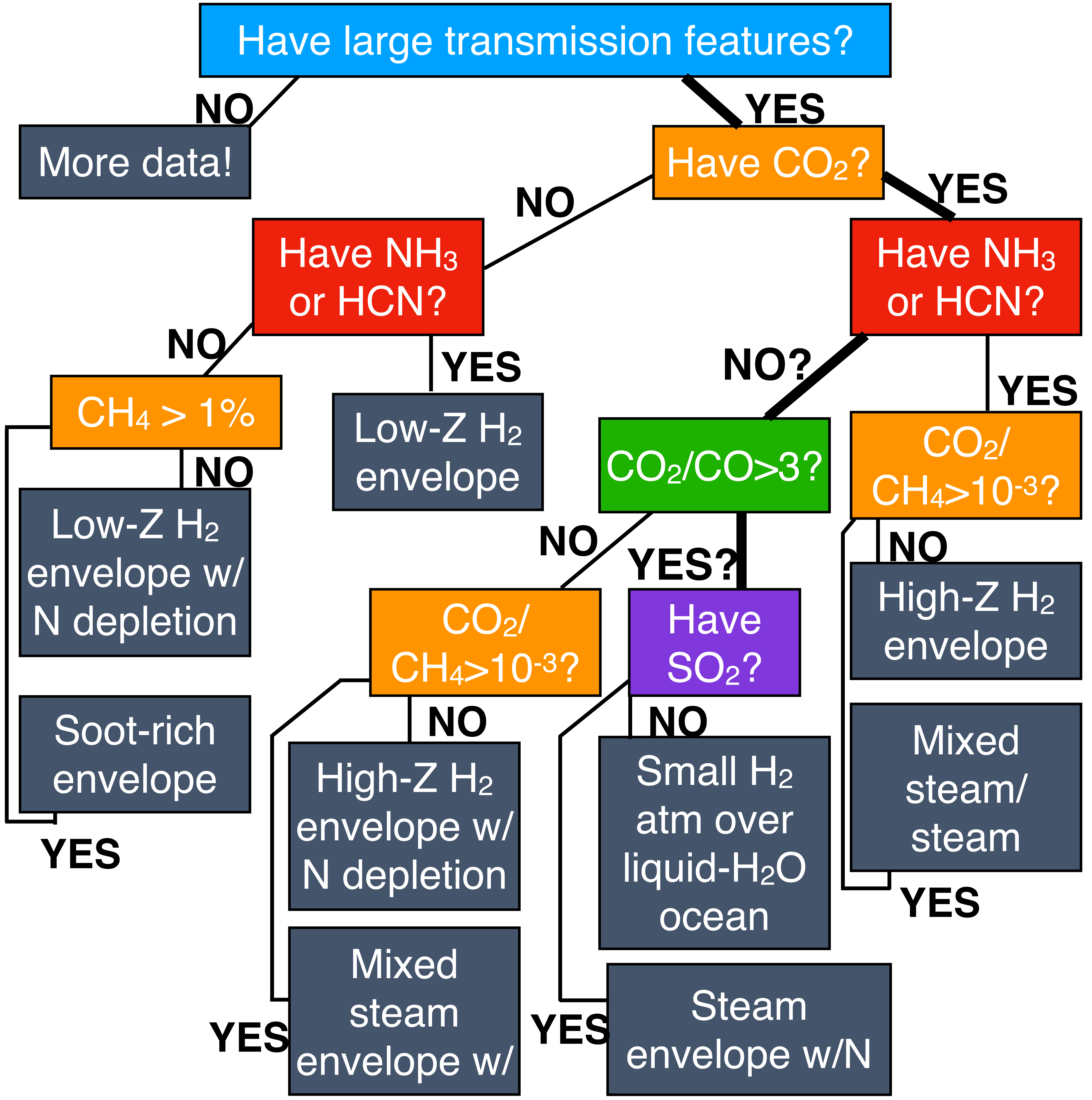

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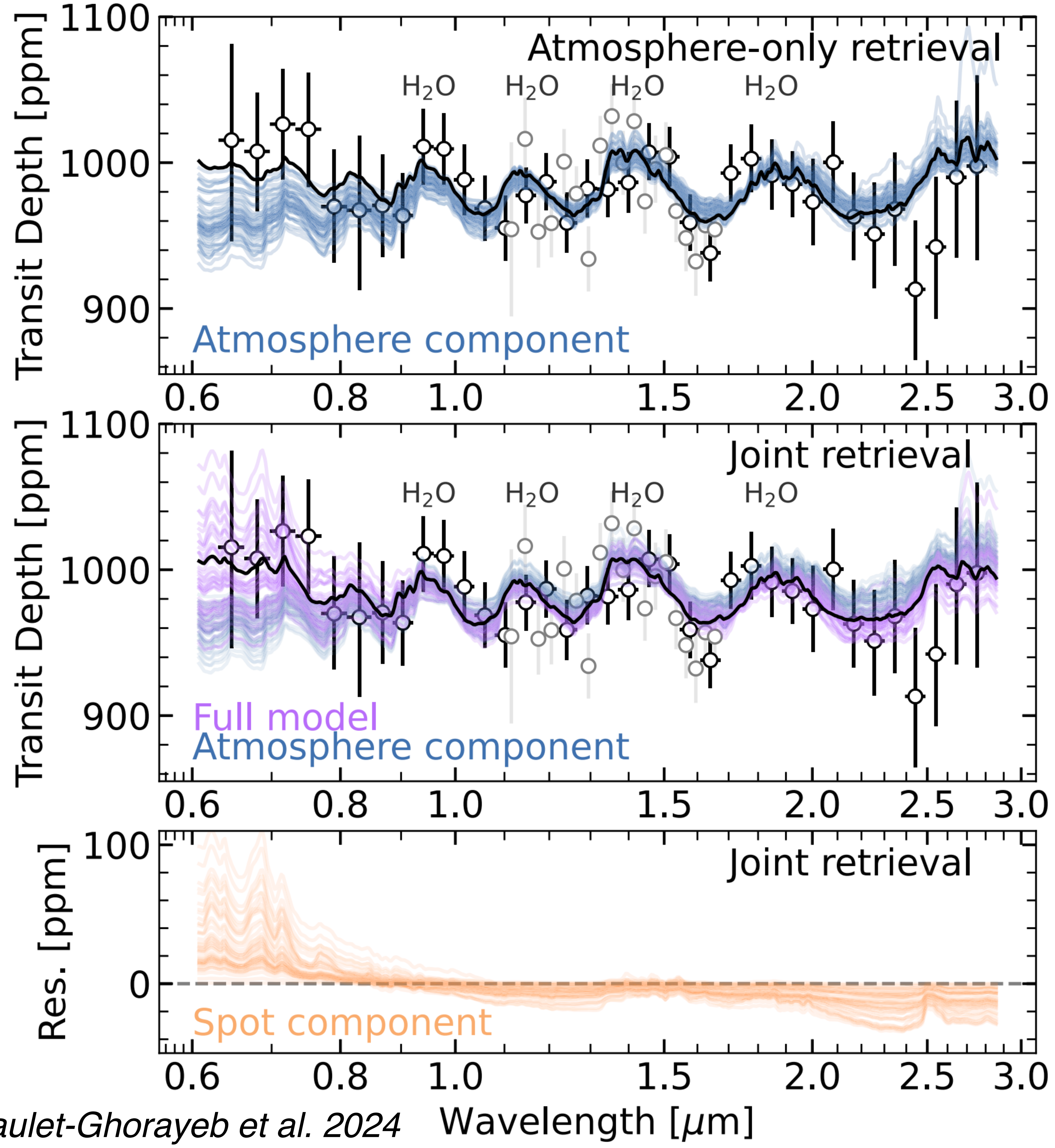
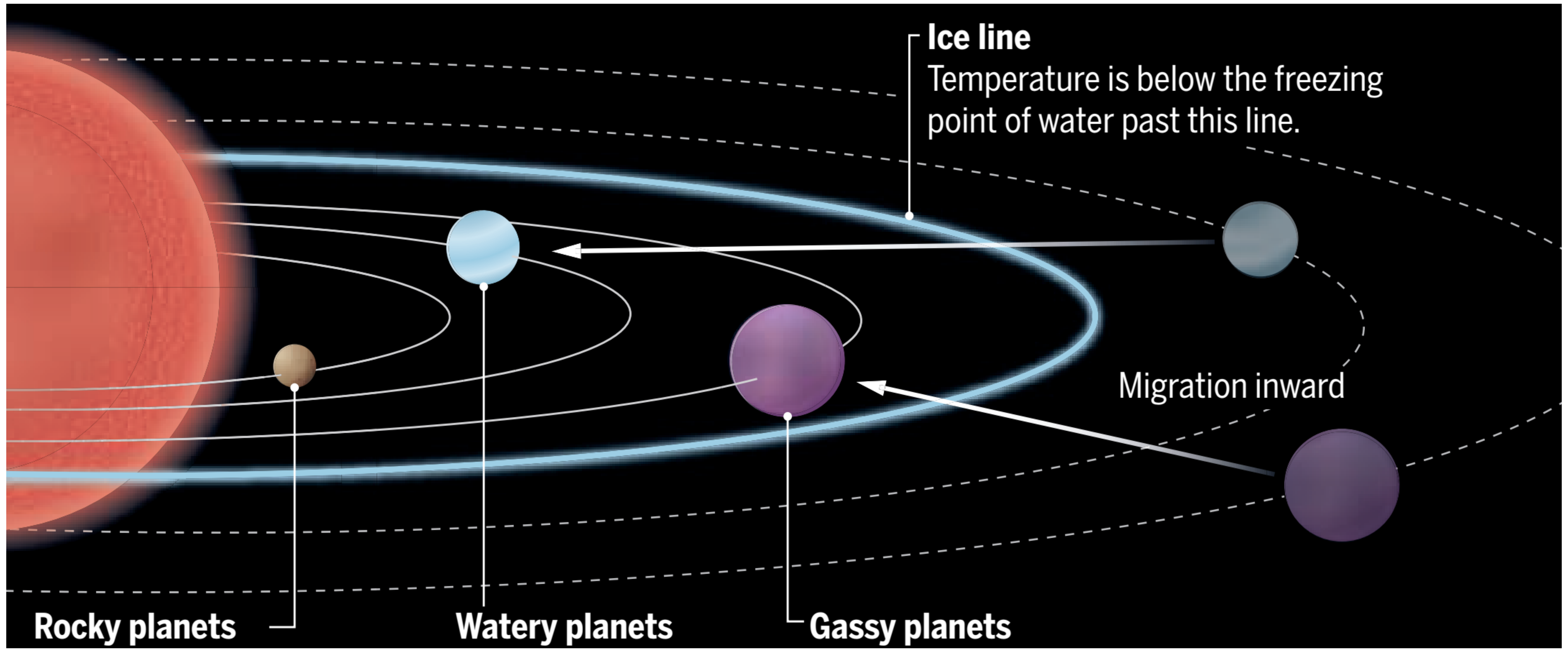
adapted from Hu et al. 2025, submitted

There are also cases that don't fit the predicted trend, and might be telling us about deeper inside planets…and complicating their

GJ 9827 d — water world?



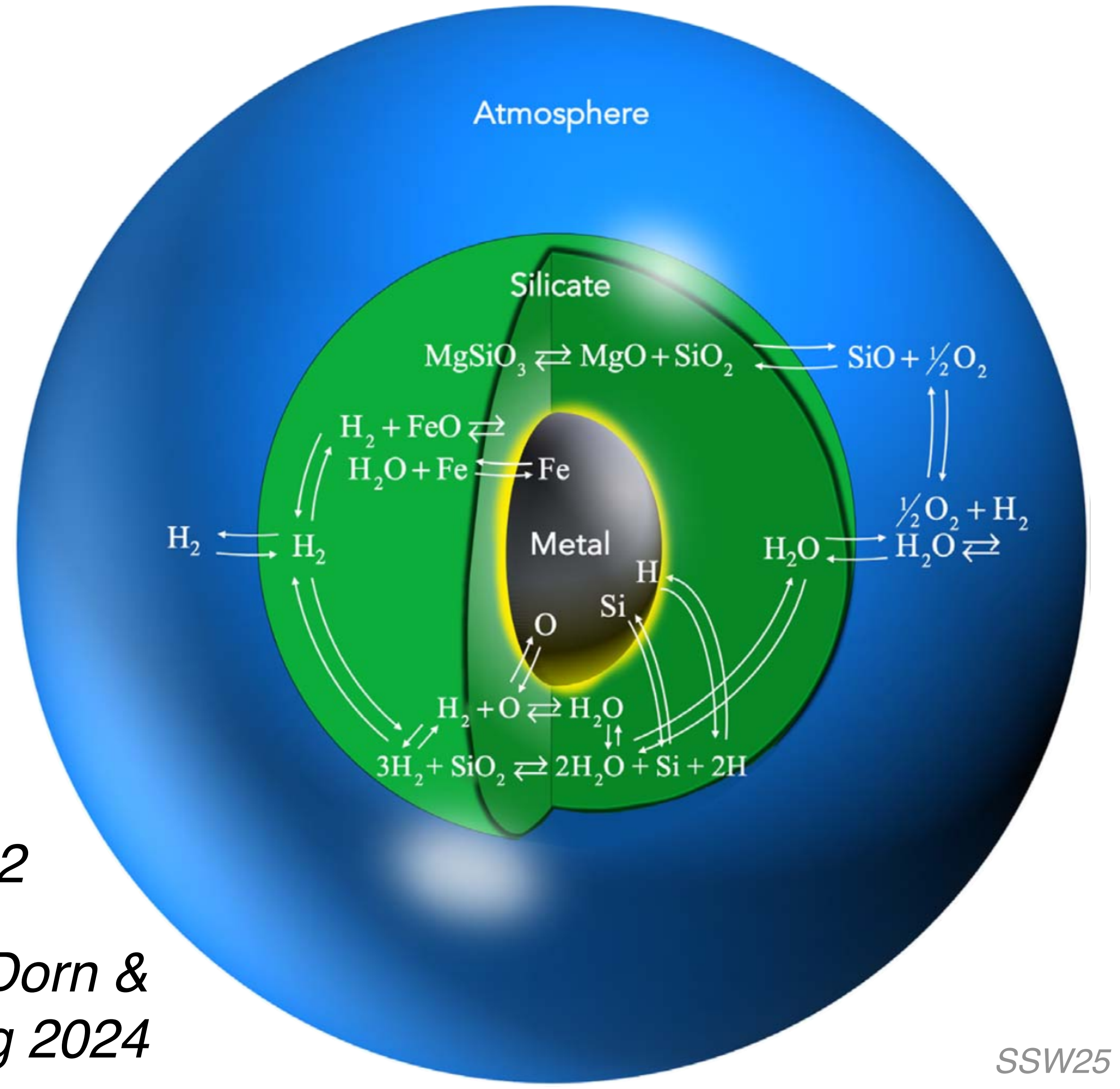
Piaulet-Ghorayeb et al. 2024



Teske 2022
Based on Luque & Pallé 2022

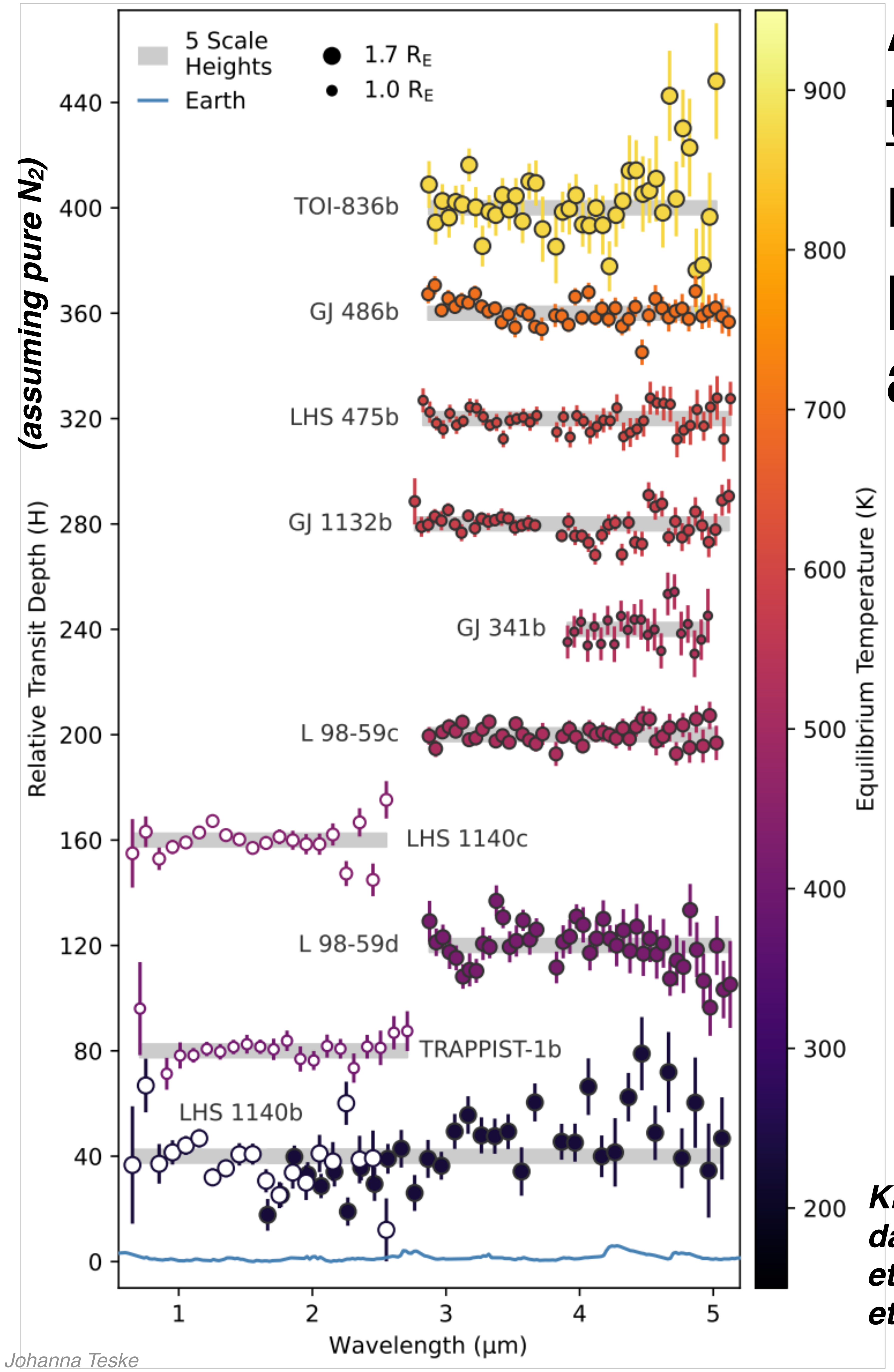
Hydrogen can dissolve into the magma ocean and produce water *endogenously*. A water-rich planet does not necessarily mean it formed beyond the ice line.

Schlichting & Young 2022



Also Kite & Schaefer 2021; Dorn & Lichtenberg 2021; Luo, Dorn, & Deng 2024

The possibilities for rocky planet atmospheres are (slowly) coming into focus.



At current precision level, "rocky" planet <u>transmission</u> spectra are not sensitive to N_2-rich (let alone CO_2-rich) compositions; the best precision is sensitive to cloud-free H_2O-rich atmospheres.

Kreidberg & Stevenson 2025
data from Alderson et al. 2024, Moran et al. 2023, Lustig-Yaeger et al. 2023, May et al. 2023, Kirk et al. 2024, Scarsdale et al. 2024, Damiano et al. 2024, Gressier et al. 2024, Lim et al. 2023, Cadieux et al. 2024

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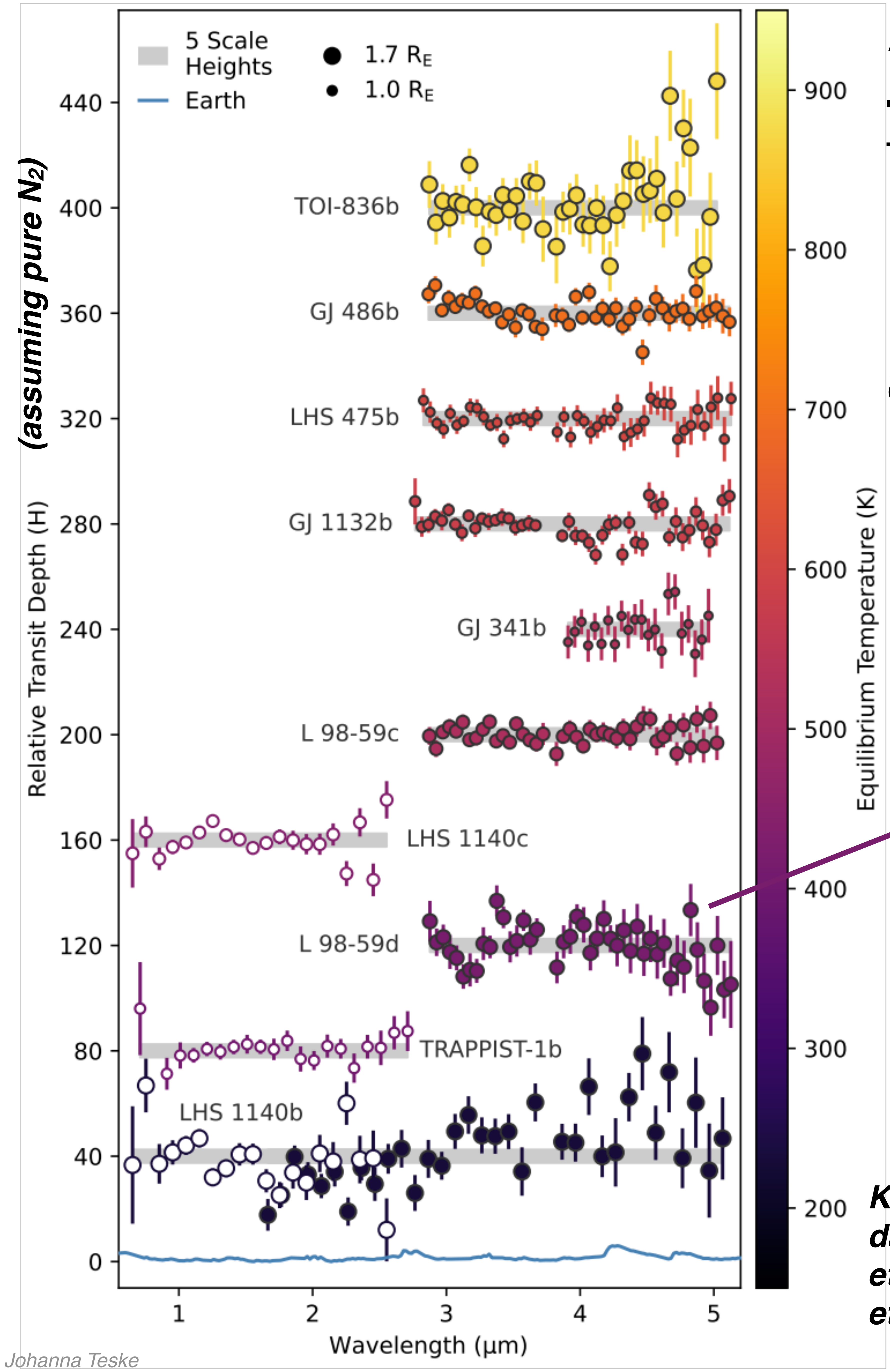
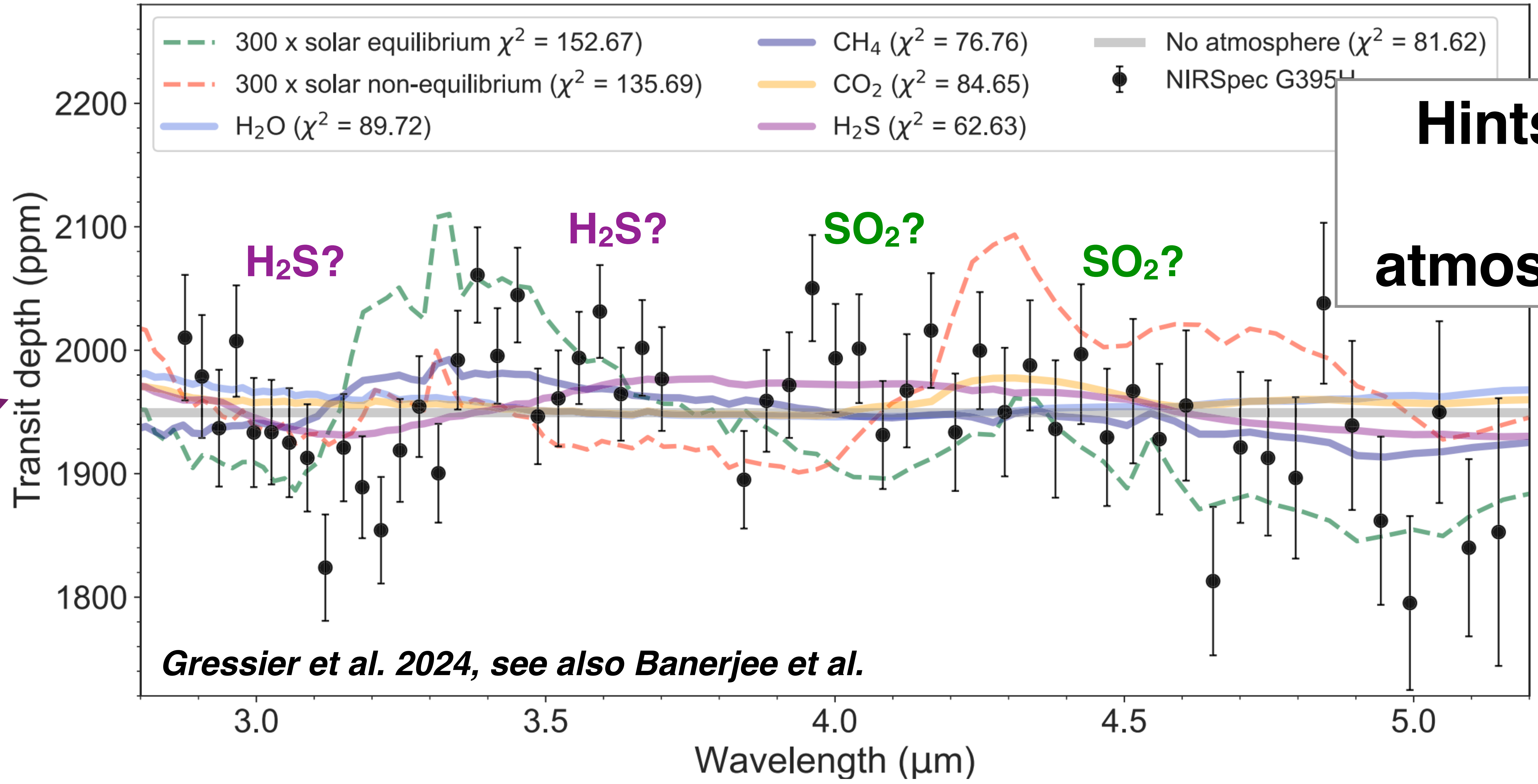


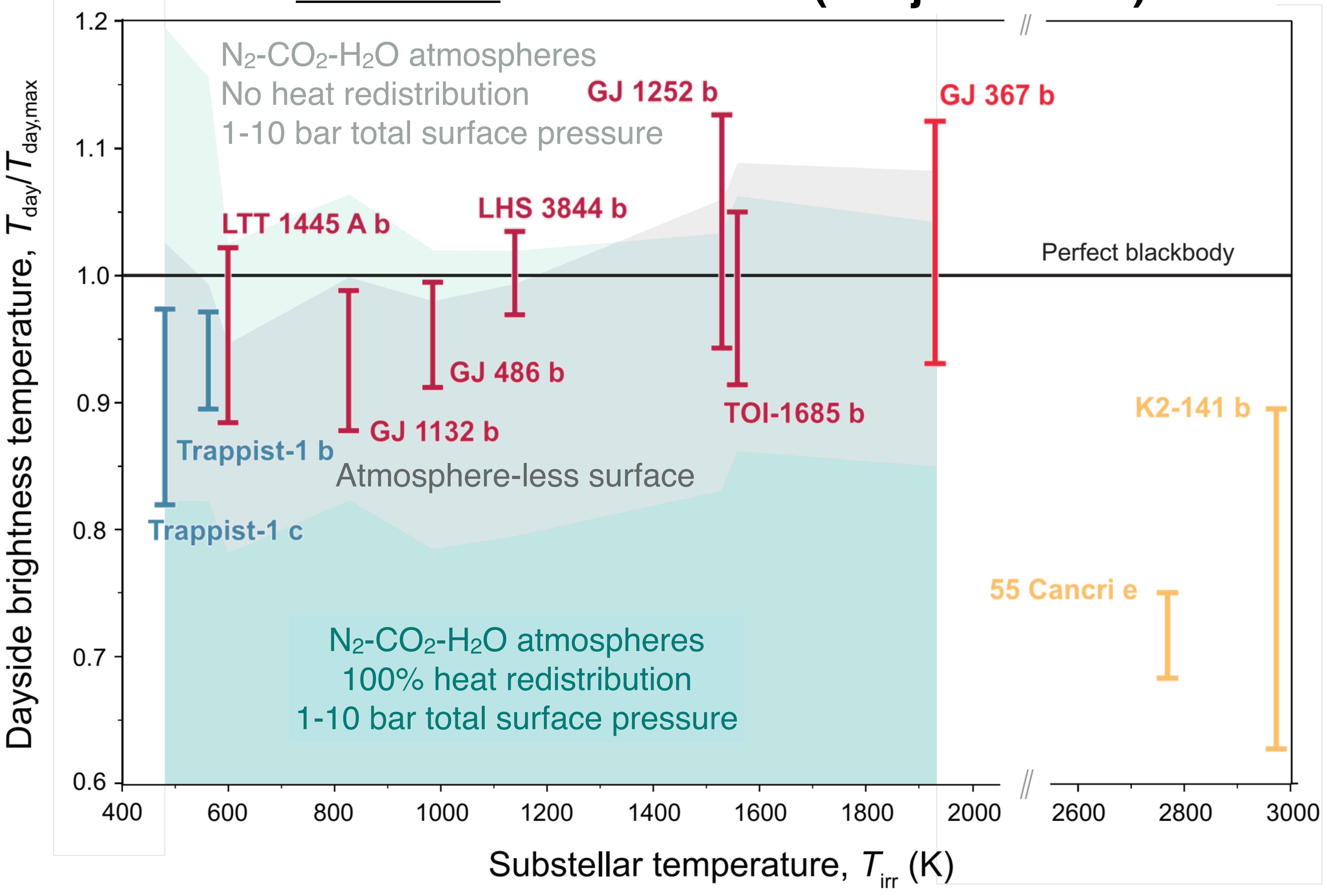


Hints of S-rich atmosphere

Kreidberg & Stevenson 2025
data from Alderson et al. 2024, Moran et al. 2023, Lustig-Yaeger et al. 2023, May et al. 2023, Kirk et al. 2024, Scarsdale et al. 2024, Damiano et al. 2024, Gressier et al. 2024, Lim et al. 2023, Cadieux et al. 2024

Still not able to distinguish bare rocks from thin atmospheres, but thick, CO_2-rich compositions are disfavored (so far).

<u>Emission</u> observations (not just JWST)



Lichtenberg, Shorttle, Teske, & Kempton in review; see also Park Coy et al. 2025
Data from Kreidberg et al. 2019, Luque et al. 2025, Zieba et al. 2023, Greene et al. 2023, Ducrot et al. 2025, Wachiraphan et al. 2025, Sue et al. 2024, Weiner Mansfield et al. 2024, Crossfield et al. 2022, Zhang et al. 2024, Hu et al. 2024, Patel et al. 2024

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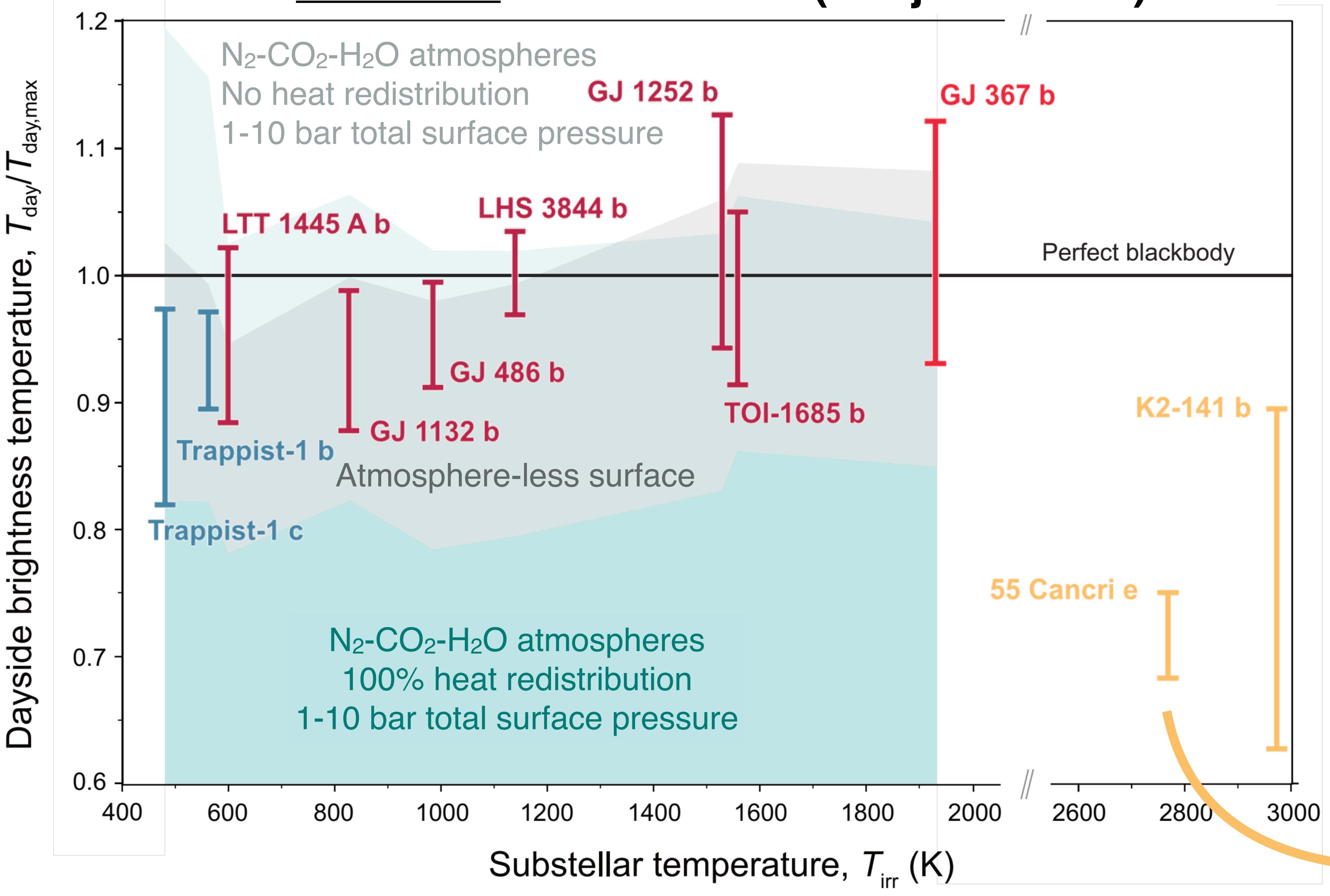

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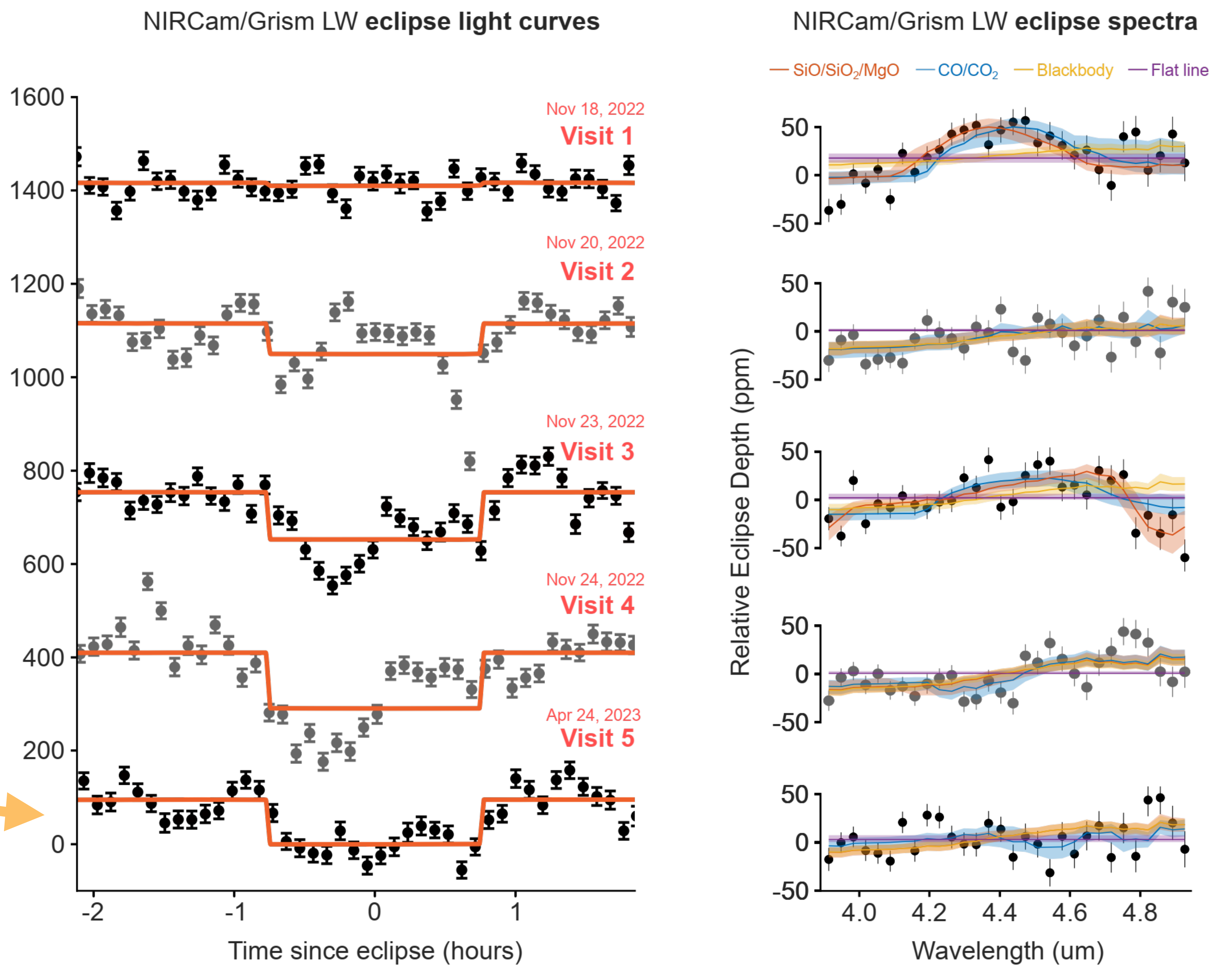
Secondary, volatile-rich atmosphere… that is also variable?

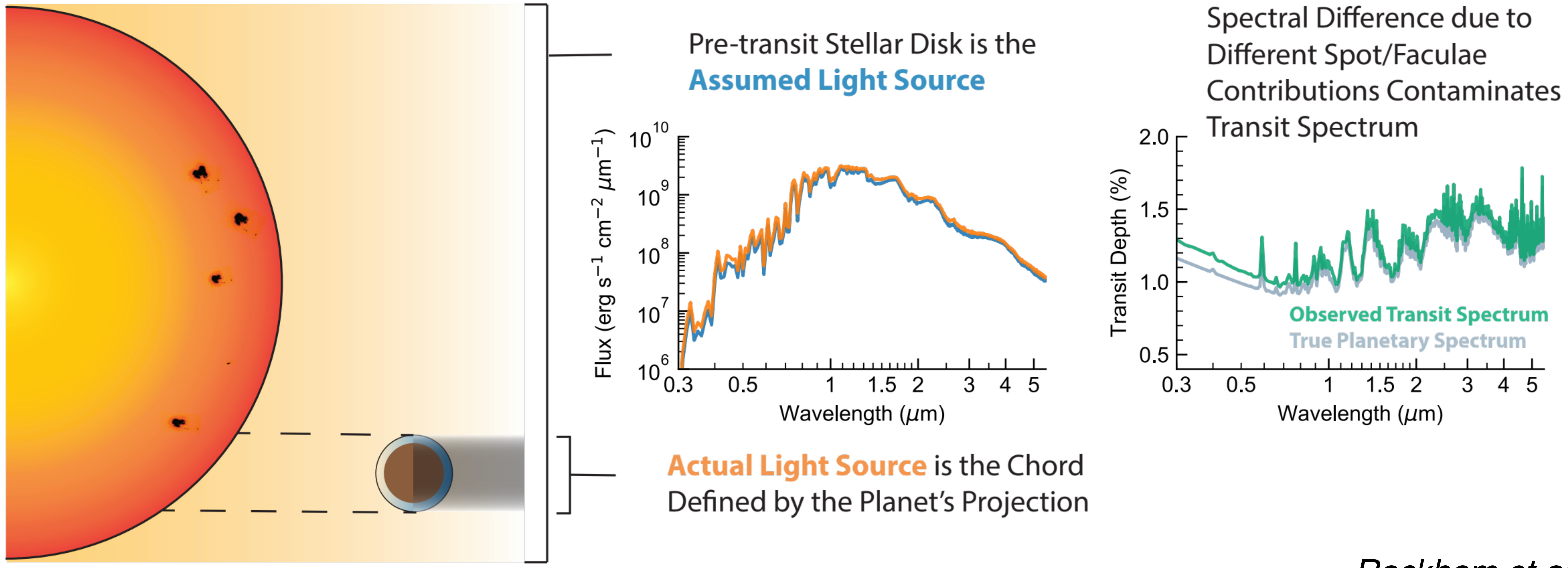


Espinoza & Perrin 2025
Adapted from Patel et al. 2024

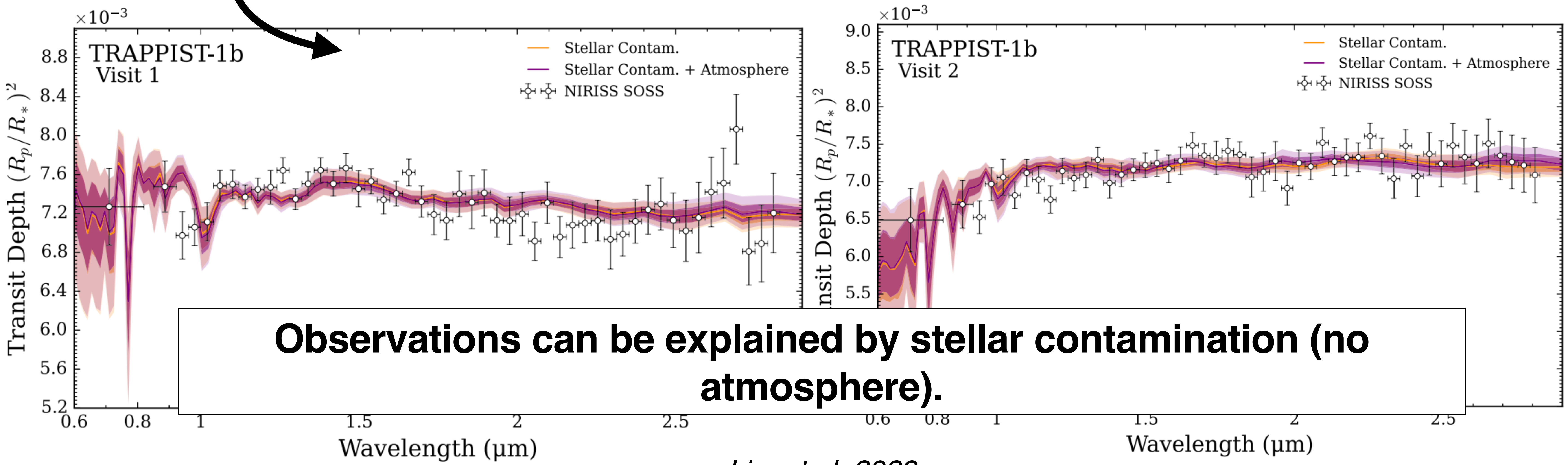
We still face perils across this new landscape.

It is challenging to disentangle stellar photosphere inhomogeneities from true exoplanet atmosphere signals.

Transit Light Source (TLS) Effect



Rackham et al. 2018



Observations can be explained by stellar contamination (no atmosphere).

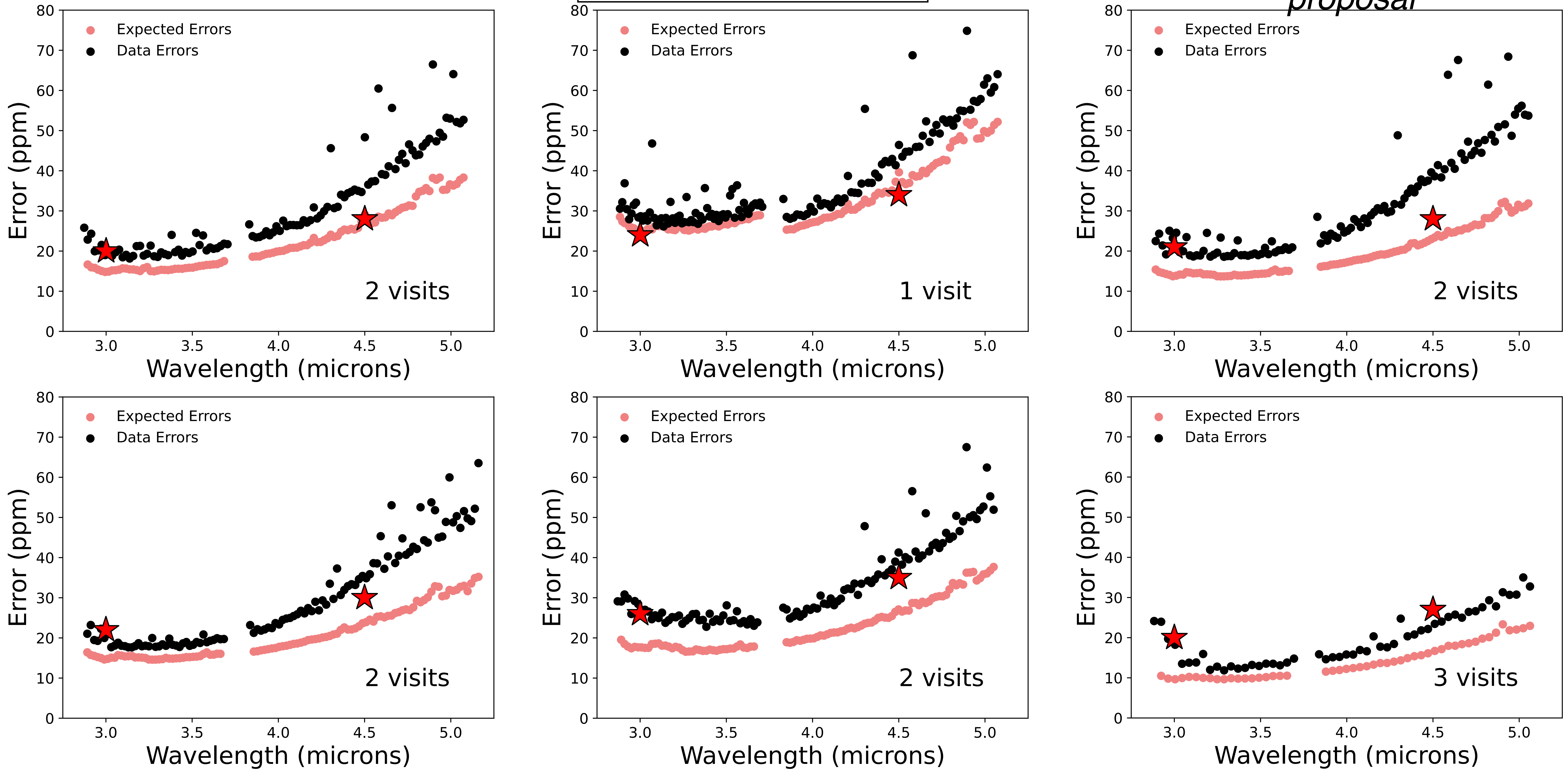
Lim et al. 2023

It is challenging to disentangle stellar photosphere inhomogeneities from true exoplanet atmosphere signals.

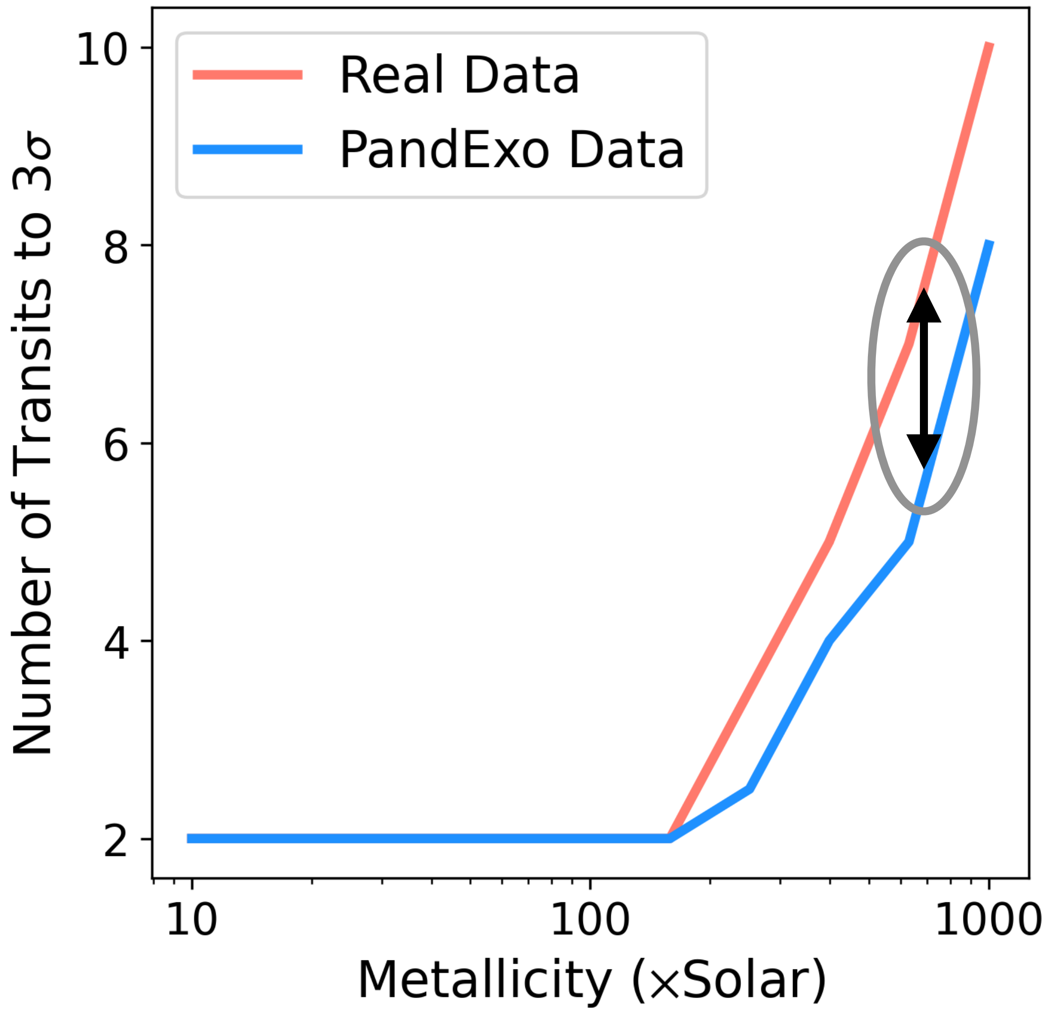
We do not yet understand sources of systematic noise in JWST instruments.

NIRSpec/ G395H

actual estimate in Cycle 1 proposal



Figures from Nicole Wallack (see, e.g., Wallack et al. 2024)
Much more work in prep!



Alderson et al. 2024

Particularly a problem for bright stars and/or high-metallicity atmospheres

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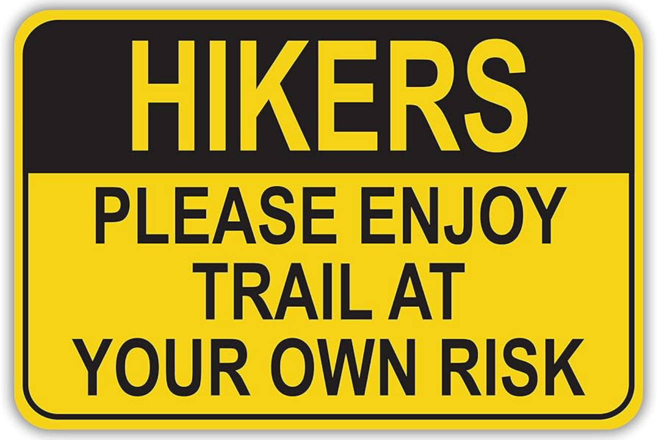
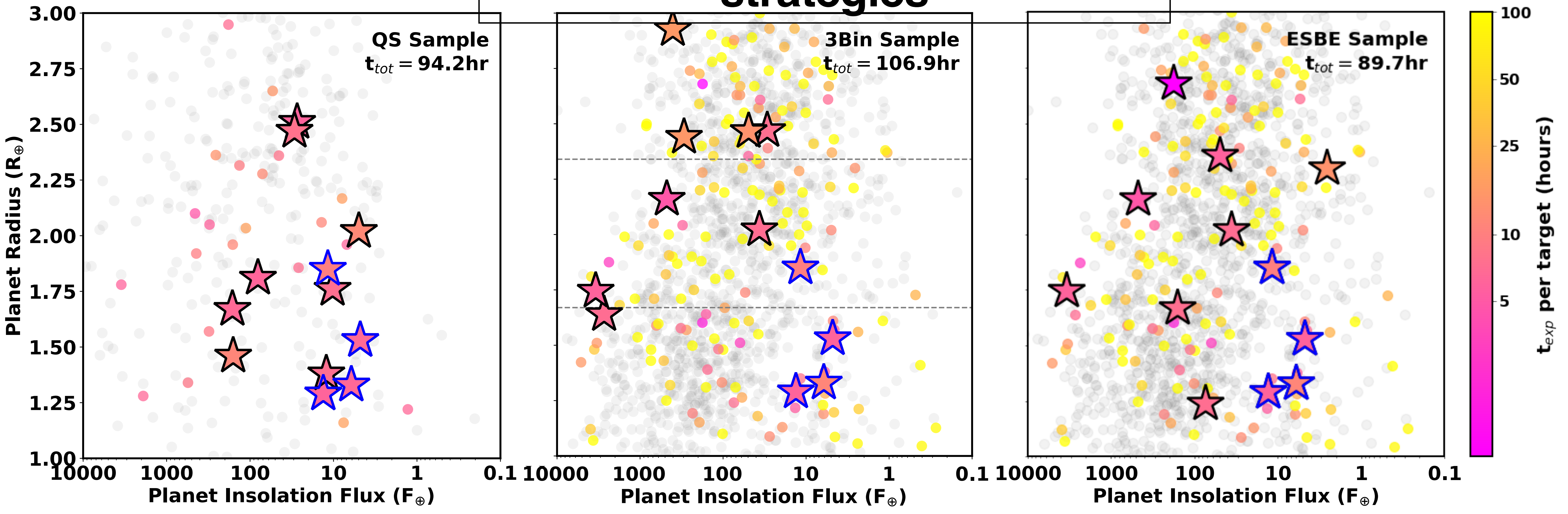


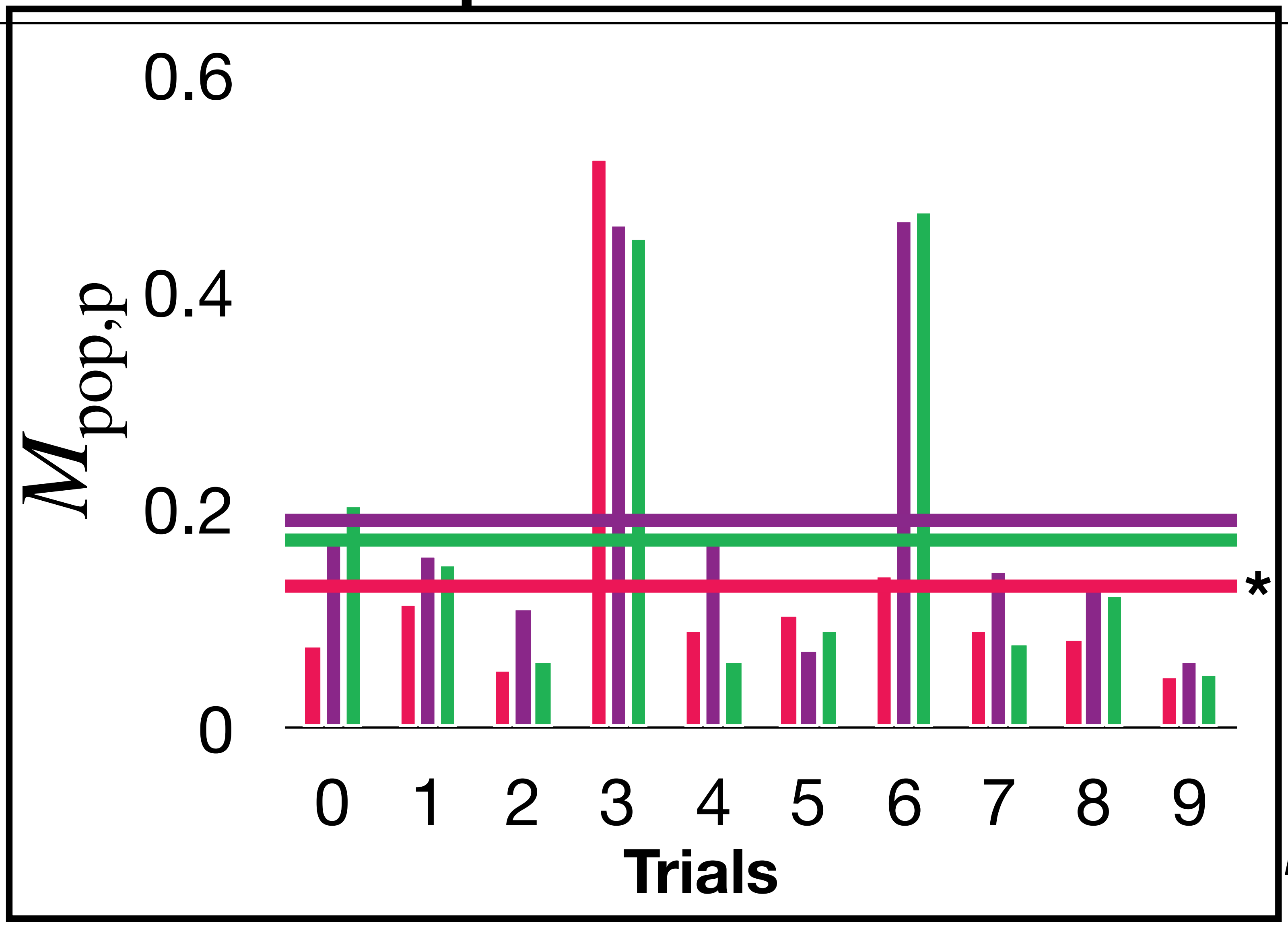
How surveys are designed and executed can leave an unintended (biased) imprint on

Different target selection strategies



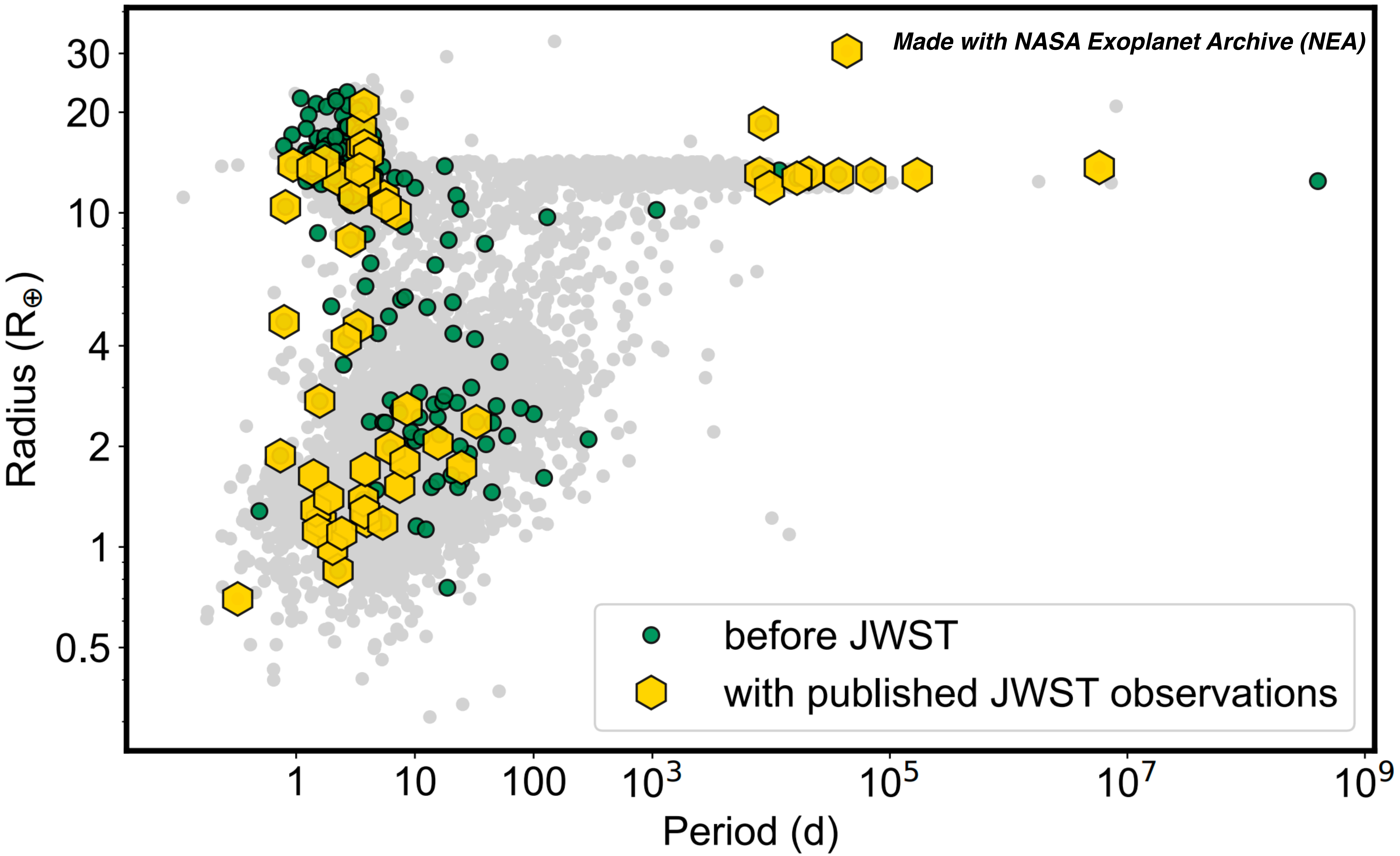
QS **3Bin** **ESBE**

Precision of derived population-level parameters



Batalha et al. 2023

We are already learning…



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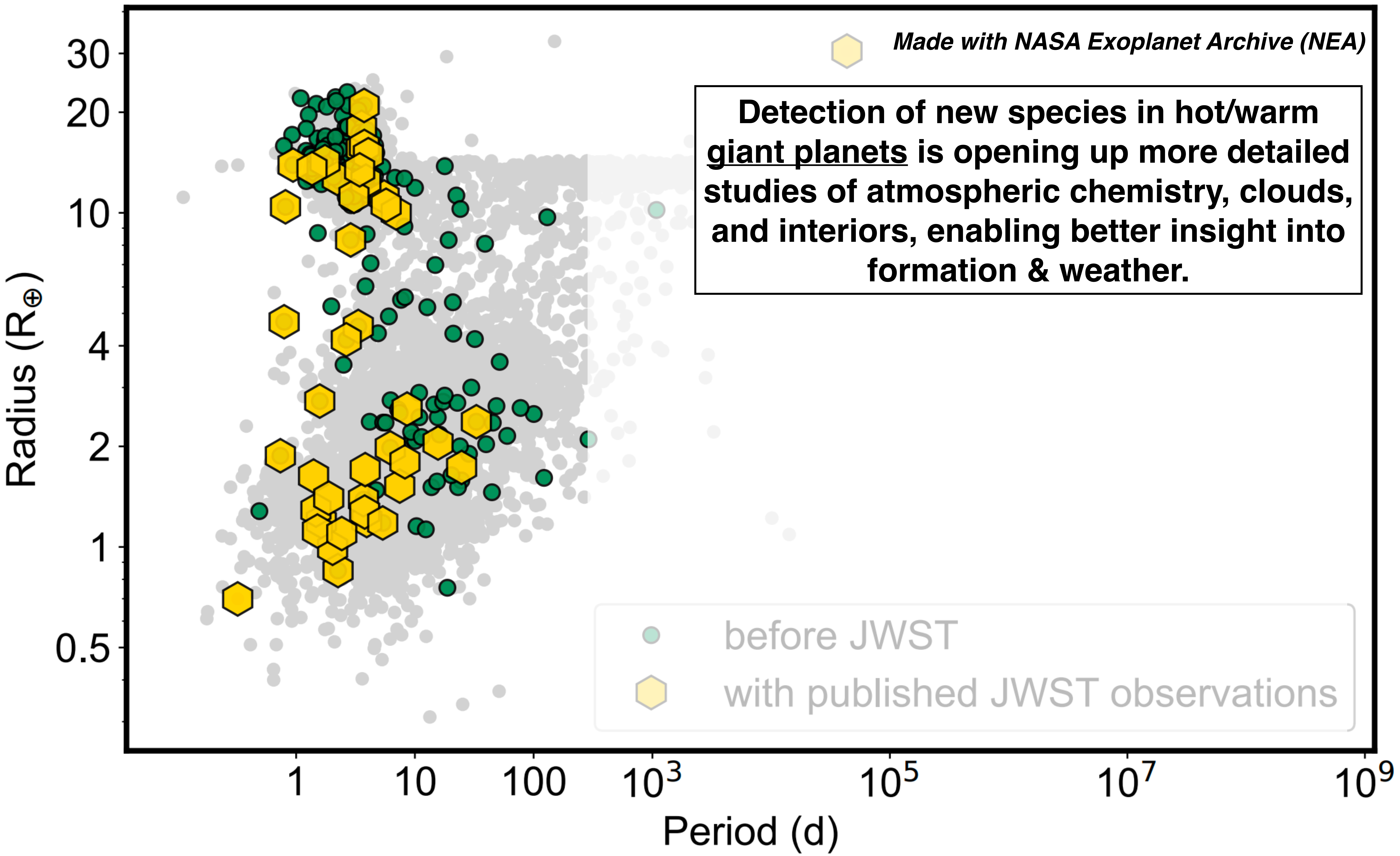

You revisit a trail with greater attention through all of your senses and discover new wonders.

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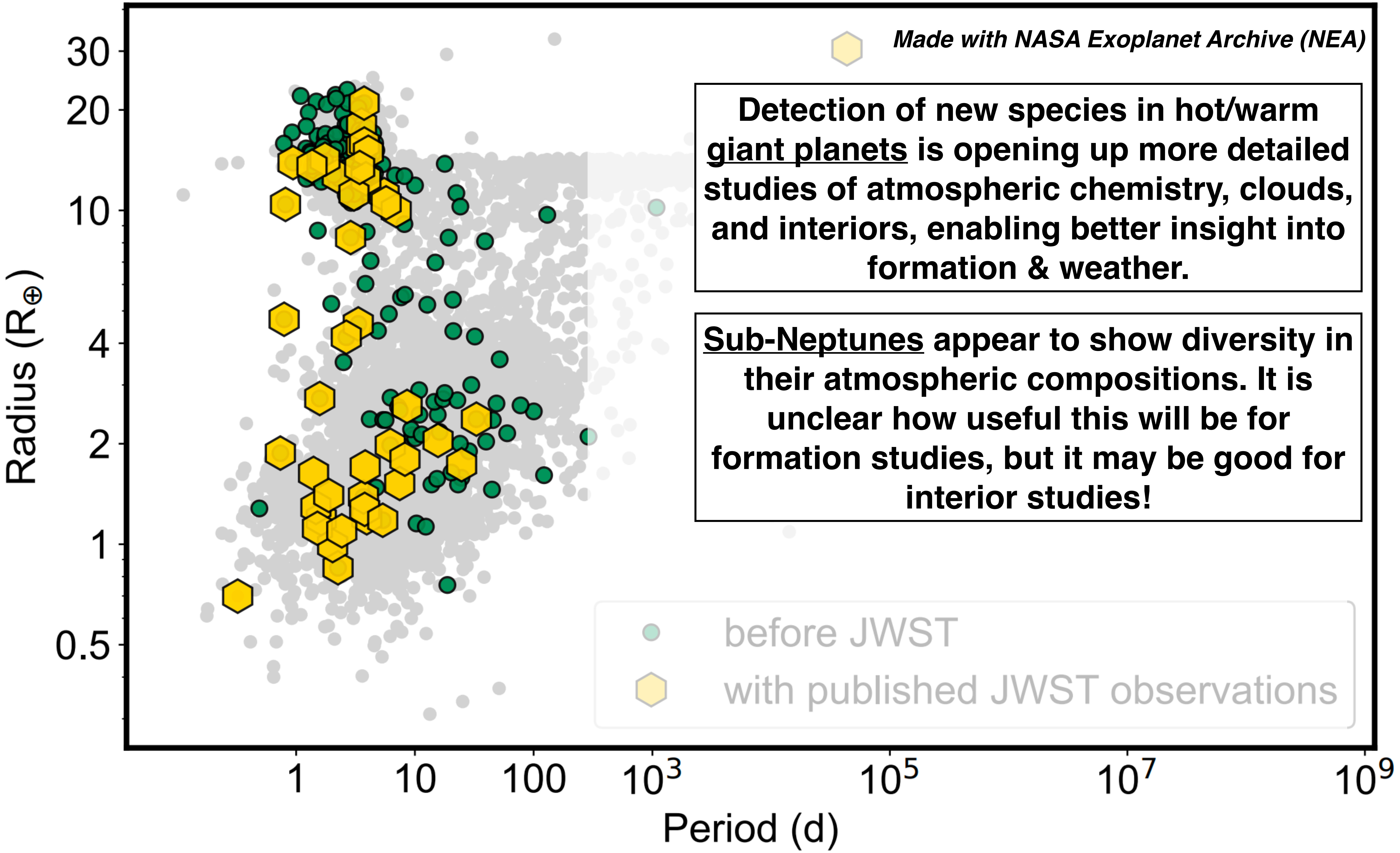

Detection of new species in hot/warm giant planets is opening up more detailed studies of atmospheric chemistry, clouds, and interiors, enabling better insight into formation & weather.

Sub-Neptunes appear to show diversity in their atmospheric compositions. It is unclear how useful this will be for formation studies, but it may be good for interior studies!

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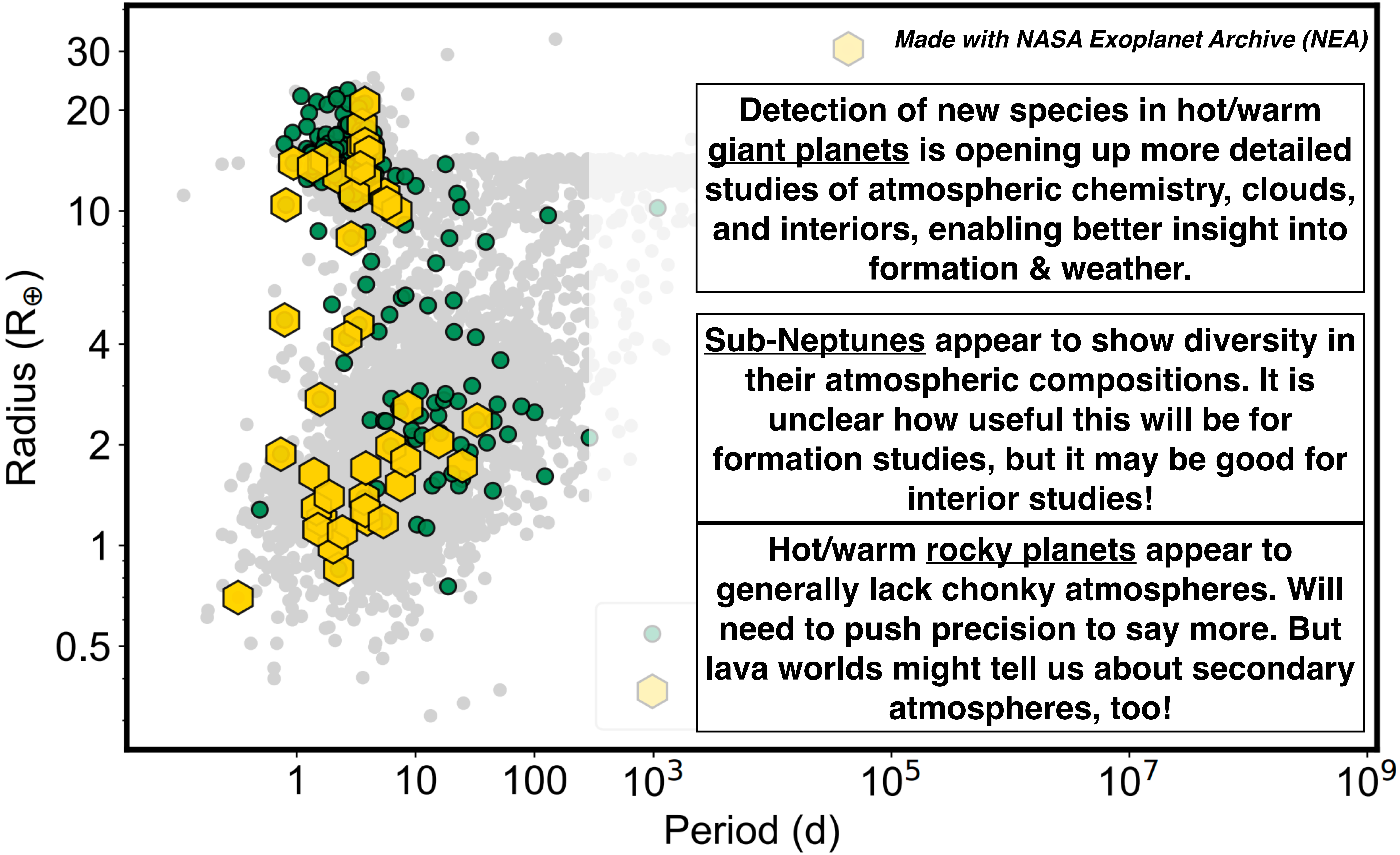

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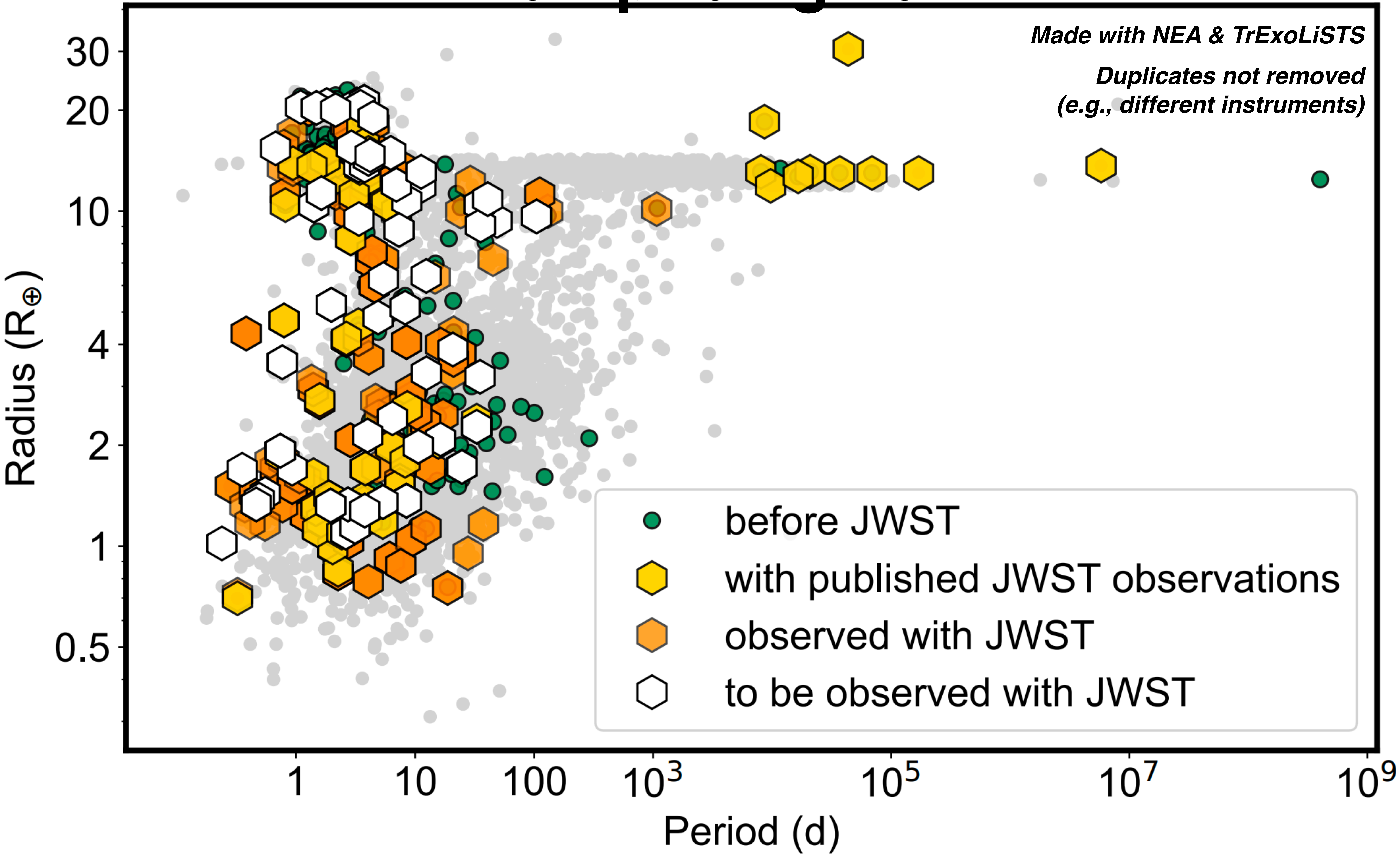
Hot/warm <u>rocky planets</u> appear to generally lack chonky atmospheres. Will need to push precision to say more. But lava worlds might tell us about secondary atmospheres, too!

You revisit a trail with greater attention through all of your senses and discover new wonders.

You are starting to see below the surface of a lake, but it's murky.

There is a high mountain top in the distance that you're not sure you can climb… but you will try.

This talk is only a quick glimpse.
The landscape is growing, deepening, and will keep surprising us!



It is a great privilege to learn about other worlds with JWST.

This is only possible because of the passion, dedication,

A crowd gathers as Nobel laureate John Mather and Northrop Grumman engineer Scott Willoughby speak in front of a model of NASA's James Webb Space Telescope at South by Southwest on March 9, 2013. Credit: Alex Evers, NPR

This is what it looks like when humans see something that no human has ever seen before. “Understanding is a kind of ecstasy.” (Sagan... who else?) We can't wait to share it with you all. Credit: Natalie Batalha, UCSC, July 15, 2022,

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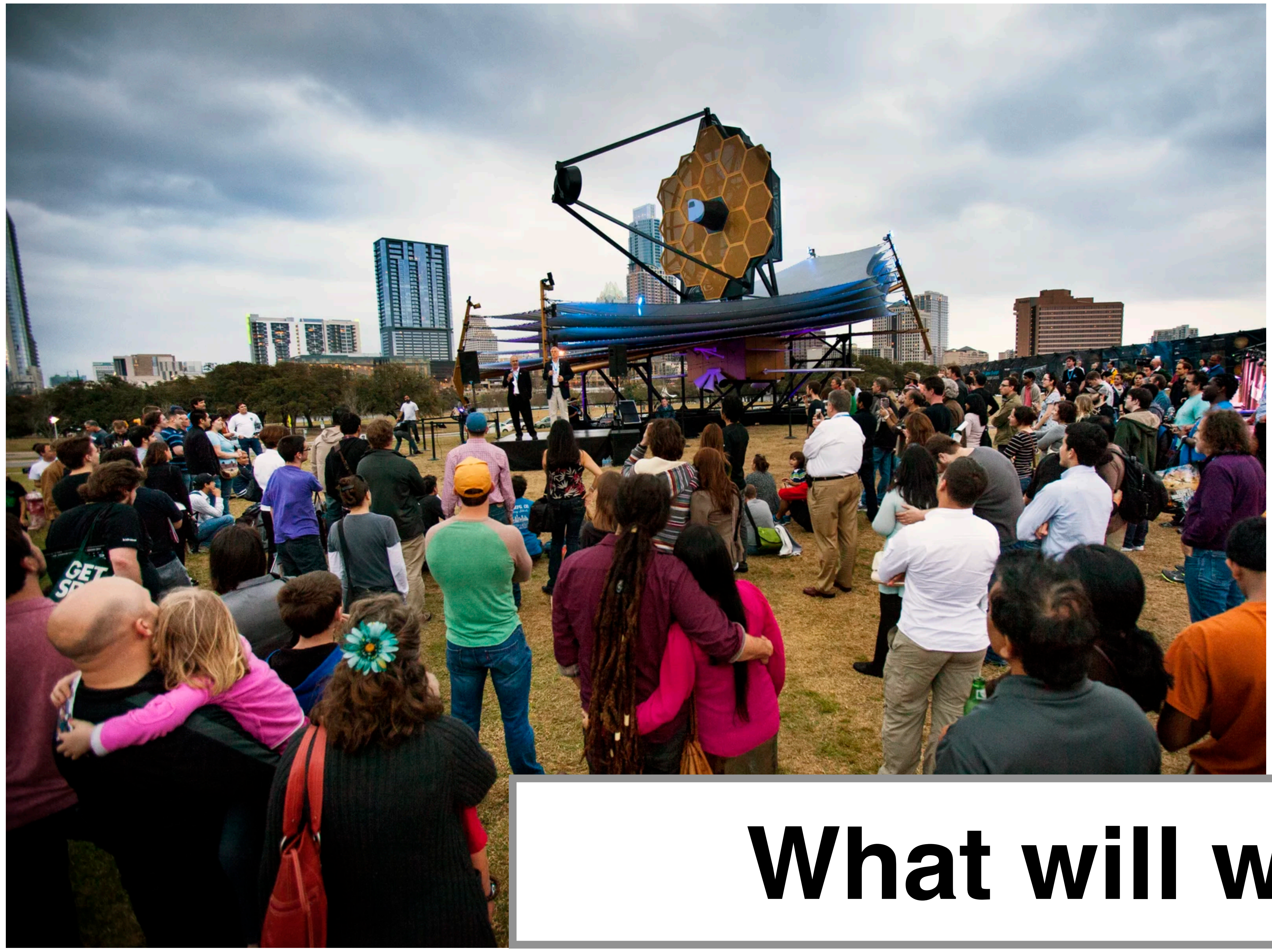

What will we discover next,

A crowd gathers as Nobel laureate John Mather and Northrop Grumman engineer Scott Willoughby speak in front of a model of NASA's James Webb Space Telescope at South by Southwest on March 9, 2013. Credit: Alex Evers, NPR

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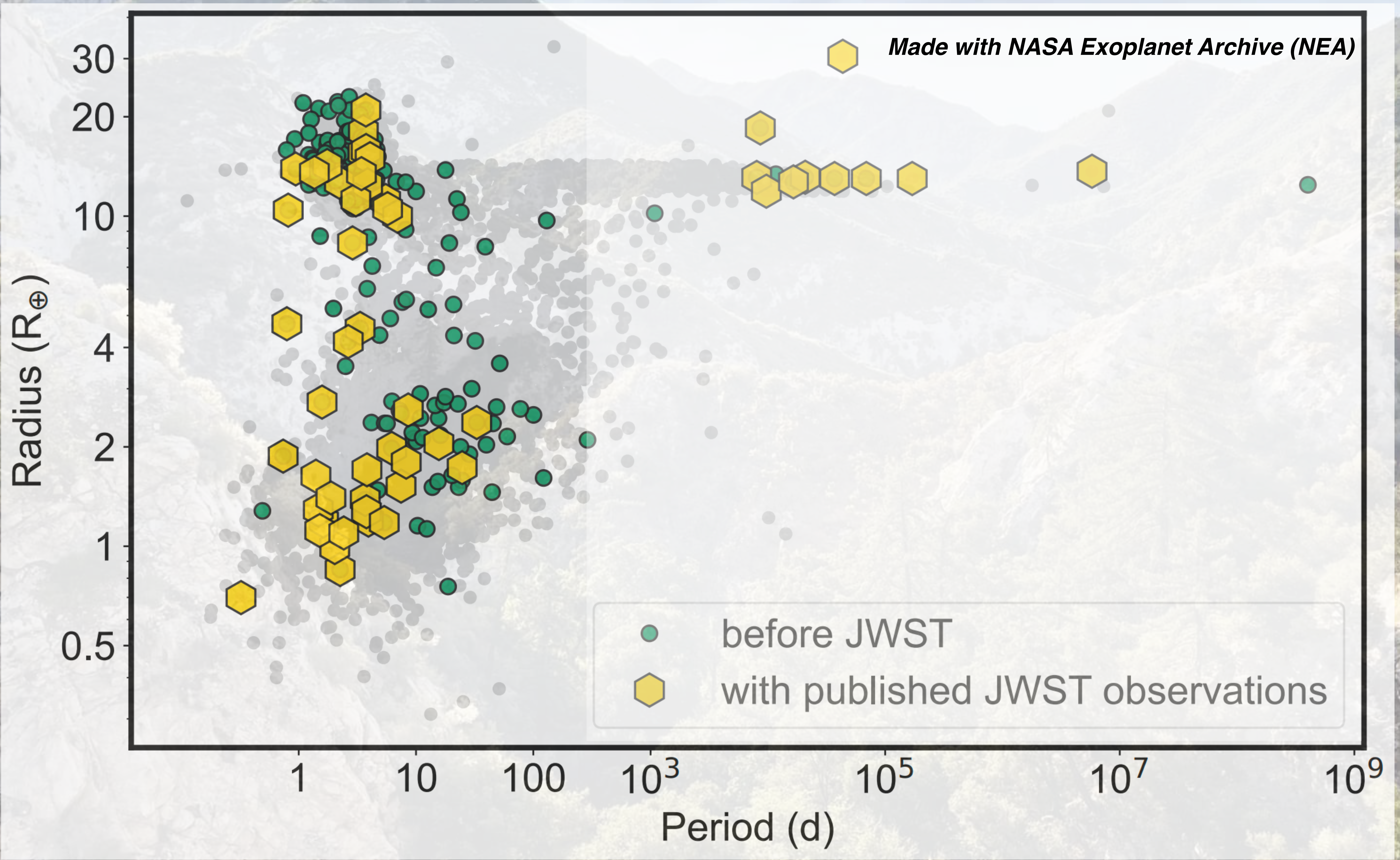
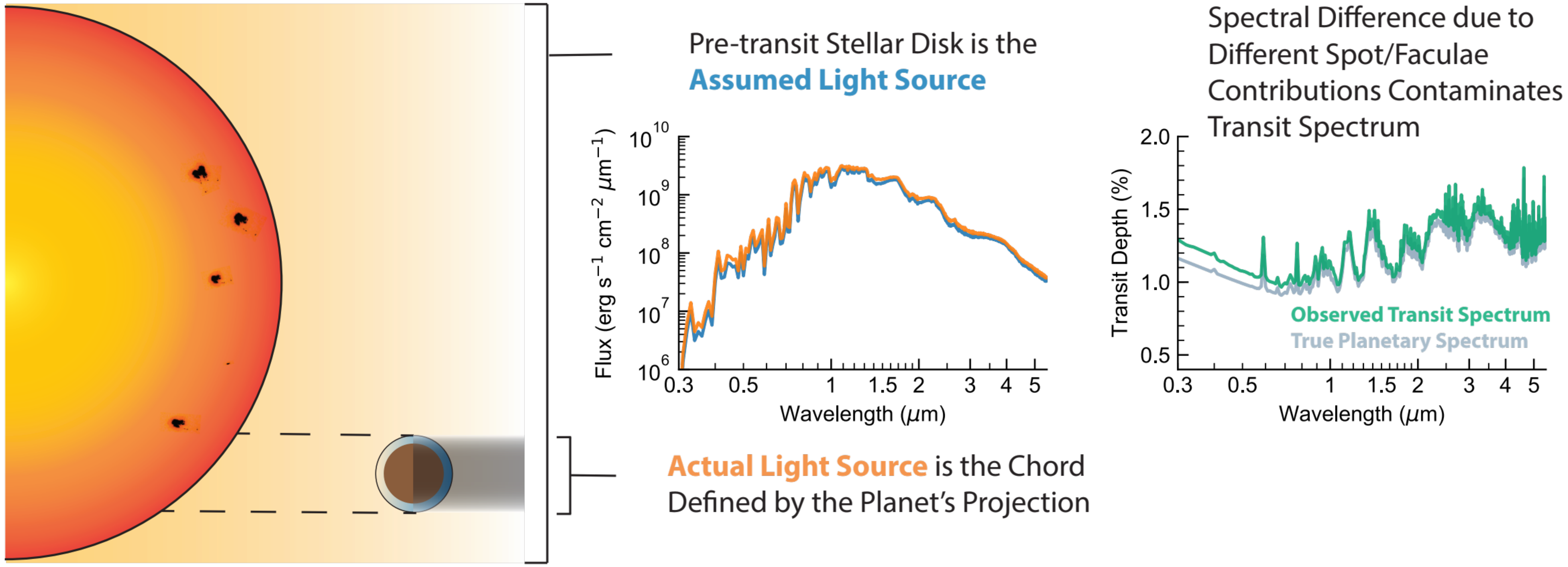


Backup

It is challenging to disentangle stellar photosphere inhomogeneities and water from true exoplanet atmosphere

Transit Light Source (TLS) Effect

Rackham et al. 2018



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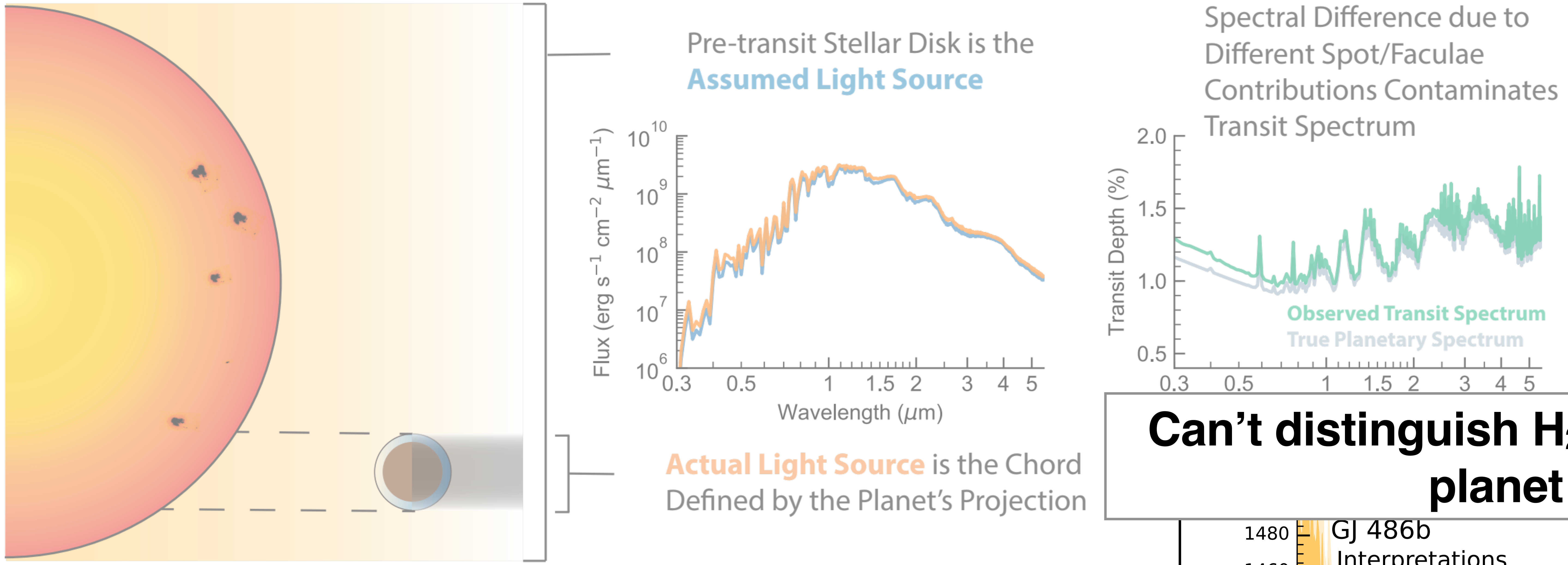
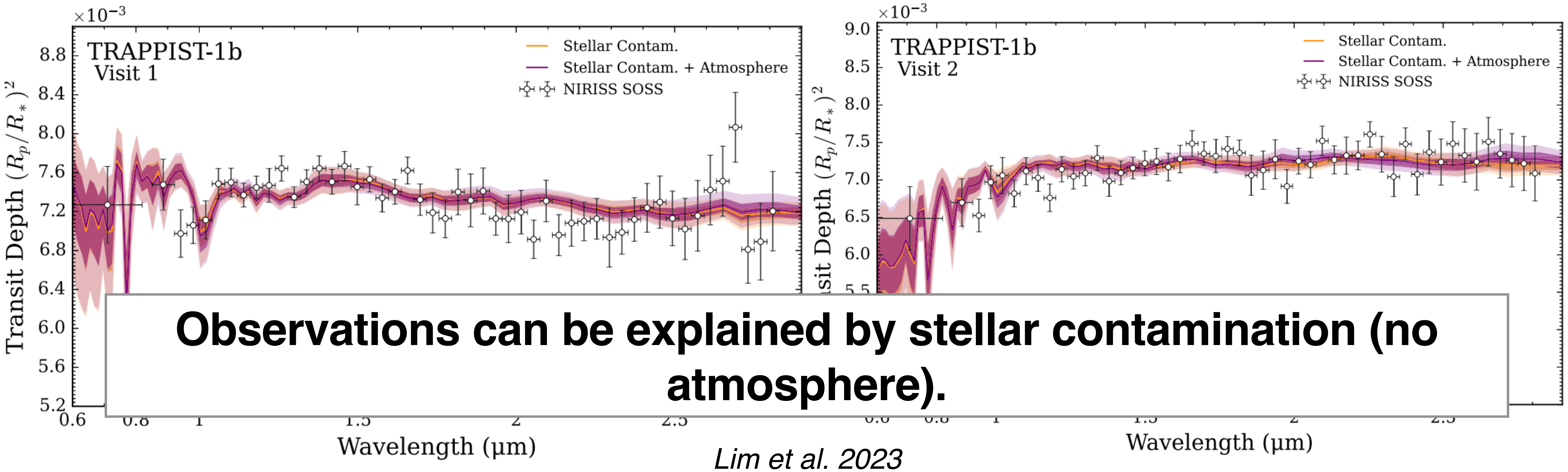
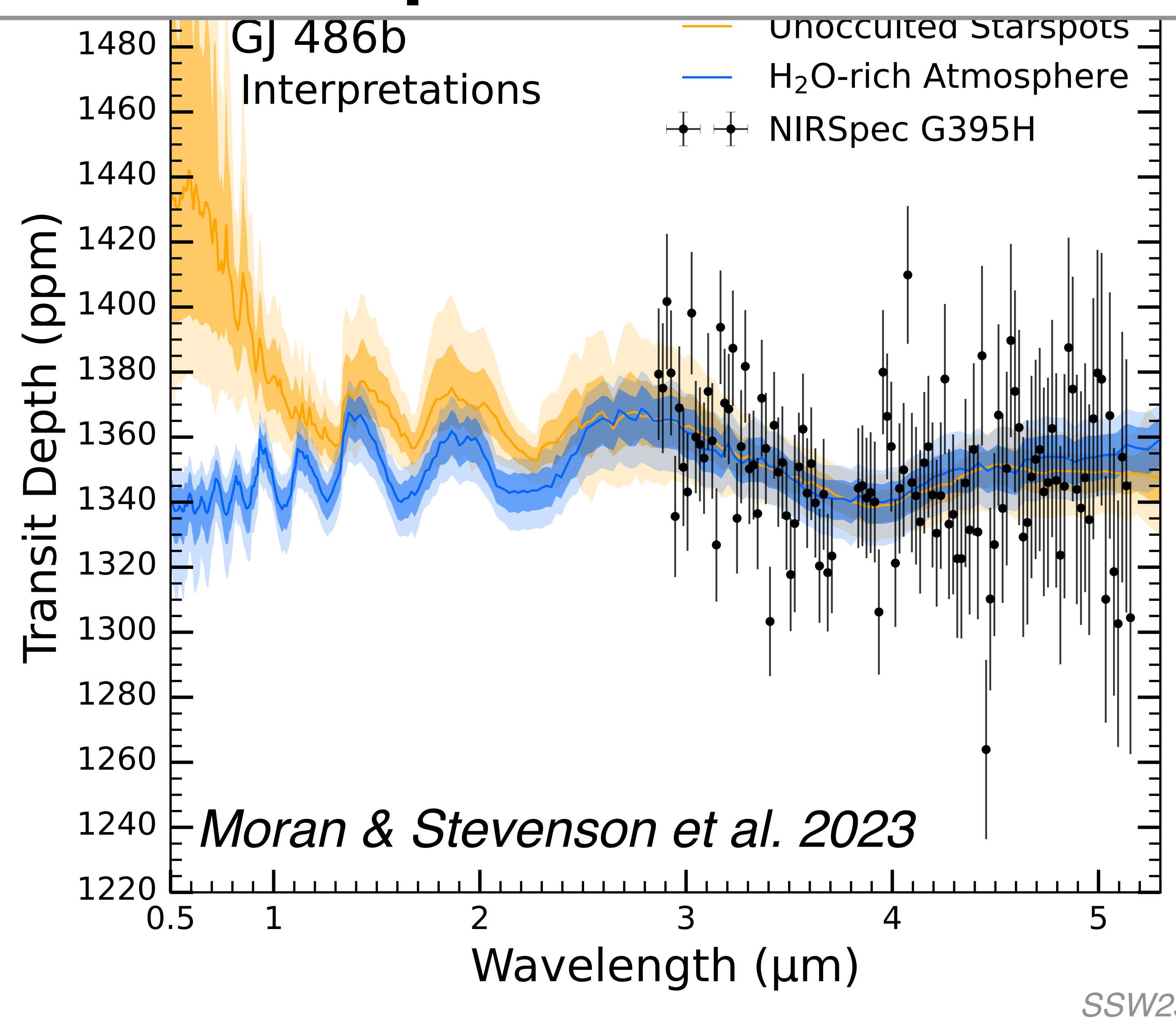


Can't distinguish H_2O in star vs. planet



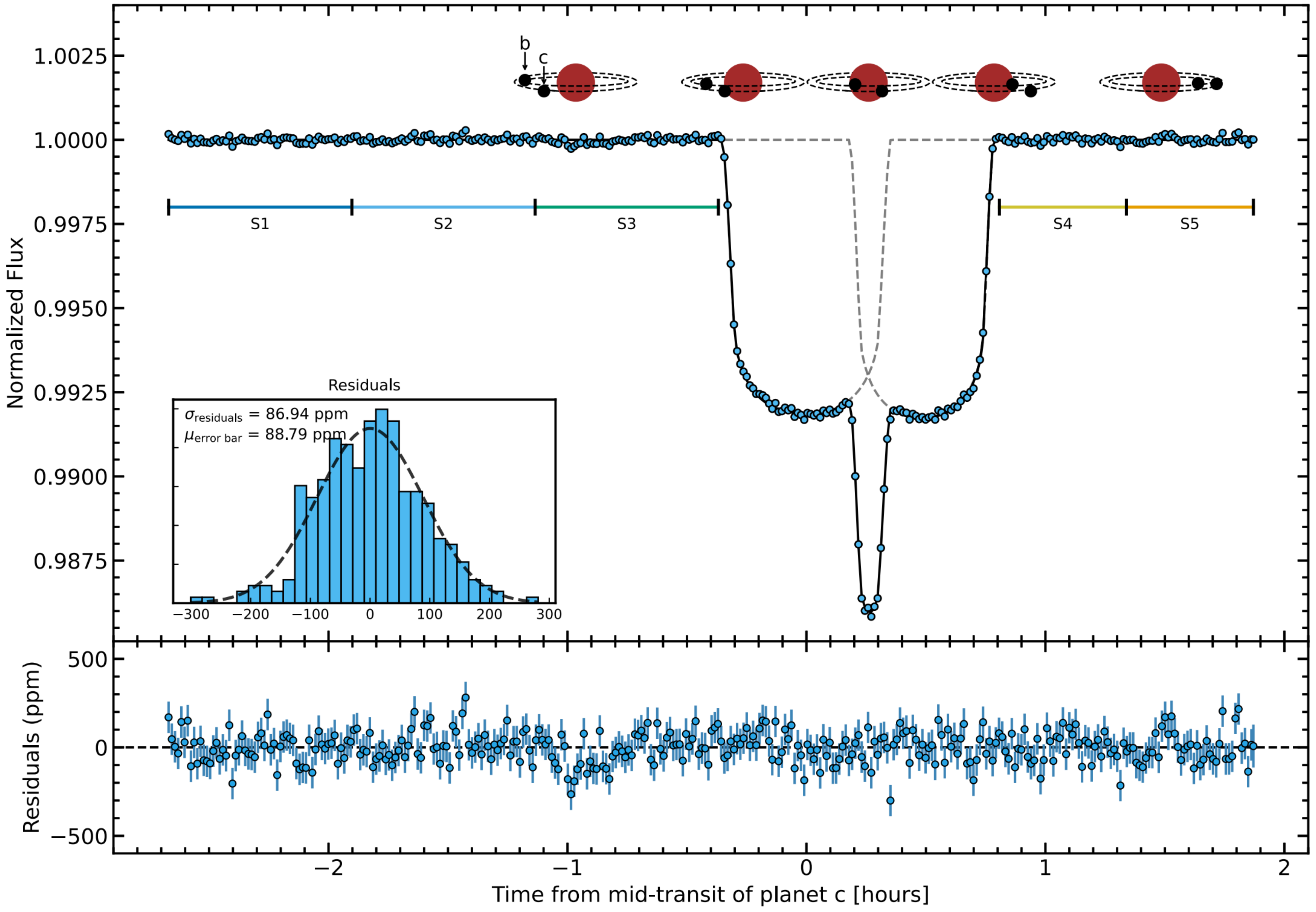
Observations can be explained by stellar contamination (no atmosphere).

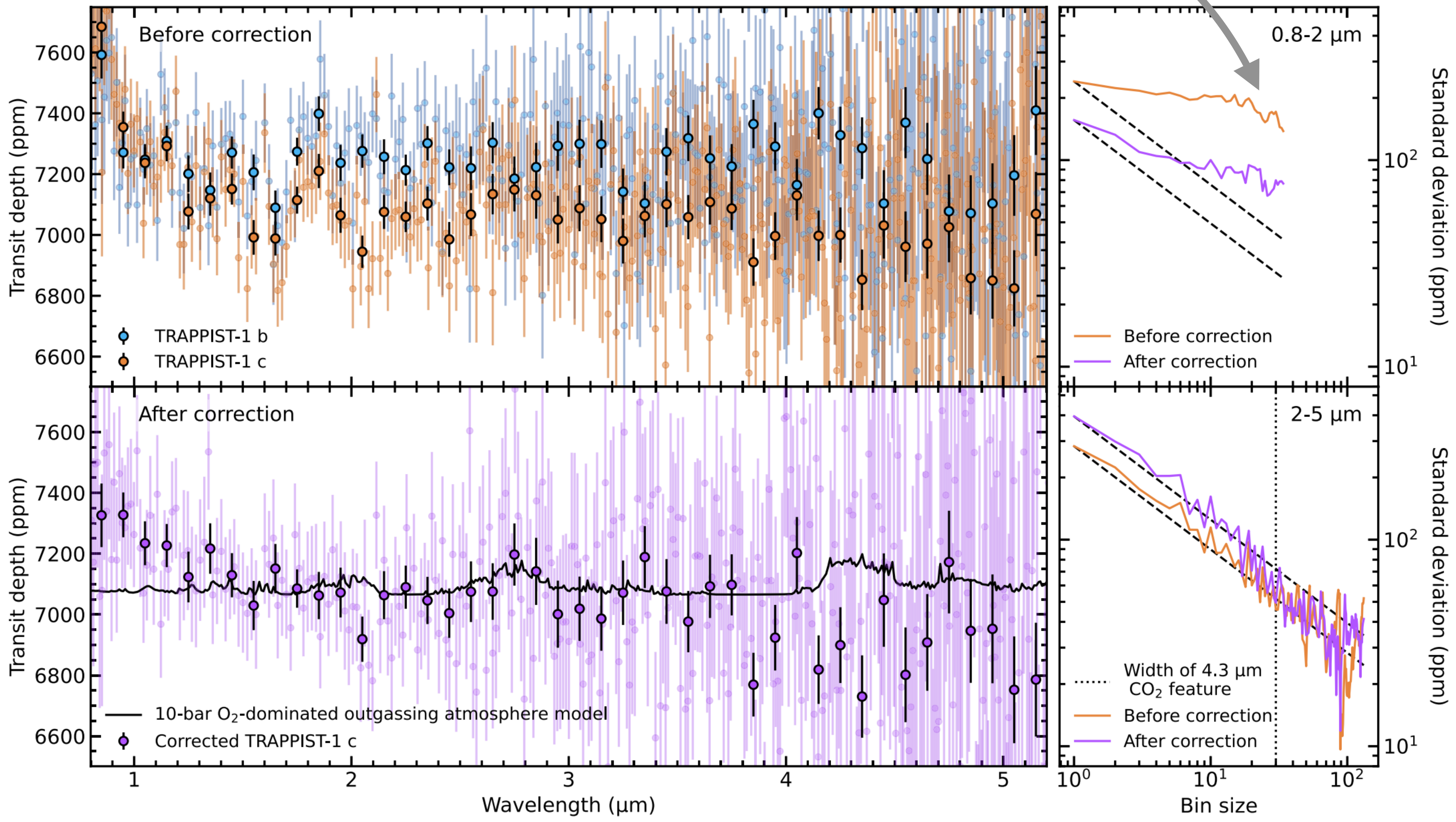
Lim et al. 2023



But there may be hope in "self-calibrating" stellar surface inhomogeneities using sibling planets around the same

Use TRAPPIST-1 b to correct transit spectrum of TRAPPIST-1 c — 2.5x reduction in stellar contamination at shortest wavelengths

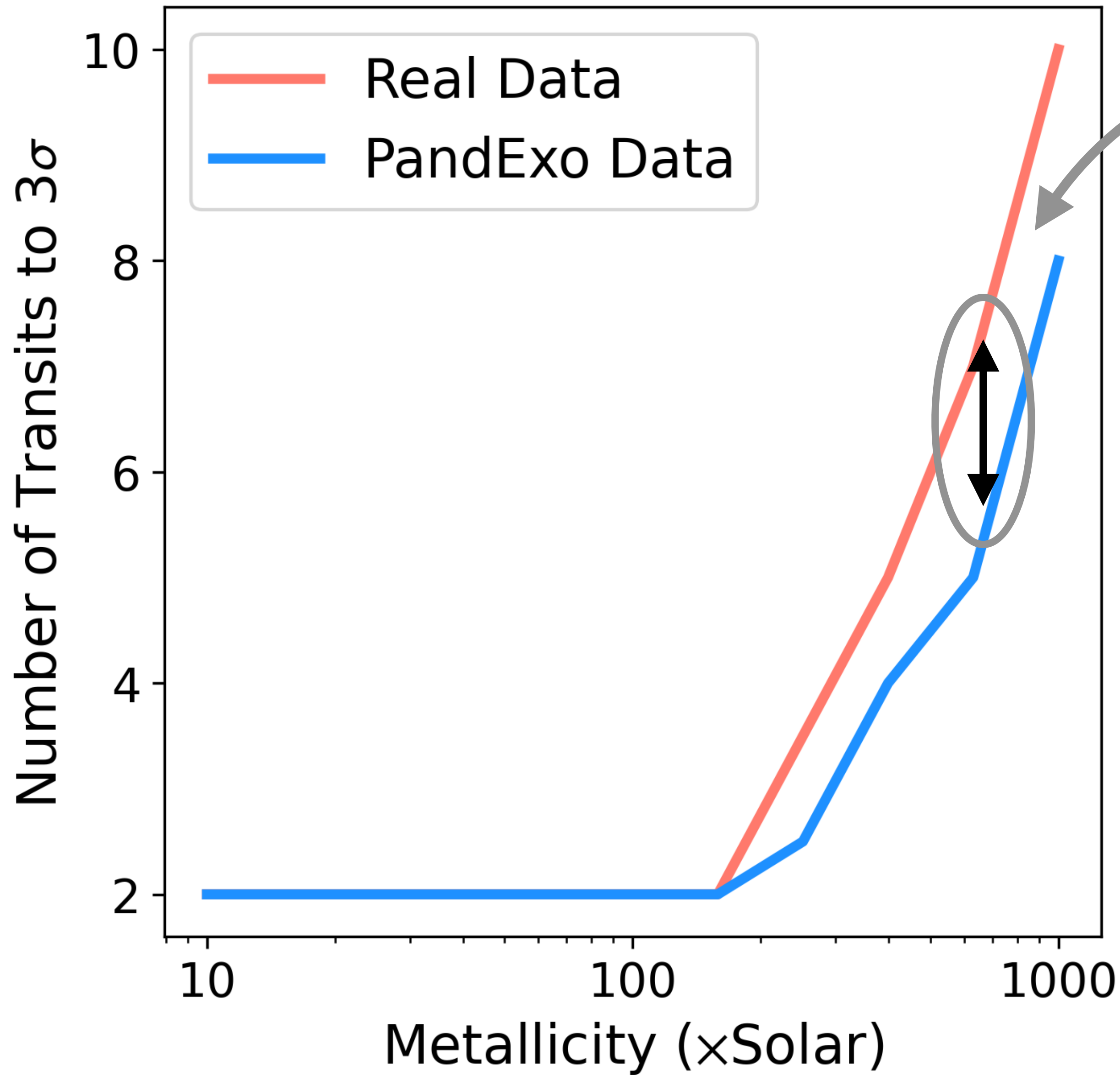




Rathcke et al. 2025, after TRAPPIST-1 JWST Community Initiative 2023

We do not yet understand sources of systematic noise in JWST instruments.

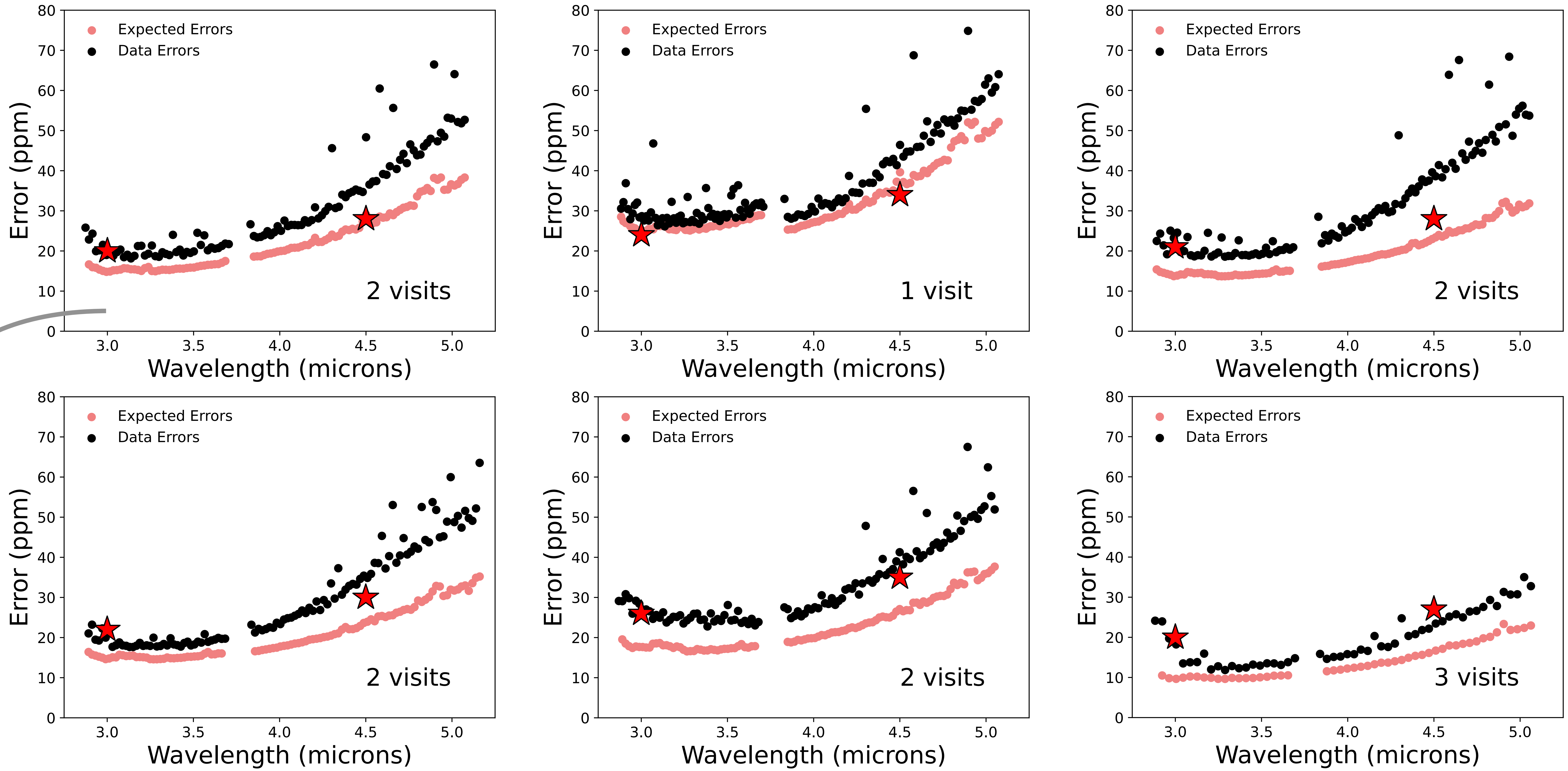
Particularly a problem for bright stars and/or high-metallicity atmospheres



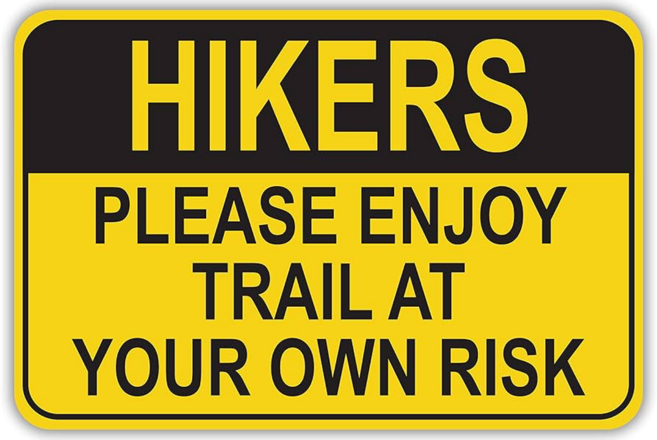
Alderson et al. 2024

NIRSpec/G395H

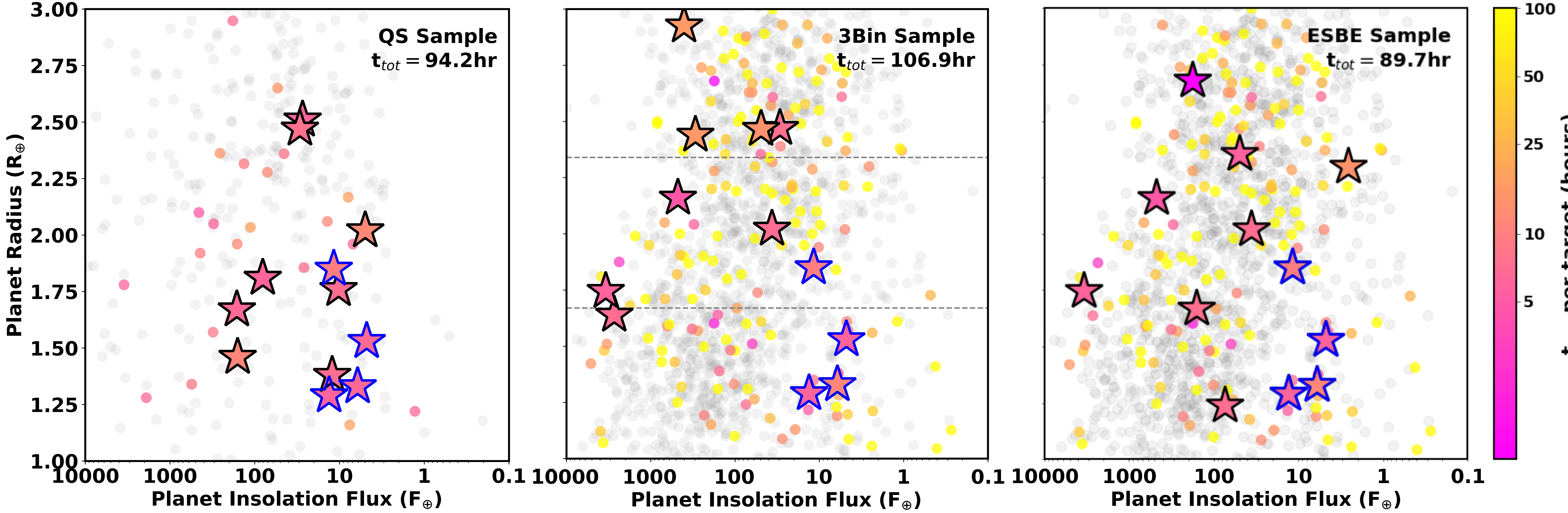
★ *actual estimate in Cycle 1 proposa*



Figures from Nicole Wallack (see, e.g., Wallack et al. 2024)
Much more work in prep!



How surveys are designed and executed can leave an unintended (biased) imprint on the results.



Selected with a two-tiered empirical function

QS

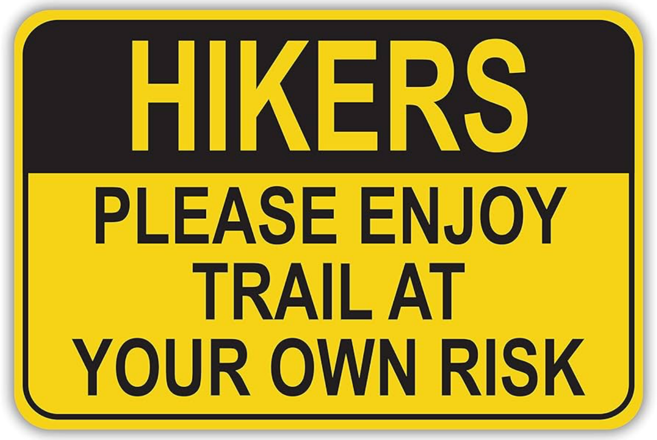
3x1 grid of R_p vs F_{insol}
rank by T_{exp}
4 targets per bin

3Bin

Filtered out high T_{exp} targets
Chose 12 ~evenly space by eye

ESBE

Batalha et al. 2023



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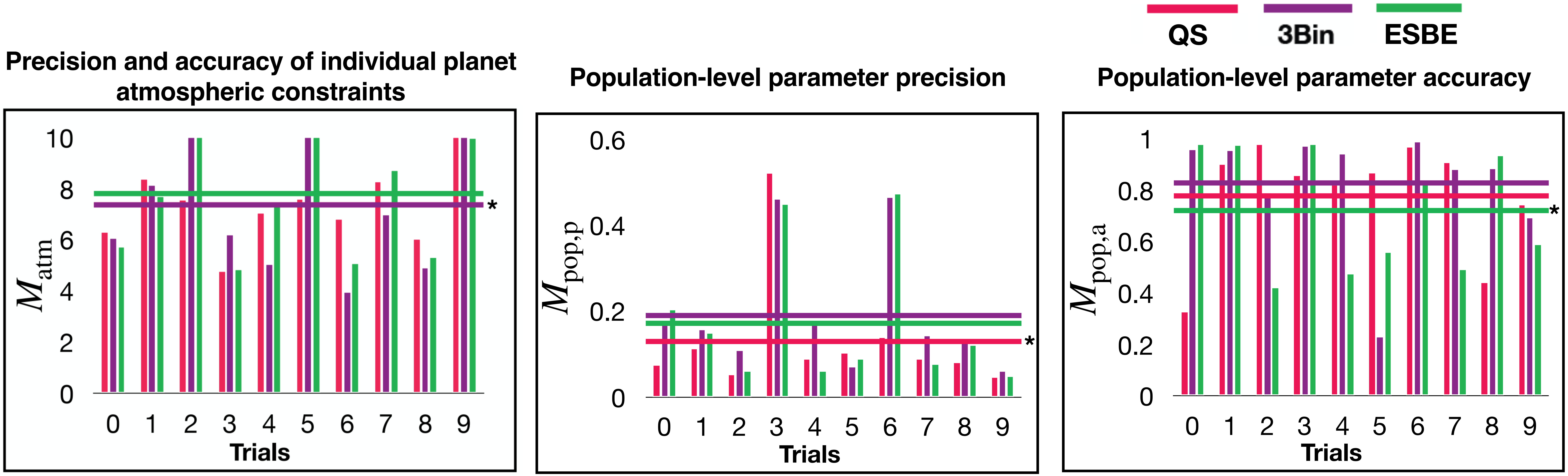

Optimizing for the best constraints on atmospheric parameters will not necessarily result in more accurate or precise constraints on population parameters.

Population studies are not meaningful if the inferred result changes depending on what subset of the underlying population is included in the sample.

Batalha et al. 2023