Revealing the first thermal emission spectra of hot and dense sub-Neptunes

+ a short and sweet review of sub-Neptune atmospheres

ExSoCal 2025
December 15th 2025

Pierre-Alexis Roy
UCLA - EPSS

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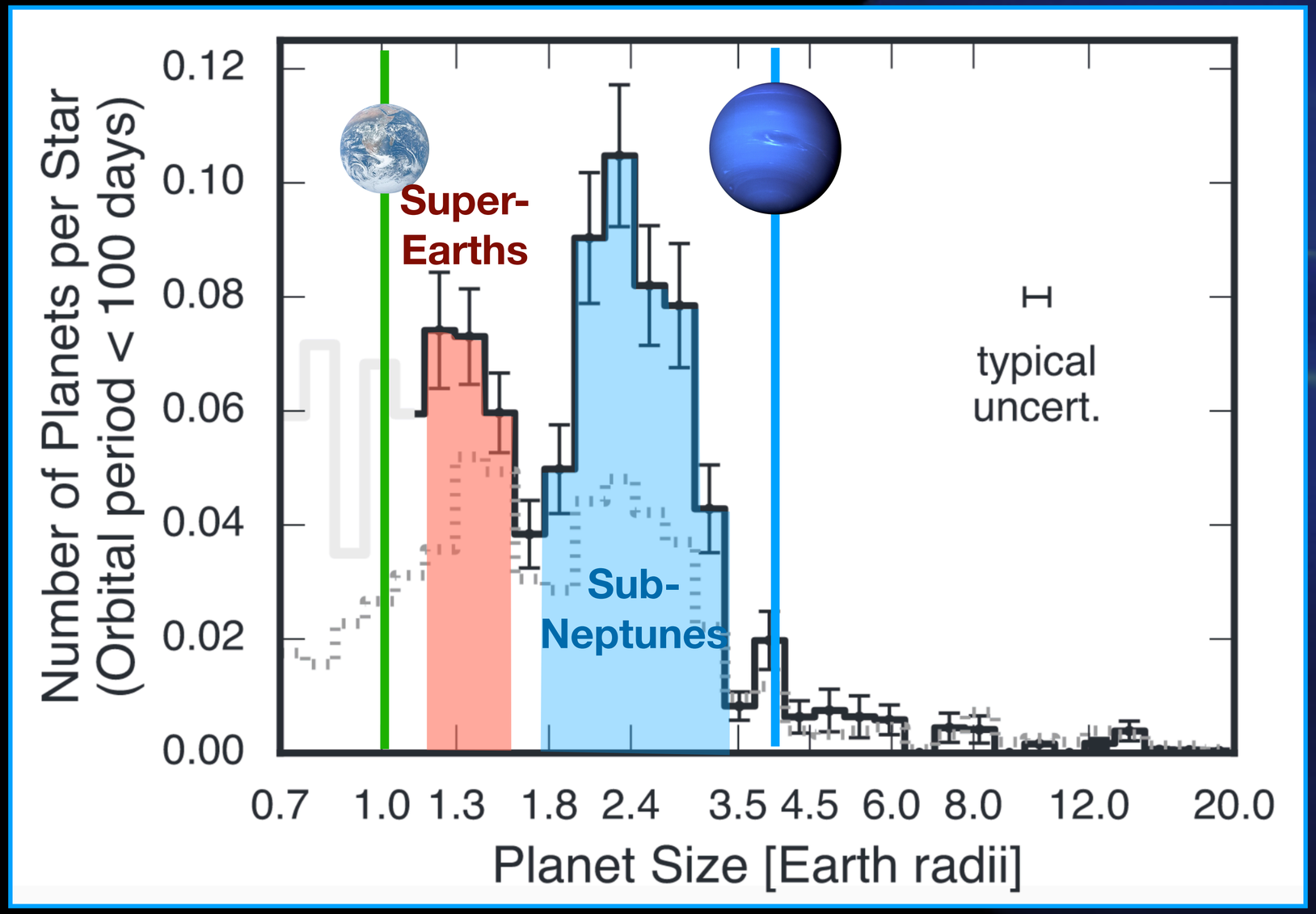
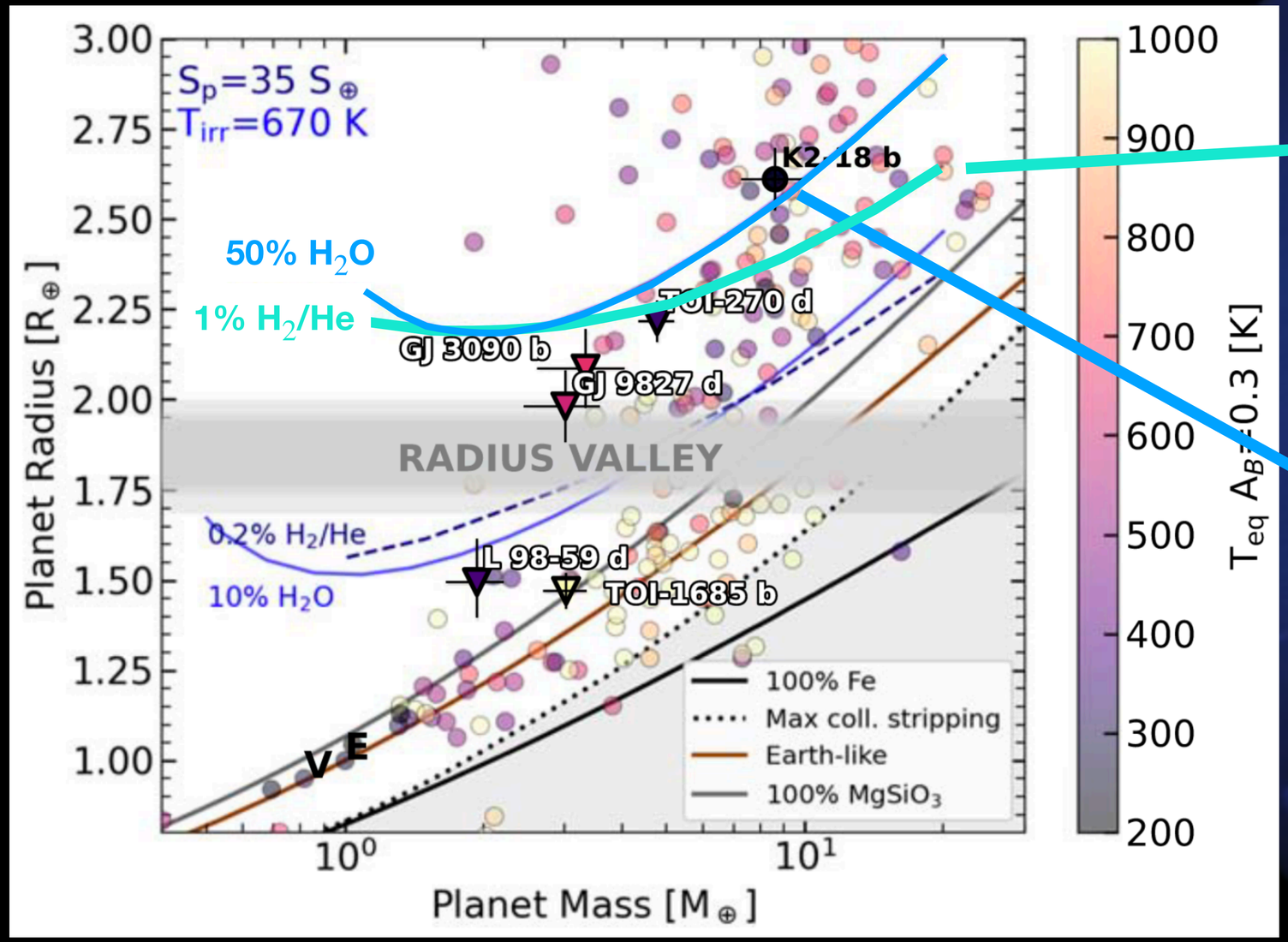
Super-Earths and sub-Neptunes are the most abundant types of planets known so far

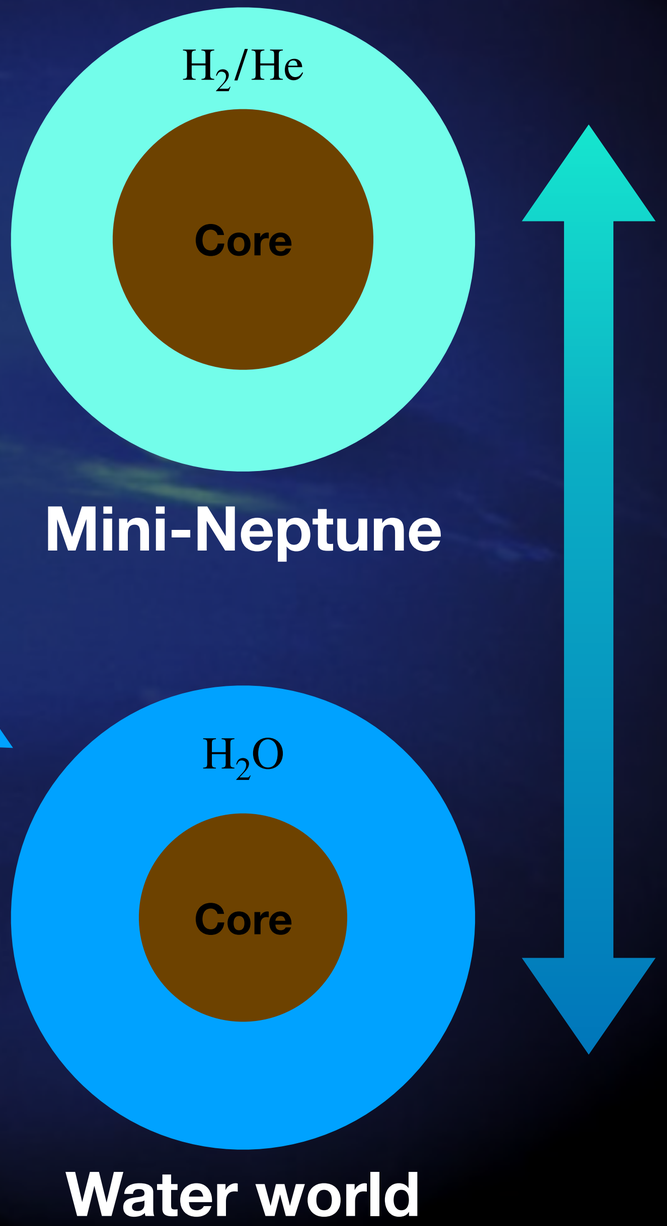


Fulton et Petigura 2018

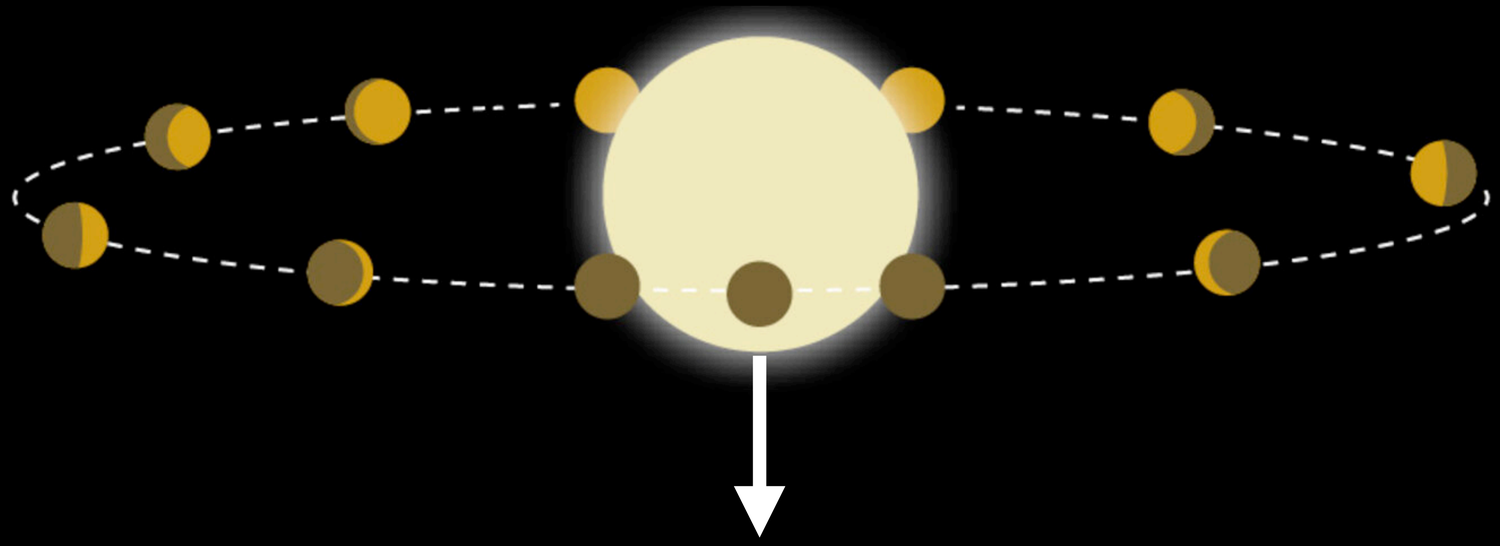
Potential compositions for sub-Neptunes are numerous



Piaulet-Ghorayeb et al., 2024 (incl. Roy)



Transmission spectroscopy as a way to understand sub-Neptune atmospheres and their composition



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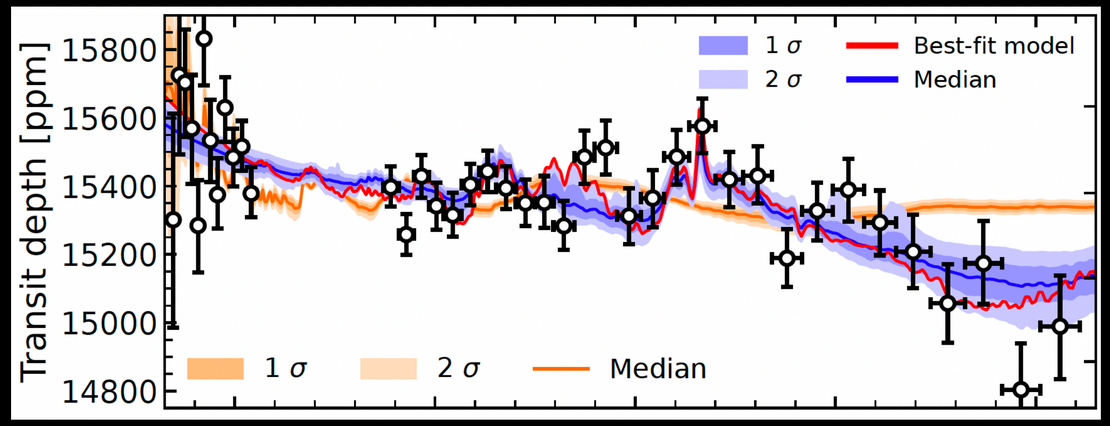
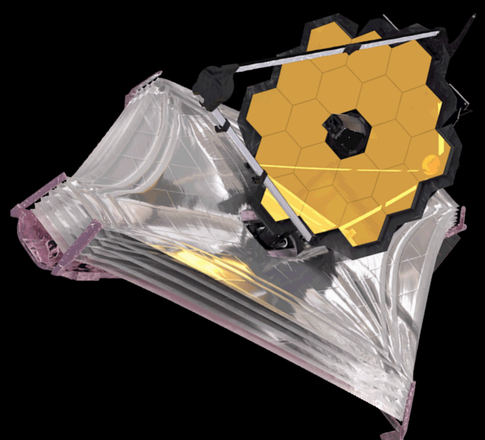
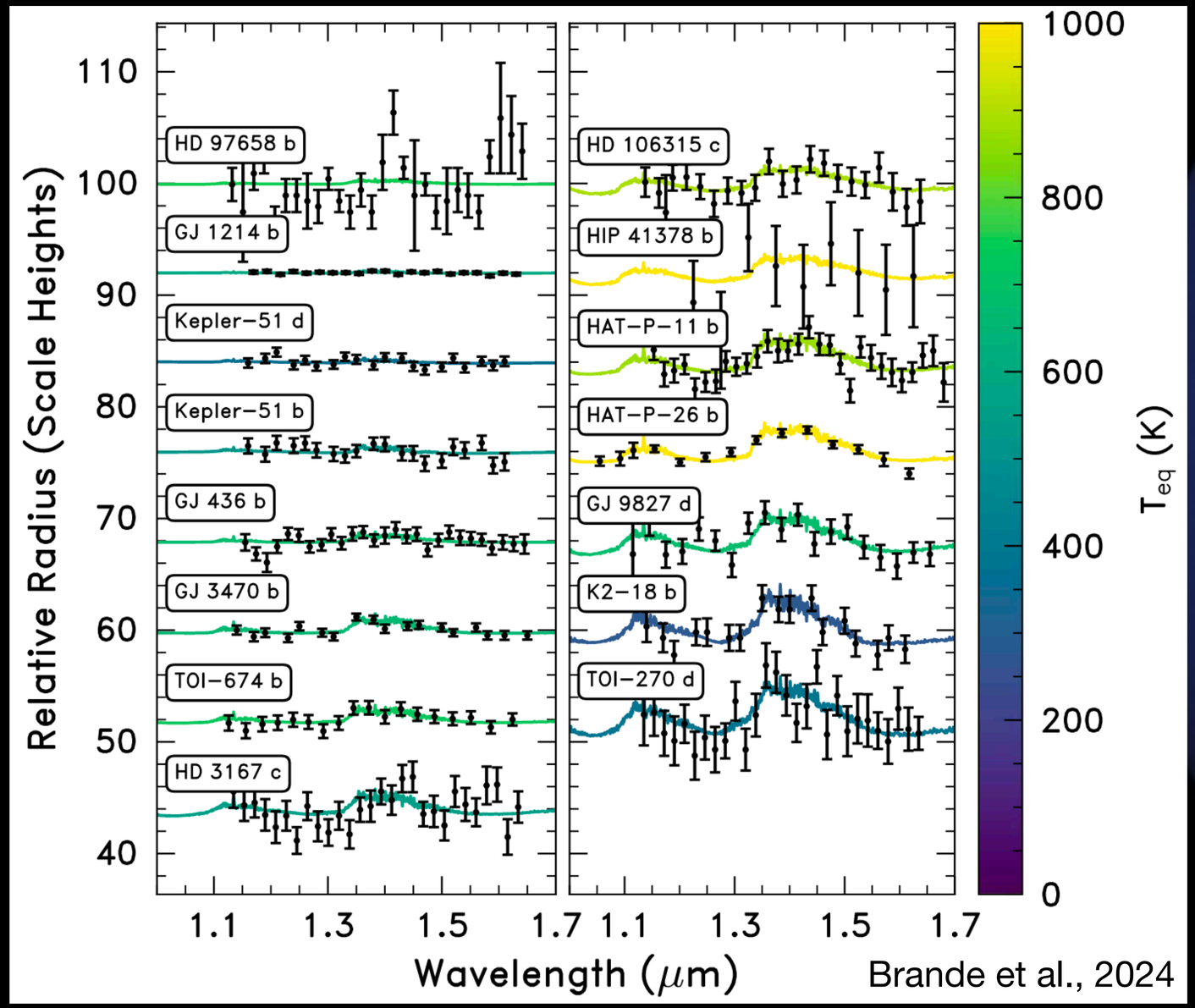




The Hubble survey: Cool sub-Neptunes are cloud-free?



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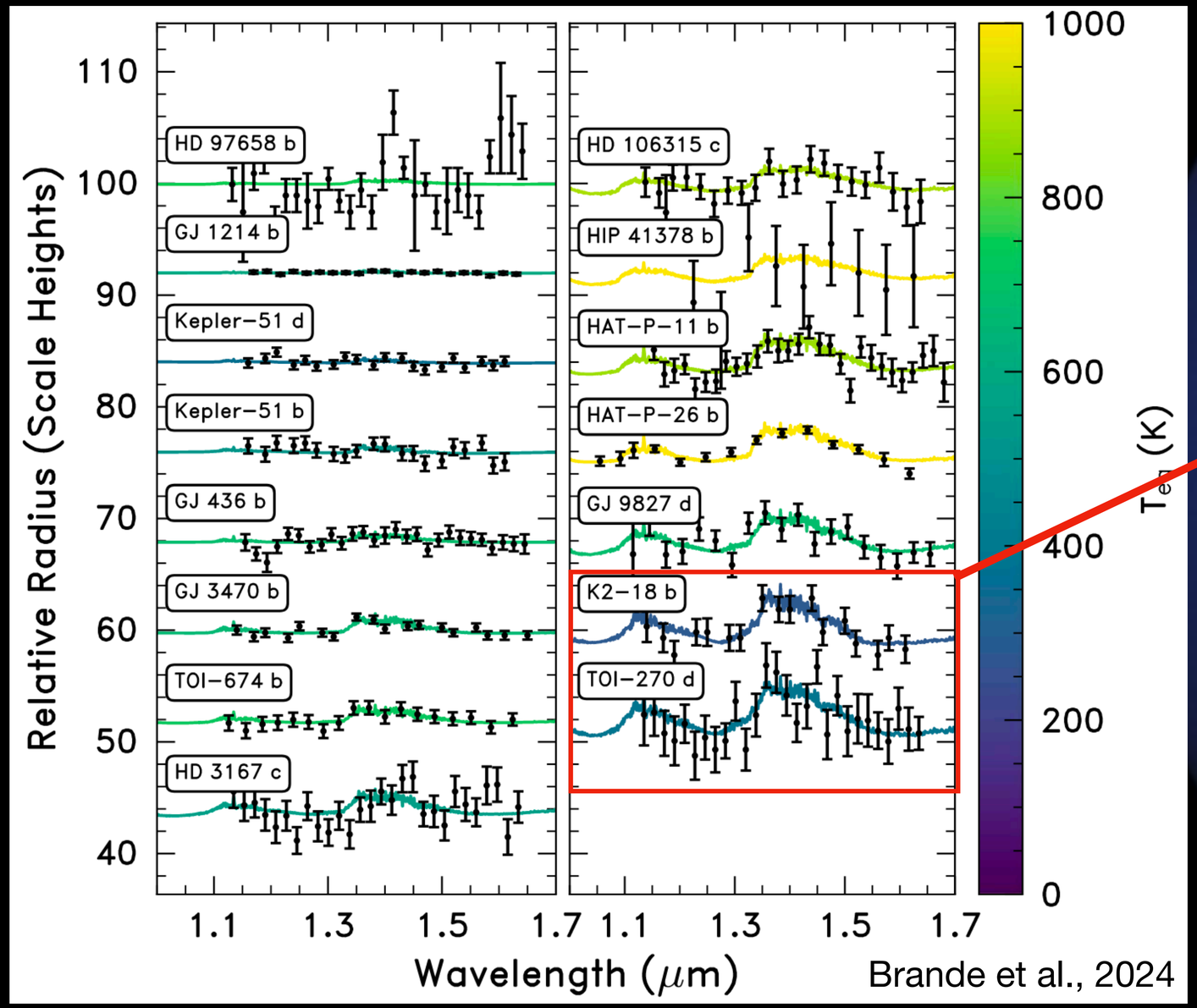
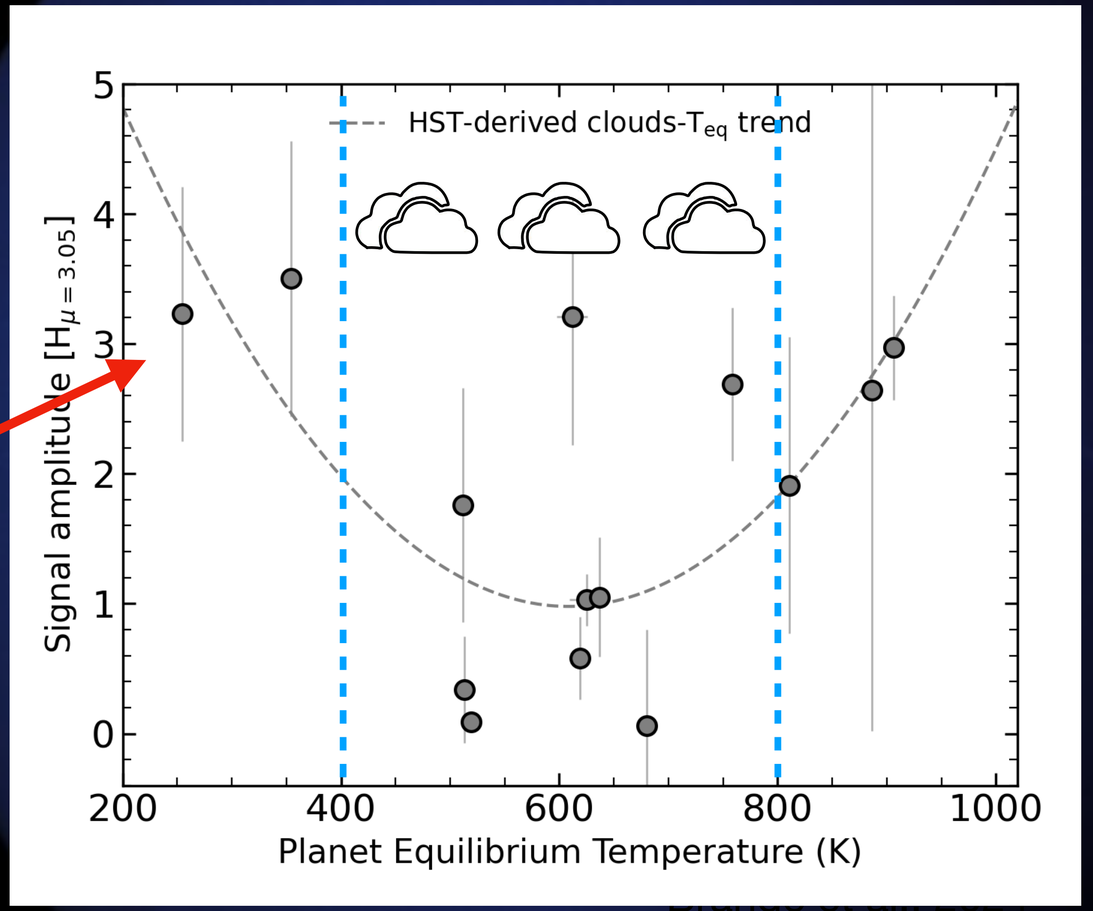
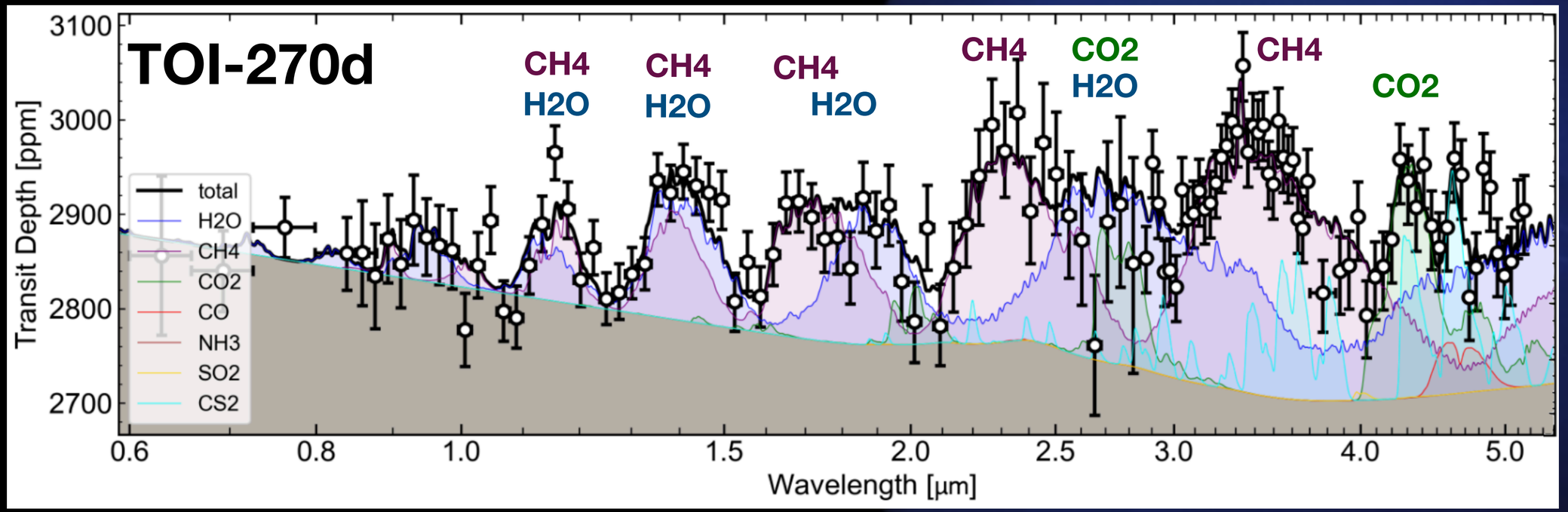




Brande et al., 2024

K2-18b and TOI-270d : first temperate sub-Neptunes with JWST

No high-altitude clouds - all CH4 bands - CO2



Benneke, **Roy**, et al., 2024

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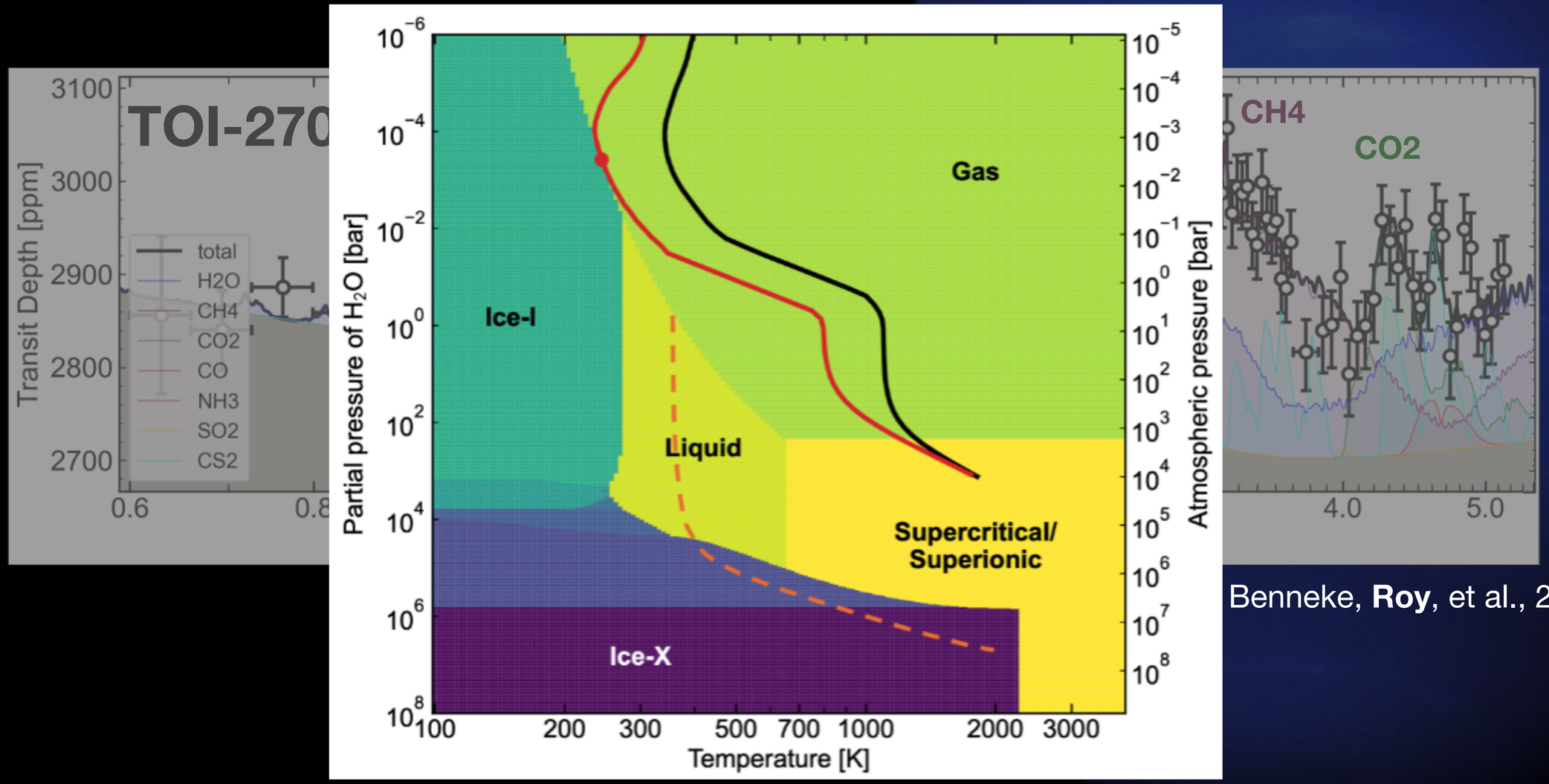

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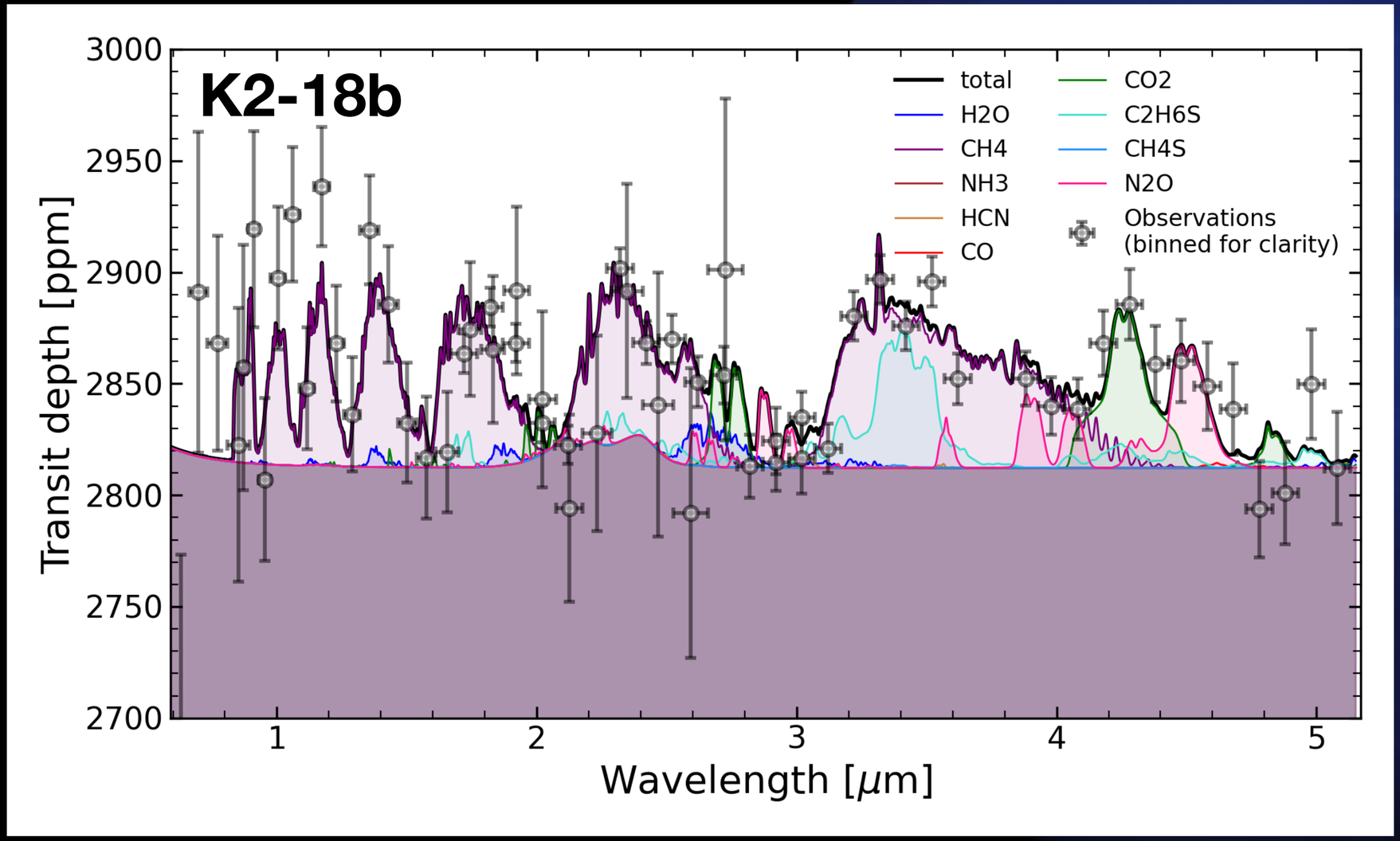
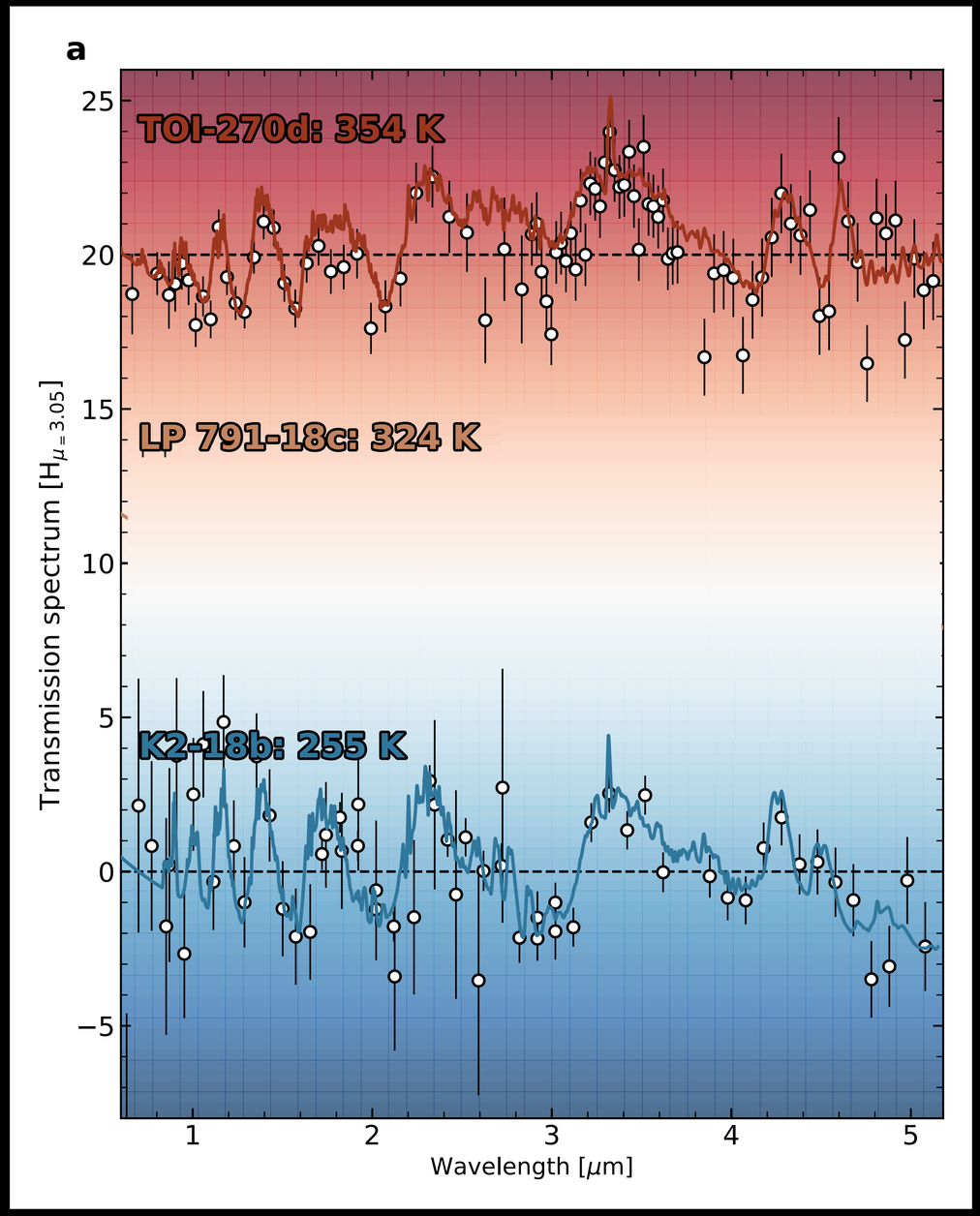


Hu et al., 2025 (incl. Roy)

Diversity in the cloudiness of temperate sub-Neptunes



Roy et al., 2025

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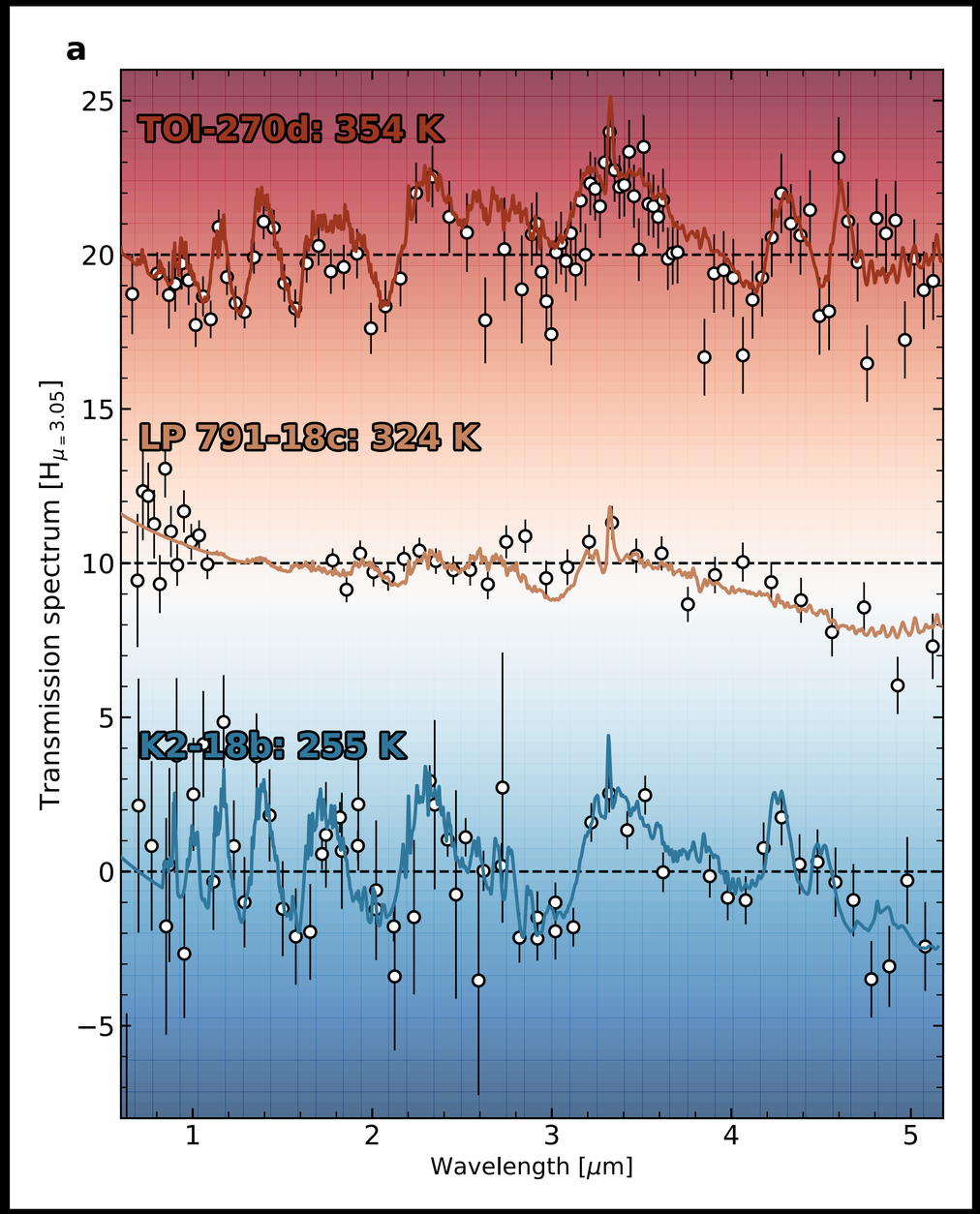
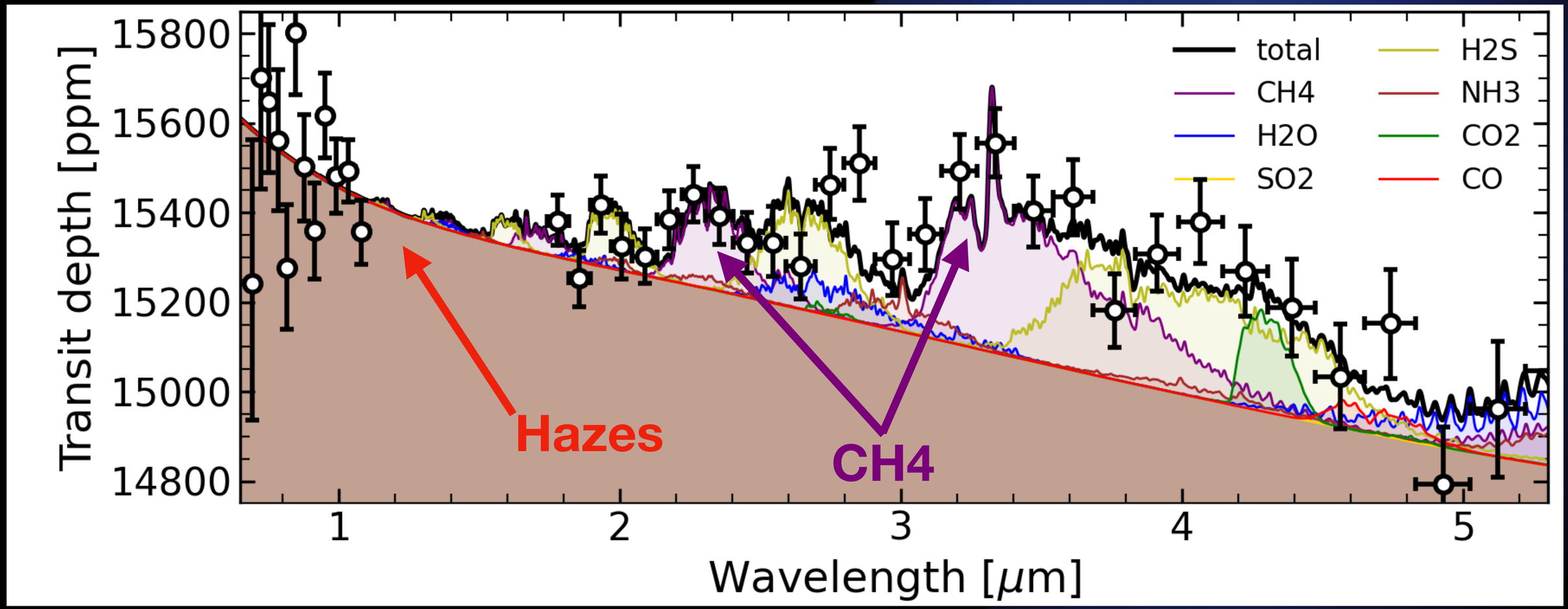


Roy et al., 2025

LP 791-18c's transit spectrum is very different

Haze opacity (Rayleigh scattering) - Only two CH4 bands peaking through



Roy et al., 2025

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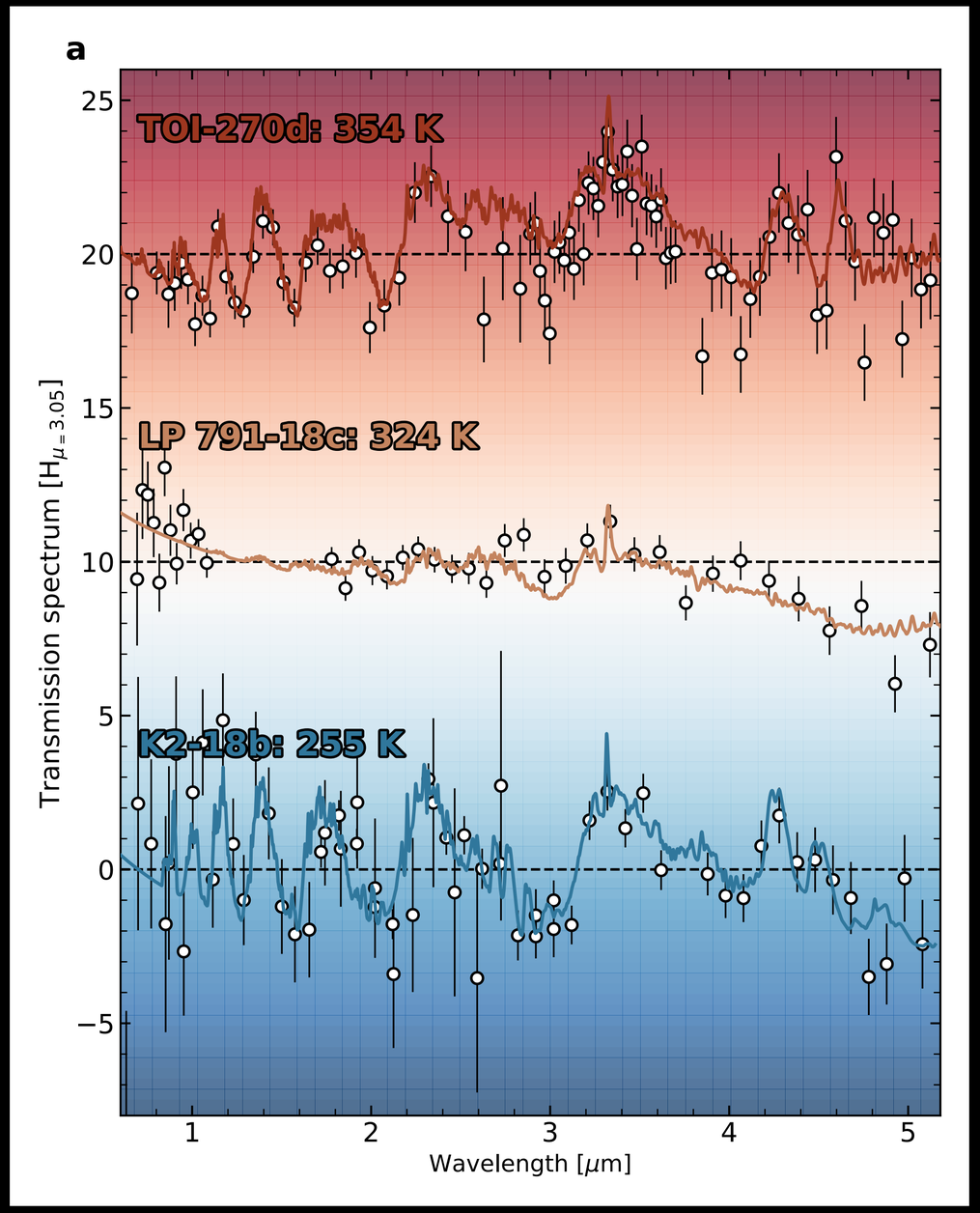
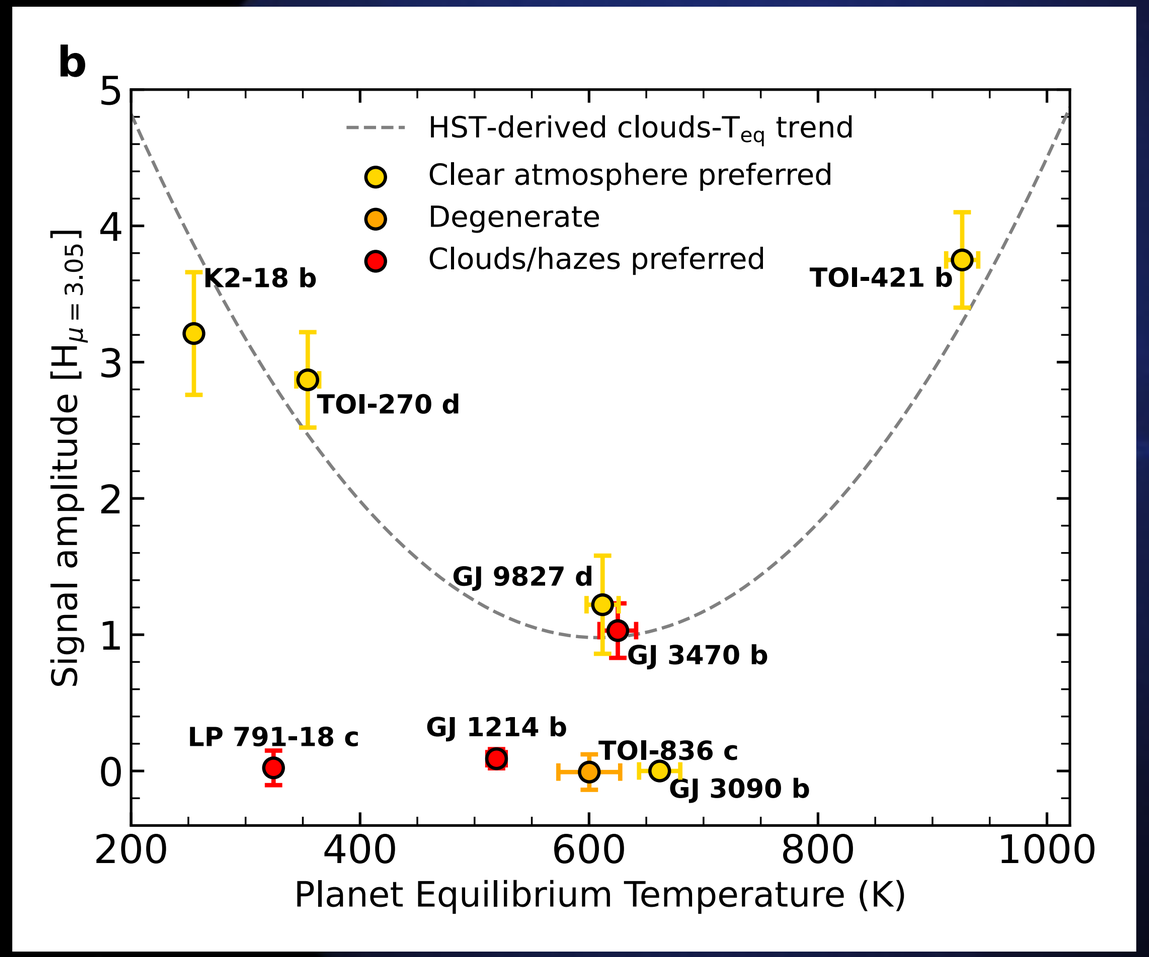
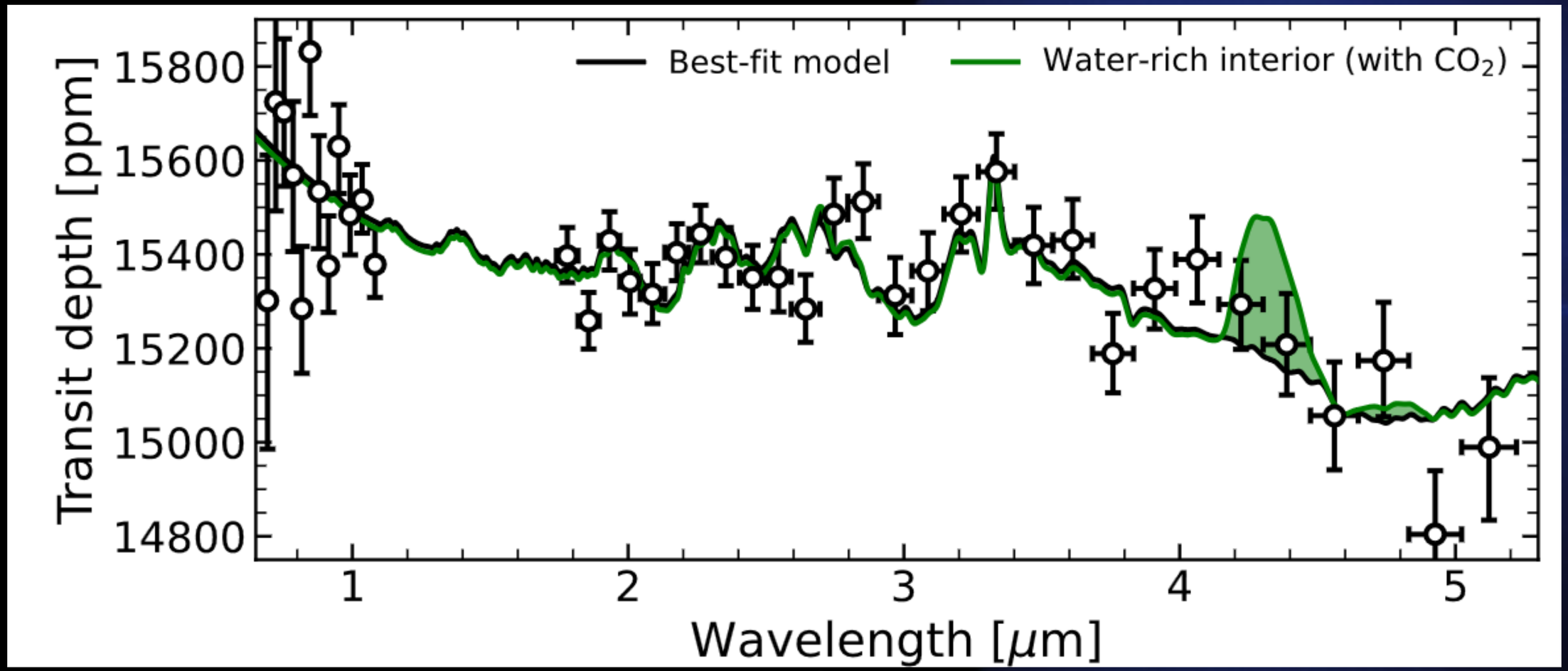




Roy et al., 2025

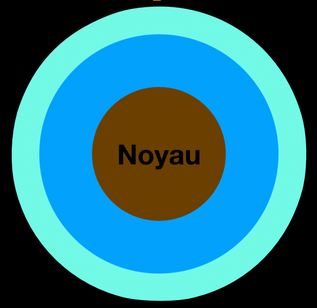
No large CO2 abundance —> A drier composition?

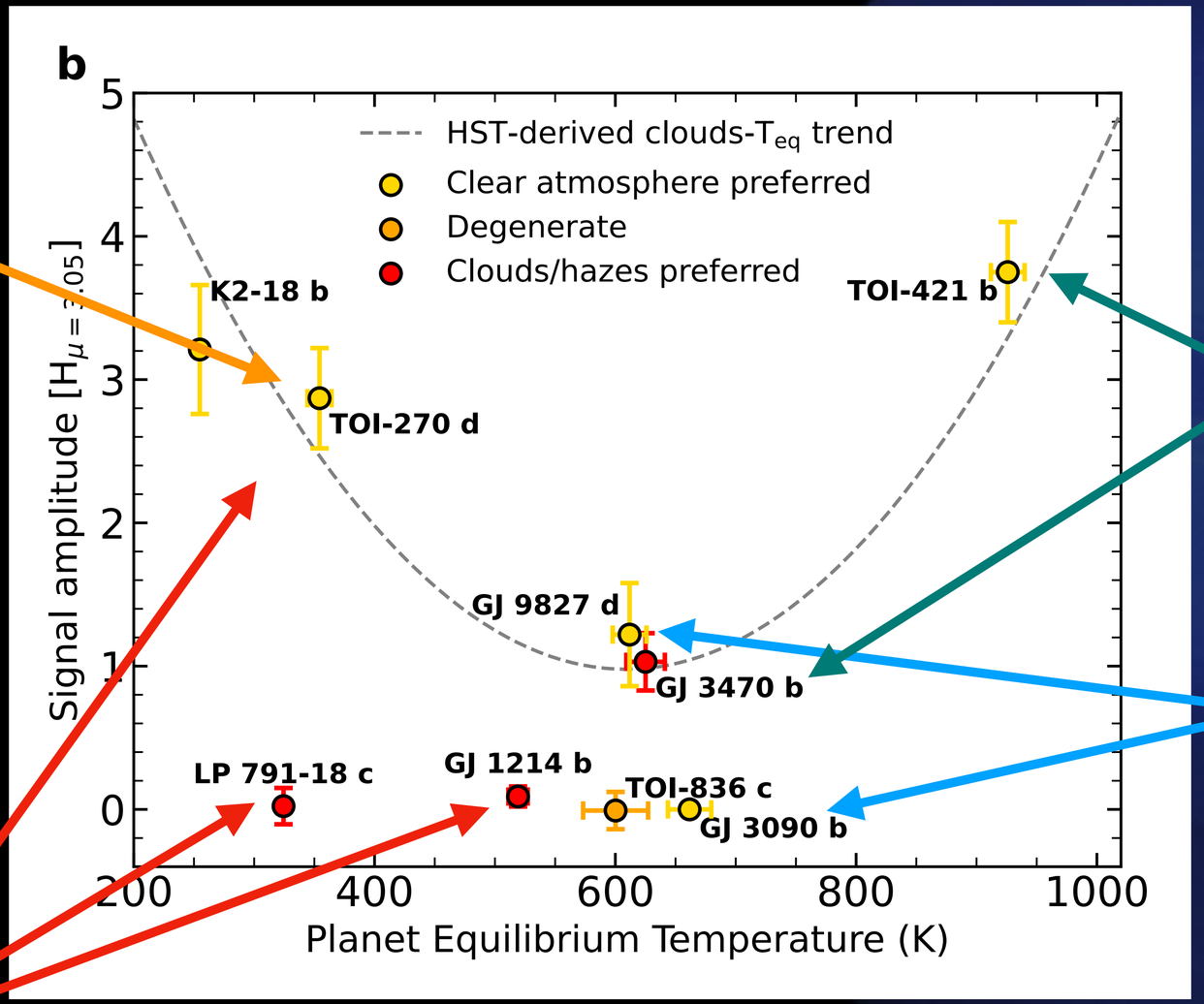


Roy et al., 2025

An emerging diversity among sub-Netpunes

Miscible envelope sub-Neptunes?





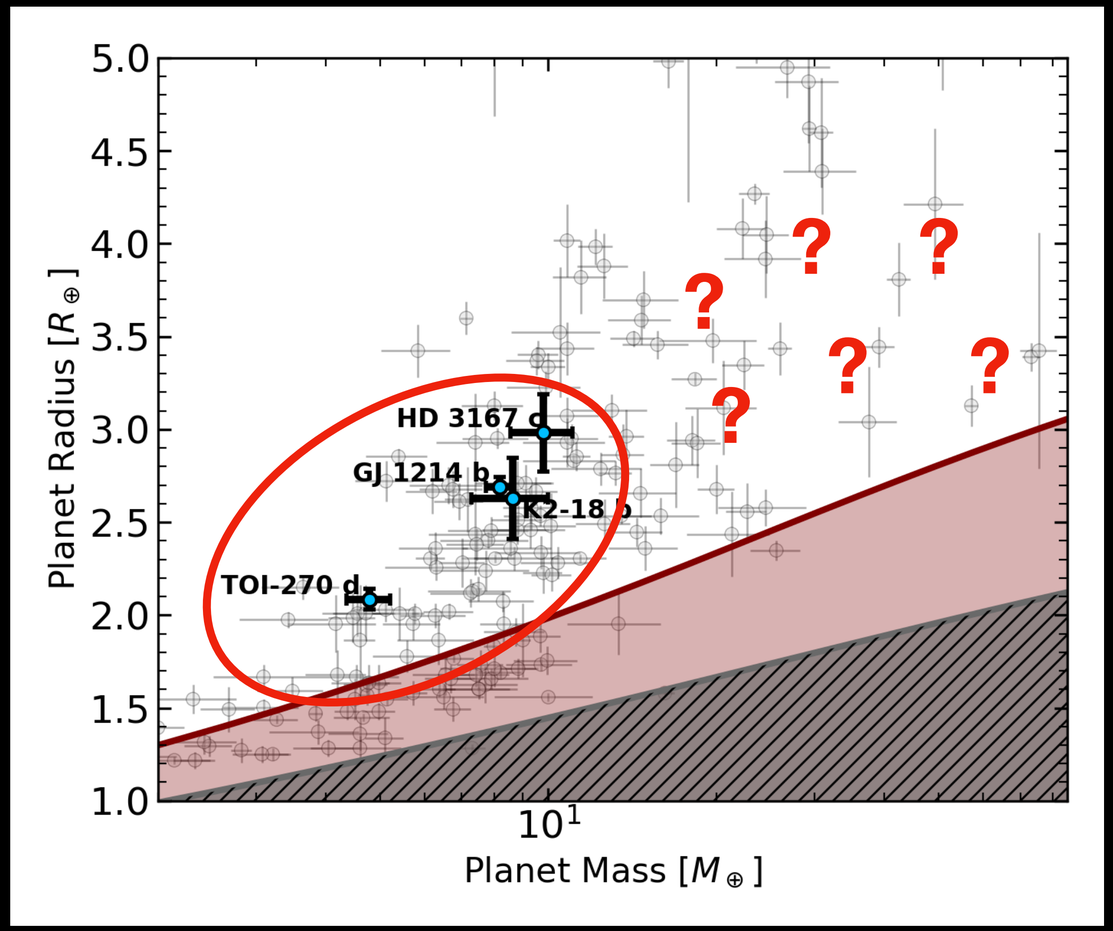
Mini-Neptunes?

Water worlds?

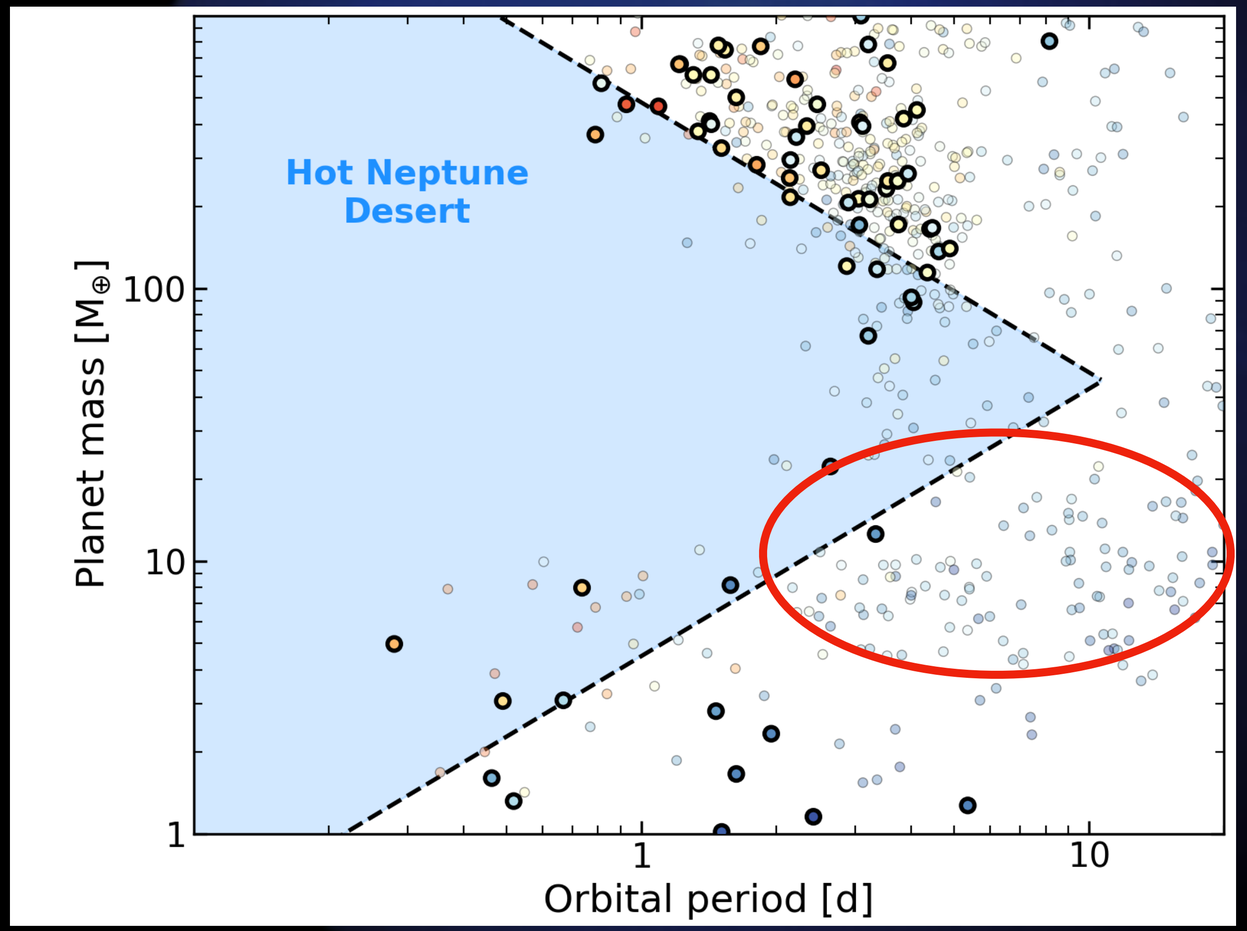
Aerosols diversity

Roy et al., 2025

All these discoveries come from low-density, cold (<1000K) sub-Neptunes in transmission



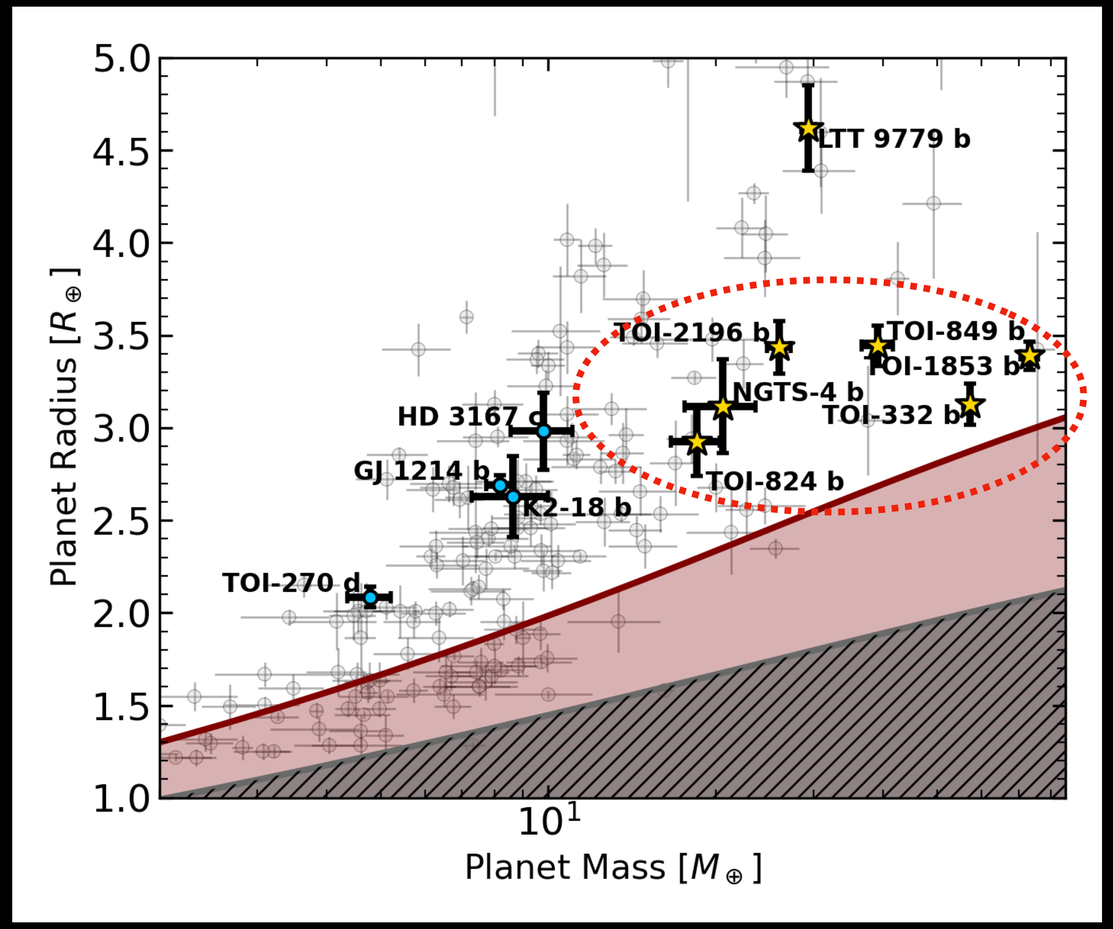
Zeng et al., 2016, 2019



Mazeh et al., 2016

“The Hot Neptune Desert is no longer empty.”

- Vissapragada and Behmard, 2025



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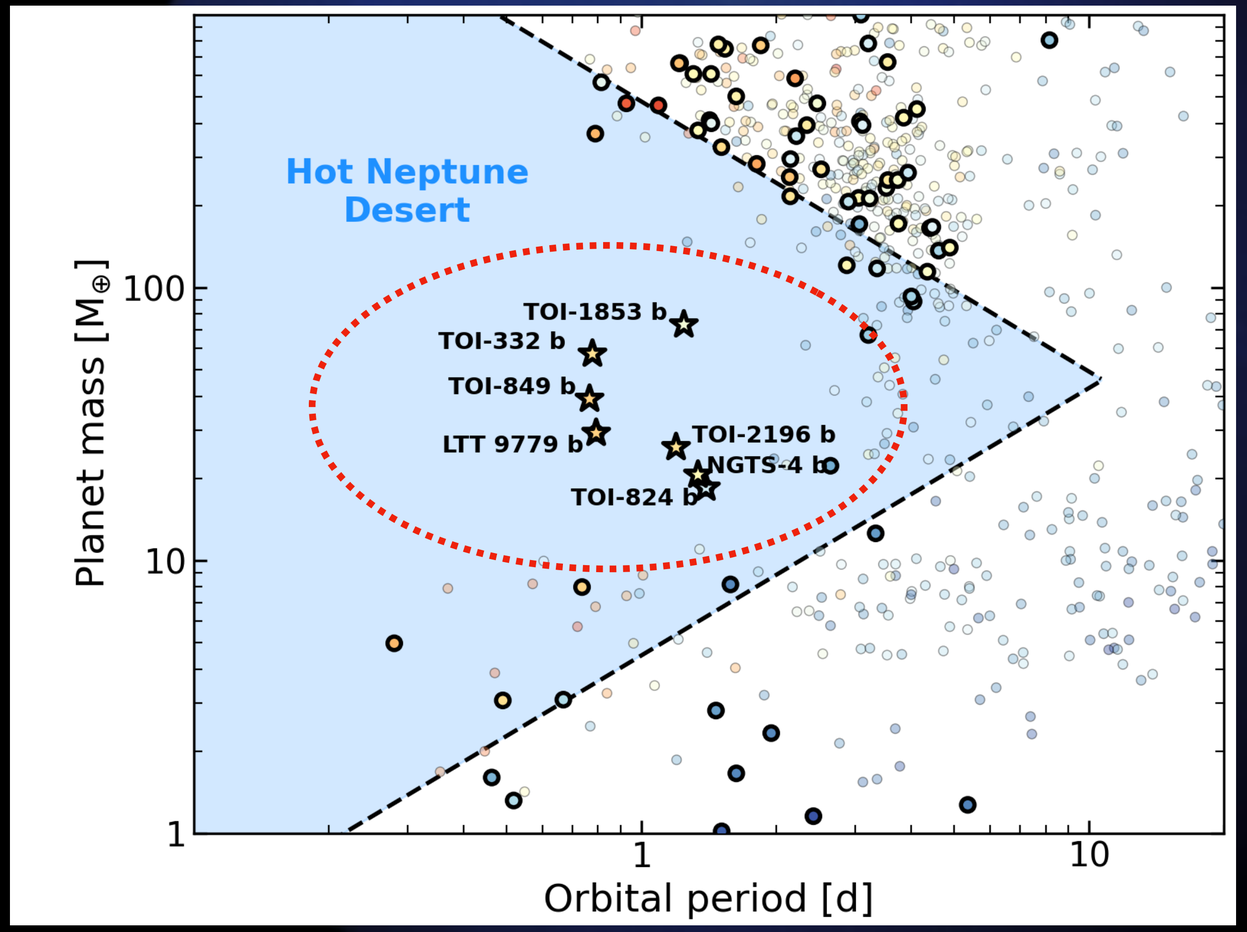
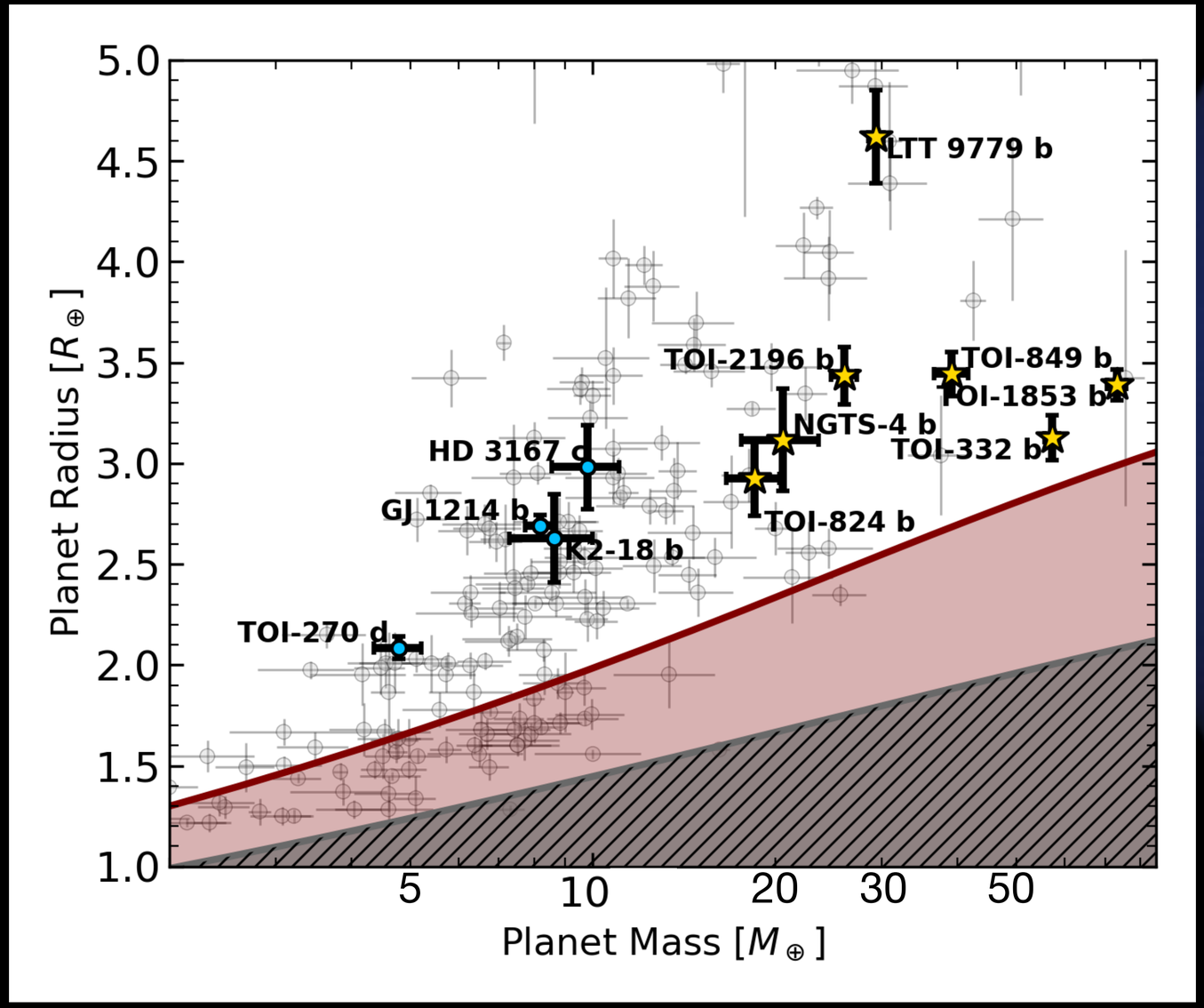


Mazeh et al., 2016

Neptune Desert “dwellers” are an intriguing type of exoplanets



Despite having sub-Neptune (< 4 $R_\oplus$) radii, they have many times the mass of the “standard” sub-Neptunes!

Zeng et al., 2016, 2019

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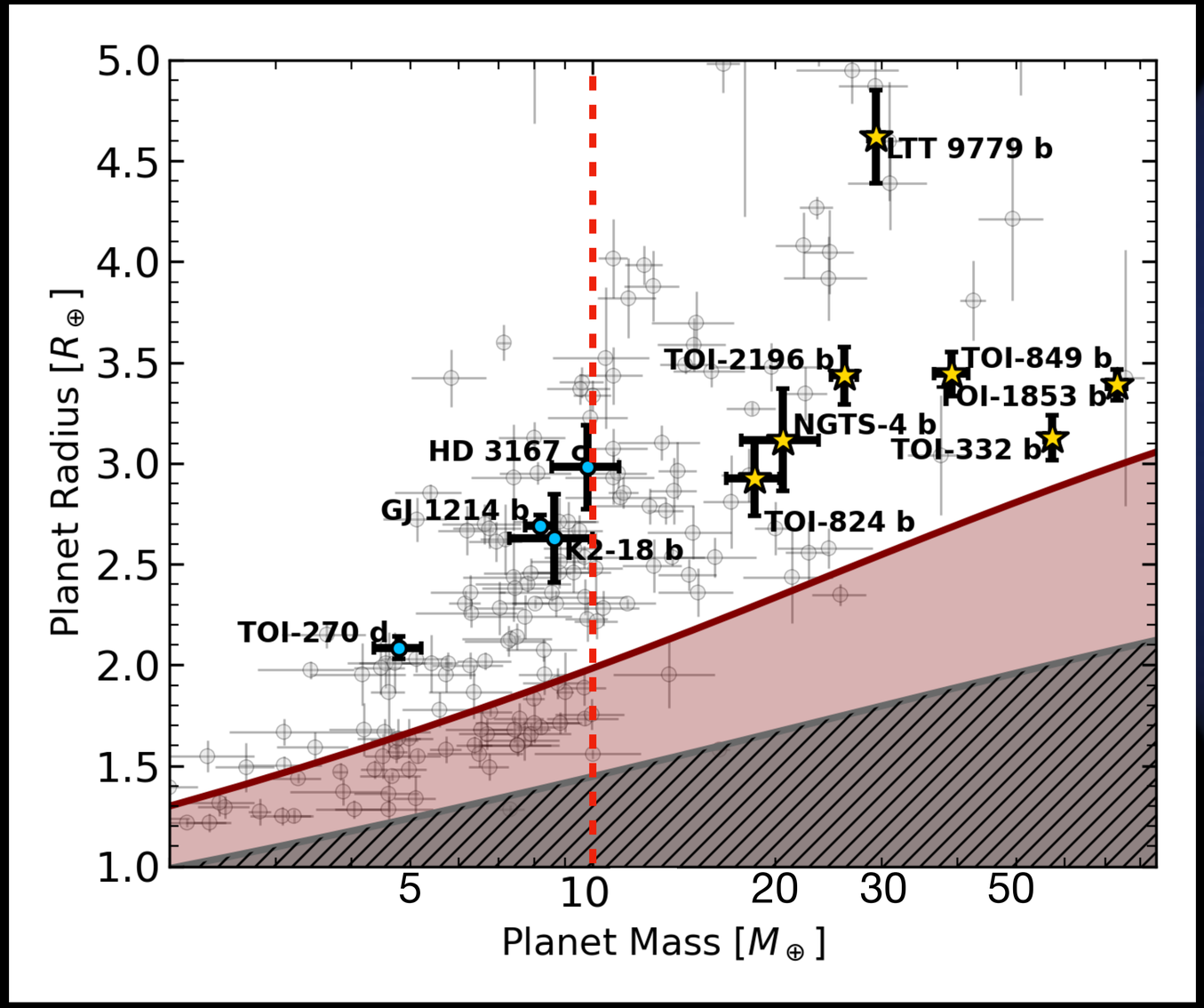

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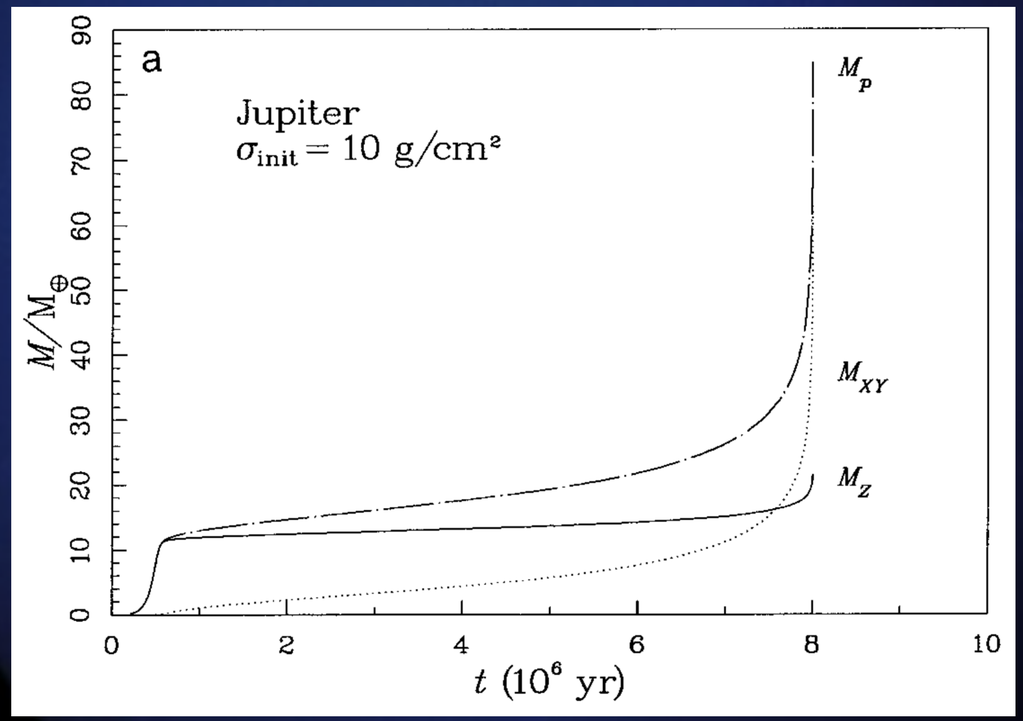
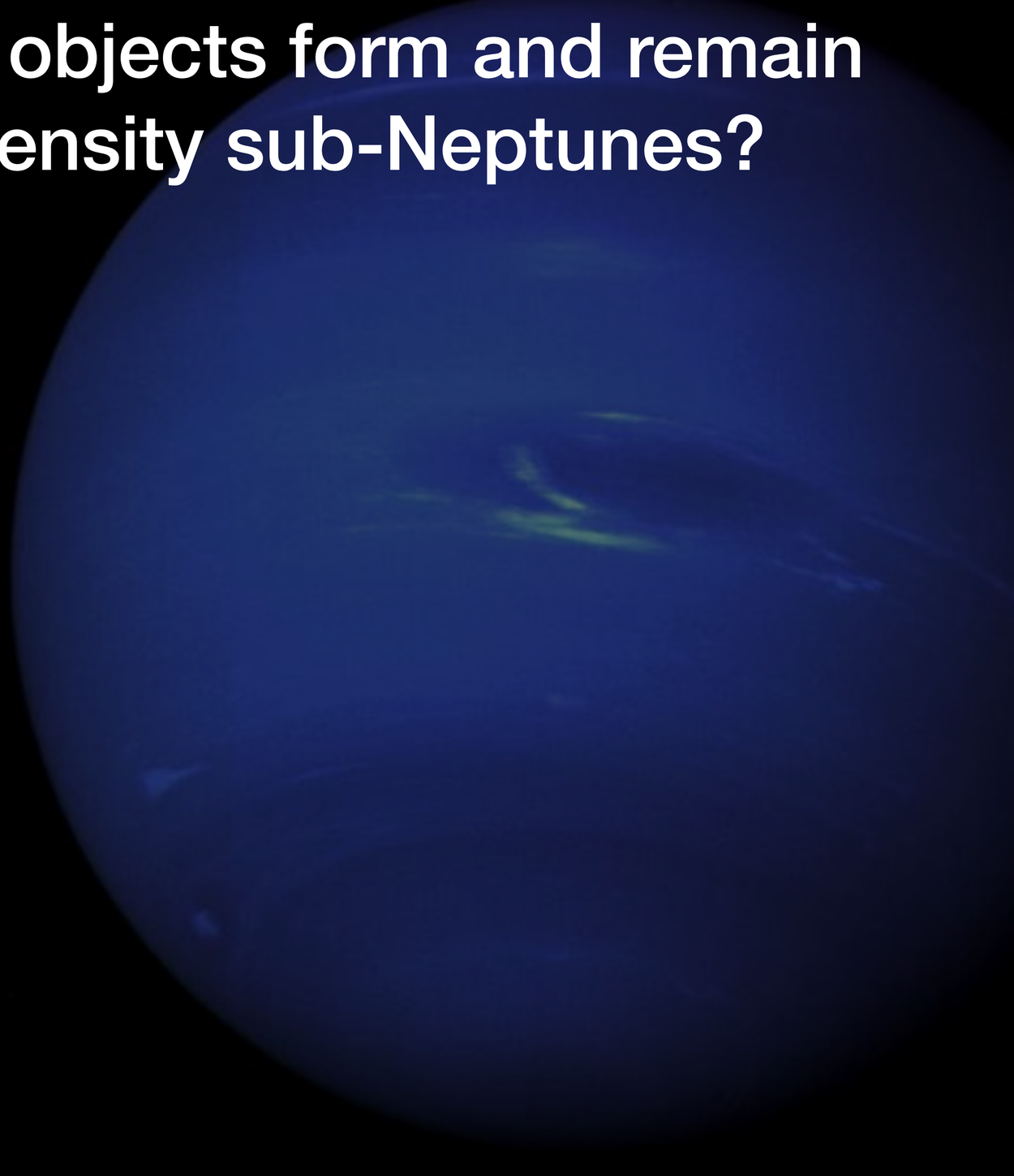


Pollack et al., 1996; Lee, 2019

So how can such massive objects form and remain high-core-mass, high-density sub-Neptunes?

1. **Formation in gas-poor environment**



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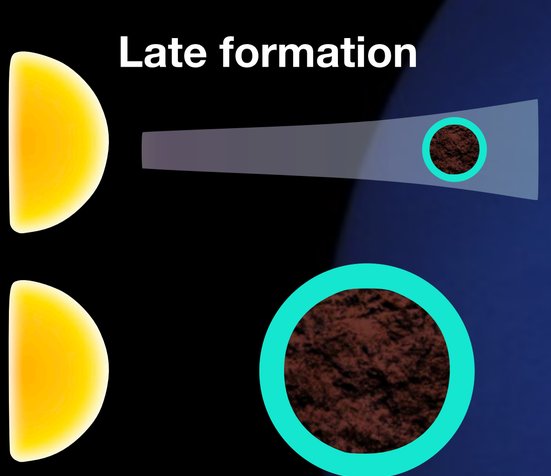

Lee, 2019

Crida et al., 2006
Duffell and MacFadyen 2013

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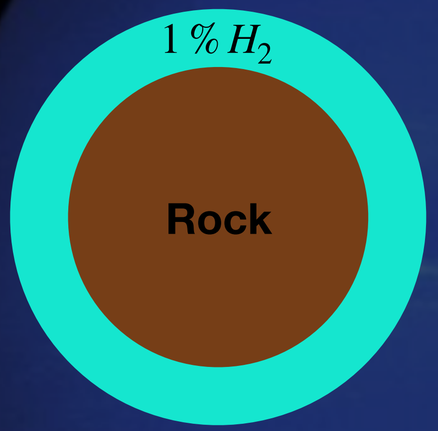

“Standard” rock + H2 sub-Neptune

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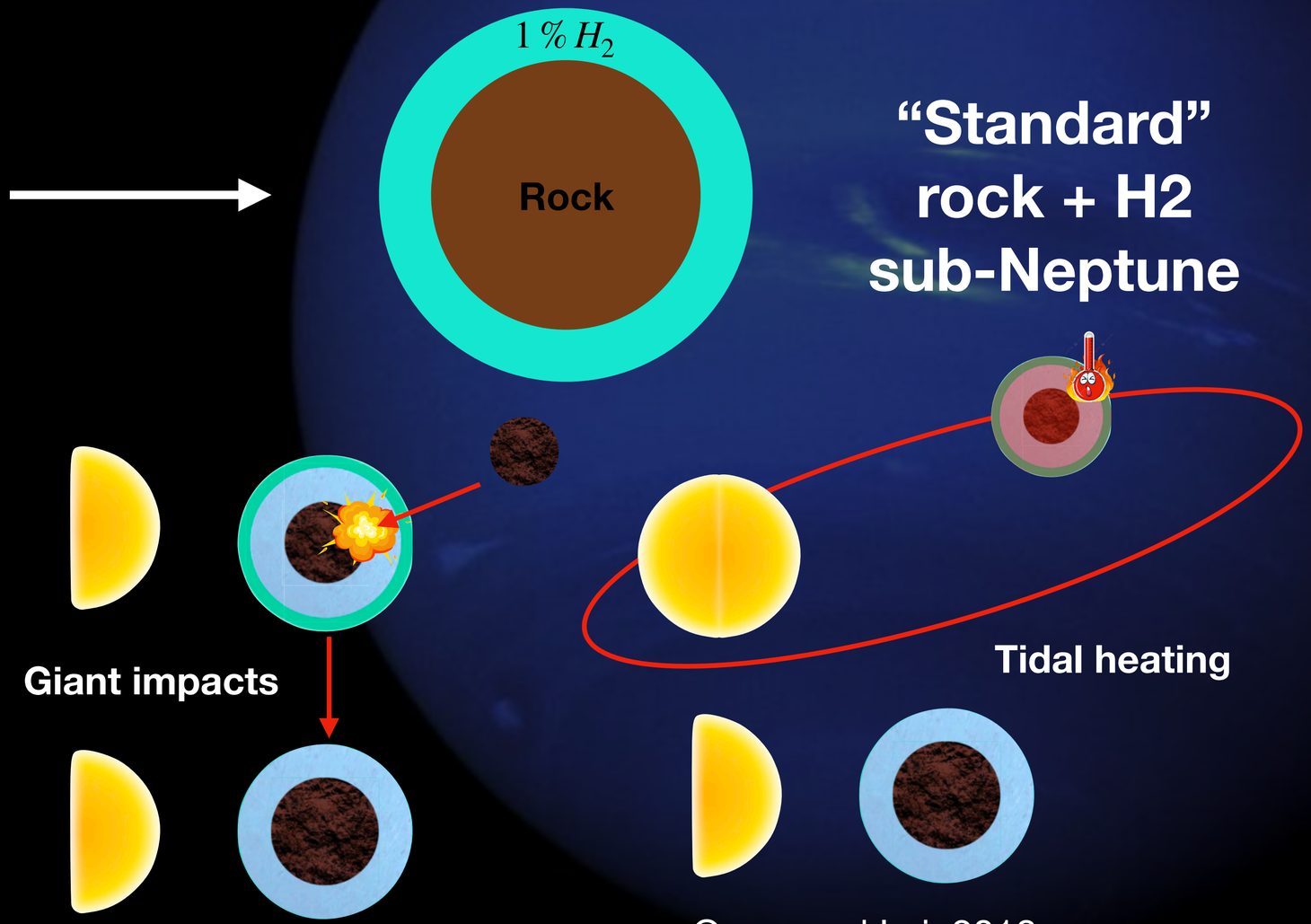

Biersteker and Schlichting, 2019

Owen and Lai, 2018

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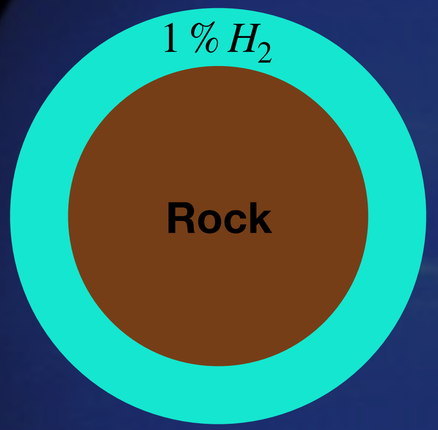

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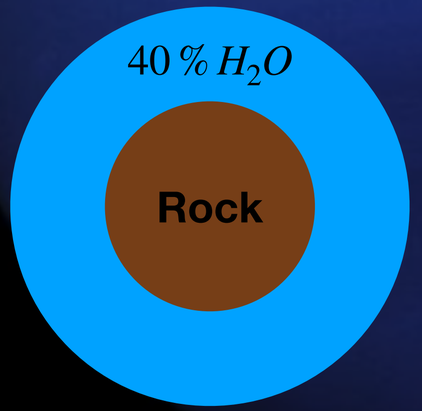
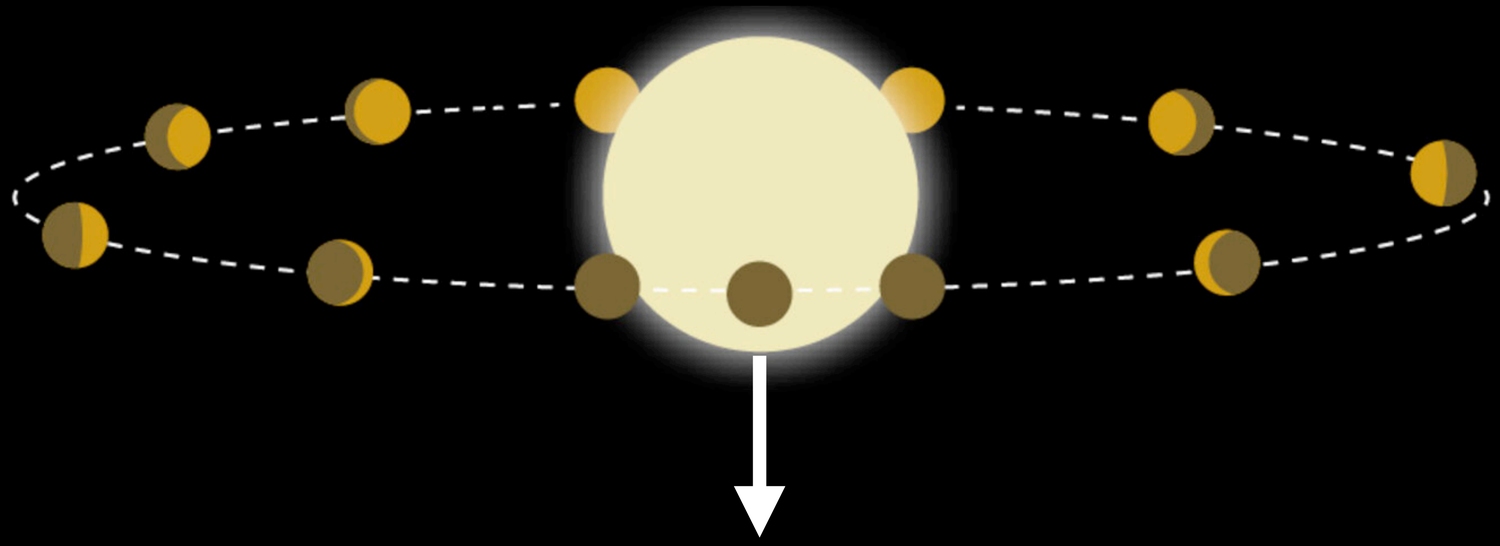


Exposed core/mantle with high-metallicity

Transmission spectroscopy as a way to understand sub-Neptune atmospheres and their composition



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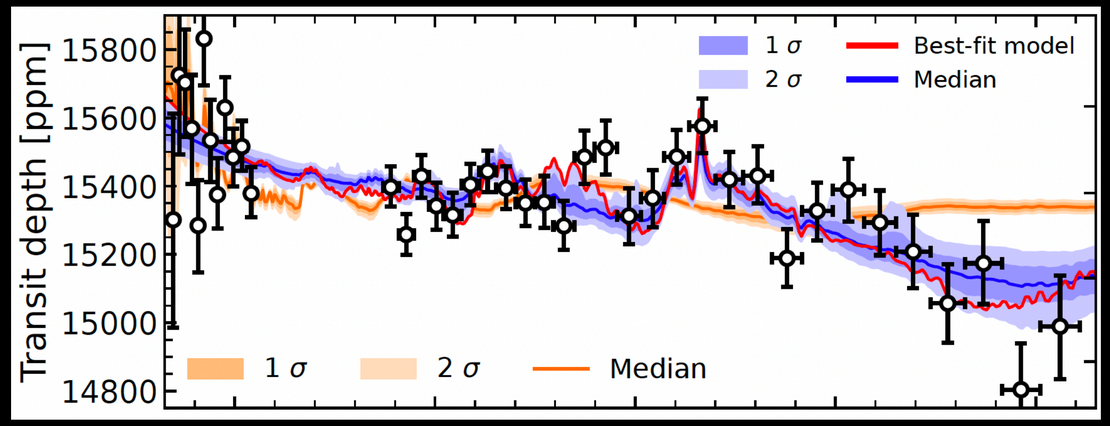
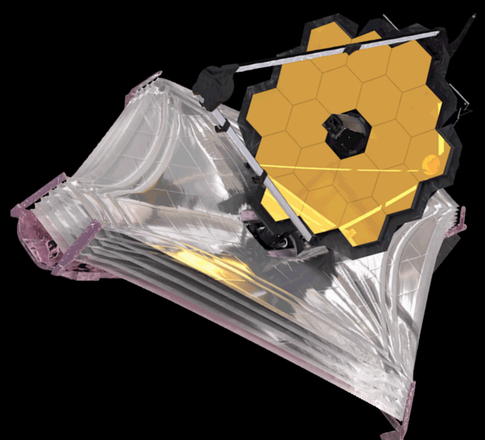
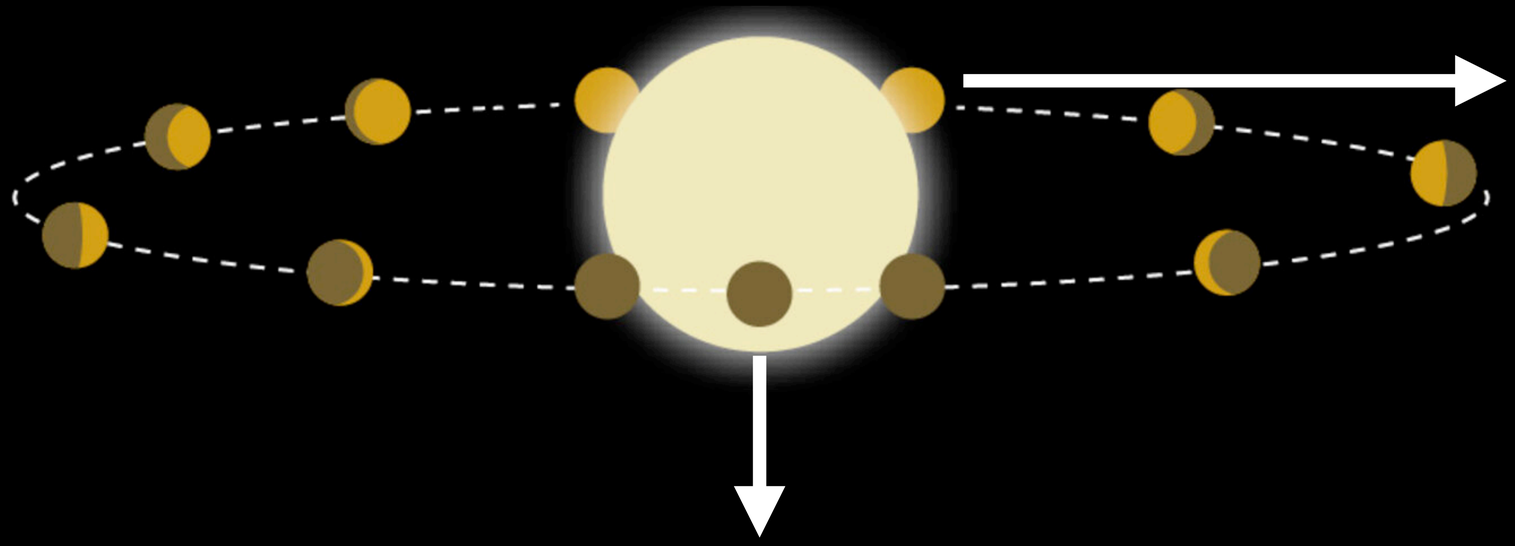
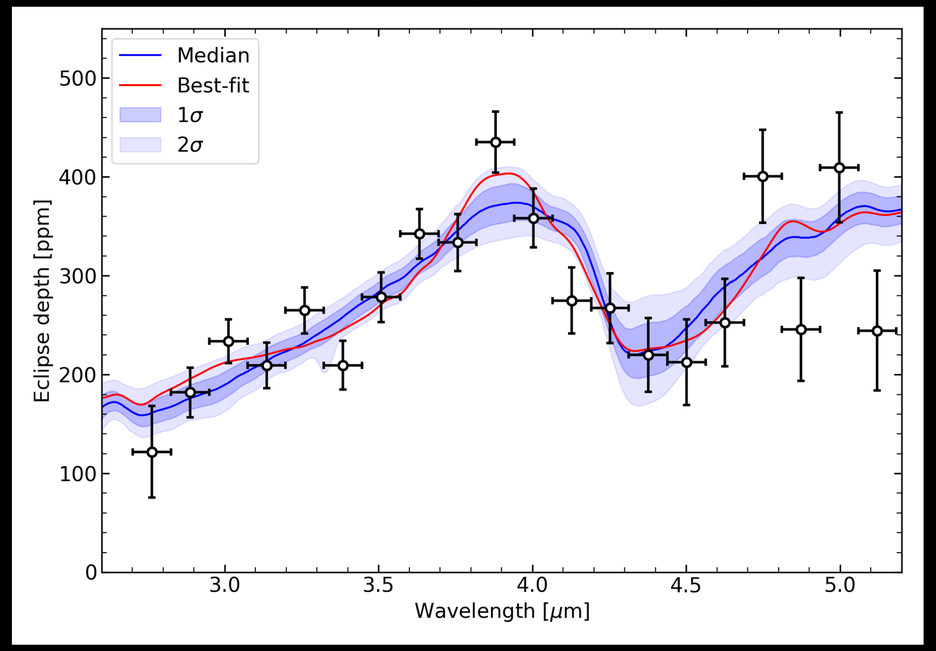




~~Transmission~~ Emission spectroscopy as a way to understand ~~hot~~ sub-Neptune atmospheres and their composition



Emission spectroscopy



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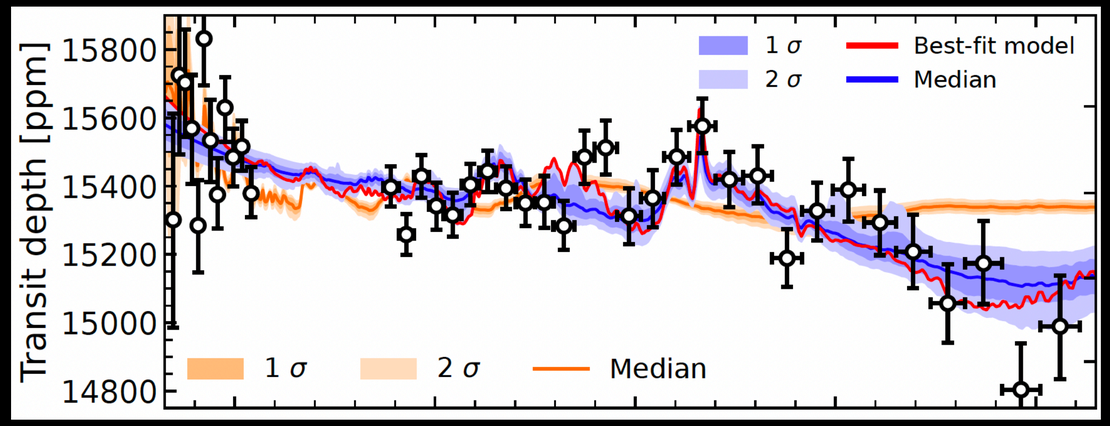
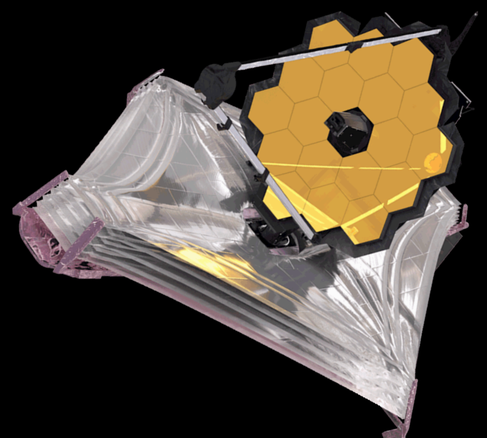
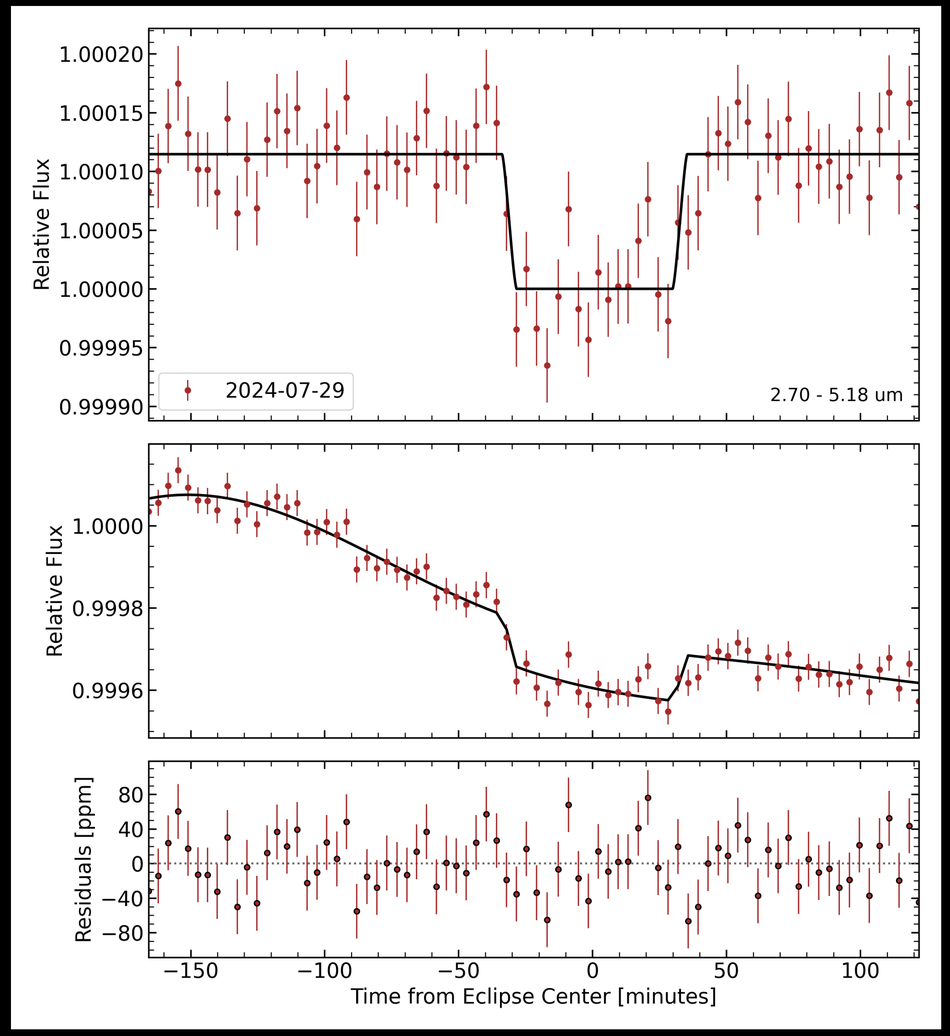
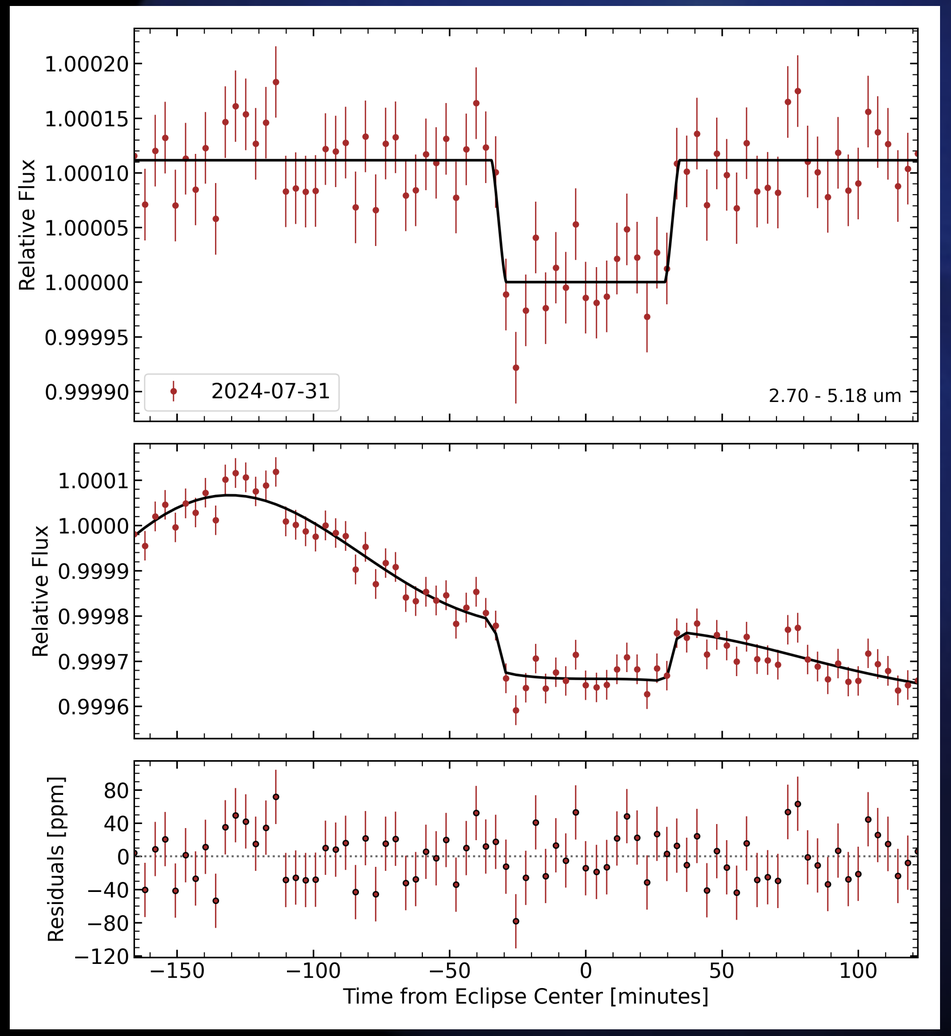




JWST eclipse spectroscopy of TOI-824b

GO 4102: 2 NIRSpec/G395M eclipse observations of TOI-824b (3 Rearth, 18 Mearth, 1250K)





Roy et al, in prep.

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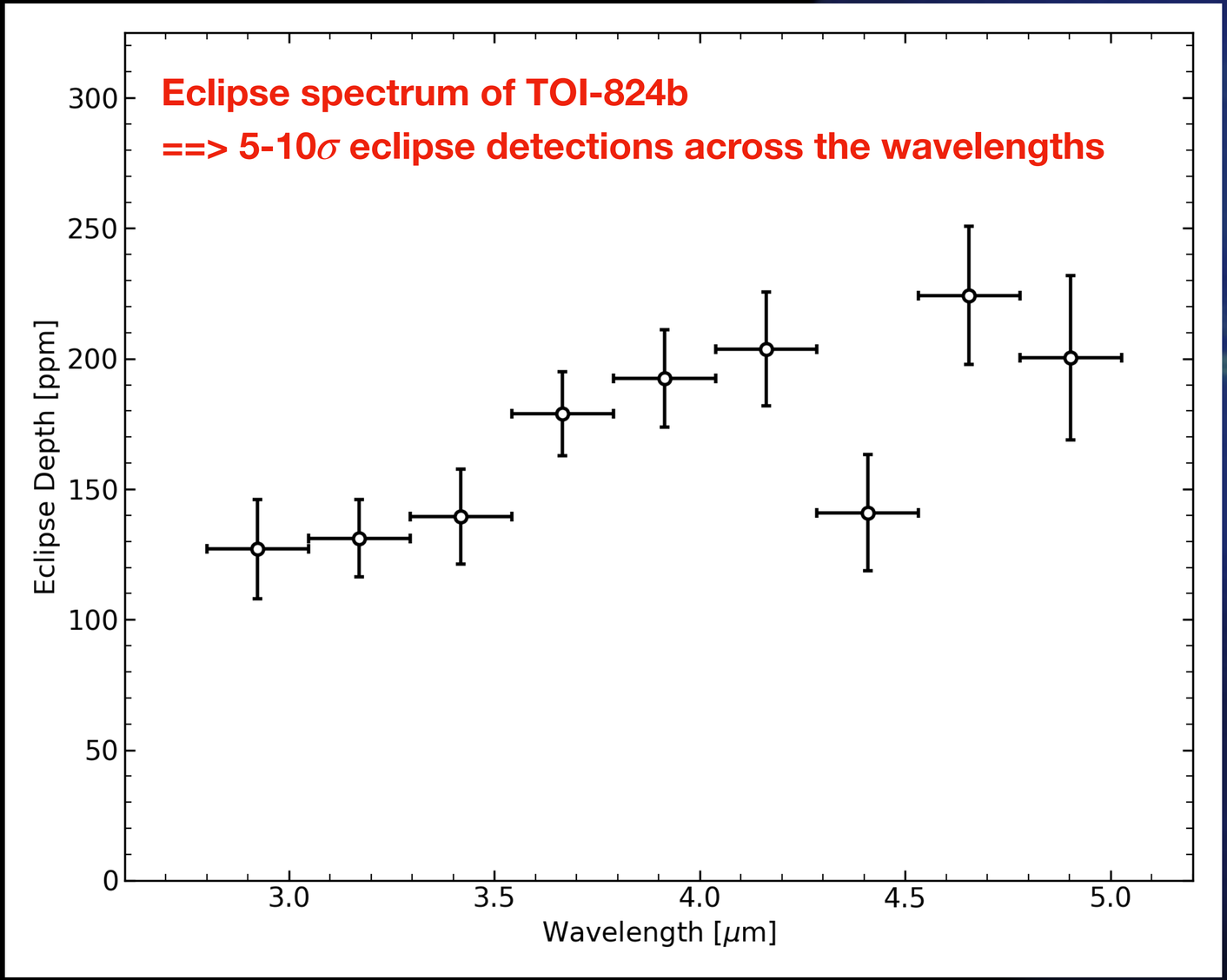
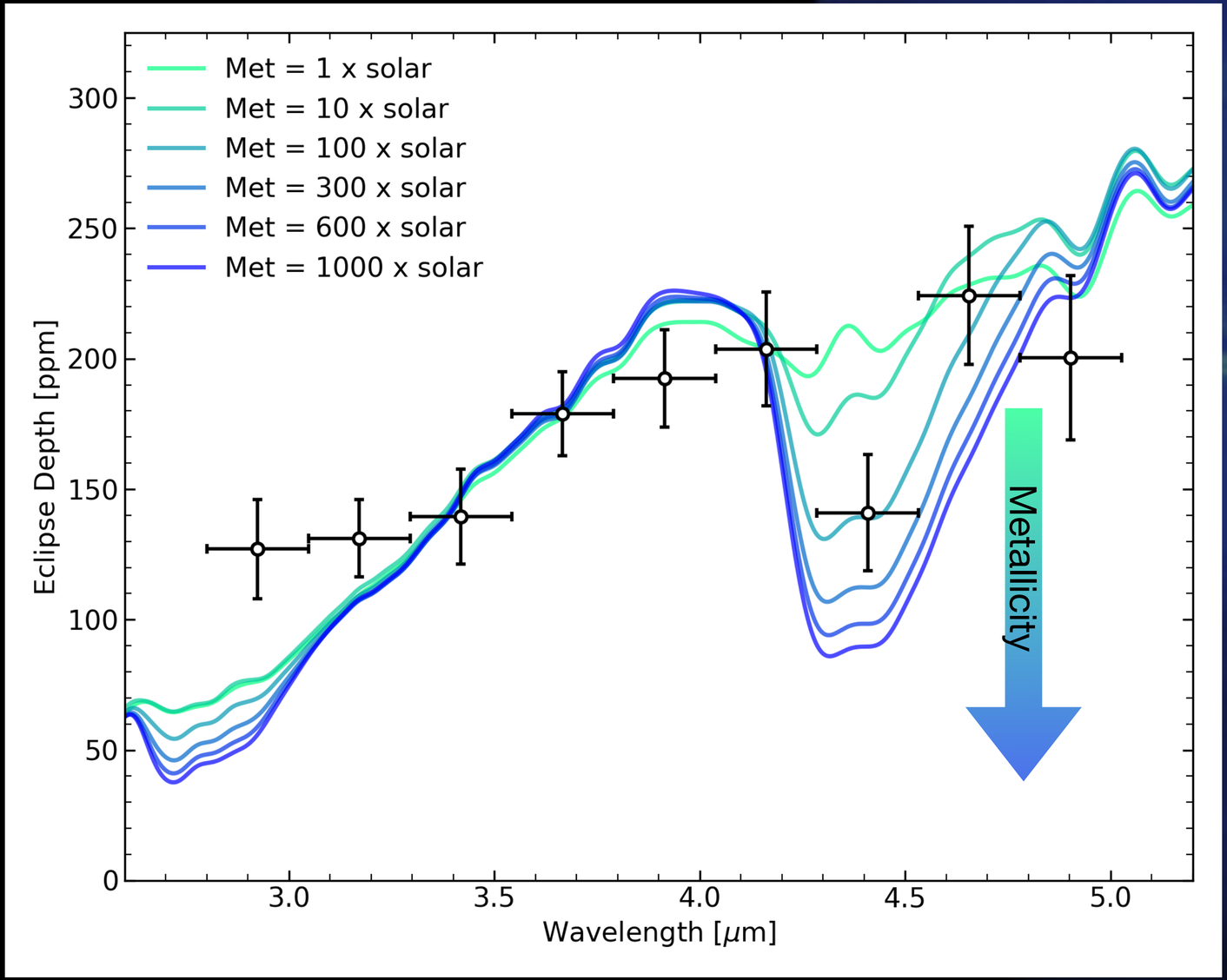


Roy et al, in prep.

CO_2 absorption in the eclipse spectrum points to high-metallicity envelope

Metallicity cannot be too low.

CO_2 depth seems consistent with the ~100 solar range



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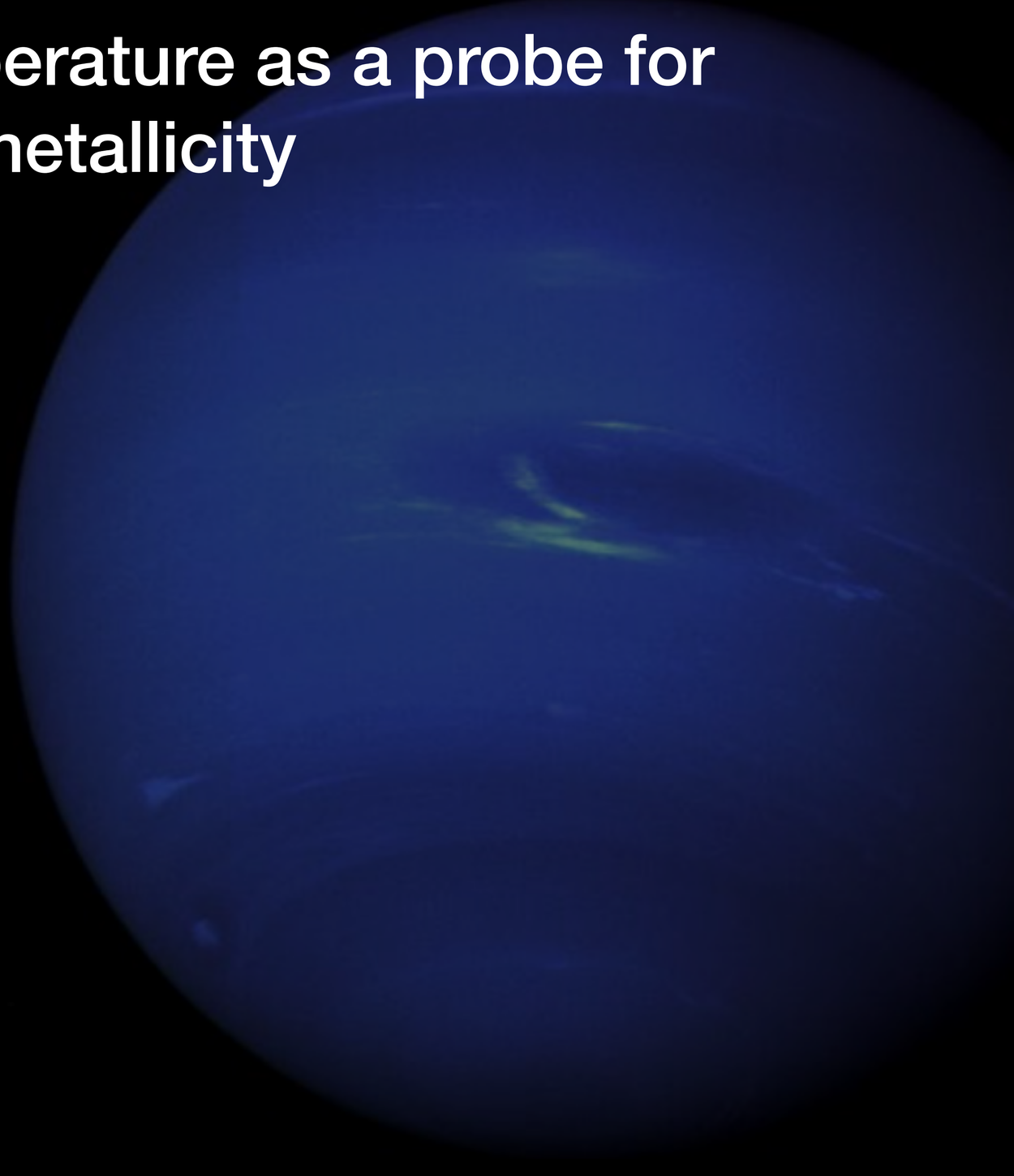
Using the dayside temperature as a probe for envelope metallicity



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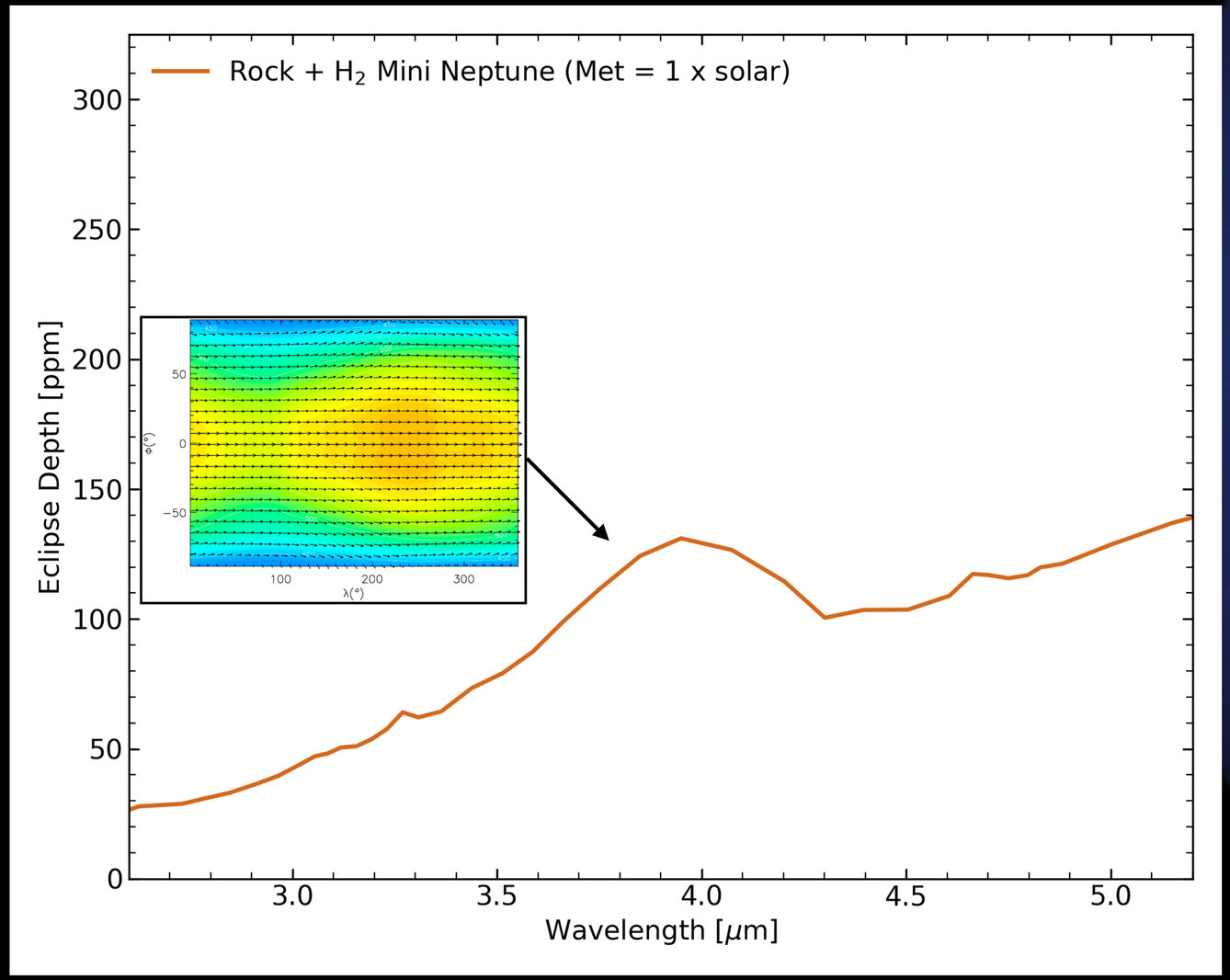

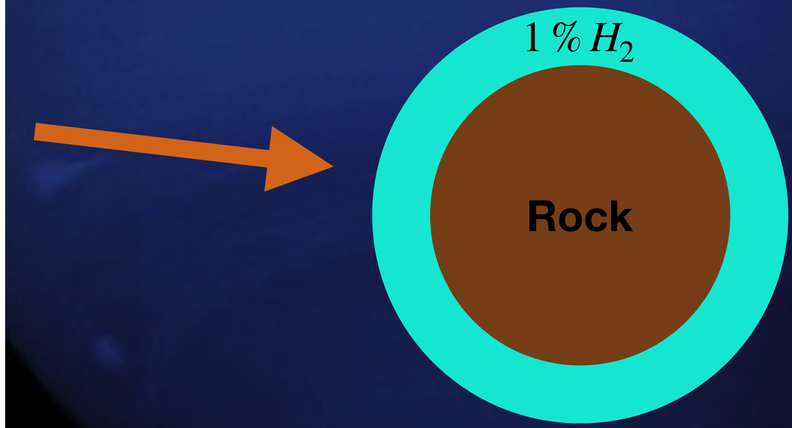

Roy et al, 2022, Drummond et al., 2018
GCM models by Vivien Parmentier

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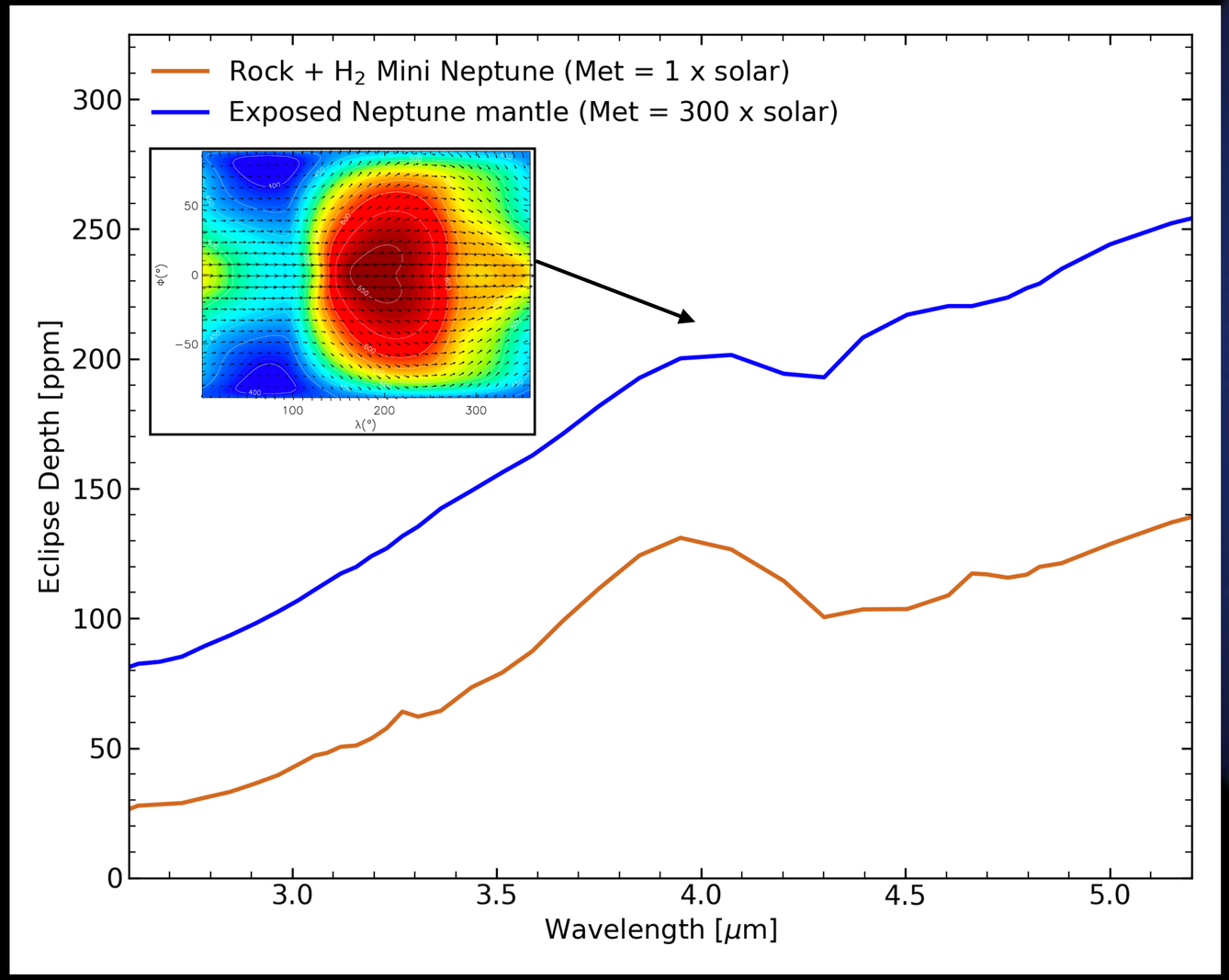

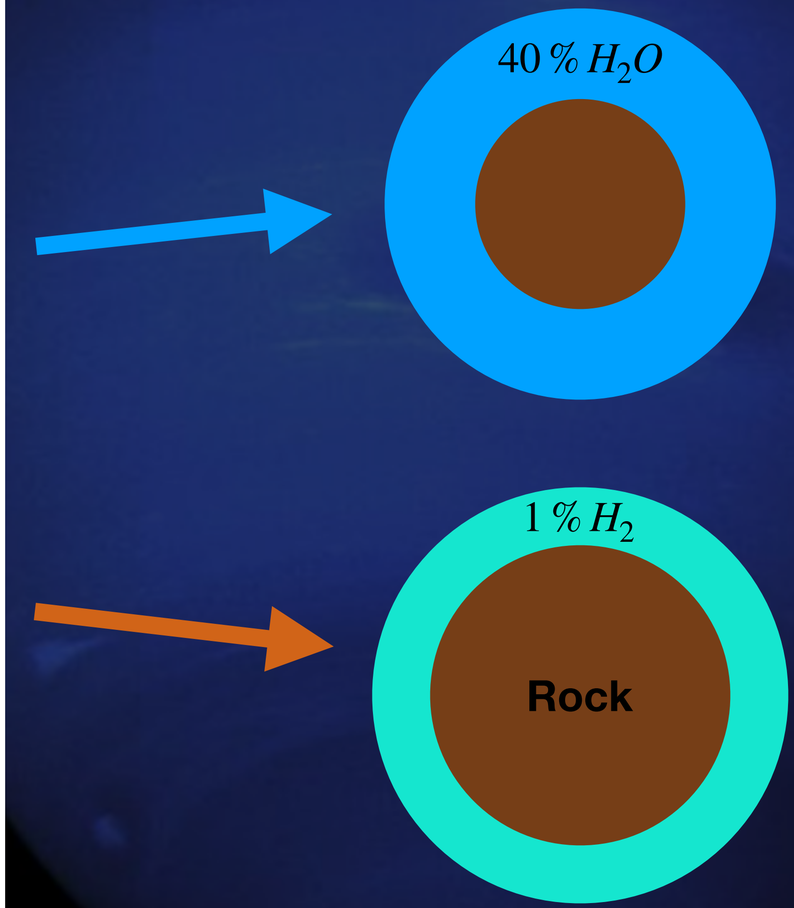

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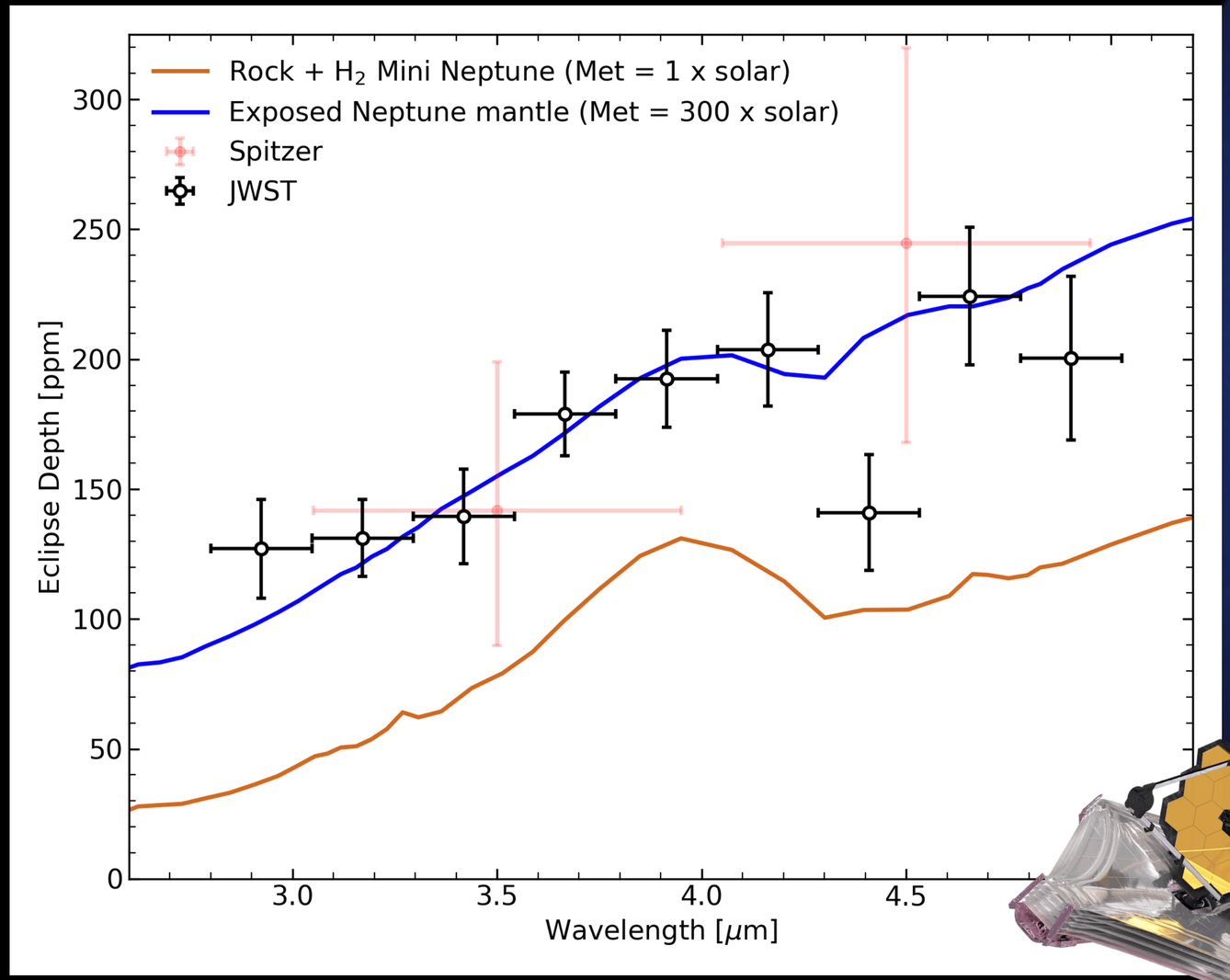
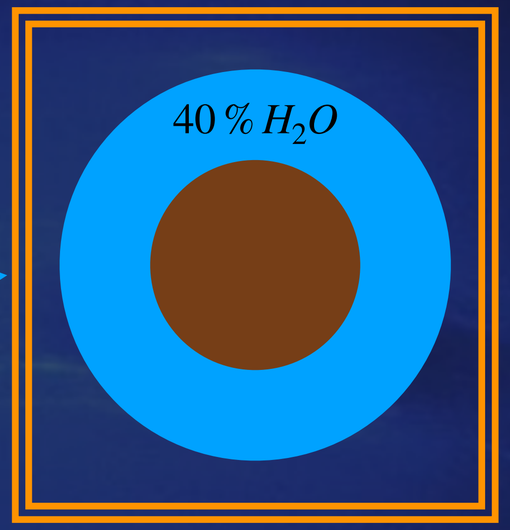
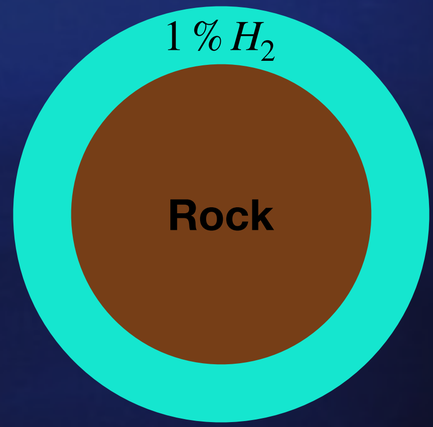
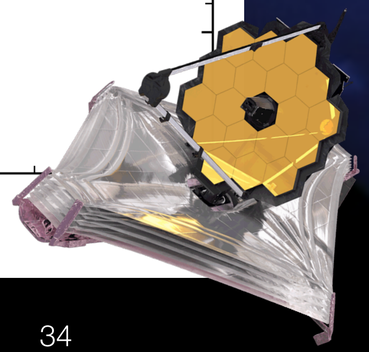
The hot dayside temperature of TOI-824b is a strong indicator of a high-metallicity envelope





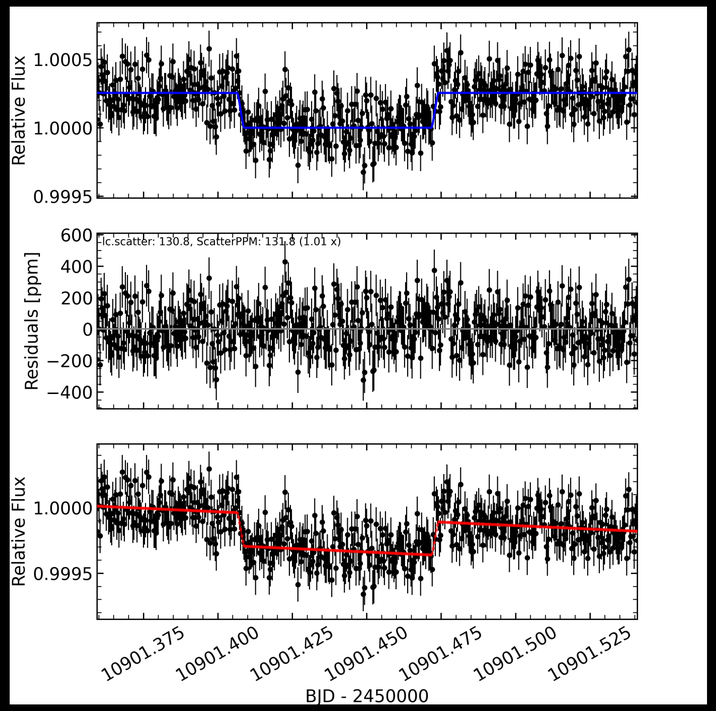


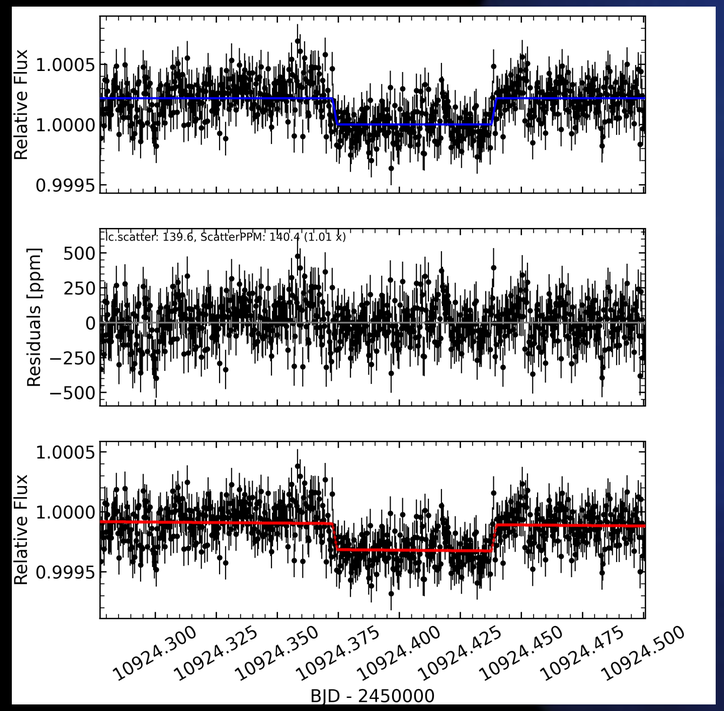


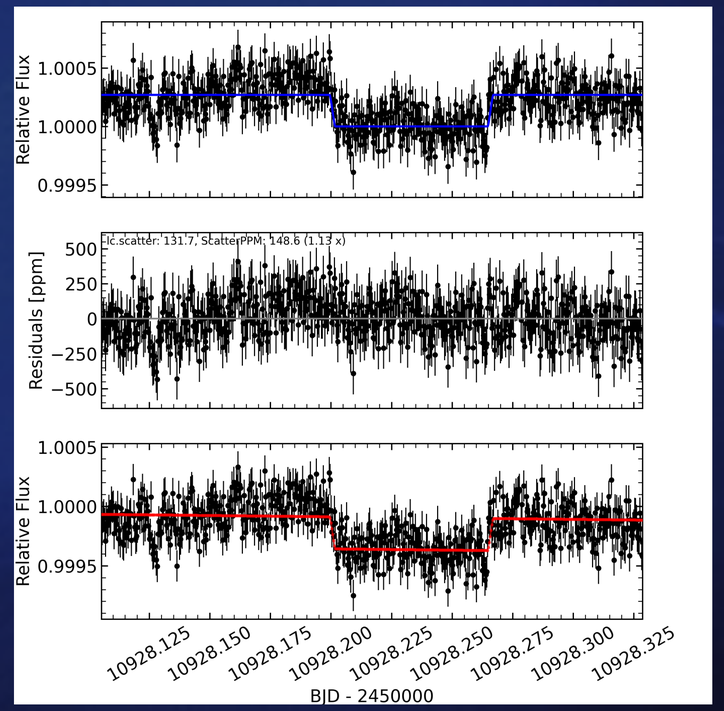
Roy et al, in prep, Drummond et al., 2018
GCM models by Vivien Parmentier

JWST eclipse spectroscopy of TOI-849b

GO 5967: 3 NIRSpec/G395M eclipse observations of TOI-849b (3 Rearth, 40 Mearth, 2000K)



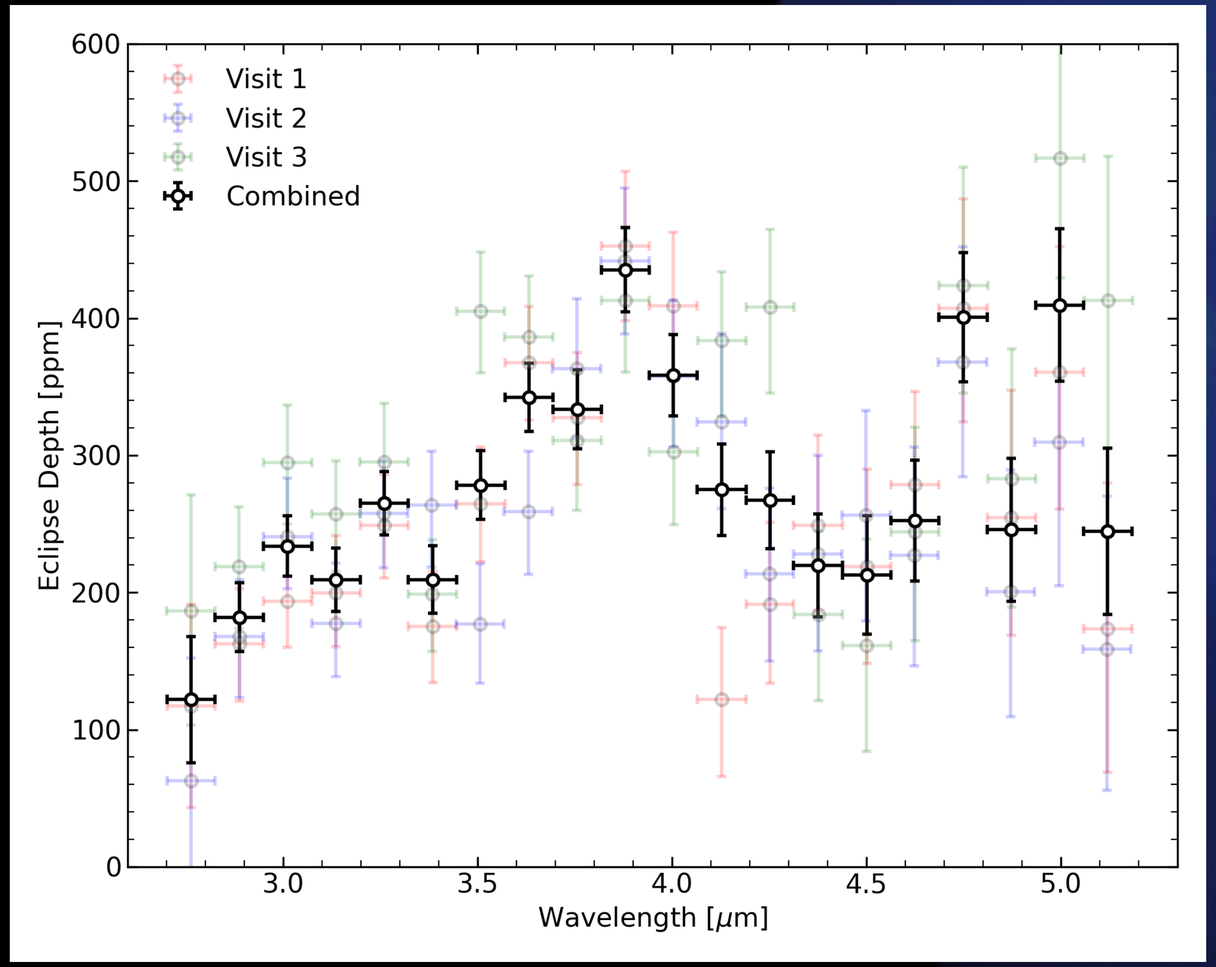




Roy et al, in prep.

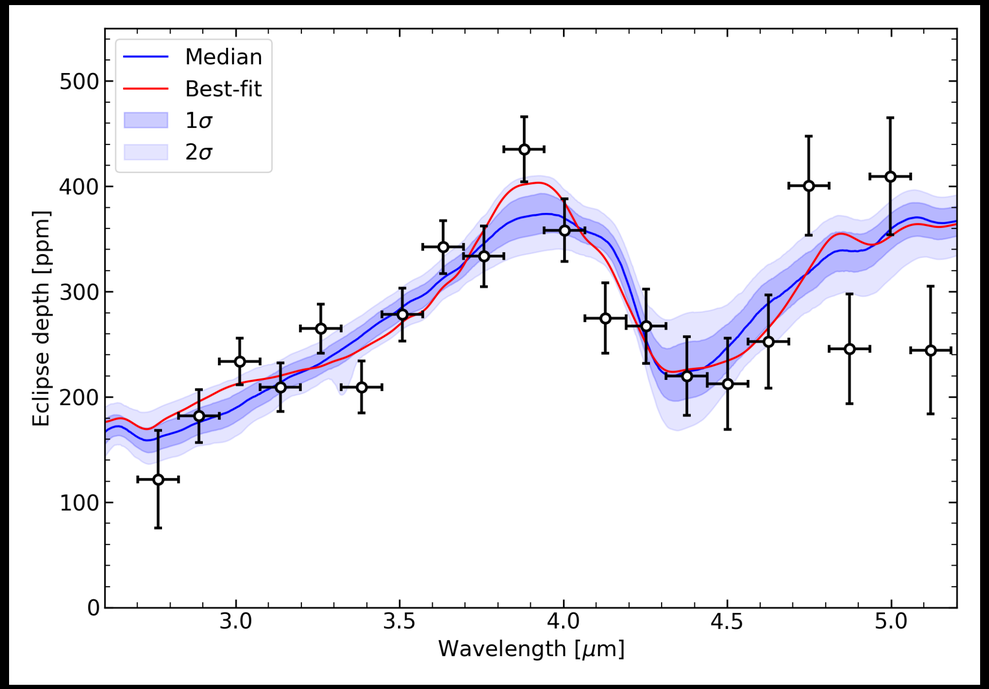
Secondary eclipse spectrum of TOI-849b

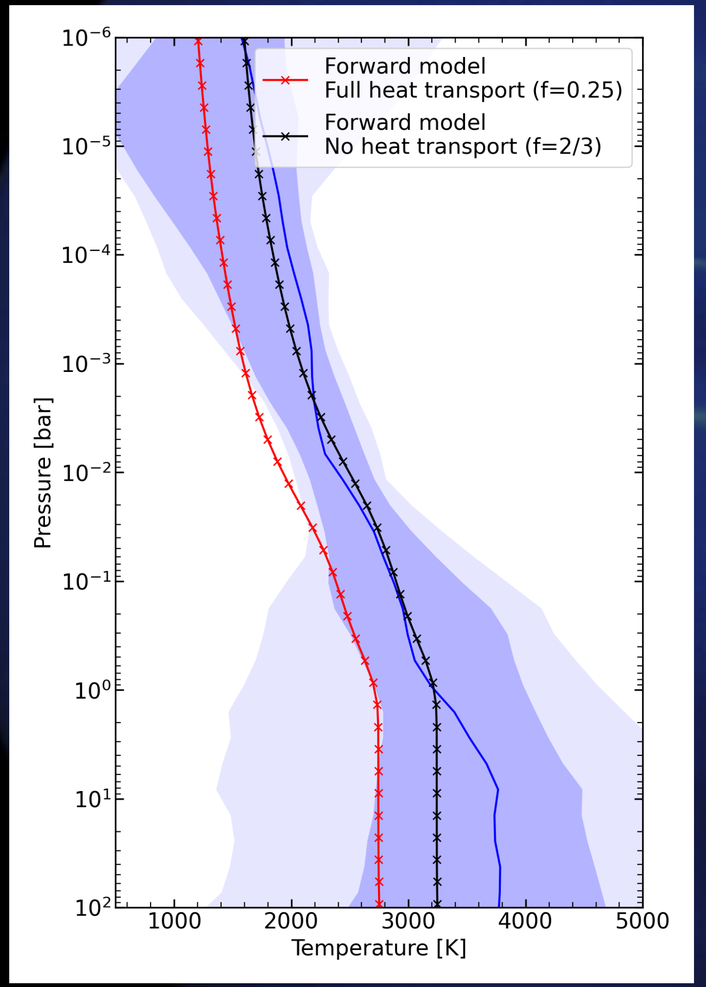
GO 5967: 3 NIRSpec/G395M eclipse observations of TOI-849b (3 Rearth, 40 Mearth, 2000K)



Roy et al, in prep.

TOI-849b shows a hot, CO2-rich dayside as well!

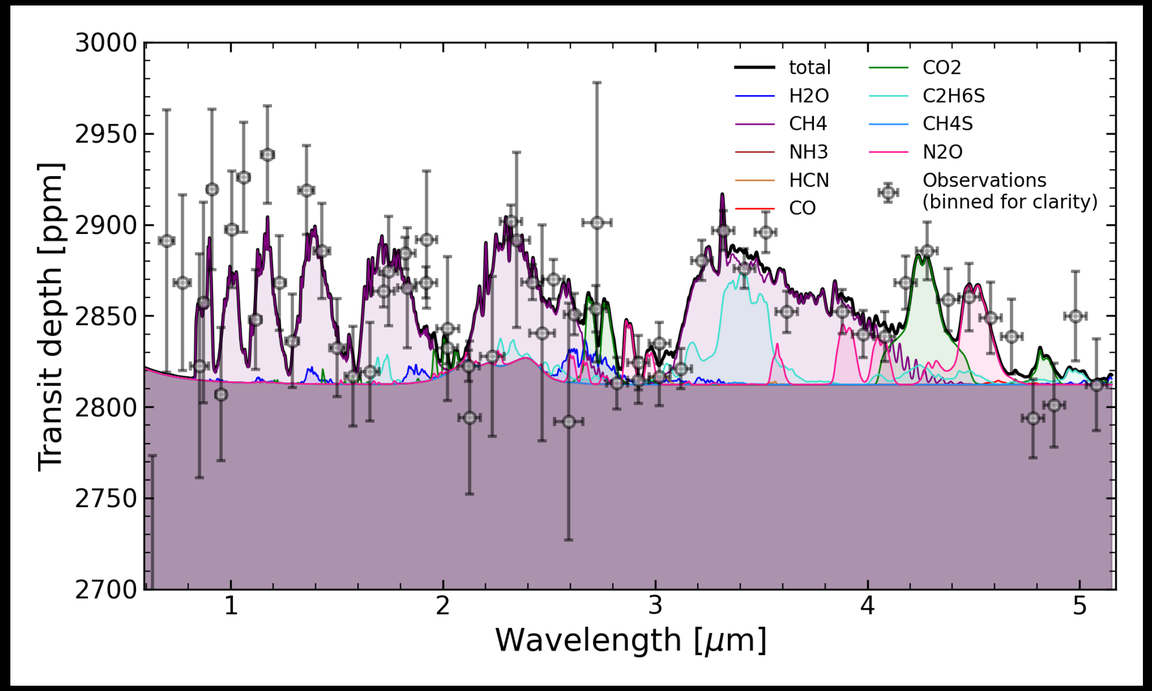




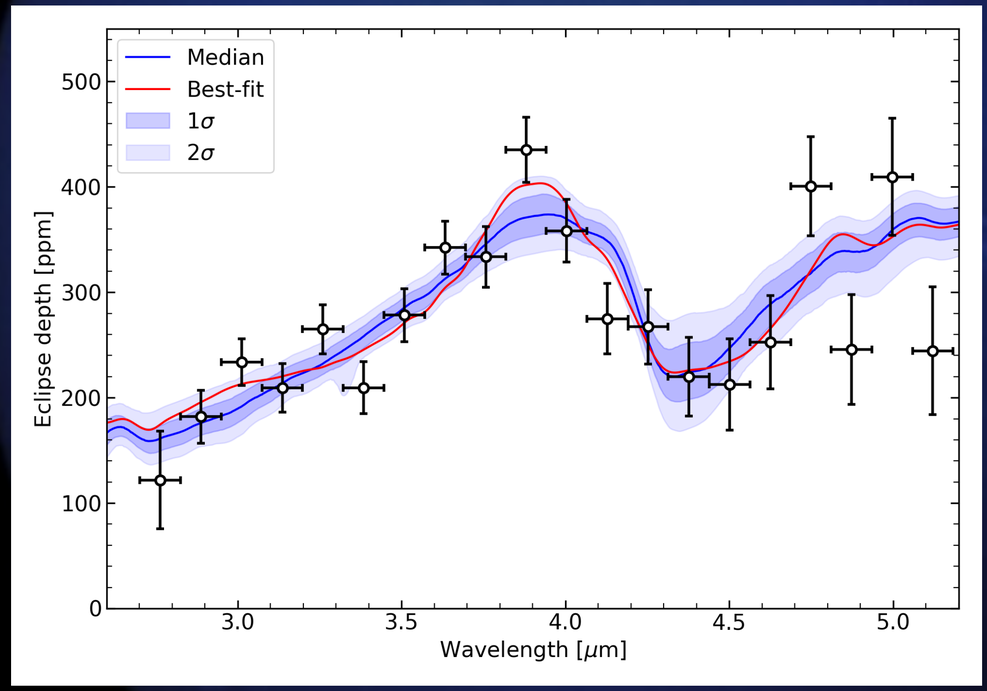
Roy et al, in prep.

JWST is creating an amazing era for sub-Neptune science

Producing high-precision transit spectroscopy

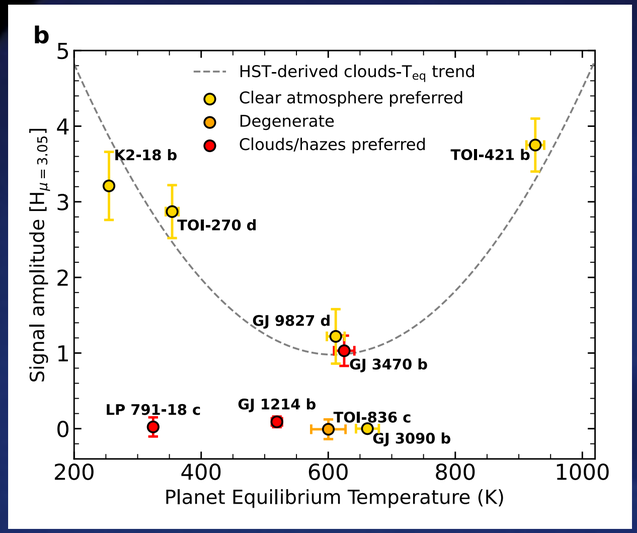


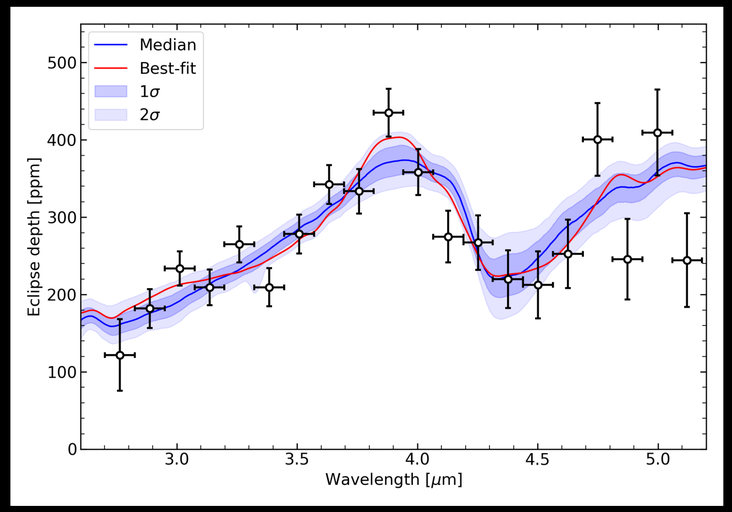
… and opening the door to emission work!



Take home messages

There is an emerging diversity in sub-Neptunes, from miscible envelopes to cold traps, to water worlds. And with diverse cloud and haze regimes.





JWST is allowing the thermal emission study of hot and super-dense sub-Neptunes, and we find evidence for high-metallicity envelopes, hinting at the "eroded gas giant" formation scenario