Detecting and Characterizing Terrestrial Atmospheres in the TRAPPIST-1 System with JWST

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Image credit: NASA

The TRAPPIST-1 System is Observationally Favorable and a High Priority Target for JWST

- Seven known Earth-sized planets (Gillon et al. 2016; 2017; Luger et al. 2017)
- Transiting a small (0.12 $R_{\odot}$) and cool (2500 K) late M dwarf (Van Grootel et al. 2018)
- Only 12.2 pc away
- Planets unlikely to have low mean molecular weight atmospheres (de Wit et al. 2016; 2018; Moran et al. 2018)

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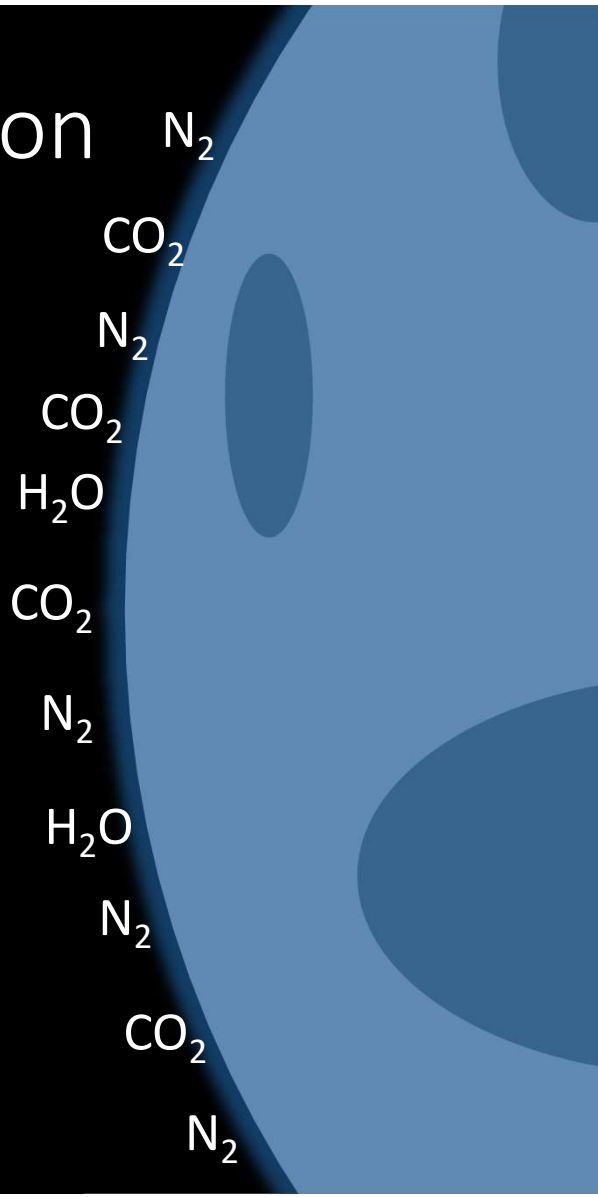

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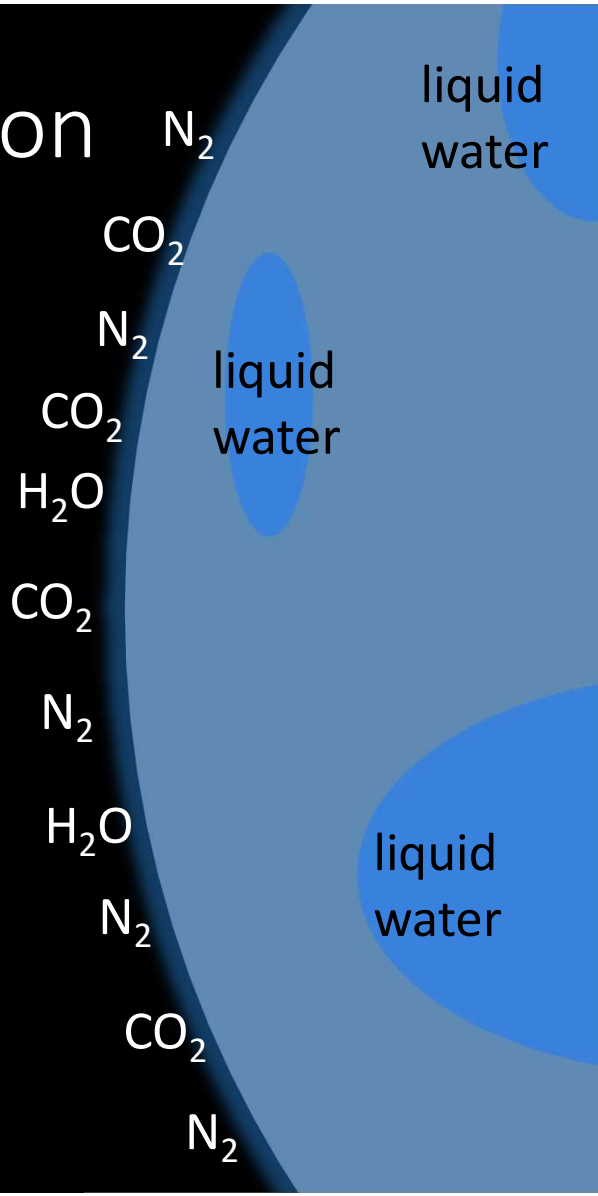

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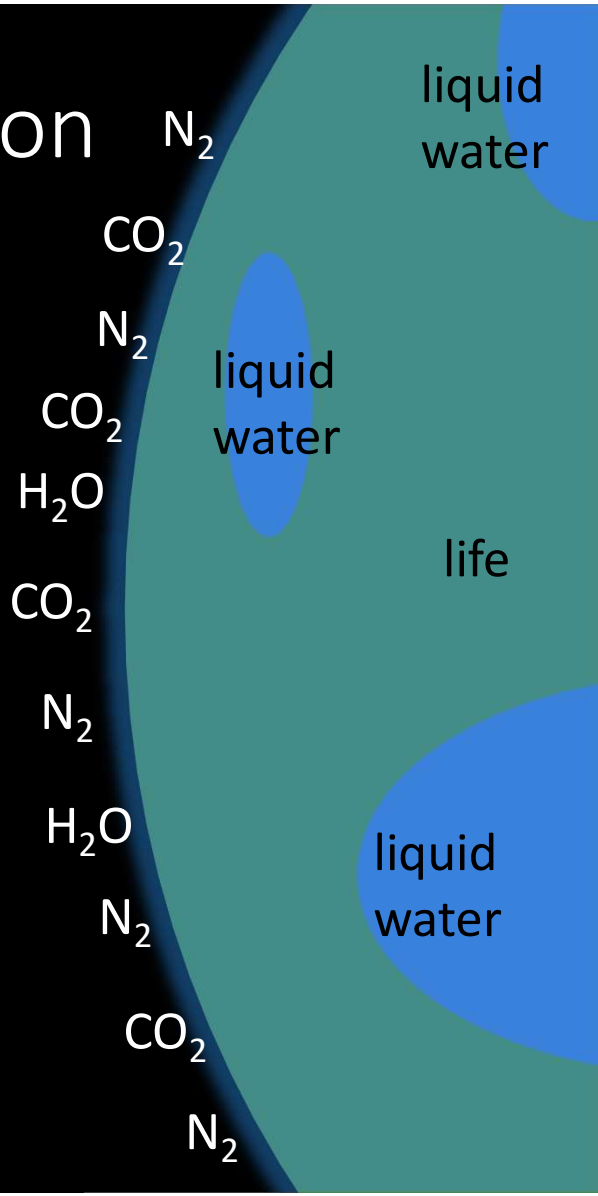

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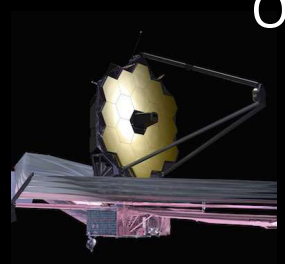
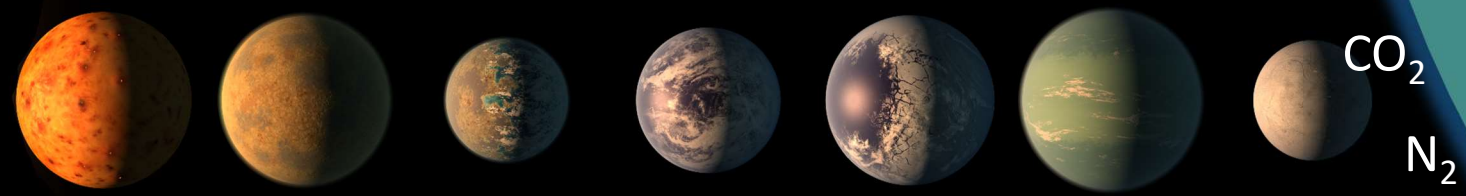
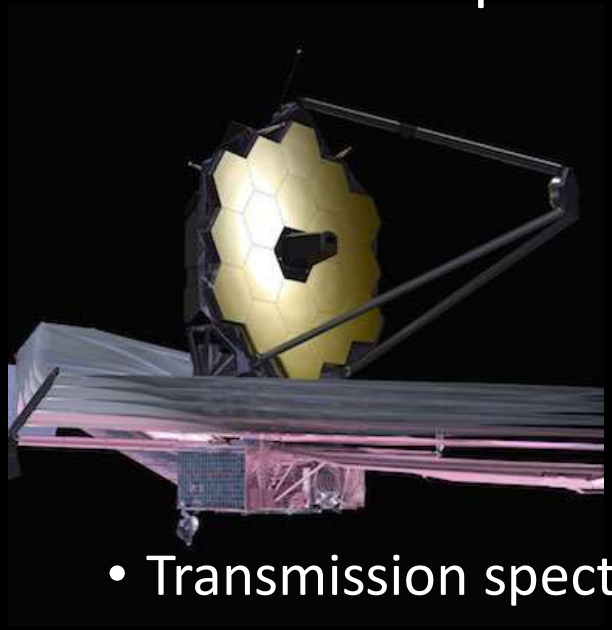
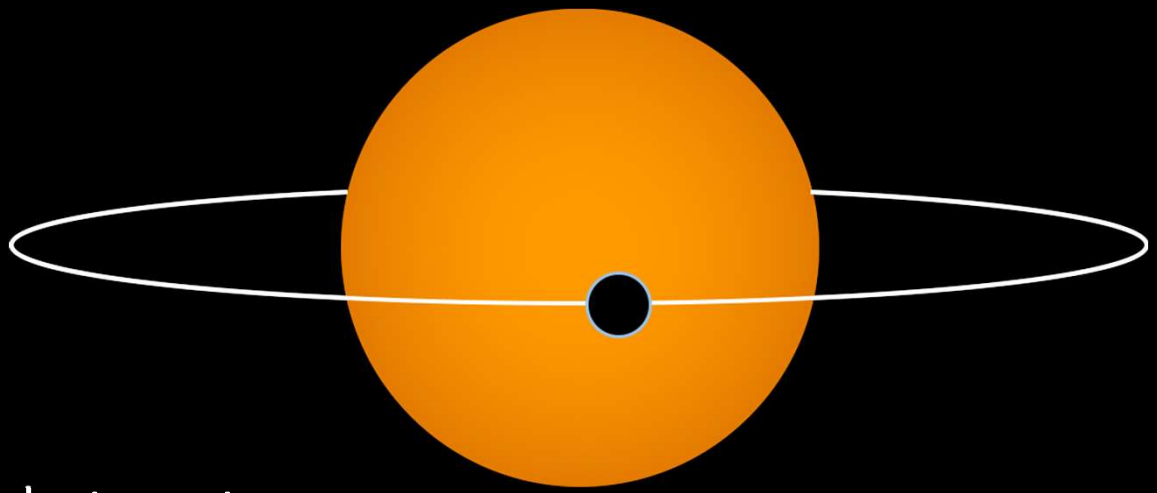




Observational tools for detecting and characterizing exoplanet atmospheres with JWST





- Transmission spectroscopy/photometry
- Eclipse spectroscopy/photometry
- {Thermal Phase curves, eclipse mapping, MIRI direct imaging, planet-planet occultations}

Posit a variety of evolved environments for spectroscopic modeling

TRAPPIST-1
climate-photochemical-spectral modeling by
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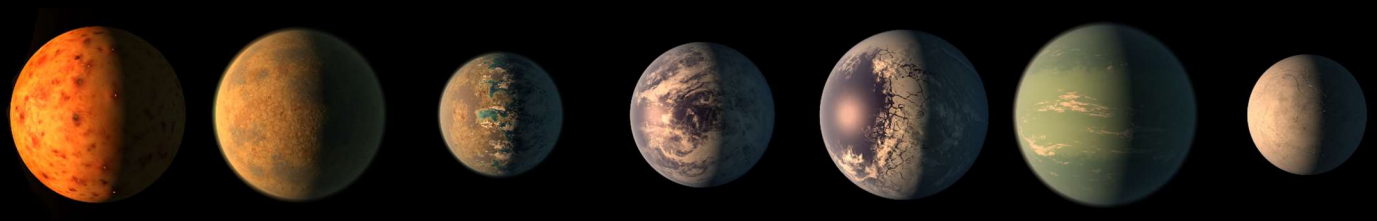

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0.05 bar CO_2

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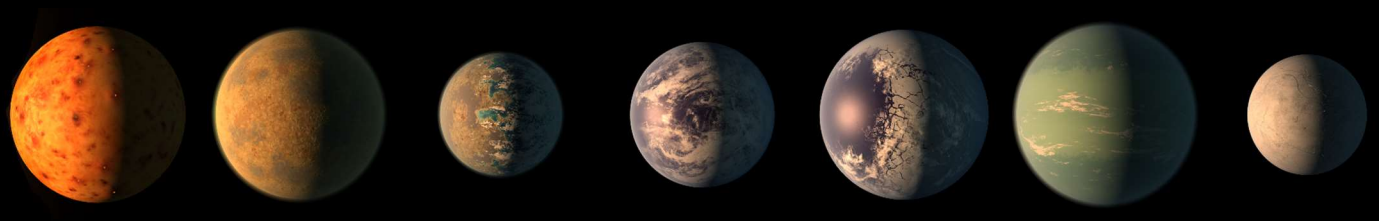

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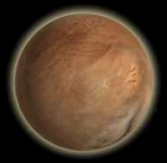

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<u>Earth geological fluxes</u>:
H_2O, CO_2, SO_2, OCS, H_2S

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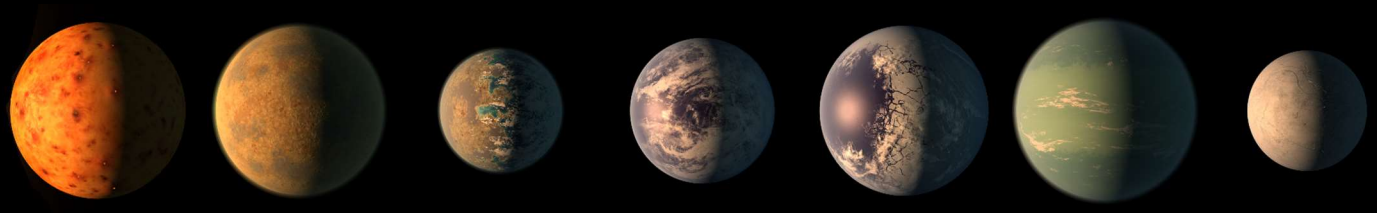

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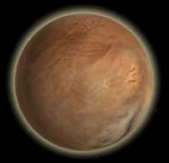

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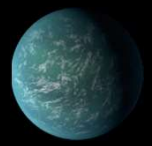

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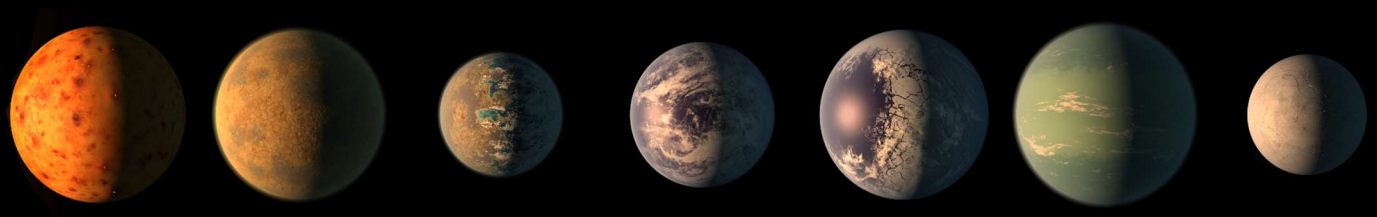

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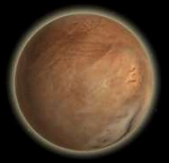

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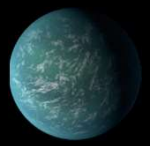

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28 ppm SO_2
30 ppm H_2O
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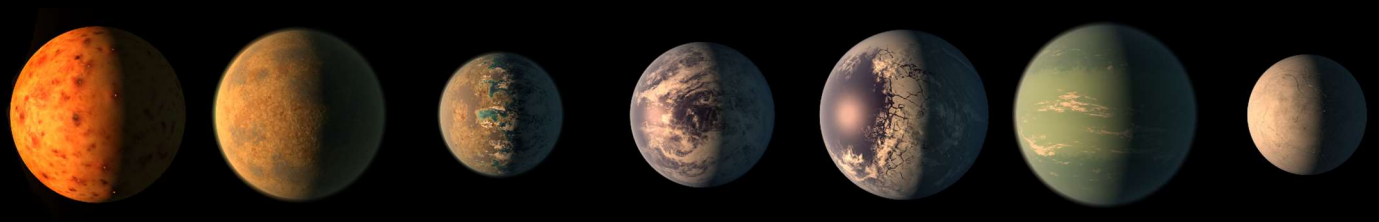

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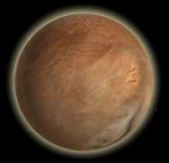

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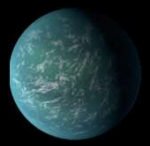

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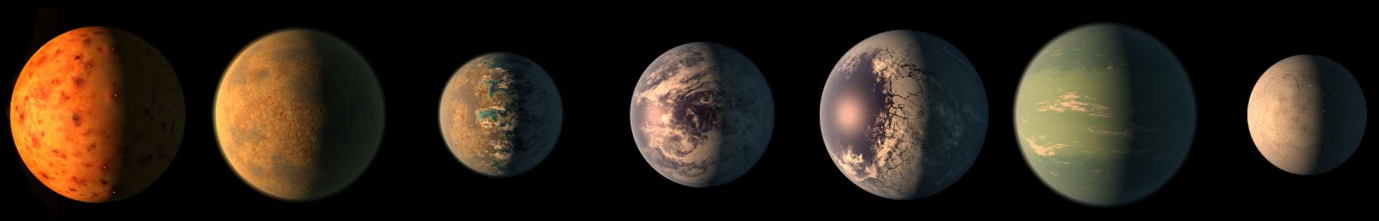
Recent ocean-loss

More outgassing over time



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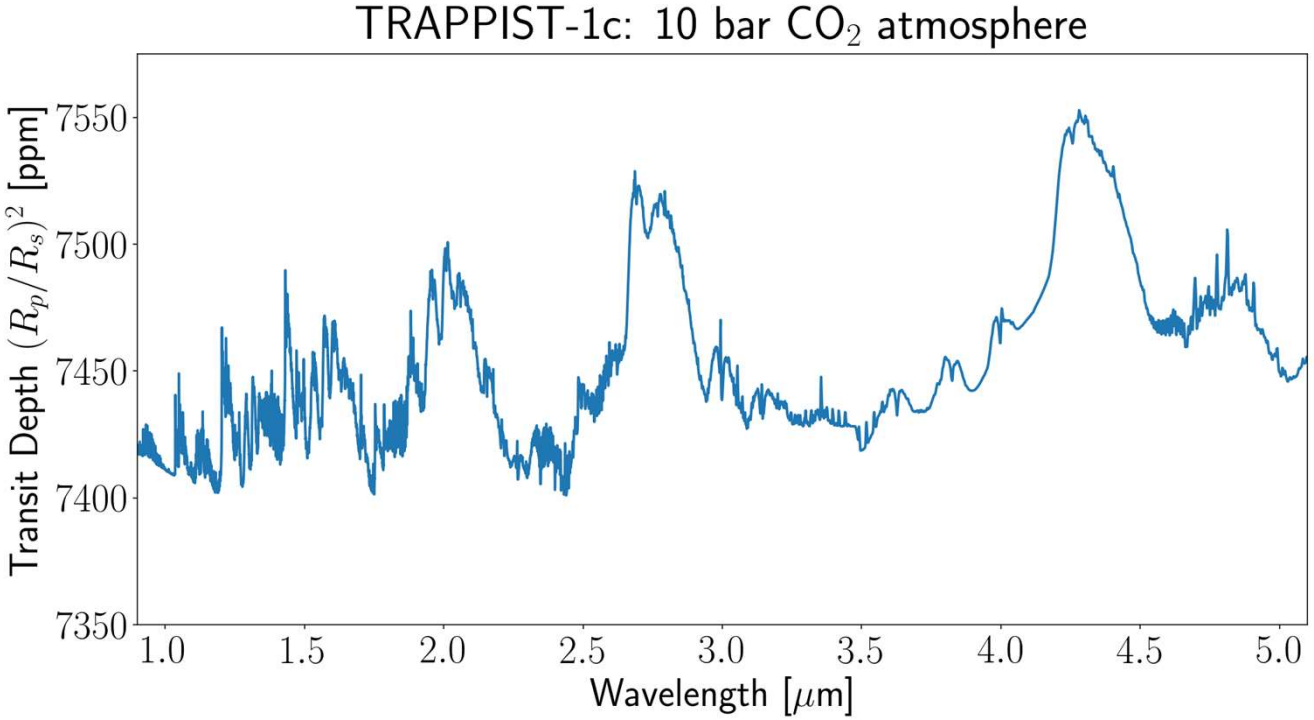
Can JWST tell if the TRAPPIST-1 planets have *atmospheres*?

Use absorption features to detect the atmosphere



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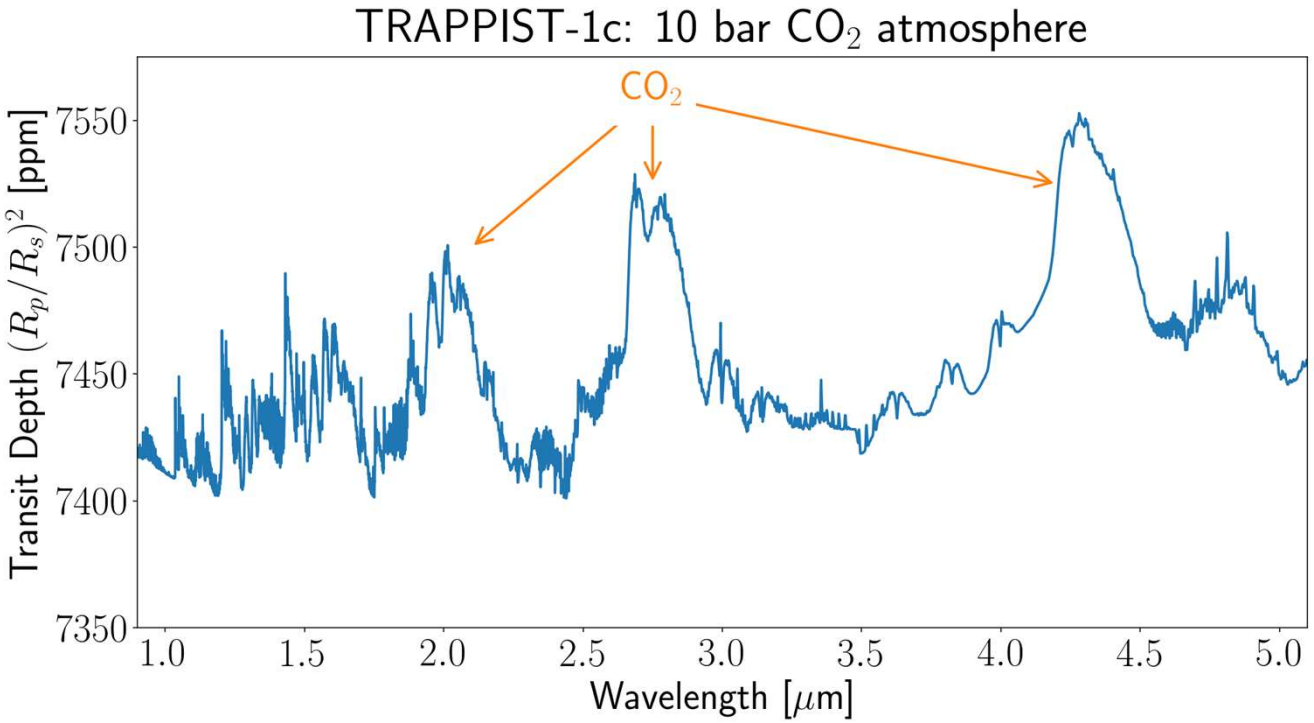

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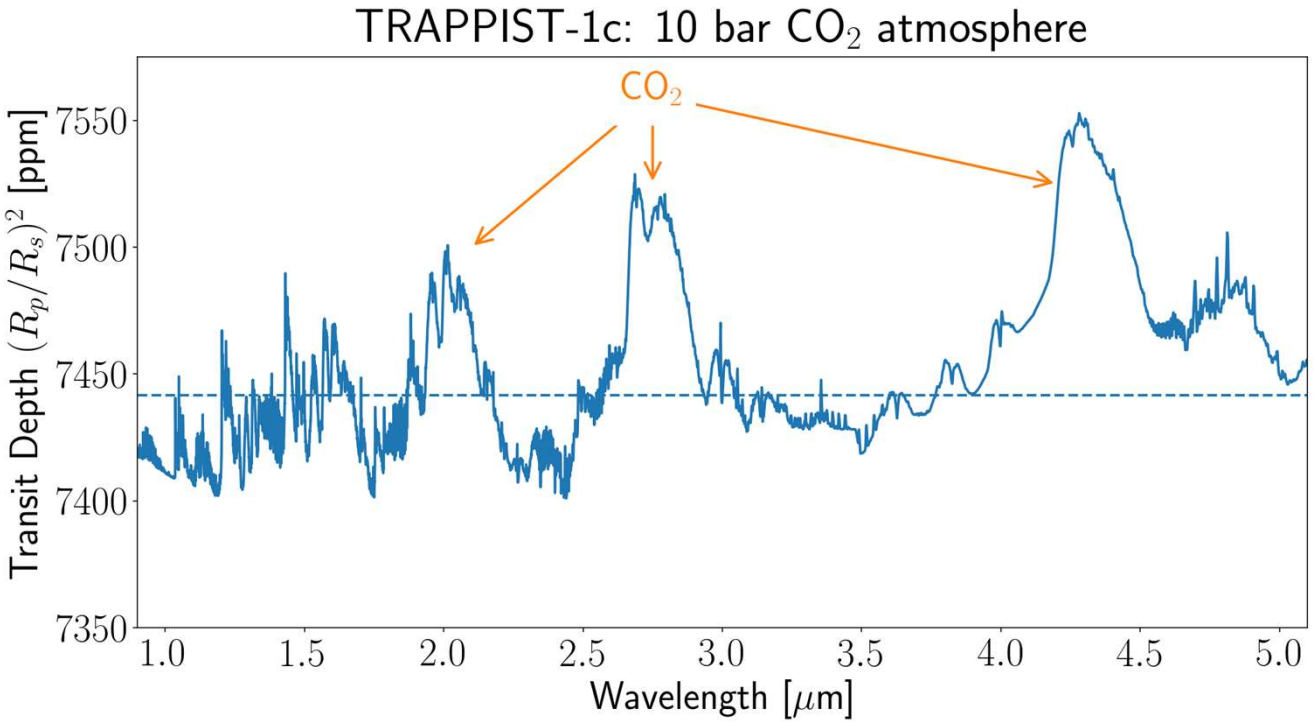

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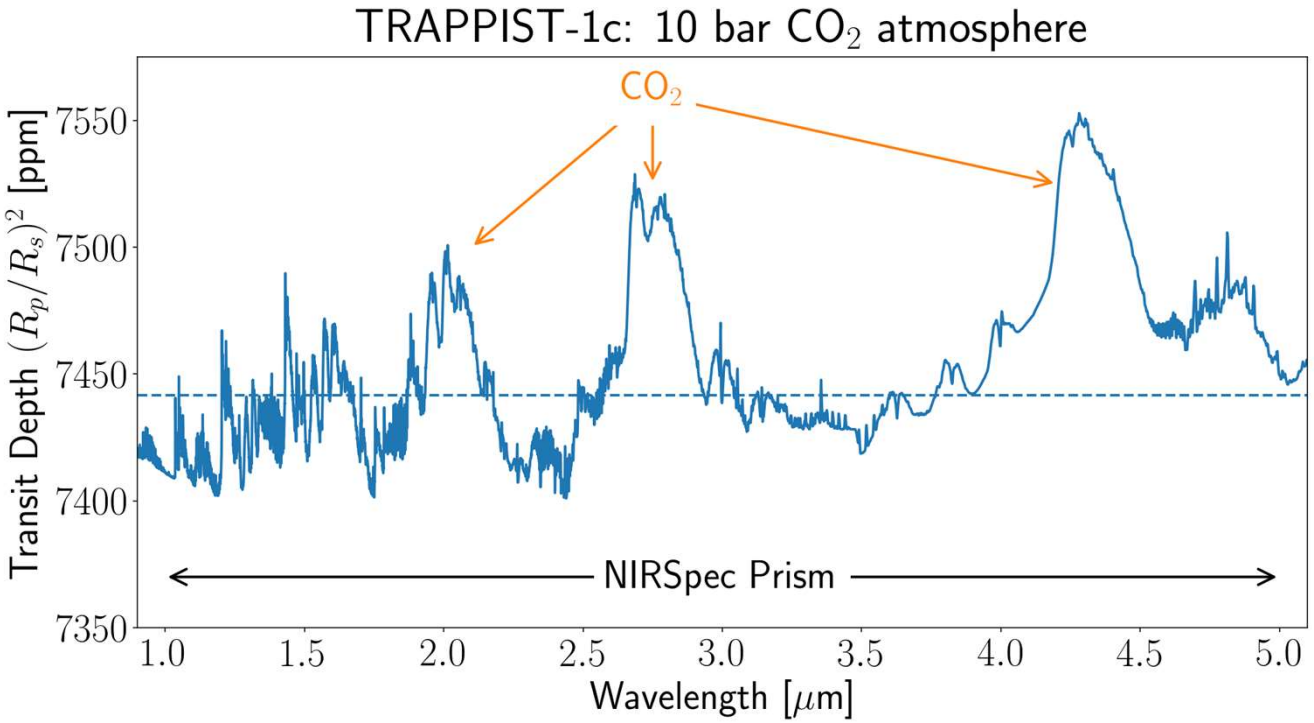

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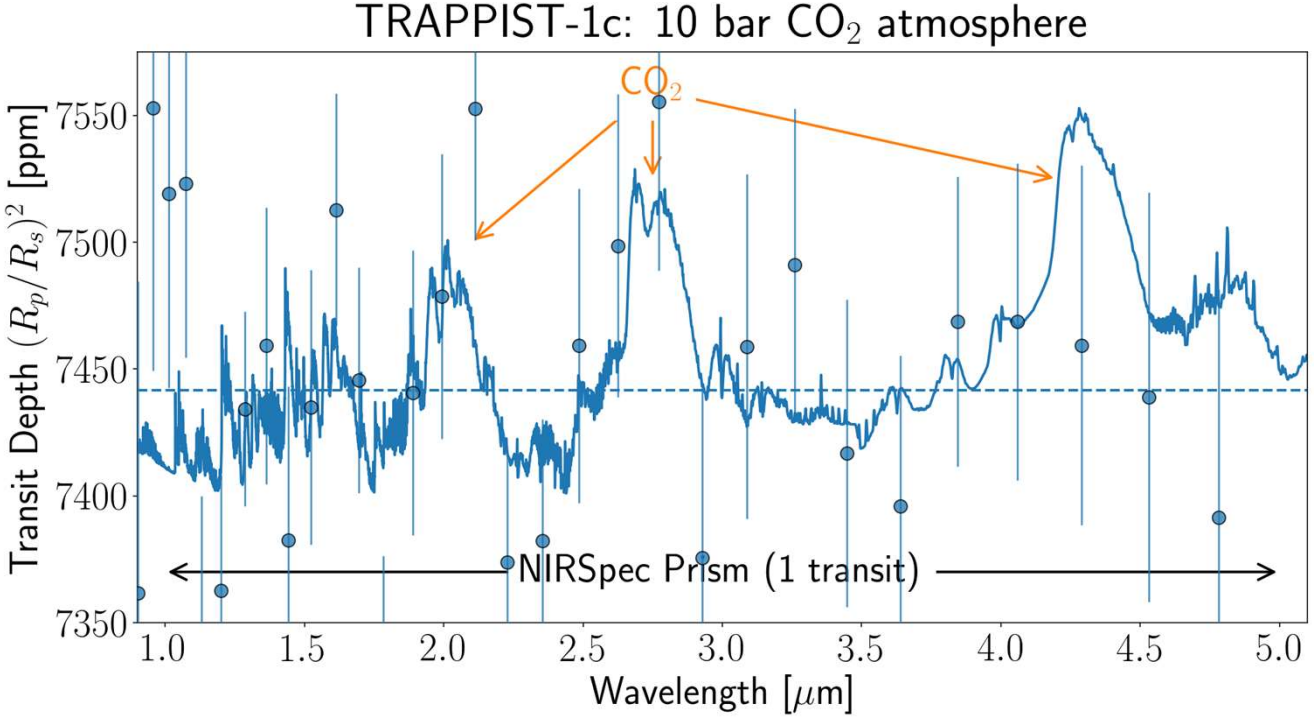
Use absorption features to detect the atmosphere

JWST noise modeling using `PandExo` (Batalha et al. 2017)



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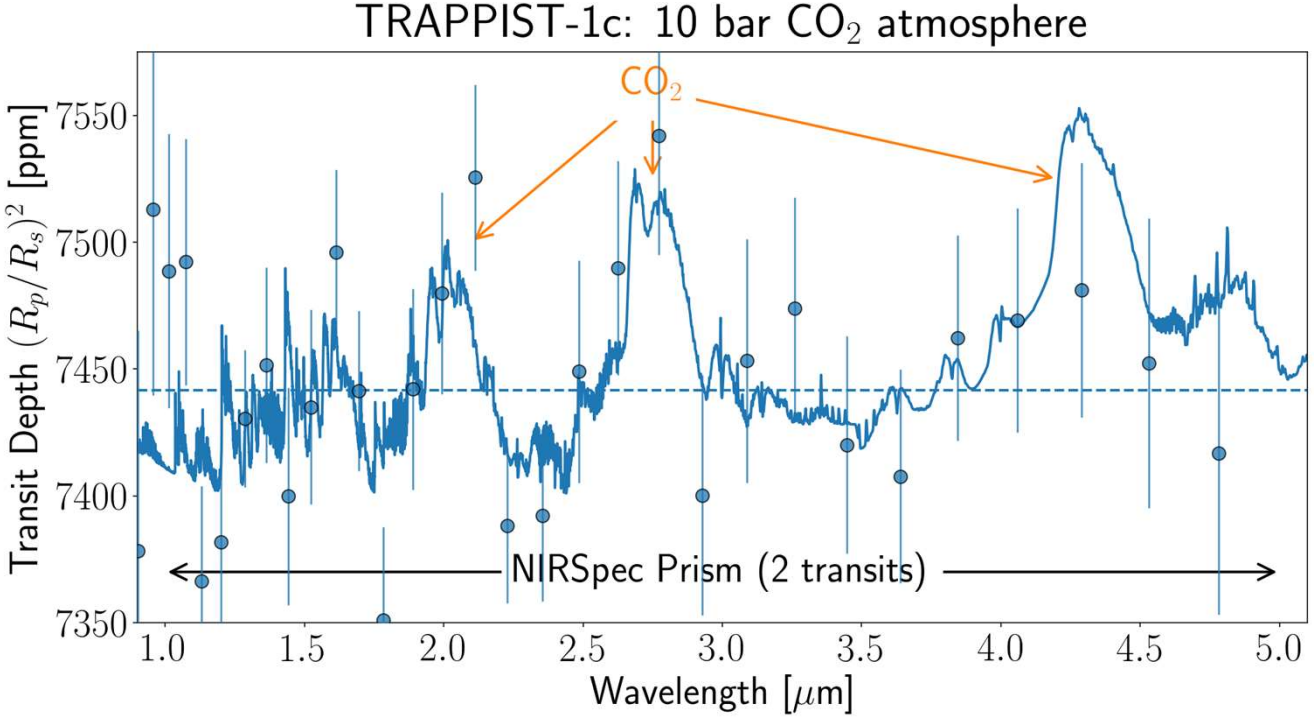

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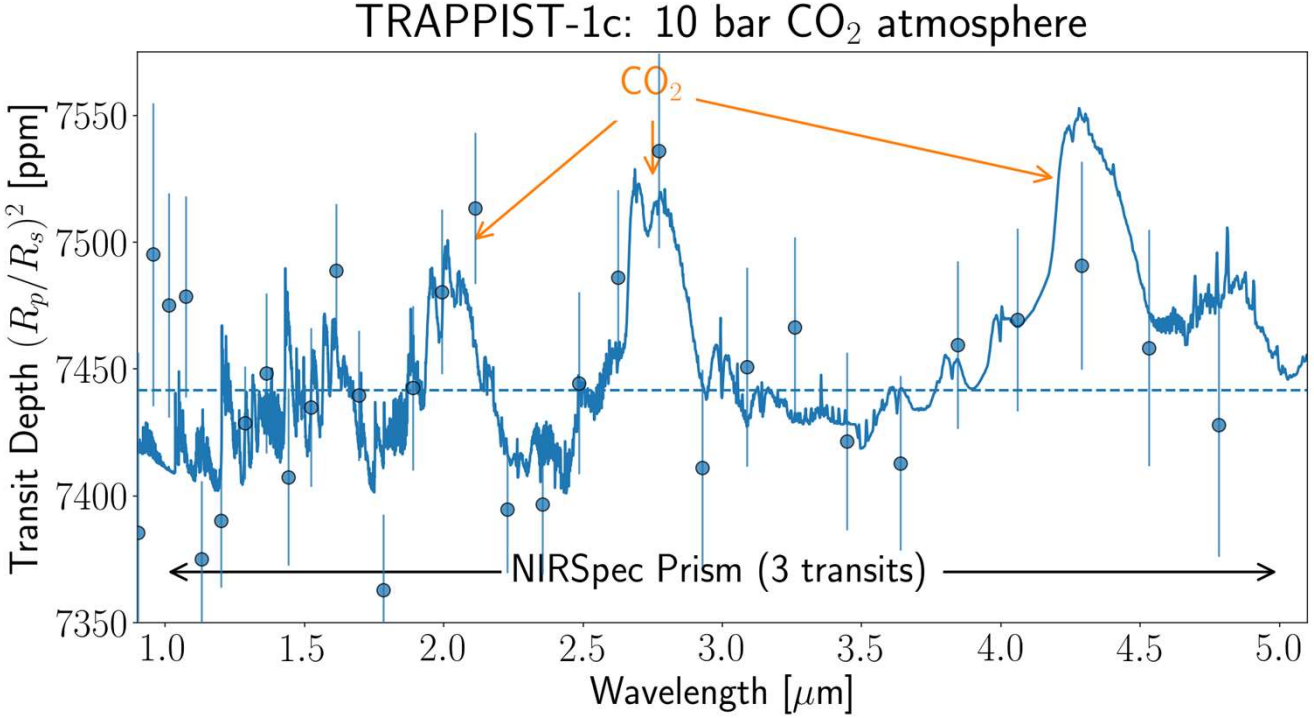

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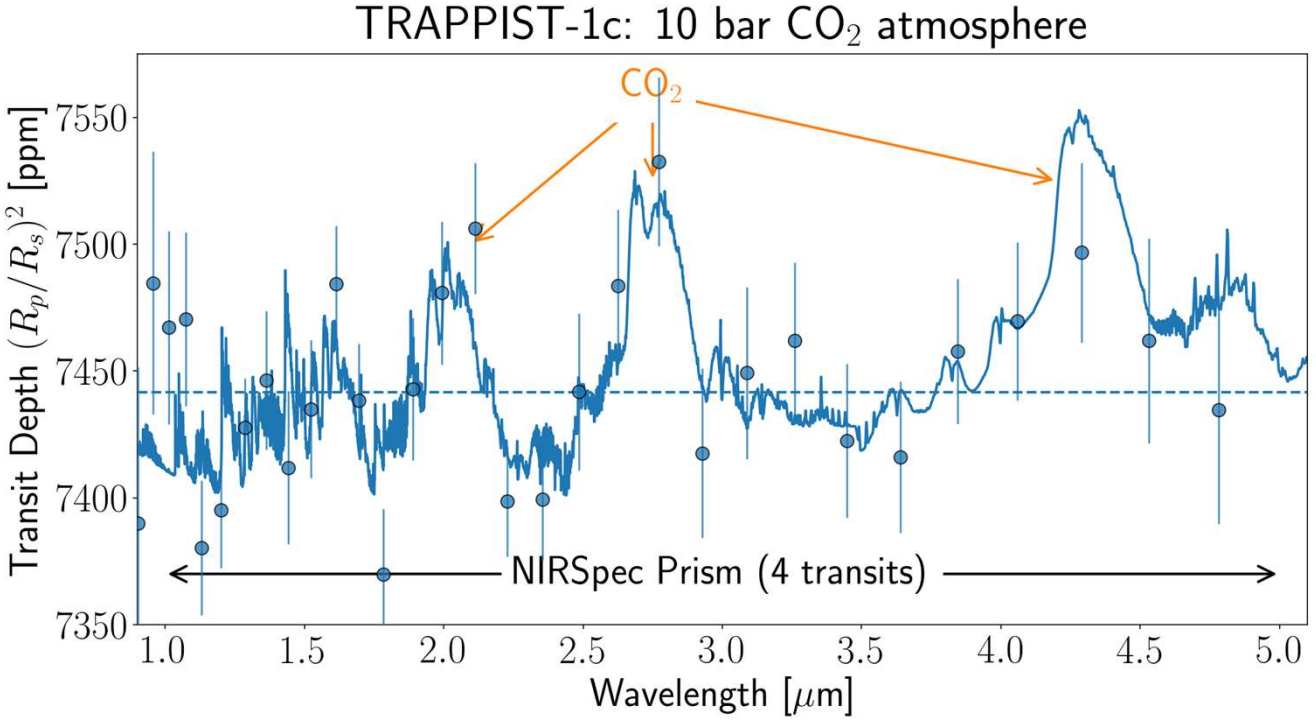

4 transits can rule out a featureless spectrum with a SNR=5

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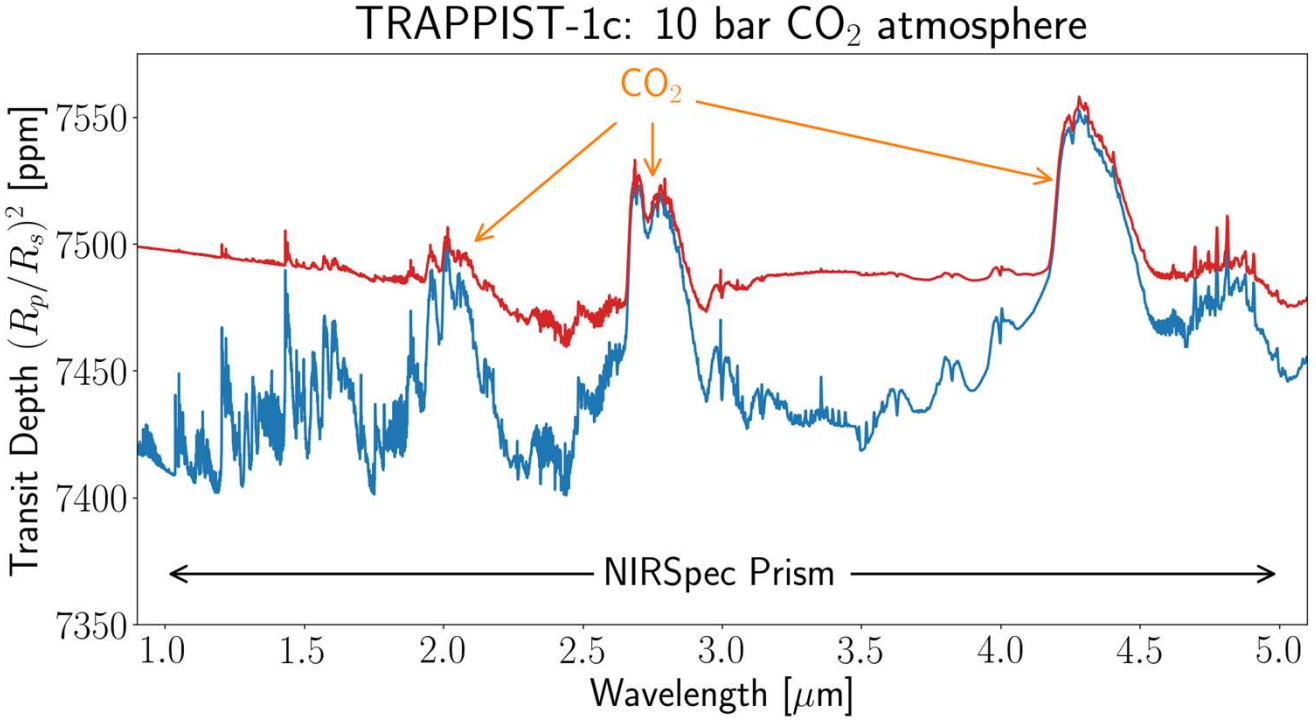

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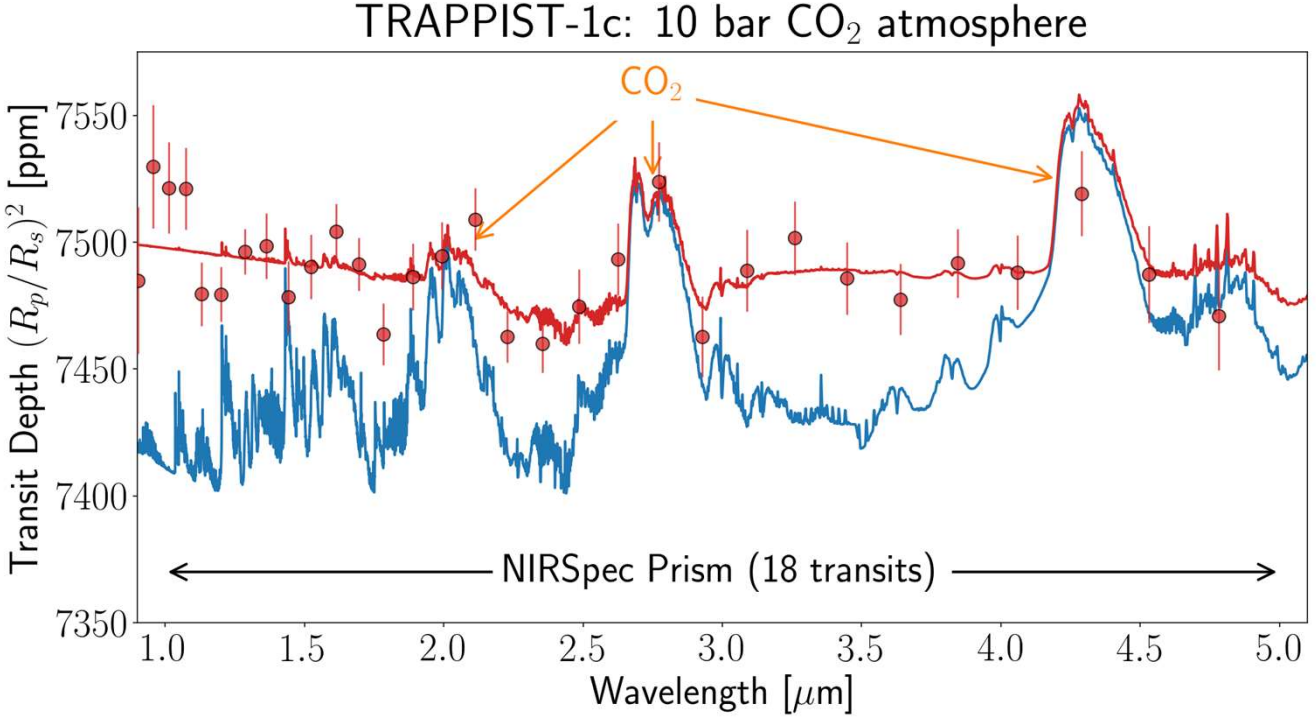

18 transits needed if planet has H_2SO_4 clouds

4 transits can rule out a featureless spectrum with a SNR=5

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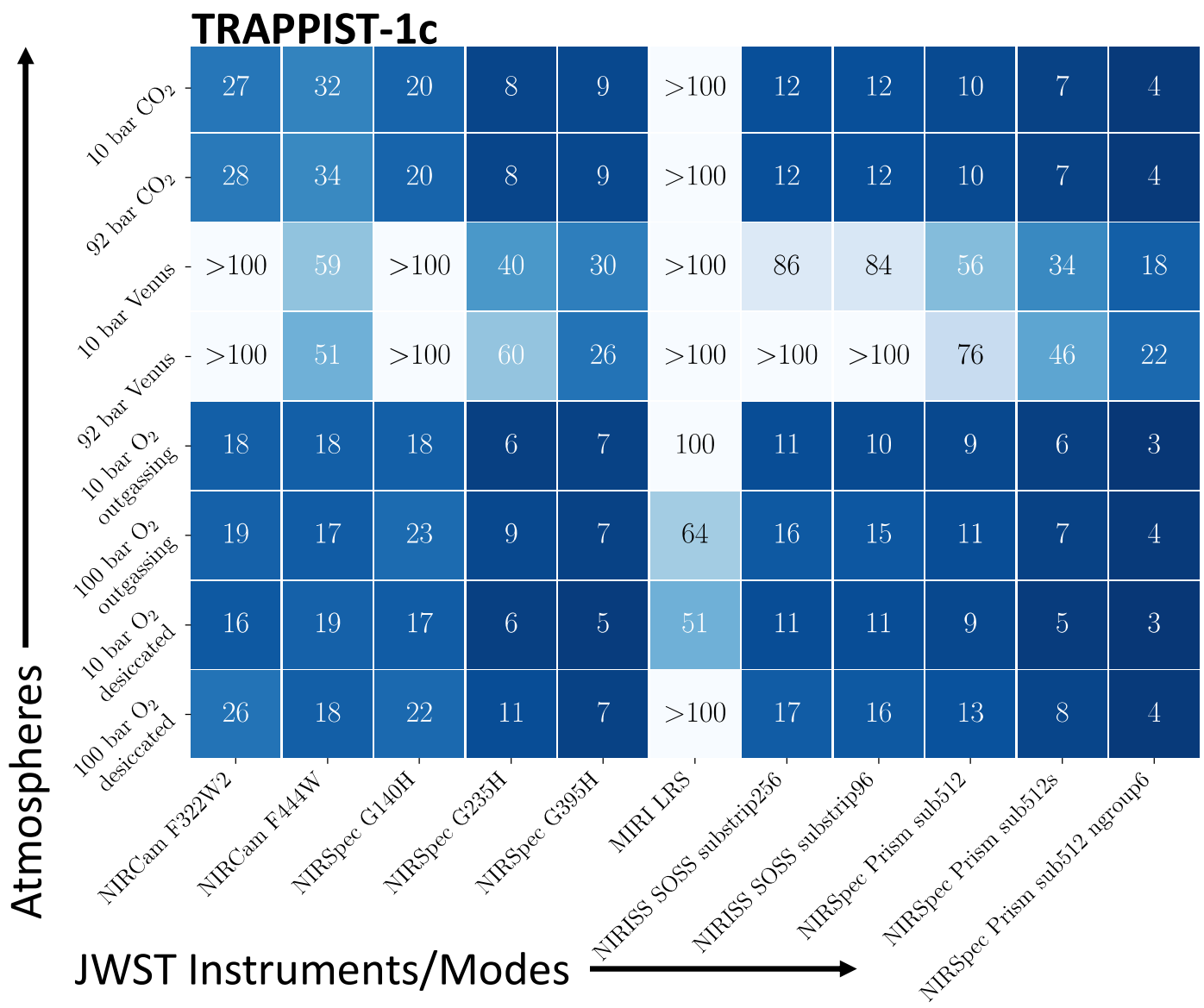
Number of transits to detect atmosphere with SNR=5



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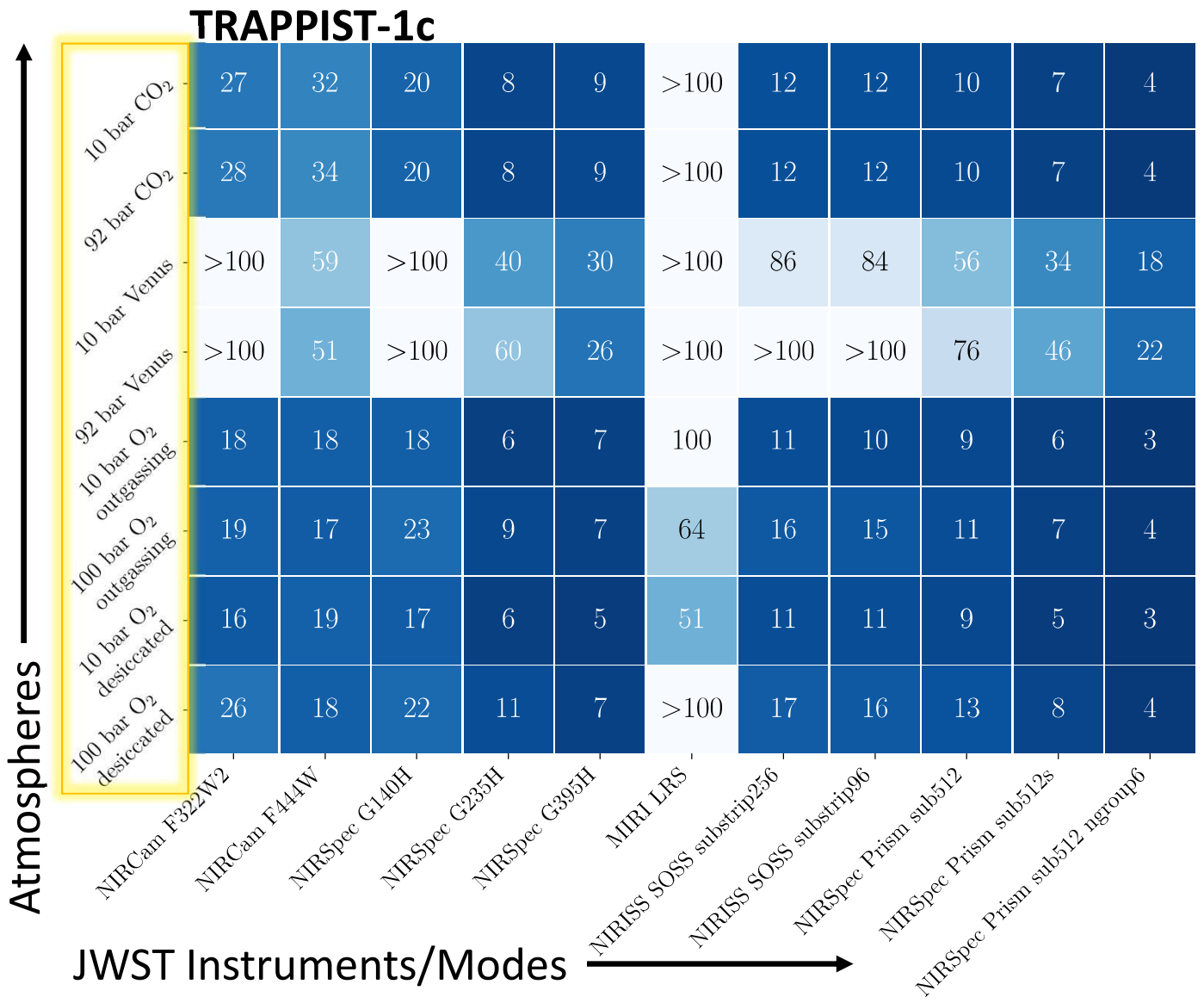

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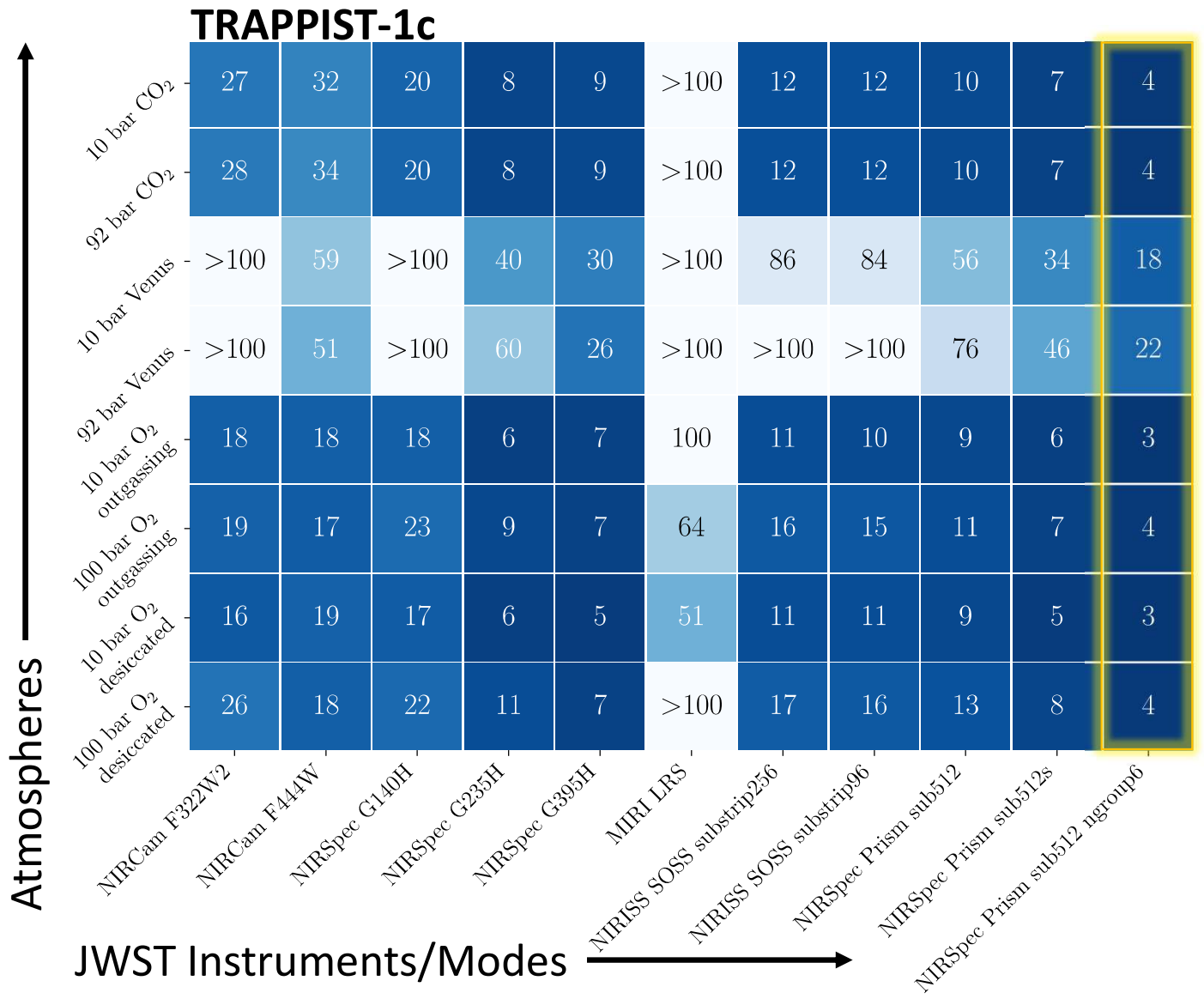
- NIRSpec Prism with partial saturation (Batalha et al. 2018) is optimal



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- Nominal NIRSpec Prism sub512s and NIRSpec G395 are comparable

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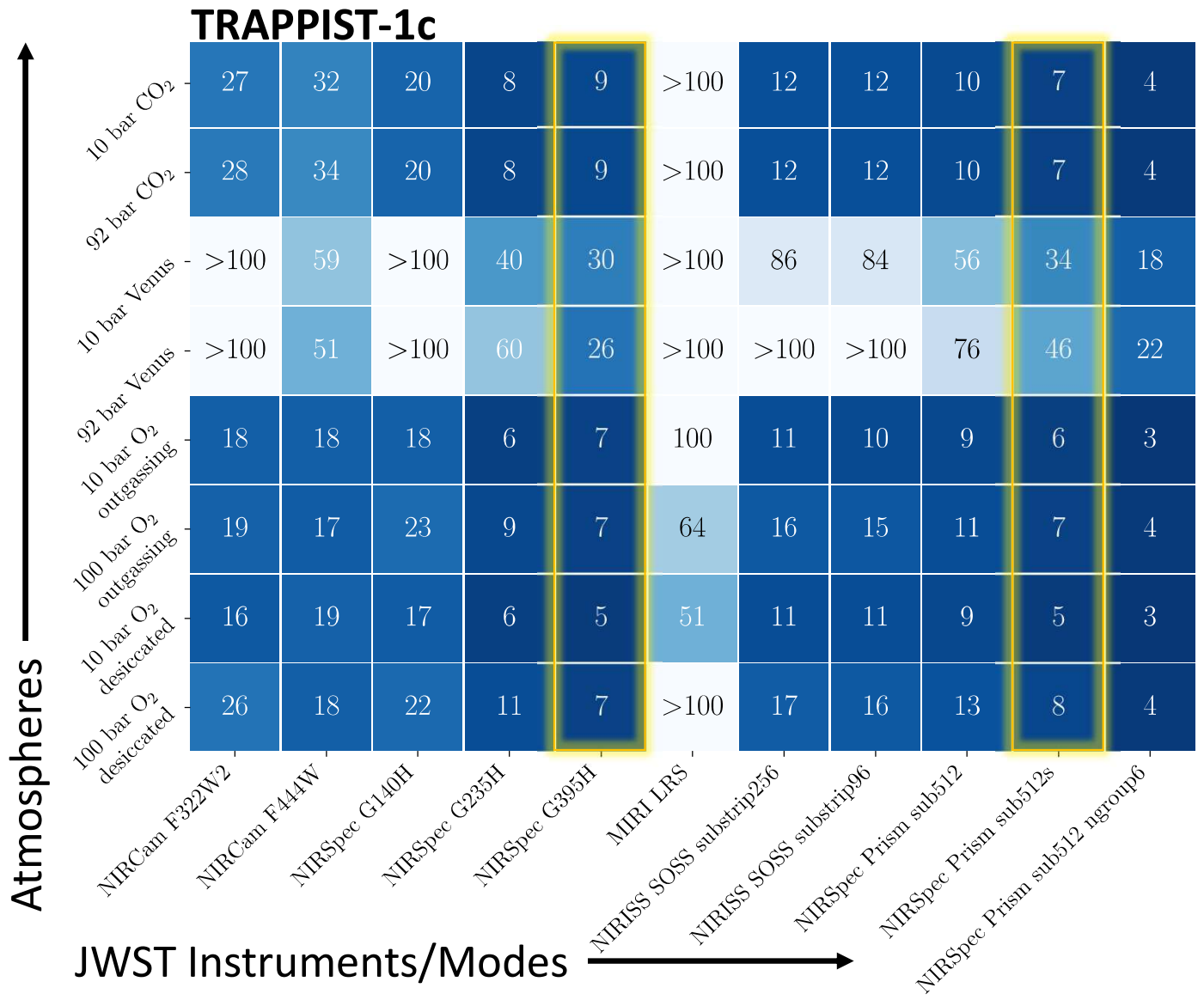

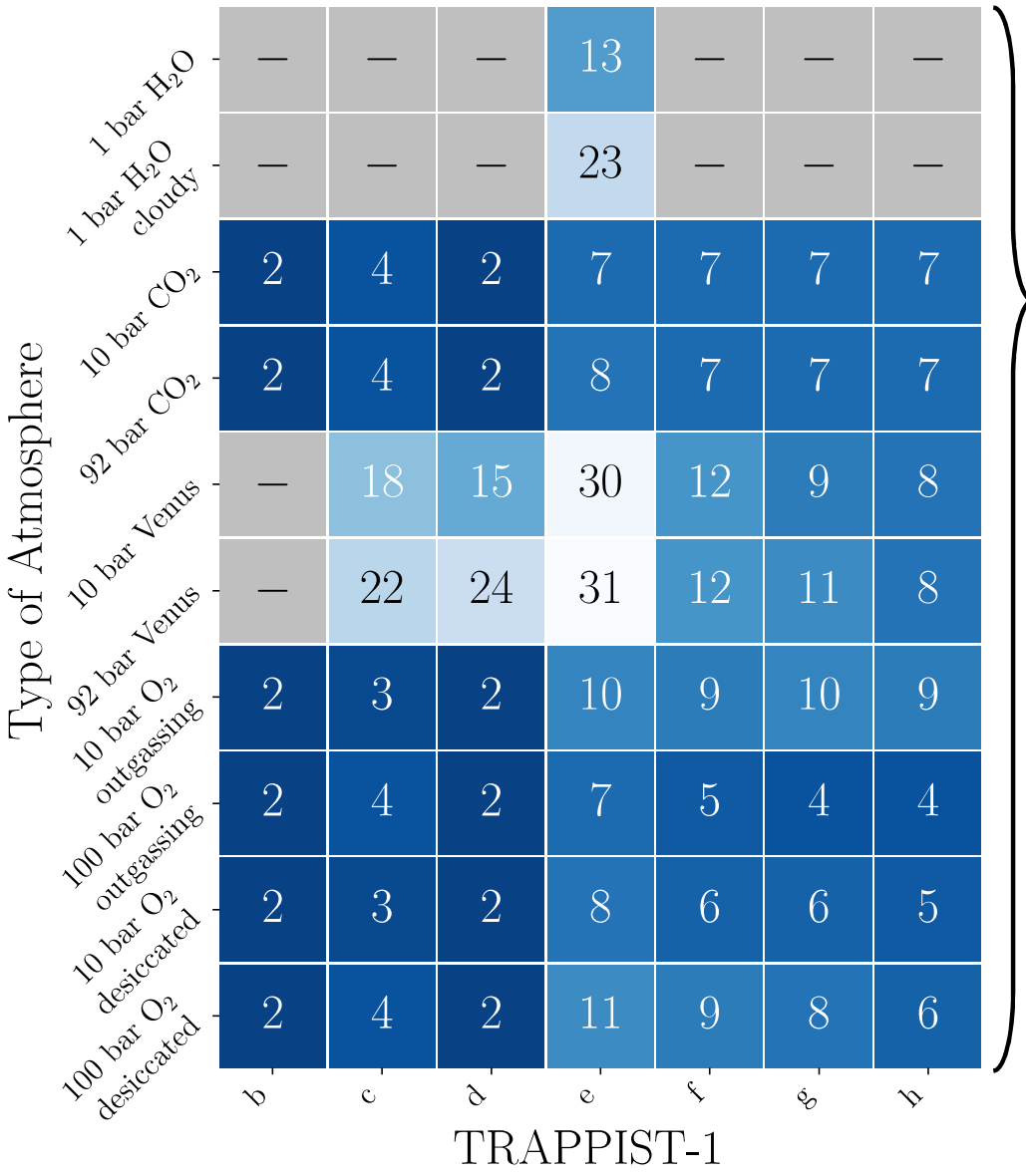

Number of transits to detect atmosphere (SNR=5) with optimal use of the NIRSpec Prism

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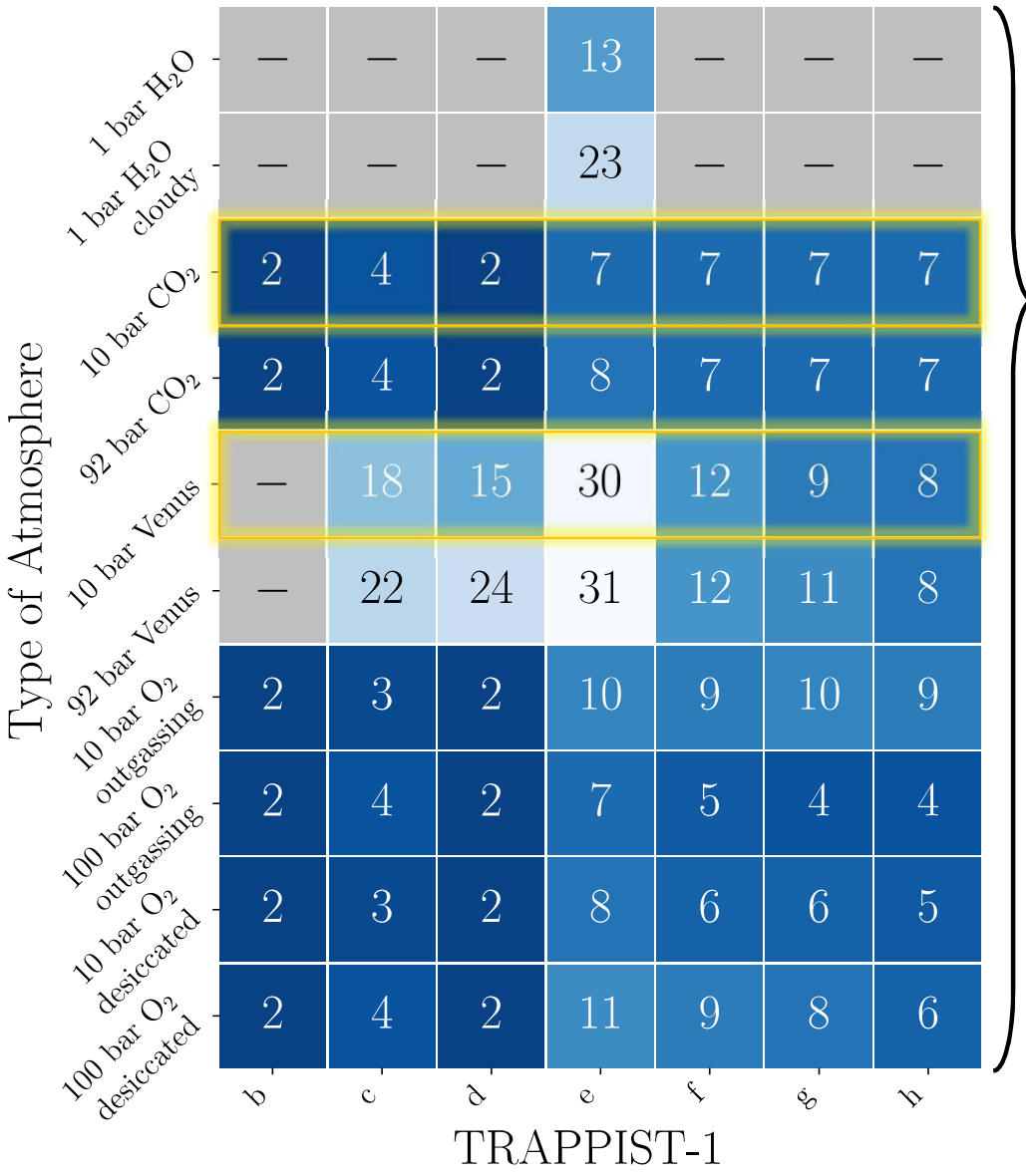

Number of transits to detect atmosphere (SNR=5) with optimal use of the NIRSpec Prism

- Detect thick terrestrial atmospheres in roughly 2-10 transits *for all of the TRAPPIST-1 planets*

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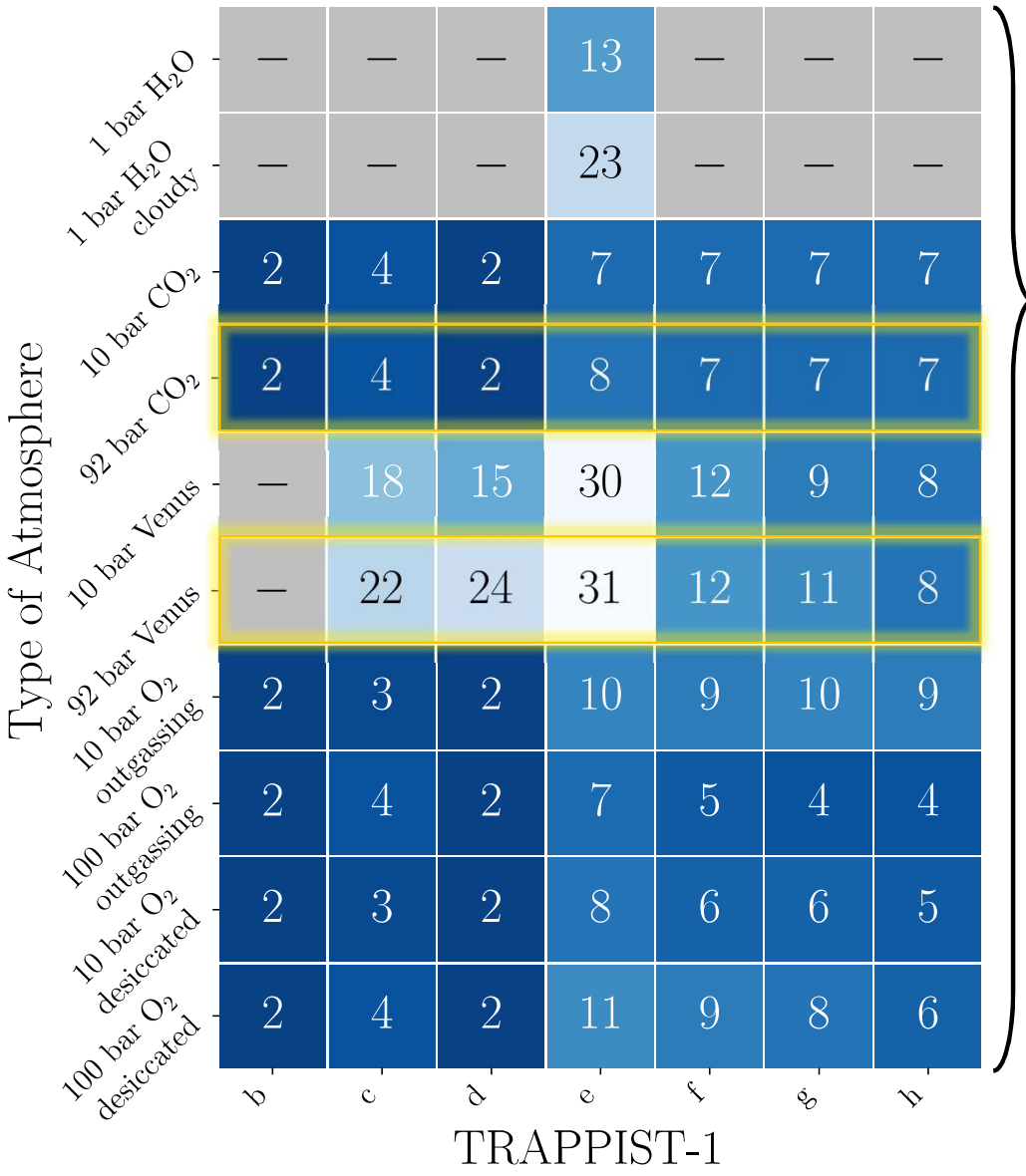

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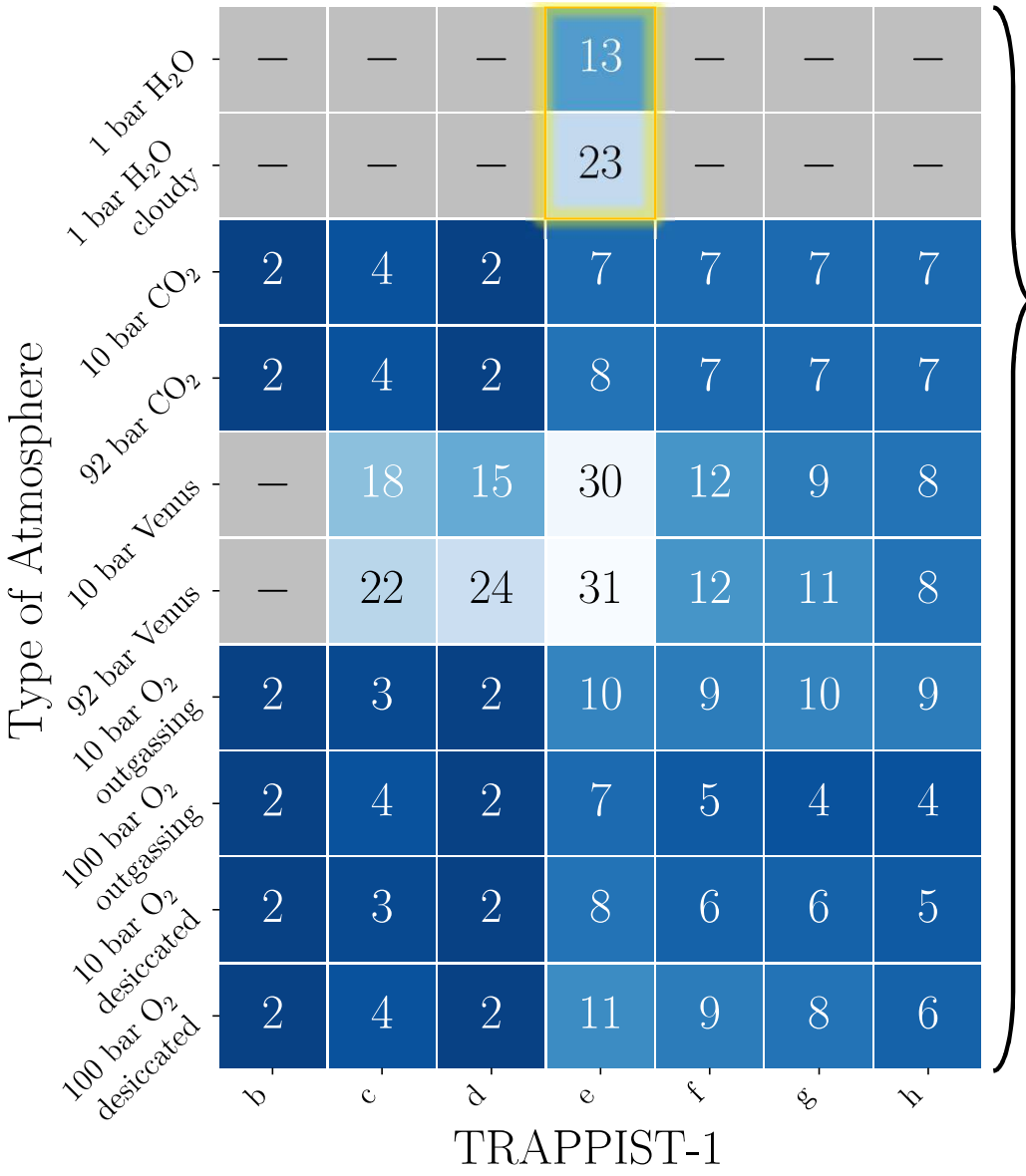

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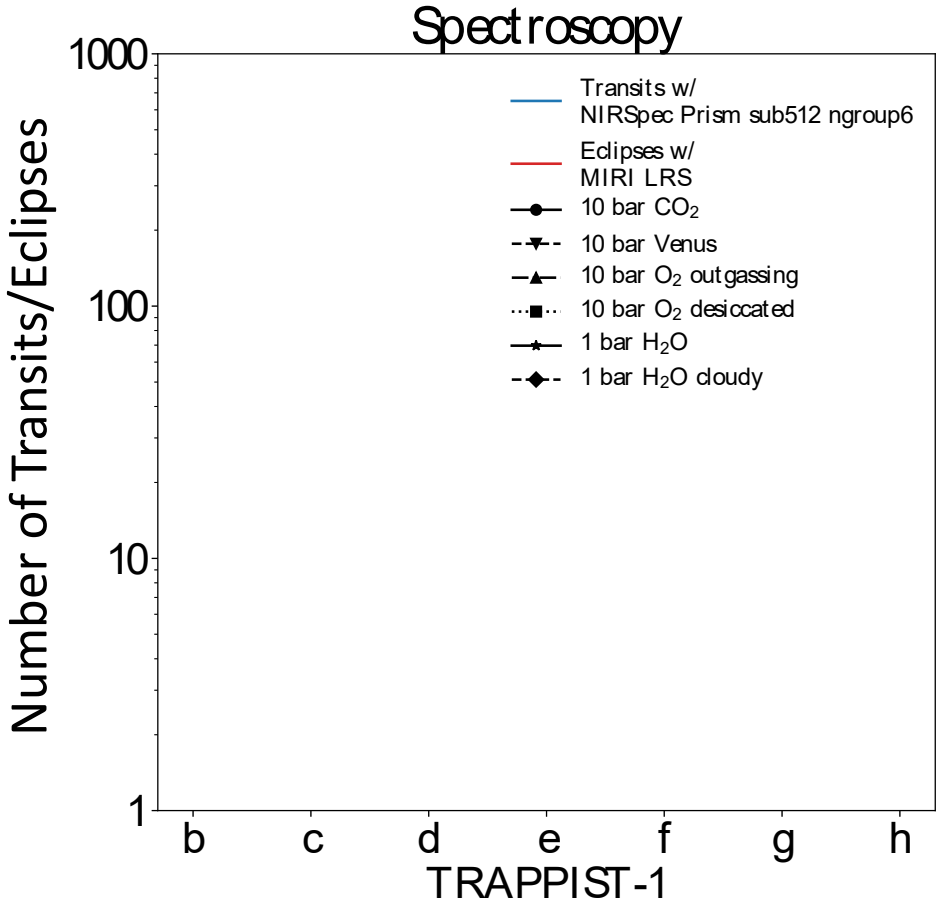
Detecting Atmospheres in Transmission should be much easier than Emission



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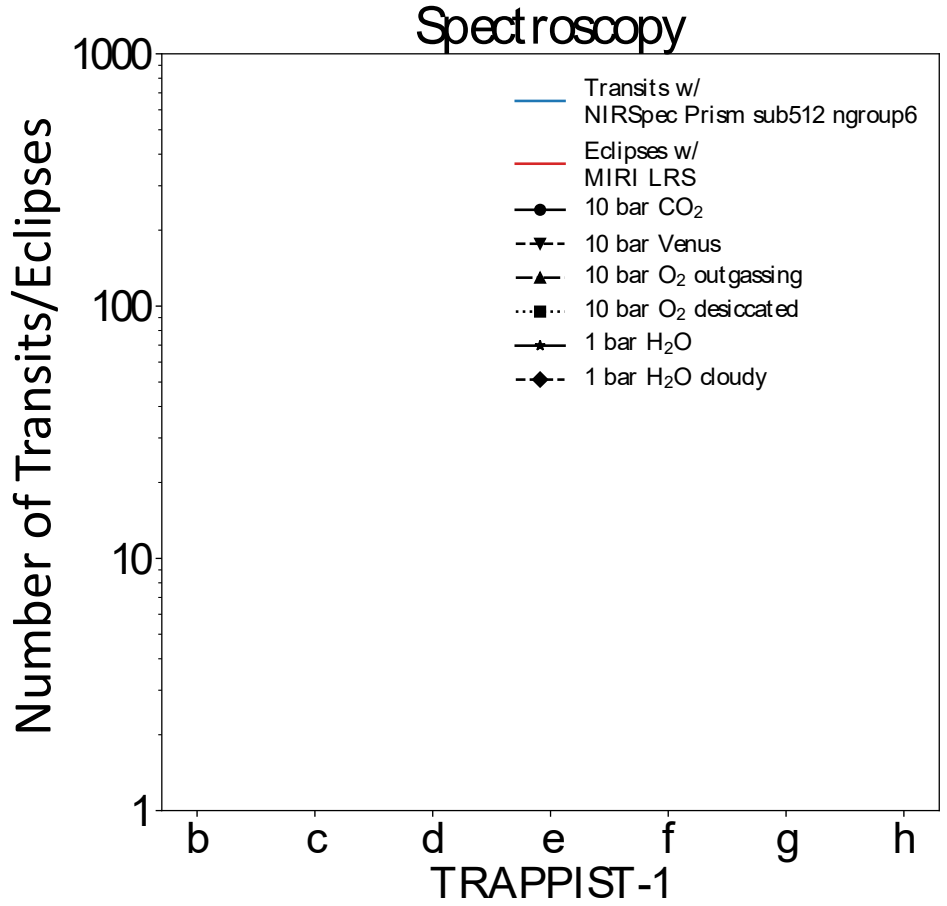

Transits using **NIRSpec Prism** (optimal)

Eclipses using **MIRI LRS** (optimal)

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Secondary eclipse is viable only for the inner planets

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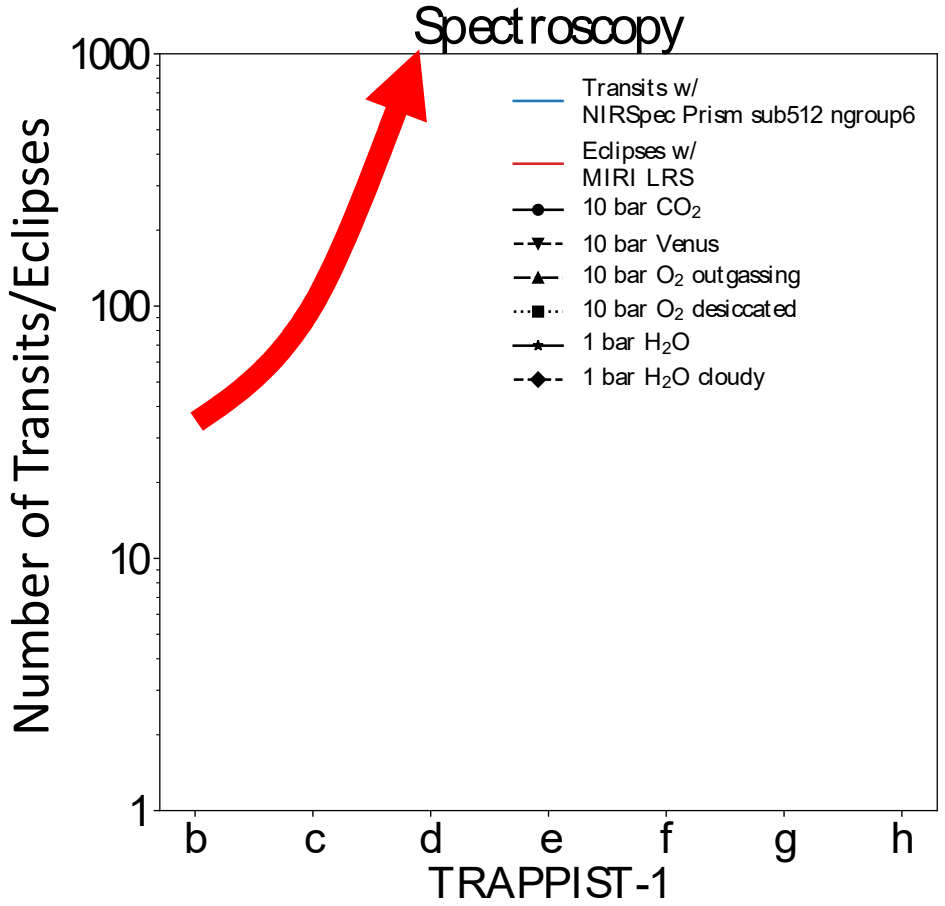

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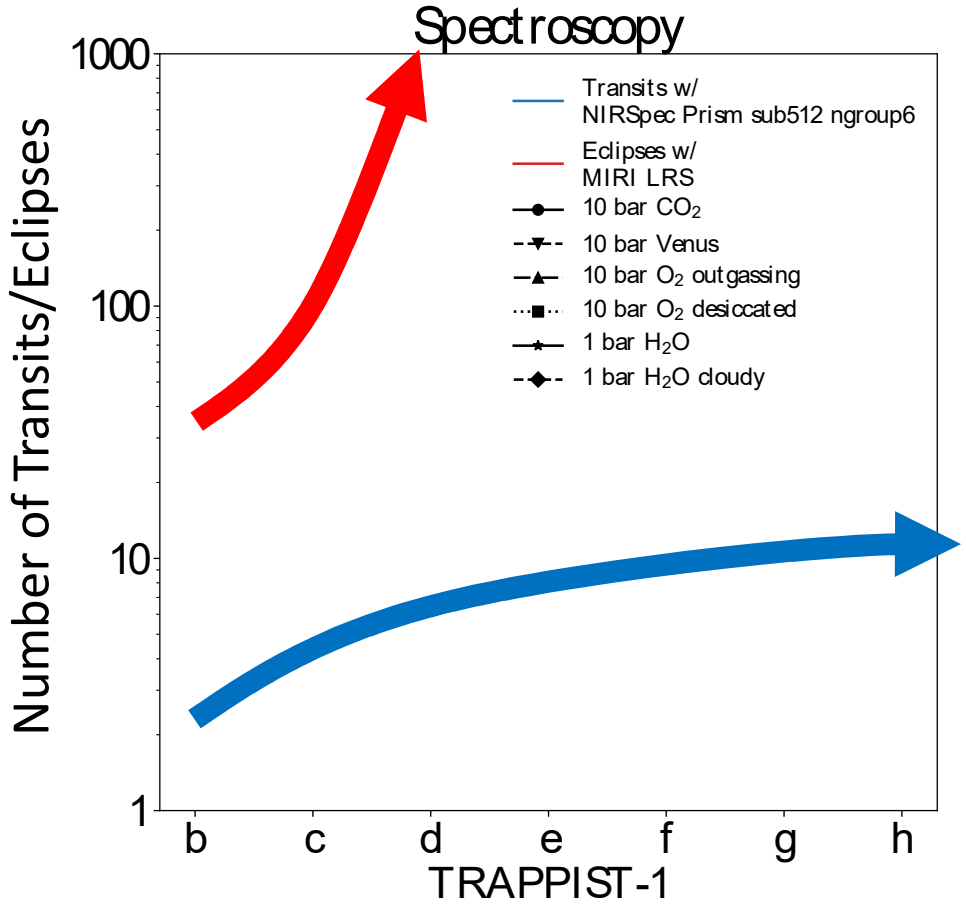

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Transmission is much more forgiving for the outer planets

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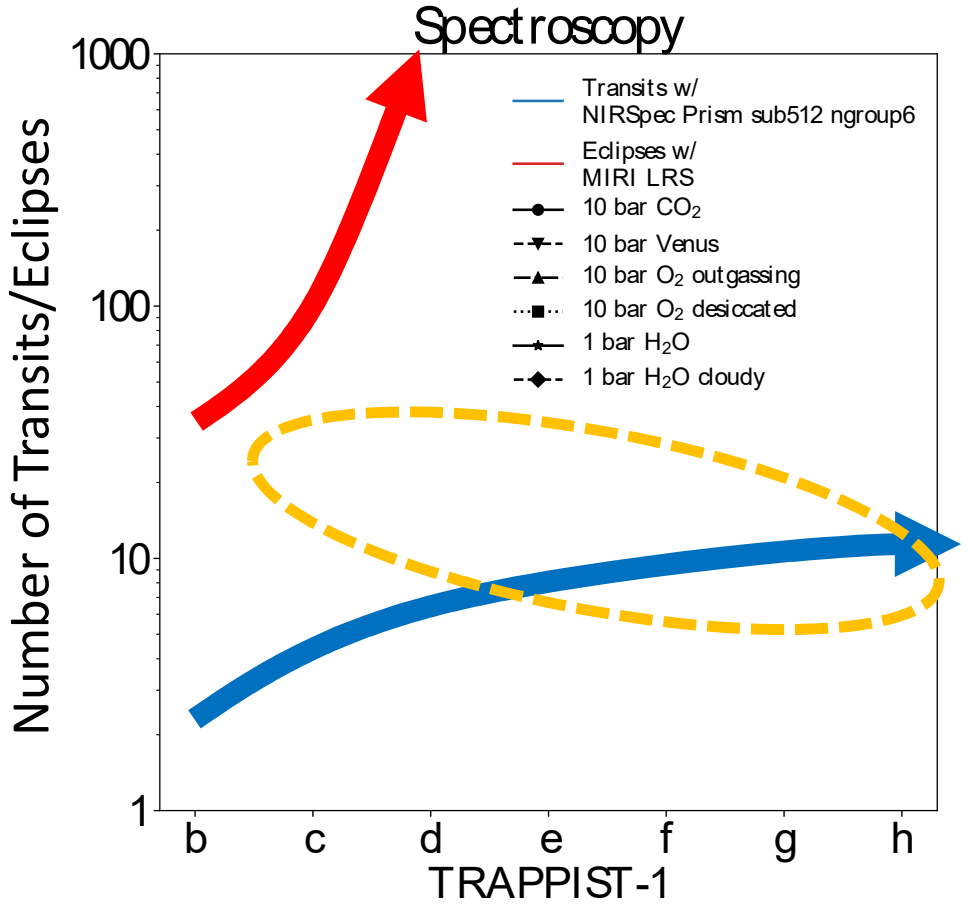
Detecting Atmospheres in Transmission should be much easier than Emission

Secondary eclipse is viable only for the inner planets

Sulfuric acid clouds are less of a concern for the colder planets

Transits using **NIRSpec Prism** (optimal)

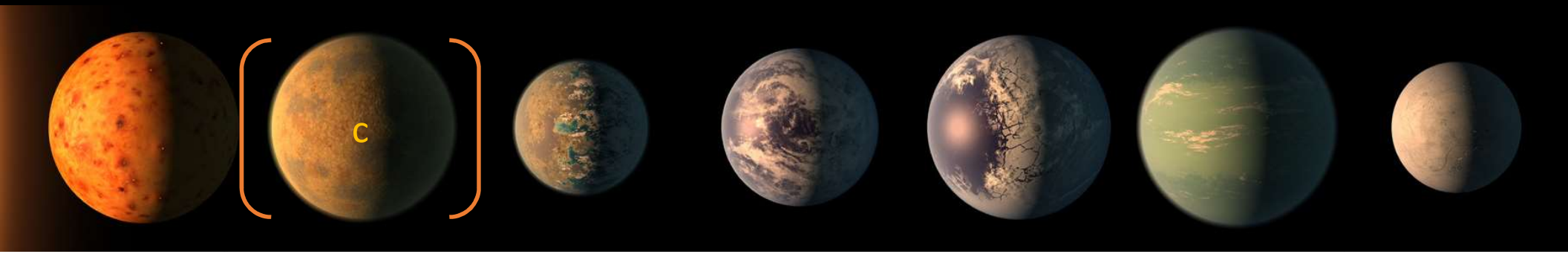


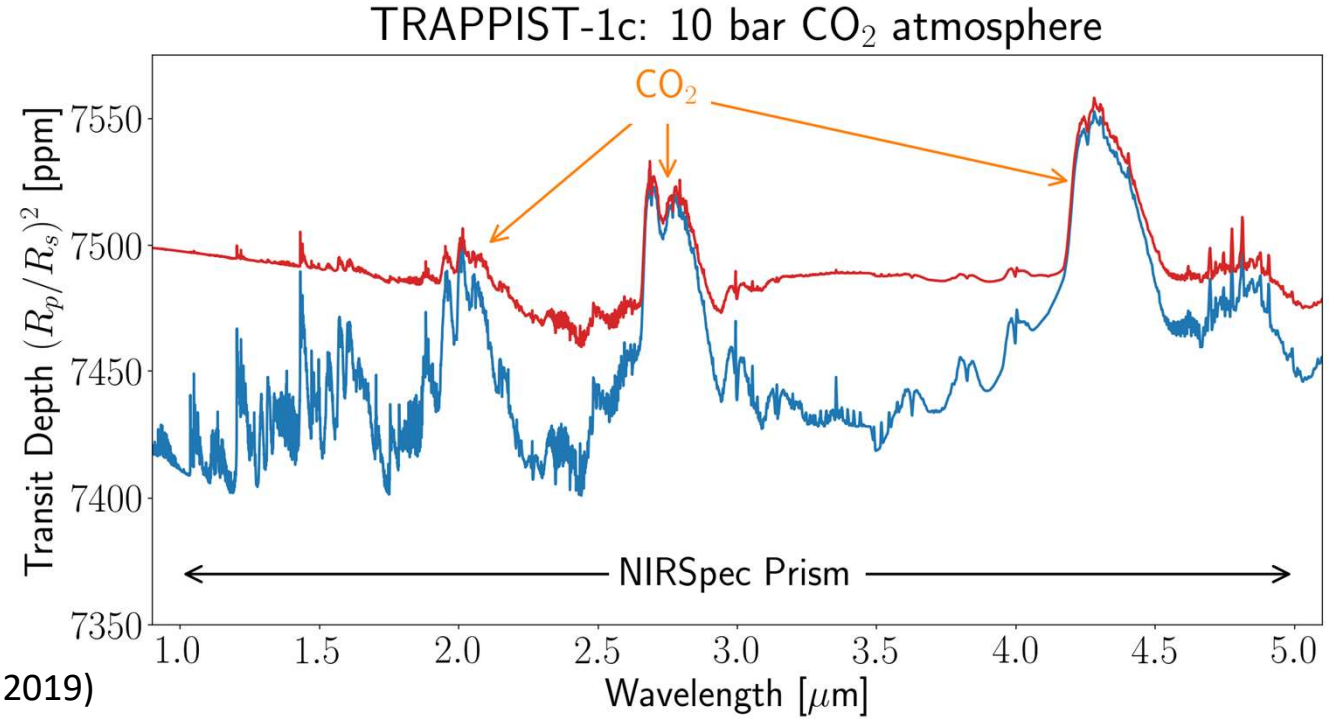
Eclipses using **MIRI LRS** (optimal)

Transmission is much more forgiving for the outer planets

Lustig-Yaeger et al. (2019)

*The diminishing effect of **sulfuric acid clouds** with semi-major axis*



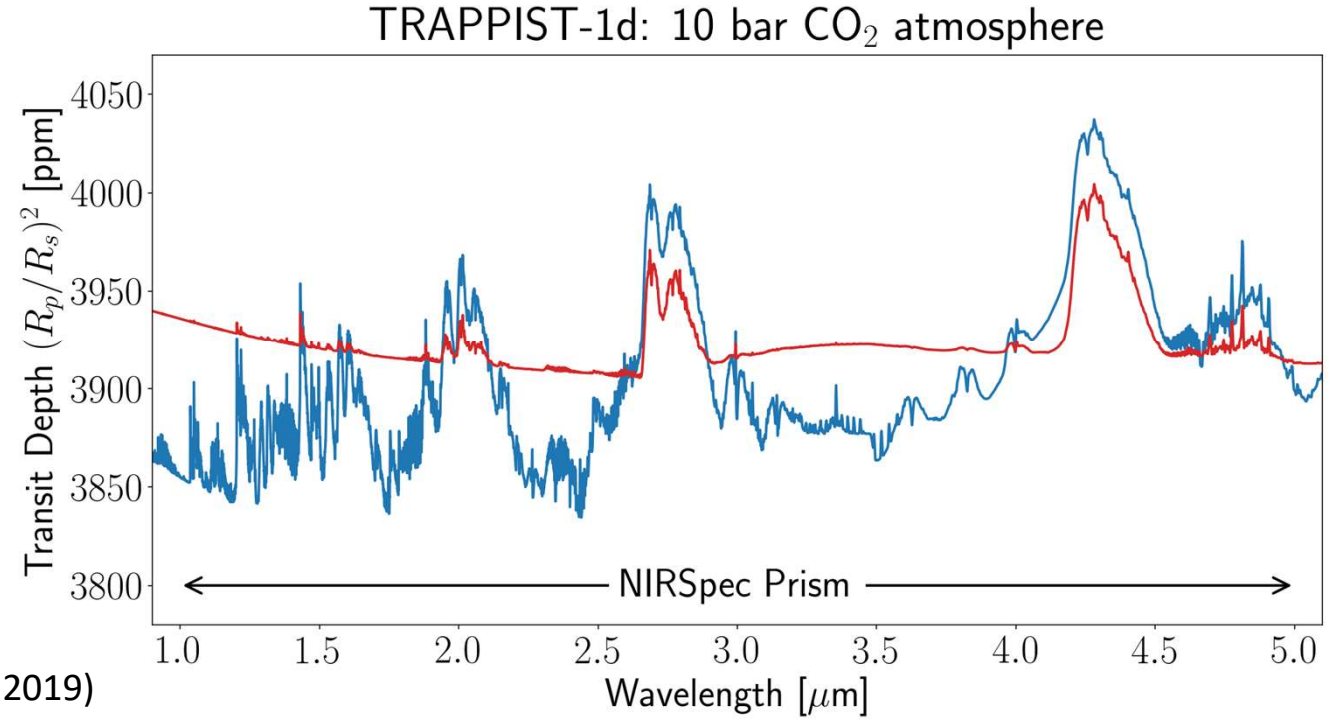


With clouds:
18 transits

No clouds:
4 transits

Lustig-Yaeger et al. (2019)

*The diminishing effect of **sulfuric acid clouds** with semi-major axis*

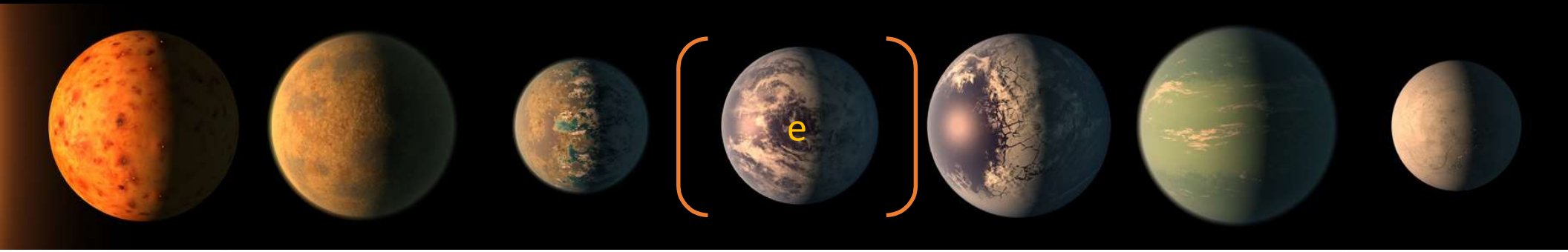


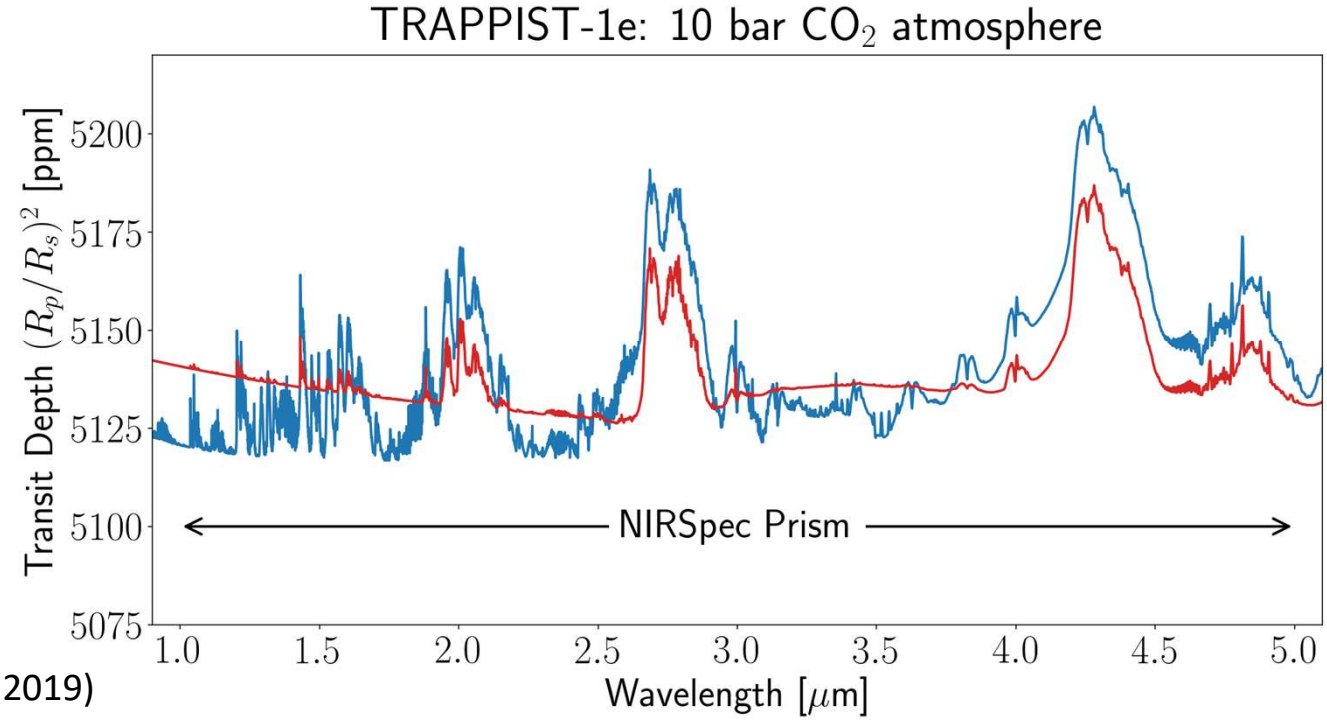
With clouds:
15 transits

No clouds:
2 transits

Lustig-Yaeger et al. (2019)

*The diminishing effect of **sulfuric acid clouds** with semi-major axis*



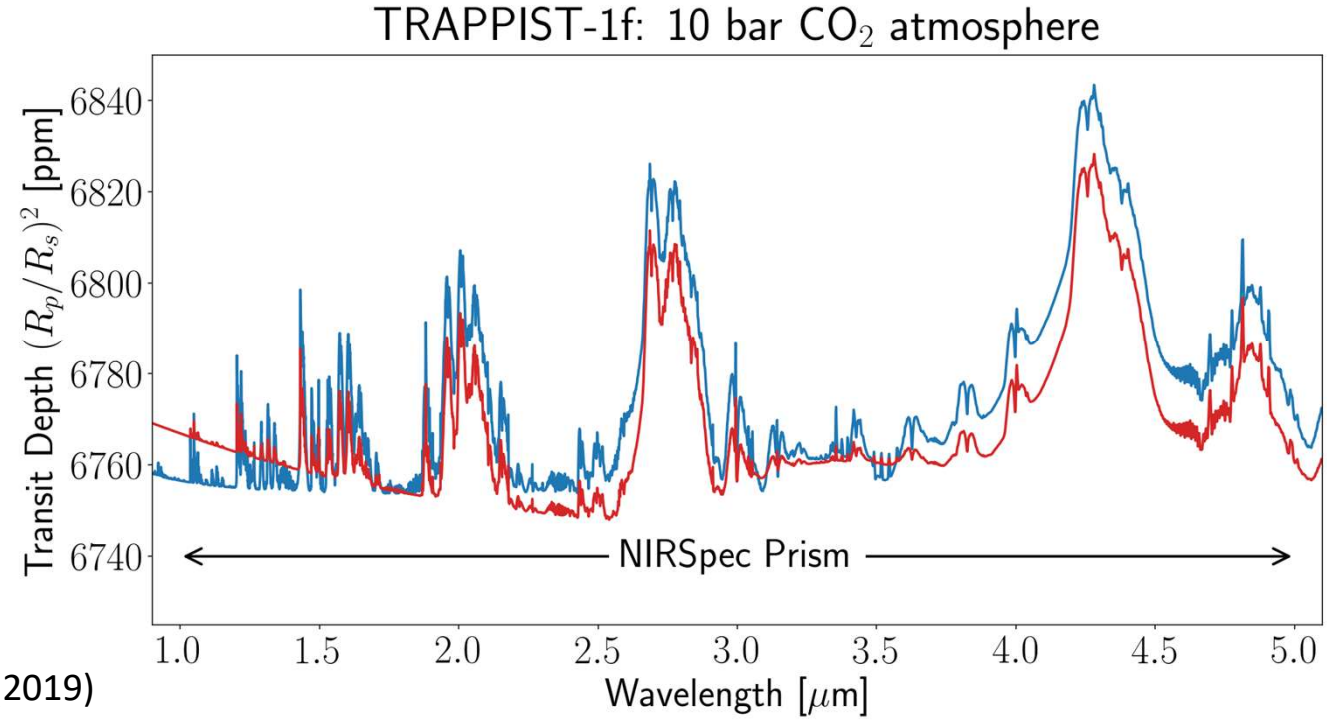


With clouds:
30 transits

No clouds:
7 transits

Lustig-Yaeger et al. (2019)

*The diminishing effect of **sulfuric acid clouds** with semi-major axis*

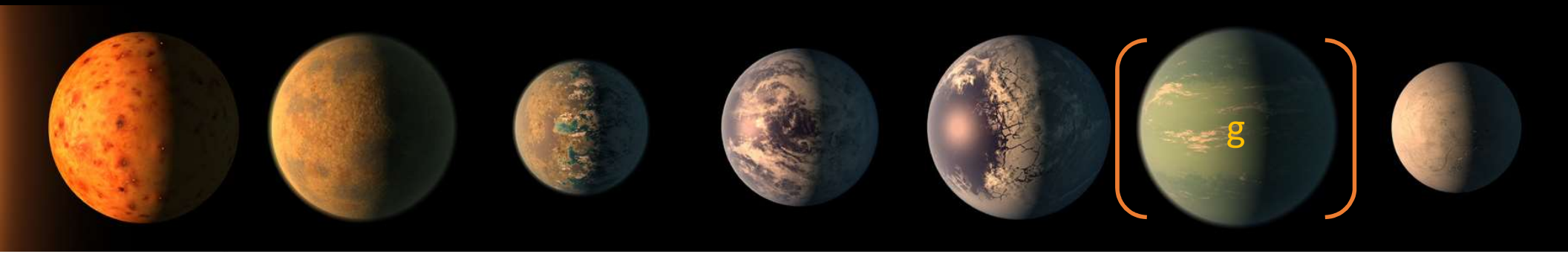


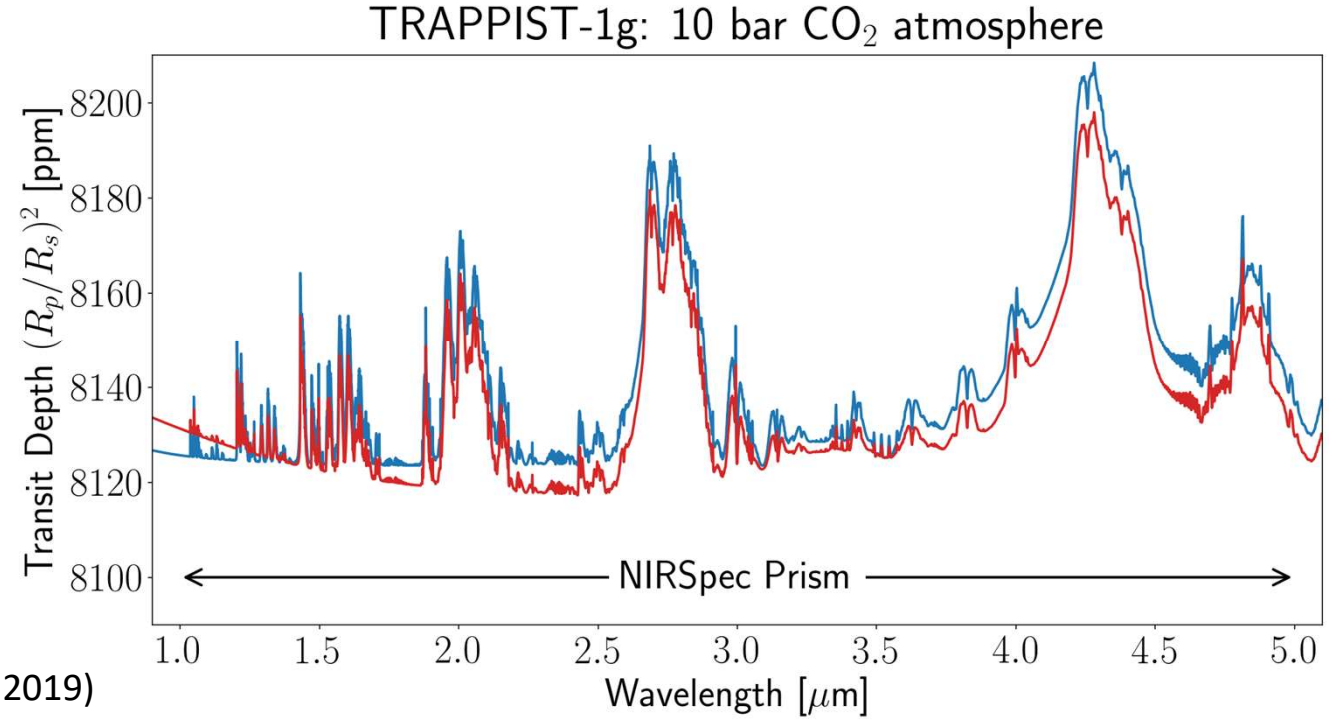
With clouds:
12 transits

No clouds:
7 transits

Lustig-Yaeger et al. (2019)

*The diminishing effect of **sulfuric acid clouds** with semi-major axis*



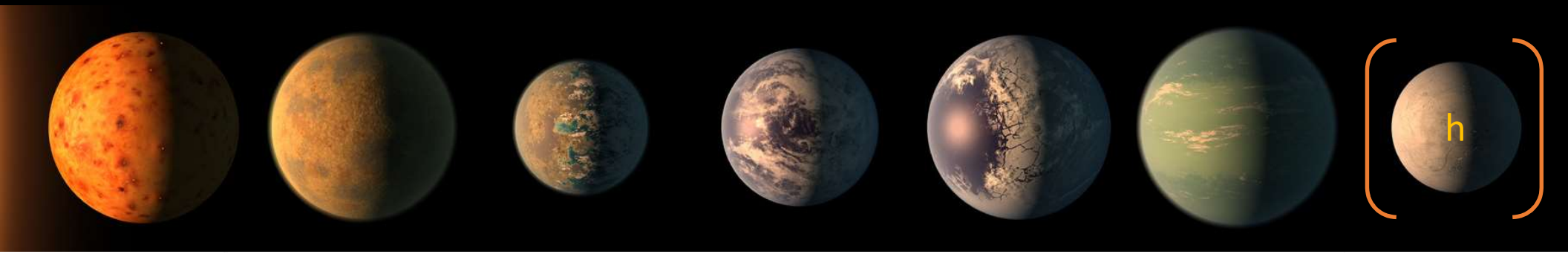


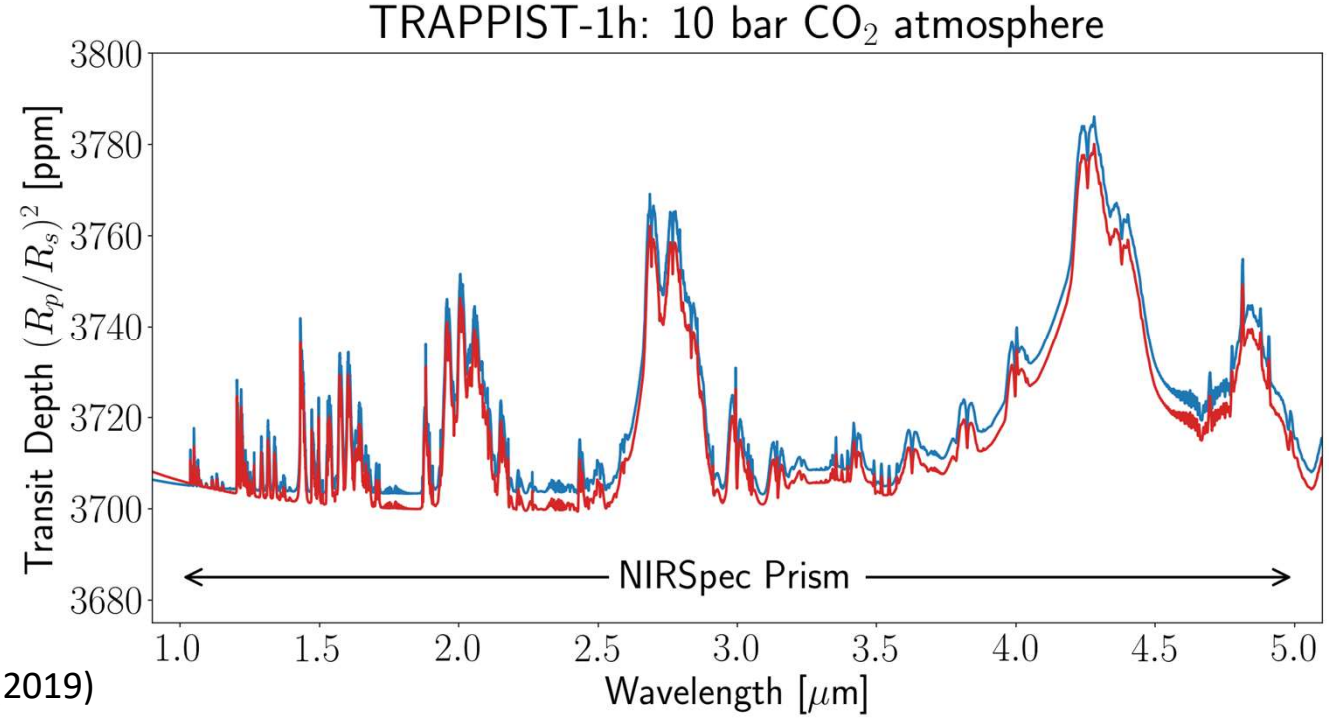
With clouds:
9 transits

No clouds:
7 transits

Lustig-Yaeger et al. (2019)

*The diminishing effect of **sulfuric acid clouds** with semi-major axis*



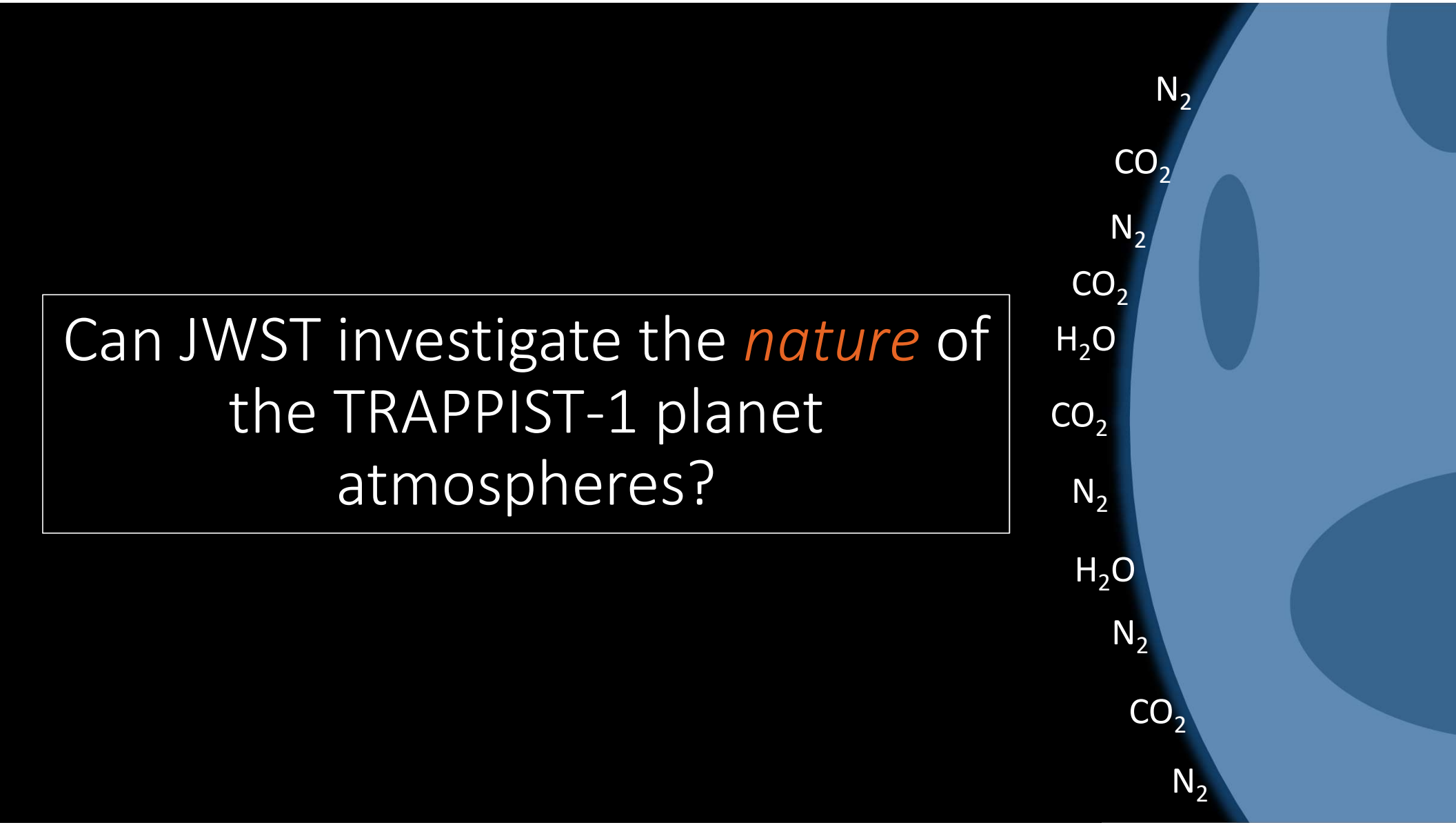


With clouds:
8 transits

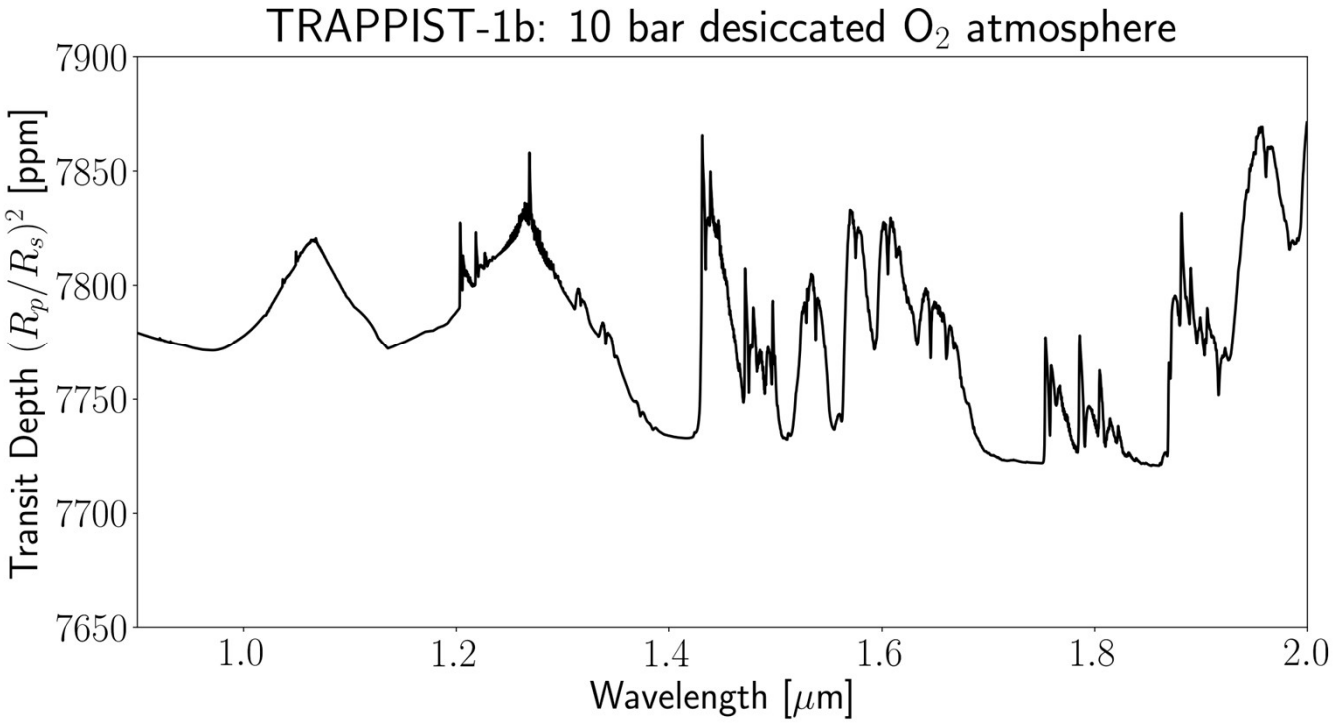
No clouds:
7 transits

Lustig-Yaeger et al. (2019)

Can JWST investigate the *nature* of the TRAPPIST-1 planet atmospheres?



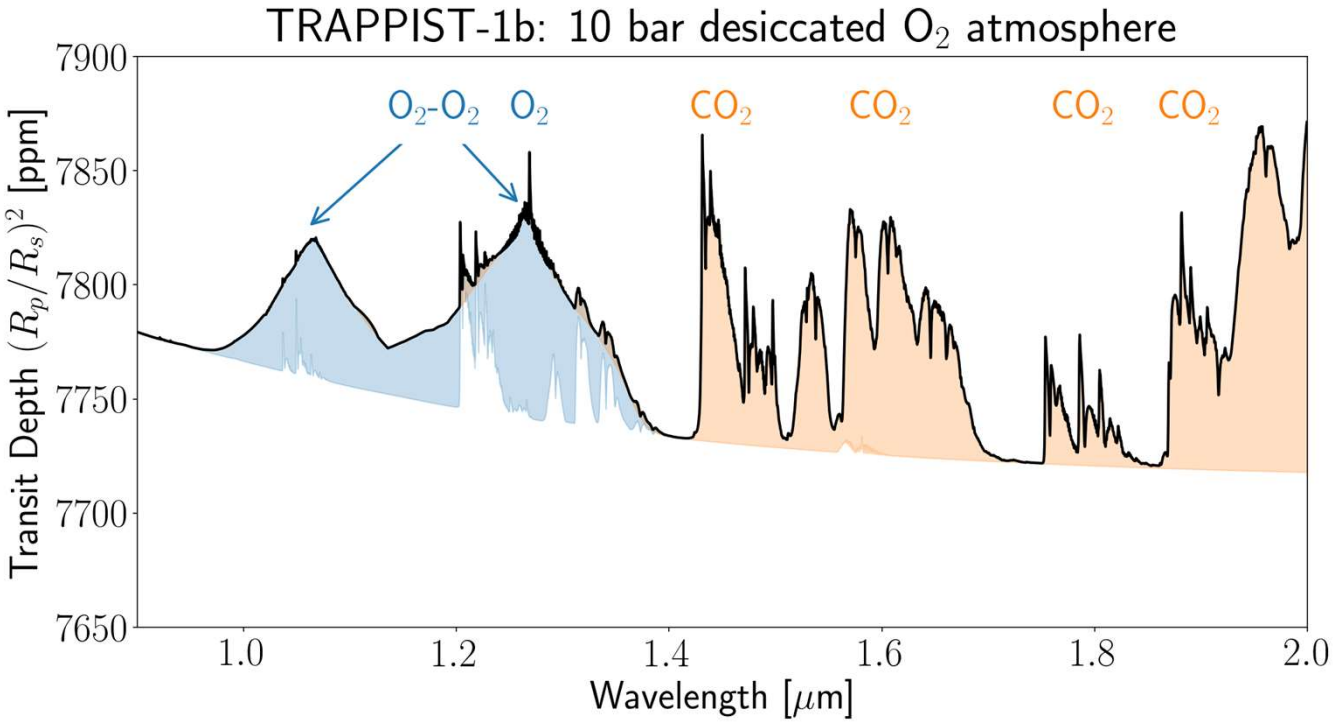
JWST may be able to detect signs of severe ocean-loss



Lustig-Yaeger et al. (2019)

JWST may be able to detect signs of severe ocean-loss

O_2-O_2 CIA can be used to discriminate between an O_2-dominated and a CO_2-dominated atmosphere



Lustig-Yaeger et al. (2019)

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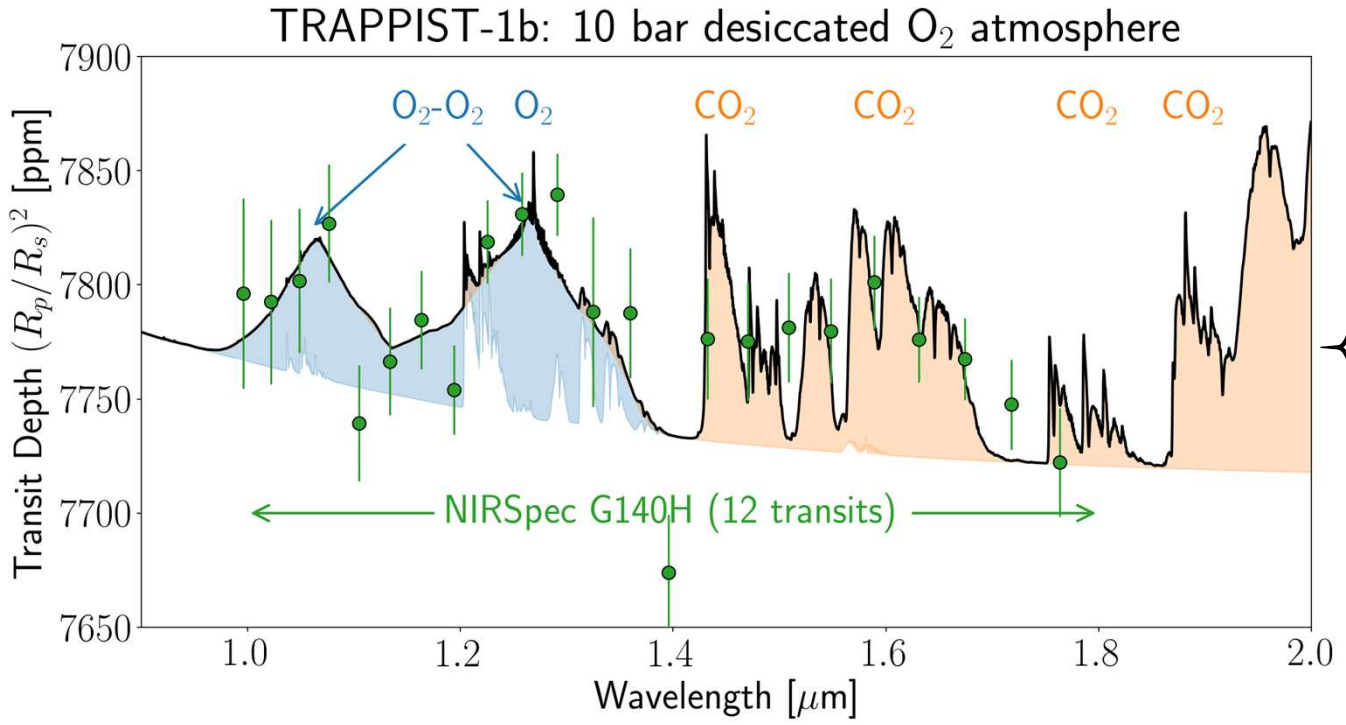
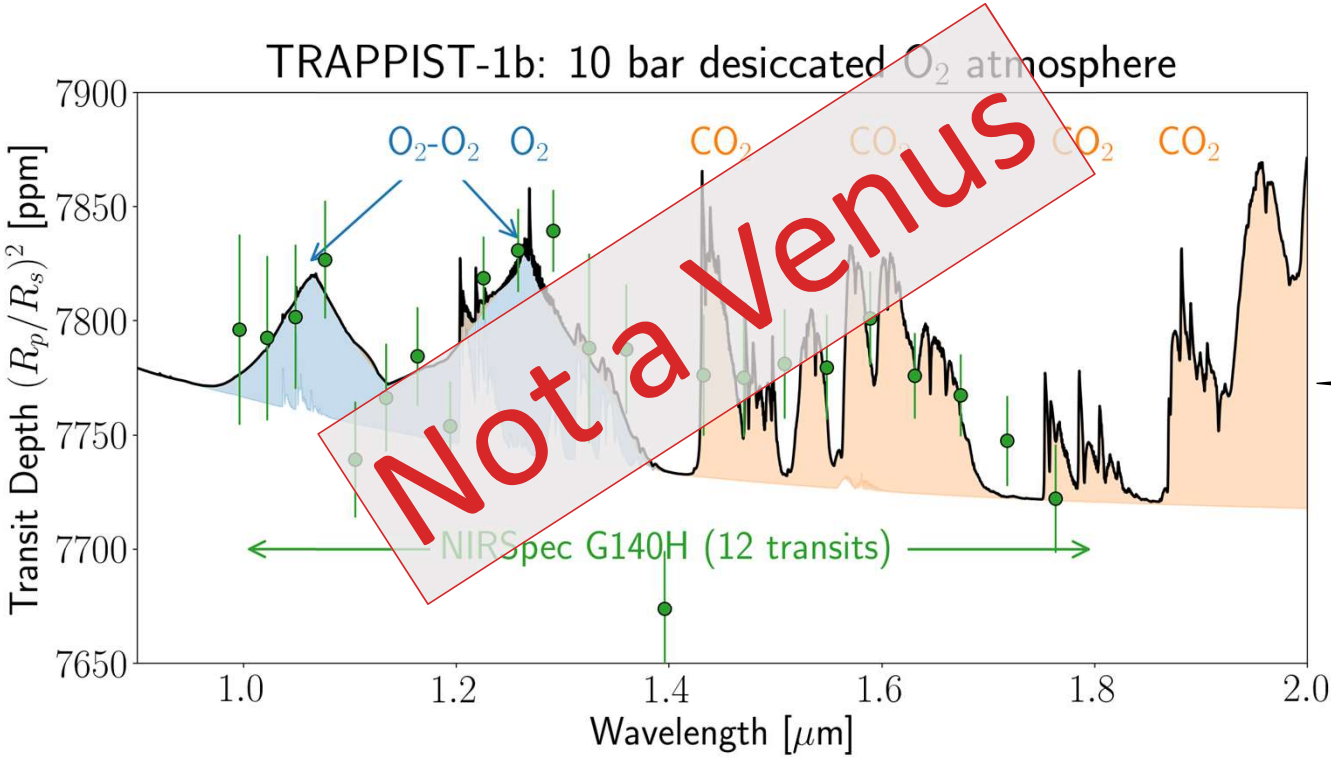


12 transits could reveal massive quantities of oxygen in the atmosphere of a desiccated world

Lustig-Yaeger et al. (2019)

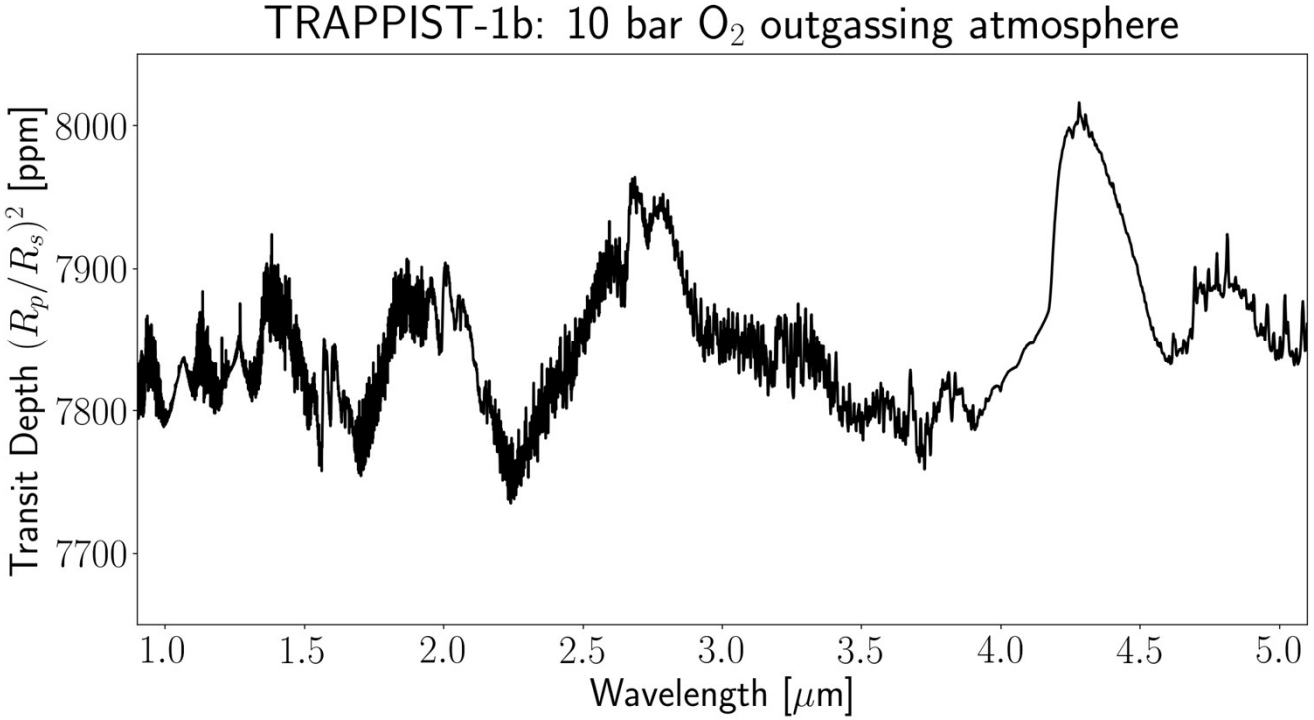
JWST may be able to detect signs of severe ocean-loss

O_2-O_2 CIA can be used to discriminate between an O_2-dominated and a CO_2-dominated atmosphere



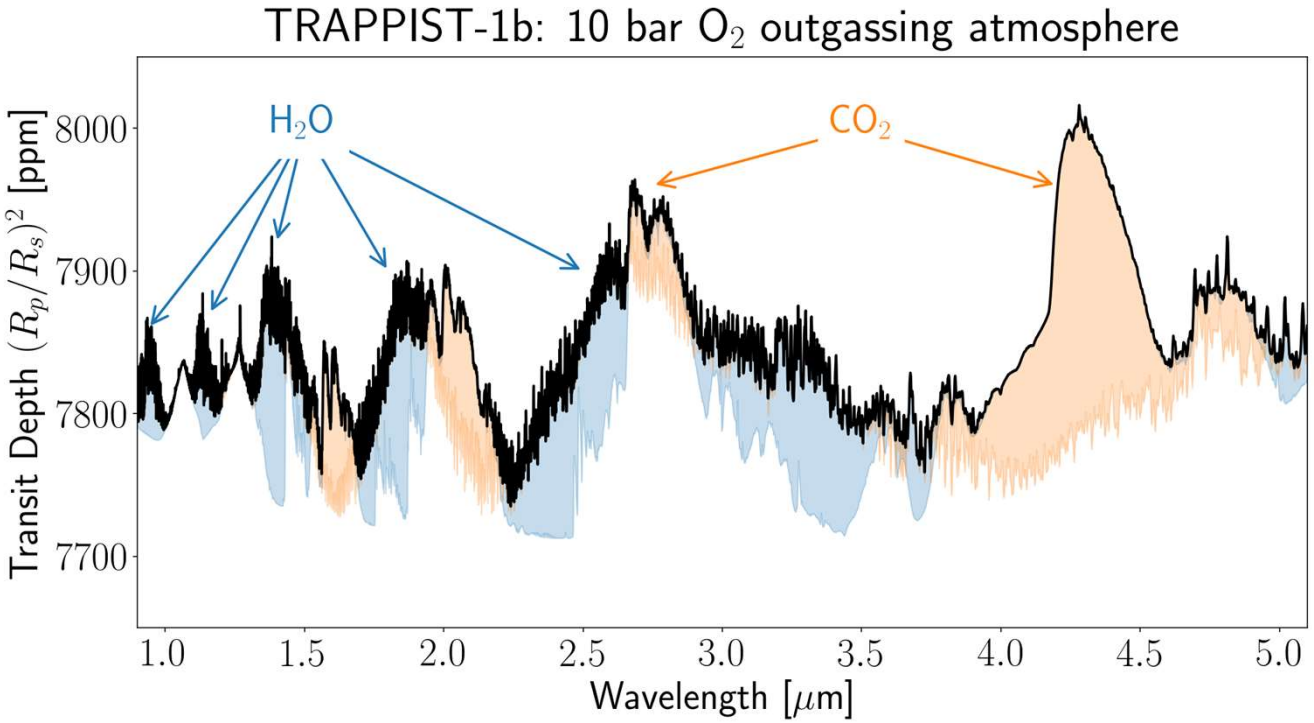
12 transits could reveal massive quantities of oxygen in the atmosphere of a desiccated world

Water in an oxygen atmosphere could rule out complete interior and atmospheric desiccation



Lustig-Yaeger et al. (2019)

Water in an oxygen atmosphere could rule out complete interior and atmospheric desiccation



Lustig-Yaeger et al. (2019)

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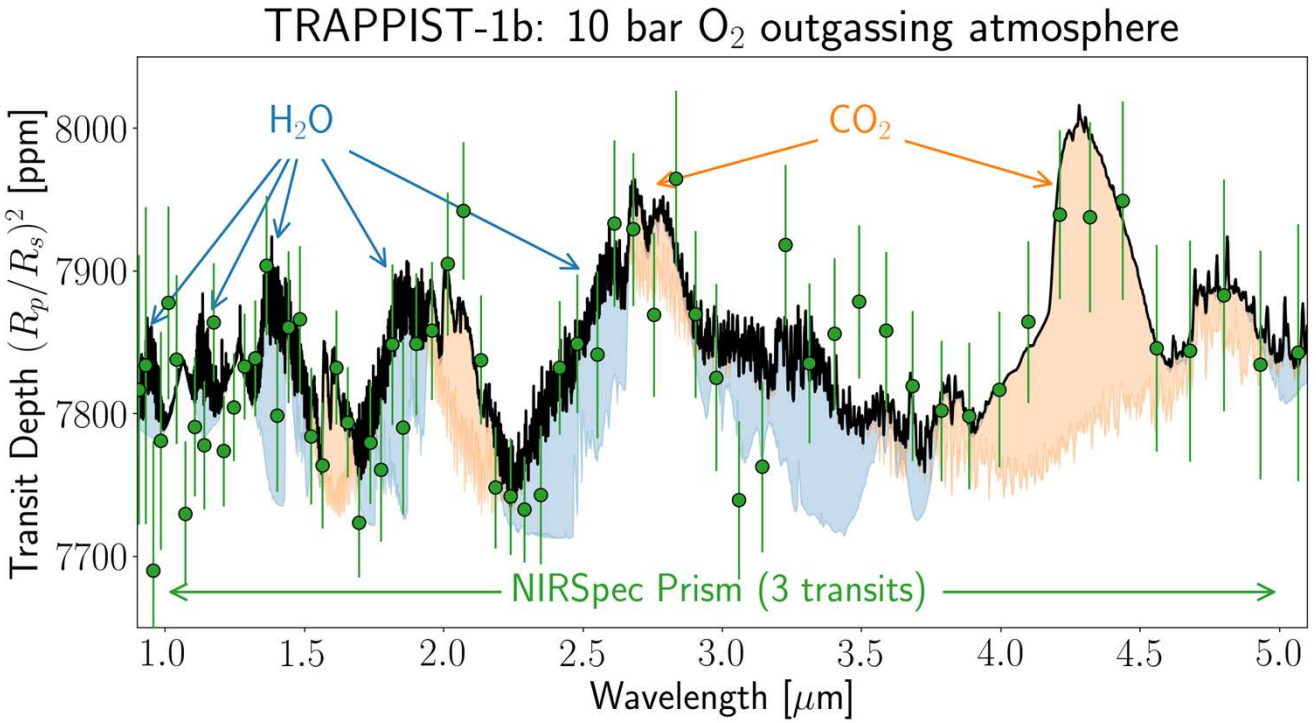
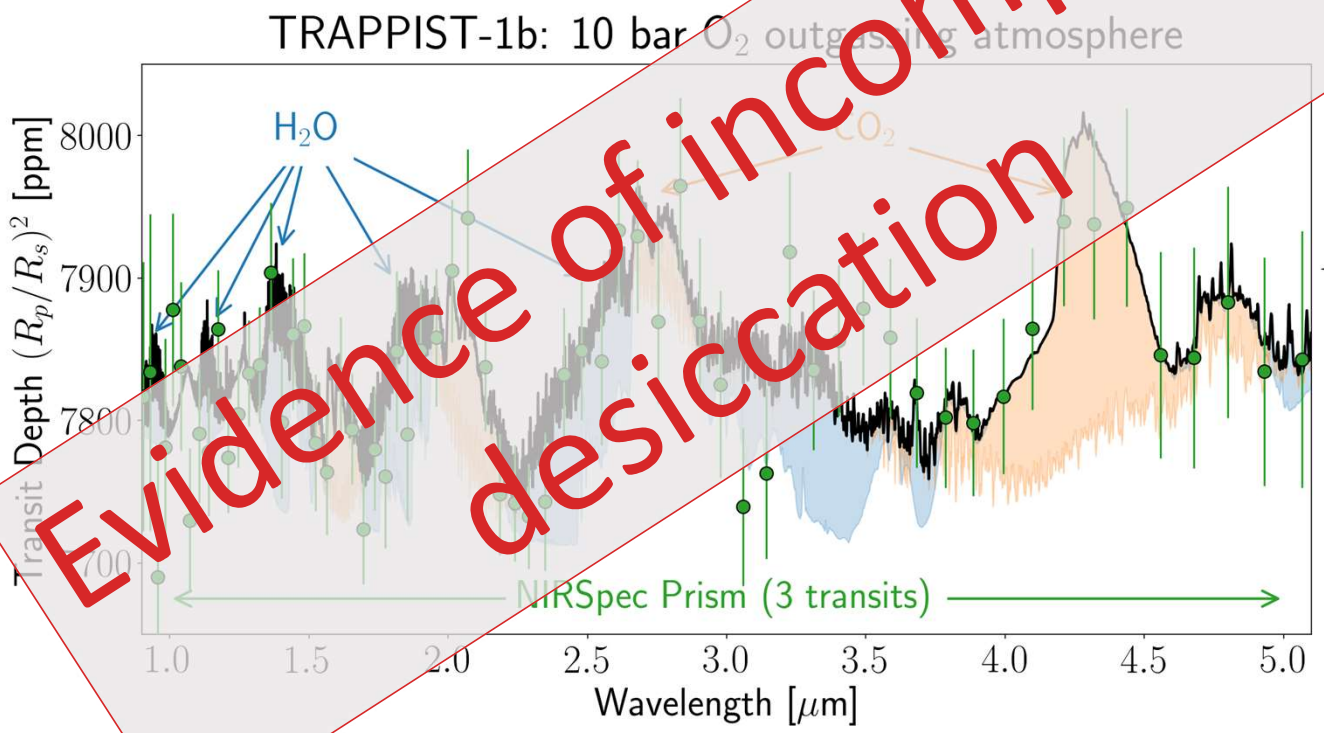


3 transits could reveal water in an oxygen atmosphere

Lustig-Yaeger et al. (2019)

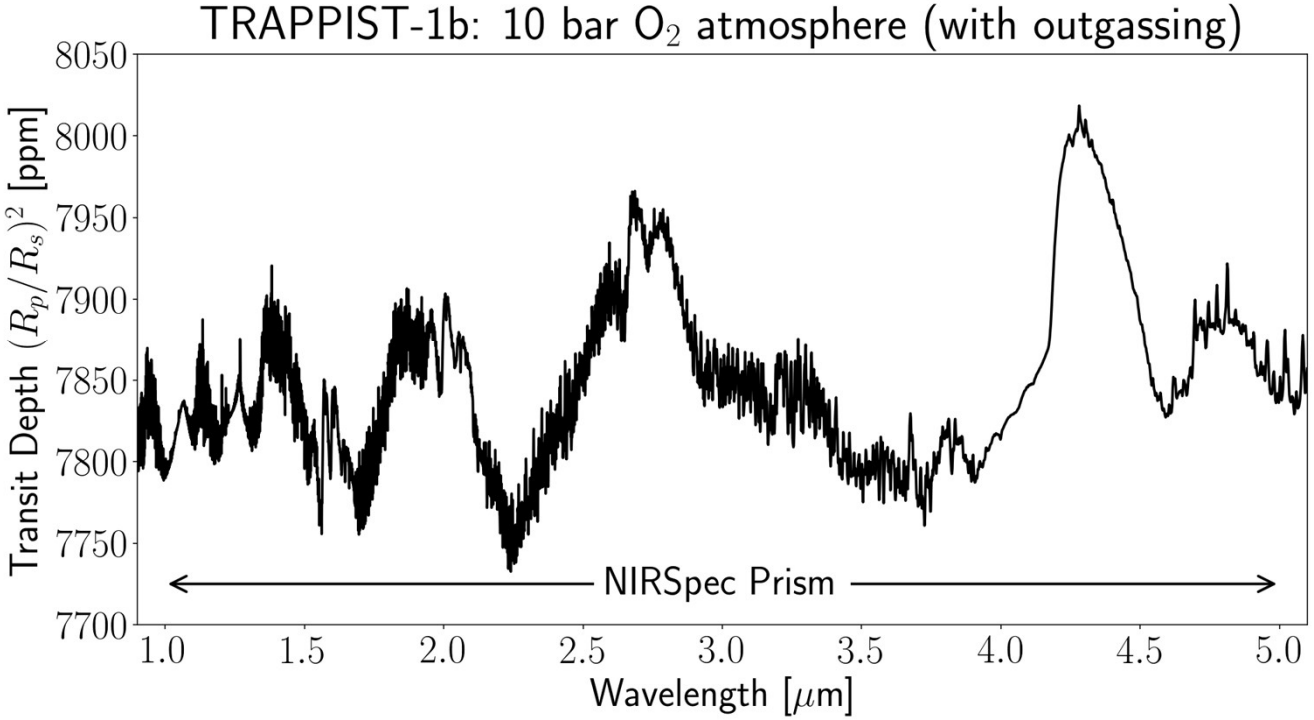
Water in an oxygen atmosphere could rule out complete interior and atmospheric desiccation



3 transits could reveal water in an oxygen atmosphere

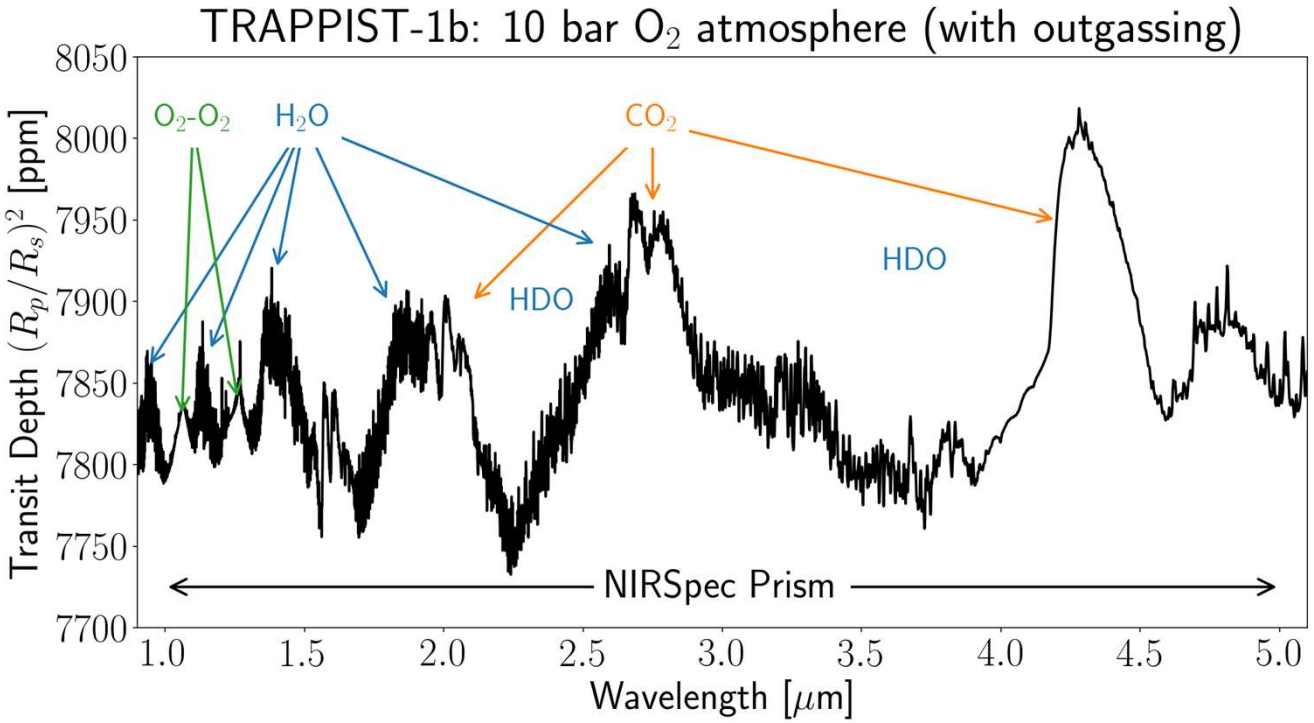
Evidence of incomplete desiccation

Isotopologue bands can reveal past atmospheric and ocean loss



Lincowski, Lustig-Yaeger, & Meadows (2019)

Isotopologue bands can reveal past atmospheric and ocean loss



Lincowski, Lustig-Yaeger, & Meadows (2019)

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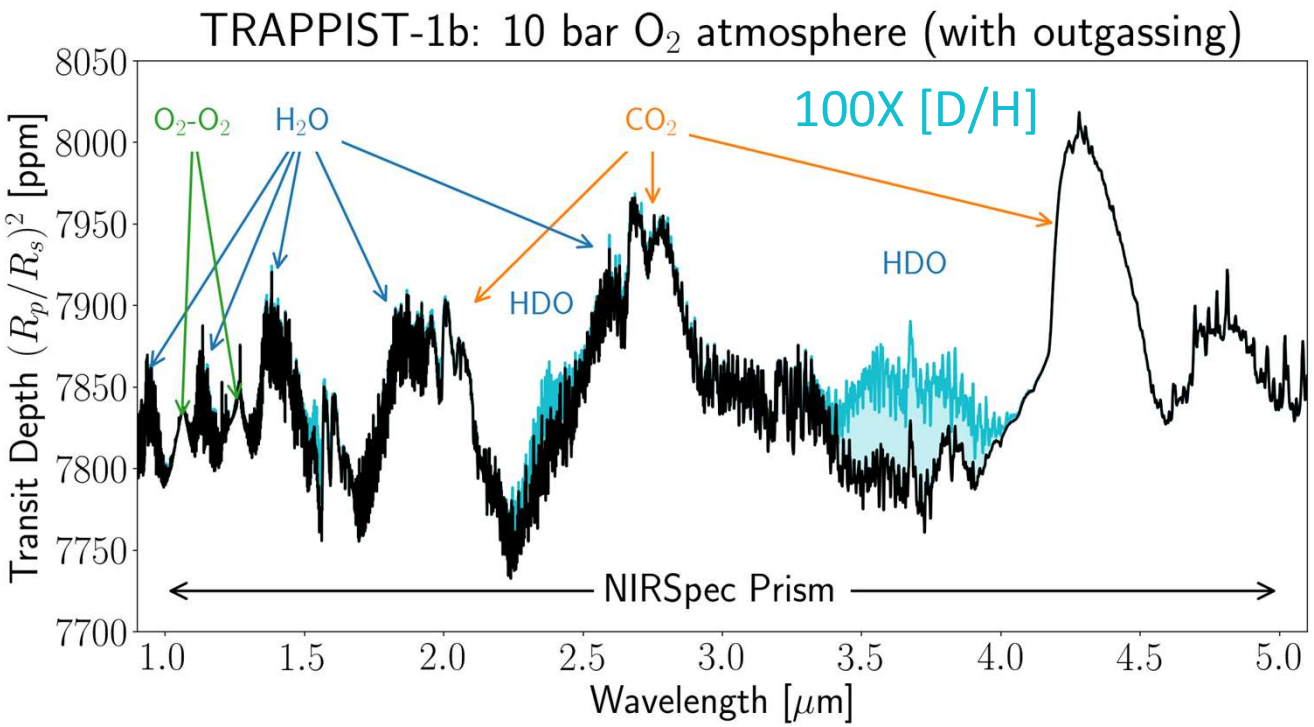
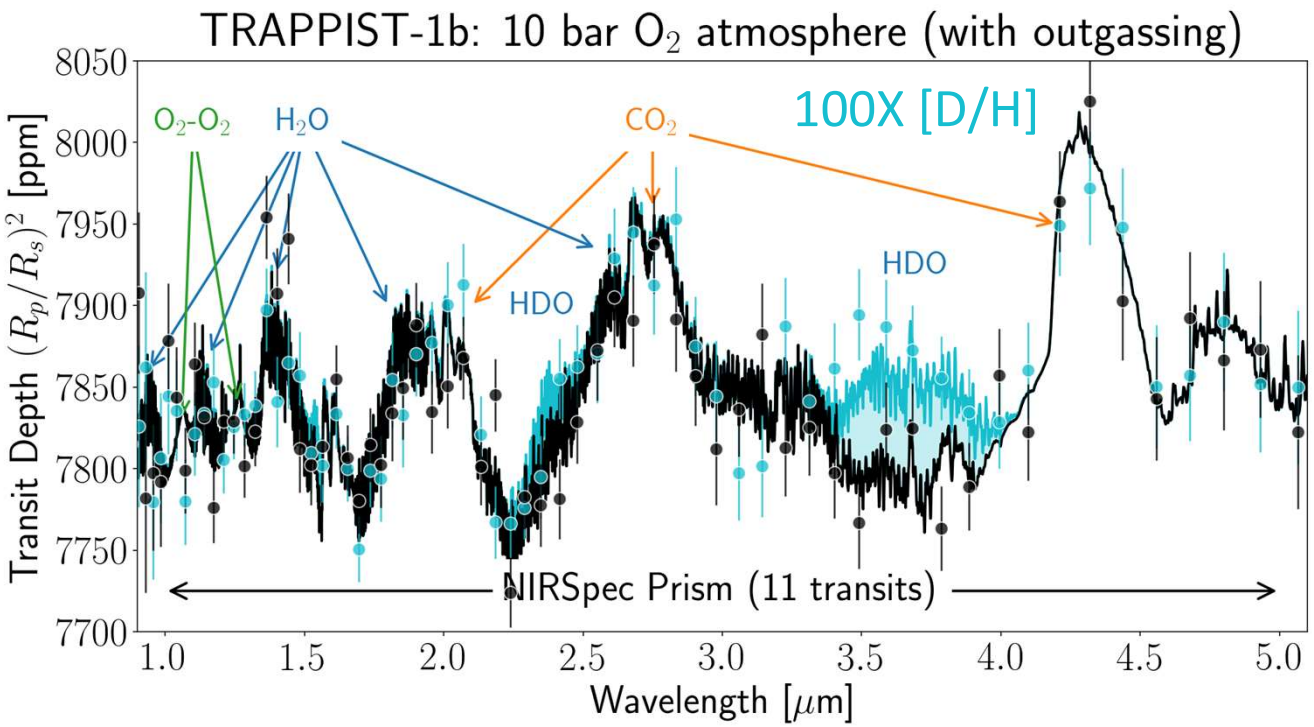


HDO bands at 2.4 and 3.7 µm have a non-negligible effect on the observable spectrum

Lincowski, Lustig-Yaeger, & Meadows (2019)

Isotopologue bands can reveal past atmospheric and ocean loss

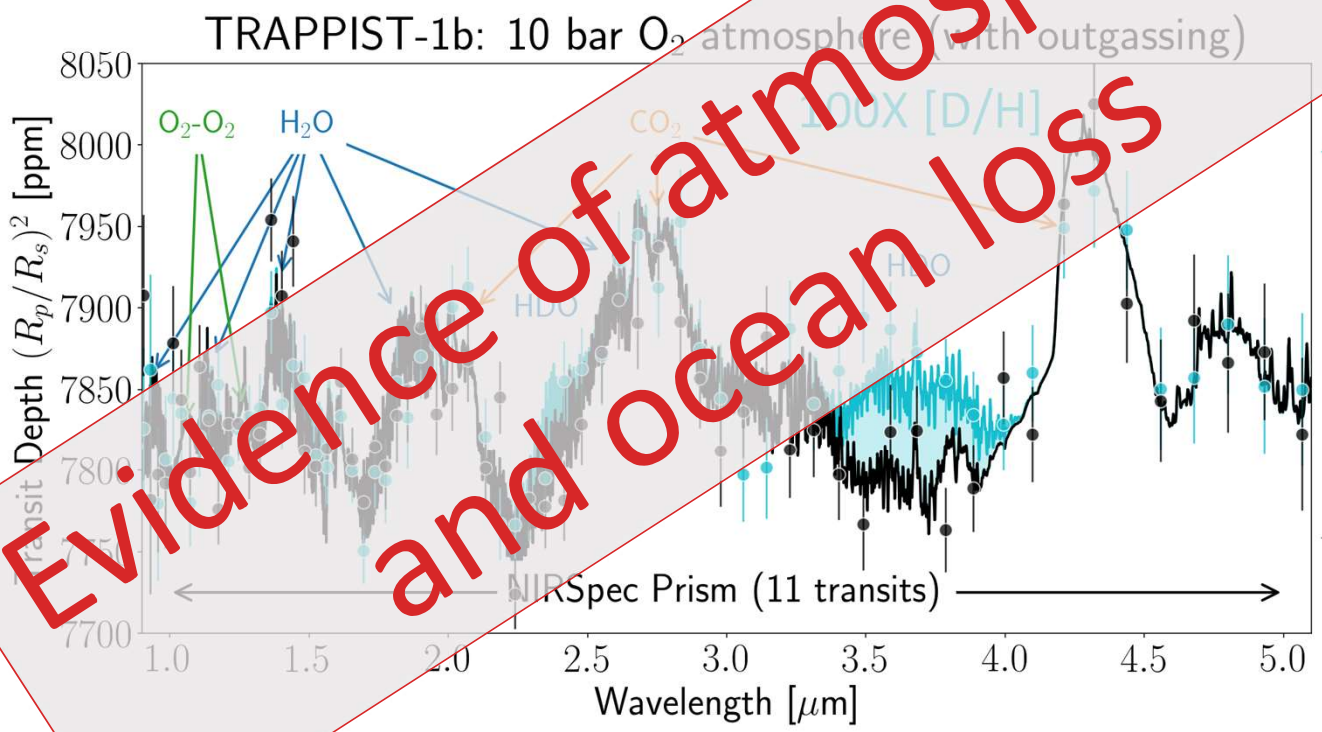


HDO bands at 2.4 and 3.7 µm have a non-negligible effect on the observable spectrum

11 transits could be sufficient to distinguish 100x D/H, similar to Venus

Lincowski, Lustig-Yaeger, & Meadows (2019)

Isotopologue bands can reveal past atmospheric and ocean loss



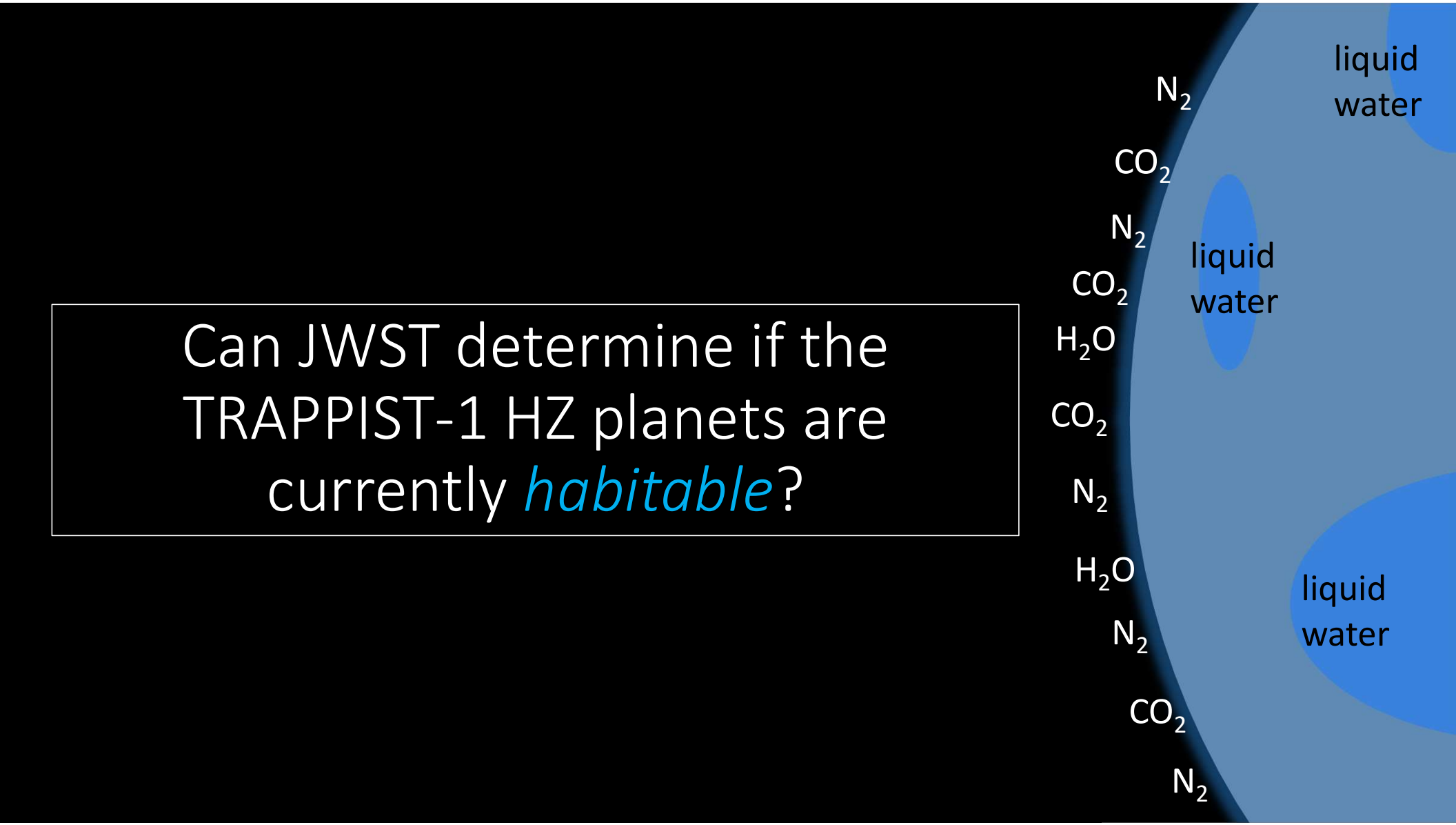
Evidence of atmospheric and ocean loss

HDO bands at 2.4 and 3.7 μm have a non-negligible effect on the observable spectrum

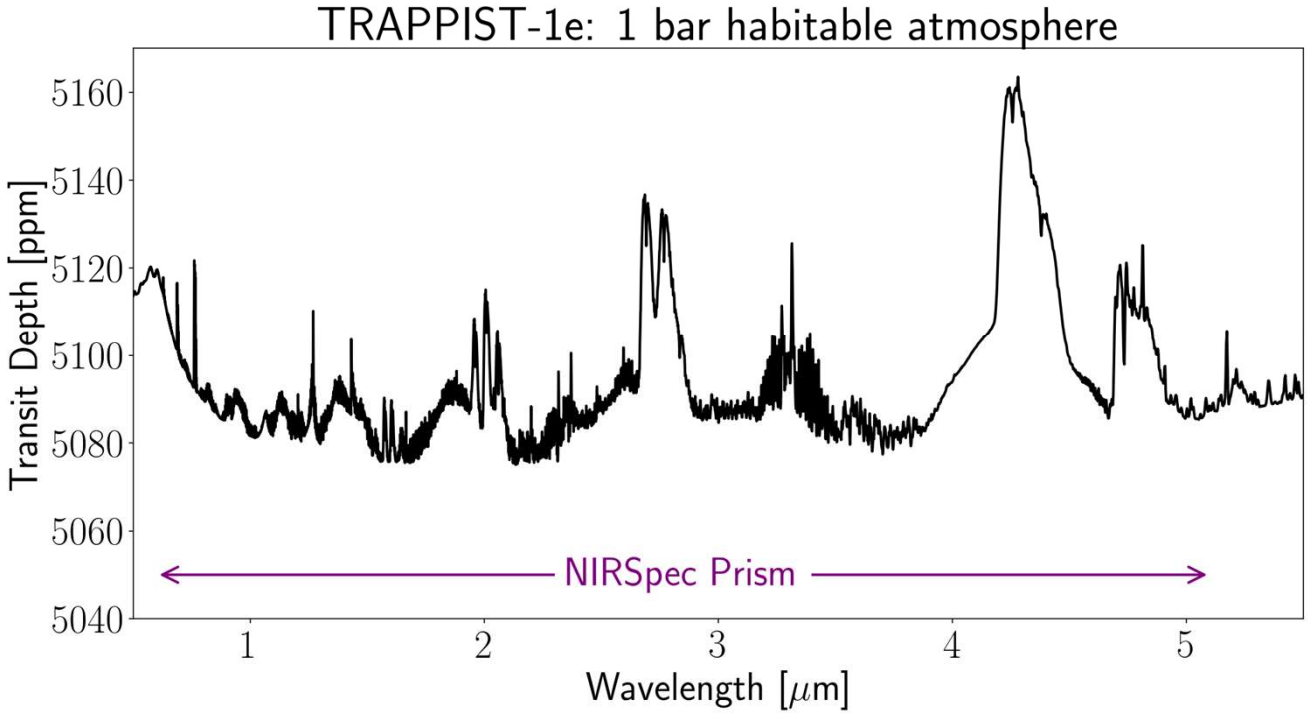
11 transits could be sufficient to distinguish such extreme D/H

See Lincowski, Lustig-Yaeger, & Meadows 2019

Can JWST determine if the TRAPPIST-1 HZ planets are currently *habitable*?

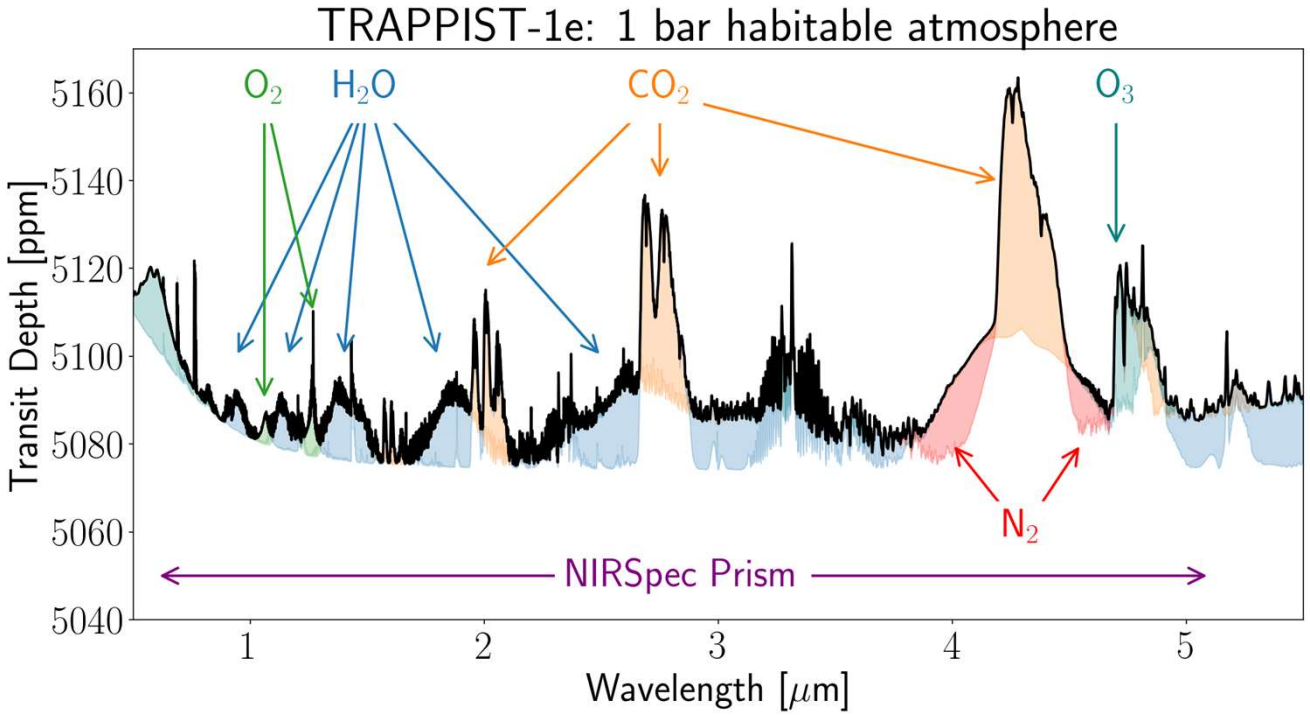


Detecting water in a habitable atmosphere



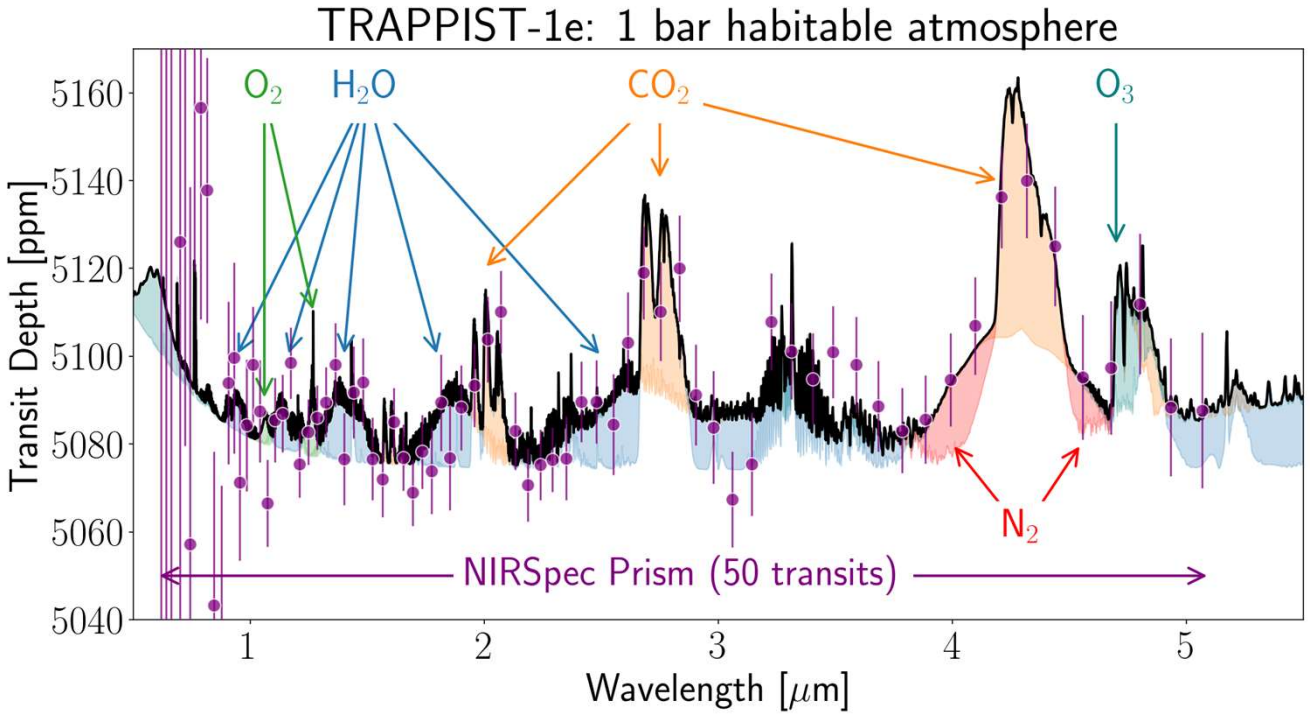
Lustig-Yaeger et al. (2019)

Detecting water in a habitable atmosphere



Lustig-Yaeger et al. (2019)

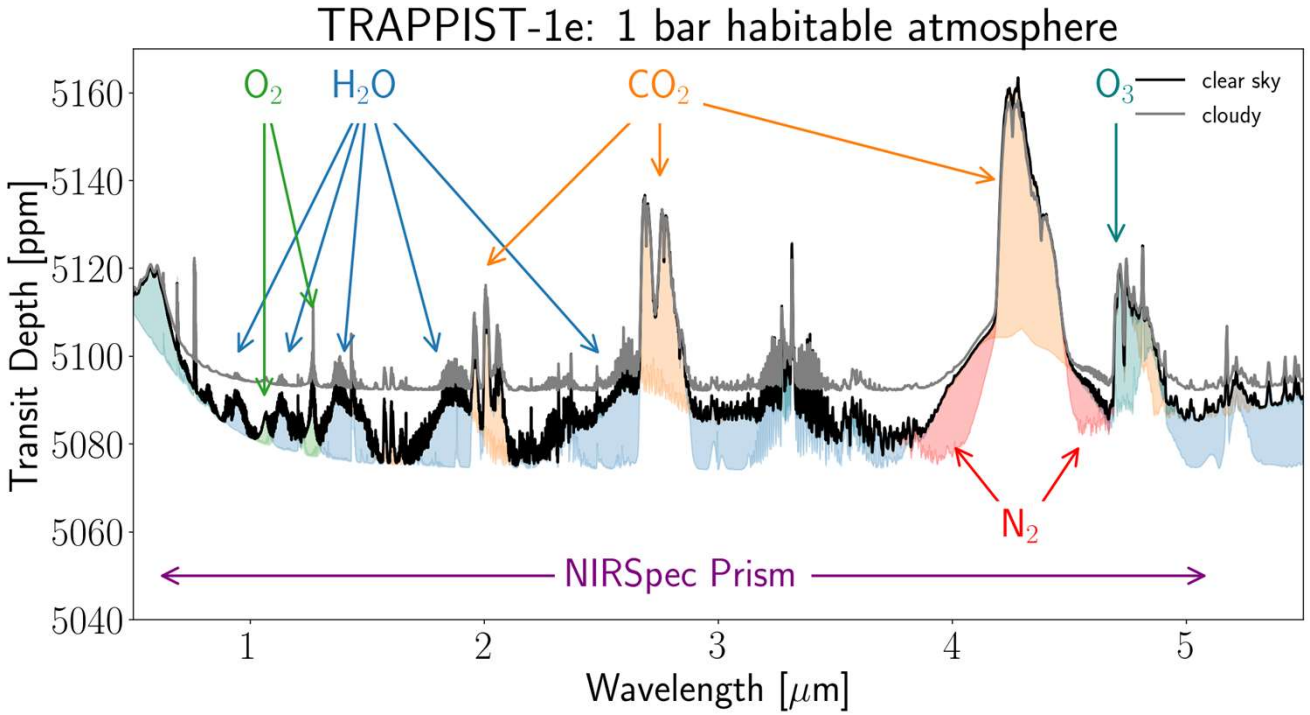
Detecting water in a habitable atmosphere may be difficult



50 transits may reveal H_2O in a cloud free habitable atmosphere

Lustig-Yaeger et al. (2019)

Detecting water in a habitable atmosphere may be difficult, and will depend on clouds



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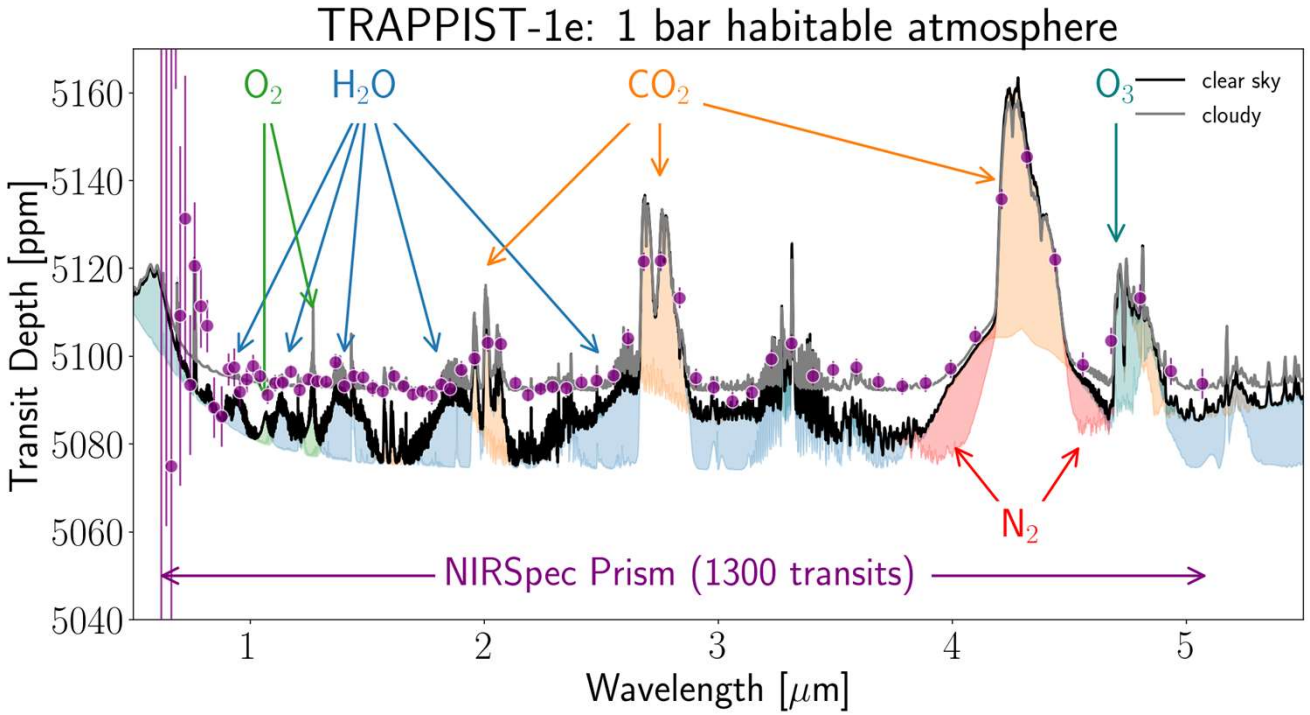
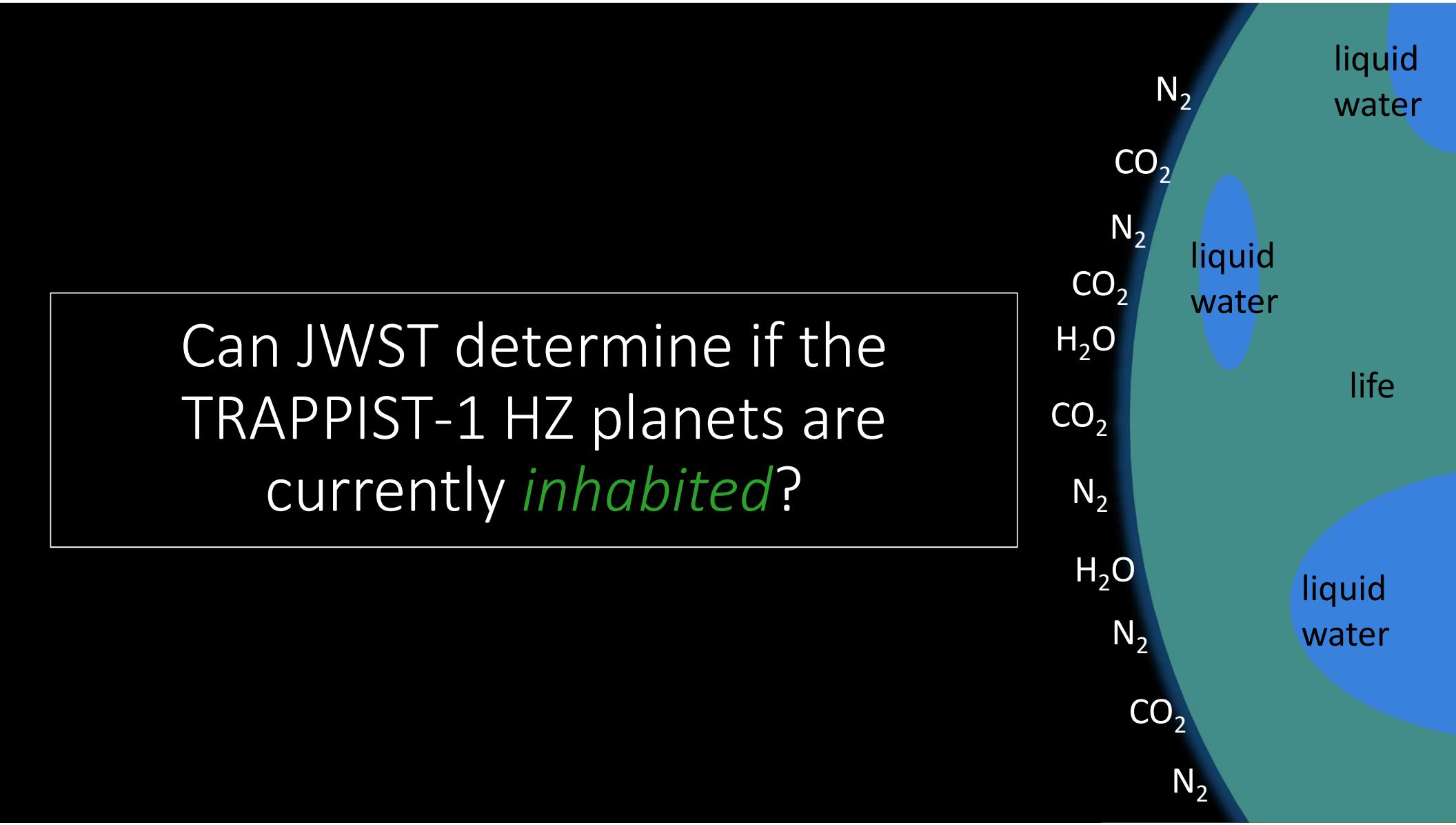


1300(!) transits needed to detect H_2O if 100% cloudy

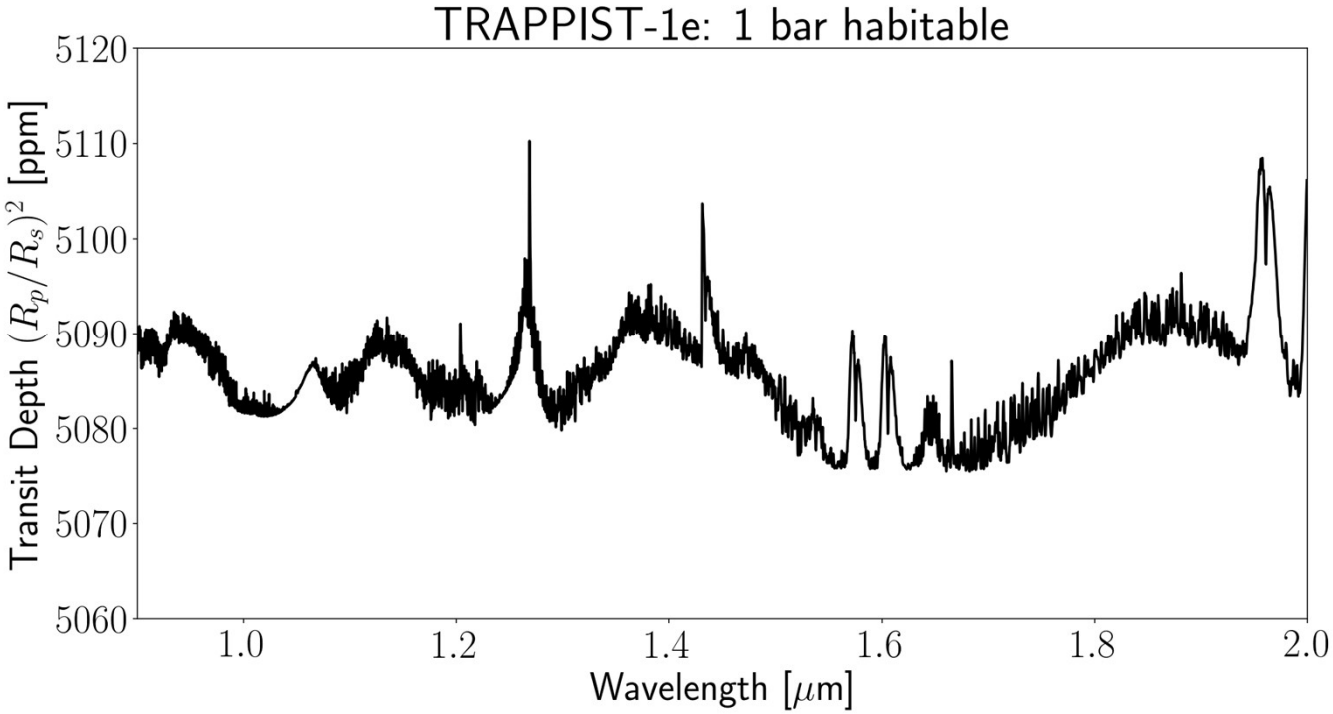
50 transits may reveal H_2O in a cloud free habitable atmosphere

Lustig-Yaeger et al. (2019)

Can JWST determine if the TRAPPIST-1 HZ planets are currently *inhabited*?



Detecting Modern Earth levels of O_2



Lustig-Yaeger et al. (2019)

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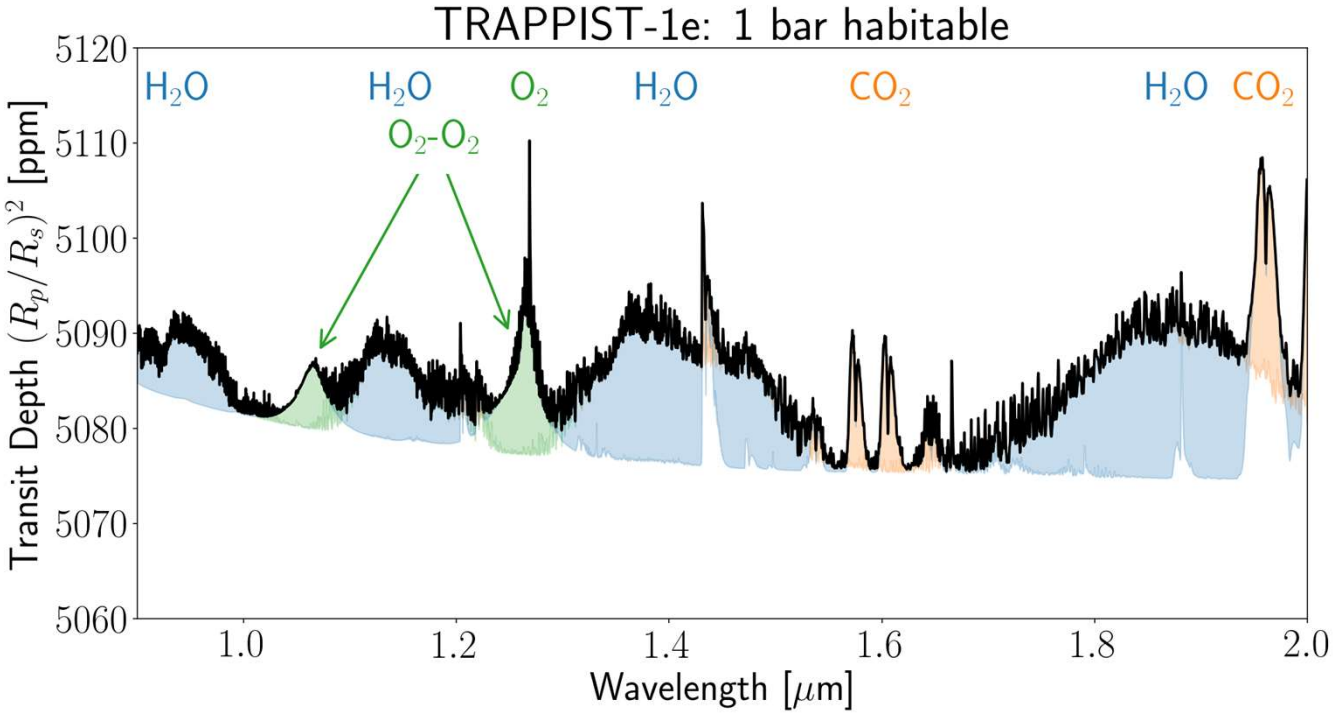
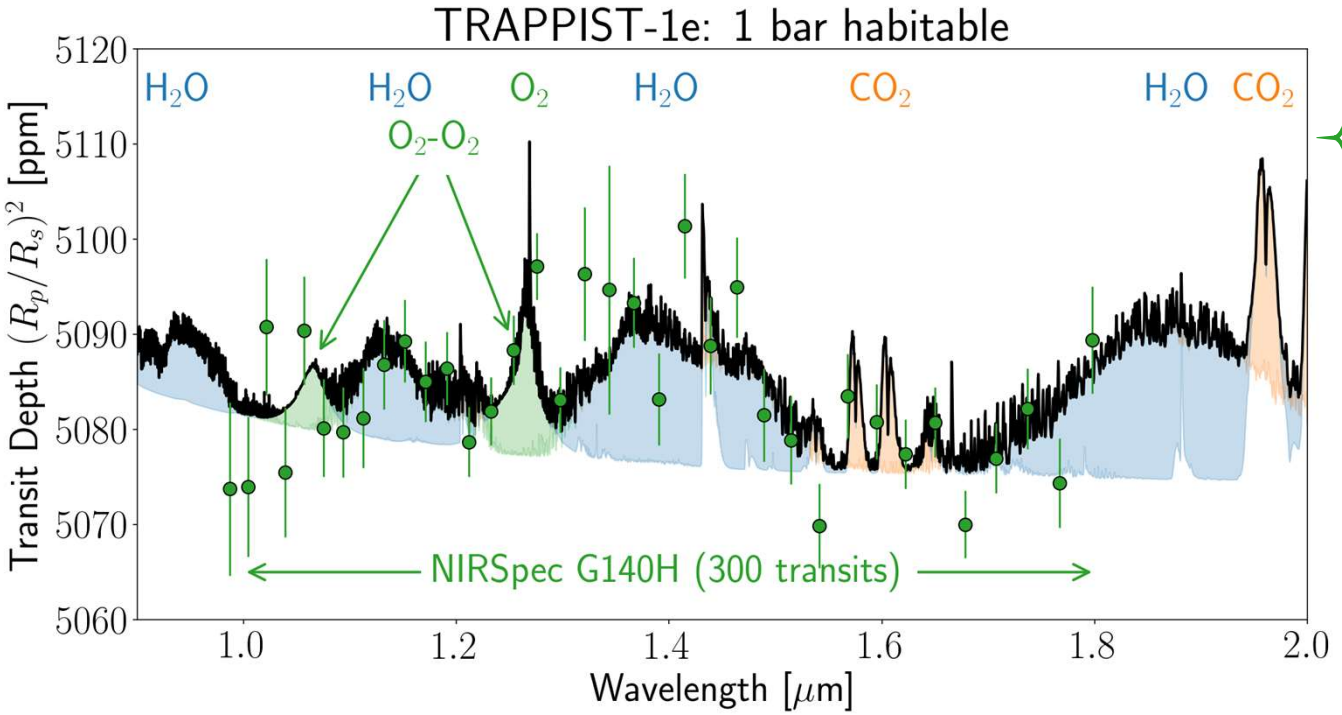


Lustig-Yaeger et al. (2019)

Detecting Modern Earth levels of O_2 may be infeasible



300 transits are needed to reveal 20% O_2 in a 1 bar N_2-dominated atmosphere

Lustig-Yaeger et al. (2019)

Conclusions

- JWST should be able to **detect** different plausible terrestrial atmospheres for all of the TRAPPIST-1 planets in about 10 transits, but up to 30 transits may be required if **clouds** are present
- CO_2 is a strong spectroscopic indicator of a terrestrial atmosphere, but a weak discriminator between atmospheric compositions
- H_2O as a weak indicator of habitability may be detectable for TRAPPIST-1e if the terminator has << 100% cloud coverage
- O_2 as a biosignature is unlikely to be detectable with JWST, but O_4 (O_2-O_2 CIA) may be detectable and would indicate an O_2-dominated post-ocean-loss atmosphere

Detecting and Characterizing Terrestrial Atmospheres in the TRAPPIST-1 System with JWST

Jacob Lustig-Yaeger

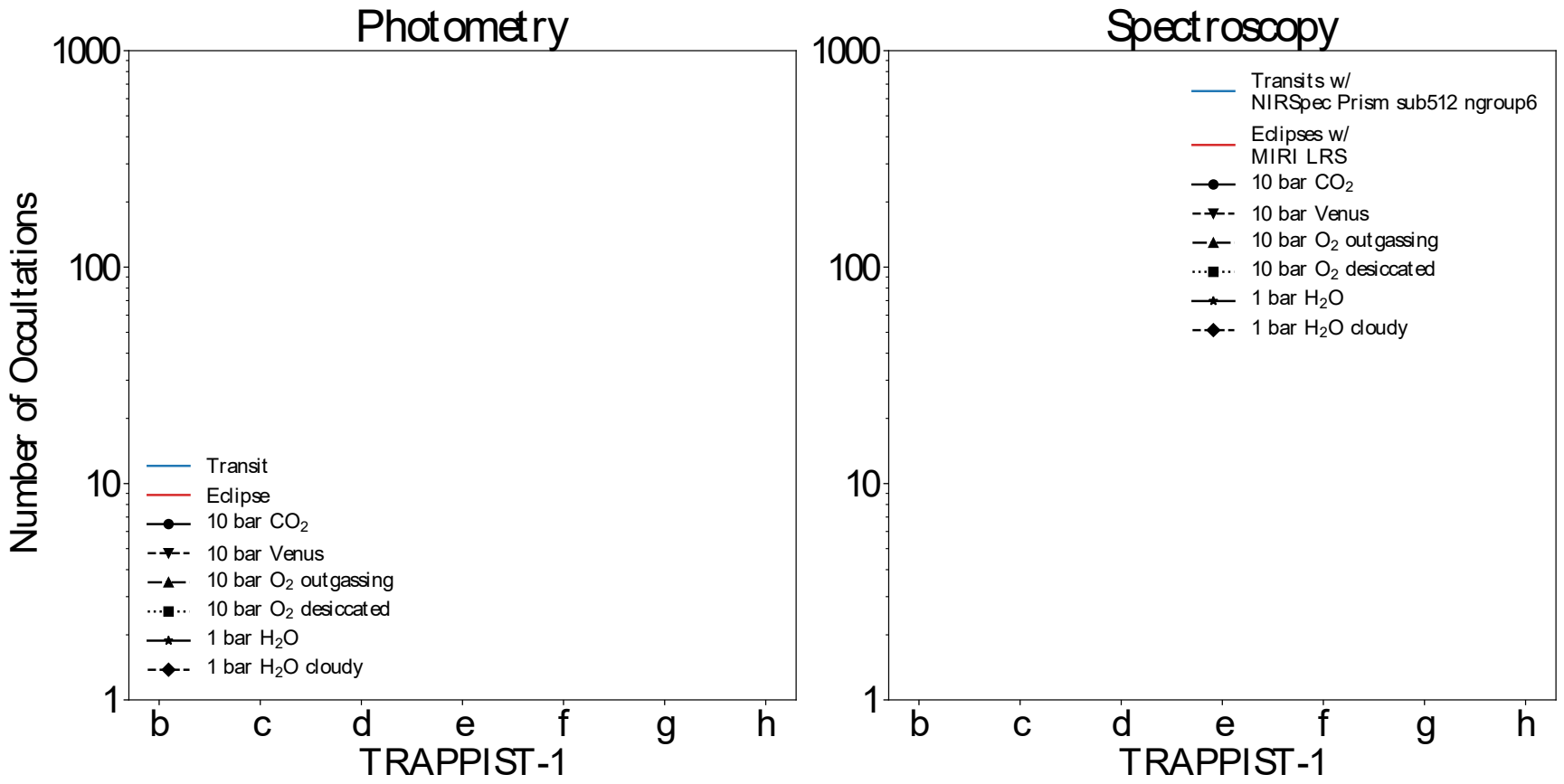
Victoria Meadows & Andrew Lincowski

Astronomy & Astrobiology, University of Washington

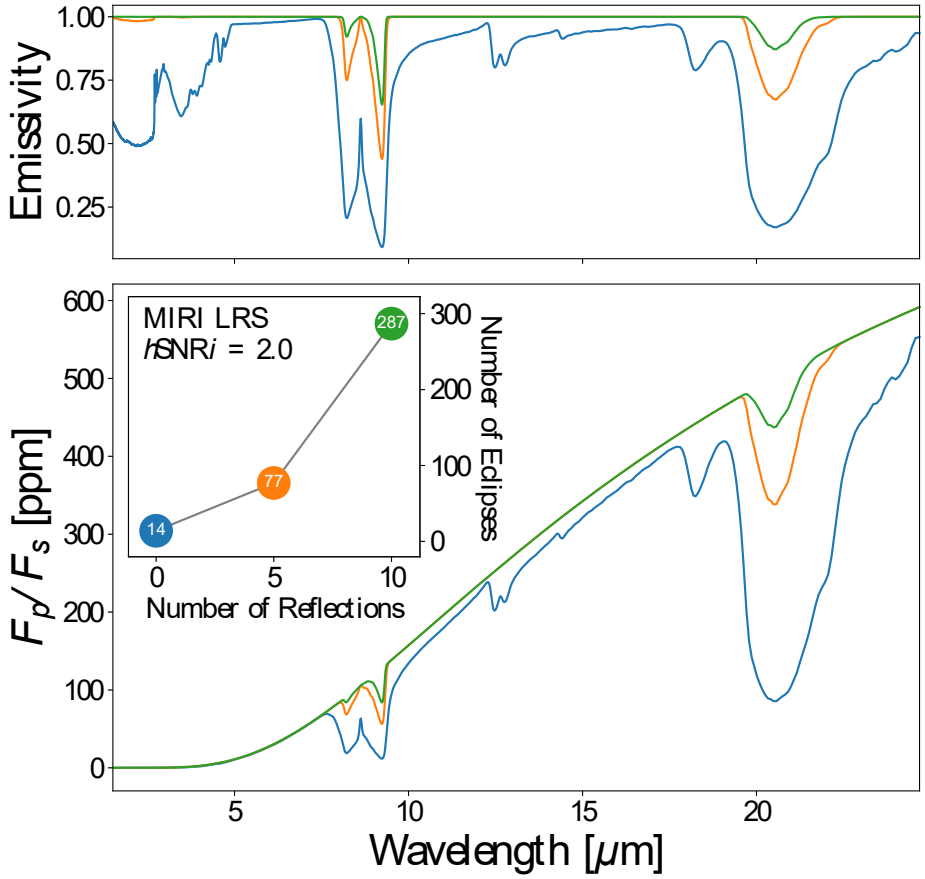
Virtual Planetary Laboratory

Image credit: NASA

Detecting Atmospheres: Photometry vs. Spectroscopy

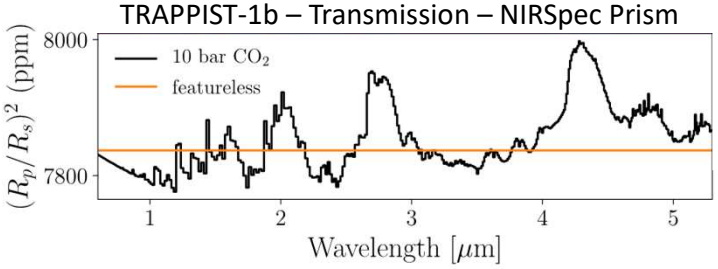


Do airless planets have featureless secondary eclipse spectra?

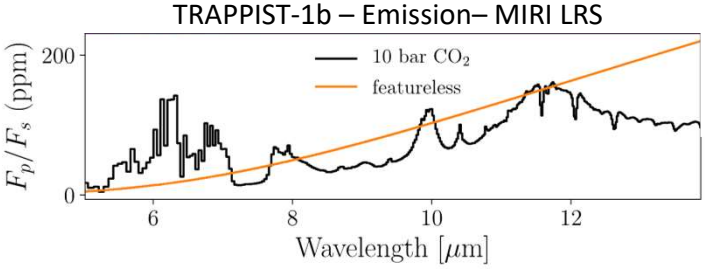


Approach: Transmission vs Emission for JWST observations of the TRAPPIST-1 planets

TRAPPIST-1b – Transmission – NIRSpec Prism



TRAPPIST-1b – Emission– MIRI LRS



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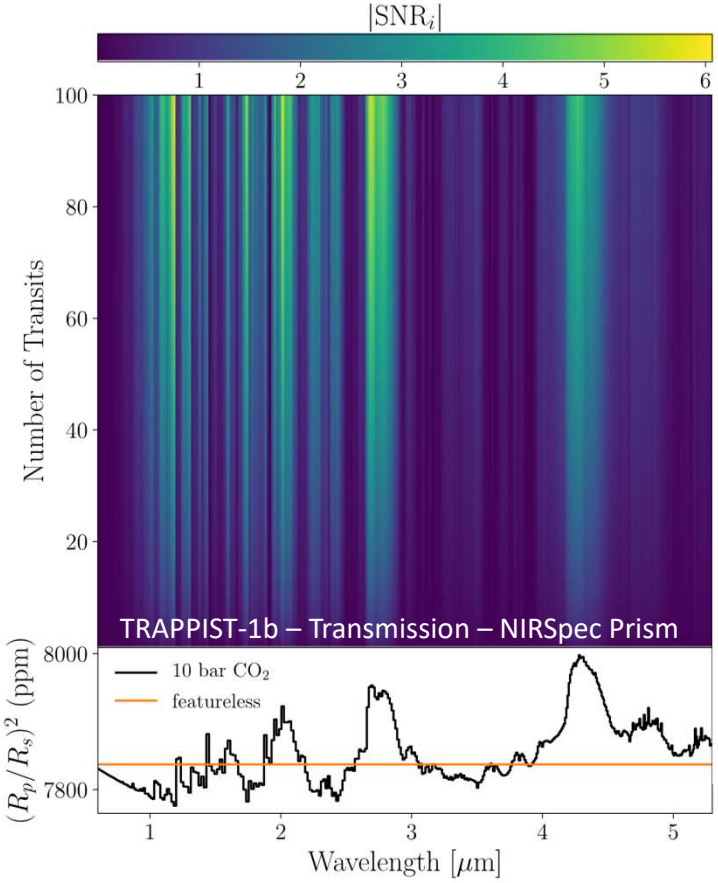

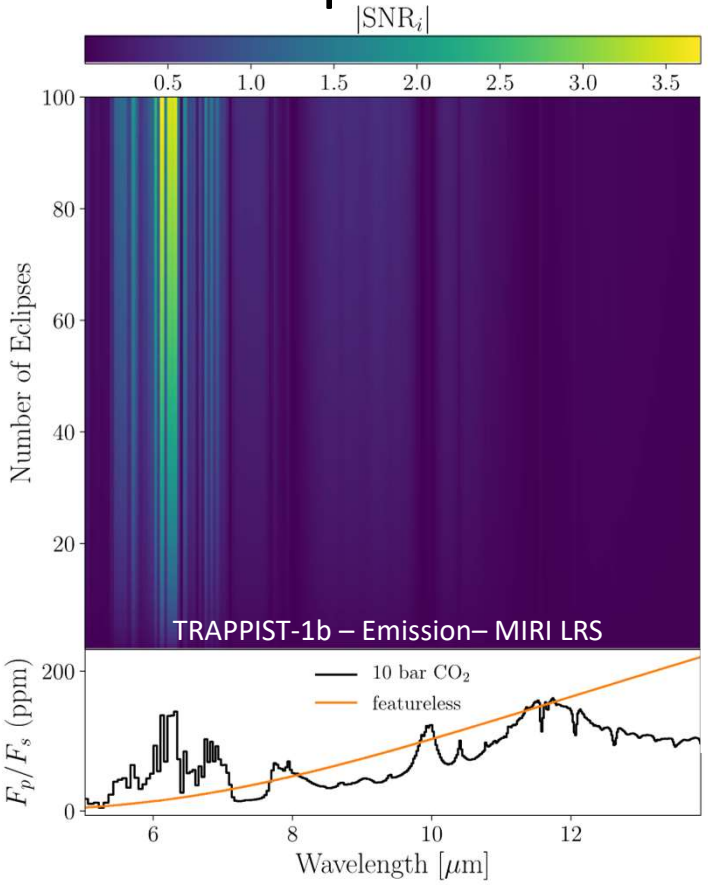

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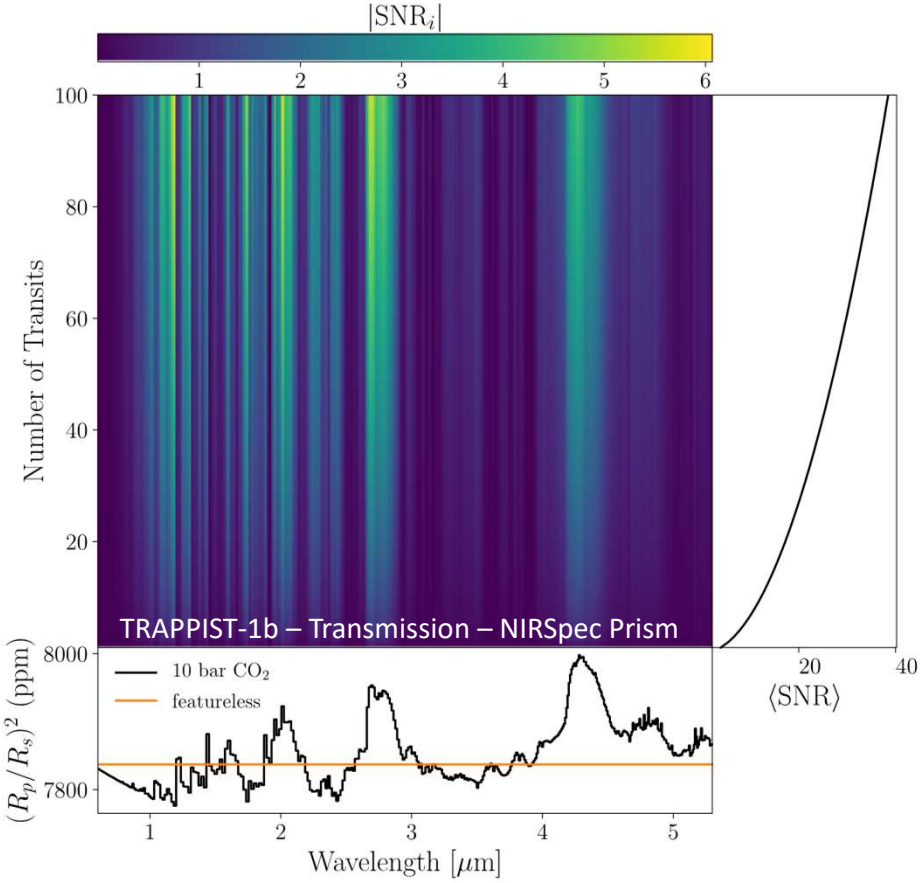
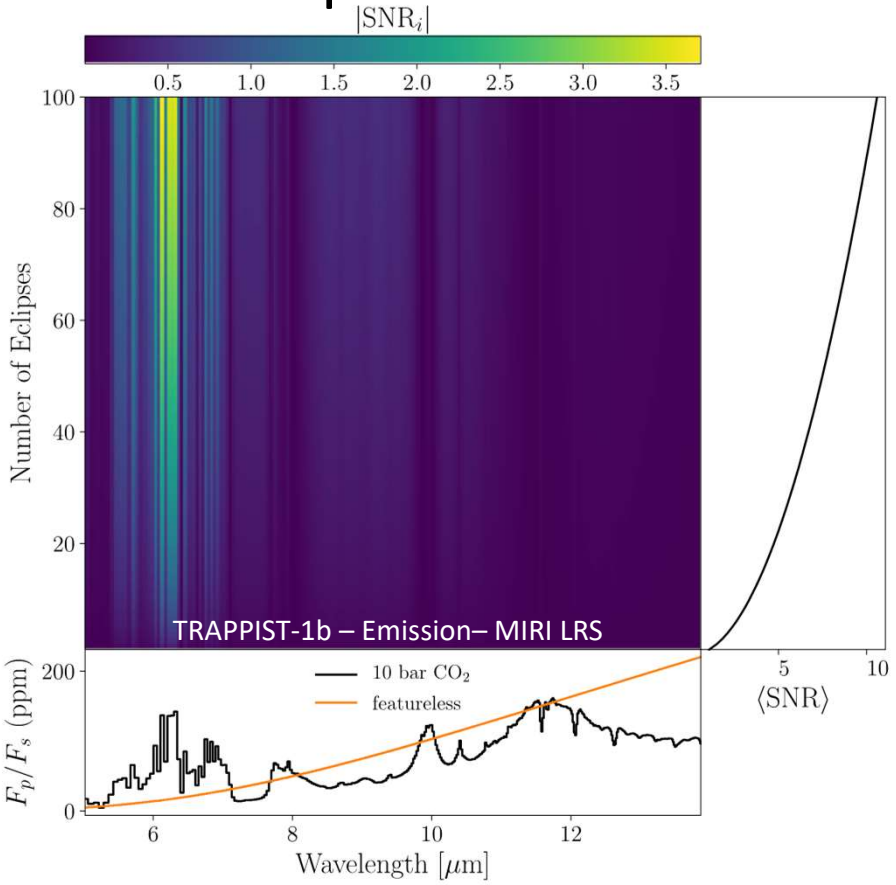
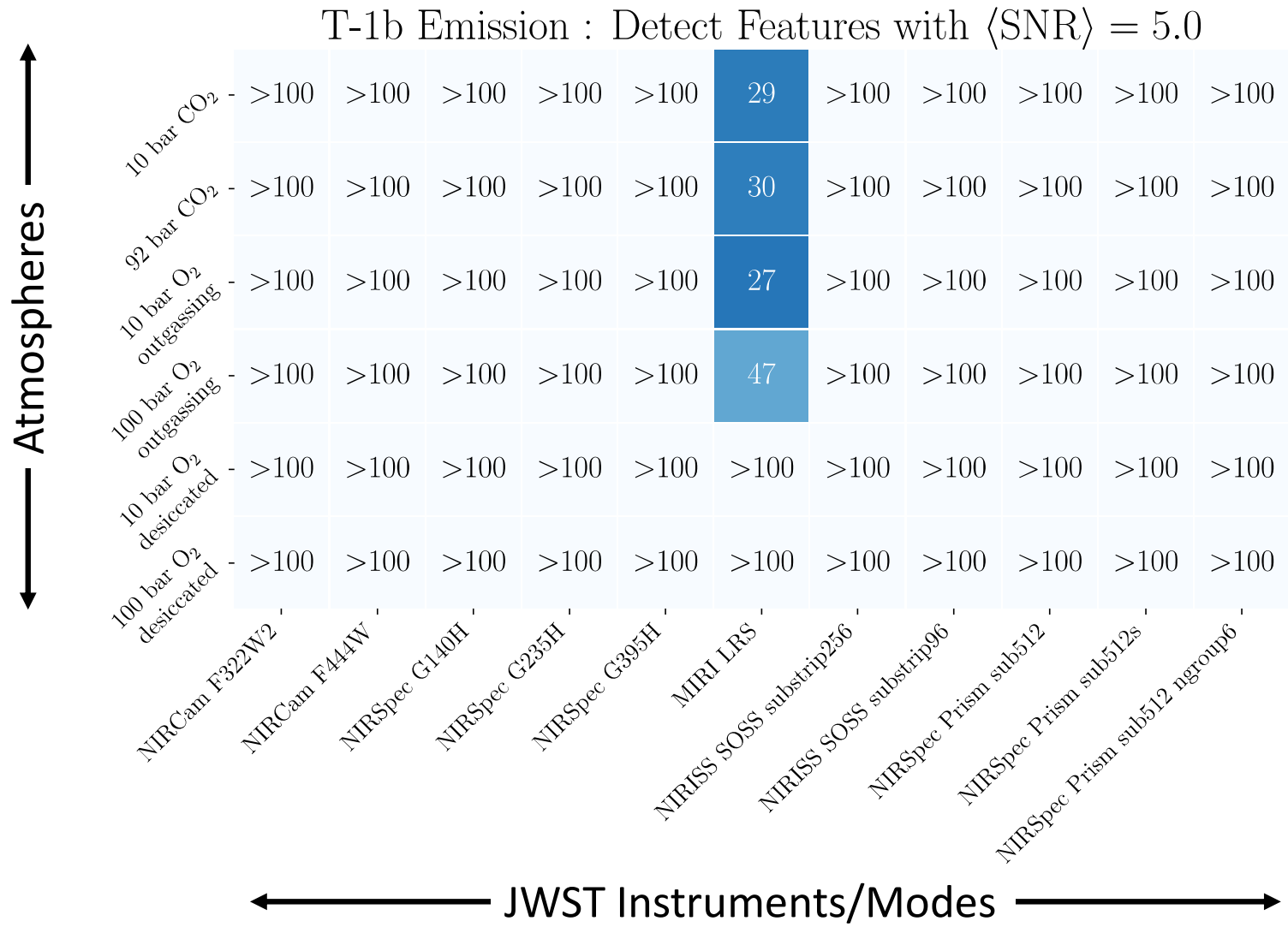
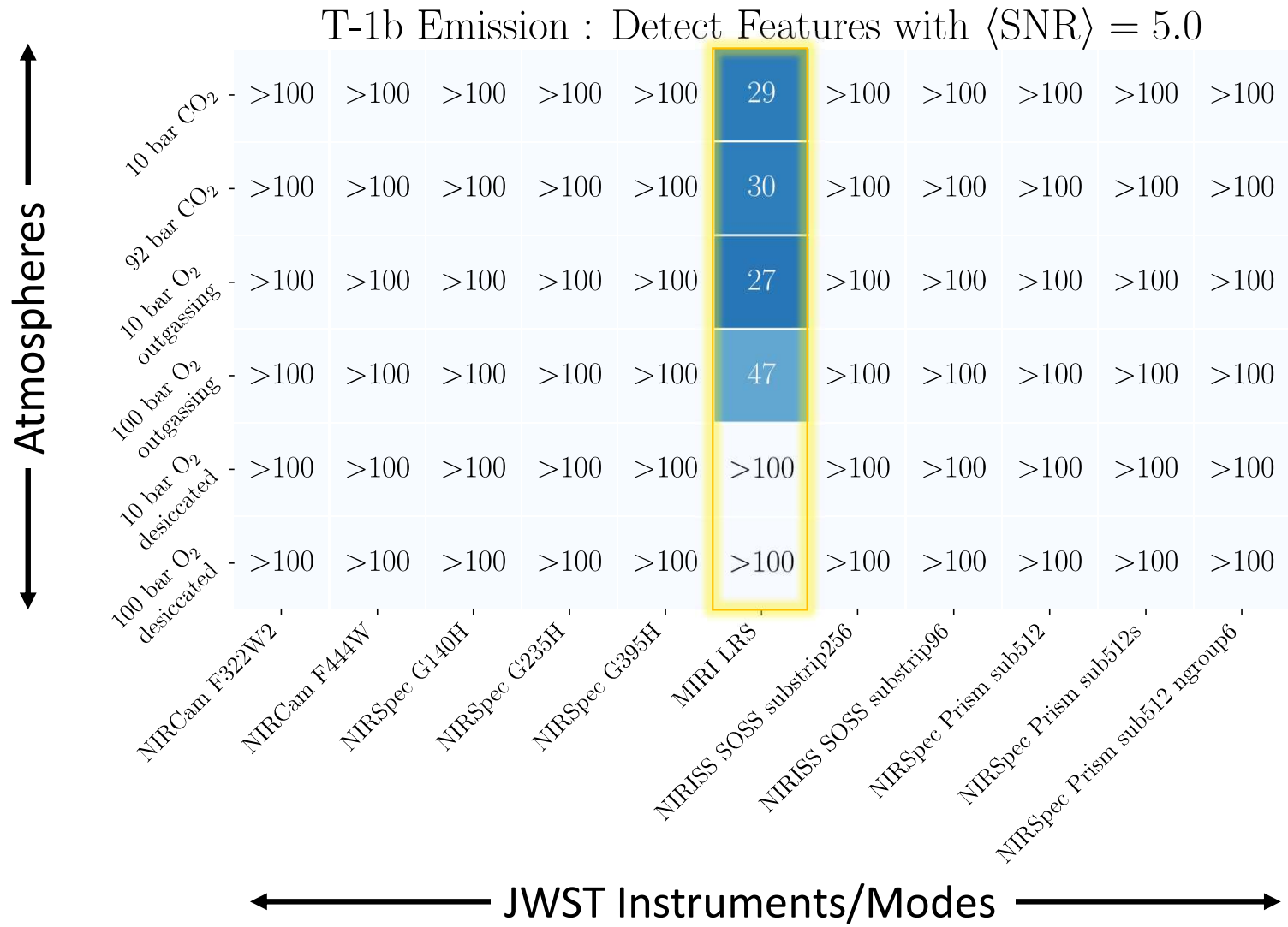





T-1b Emission : Detect Features with ⟨SNR⟩ = 5.0
Atmospheres
JWST Instruments/Modes
10 bar CO2
92 bar CO2
10 bar O2 outgassing
100 bar O2 outgassing
10 bar O2 desiccated
100 bar O2 desiccated
NIRCam F322W2
NIRCam F444W
NIRSpec G140H
NIRSpec G235H
NIRSpec G395H
MIRI LRS
NIRISS SOSS substrip256
NIRISS SOSS substrip96
NIRSpec Prism sub512
NIRSpec Prism sub512s
NIRSpec Prism sub512 ngroup6
>100
29
30
27
47


T-1b Emission : Detect Features with ⟨SNR⟩ = 5.0
Atmospheres
JWST Instruments/Modes
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10 bar O2 outgassing
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10 bar O2 desiccated
100 bar O2 desiccated
NIRCam F322W2
NIRCam F444W
NIRSpec G140H
NIRSpec G235H
NIRSpec G395H
MIRI LRS
NIRISS SOSS substrip256
NIRISS SOSS substrip96
NIRSpec Prism sub512
NIRSpec Prism sub512s
NIRSpec Prism sub512 ngroup6
>100 >100 >100 >100 >100 29 >100 >100 >100 >100 >100
>100 >100 >100 >100 >100 30 >100 >100 >100 >100 >100
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>100 >100 >100 >100 >100 >100 >100 >100 >100 >100 >100
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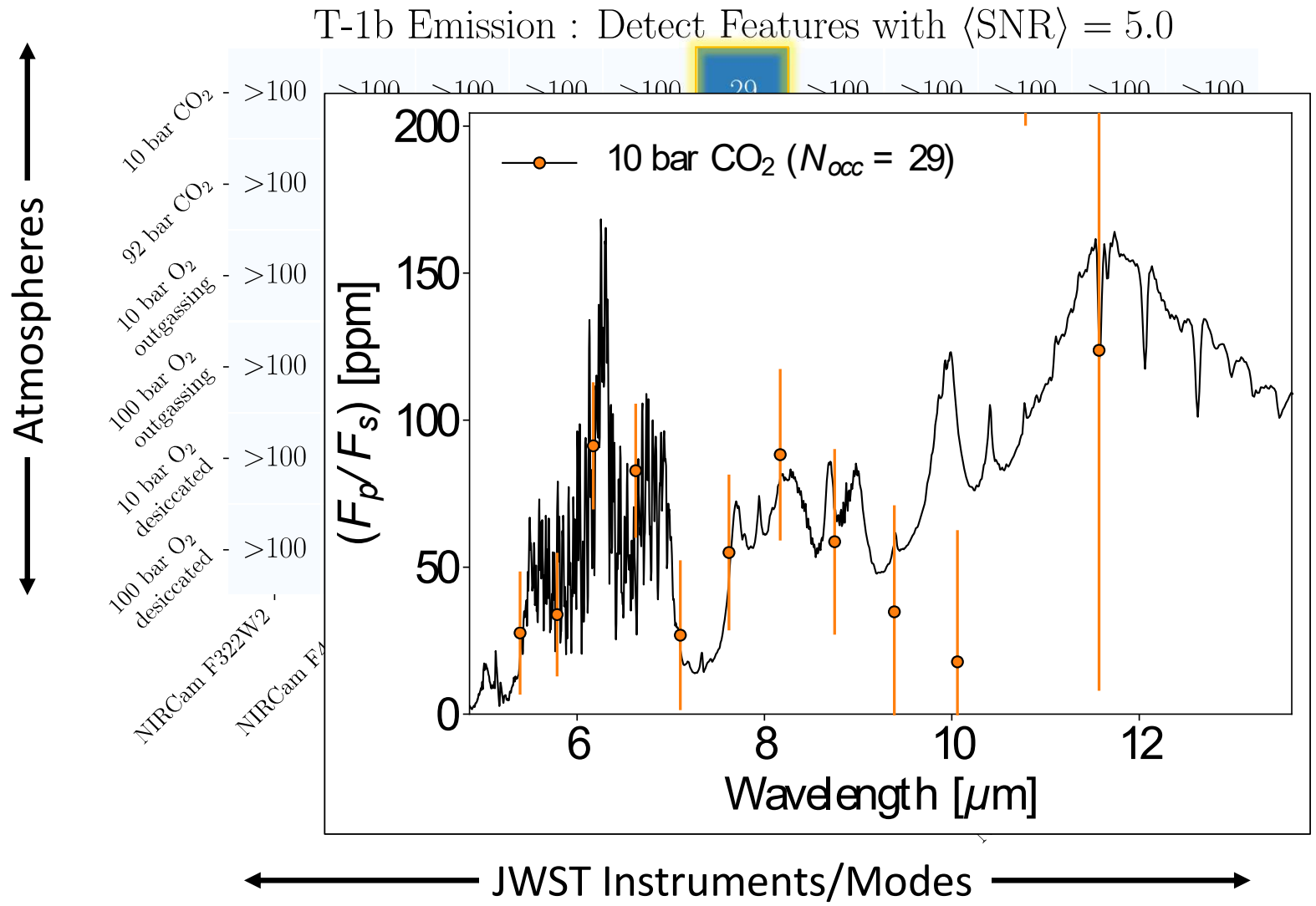
T-1b Emission : Detect Features with ⟨SNR⟩ = 5.0
Atmospheres
10 bar CO2
92 bar CO2
10 bar O2 outgassing
100 bar O2 outgassing
10 bar O2 desiccated
100 bar O2 desiccated
>100
29
NIRCam F322W2
10 bar CO2 (Nocc = 29)
(Fp/Fs) [ppm]
Wavelength [μm]
JWST Instruments/Modes