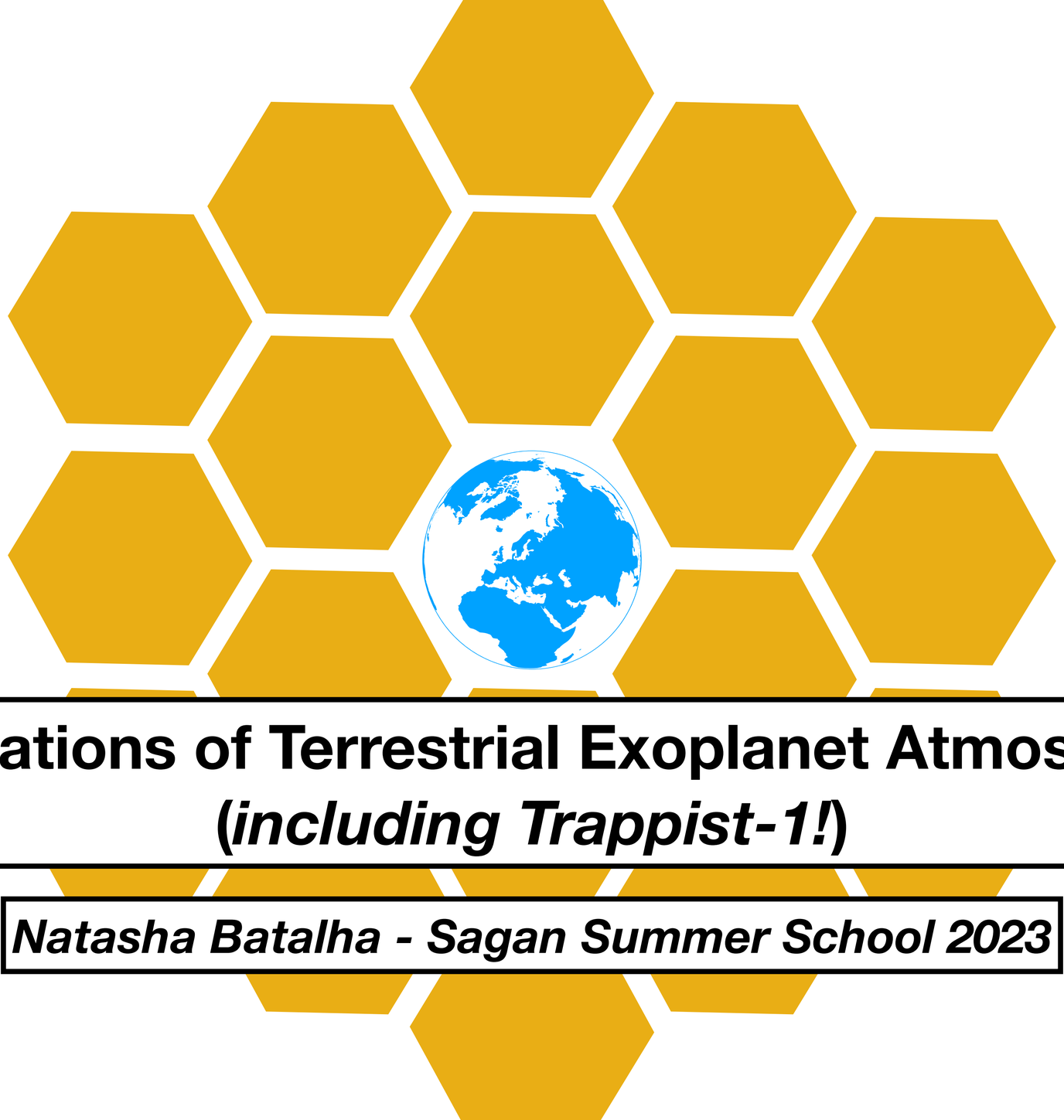
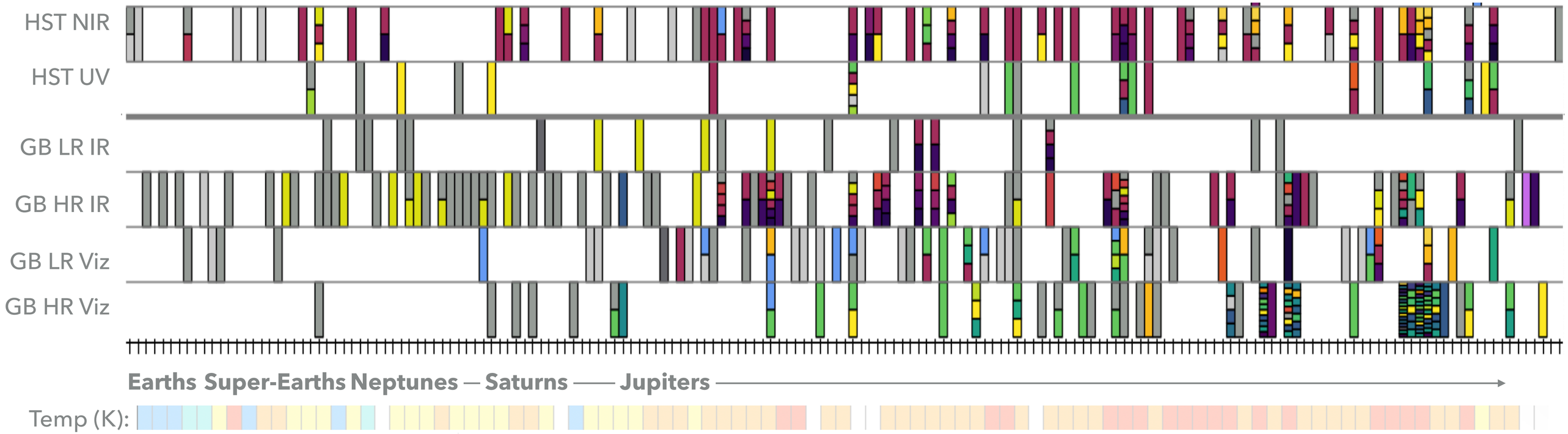
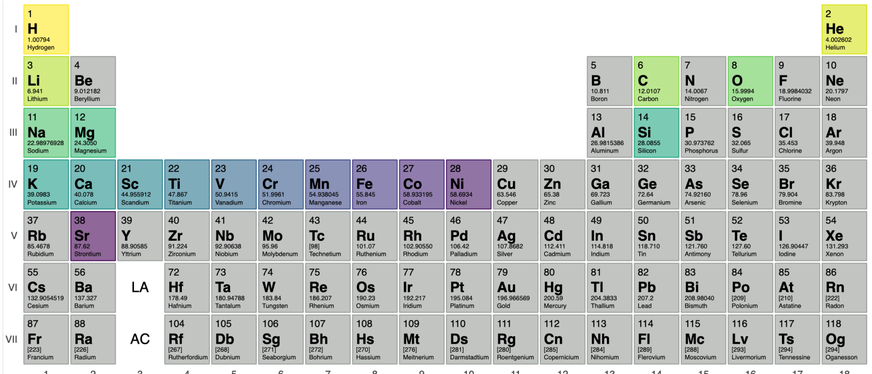


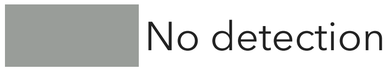
Observations of Terrestrial Exoplanet Atmospheres (*including Trappist-1!*)

Natasha Batalha - Sagan Summer School 2023

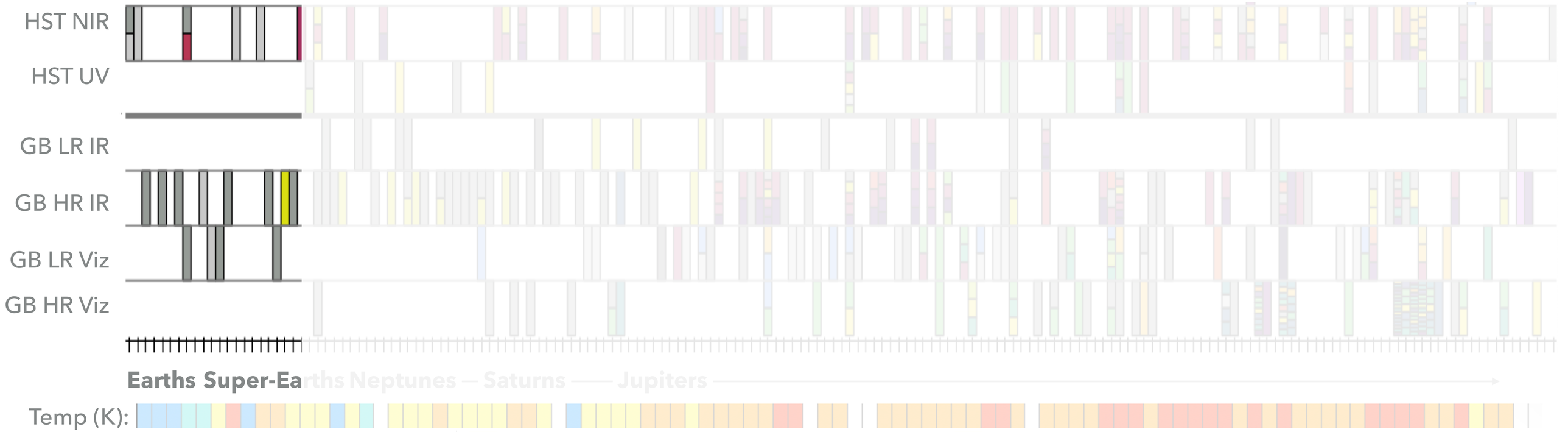
Previous observations of exoplanets have yielded tremendous chemical diversity

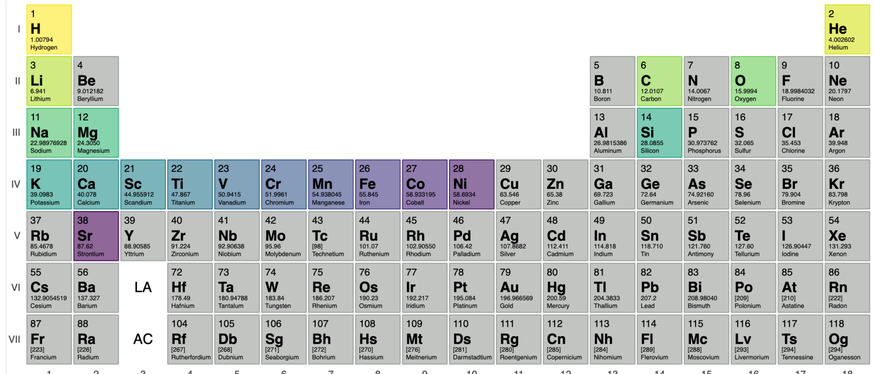




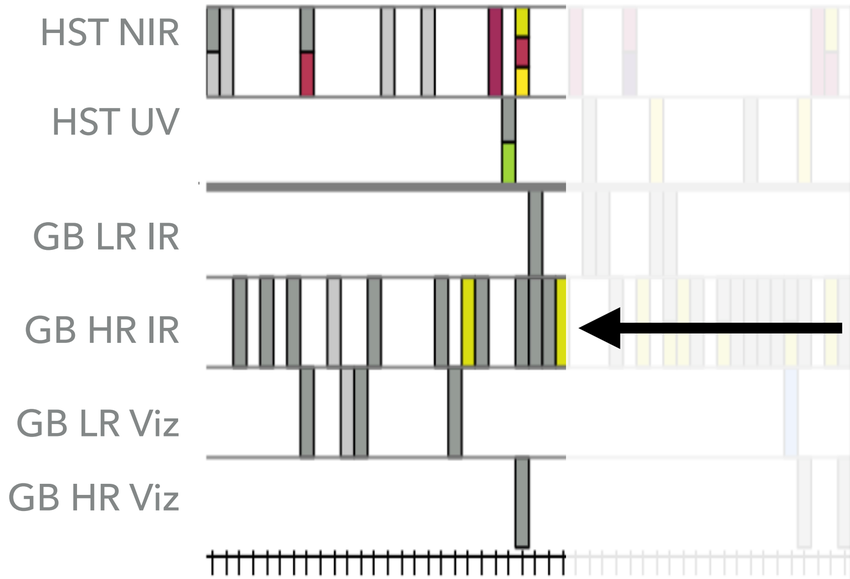


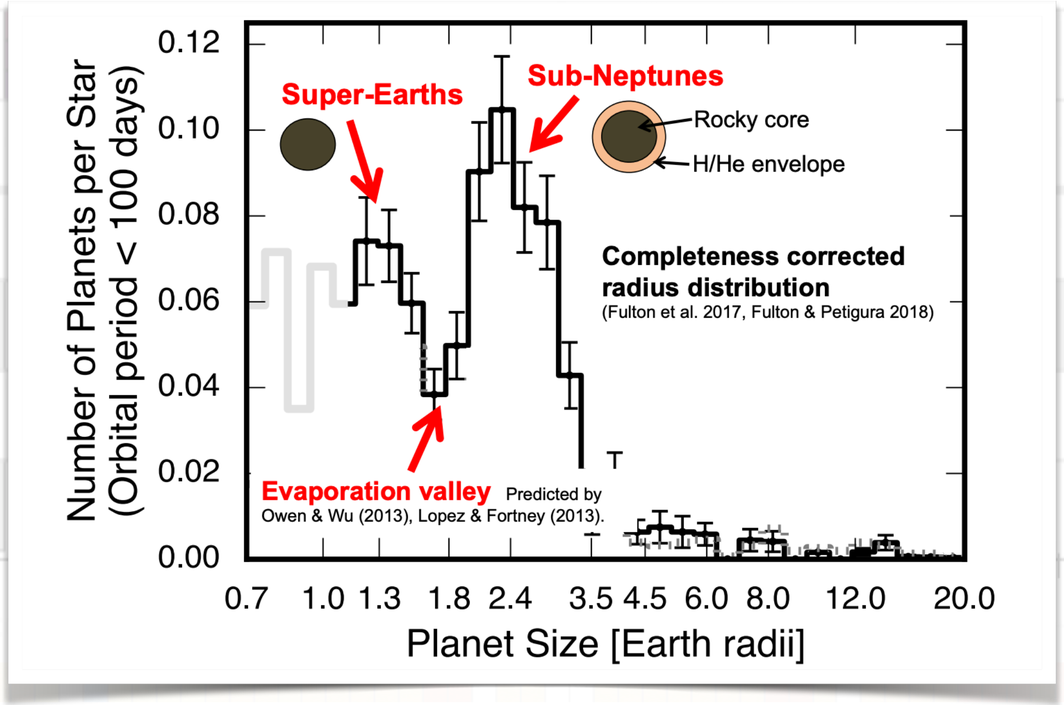
But what about for terrestrial planets only?





But what about for terrestrial planets only?



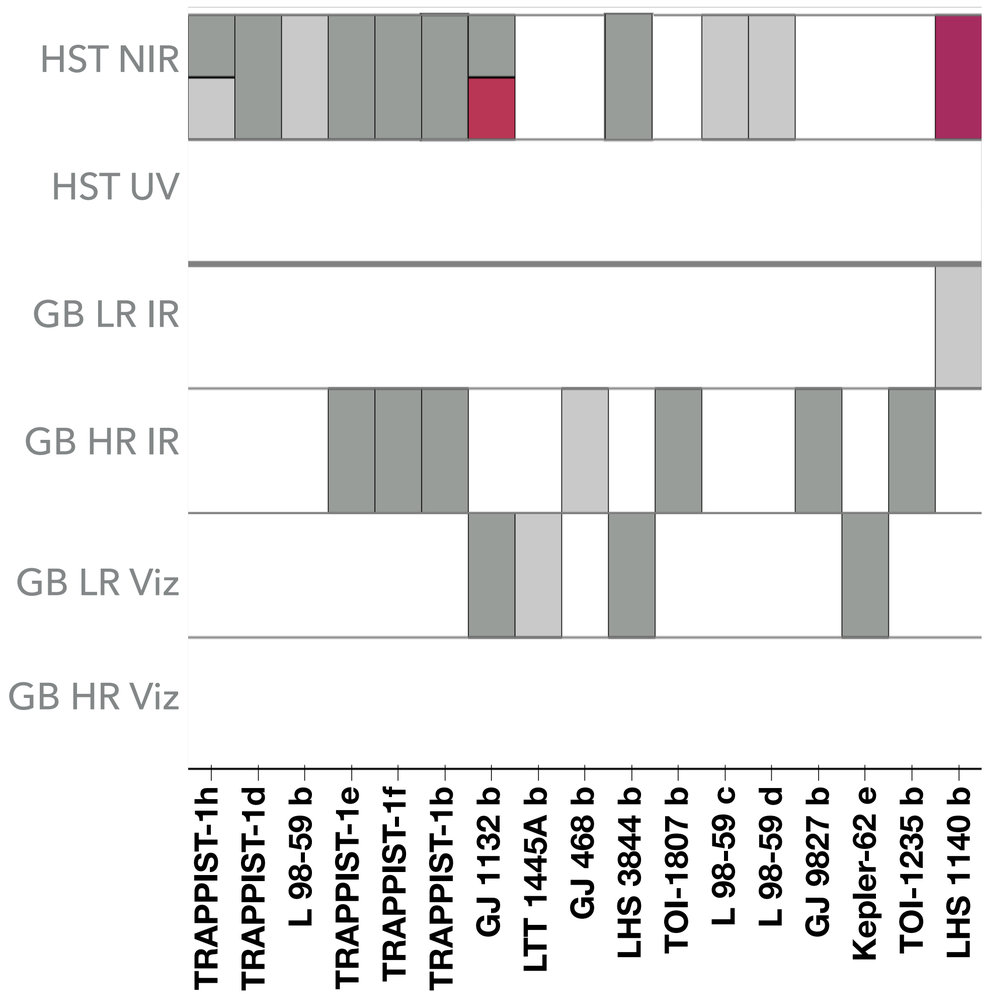


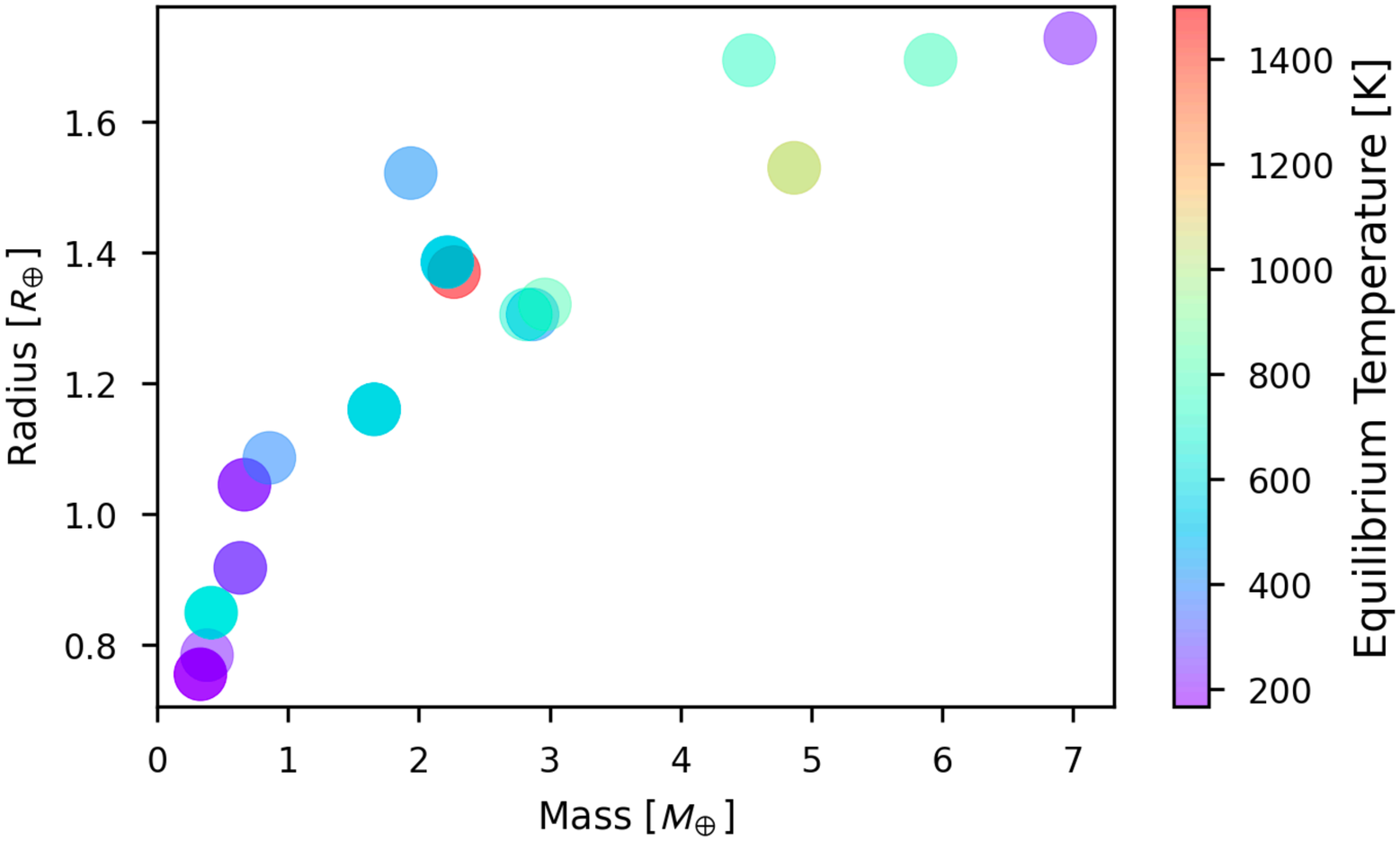
Heather Knutson's talk we learned about the "Evaporation Valley"

Cutoff R ~1.8 $R_\oplus$

No detection

An overview of R<1.8 R⊕ observations with HST and G-B instruments



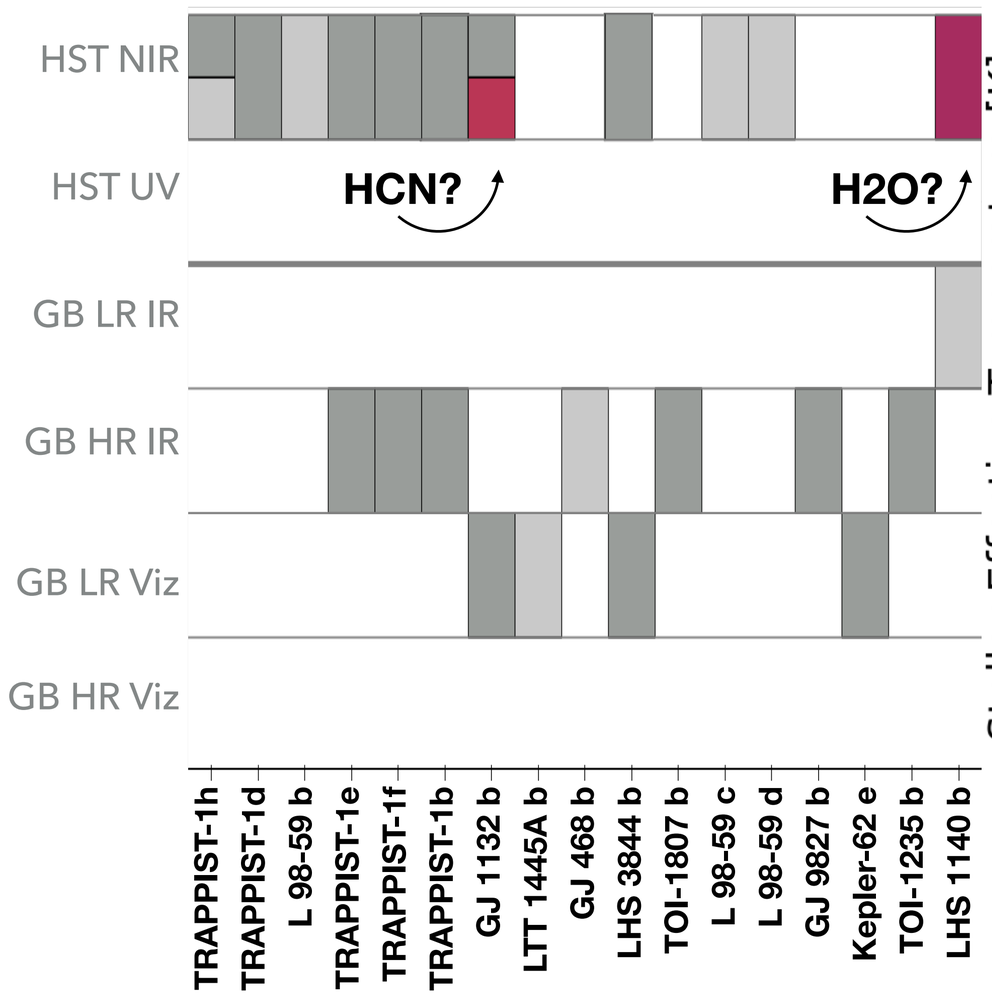


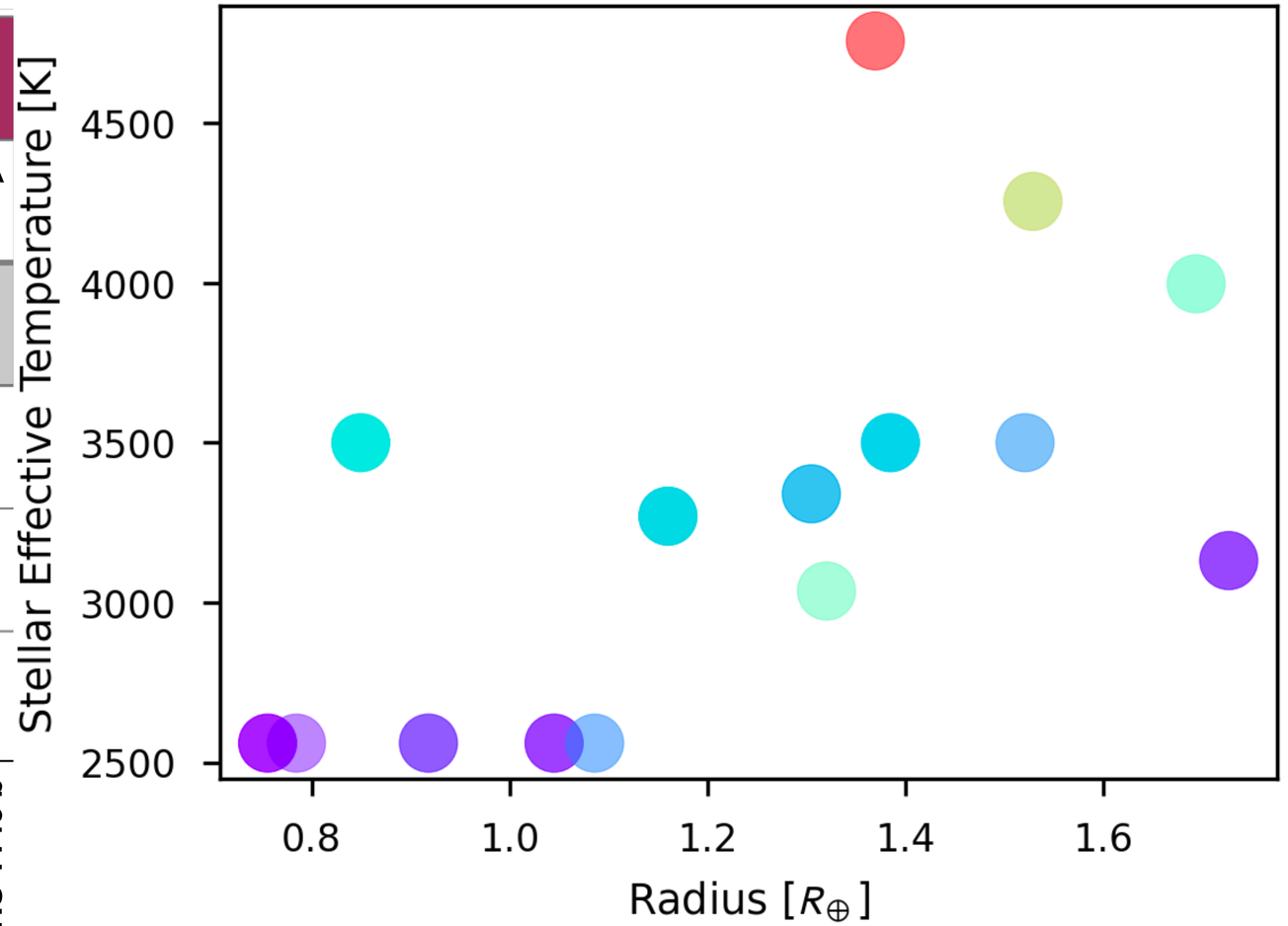
No detection

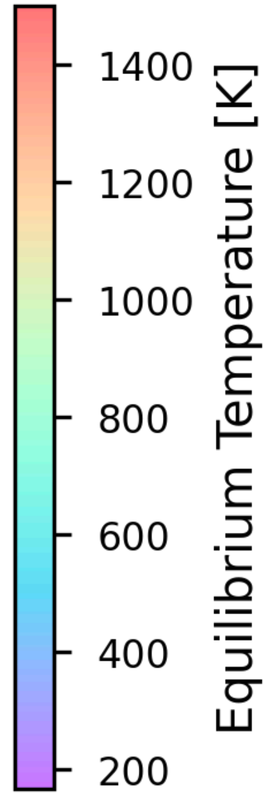
ExoAtmospheres

IAC community database for exoplanet atmospheric observations

An overview of R<1.8 R⊕ observations with HST and G-B instruments

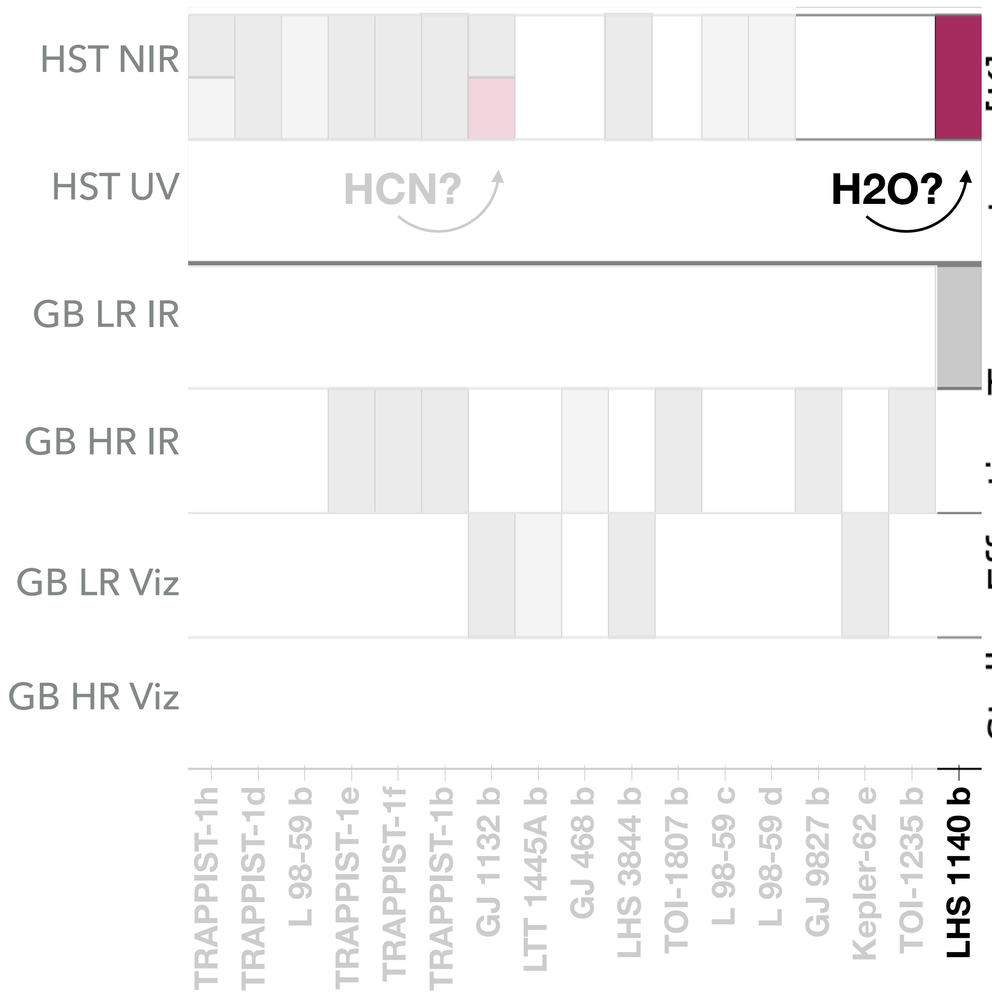


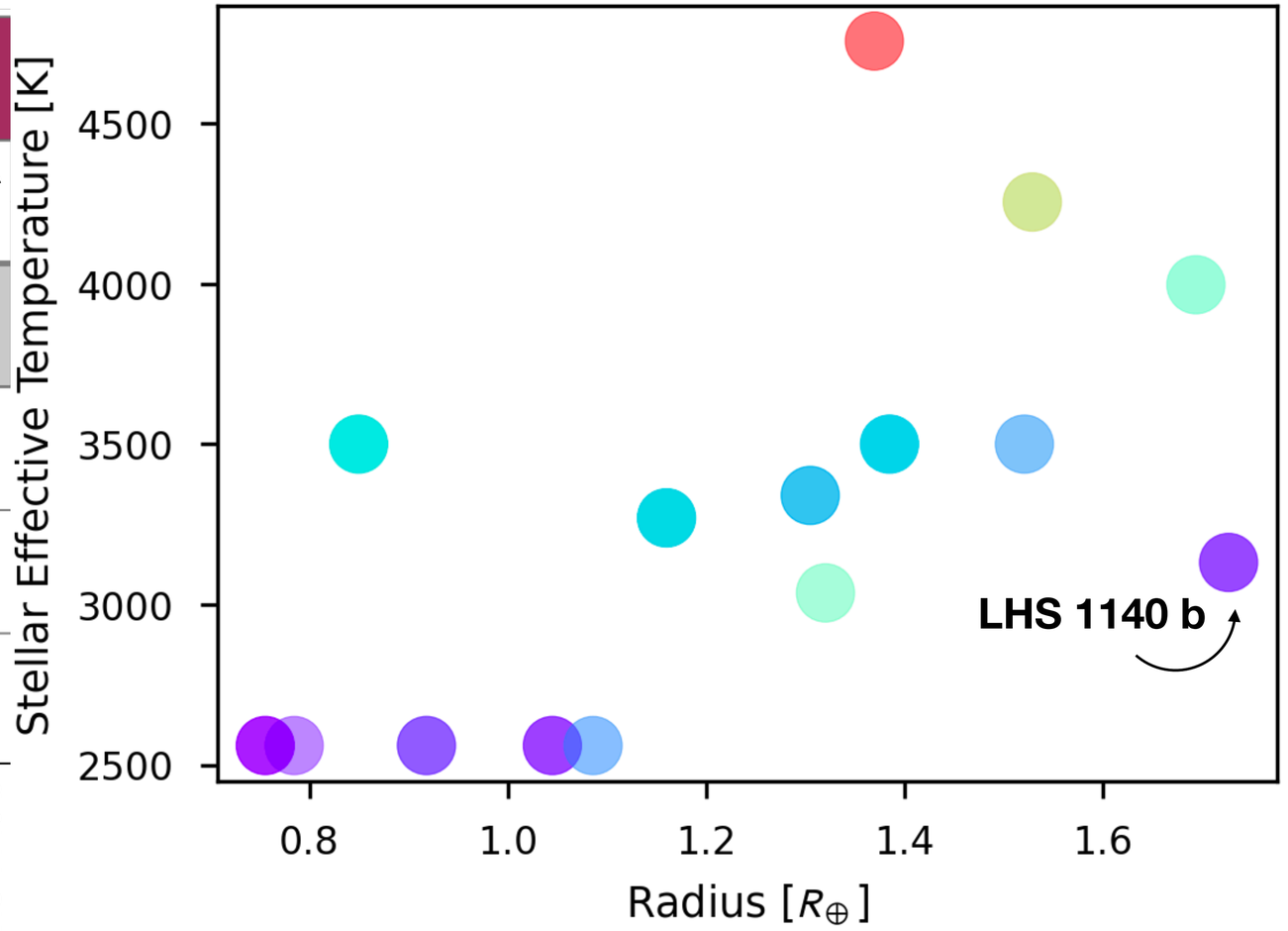


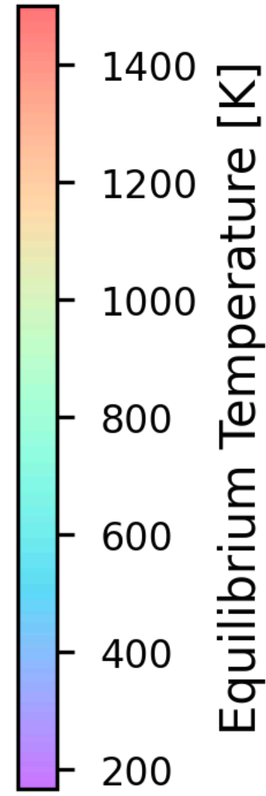


No detection

An overview of R<1.8 R⊕ observations with HST and G-B instruments

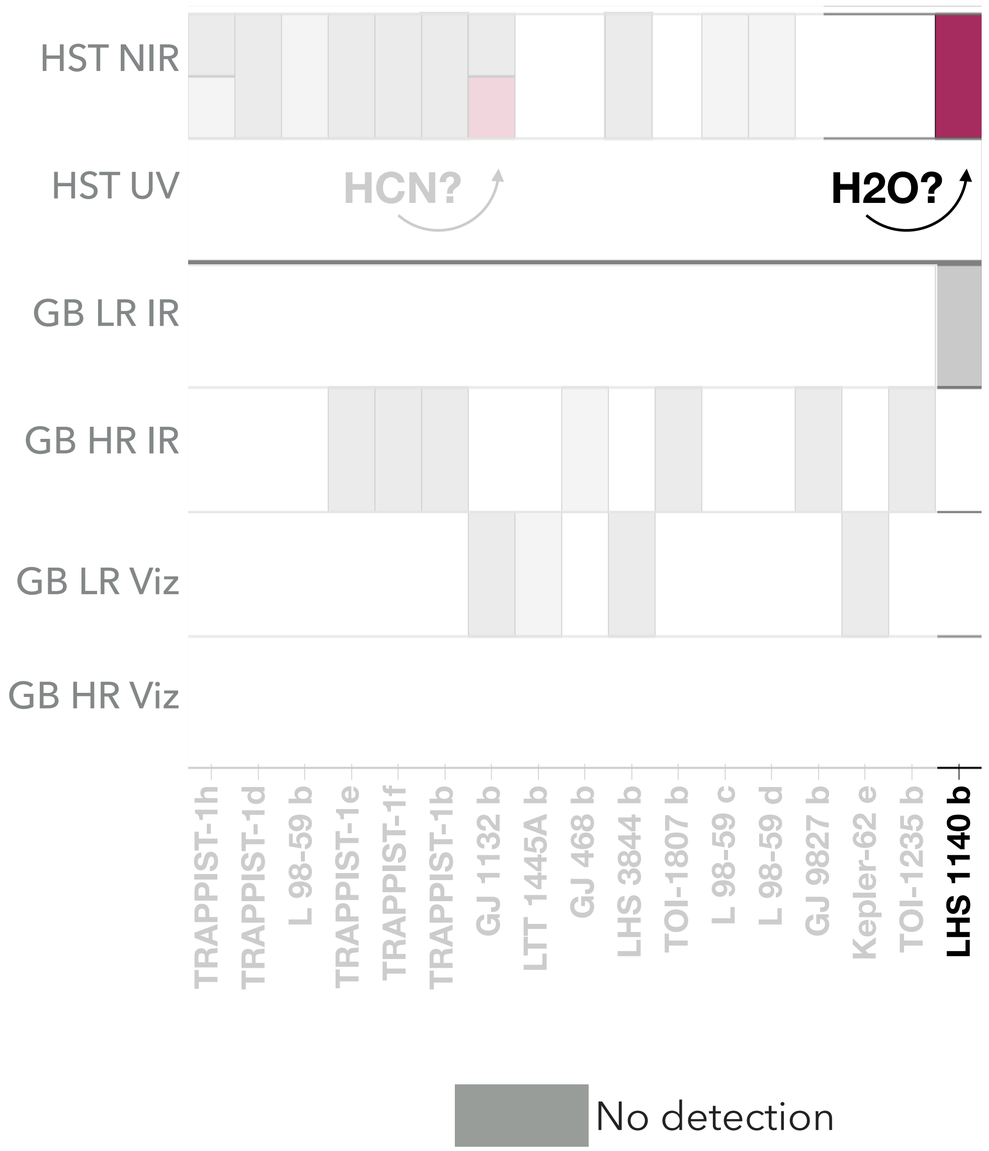


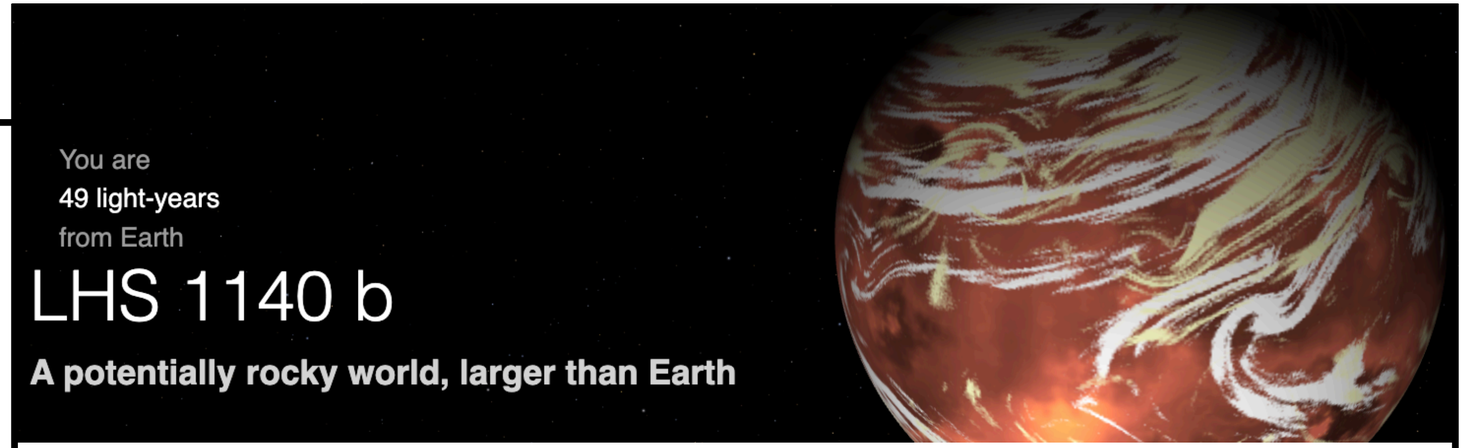




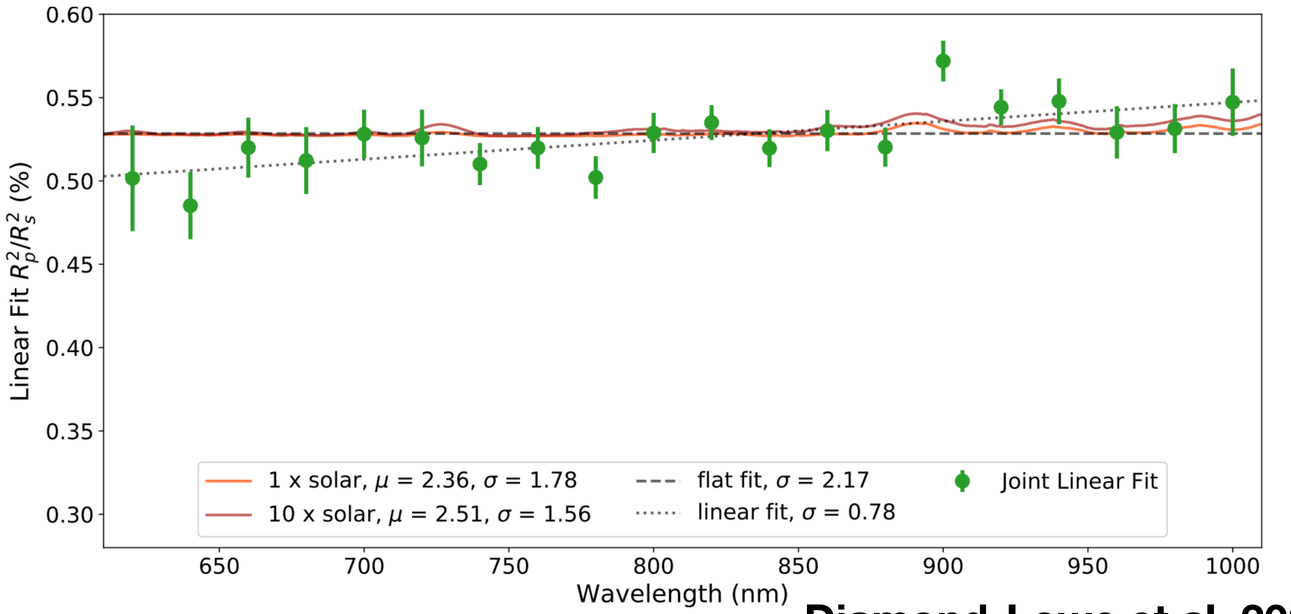
No detection

An overview of R<1.8 R⊕ observations with HST and G-B instruments



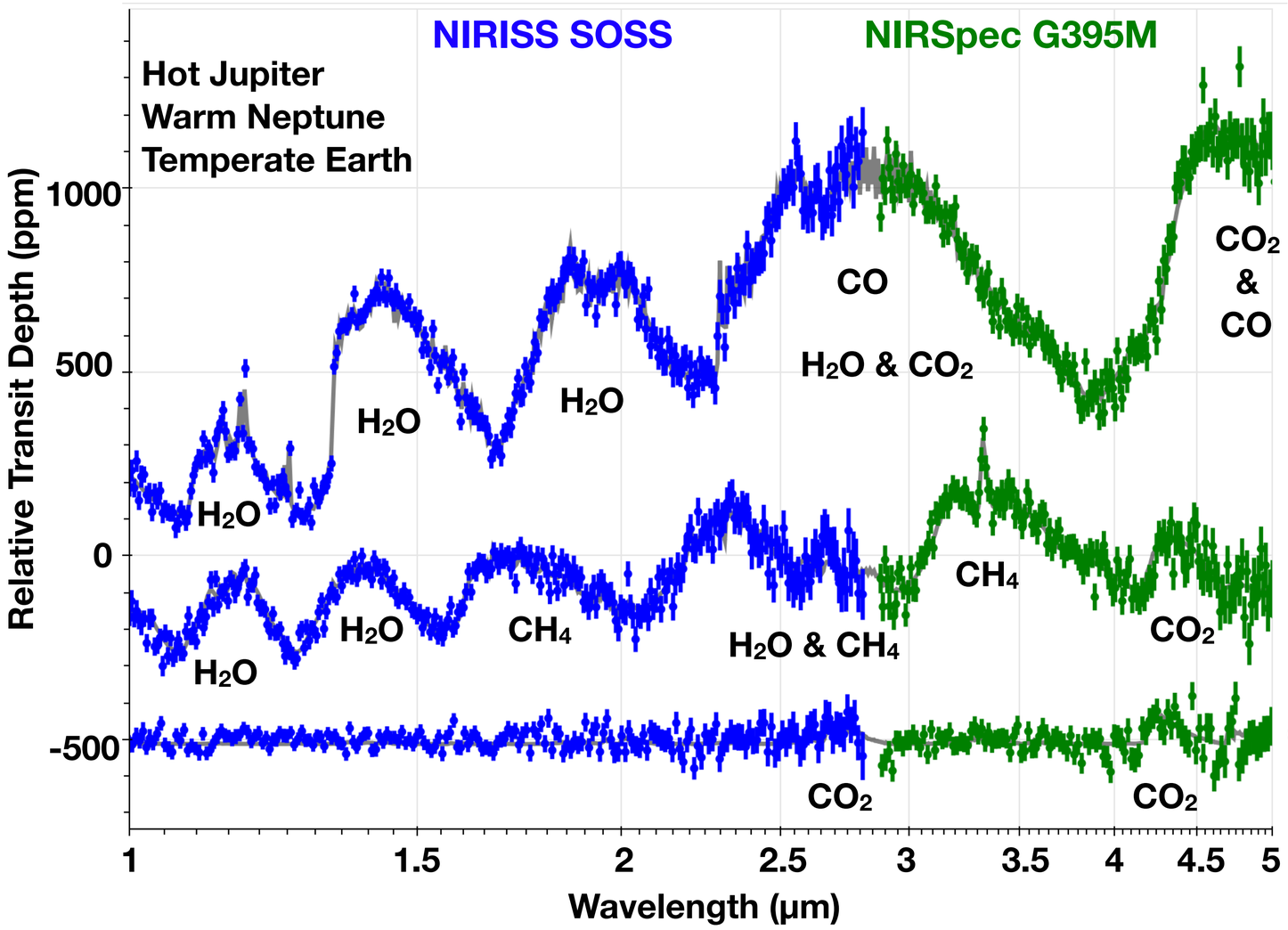


1.635 x Earth **6.38 Earth Masses** **T ~ 230 K**



Diamond-Lowe et al. 2020

Frame of reference for spectral feature size of “1xSolar” models



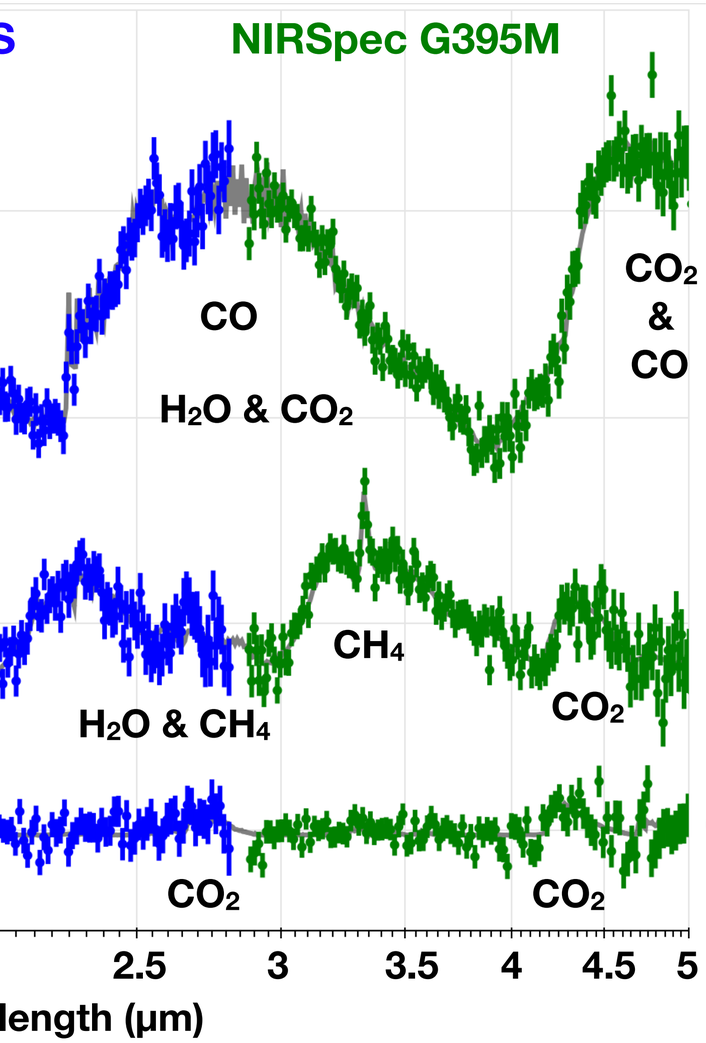
1xSolar ~ 99.9% H2/He

3xSolar ~ 99.7% H2/He

100xSolar ~ 91.1% H2/He

CO_2-dominated ~ 0% H2/He

Frame of reference for spectral feature size of “1xSolar” models



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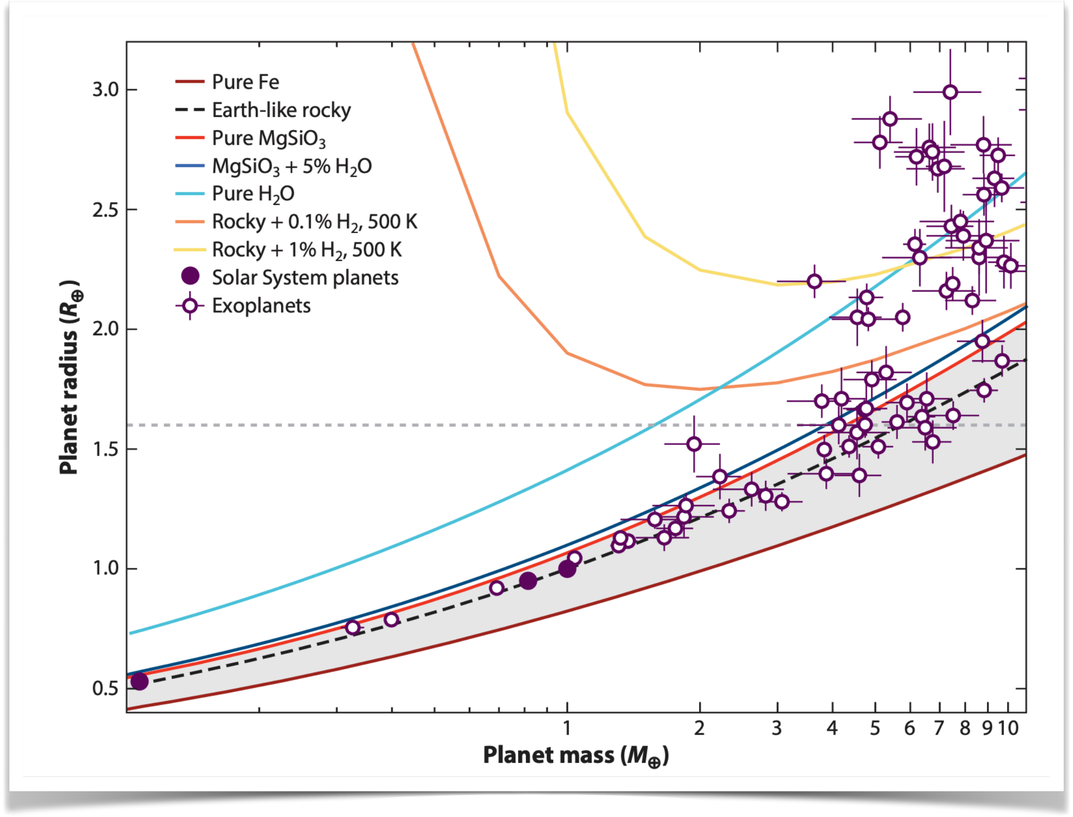
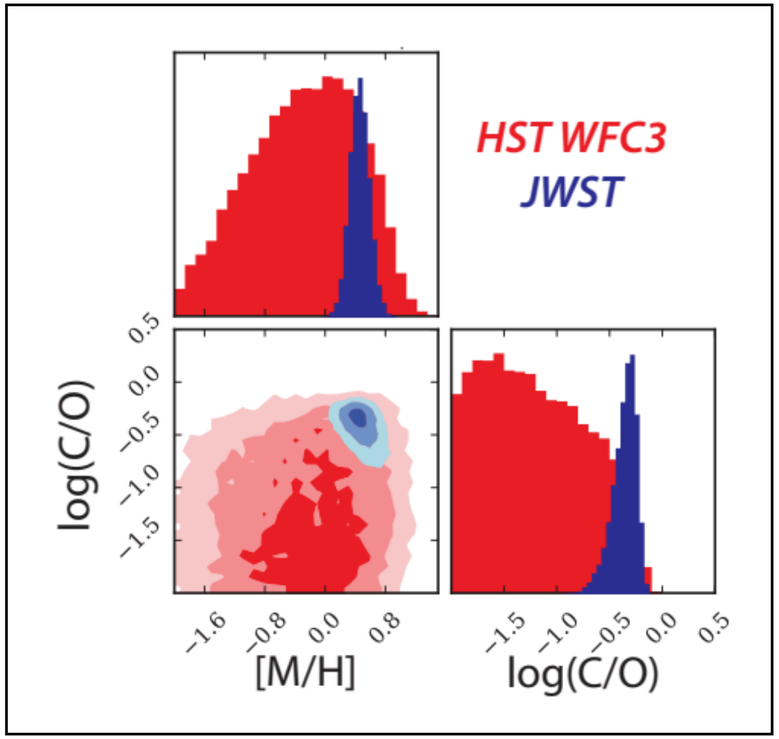


Img Credit/Additional Reading:
“Atmospheres of Rocky Exoplanets”
Annual Reviews
Wordsworth & Kreidberg

Frame of reference for spectral feature size of “1xSolar” models

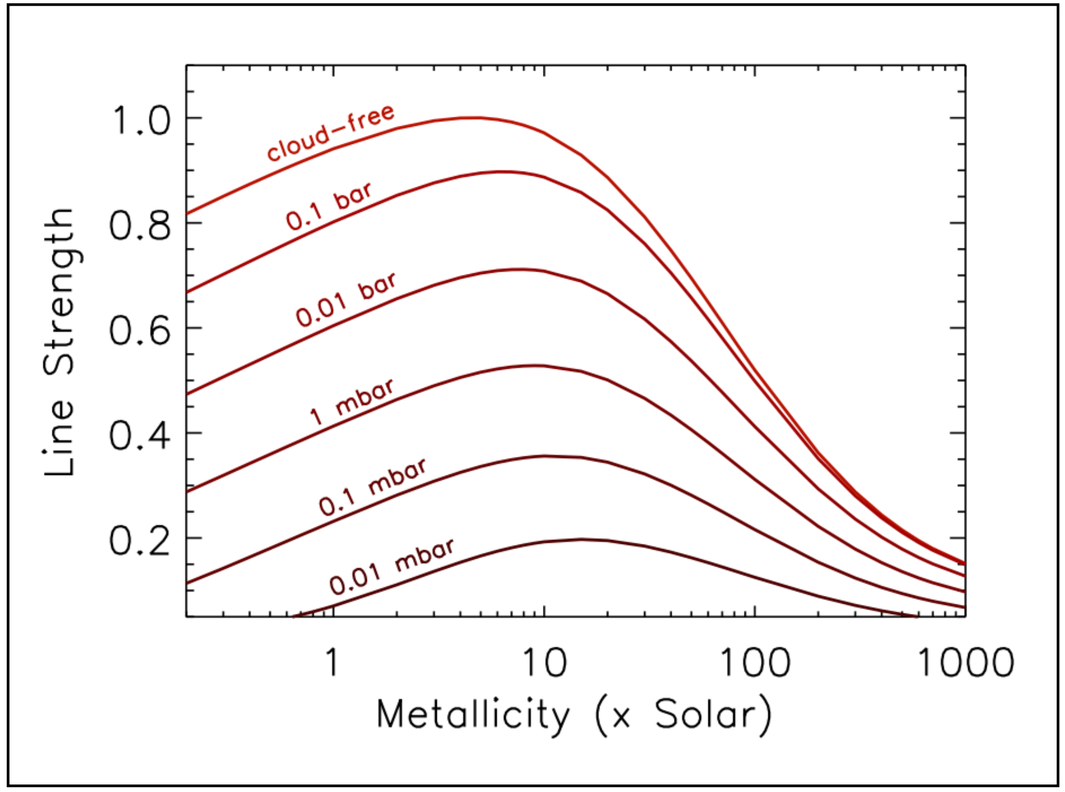
At high SNR expect to see:



Constrained atmospheric physical parameters with upper and lower bounds

Talk from Mike Line and petitRadTrans hands on activity

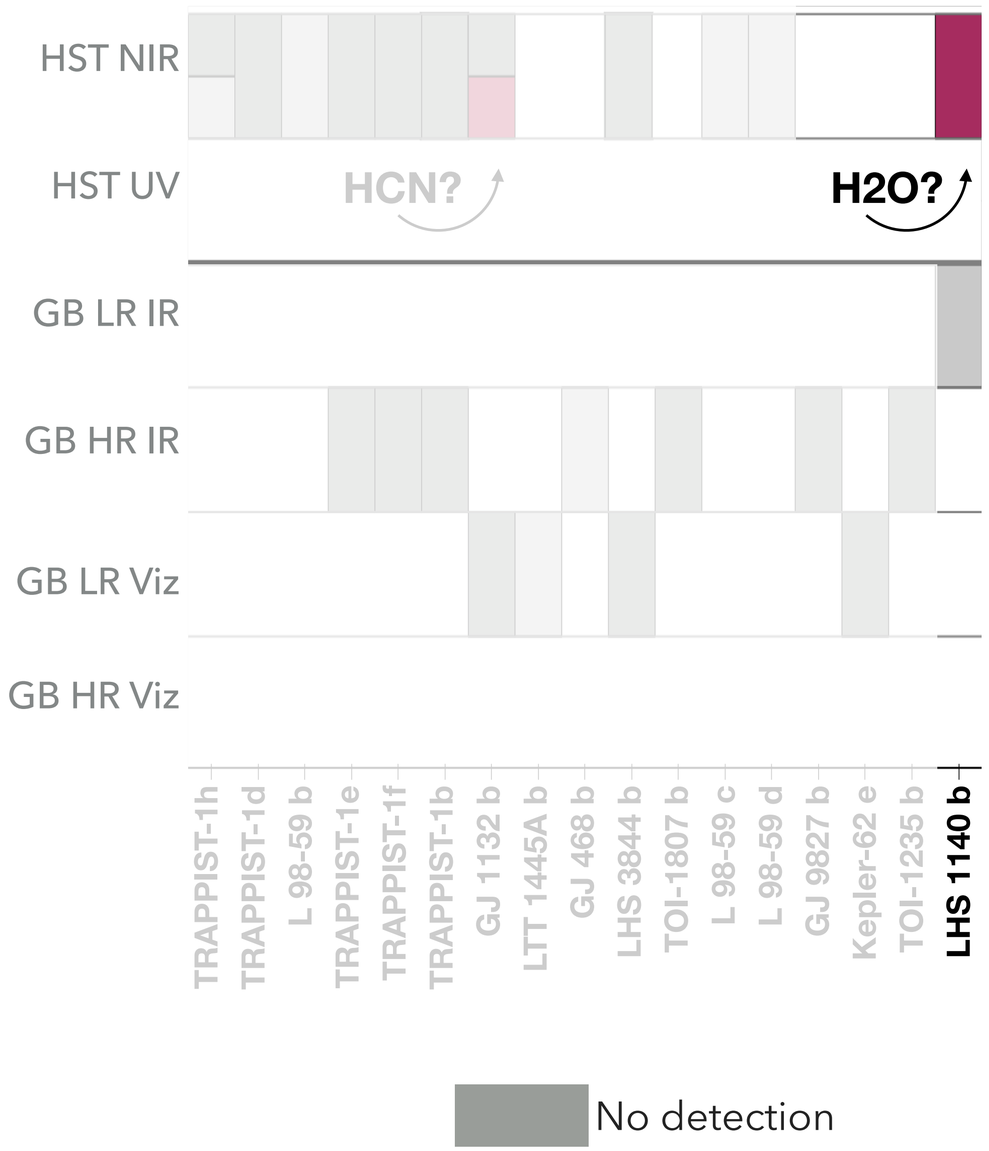
At low SNR expect to see:

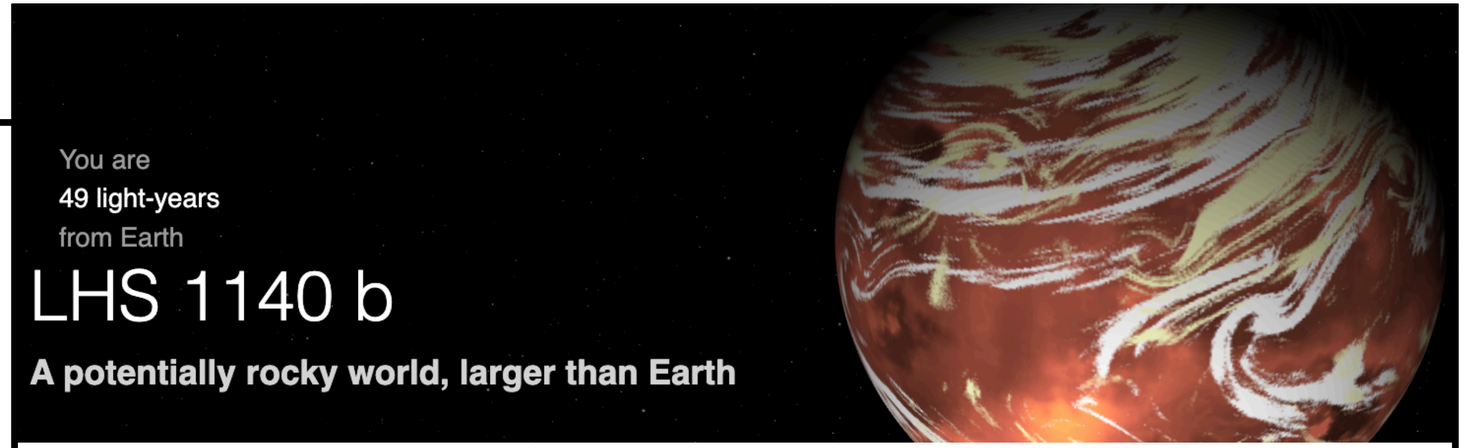


“Rule-out” method: Different cloud-metallicity scenarios are ruled out with certain confidence when compared to a flat line

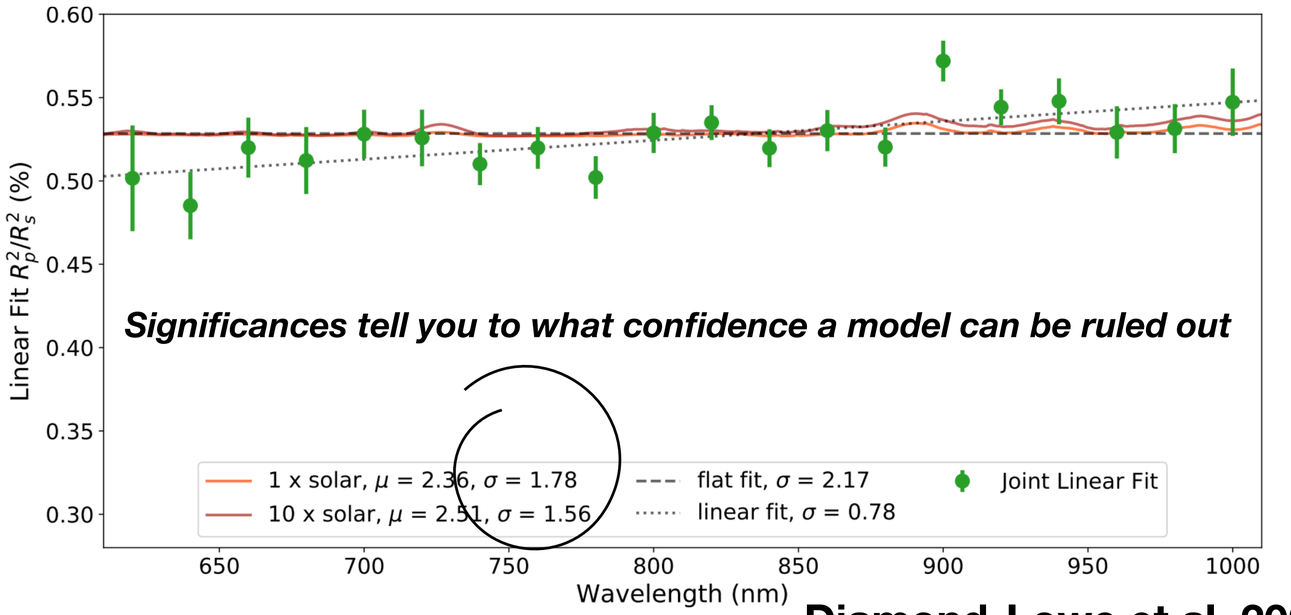
Similar to PICASO hands on activity

An overview of R<1.8 R⊕ observations with HST and G-B instruments





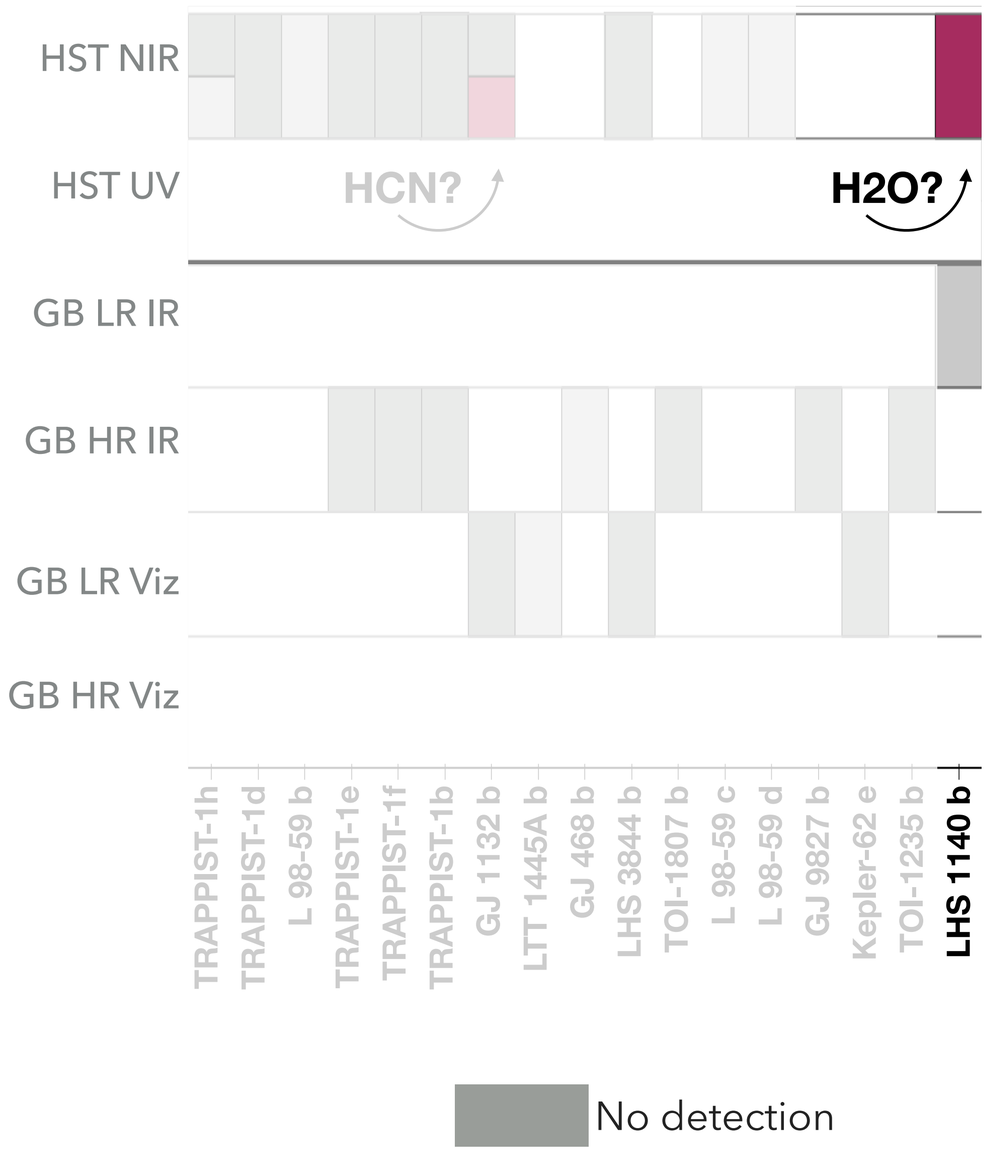
1.635 x Earth **6.38 Earth Masses** **T ~ 230 K**



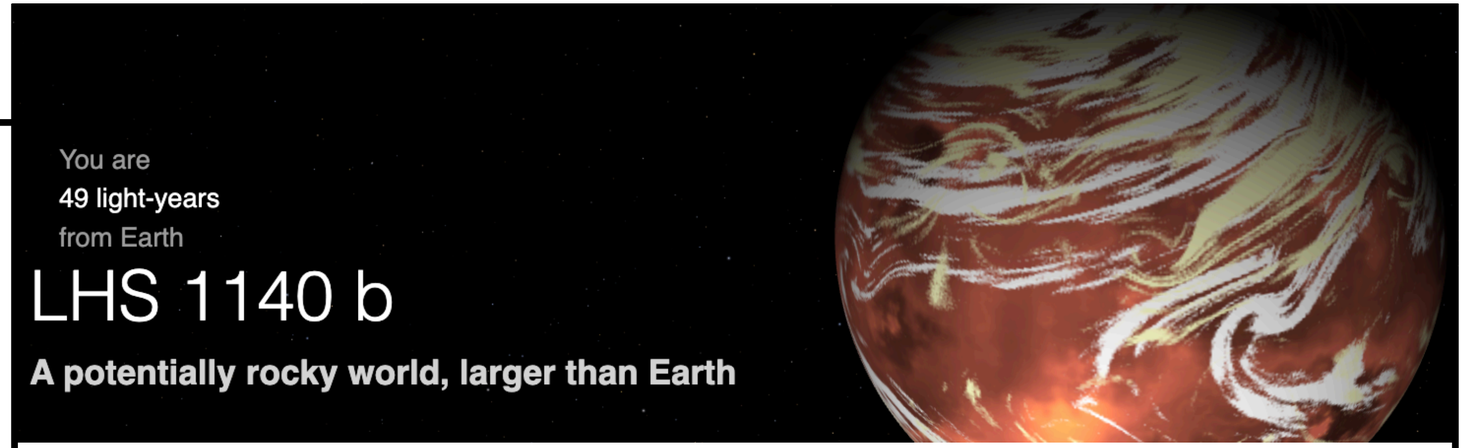
Significances tell you to what confidence a model can be ruled out

Diamond-Lowe et al. 2020

An overview of R<1.8 R⊕ observations with HST and G-B instruments



No detection



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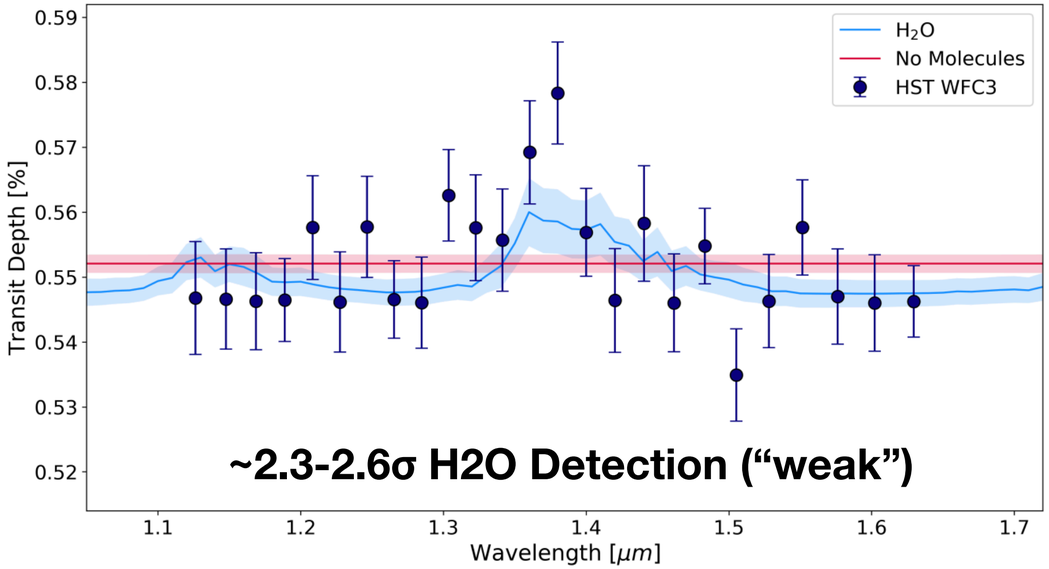
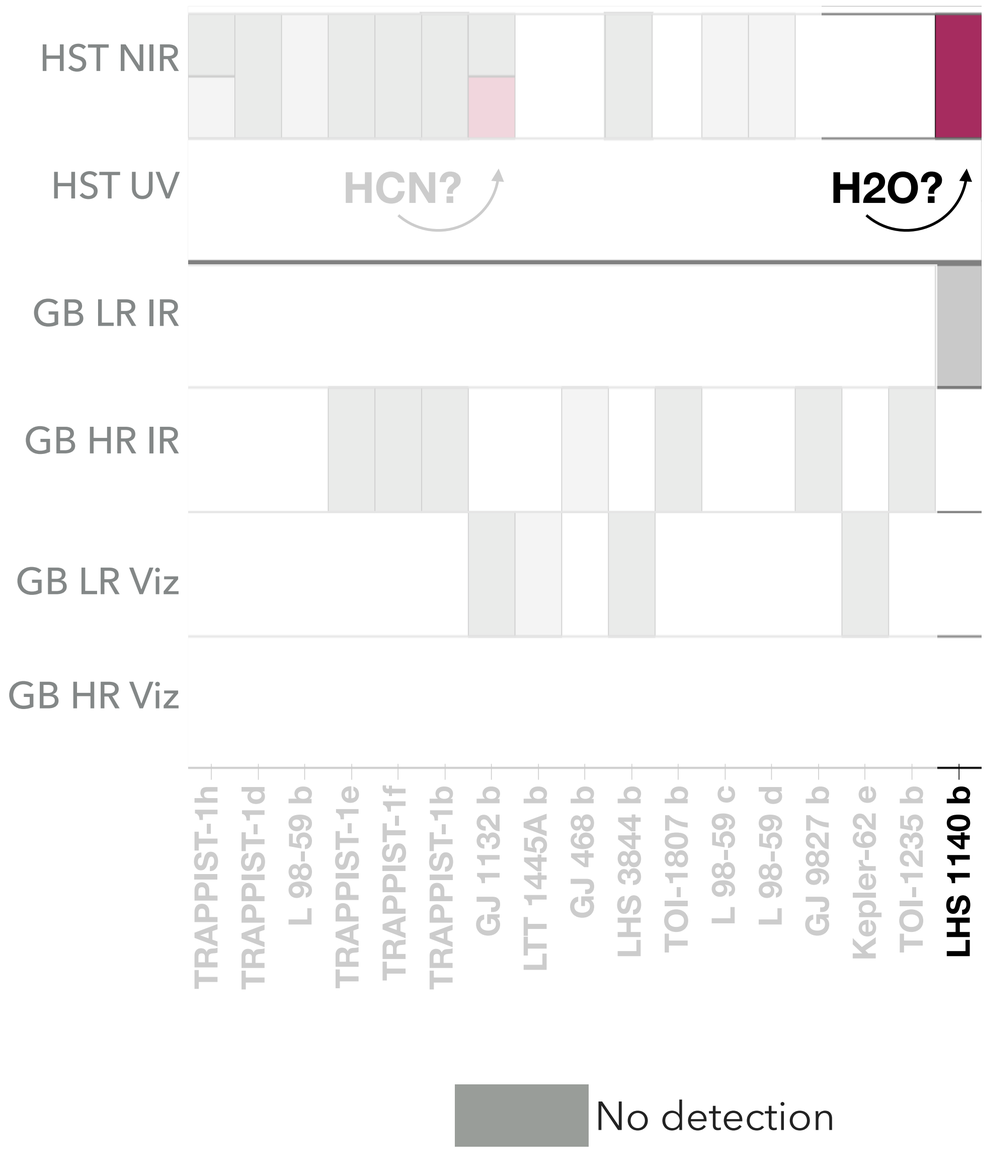
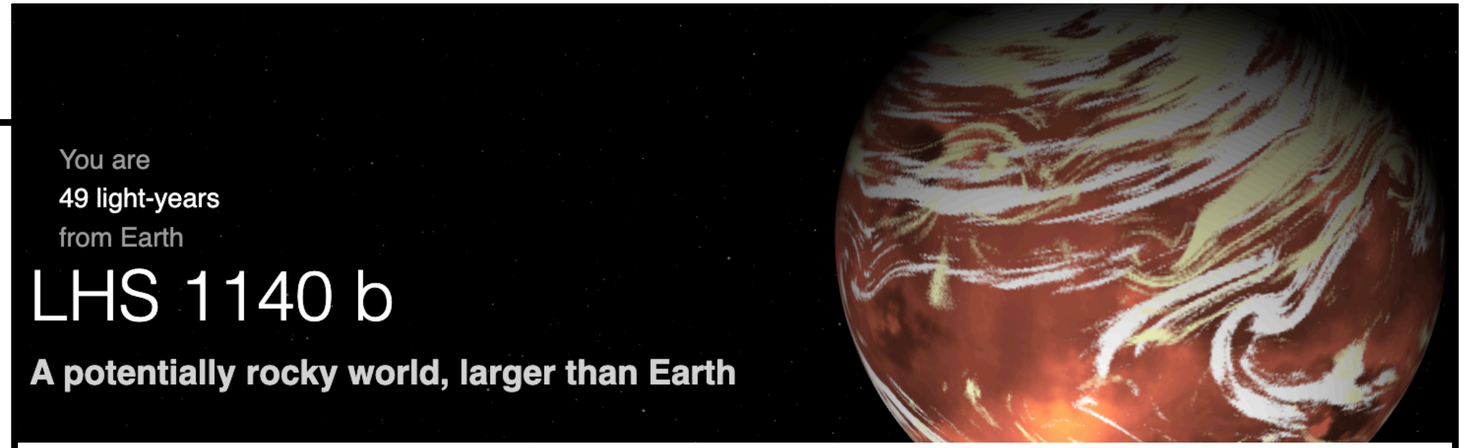


~2.3-2.6σ H2O Detection (“weak”)

Edwards et al. 2020

An overview of R<1.8 R⊕ observations with HST and G-B instruments





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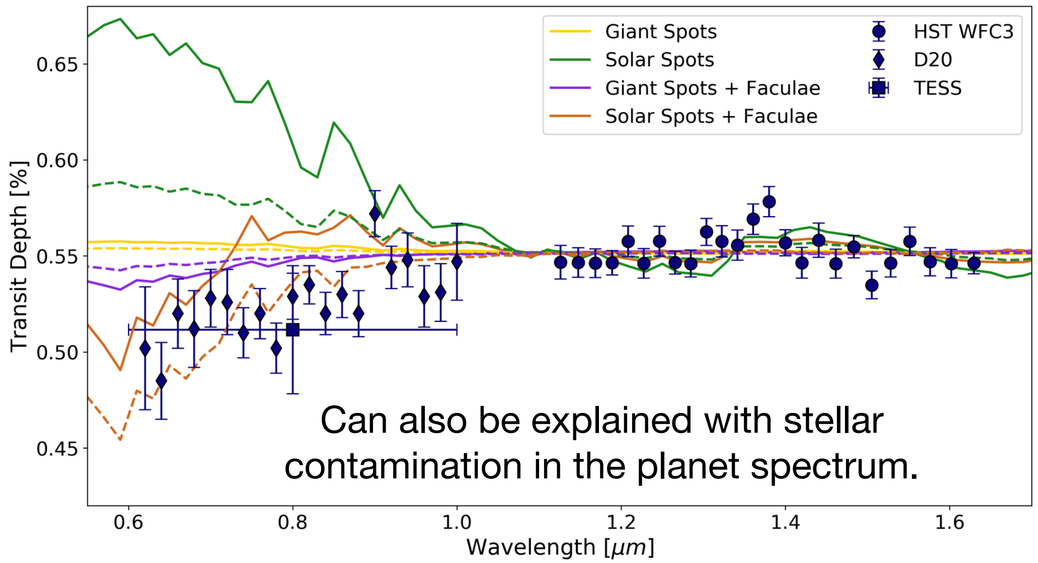
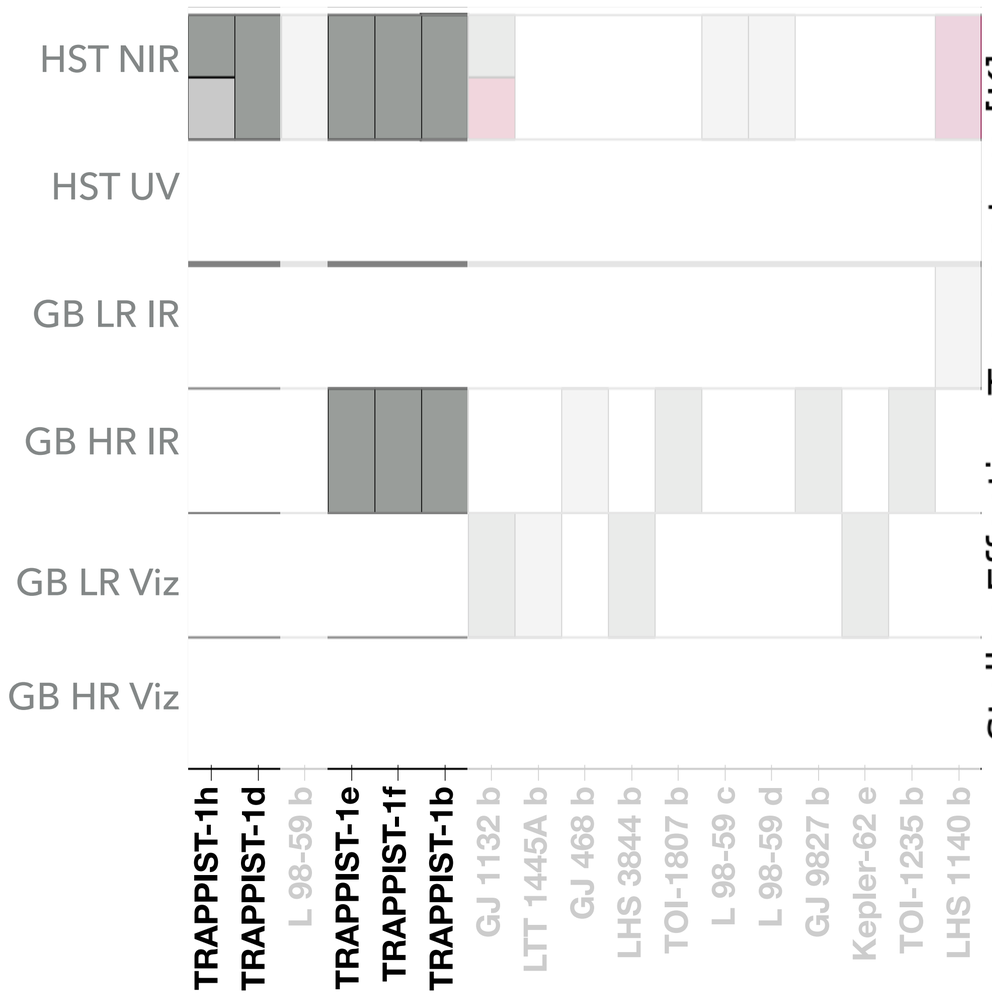
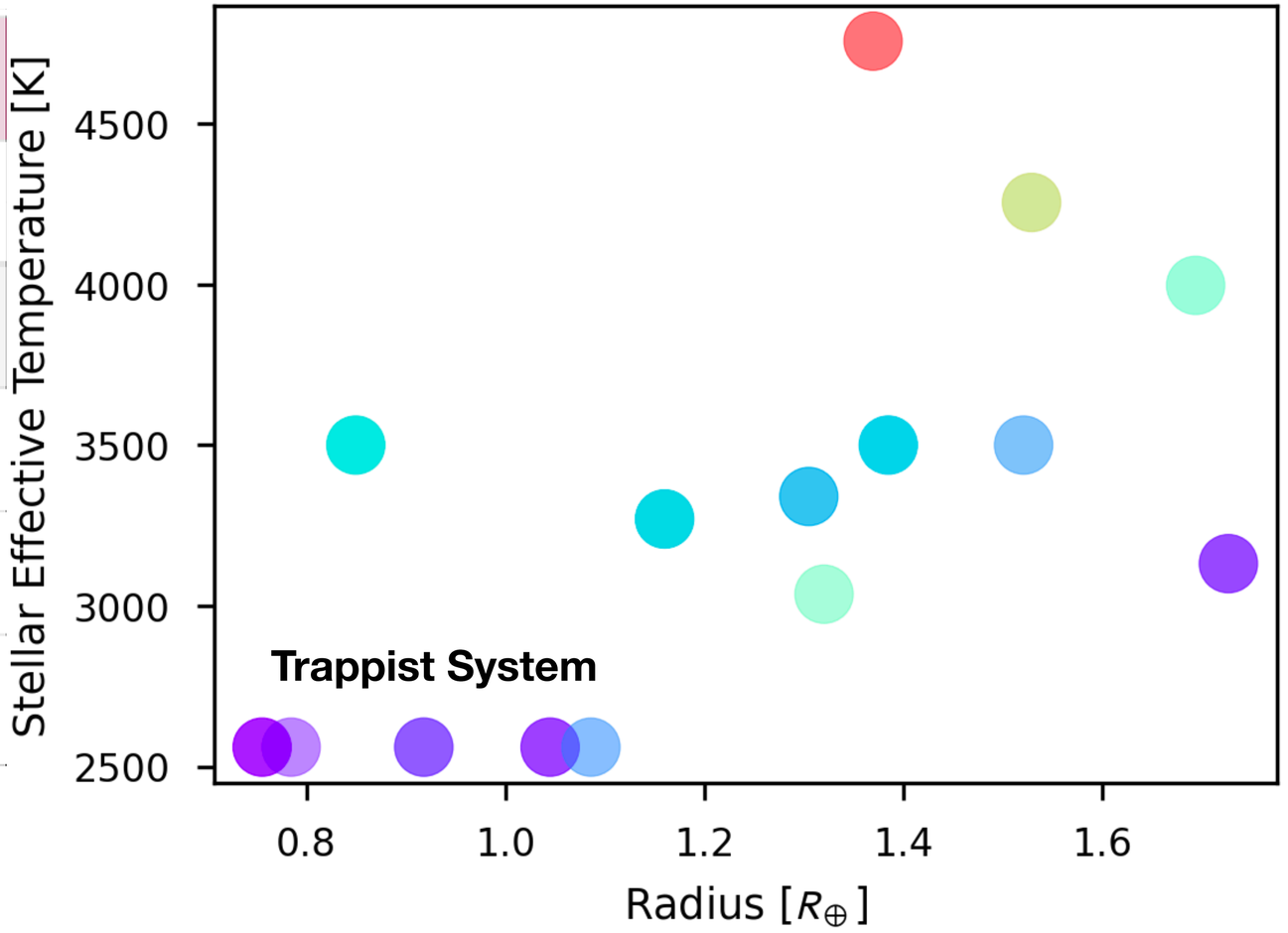
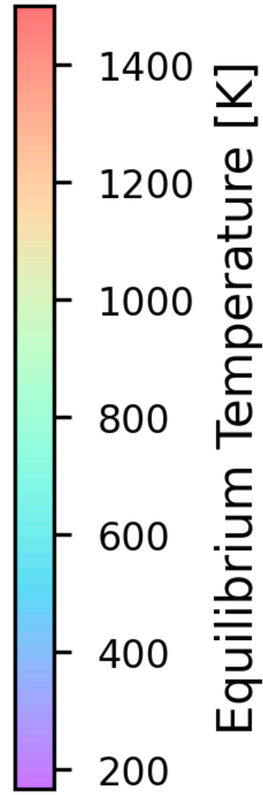


Edwards et al. 2020+Diamond-Lowe et al. 2020

An overview of R<1.8 R⊕ observations with HST and G-B instruments

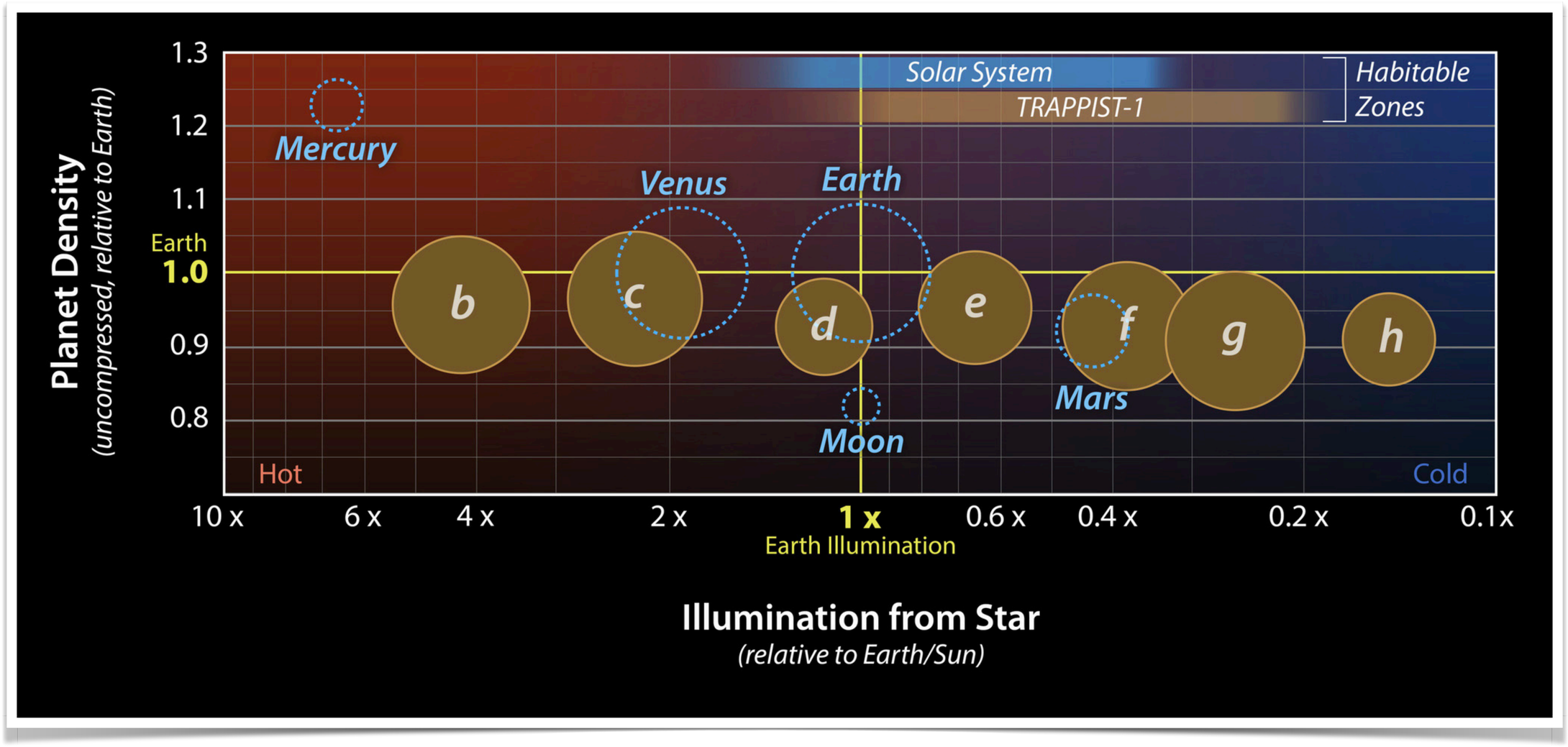






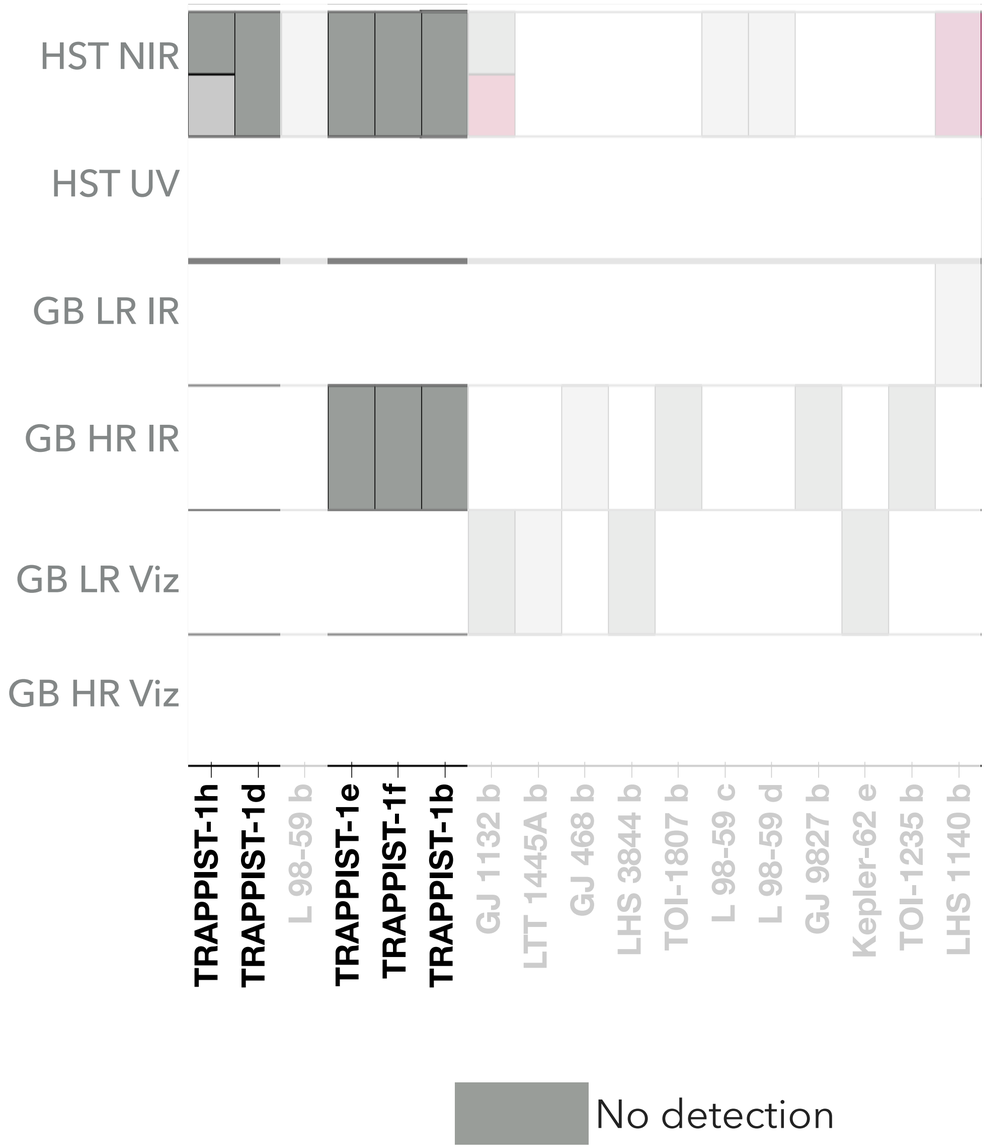
No detection

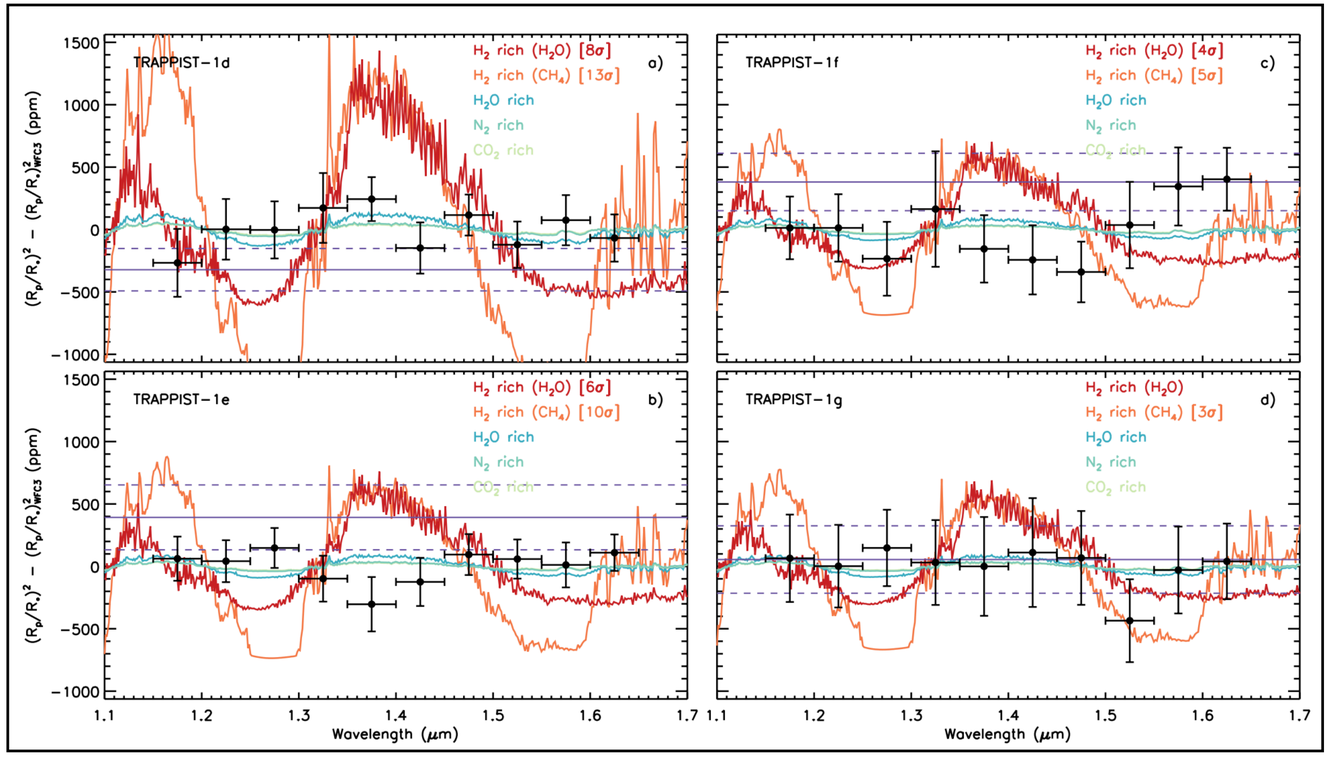
TRAPPIST-1 System Compared to Our Solar System



https://exoplanets.nasa.gov/resources/2252/trappist-1-exoplanets-solar-system-comparison/

An overview of R<1.8 R⊕ observations with HST and G-B instruments



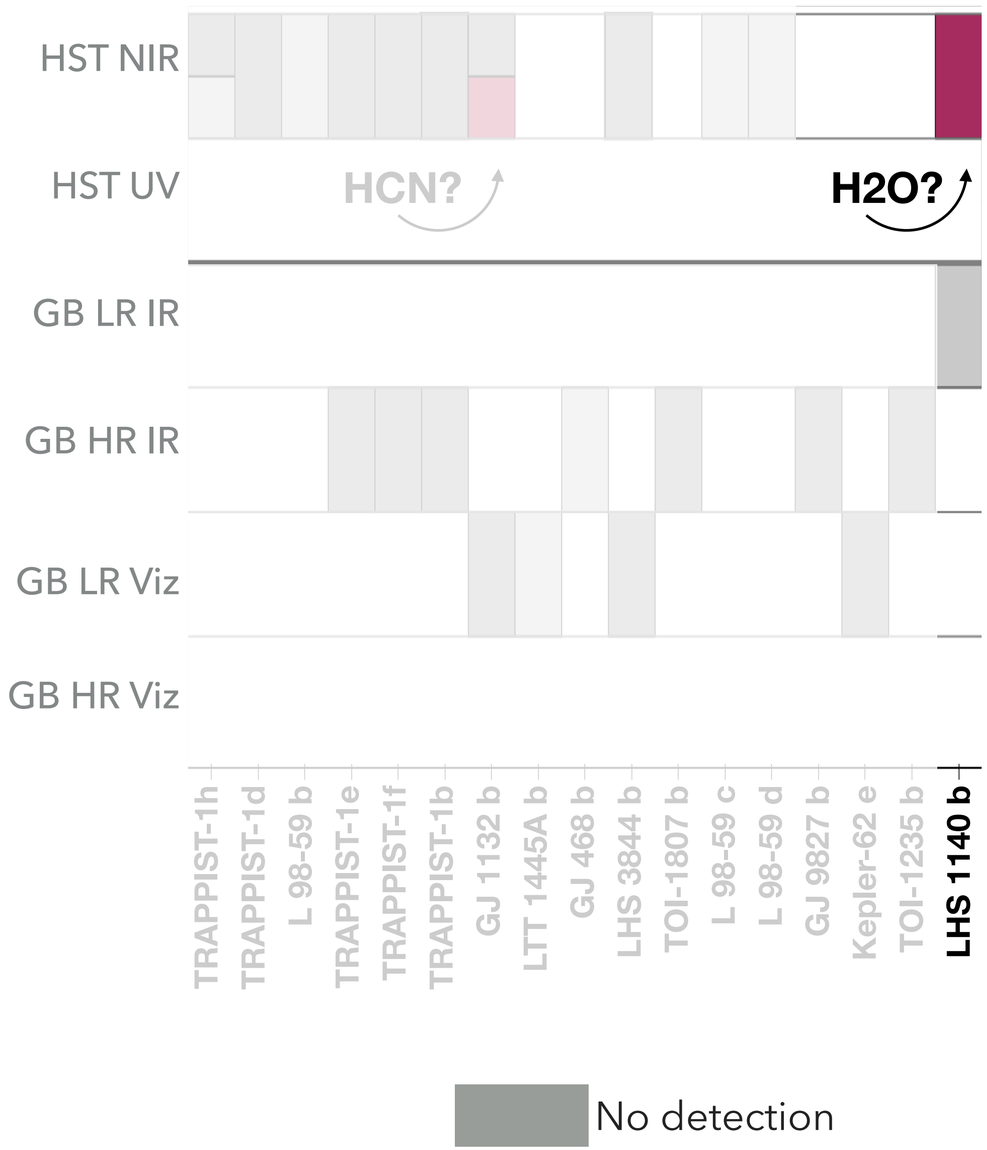


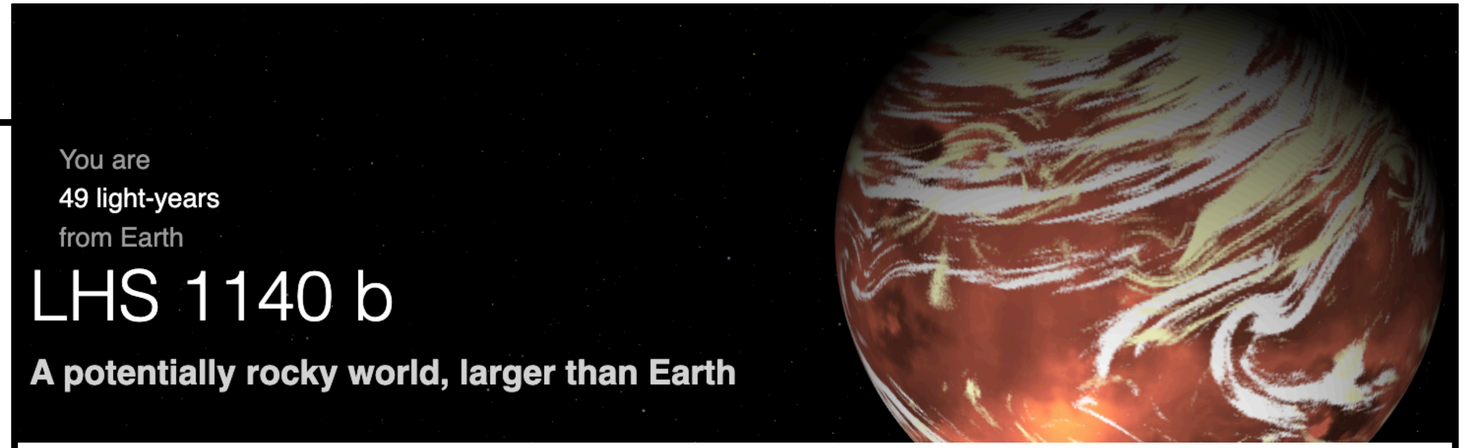
De Wit et al. 2018

"These spectra demonstrate how stellar contamination can overwhelm planetary absorption features in low-resolution exoplanet transit spectra…"

- Zhang, Zhou, Rackham et al. 2018

An overview of R<1.8 R⊕ observations with HST and G-B instruments





1.635 x Earth

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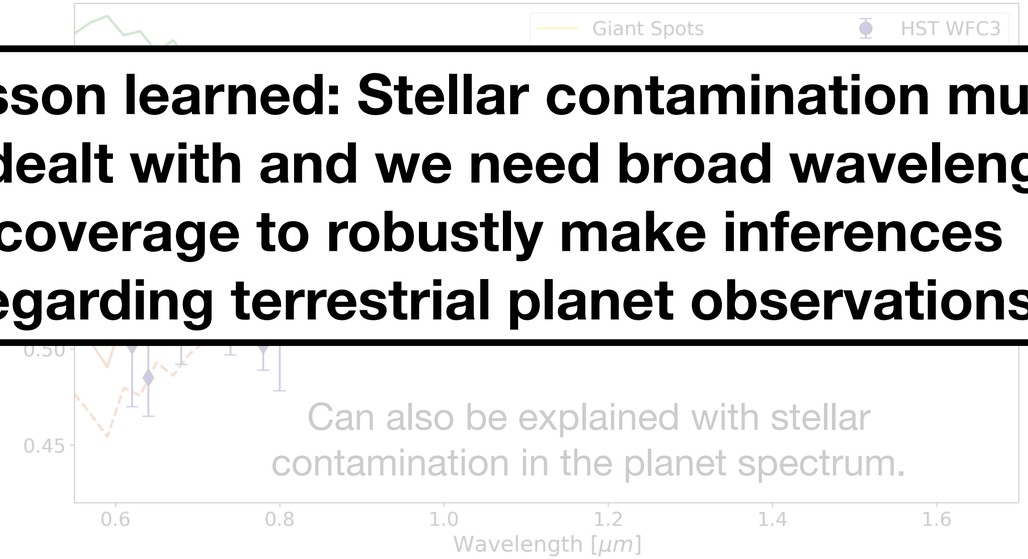
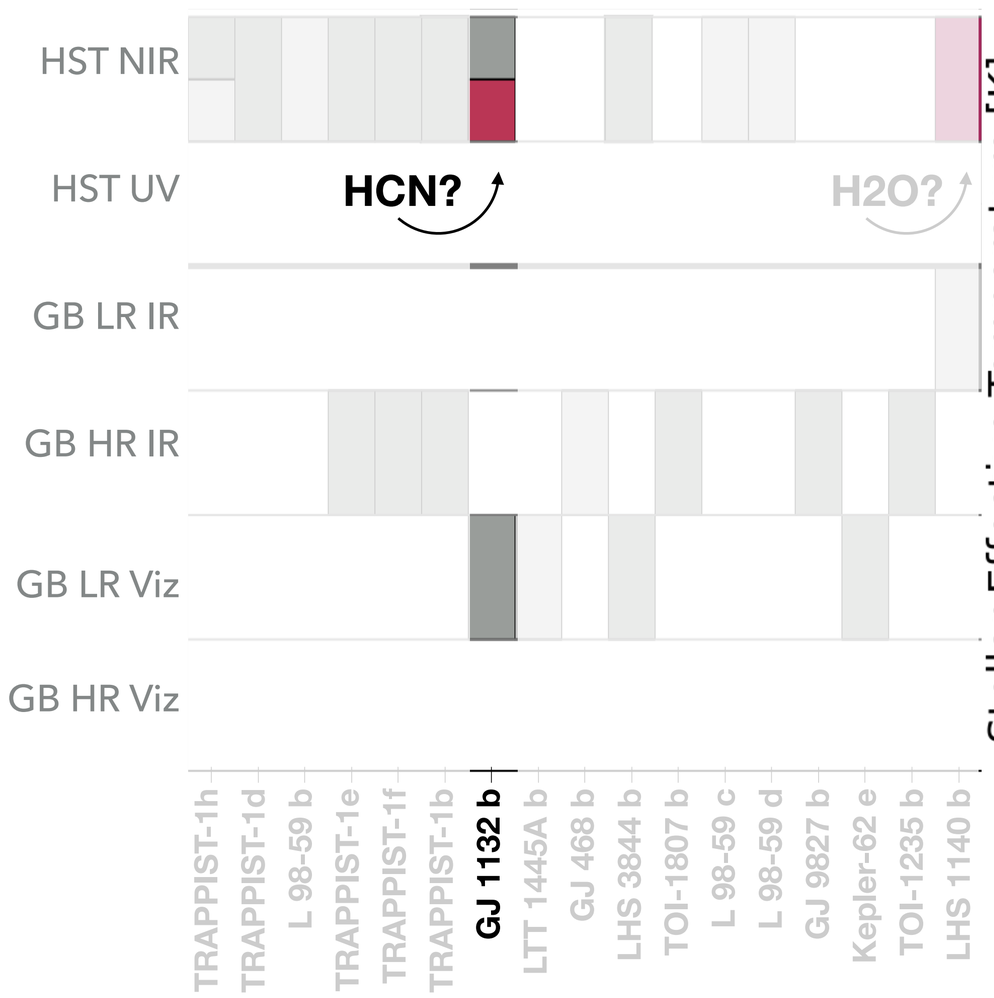
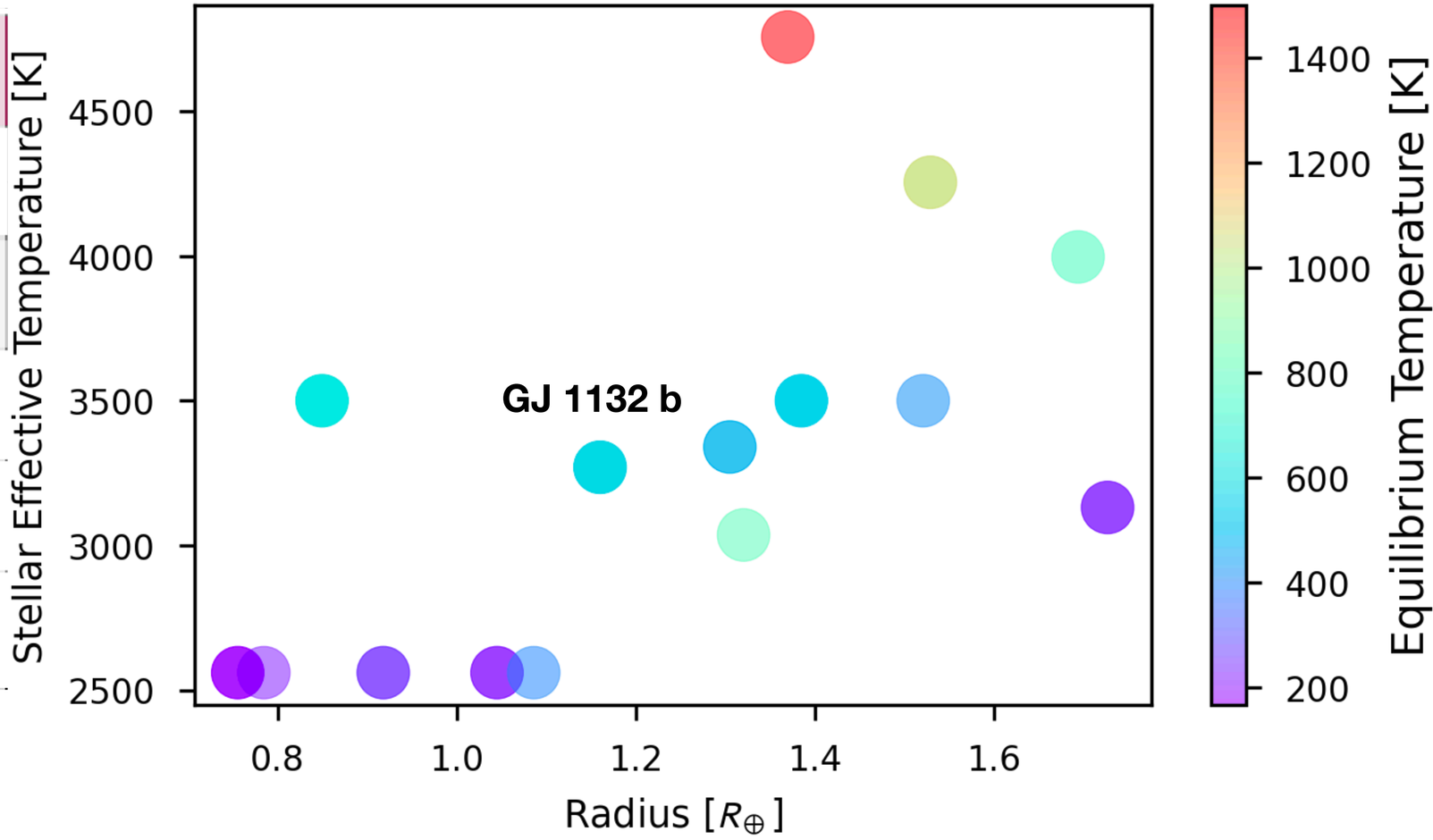


Lesson learned: Stellar contamination must be dealt with and we need broad wavelength coverage to robustly make inferences regarding terrestrial planet observations

Edwards et al. 2020+Diamond-Lowe et al. 2020

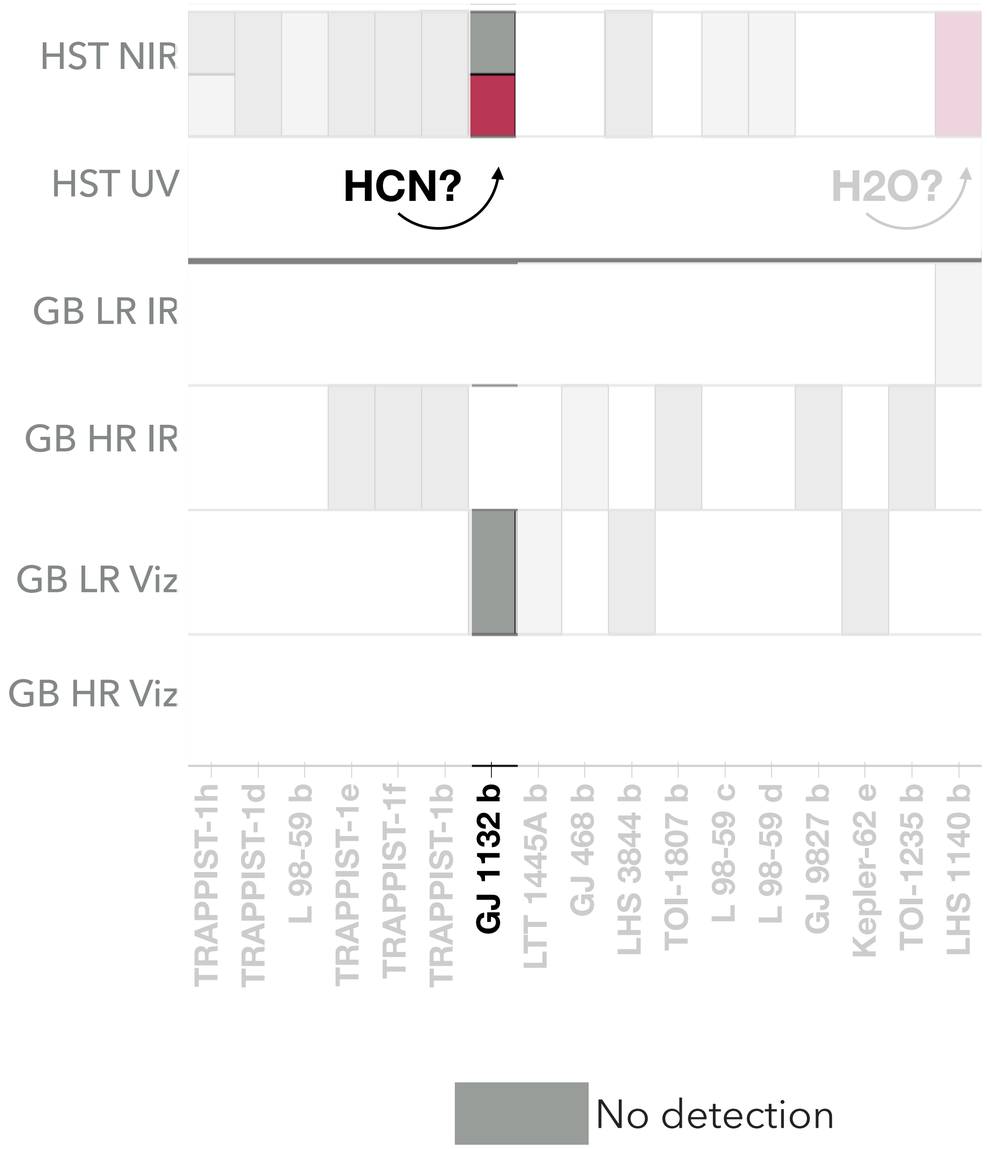
An overview of R<1.8 R⊕ observations with HST and G-B instruments

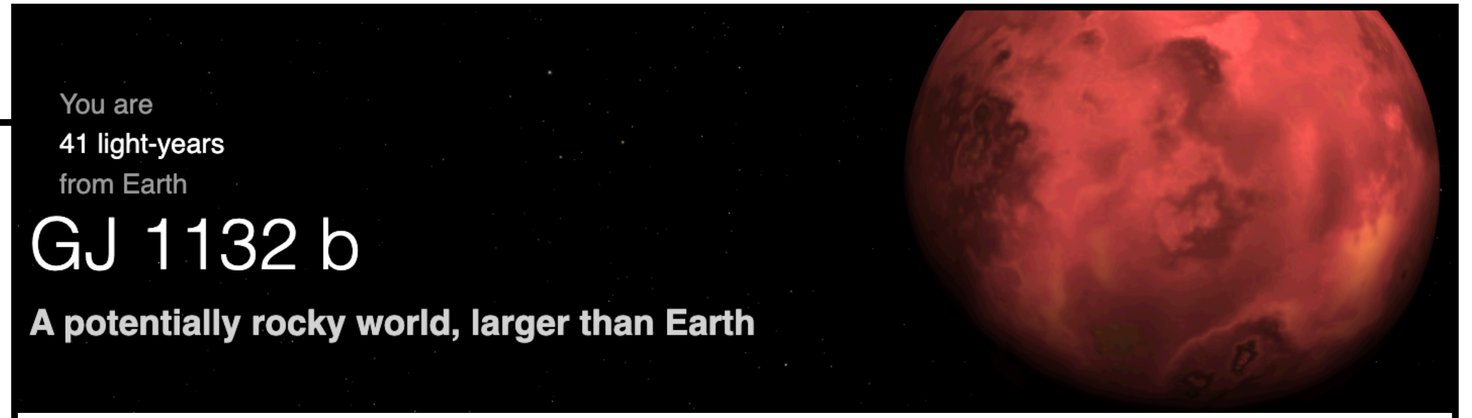




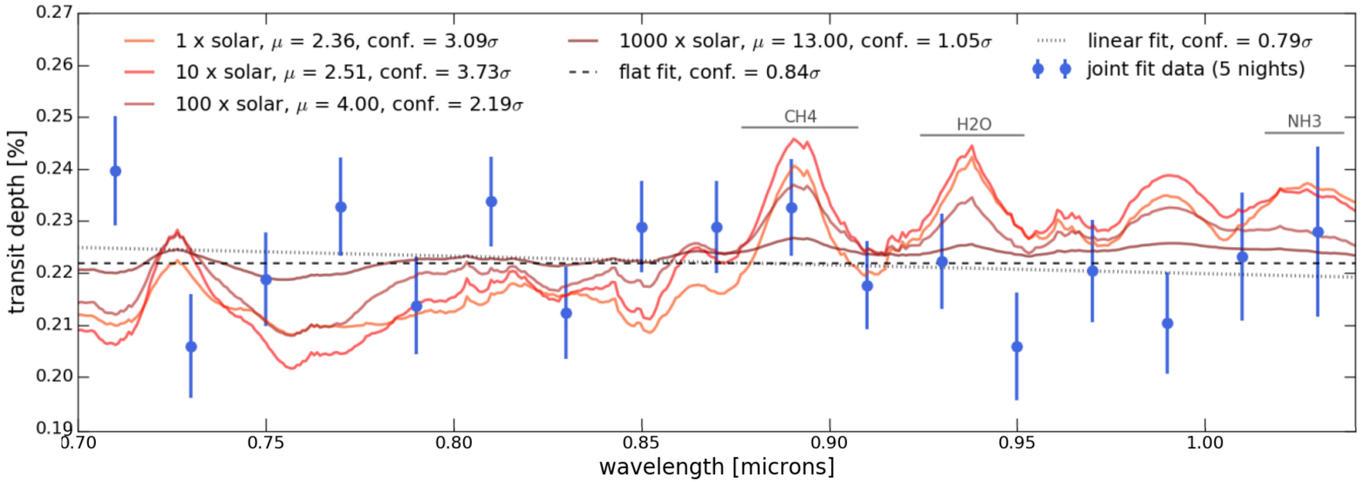
No detection

An overview of R<1.8 R⊕ observations with HST and G-B instruments



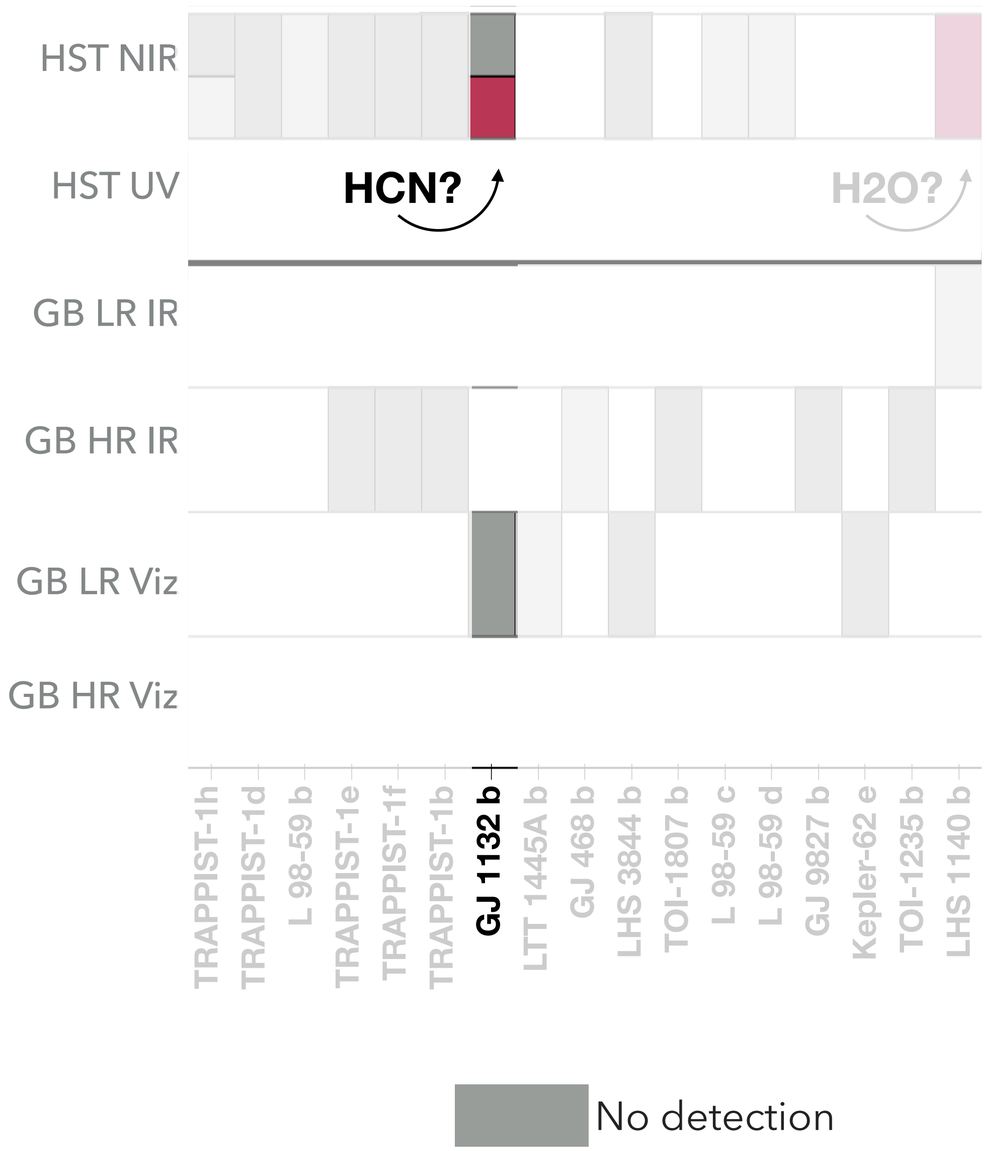


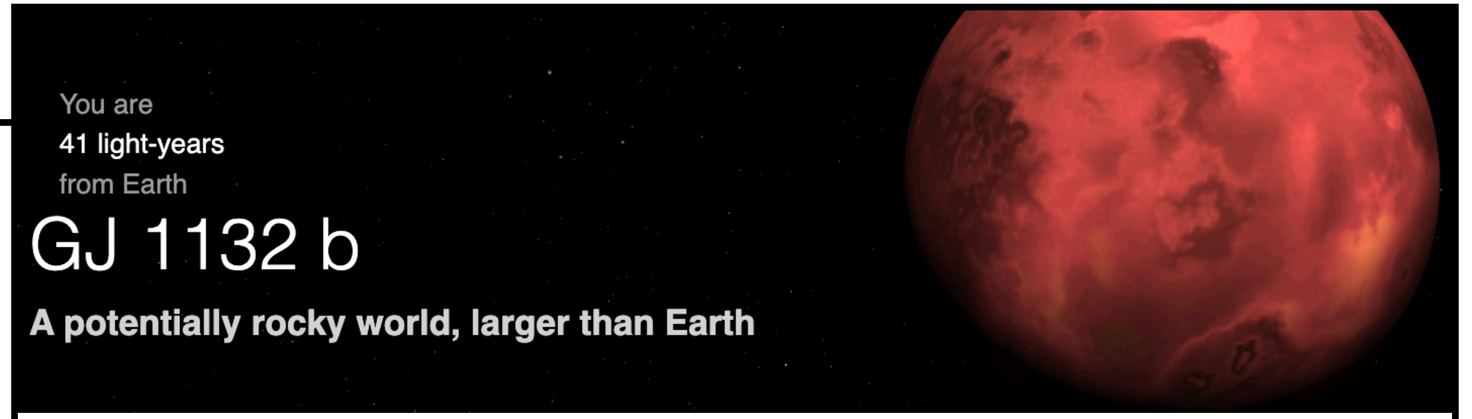
1.13 x Earth Radius **1.66 Earth Masses** **T ~ 580 K**



Diamond-Lowe et al. 2018

An overview of R<1.8 R⊕ observations with HST and G-B instruments





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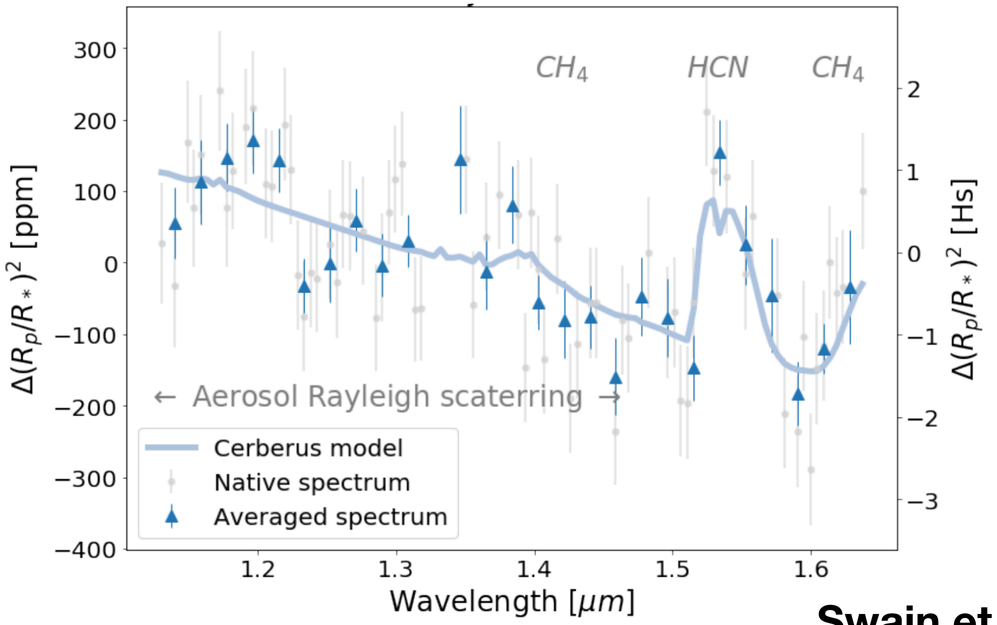
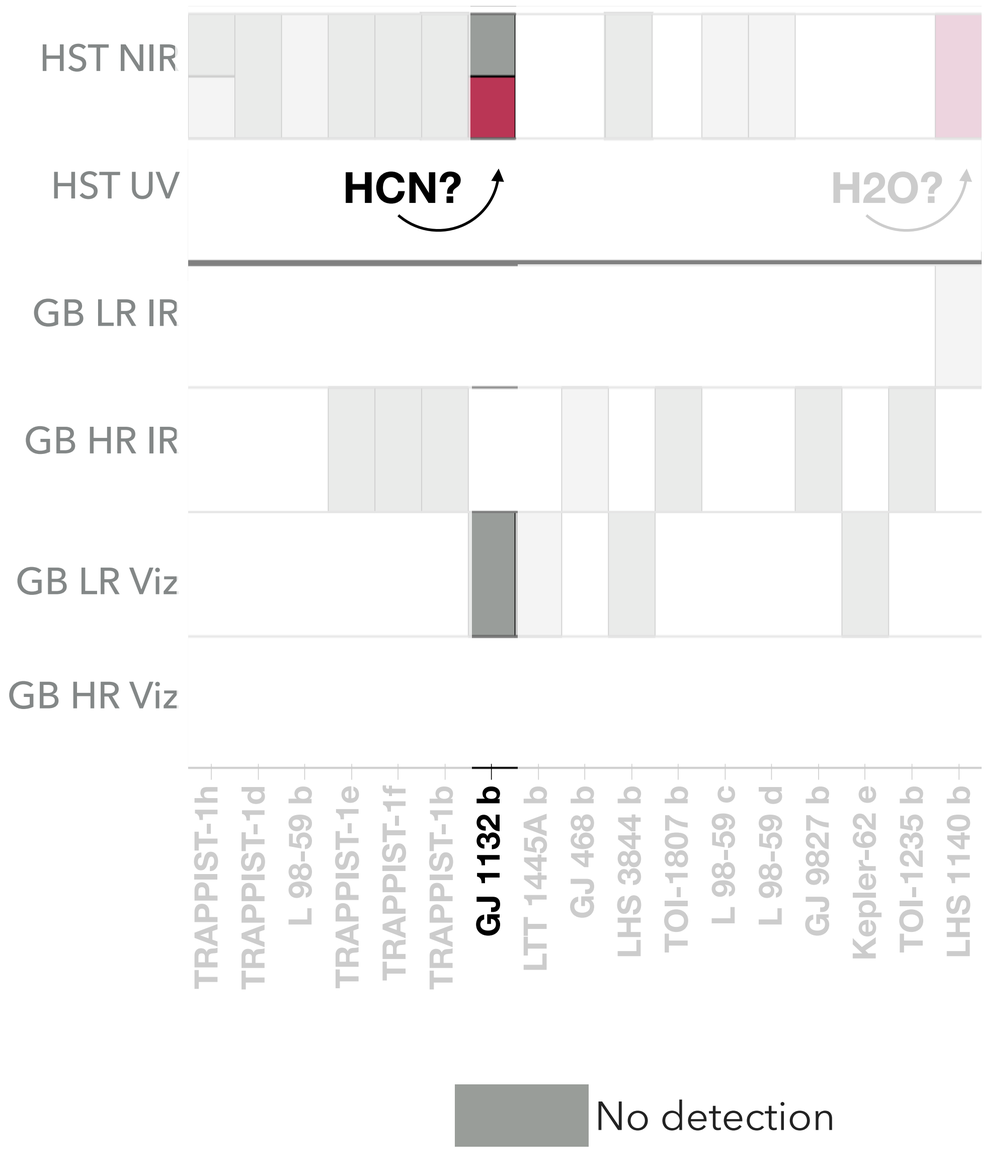
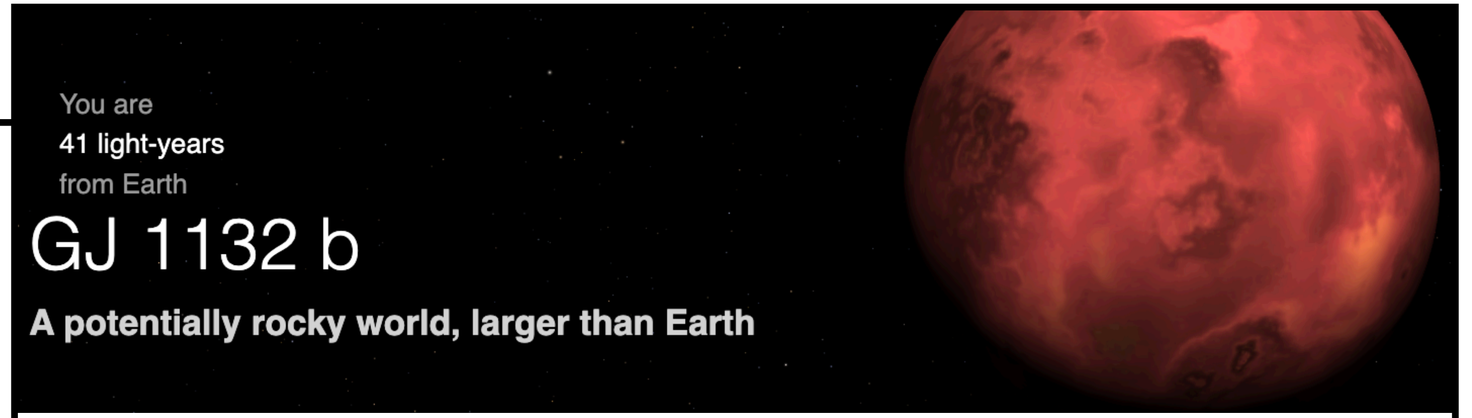


Swain et al. 2021

An overview of R<1.8 R⊕ observations with HST and G-B instruments





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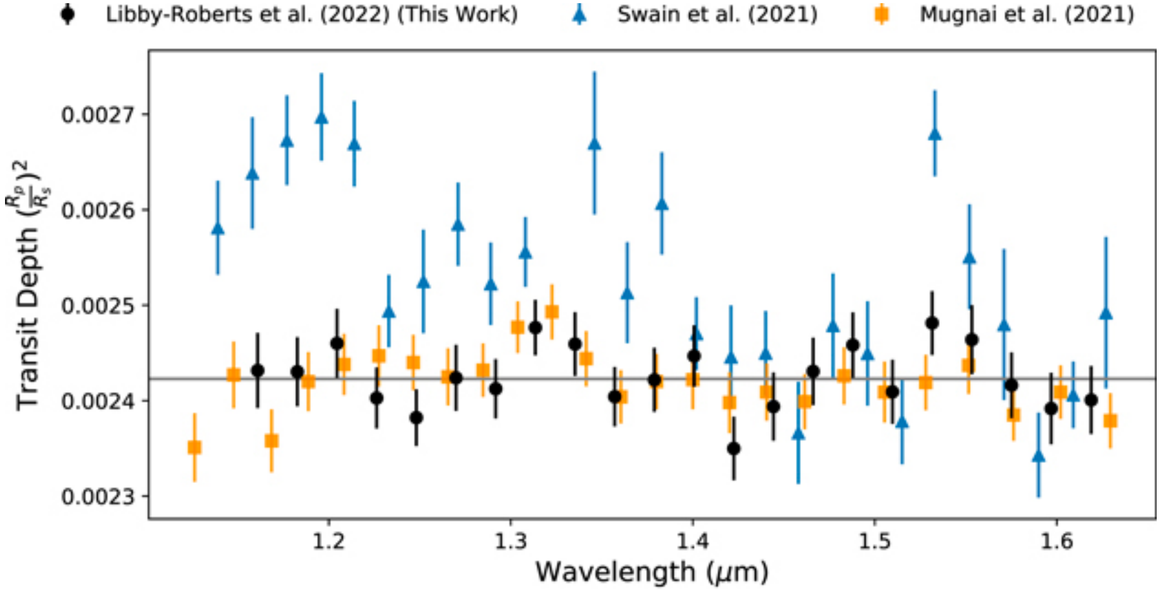
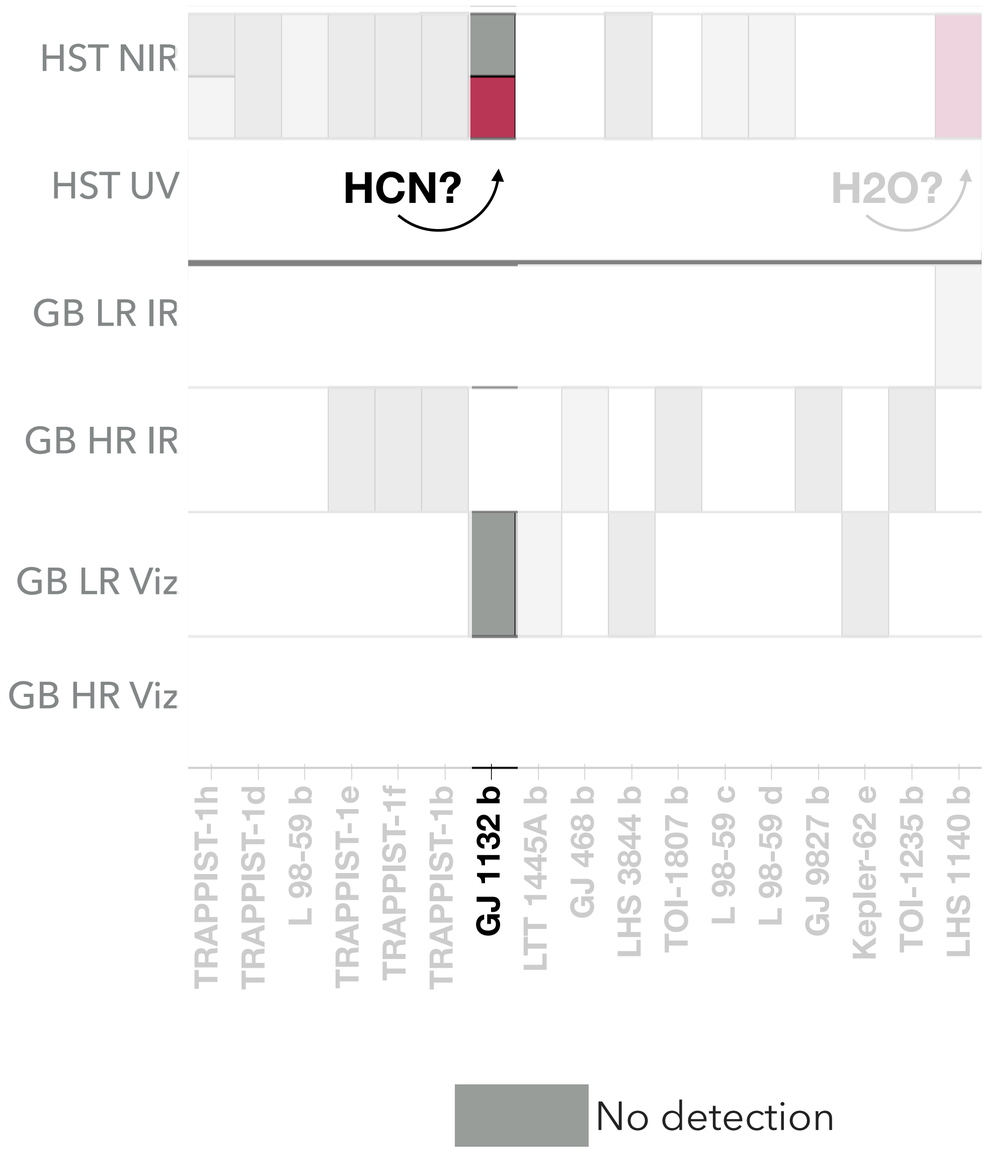
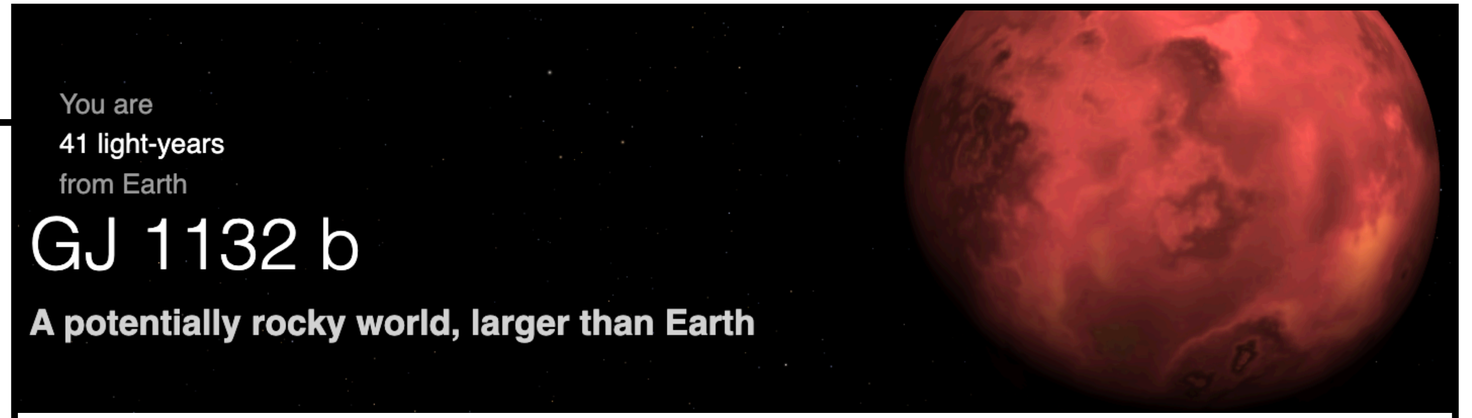


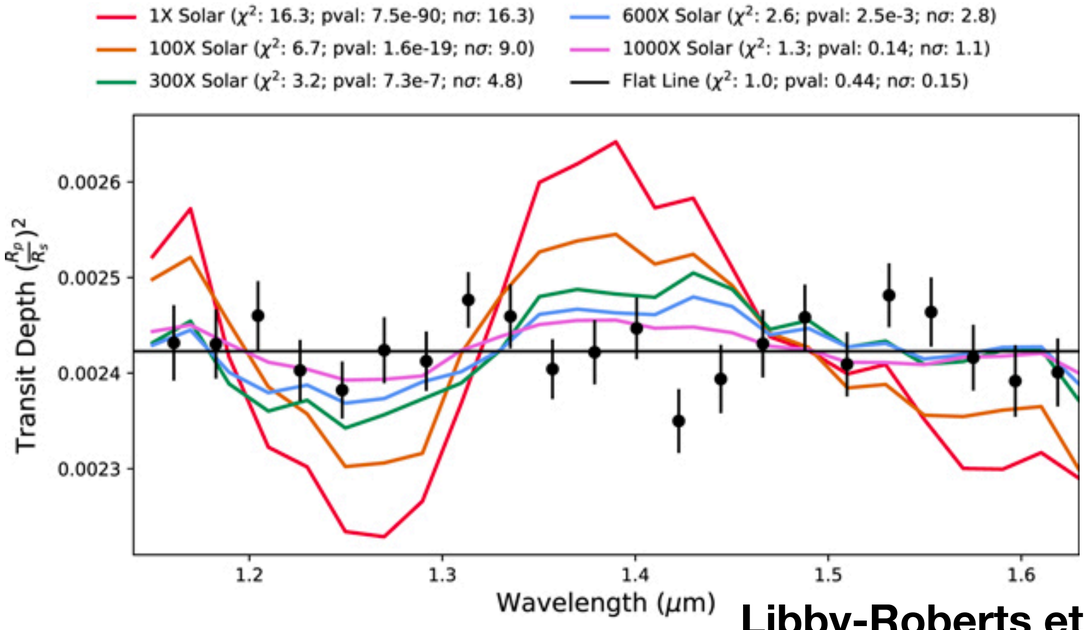
Libby-Roberts et al. 2022

An overview of R<1.8 R⊕ observations with HST and G-B instruments



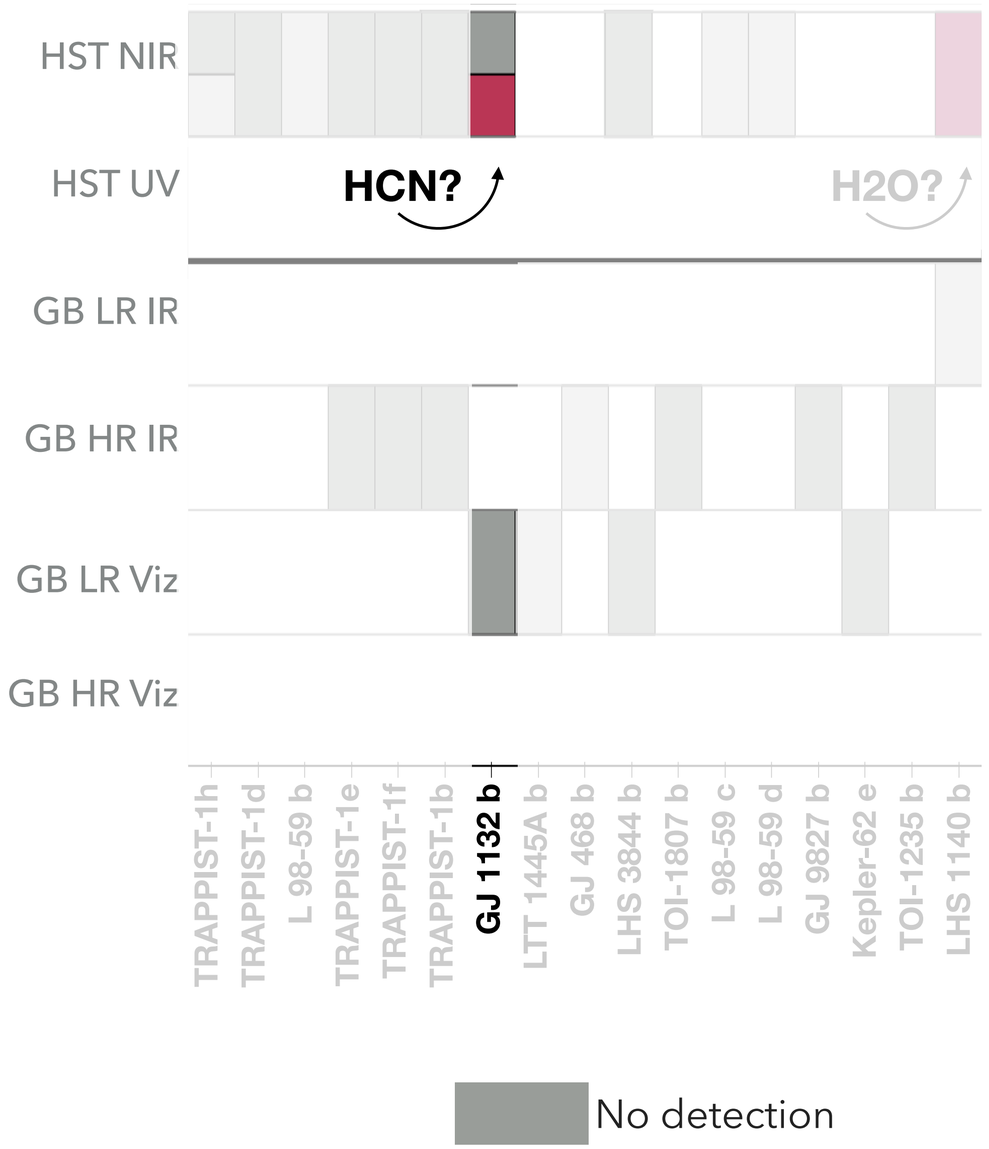


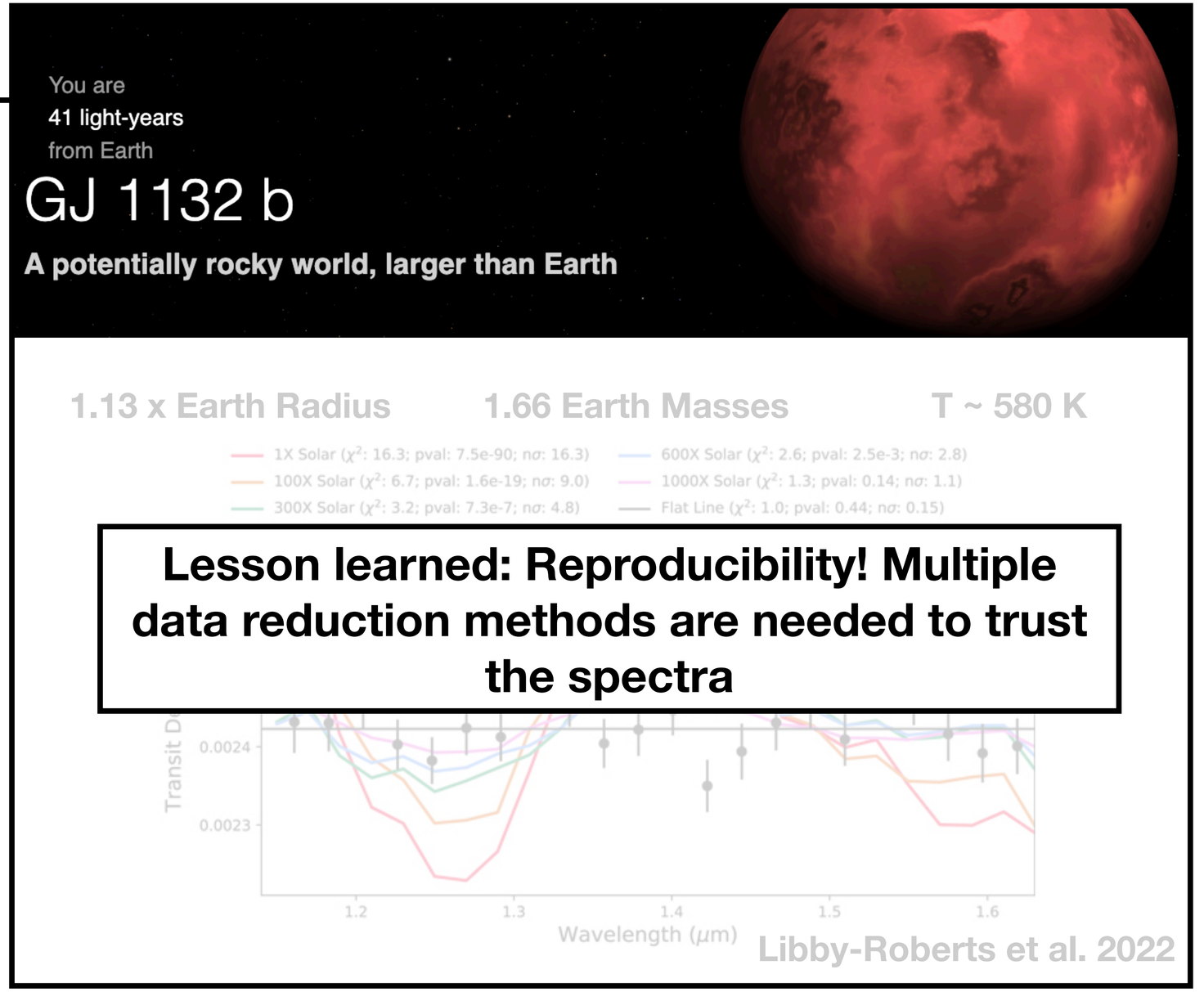
1.13 x Earth Radius **1.66 Earth Masses** **T ~ 580 K**



Libby-Roberts et al. 2022

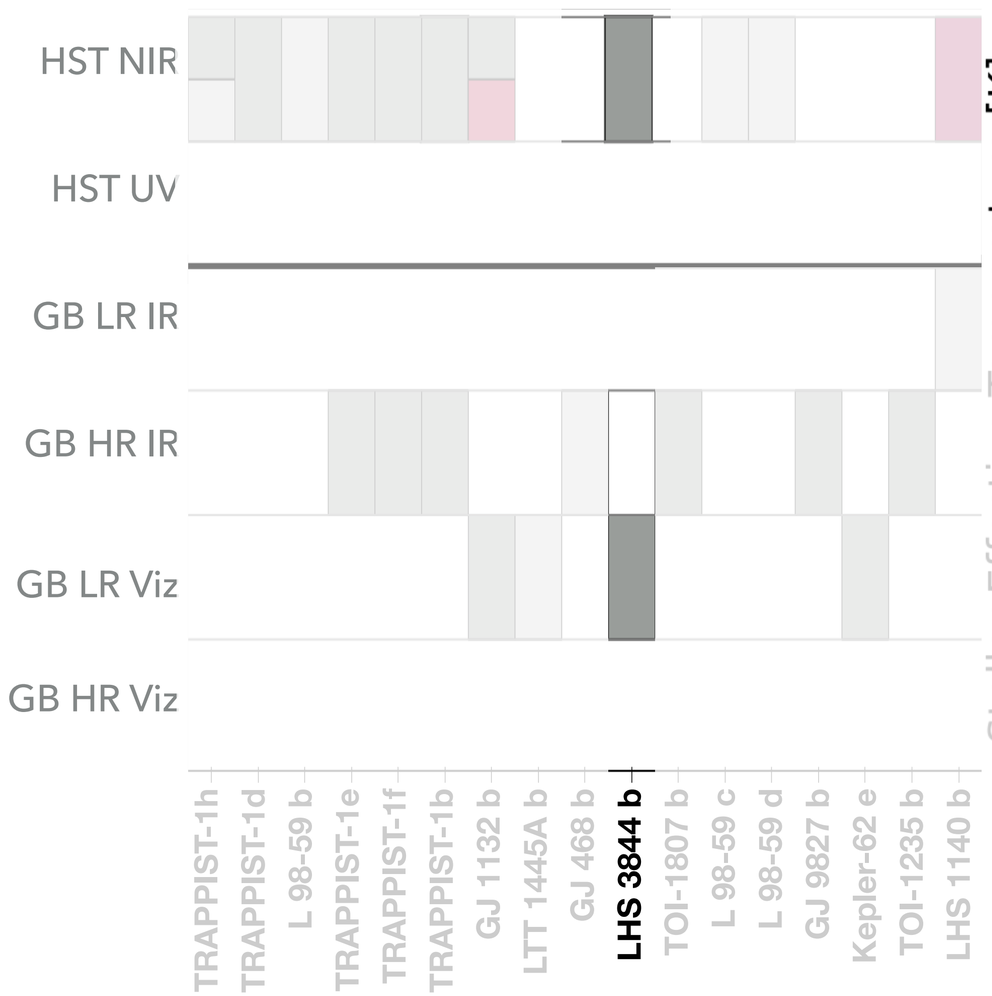
An overview of R<1.8 R⊕ observations with HST and G-B instruments

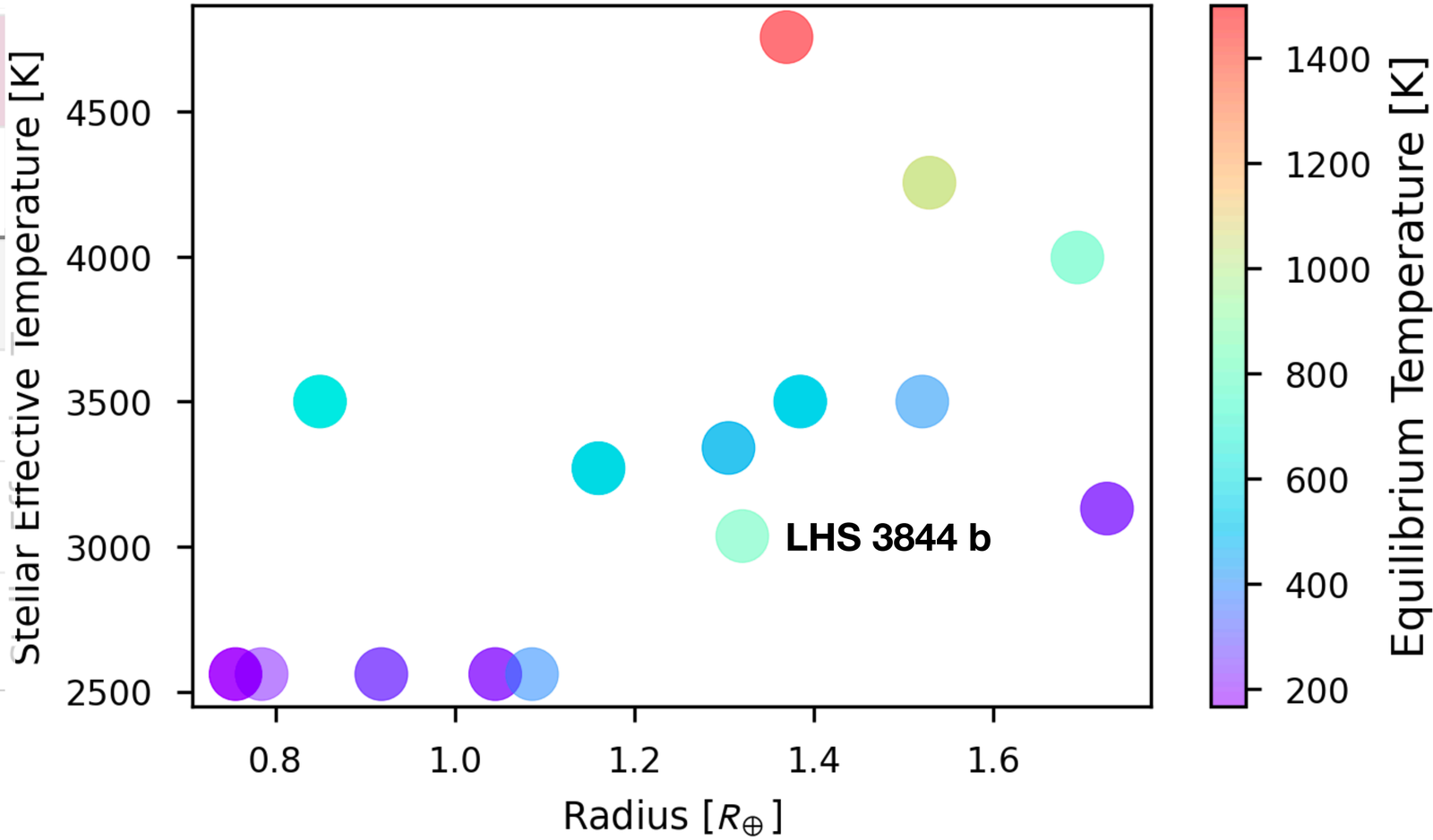




Lesson learned: Reproducibility! Multiple data reduction methods are needed to trust the spectra

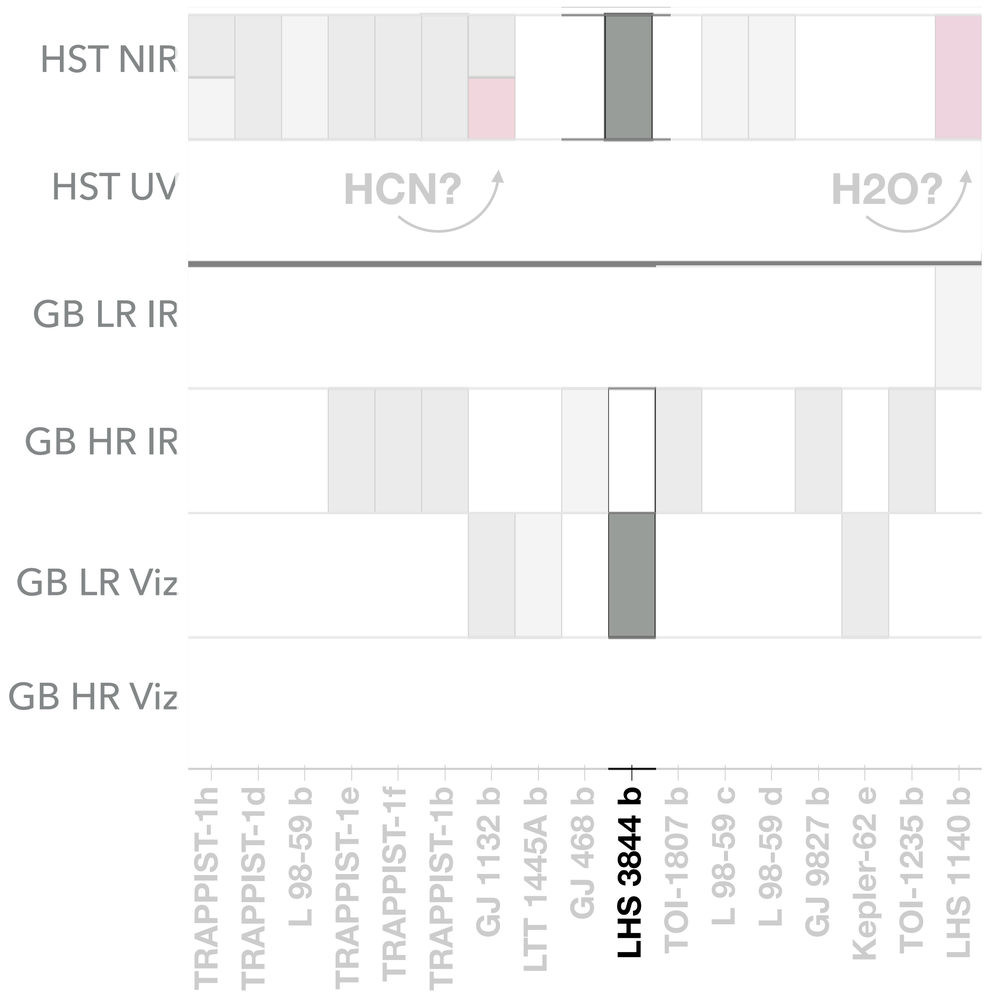
An overview of R<1.8 R⊕ observations with HST and G-B instruments





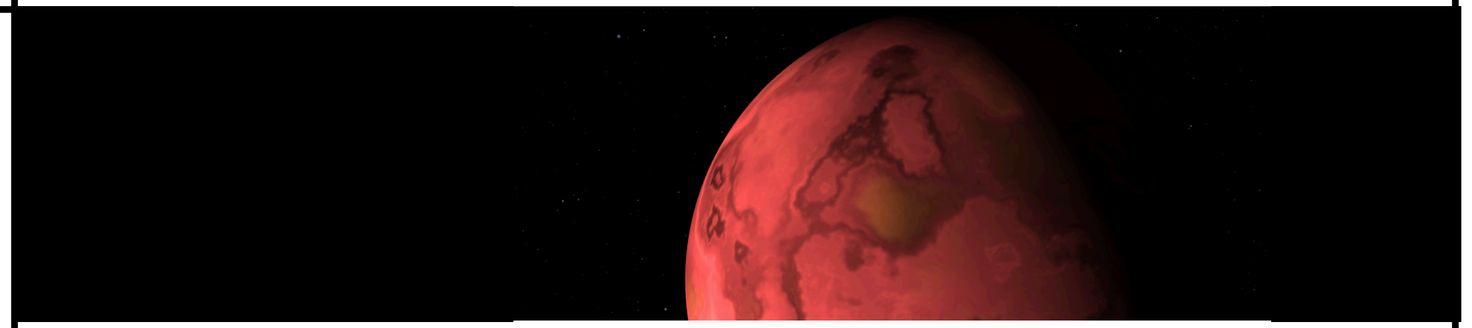
No detection

An overview of R<1.8 R⊕ observations with HST and G-B instruments

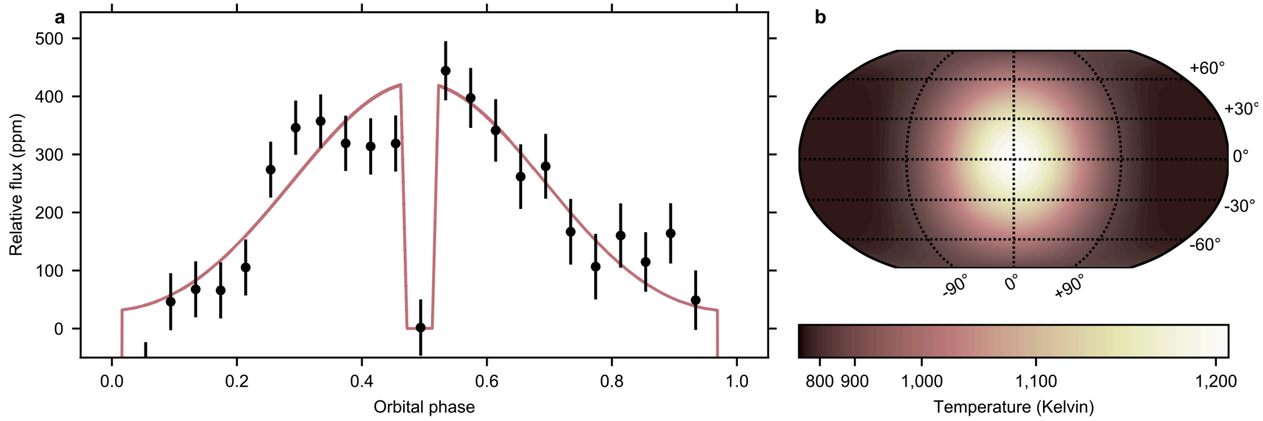


No detection

LHS 3844 b



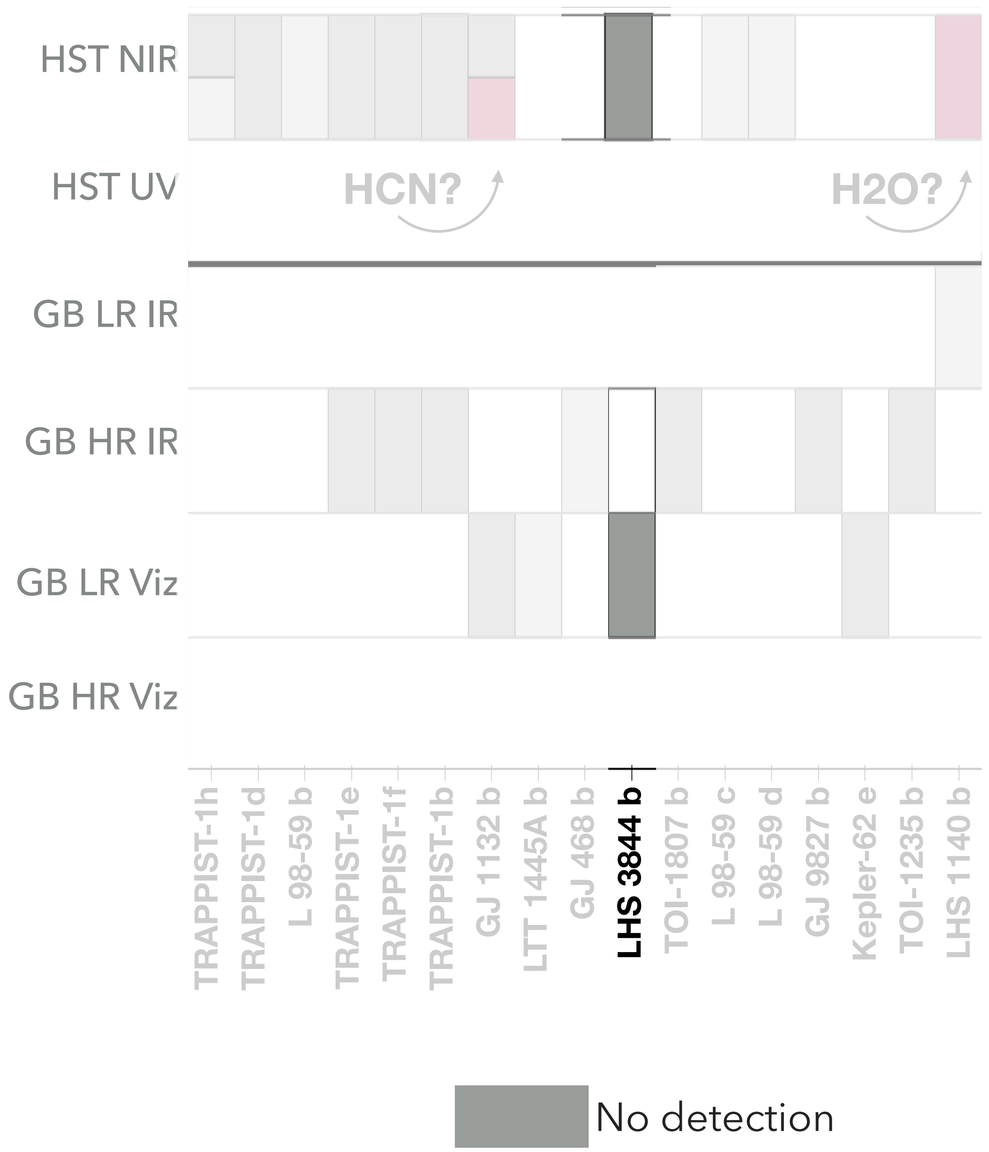
1.3 x Earth Radius **2.25 Earth Masses** **T ~ 800 K**



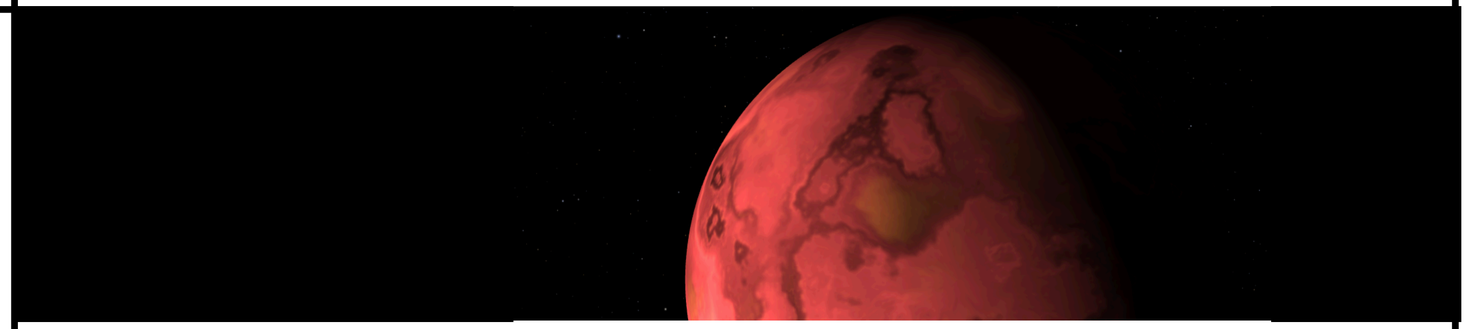
Remember from Laura Kreidberg's talk on Tues!

Kreidberg et al. 2019

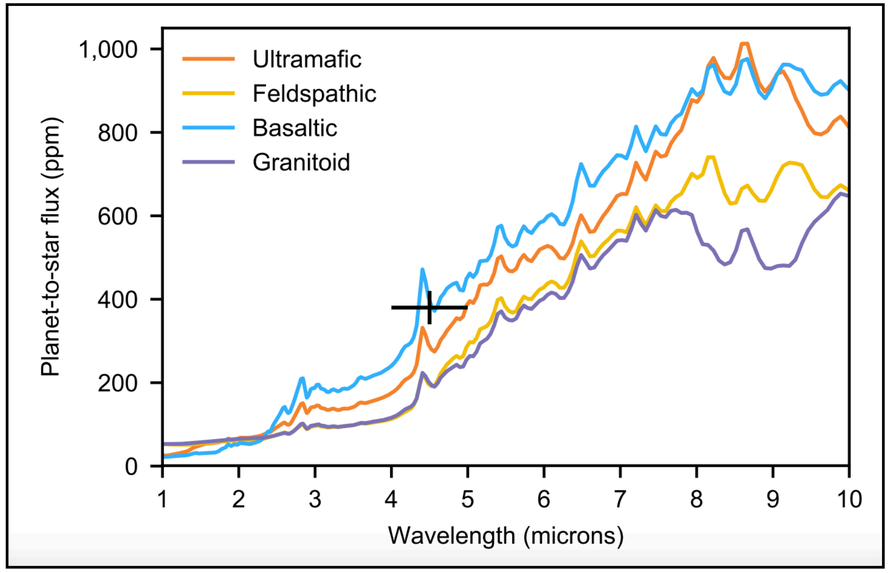
An overview of R<1.8 R⊕ observations with HST and G-B instruments



LHS 3844 b



1.3 x Earth Radius **2.25 Earth Masses** **T ~ 800 K**

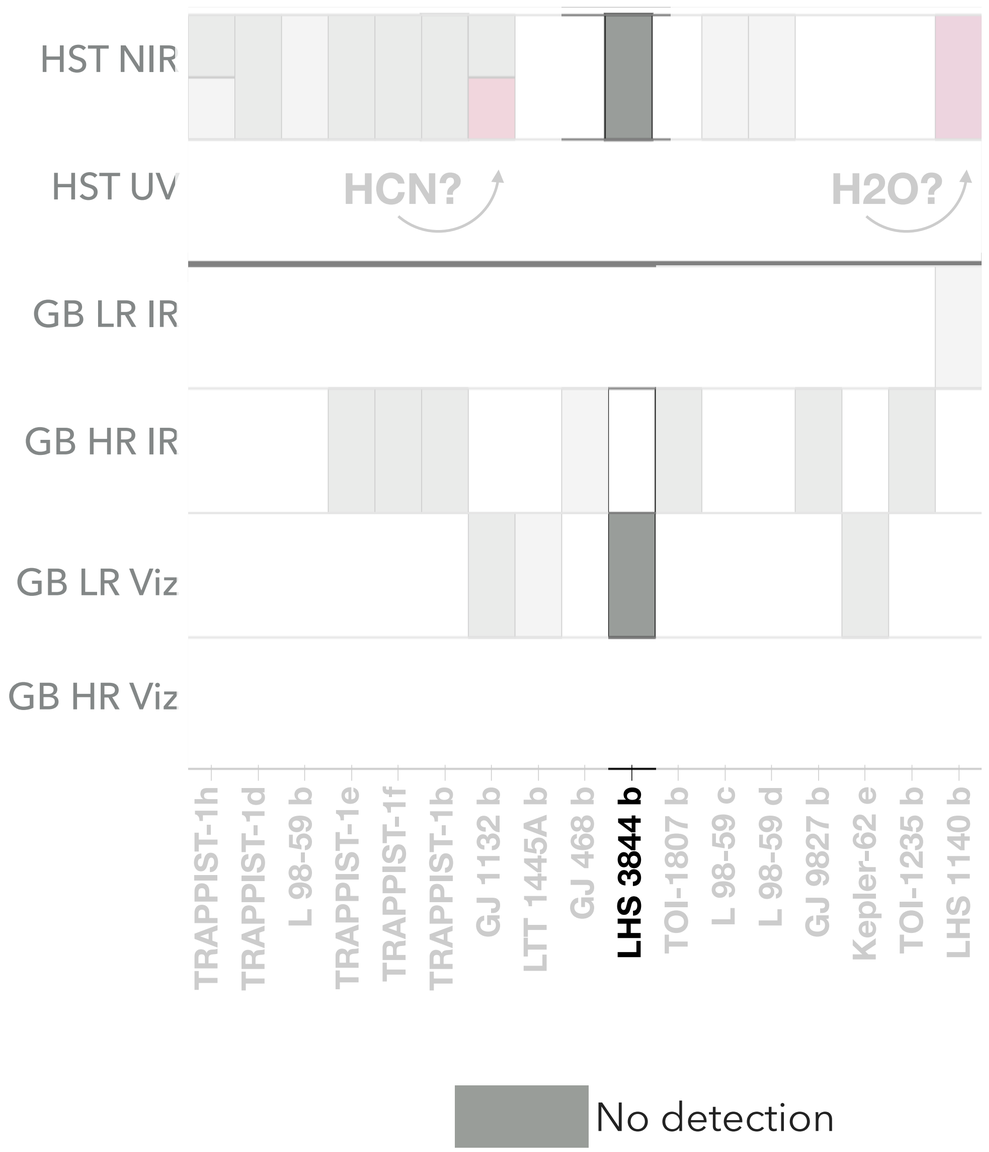


Surface materials have different absorptive properties

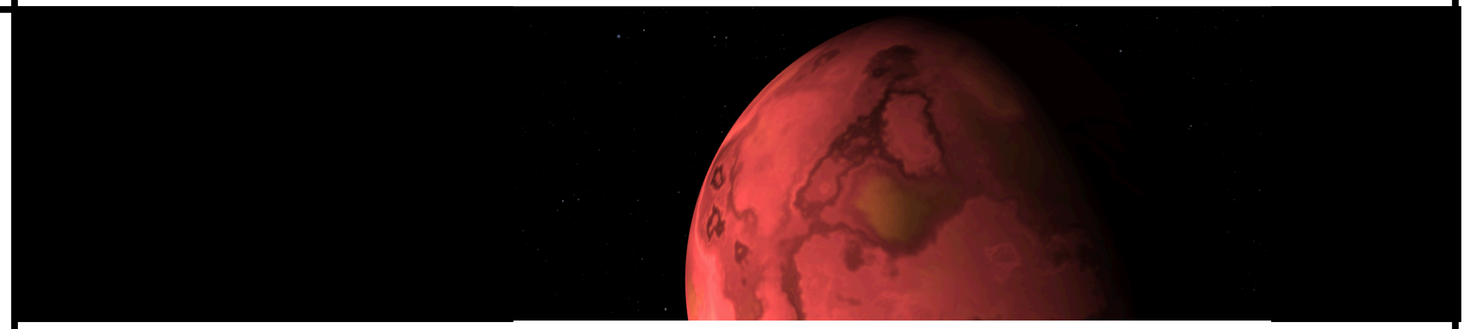
Models require at least 40% basalt or 75% ultramafic rock to be consistent with the data at 3σ confidence

Kreidberg et al. 2019

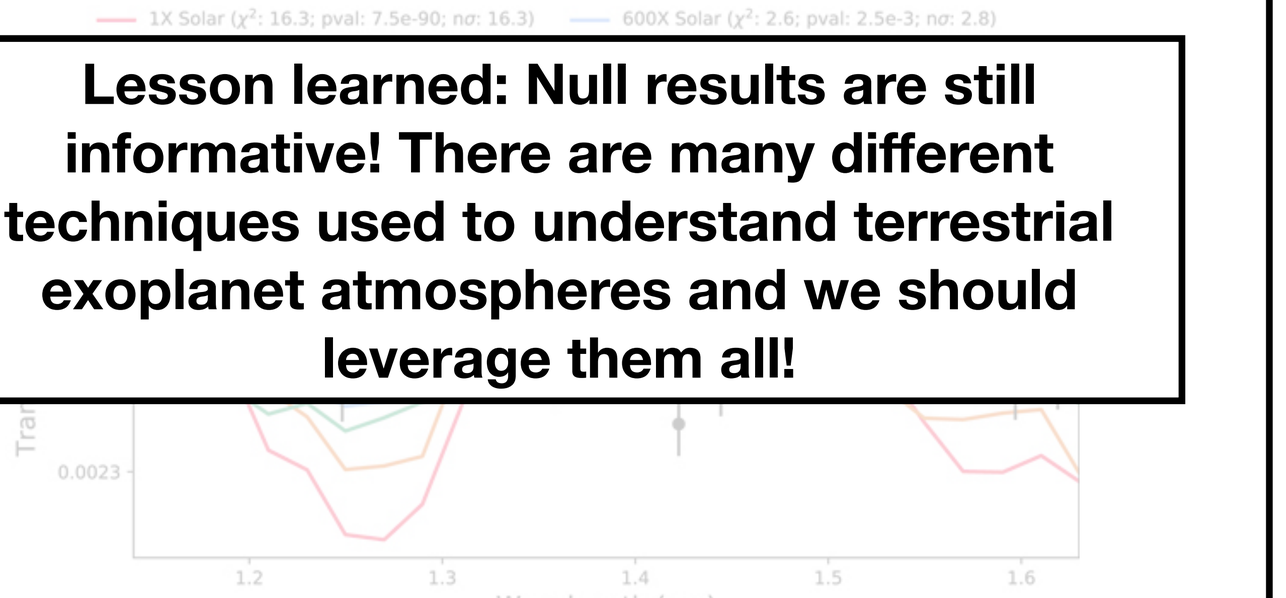
An overview of R<1.8 R⊕ observations with HST and G-B instruments



LHS 3844 b



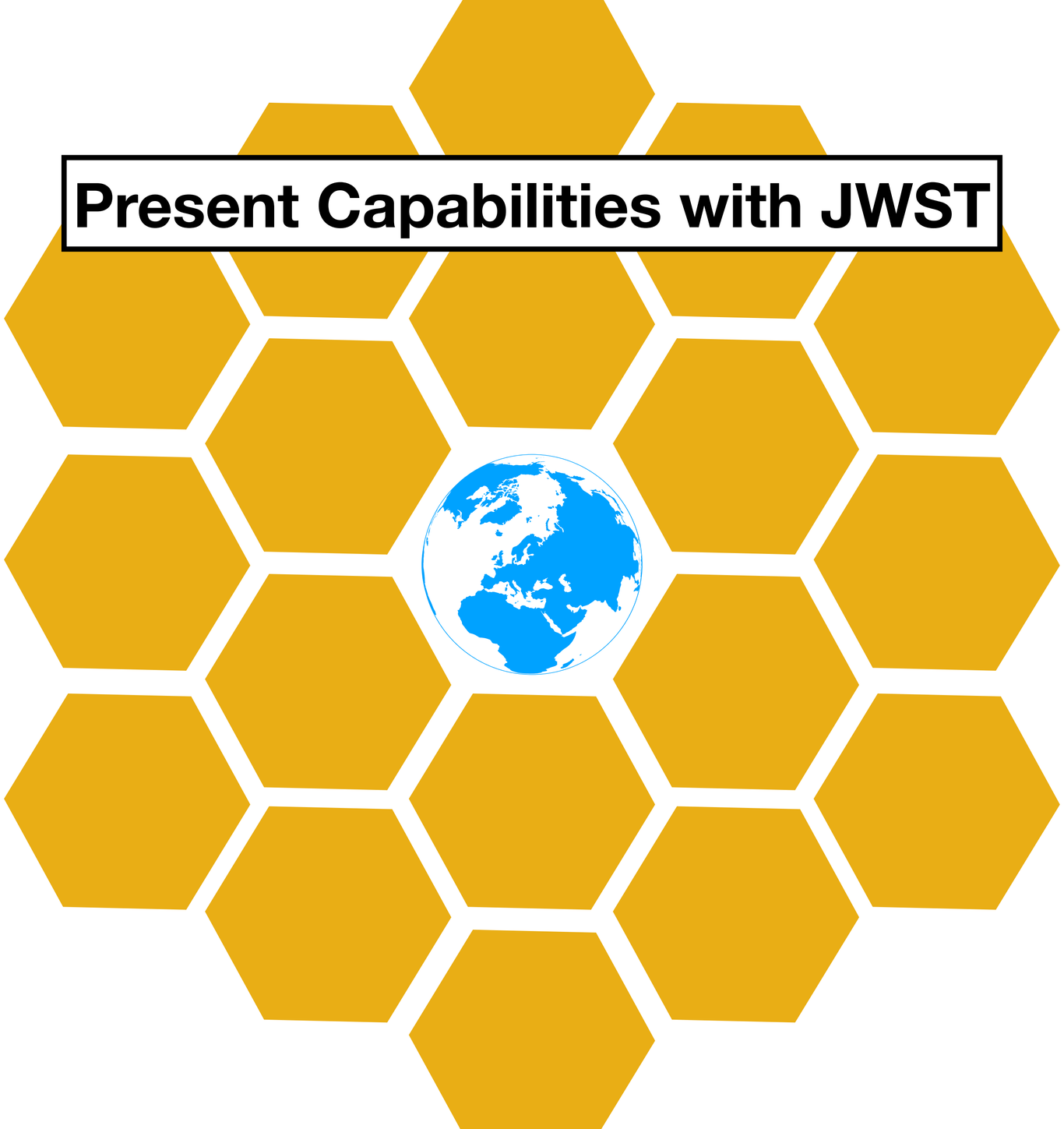
1.13 x Earth Radius 1.66 Earth Masses T ~ 580 K

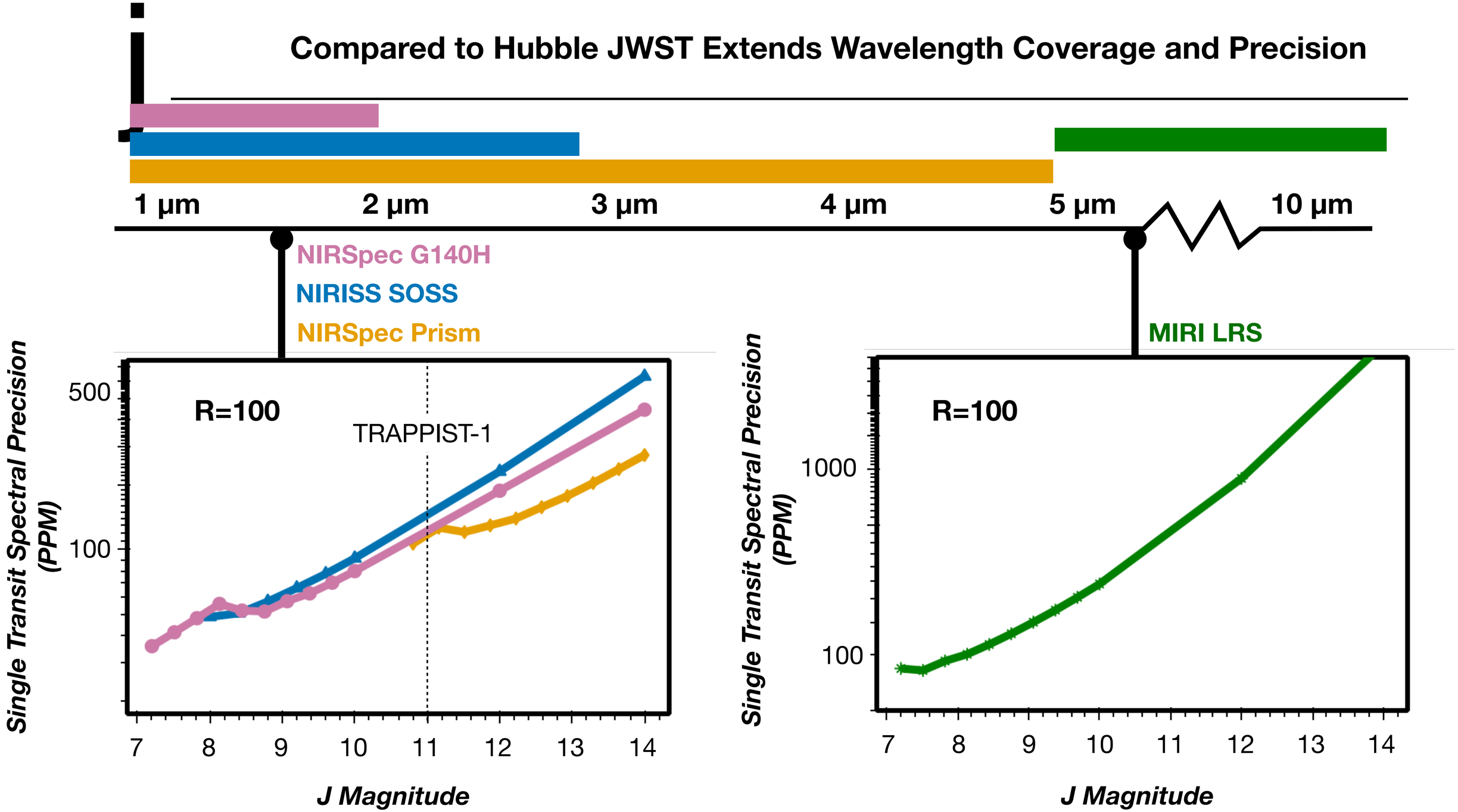


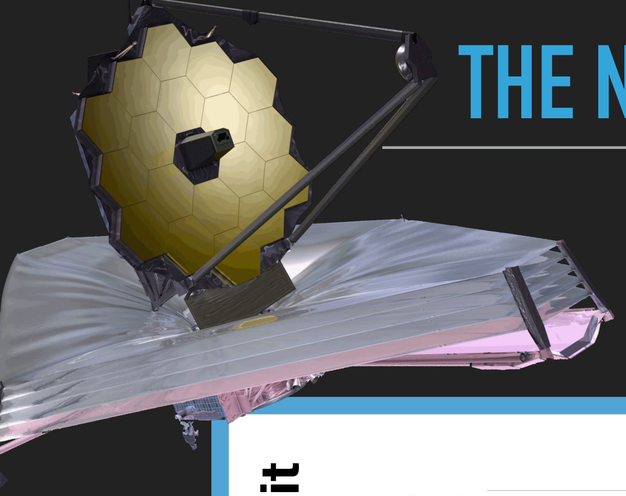
Lesson learned: Null results are still informative! There are many different techniques used to understand terrestrial exoplanet atmospheres and we should leverage them all!

Libby-Roberts et al. 2022

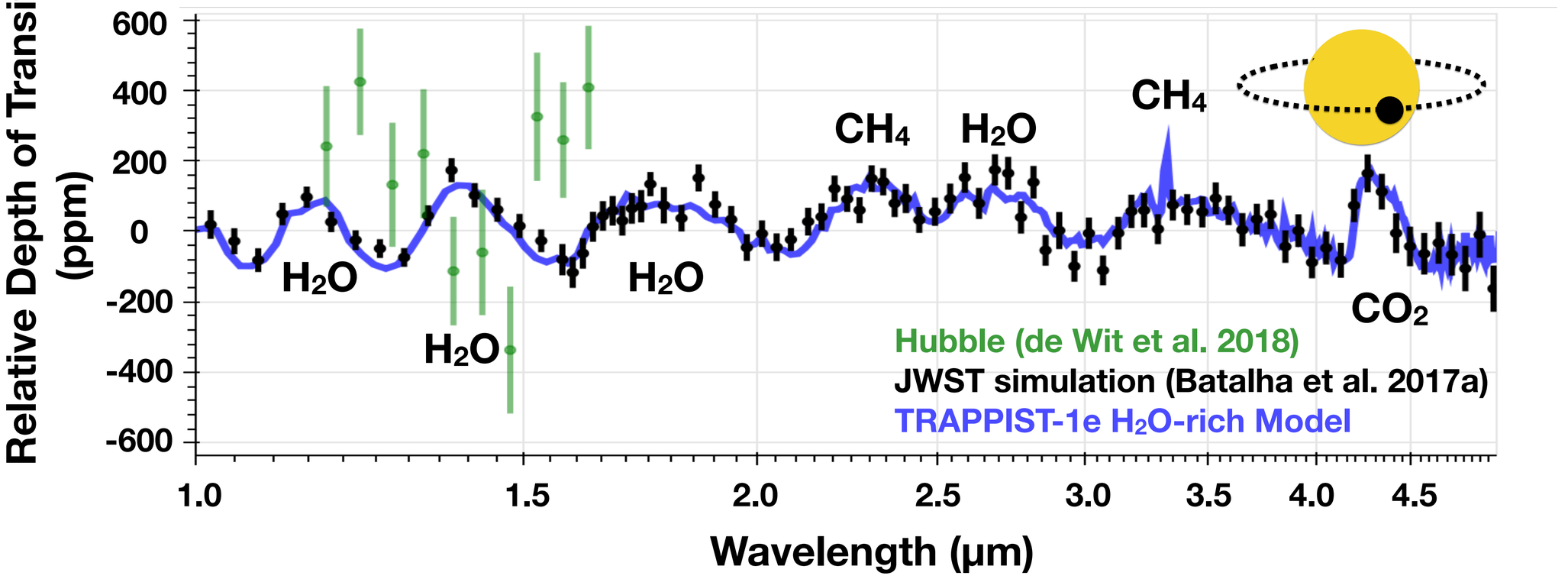
Present Capabilities with JWST



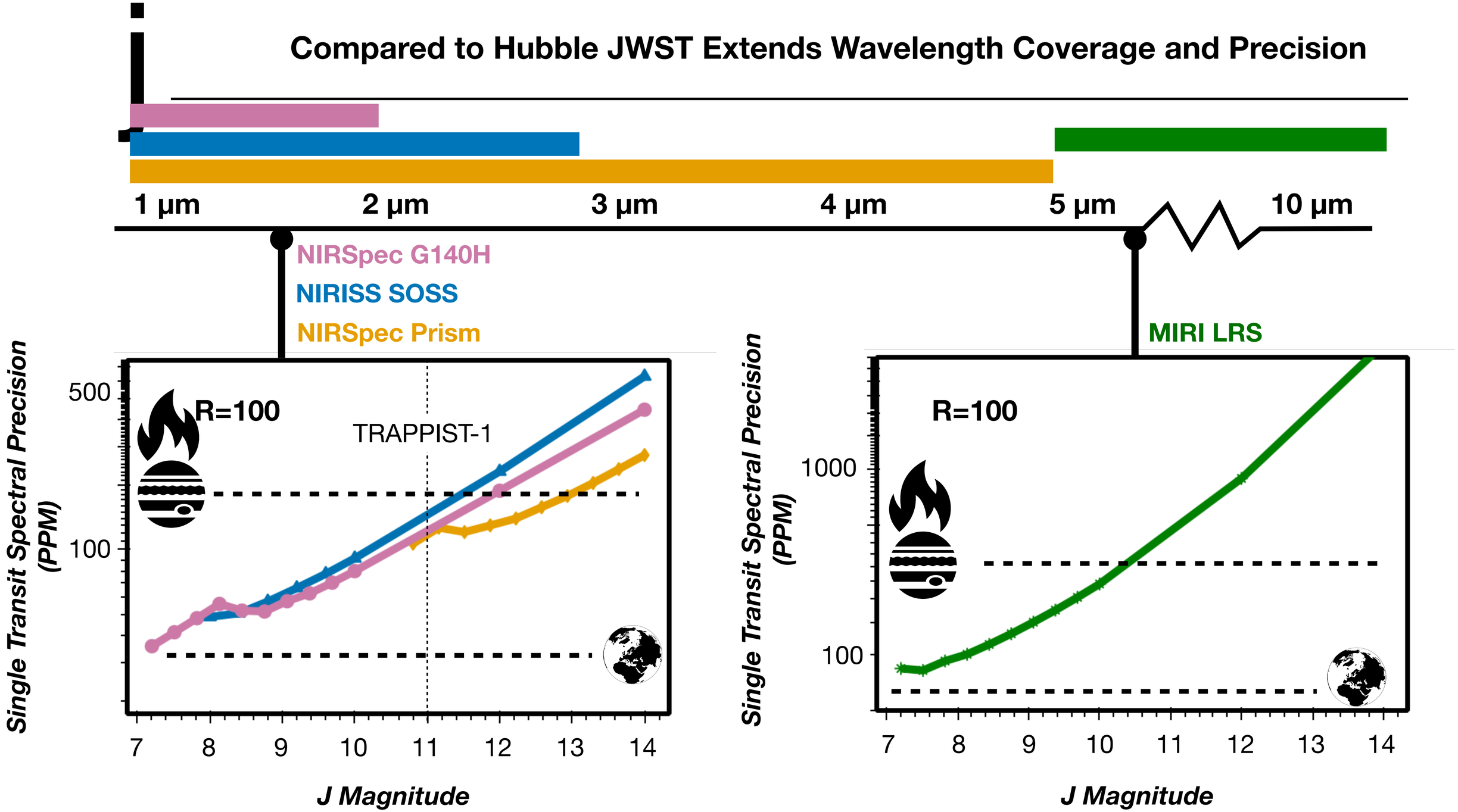

Compared to Hubble JWST Extends Wavelength Coverage and Precision
1 µm
2 µm
3 µm
4 µm
5 µm
10 µm
NIRSpec G140H
NIRISS SOSS
NIRSpec Prism
MIRI LRS
R=100
TRAPPIST-1
Single Transit Spectral Precision (PPM)
500
100
7
8
9
10
11
12
13
14
J Magnitude
R=100
1000
100
Single Transit Spectral Precision (PPM)
7
8
9
10
11
12
13
14
J Magnitude



THE NEXT ERA OF EXO-ATMOSPHERE OBSERVATIONS



22.2 NIRSpec Prism hrs: PI N. Lewis/M. Mountain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MIRI LRS
R=100
TRAPPIST-1
Single Transit Spectral Precision (PPM)
500
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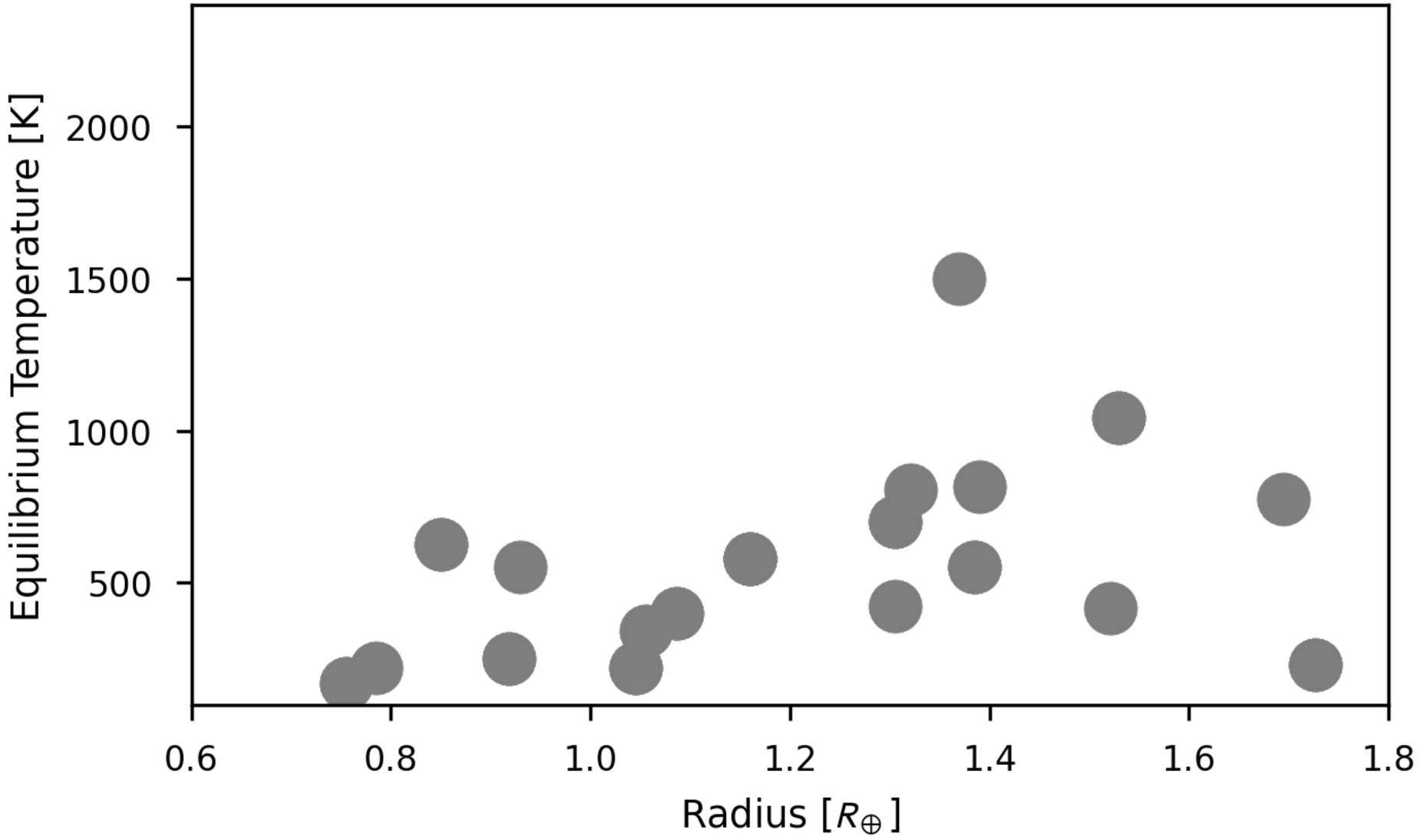
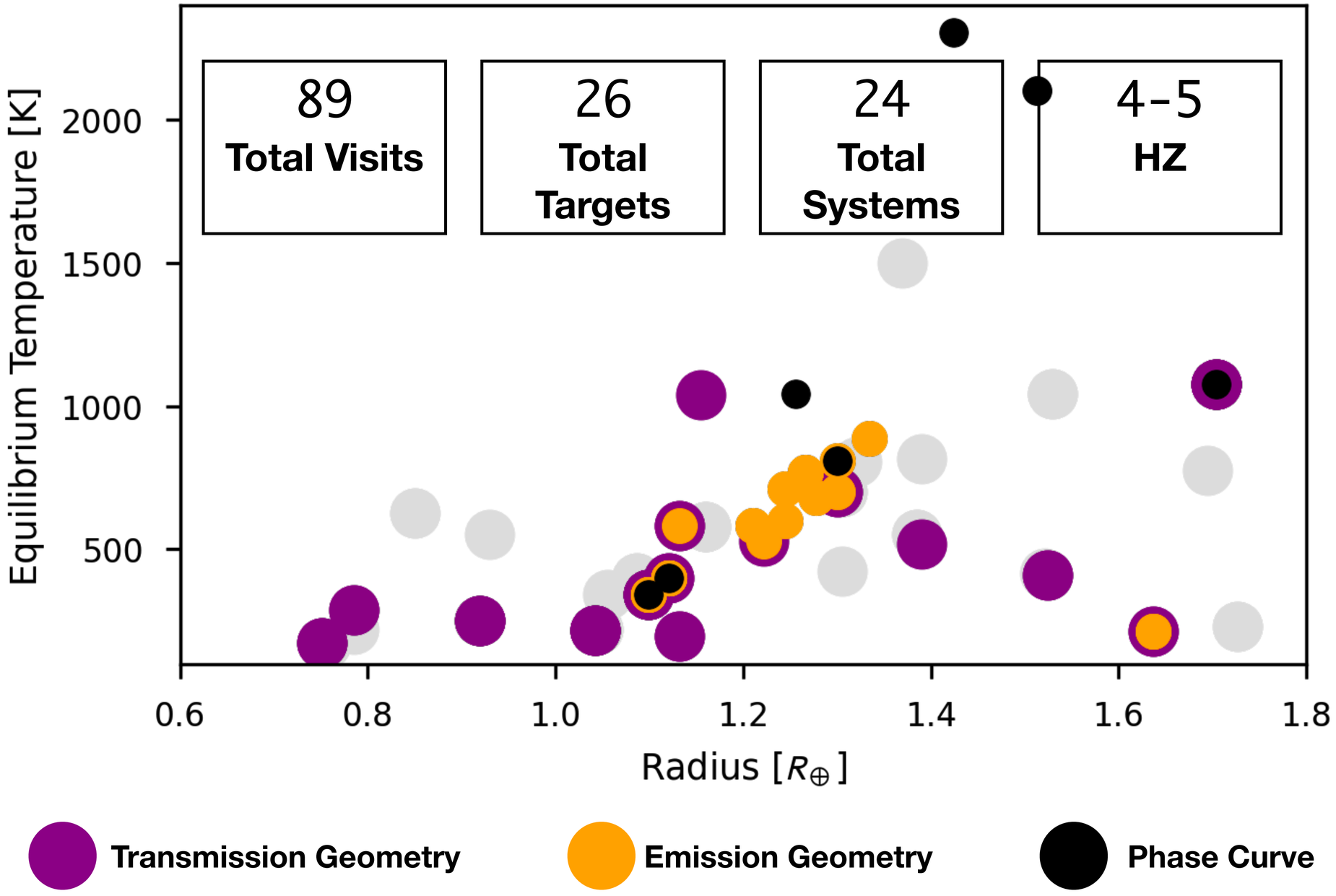
7
8
9
10
11
12
13
14
J Magnitude
R=100
1000
100
Single Transit Spectral Precision (PPM)
7
8
9
10
11
12
13
14
J Magnitude

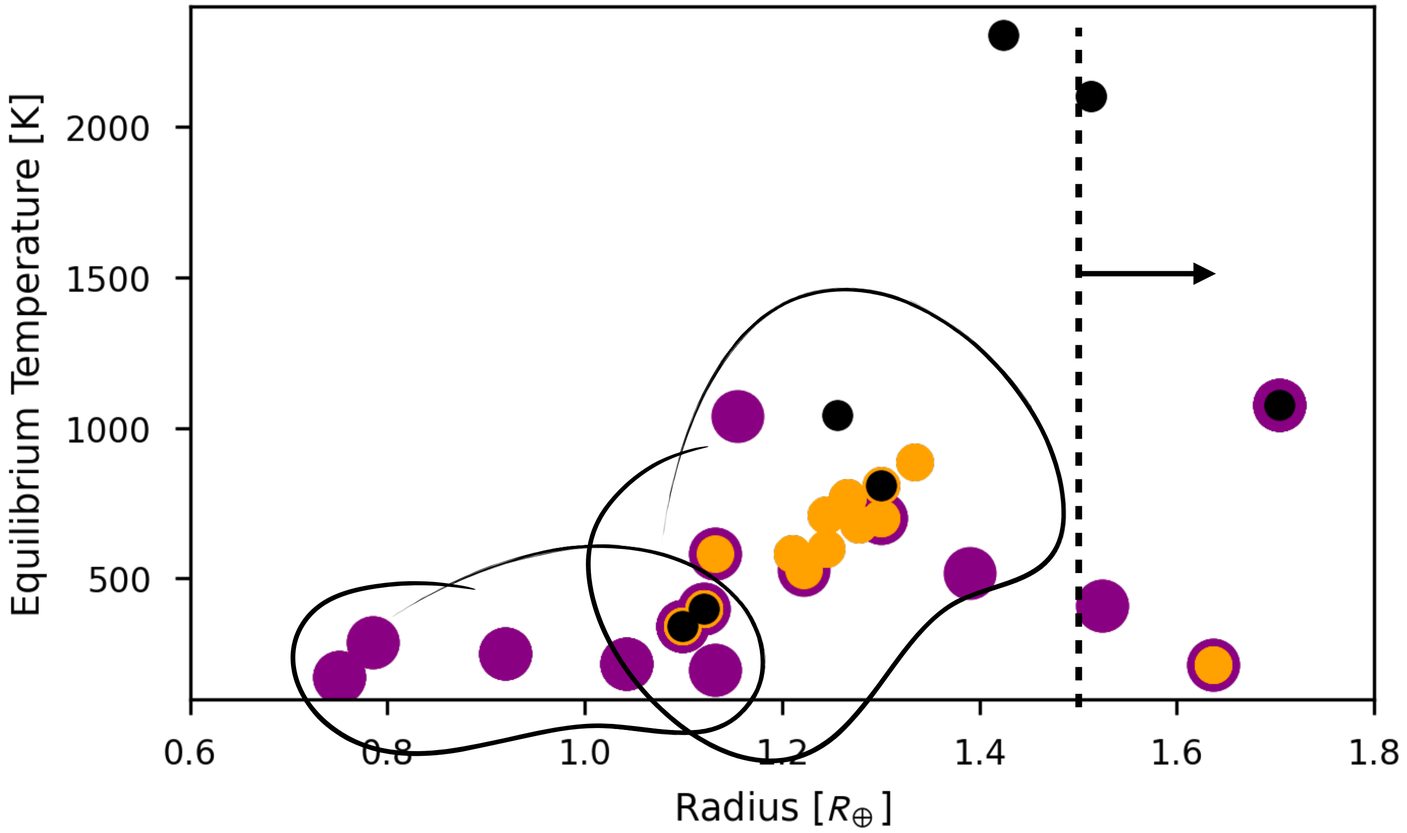
Previous HST/G-B Observations



Present Capabilities with JWST



Present Goals with JWST



1. Do the planets of the TRAPPIST-1 system have atmospheres? Biosignatures?

2. Is there a compositional divide between super-Earth and sub-Neptune atmospheres?

3. Do M-dwarf planets have atmospheres?

3a. Cycle 1: Transmission signals?

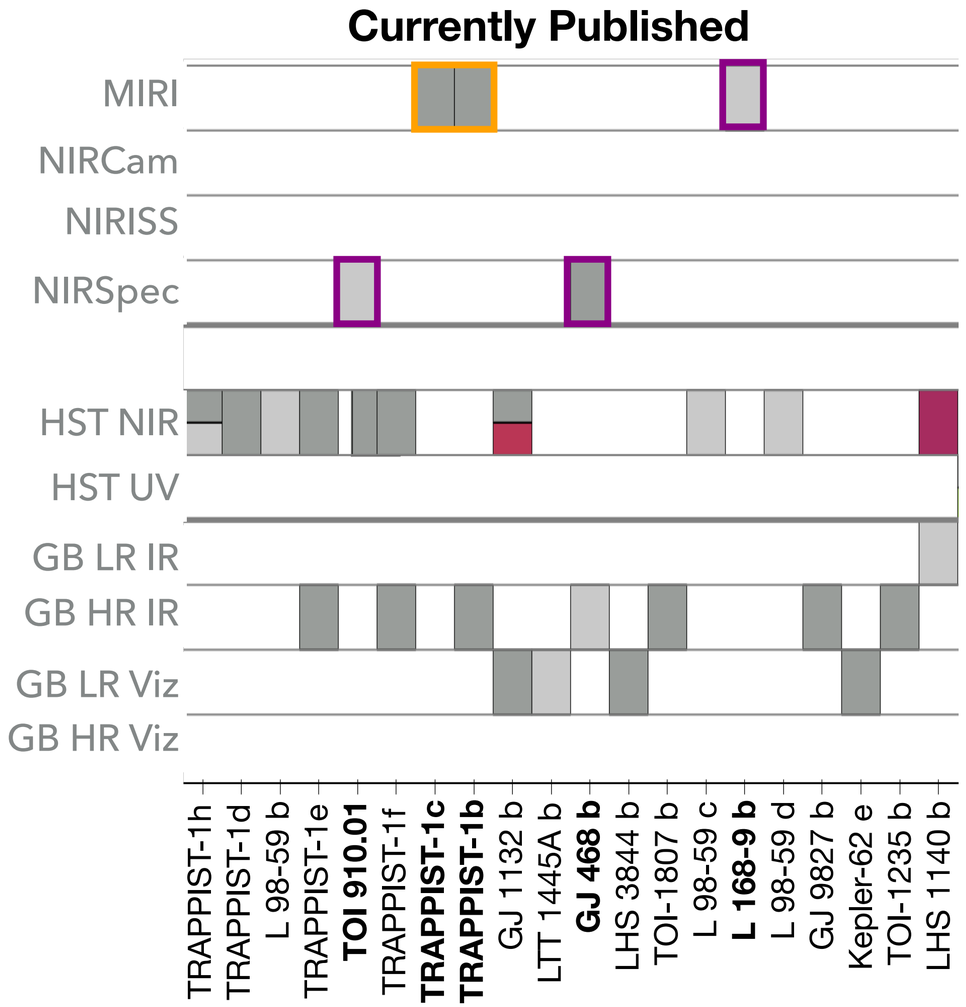
3b. Cycle 2: Emission signals?

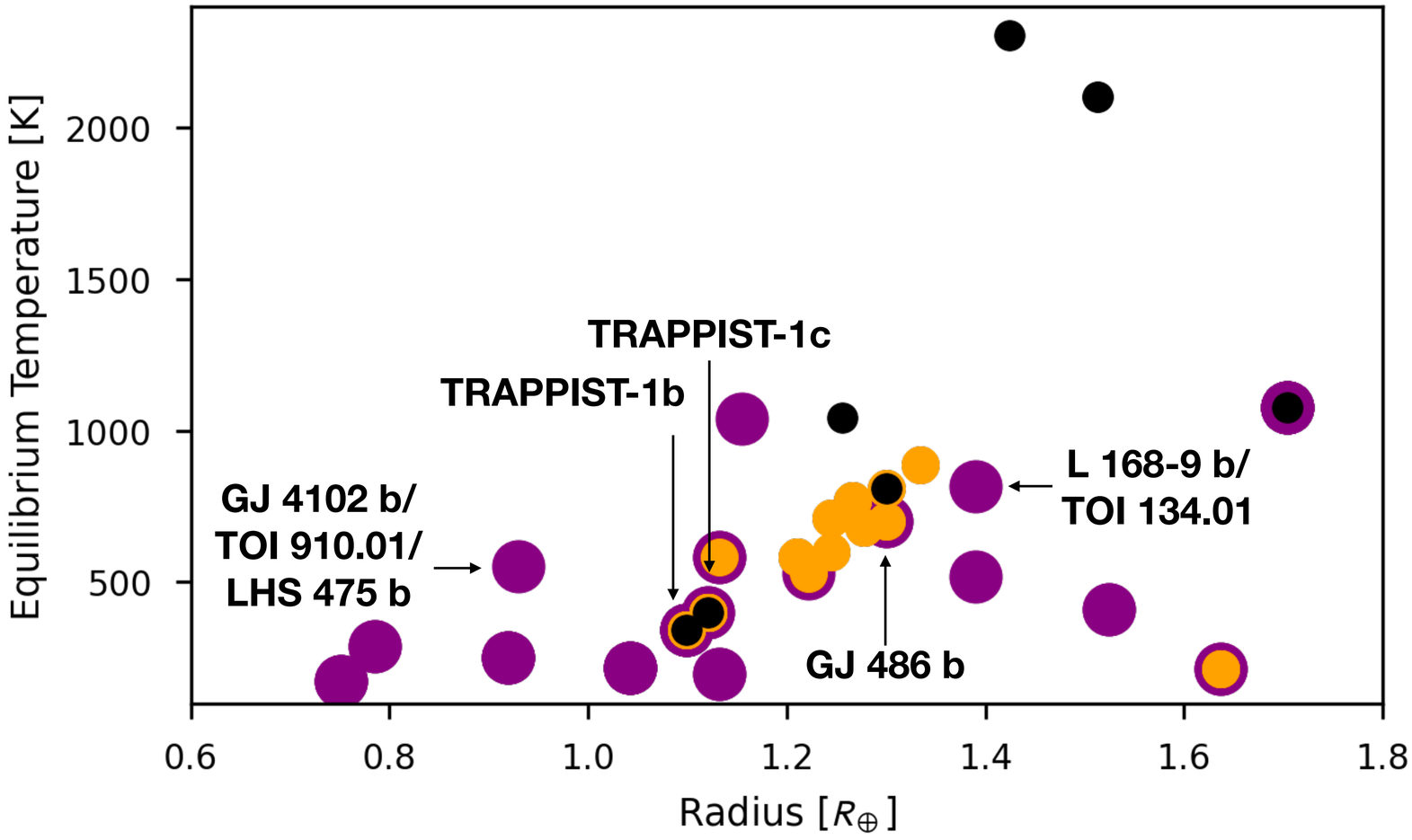
Transmission Geometry

Emission Geometry

Phase Curve

Currently Published JWST Observations





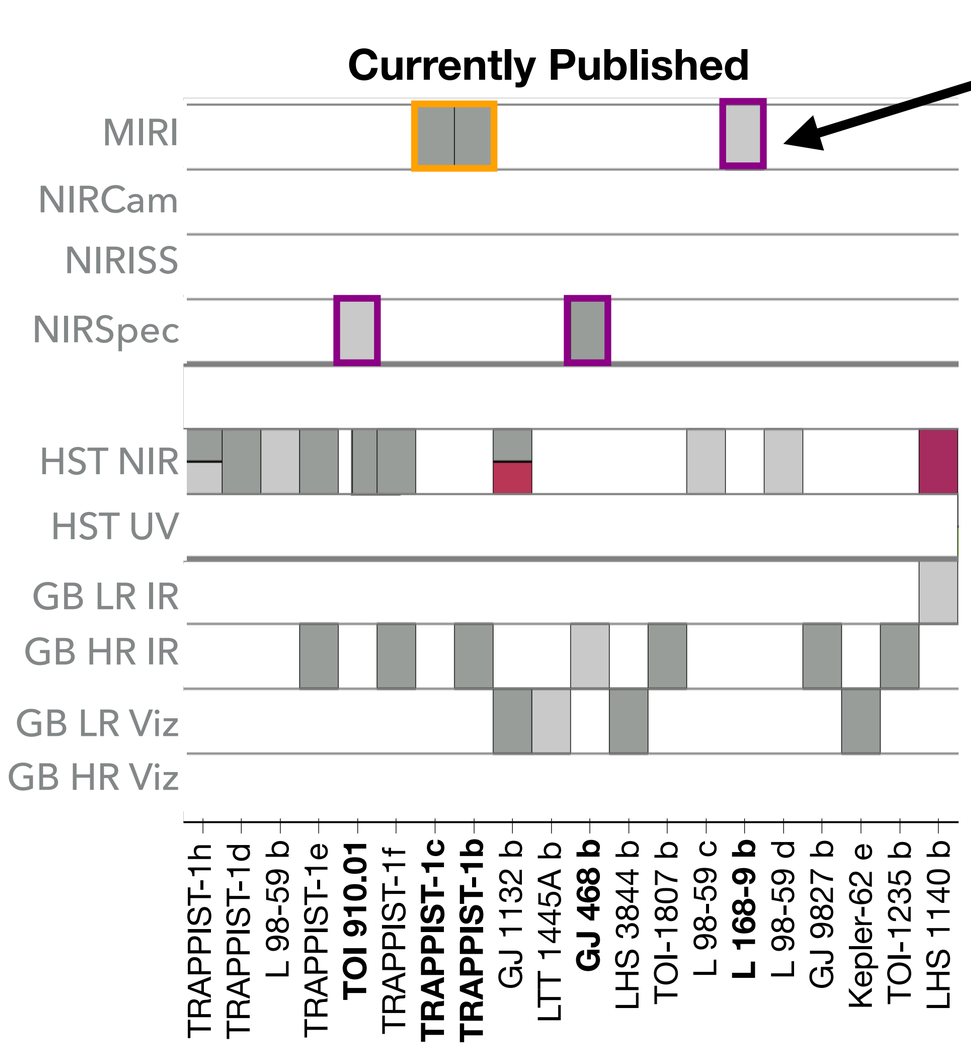
No detection

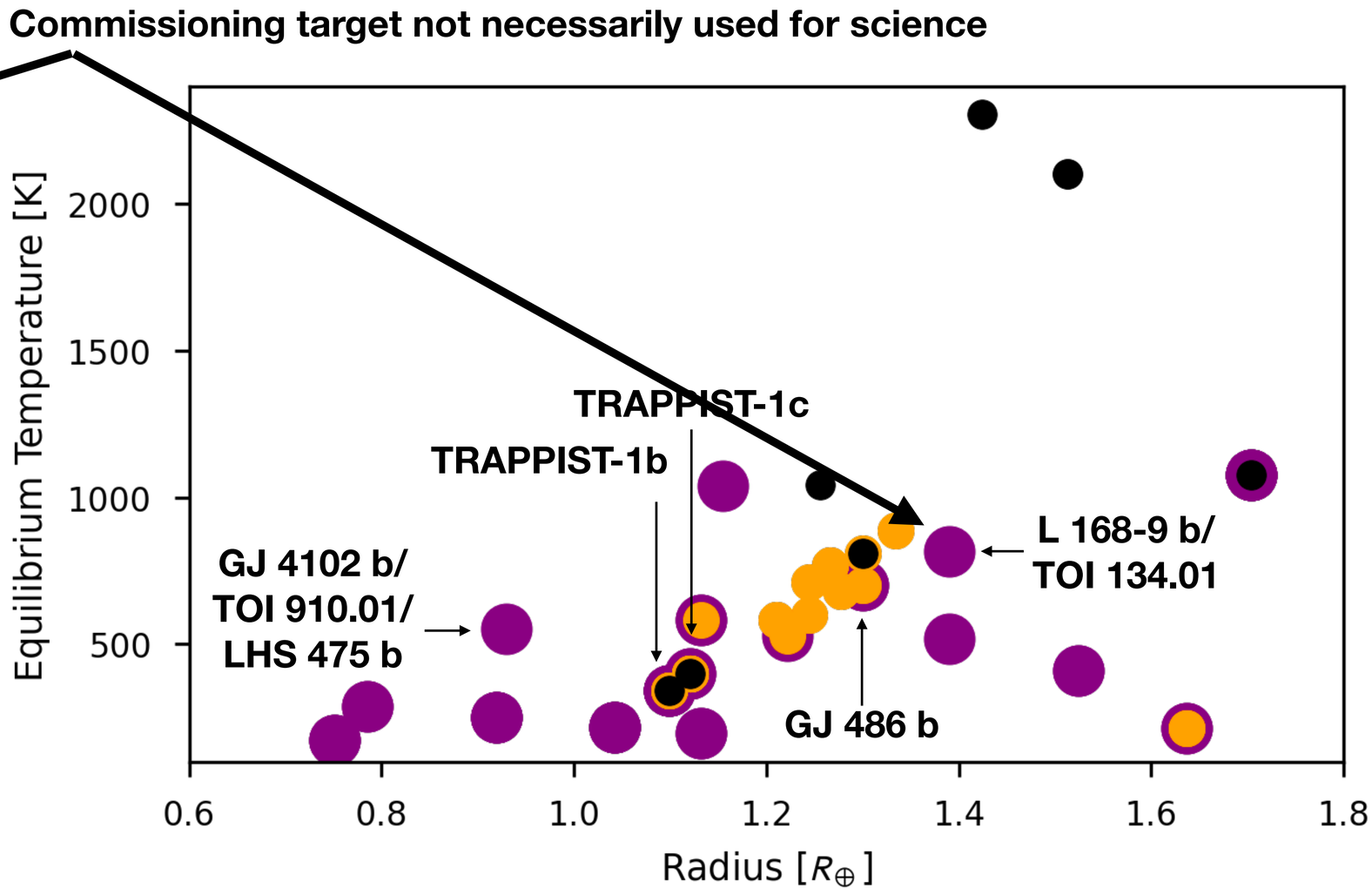
Transmission Geometry

Emission Geometry

Phase Curve

Currently Published JWST Observations





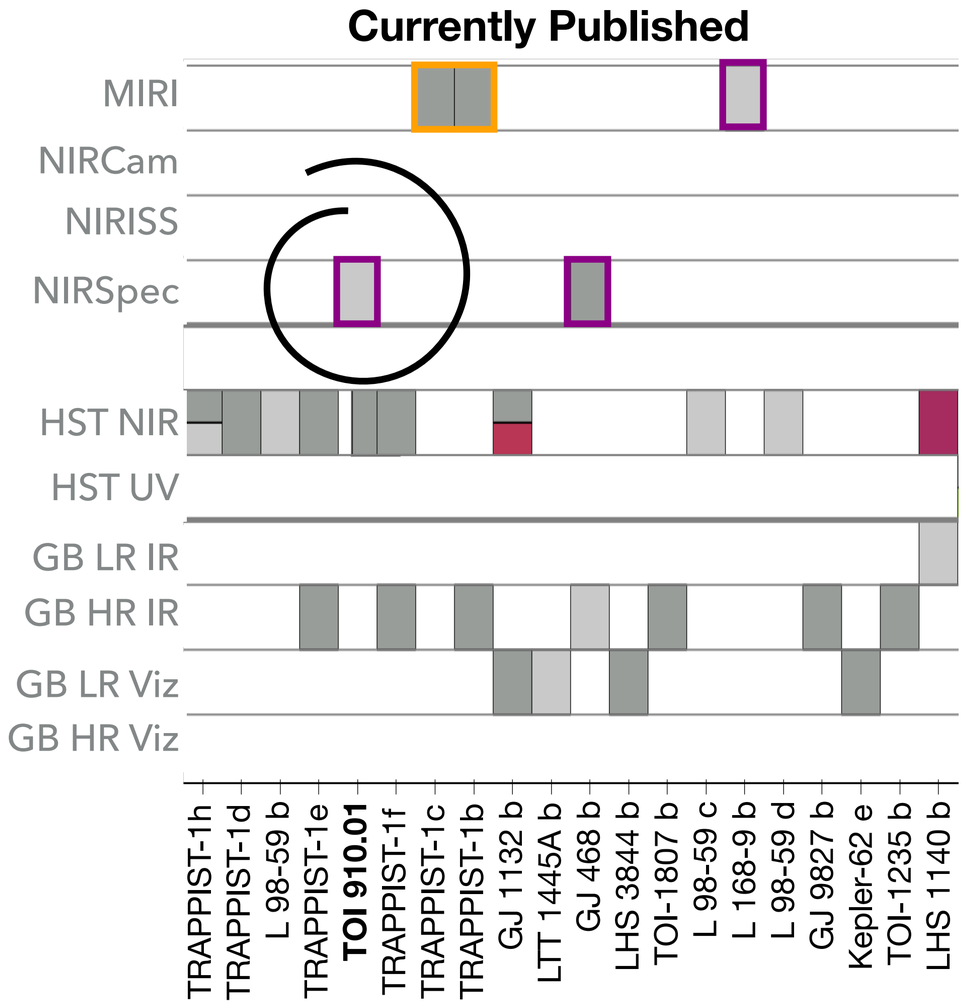
No detection

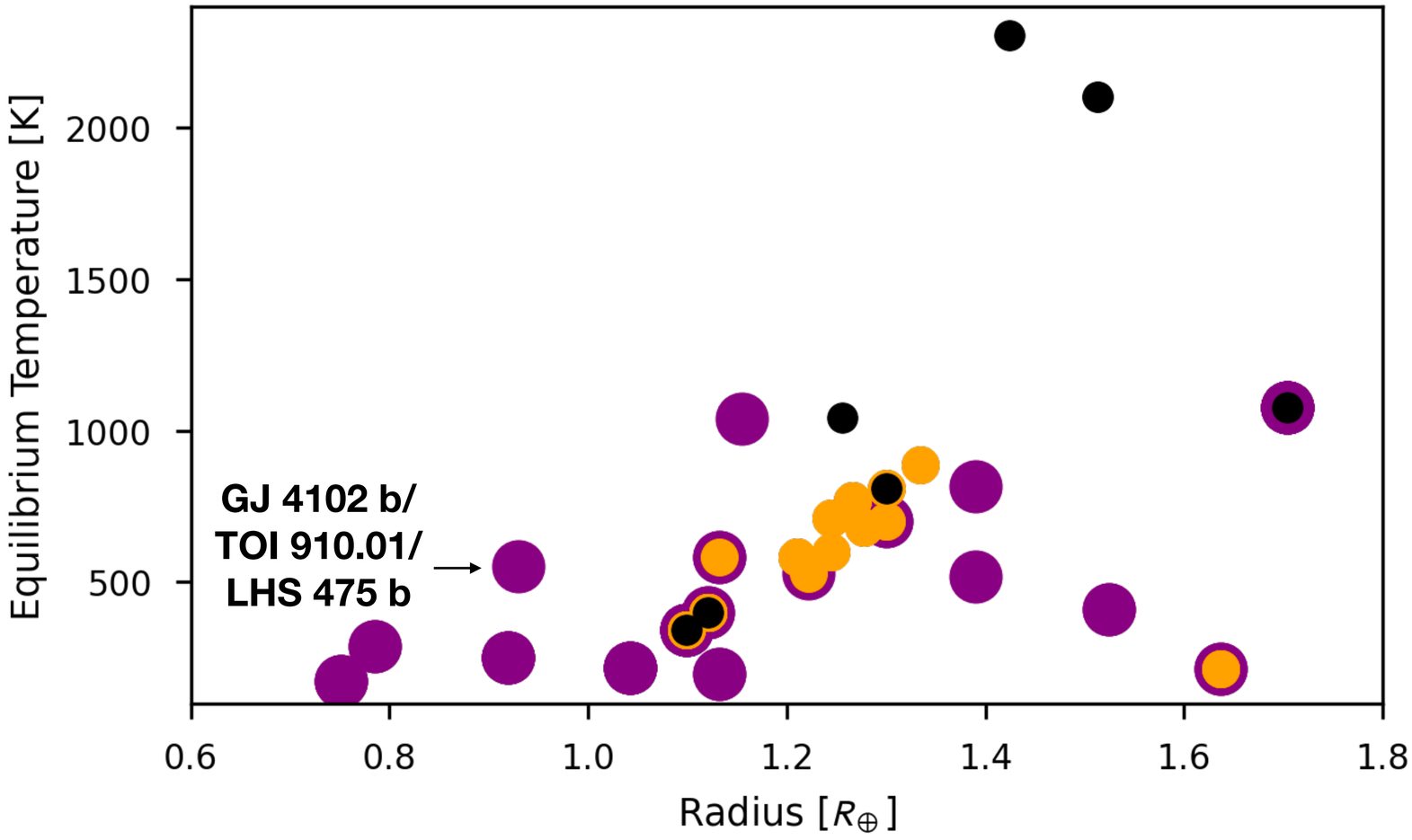
Transmission Geometry

Emission Geometry

Phase Curve

Currently Published JWST Observations





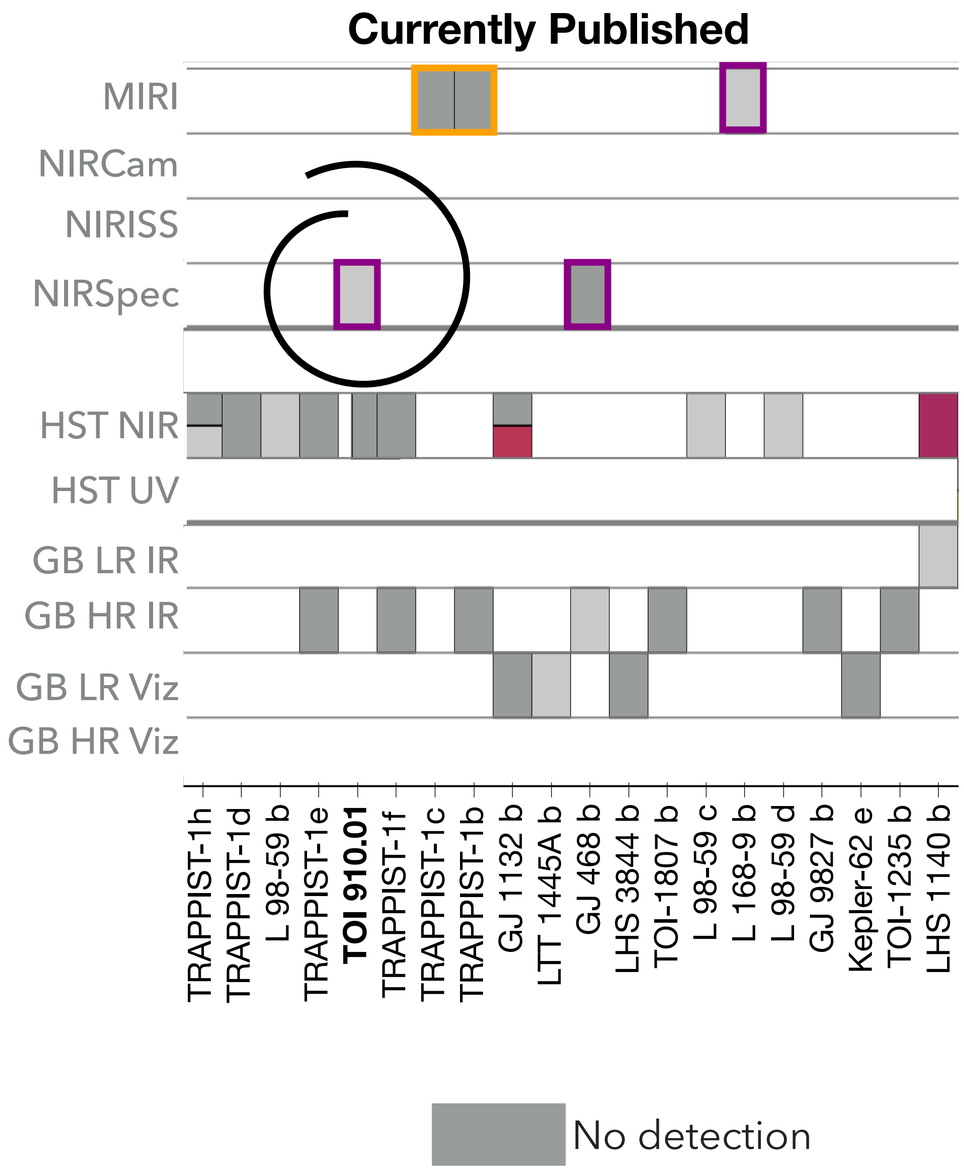
No detection

Transmission Geometry

Emission Geometry

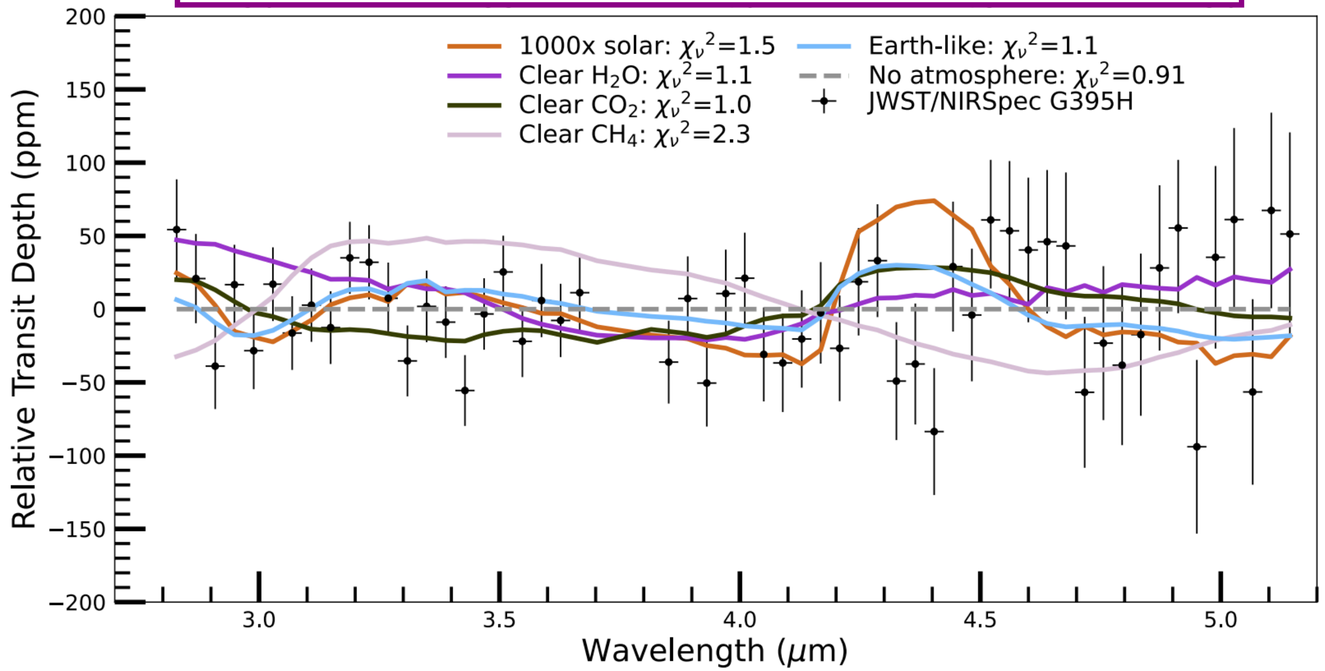
Phase Curve

Currently Published JWST Observations



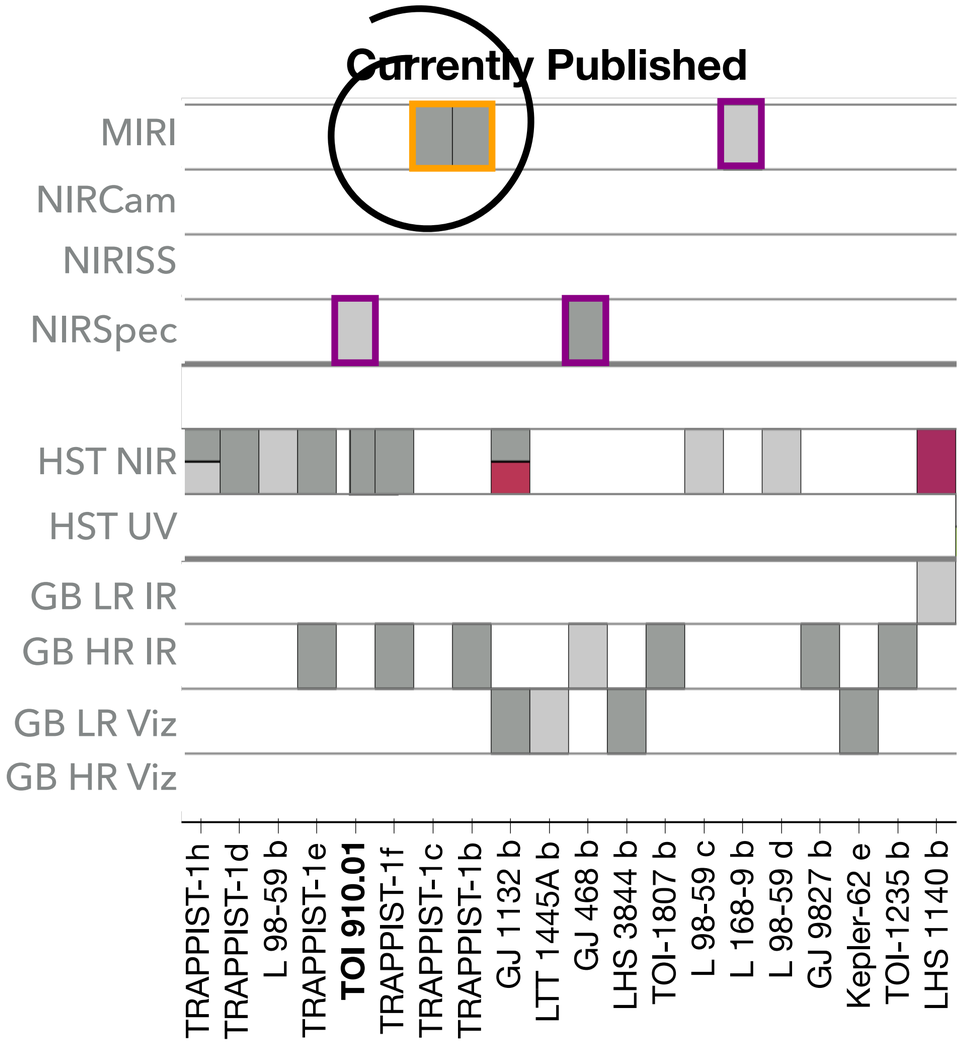
A JWST transmission spectrum of a nearby Earth-sized exoplanet

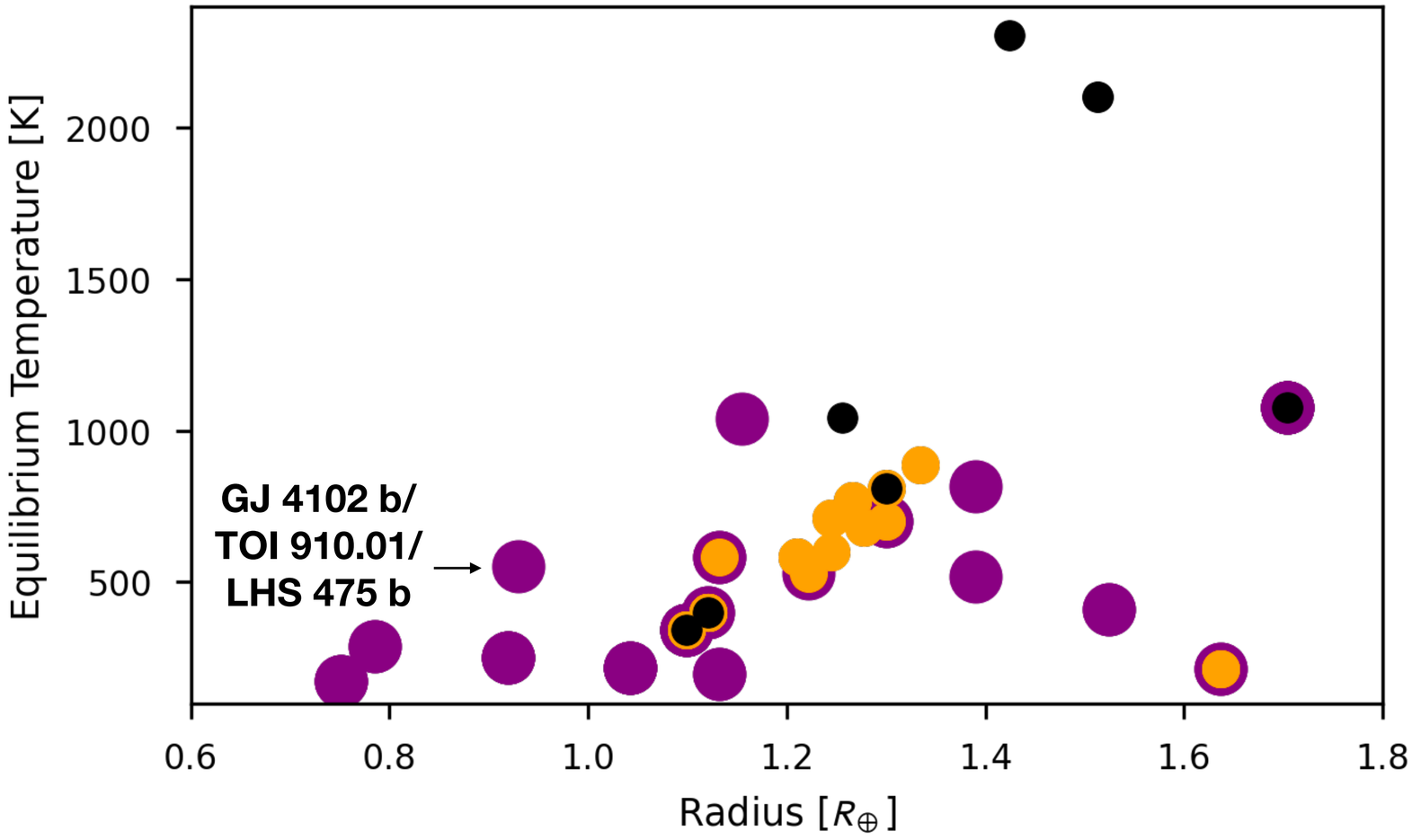
J. Lustig-Yaeger, G. Fu, E. M. May, K. N. Ortiz Ceballos, S. E. Moran, S. Peacock, K. B. Stevenson, M. López-Morales, R. J. MacDonald, L. C. Mayorga, D. K. Sing, K. S. Sotzen, J. A. Valenti, J. Adams, M. K. Alam, N. E. Batalha, K. A. Bennett, J. Gonzalez-Quiles, J. Kirk, E. Kruse, J. D. Lothringer, Z. Rustamkulov, H. R. Wakeford



Lustig-Yaeger & Fu et al. 2023

Currently Published JWST Observations





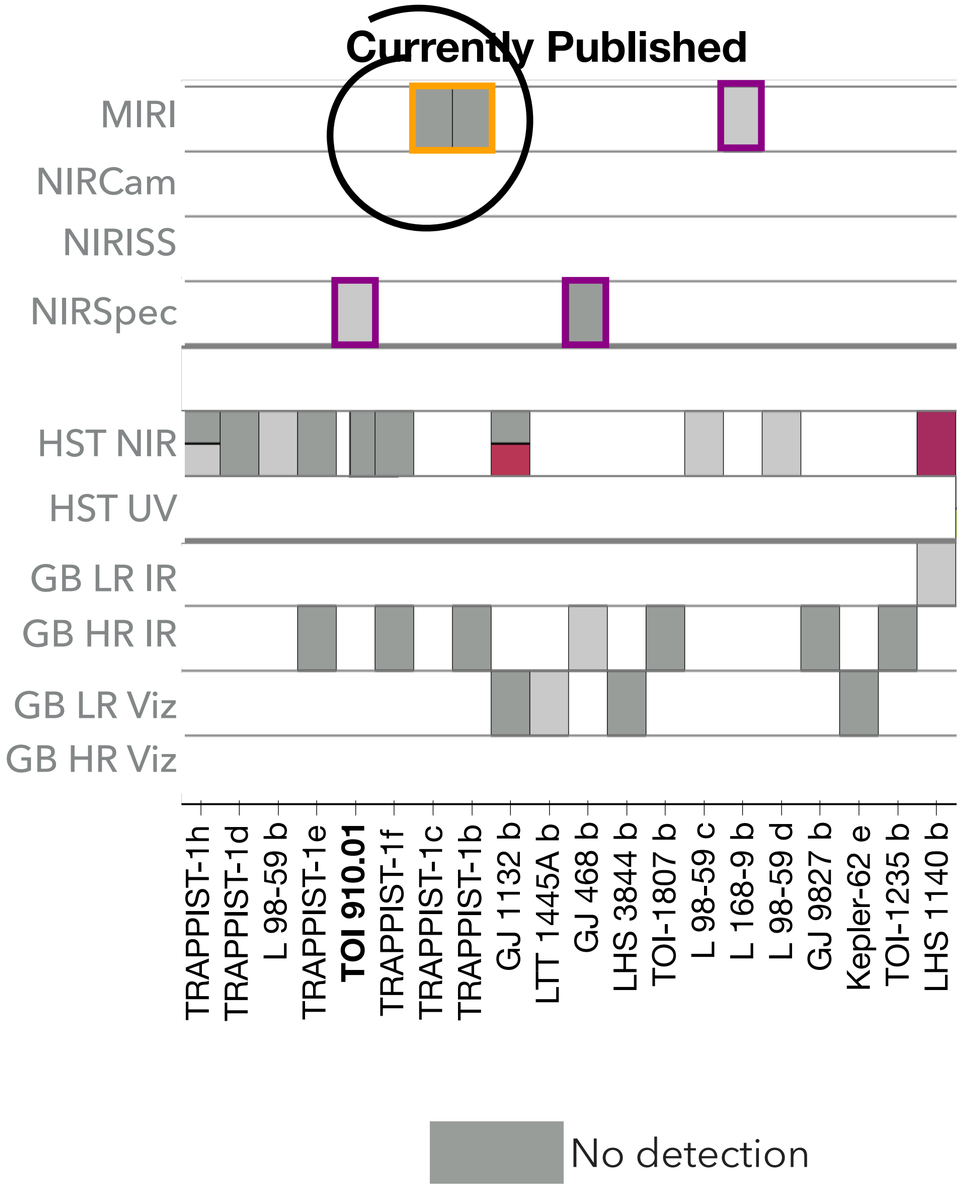
No detection

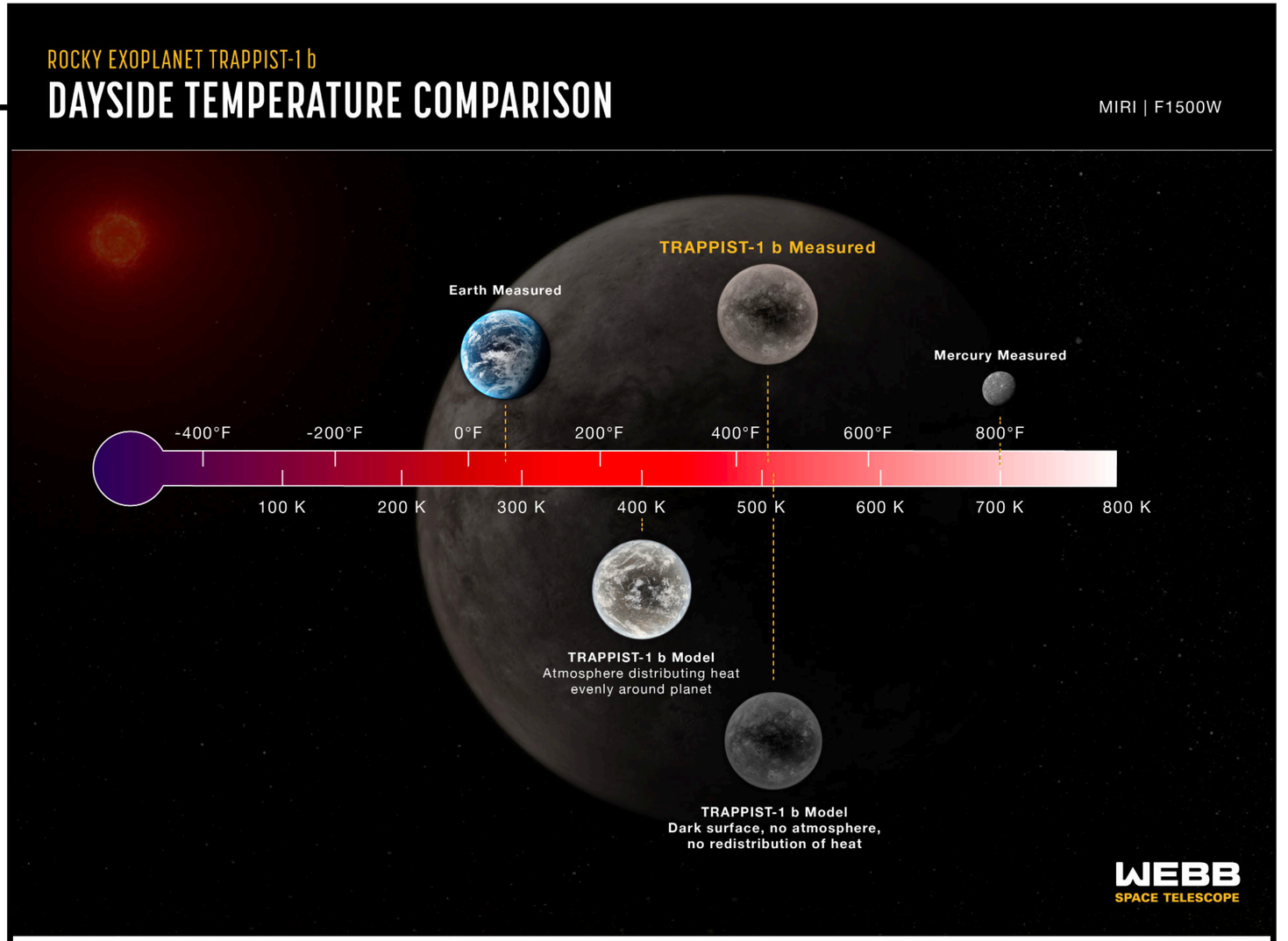
Transmission Geometry

Emission Geometry

Phase Curve

Currently Published JWST Observations

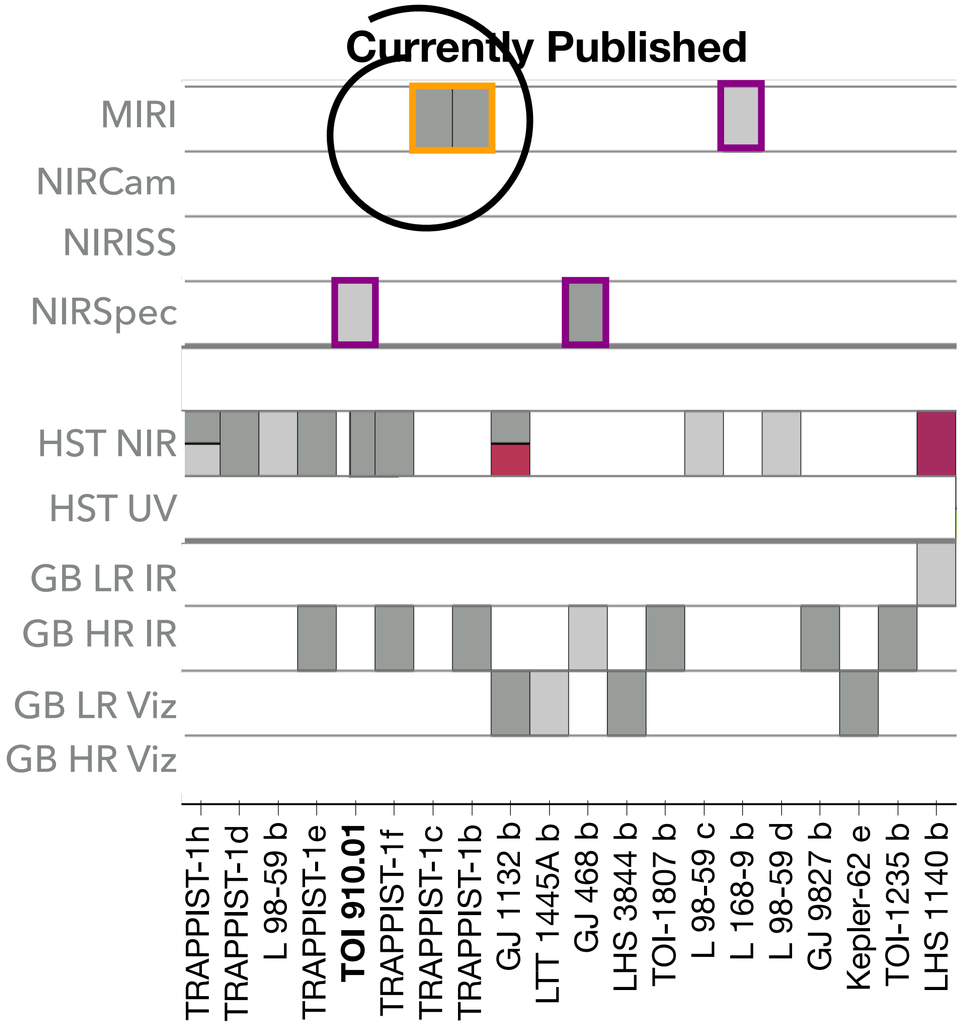


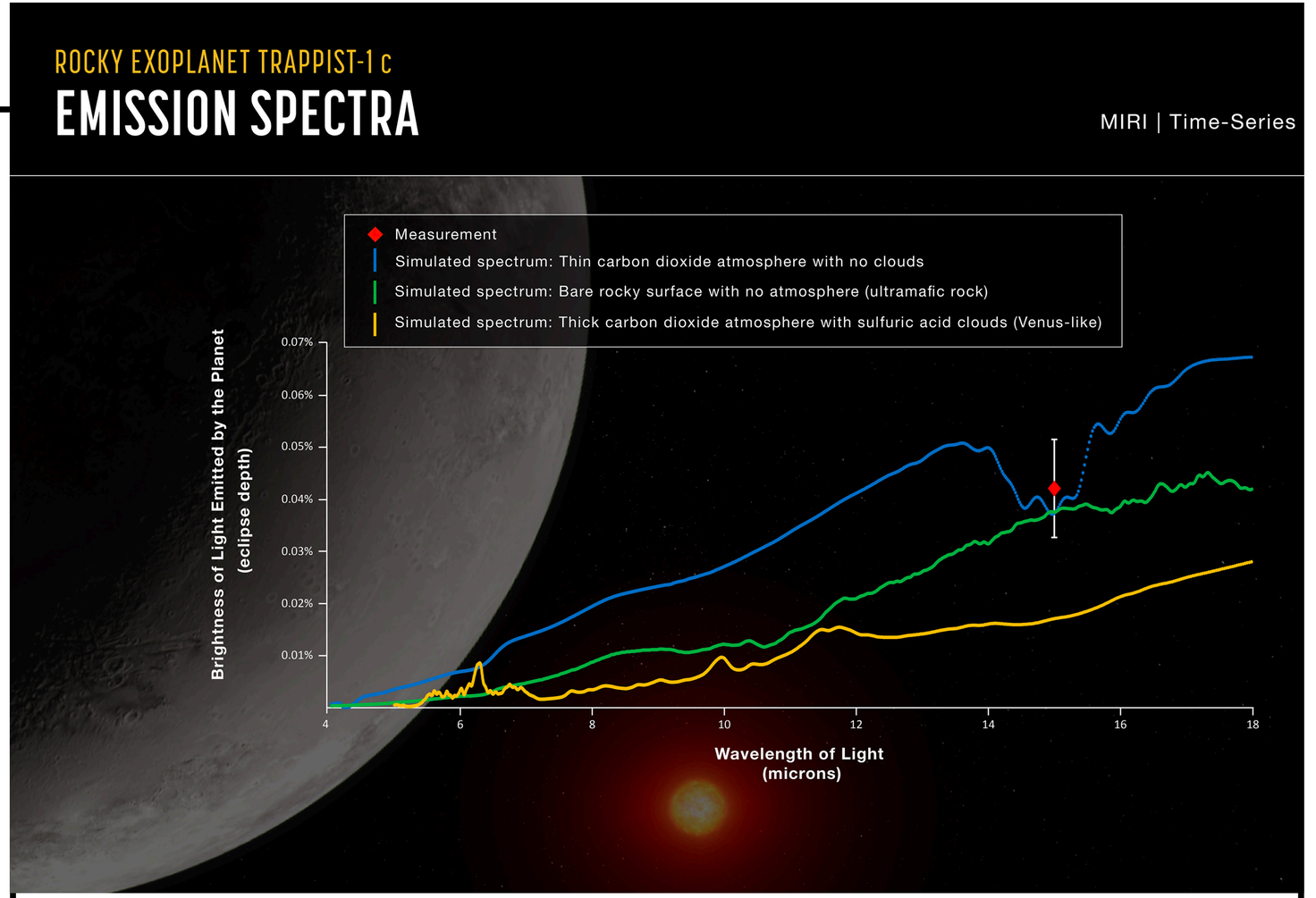


No detectable CO_2, hot temperature is consistent with no atmosphere

Greene, Bell et al. 2023

Currently Published JWST Observations

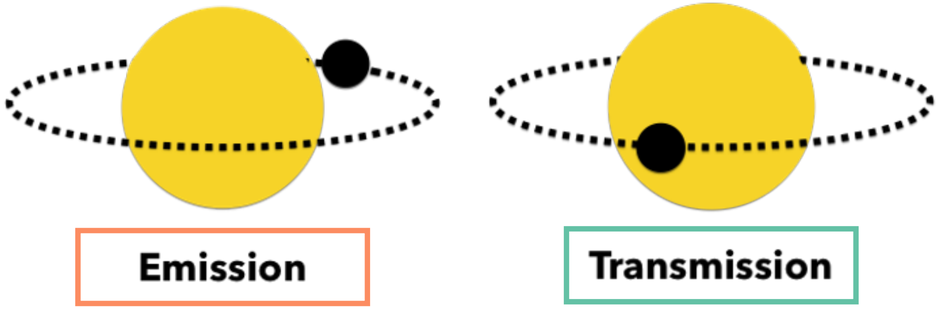




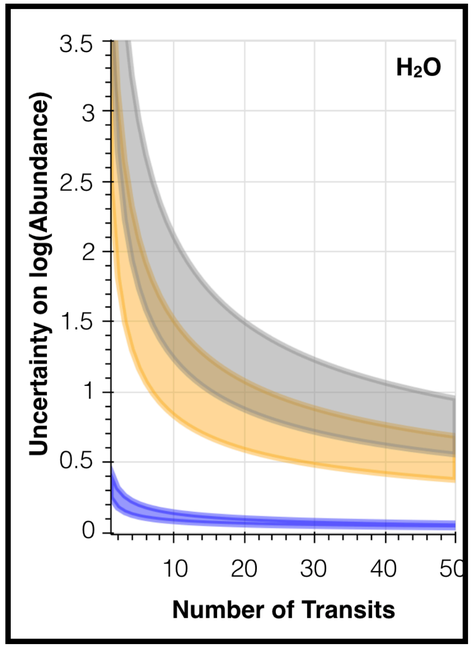
O2/CO2 mixtures with surface pressures ranging from 10 bar are ruled out, hot temperature is consistent with no atmosphere

Zieba, Kreidberg et al. 2023

WE ARE ONLY AT THE INFANCY OF OBSERVATIONS OF TRAPPIST-1 AND OTHER SYSTEMS



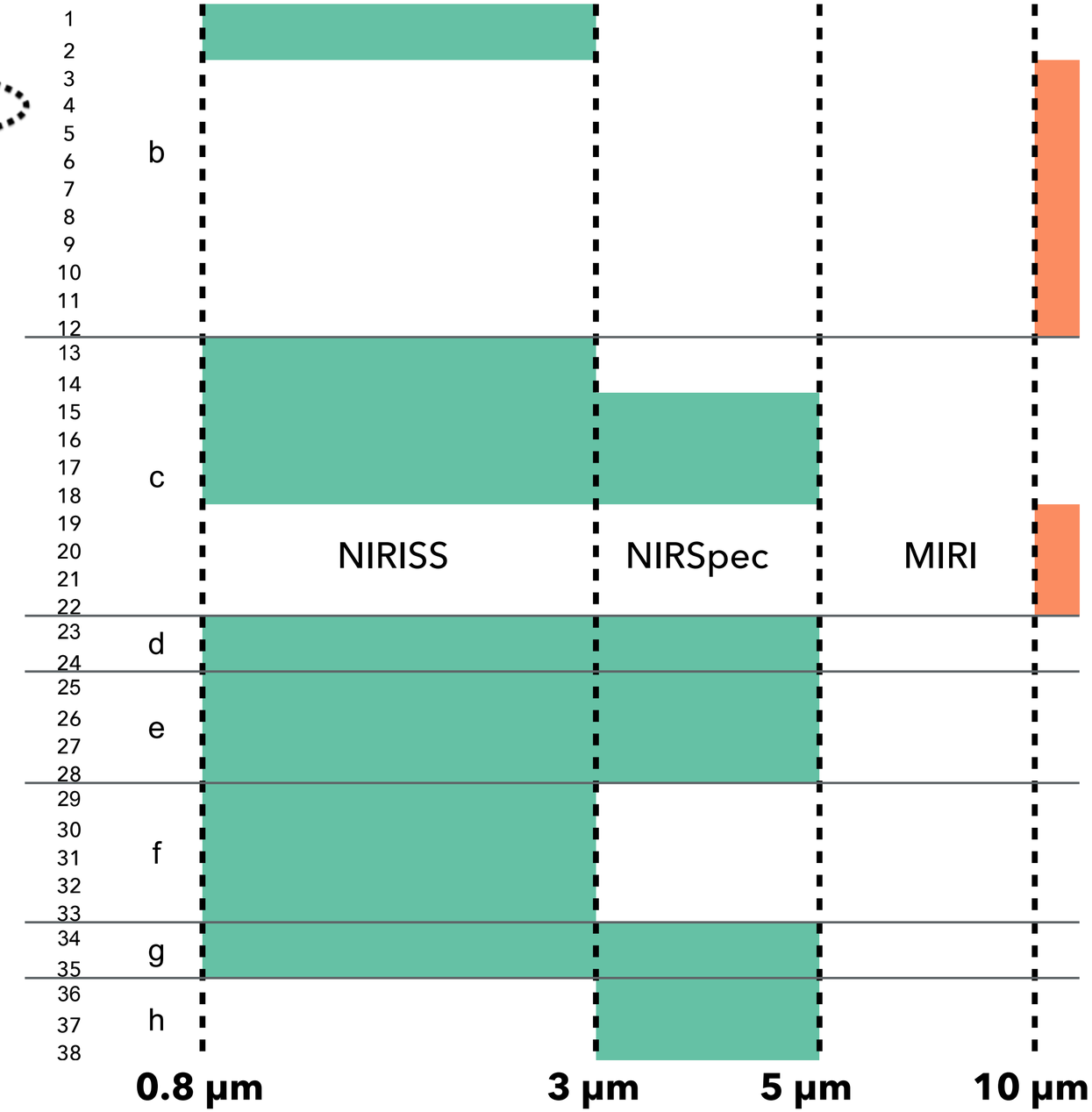
TRAPPIST-1 system makes up ~11% all exoplanet time in Cycle 1



And yet… We want more!

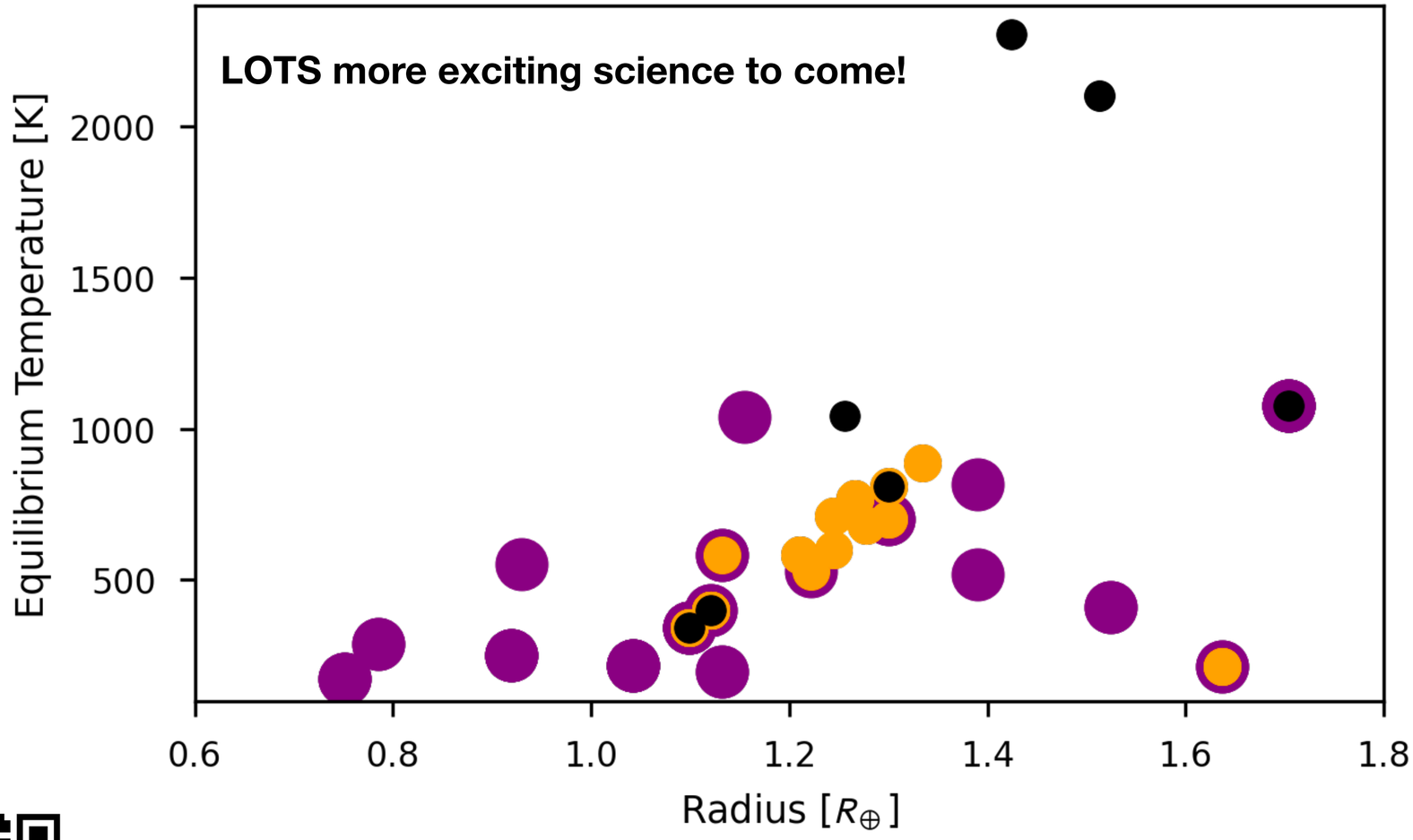
Broad consensus that HZ Trappist planets need ~10 transits to detect atmosphere

Morley+2017, Batalha+2018, Lustig-Yaeger+2019



OBSERVATIONS OF TERRESTRIAL PLANETS

1. **Null results are still results**
2. **Broad wavelength coverage is needed to robustly interpret spectra**
3. **Reproducible results is key! Multiple reduction methods are needed**
4. **We have many different observational techniques to tackle exoplanets. We should use them all!**
5. **We are at the infancy of terrestrial exoplanet observations**



Additional Reading:
“Atmospheres of Rocky Exoplanets”
Annual Reviews
Wordsworth & Kreidberg