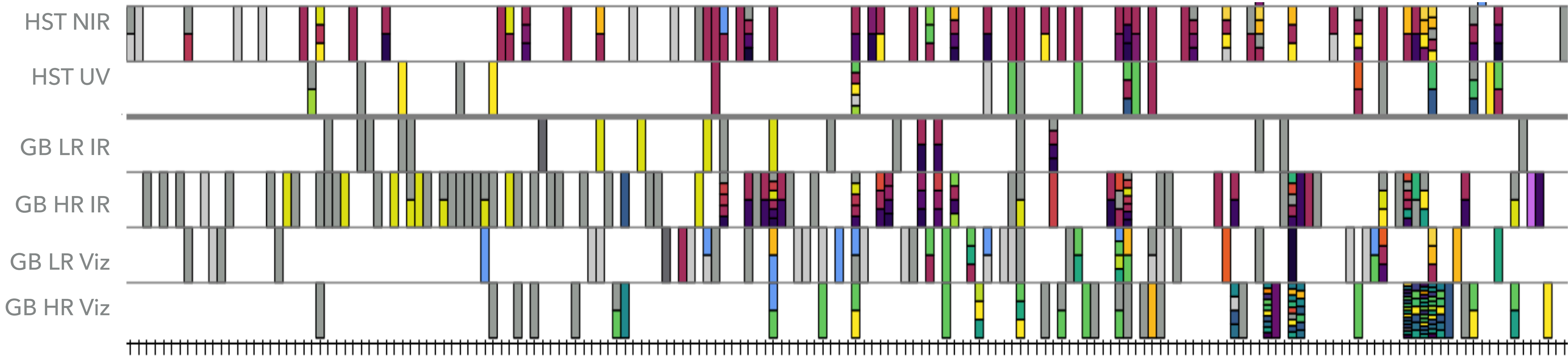




Observations of Terrestrial Exoplanet Atmospheres
(including Trappist-1!)

Natasha Batalha - Sagan Summer School 2023

Previous observations of exoplanets have yielded tremendous chemical diversity



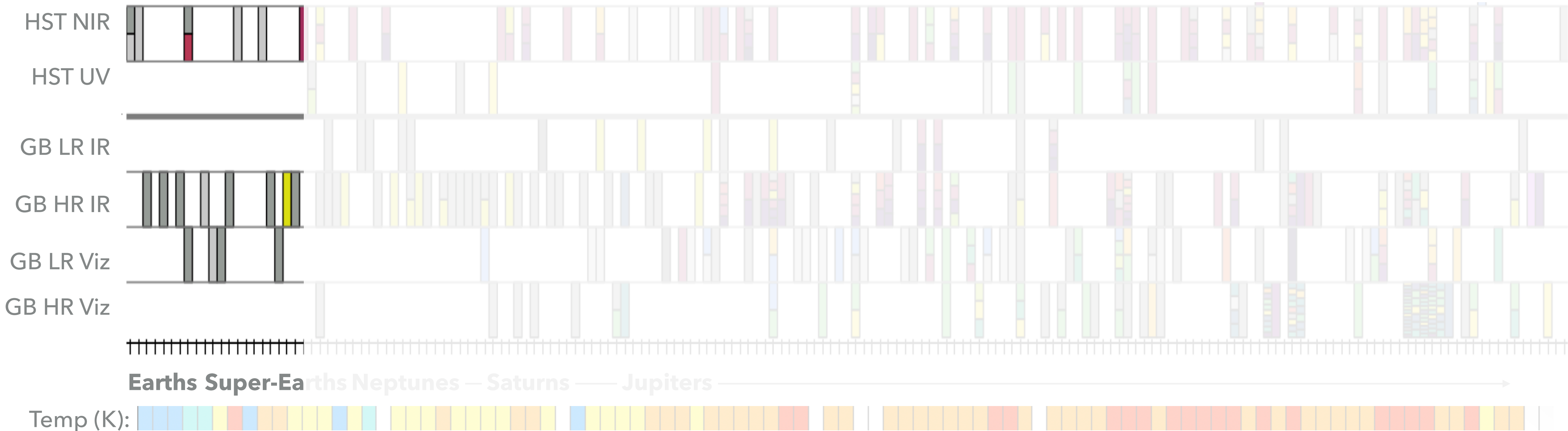
Earths Super-Earths Neptunes — Saturns — Jupiters →



1 H 1.00794 Hydrogen																	2 He 4.002602 Helium
3 Li 6.941 Lithium	4 Be 9.012182 Beryllium											5 B 10.811 Boron	6 C 12.0107 Carbon	7 N 14.0067 Nitrogen	8 O 15.9994 Oxygen	9 F 18.9984032 Fluorine	10 Ne 20.1797 Neon
11 Na 22.98976928 Sodium	12 Mg 24.3050 Magnesium											13 Al 26.9815386 Aluminum	14 Si 28.0855 Silicon	15 P 30.973762 Phosphorus	16 S 32.065 Sulfur	17 Cl 35.453 Chlorine	18 Ar 39.948 Argon
19 K 39.0983 Potassium	20 Ca 40.078 Calcium	21 Sc 44.955912 Scandium	22 Ti 47.887 Titanium	23 V 50.9415 Vanadium	24 Cr 51.9961 Chromium	25 Mn 54.938045 Manganese	26 Fe 55.845 Iron	27 Co 58.933195 Cobalt	28 Ni 58.6934 Nickel	29 Cu 63.546 Copper	30 Zn 65.38 Zinc	31 Ga 69.723 Gallium	32 Ge 72.64 Germanium	33 As 74.92160 Arsenic	34 Se 78.96 Selenium	35 Br 79.904 Bromine	36 Kr 83.798 Krypton
37 Rb 85.4678 Rubidium	38 Sr 87.62 Strontium	39 Y 88.90585 Yttrium	40 Zr 91.224 Zirconium	41 Nb 92.90638 Niobium	42 Mo 95.96 Molybdenum	43 Tc [98] Technetium	44 Ru 101.07 Ruthenium	45 Rh 102.90550 Rhodium	46 Pd 106.42 Palladium	47 Ag 107.8682 Silver	48 Cd 112.411 Cadmium	49 In 114.818 Indium	50 Sn 118.710 Tin	51 Sb 121.760 Antimony	52 Te 127.60 Tellurium	53 I 126.90447 Iodine	54 Xe 131.293 Xenon
55 Cs 132.9054519 Cesium	56 Ba 137.327 Barium	LA	72 Hf 178.49 Hafnium	73 Ta 180.94788 Tantalum	74 W 183.84 Tungsten	75 Re 186.207 Rhenium	76 Os 190.23 Osmium	77 Ir 192.222 Iridium	78 Pt 195.084 Platinum	79 Au 196.966569 Gold	80 Hg 200.59 Mercury	81 Tl 204.3833 Thallium	82 Pb 207.2 Lead	83 Bi 208.98040 Bismuth	84 Po [209] Polonium	85 At [210] Astatine	86 Rn [222] Radon
87 Fr [223] Francium	88 Ra [226] Radium	AC	104 Rf [261] Rutherfordium	105 Db [262] Dubnium	106 Sg [263] Seaborgium	107 Bh [264] Bohrium	108 Hs [265] Hassium	109 Mt [266] Meitnerium	110 Ds [267] Darmstadtium	111 Rg [268] Roentgenium	112 Cn [269] Copernicium	113 Nh [270] Nihonium	114 Fl [271] Flerovium	115 Mc [272] Moscovium	116 Lv [273] Livermorium	117 Ts [274] Tennessine	118 Og [276] Oganesson

■ No detection

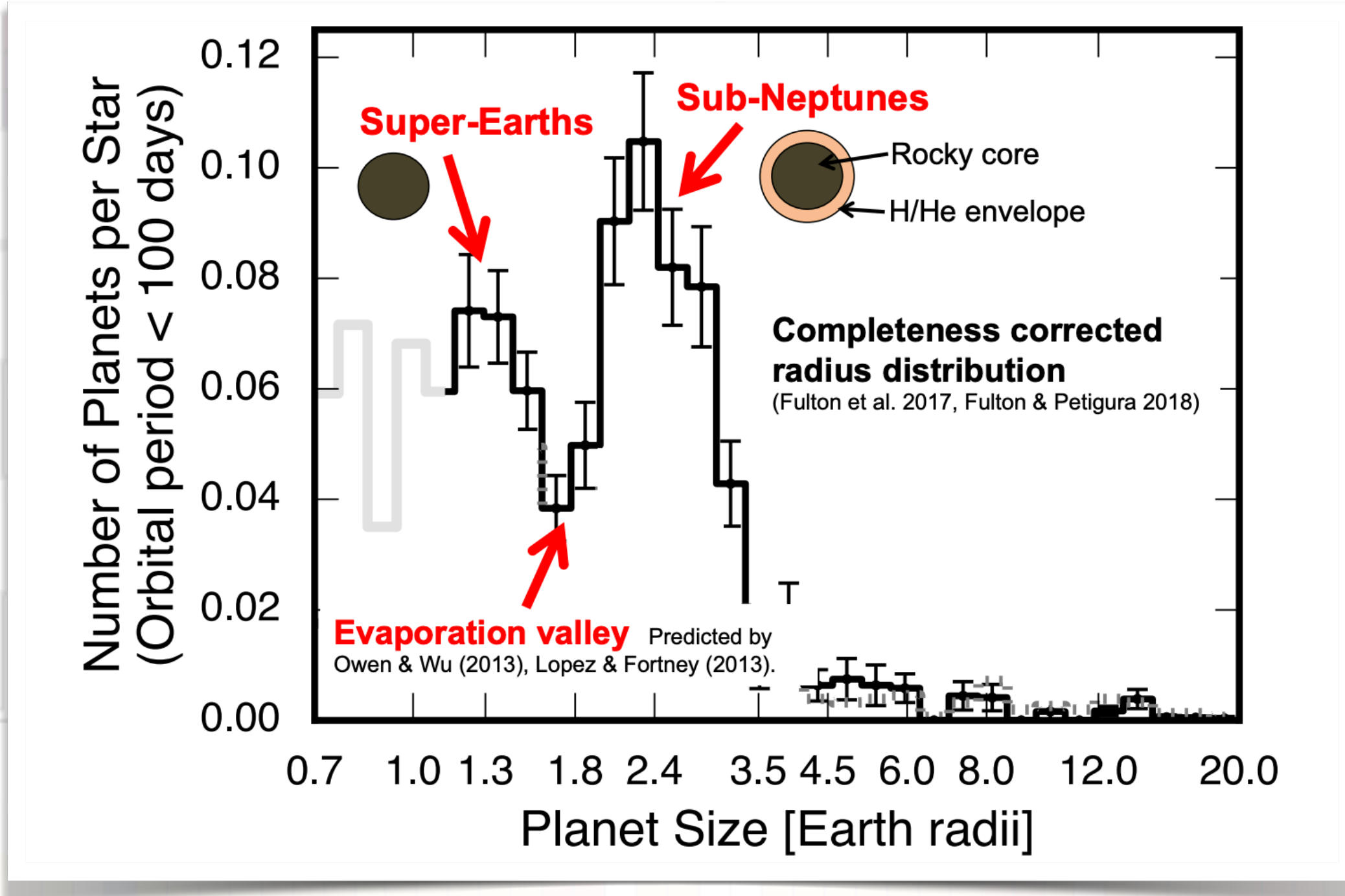
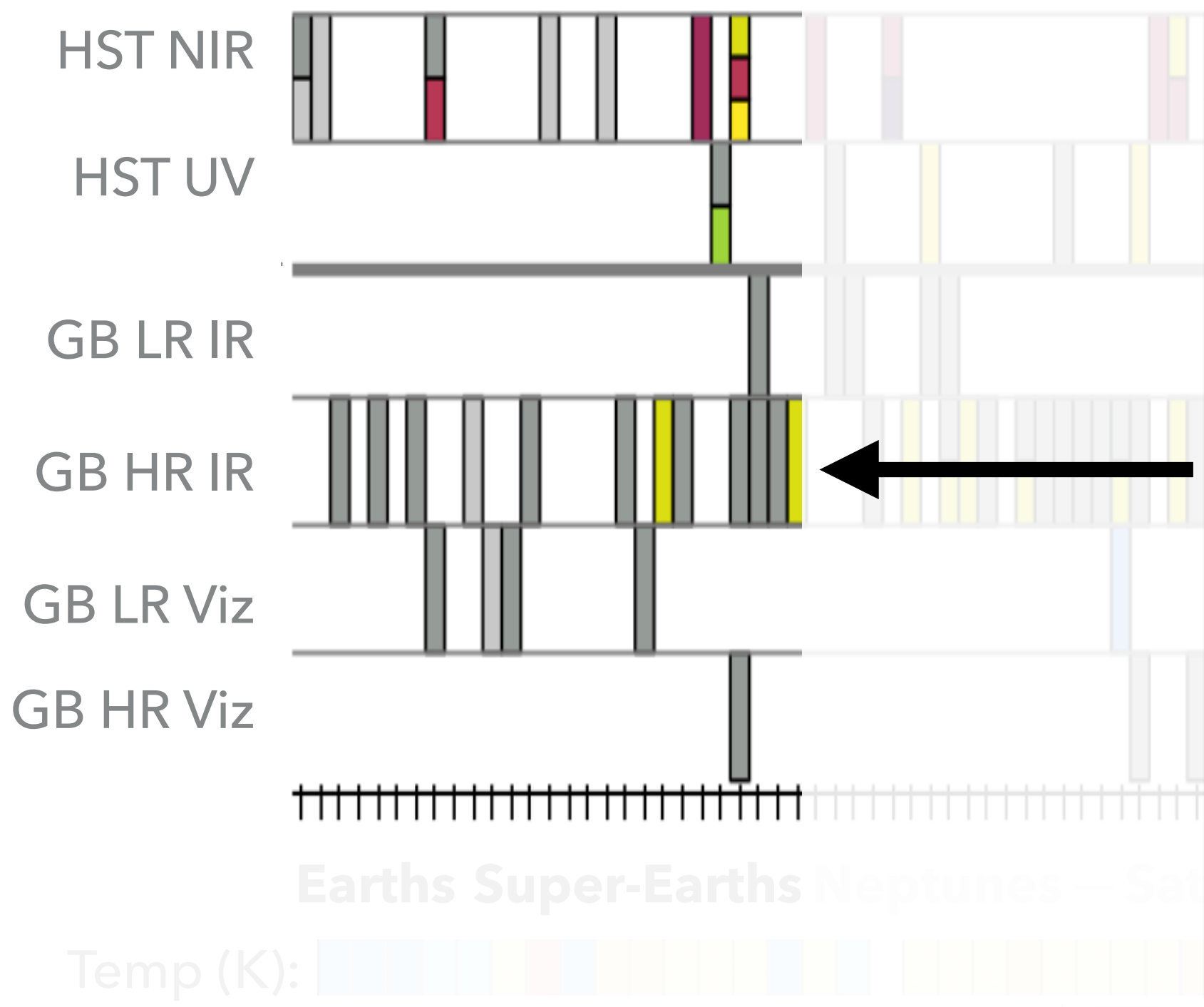
But what about for terrestrial planets only?



I	1 H 1.00794 Hydrogen	2 He 4.002602 Helium																							
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No detection

But what about for terrestrial planets only?



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

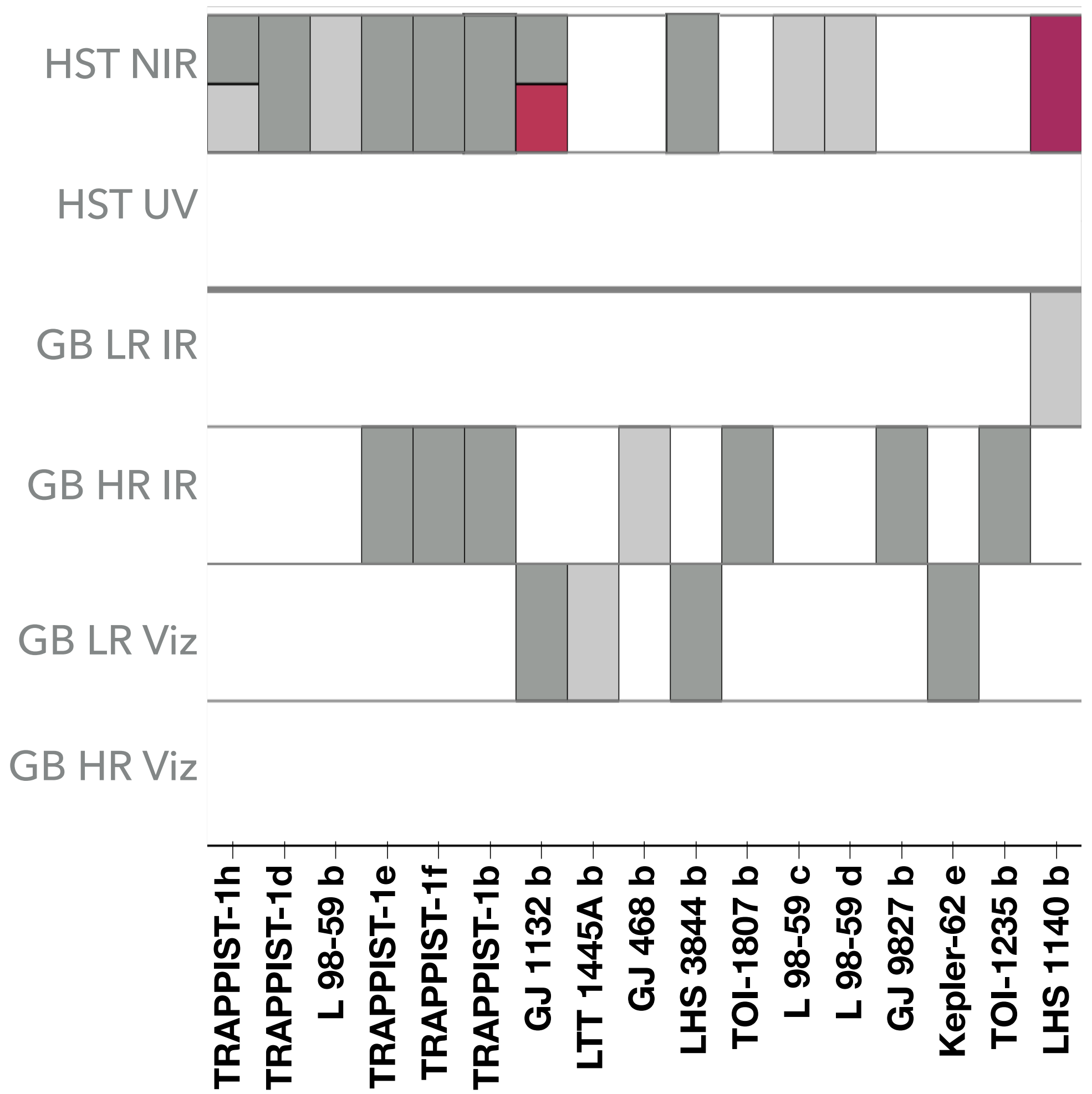
Cutoff R ~ 1.8 R_⊕



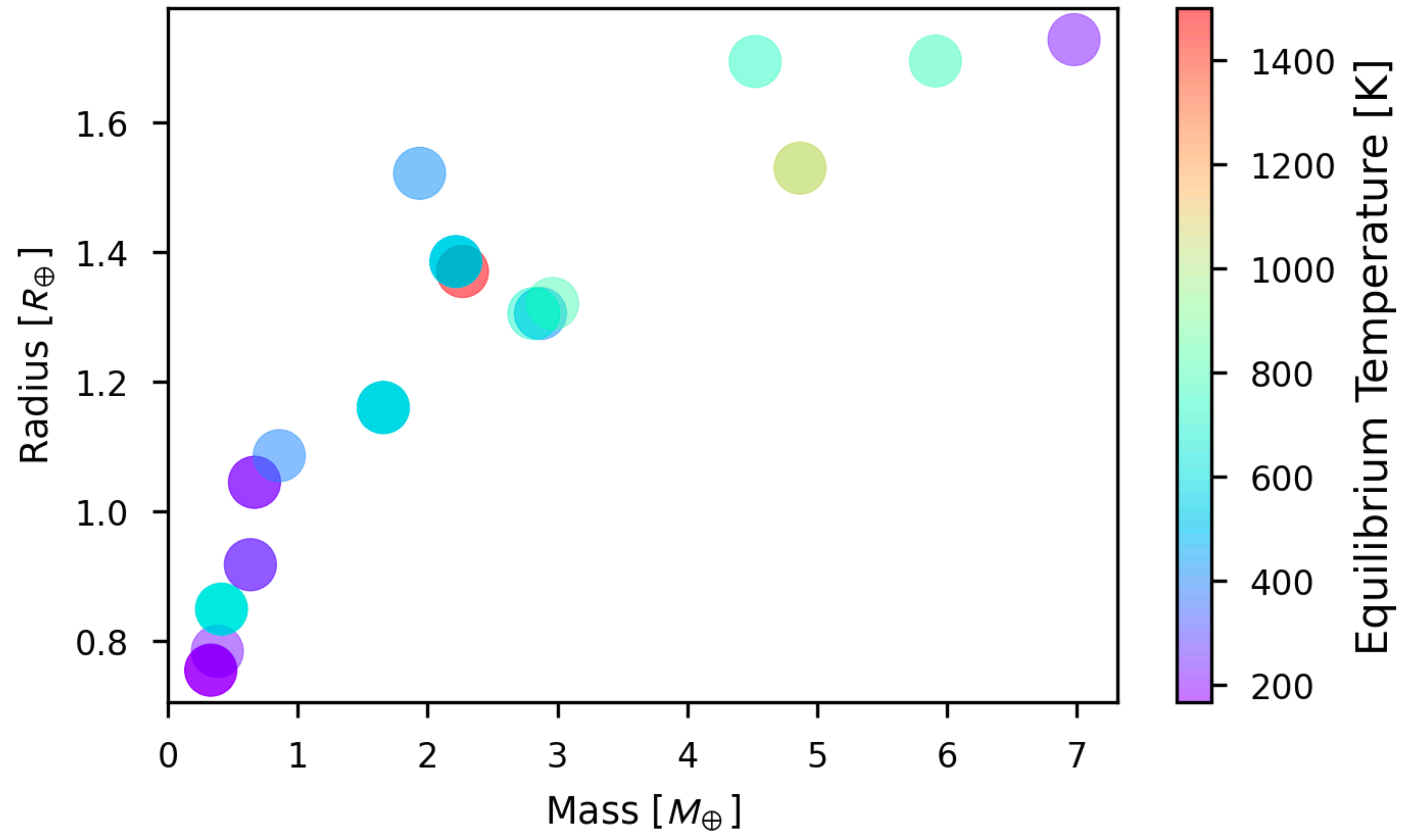
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87 Fr 223 Francium	88 Ra 226 Radium	89 Ac 227 Actinium	90 Th 232.0377 Thorium	91 Pa 231.036888 Protactinium	92 U 238.02891 Uranium	93 Np 237.048173 Neptunium	94 Pu 239.0521634 Plutonium	95 Am 243.061381 Americium	96 Cm 247.070351 Curium	97 Bk 247.070351 Berkelium	98 Cf 251.079589 Californium	99 Es 252.083219 Einsteinium	100 Fm 257.10371 Fermium	101 Md 258.10371 Mendelevium	102 No 259.10371 Nobelium	103 Lr 262.10371 Lawrencium	104 Rf 261.10371 Rutherfordium	105 Db 262.10371 Dubnium	106 Sg 263.10371 Seaborgium	107 Bh 264.10371 Bohrium	108 Hs 265.10371 Hassium	109 Mt 266.10371 Meitnerium	110 Ds 271.10371 Darmstadtium	111 Rg 272.10371 Roentgenium	112 Cn 285.10371 Copernicium	113 Nh 286.10371 Nihonium	114 Fl 289.10371 Flerovium	115 Mc 290.10371 Moscovium	116 Lv 293.10371 Livermorium	117 Ts 294.10371 Tennessine	118 Og 294.10371 Oganesson																		

No detection

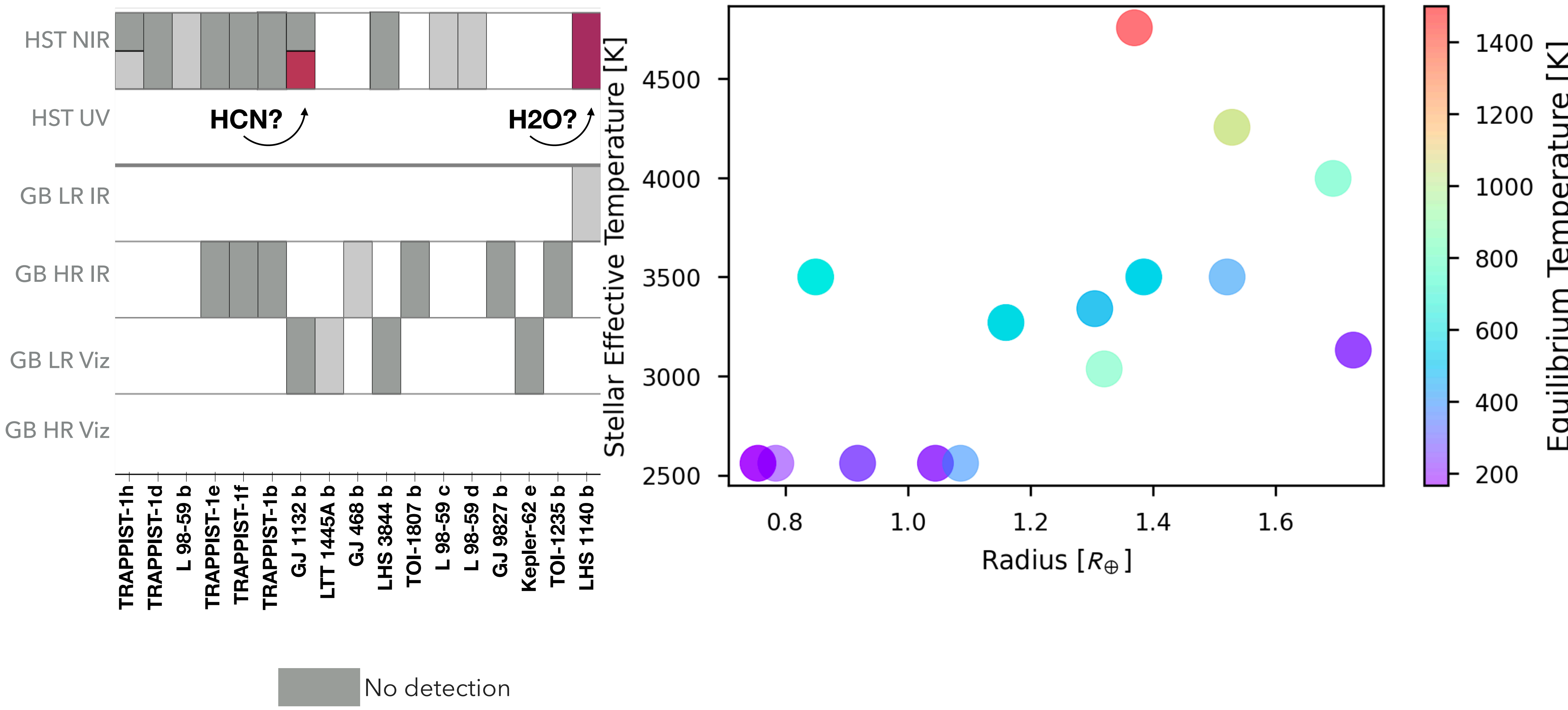
An overview of $R < 1.8 R_{\oplus}$ observations with HST and G-B instruments



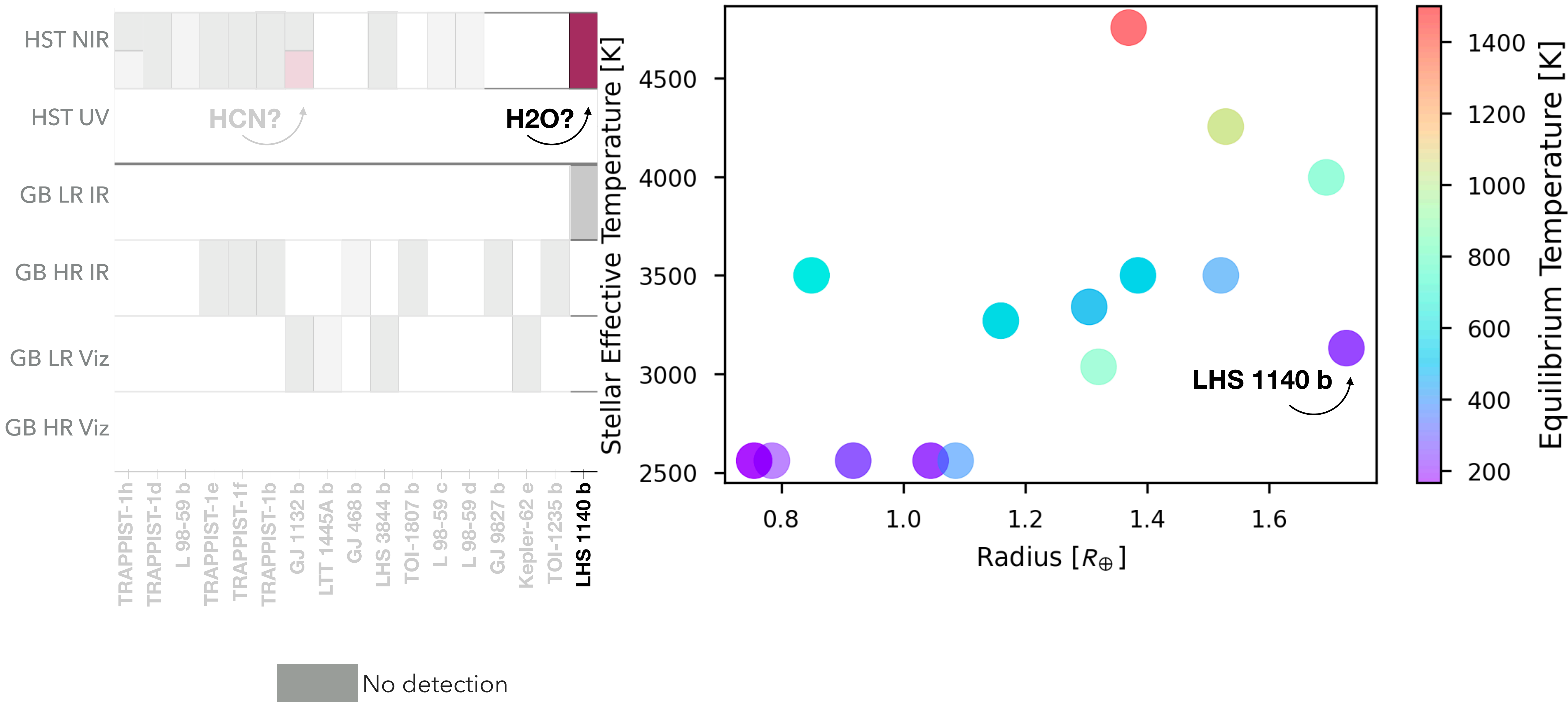
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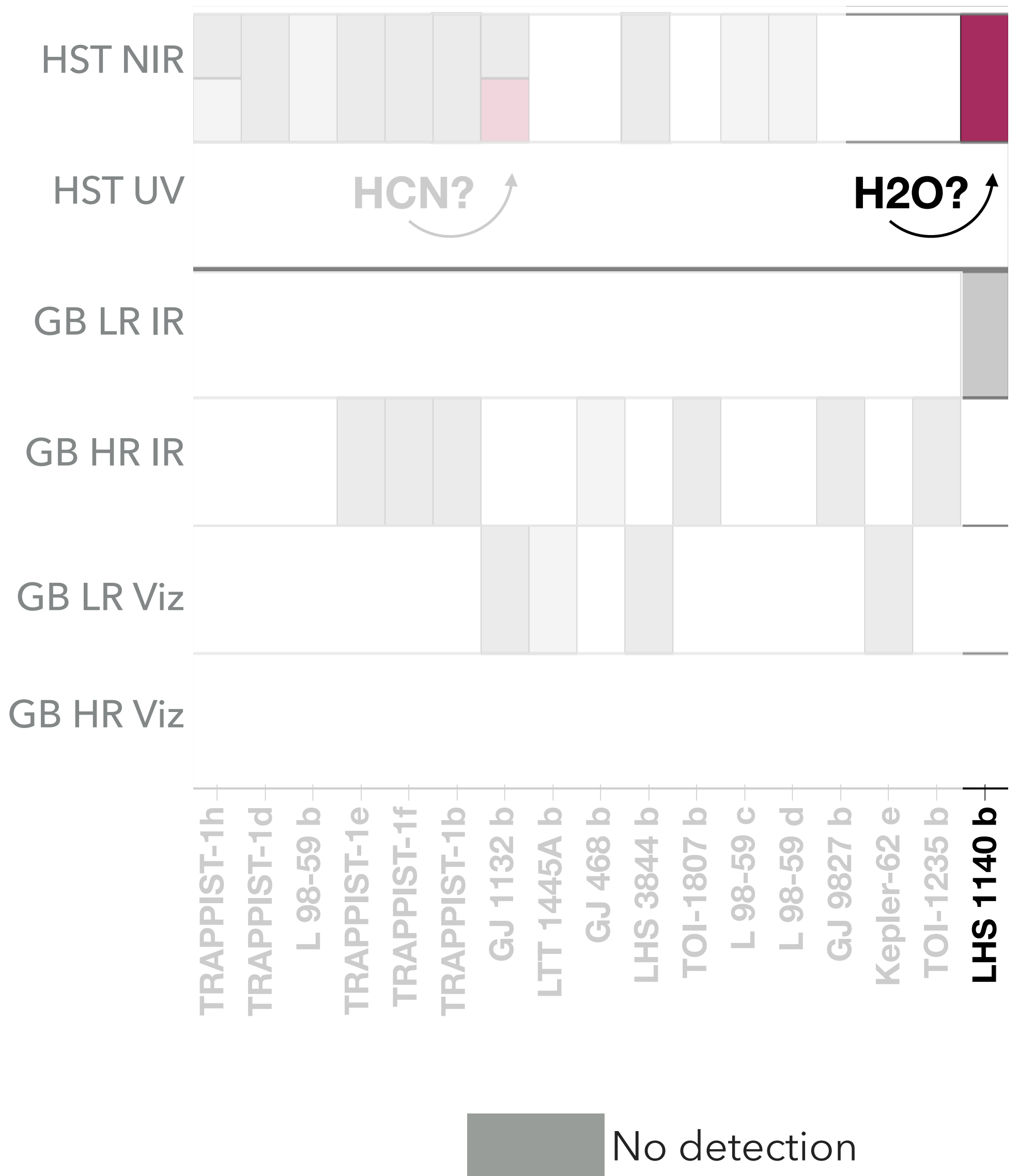
An overview of $R < 1.8 R_{\oplus}$ observations with HST and G-B instruments



An overview of $R < 1.8 R_{\oplus}$ observations with HST and G-B instruments



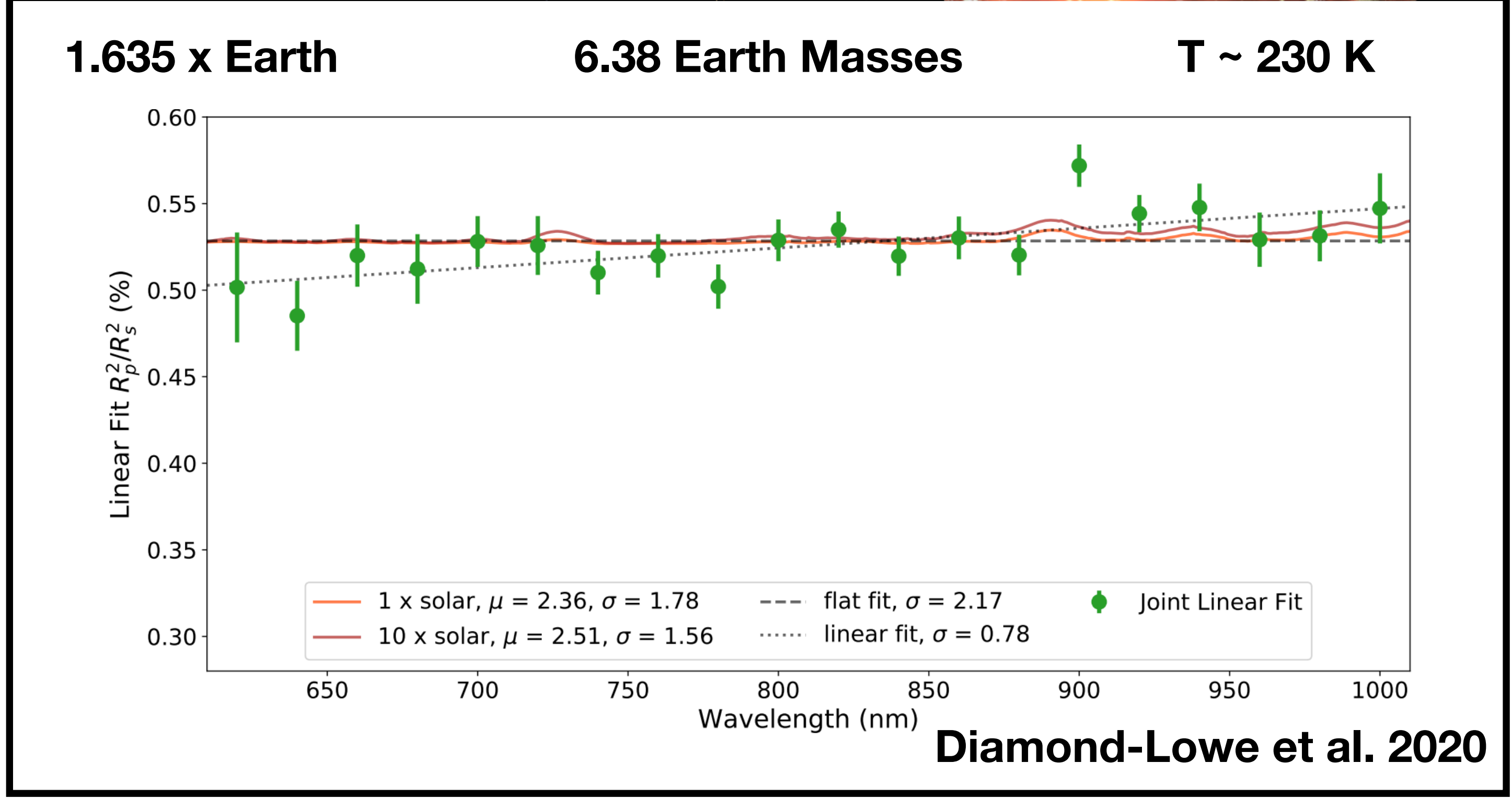
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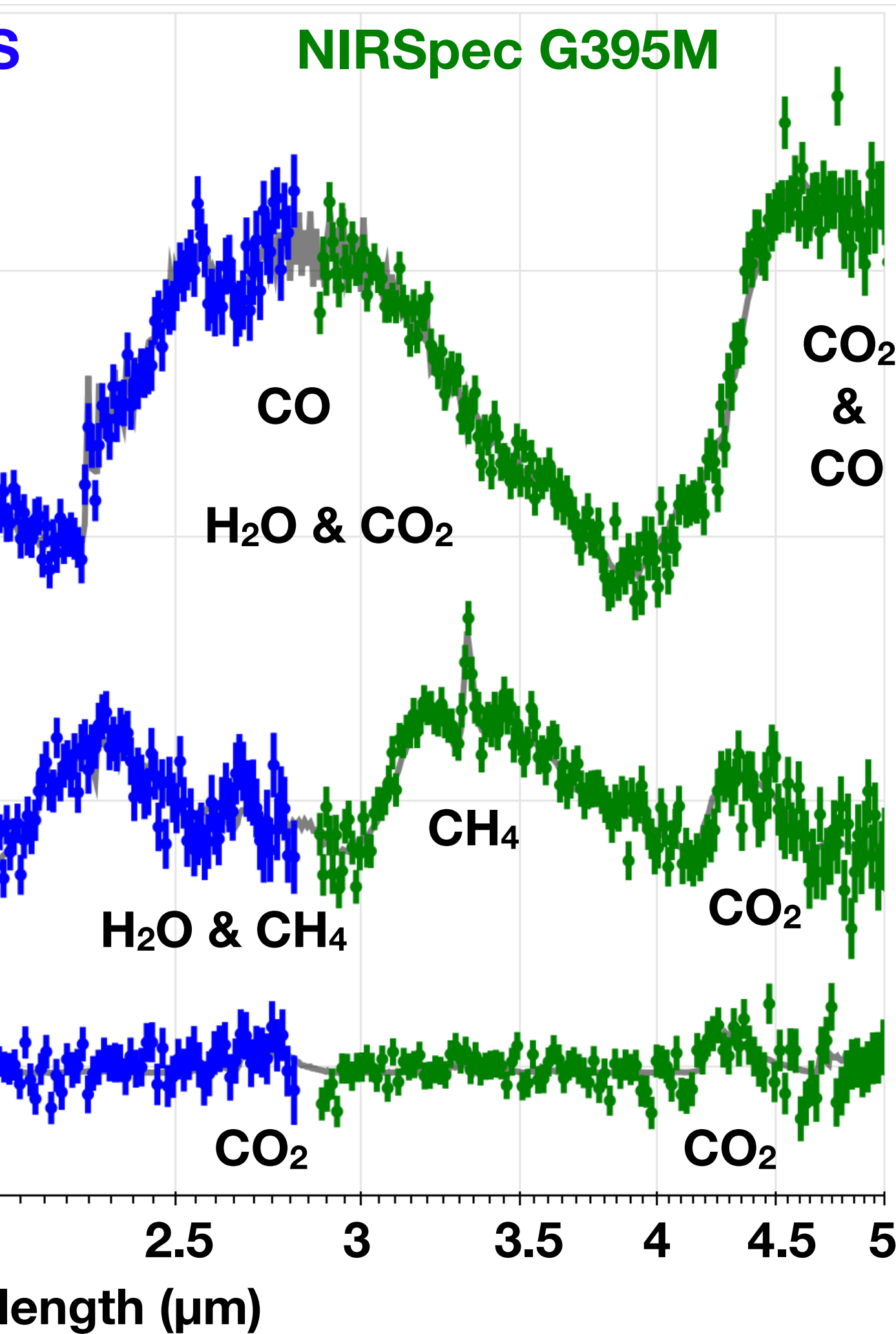
You are
49 light-years
from Earth

LHS 1140 b

A potentially rocky world, larger than Earth



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

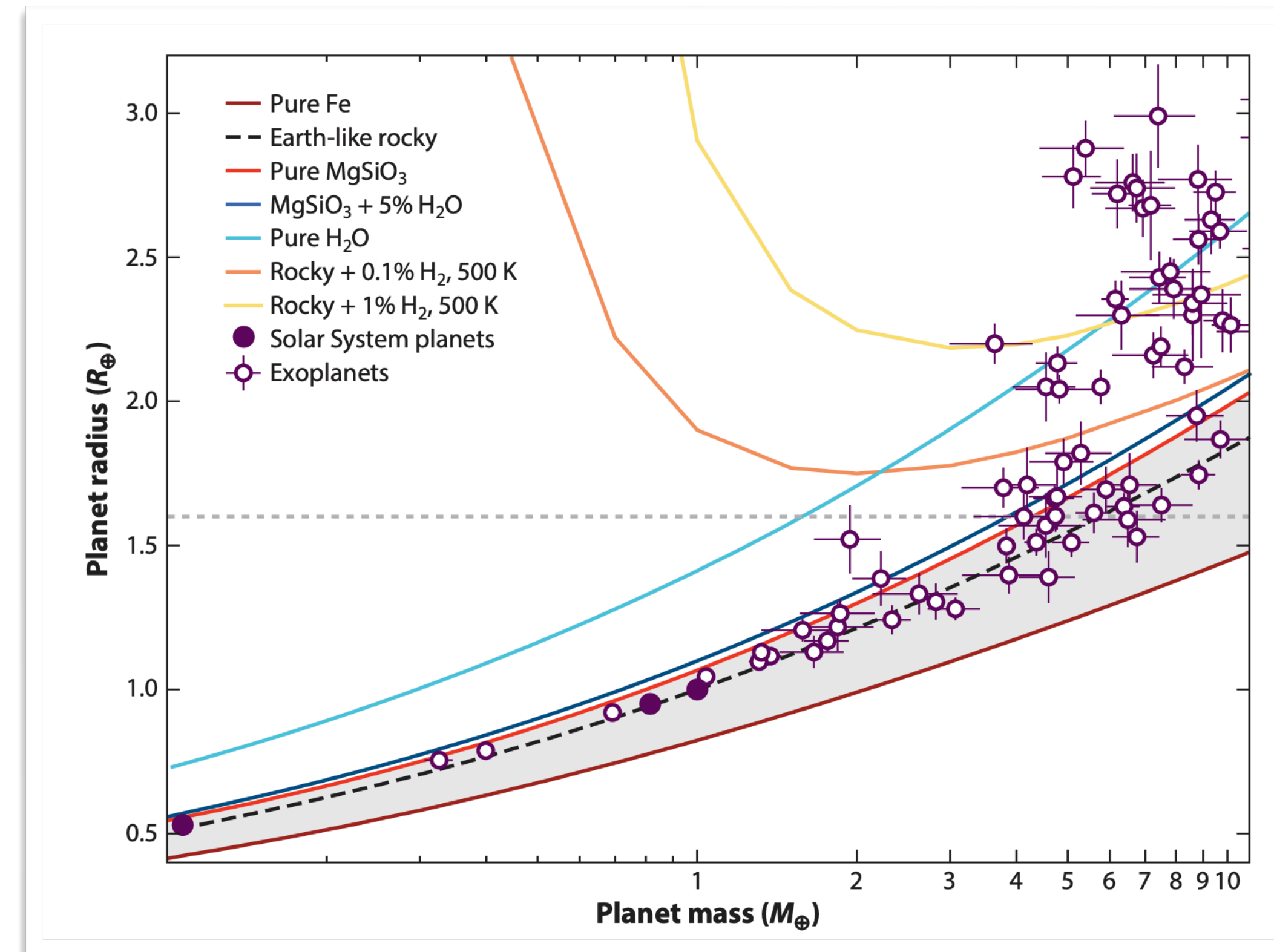


1xSolar ~ **99.9% H₂/He**

3xSolar ~ **99.7% H₂/He**

100xSolar ~ **91.1% H₂/He**

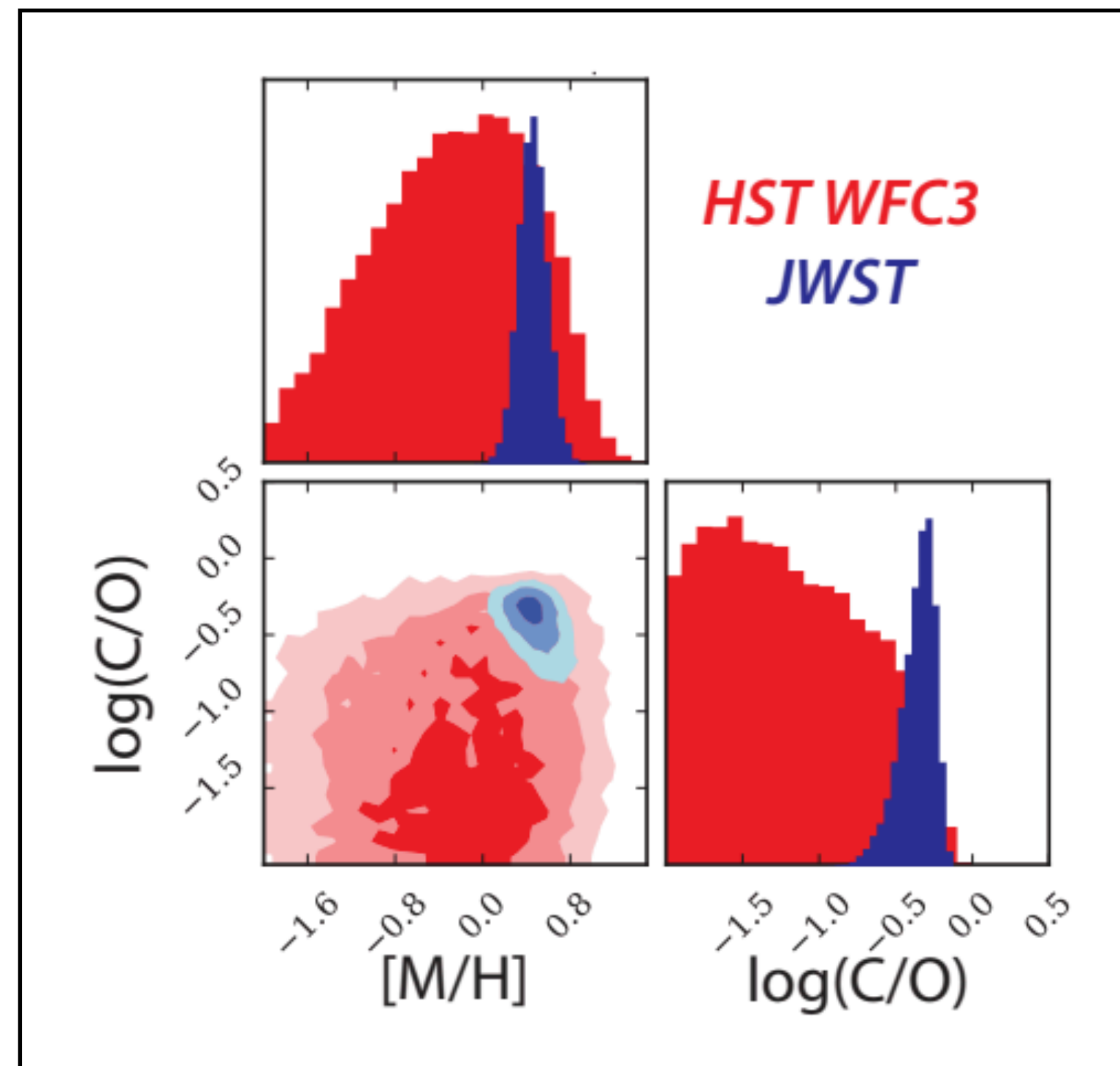
CO₂-dominated ~ **0% H₂/He**



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

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

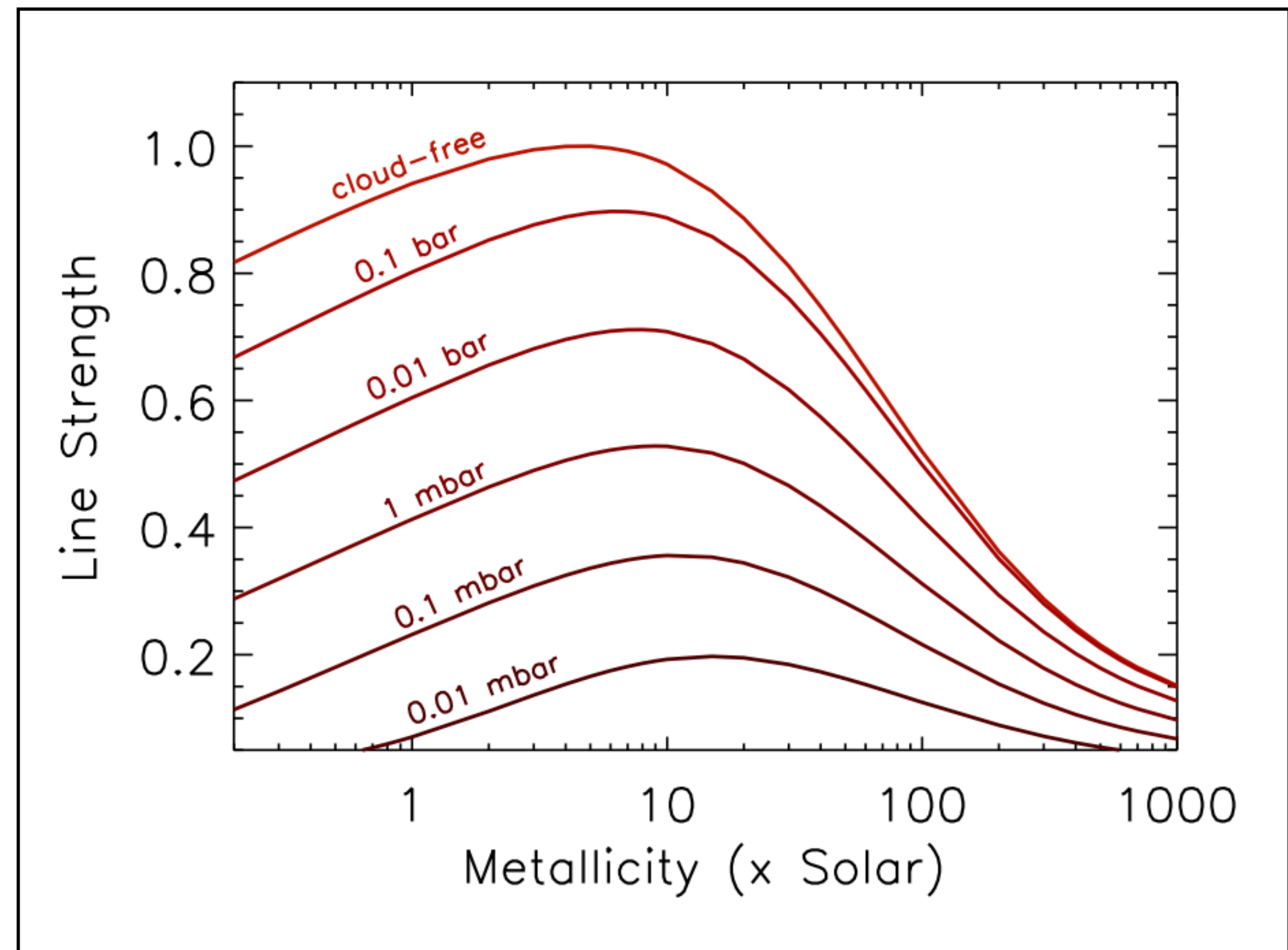
At high SNR expect to see:



**Constrained
atmospheric
physical parameters
with upper and
lower bounds**

Talk from Mike Line and petitRadTrans hands on activity

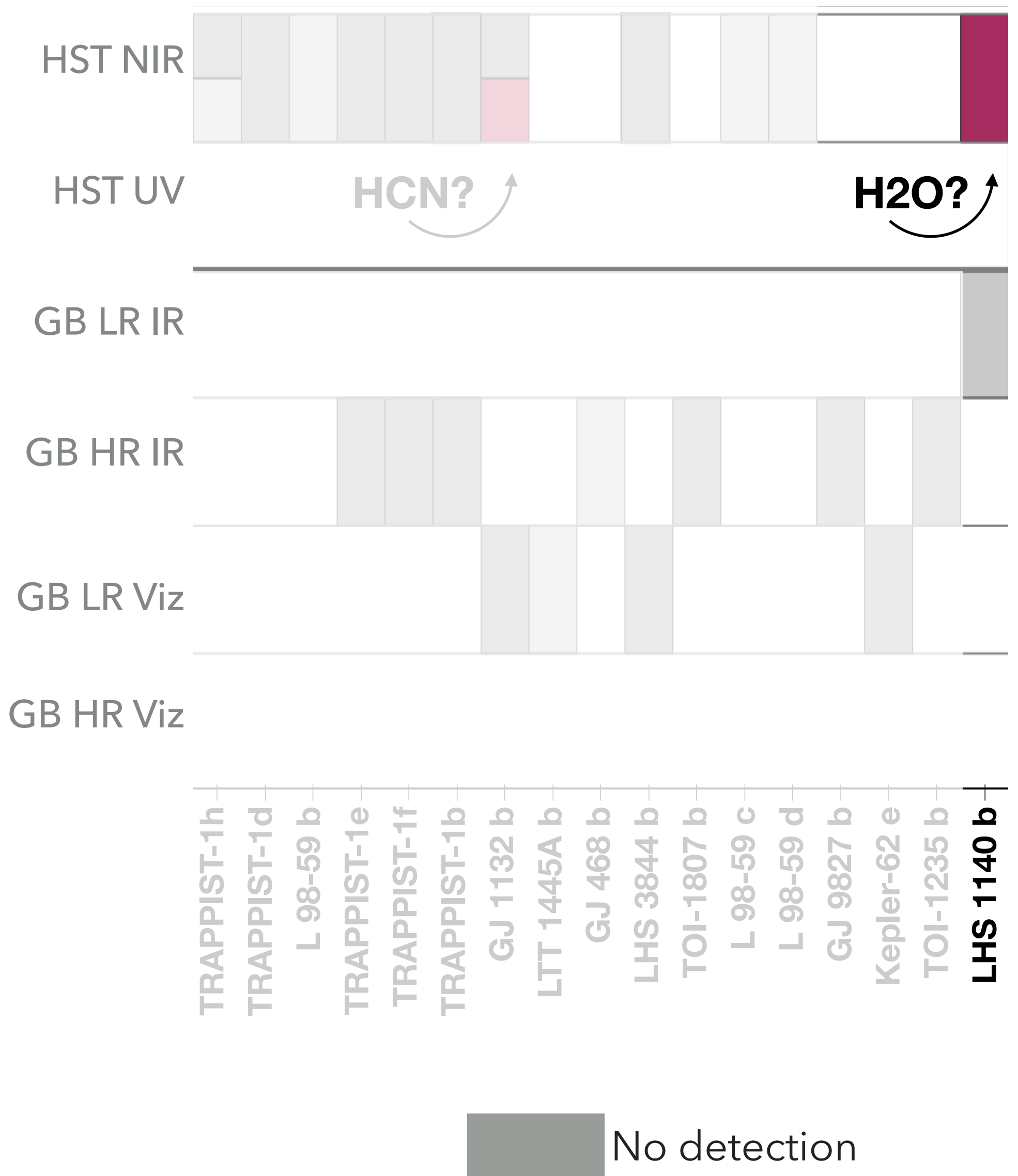
At low SNR expect to see:



**“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

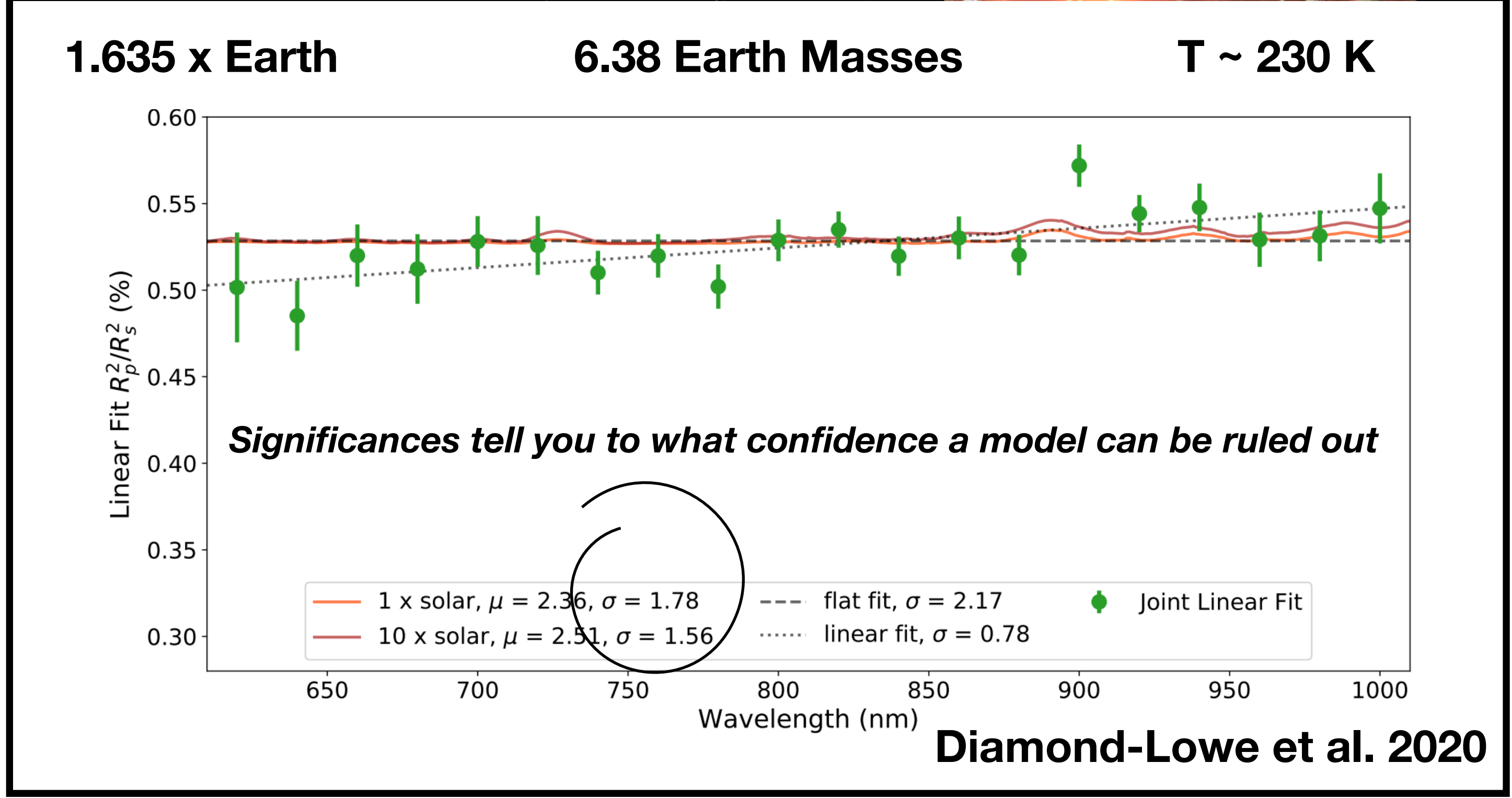
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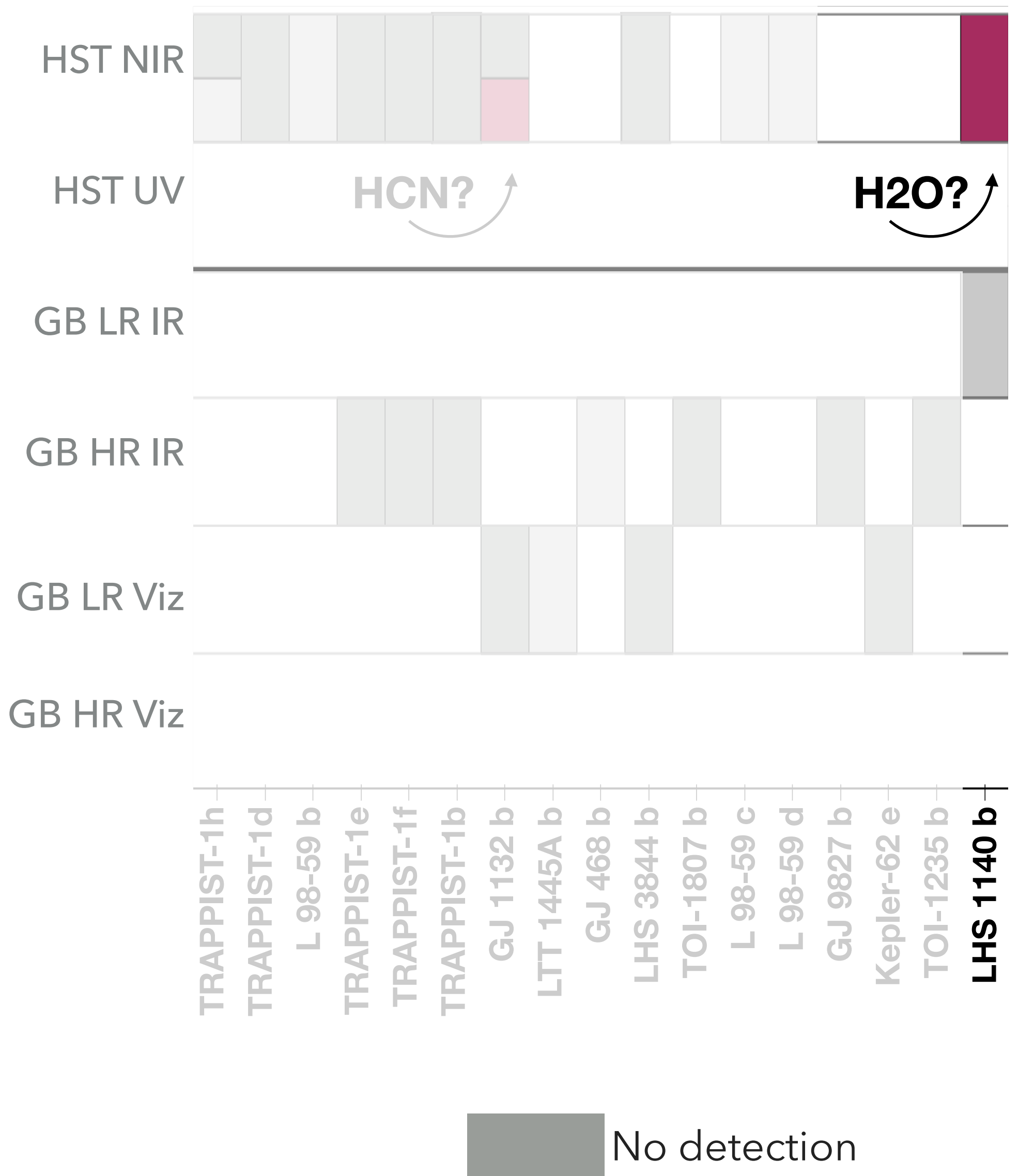
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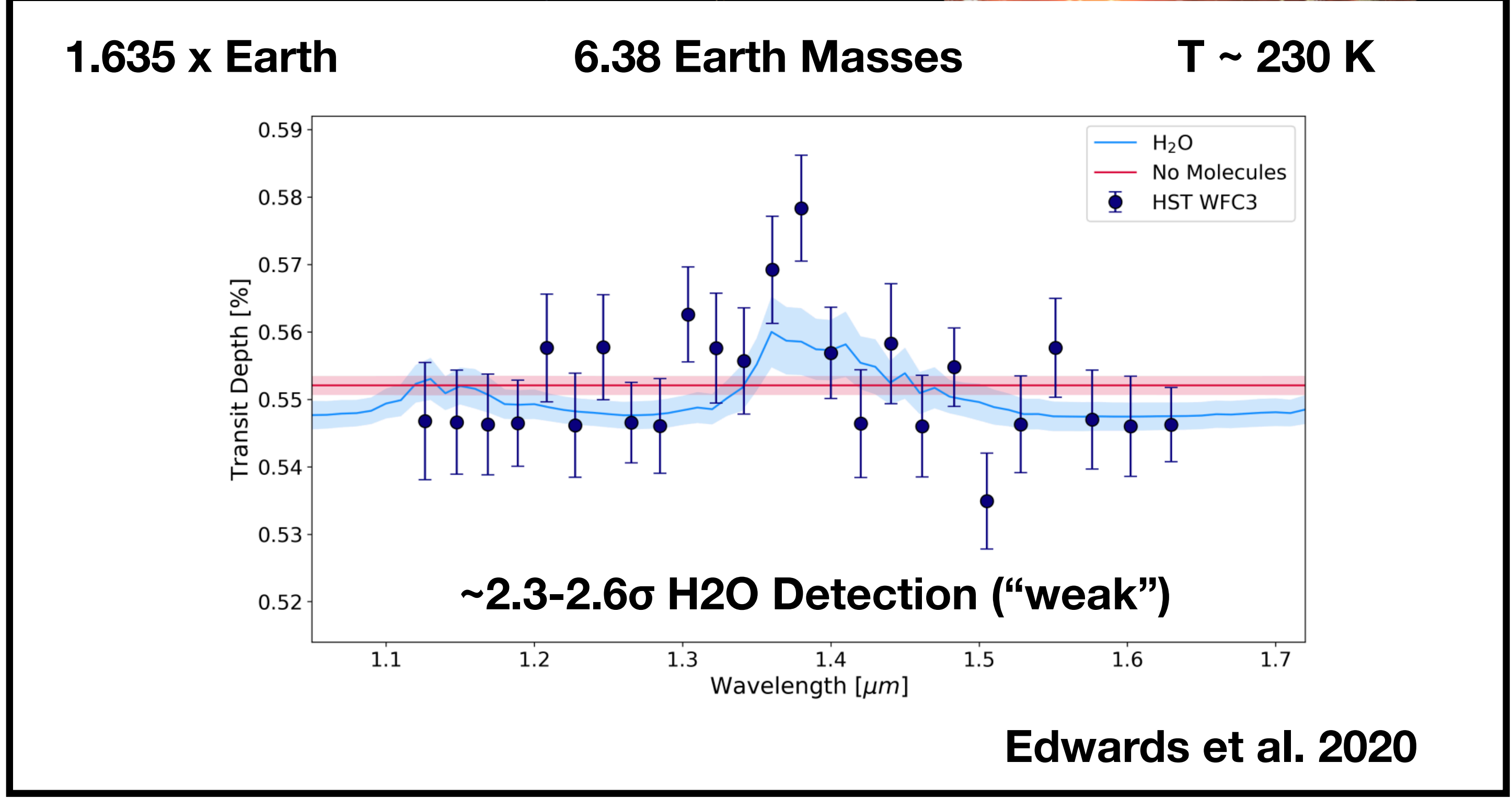
An overview of $R < 1.8 R_{\oplus}$ observations with HST and G-B instruments



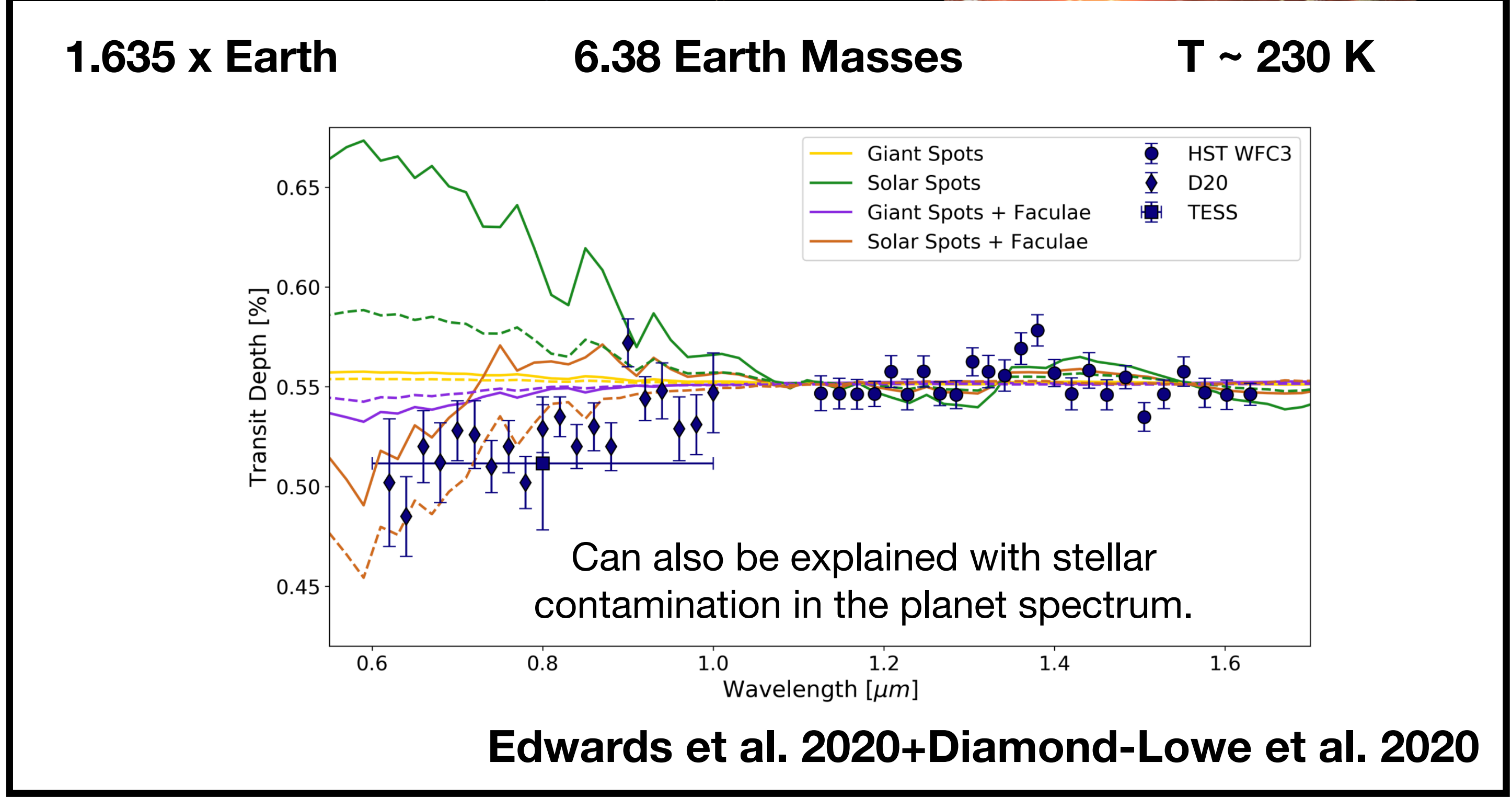
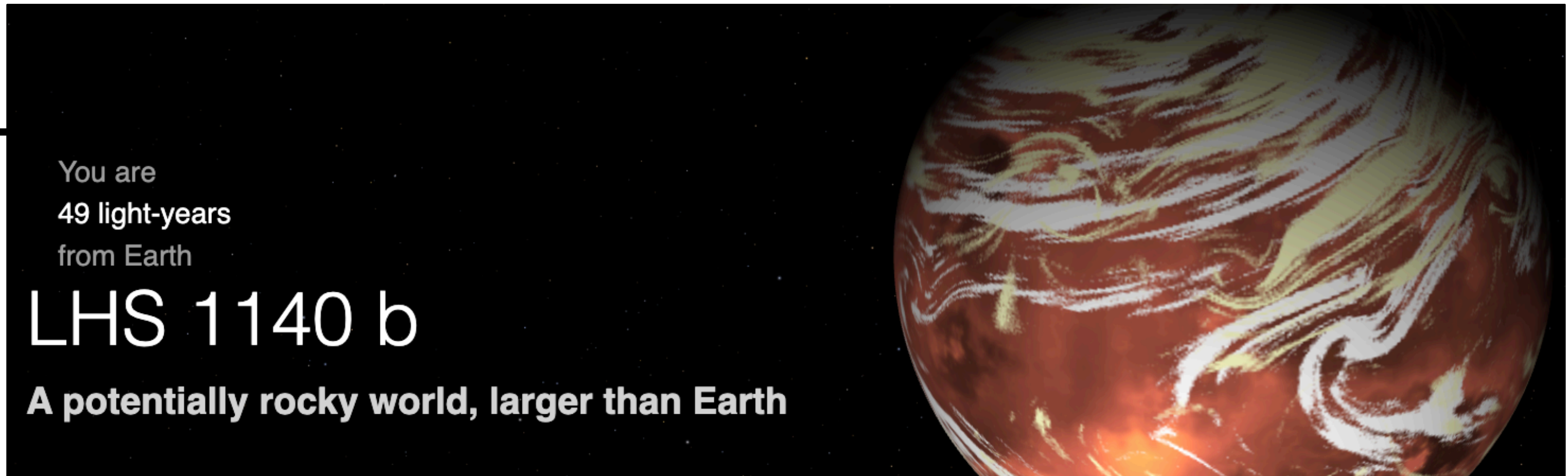
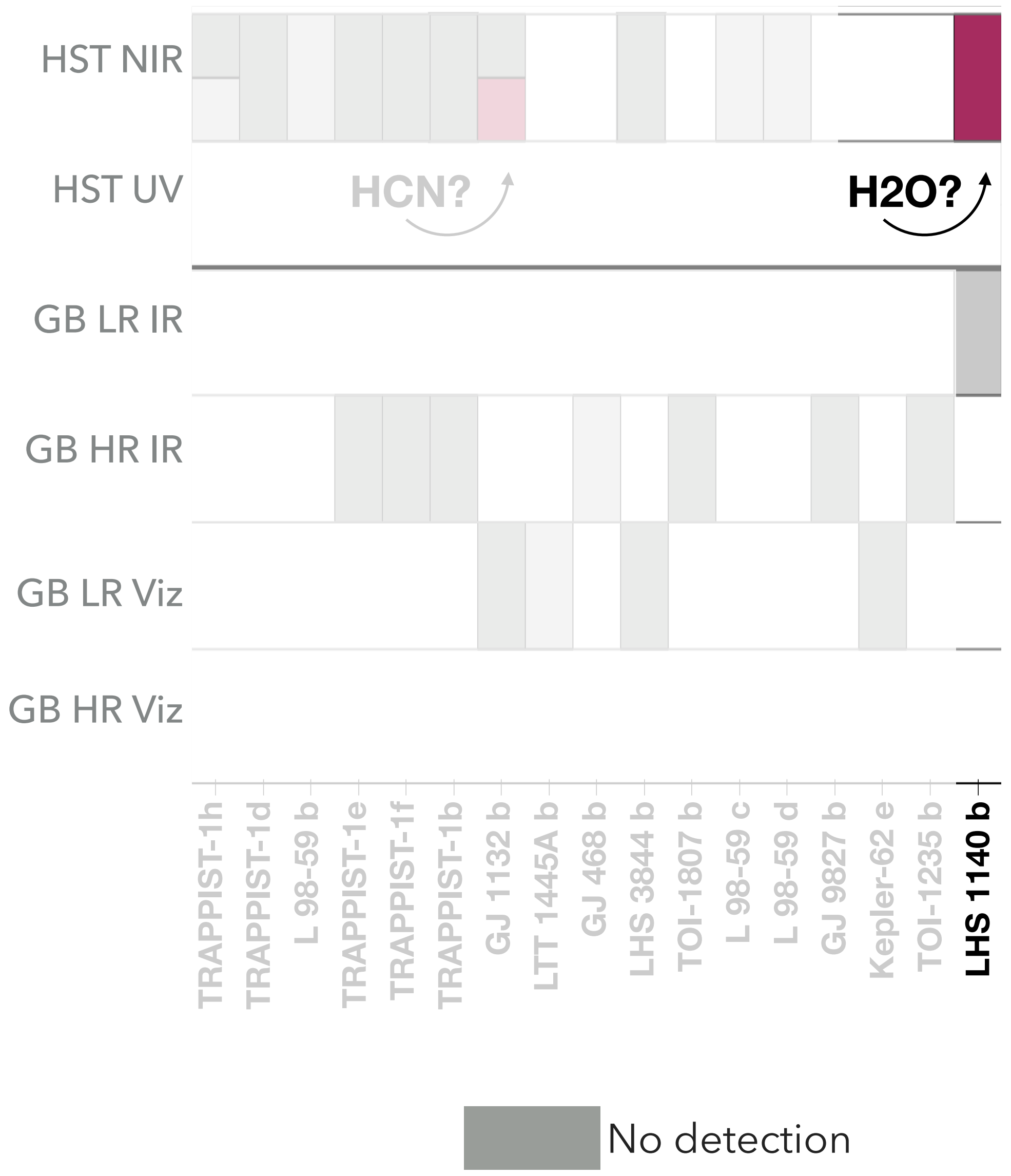
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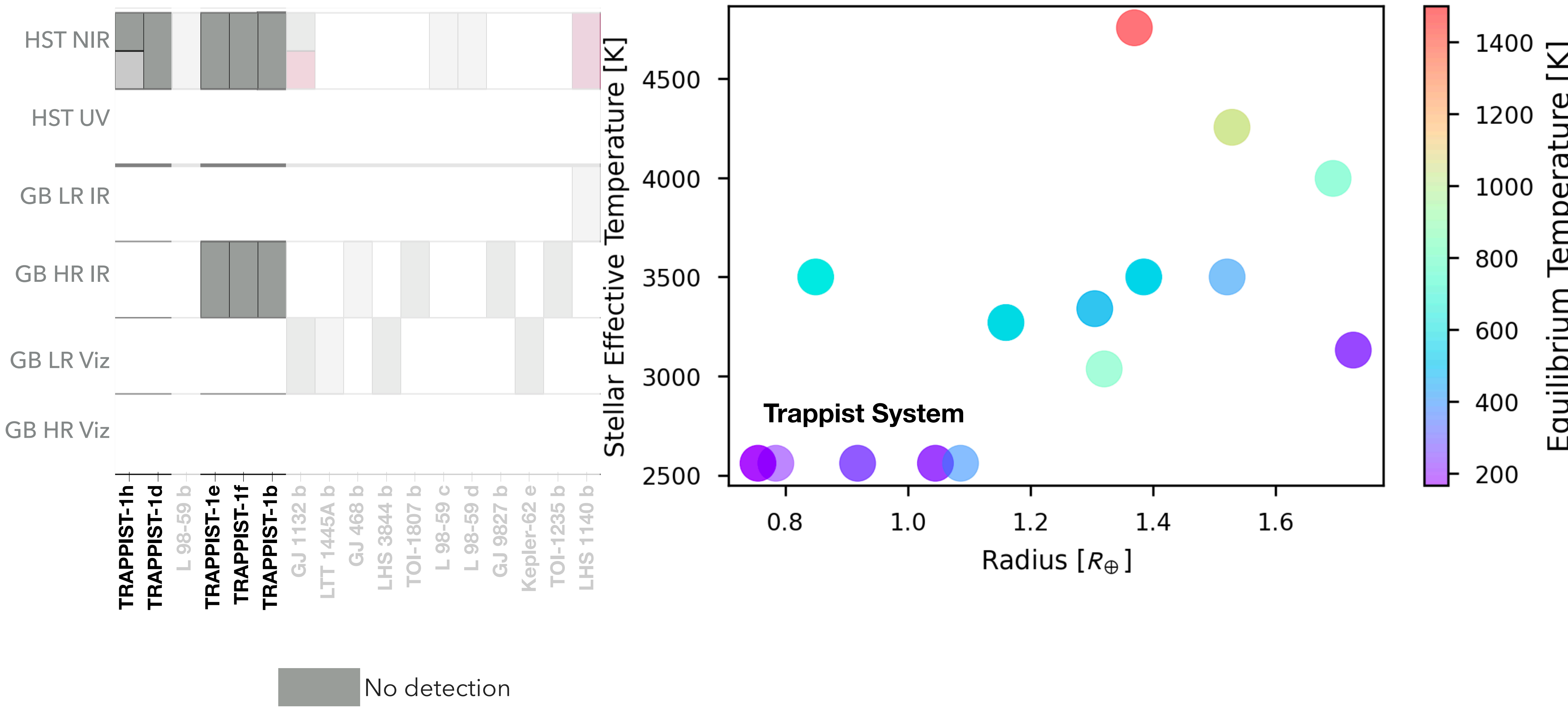
A potentially rocky world, larger than Earth



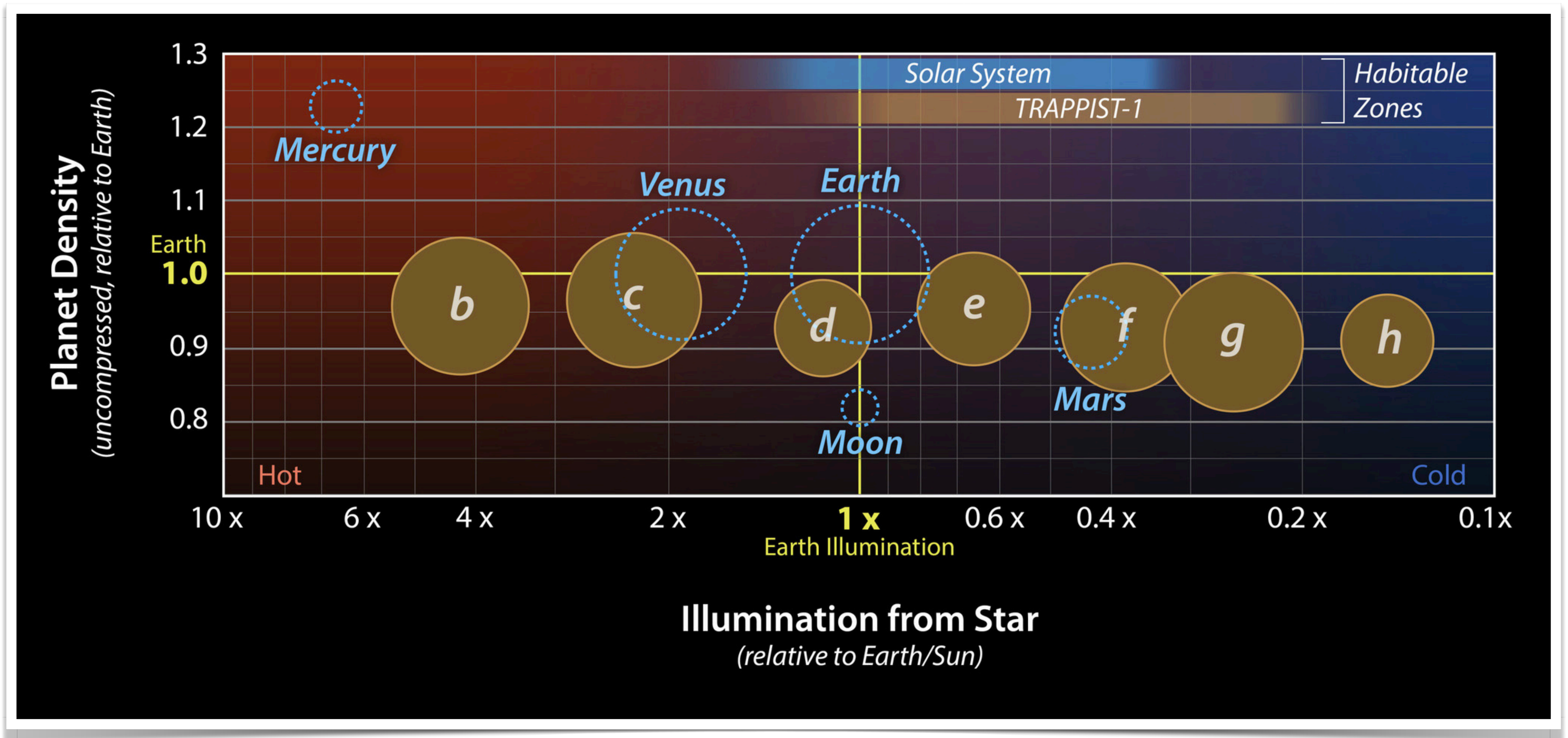
An overview of $R < 1.8 R_{\oplus}$ observations with HST and G-B instruments



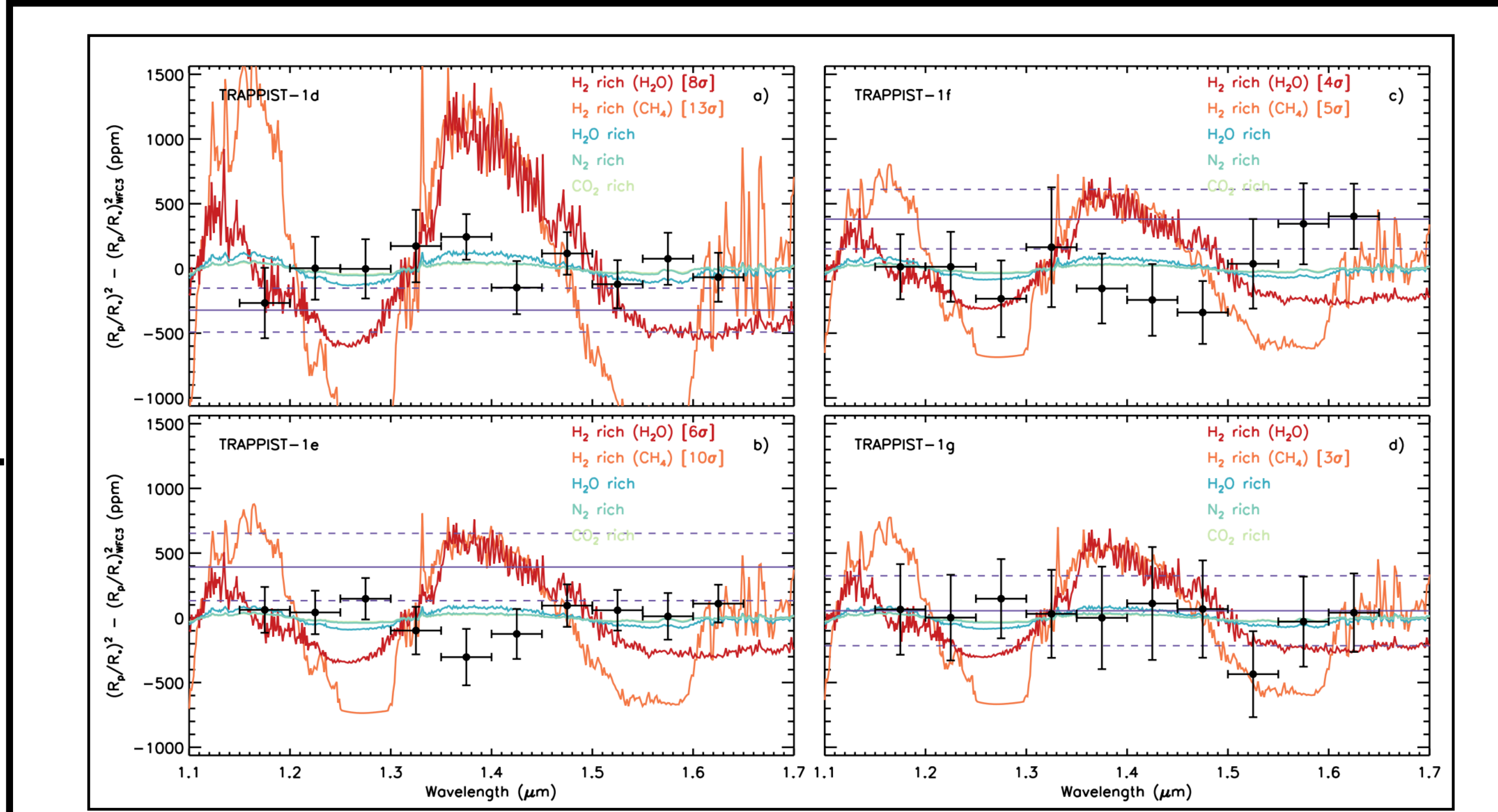
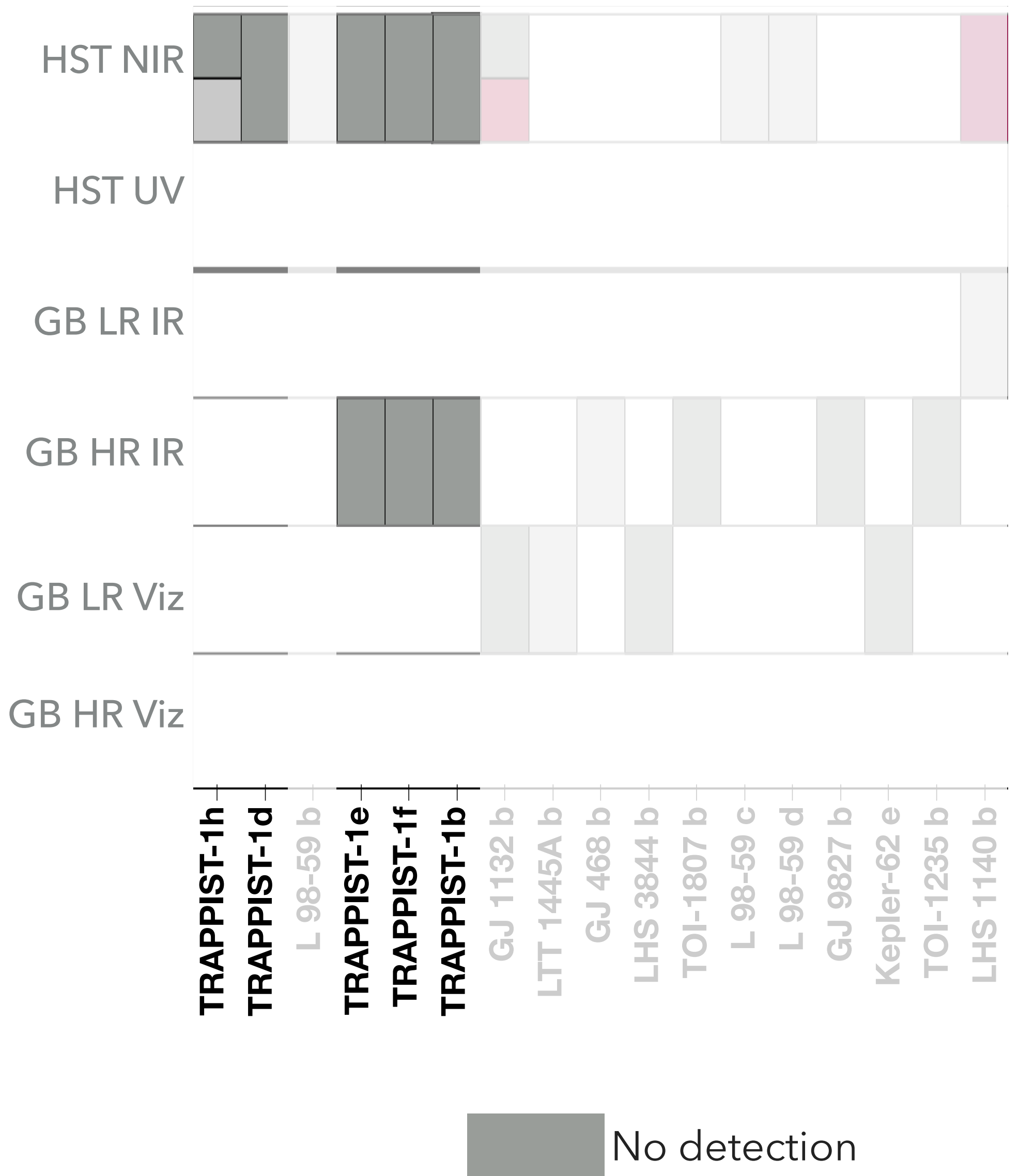
An overview of $R < 1.8 R_{\oplus}$ observations with HST and G-B instruments



TRAPPIST-1 System Compared to Our Solar System



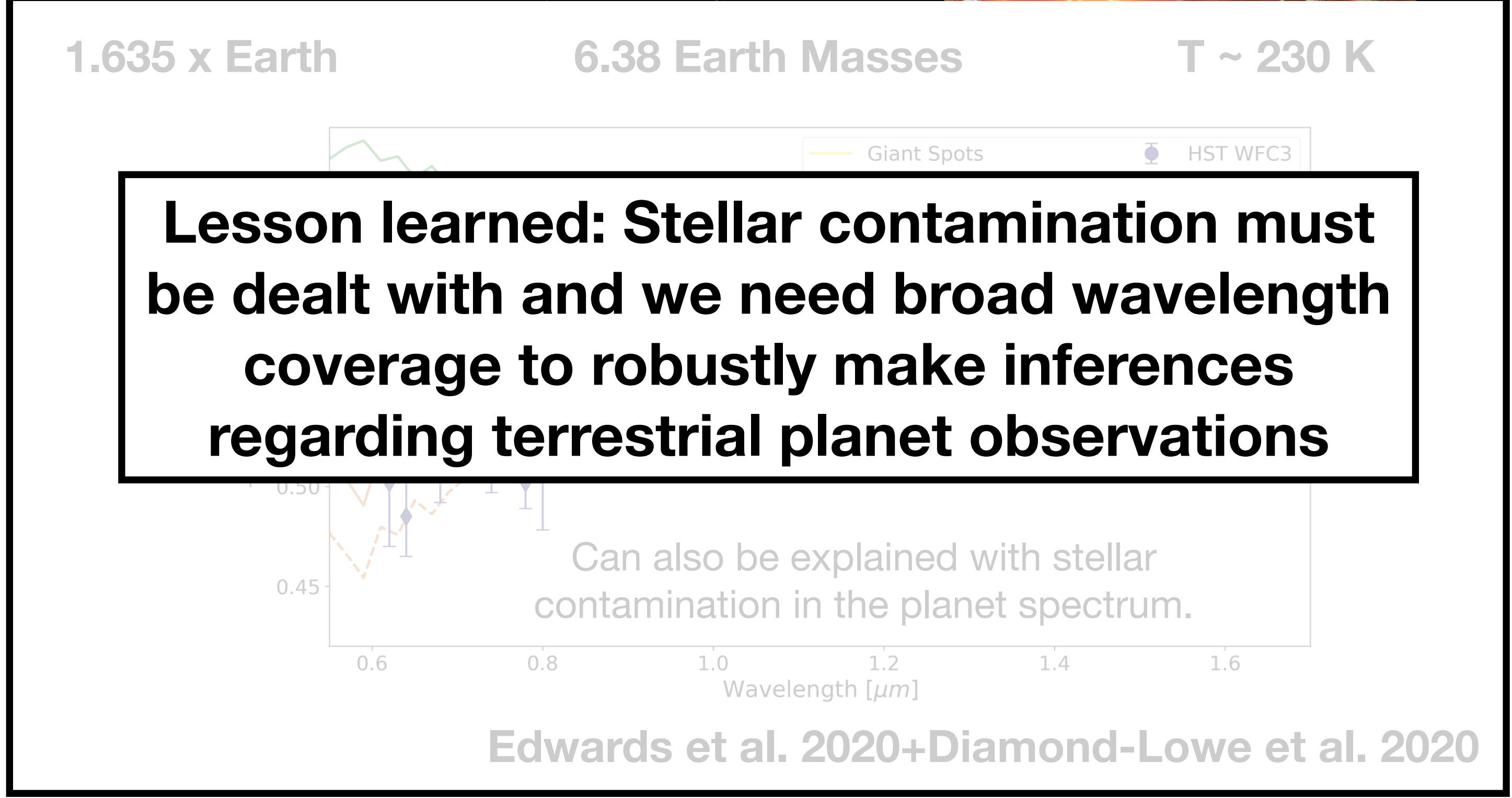
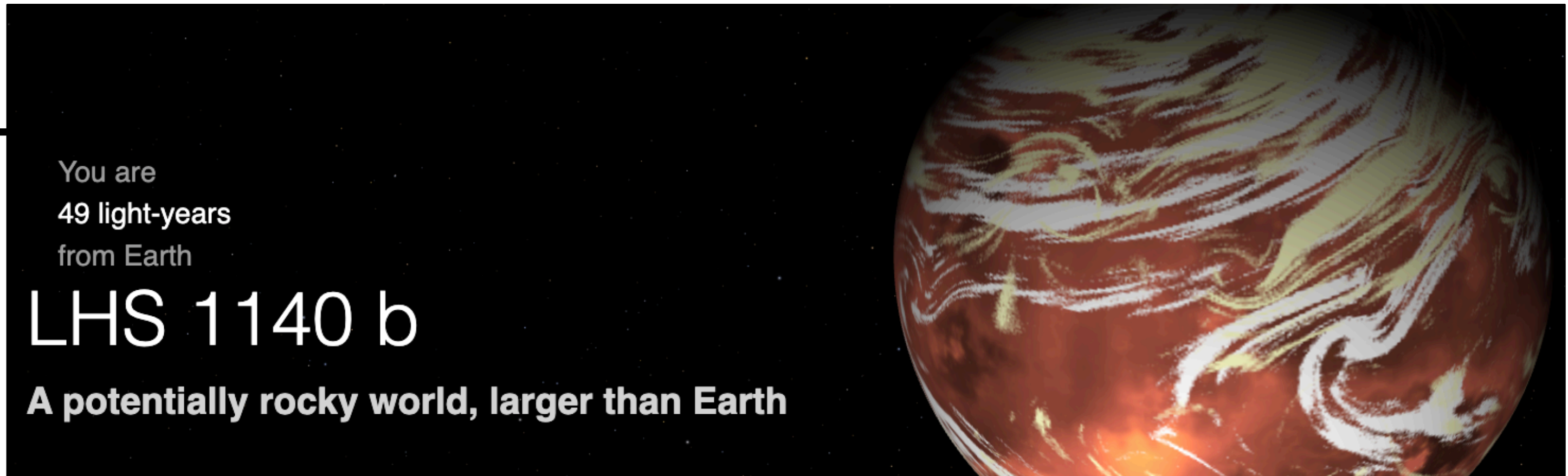
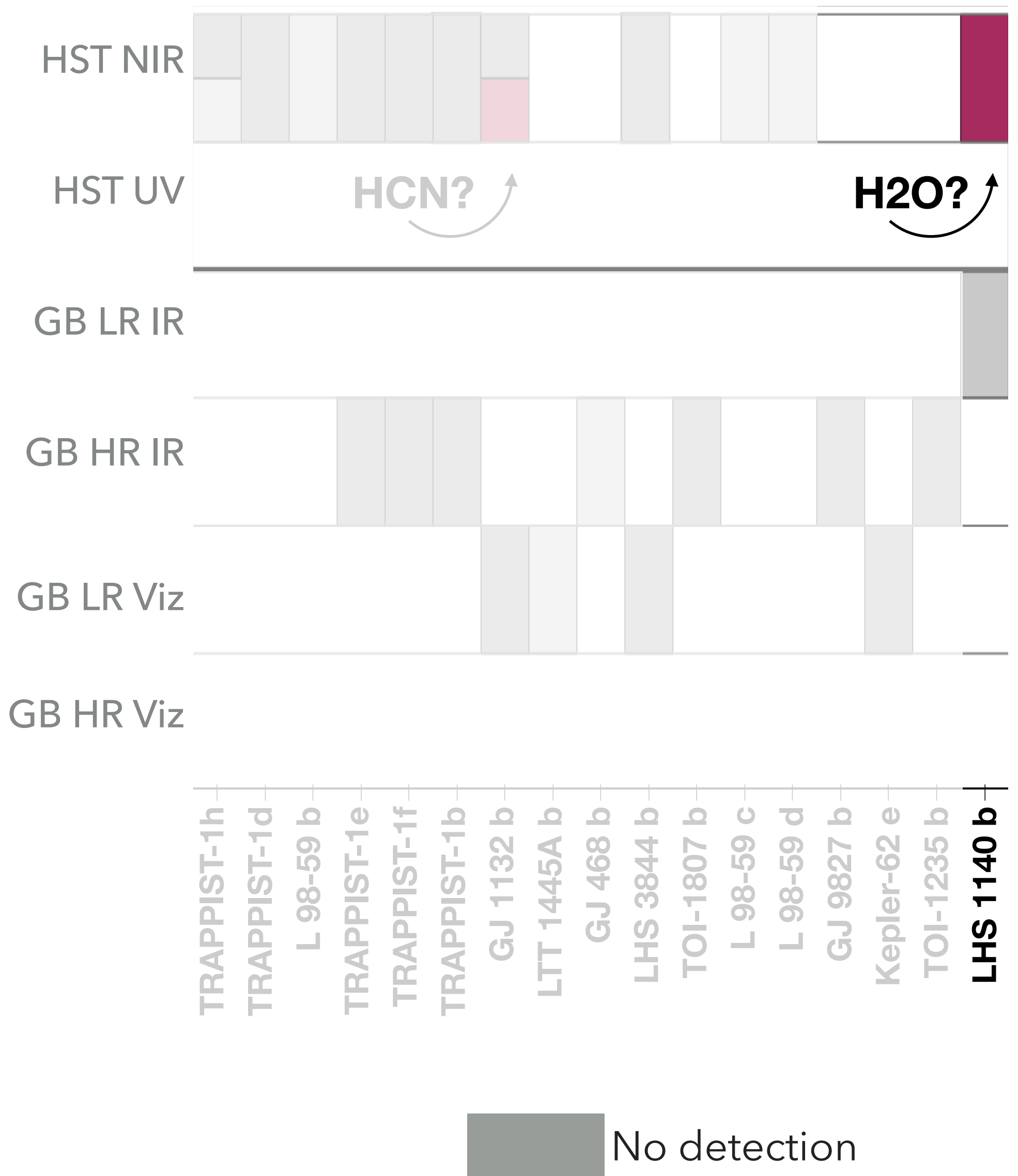
An overview of $R < 1.8 R_{\oplus}$ observations with HST and G-B instruments



De Wit et al. 2018

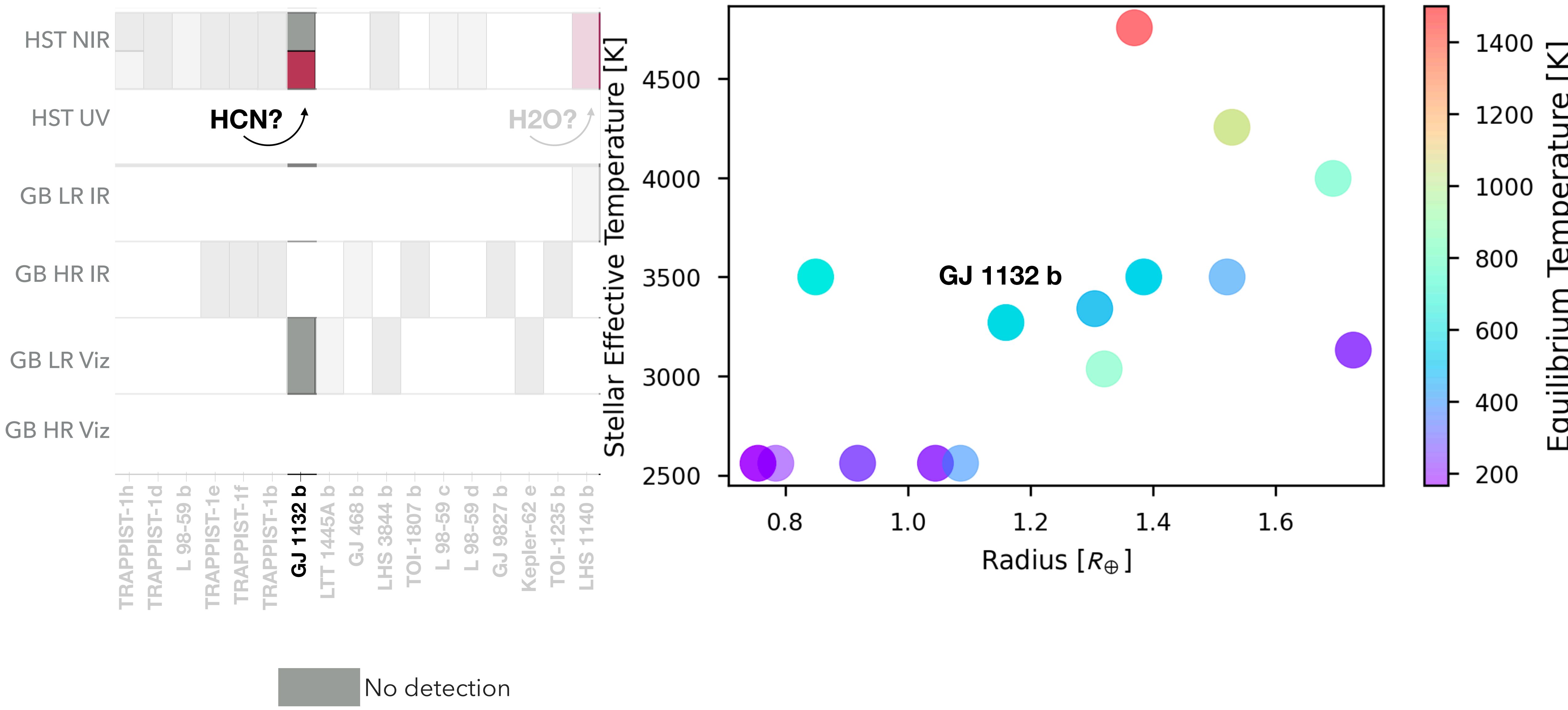
“These spectra demonstrate how stellar contamination can overwhelm planetary absorption features in low-resolution exoplanet transit spectra...”
 - Zhang, Zhou, Rackham et al. 2018

An overview of $R < 1.8 R_{\oplus}$ observations with HST and G-B instruments

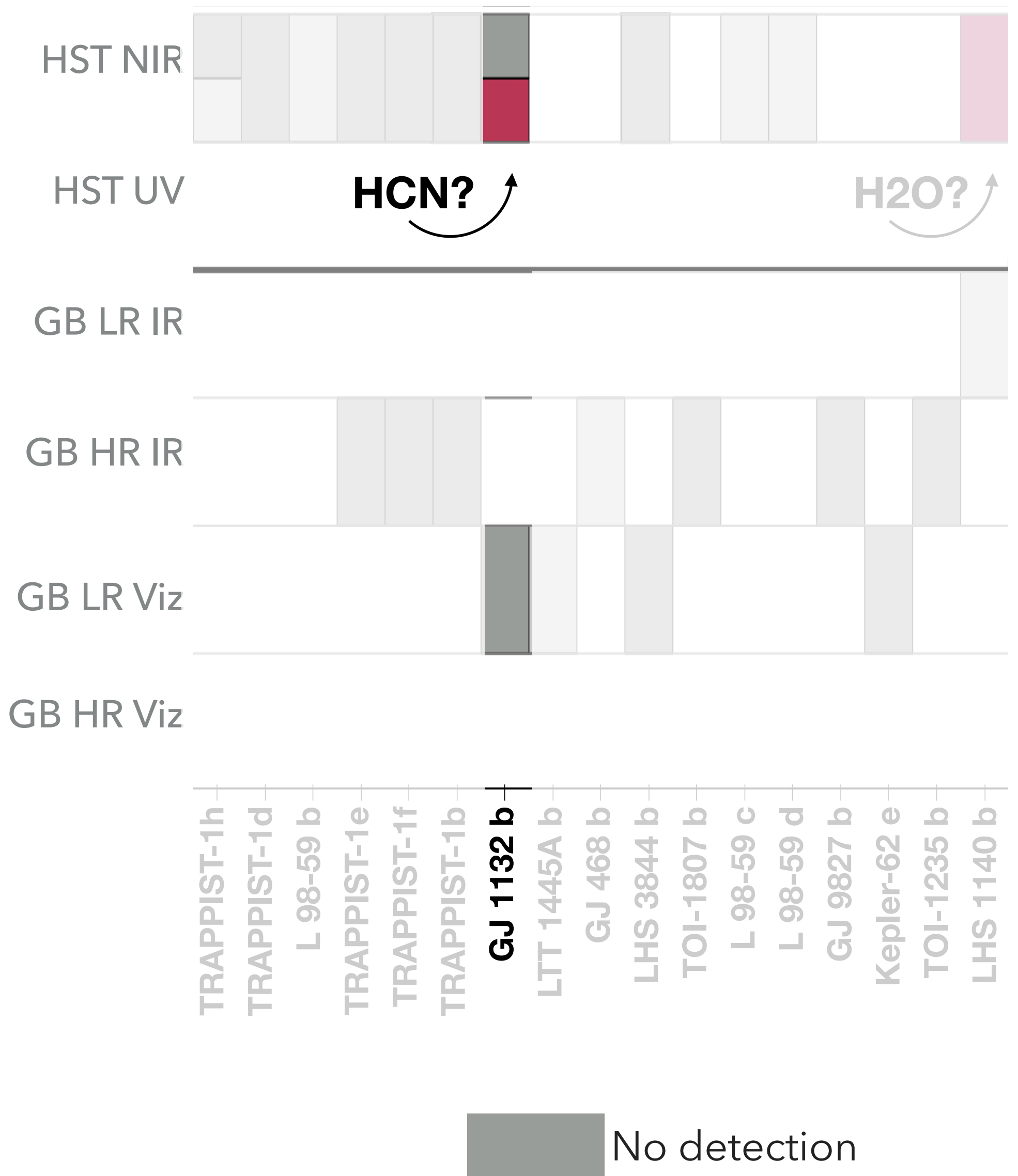


Edwards et al. 2020+Diamond-Lowe et al. 2020

An overview of $R < 1.8 R_{\oplus}$ observations with HST and G-B instruments



An overview of $R < 1.8 R_{\oplus}$ observations with HST and G-B instruments



You are
41 light-years
from Earth

GJ 1132 b

A potentially rocky world, larger than Earth

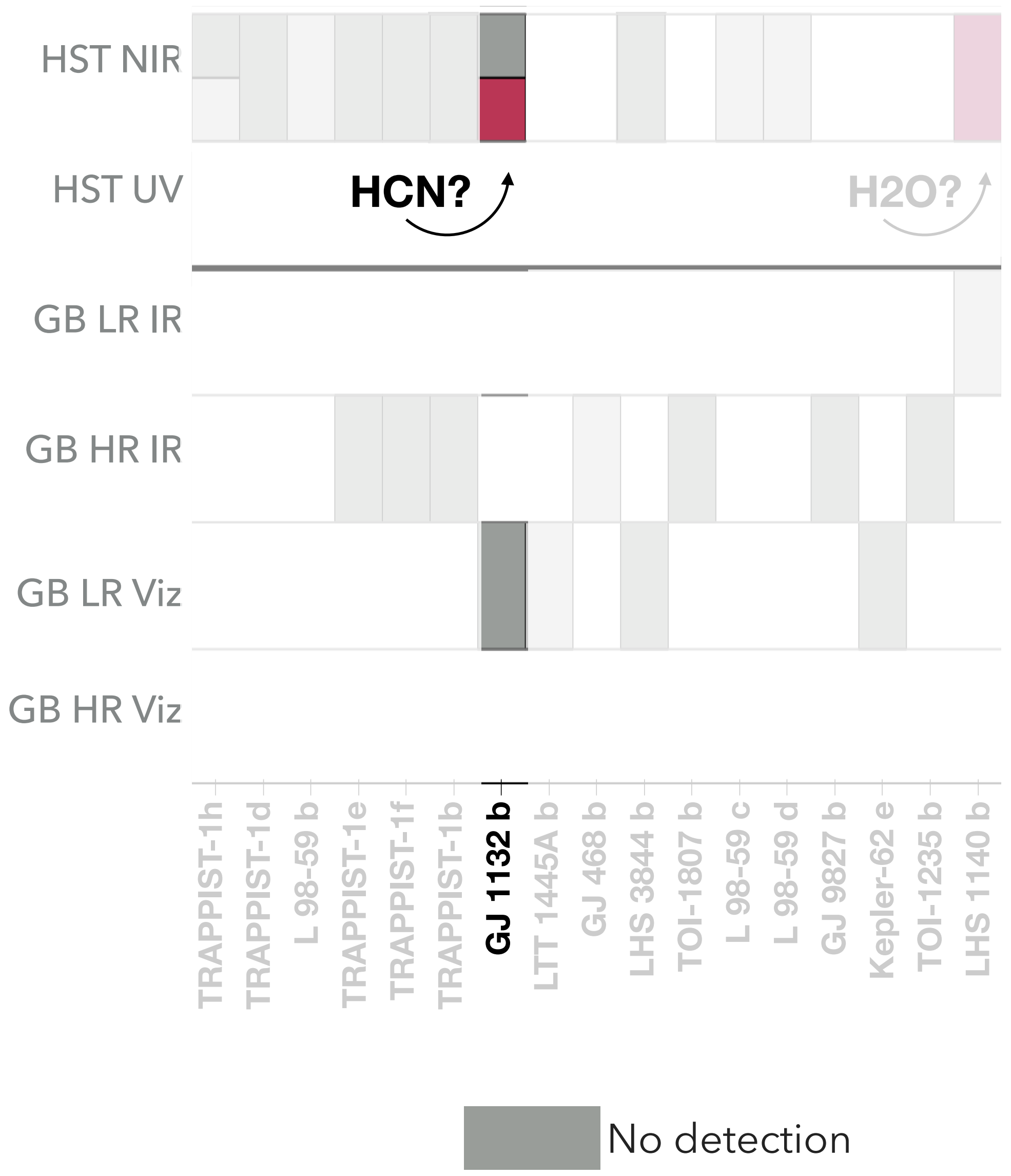
1.13 x Earth Radius

1.66 Earth Masses

T ~ 580 K

Diamond-Lowe et al. 2018

An overview of $R < 1.8 R_{\oplus}$ observations with HST and G-B instruments

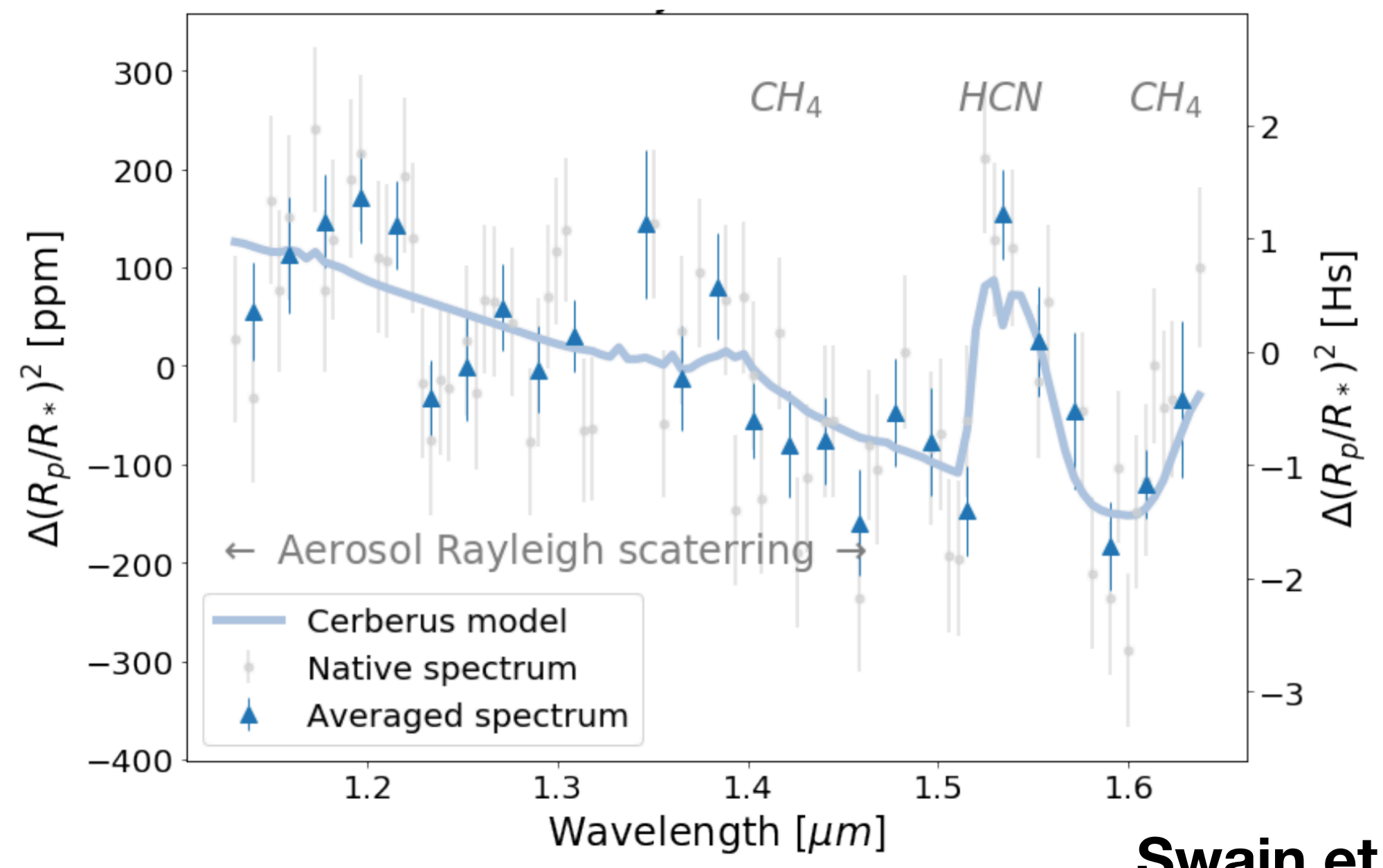


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GJ 1132 b

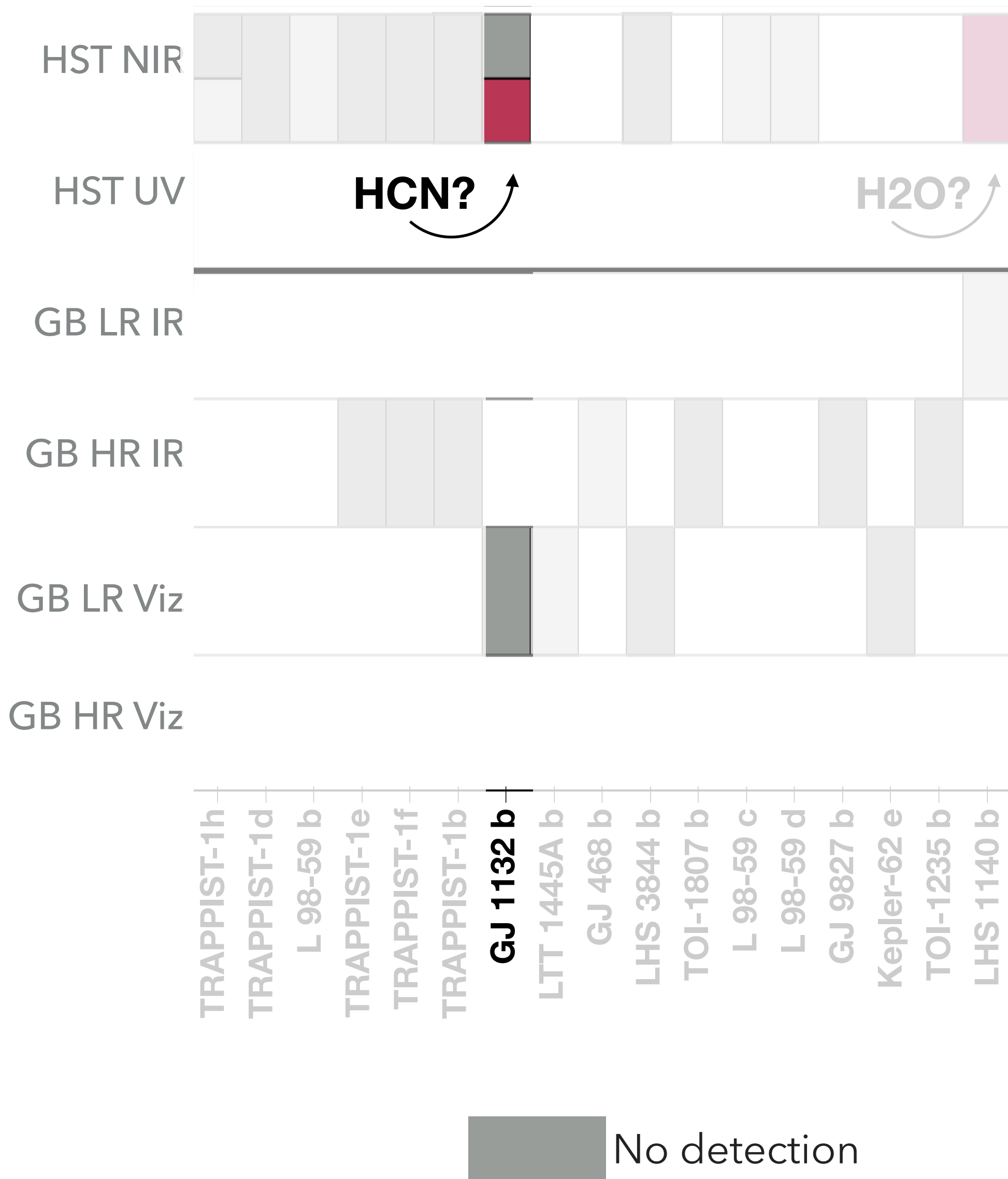
A potentially rocky world, larger than Earth

1.13 x Earth Radius 1.66 Earth Masses T ~ 580 K



Swain et al. 2021

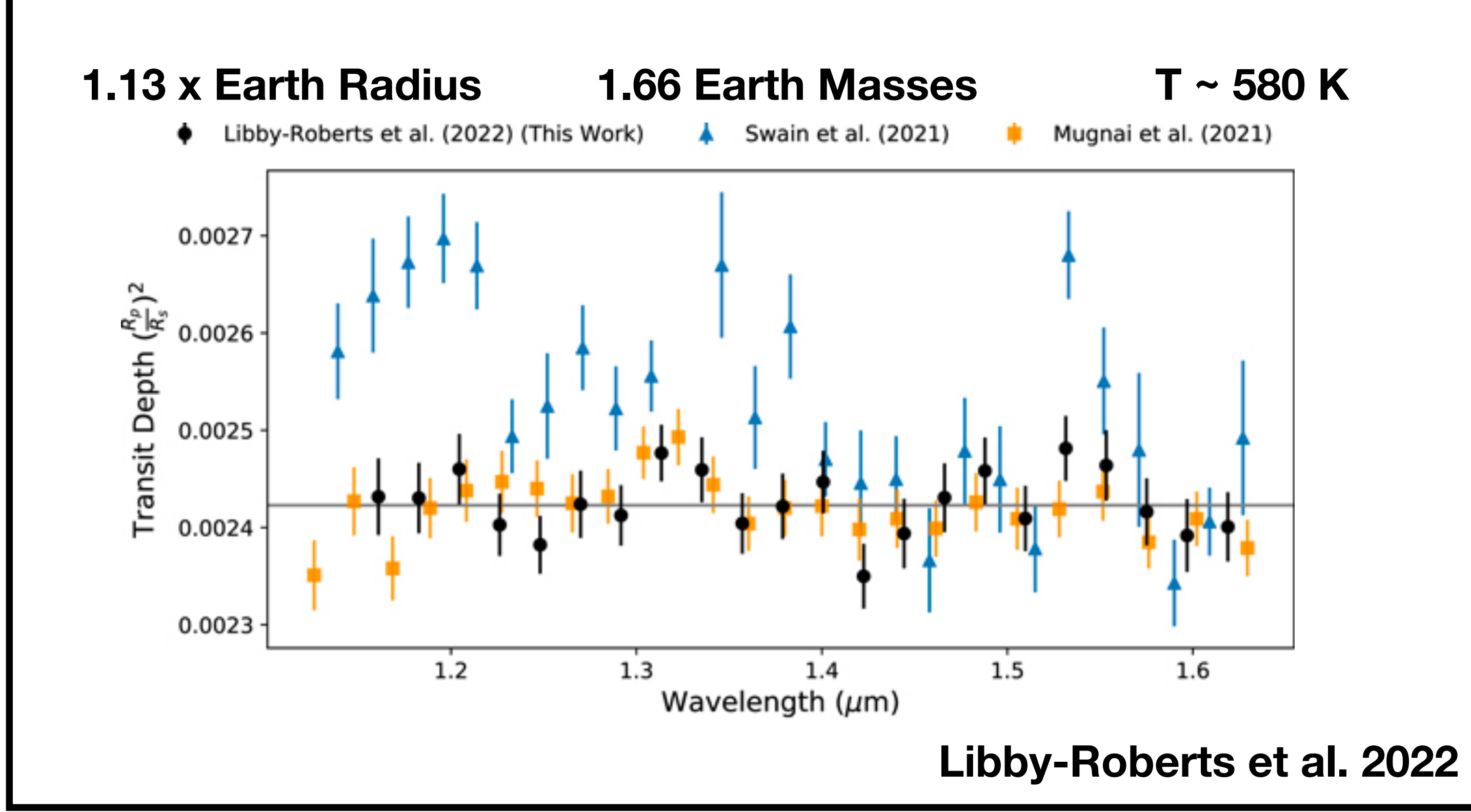
An overview of $R < 1.8 R_{\oplus}$ observations with HST and G-B instruments



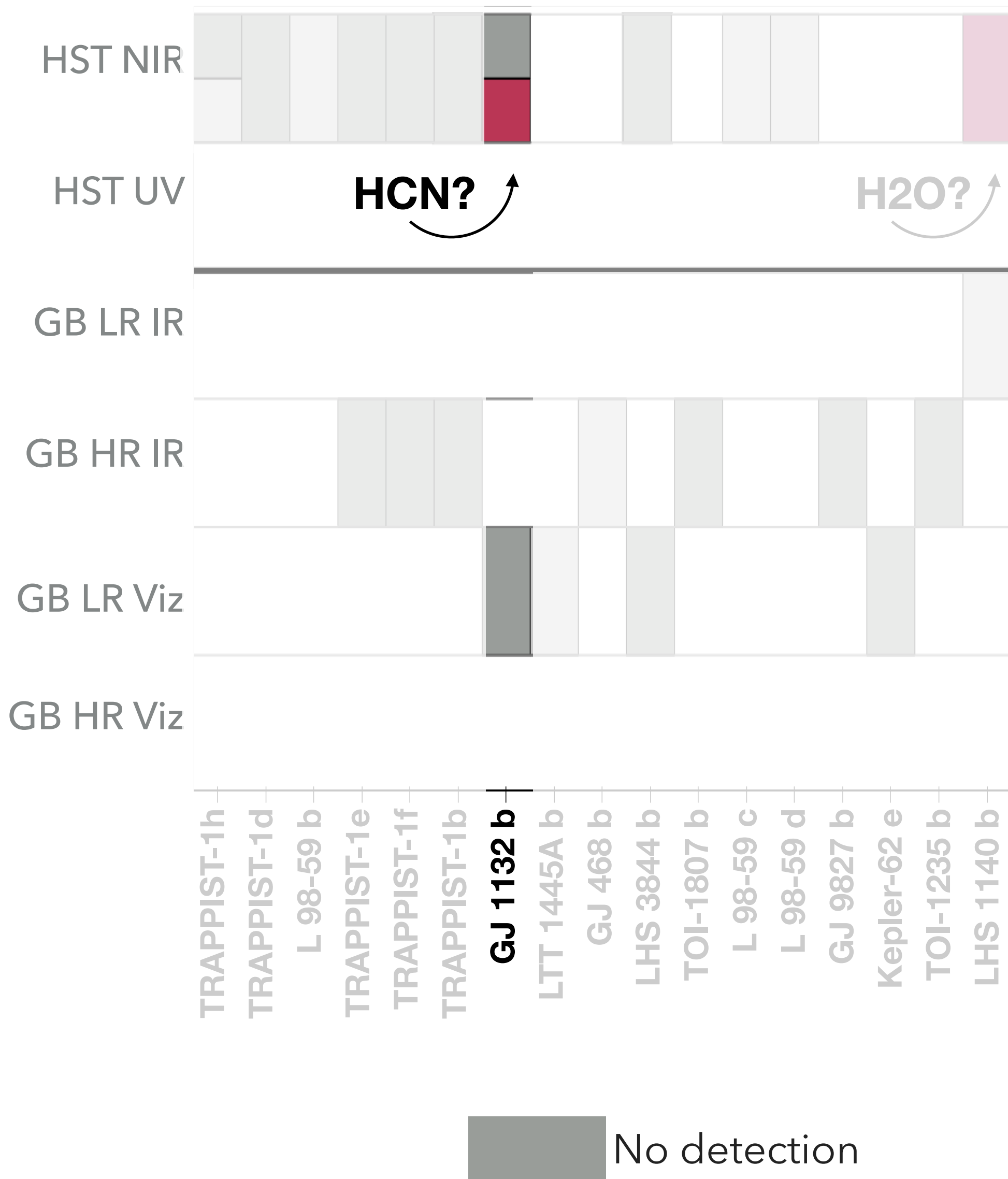
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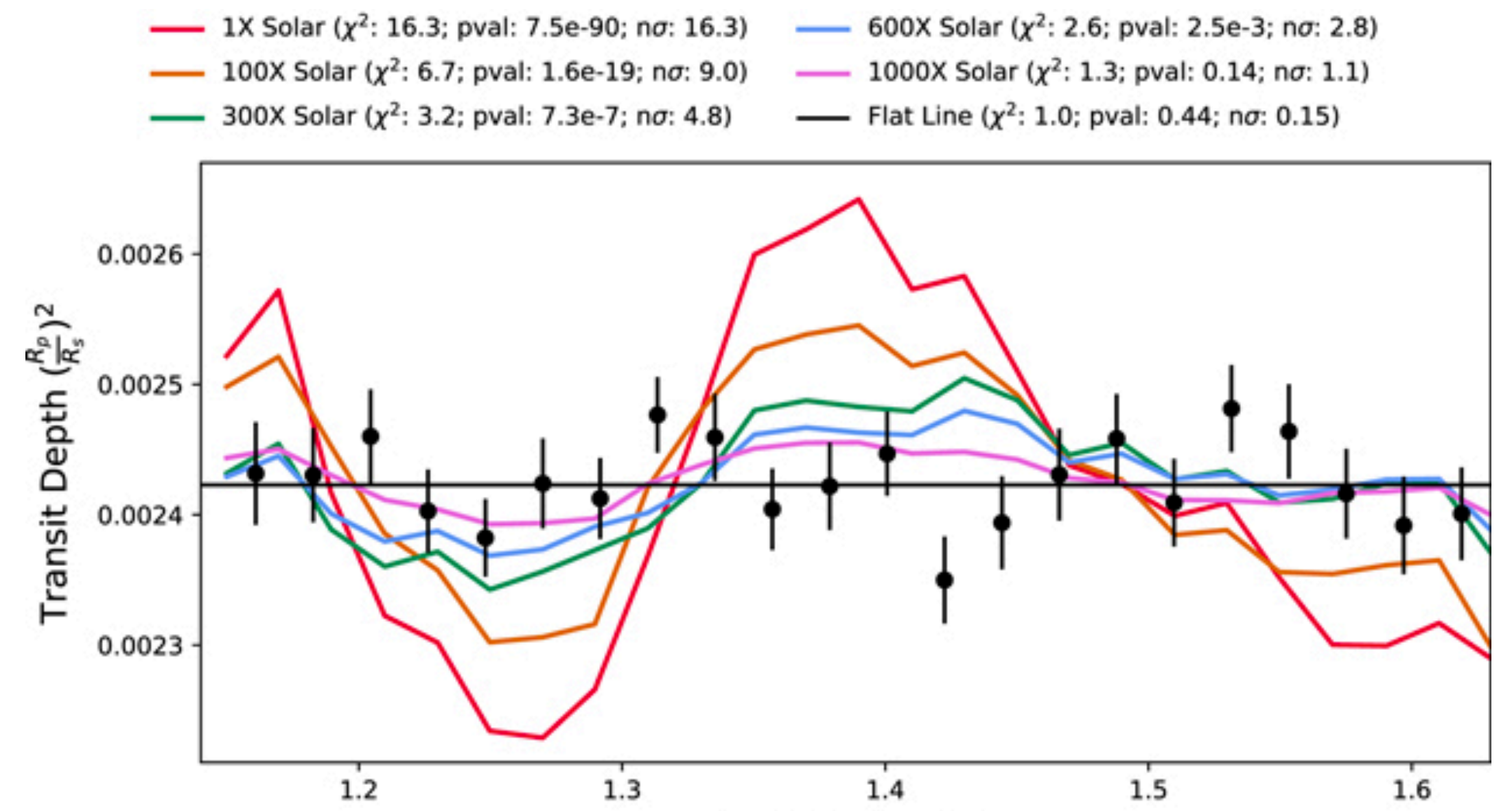


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GJ 1132 b

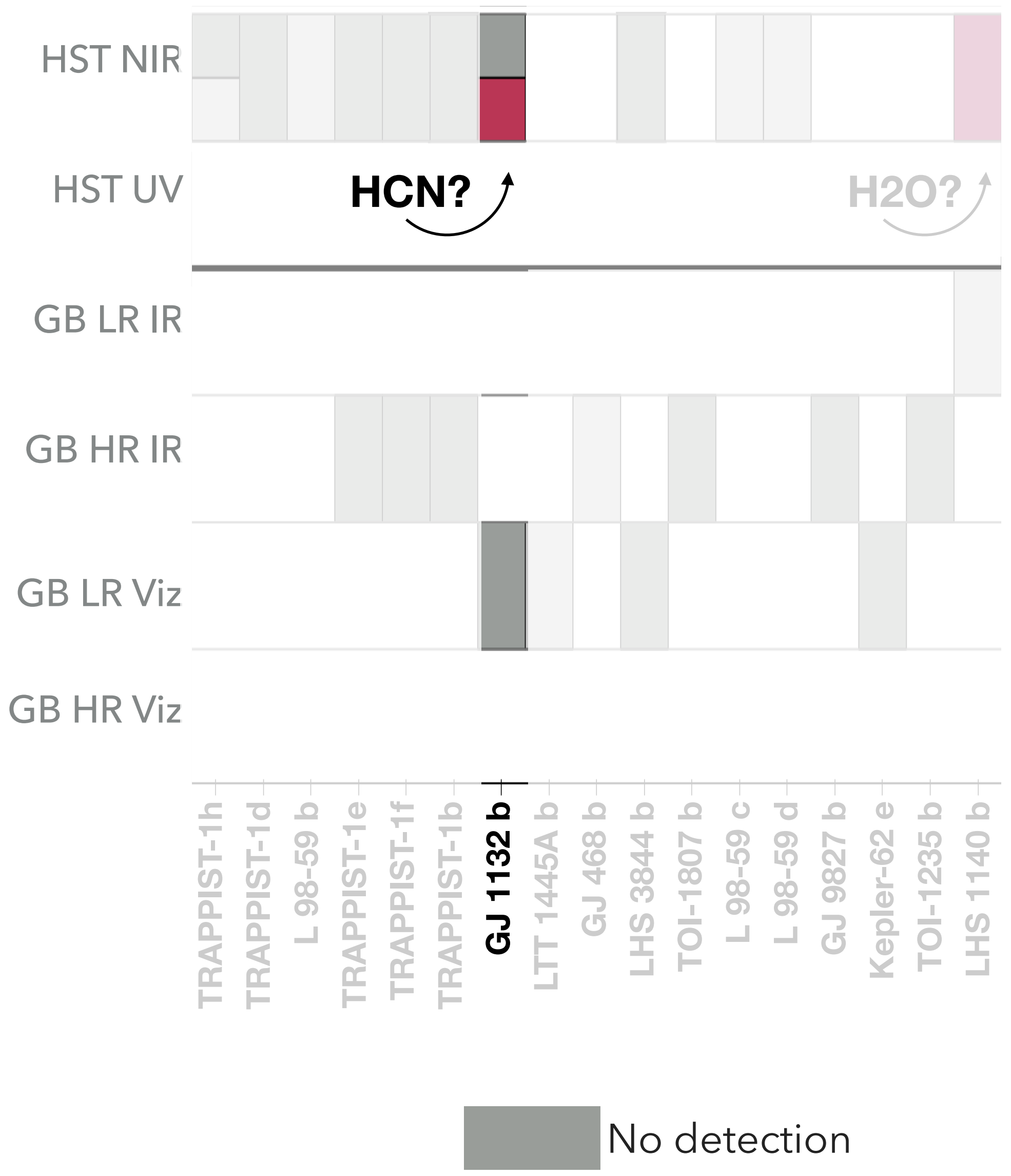
A potentially rocky world, larger than Earth

1.13 x Earth Radius 1.66 Earth Masses T ~ 580 K



Libby-Roberts et al. 2022

An overview of $R < 1.8 R_{\oplus}$ observations with HST and G-B instruments



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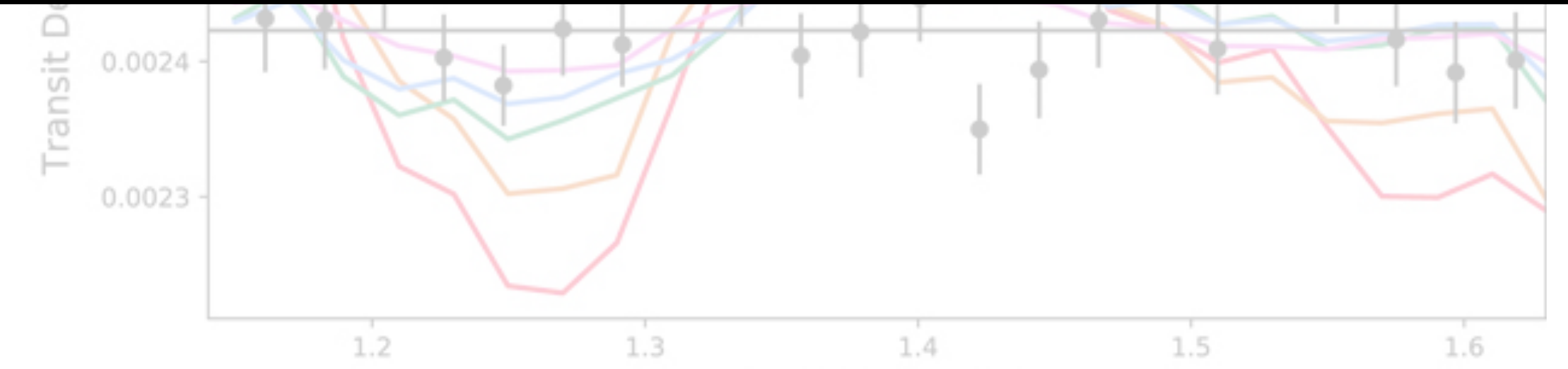
GJ 1132 b

A potentially rocky world, larger than Earth

1.13 x Earth Radius 1.66 Earth Masses T ~ 580 K

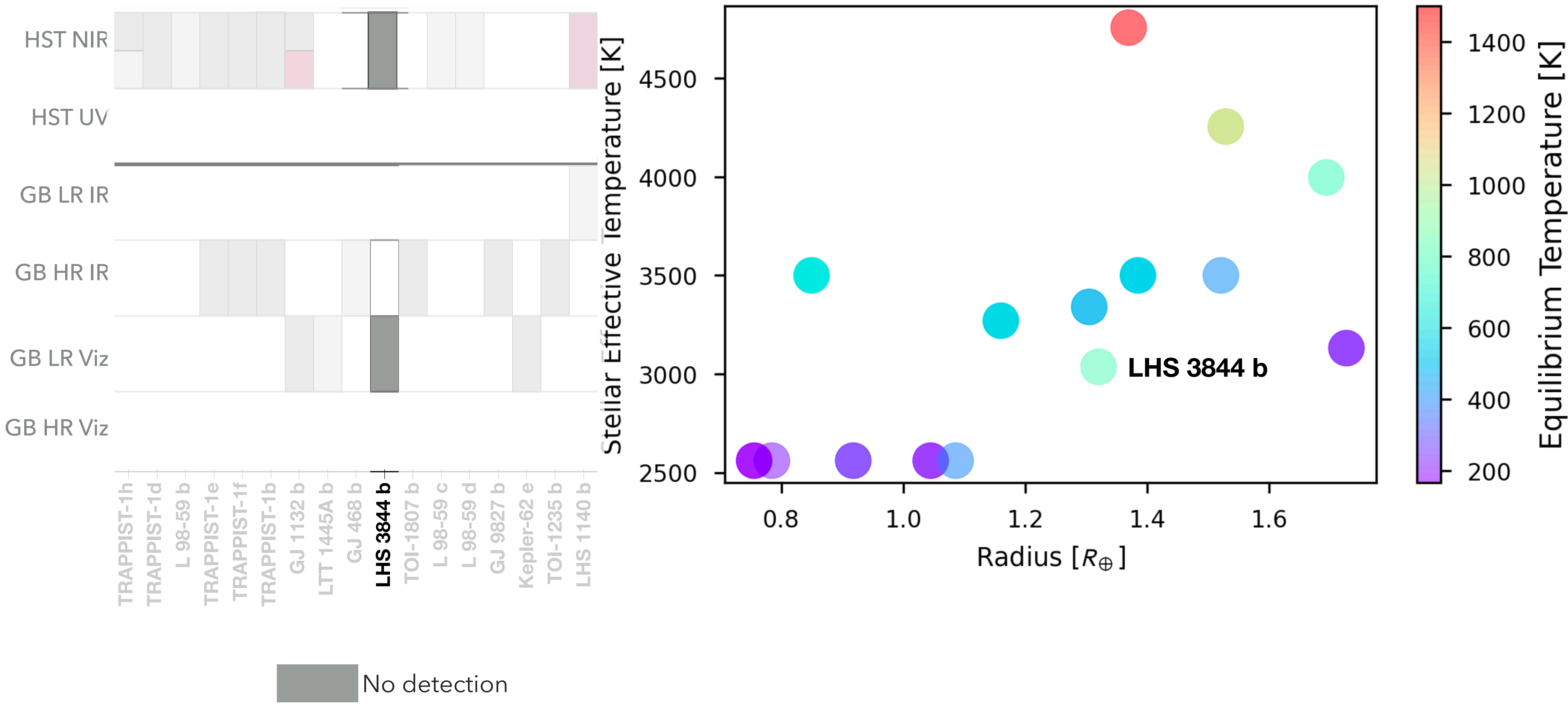
- 1X Solar (χ^2 : 16.3; pval: 7.5e-90; $n\sigma$: 16.3)
- 100X Solar (χ^2 : 6.7; pval: 1.6e-19; $n\sigma$: 9.0)
- 300X Solar (χ^2 : 3.2; pval: 7.3e-7; $n\sigma$: 4.8)
- 600X Solar (χ^2 : 2.6; pval: 2.5e-3; $n\sigma$: 2.8)
- 1000X Solar (χ^2 : 1.3; pval: 0.14; $n\sigma$: 1.1)
- Flat Line (χ^2 : 1.0; pval: 0.44; $n\sigma$: 0.15)

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

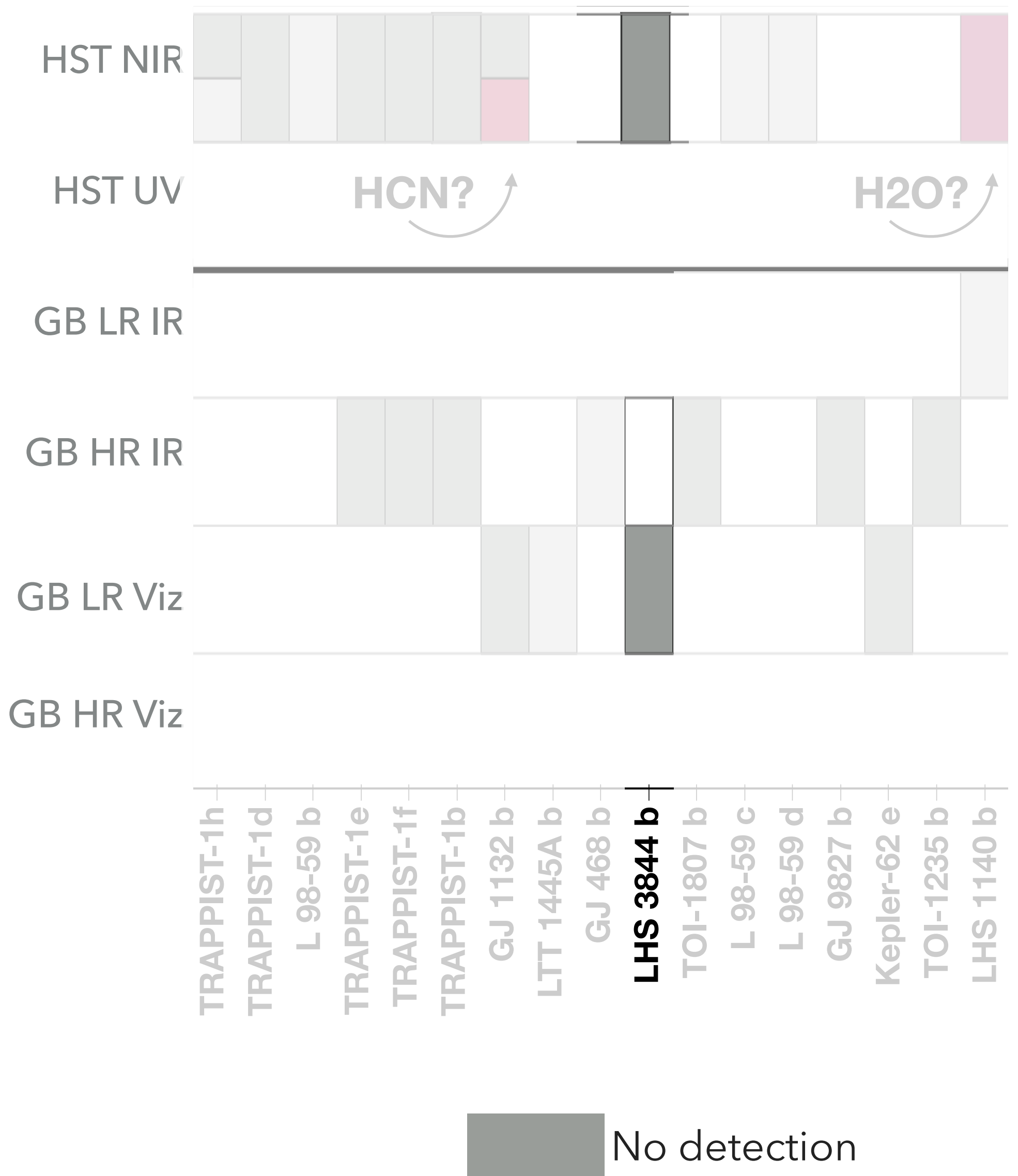


Libby-Roberts et al. 2022

An overview of $R < 1.8 R_{\oplus}$ observations with HST and G-B instruments



An overview of $R < 1.8 R_{\oplus}$ observations with HST and G-B instruments



LHS 3844 b

1.3 x Earth Radius

2.25 Earth Masses

T ~ 800 K

a

Orbital phase

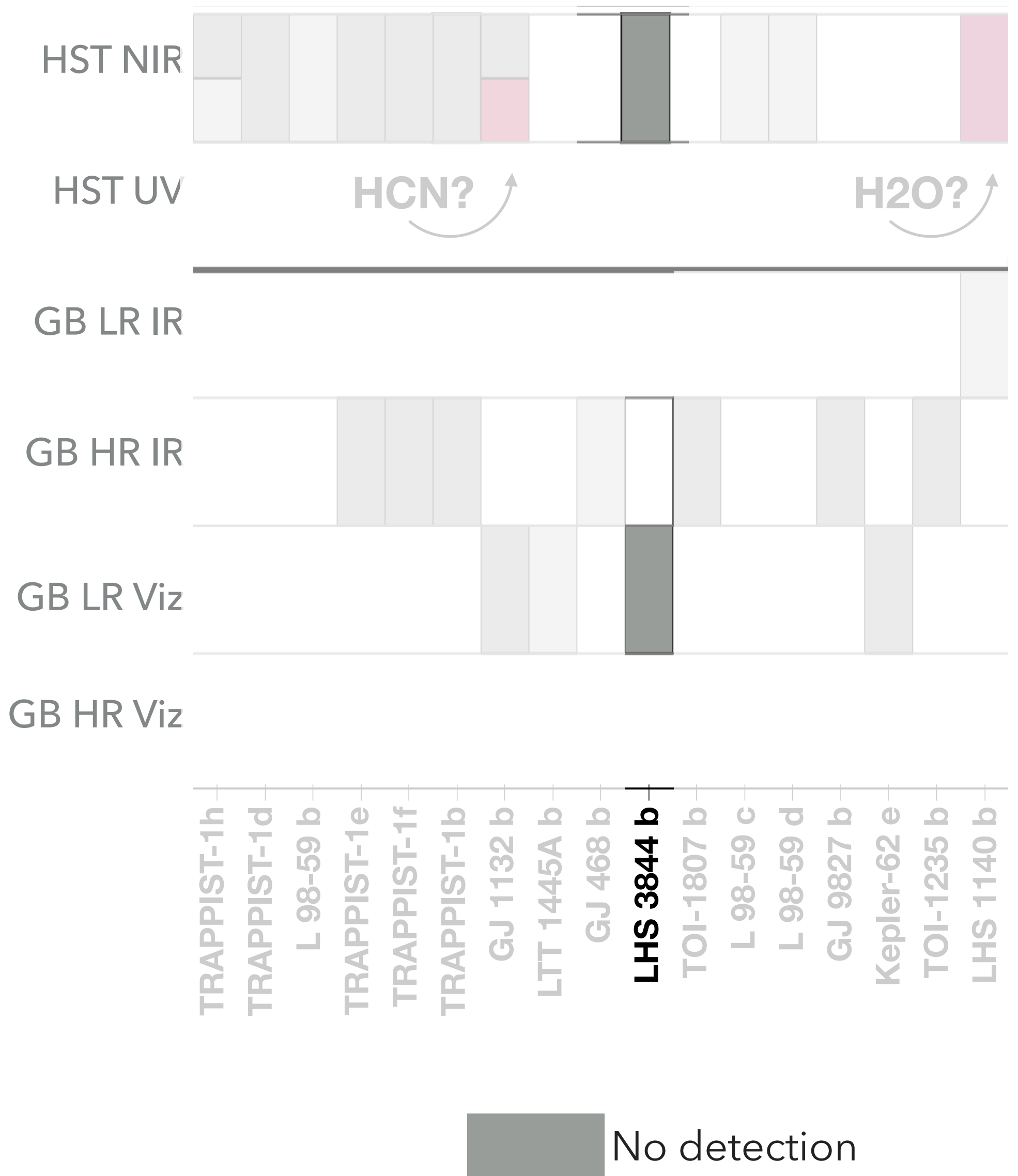
b

Temperature (Kelvin)

Remember from Laura Kreidberg's talk on Tues!

Kreidberg et al. 2019

An overview of $R < 1.8 R_{\oplus}$ observations with HST and G-B instruments



LHS 3844 b

1.3 x Earth Radius

2.25 Earth Masses

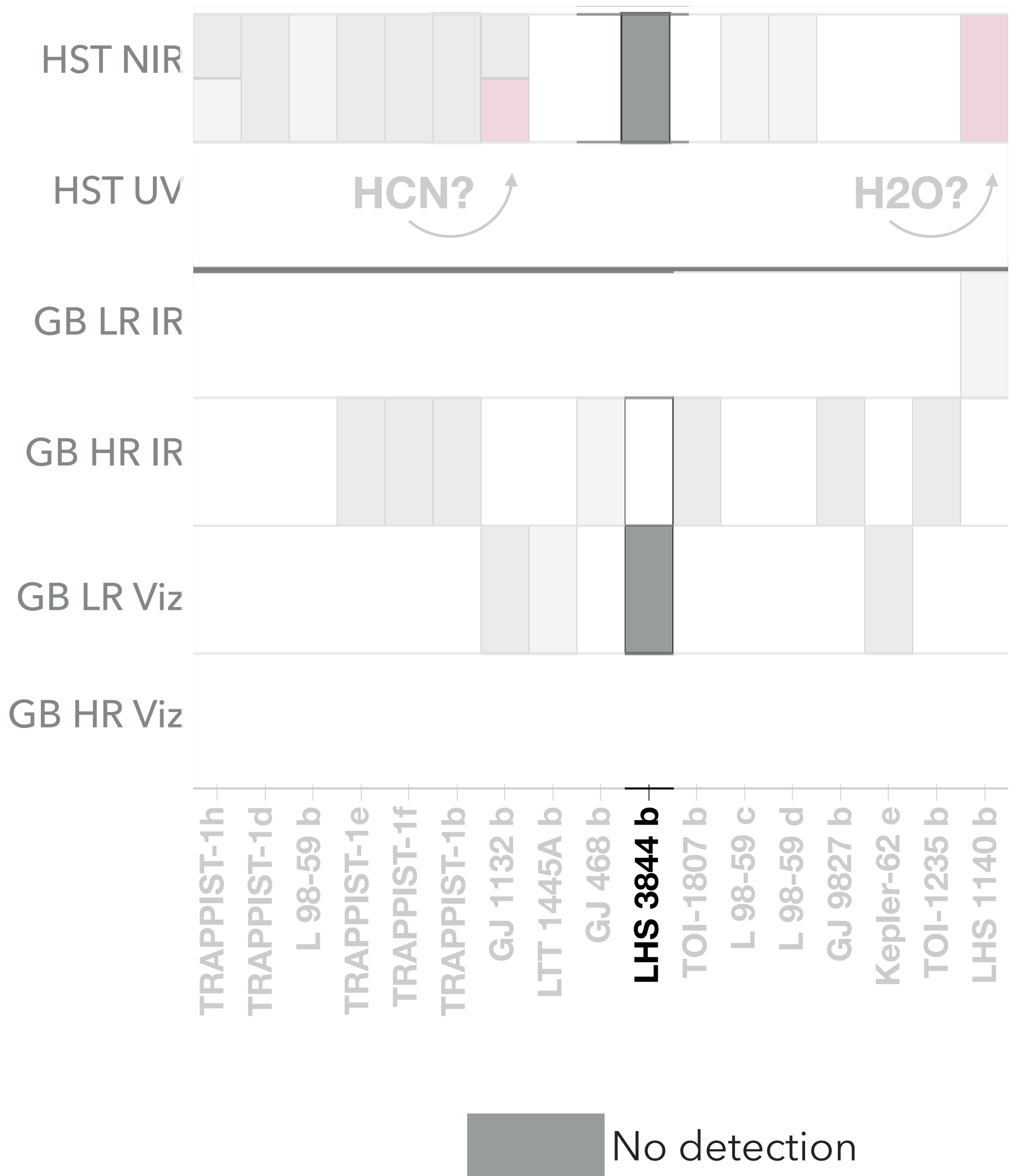
T ~ 800 K

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 $R < 1.8 R_{\oplus}$ observations with HST and G-B instruments



LHS 3844 b

1.13 x Earth Radius

1.66 Earth Masses

T ~ 580 K

— 1X Solar (χ^2 : 16.3; pval: 7.5e-90; n σ : 16.3)
 — 600X Solar (χ^2 : 2.6; pval: 2.5e-3; n σ : 2.8)

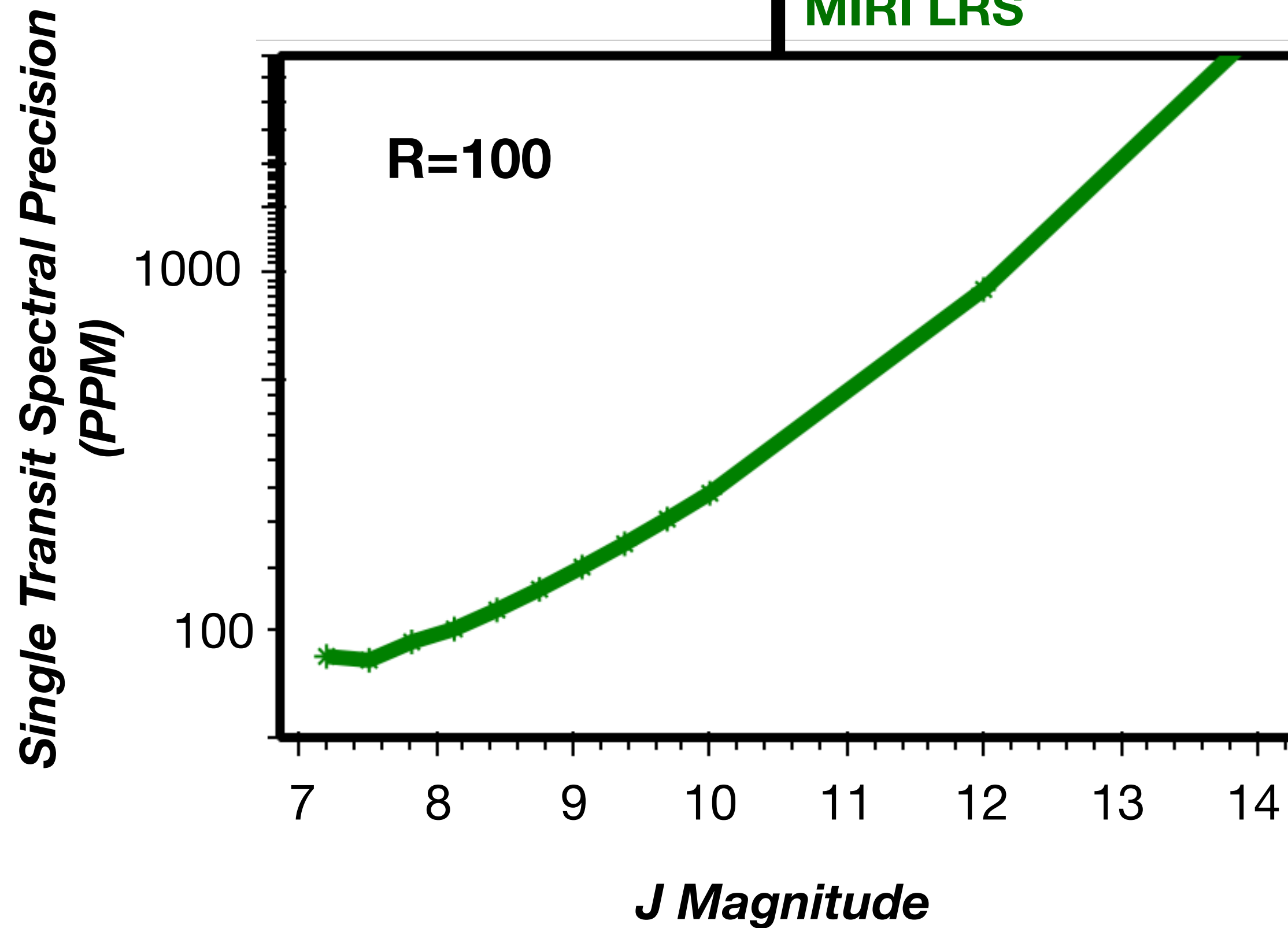
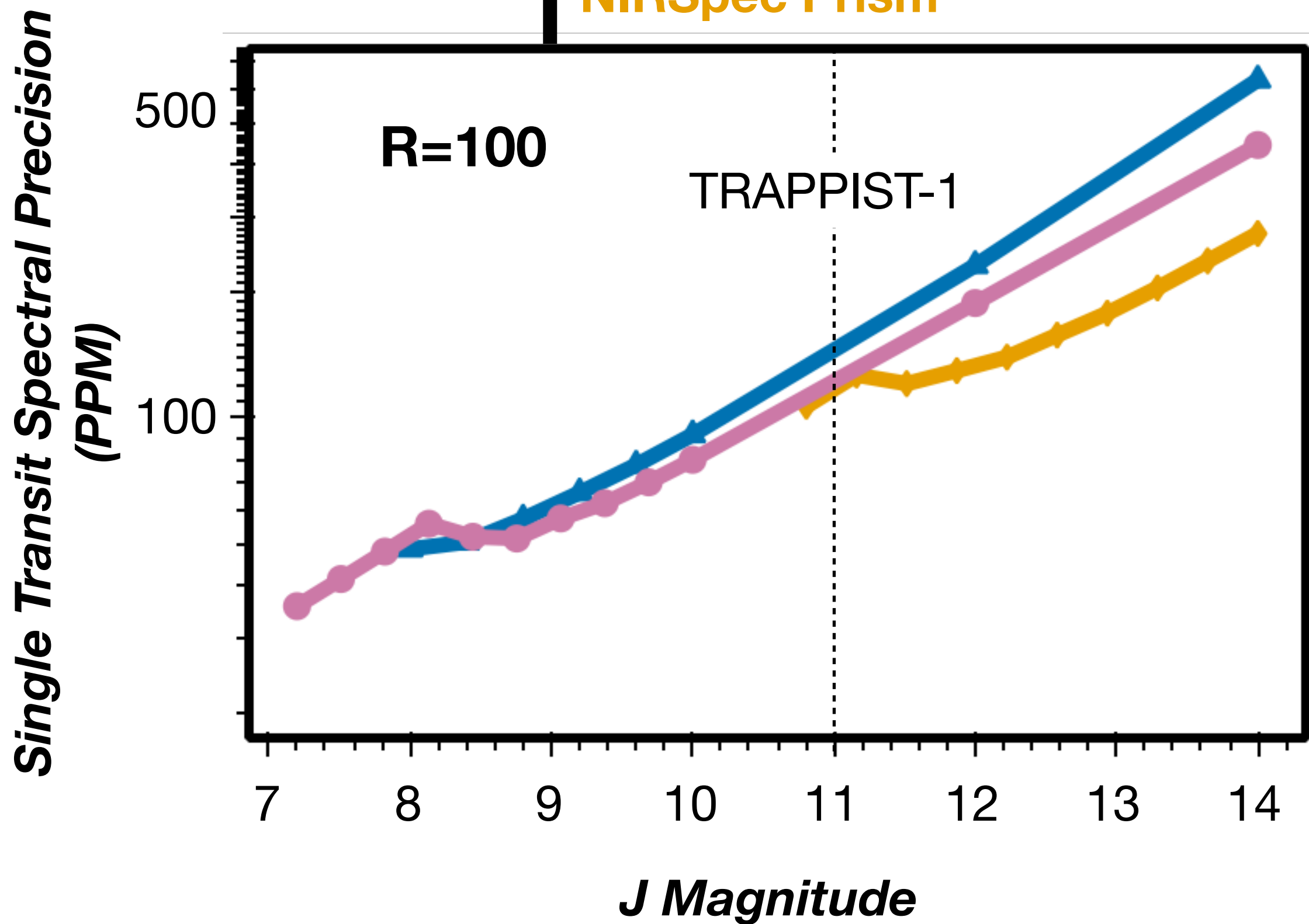
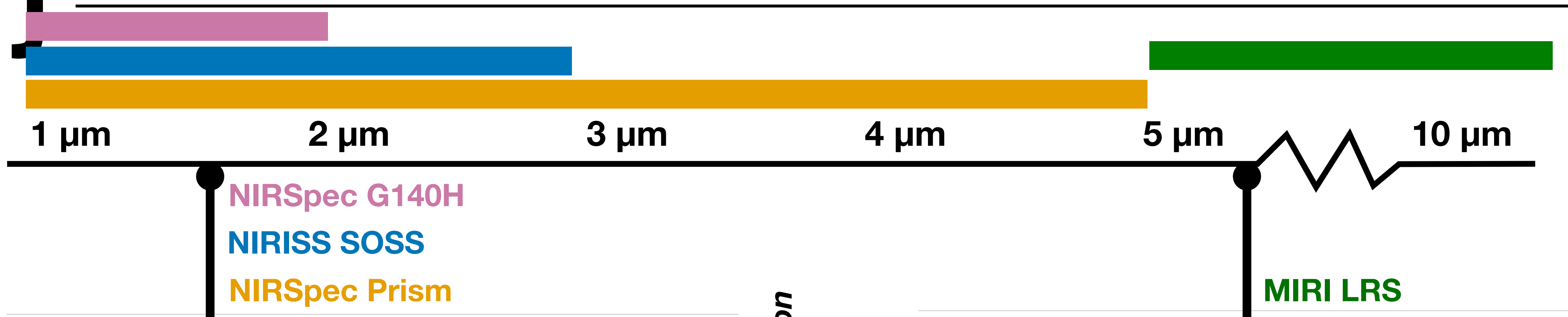
Lesson learned: Null results are still informative! There are many different techniques used to understand terrestrial exoplanet atmospheres and we should leverage them all!

Libby-Roberts et al. 2022

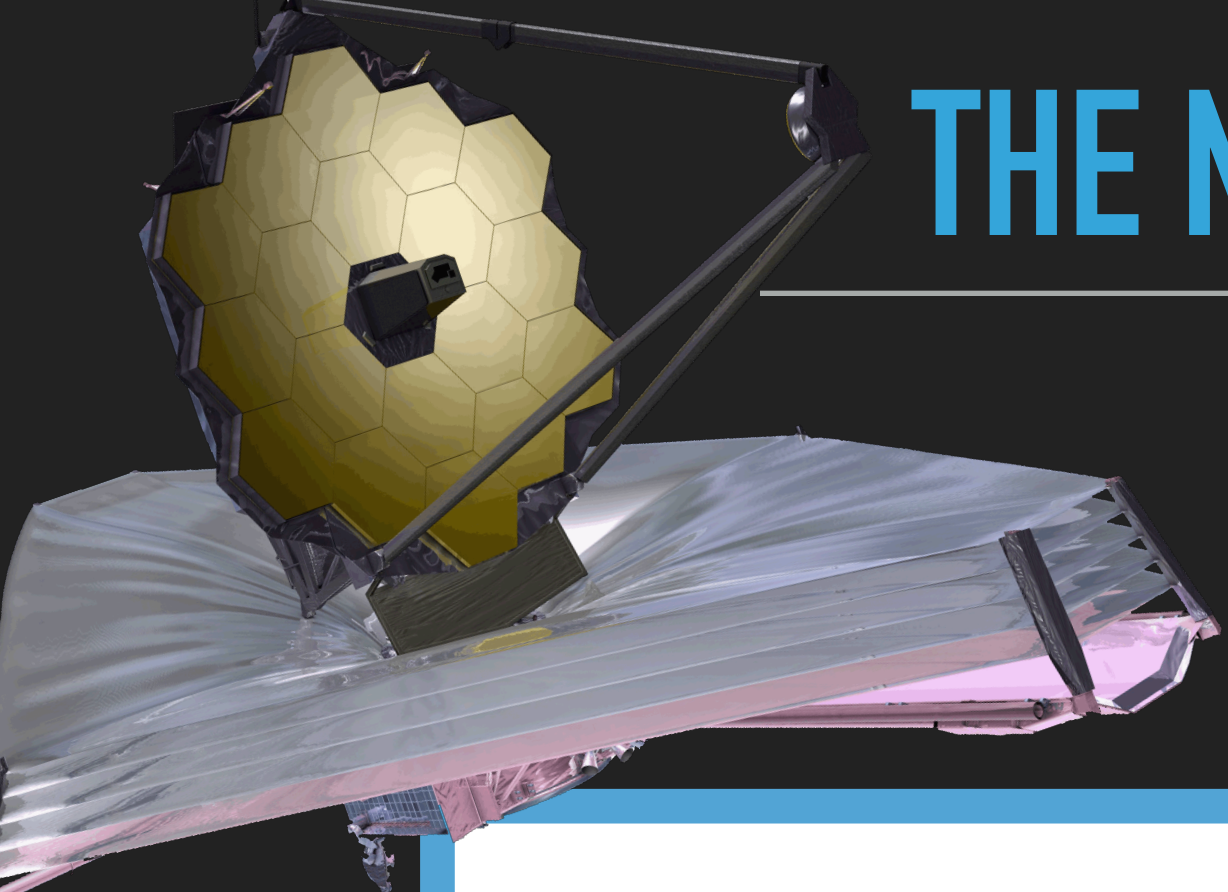
Present Capabilities with JWST



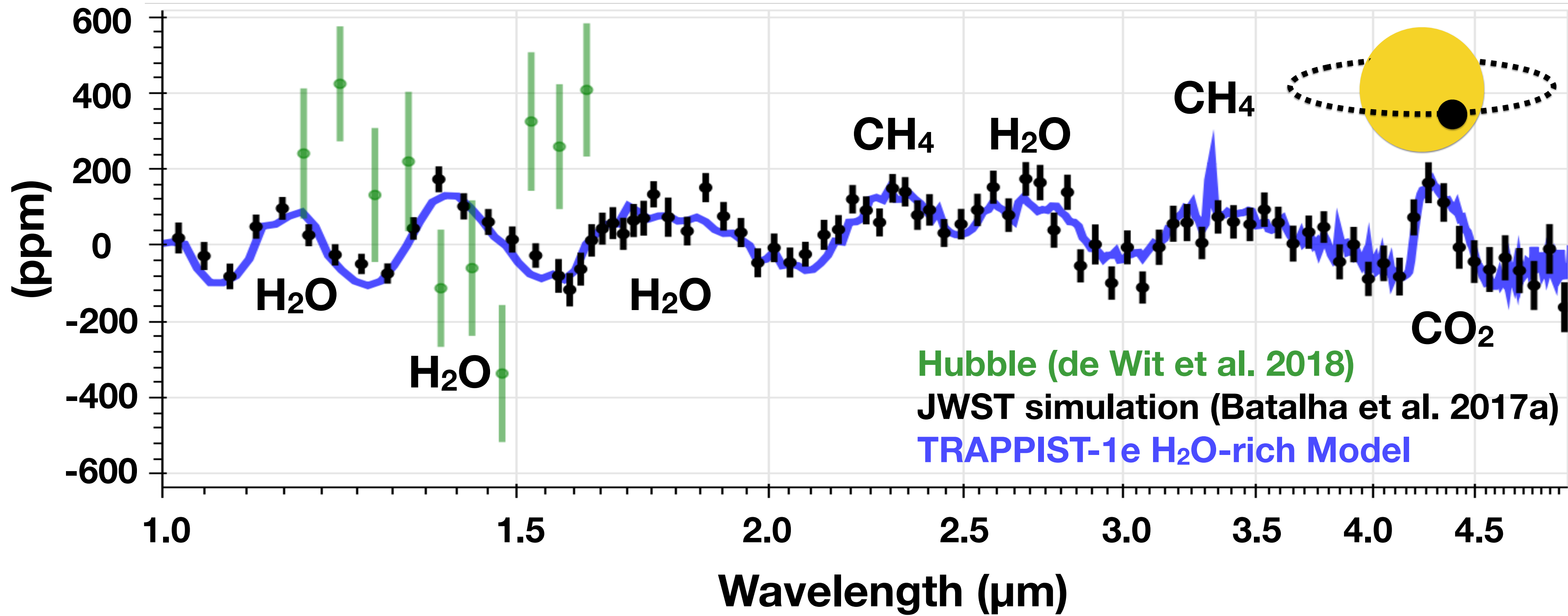
Compared to Hubble JWST Extends Wavelength Coverage and Precision



THE NEXT ERA OF EXO-ATMOSPHERE OBSERVATIONS

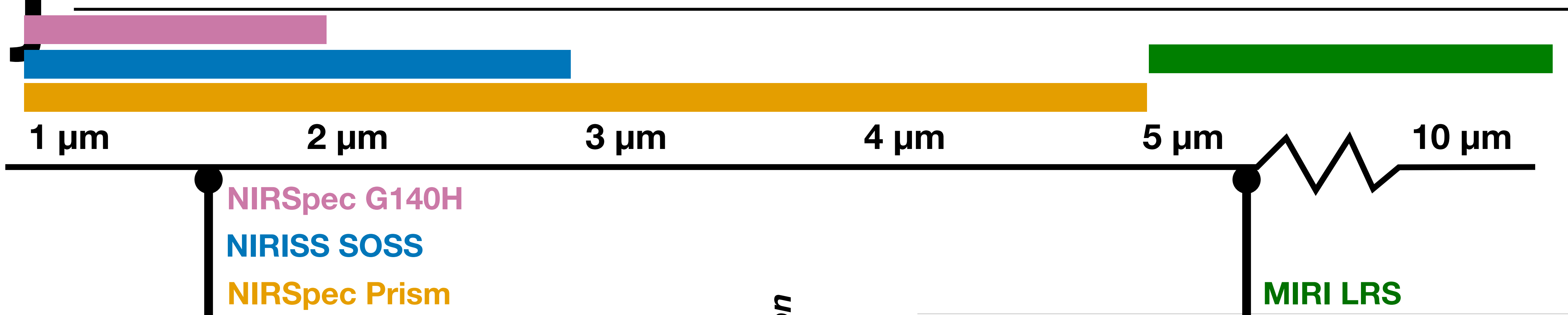


Relative Depth of Transit (ppm)



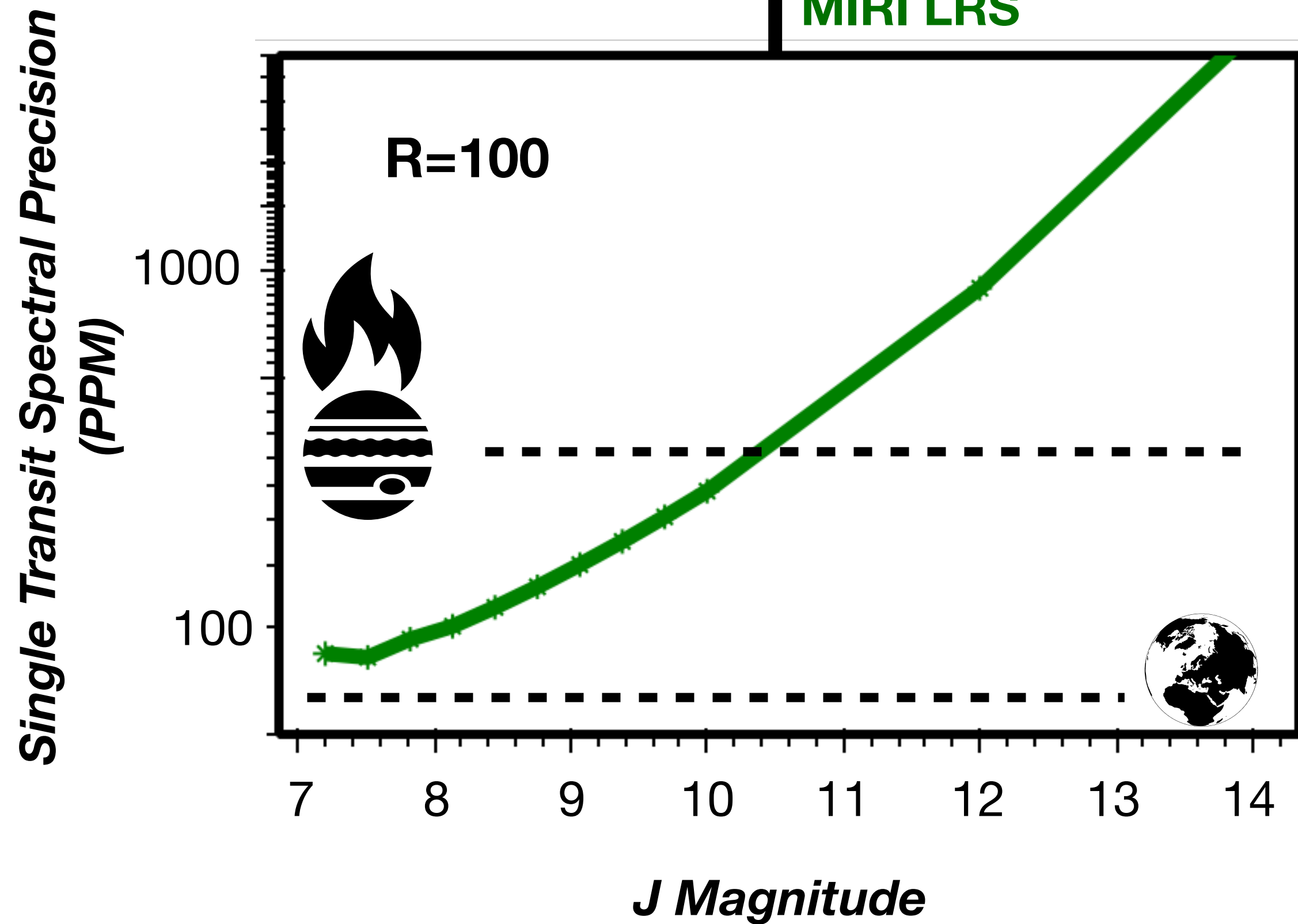
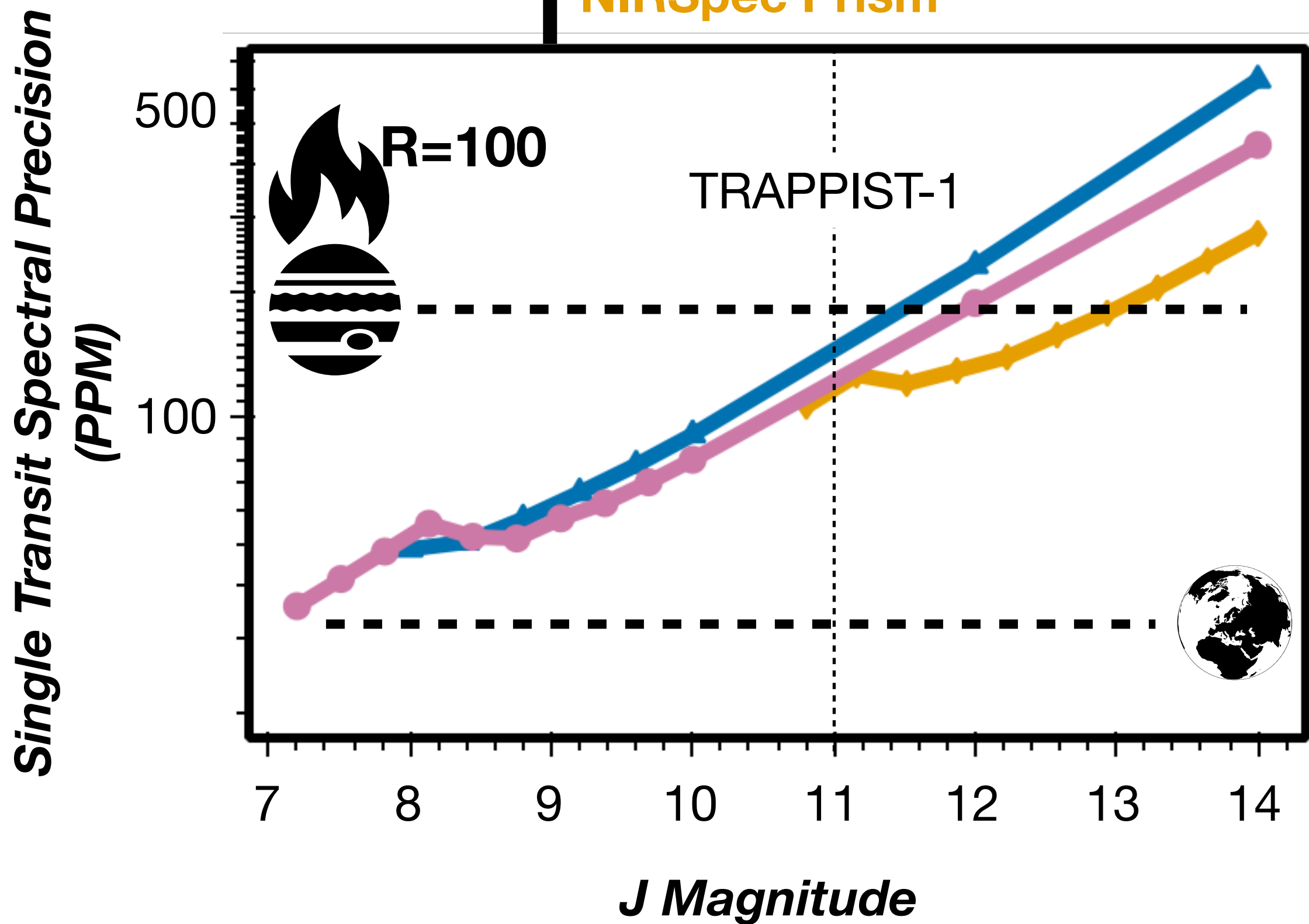
22.2 NIRSpec Prism hrs: PI N. Lewis/M. Mountain

Compared to Hubble JWST Extends Wavelength Coverage and Precision

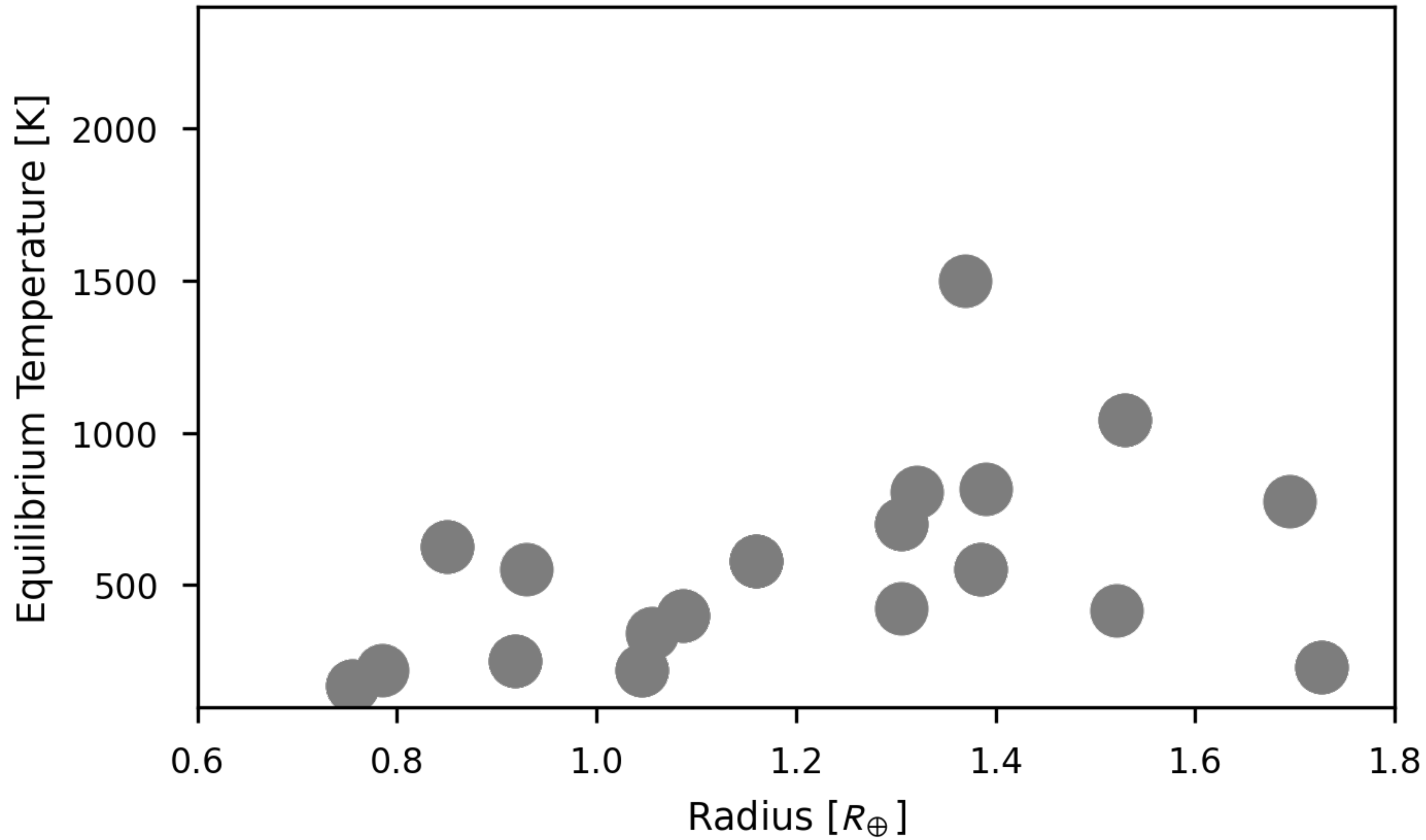


NIRSpec G140H
NIRISS SOSS
NIRSpec Prism

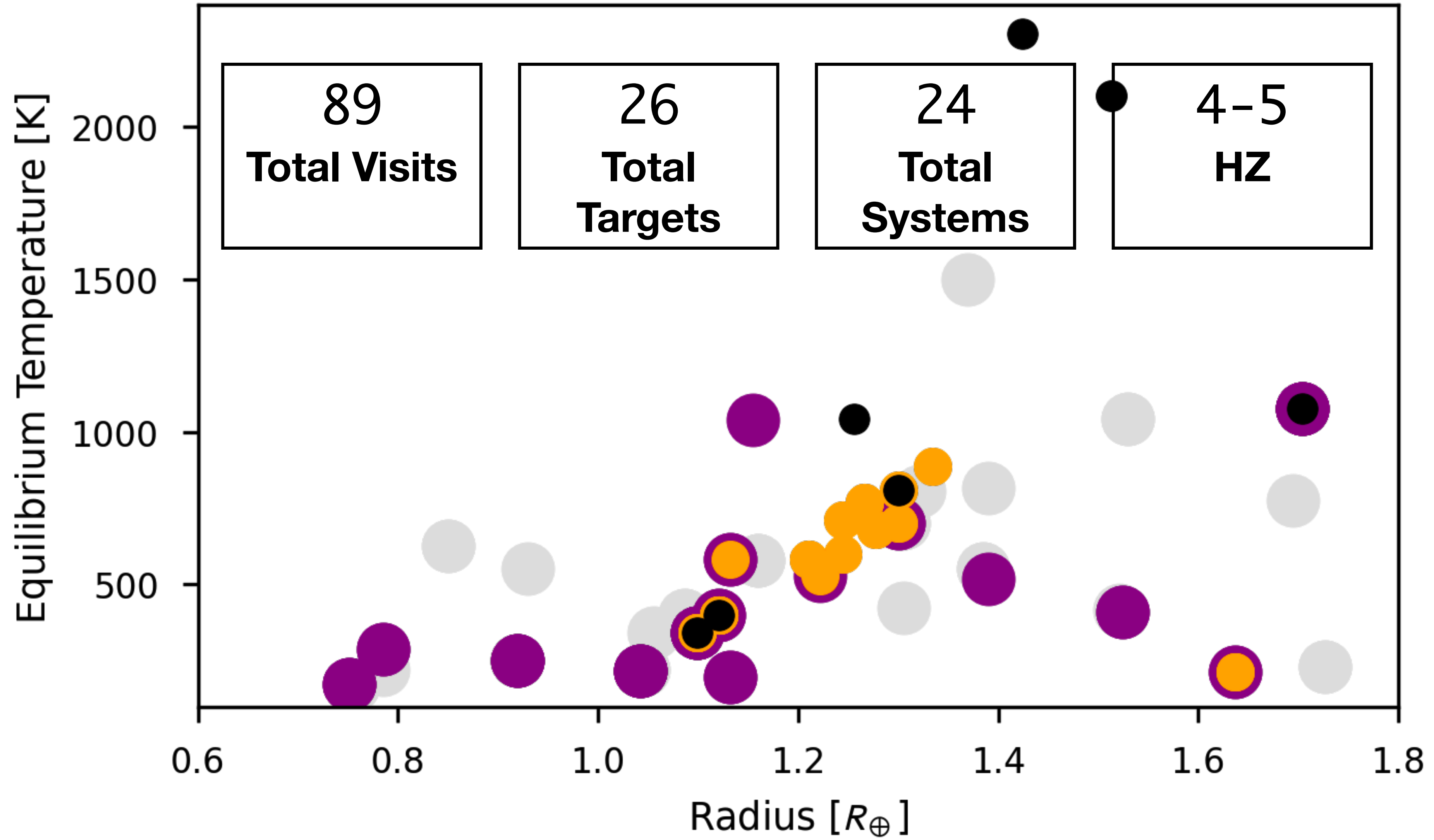
MIRI LRS



Previous HST/G-B Observations



Present Capabilities with JWST



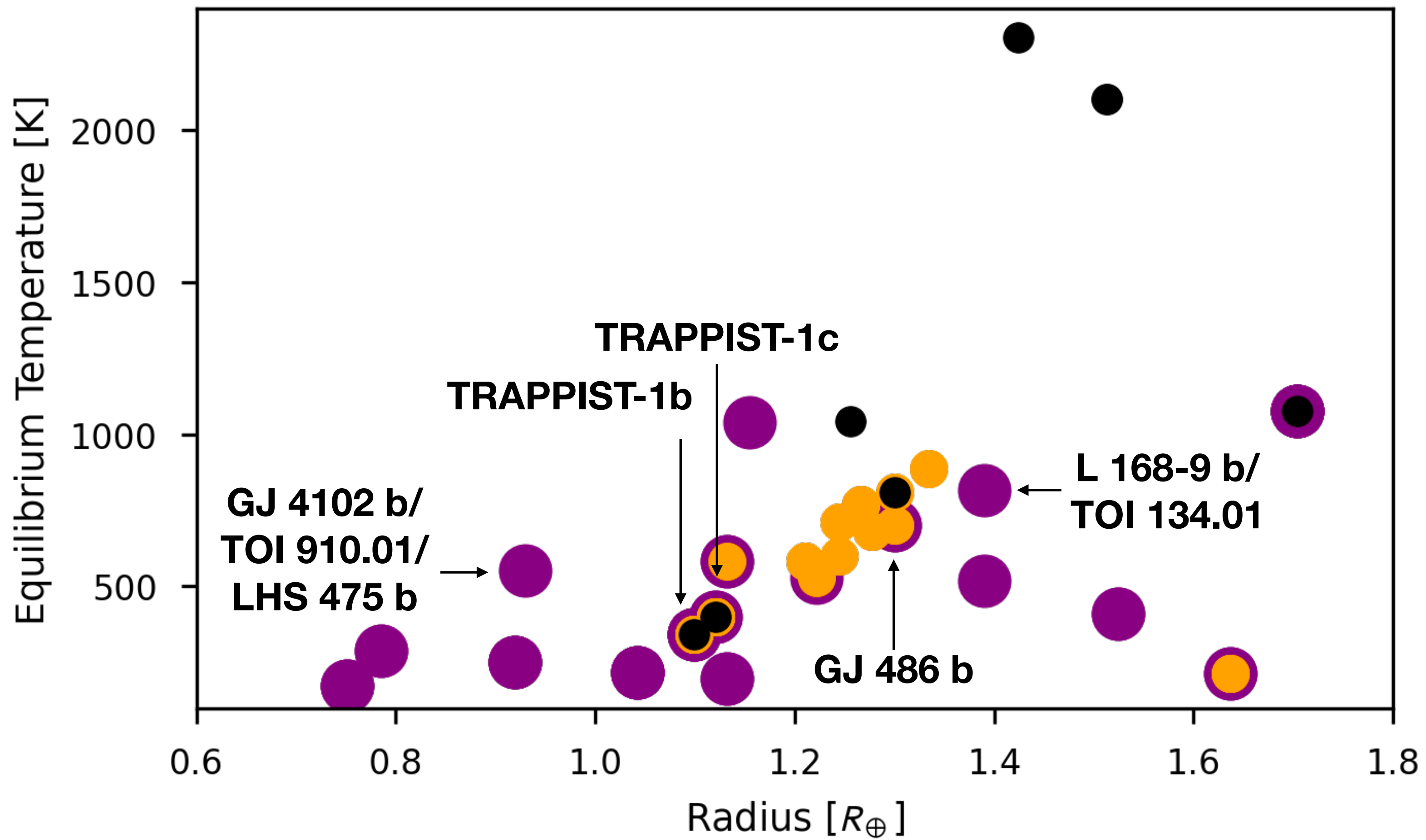
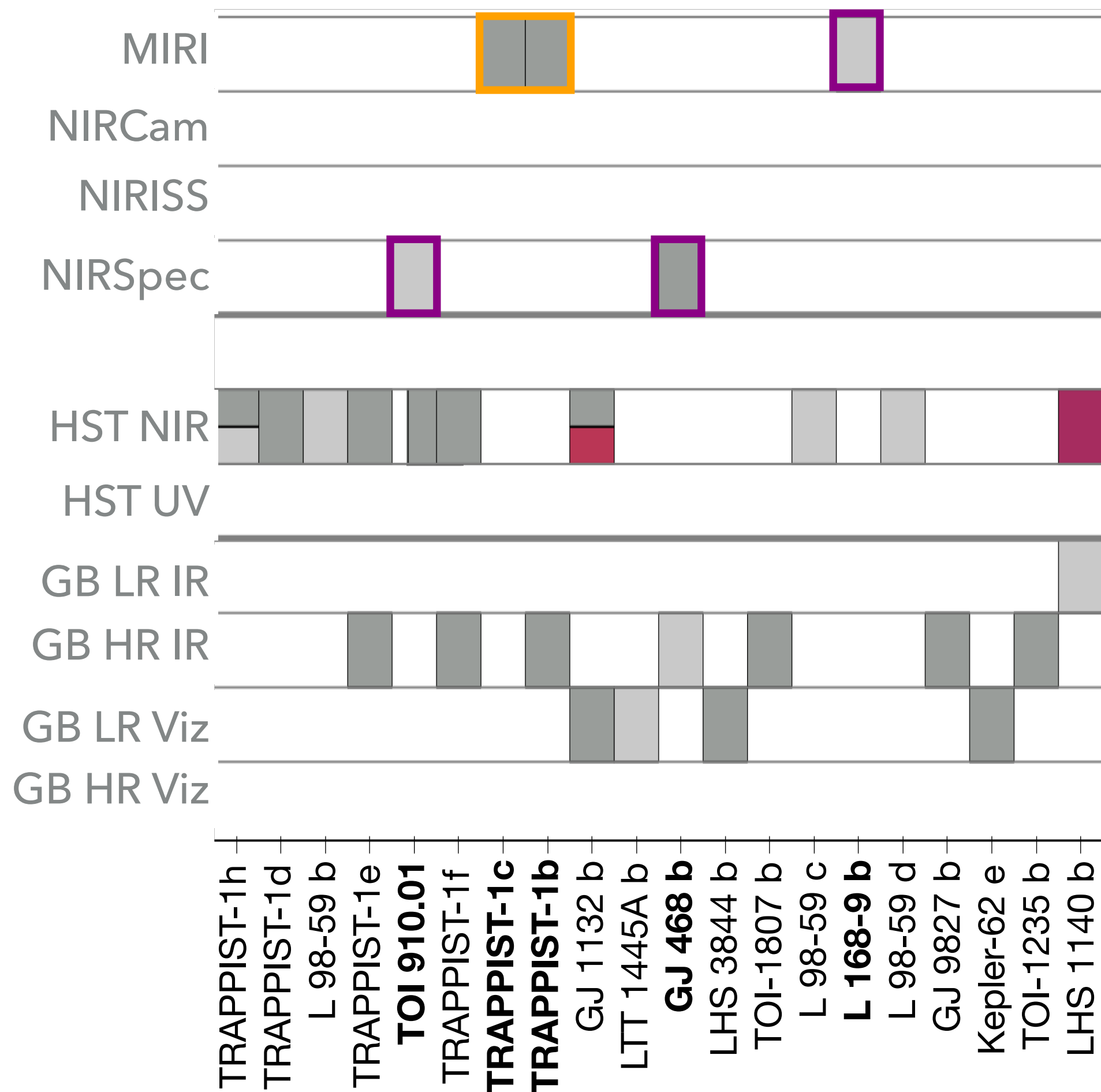
 Transmission Geometry

 Emission Geometry

 Phase Curve

Currently Published JWST Observations

Currently Published



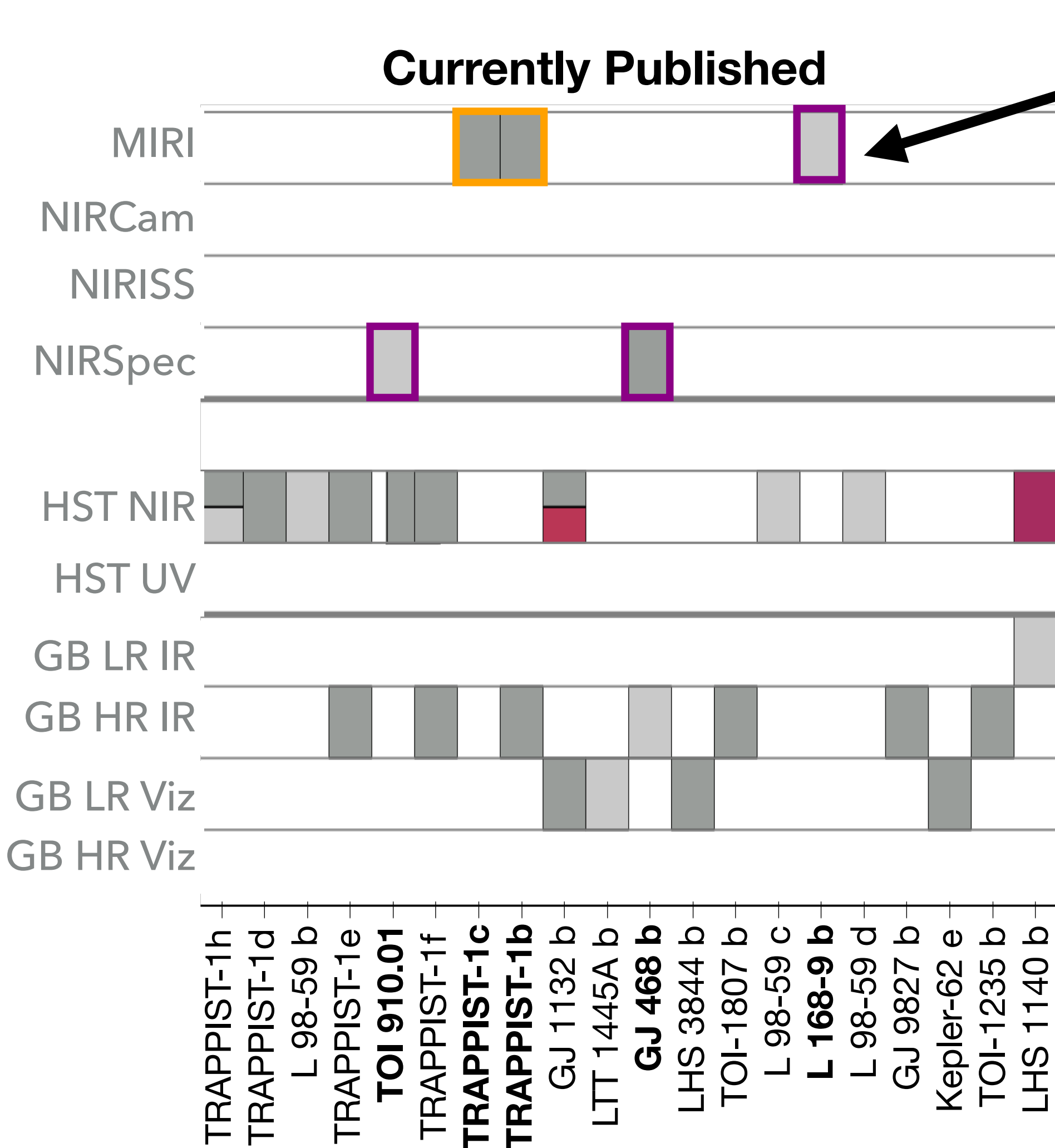
No detection

Transmission Geometry

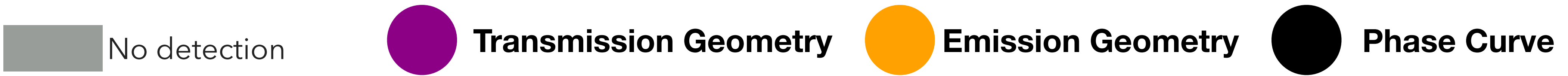
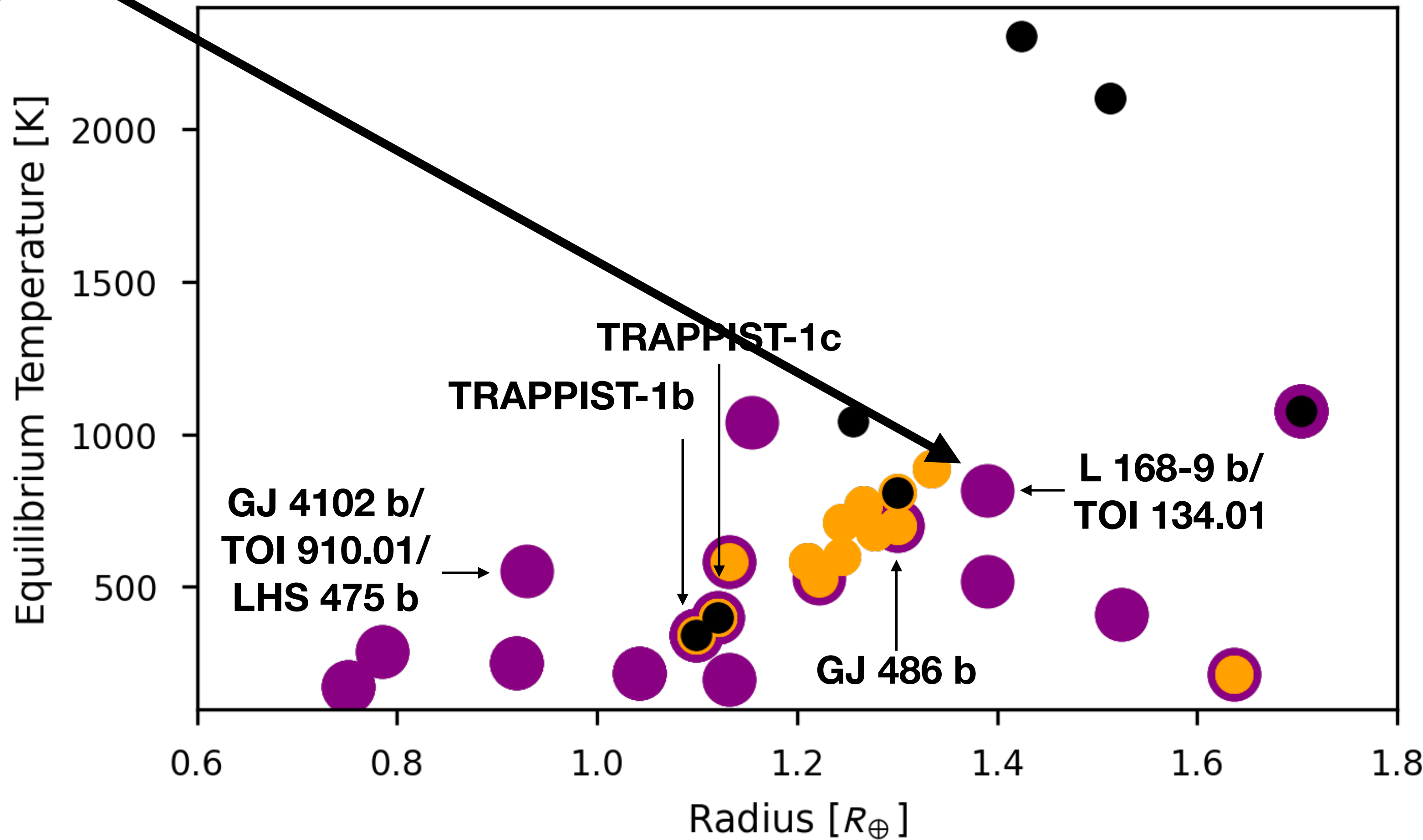
Emission Geometry

Phase Curve

Currently Published JWST Observations

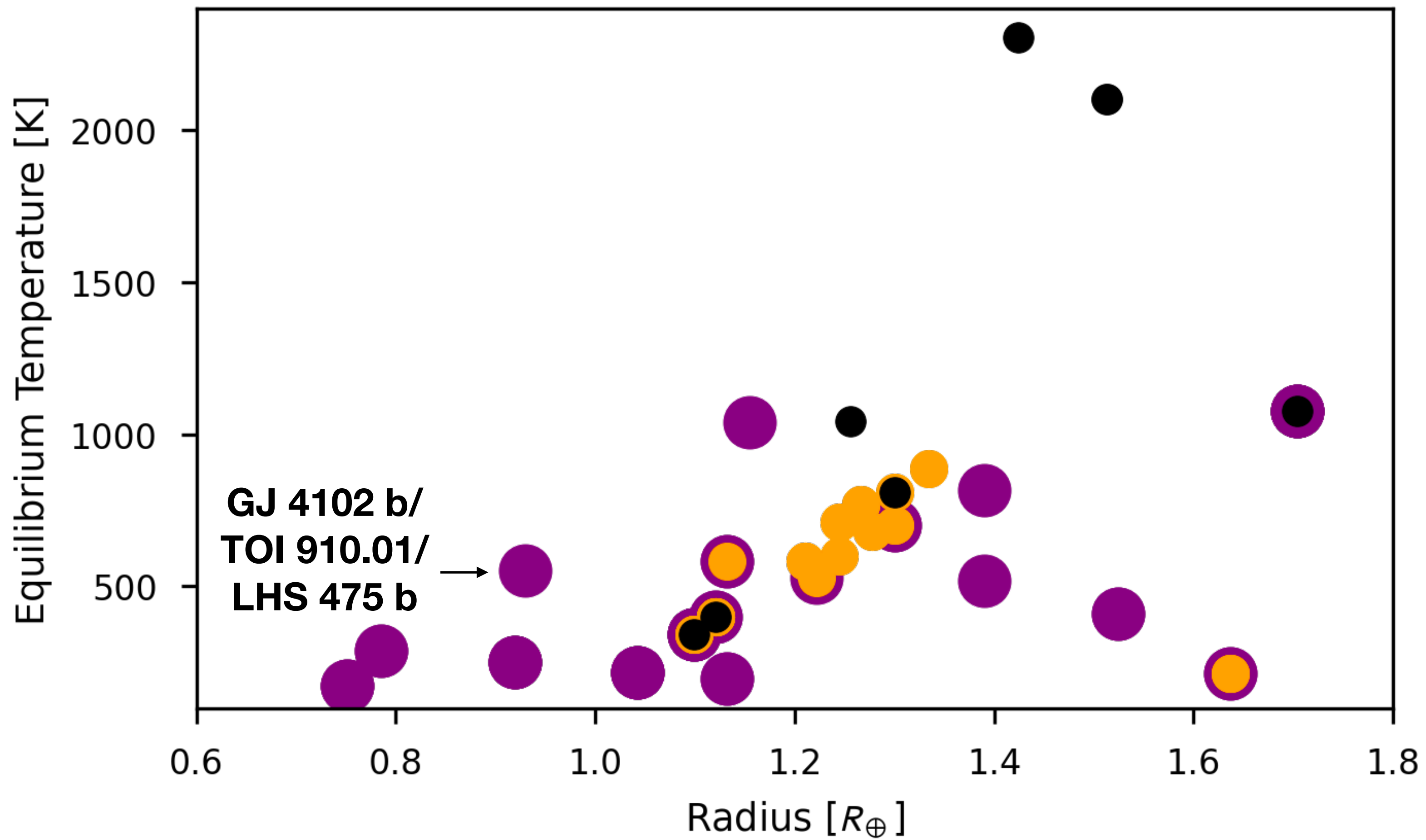
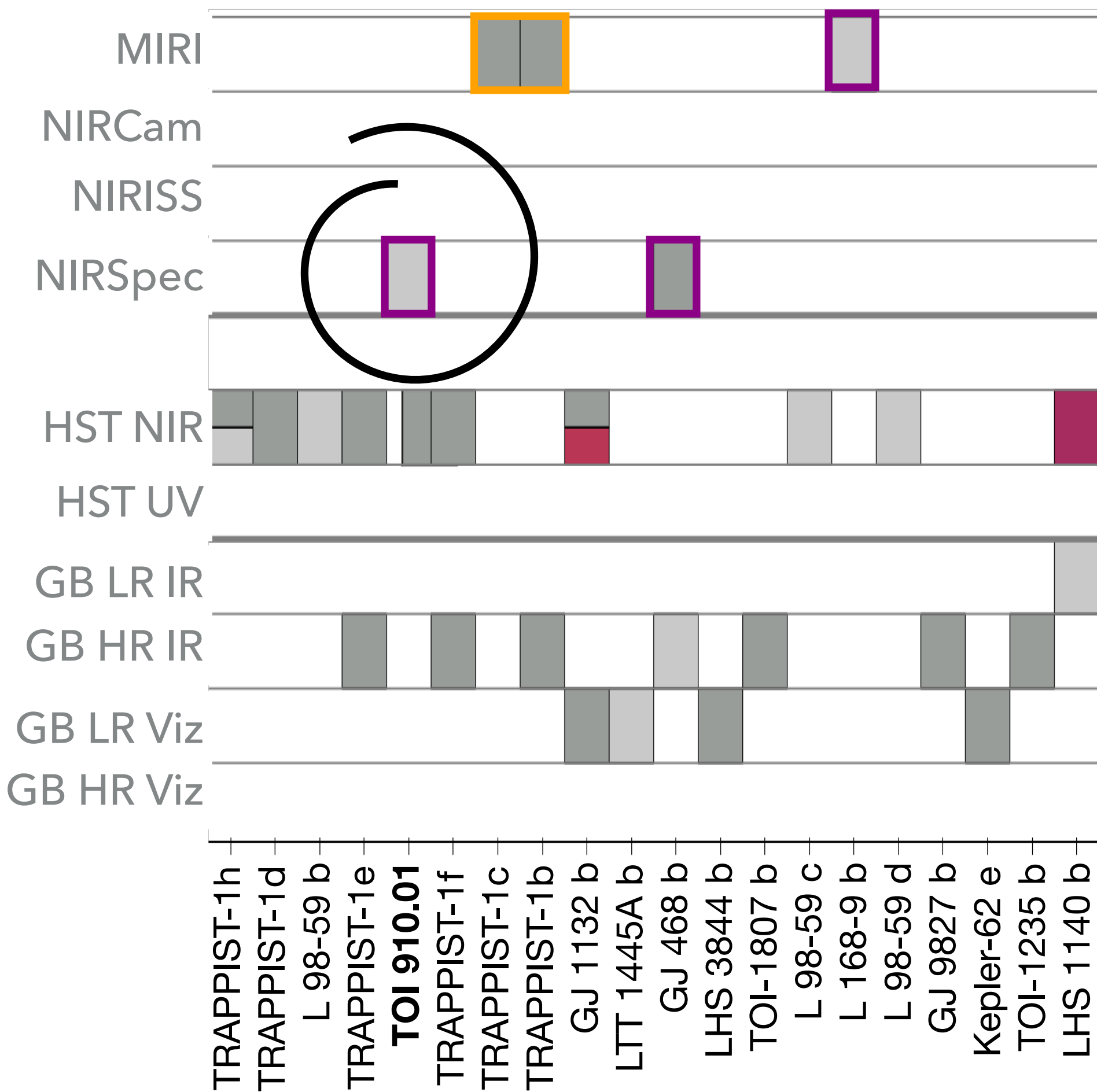


Commissioning target not necessarily used for science



Currently Published JWST Observations

Currently Published



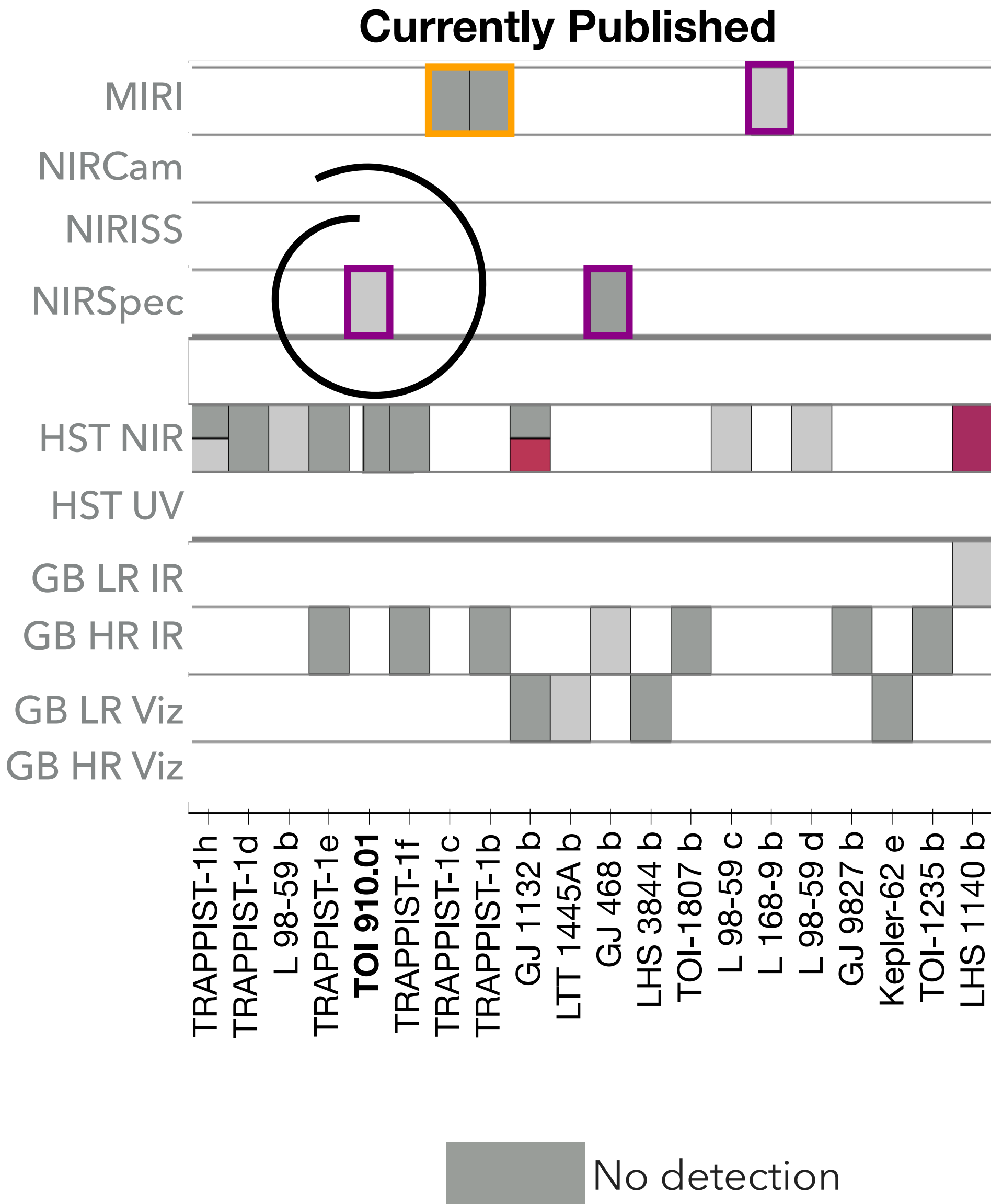
■ No detection

● Transmission Geometry

● Emission Geometry

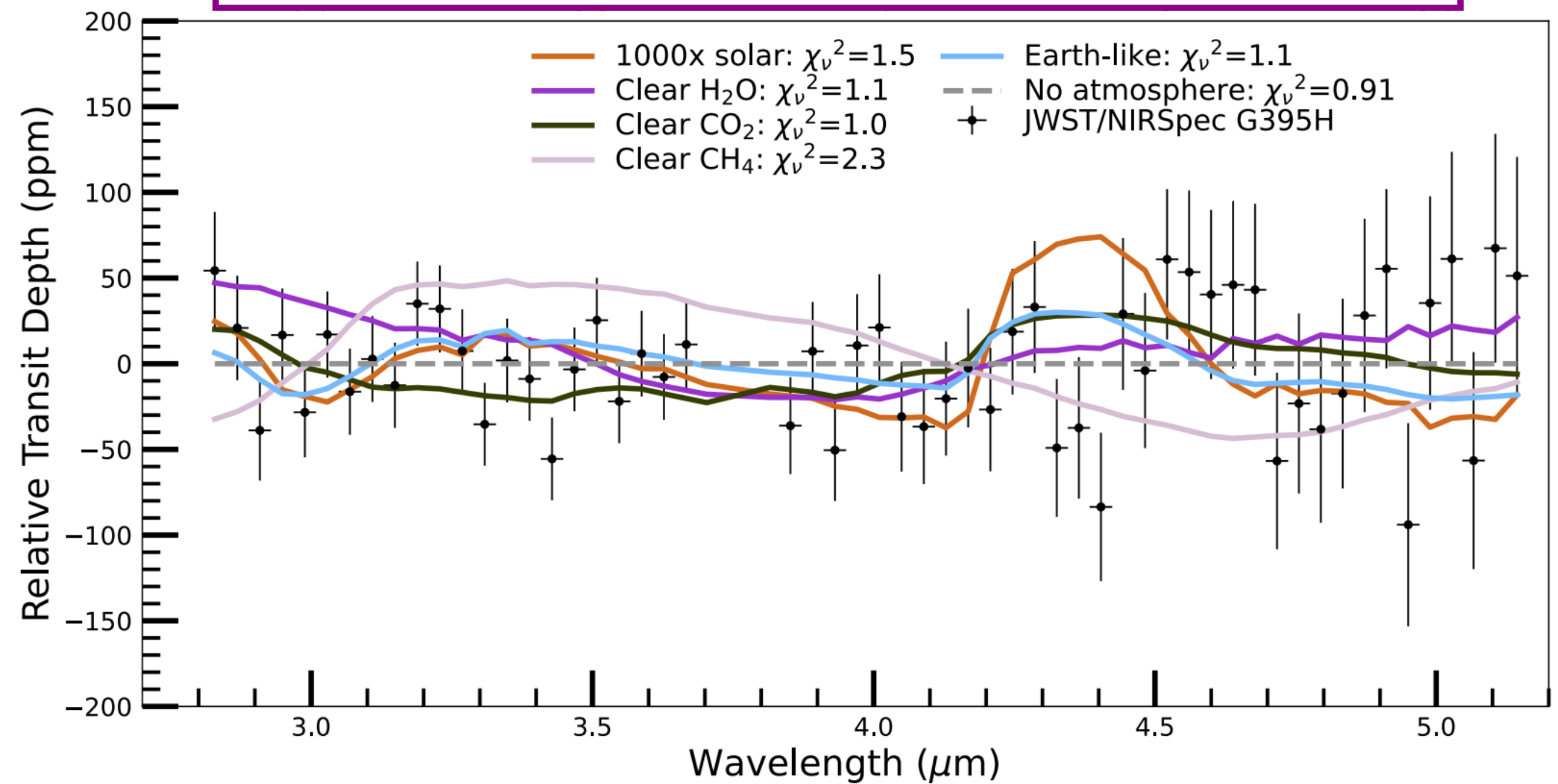
● Phase Curve

Currently Published JWST Observations

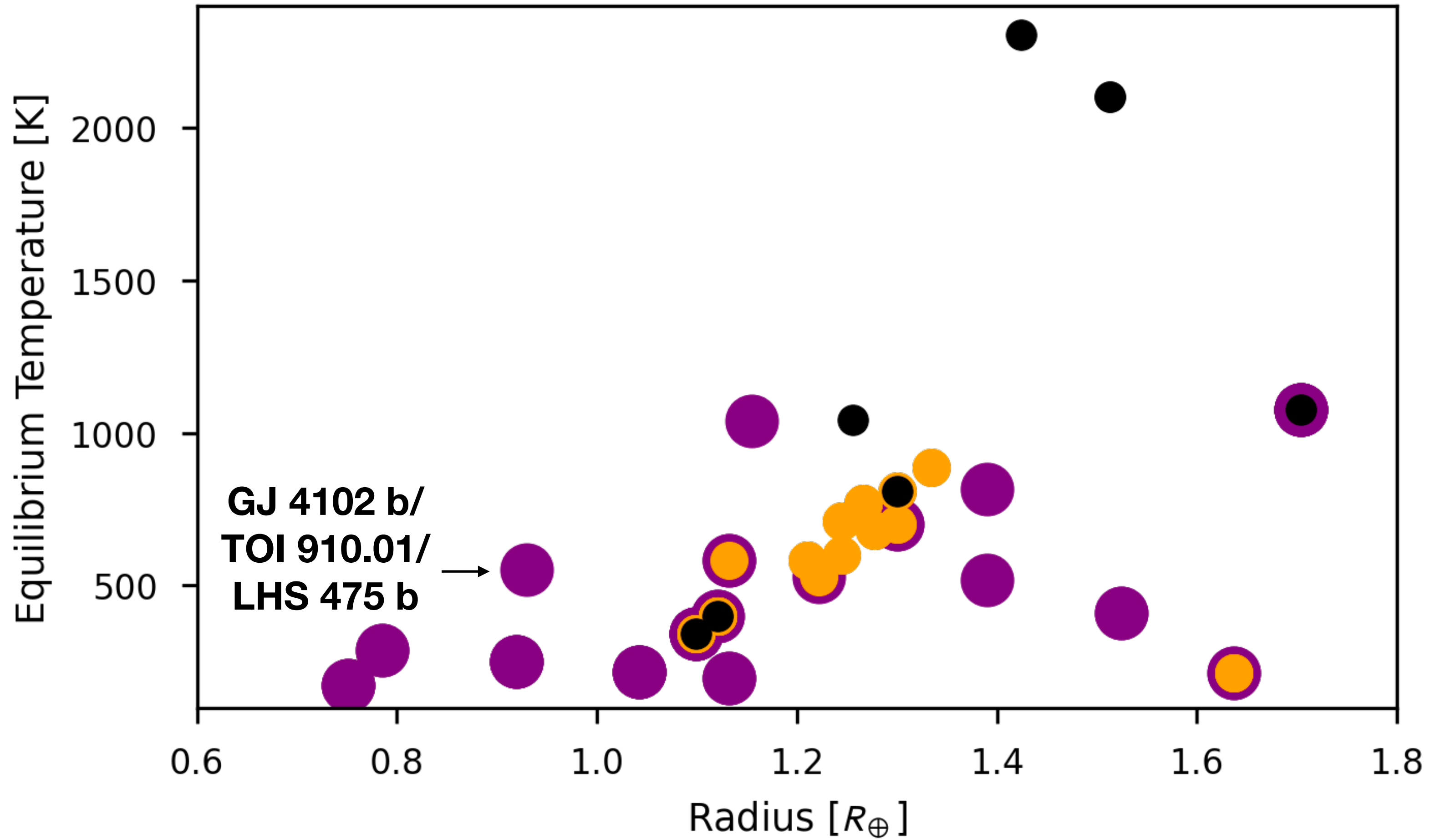
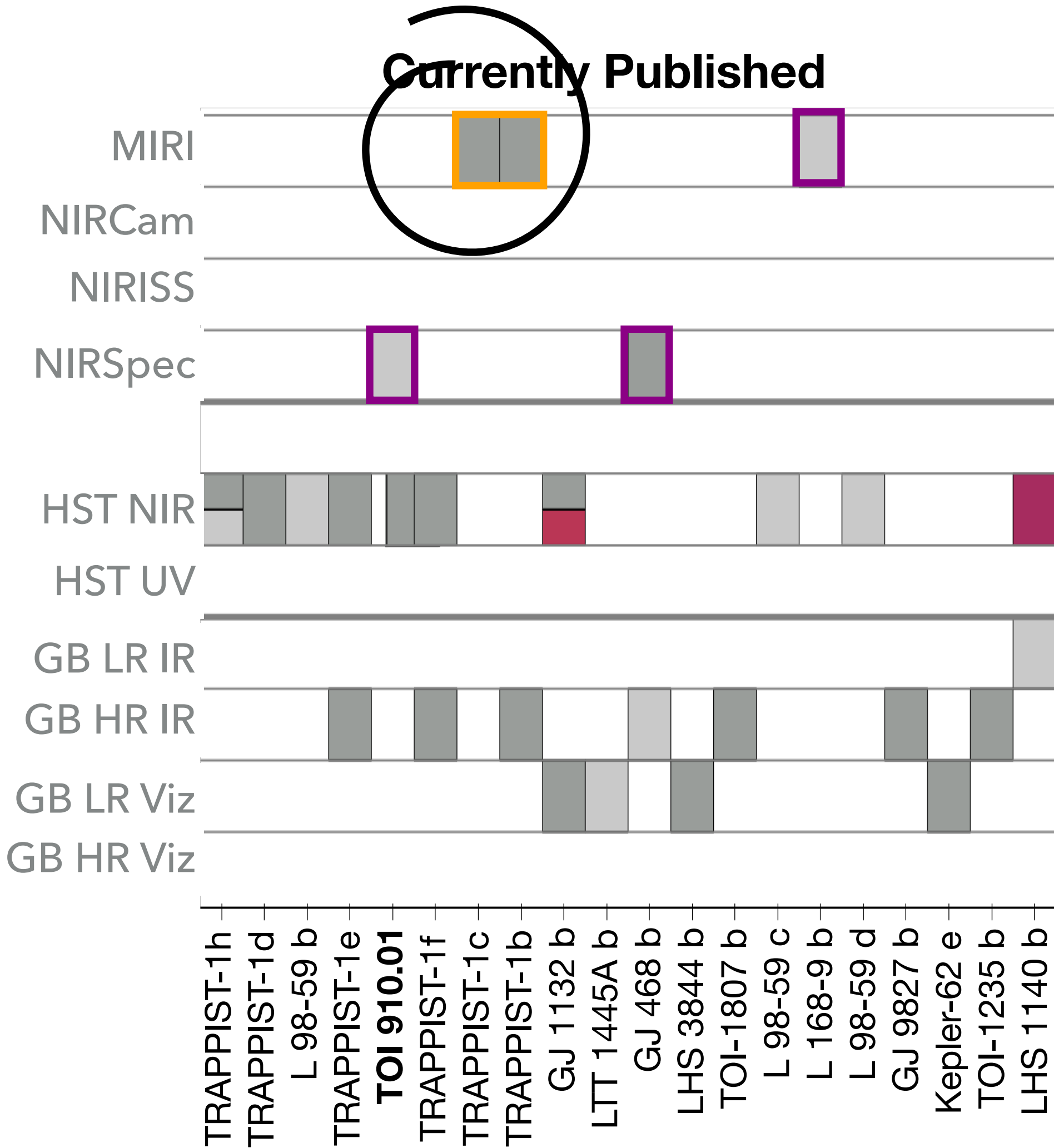


A JWST transmission spectrum of a nearby Earth-sized exoplanet

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



Currently Published JWST Observations



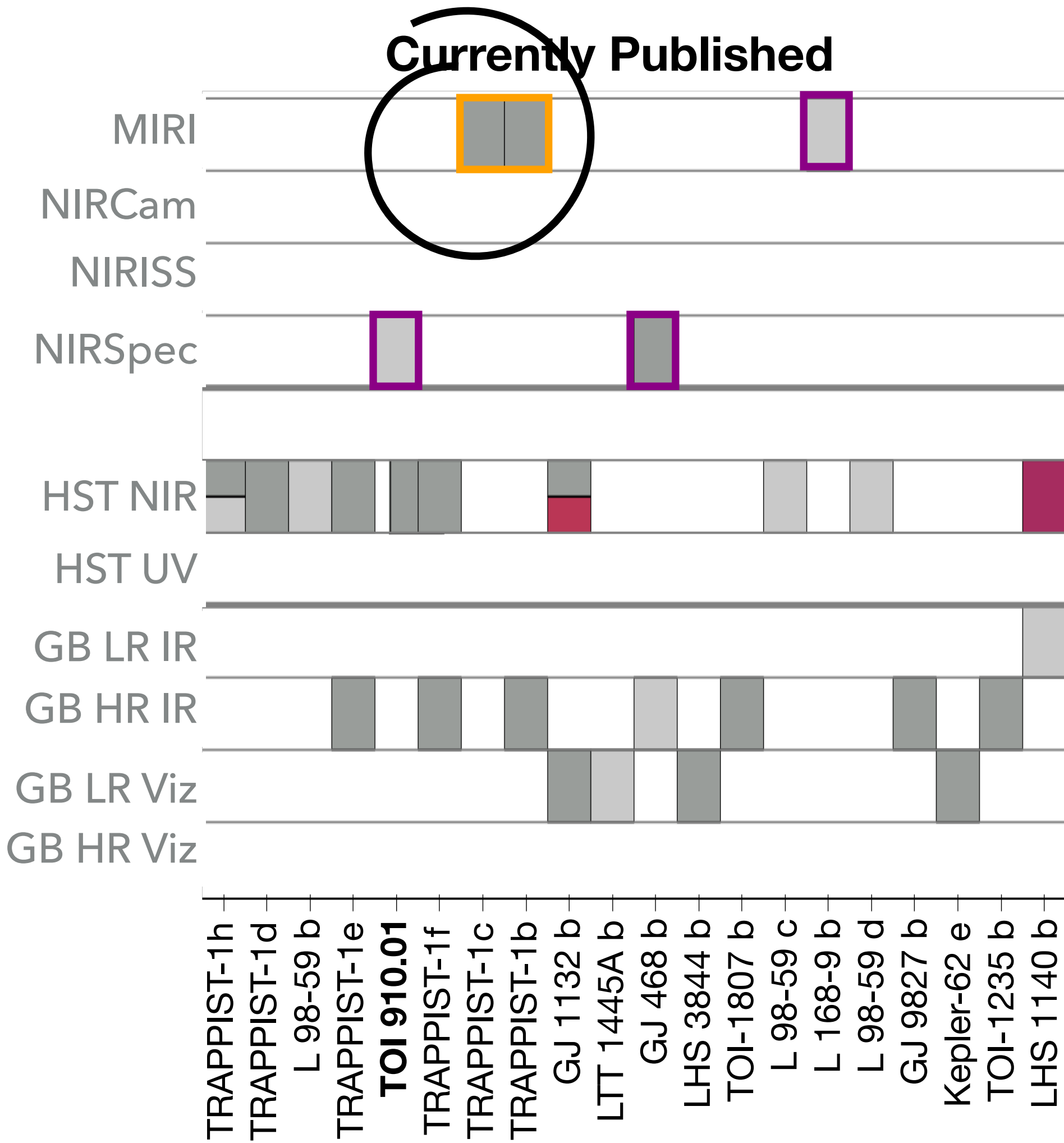
Gray box: No detection

Purple circle: Transmission Geometry

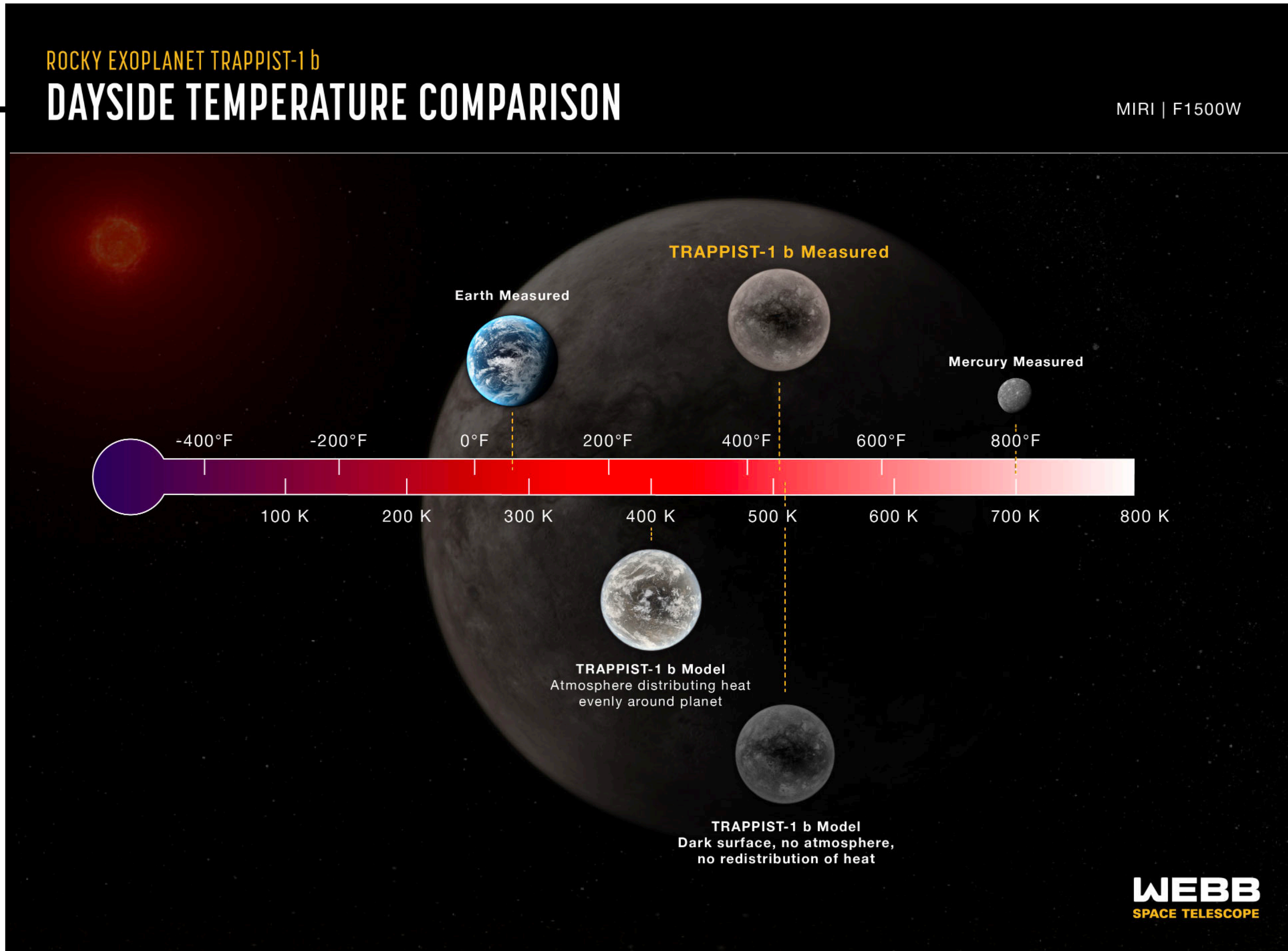
Orange circle: Emission Geometry

Black circle: Phase Curve

Currently Published JWST Observations



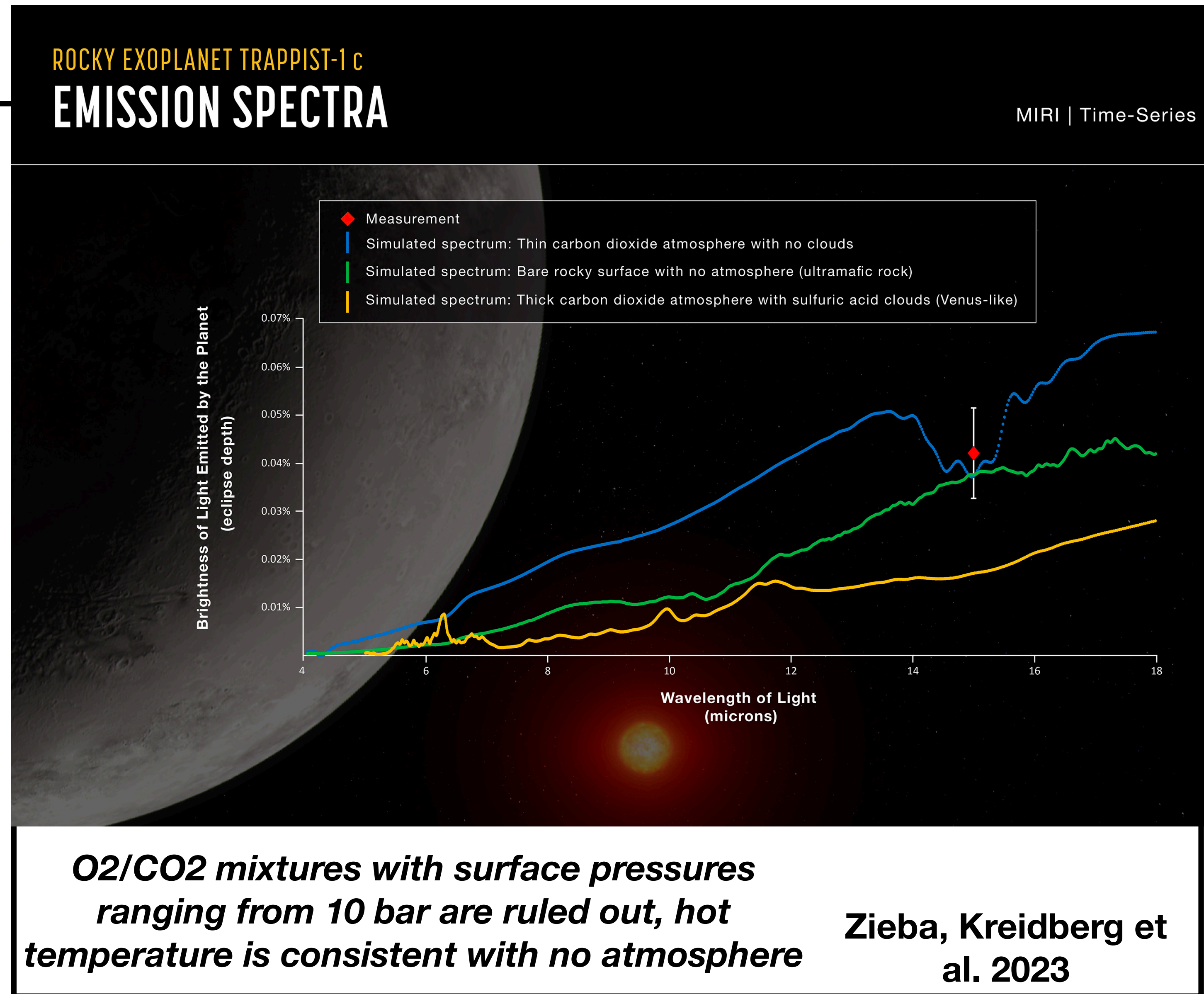
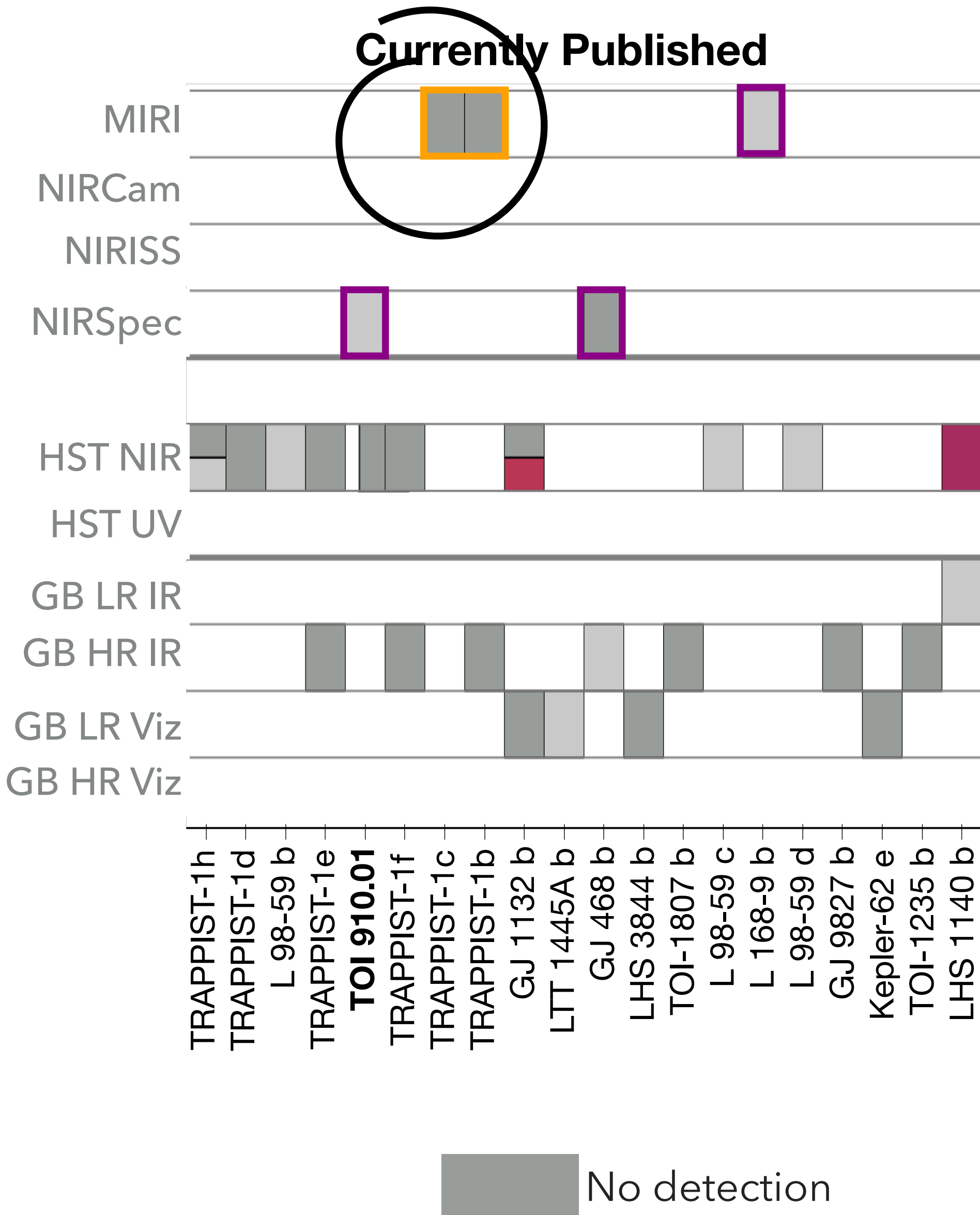
 No detection



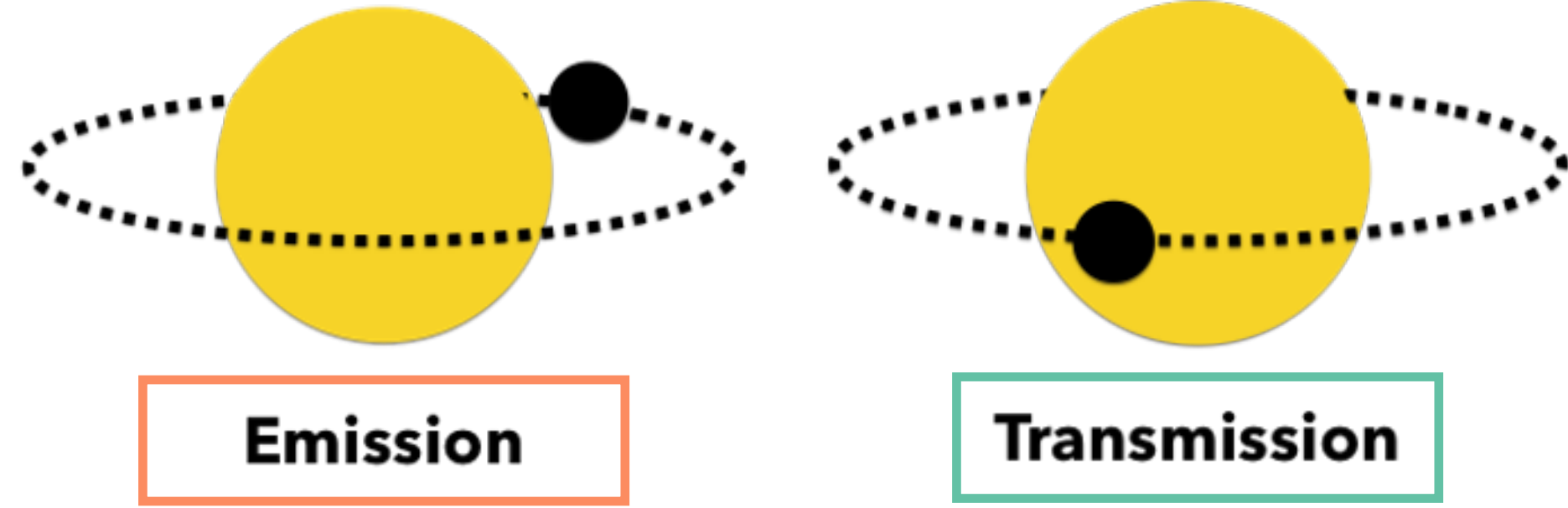
No detectable CO₂, hot temperature is consistent with no atmosphere

Greene, Bell et al. 2023

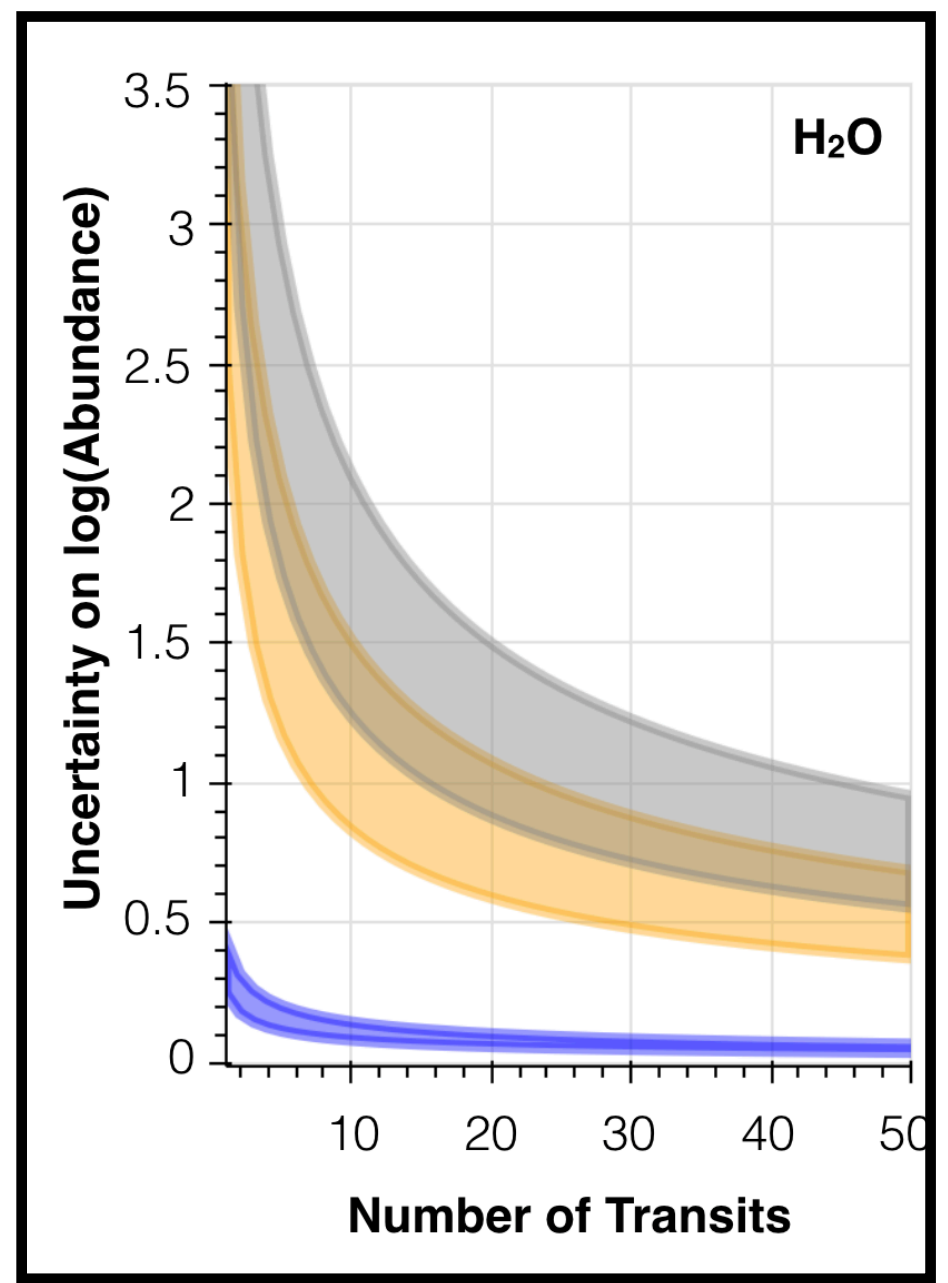
Currently Published JWST Observations



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



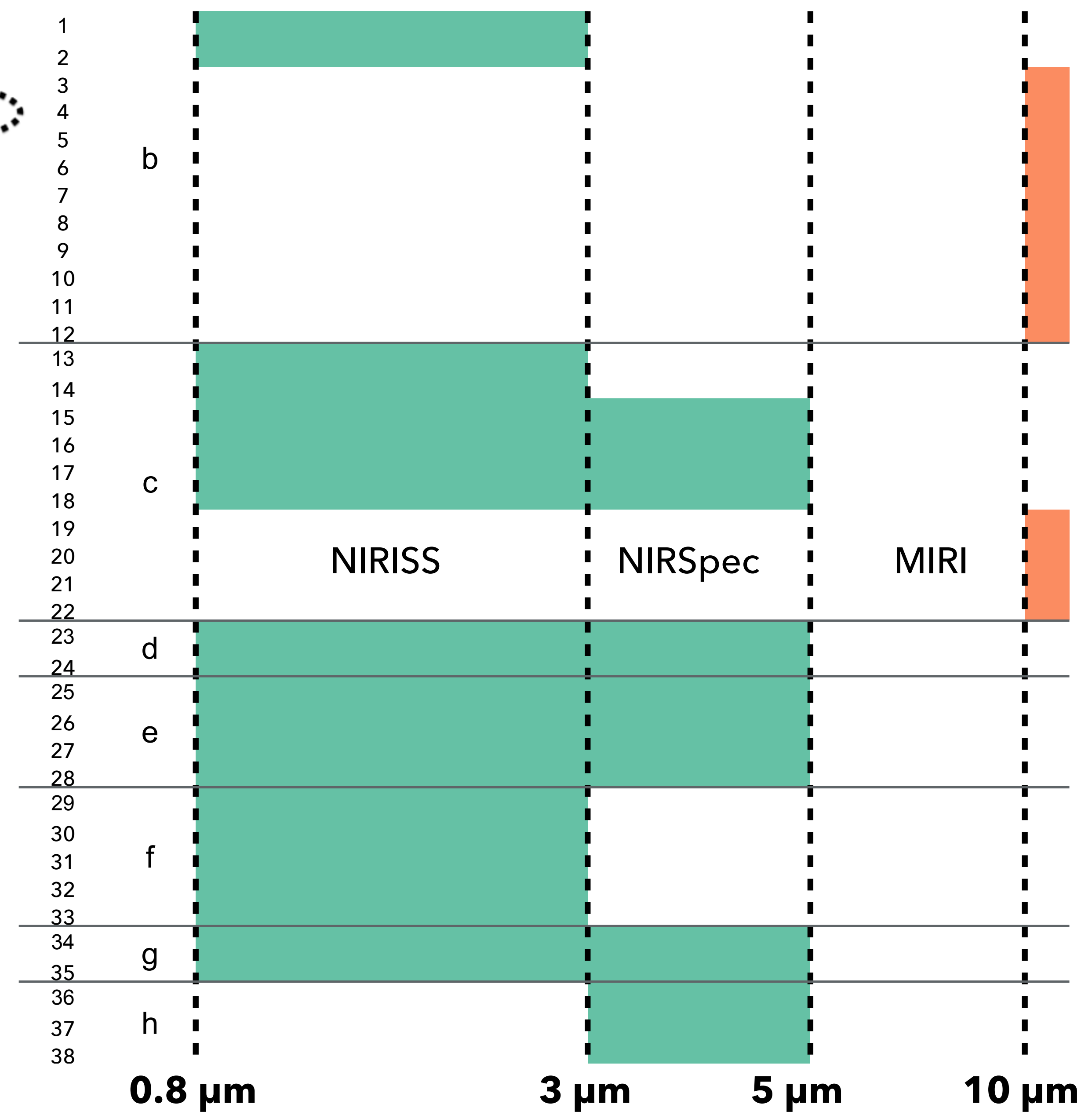
TRAPPIST-1 system makes up ~11% all exoplanet time in Cycle 1



And yet... We want more!

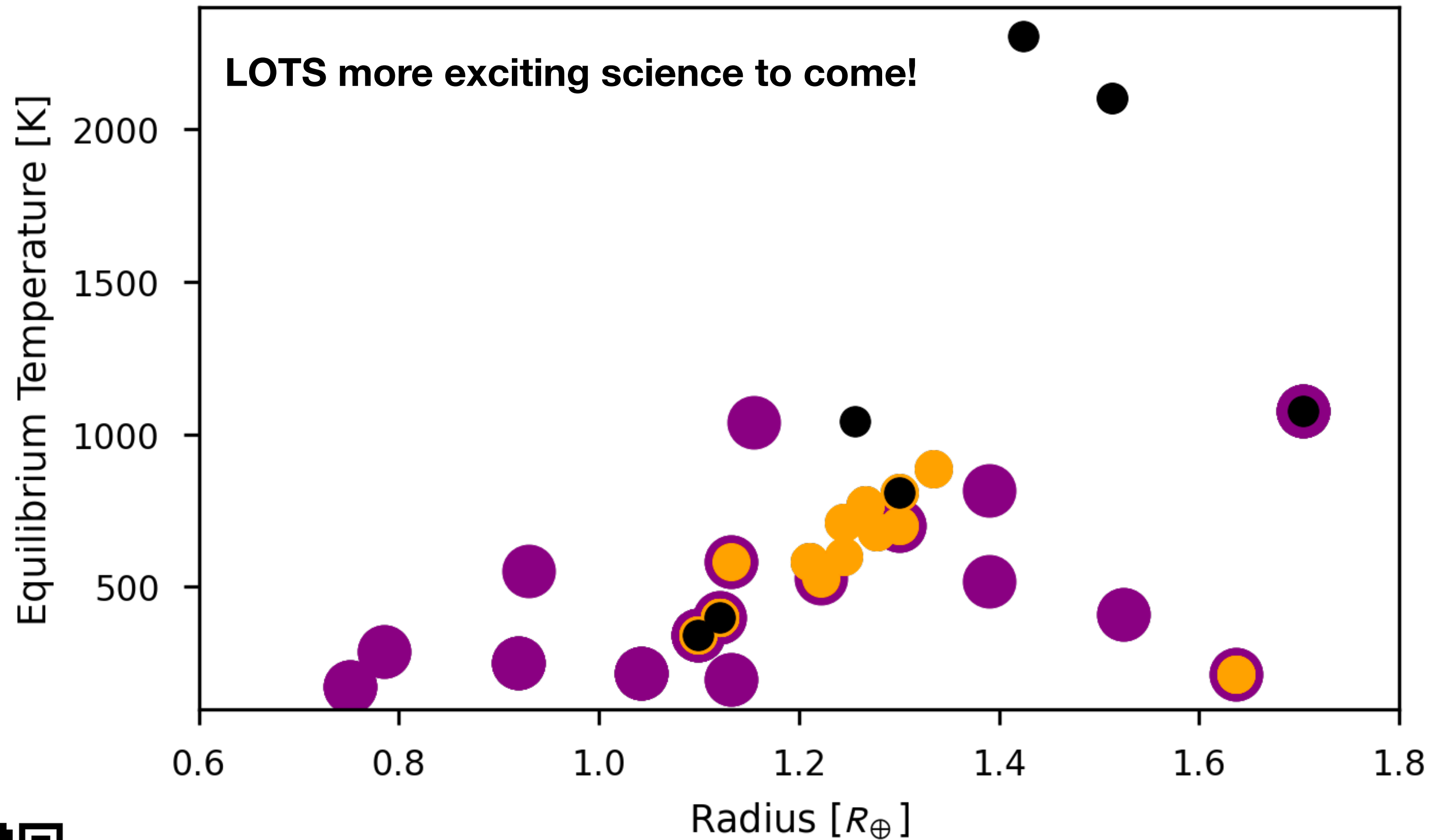
Broad consensus that HZ Trappist planets need ~10 transits to detect atmosphere

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

