Atmospheres on Rocky Exoplanets: Promising Early Results from JWST

UNIVERSITY OF MICHIGAN

NHFP

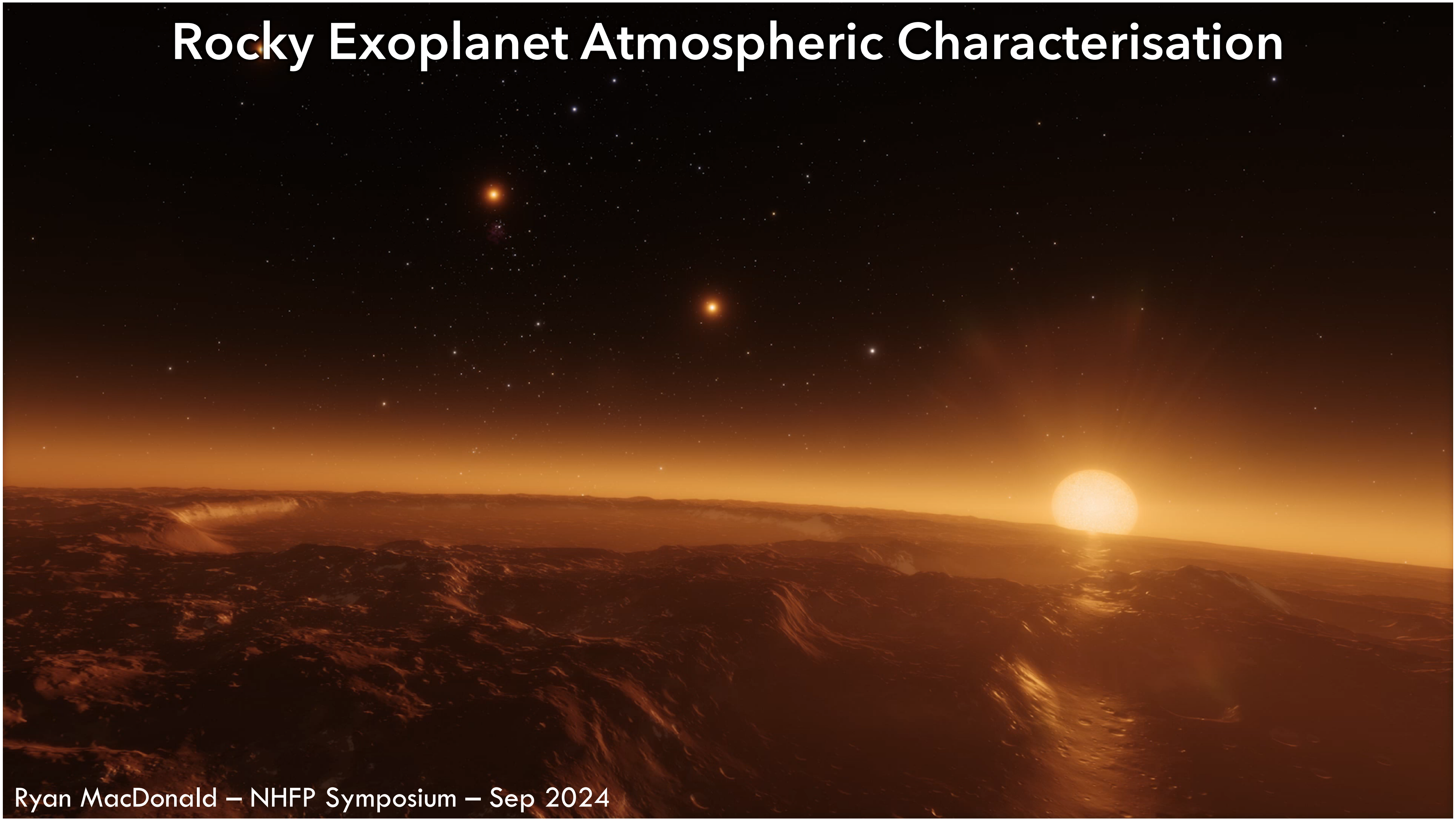
NASA Hubble Fellowship Program

Ryan MacDonald

Sagan Fellow, University of Michigan

NHFP Symposium

September 16, 2024


Rocky Exoplanet Atmospheric Characterisation
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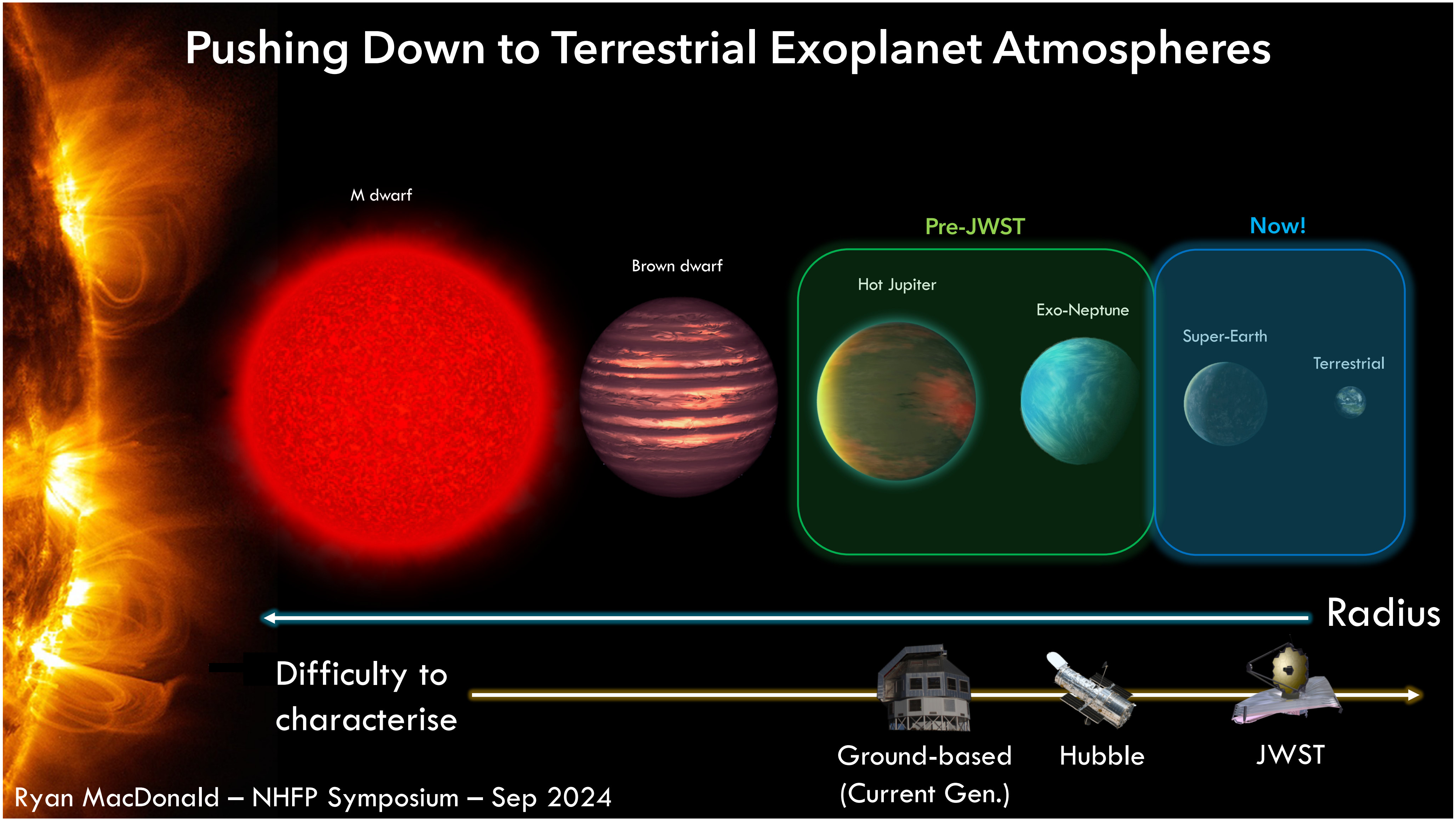
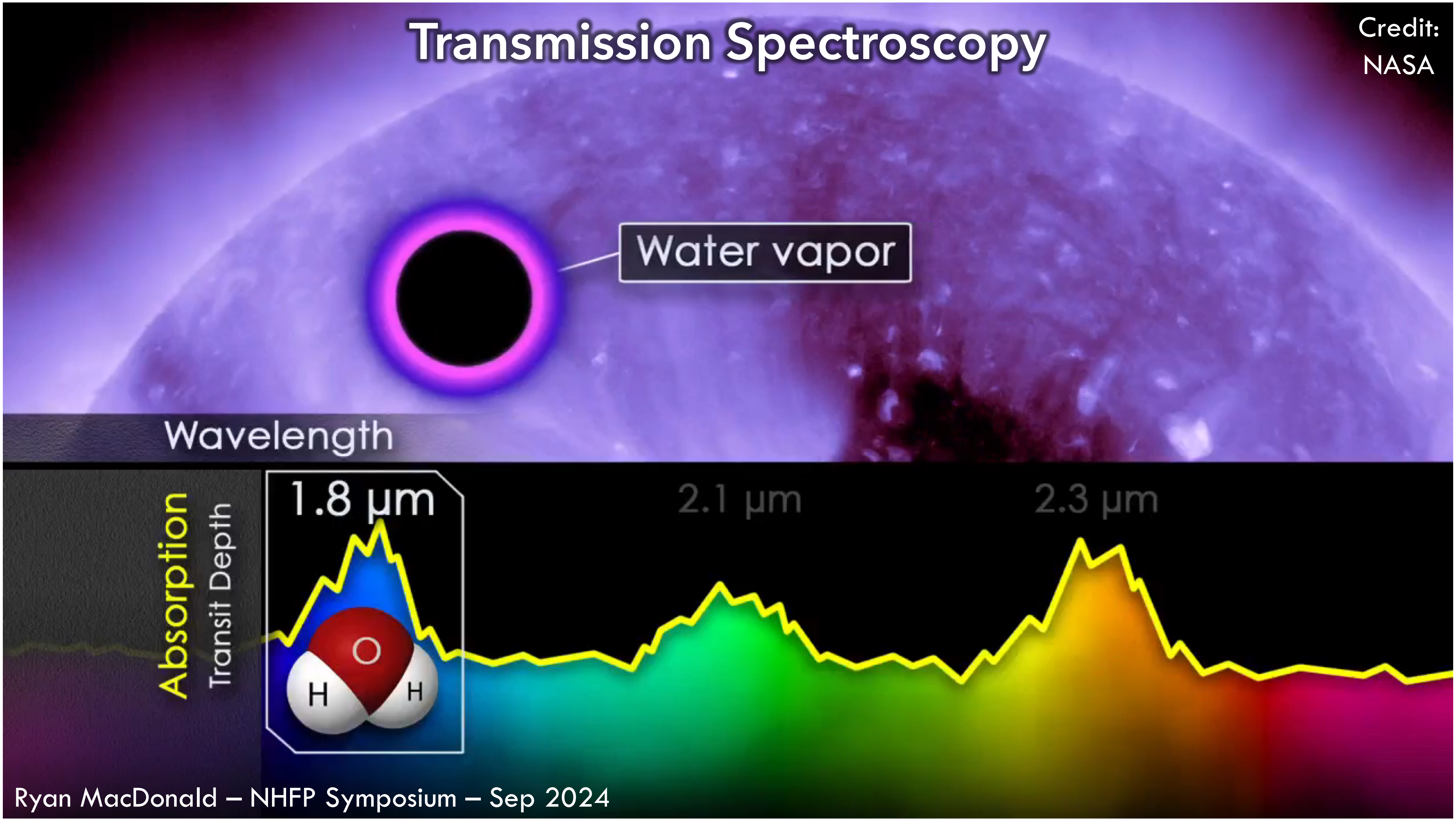

Pushing Down to Terrestrial Exoplanet Atmospheres
M dwarf
Brown dwarf
Pre-JWST
Hot Jupiter
Exo-Neptune
Now!
Super-Earth
Terrestrial
Radius
Difficulty to characterise
Ground-based (Current Gen.)
Hubble
JWST
Ryan MacDonald – NHFP Symposium – Sep 2024


Transmission Spectroscopy
Credit: NASA
Water vapor
Wavelength
Absorption
Transit Depth
1.8 μm
2.1 μm
2.3 μm
O
H
H
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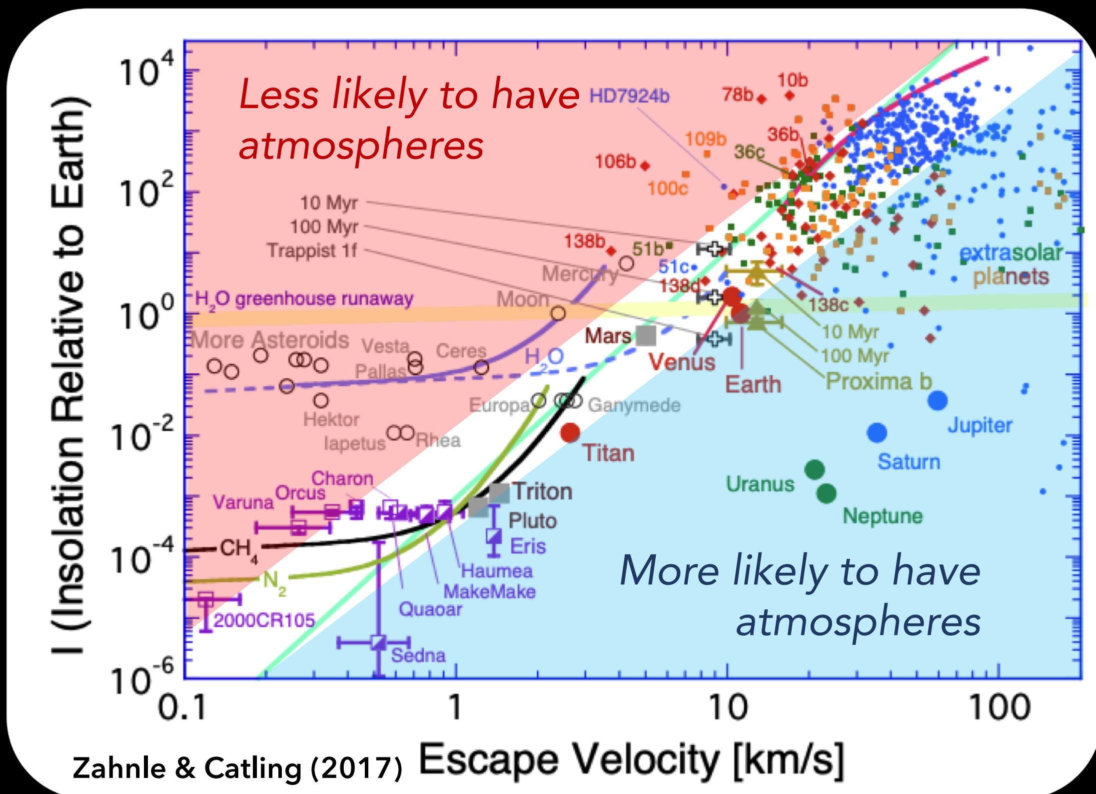
The Cosmic Shoreline: Lessons from the Solar System

Energy Received from Star



Escape Velocity

Solar System objects with and without atmospheres are divided by an empirical $I \propto v_{esc}^4$ relation

This cosmic shoreline can serve as a first prediction for which rocky exoplanets can retain substantial atmospheres

Does the cosmic shoreline differ for other solar systems, especially for M-dwarfs?

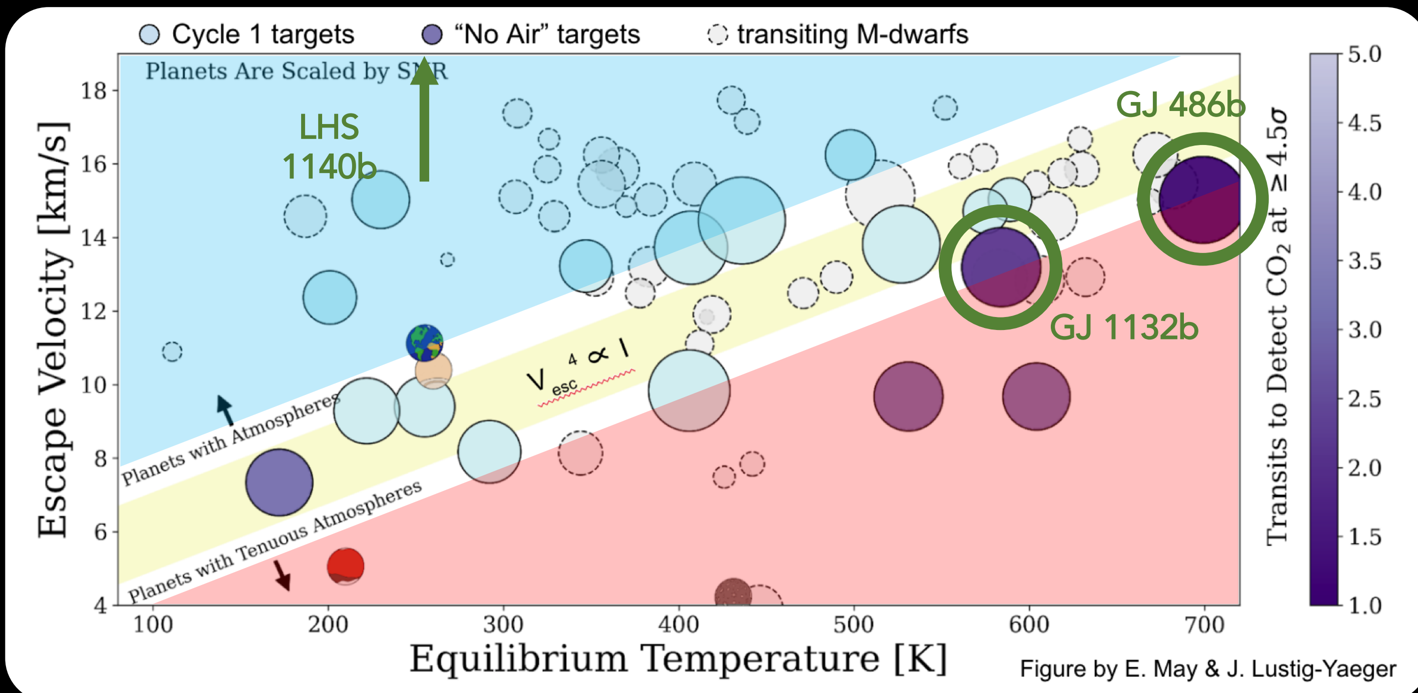
JWST GO 1981: A Search for Rocky Exoplanet Atmospheres

"Tell Me How I'm Supposed To Breath With No Air"

(PIs: K. Stevenson & J. Lustig-Yaeger)

We are conducting a Large Cycle 1 GO program (76 hours) to survey **5 rocky exoplanets** around the 'cosmic shoreline'.

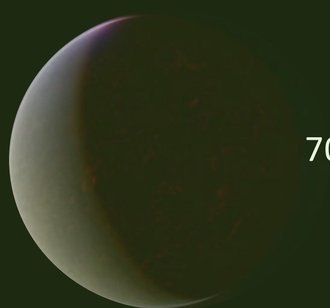
+ JWST Cycle 2
DDT 6543



Three Terrestrial Exoplanets Observed by JWST

GJ 486b

1.3 R_E

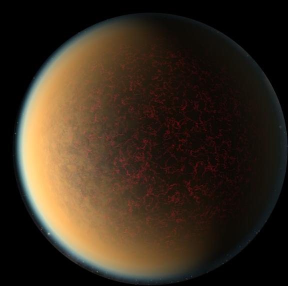


700 K

Moran & Stevenson + 2023

GJ 1132b

1.1 R_E

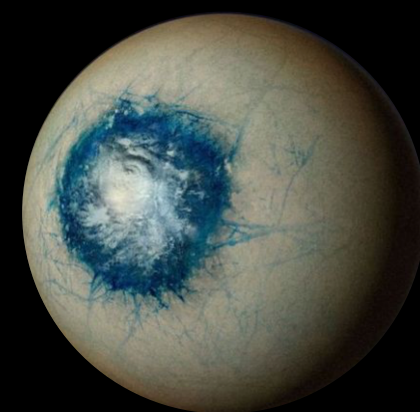


580 K

May & MacDonald + 2023

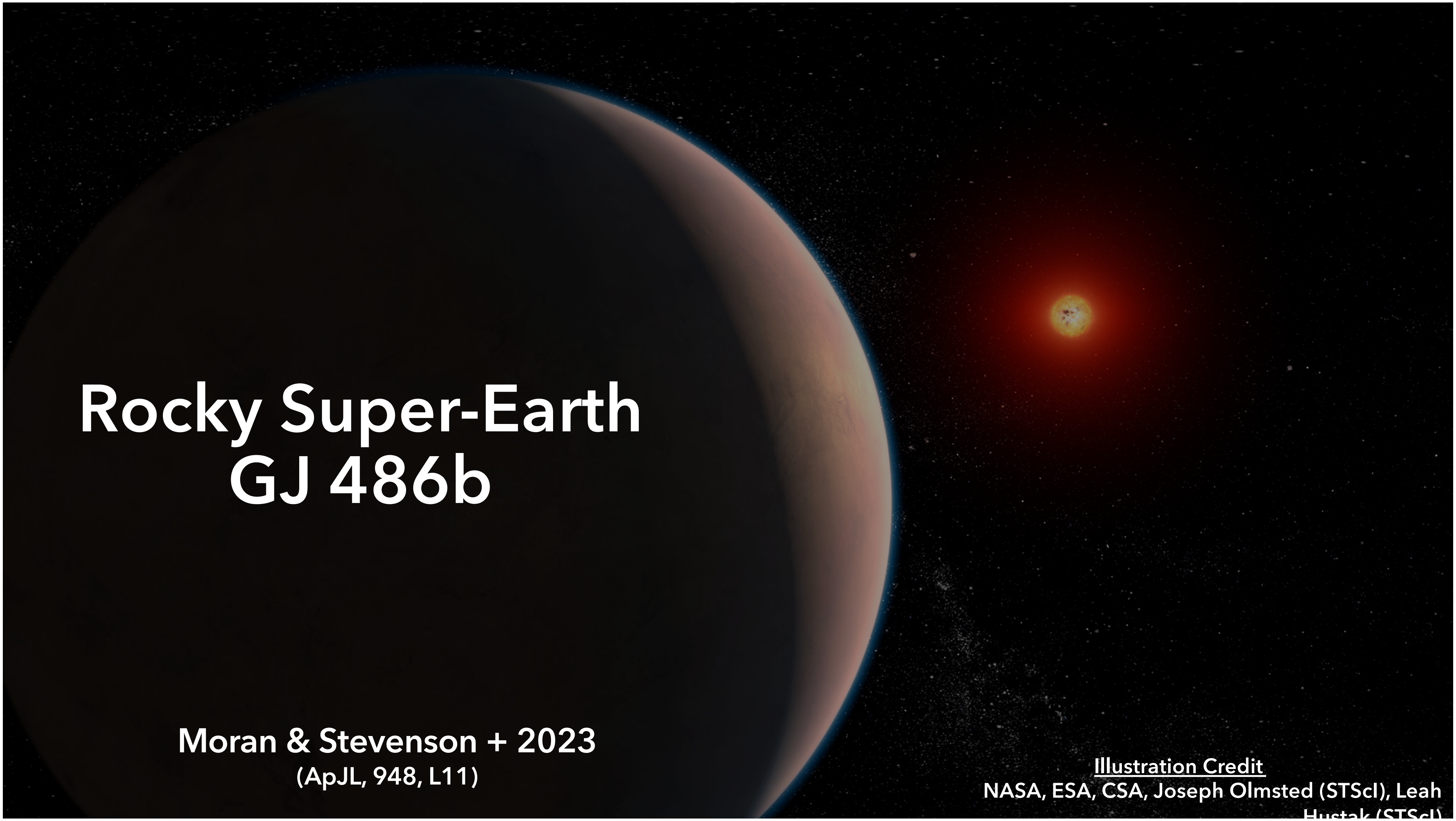
LHS 1140b

1.7 R_E



230 K

Cadieux**+2024**


Rocky Super-Earth
GJ 486b
Moran & Stevenson + 2023
(ApJL, 948, L11)
Illustration Credit
NASA, ESA, CSA, Joseph Olmsted (STScI), Leah
Hustak (STScI)

GJ 486b

JWST Observations

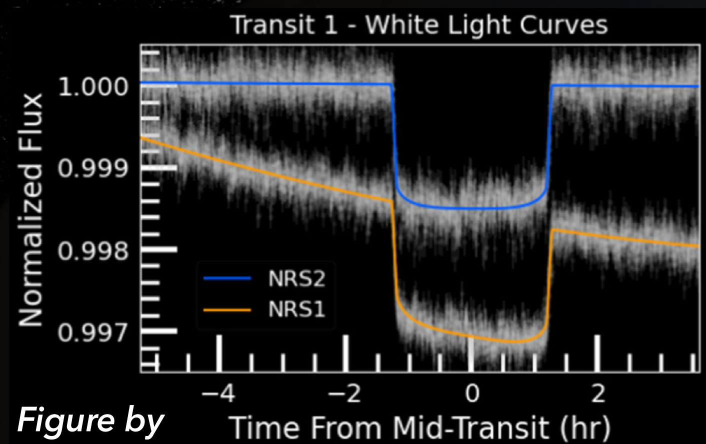
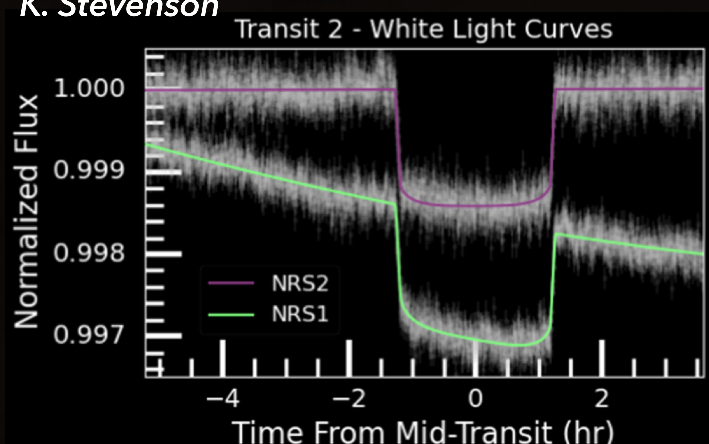


Figure by K. Stevenson



1.3 R_{Earth} 700 K

Star

Rs [$R_\odot$] 0.33 ±0.01	**V mag** 11.4
Ms [$M_\odot$] 0.32 ±0.02	**K mag** 6.4
[Fe/H] 0.07 ±0.16	**RA** [h:m:s] 12:47:55.567
$log_{10}(g)$ [cgs] 4.89	**Dec** [h:m:s] +09:44:57.91
Teff [K] 3340 ±54	**Distance** [pc] 8.07 ±0
Constellation Virgo	

Planet

R_p [R_j] 0.116 ±0.01	**T_{eq}** [K] 702.61 ±13
M_p [M_j] 0.0089 ±0	**$log_{10}(g)$** [cgs] 3.2132

System

Period [day] 1.467119 +3.1e-5/-3e-5	**a** [AU] 0.017 ±0
Transit Epoch [MJD] 58930.65935 ±4.2e-4	**Inclination** [°] 88.4
Transit Duration [hour] 1.0069 ±0.1085	**Depth** [%] 0.1305
Impact Parameter null	**Eccentricity** 0.05
ω [°] null	**a/Rs** 11.299

Moran & Stevenson + 2023

GJ 486b

Transmission Spectrum

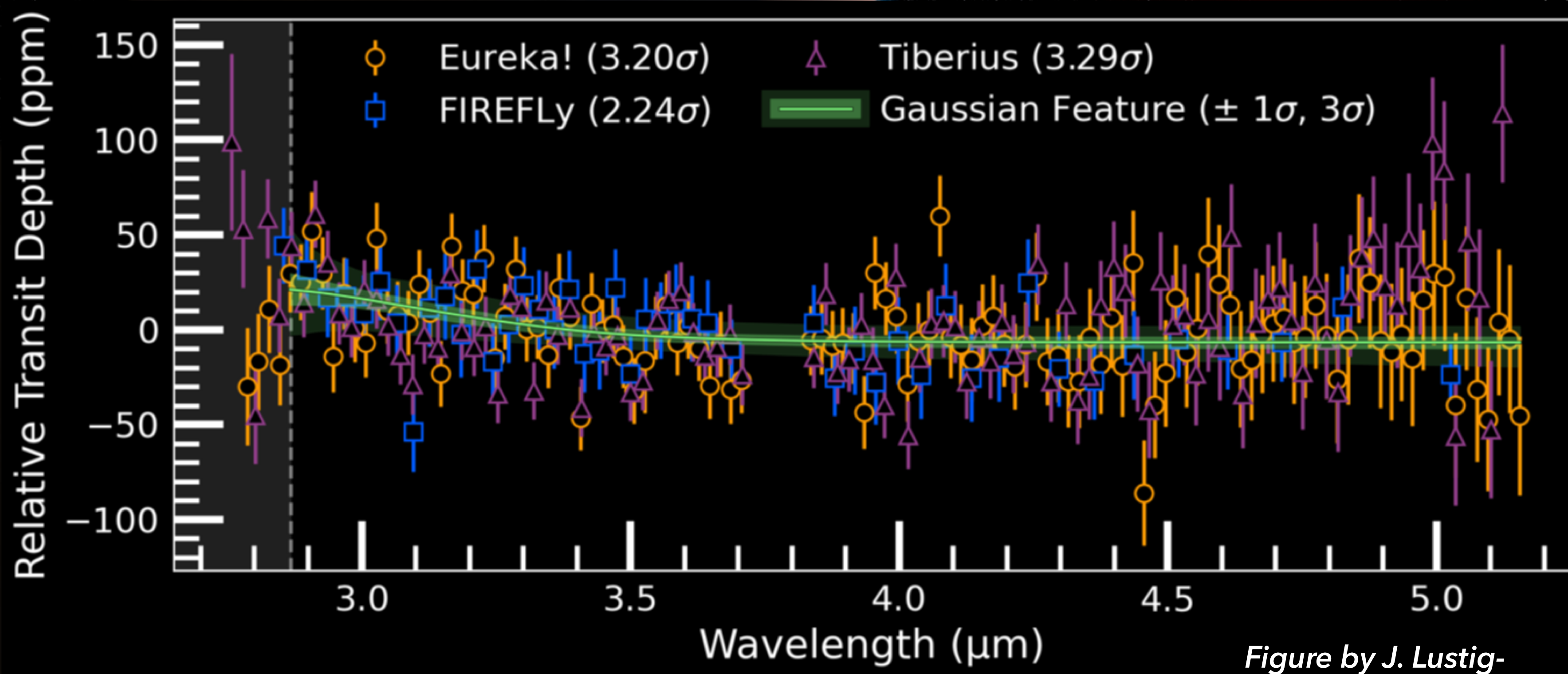
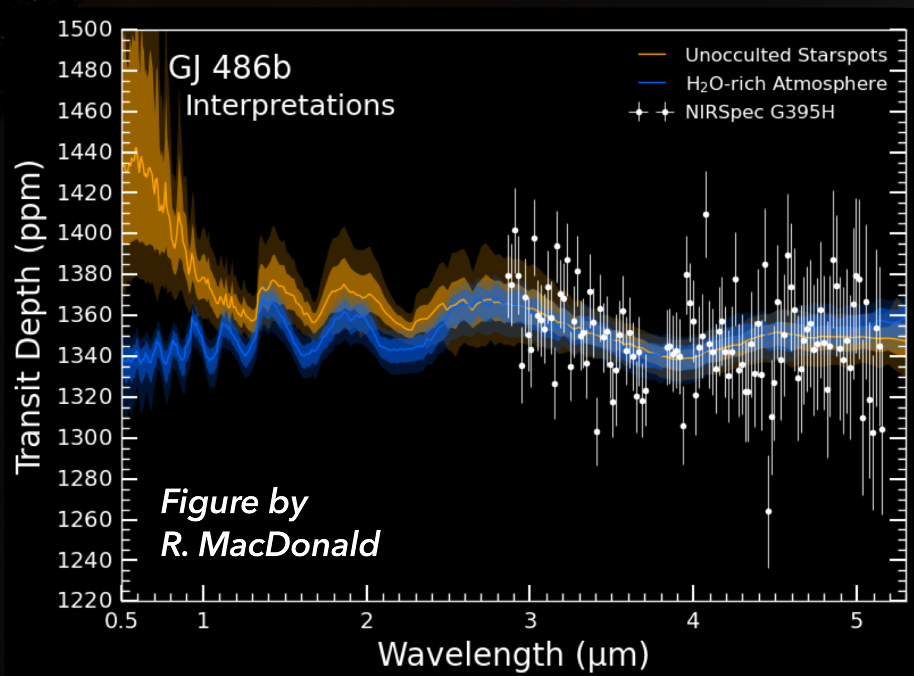


Figure by J. Lustig-Yaeger

Moran & Stevenson + 2023

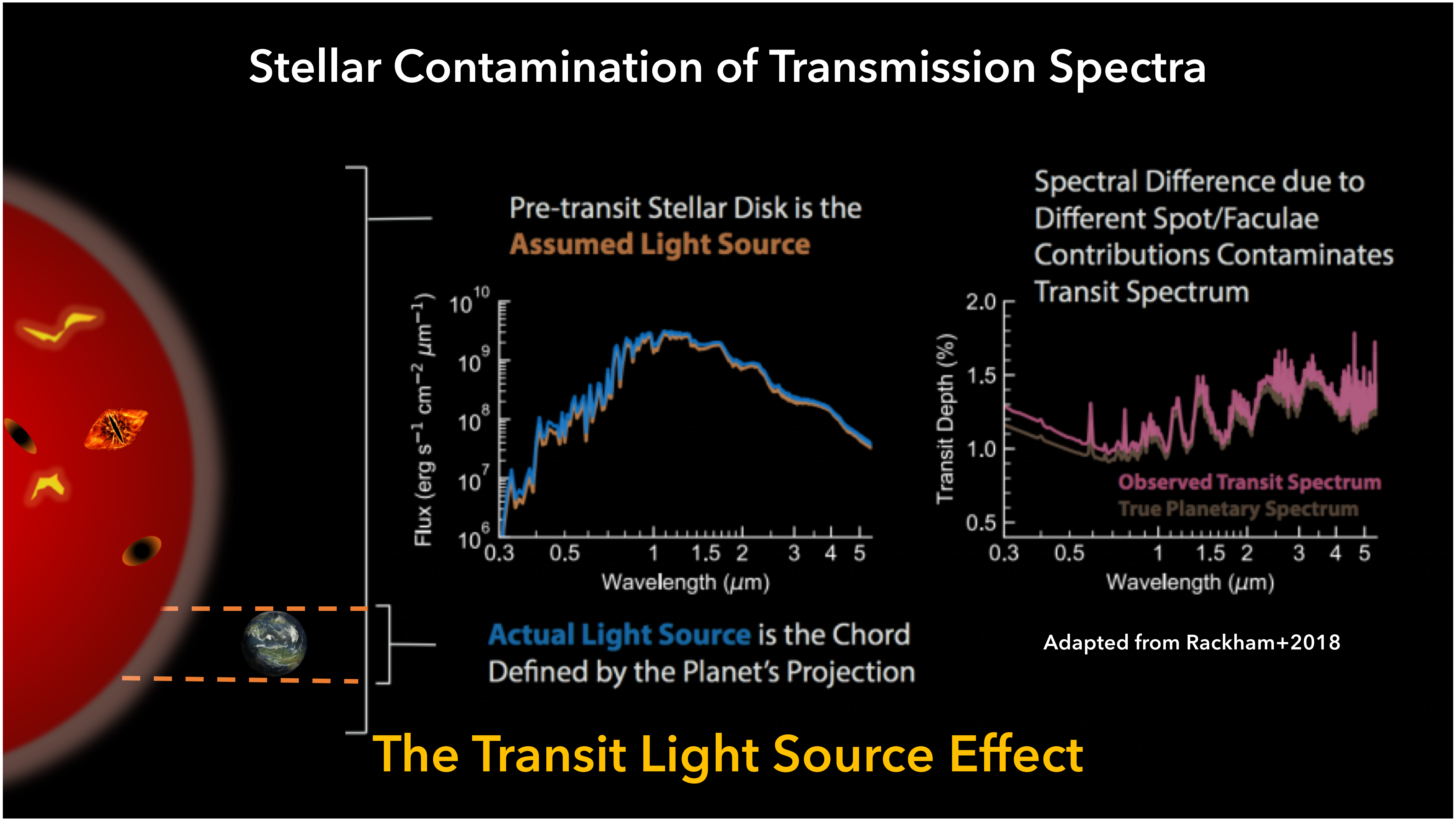
GJ 486b

Transmission Retrievals



Meme also by R. MacDonald

Moran & Stevenson + 2023


Stellar Contamination of Transmission Spectra
Pre-transit Stellar Disk is the
Assumed Light Source
Flux (erg s^{-1} cm^{-2} μm^{-1})
10^{10}
10^{9}
10^{8}
10^{7}
10^{6}
0.3 0.5 1 1.5 2 3 4 5
Wavelength (μm)
Actual Light Source is the Chord
Defined by the Planet's Projection
Spectral Difference due to
Different Spot/Faculae
Contributions Contaminates
Transit Spectrum
Transit Depth (%)
2.0
1.5
1.0
0.5
Observed Transit Spectrum
True Planetary Spectrum
0.3 0.5 1 1.5 2 3 4 5
Wavelength (μm)
Adapted from Rackham+2018
The Transit Light Source Effect

GJ 486b

Atmospheric / Stellar Constraints

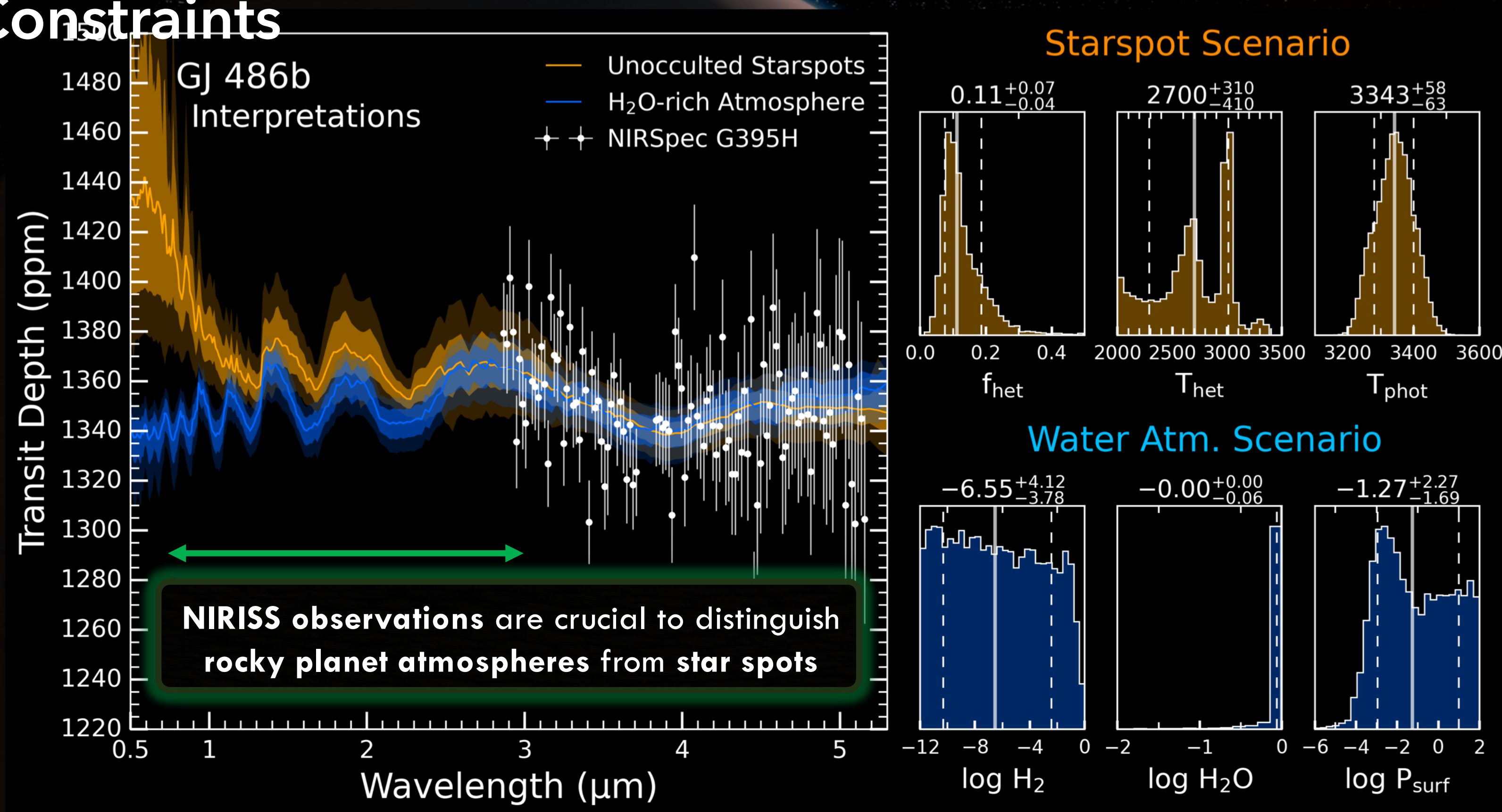
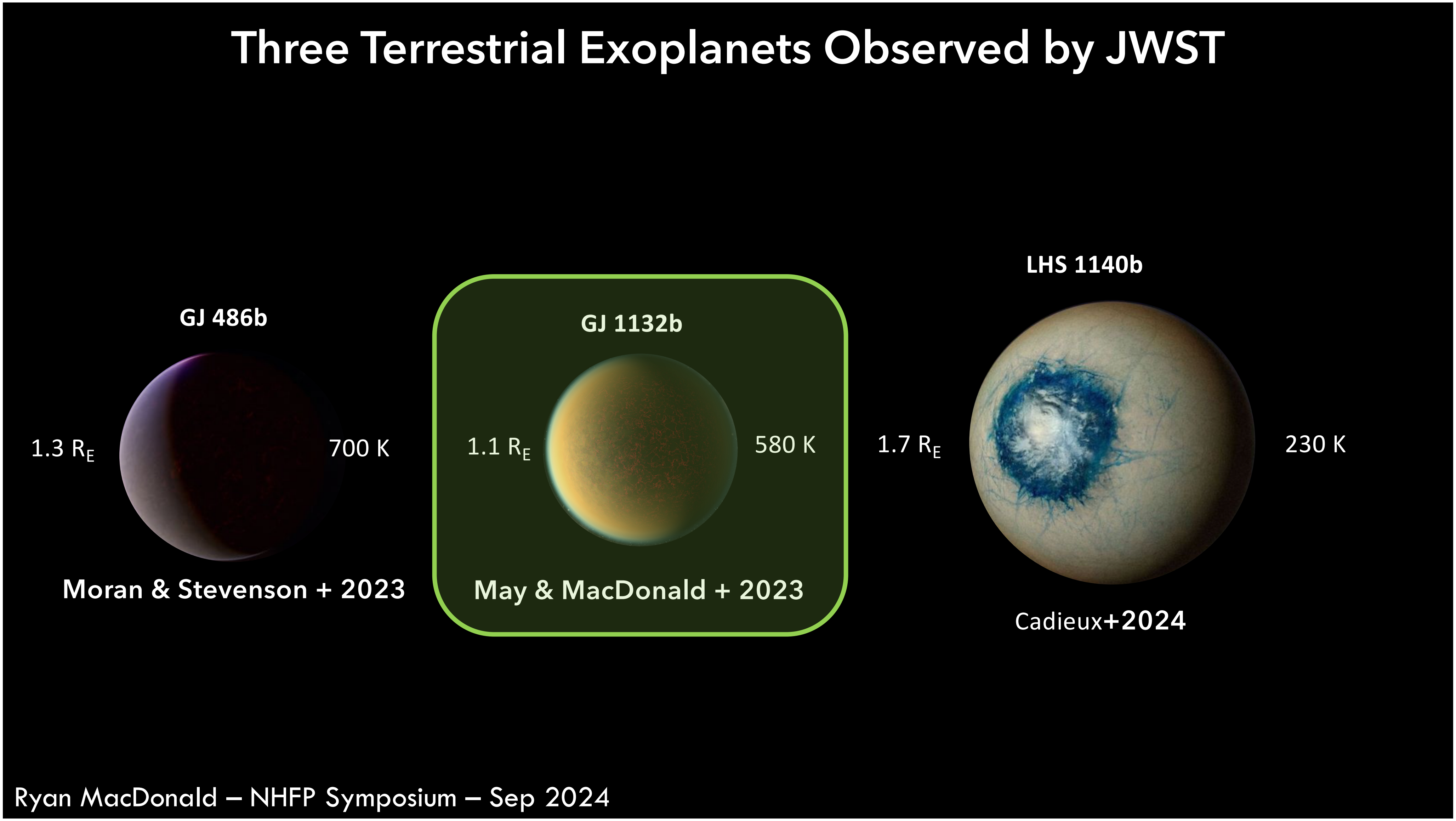


Figure by R. MacDonald

Moran & Stevenson + 2023


Three Terrestrial Exoplanets Observed by JWST
GJ 486b
1.3 R_E
700 K
Moran & Stevenson + 2023
GJ 1132b
1.1 R_E
580 K
May & MacDonald + 2023
LHS 1140b
1.7 R_E
230 K
Cadieux+2024
Ryan MacDonald – NHFP Symposium – Sep 2024


Rocky Super-Earth
GJ 1132b
May & MacDonald + 2023
(ApJL, 959, L9)
Illustration Credit
NASA, ESA, Robert L. Hurt

GJ 1132b

A Contentious History

Atmospheric Detections

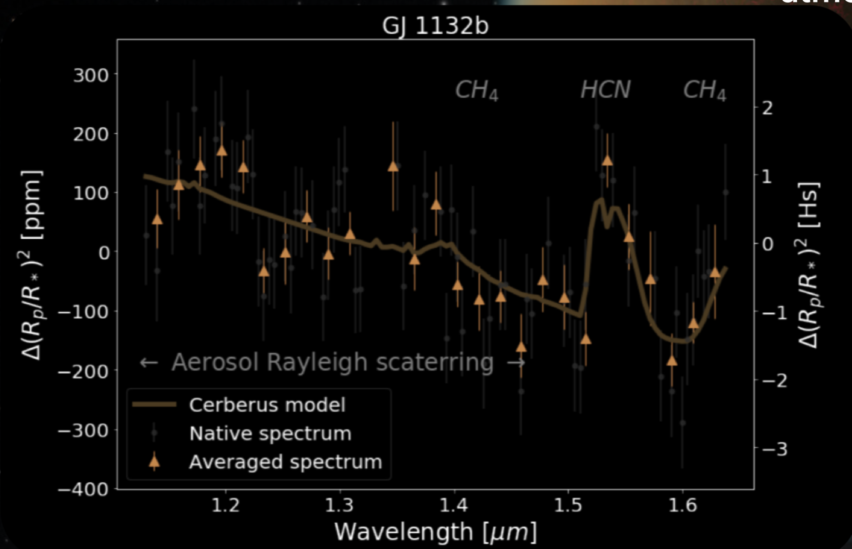
Southworth + 2017 *Swain + 2021*

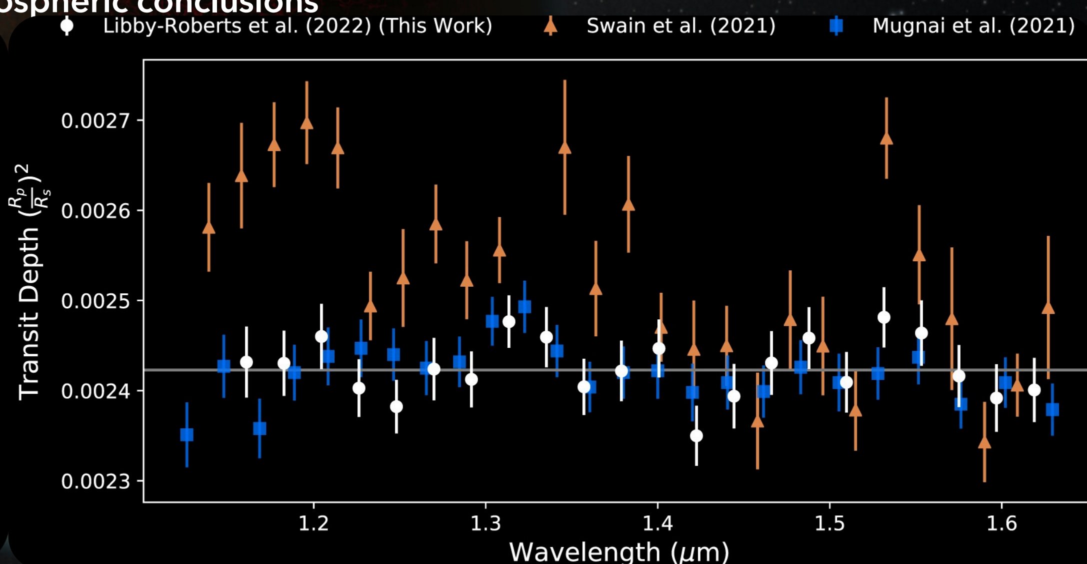
Existing ground-based and HST WFC3 data conclusions conflict

Different instruments do not agree. Different reductions of the same data yield different atmospheric conclusions

Non-detection of an atmosphere

Diamond-Lowe + 2018 *Mugnai + 2021 Libby-Roberts + 2022*





GJ 1132b

JWST Observations

Visit 1 – Feb. 25, 2023
Visit 2 – Mar. 5, 2023

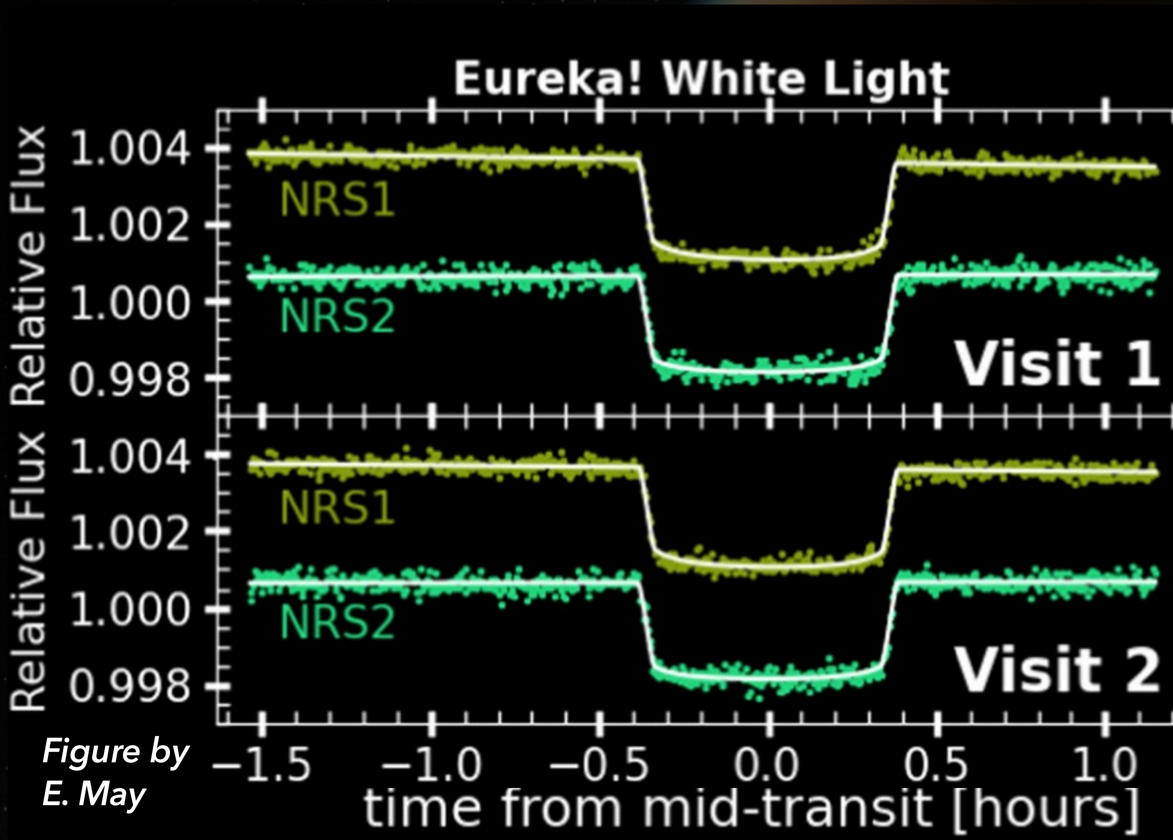


Figure by E. May

1.13 R_{Earth} 580 K

Star

Rs [$R_{\odot}$] 0.21 ±0.01	**V mag** 13.7
Ms [$M_{\odot}$] 0.18 ±0.02	**K mag** 8.3
[Fe/H] -0.12 ±0.15	**RA** [h:m:s] 10:14:50.177
$log_{10}(g)$ [cgs] 4.88 ±0.07	**Dec** [h:m:s] -47:09:17.77
Teff [K] 3270 ±140	**Distance** [pc] 12.61 ±0.01
Constellation Vela	

Planet

R_p [R_j] 0.101 ±0.01	**T_{eq}** [K] 584.18 ±9
M_p [M_j] 0.0052 ±0	**$log_{10}(g)$** [cgs] 3.1032

System

Period [day] 1.628931 ±2.7e-5	**a** [AU] 0.015 ±0.001
Transit Epoch [MJD] 57184.05759 ±3e-4	**Inclination** [°] 86.58
Transit Duration [hour] 0.8093 ±0.0964	**Depth** [%] 0.2443
Impact Parameter 0.38 ±0.14	**Eccentricity** 0.22
ω [°] null	**a/Rs** 15.667

May & MacDonald + 2023

GJ 1132b
Transmission Spectrum

Visit 1 – Feb. 25, 2023
Visit 2 – Mar. 5, 2023

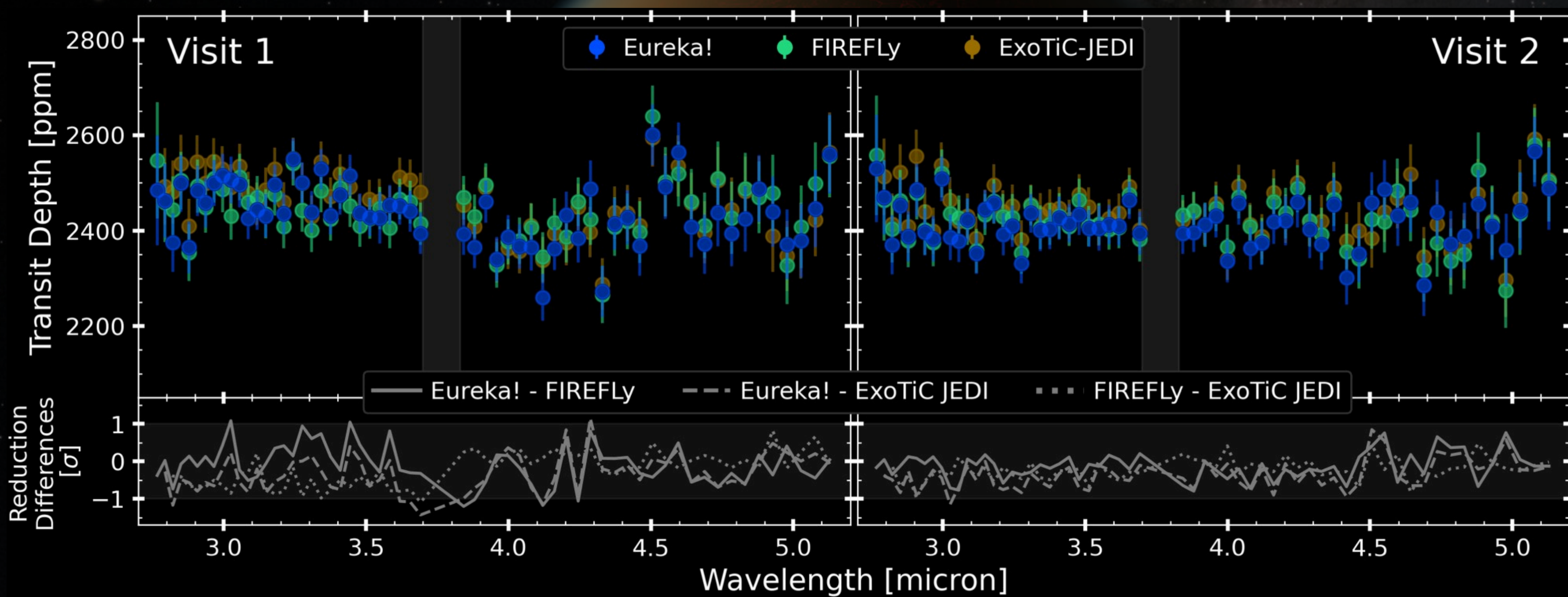


Figure by E. May

May & MacDonald + 2023

GJ 1132b

Atmospheric / Stellar

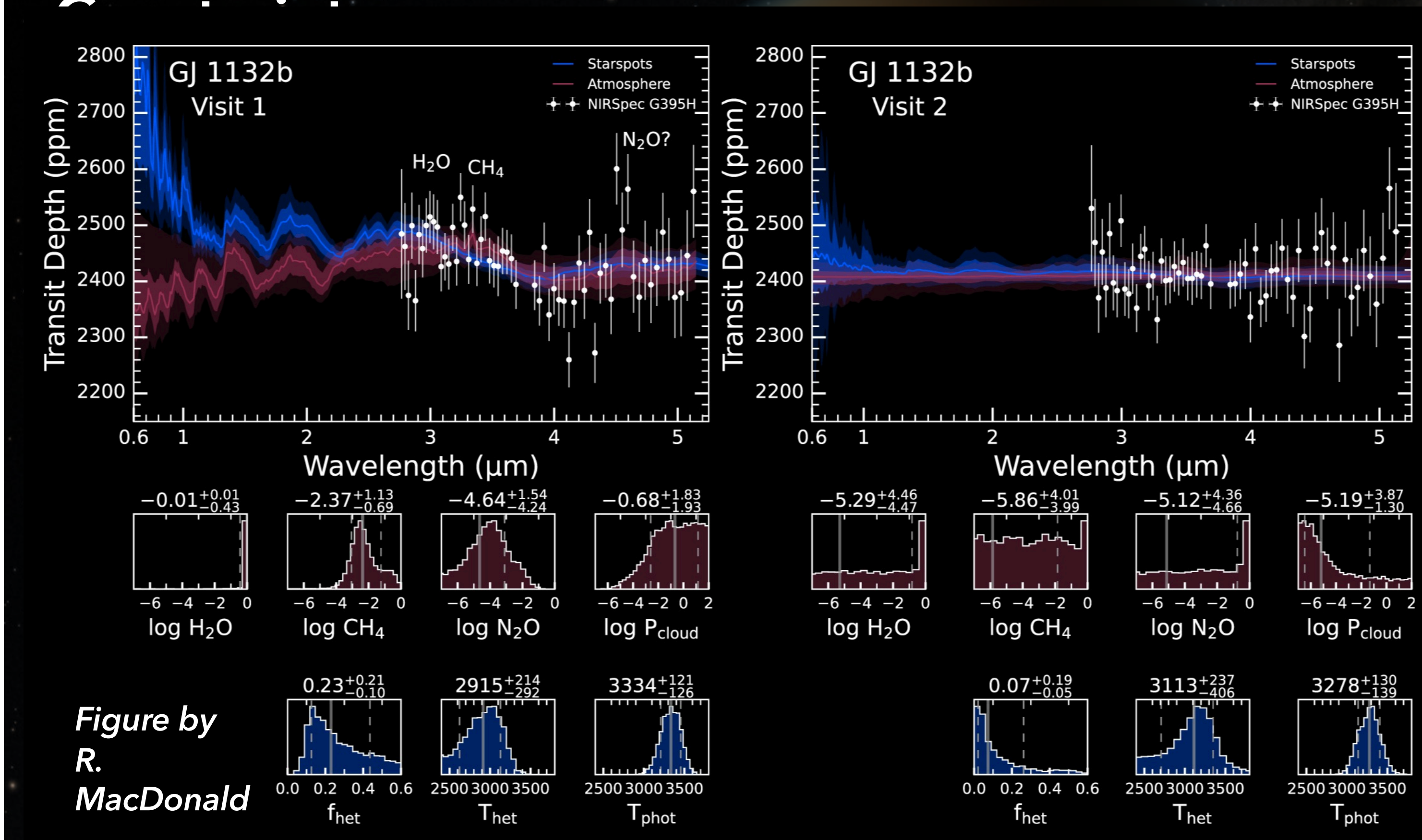


Figure by R. MacDonald

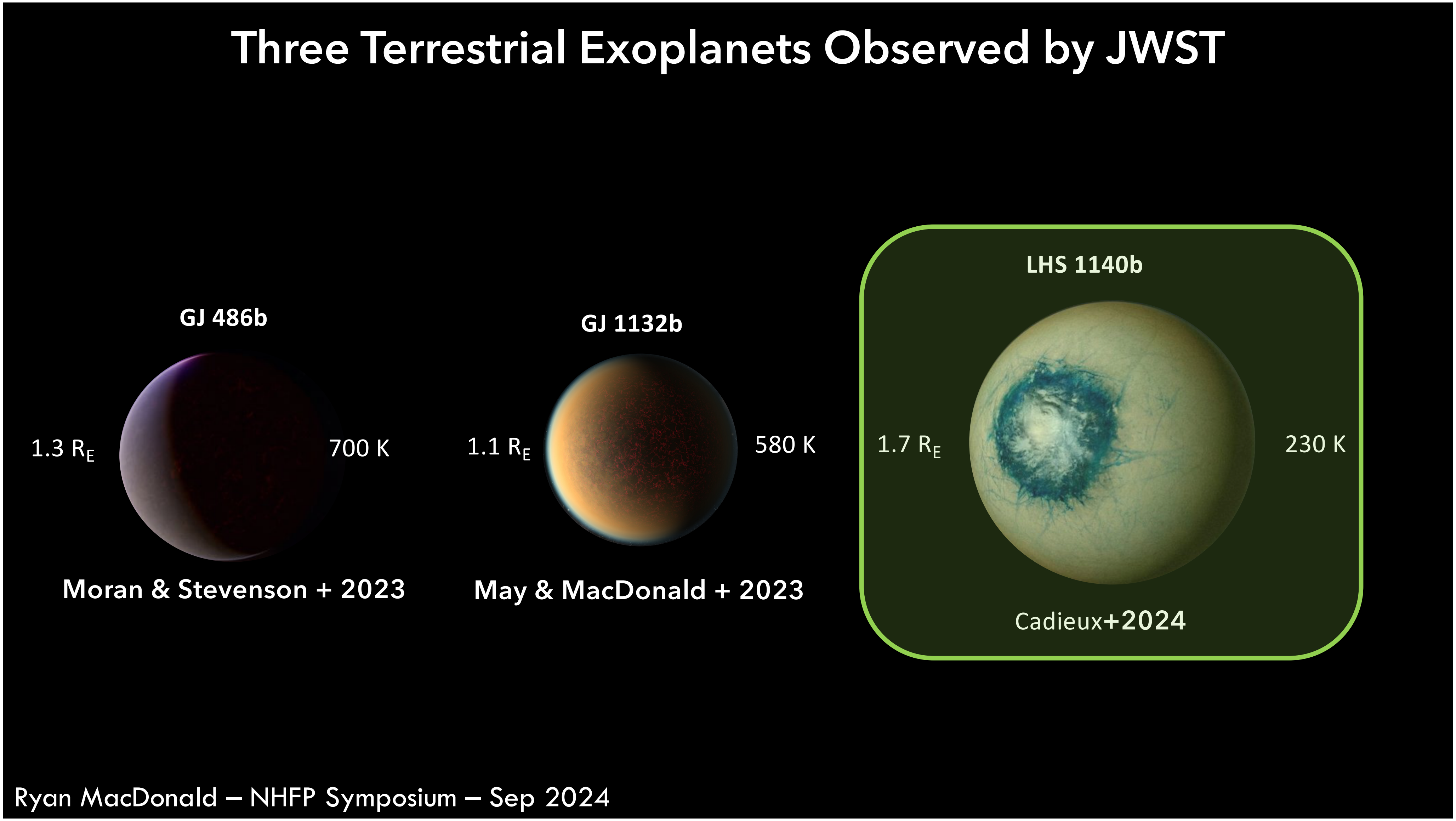
GJ 1132b has inconsistent spectra between two JWST transits

The first transit marginally favours an atmosphere over stellar contamination

The second transit has a featureless spectrum

Multi-transit repeatability is key before claiming a detection of a rocky planet atmosphere

May & MacDonald + 2023



Three Terrestrial Exoplanets Observed by JWST
GJ 486b
1.3 R_E
700 K
Moran & Stevenson + 2023
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LHS 1140b
1.7 R_E
230 K
Cadieux+2024
Ryan MacDonald – NHFP Symposium – Sep 2024

Habitable Zone Super-Earth
LHS 1140b

Cadieux + 2024
(ApJL, 970, L2)

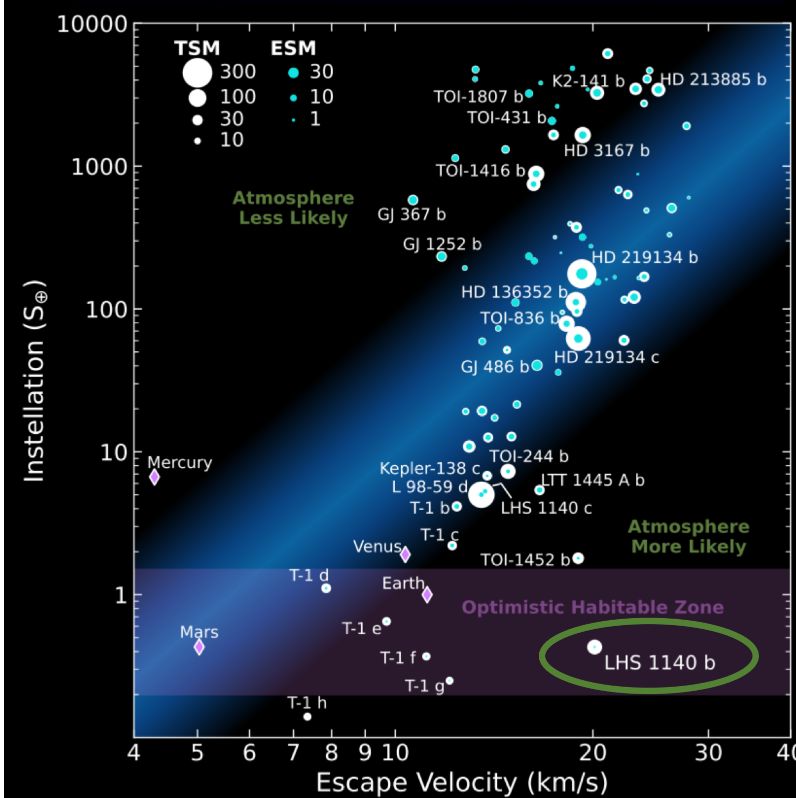
Illustration Credit
B. Bougeon /

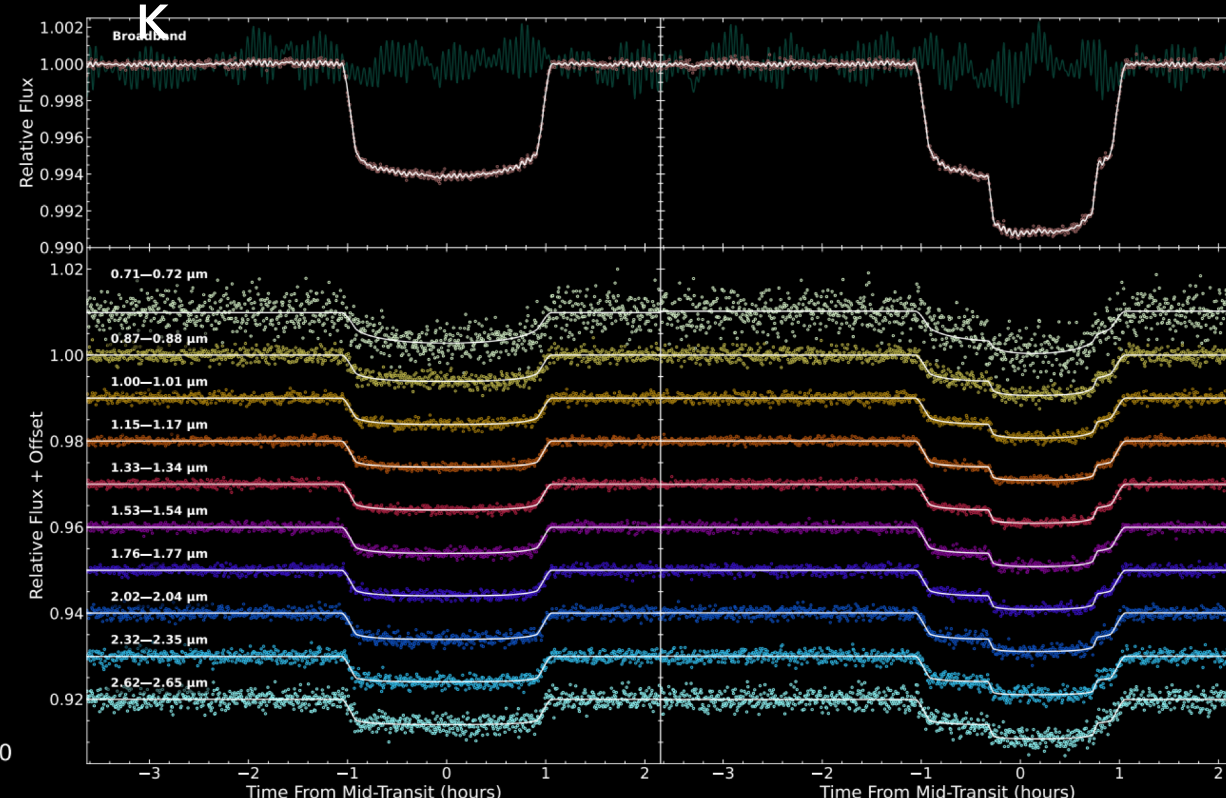
LHS 1140b

JWST Observations

Visit 1 – Dec. 1, 2023
Visit 2 – Dec. 26, 2023

1.7 R_{Earth} 5.6 M_{Earth} 228 K

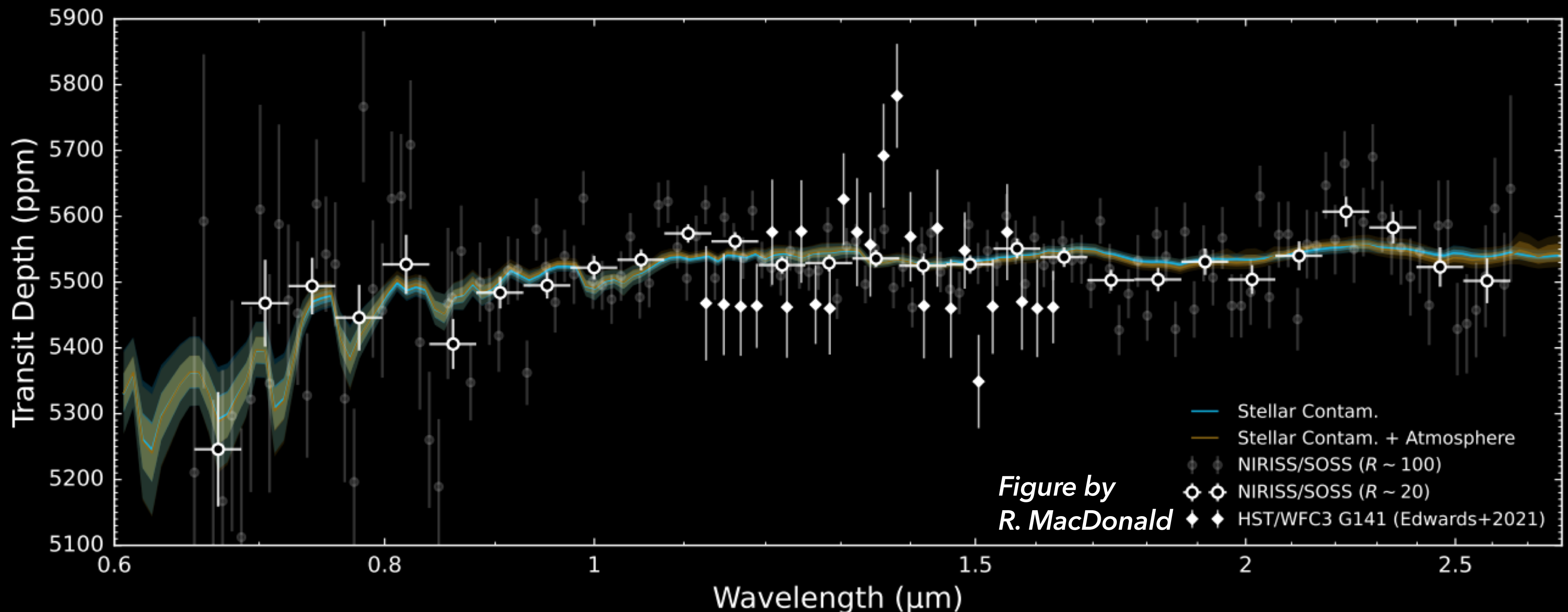




Figures by C. Cadieux

Cadieux + 2024

LHS 1140b
Transmission Spectrum



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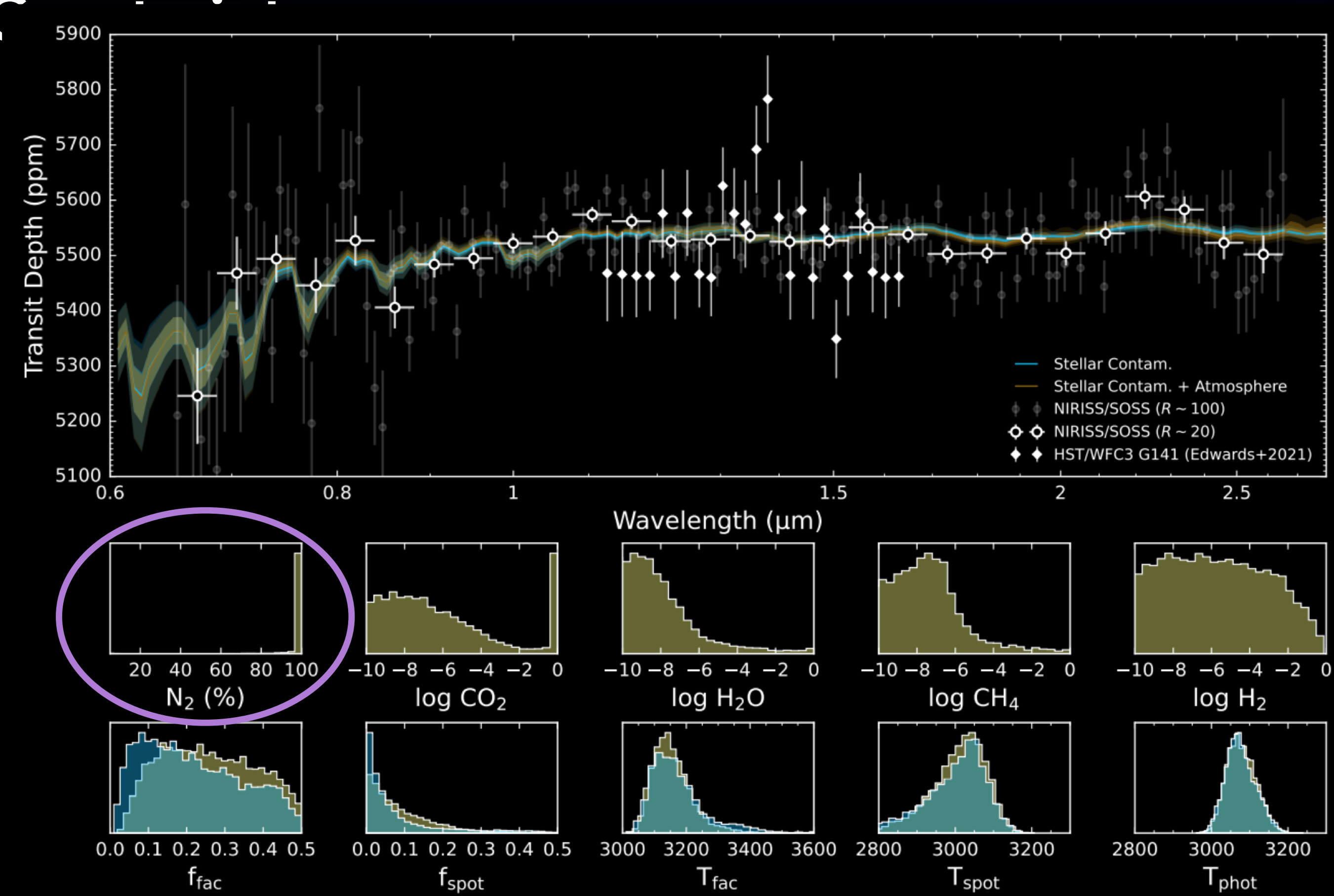
LHS 1140b

Atmospheric / Stellar



LHS 1140b has weaker stellar contamination than other systems

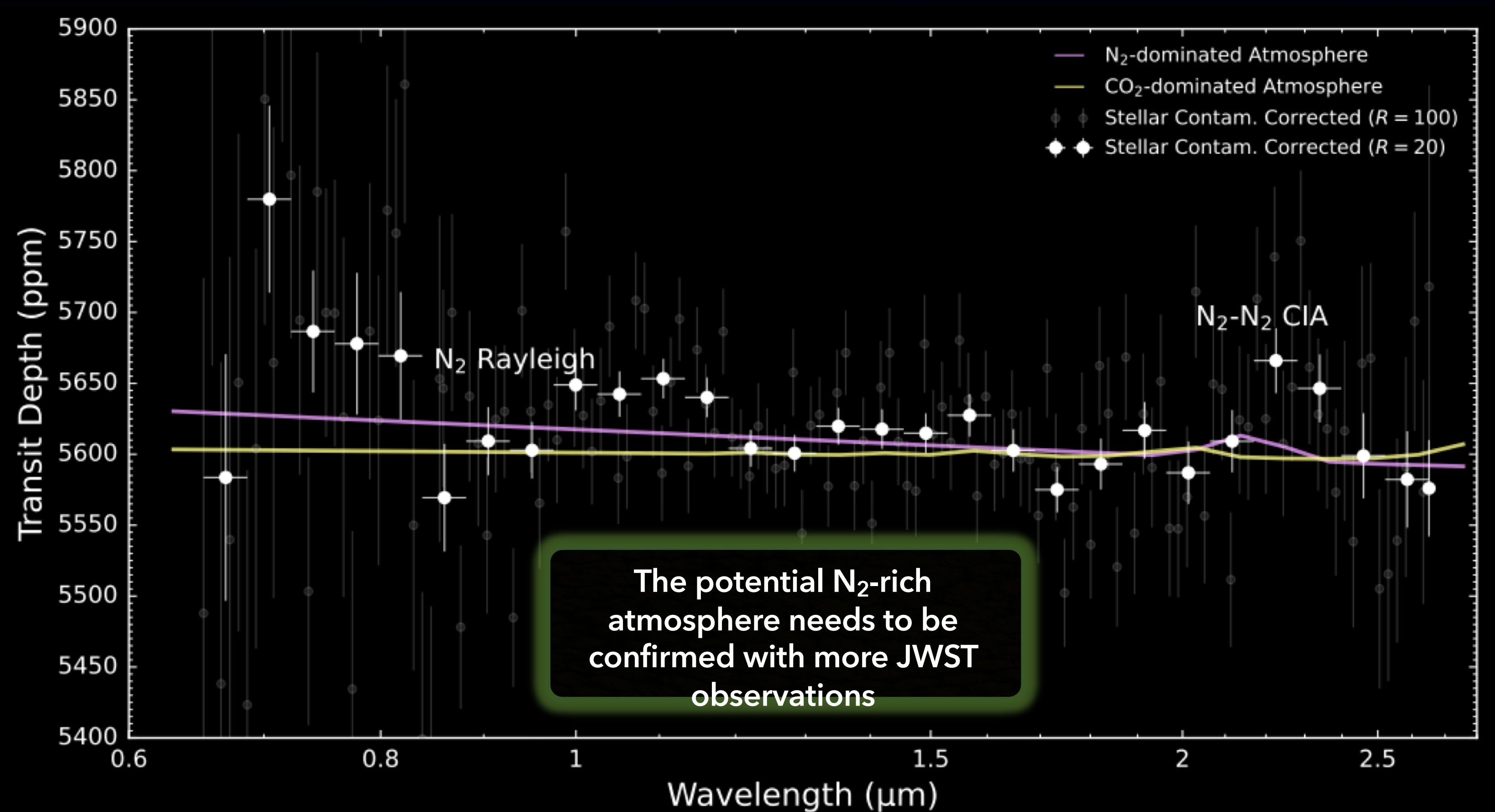
The stellar contamination is consistent between 2 visits spaced 25 days apart

The fit is improved by 2.3σ by adding a N_2-rich atmosphere

Cadieux + 2024

LHS 1140b

An Atmosphere on a Habitable Zone Super-Earth?



Cadieux + 2024

LHS 1140b

Potential Interpretations

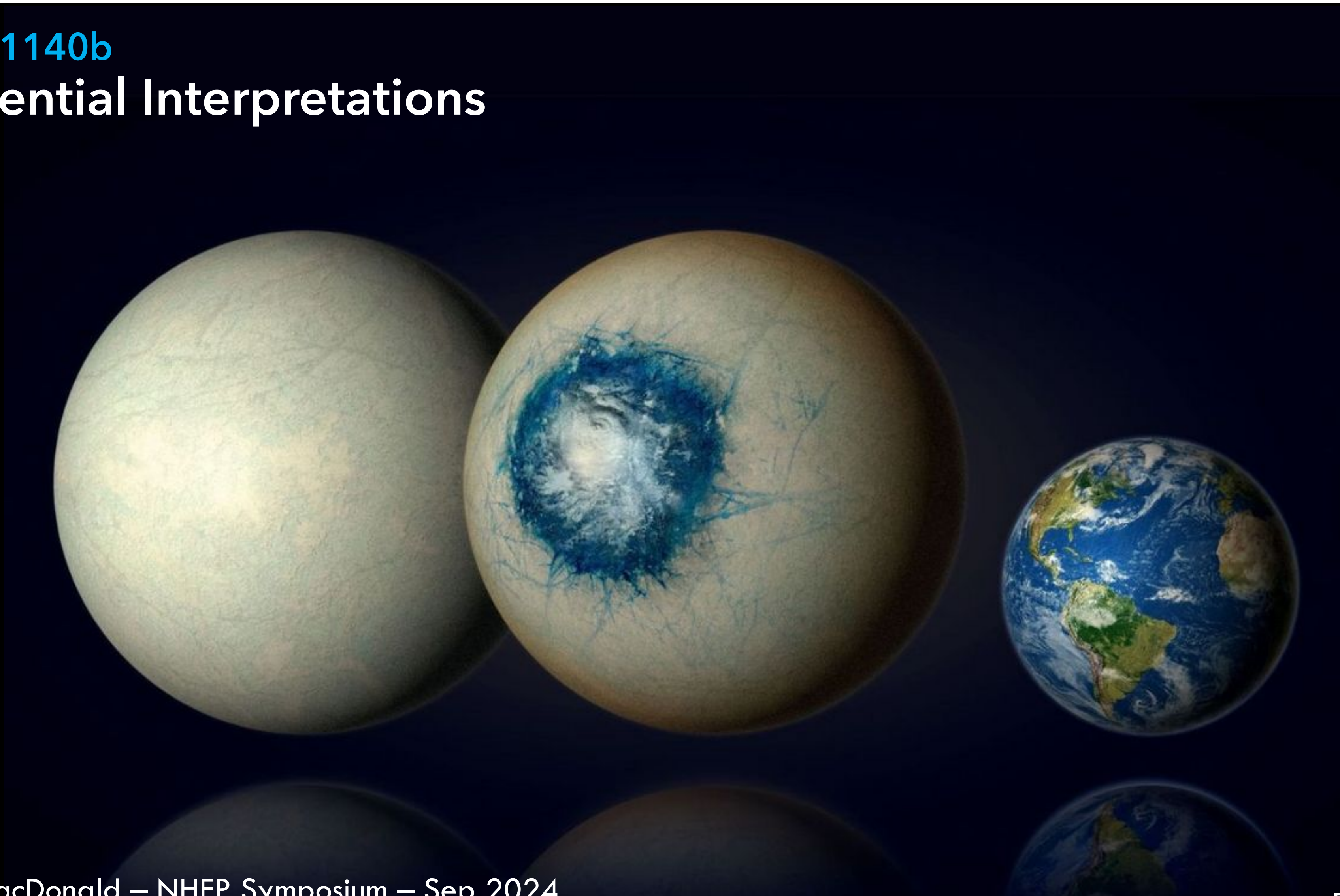


Illustration Credit
B. Bougeon /

KEY TAKEAWAYS

JWST spectra are now offering tantalising glimpses into rocky exoplanet atmospheres

1. JWST can detect atmospheres on rocky worlds orbiting M-dwarfs.
2. GJ 486b and GJ 1132b have non-flat transmission spectra (3σ), consistent with either a H_2O-rich atmosphere or unocculted starspots.
3. LHS 1140b shows tantalising evidence of a N_2-rich atmosphere (2σ), which, if confirmed, would be the first atmosphere on a habitable zone super-Earth.

We need to be ambitious.

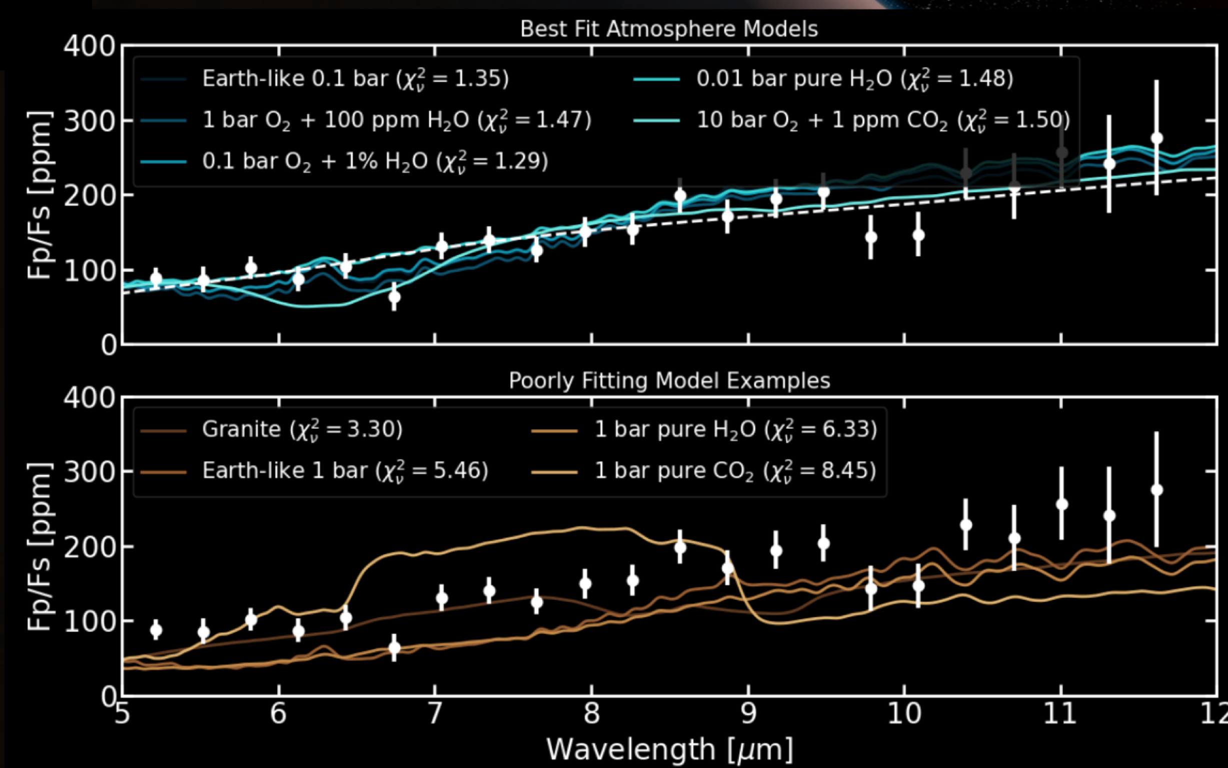
It is time to go deep, across several JWST cycles, to conclusively detect M-dwarf rocky planet atmospheres

Ryan MacDonald
NHFP Symposium
September 2024

UNIVERSITY OF MICHIGAN

GJ 486b

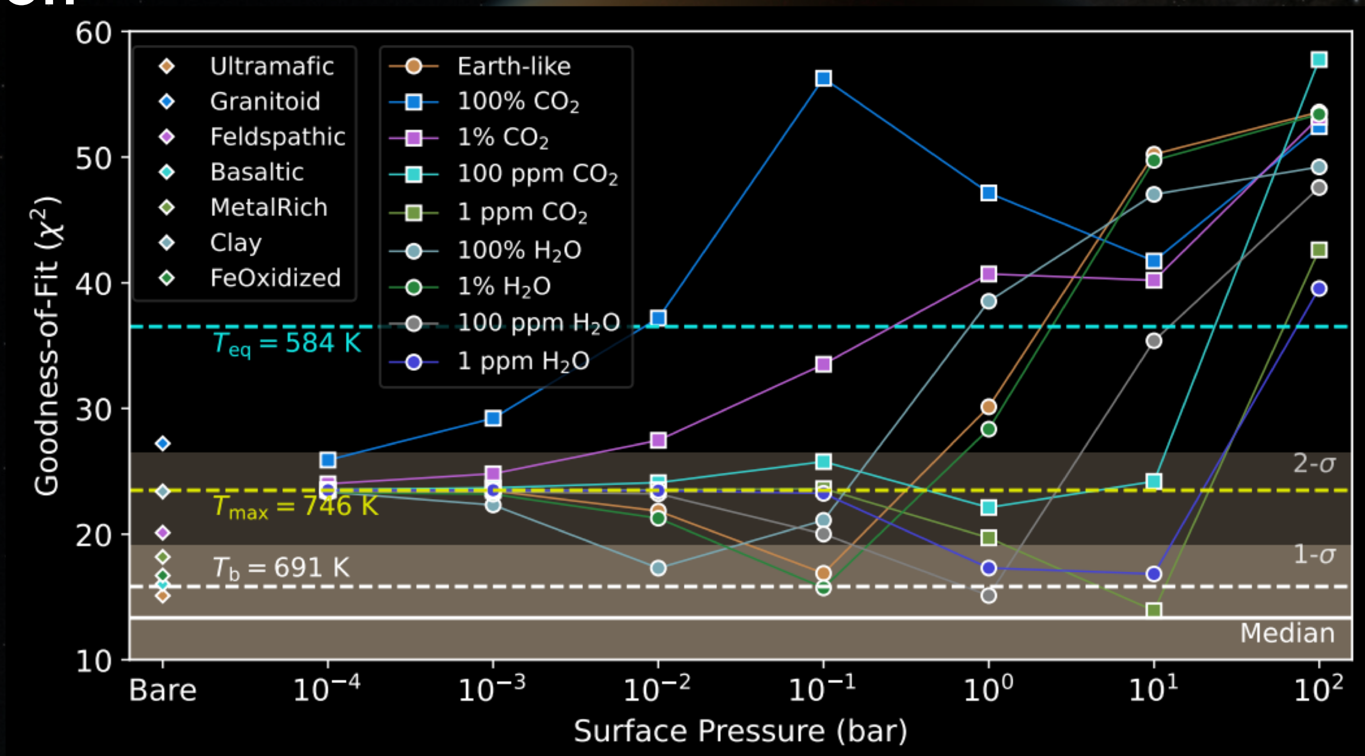
Breaking News: JWST Emission



Mansfield+2024

GJ 1132b

Breaking News: JWST Emission



Xue+2024

Robustness Tests for Rocky Planet Atmosphere Detections

Proposed questions before claiming a rocky exoplanet atmosphere

1. Is a flat line rejected?
2. Is the signal confirmed by multiple data reductions?
3. Is the signal repeatable across multiple transits?
4. Can the signal be uniquely attributed to an atmosphere?

"Our results highlight the importance of multi-visit repeatability with JWST prior to claiming atmospheric detections for these small, enigmatic planets" – *May & MacDonald + 2023*

"Our results demonstrate the unequivocal need for two or more transit observations analyzed with multiple reduction pipelines, alongside rigorous statistical tests, to determine the robustness of molecular detections for small exoplanet atmospheres." - Kirk + 2024