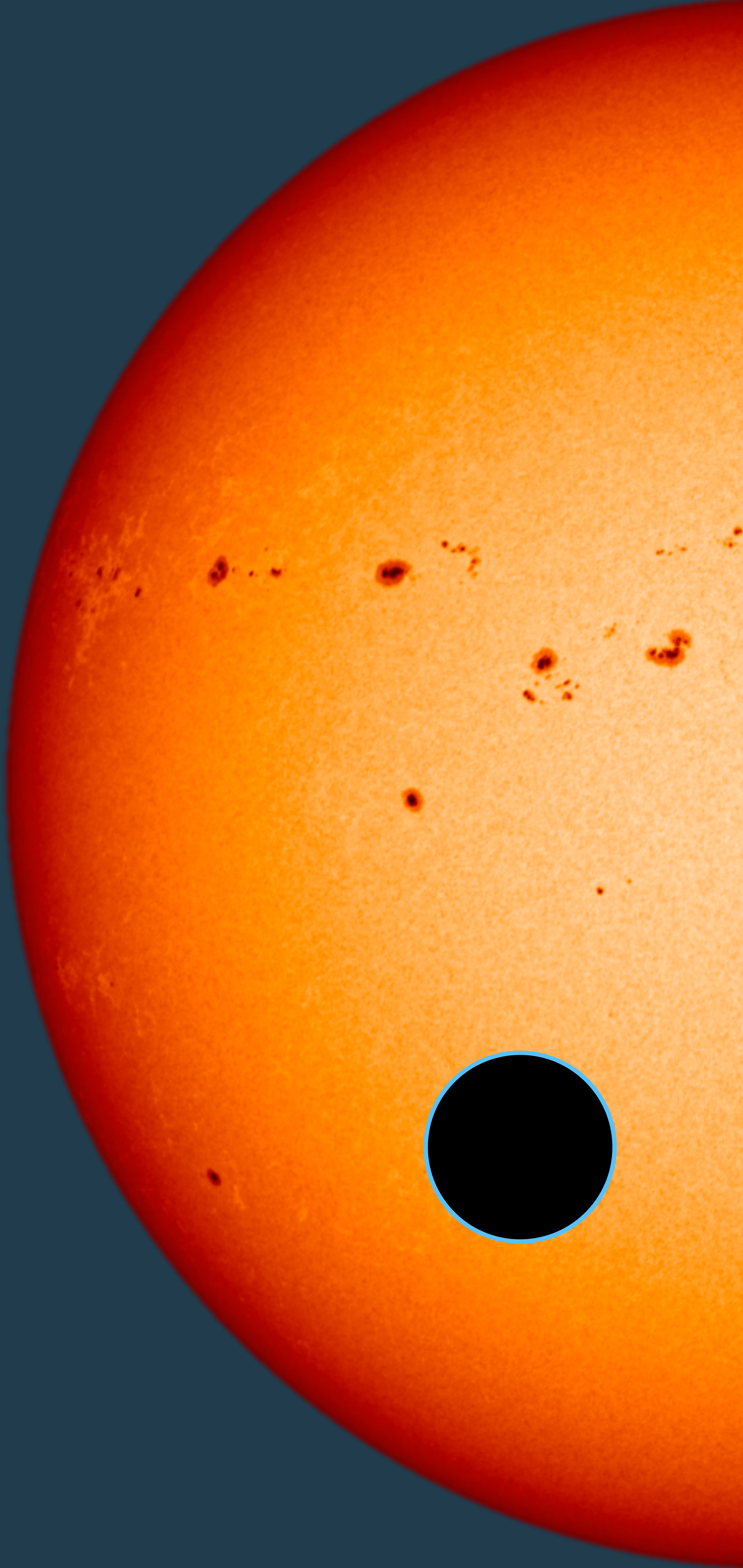
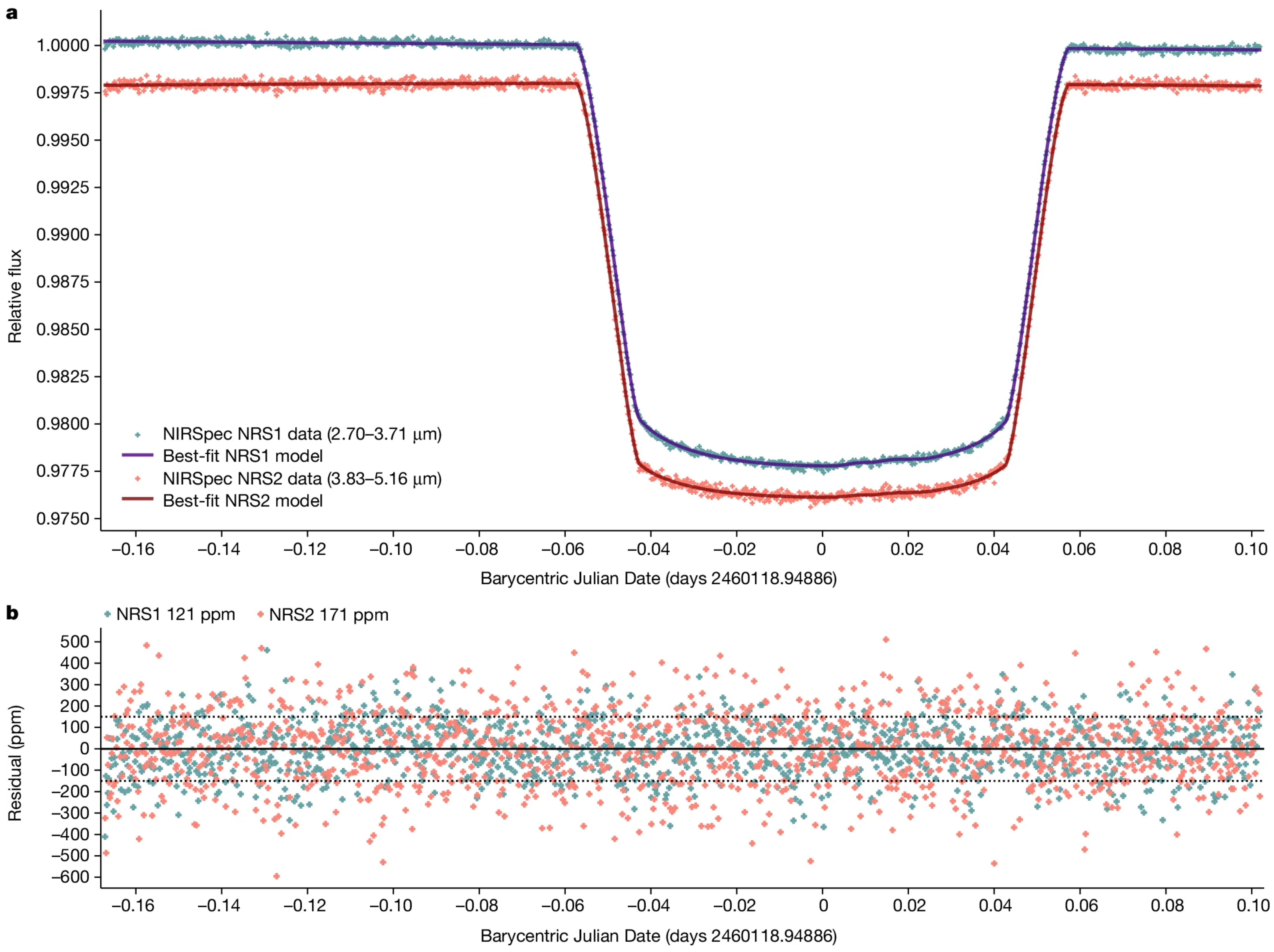
Knowing Stars, Knowing Planets:

Unlocking JWST Exploration of Exoplanet Atmospheres through New Stellar Insights

Benjamin V. Rackham

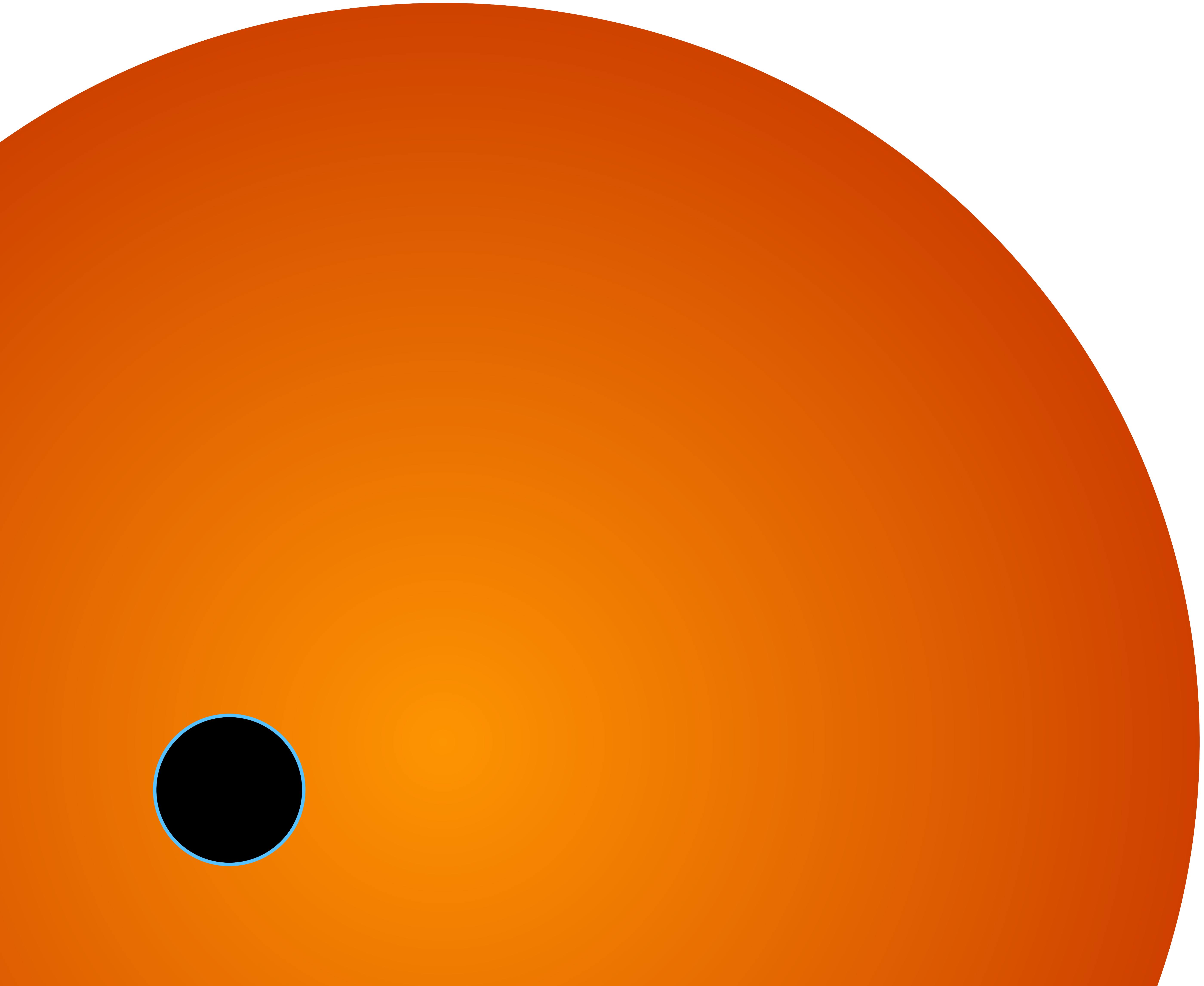


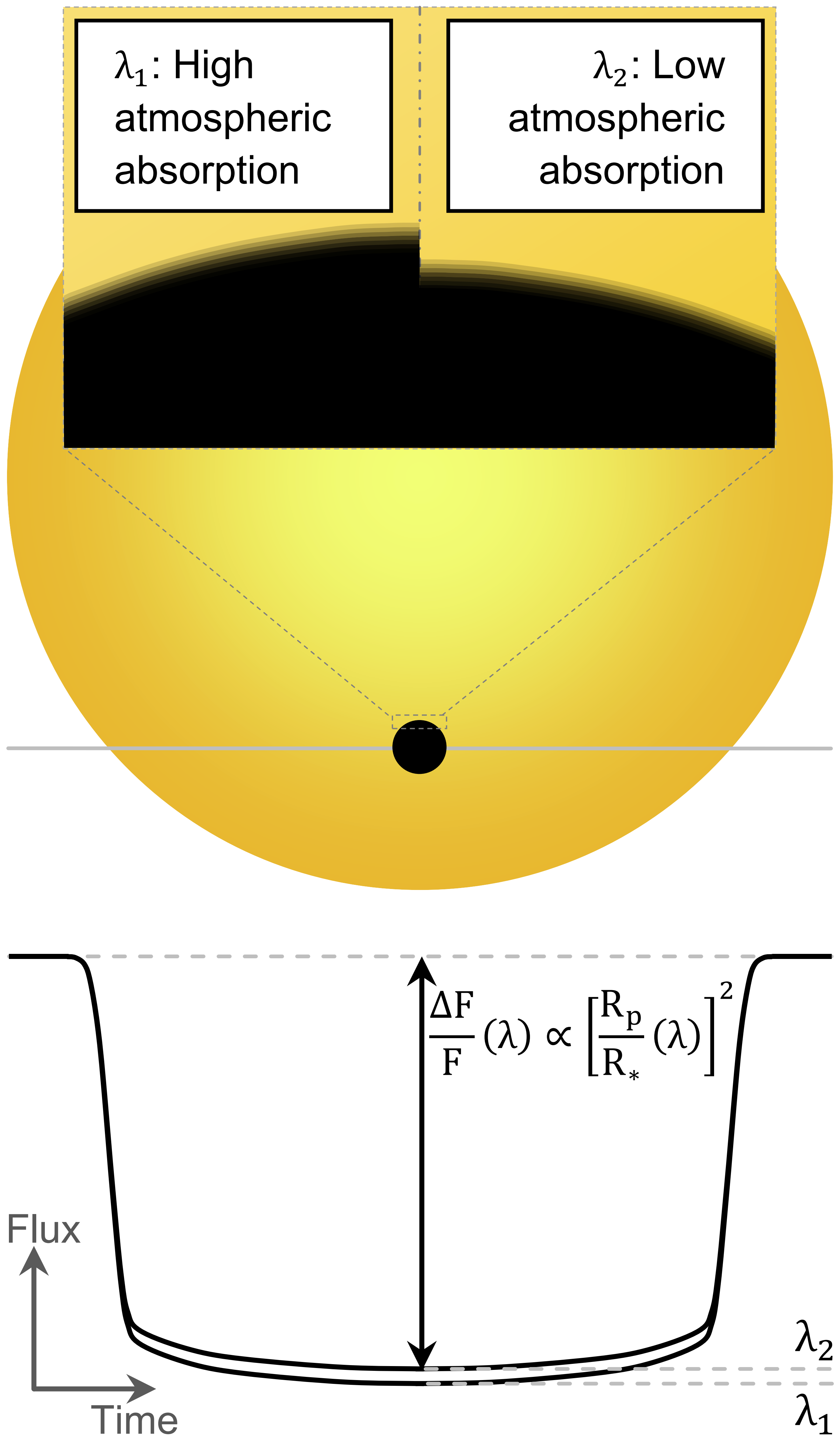
Exoplanet transits with phenomenal precision



Sing et al. (2024)

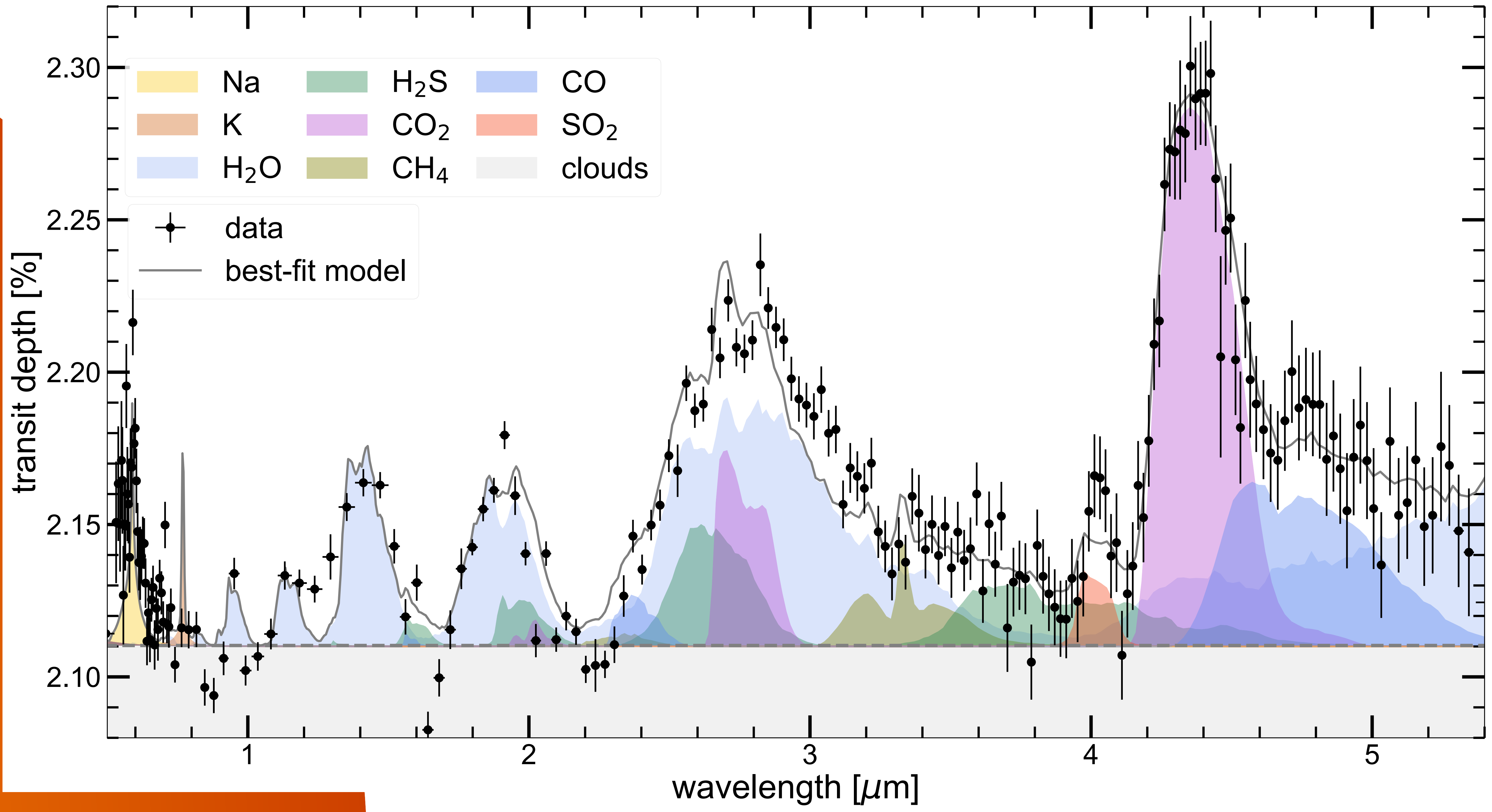
The Transit Opportunity





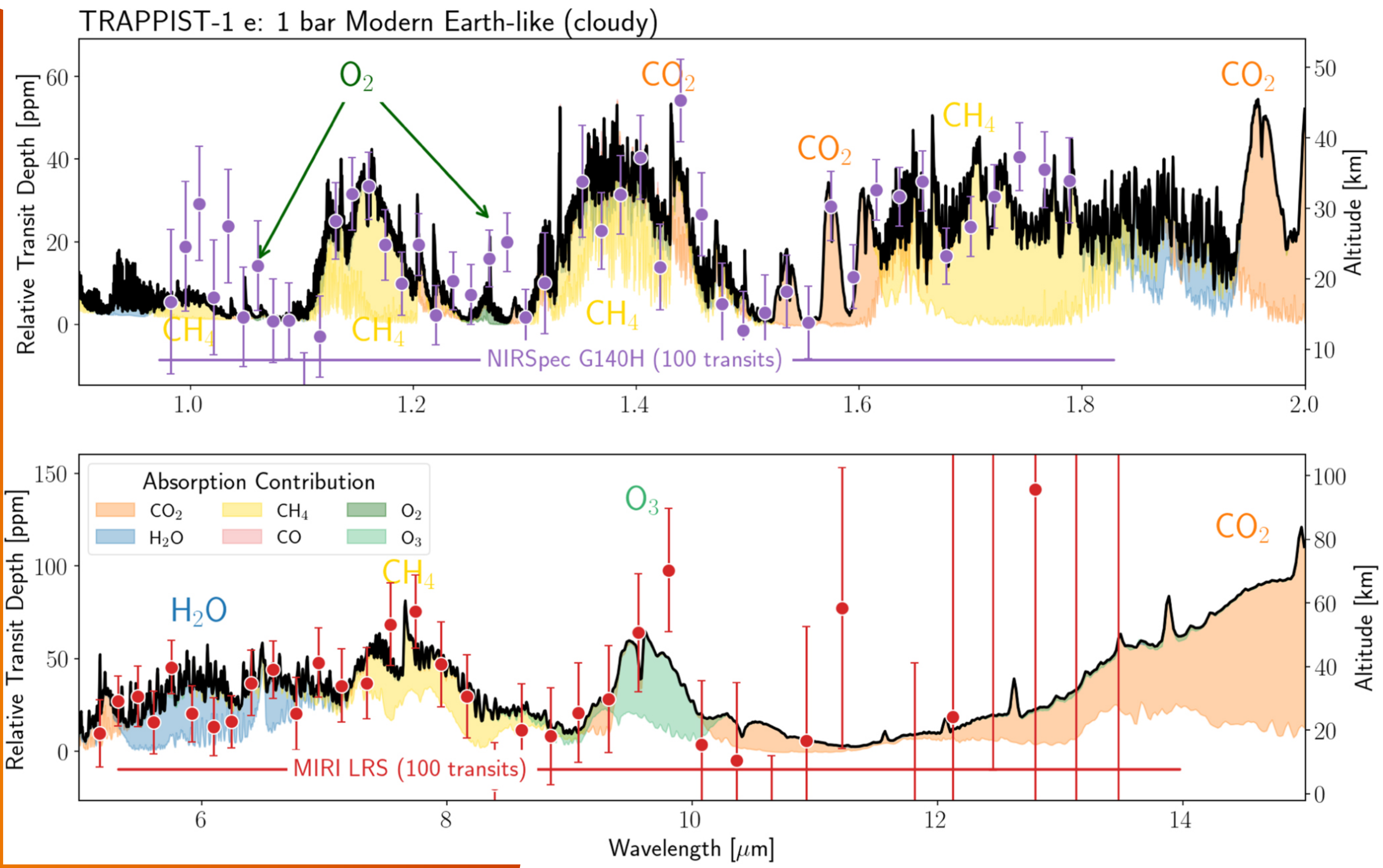
de Wit & Seager (2013)

The Transit Opportunity



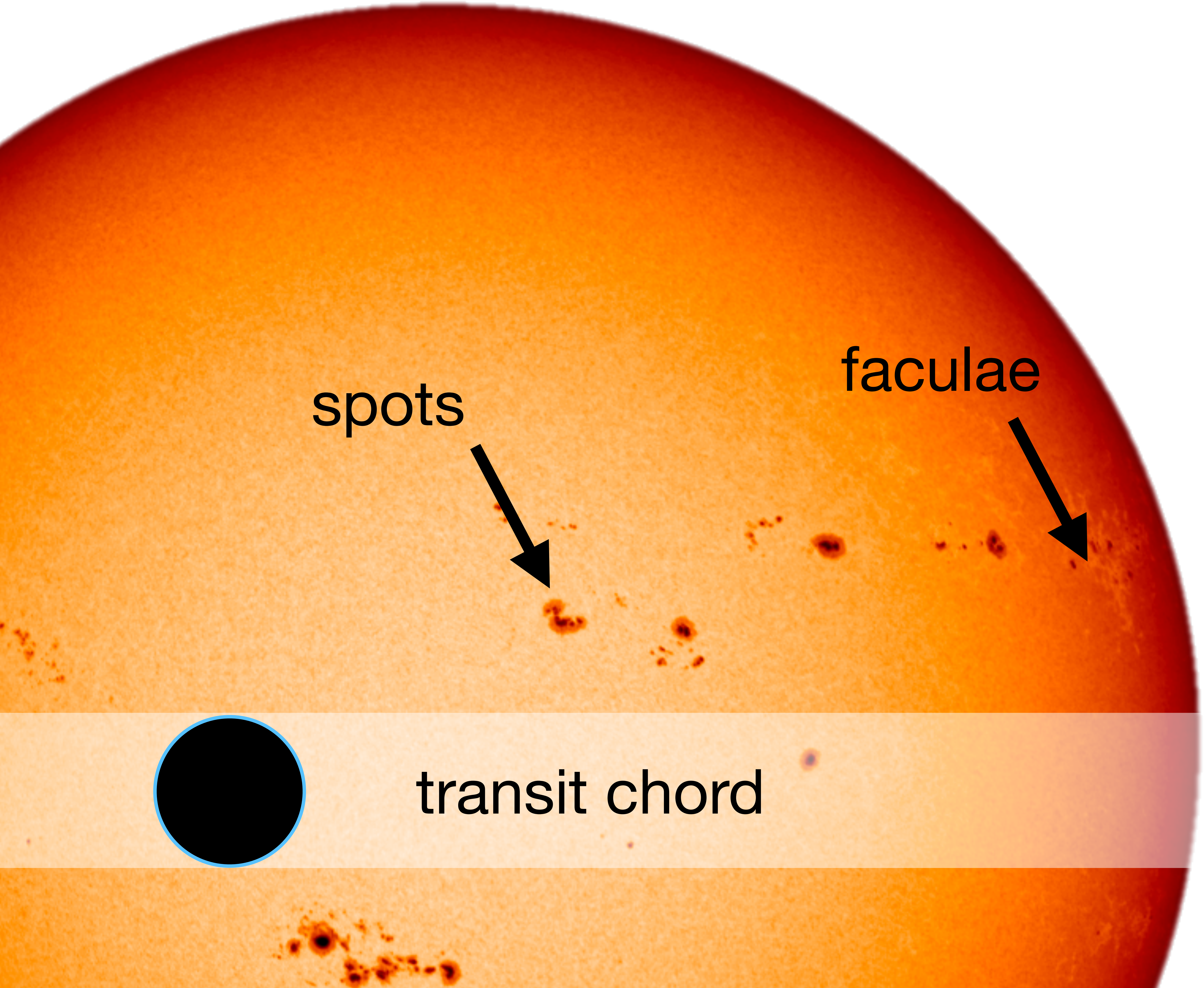
Rustamkulov et al. (2023)

The Transit Opportunity: Biosignatures?



Meadows et al. (2023)

The Transit Opportunity and Challenge



Stellar spottedness
affects transit depths too!

The Transit Light Source Effect

Rackham, Apai, & Giampapa (2018)

See also: Pont+08, Bean+10, Sing+11, Aigrain+12, Huitson+13, Jordán+13, Kreidberg+14, McCullough+14, Nikolov+15, Herrero+16, Zellem+17

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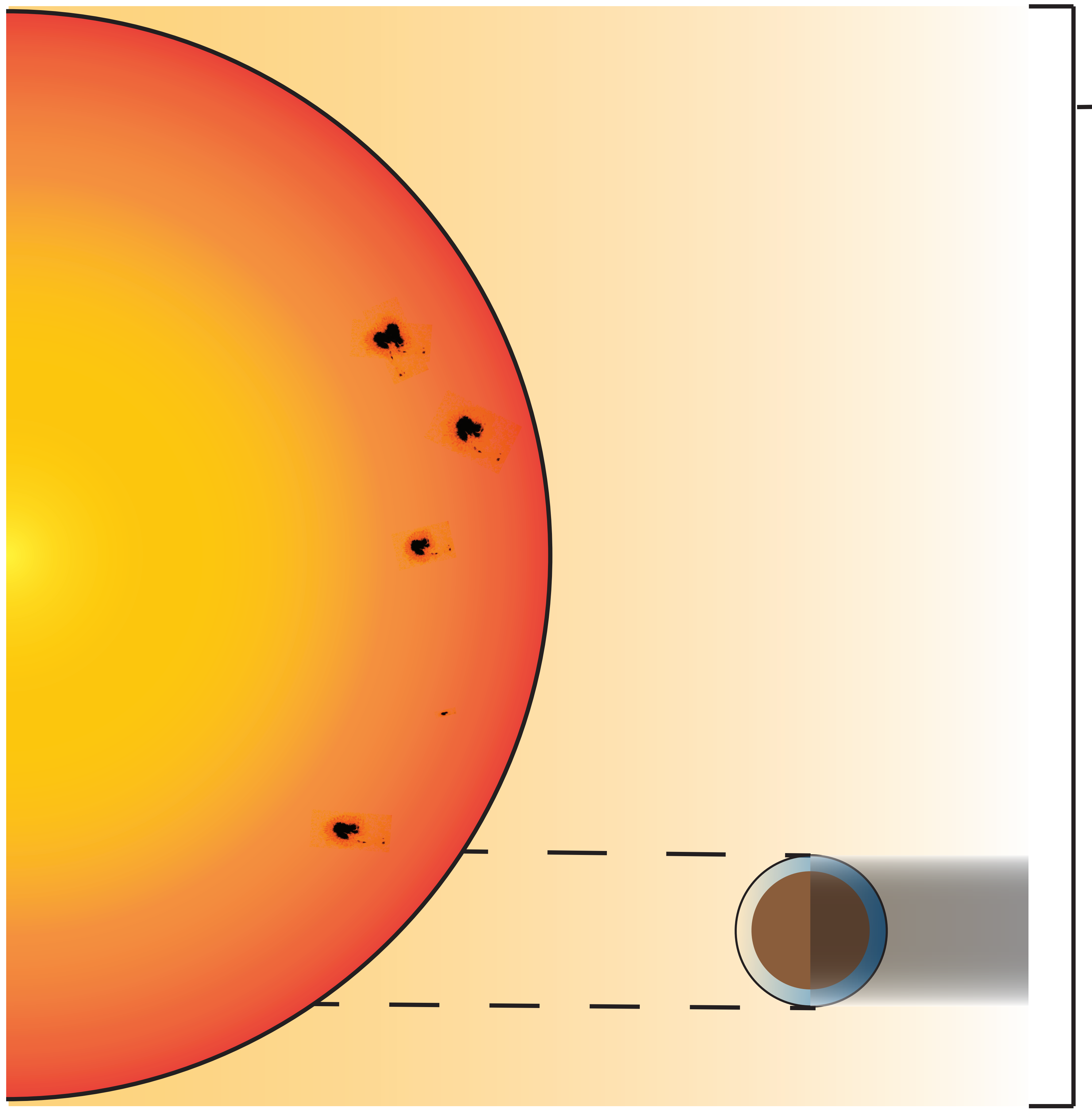
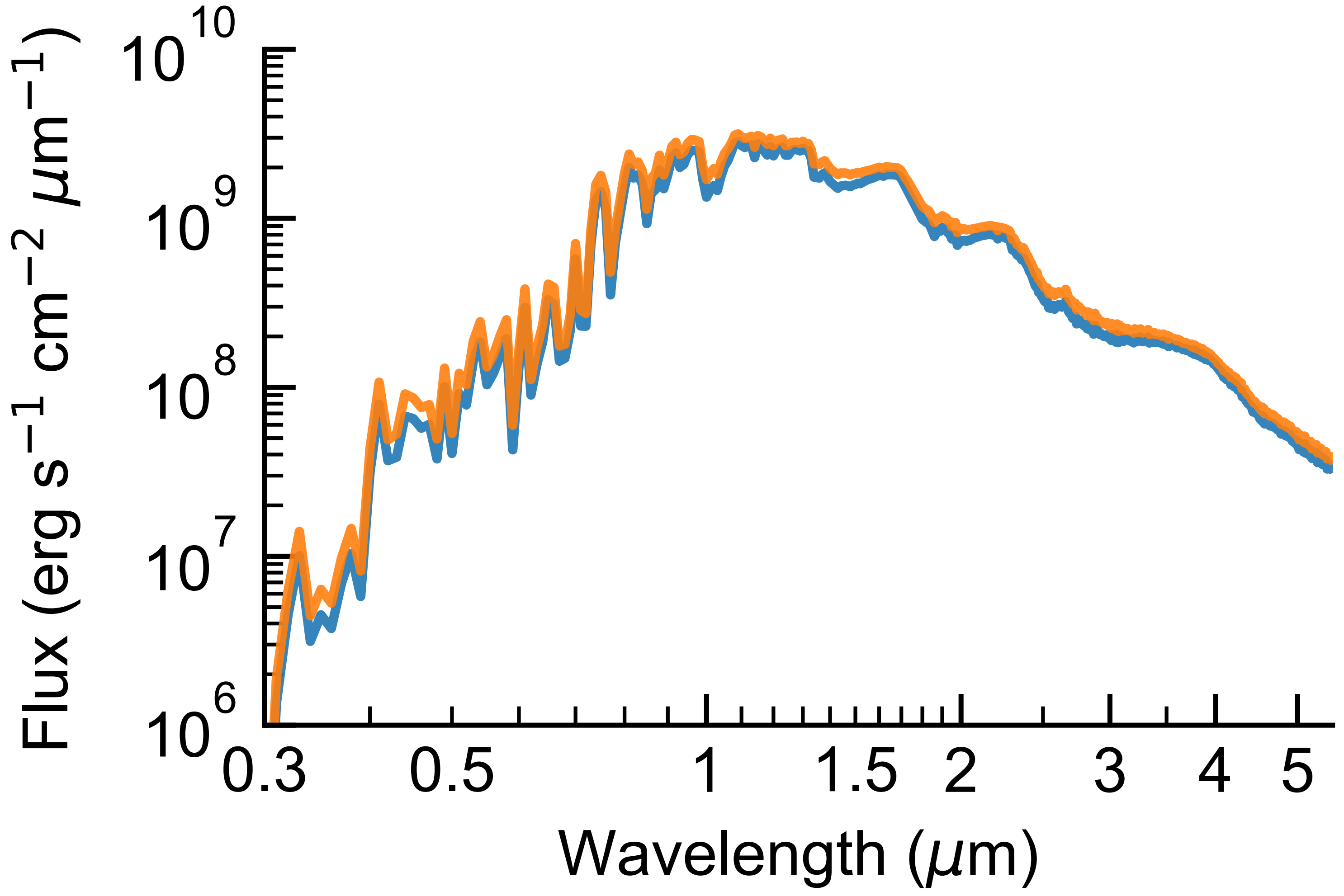


Pre-transit Stellar Disk is the **Assumed Light Source**



Actual Light Source is the Chord Defined by the Planet's Projection

Rackham, Apai, & Giampapa (2018)

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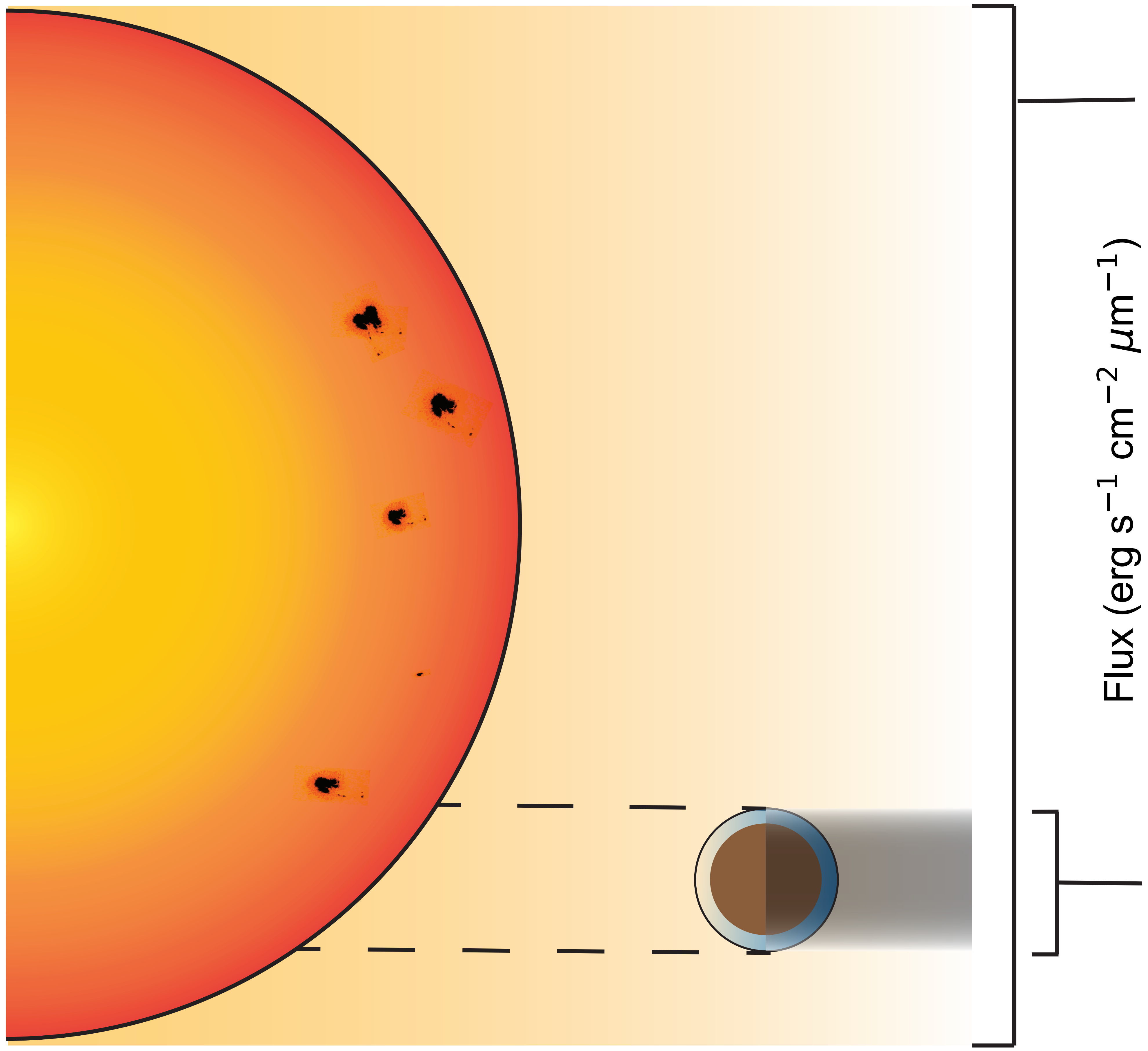

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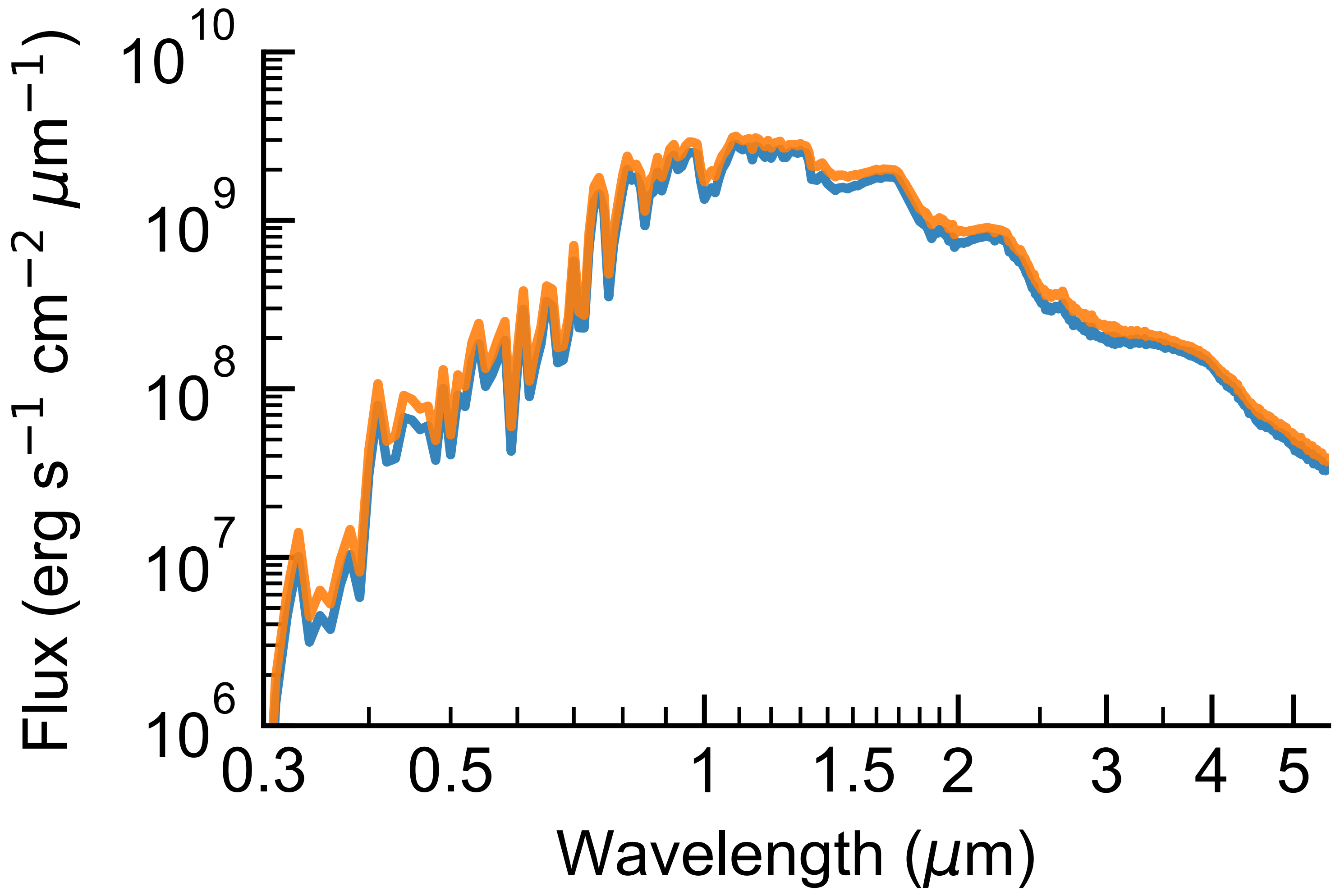
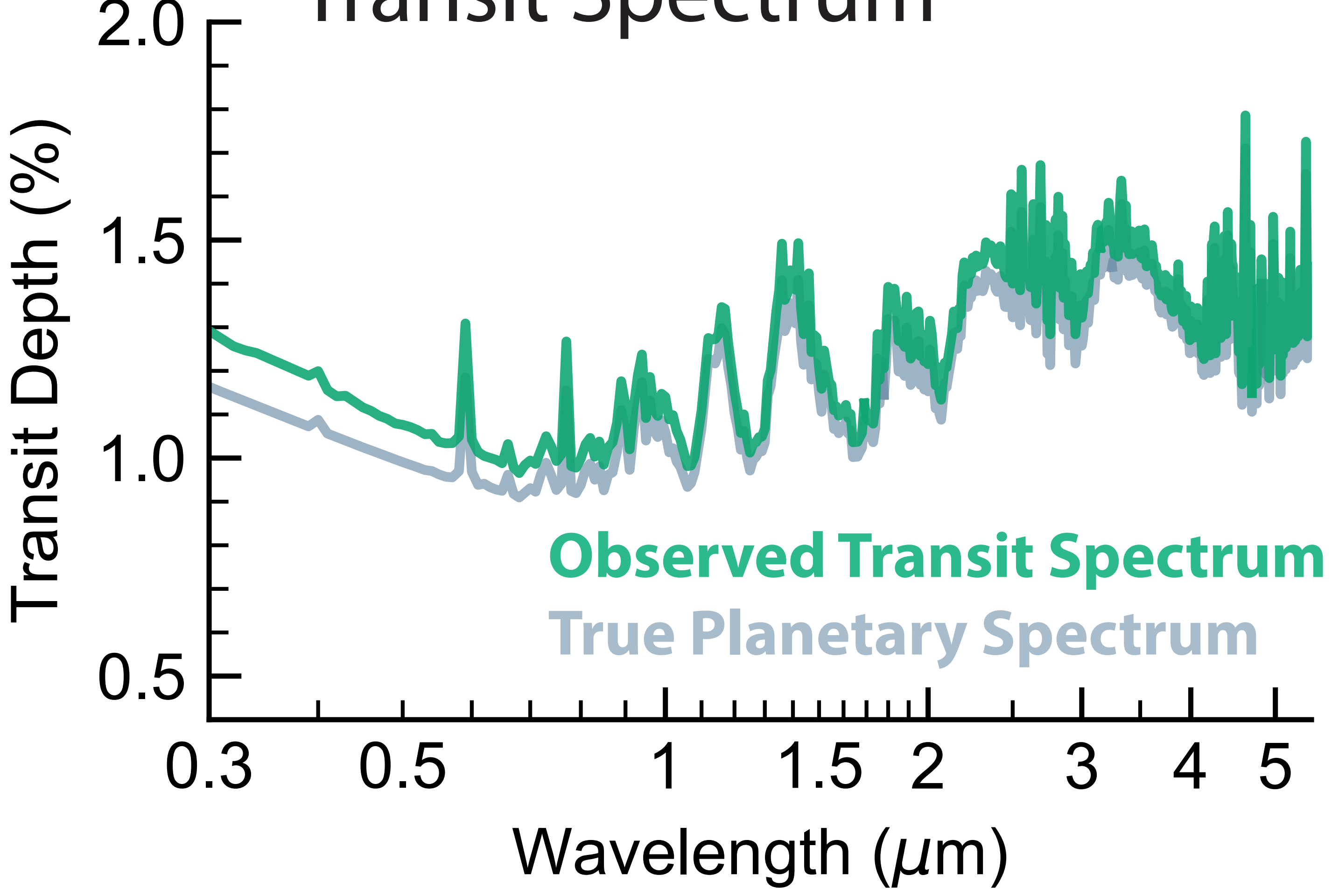


Spectral Difference due to Different Spot/Faculae Contributions Contaminates Transit Spectrum



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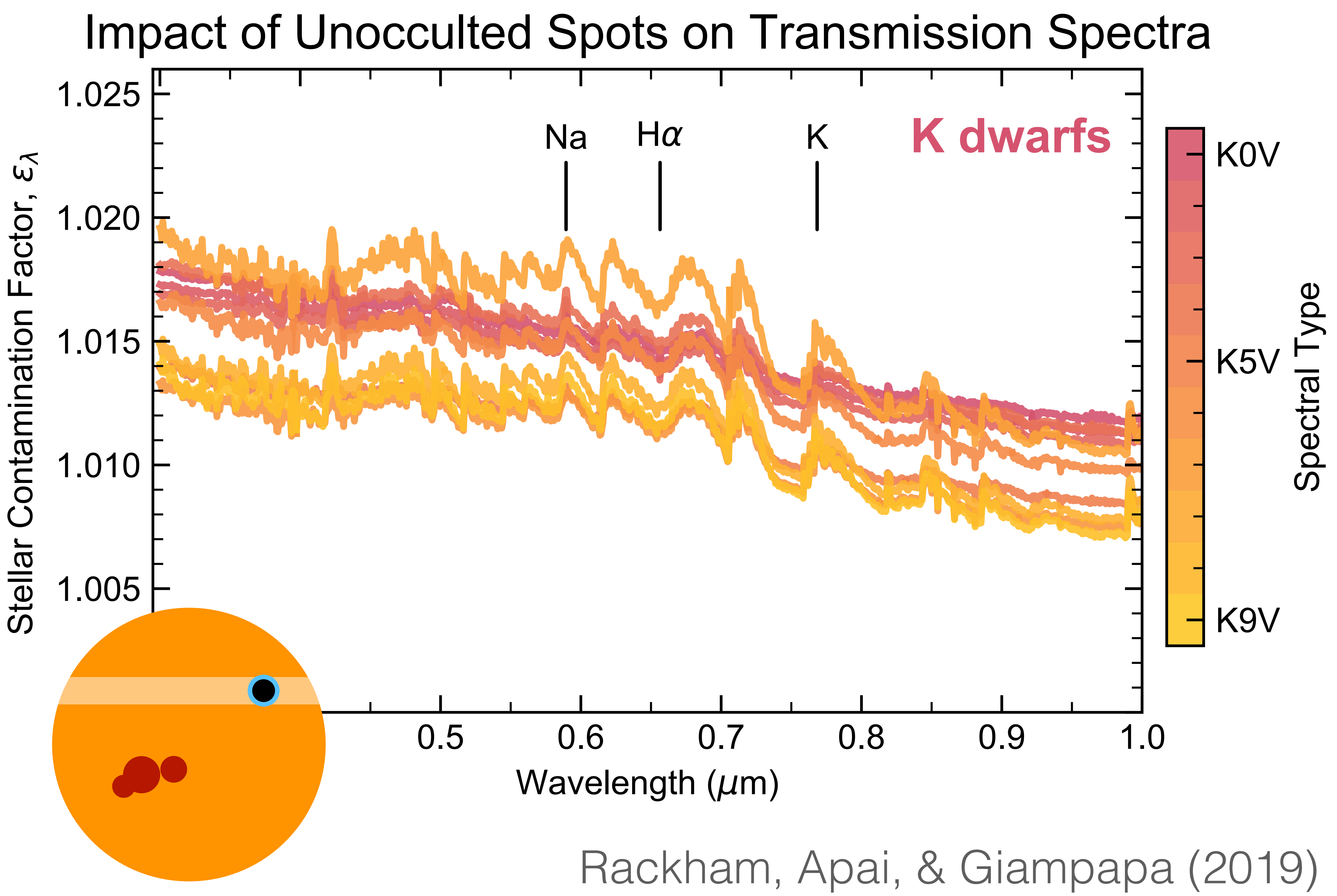
The TLS effect is largest for K and M dwarfs



Rackham, Apai, & Giampapa (2019)

Rackham, Apai, & Giampapa (2018)

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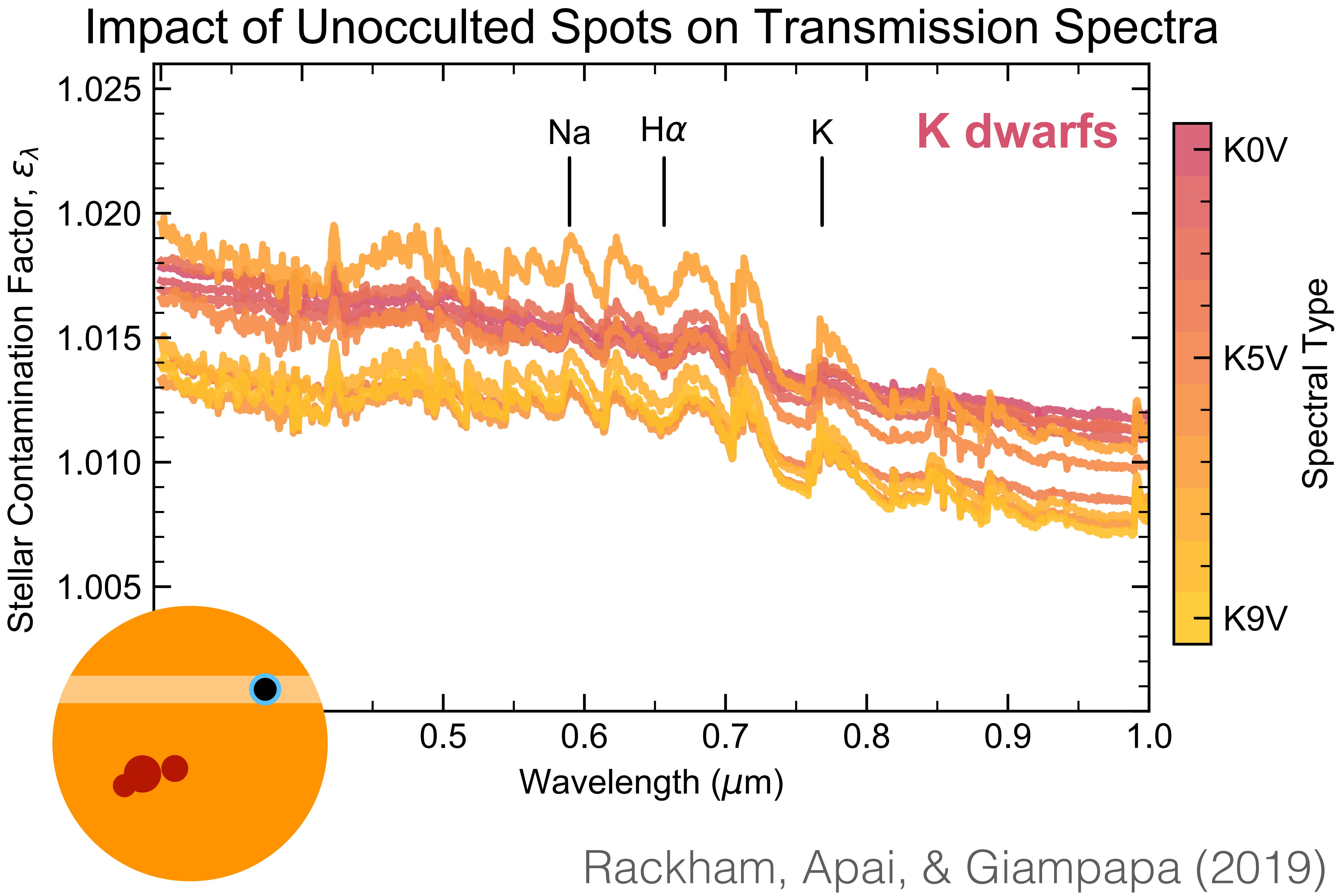

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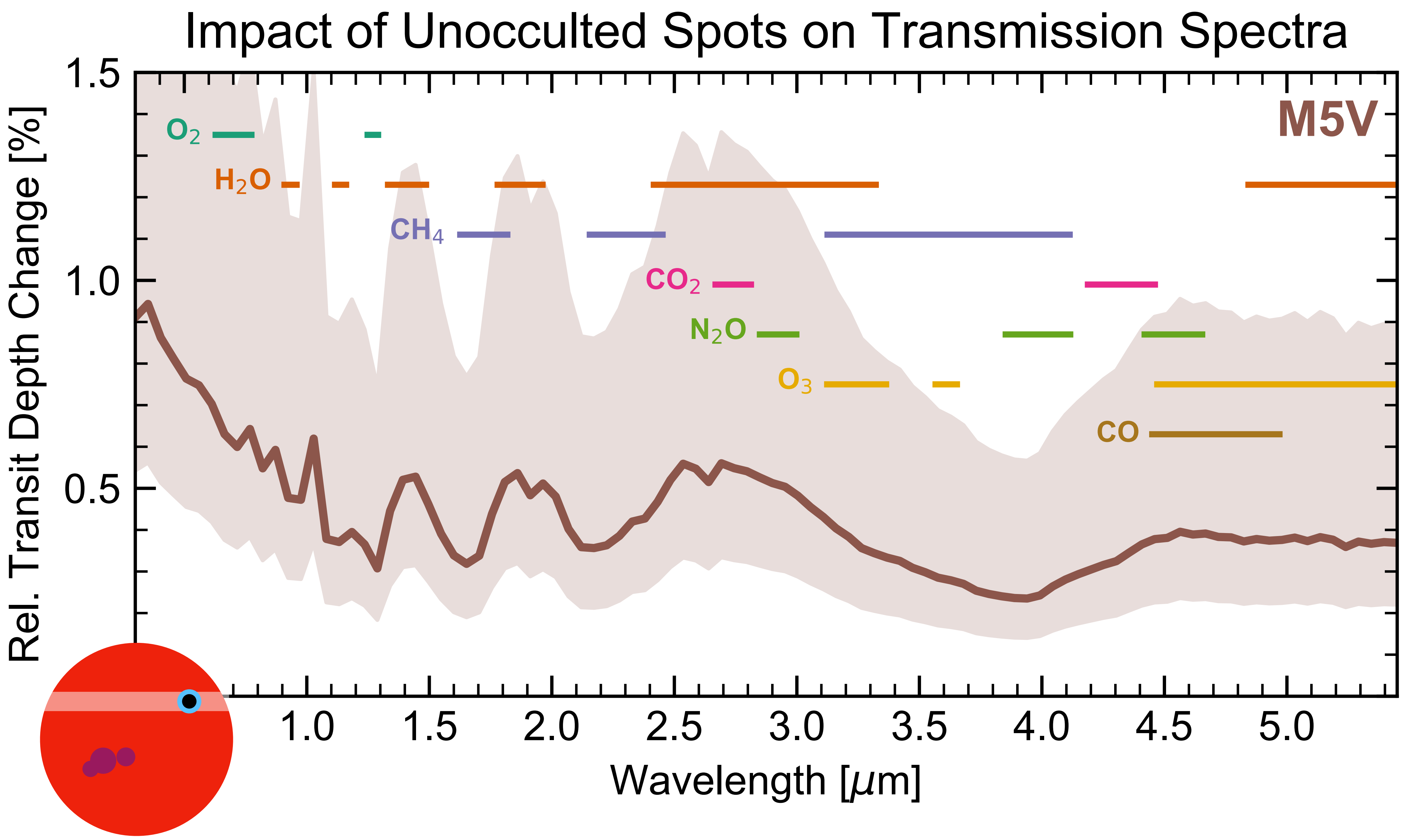

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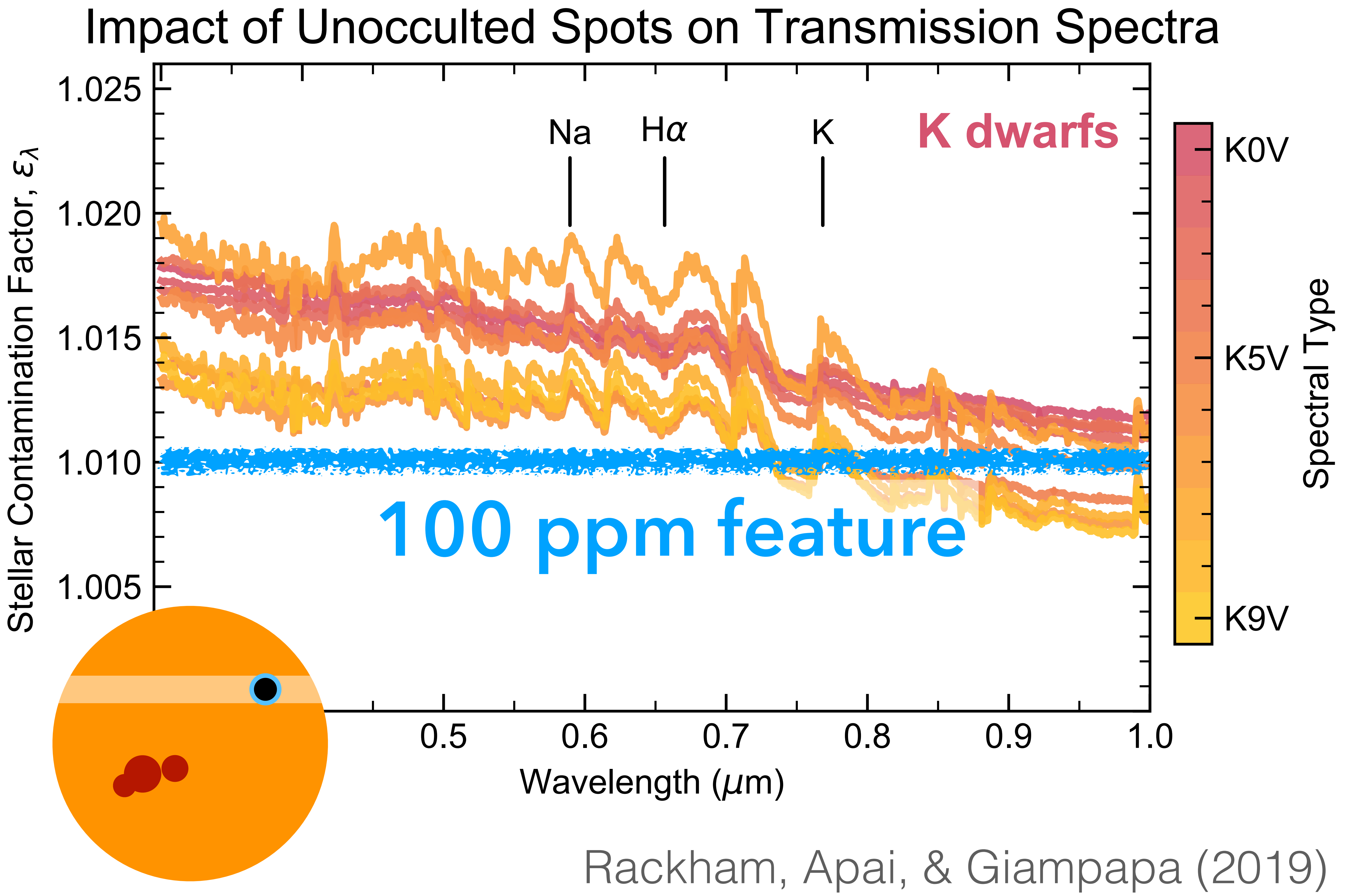

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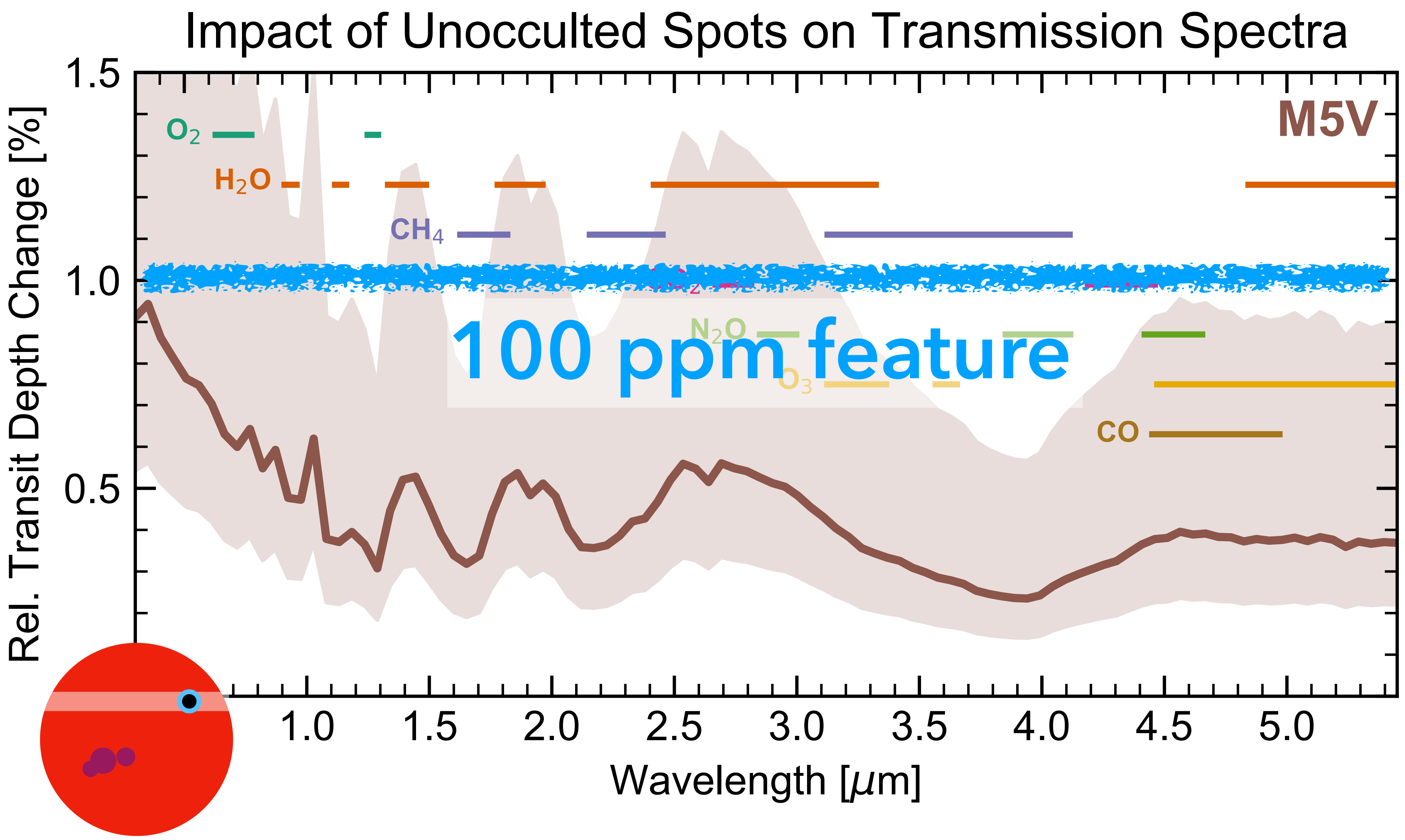

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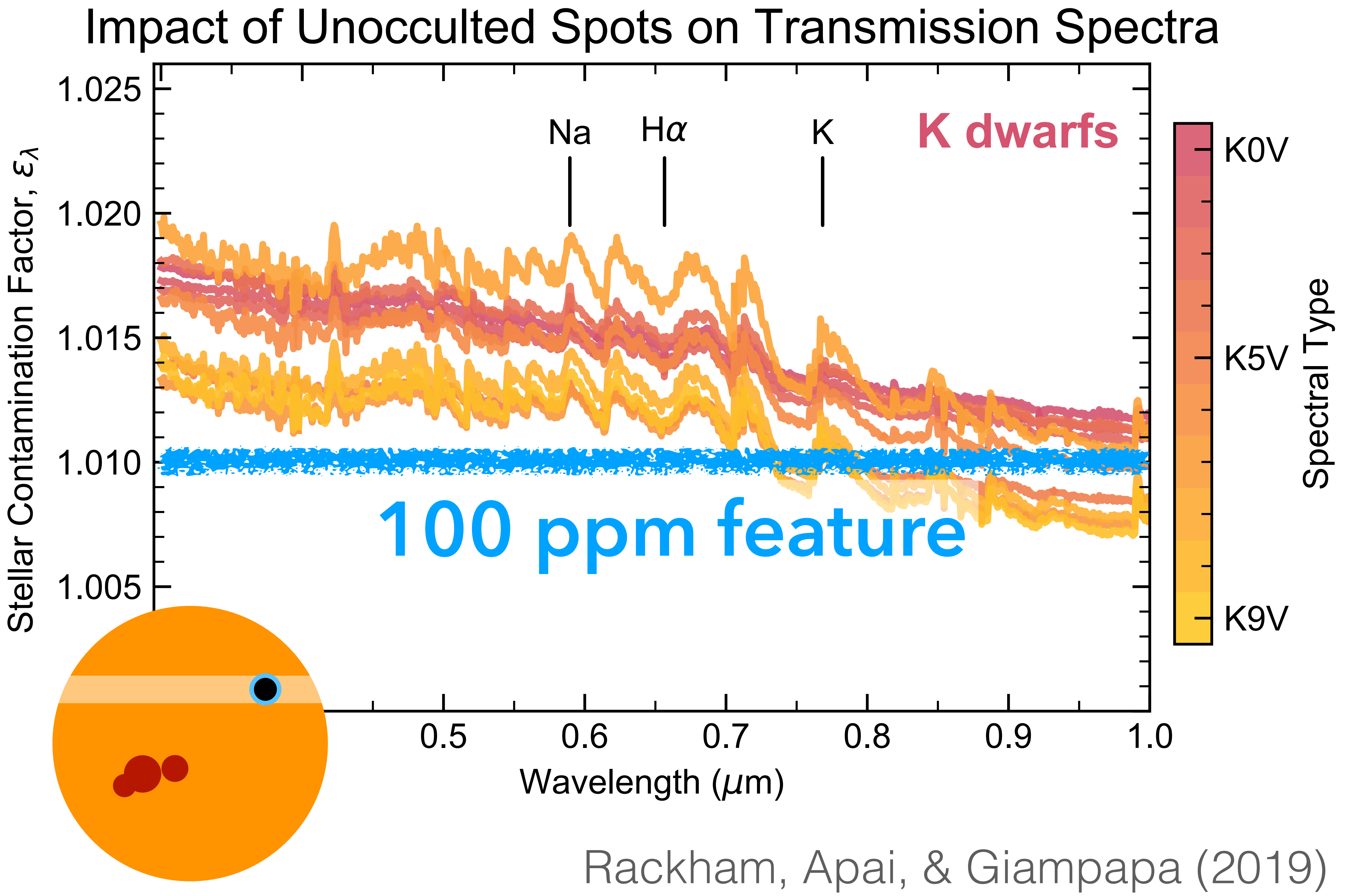
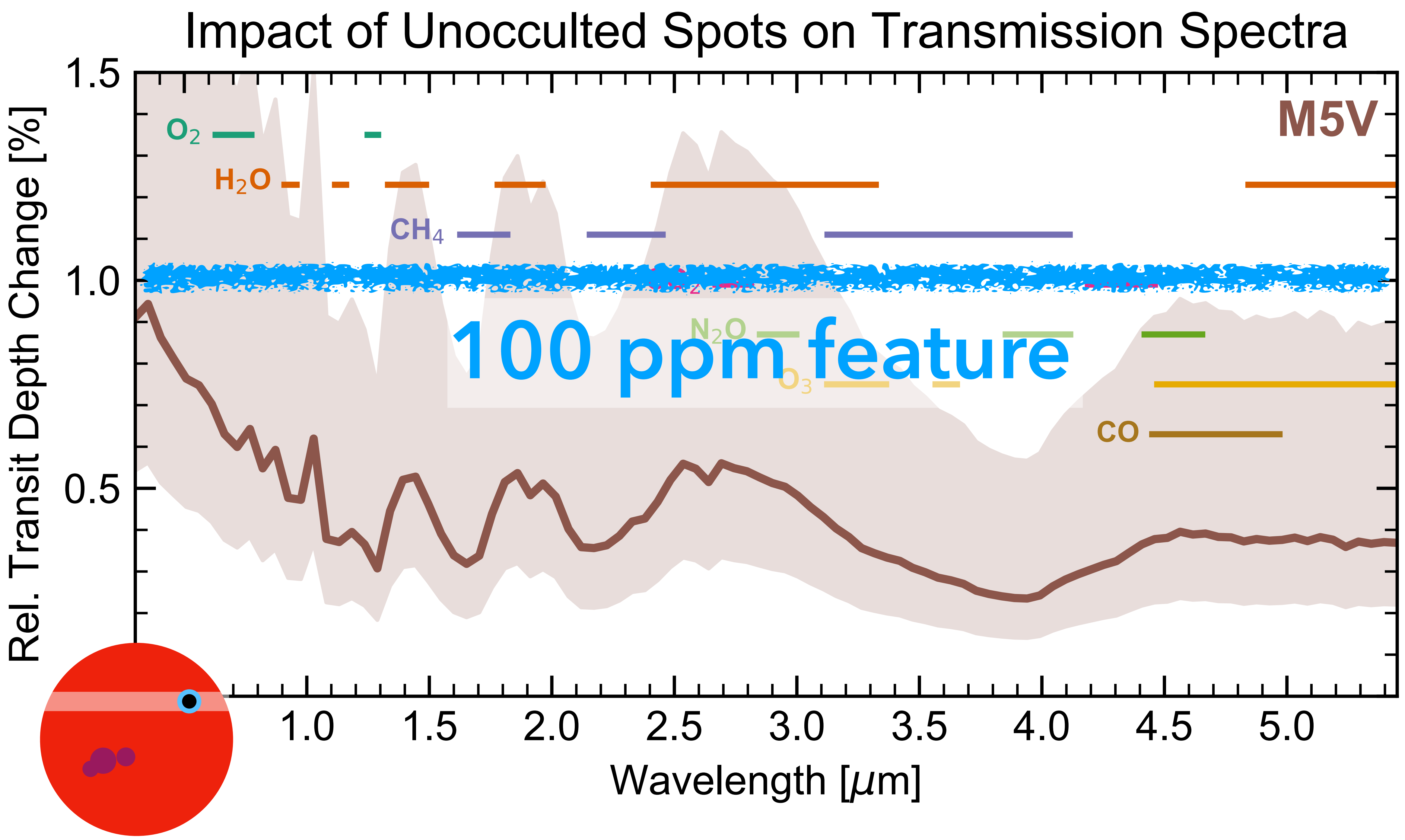
The TLS effect is largest for **K and M dwarfs**



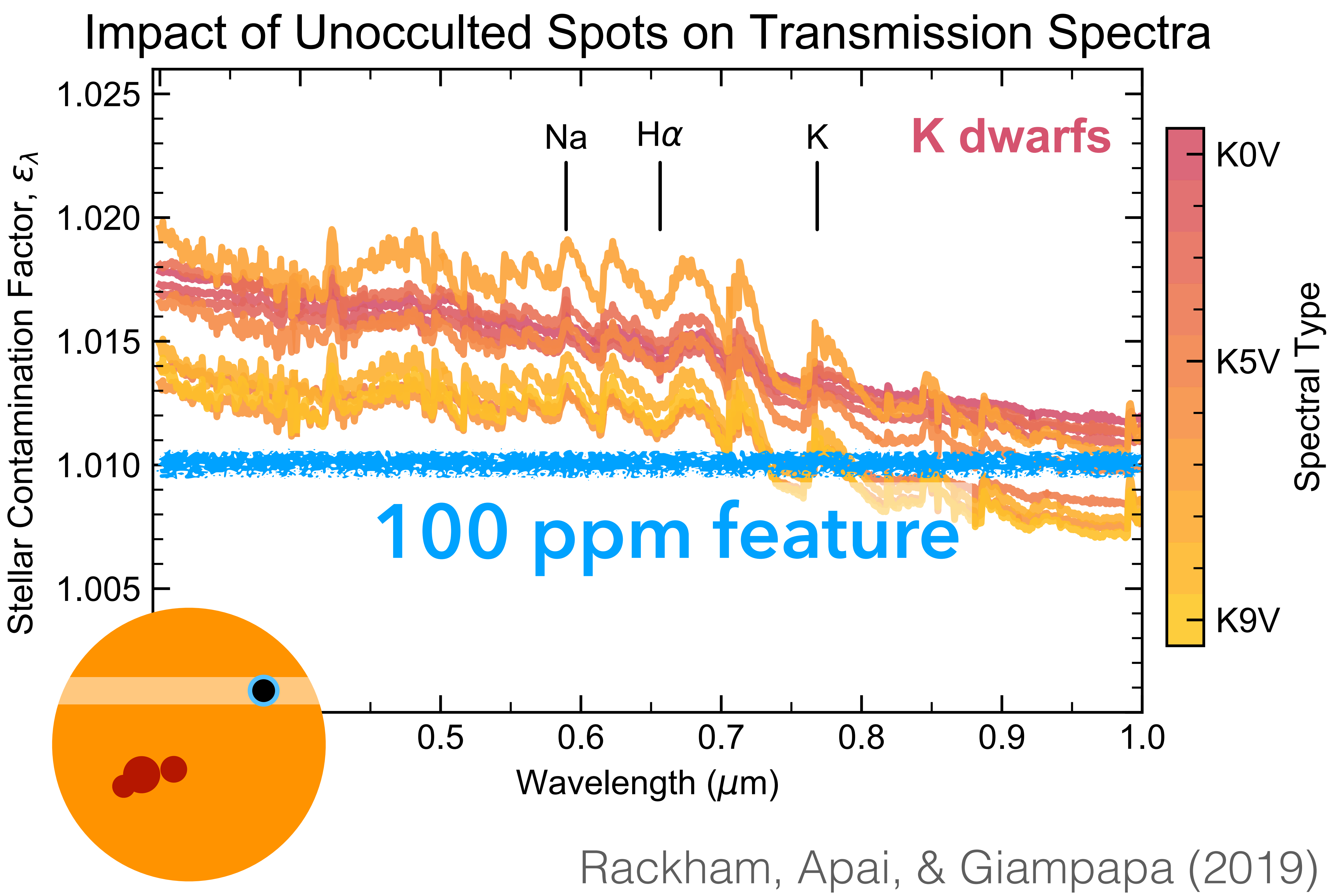
Rackham, Apai, & Giampapa (2019)



Rackham, Apai, & Giampapa (2018)

They can imprint **molecular features** on transit depths

The TLS effect is largest for **K and M dwarfs**



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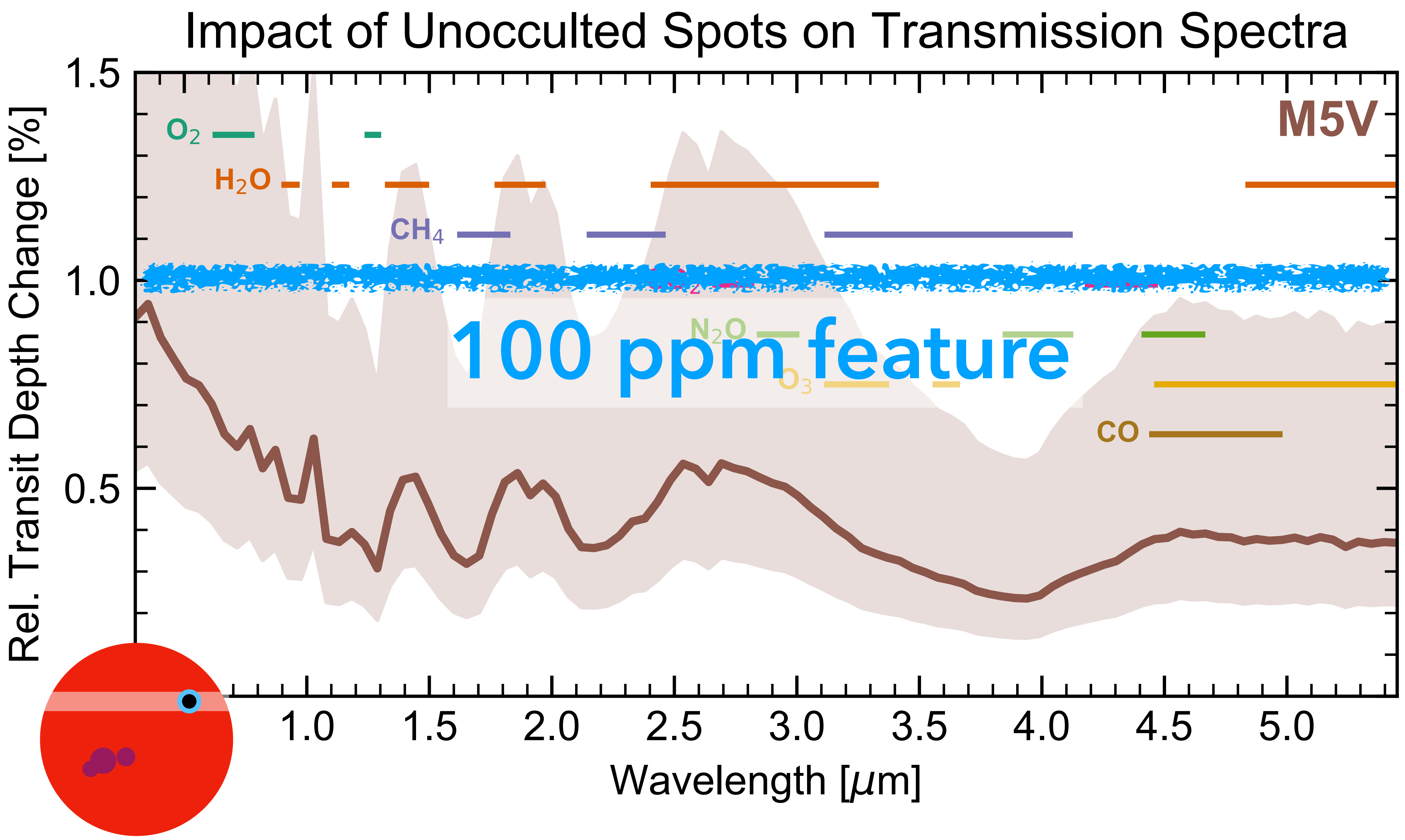


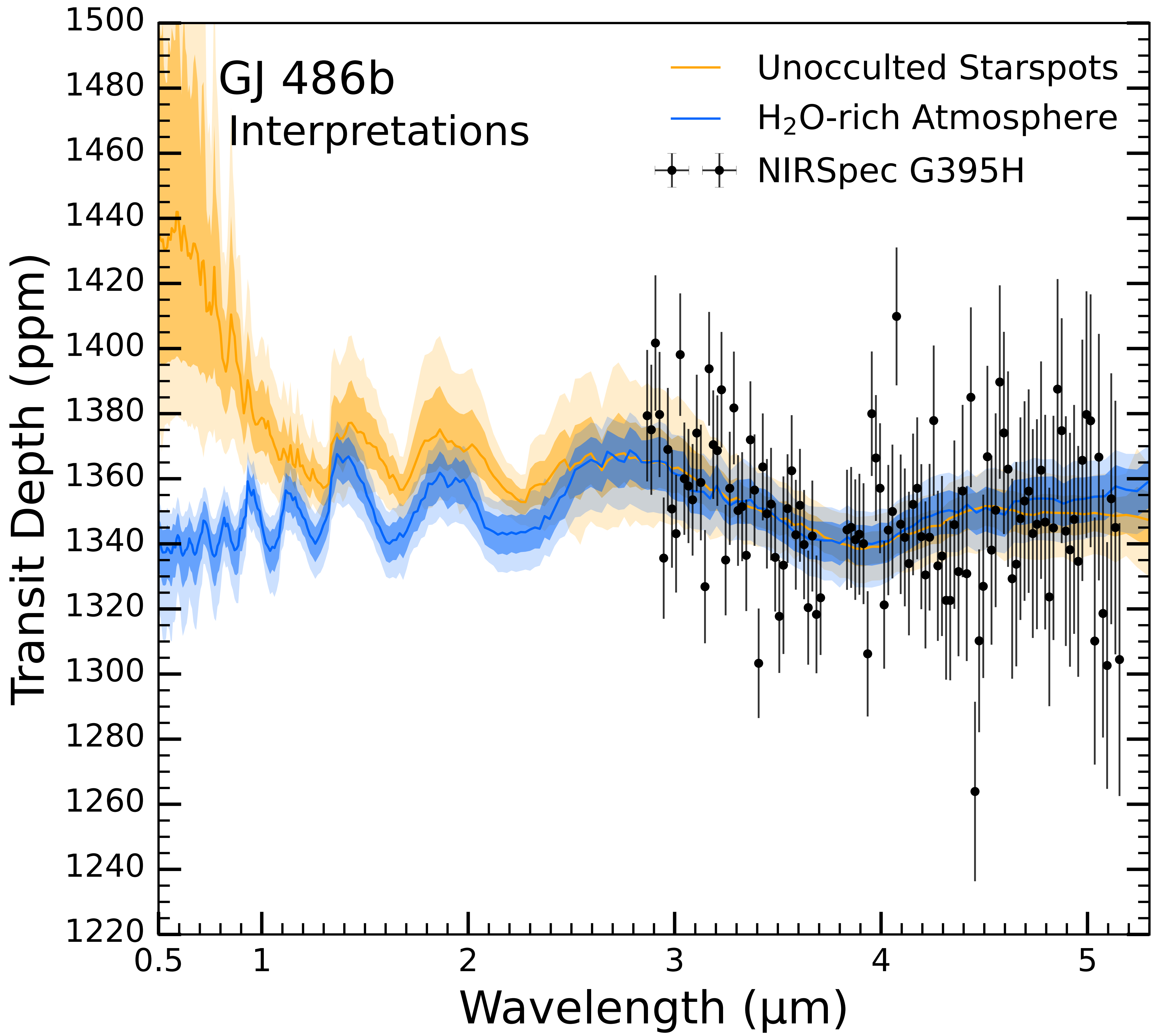
Rackham, Apai, & Giampapa (2018)

They can imprint **molecular features** on transit depths
that are **comparable to or much larger than** planetary features.

Stellar activity is the **bottleneck** for JWST transit observations of **small exoplanets**.

5 MIN READ

Webb Finds Water Vapor, But From a Rocky Planet or Its Star?



Moran, Stevenson et al. (2023)

Stellar activity is the **bottleneck** for JWST transit observations of **small exoplanets**.

See talks from **Caroline Piaulet-Ghorayeb**, **Arianna Saba, Catriona Murray**, **Natalie Allen**, **Luis Welbanks**, and **Michael Radica** and poster by **Ana Glidden**

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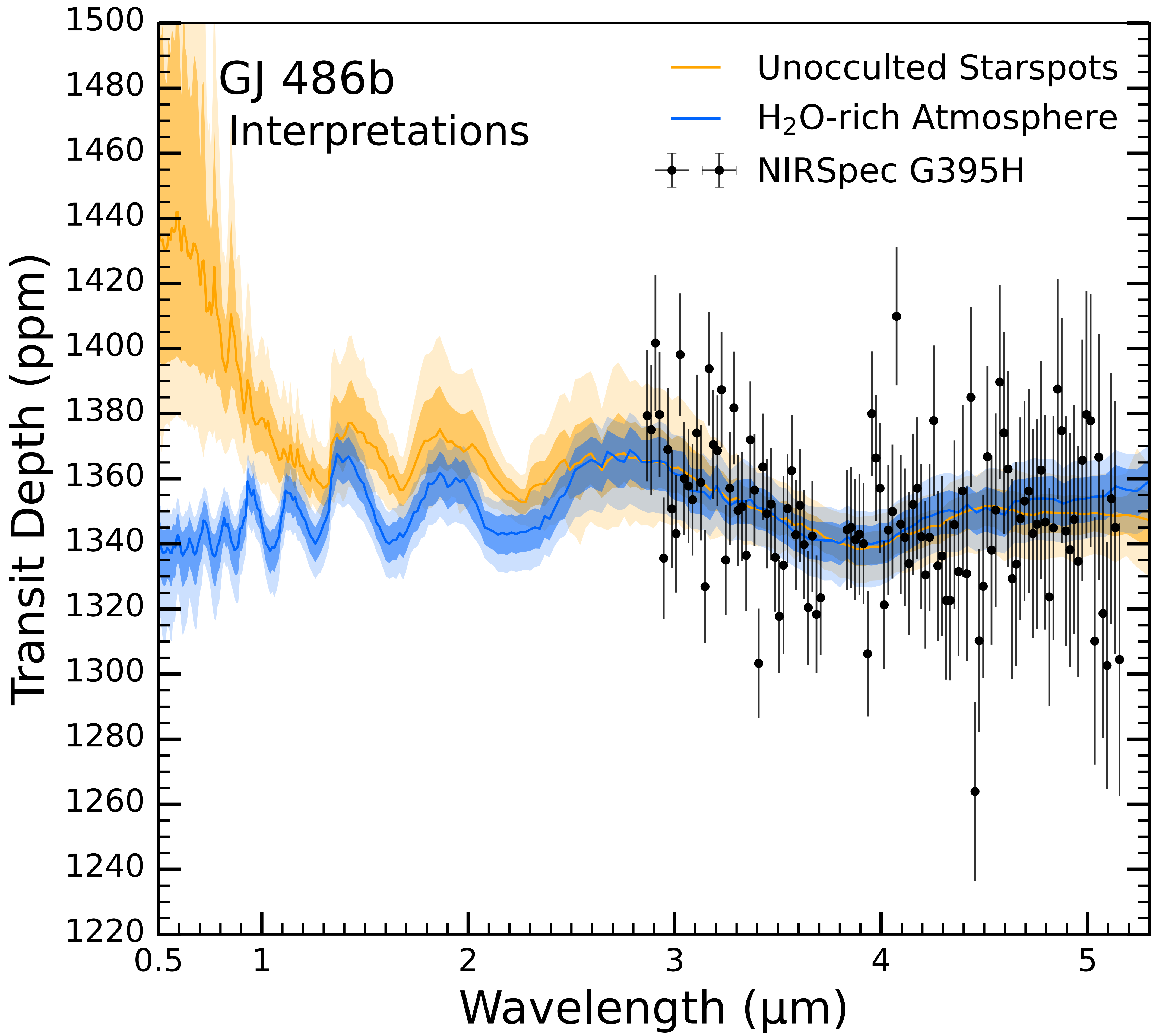

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ChatGPT:

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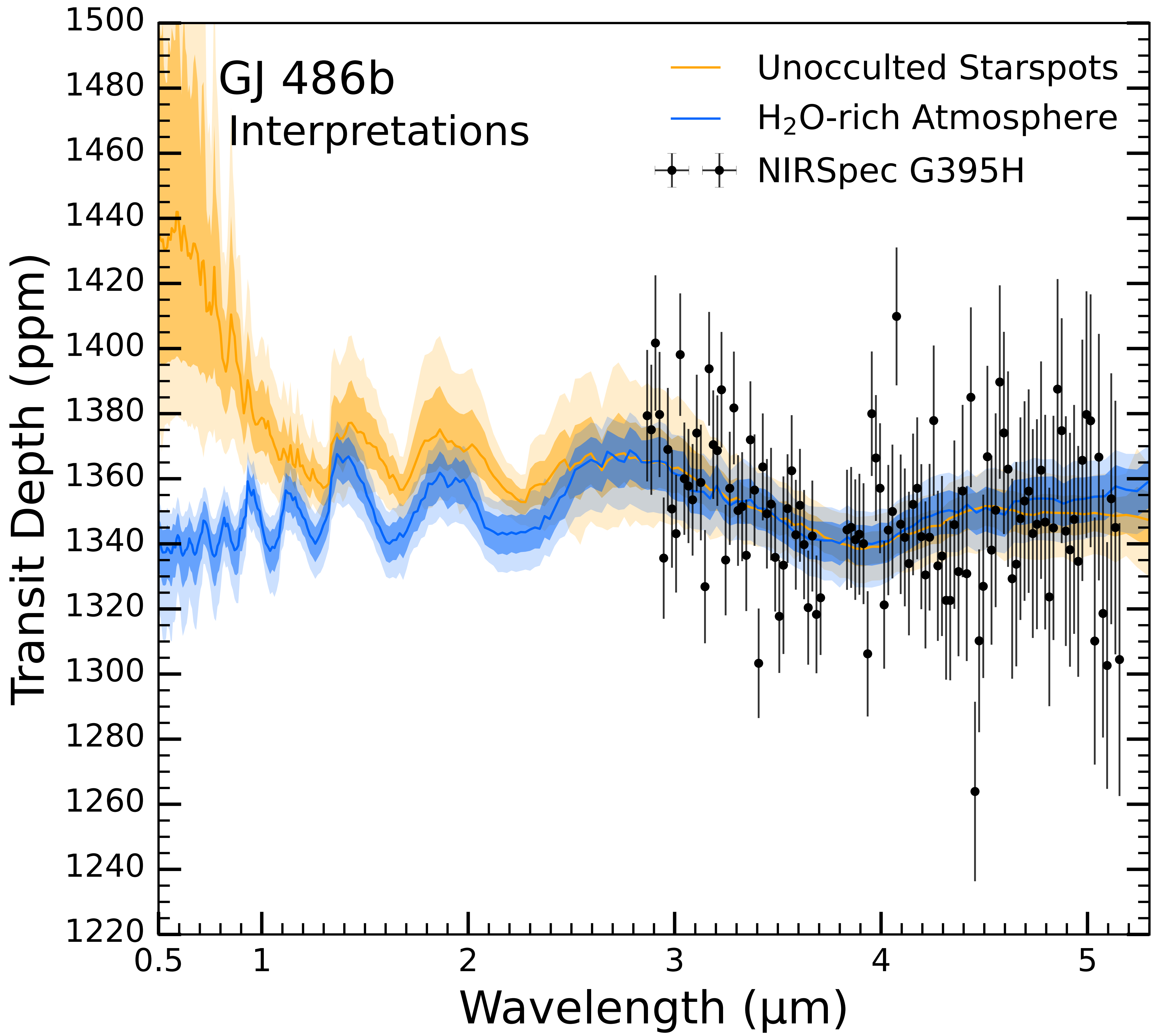

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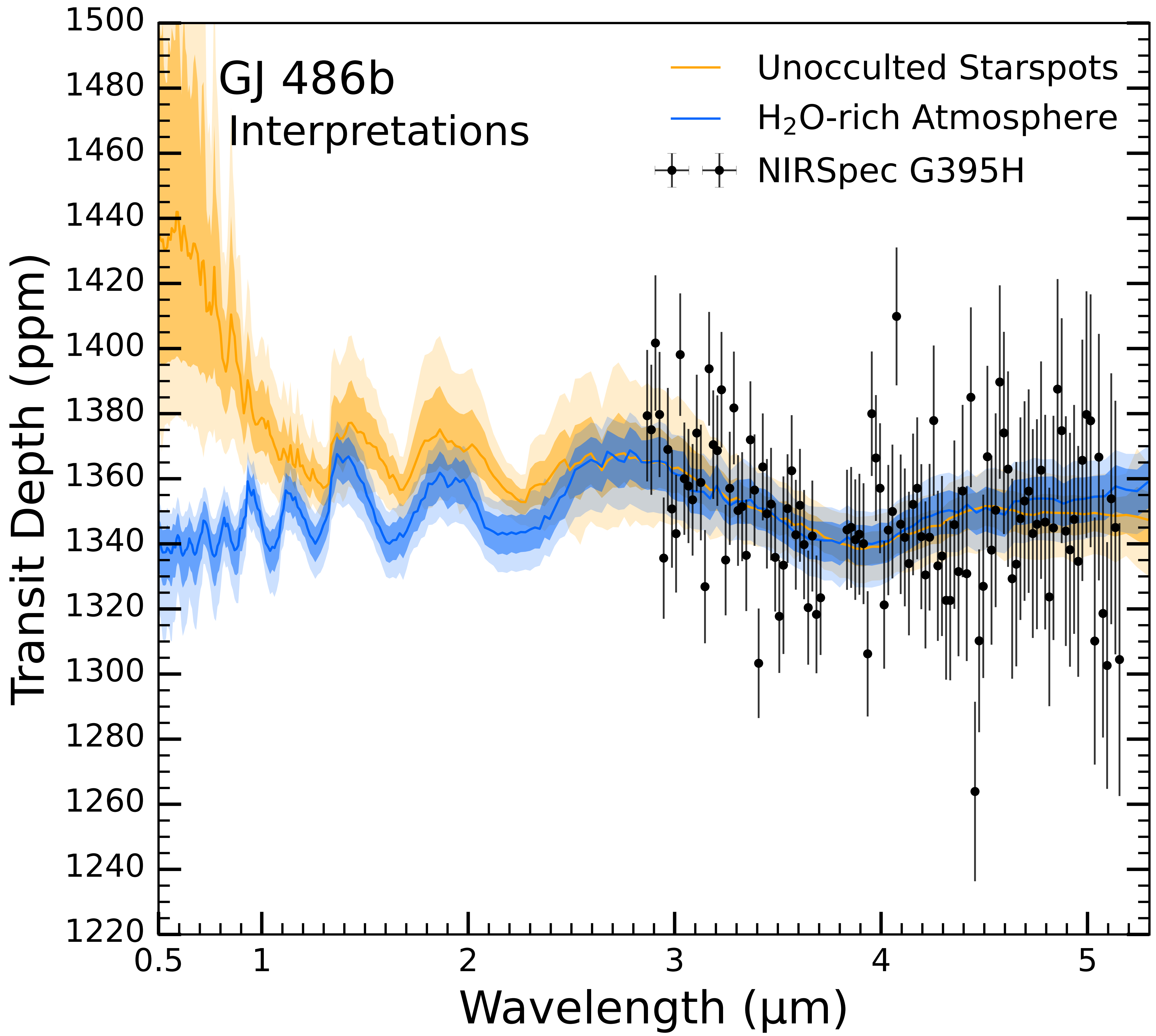
5 MIN READ

Webb Finds Water Vapor, But From a Rocky Planet or Its Star?

Stellar activity is the bottleneck for JWST transit observations of small exoplanets.

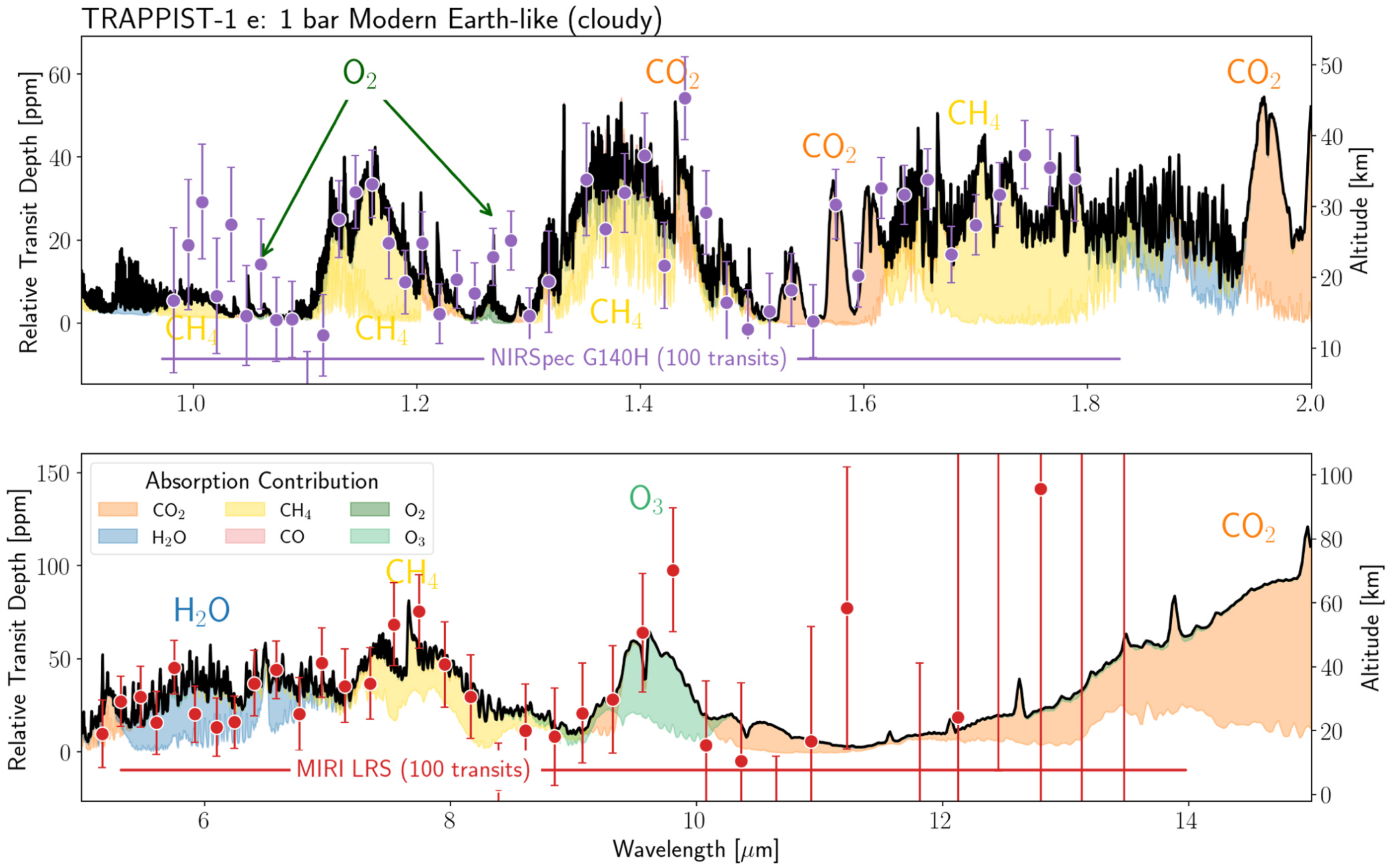
ChatGPT: JWST is revealing incredible details about exoplanet atmospheres. Or stellar atmospheres. We're still deciding.



Moran, Stevenson et al. (2023)

The stellar activity bottleneck

Goal: 10 ppm precision



Meadows et al. (2023)

Lim et al. (2023)

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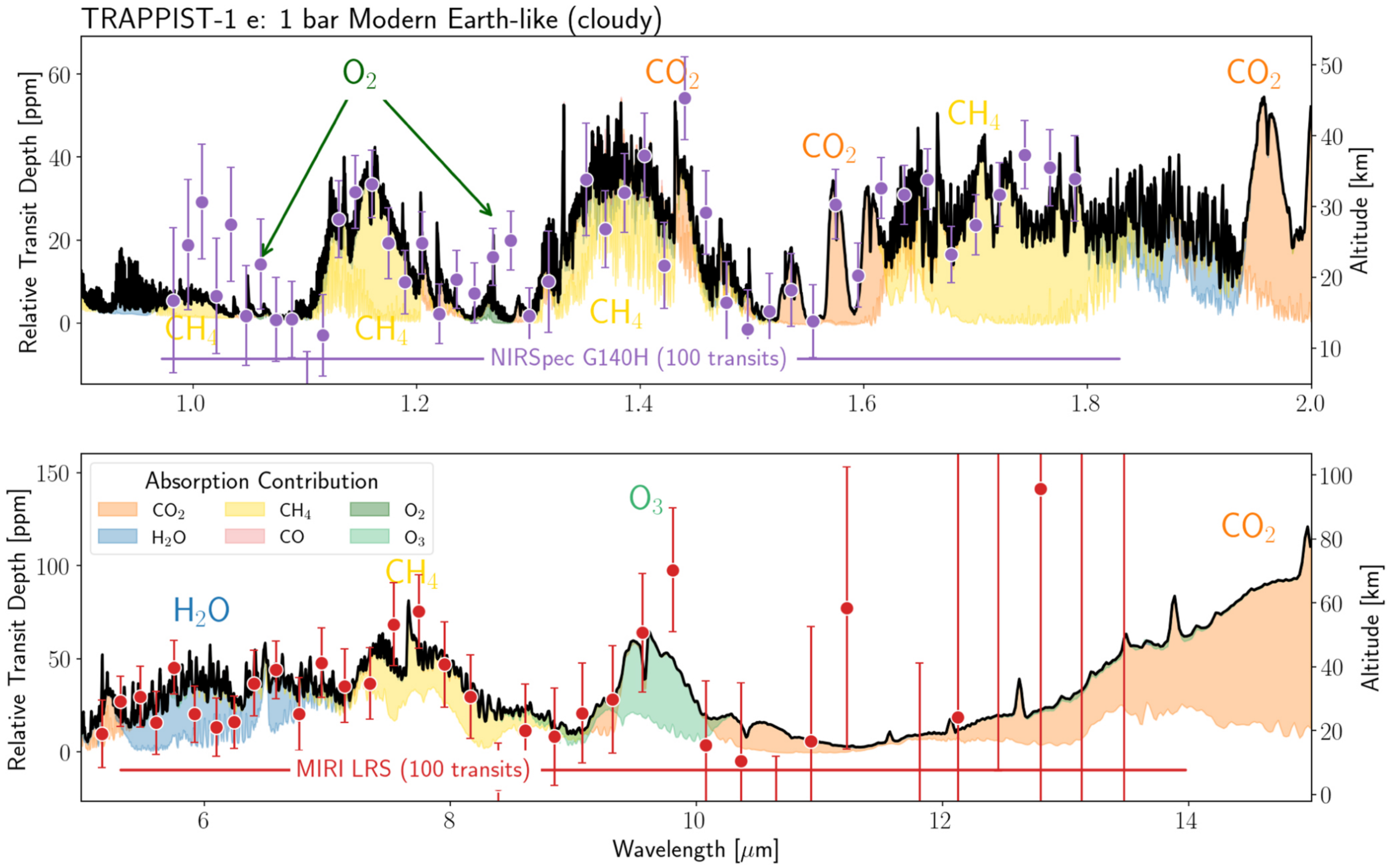
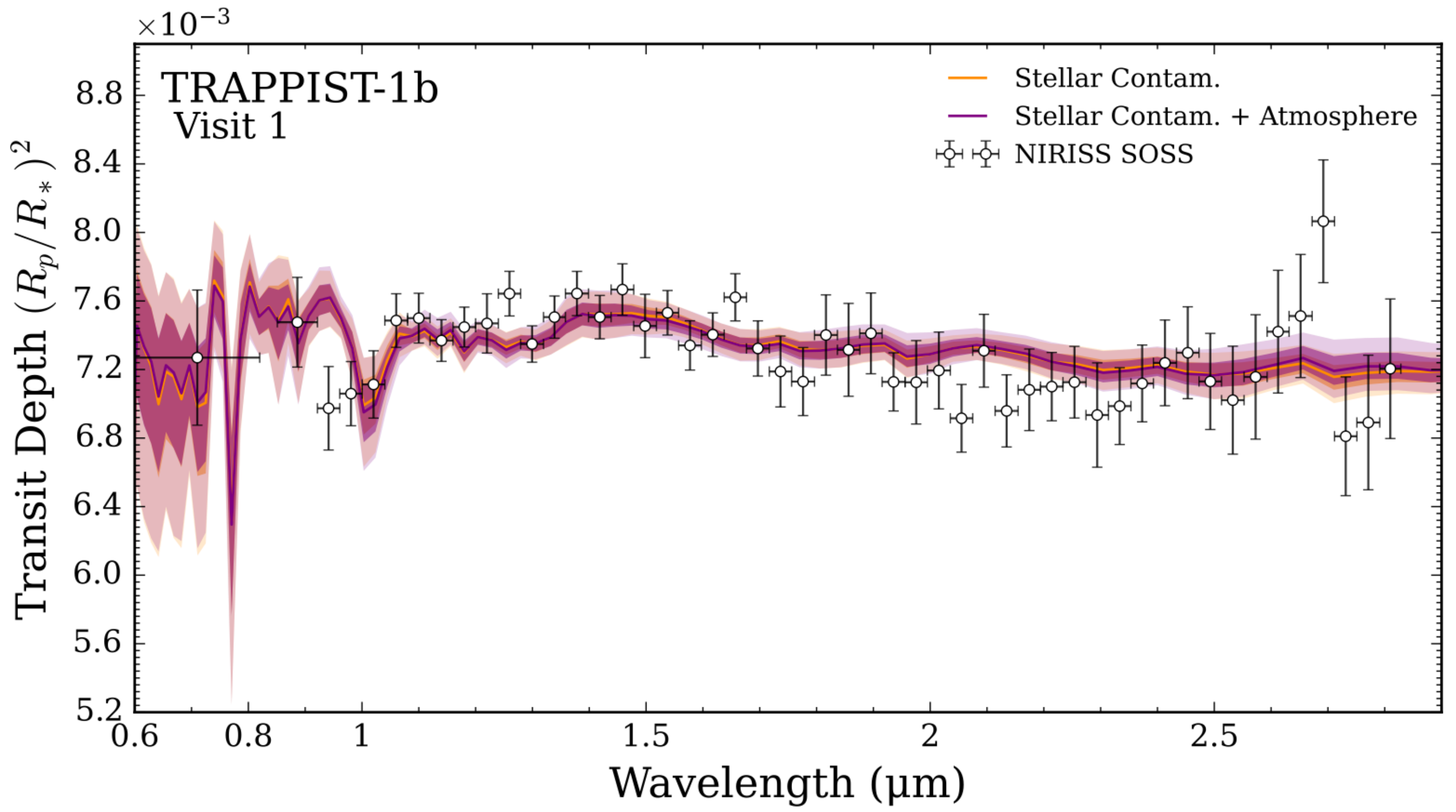


Meadows et al. (2023)

Reality: *O*(100–1000) ppm stellar signals



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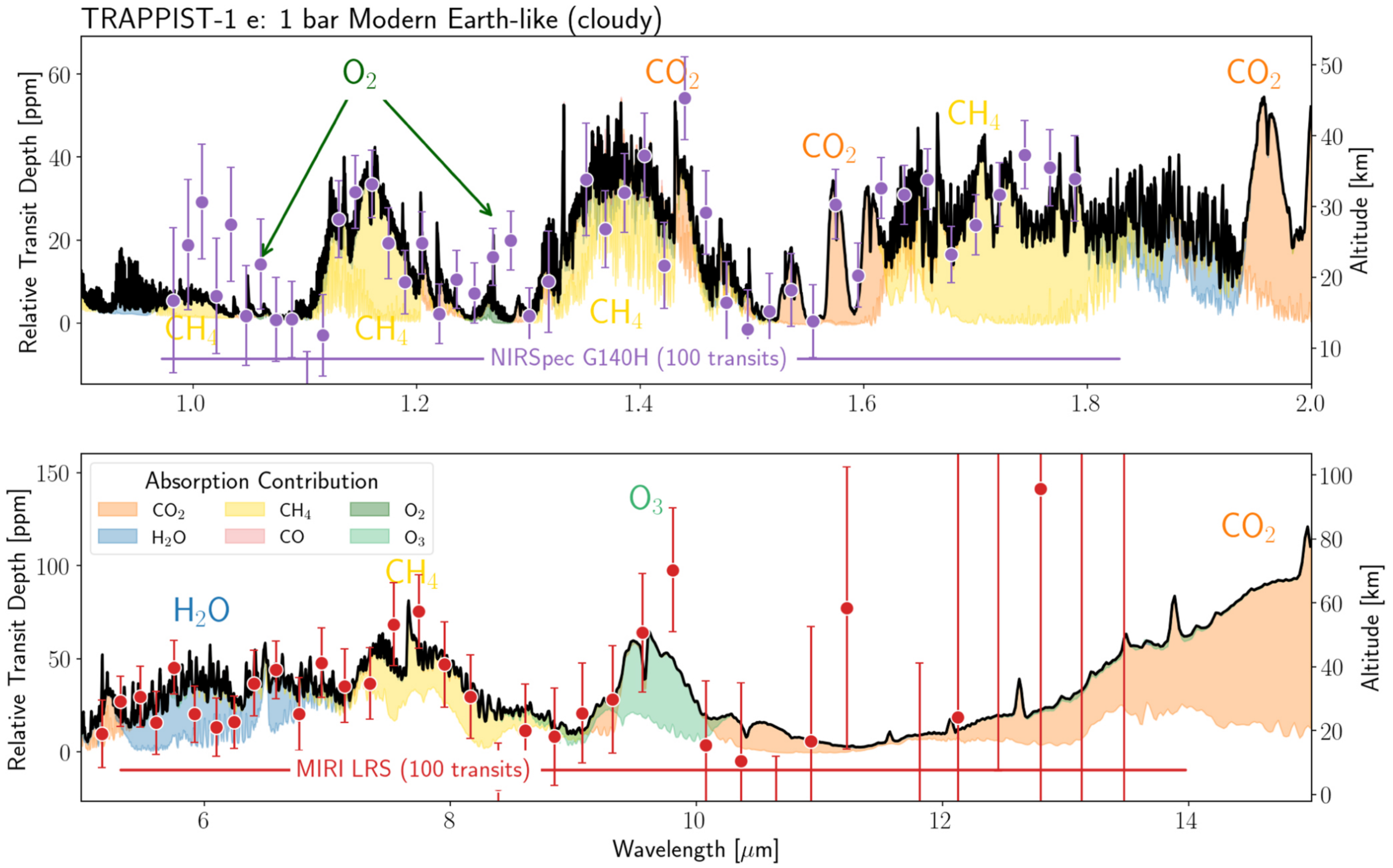

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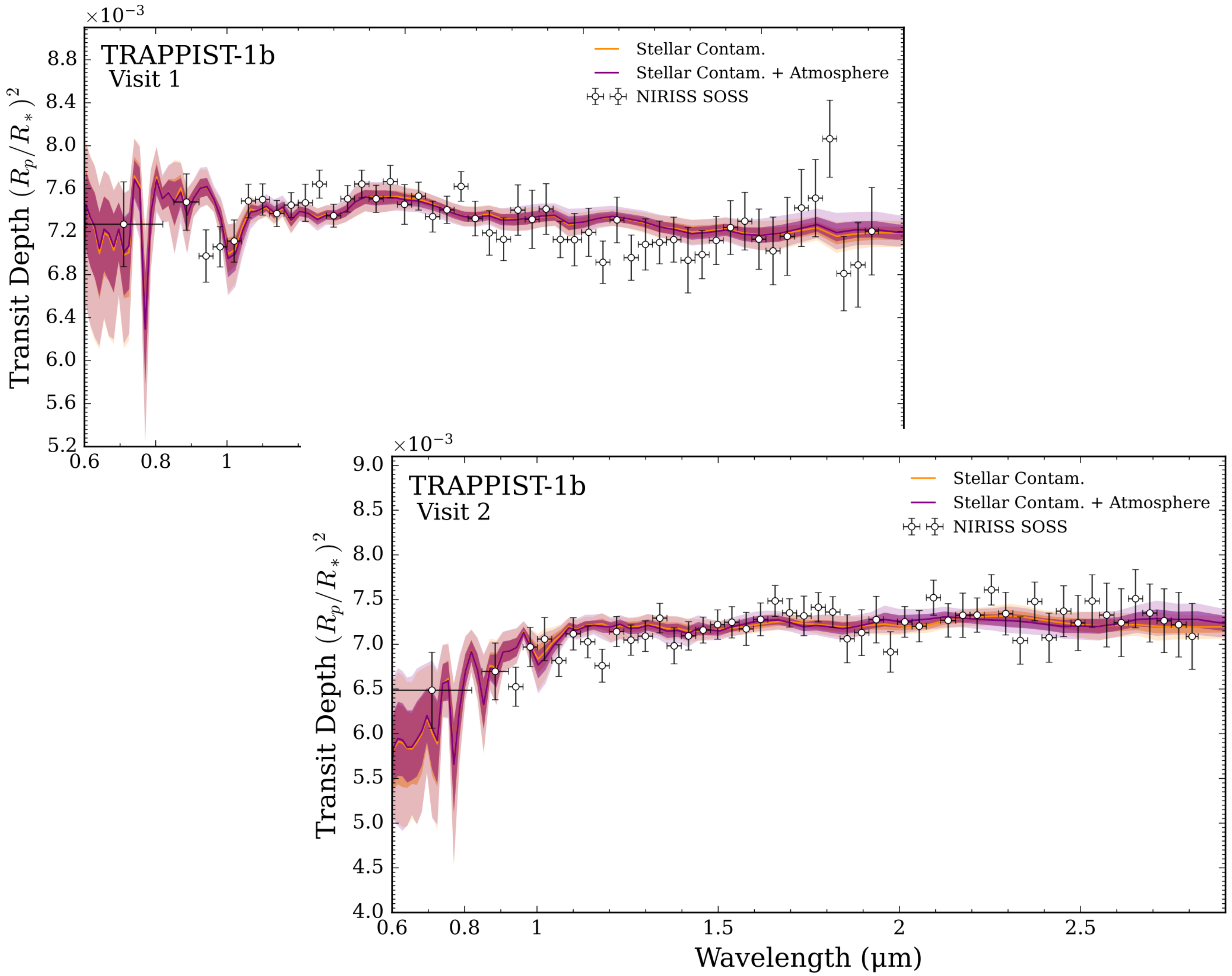

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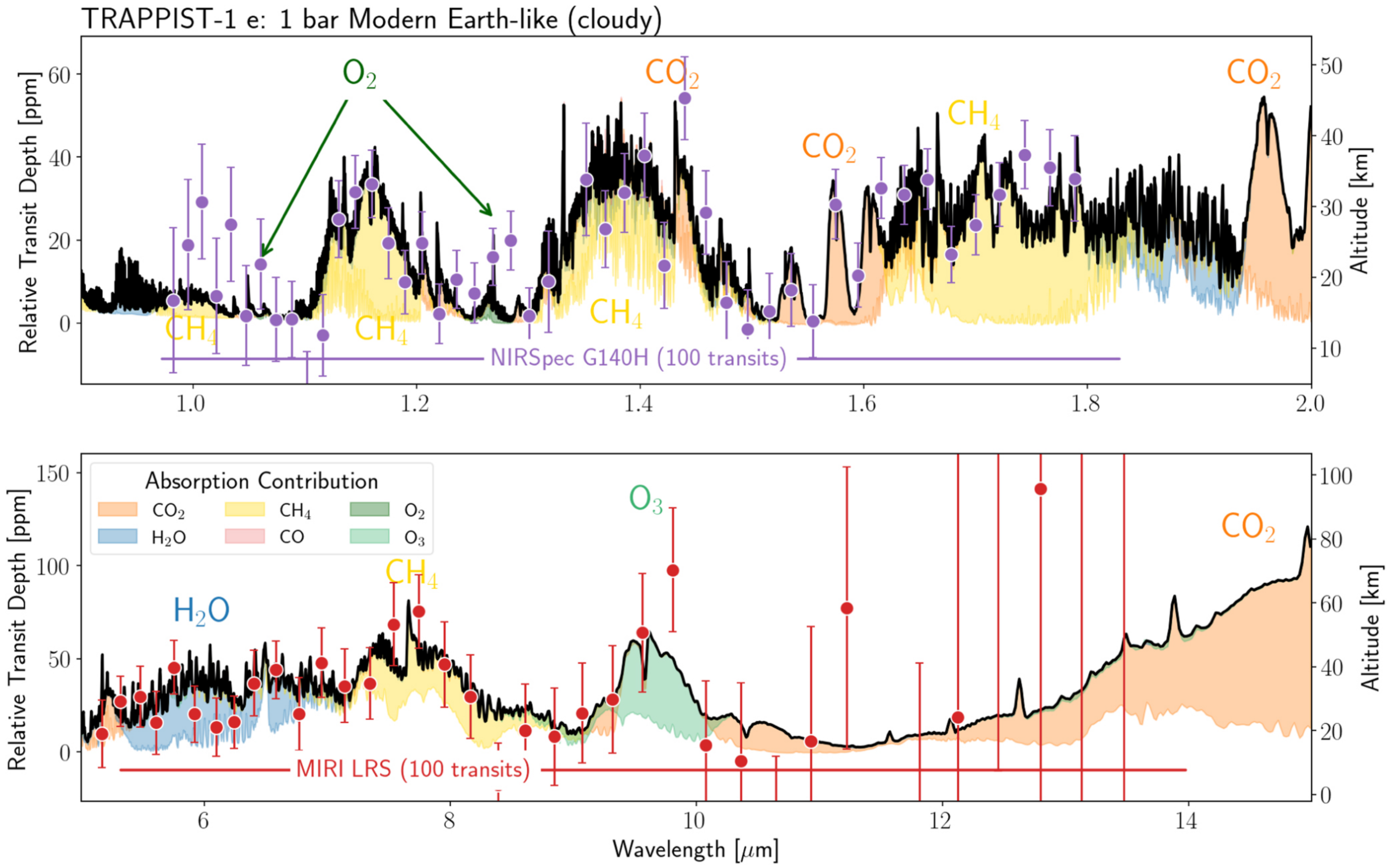

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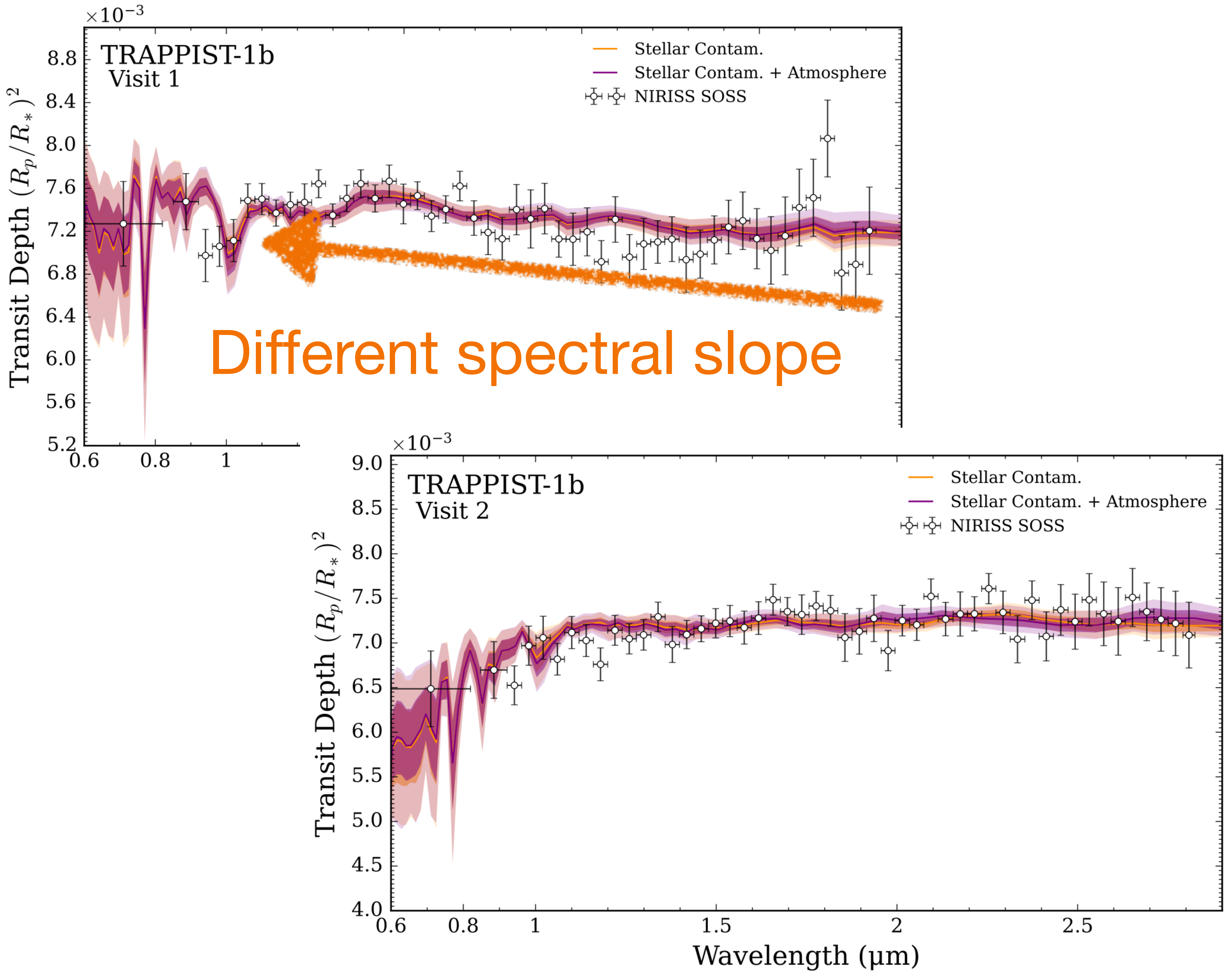

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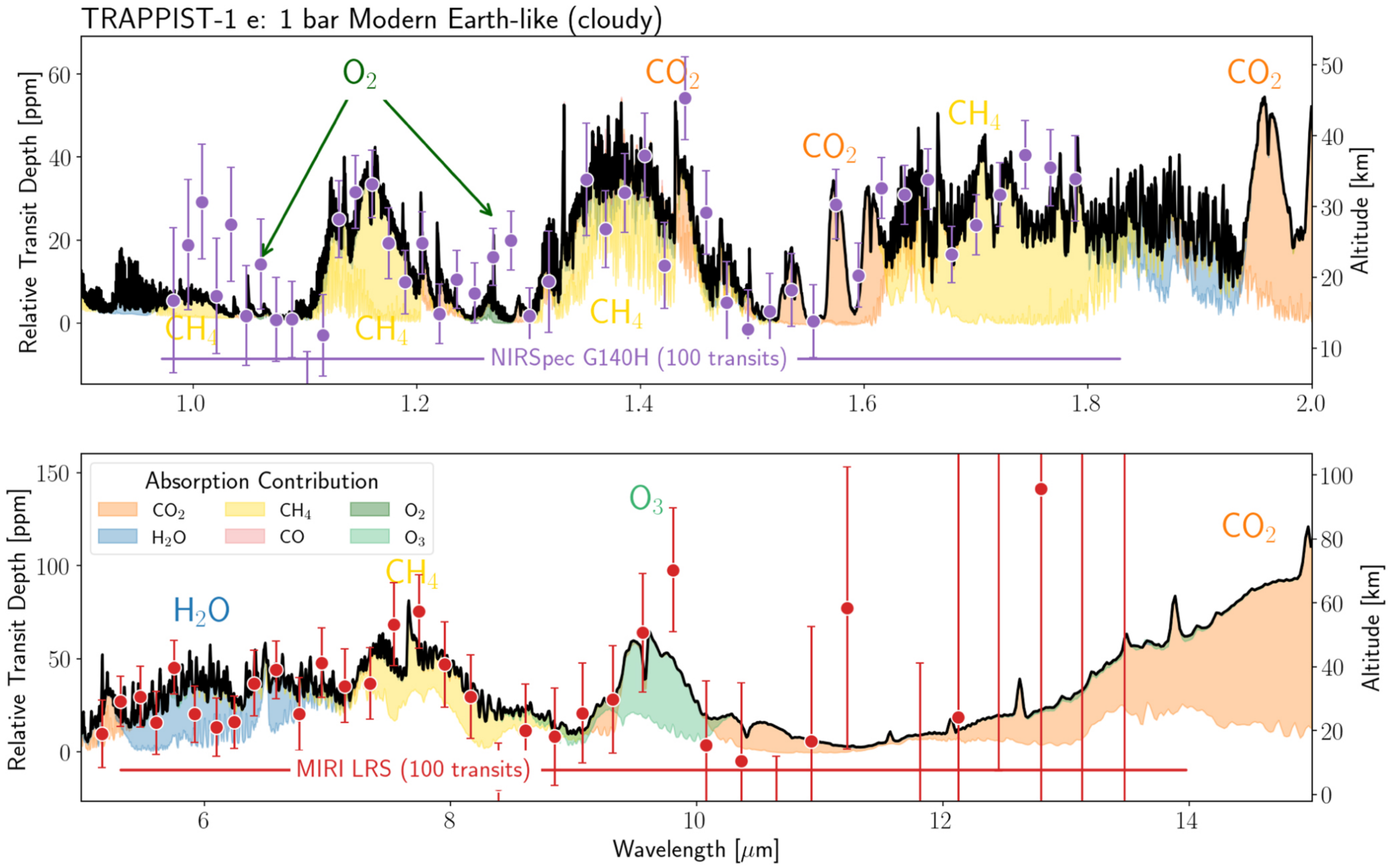

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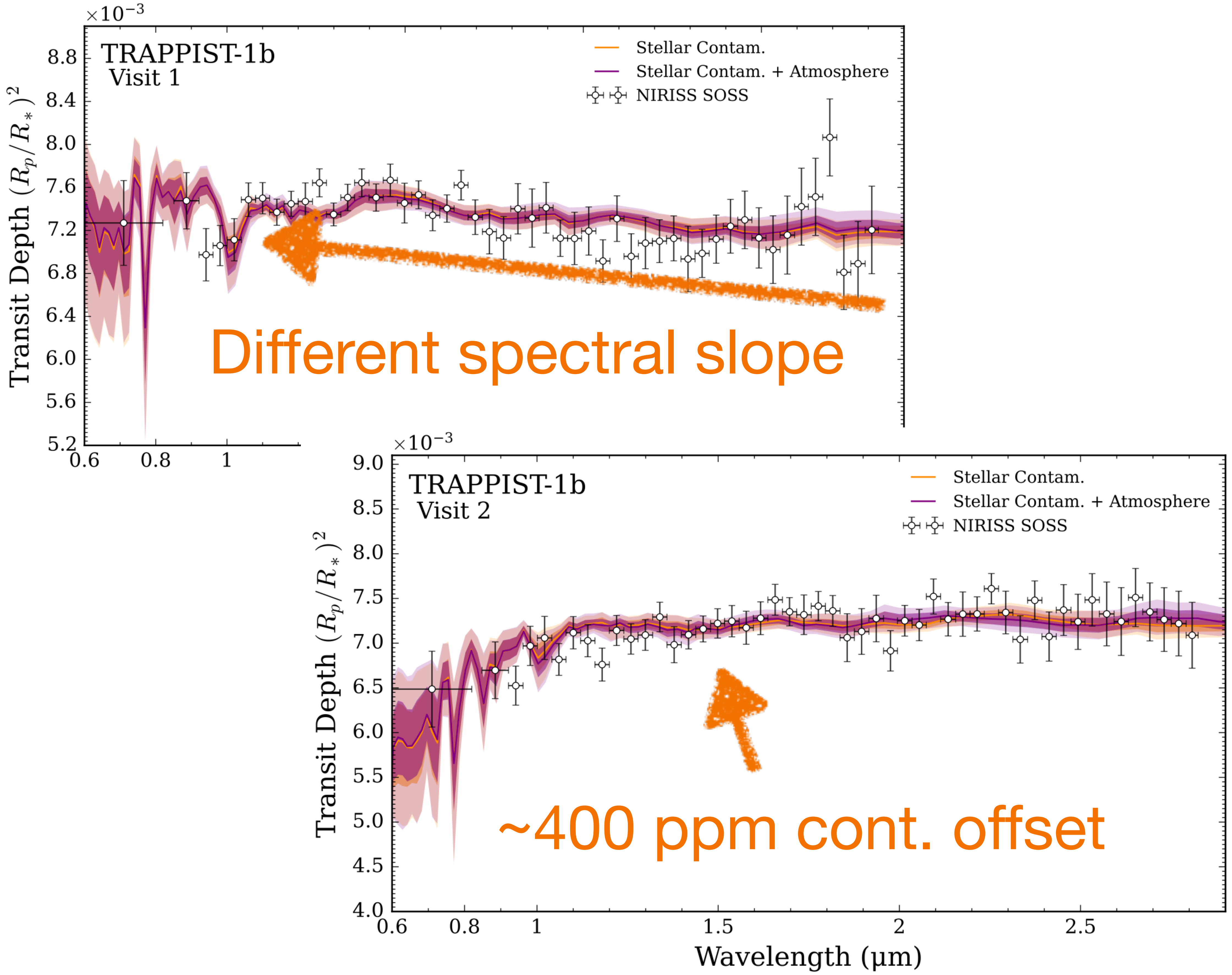
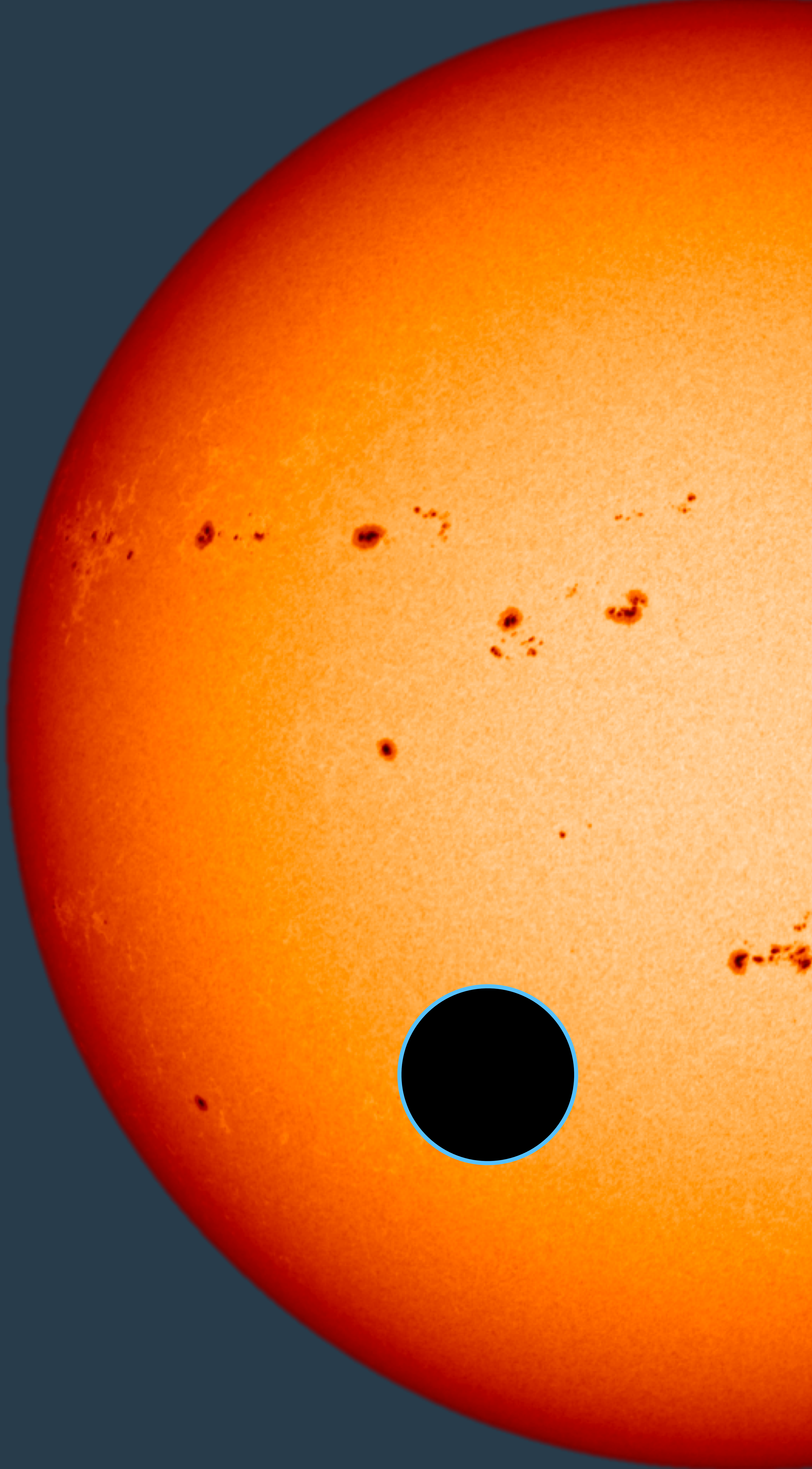


Lim et al. (2023)

The best-studied exoplanets must have the best-studied stars!



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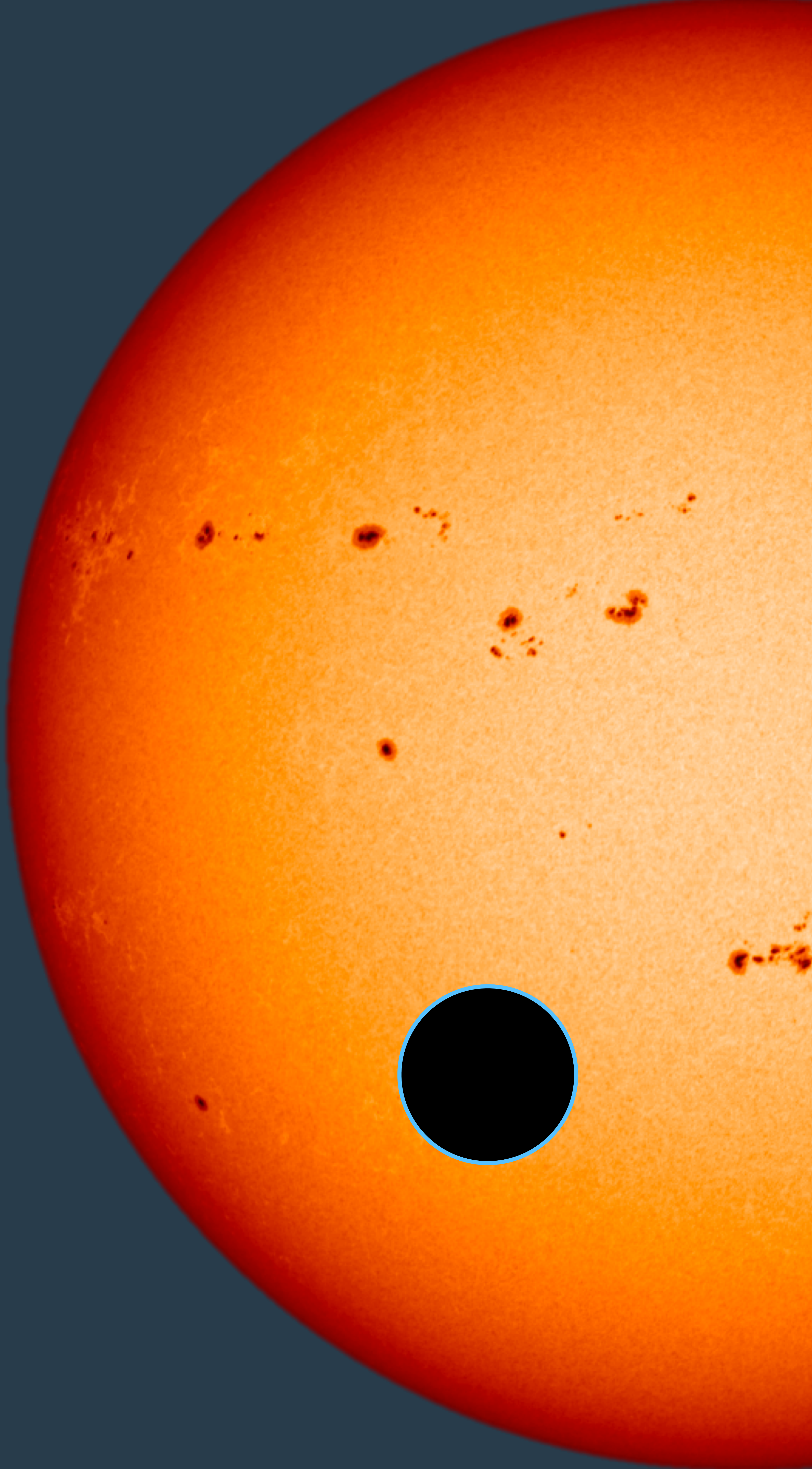
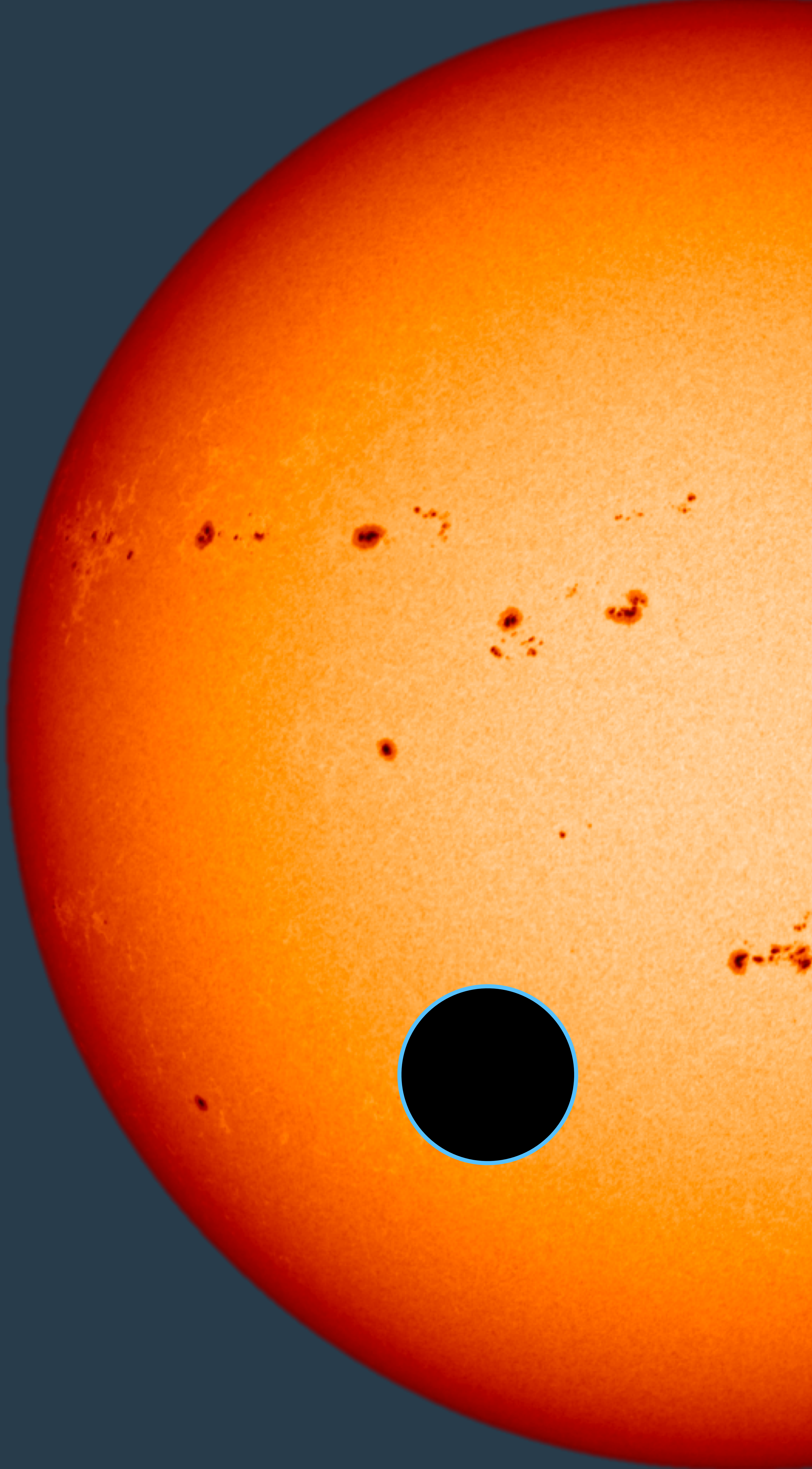
ChatGPT:



The best-studied exoplanets must have the best-studied stars!

ChatGPT: The goal is 10 ppm precision.
The reality is… not that.

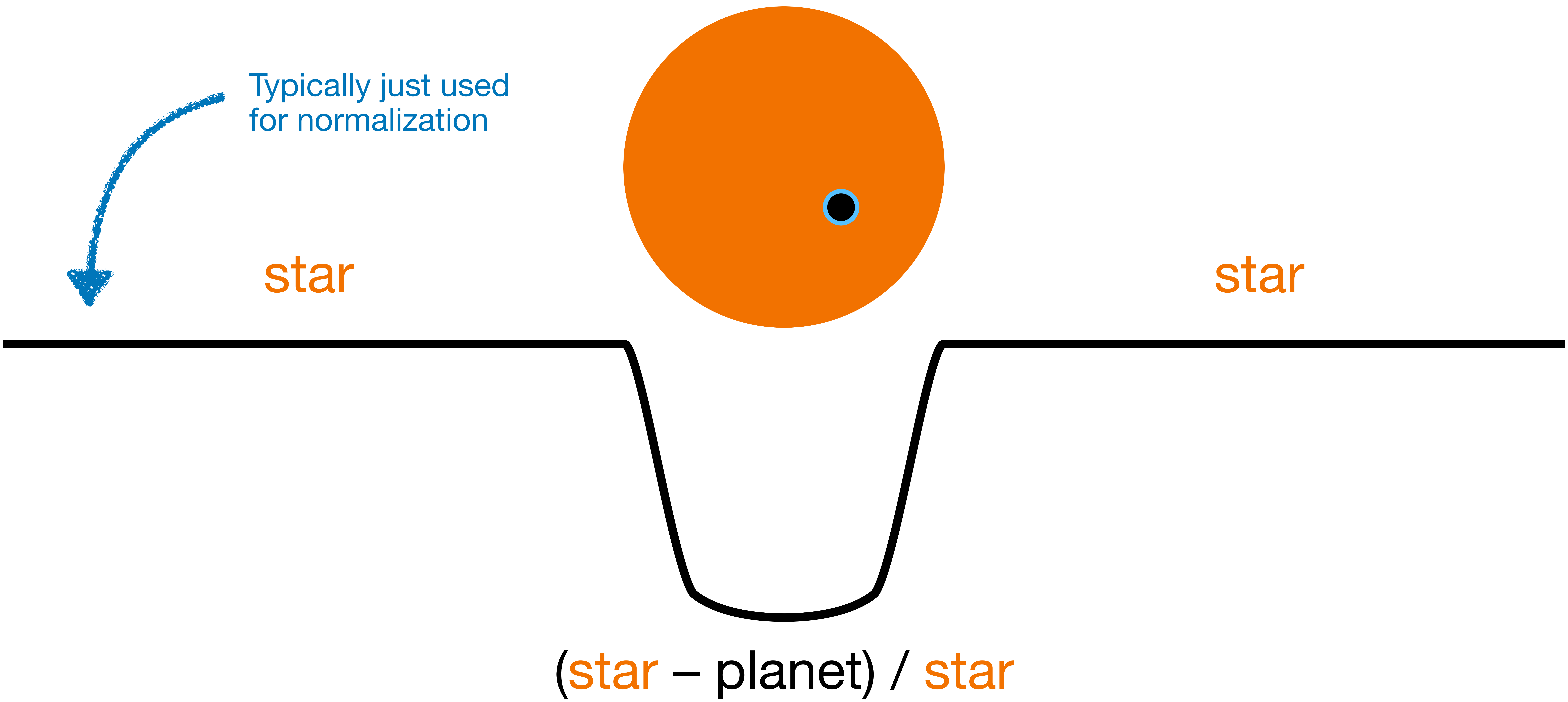


Outline

1. **Tackling Stellar Activity** in a Model-Limited Regime
2. A Roadmap to **Atmospheres of Terrestrial Exoplanets** with JWST

1. Tackling Stellar Activity in a Model-Limited Regime

This talk: TLS effect mitigation using stellar spectra



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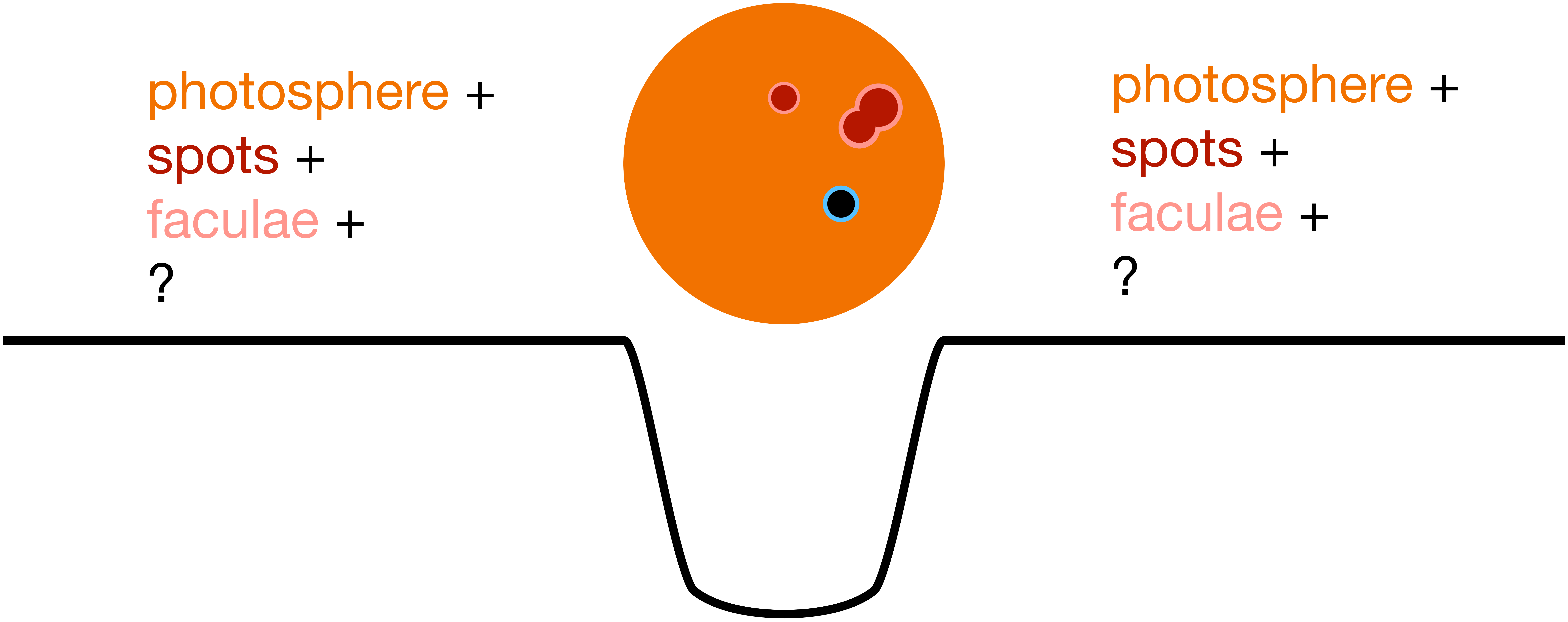
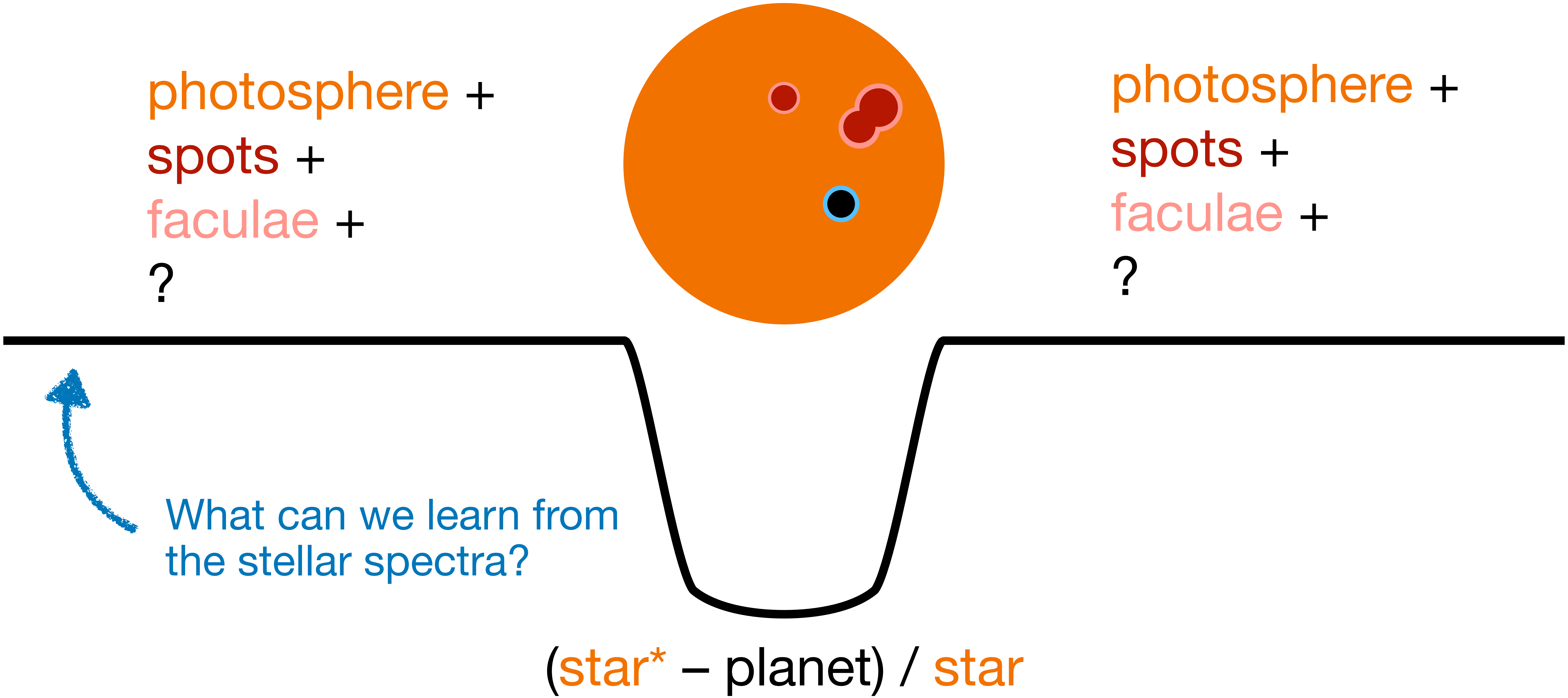


(star* – planet) / star

This talk: TLS effect mitigation using stellar spectra



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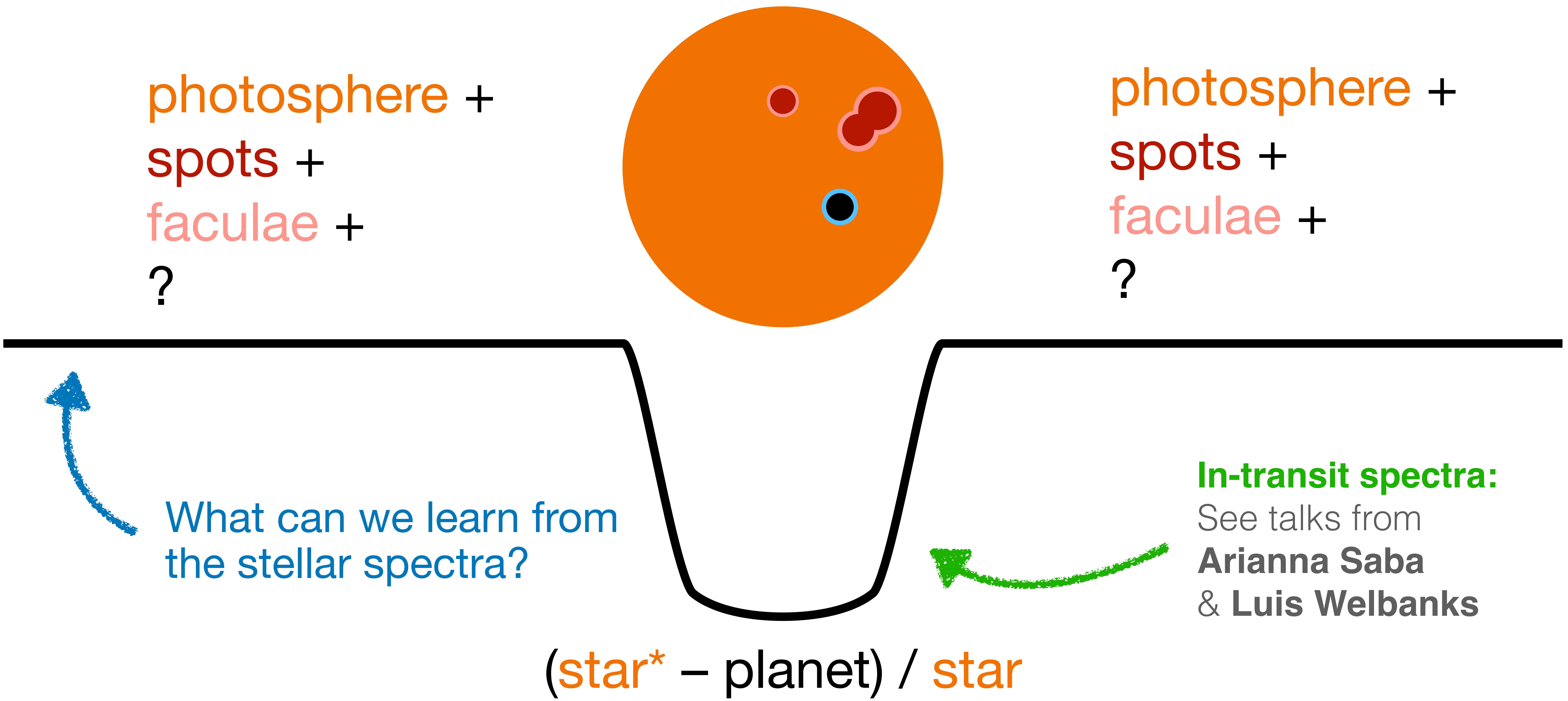


The TRAPPIST-1 System

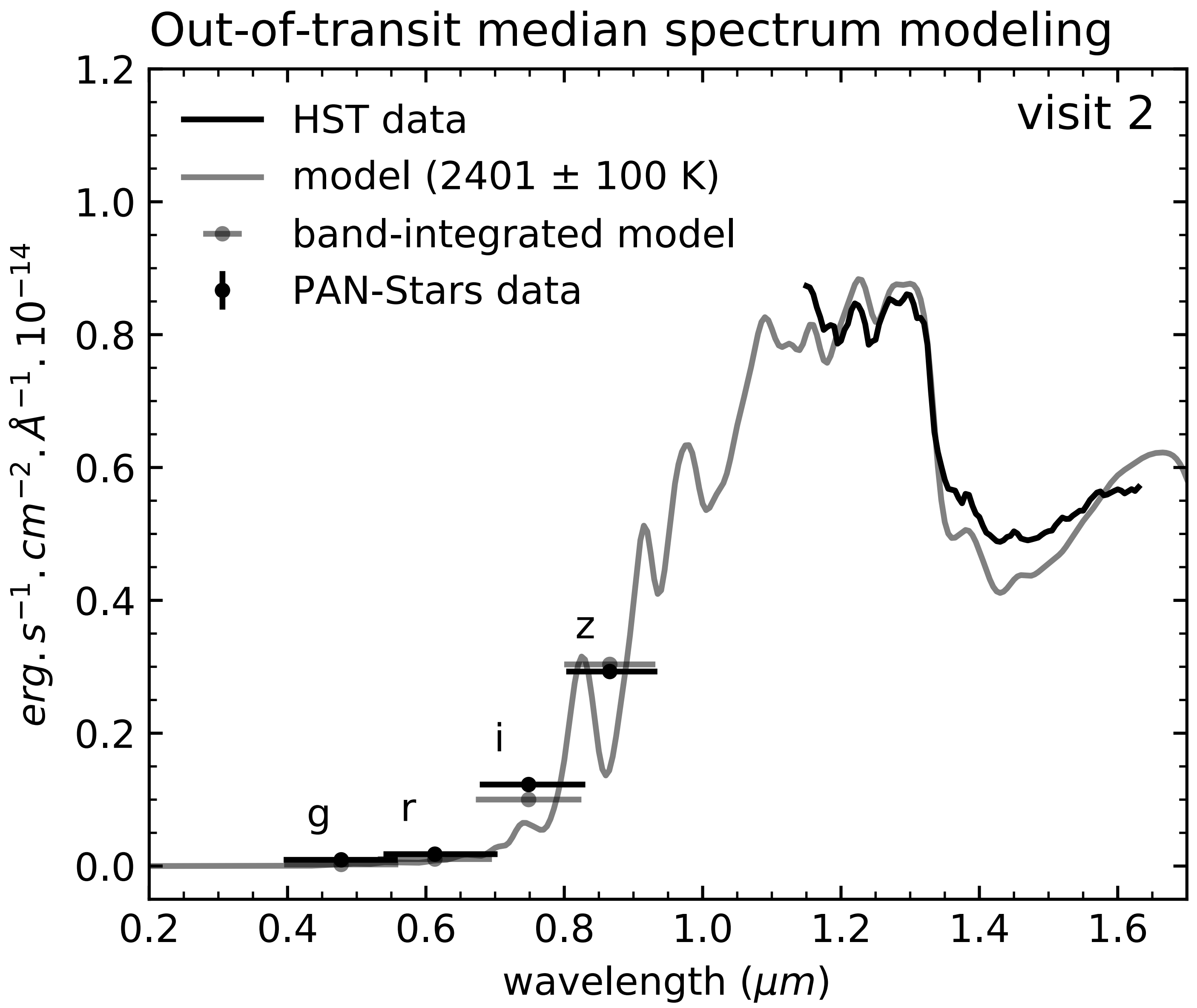
Credit: NASA/JPL-Caltech/R. Hurt, T. Pyle (IPAC)


The TRAPPIST-1 System
M8V
Disclaimer:
There are other stars than TRAPPIST-1.
Credit: NASA/JPL-Caltech/R. Hurt, T. Pyle (IPAC)

Models don’t uniquely identify spectral components

e.g., TRAPPIST-1

1 component



2 component

3 component

Lionel Garcia et al. (2022)
(see also Zhang et al. 2018, Wakeford et al. 2019)

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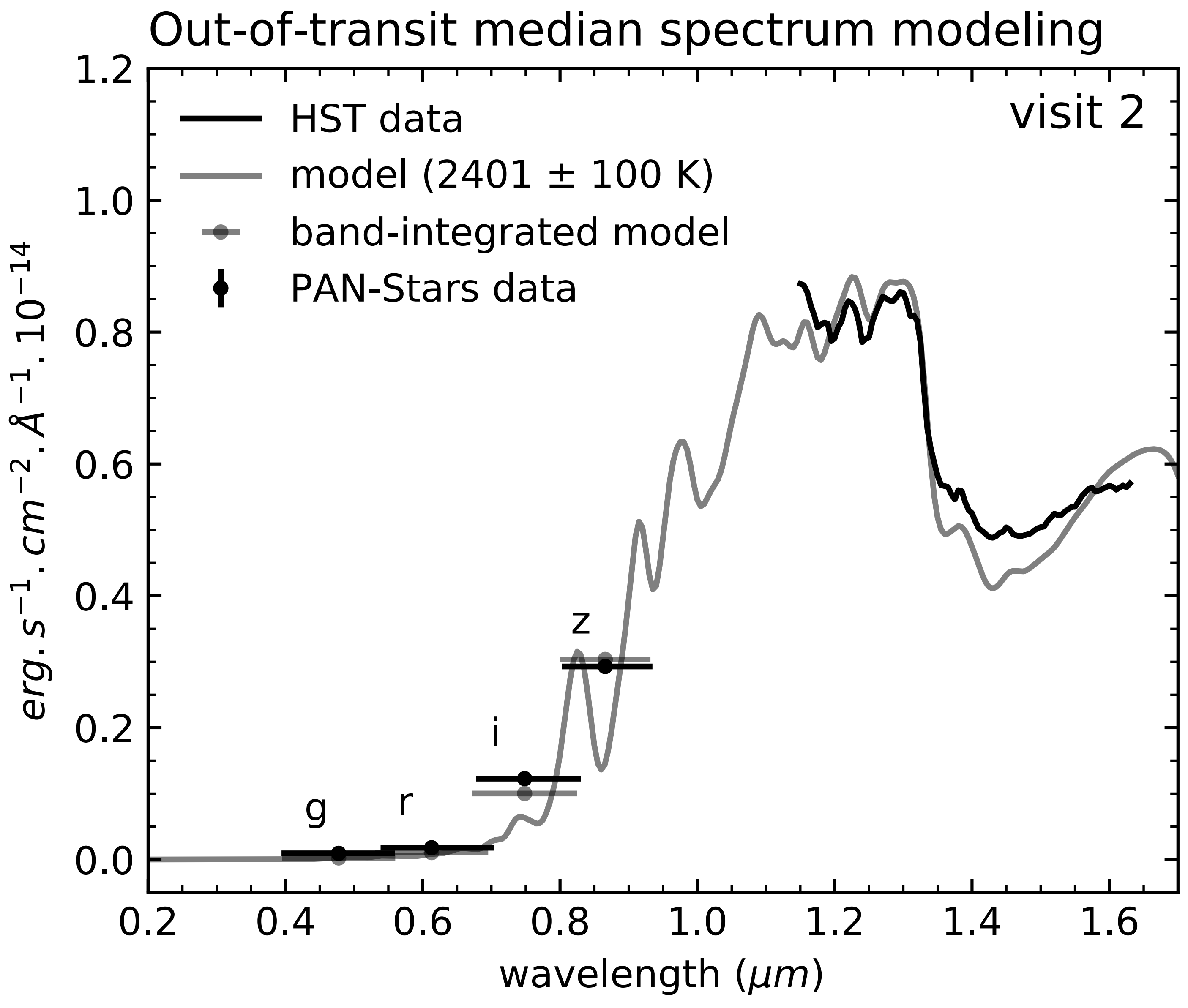
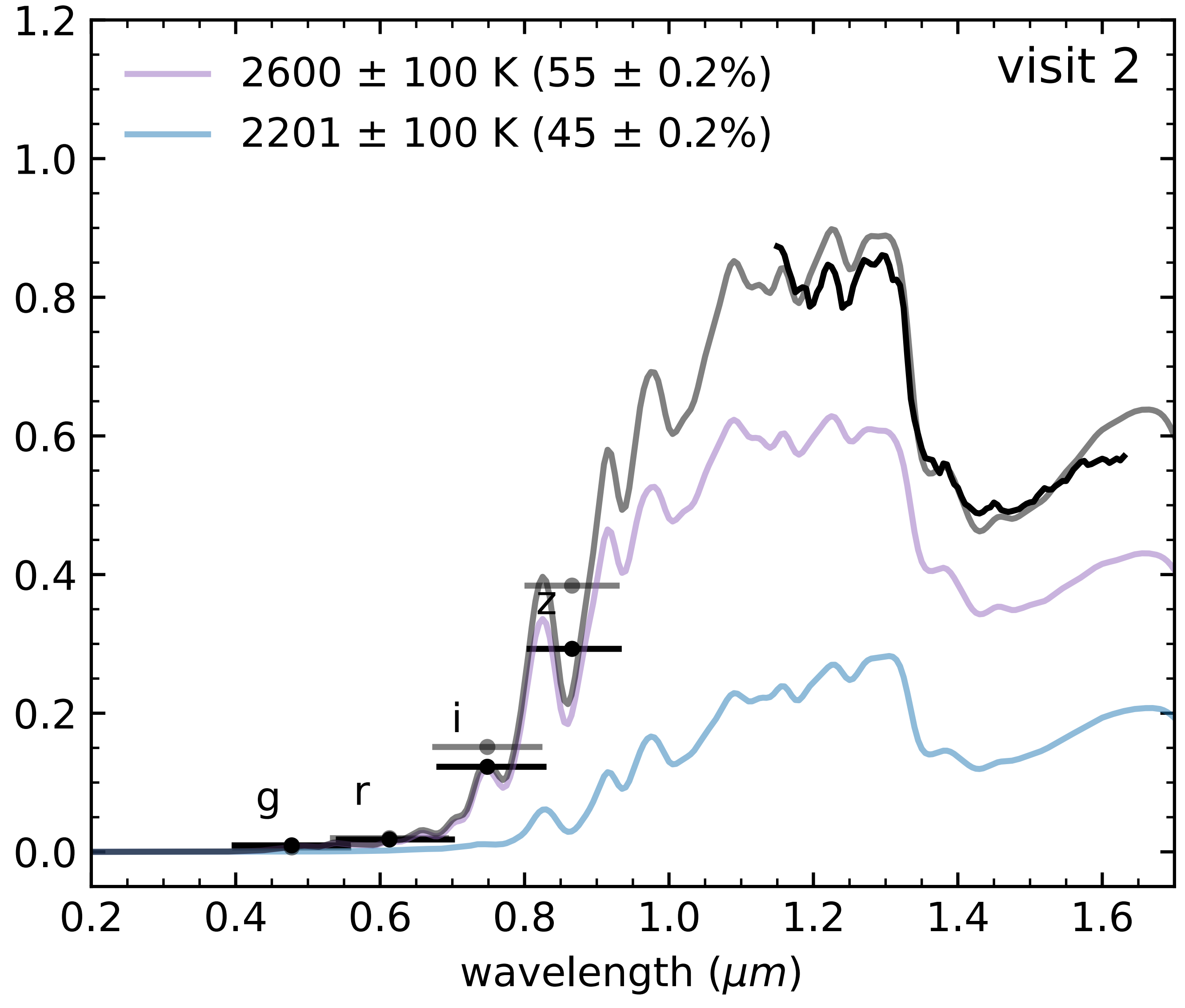
e.g., TRAPPIST-1

1 component



2 component



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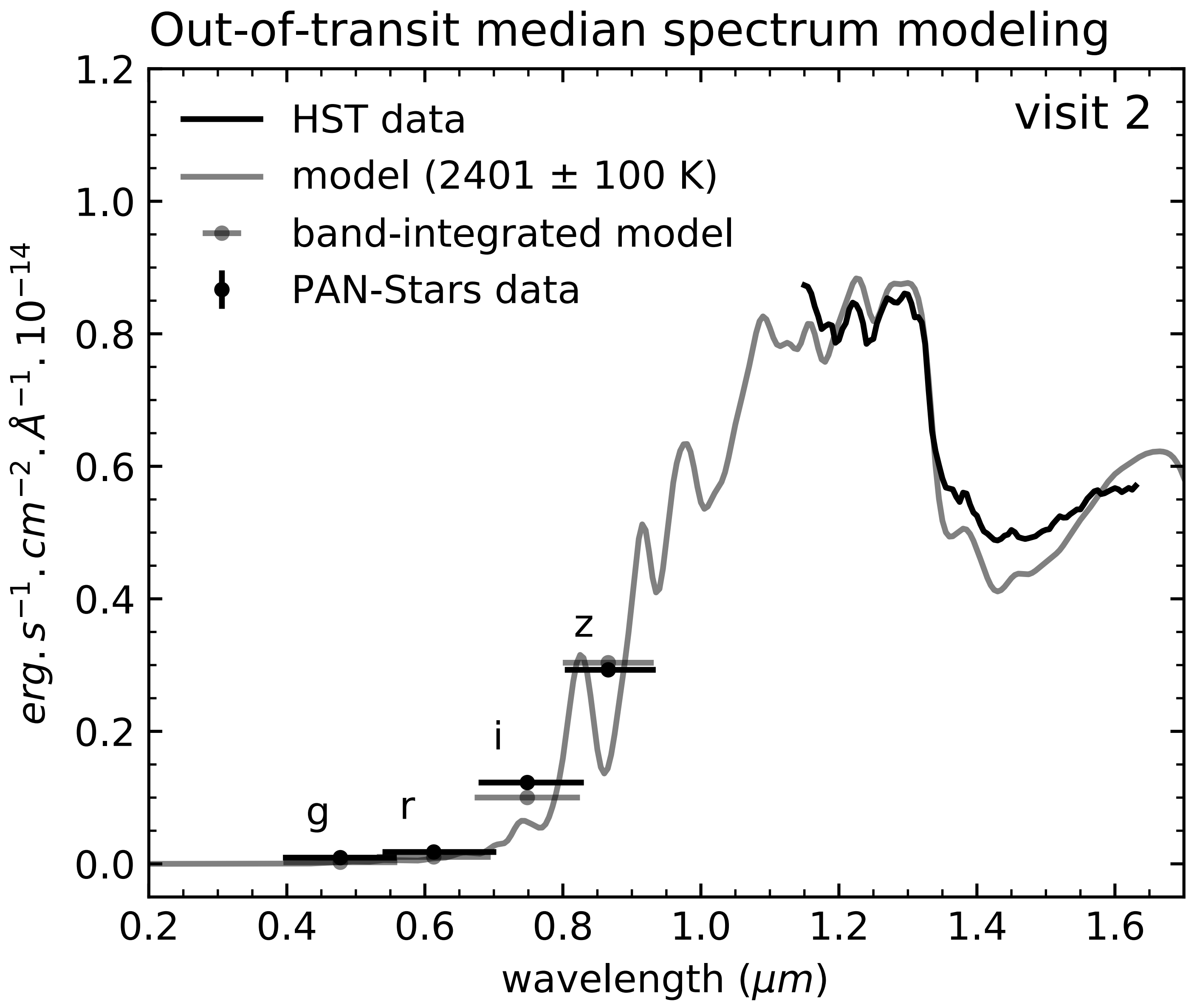
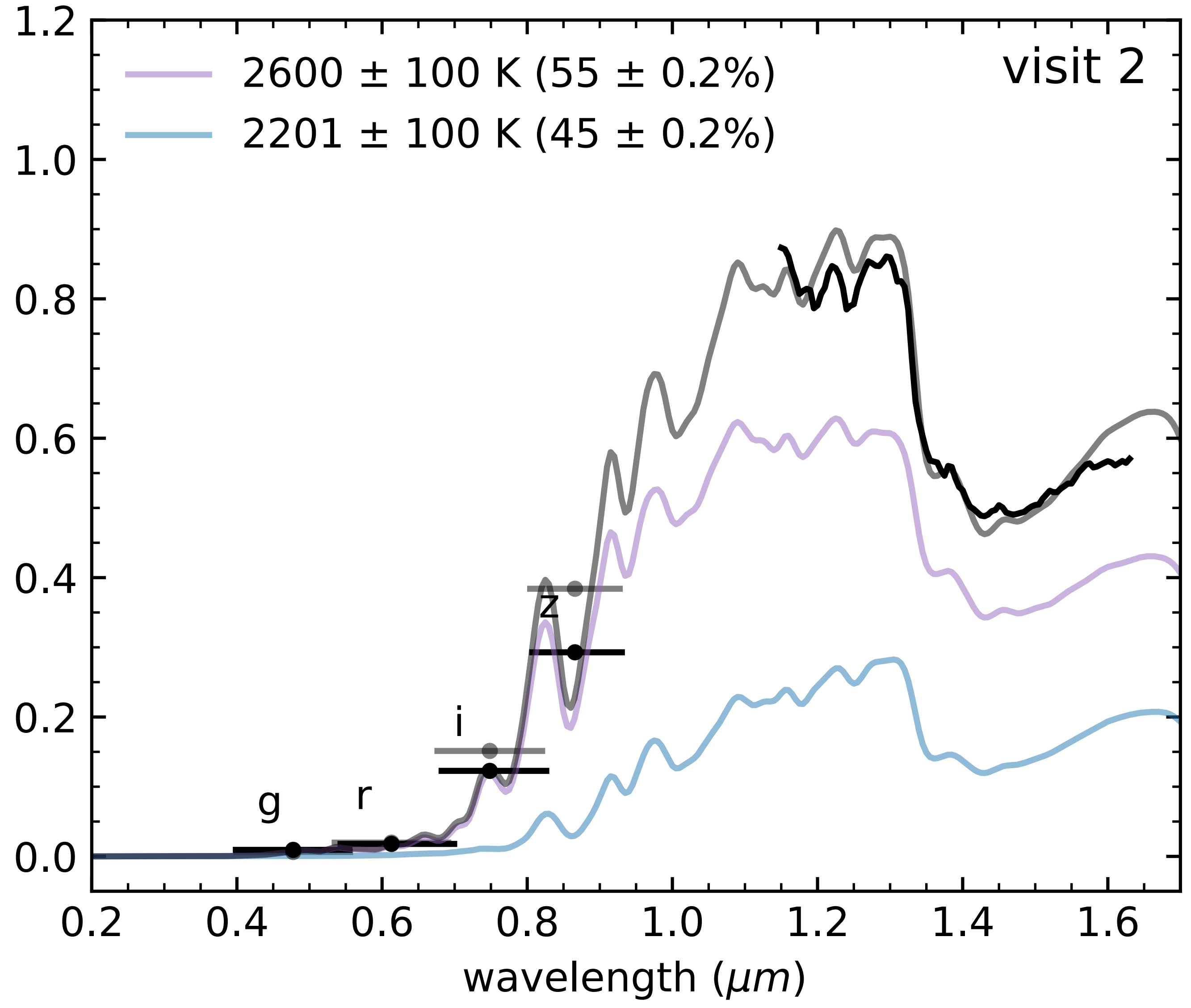
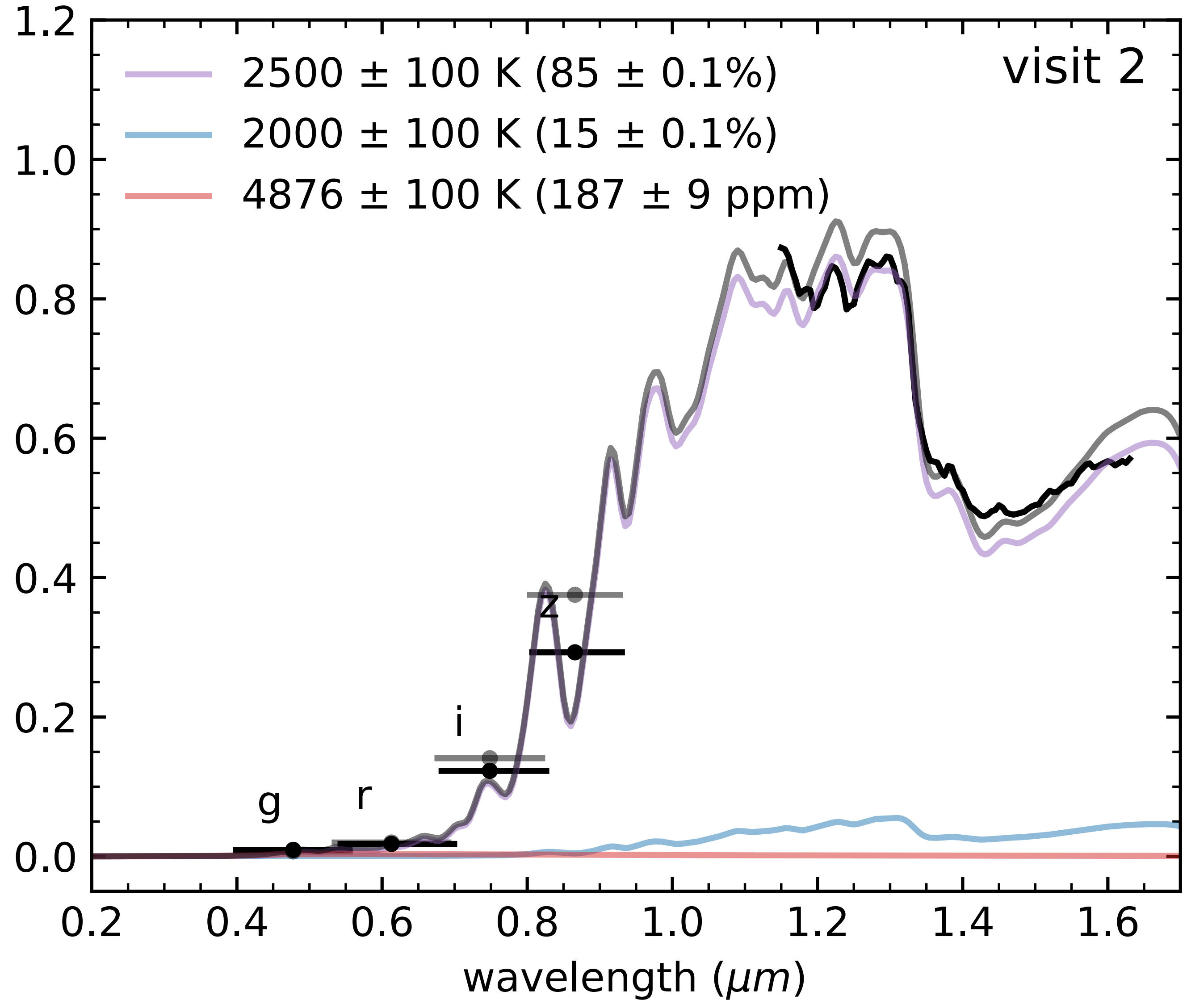


2 component



3 component

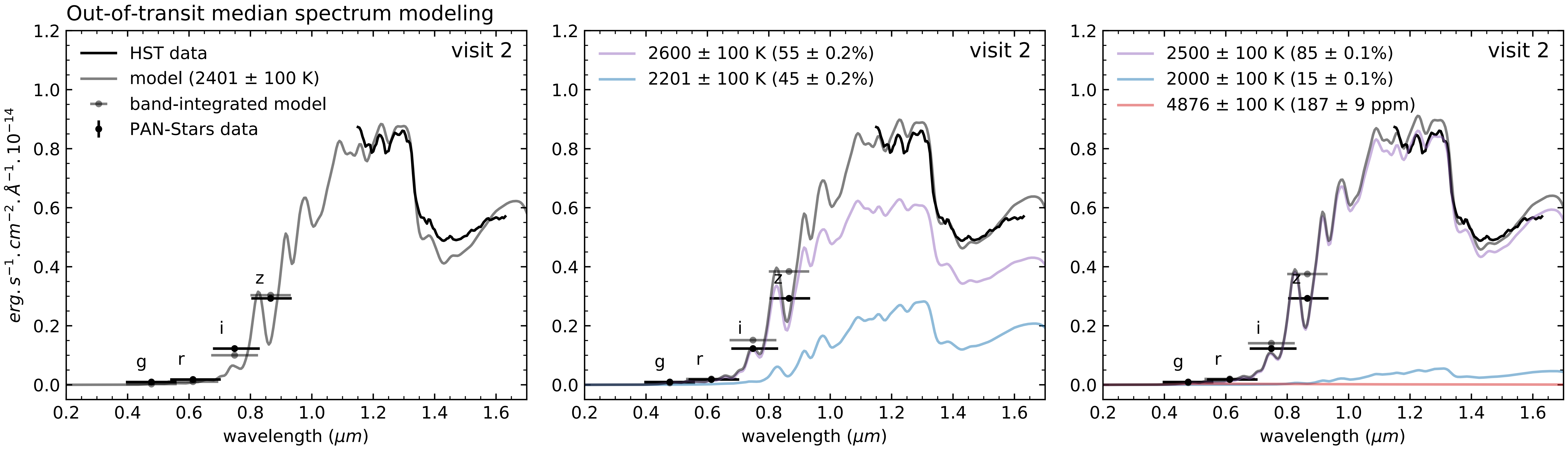


Lionel Garcia et al. (2022)
(see also Zhang et al. 2018, Wakeford et al. 2019)

Models don't uniquely identify spectral components

e.g., TRAPPIST-1

1 component **2 component** **3 component**



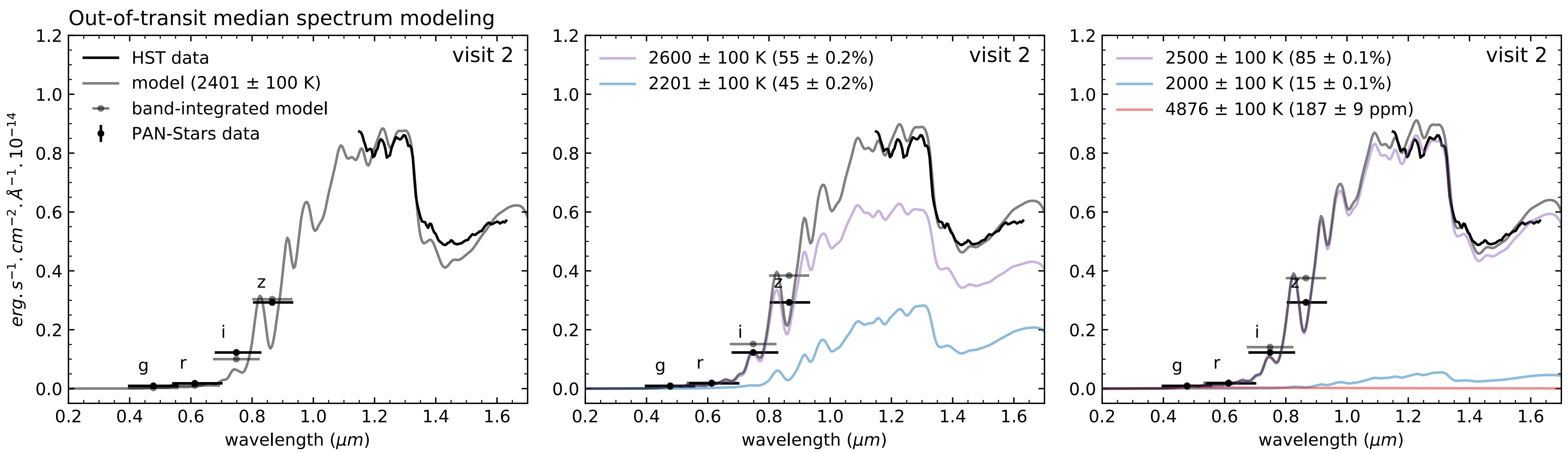
➡️ **Equally poor fits (rel. to HST precision)**

Lionel Garcia et al. (2022)
(see also Zhang et al. 2018, Wakeford et al. 2019)

Models don't uniquely identify spectral components

e.g., TRAPPIST-1

Using **out-of-transit spectra**…



Lionel Garcia et al. (2022)
(see also Zhang et al. 2018, Wakeford et al. 2019)

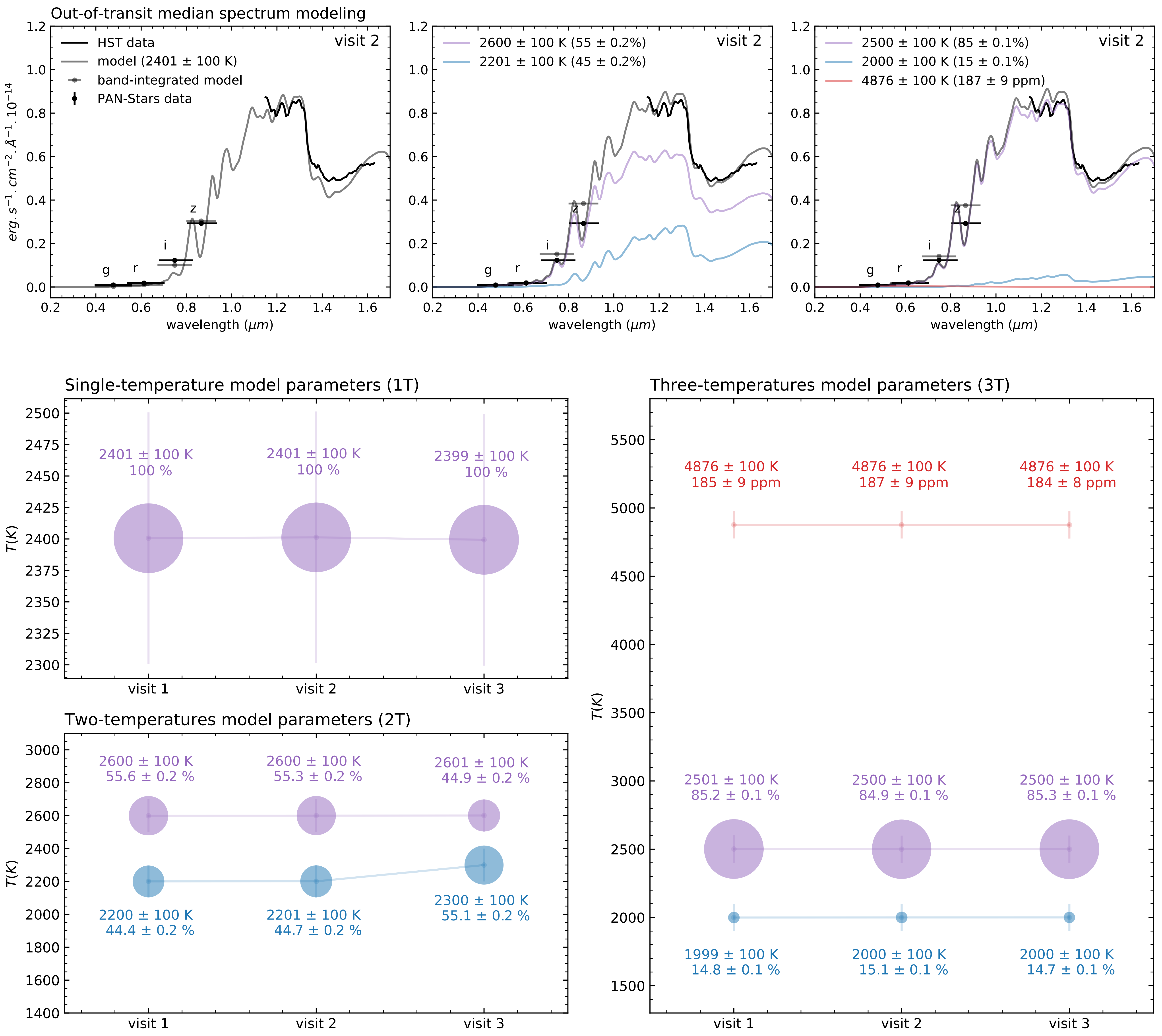
Models don’t uniquely identify spectral components

e.g., TRAPPIST-1

Using **out-of-transit spectra**…

…to **constrain heterogeneities** on the stellar surface…

Lionel Garcia et al. (2022)
(see also Zhang et al. 2018, Wakeford et al. 2019)

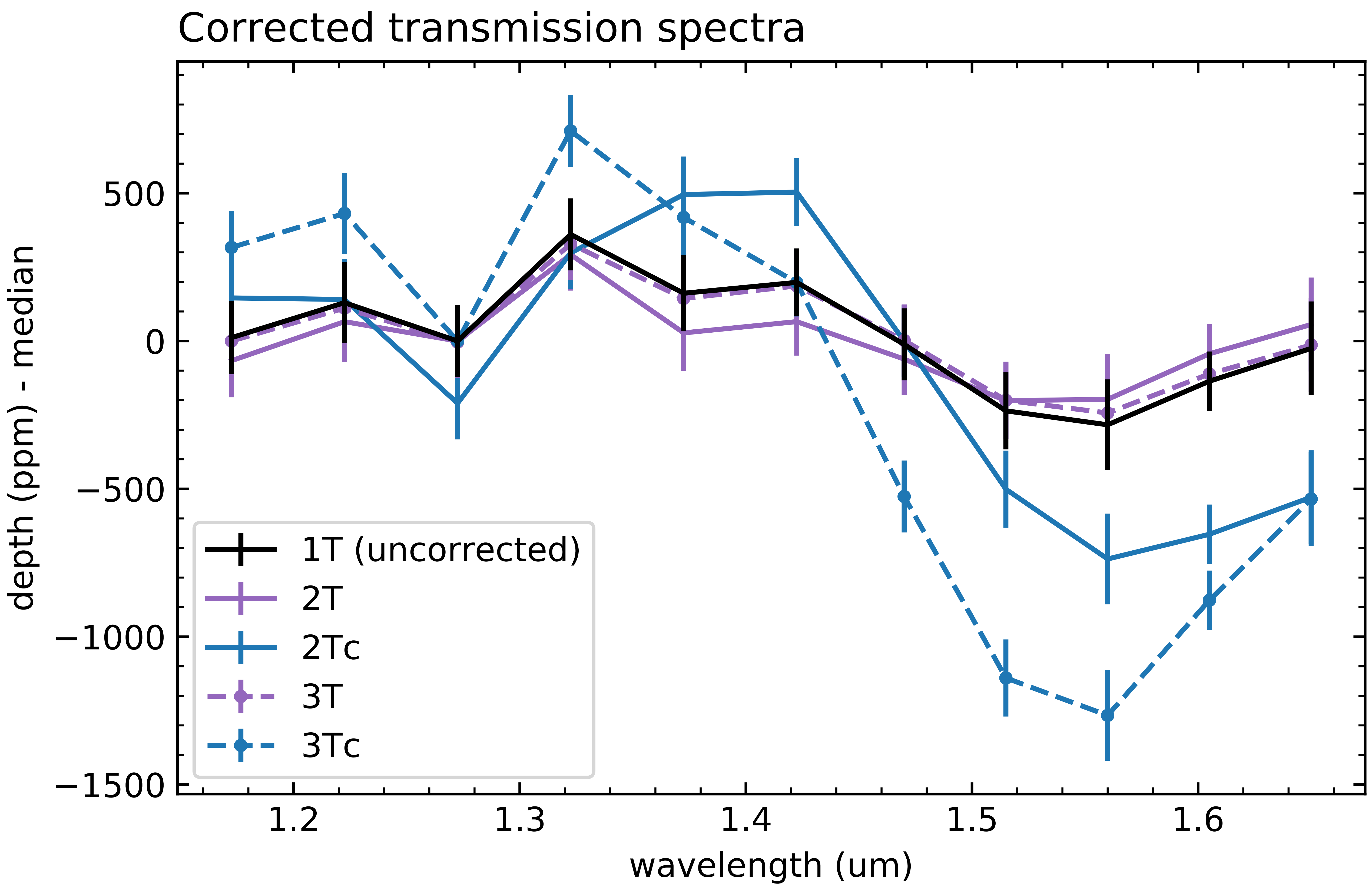


Models don’t uniquely identify spectral components

e.g., TRAPPIST-1

…yields a range of corrections, leading to **>5 x increase** in uncertainty

➡️ **Not photon-limited**

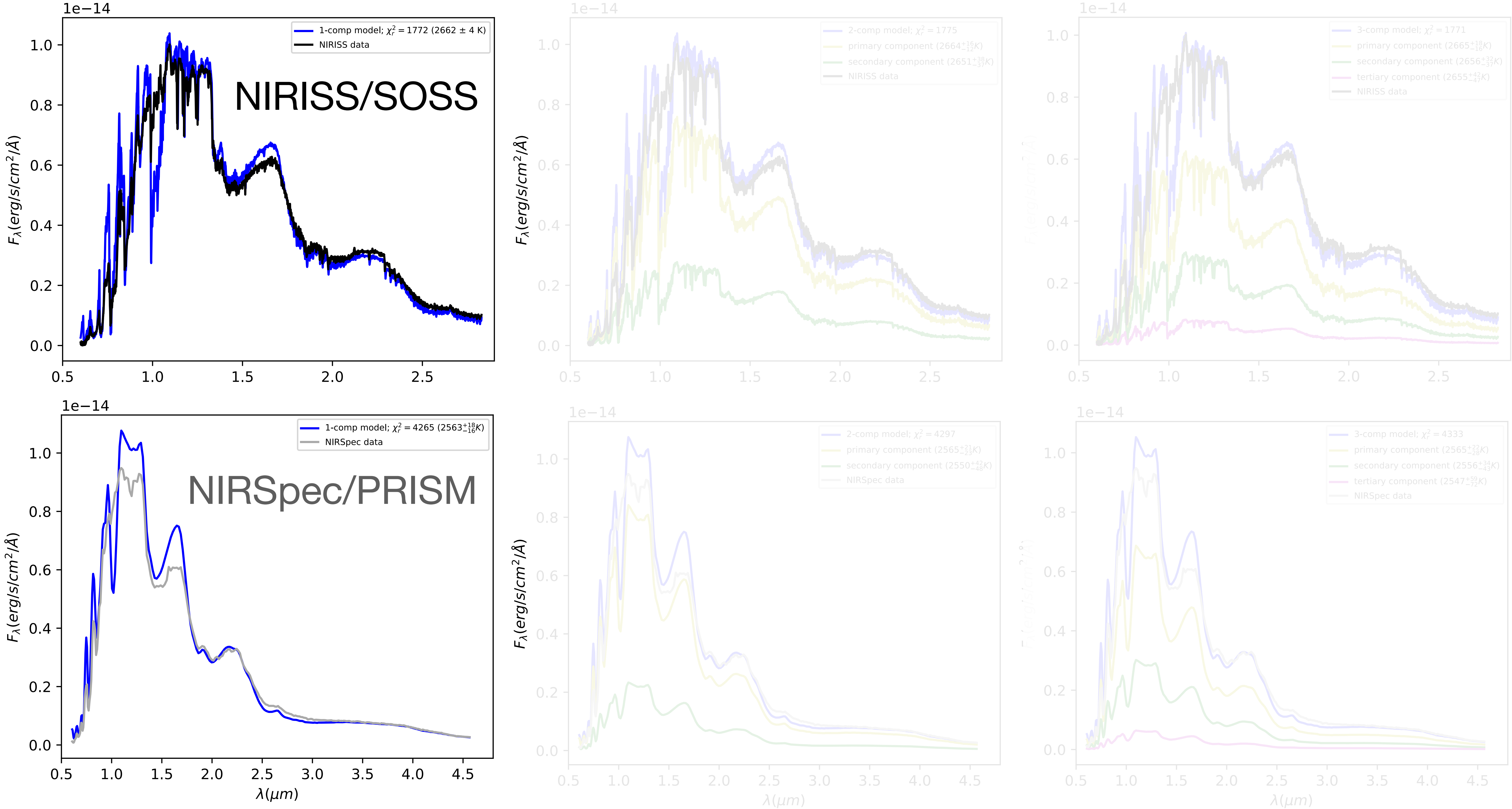


Lionel Garcia et al. (2022)
(see also Zhang et al. 2018, Wakeford et al. 2019)

Model fidelity issue is more pronounced for JWST

e.g., TRAPPIST-1

1 component | 2 component | 3 component



Fatemeh Davoudi et al. (2024)

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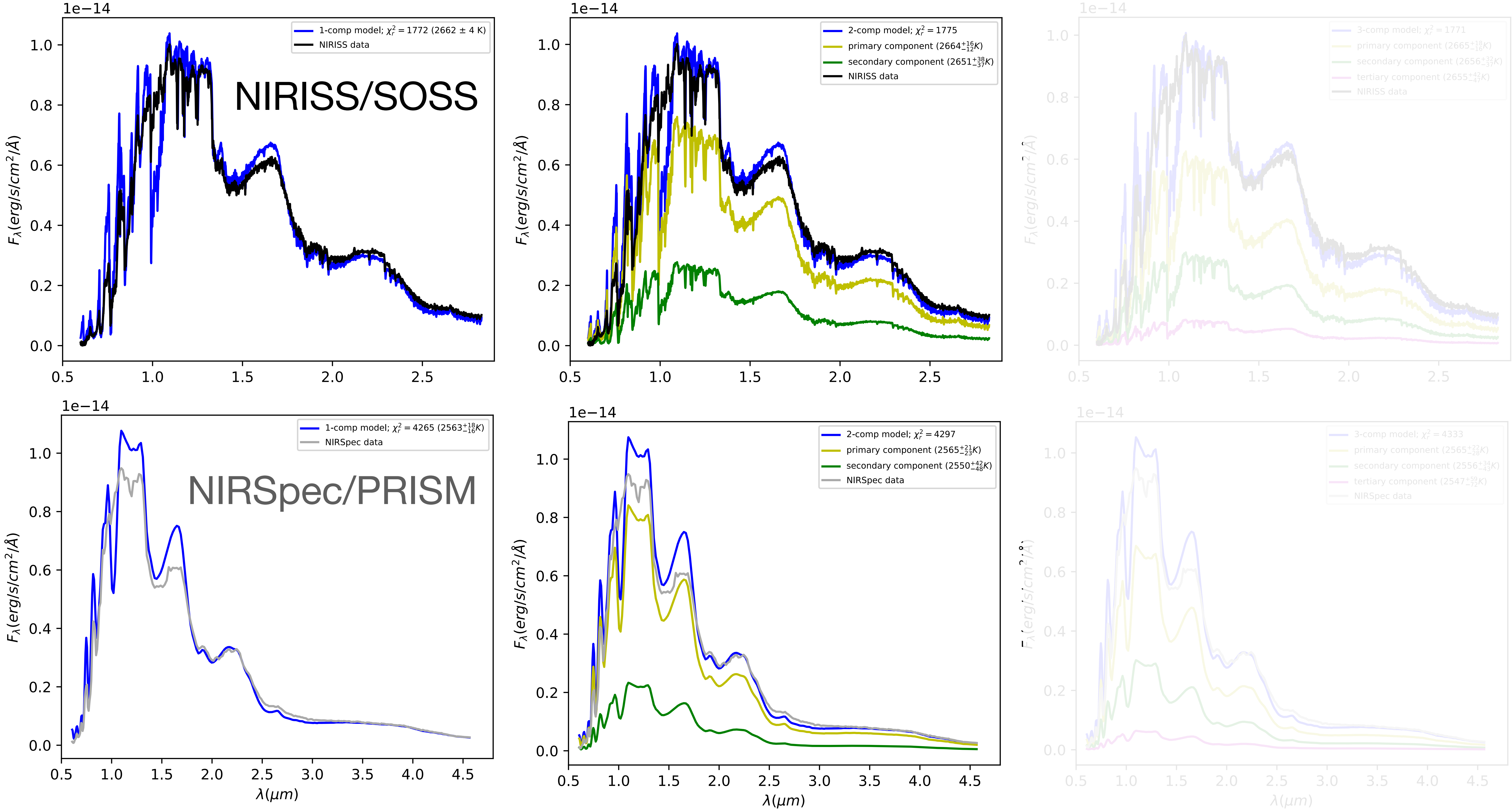

Fatemeh Davoudi et al. (2024)

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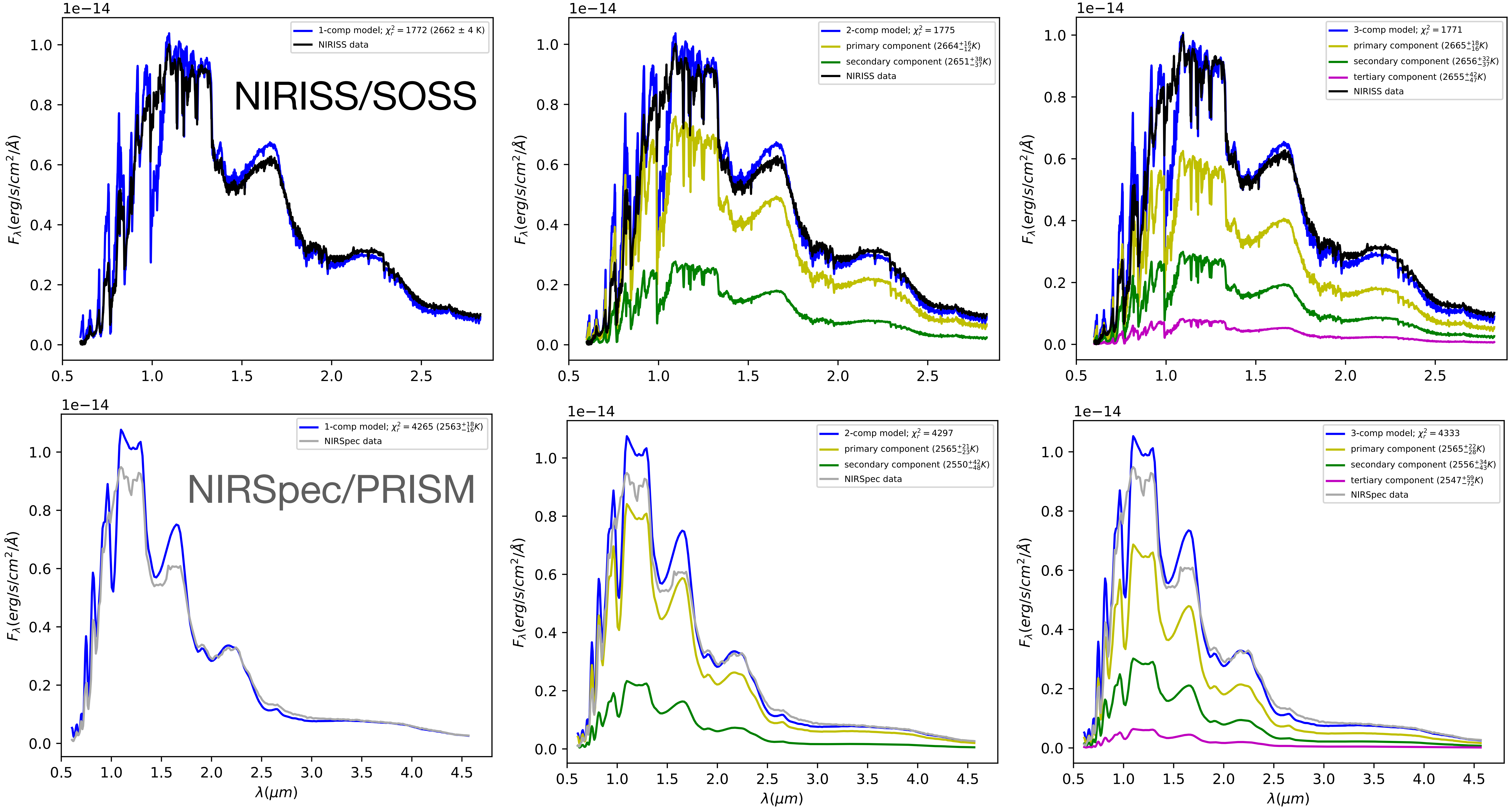

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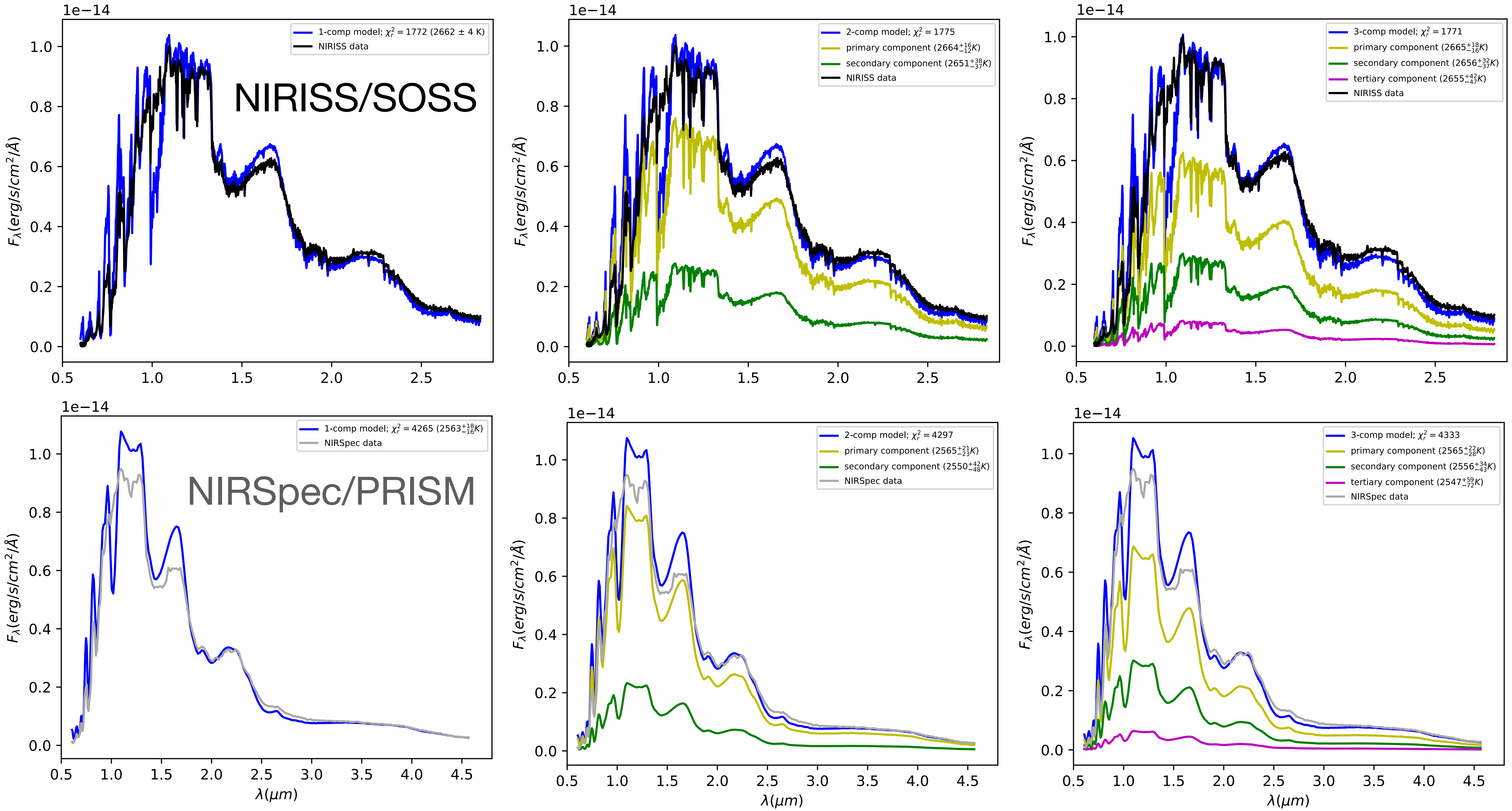
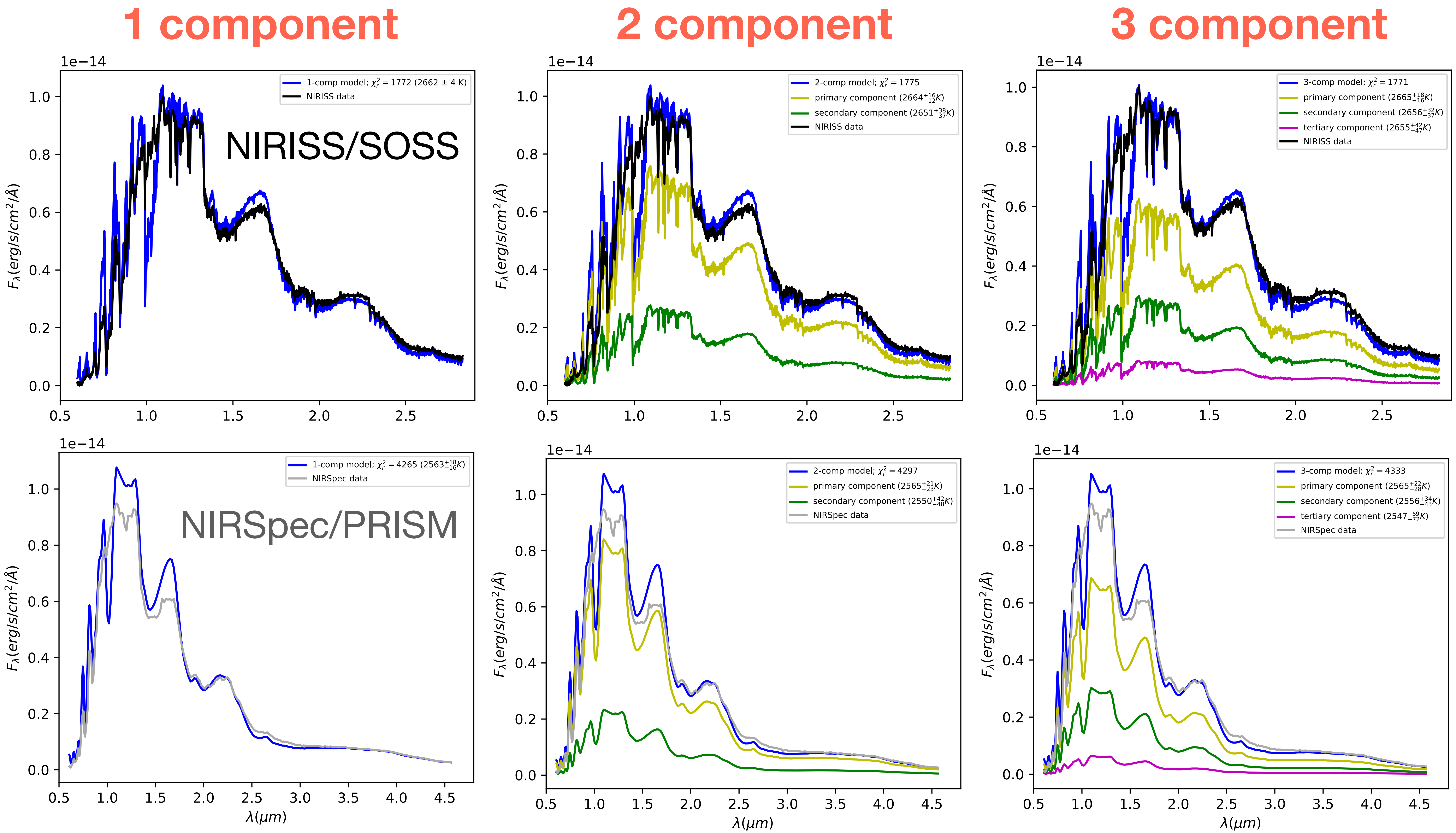


For **TRAPPIST-1 JWST spectra**, models with **multiple components** are **not clearly better**

Fatemeh Davoudi et al. (2024)

Model fidelity issue is more pronounced for JWST

e.g., TRAPPIST-1



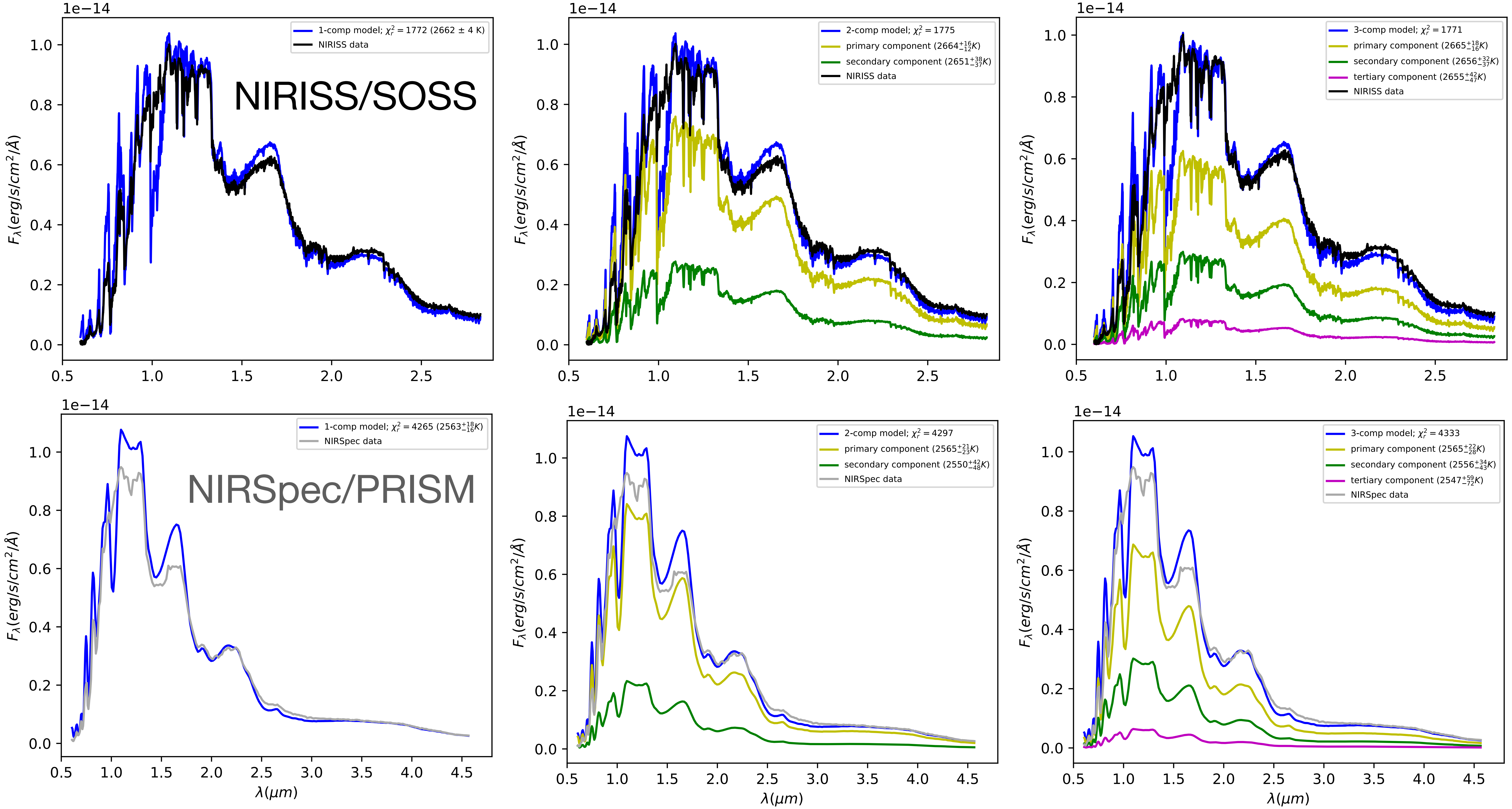
ChatGPT:

Fatemeh Davoudi et al. (2024)

Model fidelity issue is more pronounced for JWST

e.g., TRAPPIST-1

1 component **2 component** **3 component**



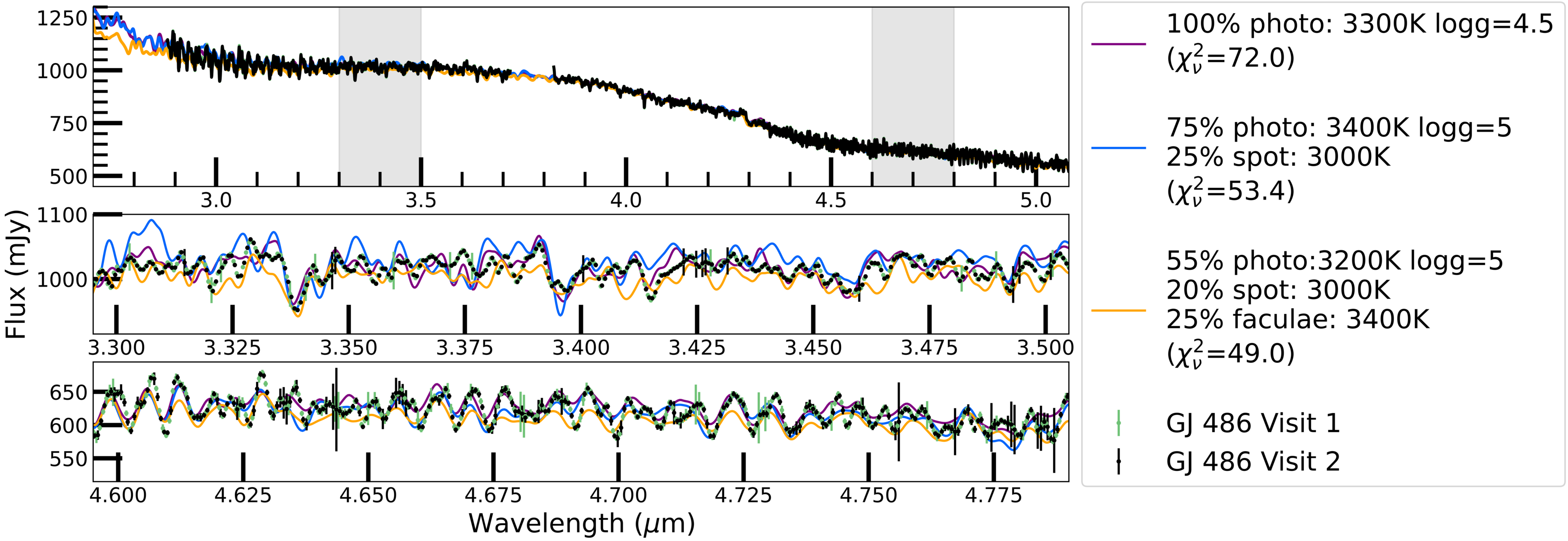
ChatGPT:

TRAPPIST-1 is a great system for testing atmospheric models. Mostly because none of them work on it.

Fatemeh Davoudi et al. (2024)

…and not just limited to TRAPPIST-1

e.g., GJ 486 (M3.5V)



Moran, Stevenson et al. (2023)

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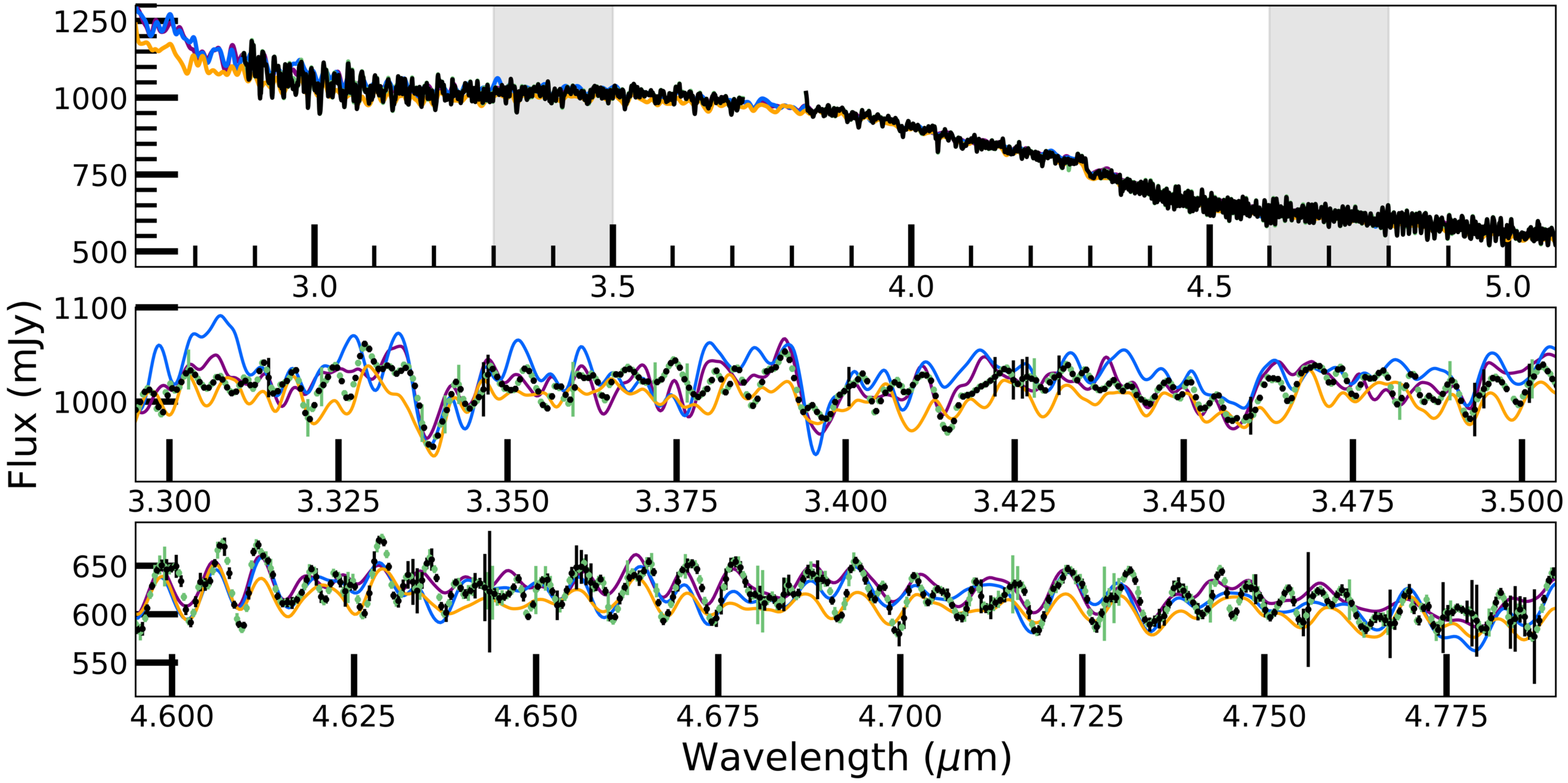
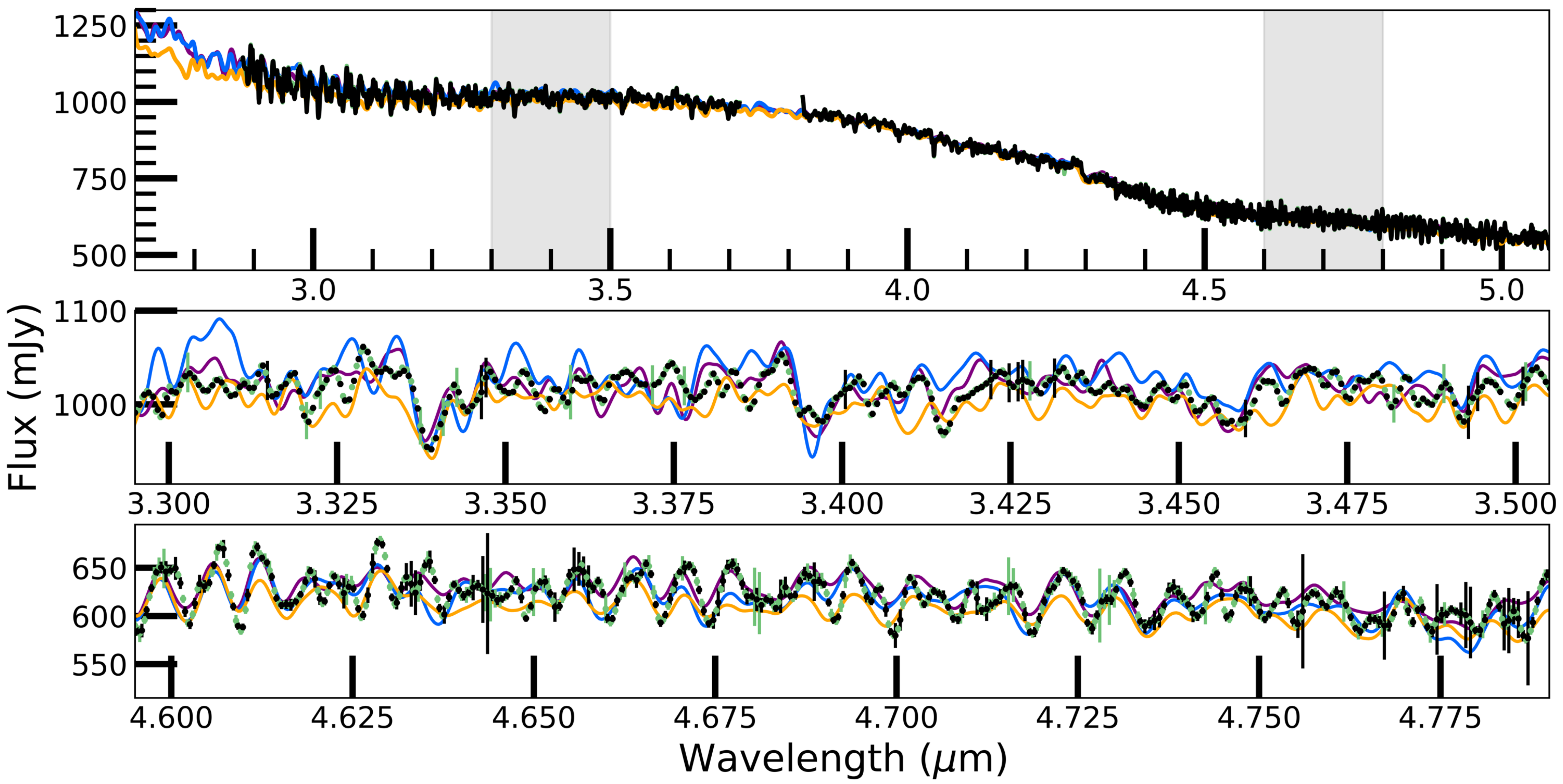


Conclusion:
1–3 component models fit the data equally well

Moran, Stevenson et al. (2023)

Can the right model complexity be identified with sufficient model fidelity?



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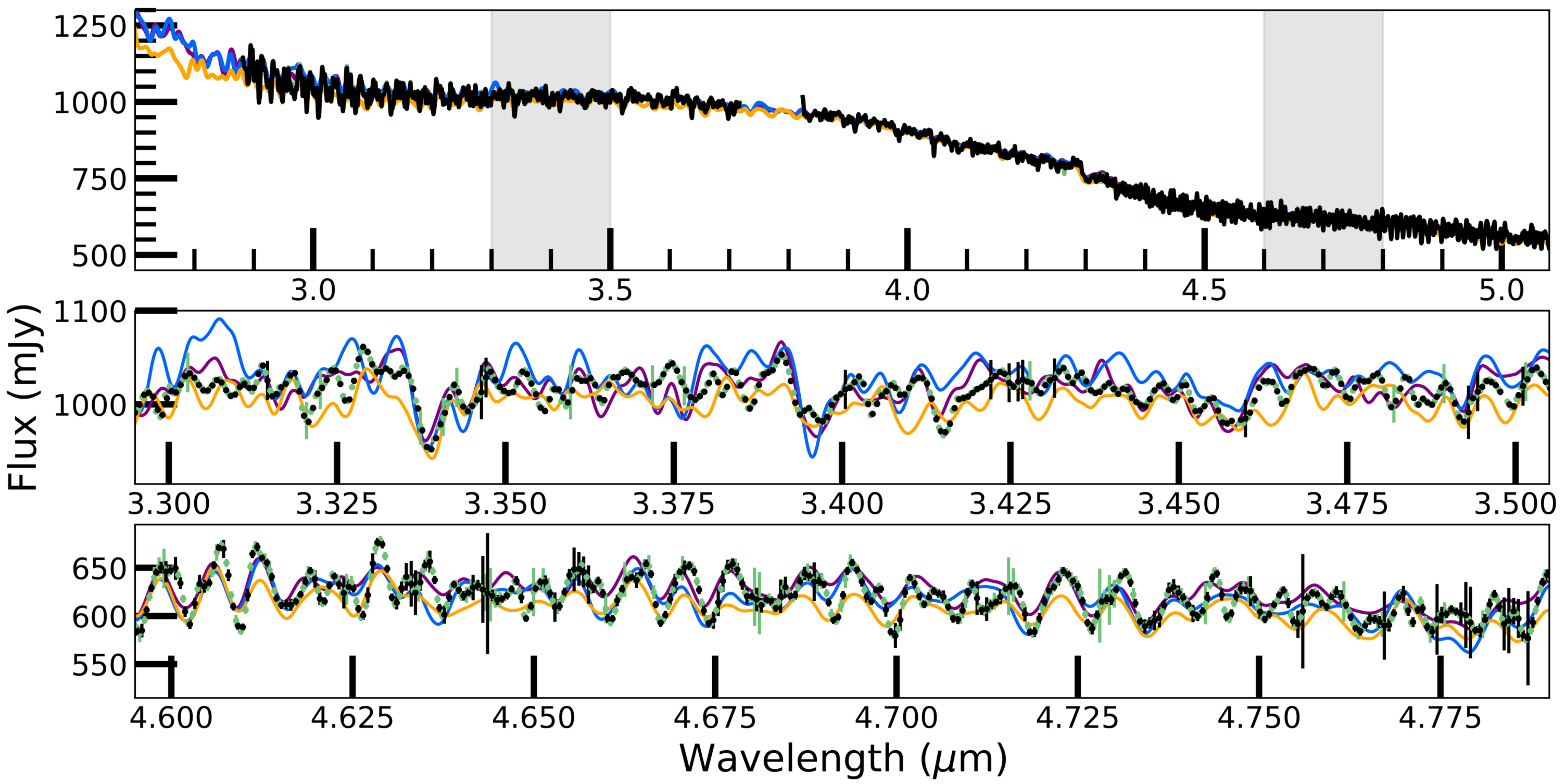

Yes. (Rackham & de Wit 2024)

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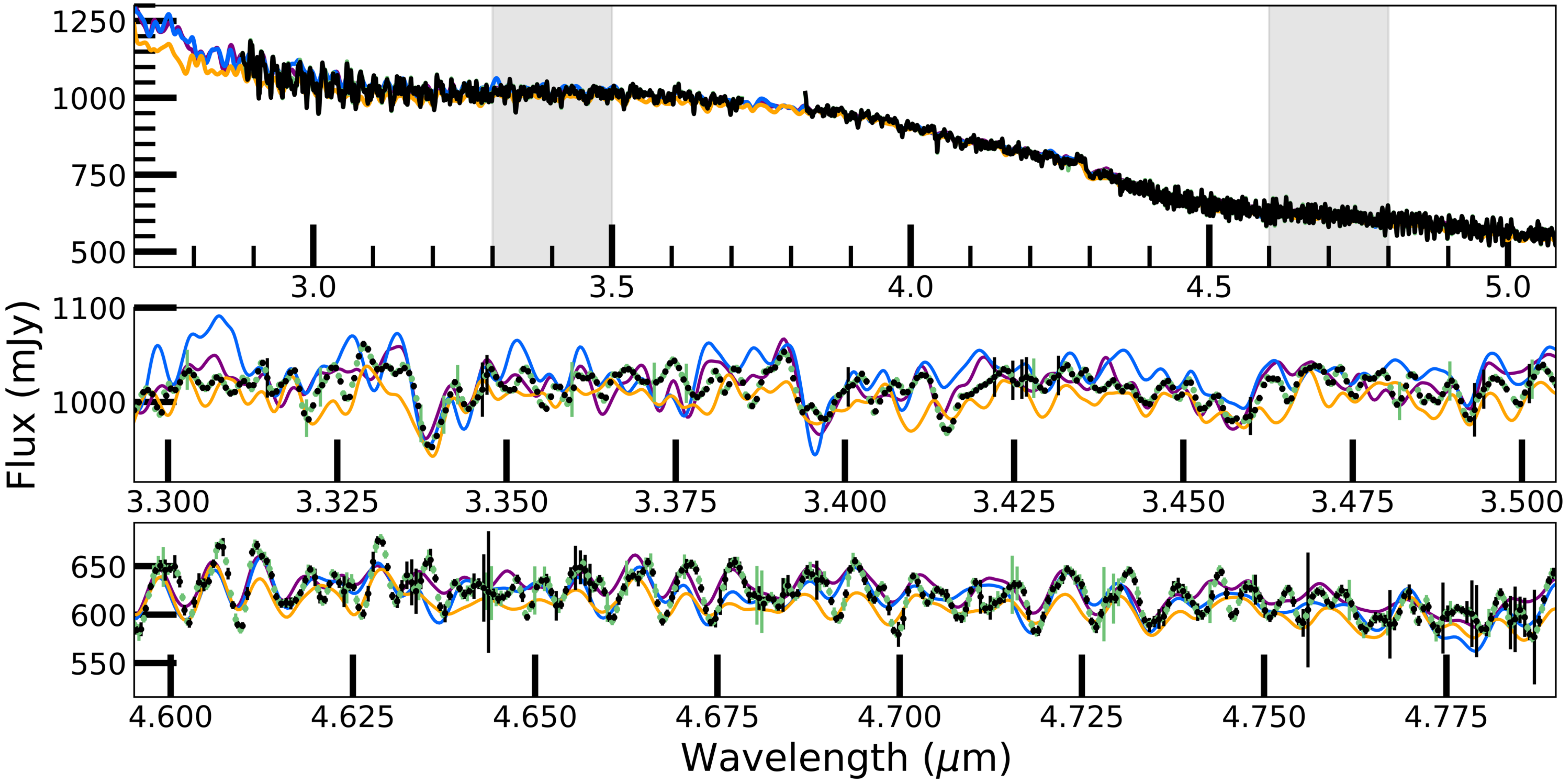

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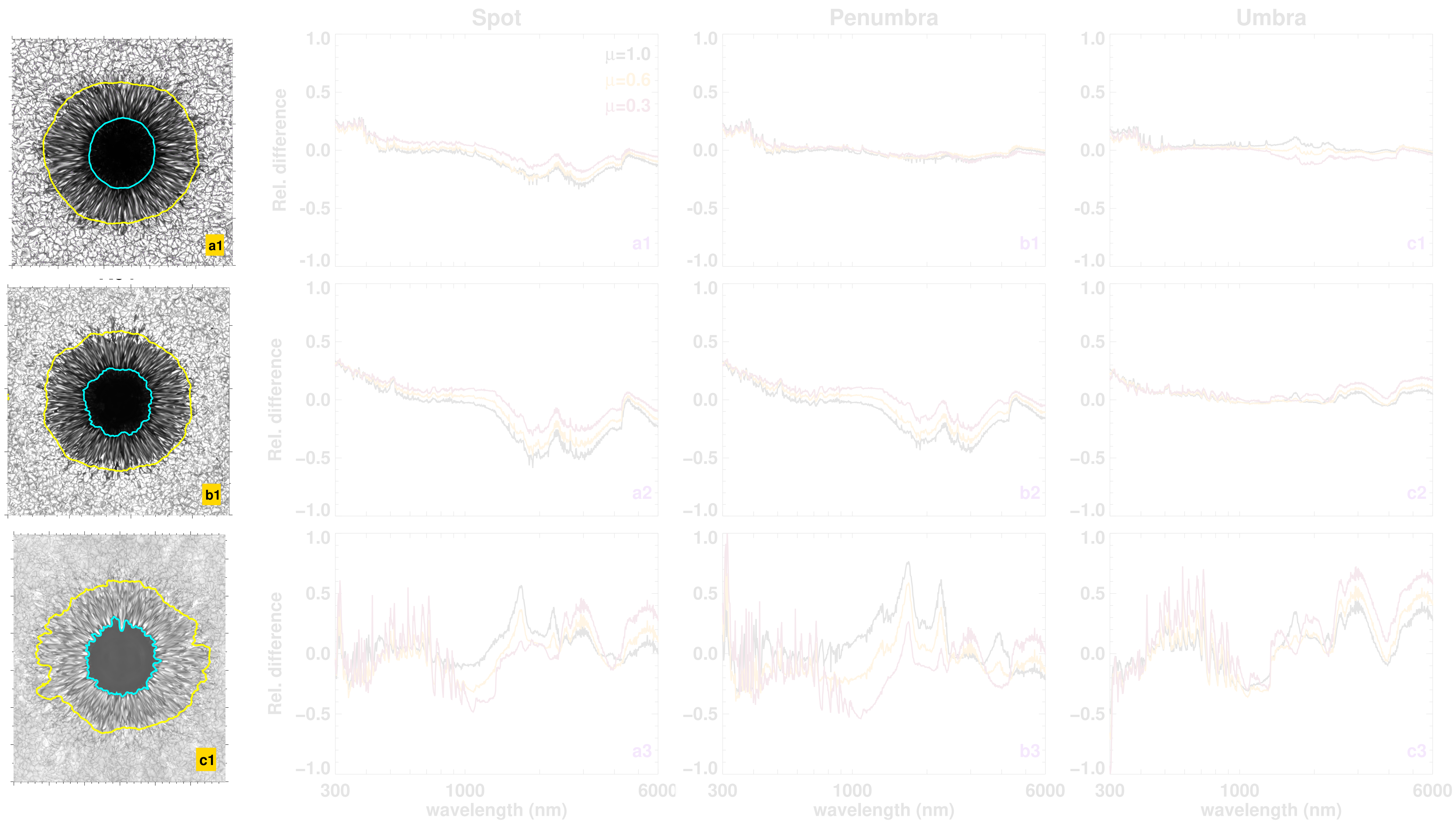
So how do we move towards the next-gen of stellar spectral models?

3D MHD spot contrasts are becoming available



G2V:

K0V:

M0V:

Smitha et al. (2024)

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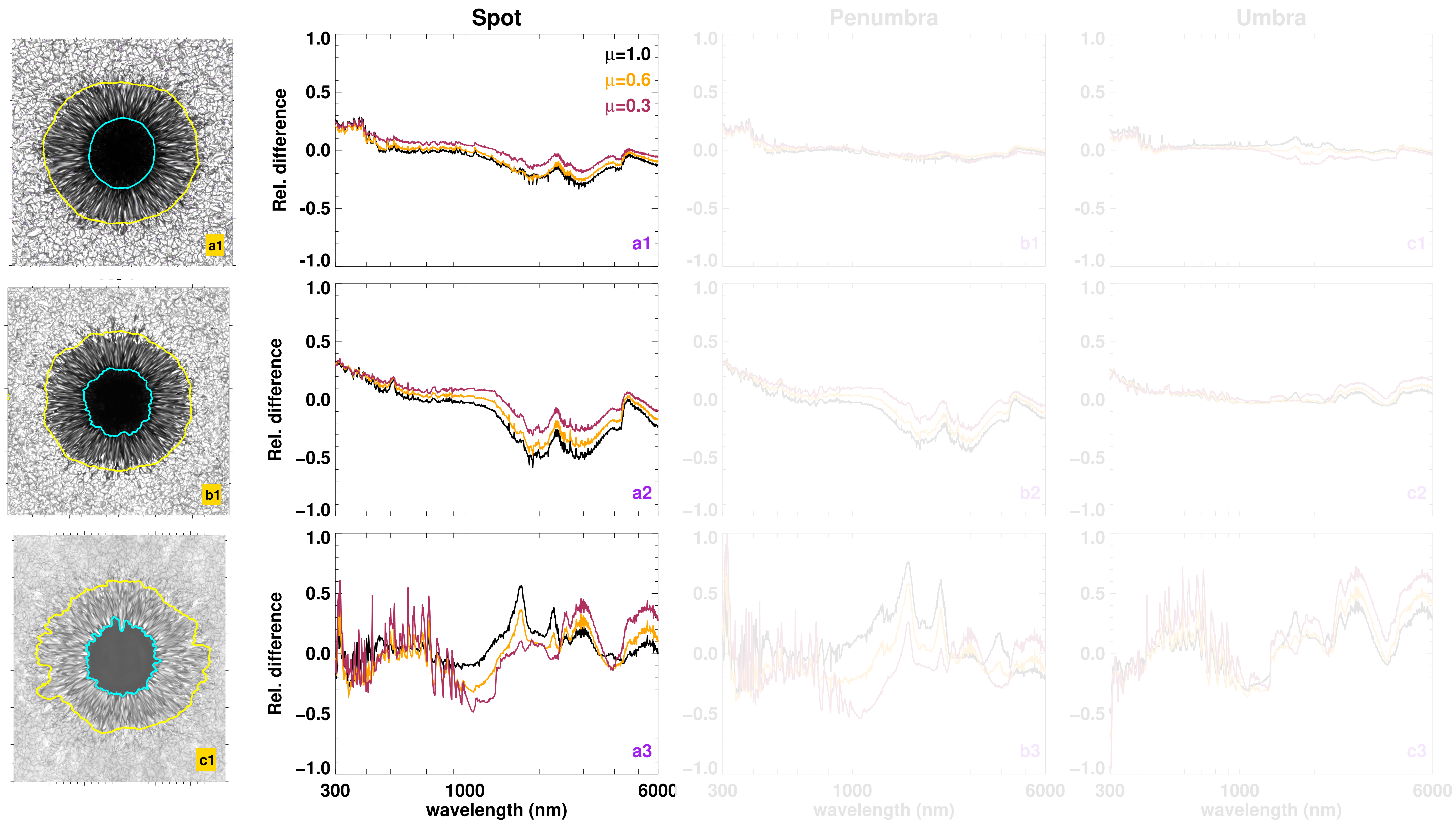

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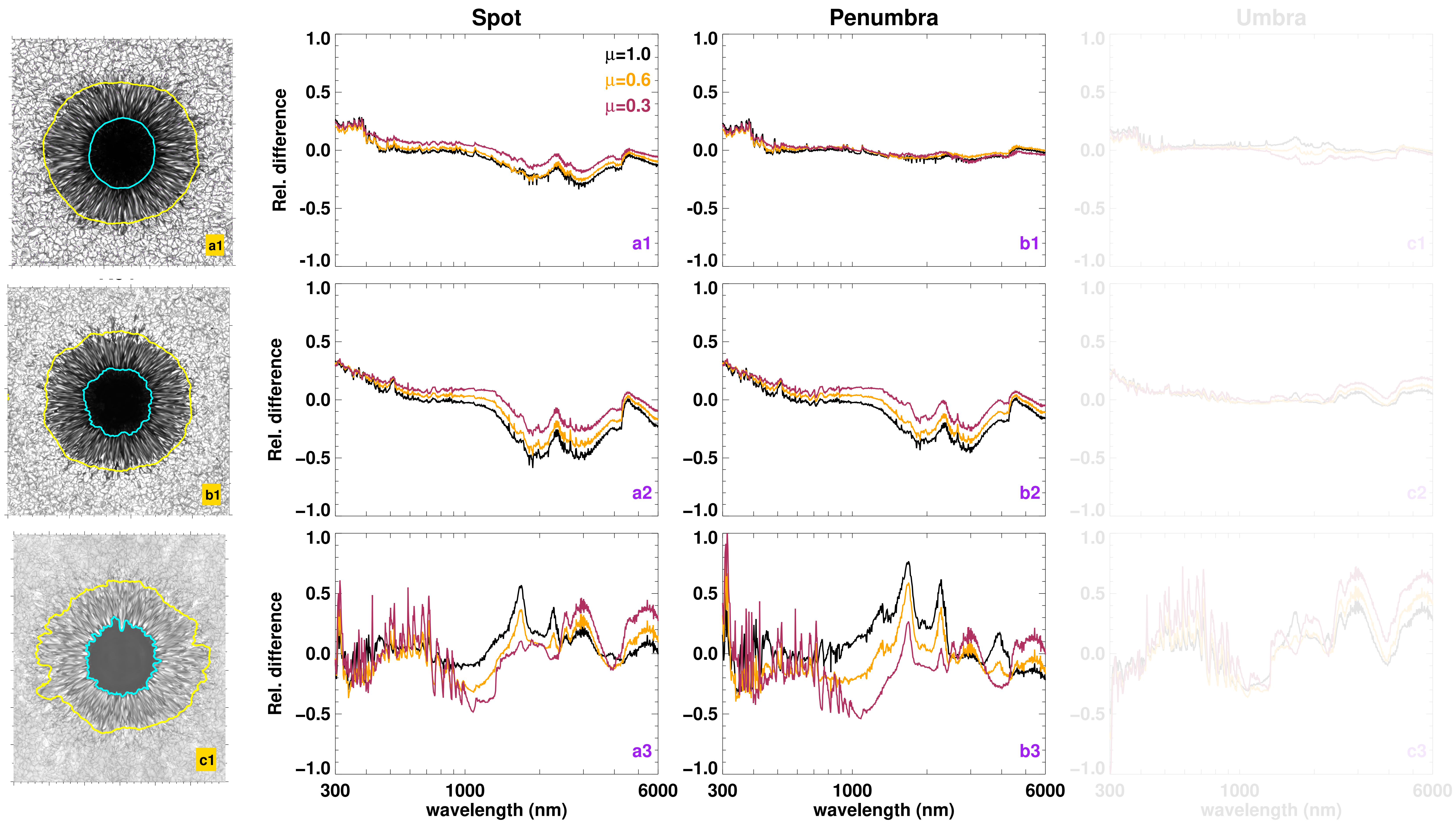

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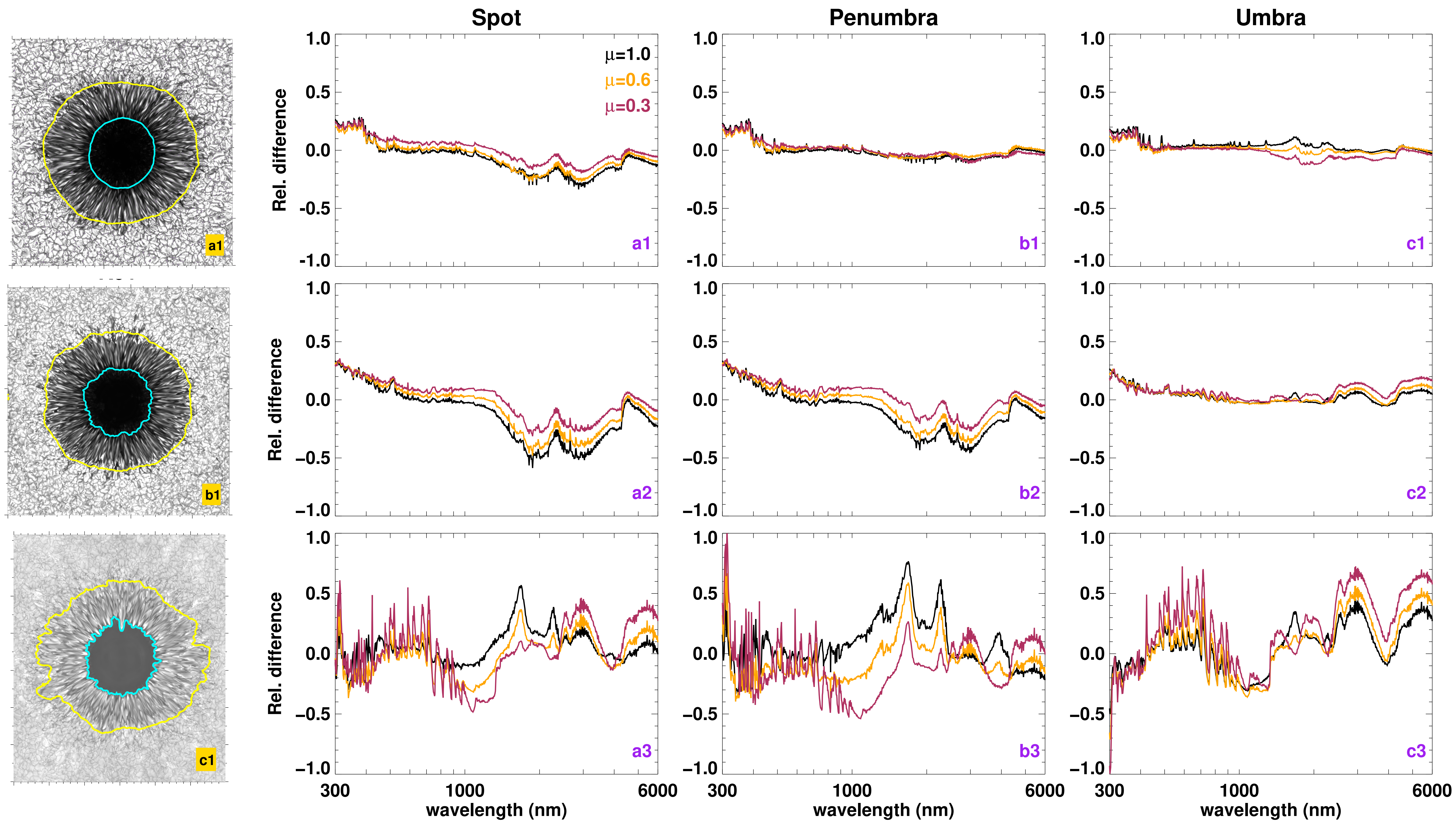

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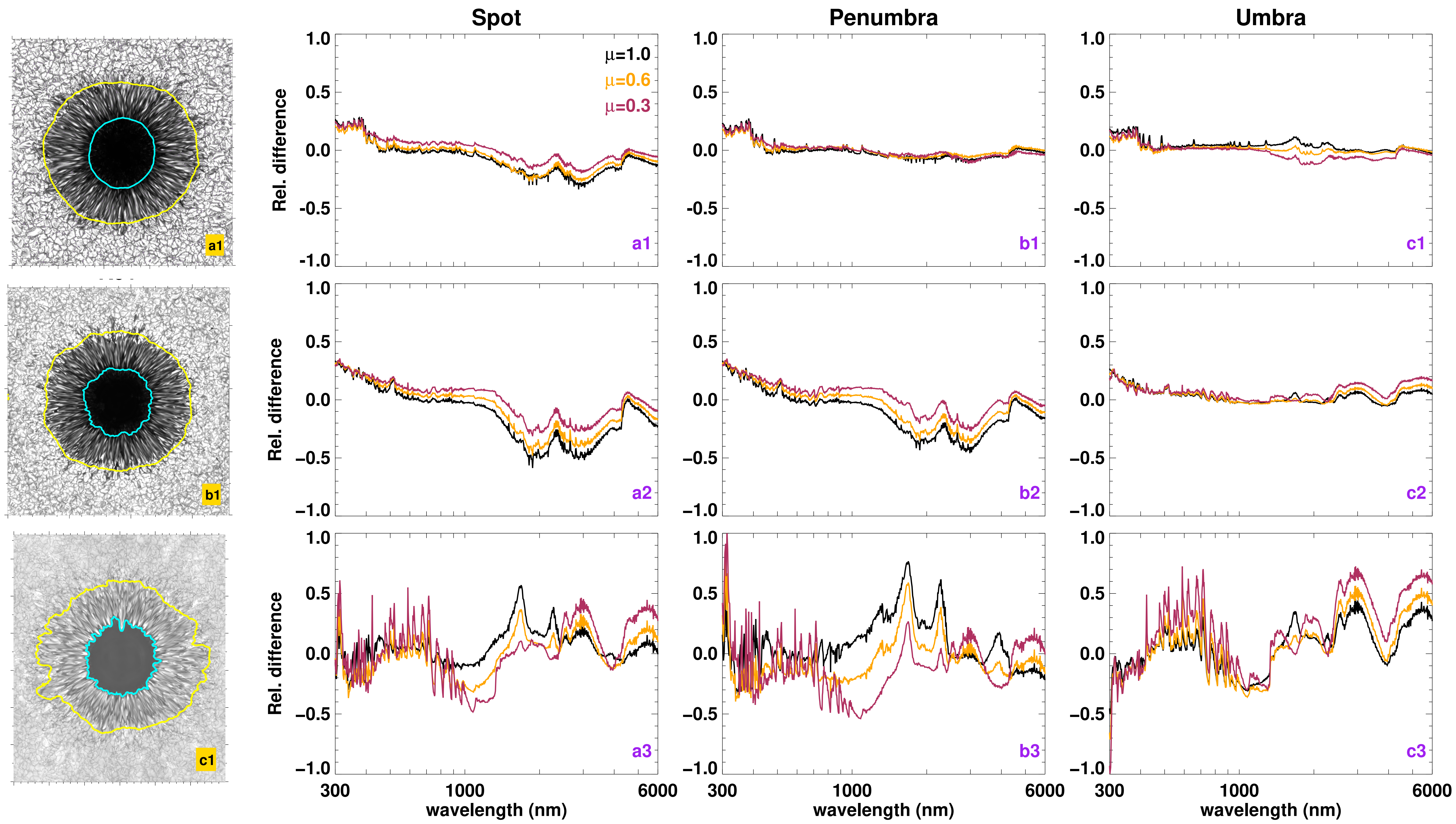

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Smitha et al. (2024)

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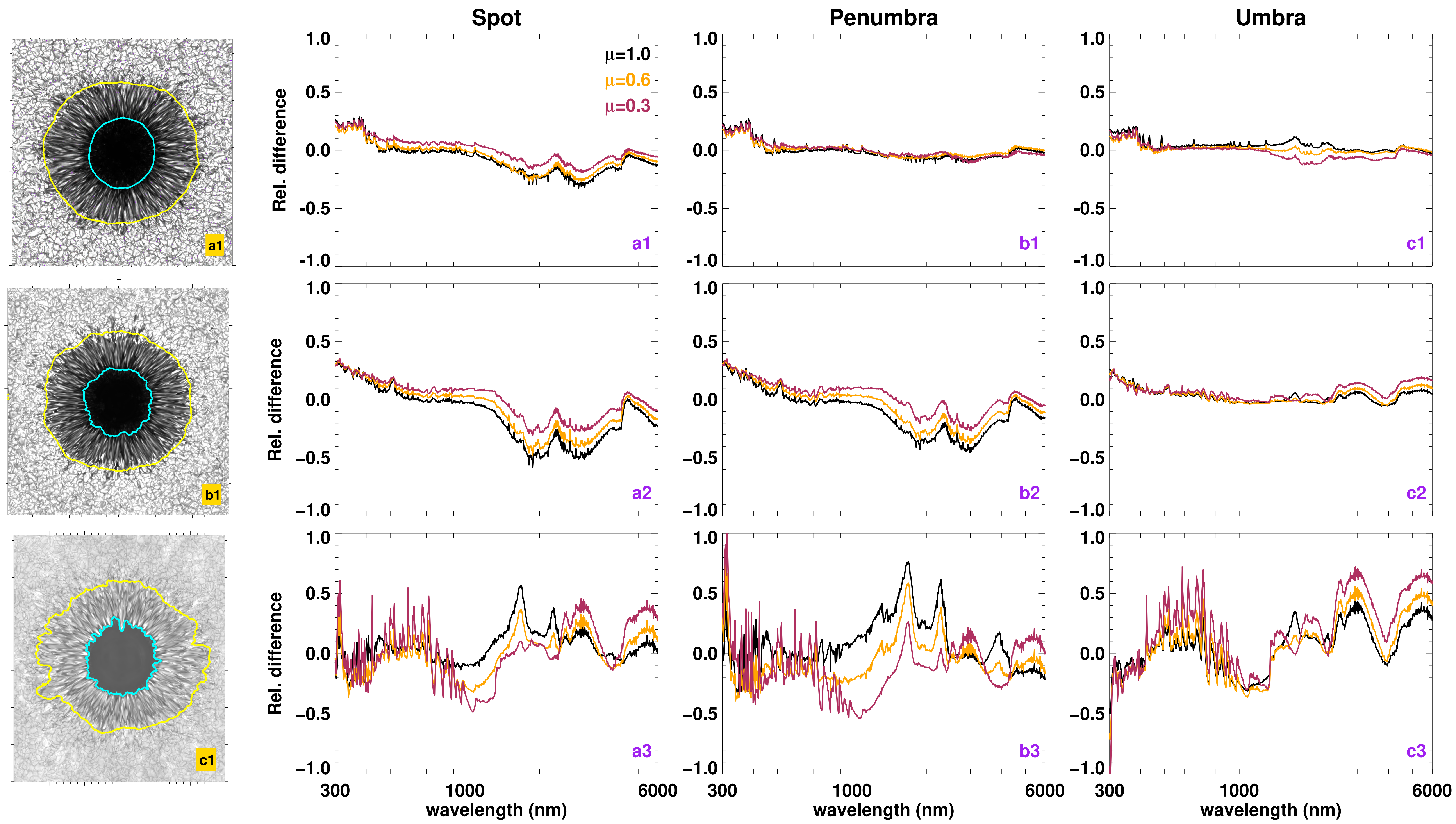

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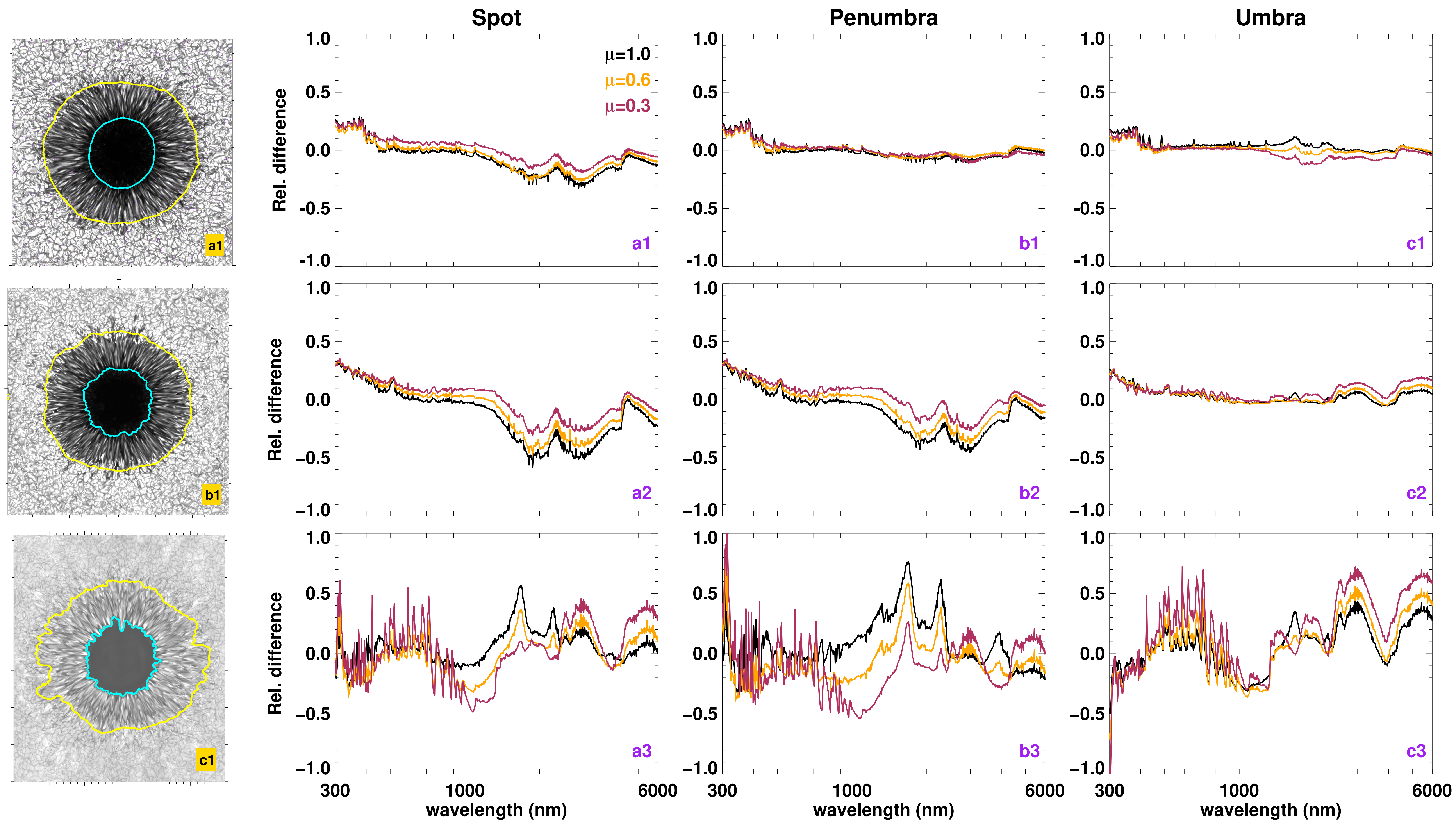

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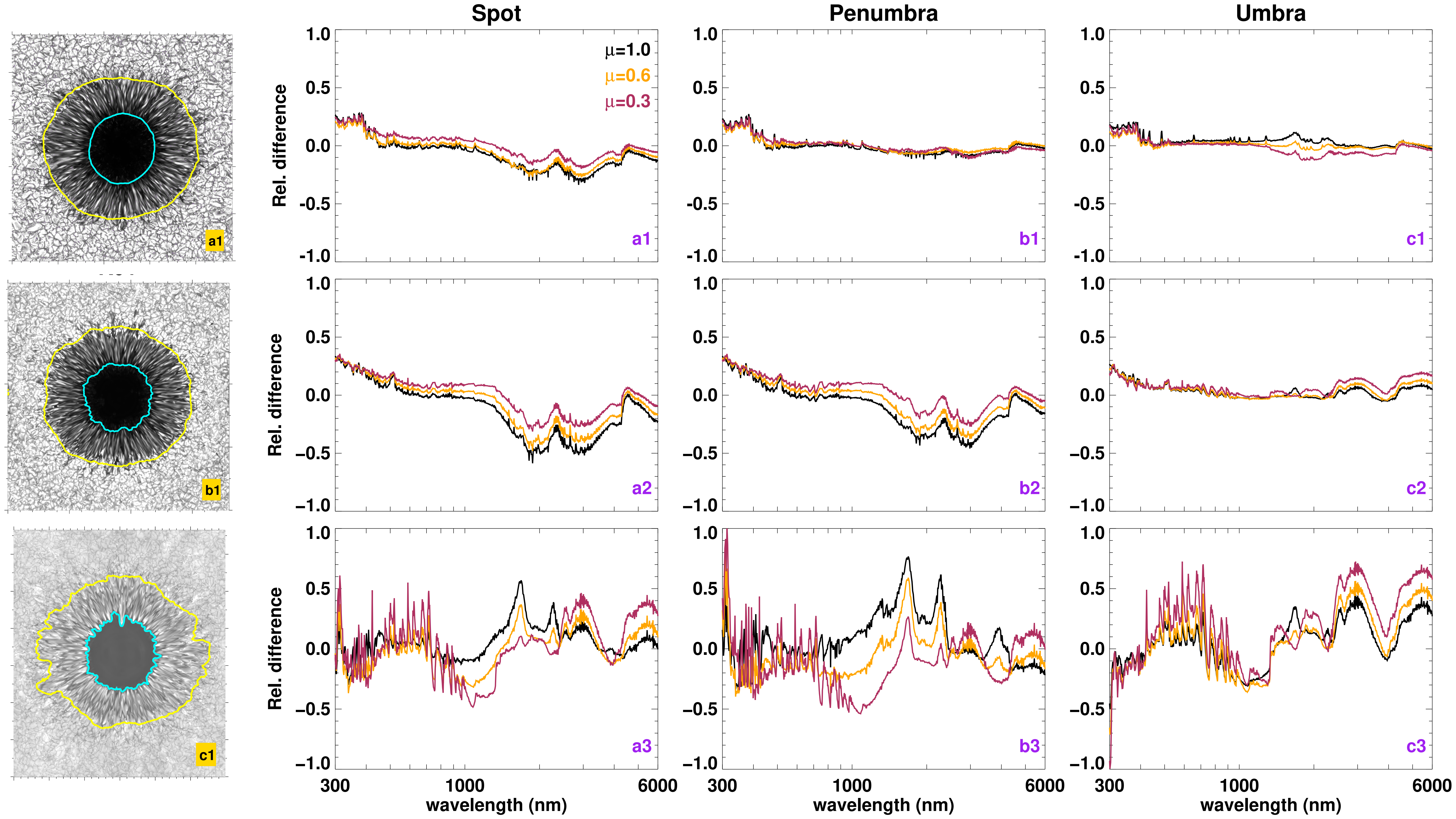

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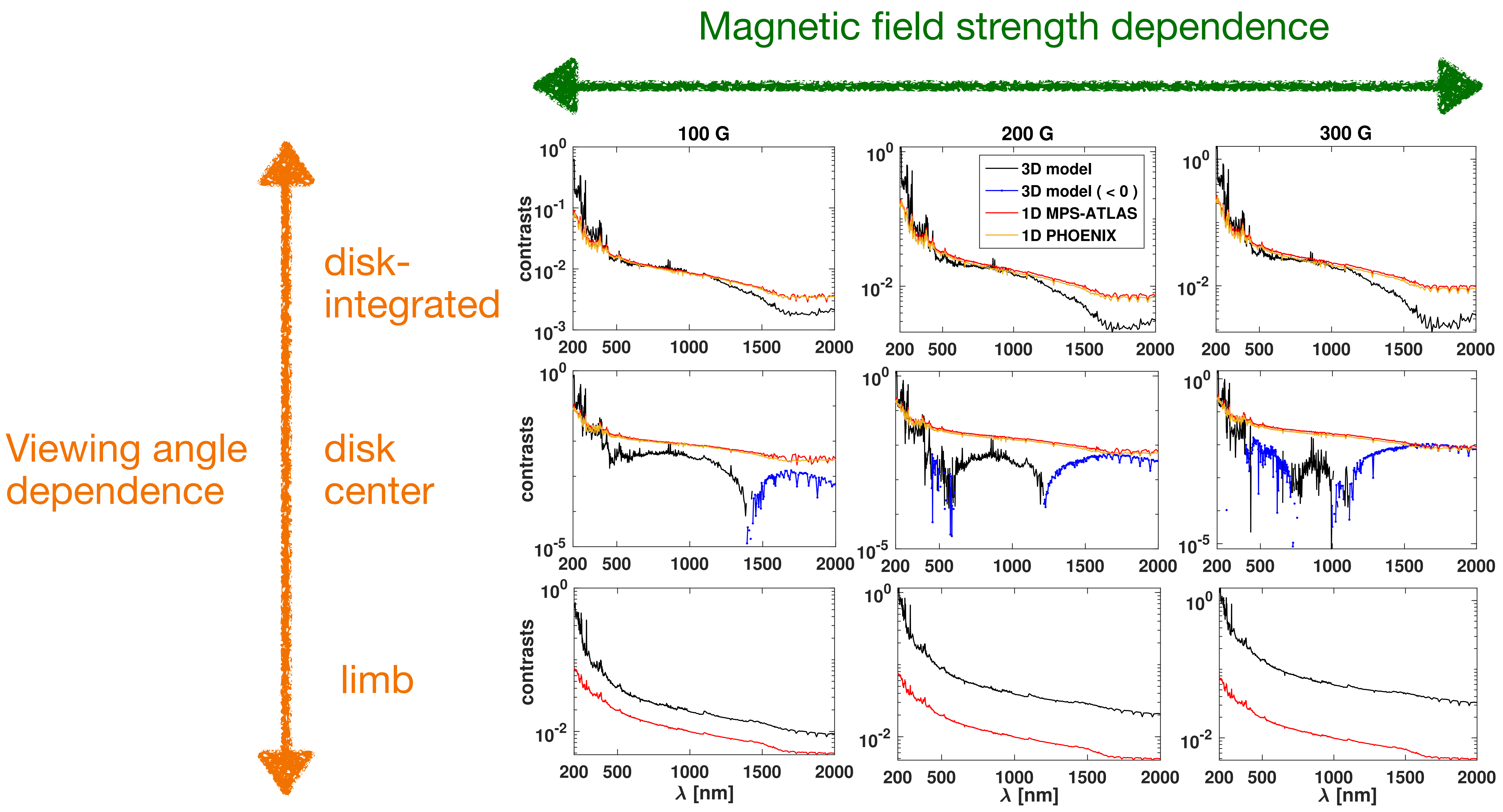


Witzke et al. (2023)

3D MHD facular contrasts are becoming available

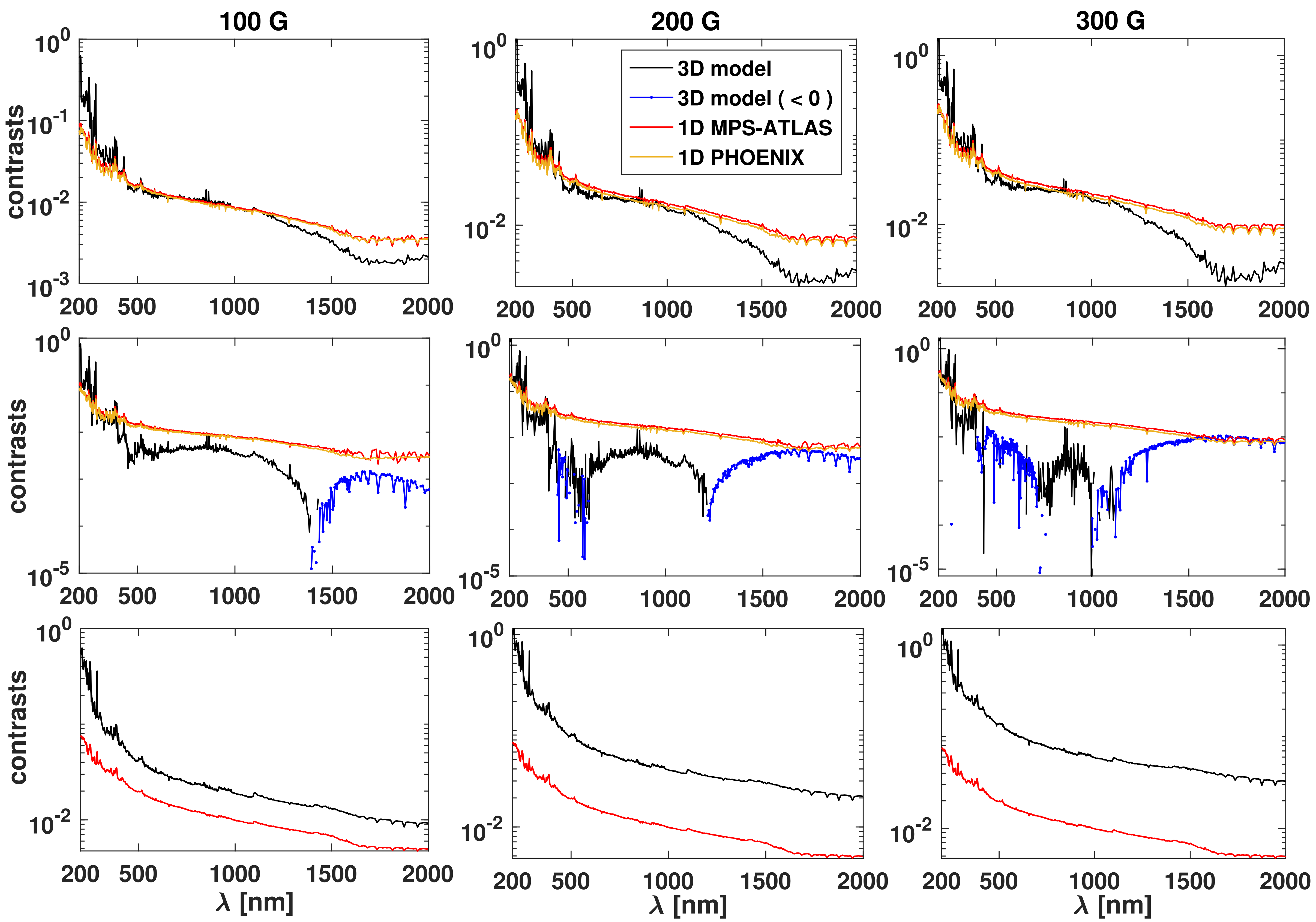
Magnetic field strength dependence

Viewing angle dependence

disk-integrated

disk center

limb



Different spectral contrasts are evident in 3D models

Witzke et al. (2023)

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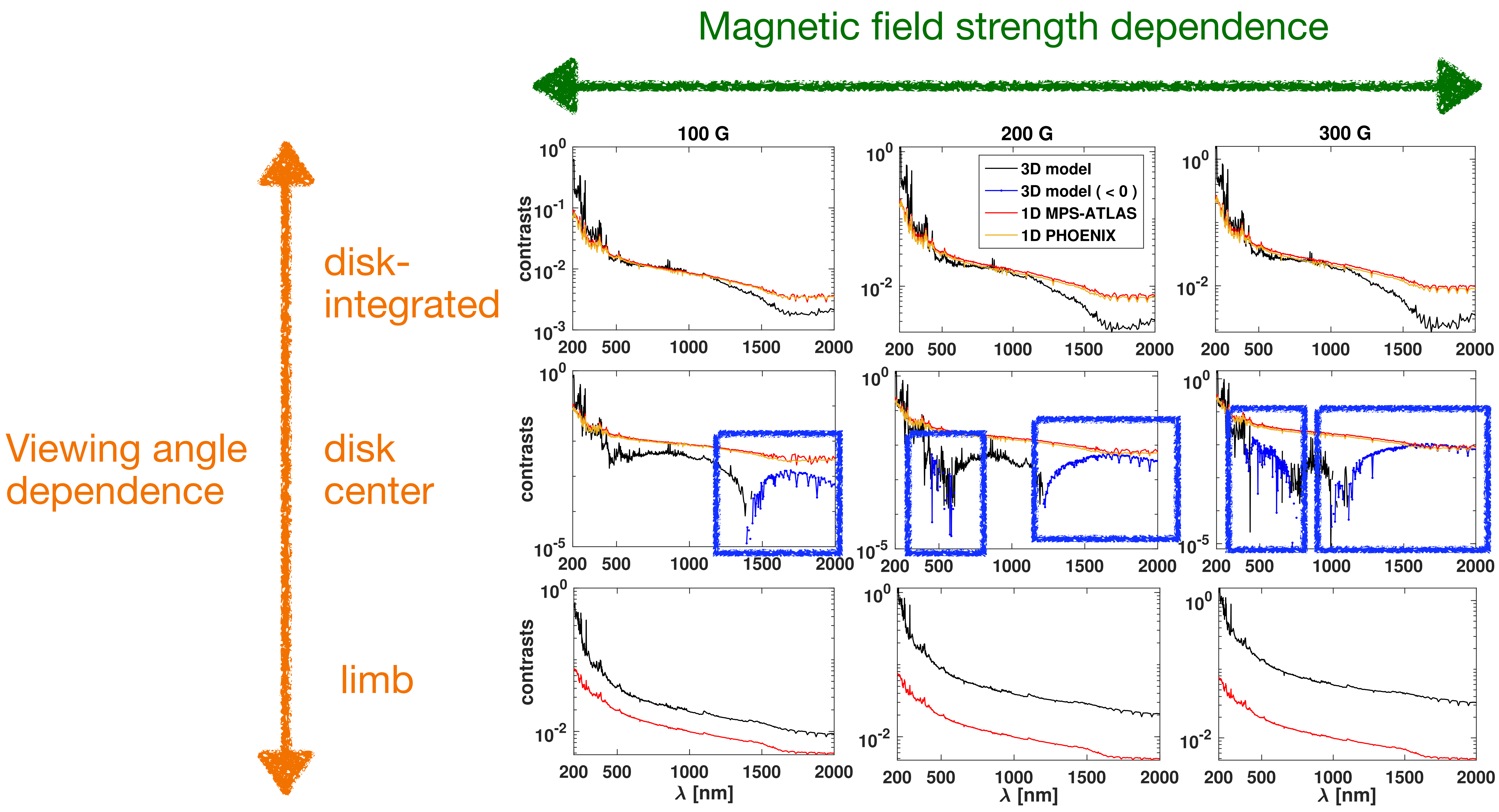

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Faculae can even be dimmer than the photosphere!

Witzke et al. (2023)

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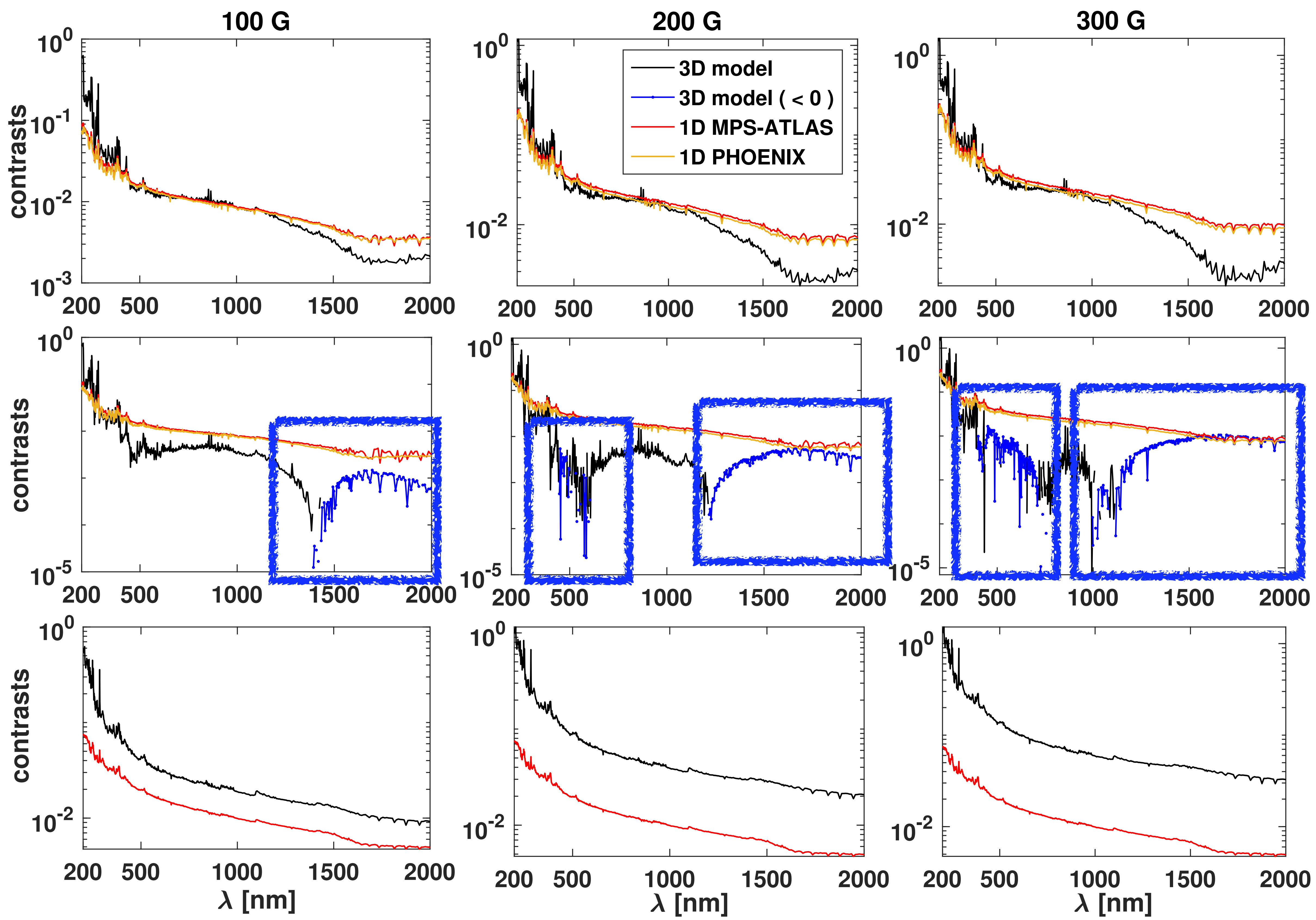

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Faculae can even be dimmer than the photosphere!

See talk from **Sara Seager**

Witzke et al. (2023)

Main Points

Our model-limited regime

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Main Points

Our model-limited regime

ChatGPT:

```
So, in summary, if we
want to characterize
exoplanets, we need
better stellar models.
Should be simple.
```

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2. A Roadmap to Atmospheres of Terrestrial Exoplanets with JWST

A roadmap for rapid and efficient JWST exoplanet exploration

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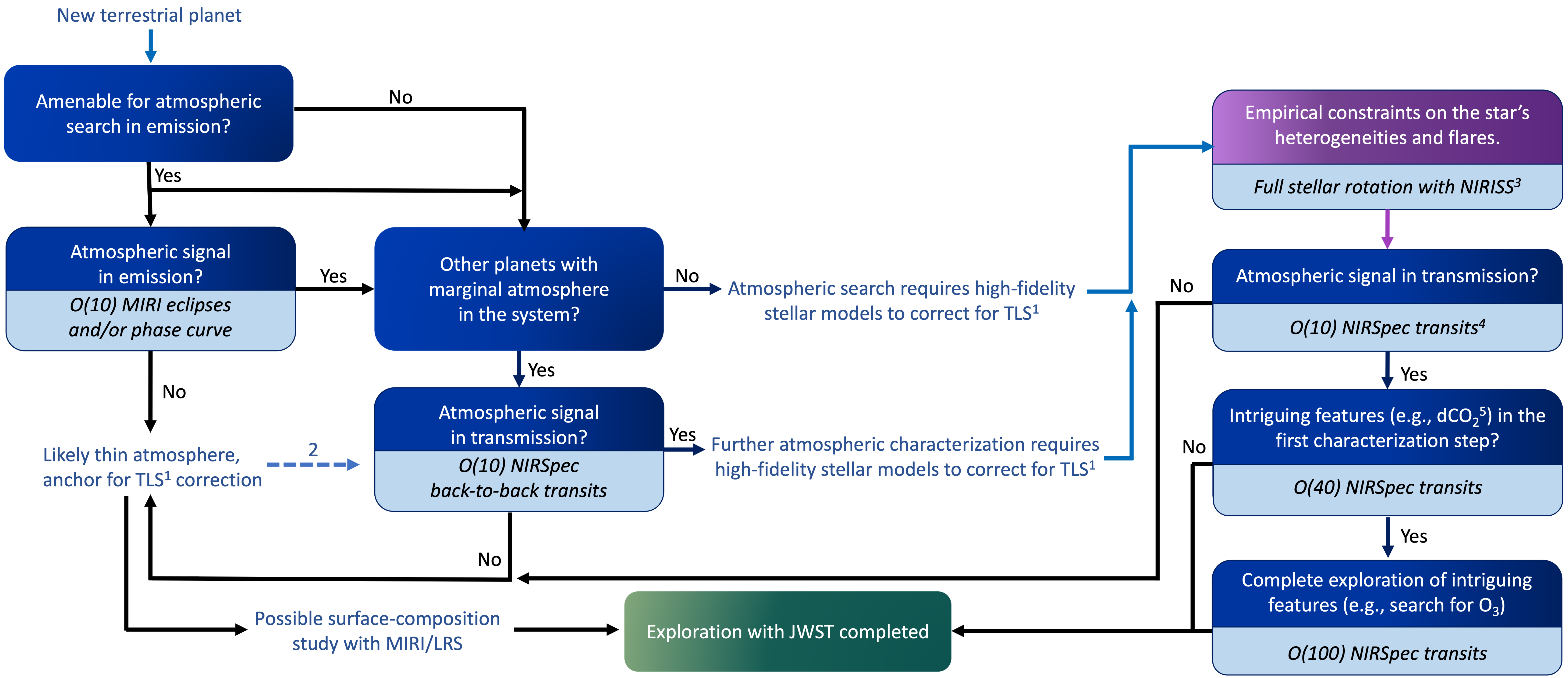
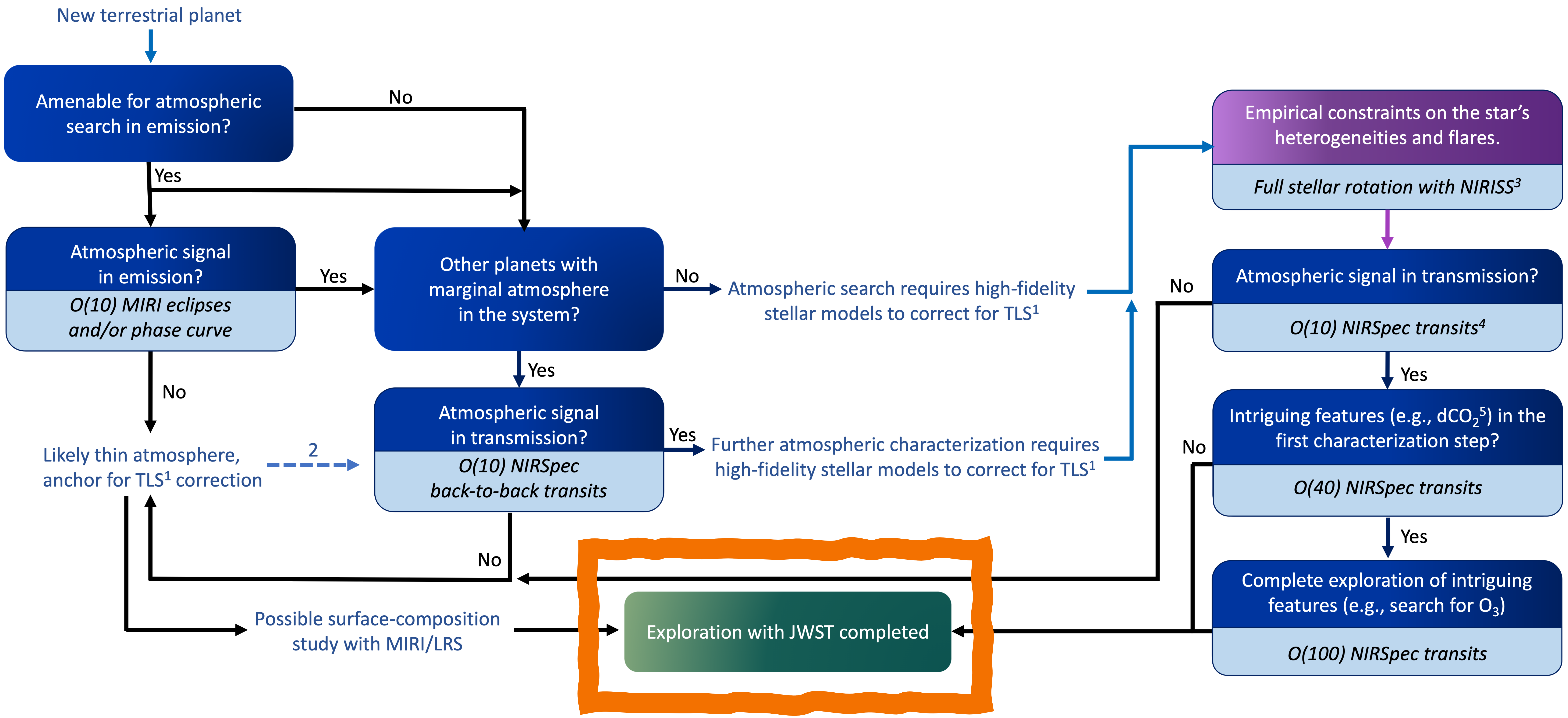


TRAPPIST-1 JWST Community Initiative (2024)

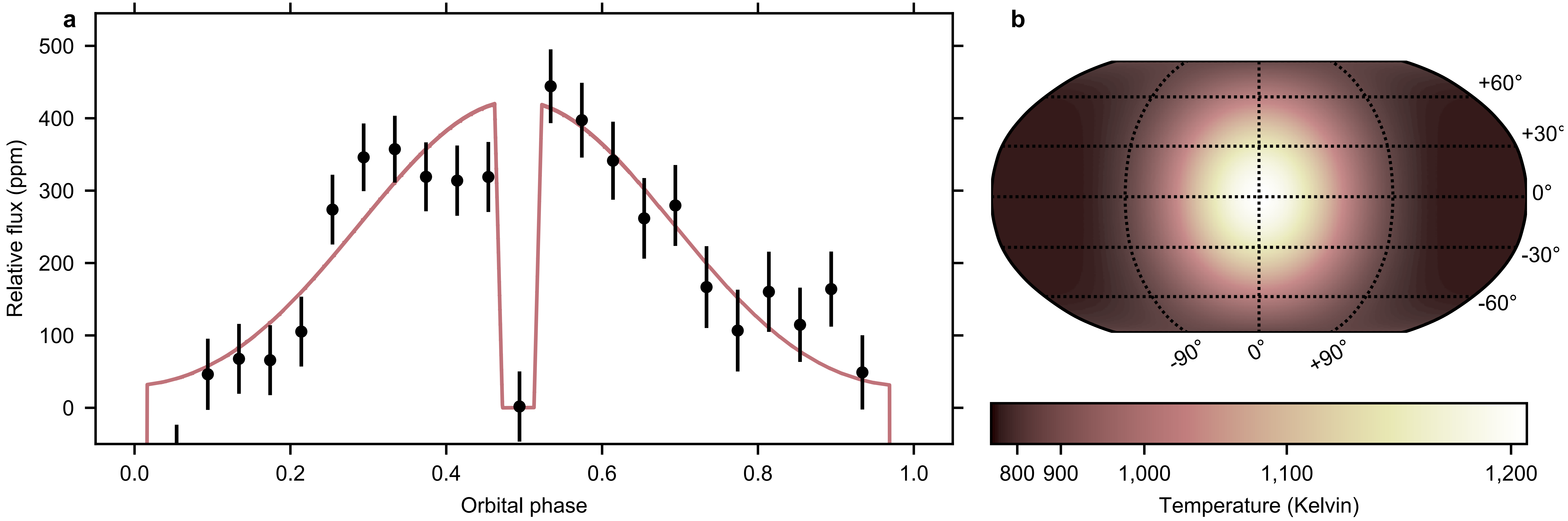
A roadmap for rapid and efficient JWST exoplanet exploration



TRAPPIST-1 JWST Community Initiative (2024)

First step: emission

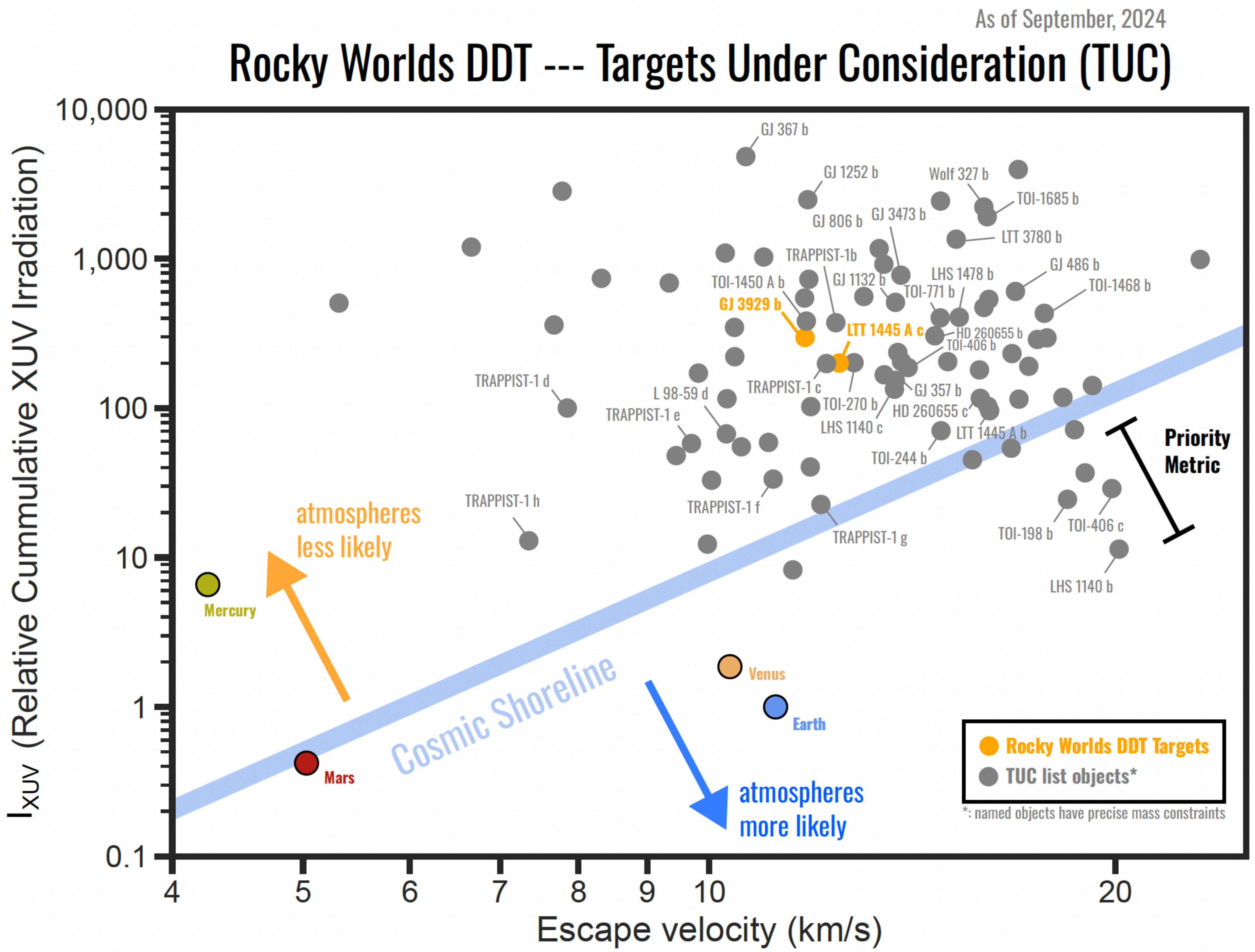
e.g., LHS 3844b: large-amplitude, symmetric phase curve rules out thick atmosphere



Kreidberg et al. (2019)

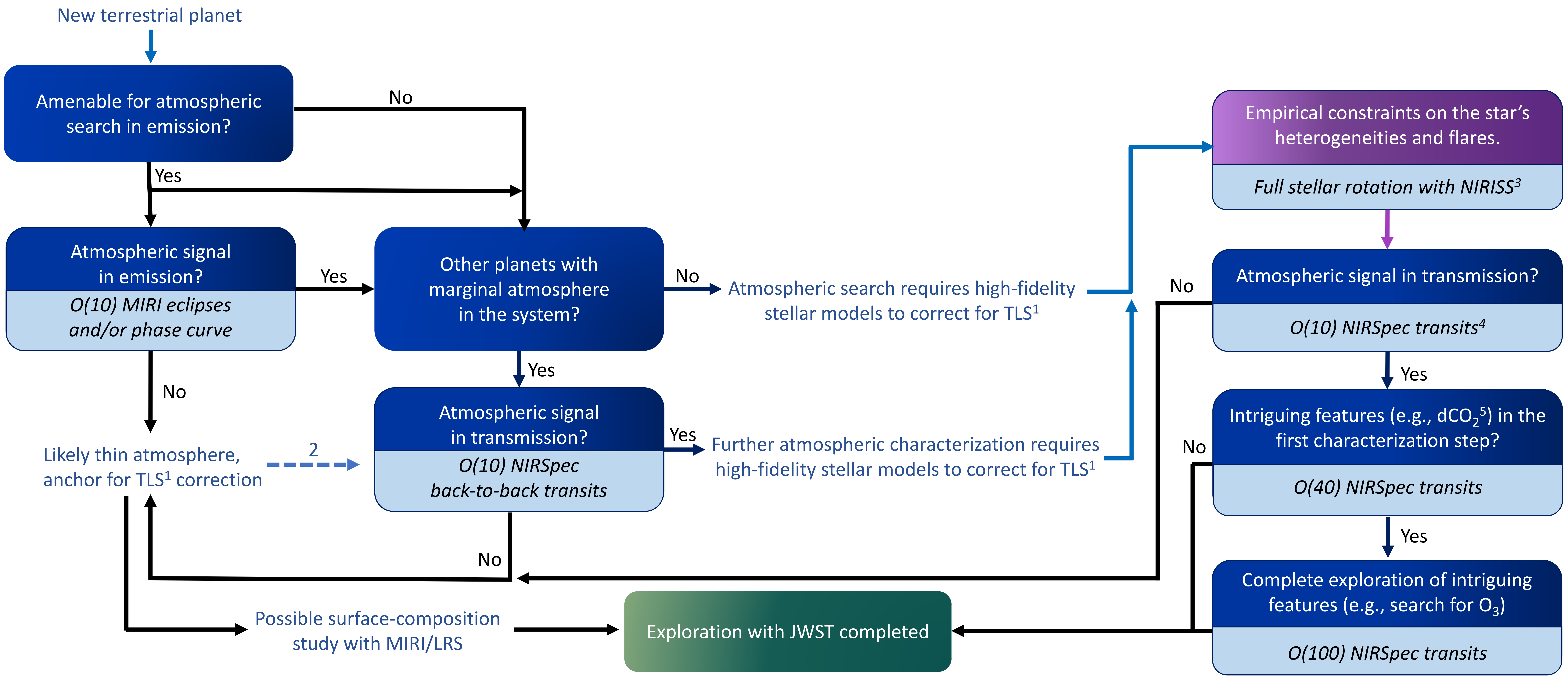
Rocky Worlds DDT

500 JWST hours and 250 HST orbits for rocky planets around low-mass stars



Lead: Néstor Espinoza
Deputy Lead: Hannah Diamond-Lowe

The road to terrestrial exoplanet characterization runs through their stars



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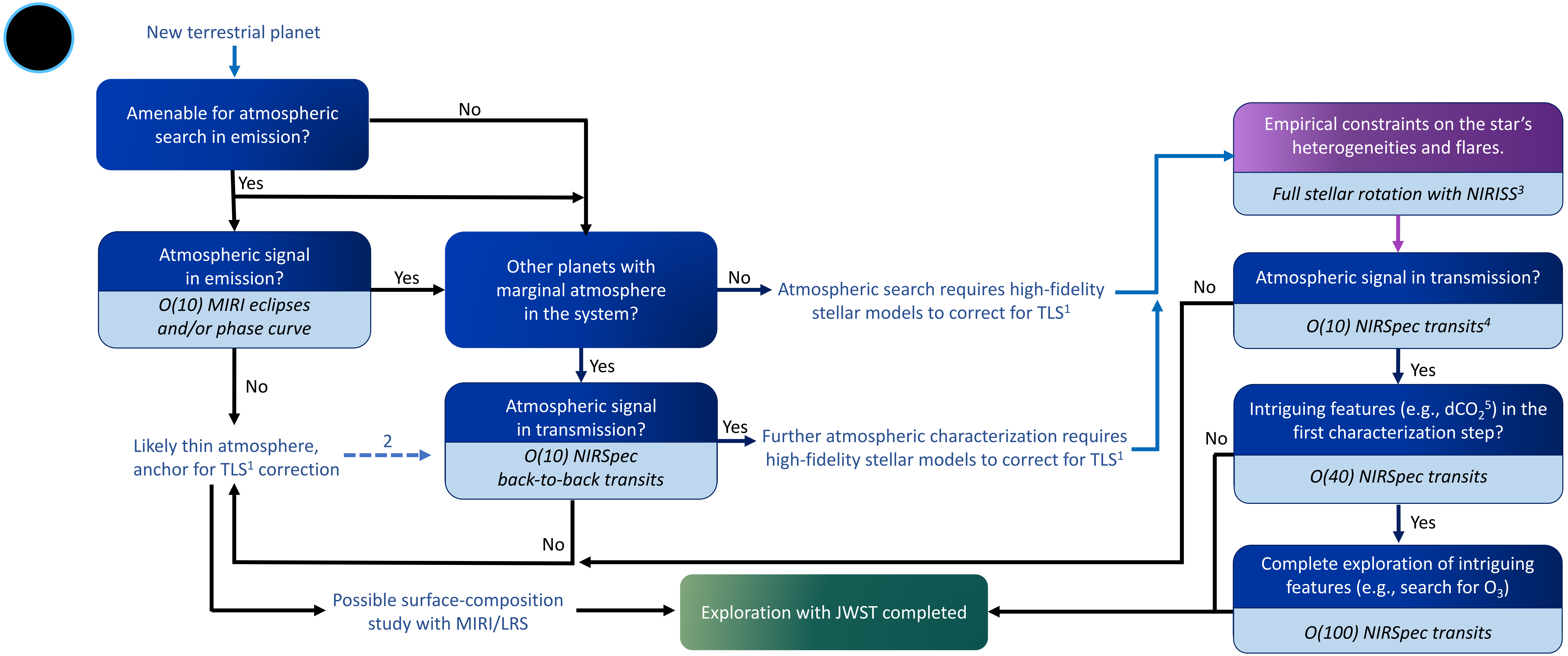

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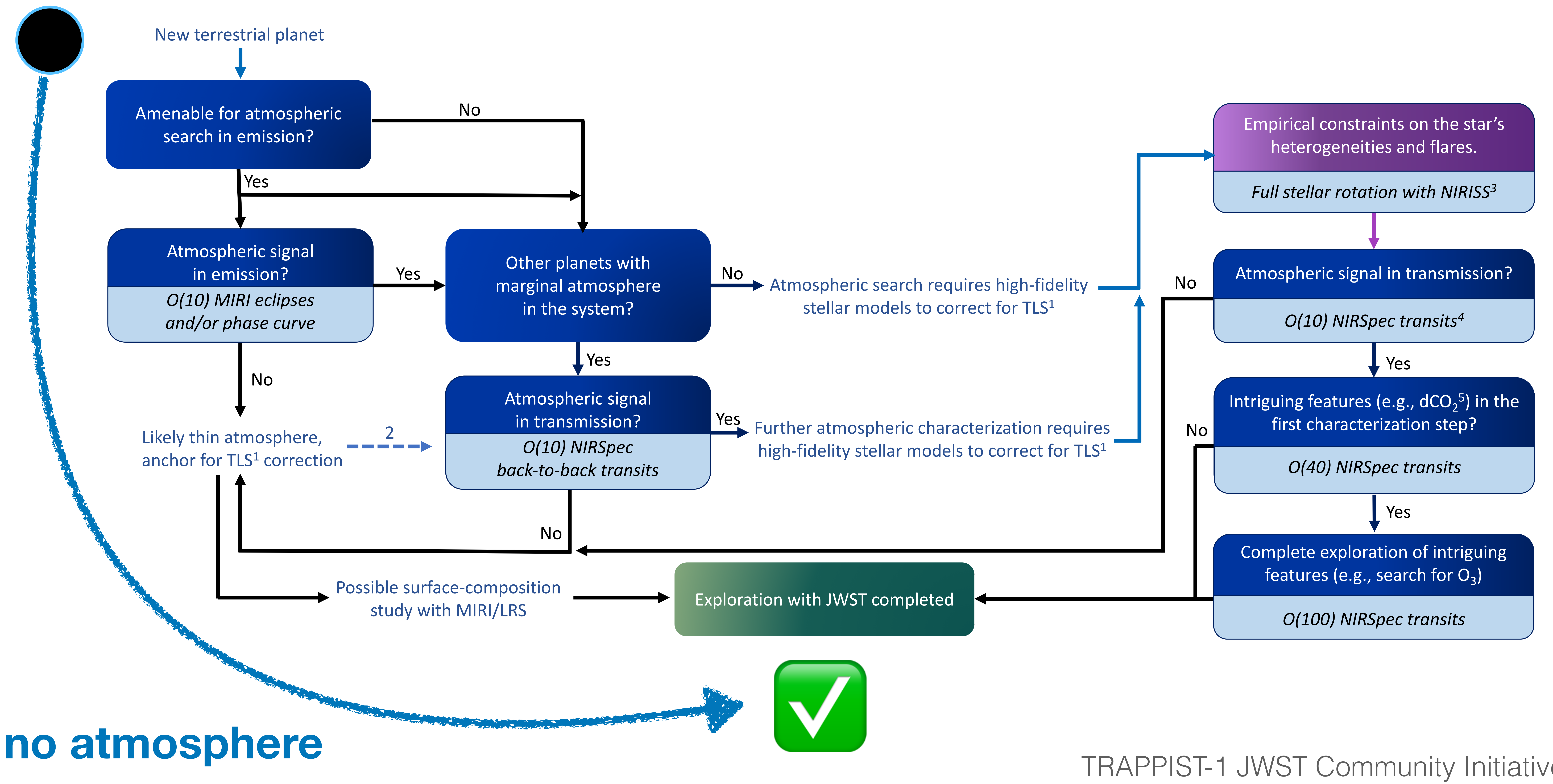

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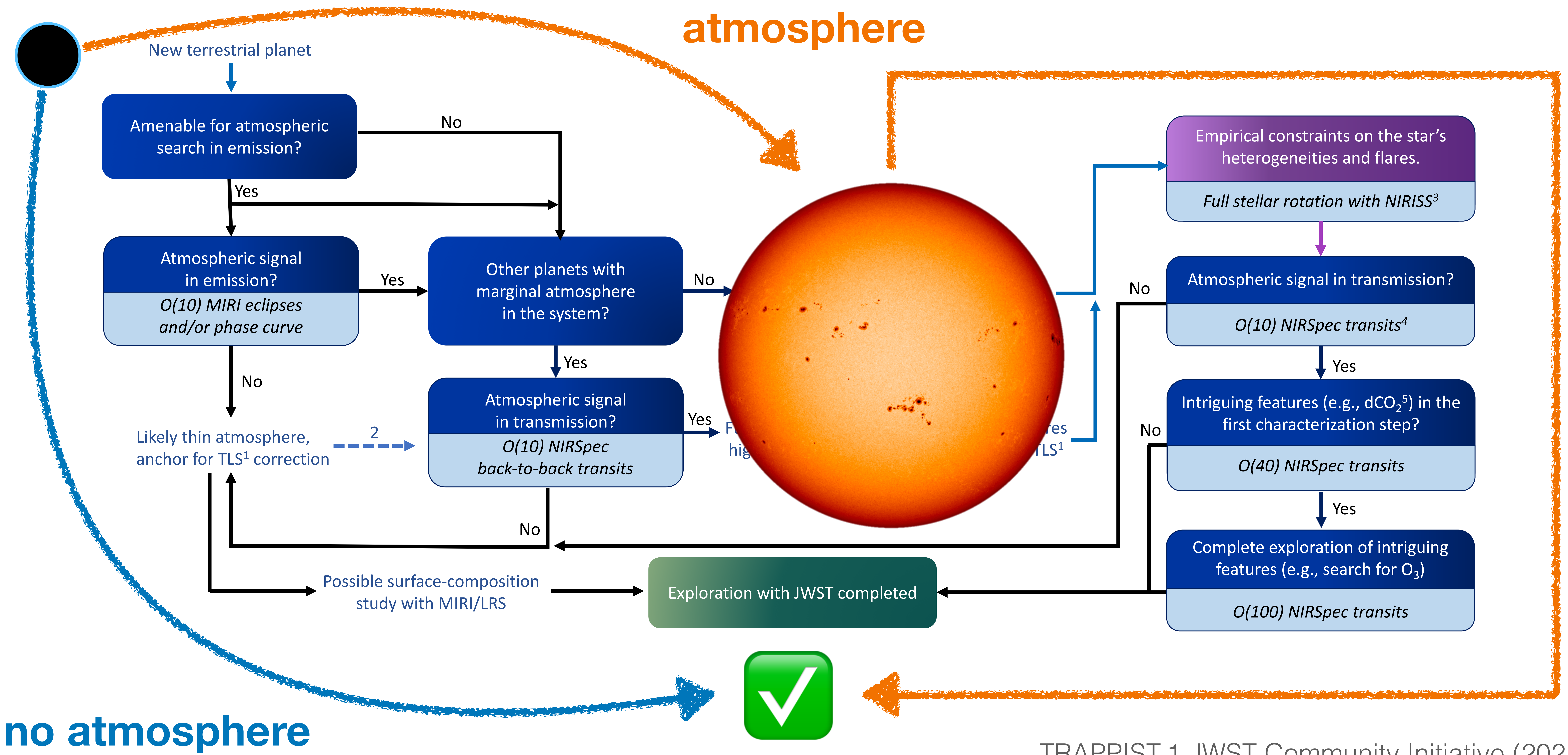

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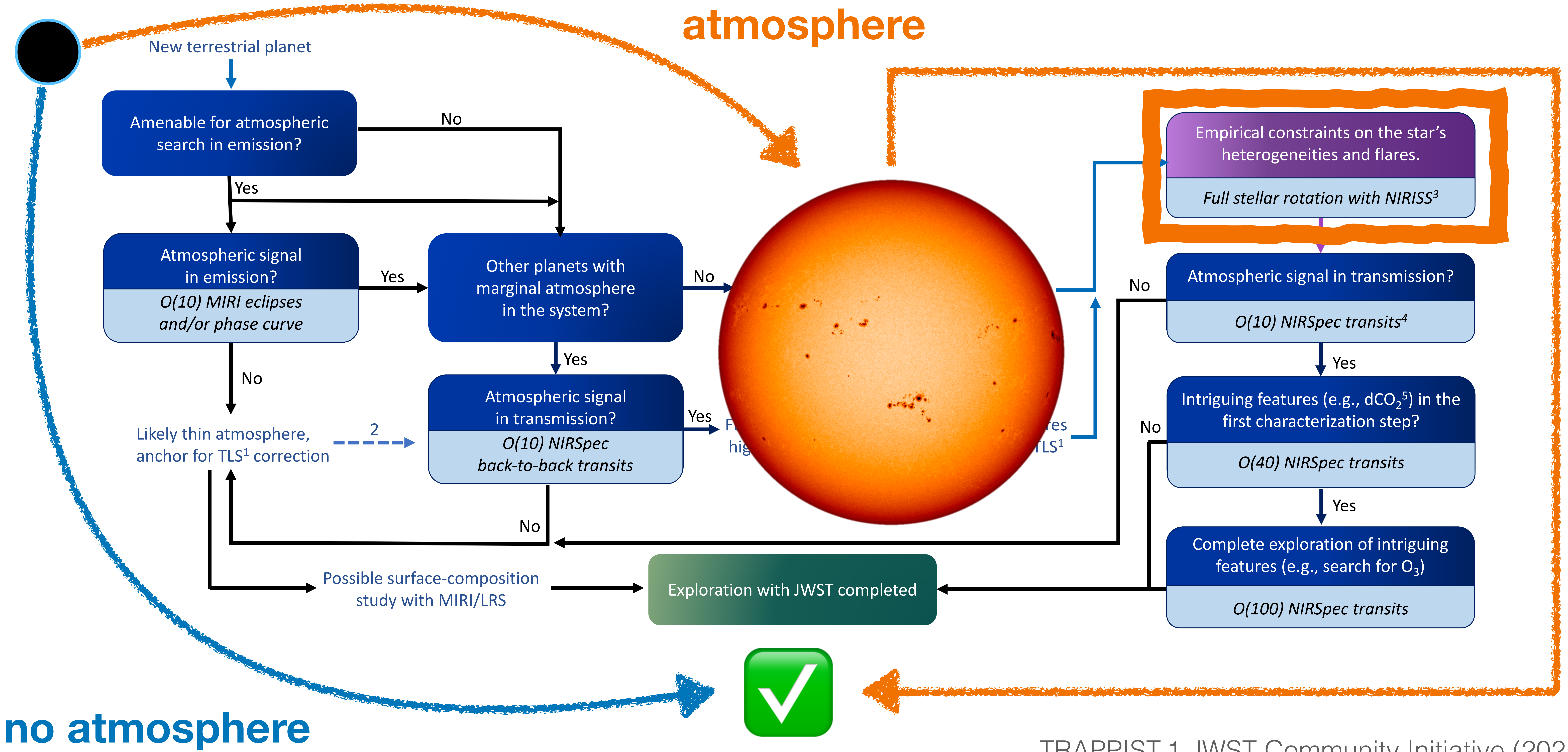
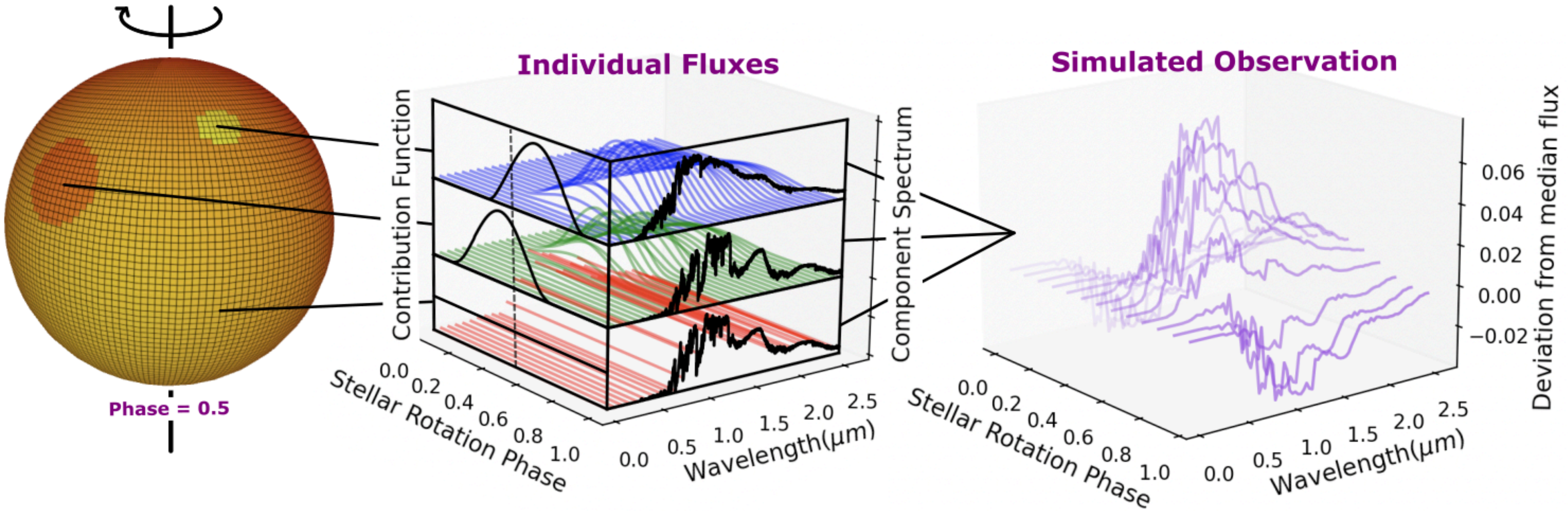


TRAPPIST-1 JWST Community Initiative (2024)

Spectroscopic phase curves offer empirical constraints

especially promising for JWST spectra of late-type stars



David Berardo, de Wit, & Rackham (2024)

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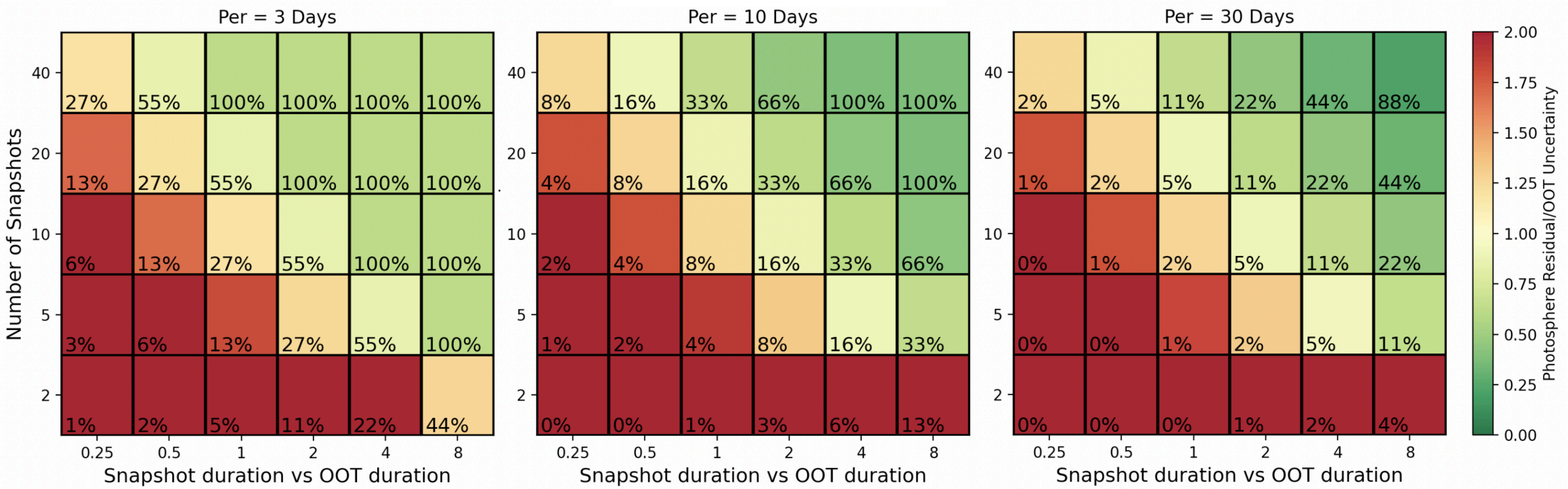

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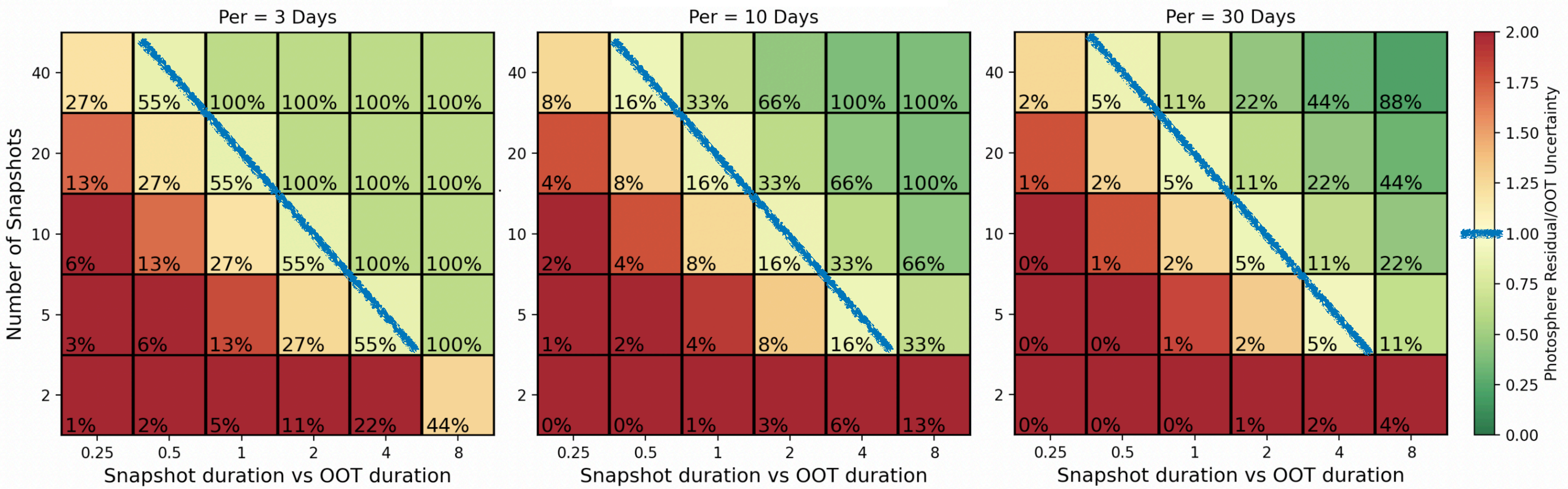

David Berardo, de Wit, & Rackham (2024)

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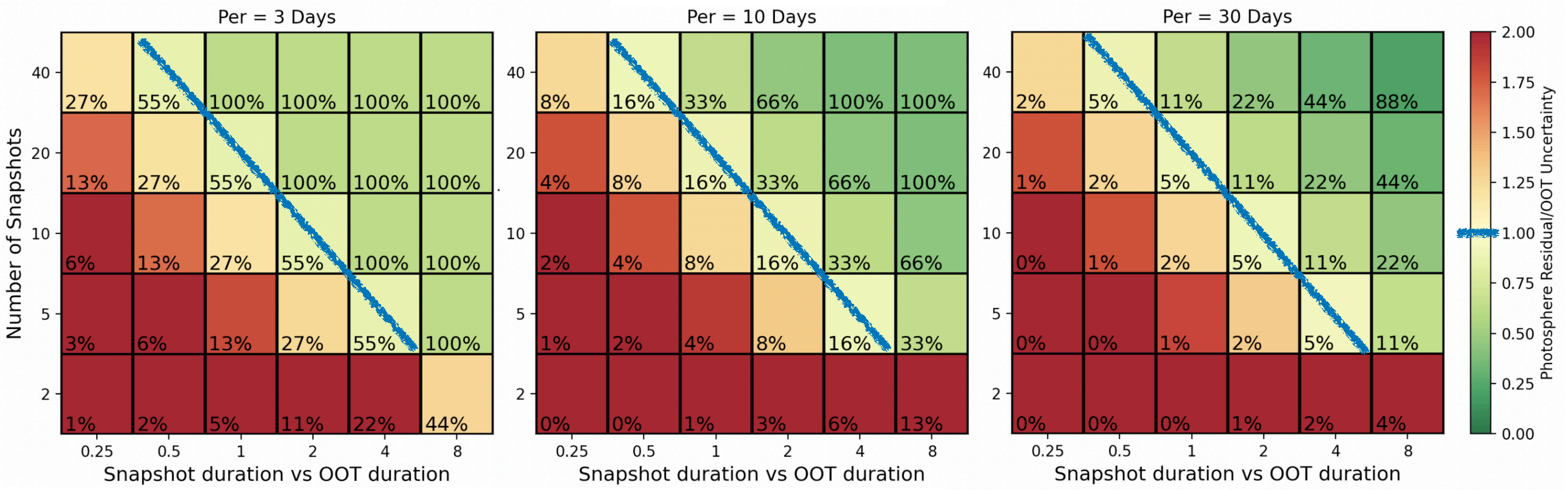
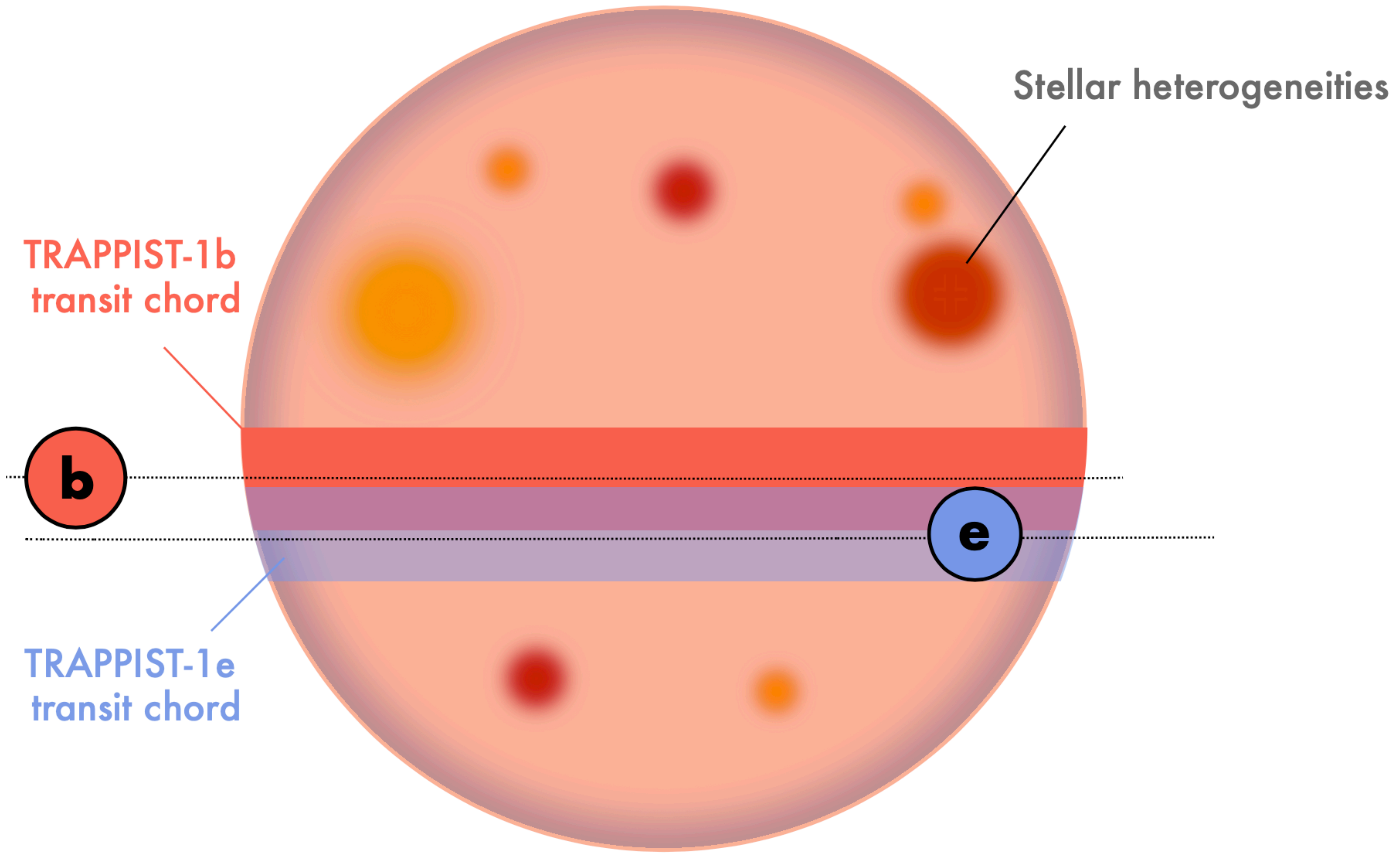


~20 hr of data enables empirical model
with uncertainty equal to data precision

David Berardo, de Wit, & Rackham (2024)

Transmission spectroscopy
without improved stellar models
or long-baseline JWST observations?

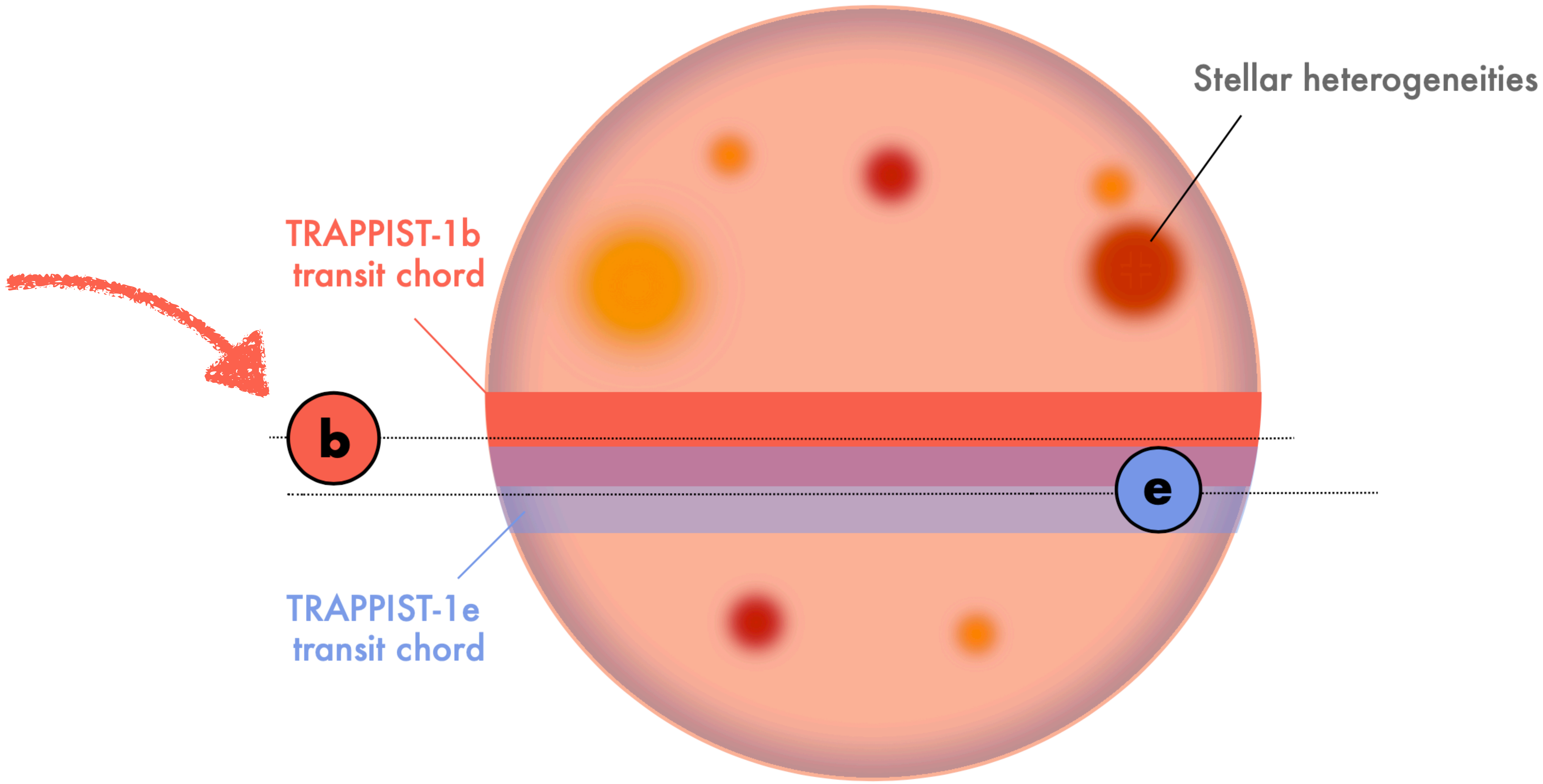
Double transits provide an empirical correction for TLS



JWST GO 6456
PI: **Natalie Allen**
Co-PI: Néstor Espinoza

Double transits provide an empirical correction for TLS

thin-to-no
atmosphere



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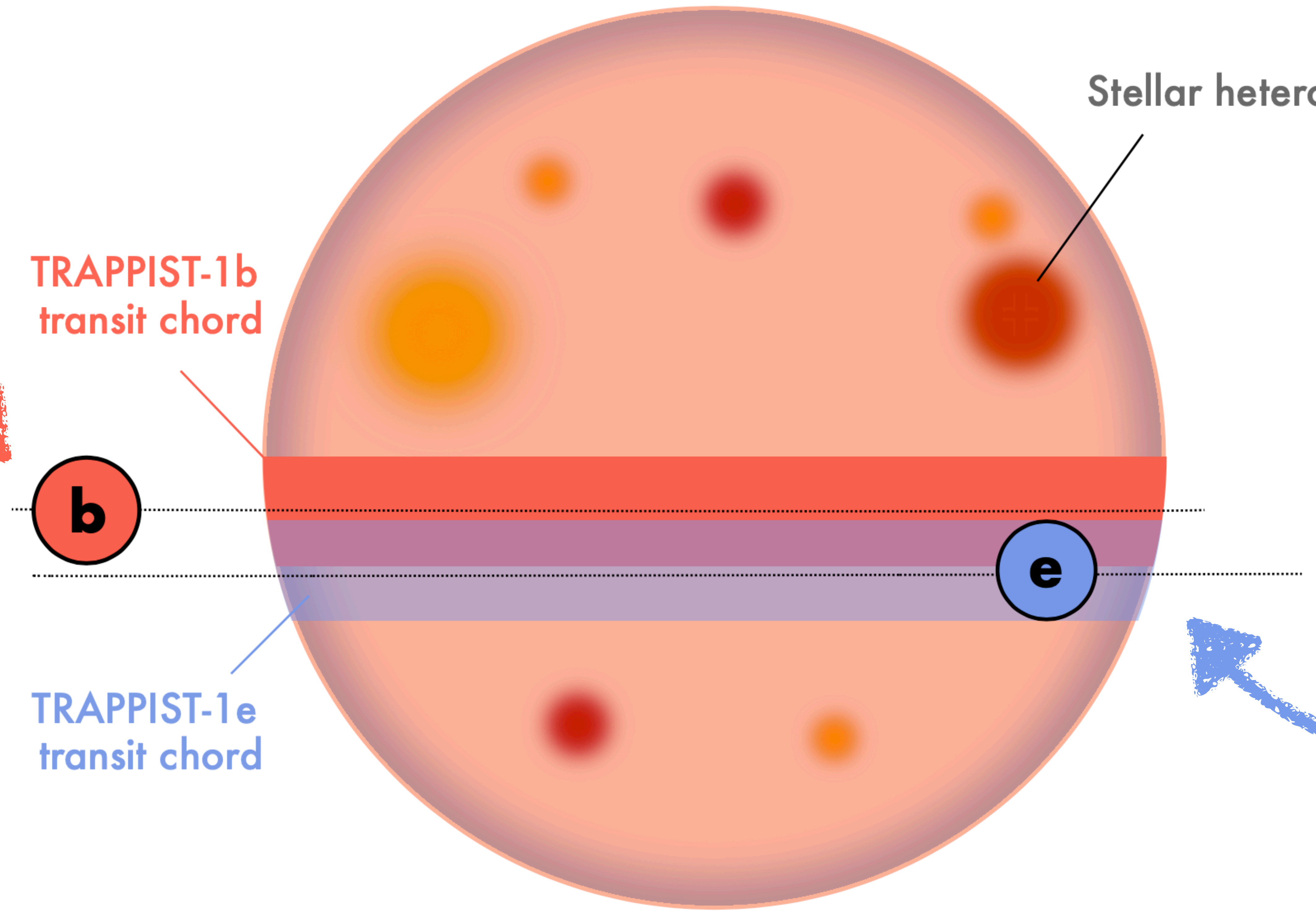

thick atmosphere

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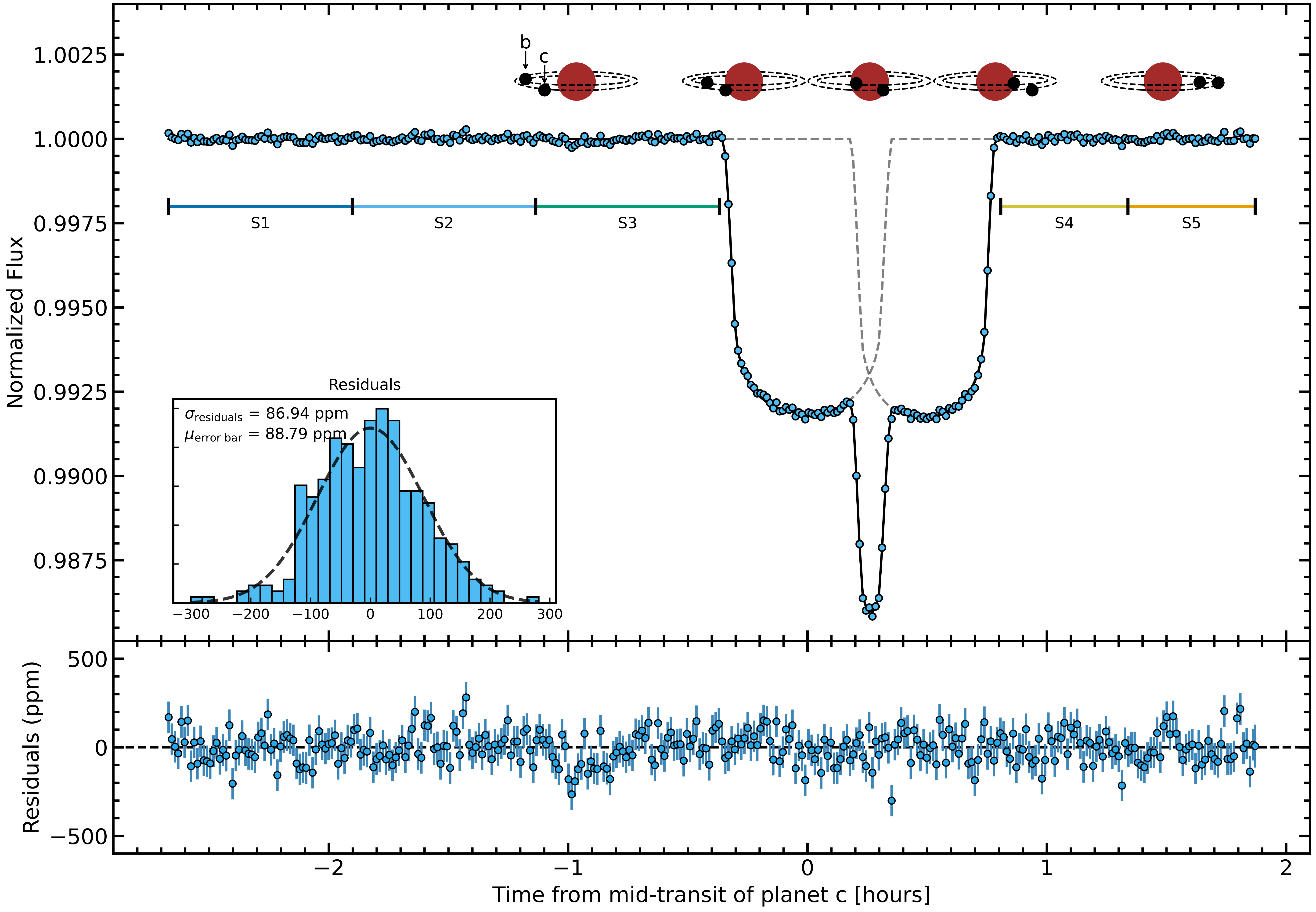
TRAPPIST-1b+c provide a test case for two “bare rocks”



Rathcke et al. (2025)

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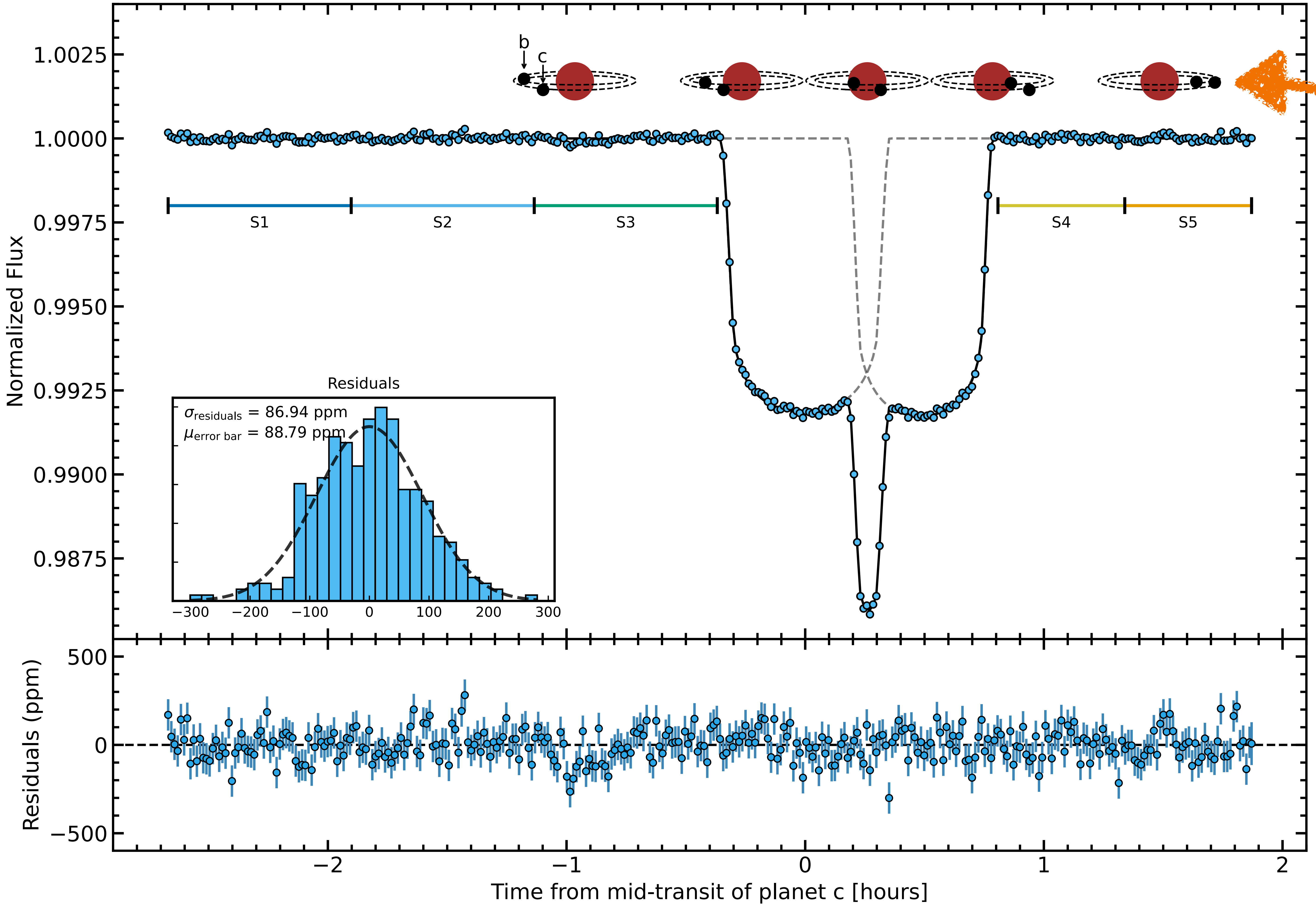
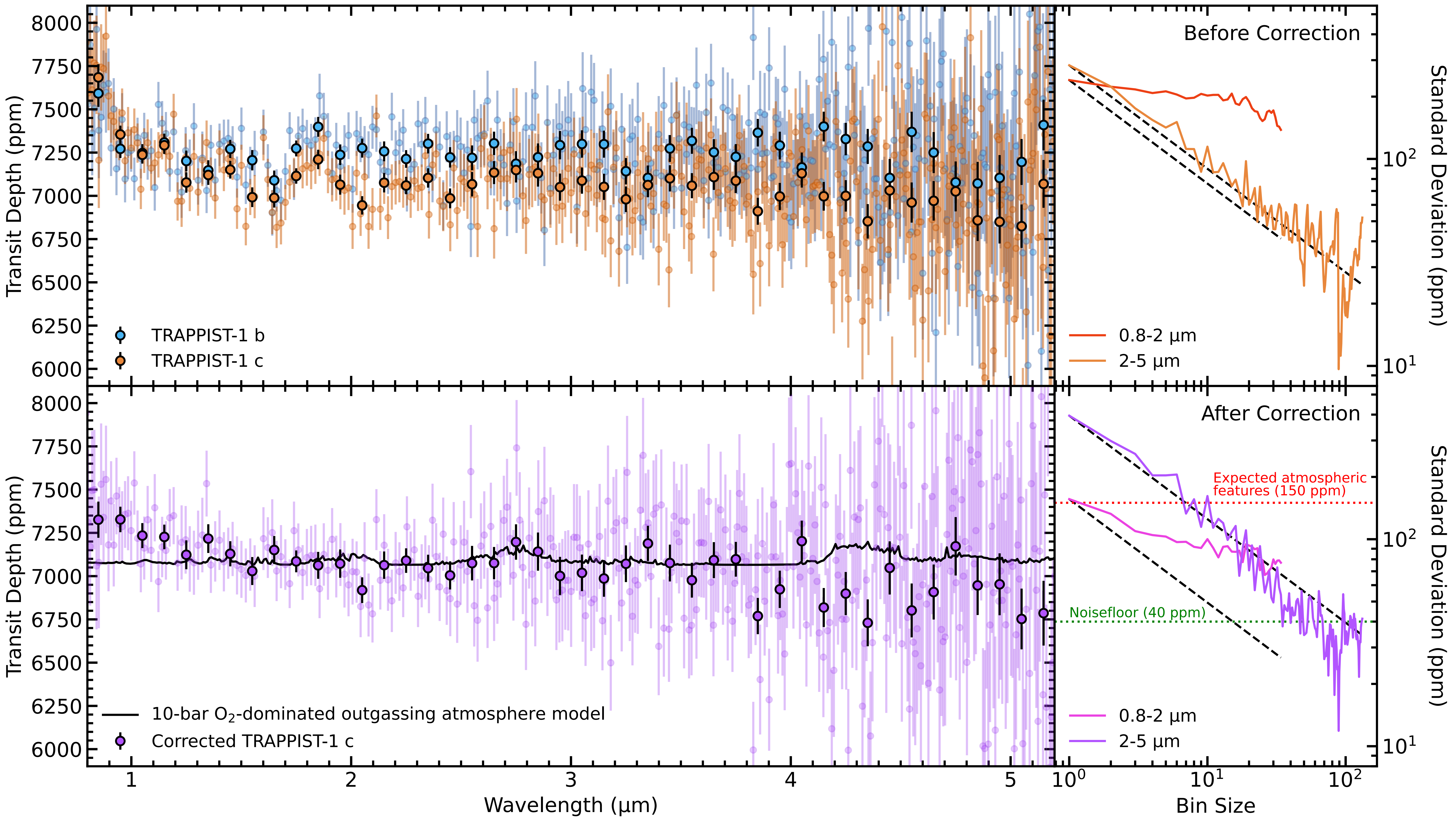


both with **thin-to-no atmosphere**

Rathcke et al. (2025)

Systematics are reduced but not eliminated



Rathcke et al. (2025)

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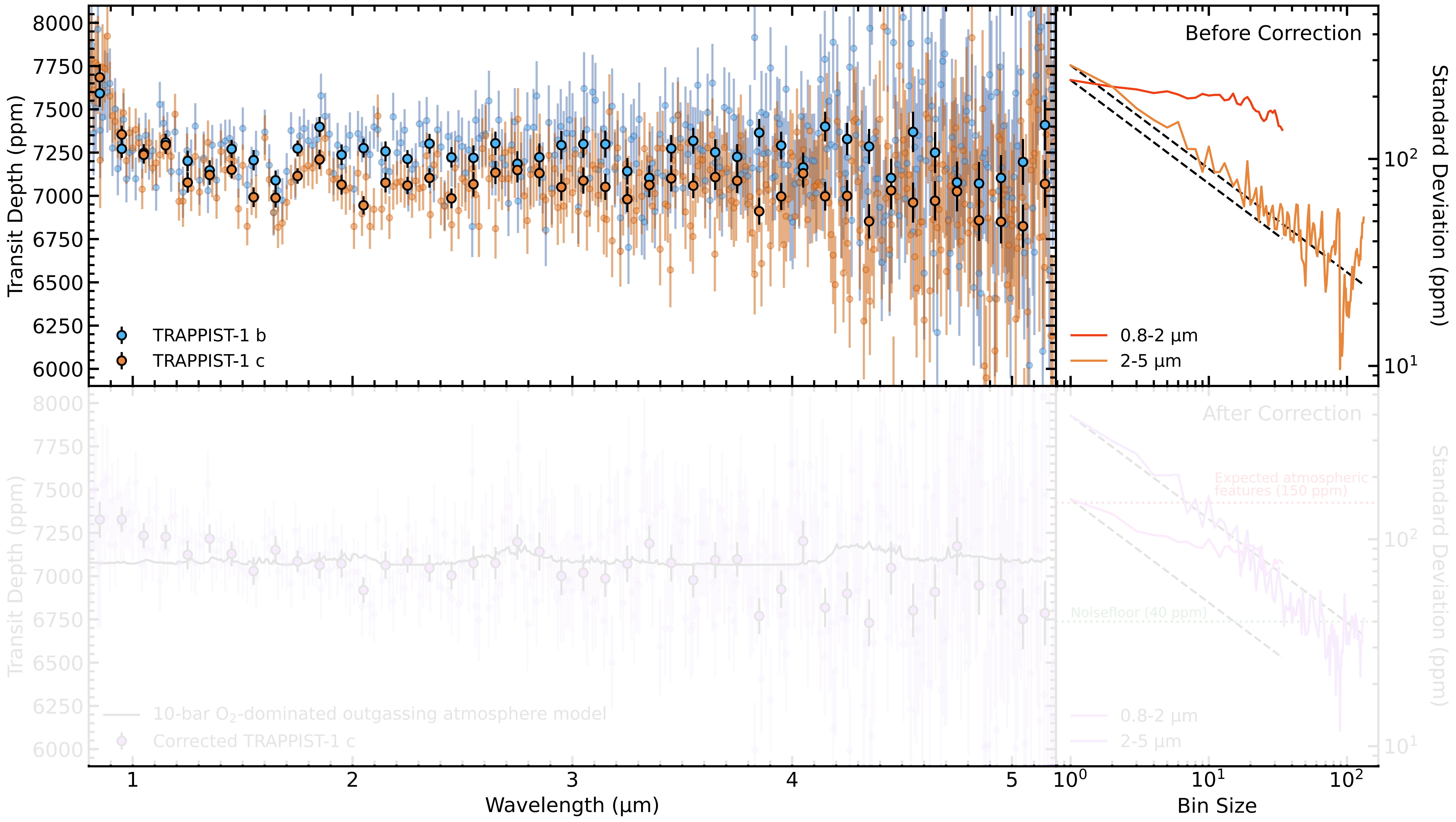

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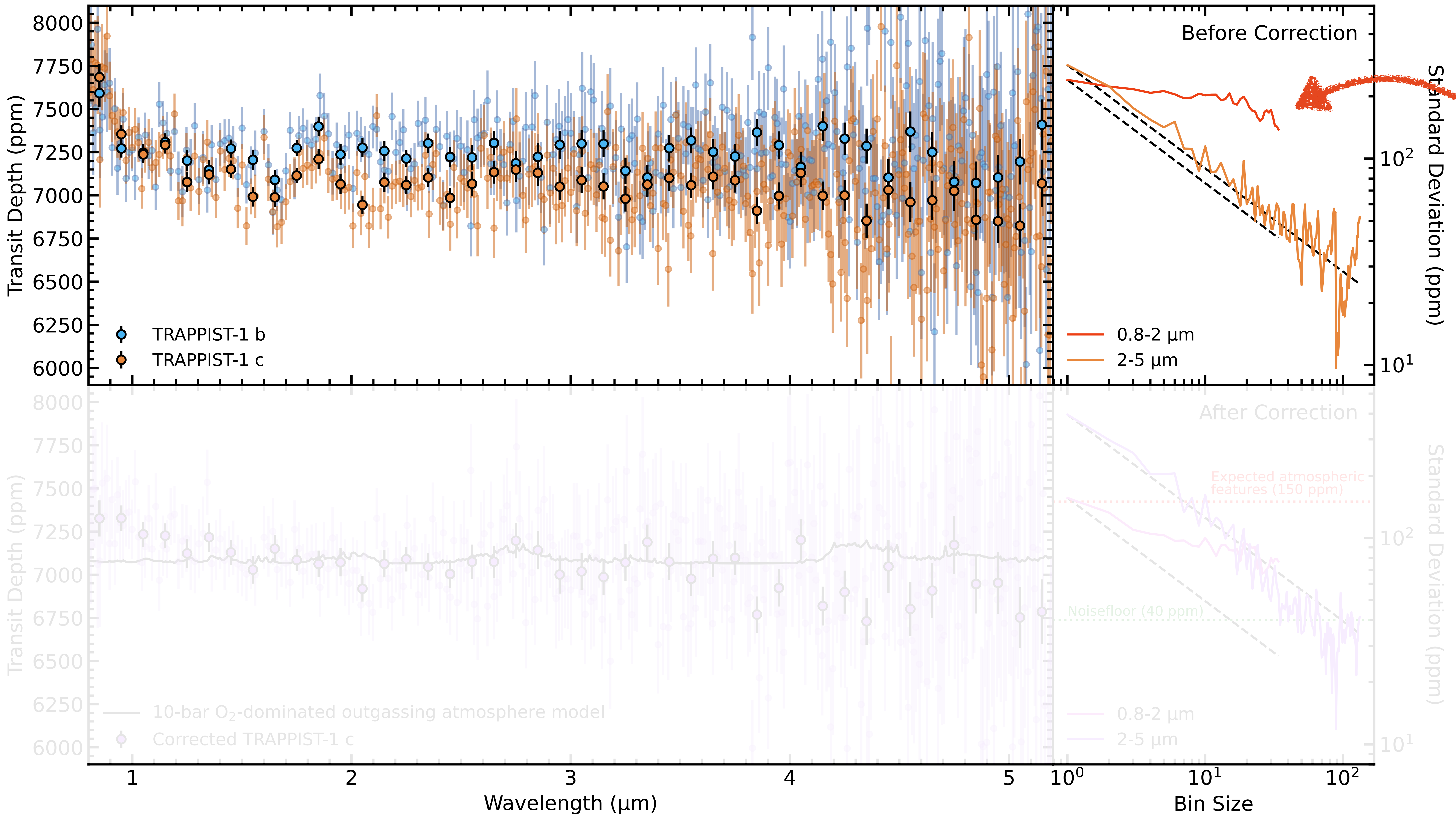

<2 µm

~200 ppm red noise floor

Rathcke et al. (2025)

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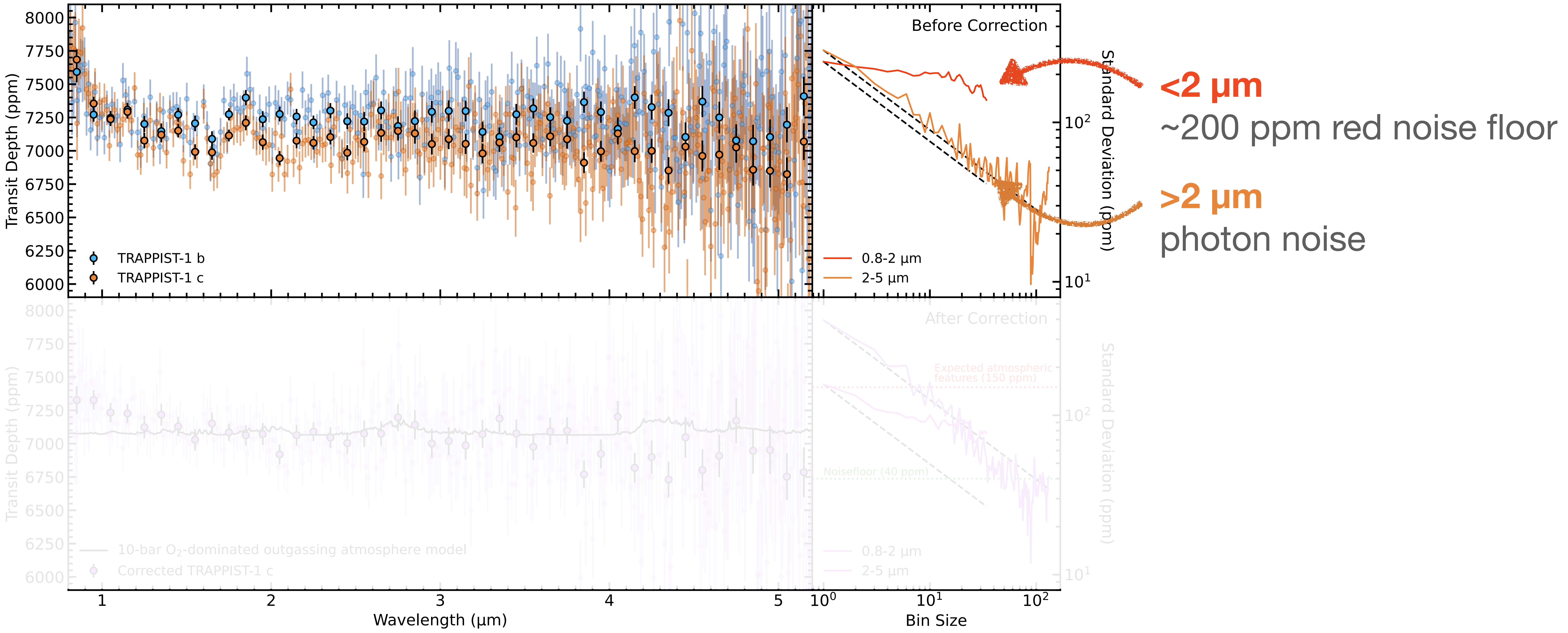

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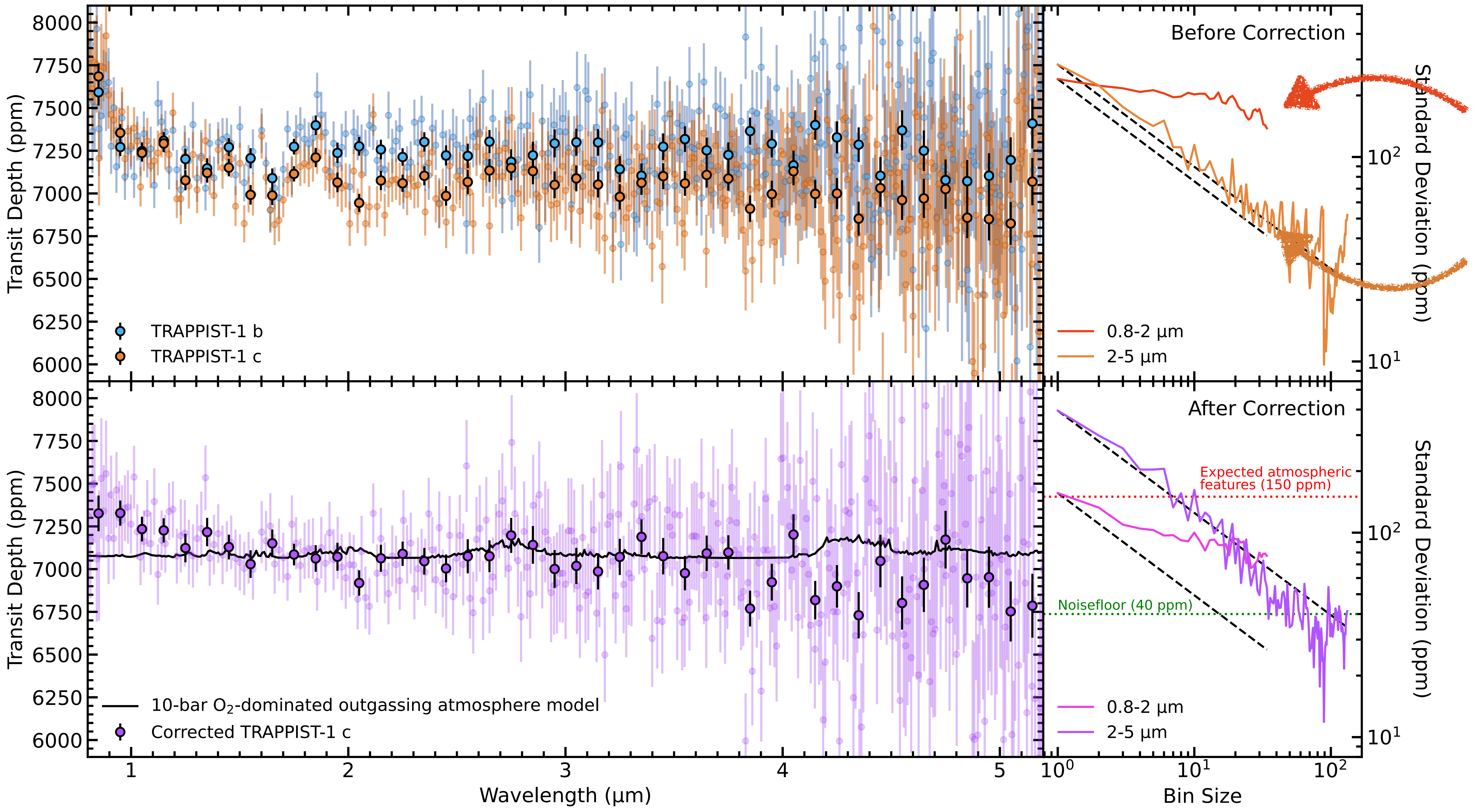

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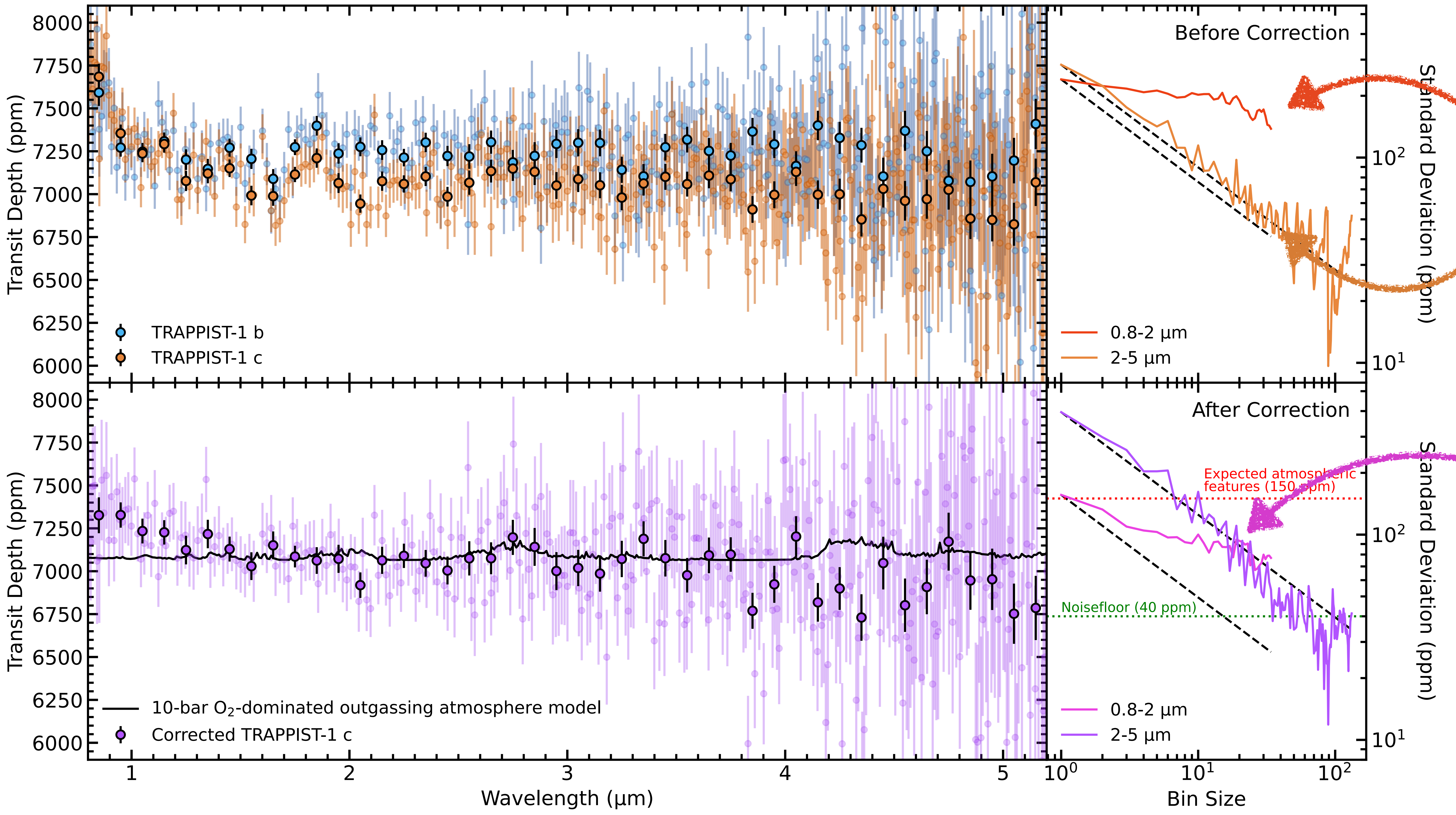

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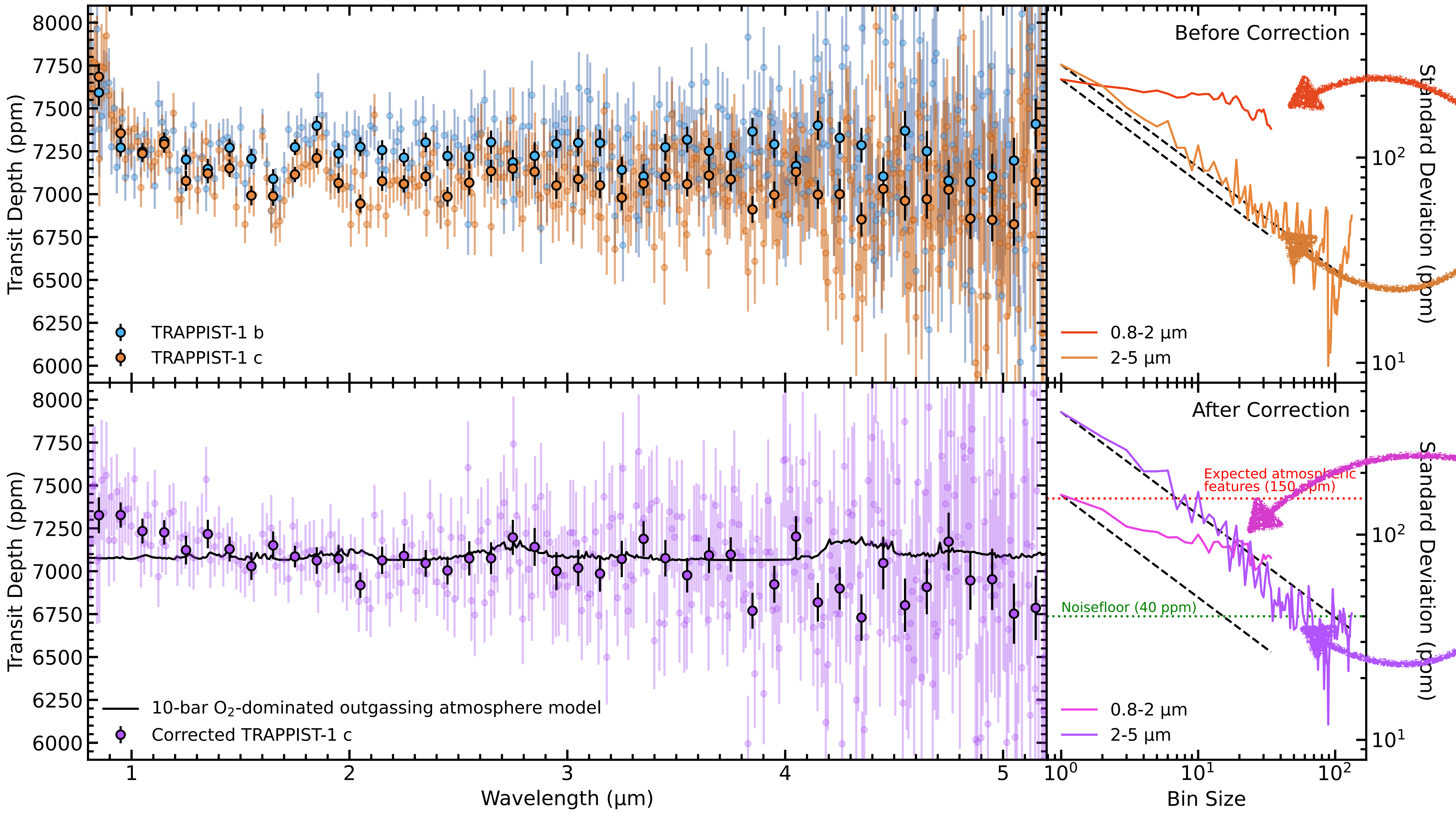

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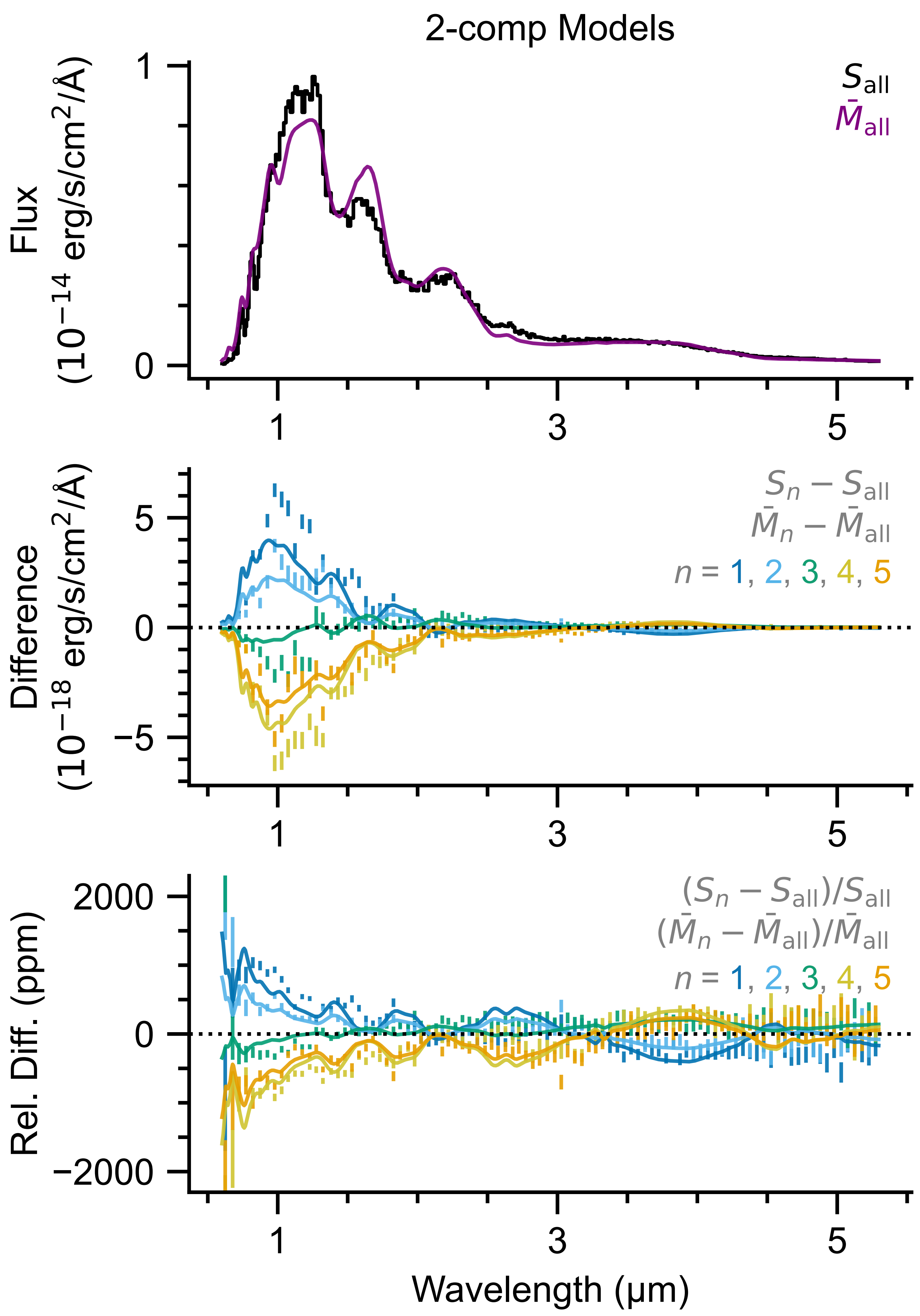
Constraints on photospheric heterogeneity



coverage of **~2000 K** component

coverage of **~2600 K** component

Rathcke et al. (2025)

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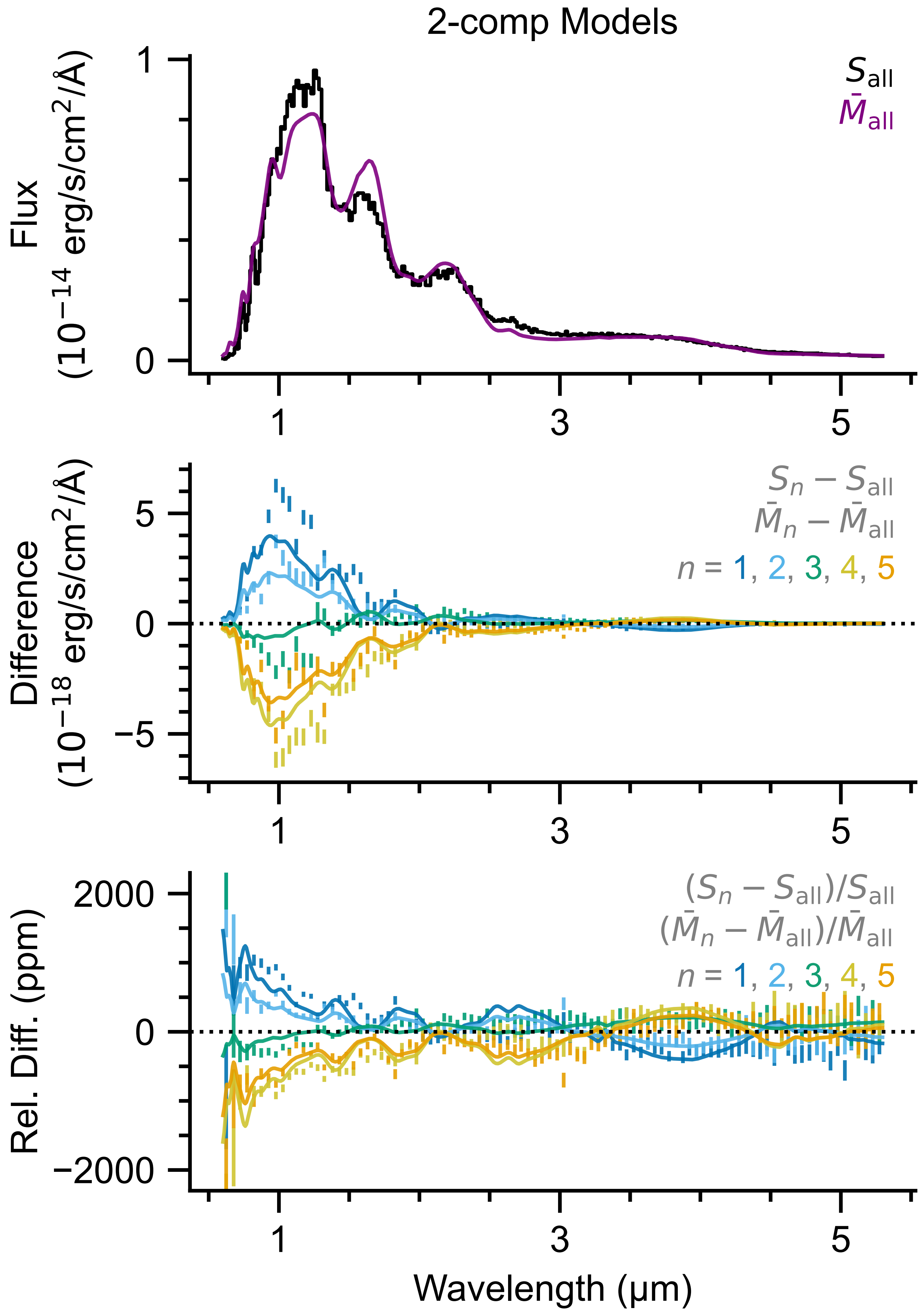

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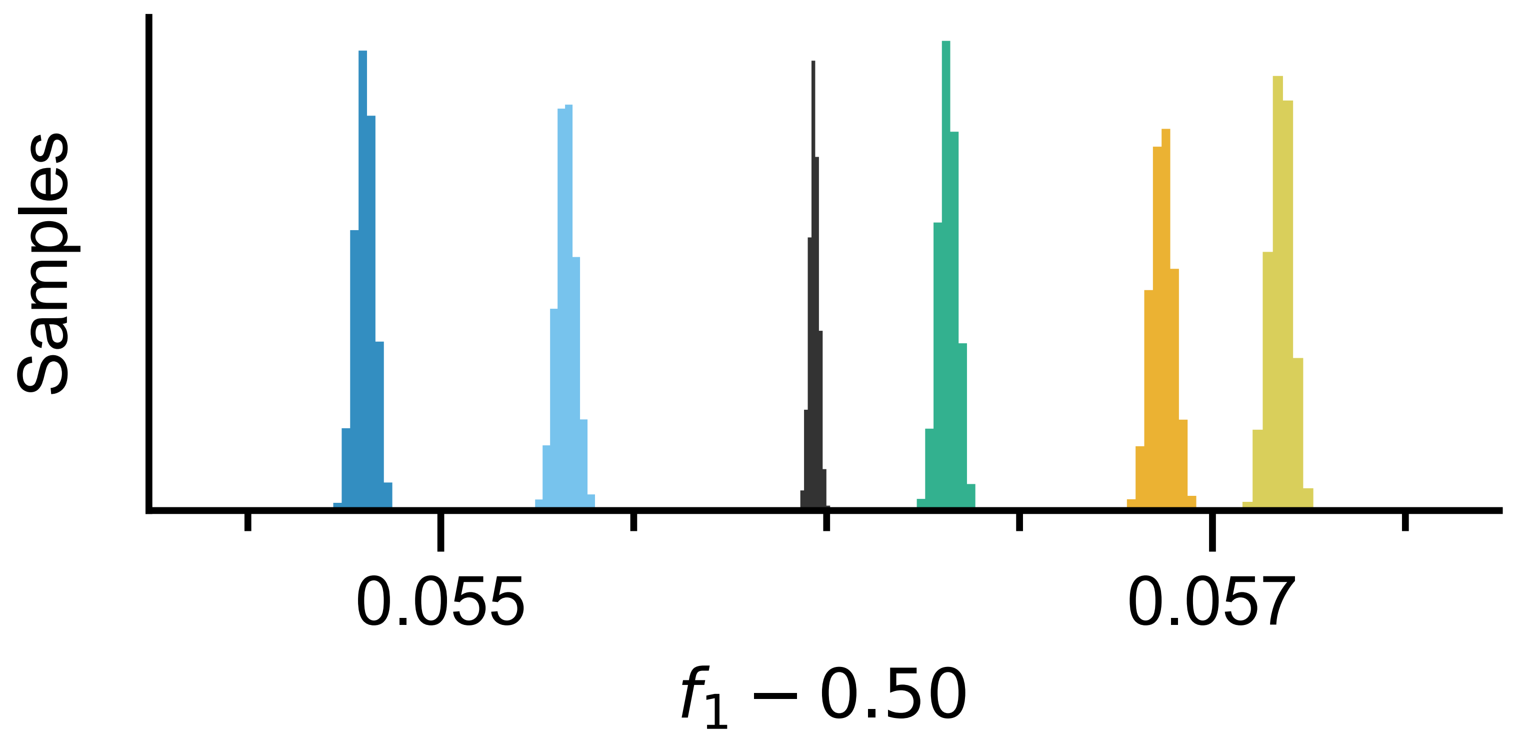

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Rathcke et al. (2025)

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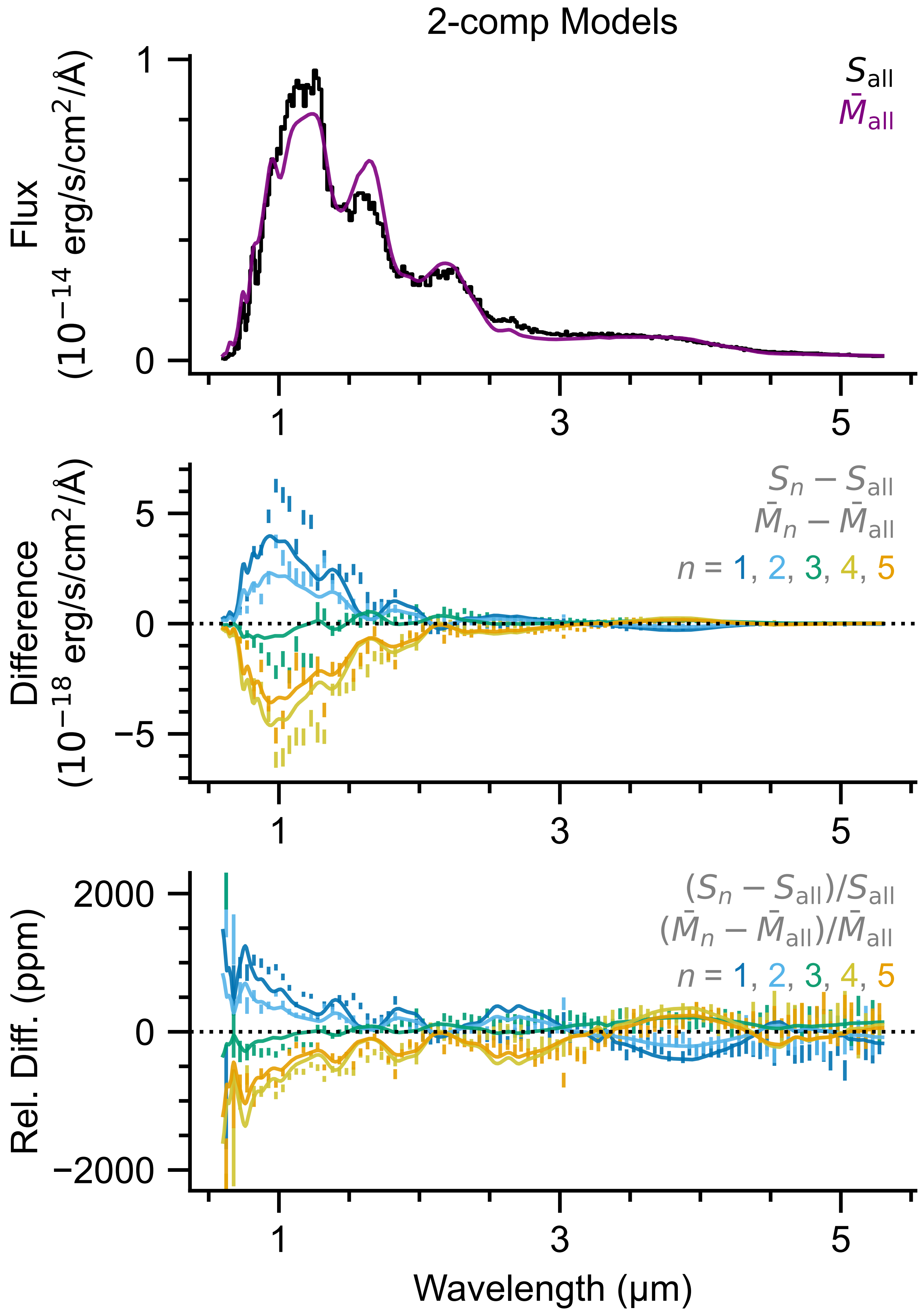
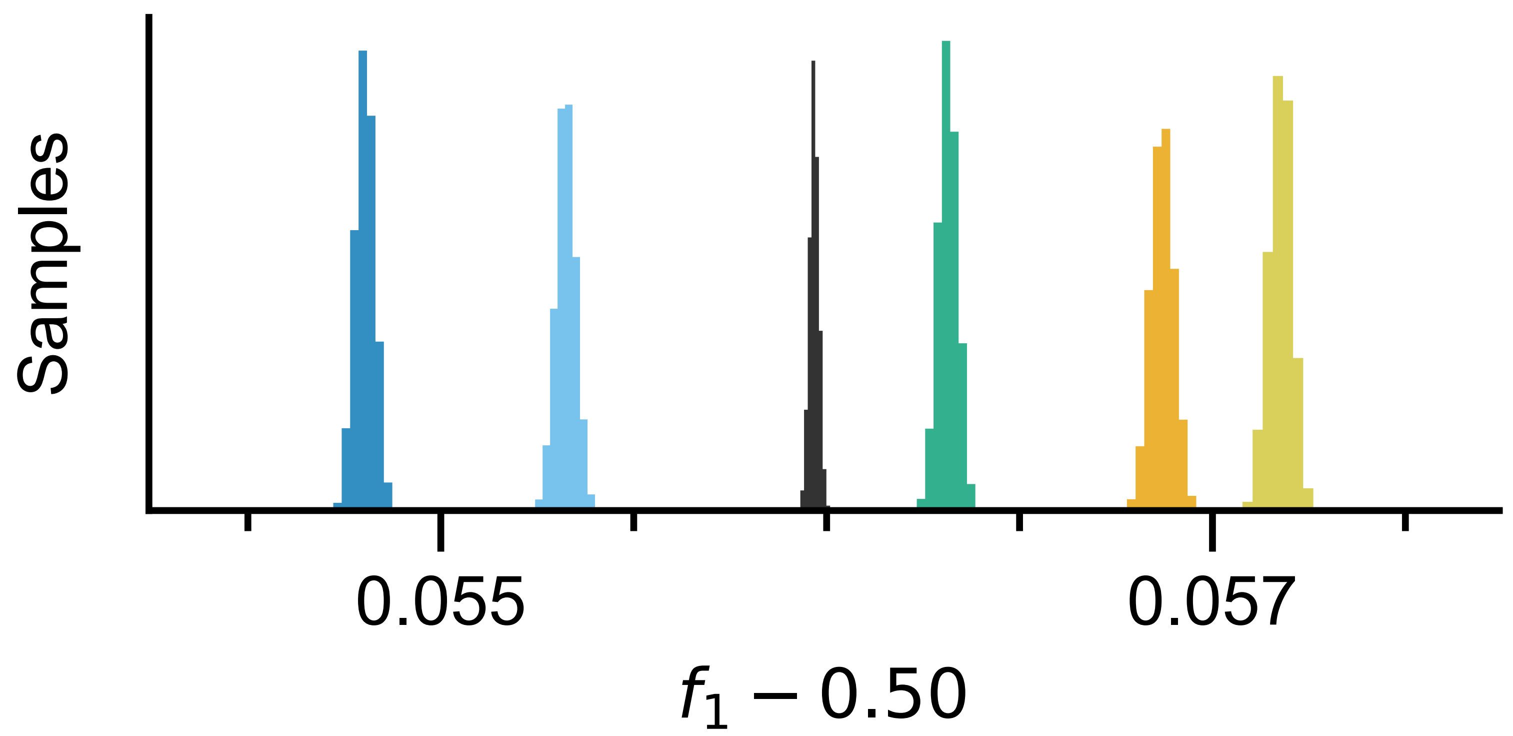
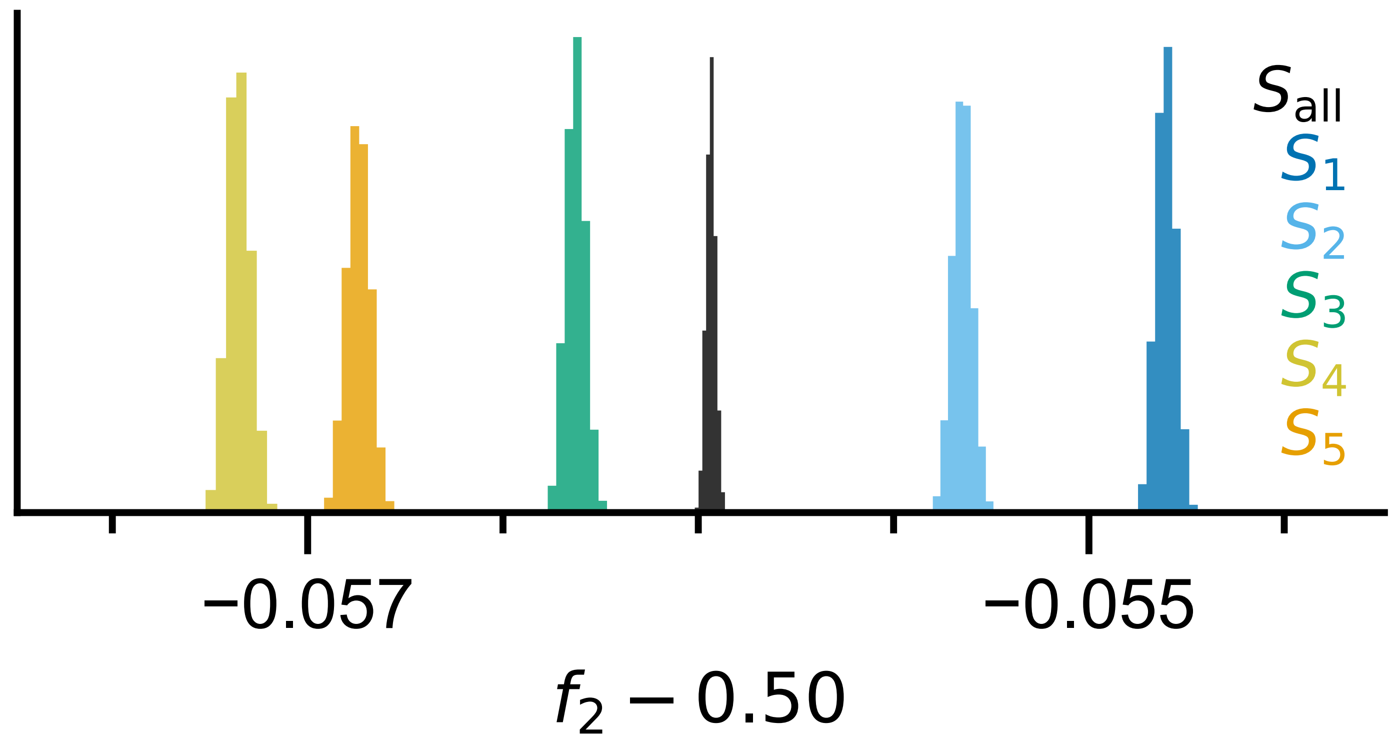


📈 coverage of **~2000 K** component

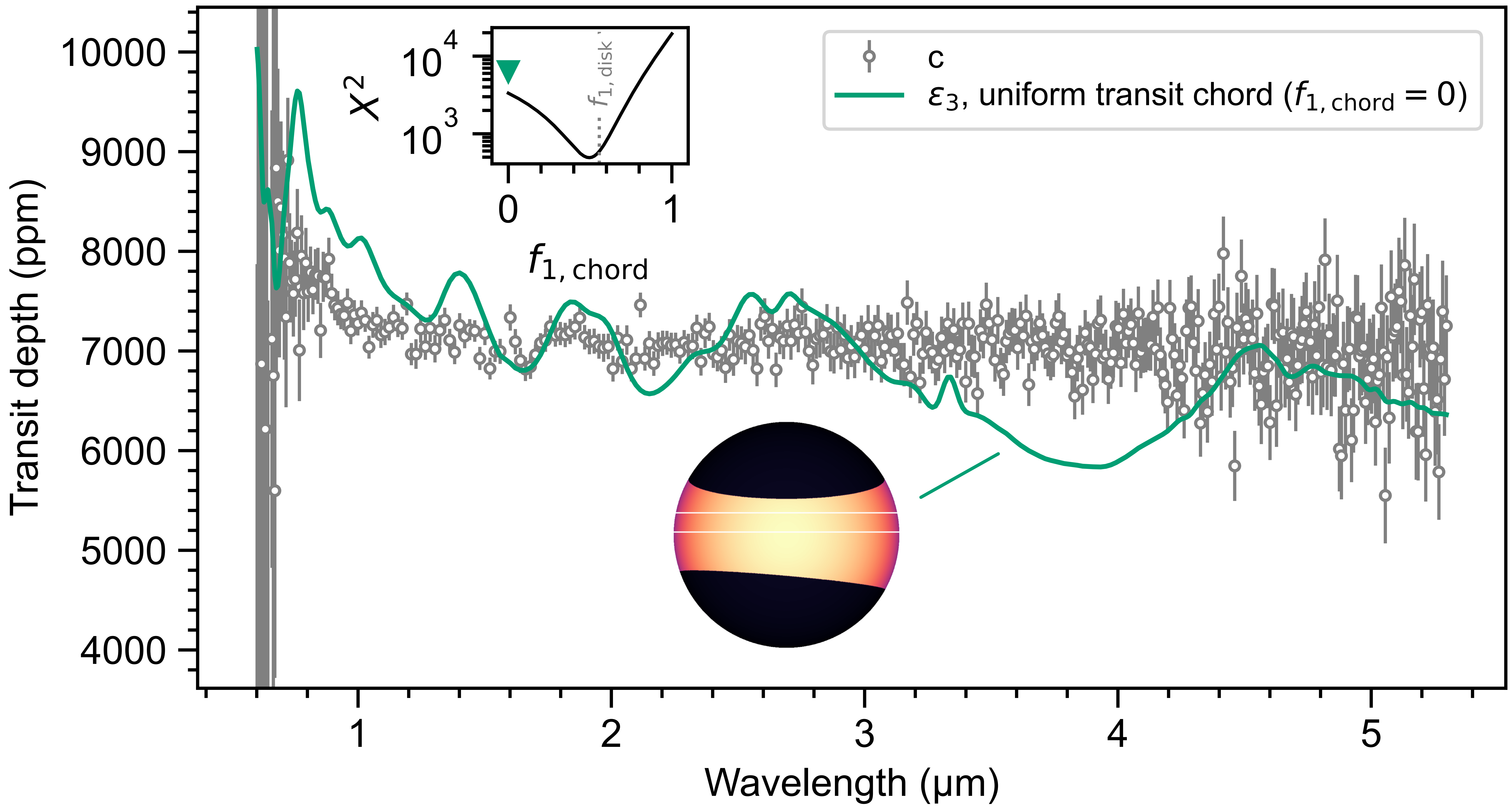


📉 coverage of **~2600 K** component



Rathcke et al. (2025)

Constraints on mixing and distribution of heterogeneities



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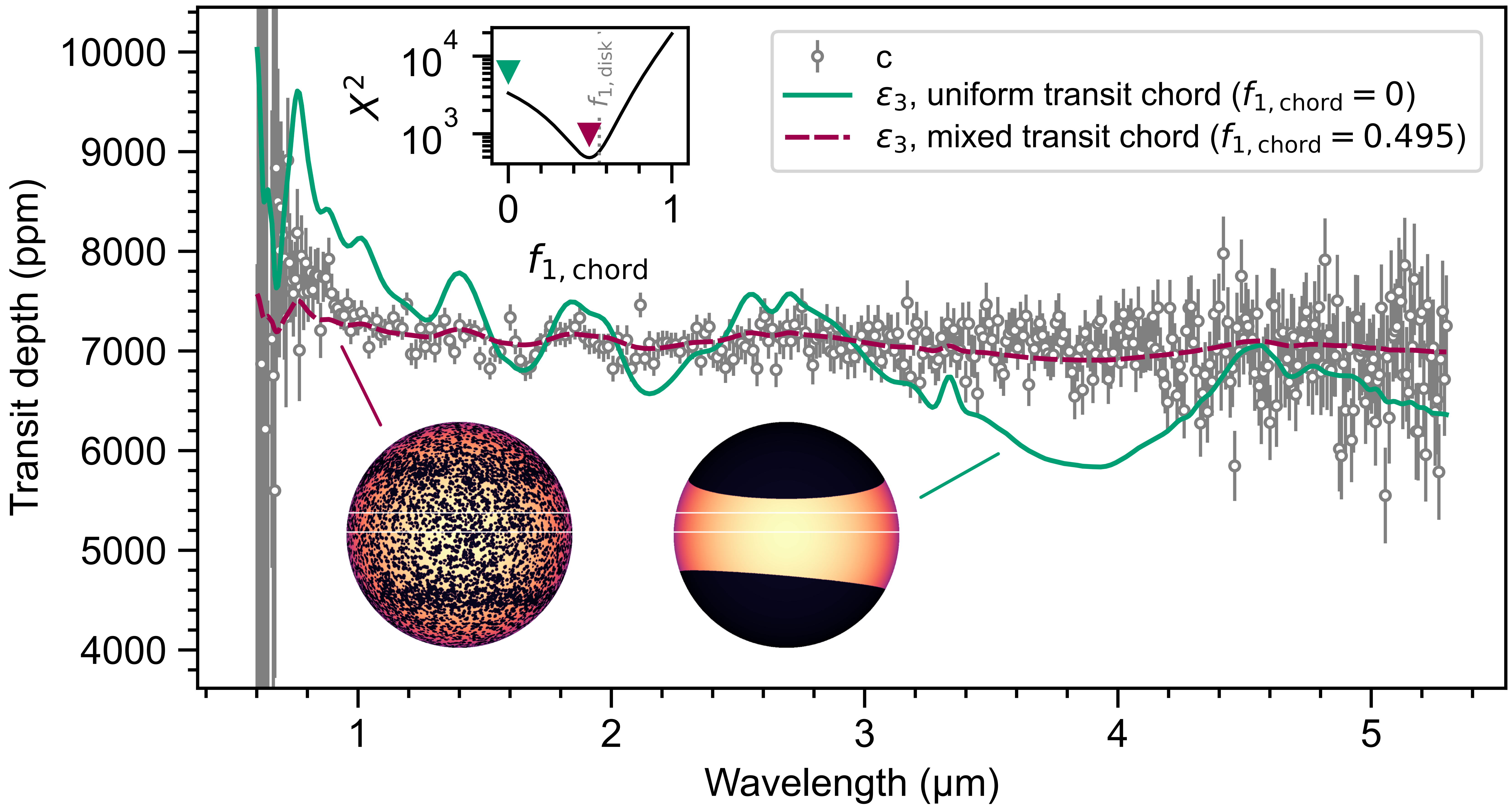

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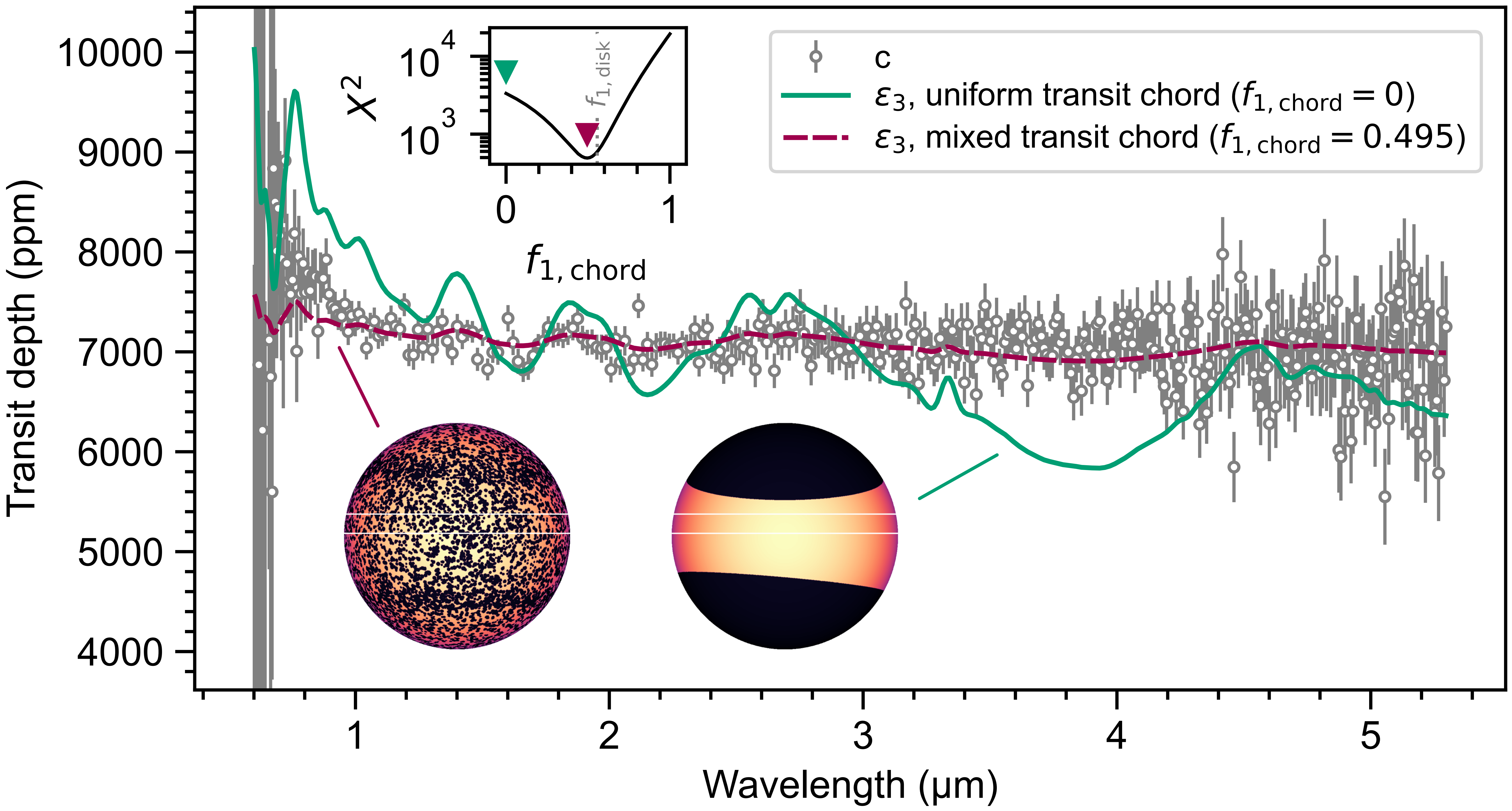
Constraints on mixing and distribution of heterogeneities



Spectral components are well-mixed in TRAPPIST-1's photosphere

Rathcke et al. (2025)

Main Points

On to rocky worlds

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2. The road to transmission spectra of terrestrial exoplanets runs through their stars.
3. Stellar spectroscopic phase curves and double transits provide opportunities for empirical constraints.
4. Latest understanding of TRAPPIST-1 is a well-mixed, two-component photosphere with some latitudinal dependence.

3. Bonus:

Future Directions for Knowing Stars & Knowing Planets

Ongoing efforts

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REVEAL

PIs: Sasha Shapiro, Sara Seager, Andrew Collier Cameron

ERC Synergy Grant
REVEALing Signatures of Habitable Worlds Hidden by Stellar Activity

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HST Stellar Treasure Trove / Eyes on the Stars

PIs: Benjamin Rackham, Dániel Apai, Julien de Wit

Legacy Archival Analyses of HST & JWST Datasets to Constrain Photospheres of Exoplanet Hosts and Quantify Stellar Contamination Signals

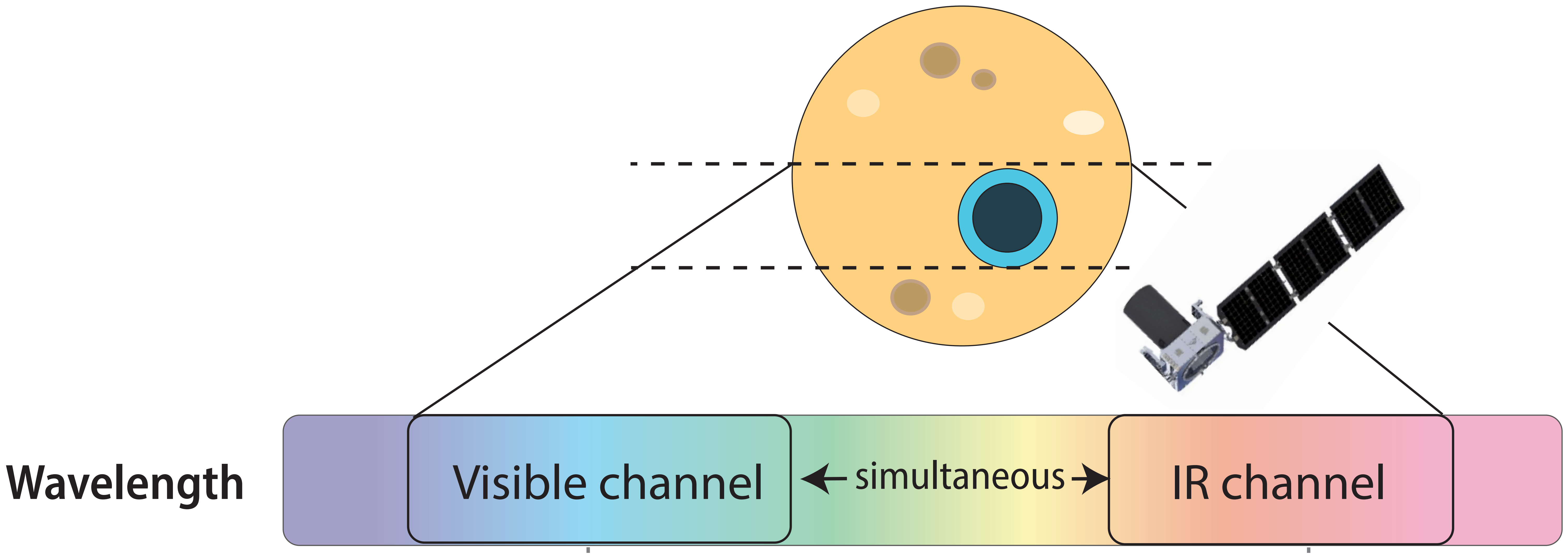
The Pandora SmallSat

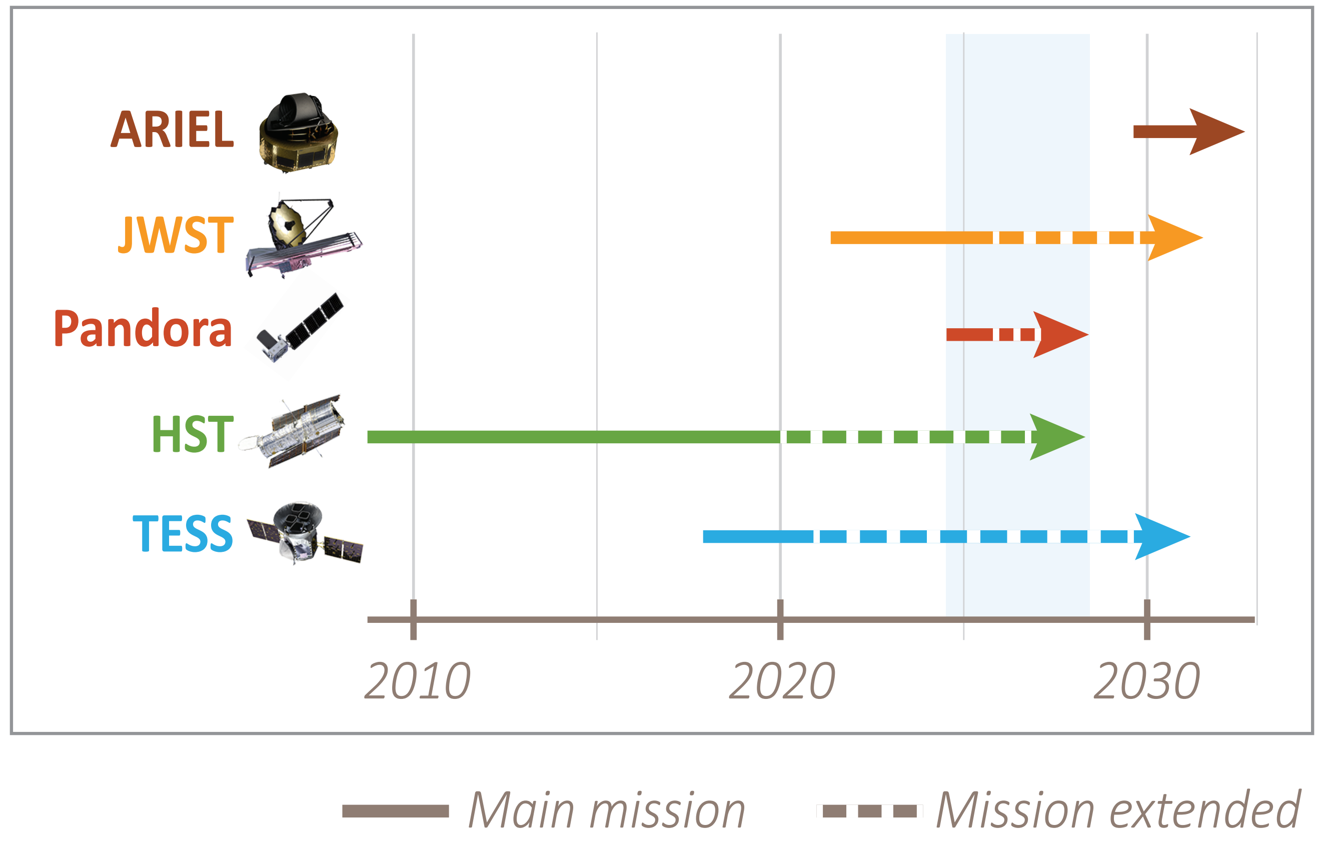
Launch readiness: Sep. 2025

A dedicated 0.45-m space telescope for transits of active K and M dwarfs

Mission Overview

Launch Date	Mid-2020s
Payload	Telescope (0.45m)
Channels	Visible photometry IR spectroscopy
Orbit	Sun-sync LEO
Science Operations	1+ years





Quintana et al. (2021)

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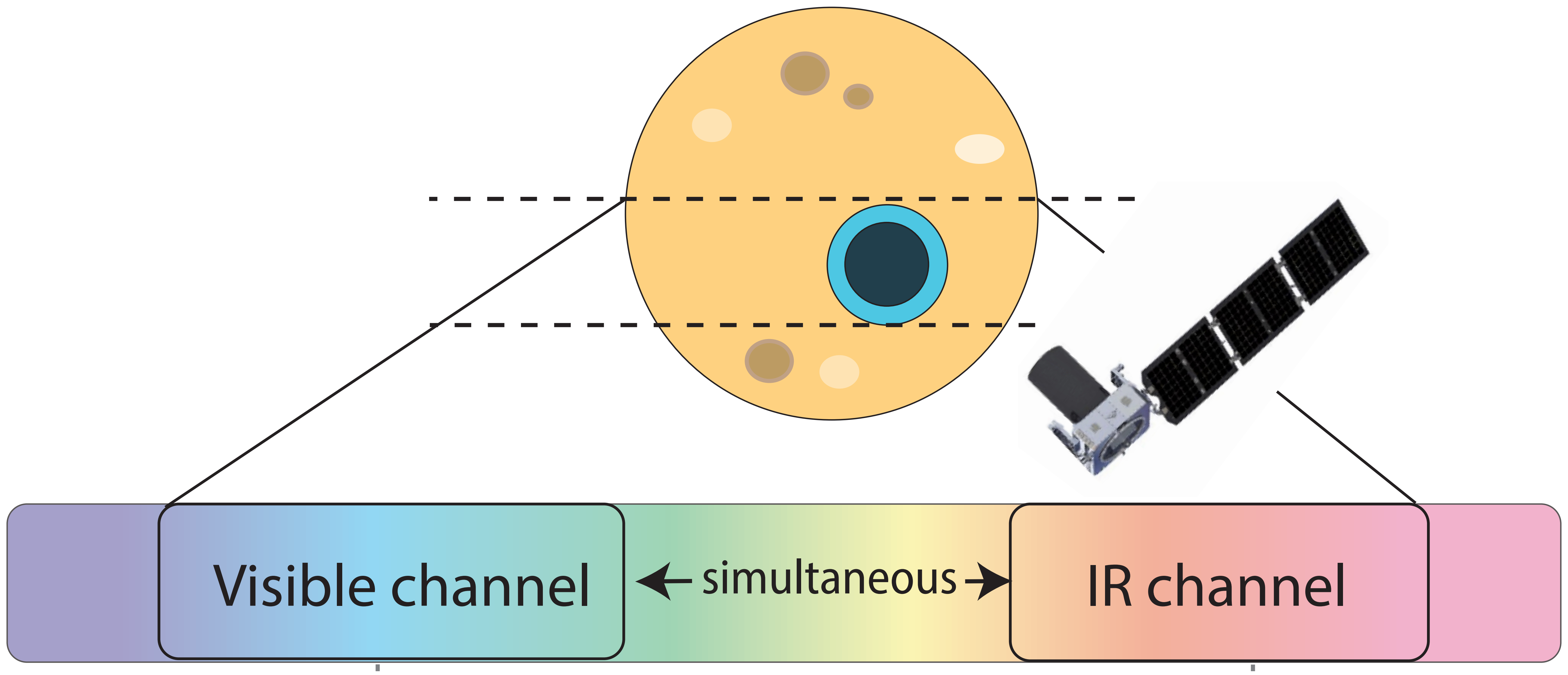
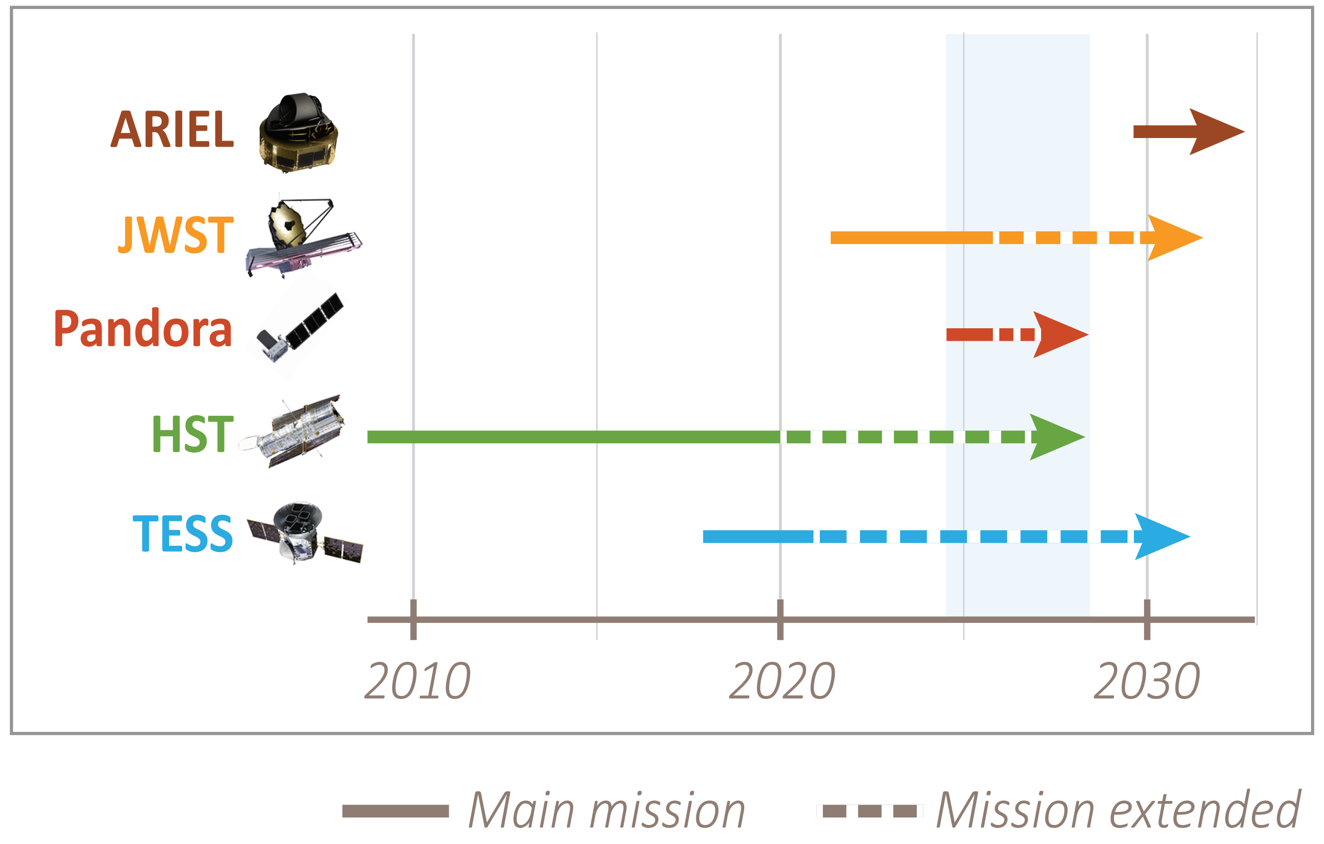
Wavelength





See talk from **Knicole Colón**

Quintana et al. (2021)

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ChatGPT:

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Take-aways

ChatGPT:

The path to understanding exoplanets is clear: first, understand the stars. And if that seems too hard—good news! There's always cosmology.

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