The Climate and Chemistry of Exoplanet Atmospheres

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Horizon Europe Funding

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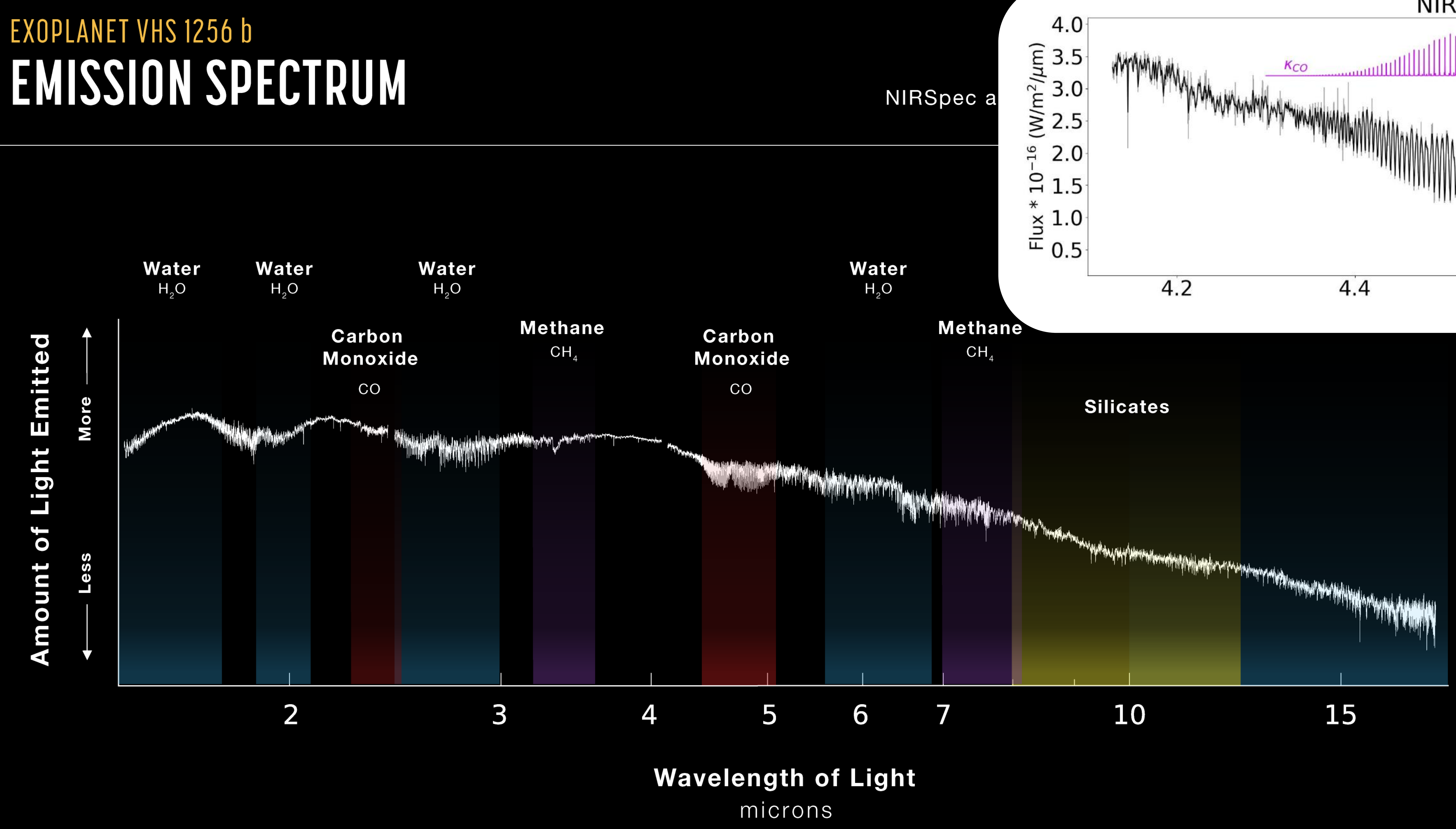
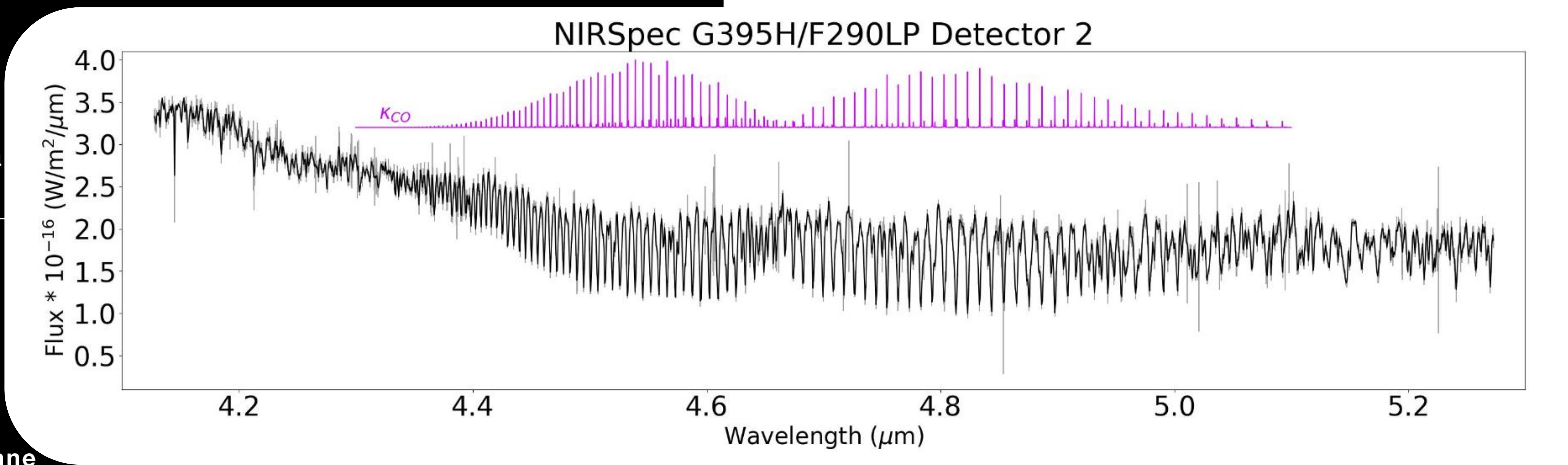
JWST Will Evaluate 100s Exoplanet Atmospheres

Cy 1-5: 205 individual exoplanets, 400+ observation set-ups, 126 giants

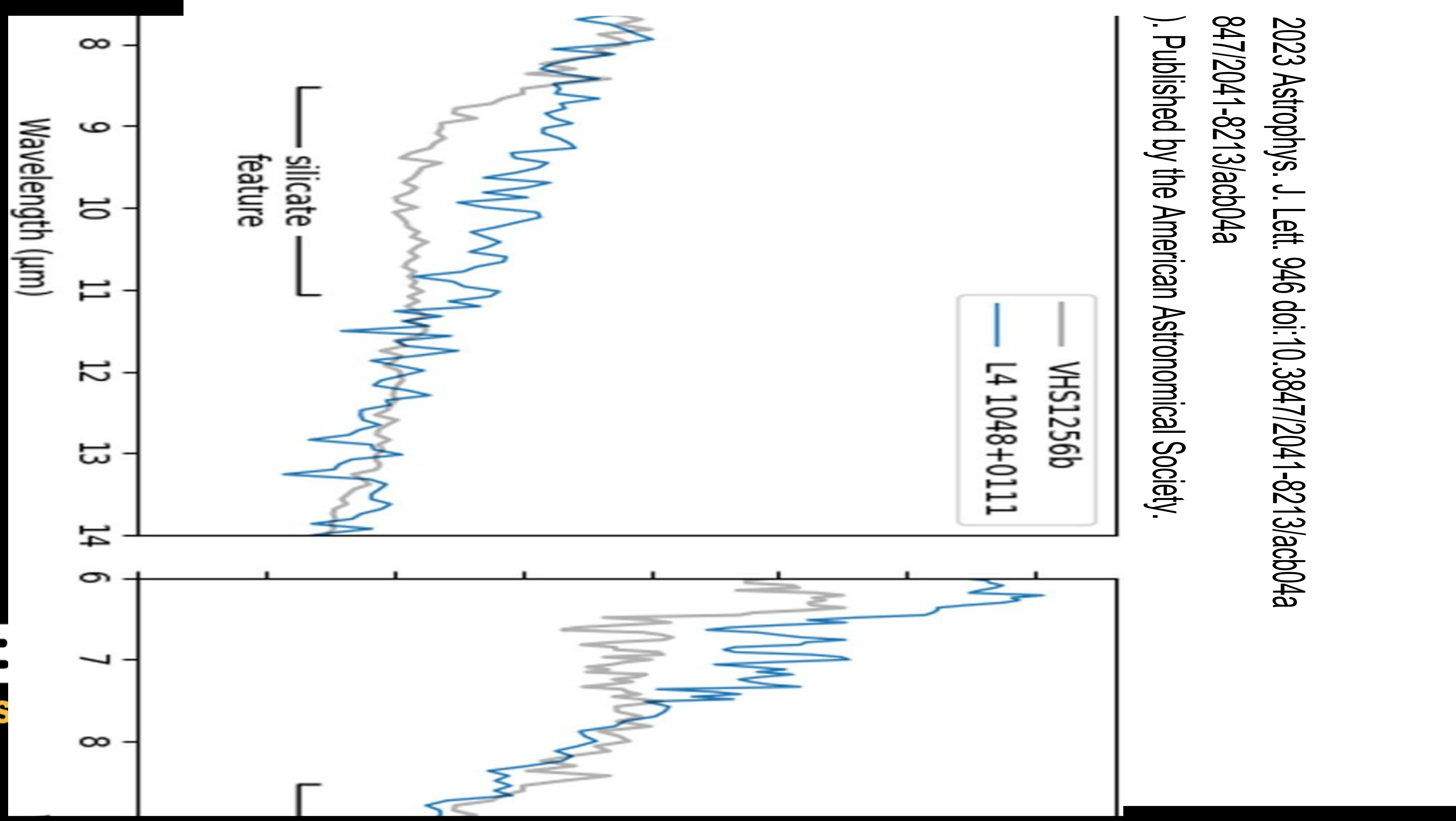
ERS Direct Imaging Spectrum of VHS 1256b

Water, CO, Methane, and Silicate Clouds





By-eye identifications of CO and silicates!



Miles+ (2023, ApJL)

Direct Imaging Will Continue to Access New Planets

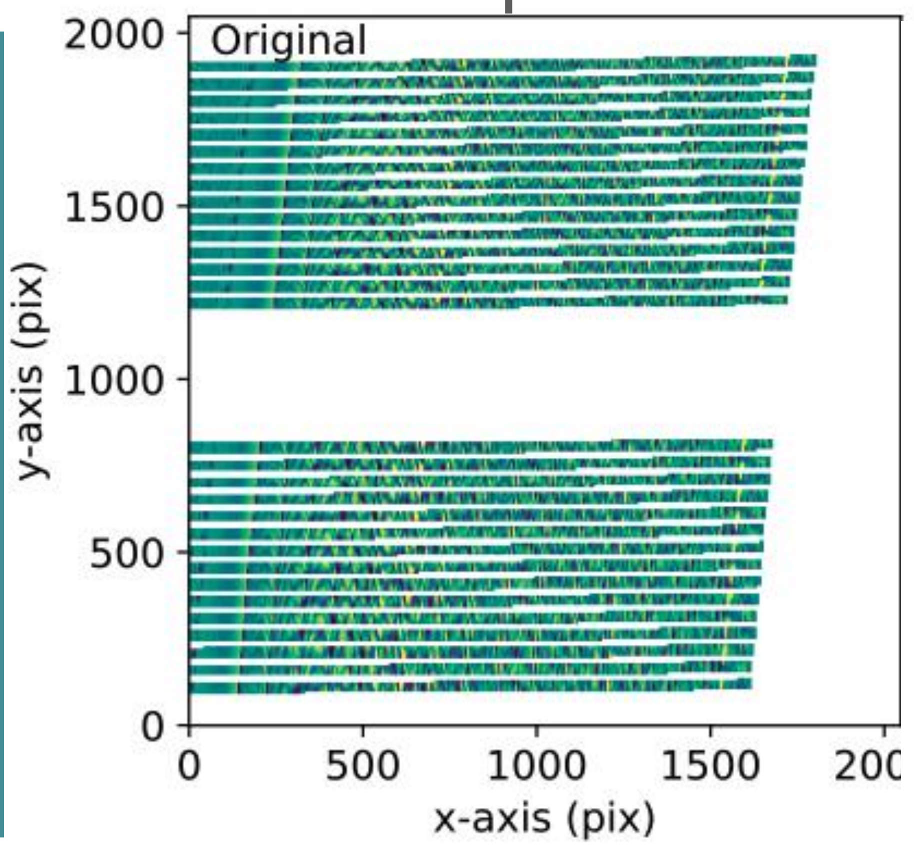
The very young do not always do as they are told

JWST has a range of instruments available for DI:

- NIRCam spectra
- NIRSpec IFU & spectra
- NIRCam & MIRI Coronagraph
- AMI with NIRISS

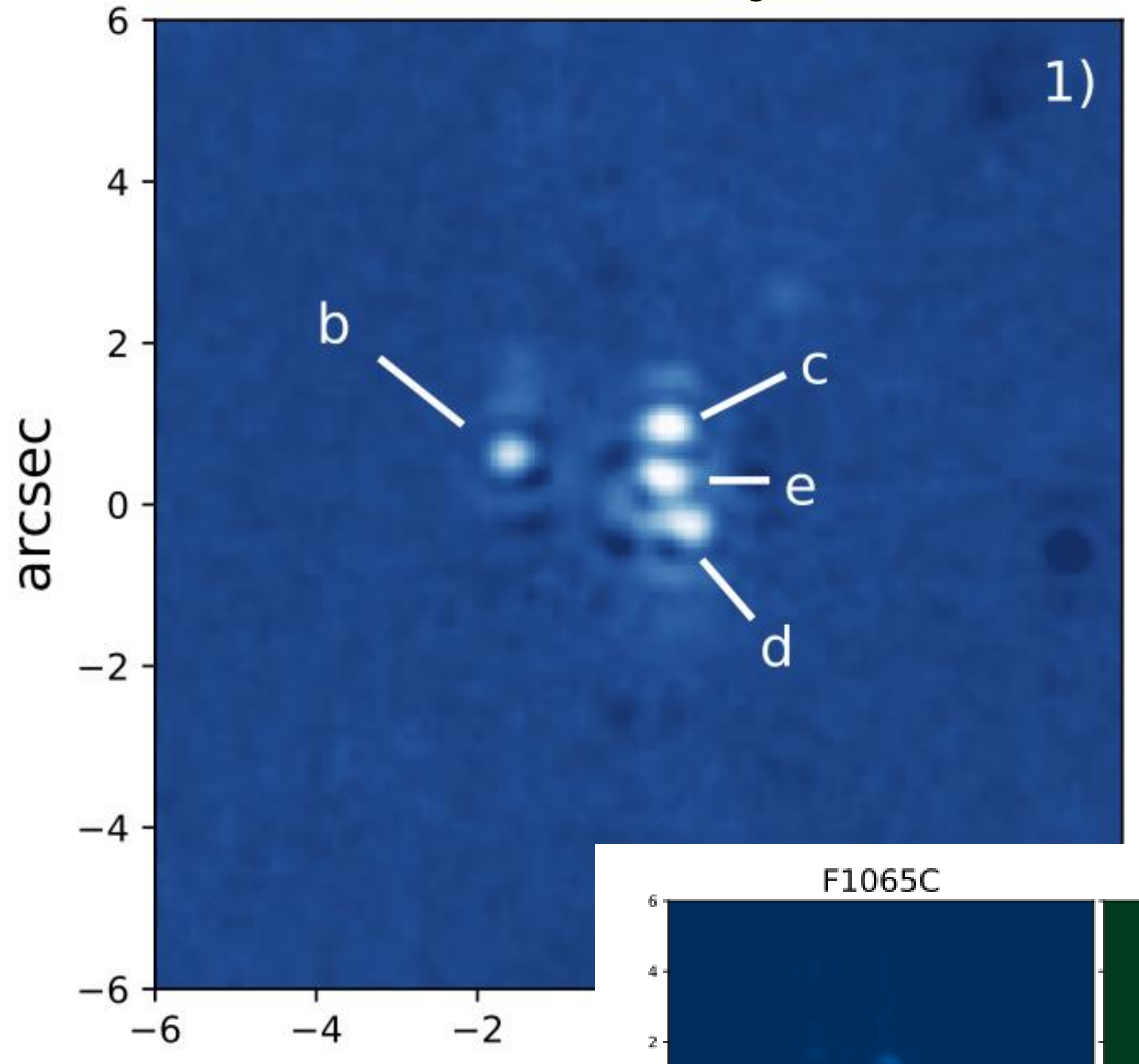
To get spectra and photometry of known directly imaged planets and brown dwarfs.

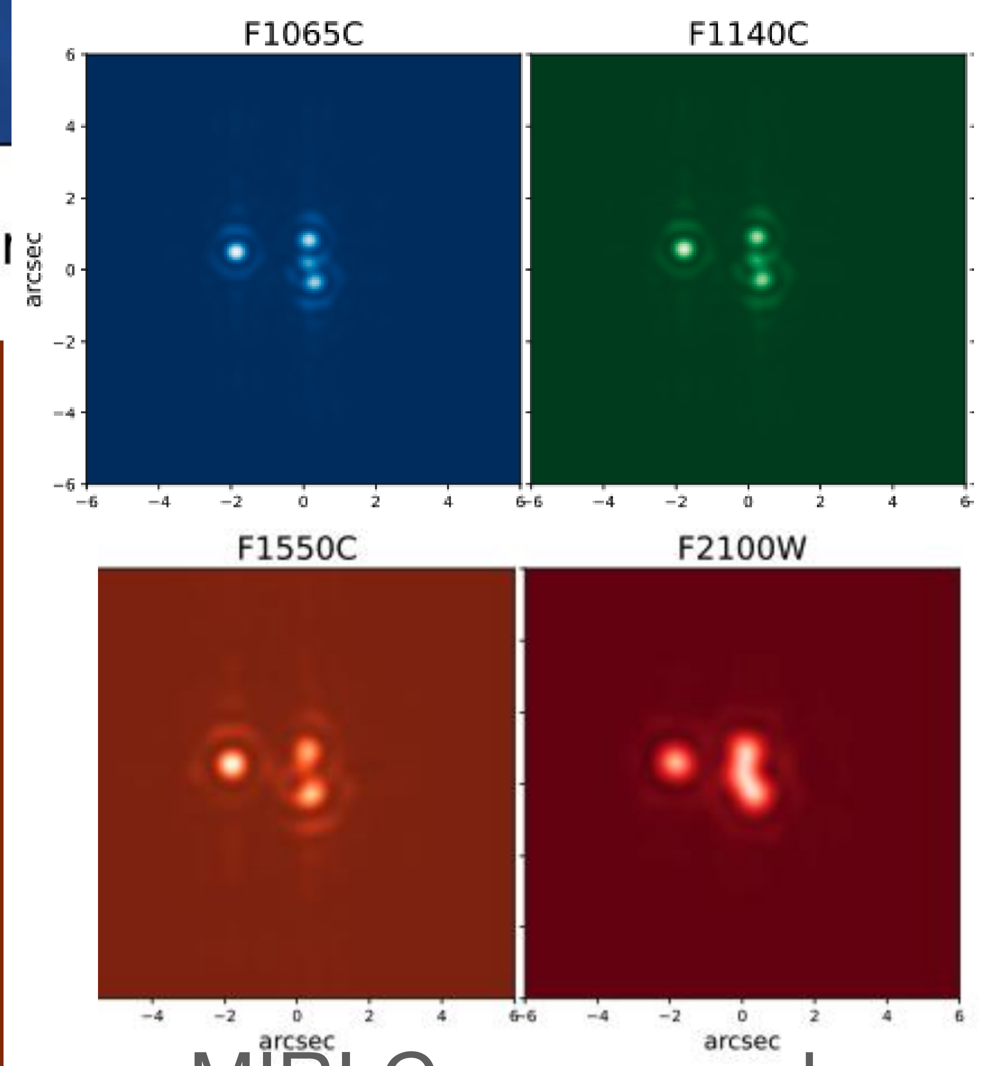
NIRSpec IFU



[Ruffio+ 2024 AJ]

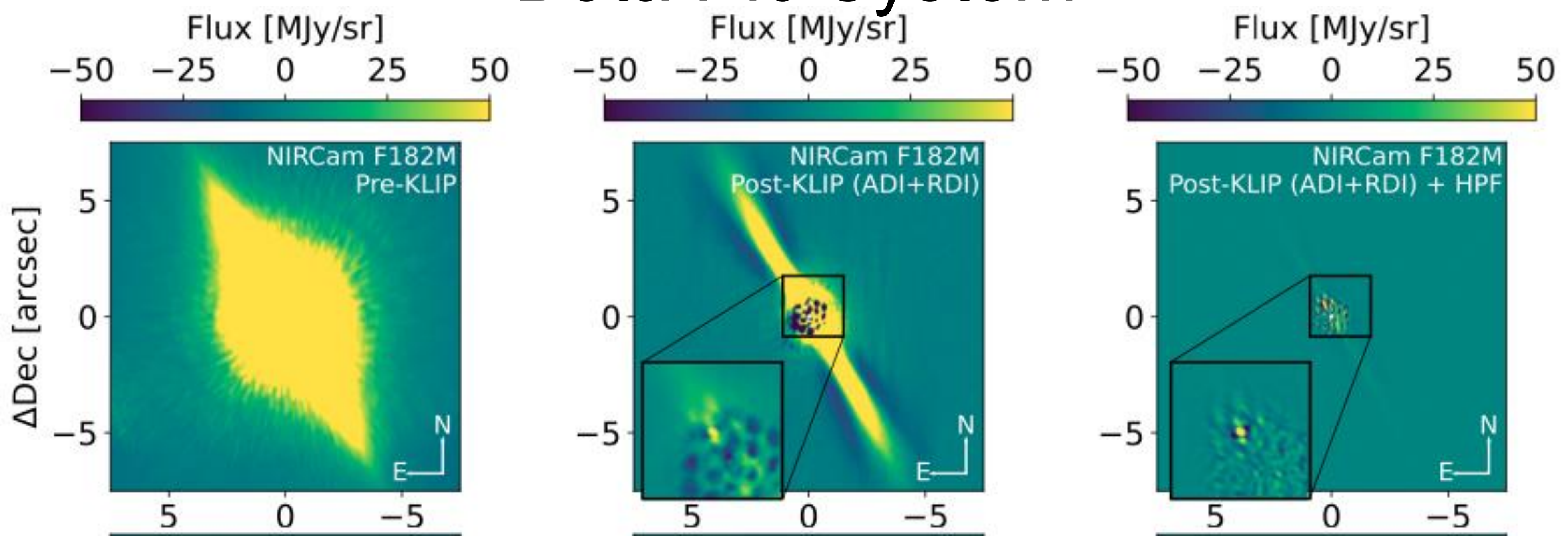
HR 8799 System



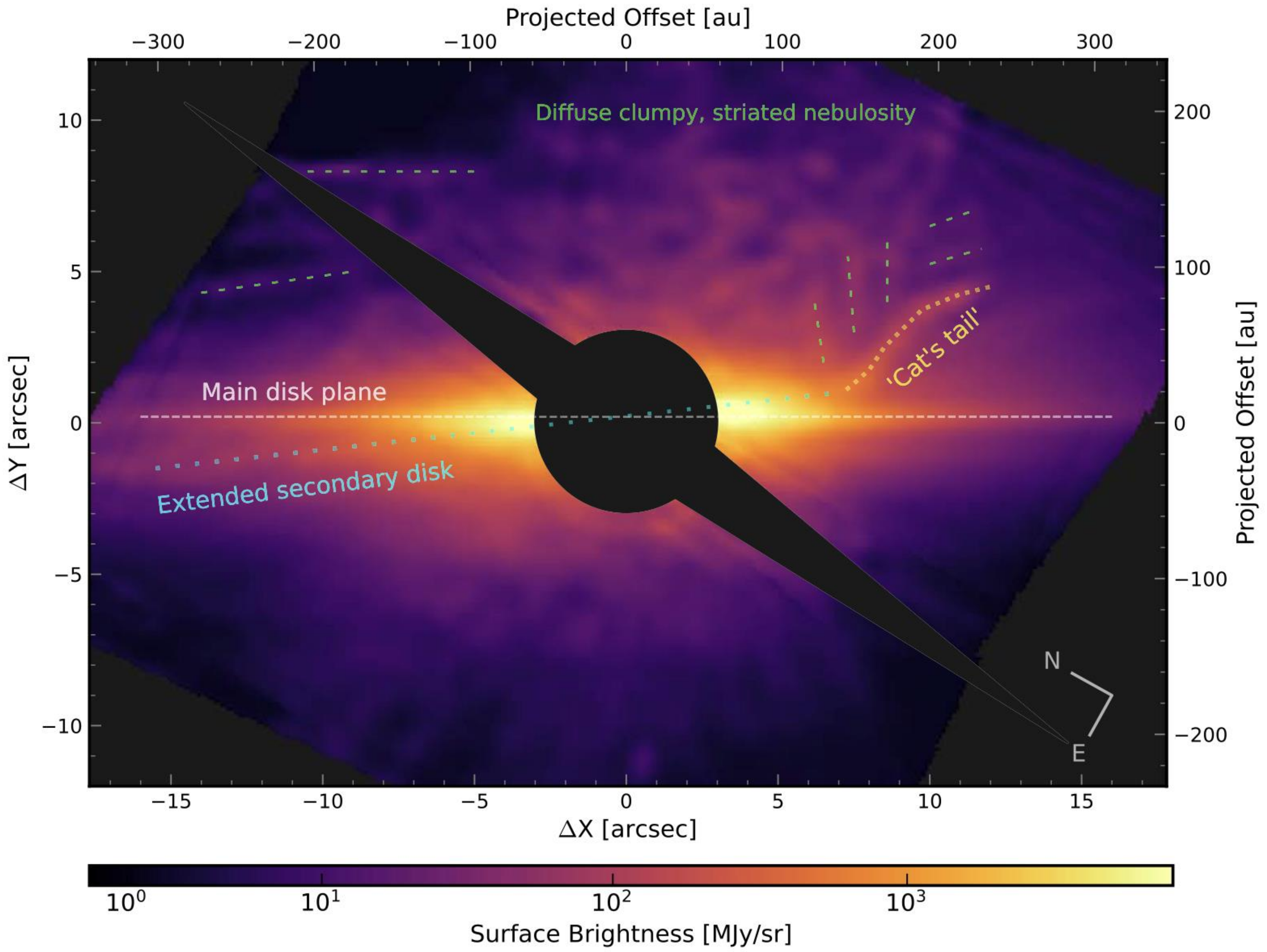


MIRI Coronagraphy [Boccaletti+ 2024 A&A]

Beta Pic System

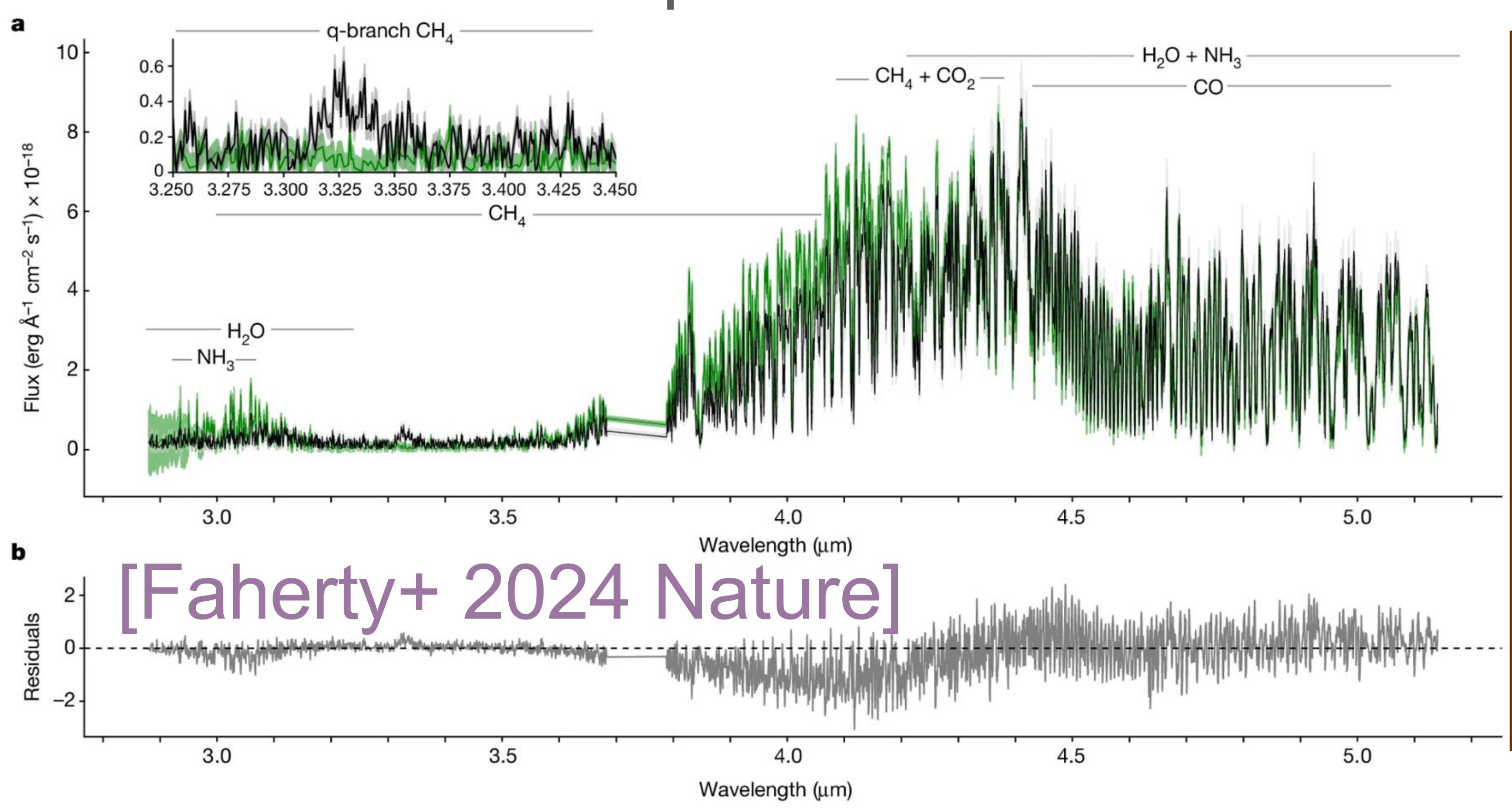


Beta Pic b NIRCam Photometry [Kammerer+ 2024, AJ]



The "Cats tail" [Rebollido+ 2024, AJ]

CH_4 in a cool brown dwarf with NIRSpec G395H

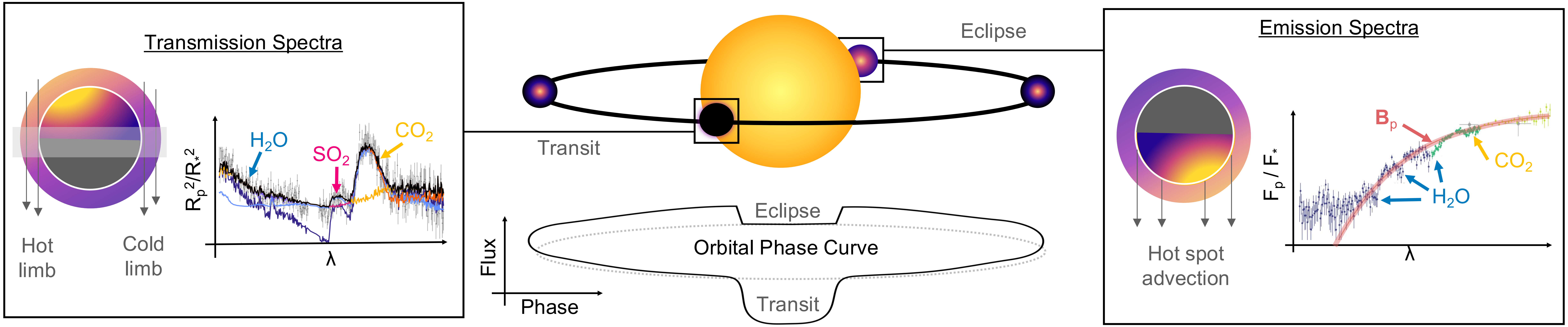


[Faherty+ 2024 Nature]

JWST has huge potential to discover new DI planets with the ability to get down to cold solar system like giants and critically overlapping with long period RV Jupiters

Transiting Exoplanet Atmospheres

How do we measure the atmosphere of a transiting exoplanet?



Scale height = $\frac{k_B T_p}{\mu g_p}$

$$\delta = \frac{A_p + H_{atm}}{A_*} = \frac{\pi\left(R_p + H_{atm}\right)^2}{\pi R_*^2}$$

$$\approx \left(\frac{R_p}{R_*}\right)^2 + \frac{2R_pH_{atm}}{R_*^2}$$

Atmospheric absorption around the day/night terminator

$$\frac{\xi_{abs} P_{(z=0)} \sigma_{ext}(\lambda)}{\tau_{eq}}$$

$$\frac{F_p}{F_*} = \frac{\pi B_p R_p^2}{\pi B_* R_*^2} = \left[\frac{e^{h\nu/k_BT_*} - 1}{e^{h\nu/k_BT_p} - 1}\right]\left(\frac{R_p}{R_*}\right)^2$$

Blackbody radiation

$$B = \frac{2h\nu^3}{c^2}\frac{1}{e^{h\nu/k_BT} - 1}$$

Thermal dayside emission

Image credits: H.R.Wakeford; Alderson+ (2023,Nature); Wakeford+ (in prep)

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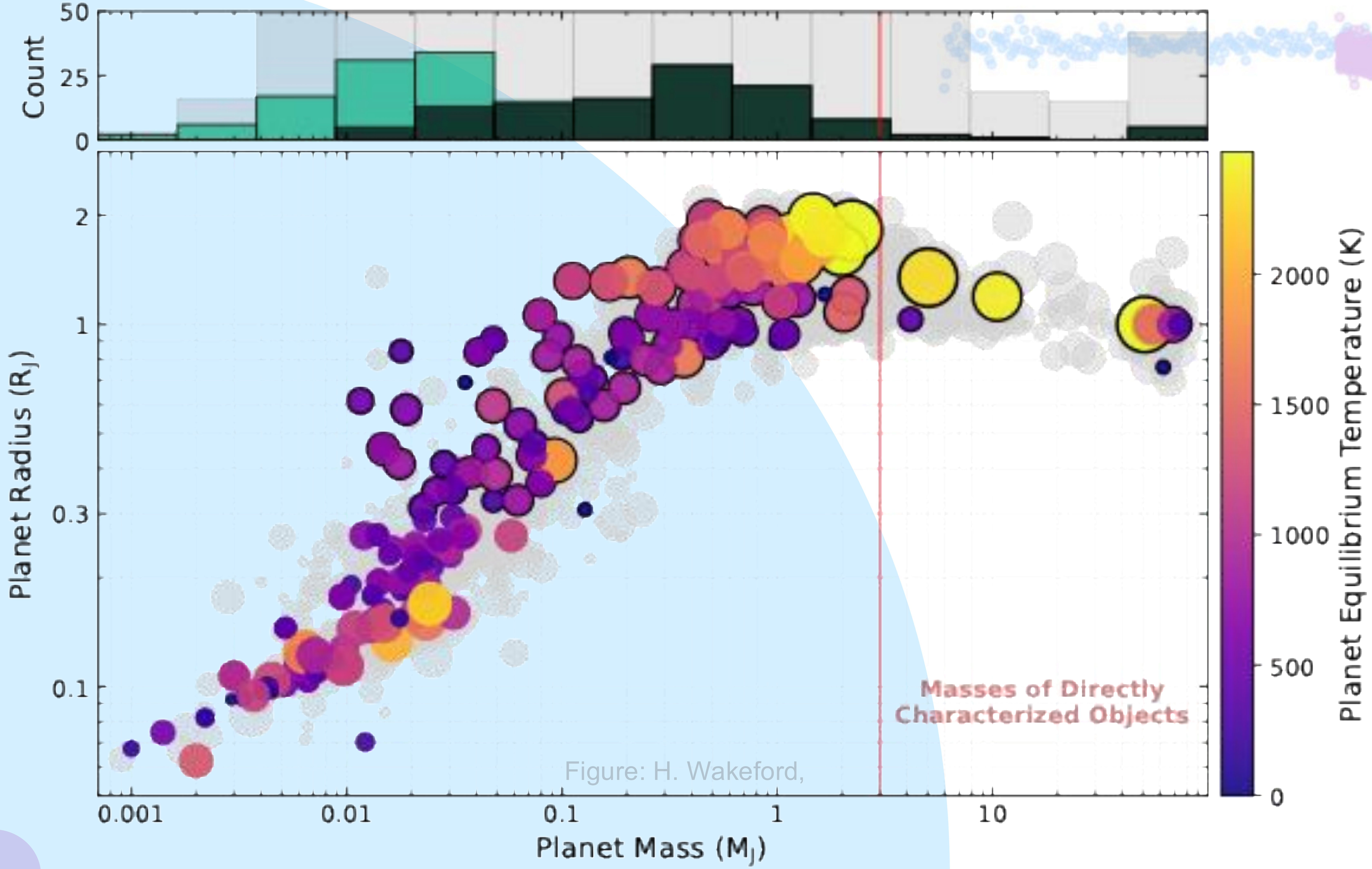
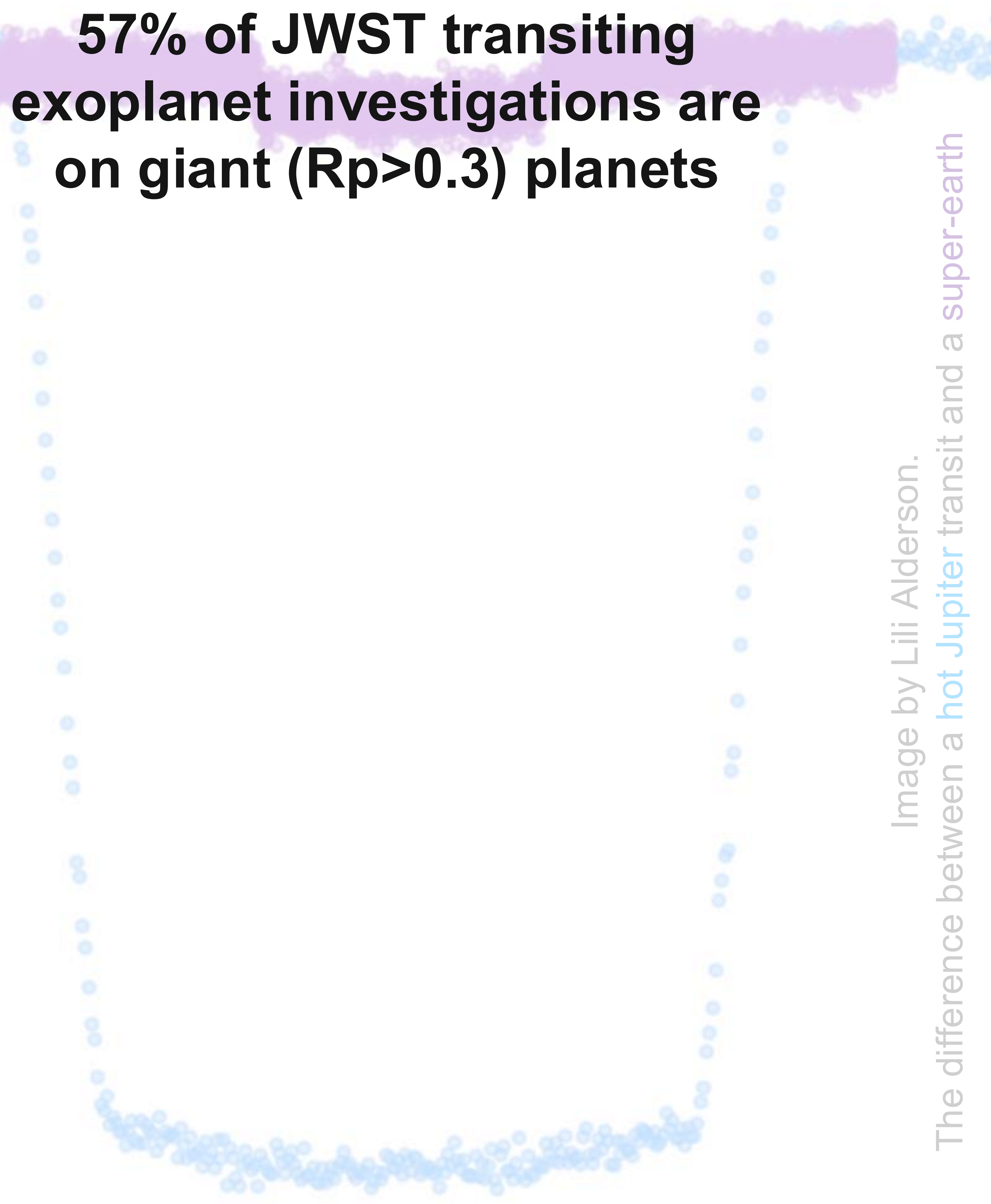
Giant Planets are the Perfect Test Subjects

Broad parameter space, high S/N, panchromatic data



57% of JWST transiting exoplanet investigations are on giant (Rp>0.3) planets



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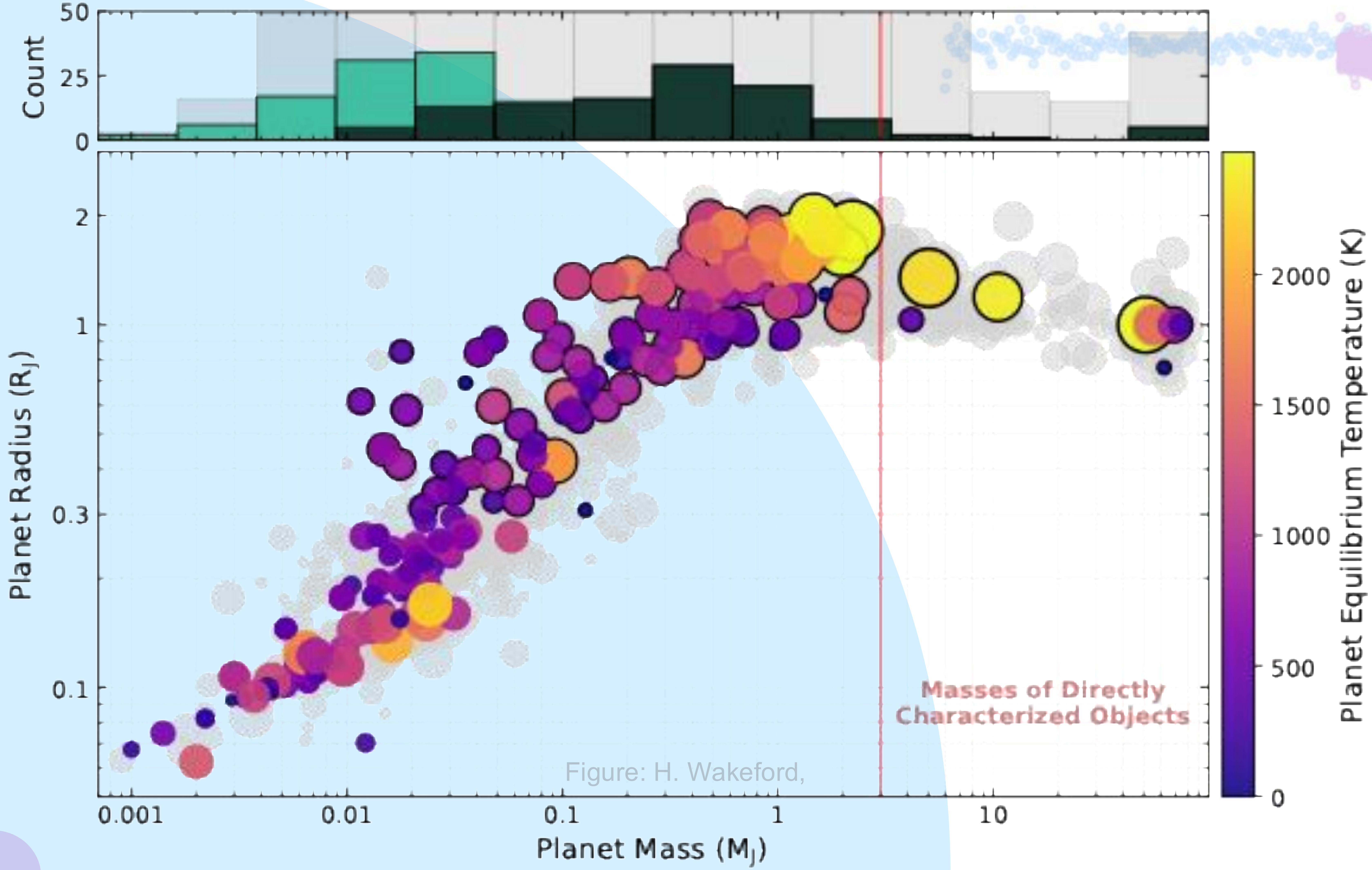

57% of JWST transiting exoplanet investigations are on giant (Rp>0.3) planets

We can get detailed information about the atmosphere under different conditions, gravity, temperature, stellar type, [M/H] forming condition

There is still so much to learn, and we are on our way!!

The difference between a hot Jupiter transit and a super-earth

Image by Lili Alderson.

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Each Atom and Molecule Uniquely Interacts with Light

Atoms in the optical, molecules through the IR

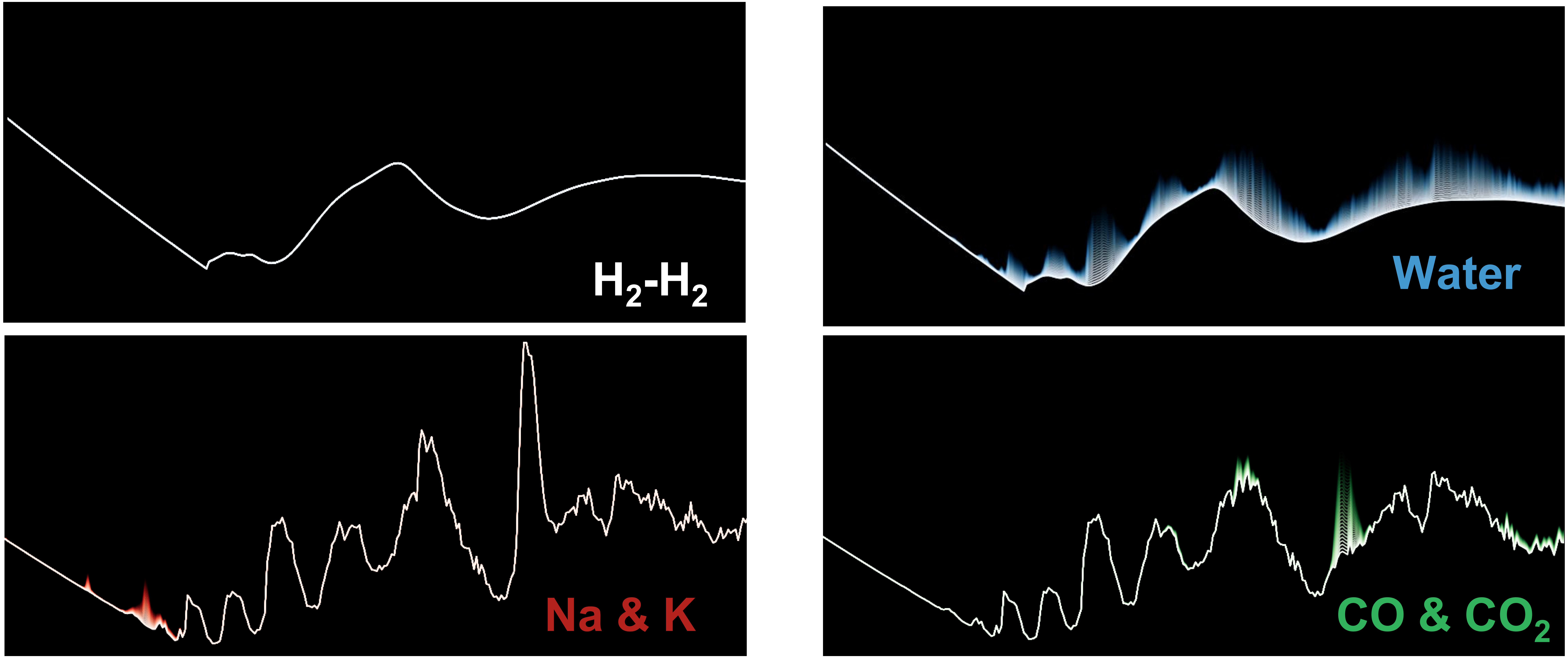

Image credits: David Grant using POSEIDON (MacDonald 2021)

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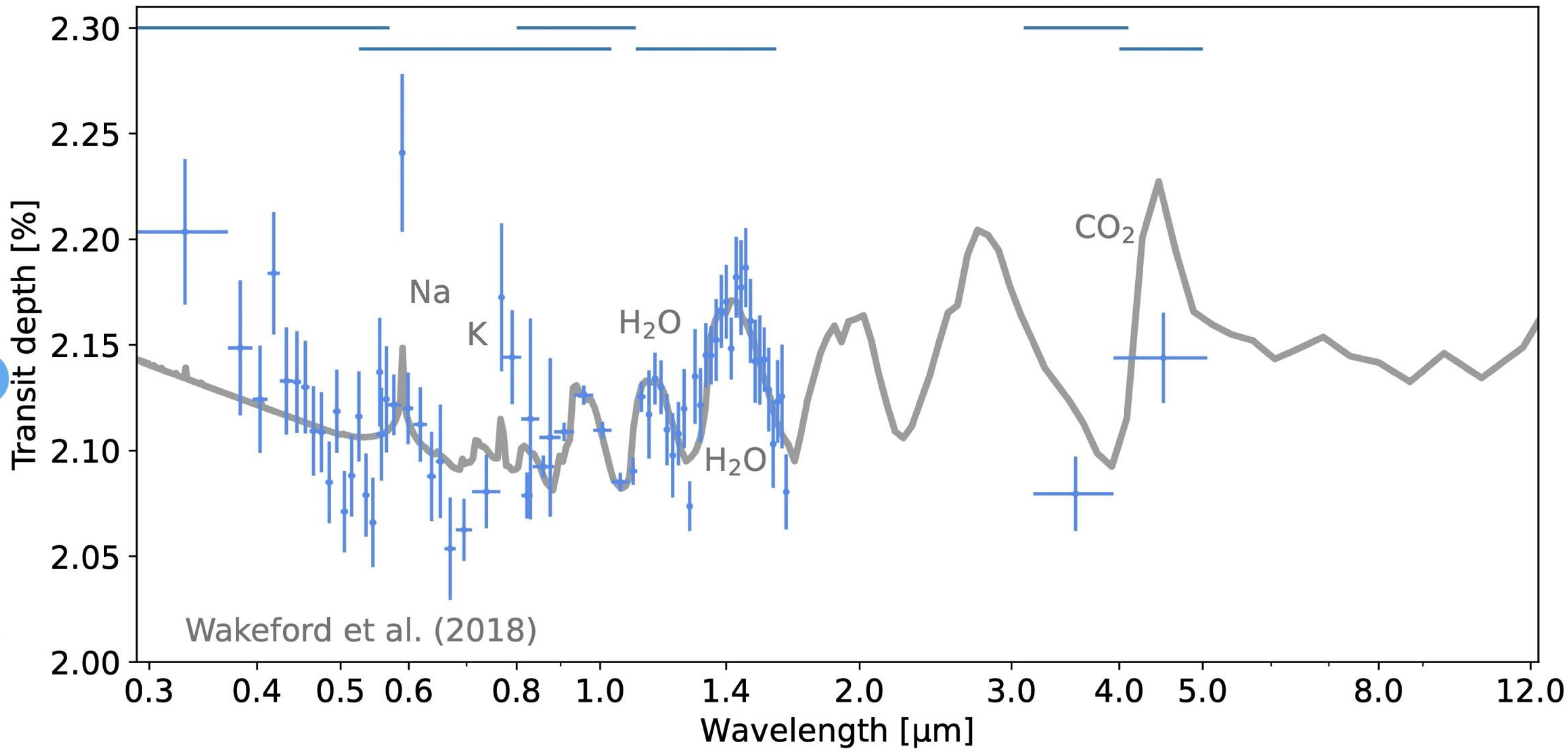
A Community Transforming Spectrum

Five datasets, brand new chemistry, and a massive challenge to model



This is what we learned with 5 JWST measurements compared to 7 with HST + Spitzer

JTEC team+ (2022), Ahrer+ (2023), Alderson+ (2023), Feinstein+ (2023), Rustamkulov+ (2023), Tsai+ (2023), Grant+ (2023), Esparaza-Borges+ (2024), Powell+ (2024), May & Carter+ (2024), Espinoza+ (2025), Steinrueck+ (2025), Welbanks+ (in prep), …

Thanks to Luis Welbanks and Jo Barstow for the model and data

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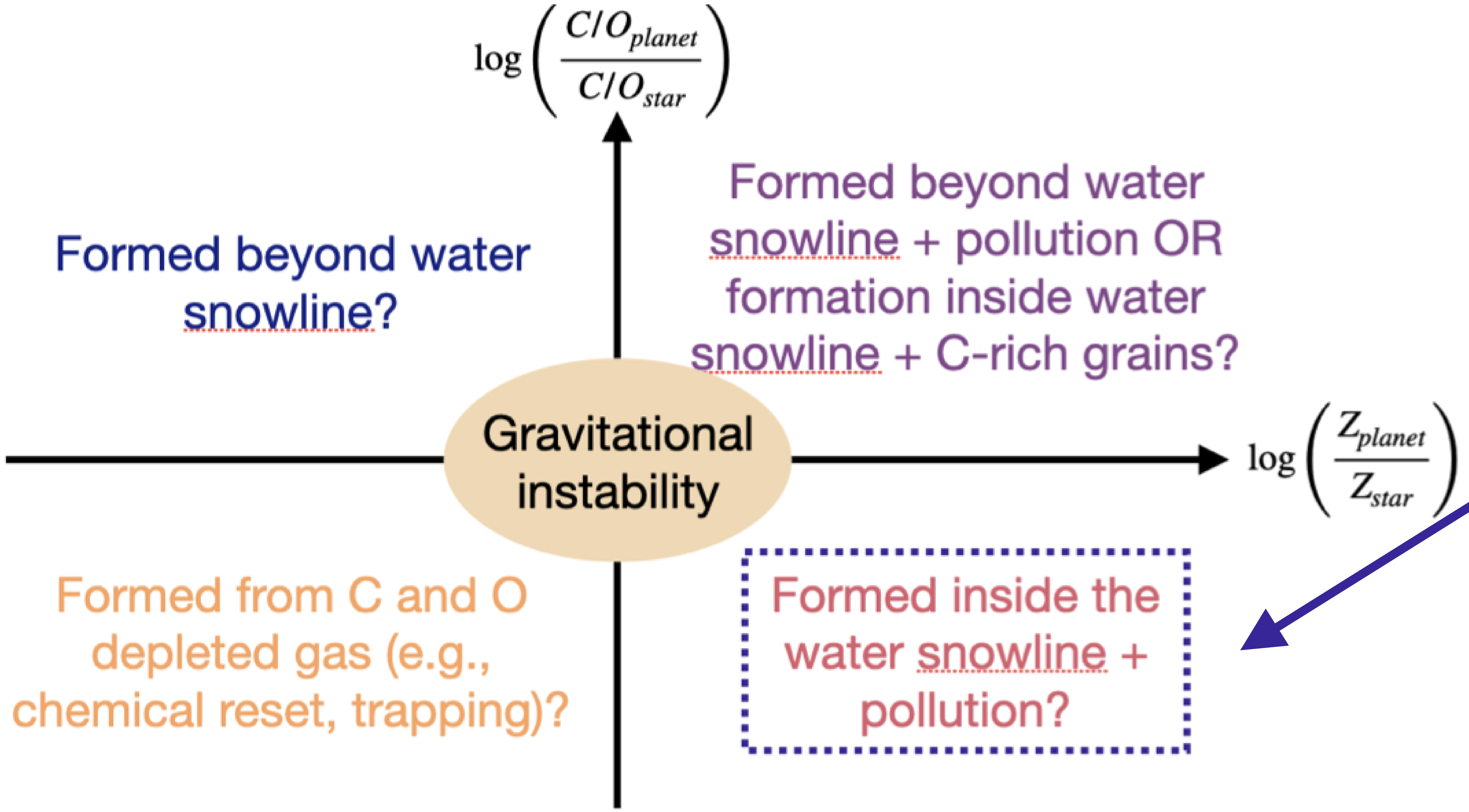
Why is Chemistry important?

The role of metallicity and C/O in formation processes



The abundance of material in a planets atmosphere can be used to inform about their formation locations relative to snowlines in the disk (below)

Thus far a majority of giant transiting planets sit in the bottom right

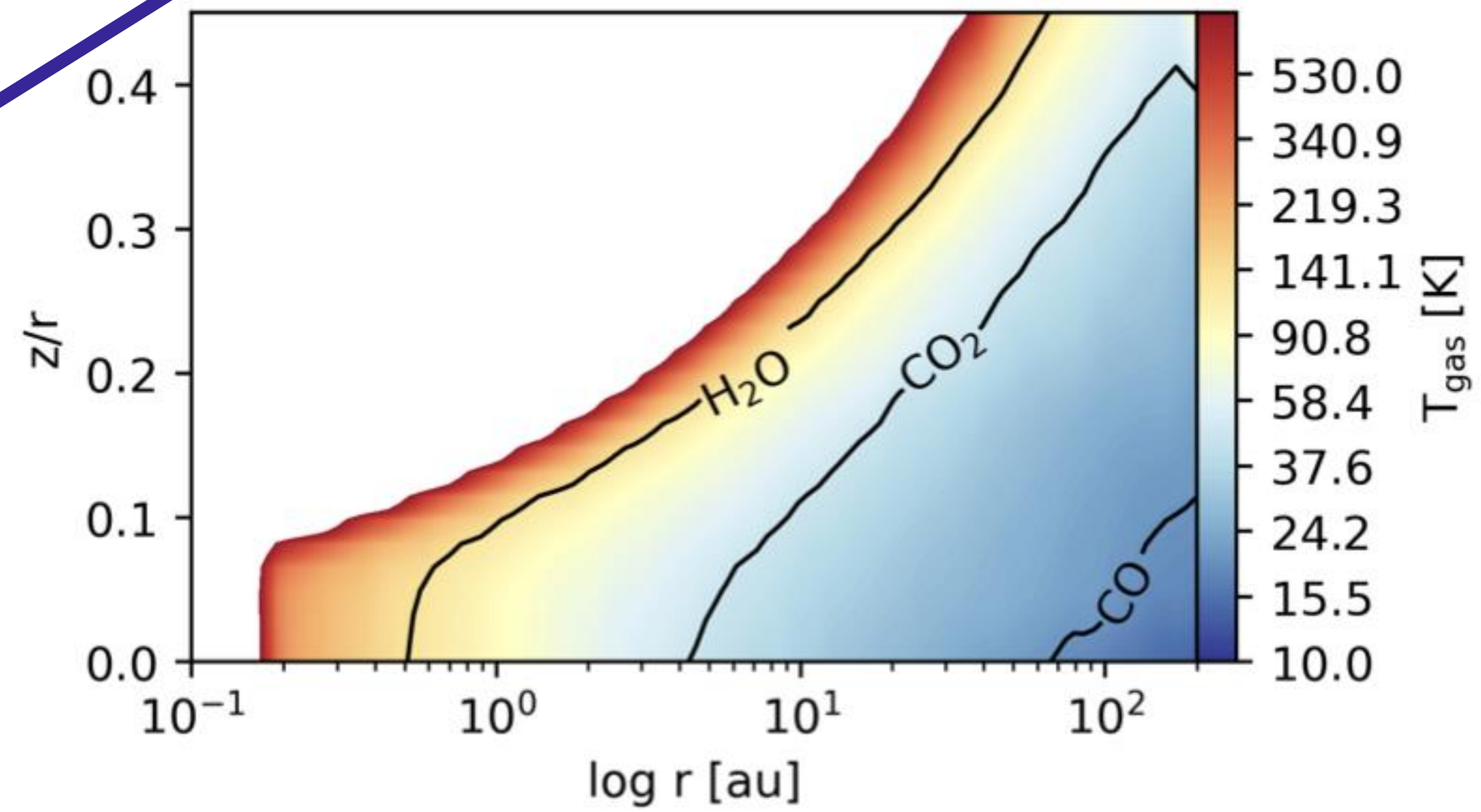


Figure credits: Walsh (2025), Booth+ (2025)

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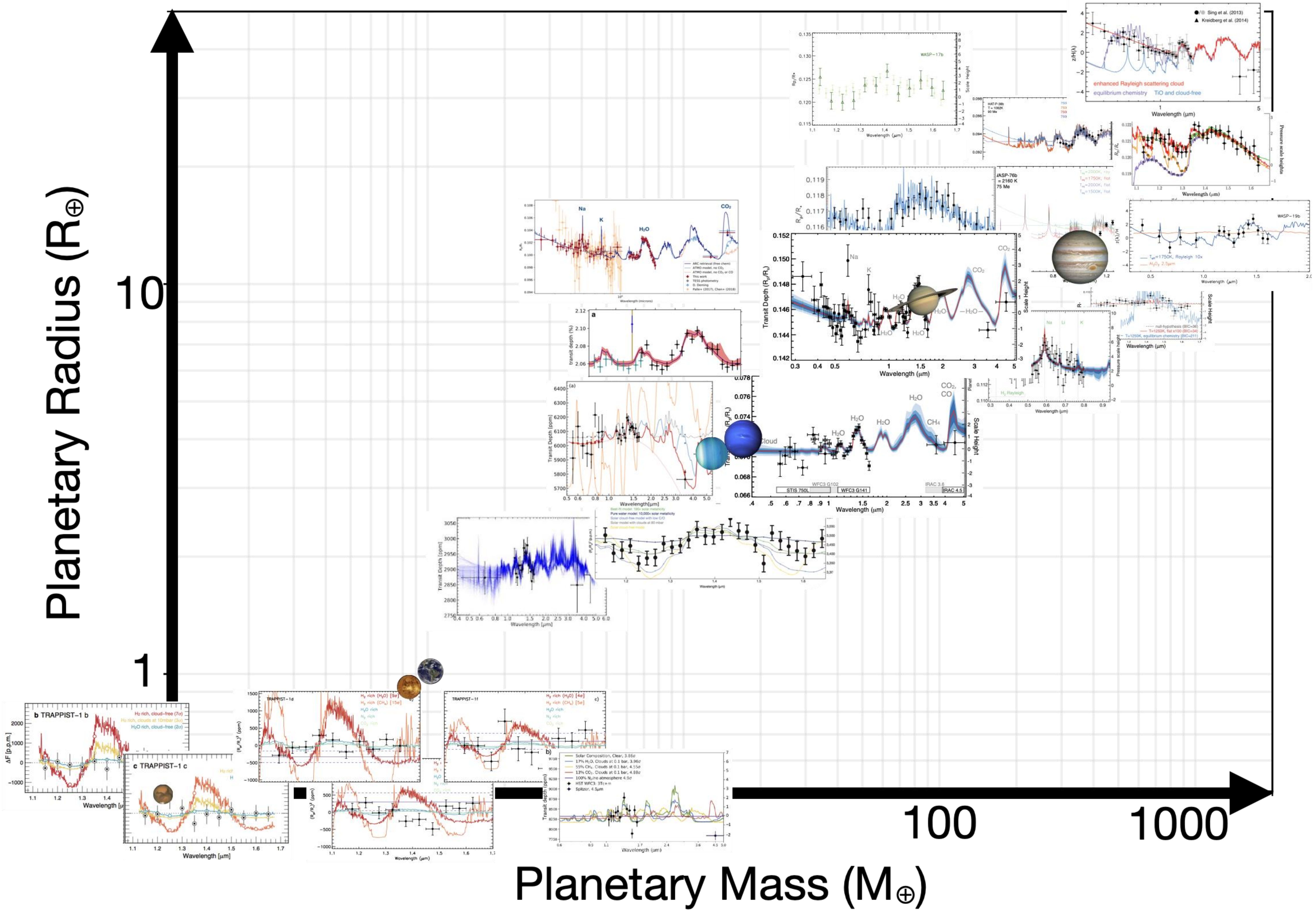
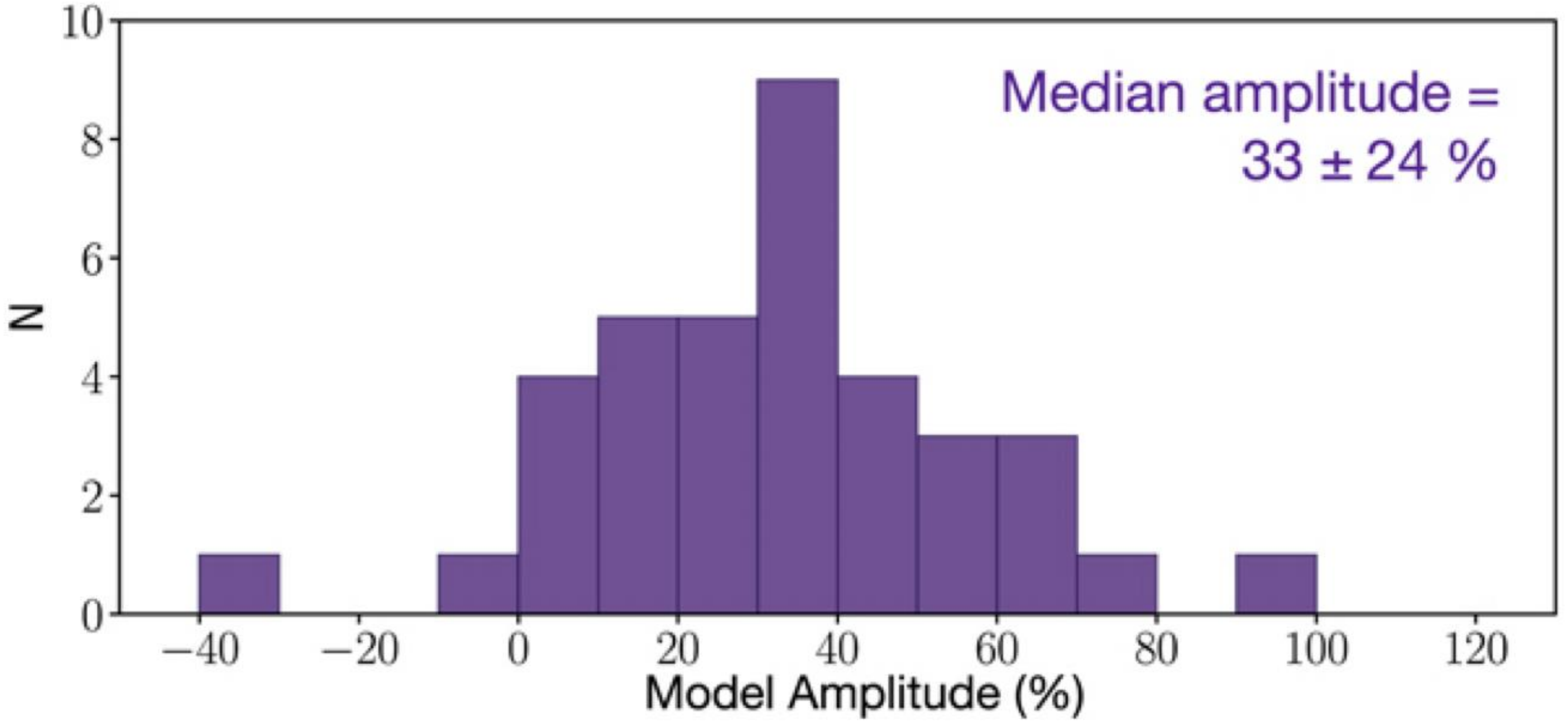
Hubble Provided Access to Water in the near-IR

We measured over 70 planets across the whole range of planetary sizes



Water vapor has been measured in over 80% of planets



But it is often muted to around 1/3 of expected

Wakeford+ (2019, RNAAS)

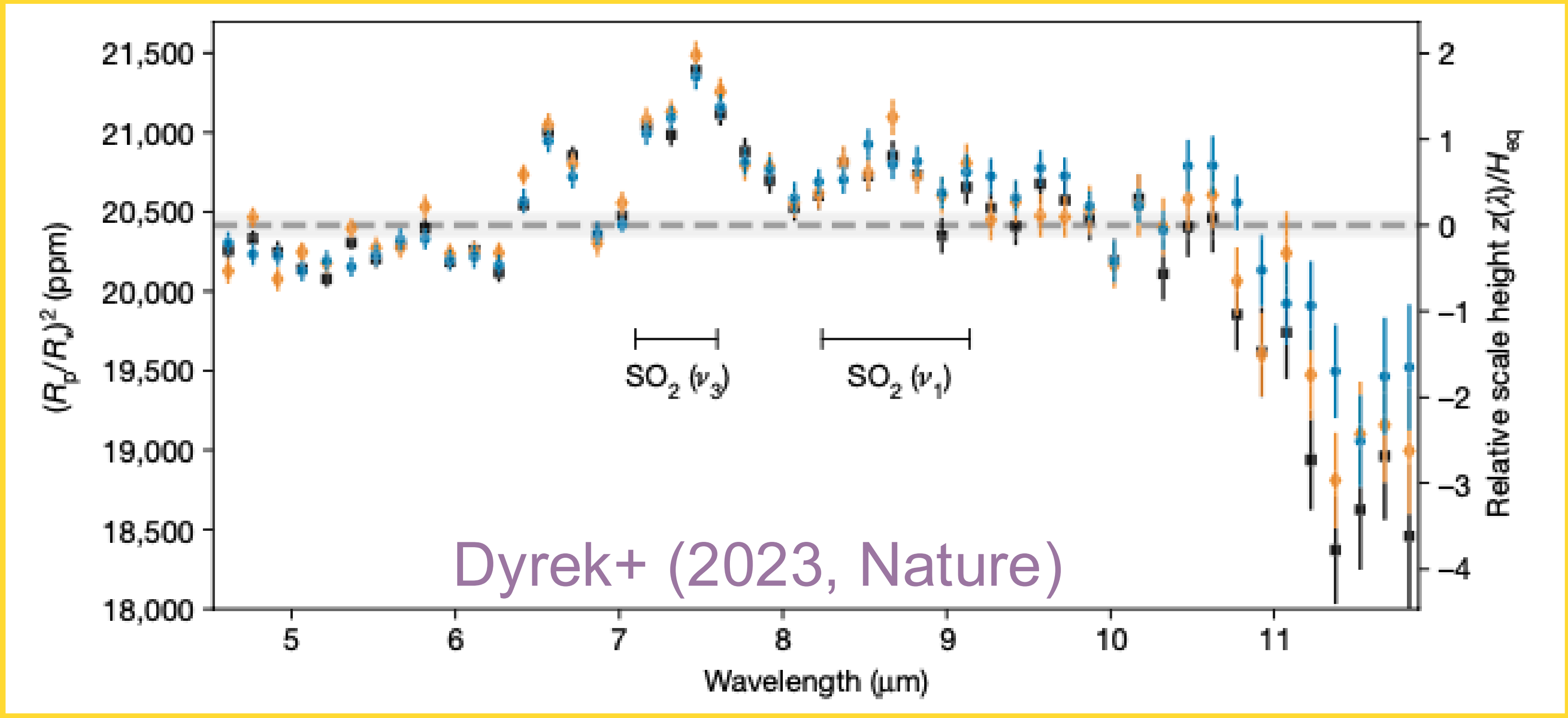
New Access to Carbon Chemistry with JWST

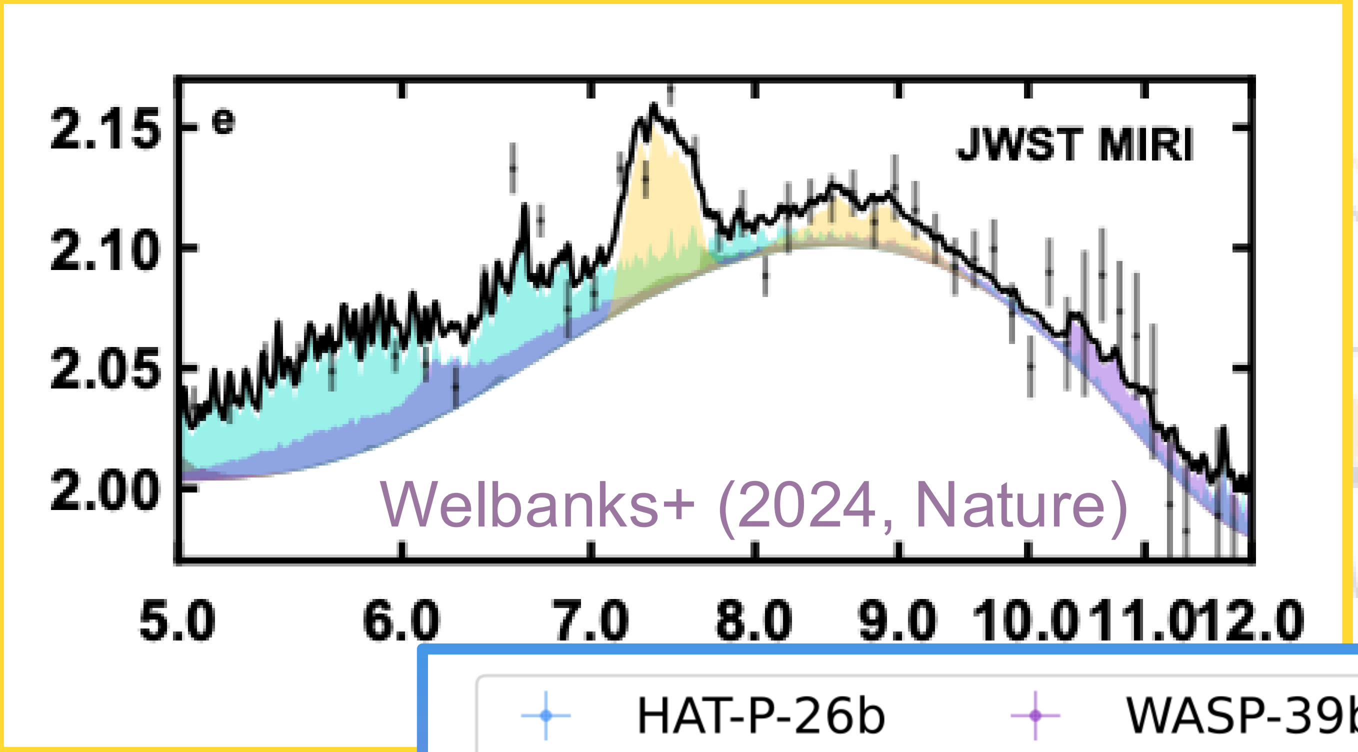
CO, CO_2, CH_4 revealed in emission and transmission

Dis-equilibrium / Photochemistry

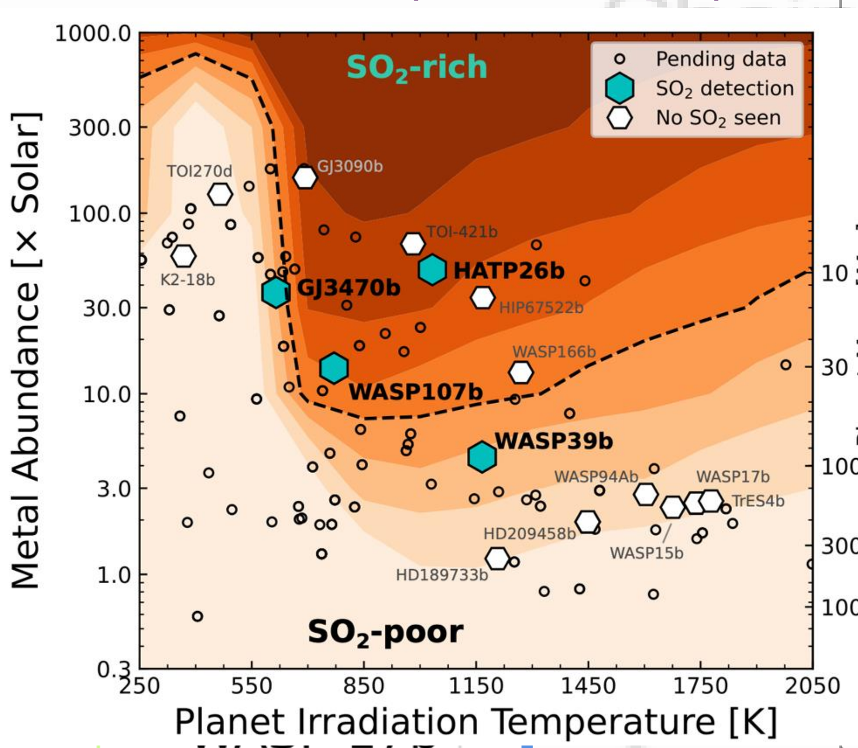
Revealing sulphur chemical pathways over a wide range of conditions

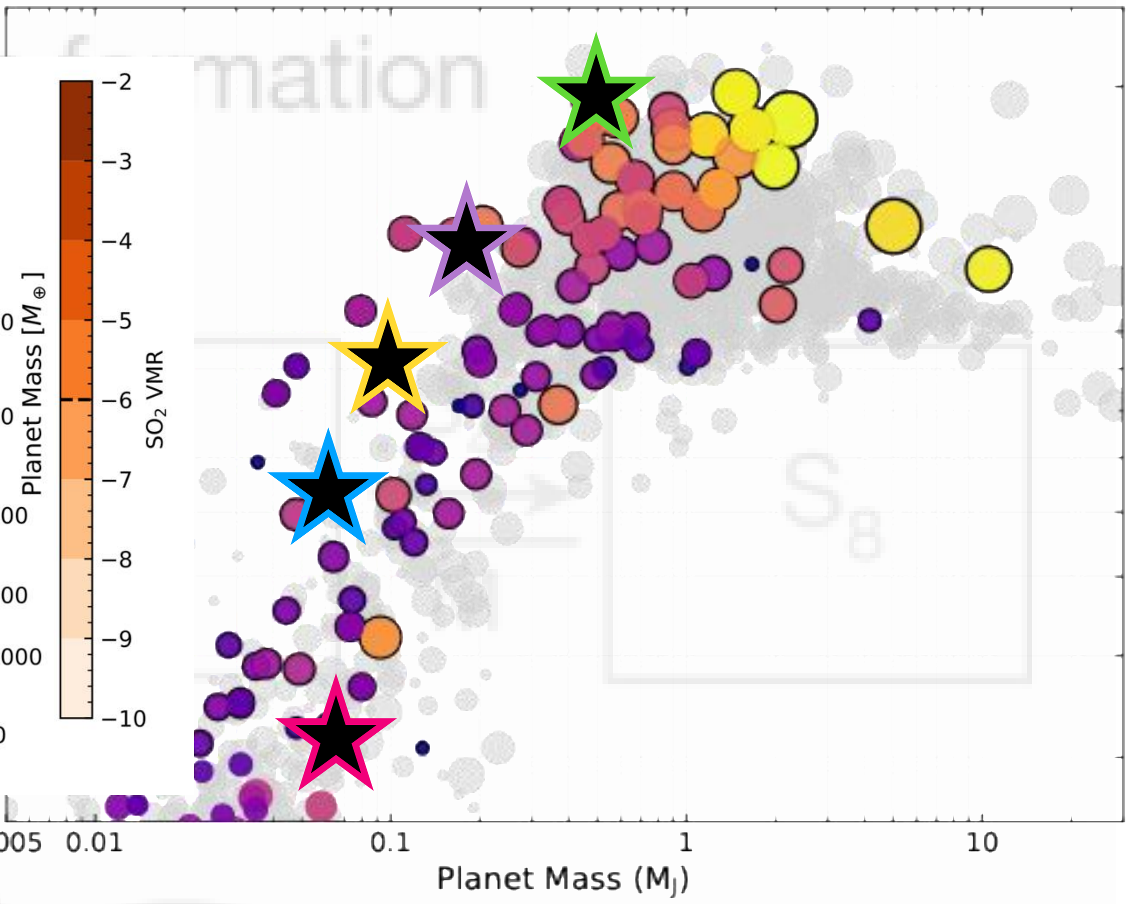
WASP-107b

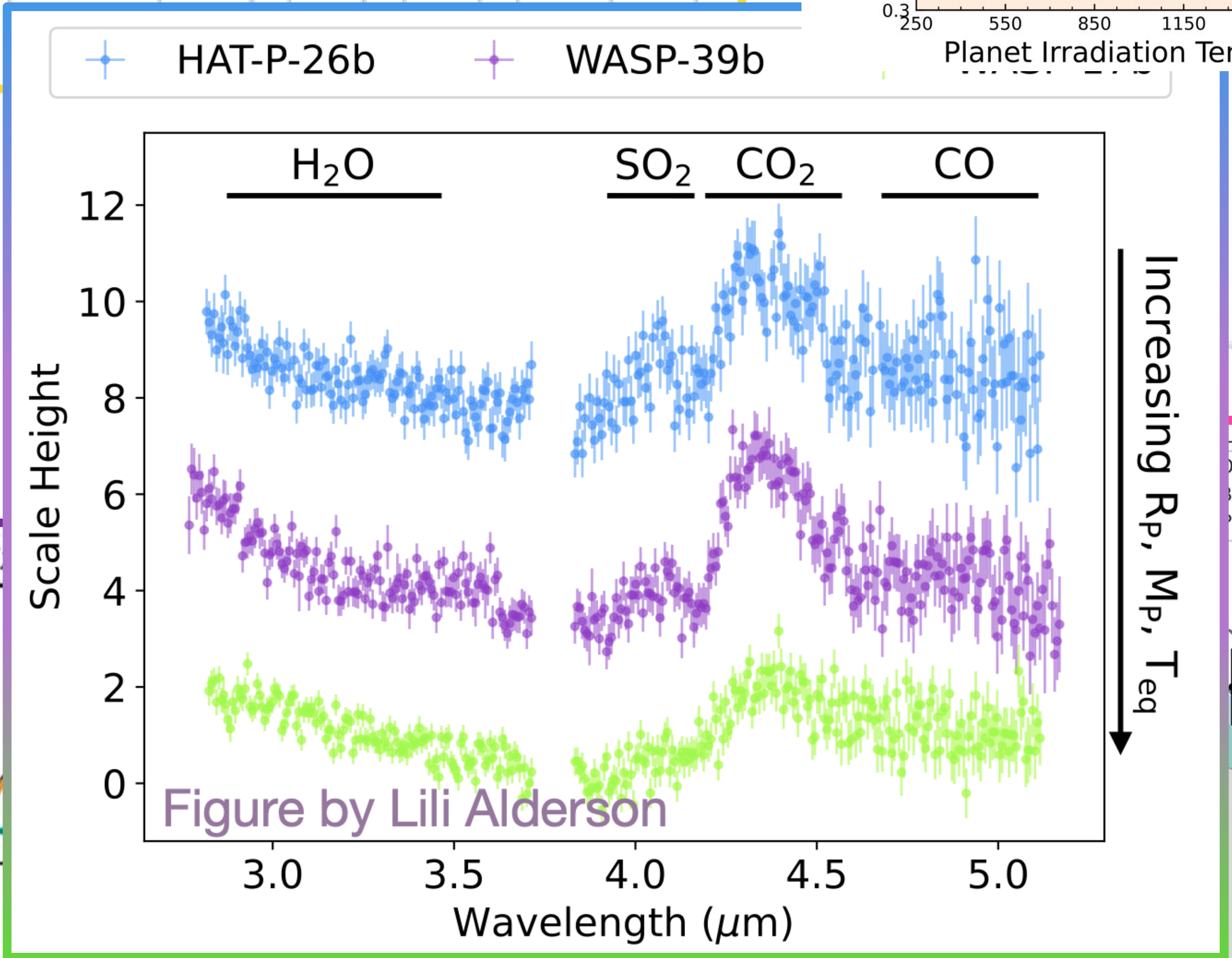




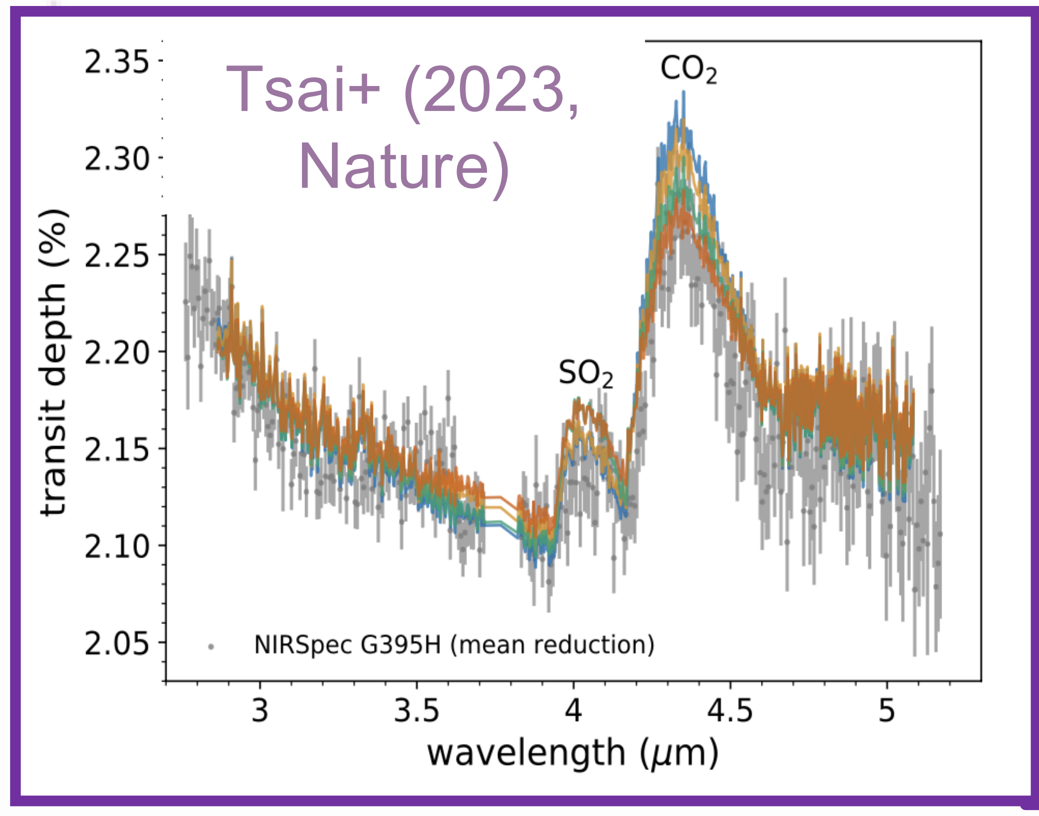
Crossfield+ (2025, ApJ)

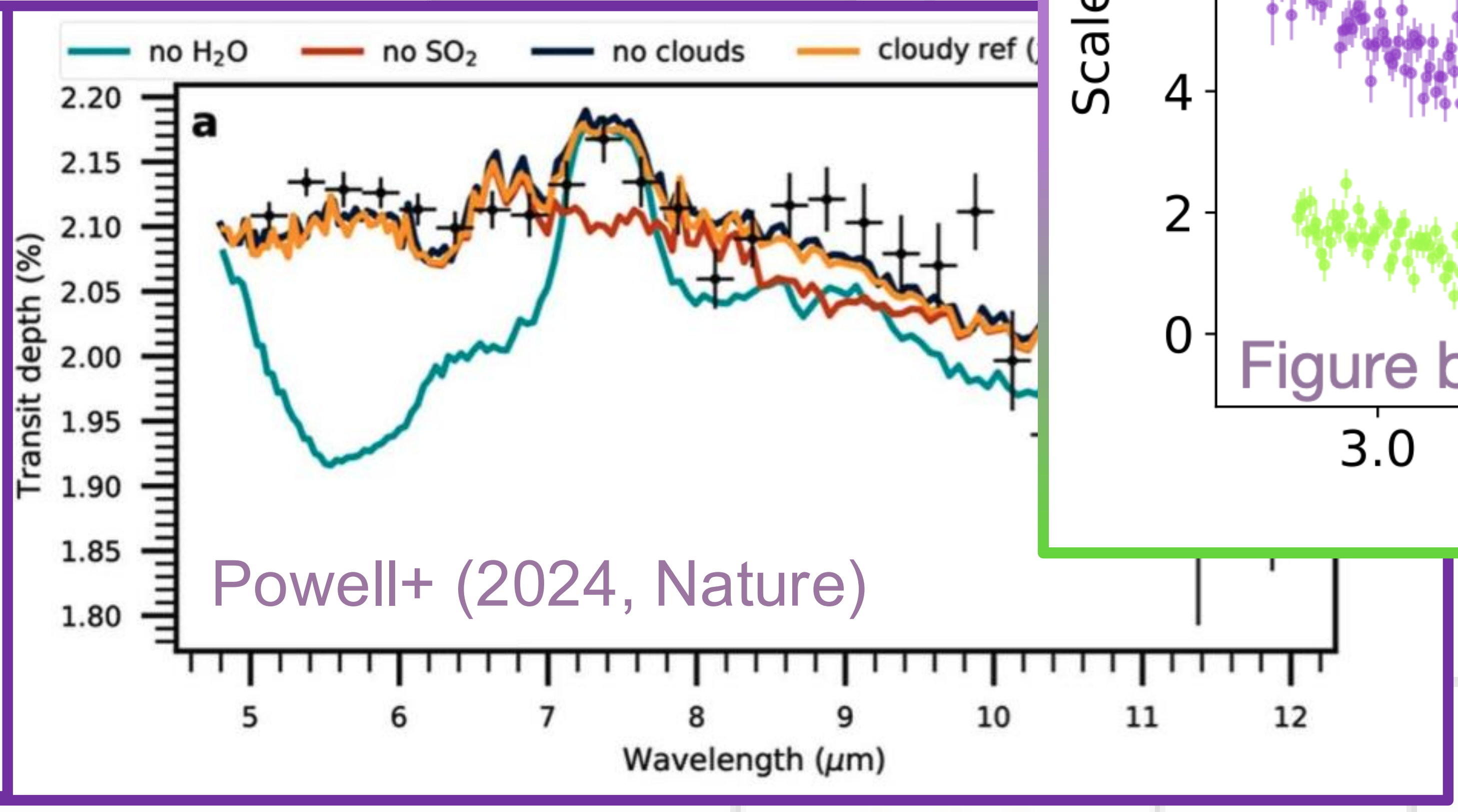


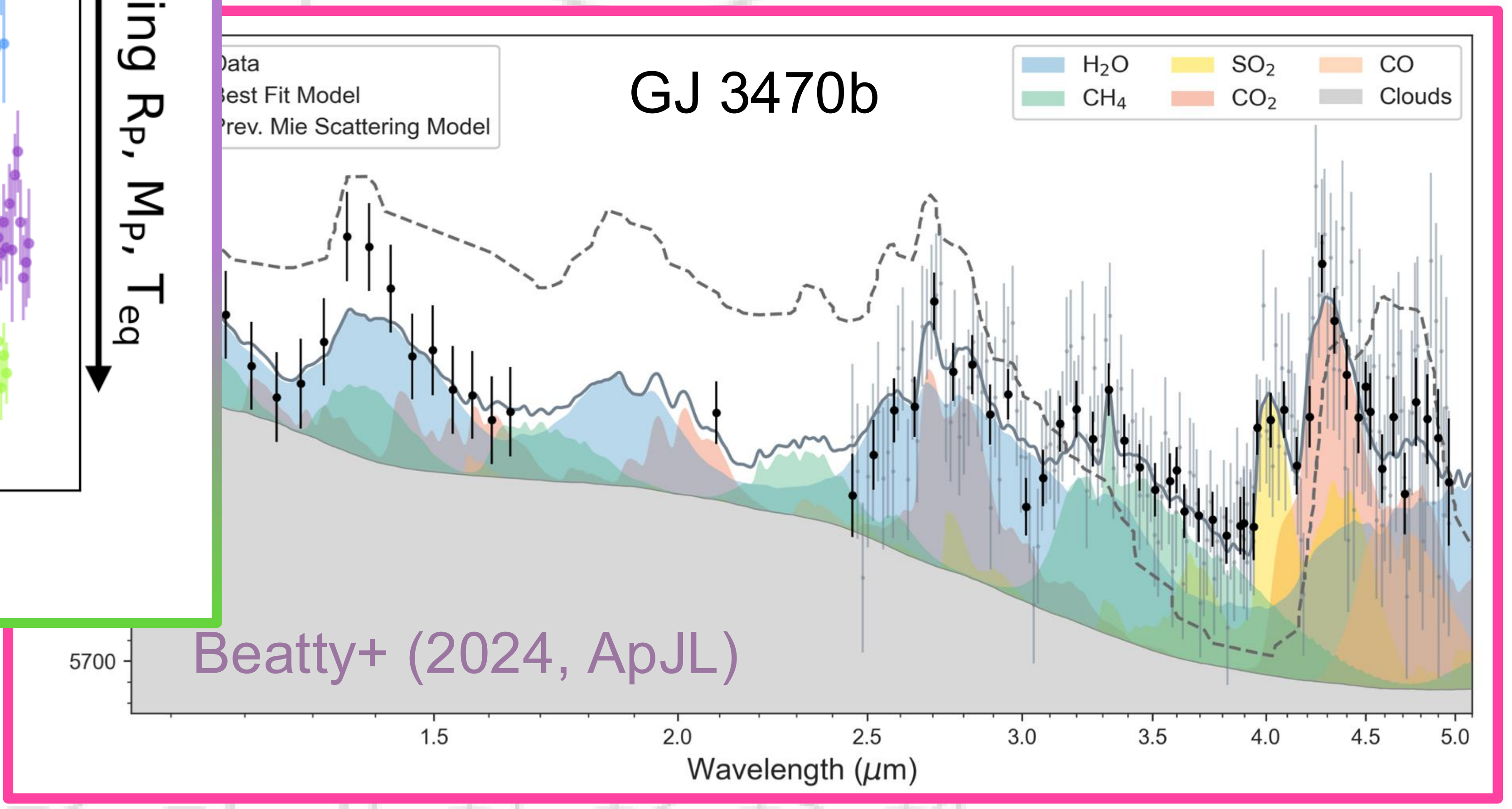




WASP-39b







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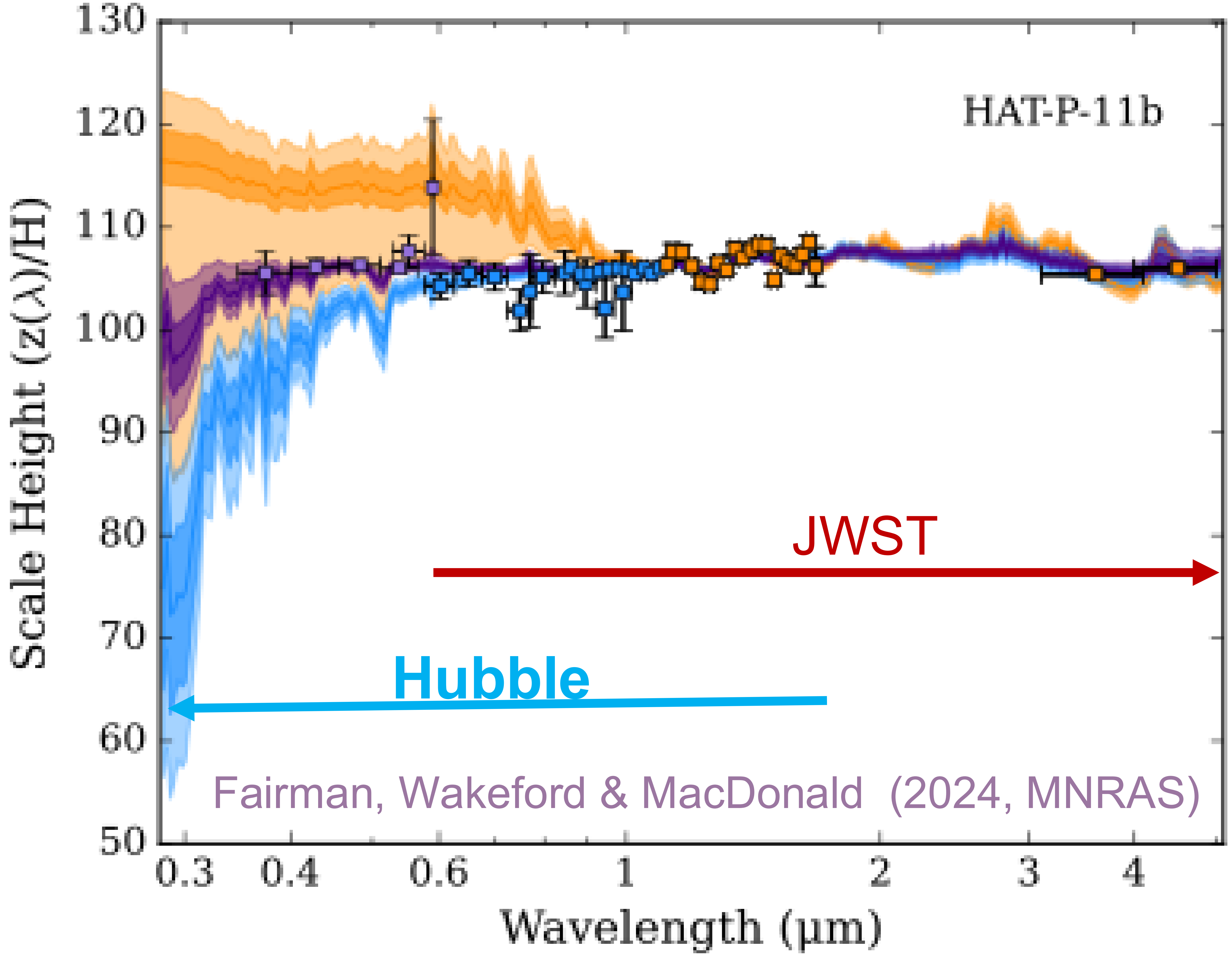
But the Star Plays a Big Role in Characterization

Hubble plays a core role in assessing the transit light source effect of an active star



The optical is vital to understand the impact of the star on the measured spectrum with the IR as a poor predictor of stellar activity indicators.

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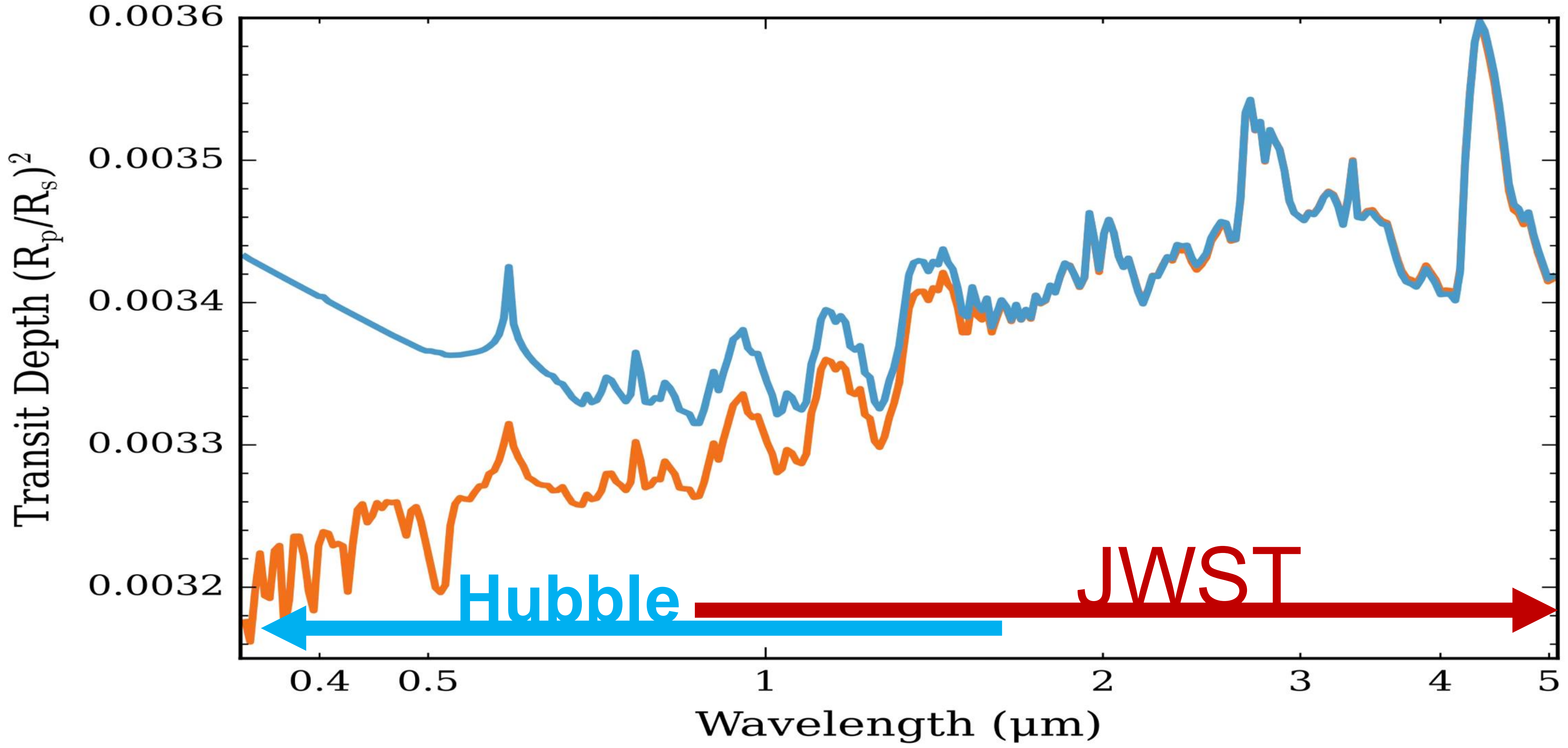
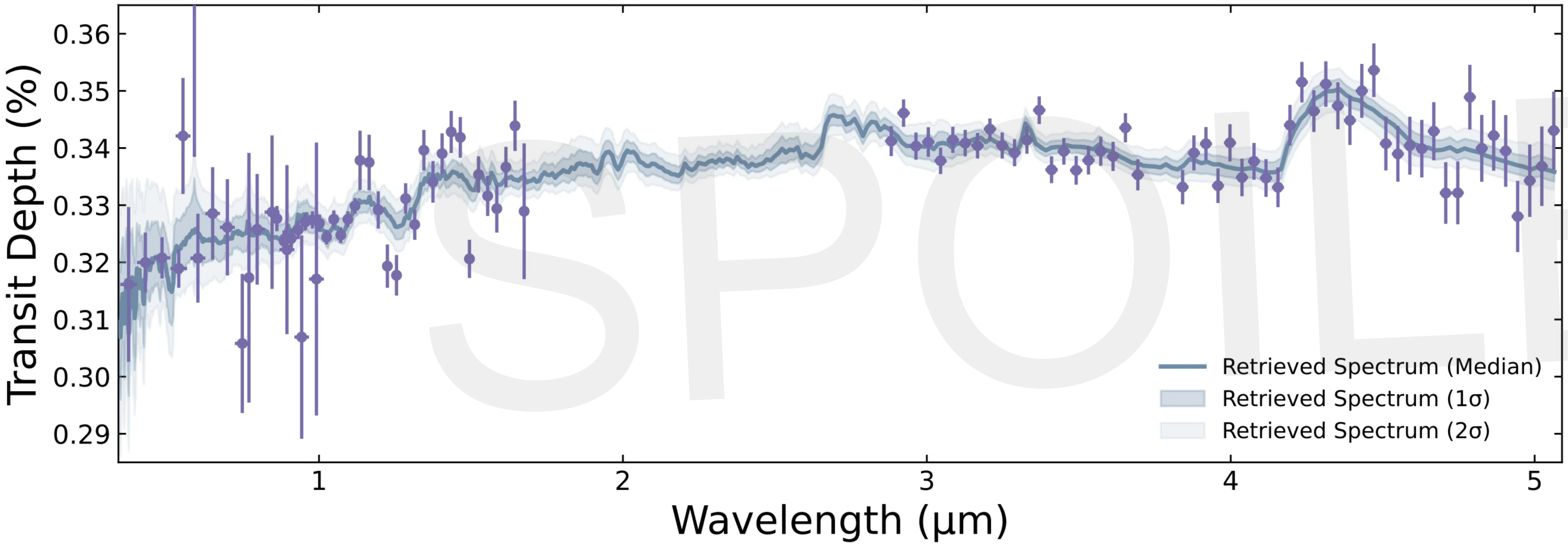
Constraining the Chemistry of HAT-P-11b

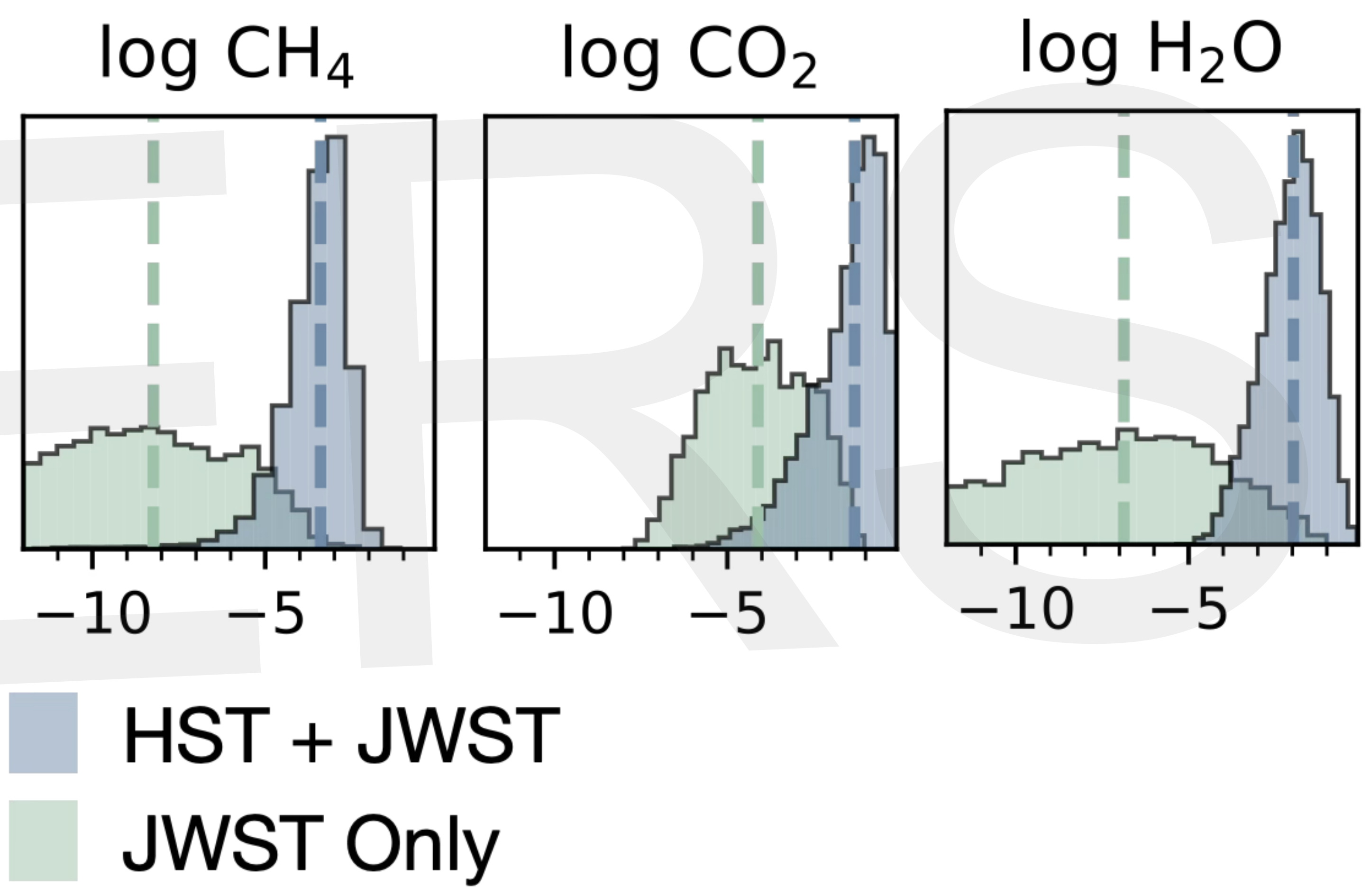
Hubble plays a core role in assessing the transit light source effect



The optical is vital to understand the impact of the star on the measured spectrum.

Alderson & Fairman+ (2026, in prep)





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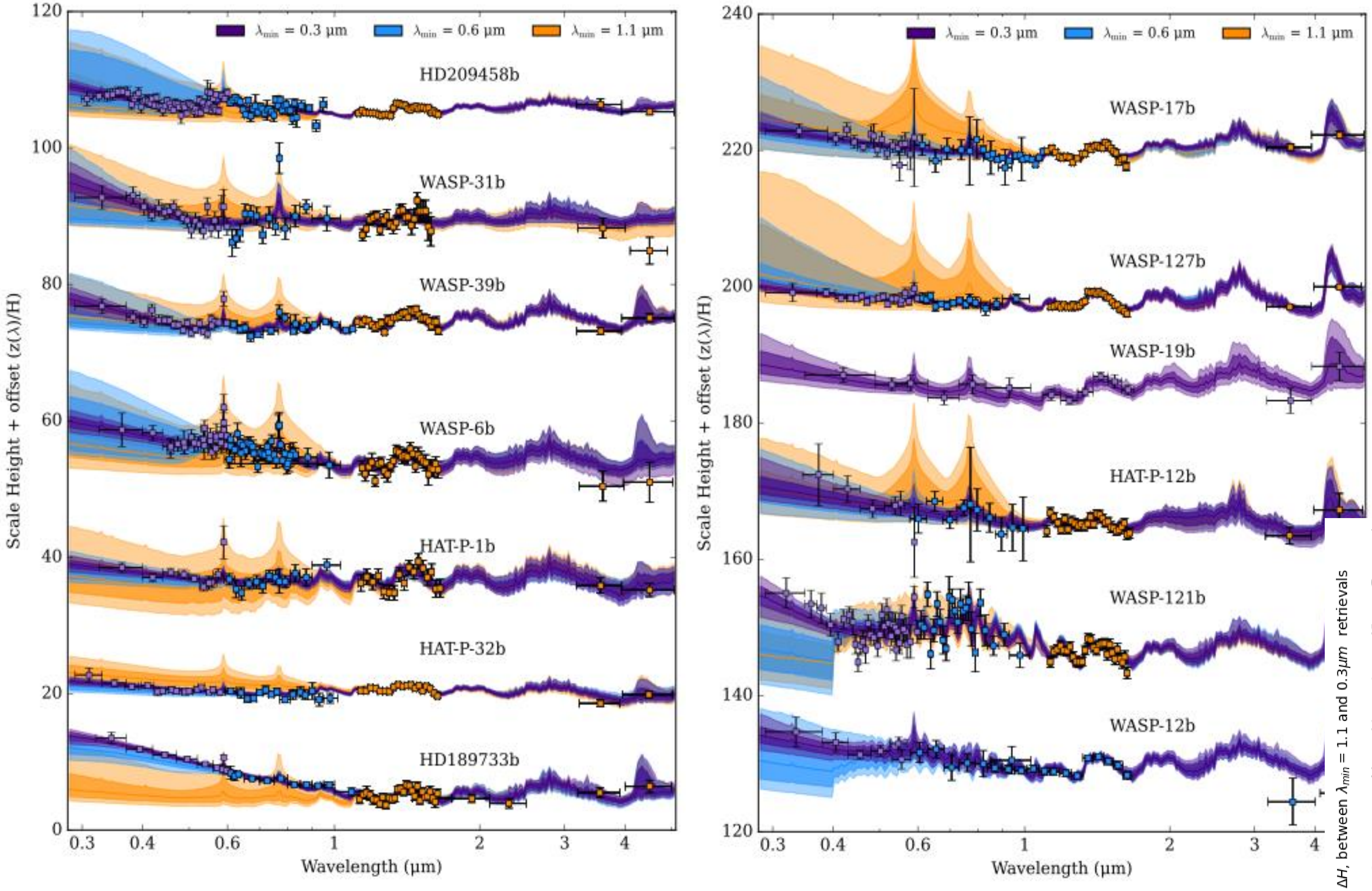
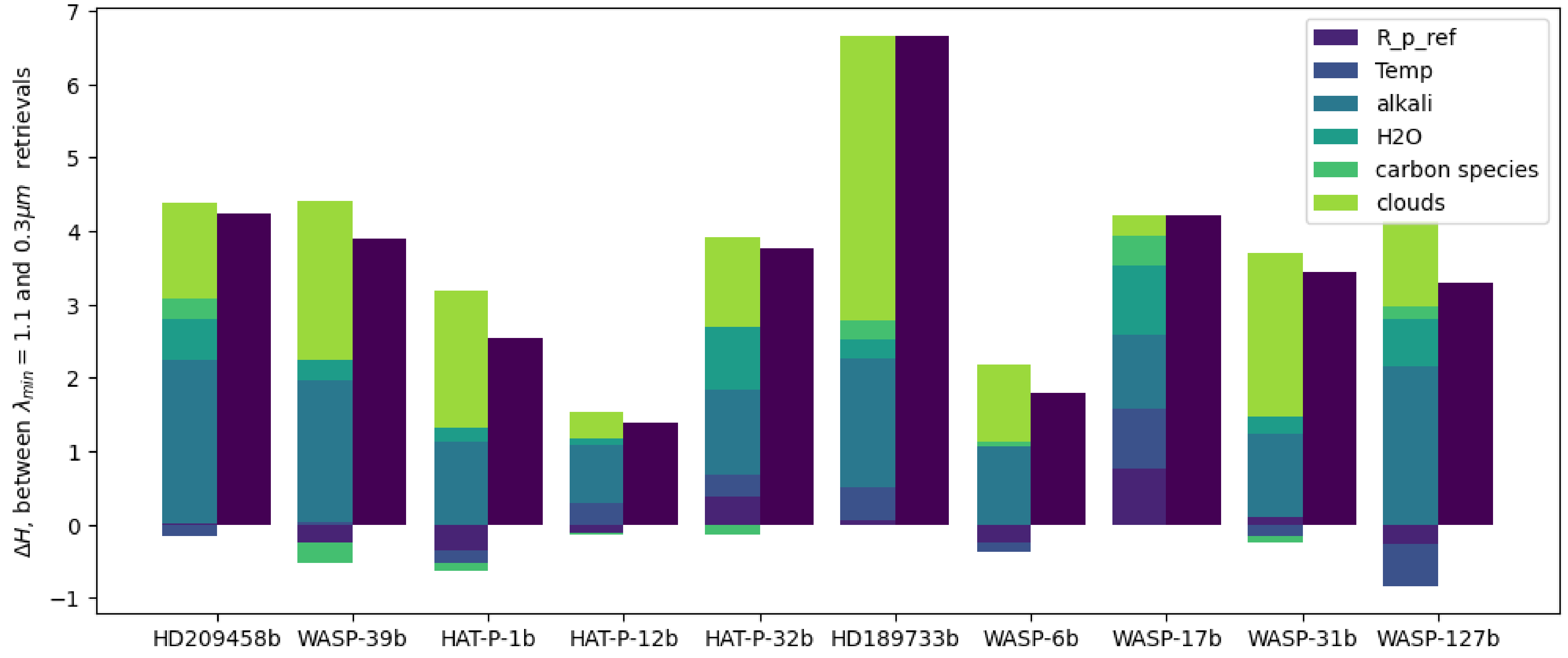
Absorption in Exoplanet Atmospheres

Hubble plays a core role in assessing aerosols in exoplanet spectra



Without information below 0.6 μm (JWST's blue limit) we cannot properly account for the impact of **aerosols** on the spectra

Fairman, Wakeford & MacDonald (2024, AJ)



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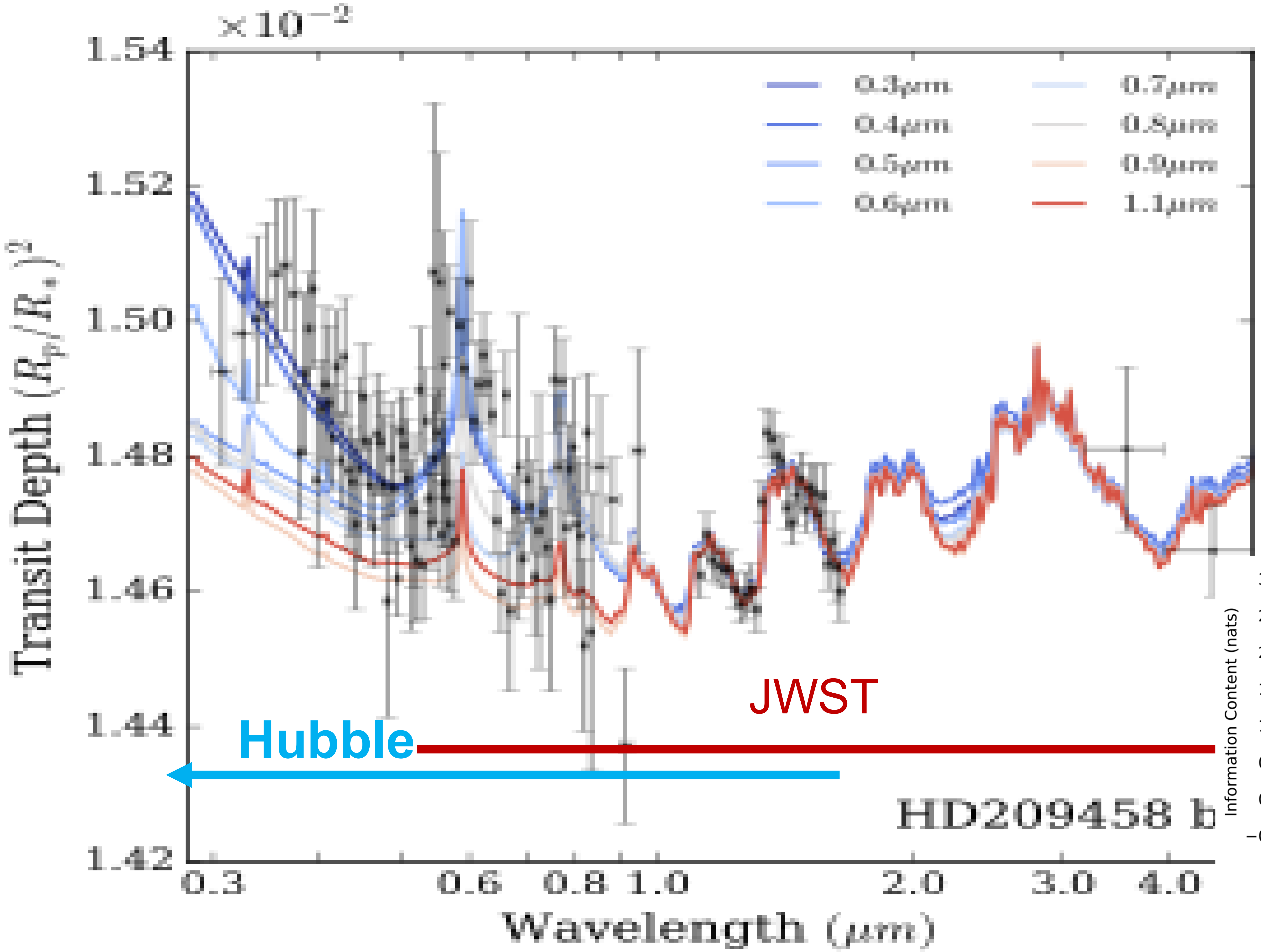

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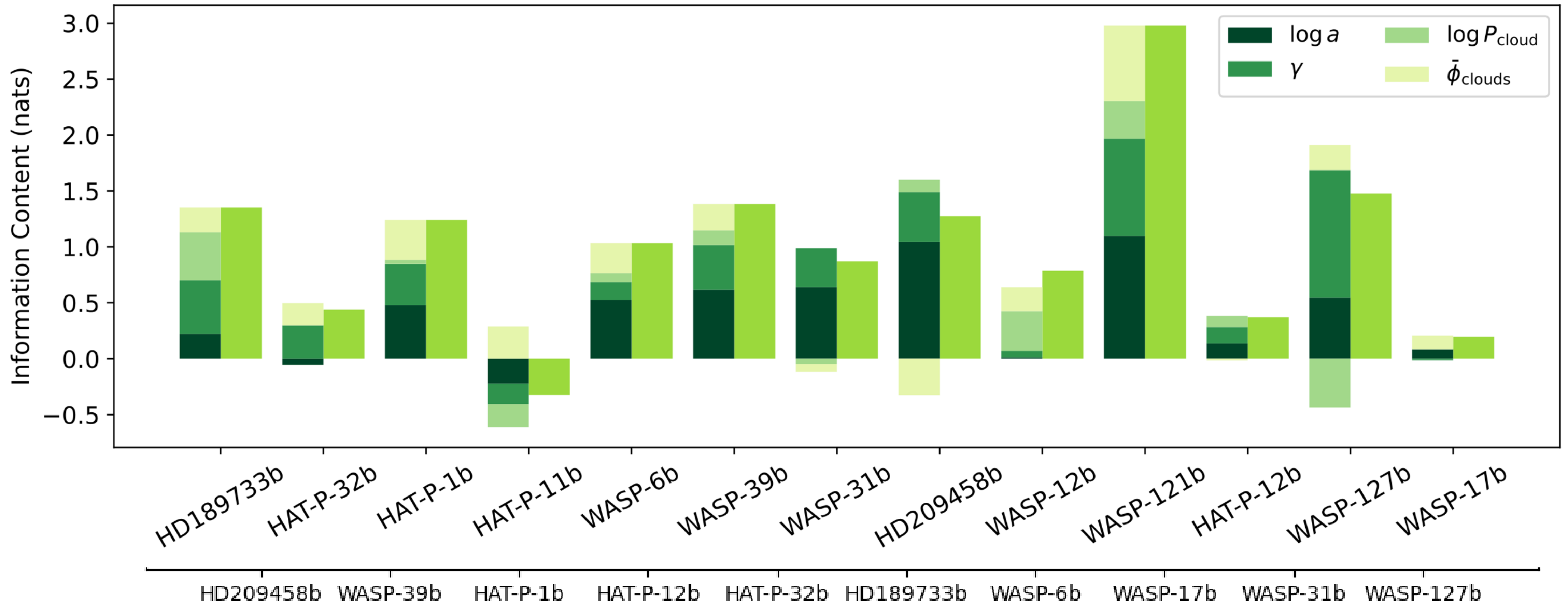

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Constraining the Clouds of HAT-P-26b

HUSTLE GO-17183 Hubble UVIS G280 + DREAMS GTO-1312 JWST NIRISS SOSS

Campbell+ (2026, in prep)

MacDonald+ (2026, in prep)

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Large Hubble Treasury Program: HUSTLE GO-17183

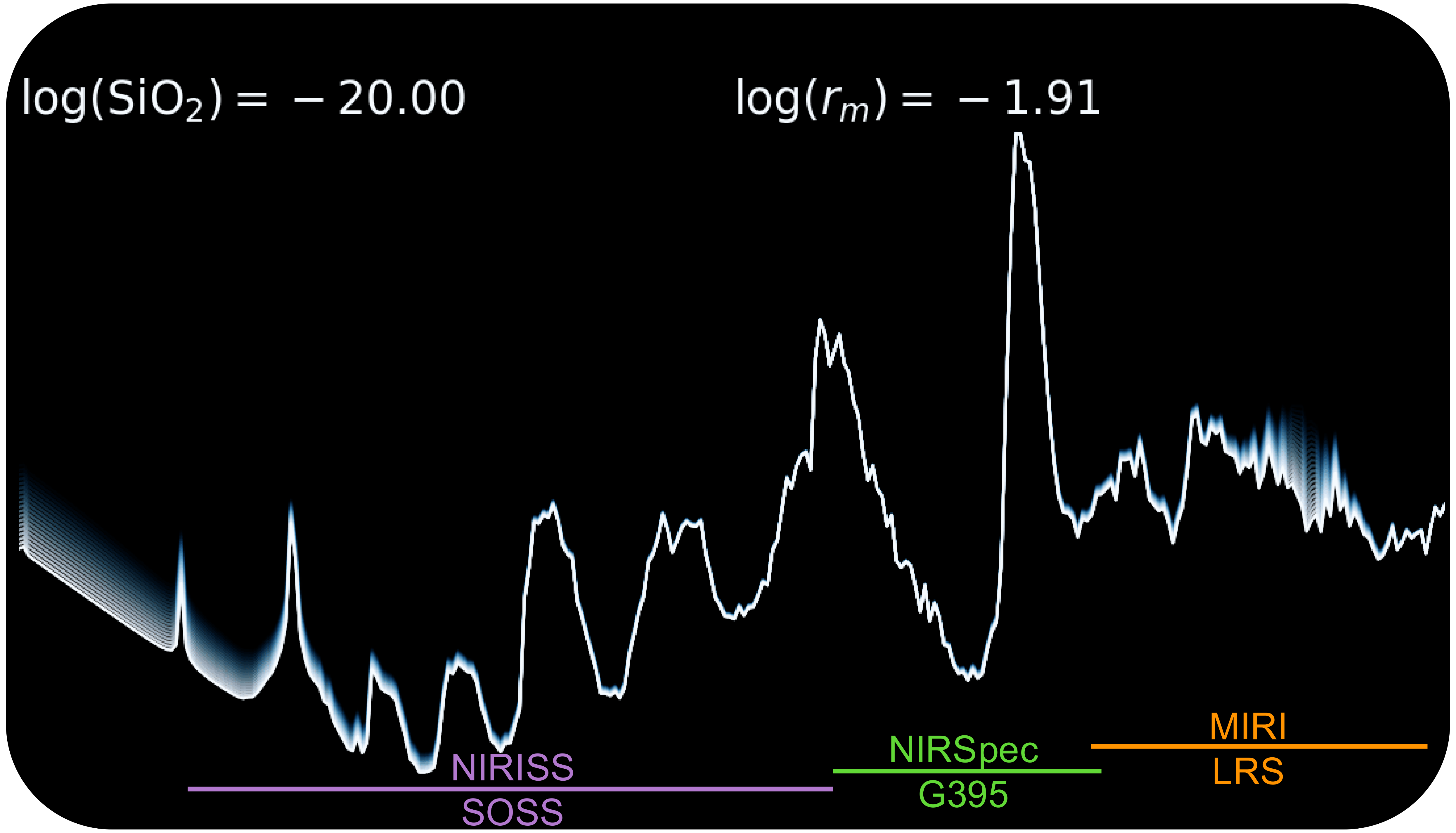
Evaluate the cloud sequence in the UV for 16 exoplanets

Mineral Clouds Change the Absorption in UV and Mid-IR

JWST MIRI is key to measuring the absorbing properties of cloud species

Specific mineral cloud condensate absorption impact the UV-optical and mid-IR, with minimal impact on the NIR!

Cloud particle sizes can impact the whole spectrum but cannot tell you what it is made from. The influence of clouds can be hidden in low abundance measurements.



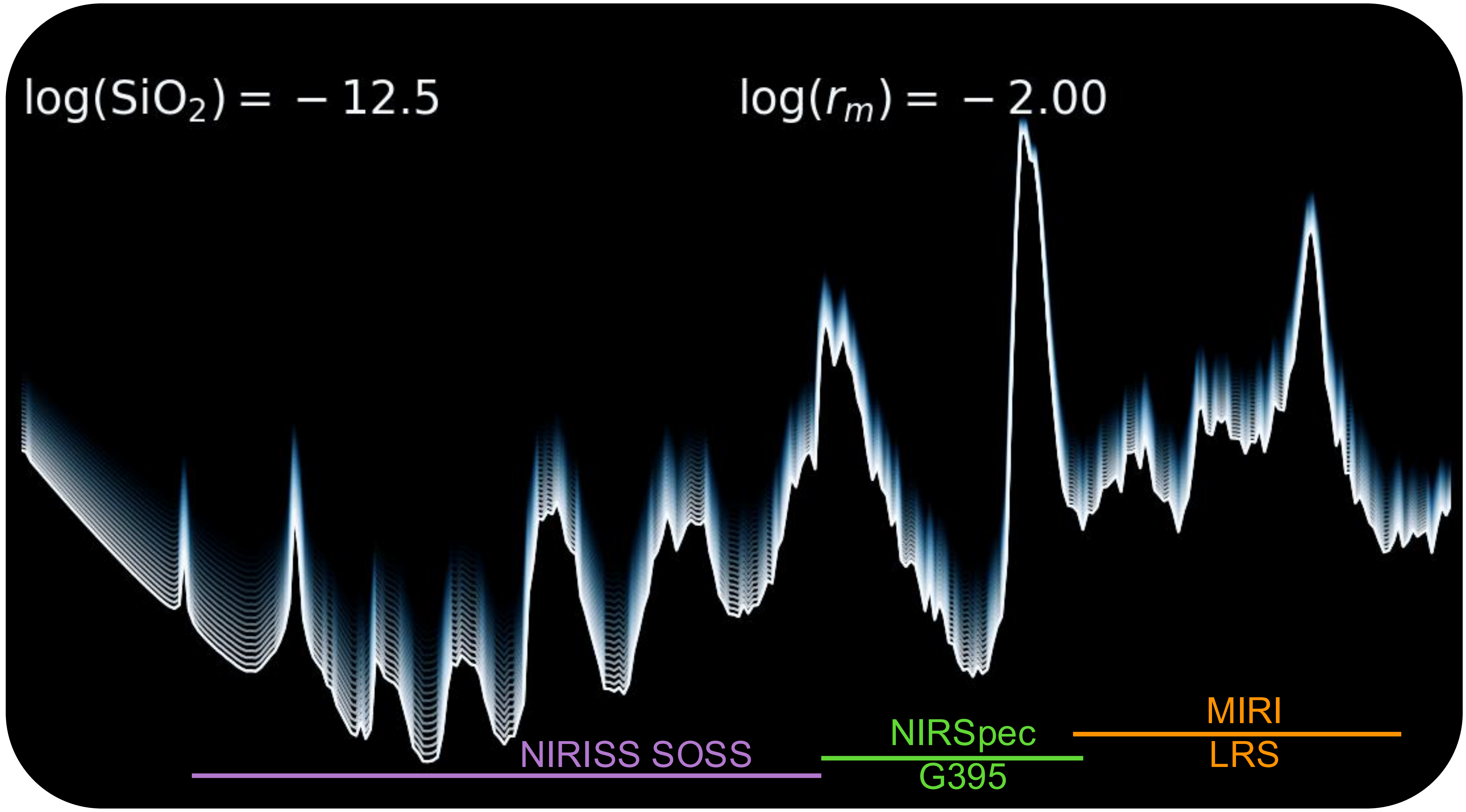
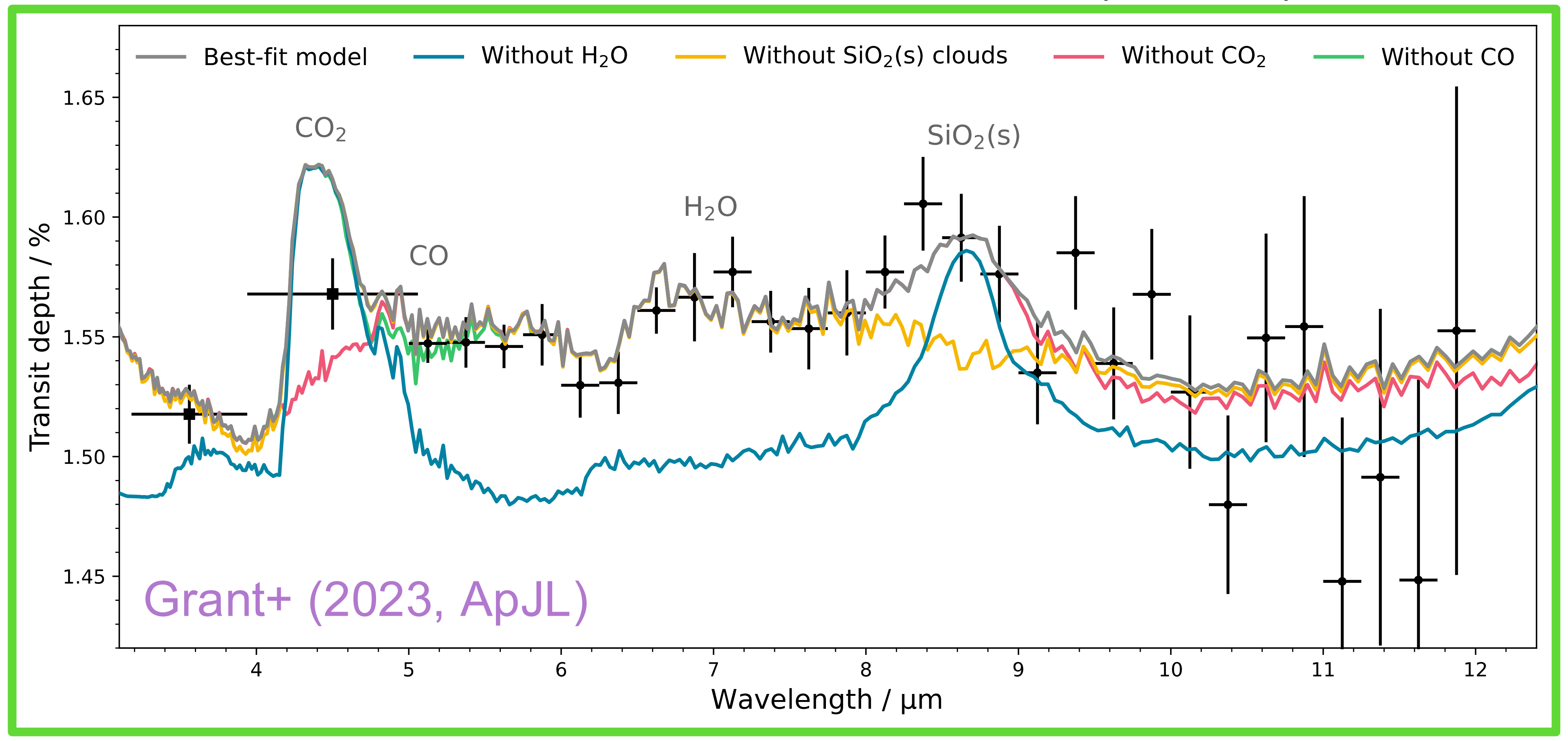


Image credit: D. Grant, using POSEIDON (MacDonald 2023) with modification by E. Mullens (Mullens+ in prep)

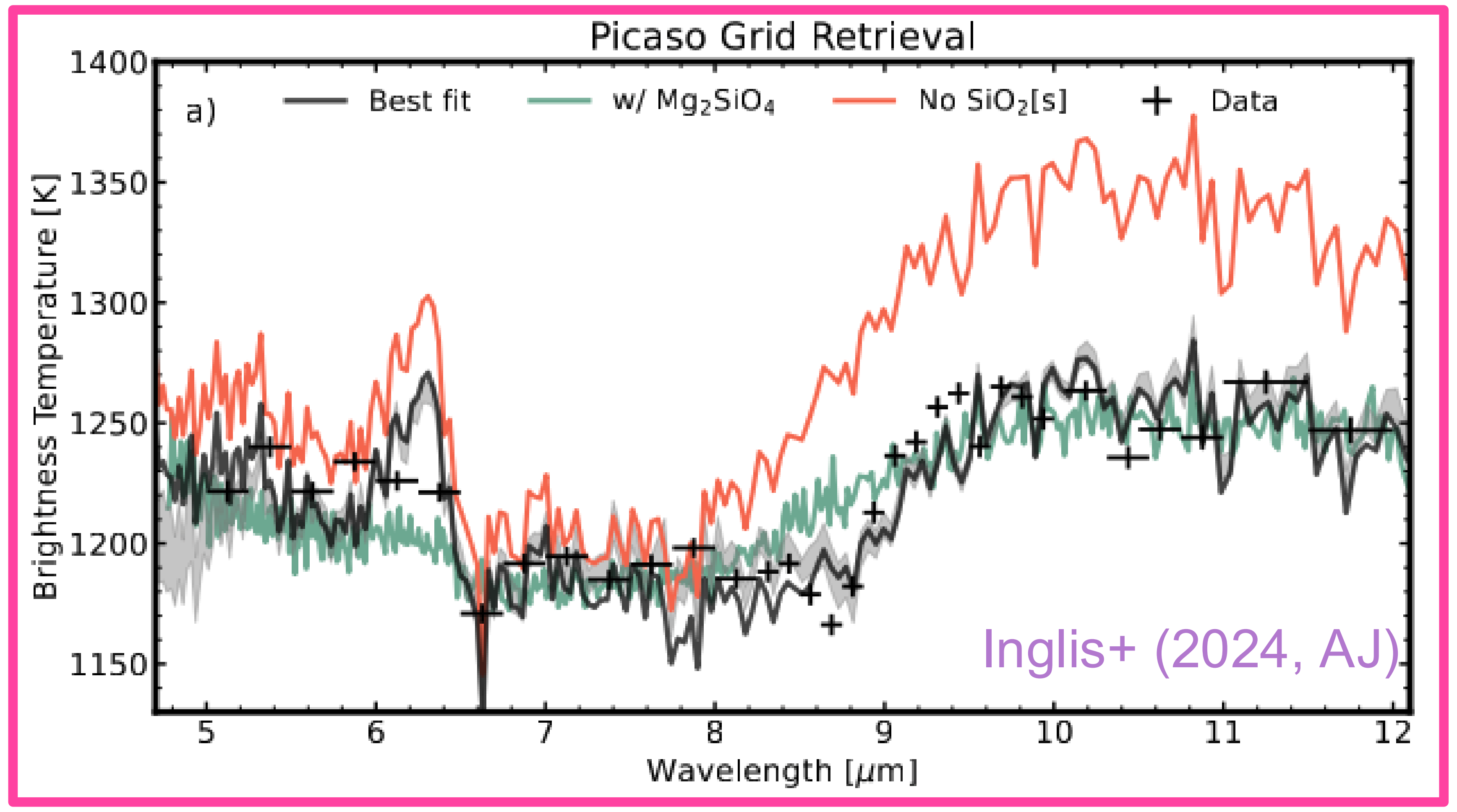
Reservoirs of Oxygen Locked up in Clouds

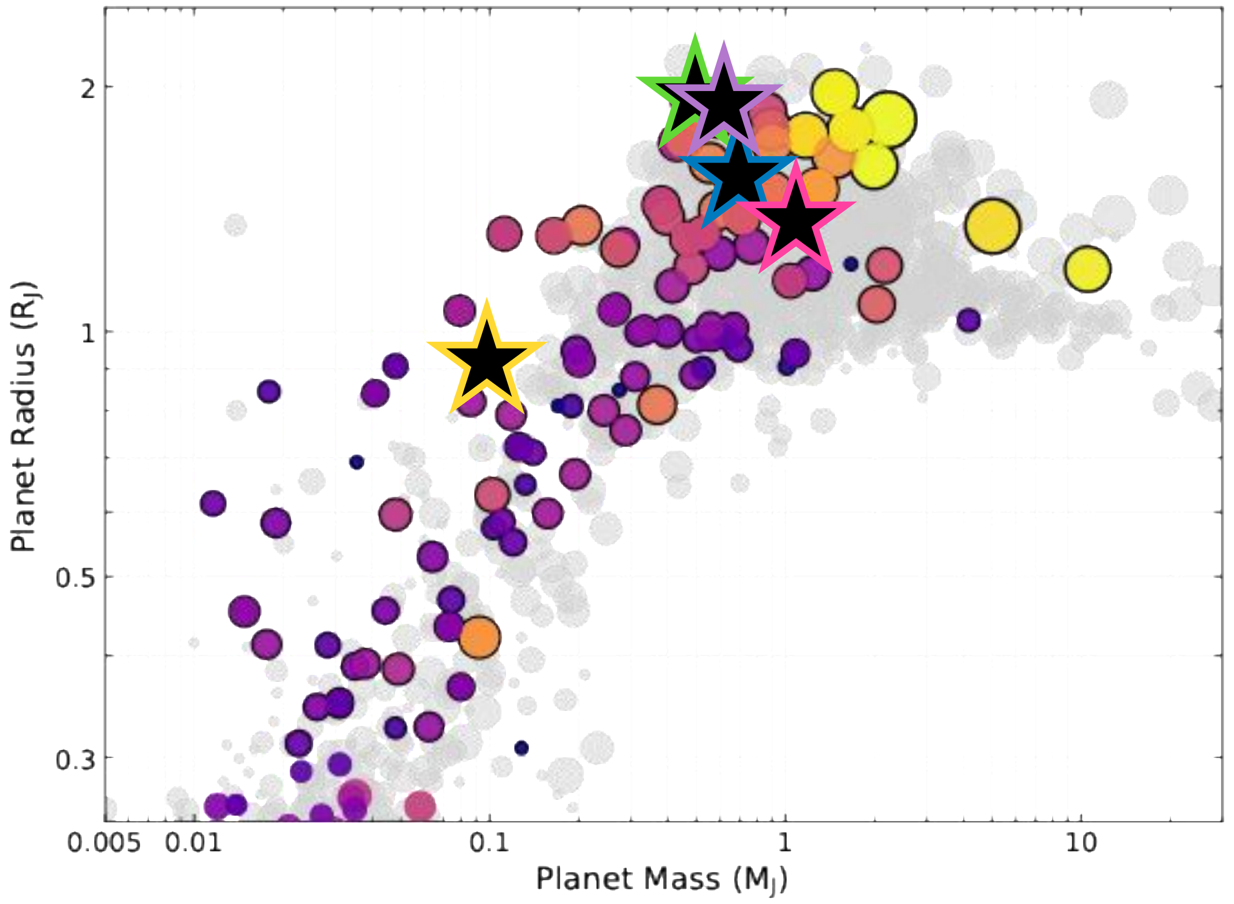
Identifying the specific cloud species with MIRI

SiO2 in WASP-17b transmission (~1750K)

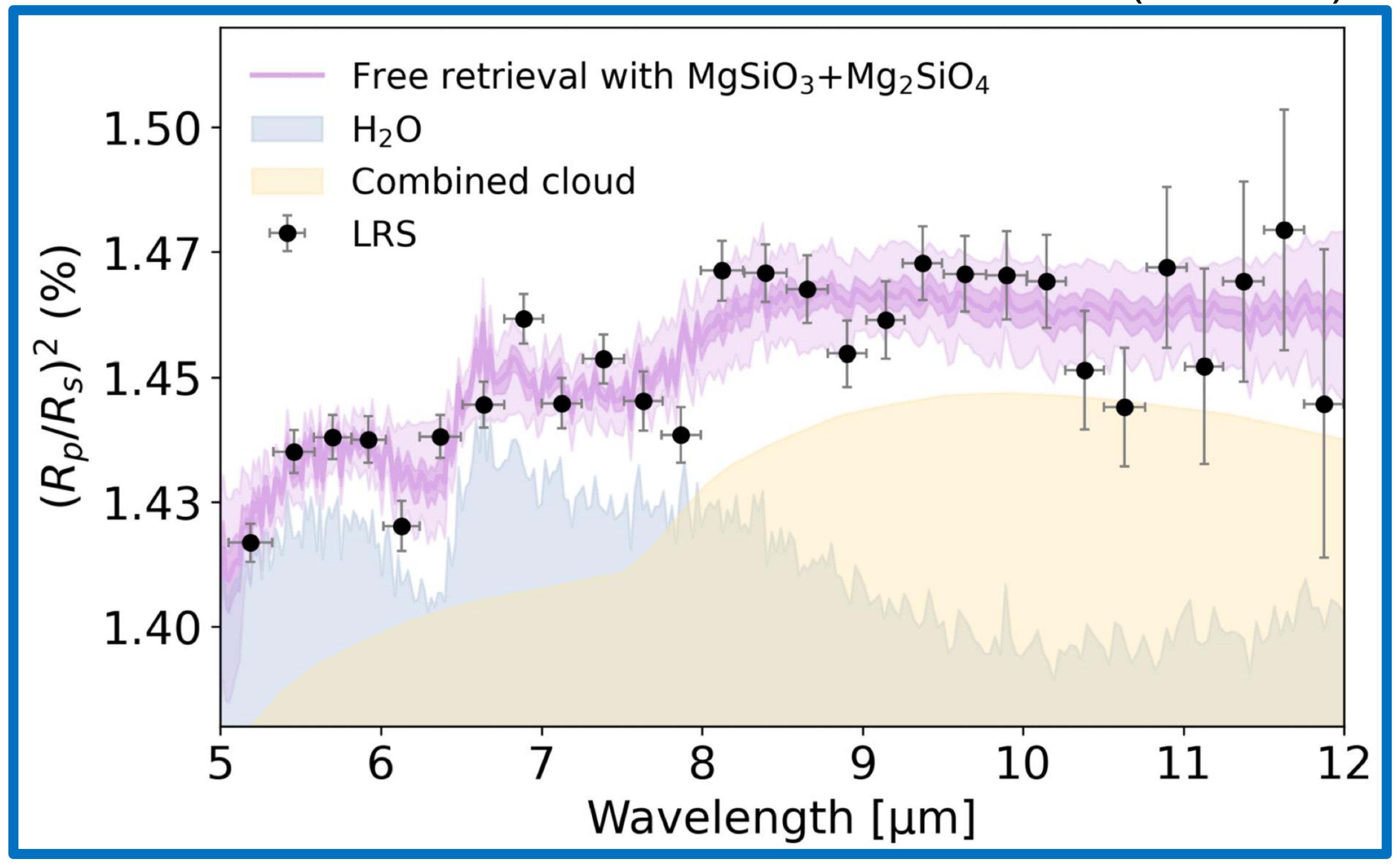


SiO2 in HD 189733b emission (~1000-1300K)



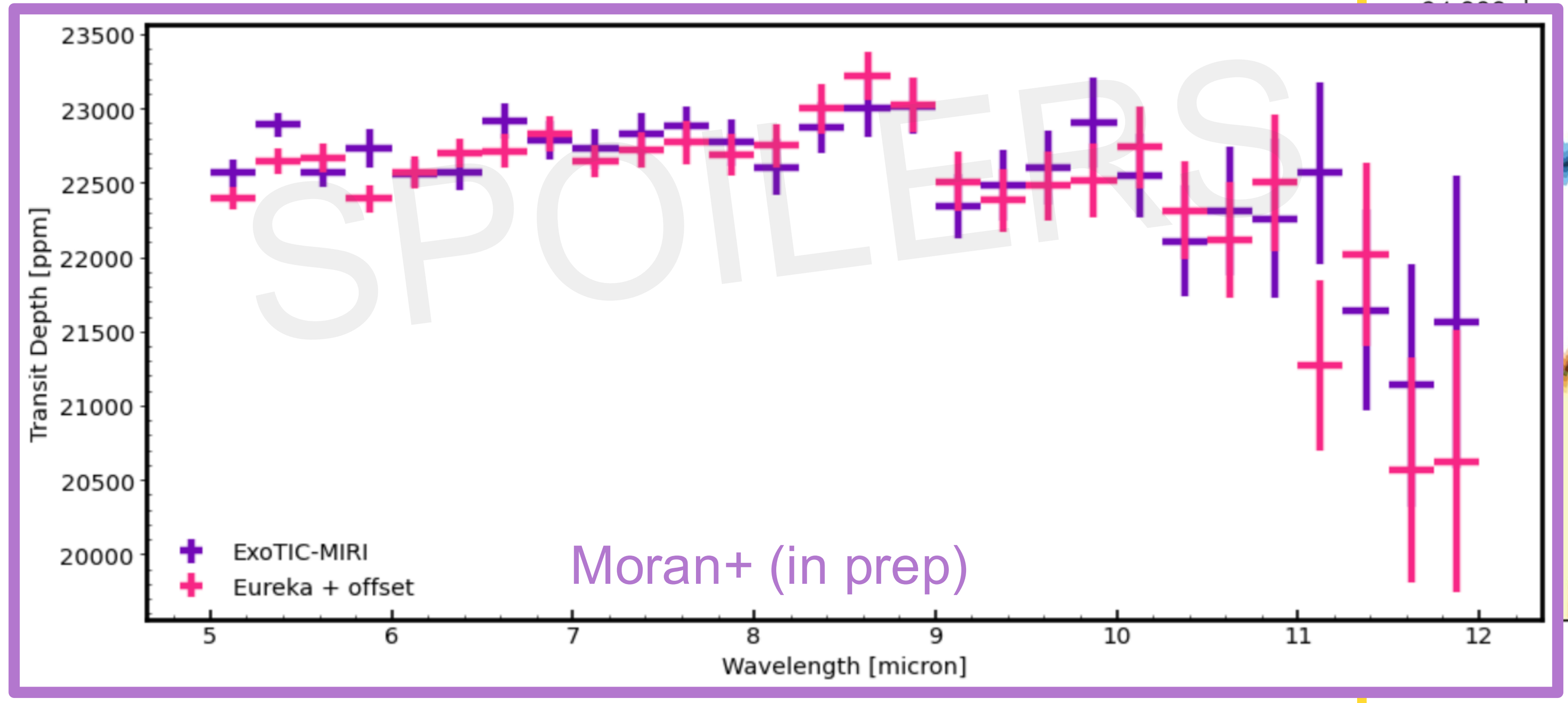


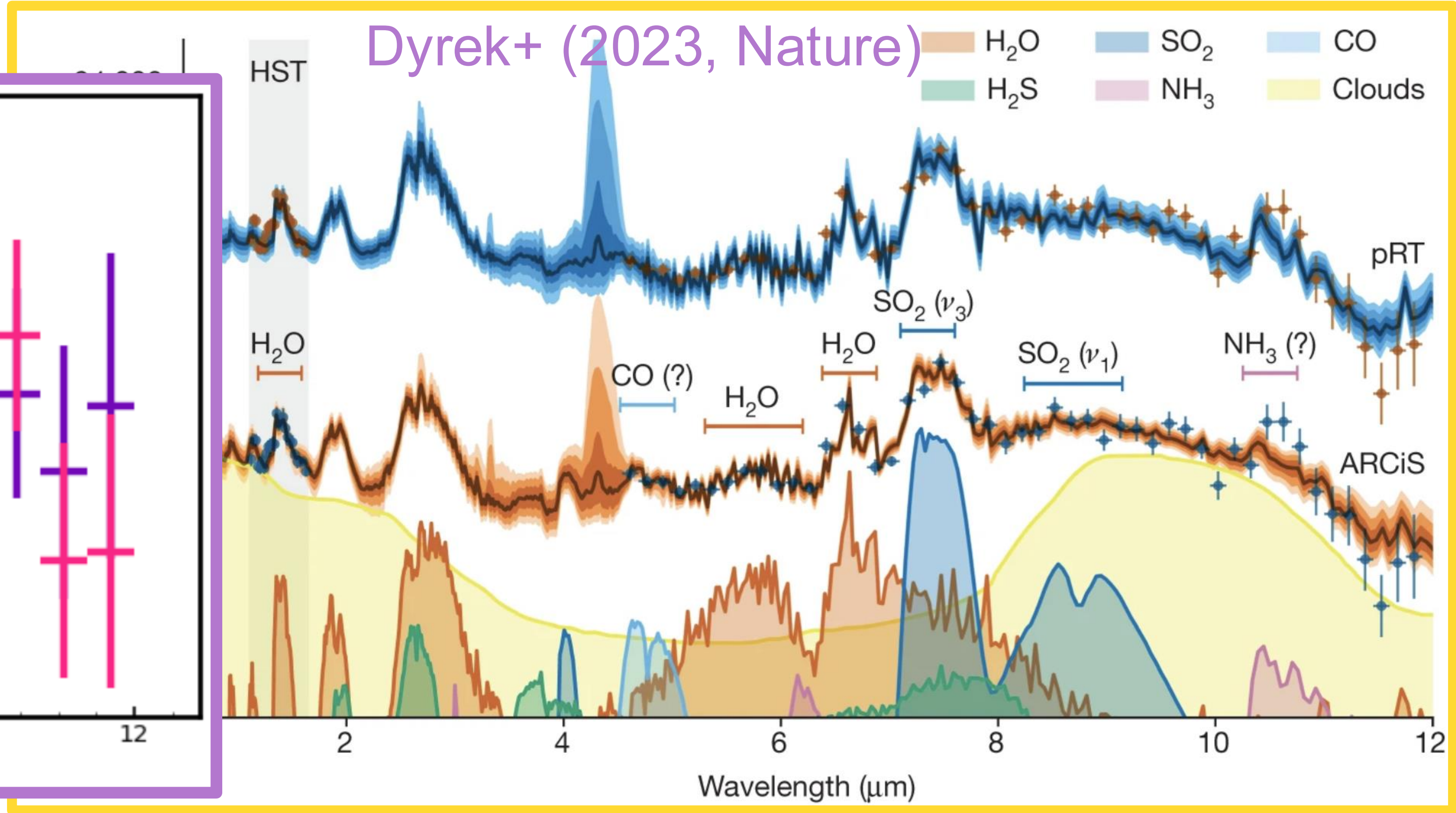
Mixed silicates in HD 209458b transmission (~1300K)



Mixed silicates in WASP-107b transmission (~600-900K)

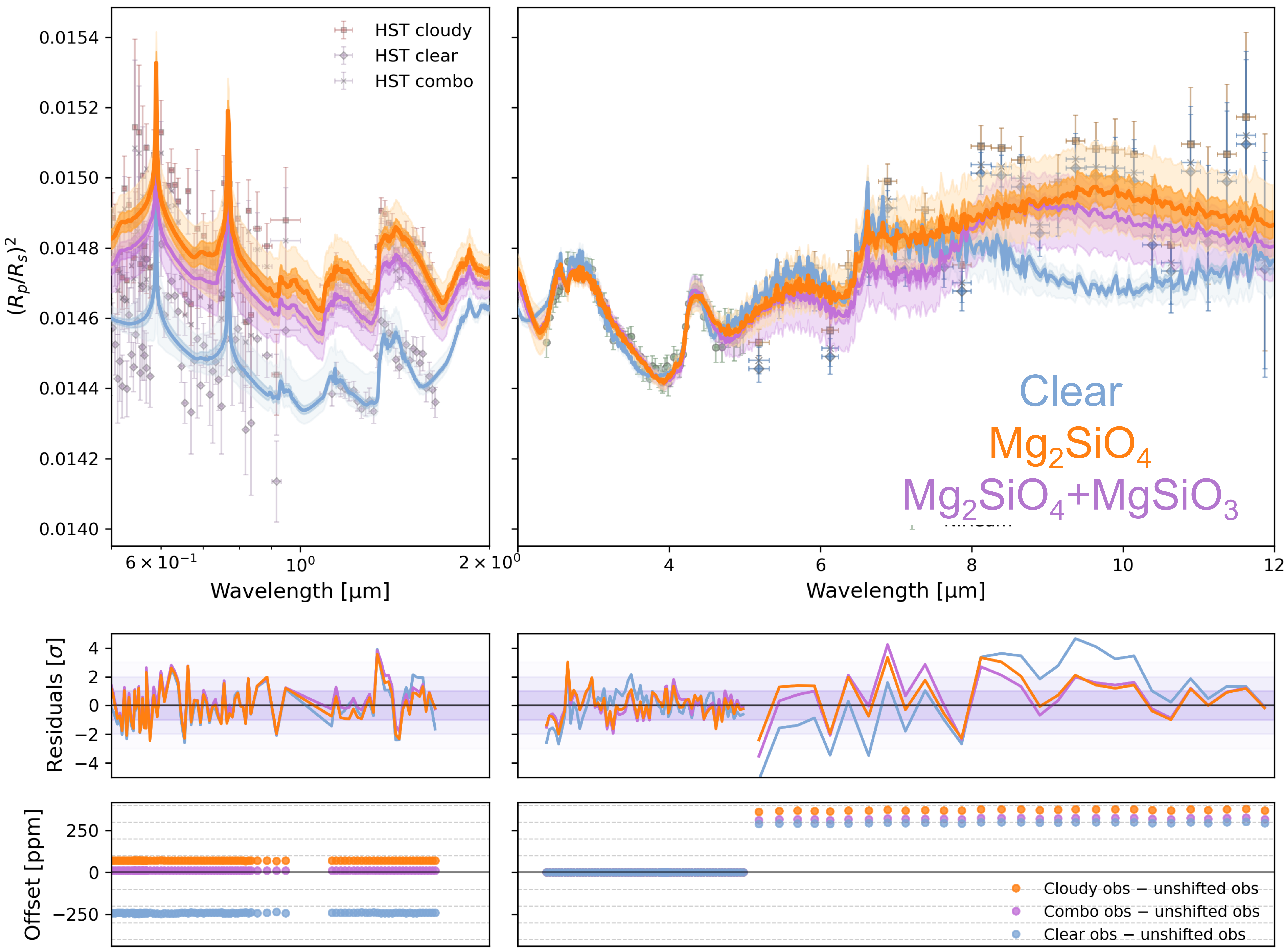
SiO2 in HAT-P-32b transmission (1700K)

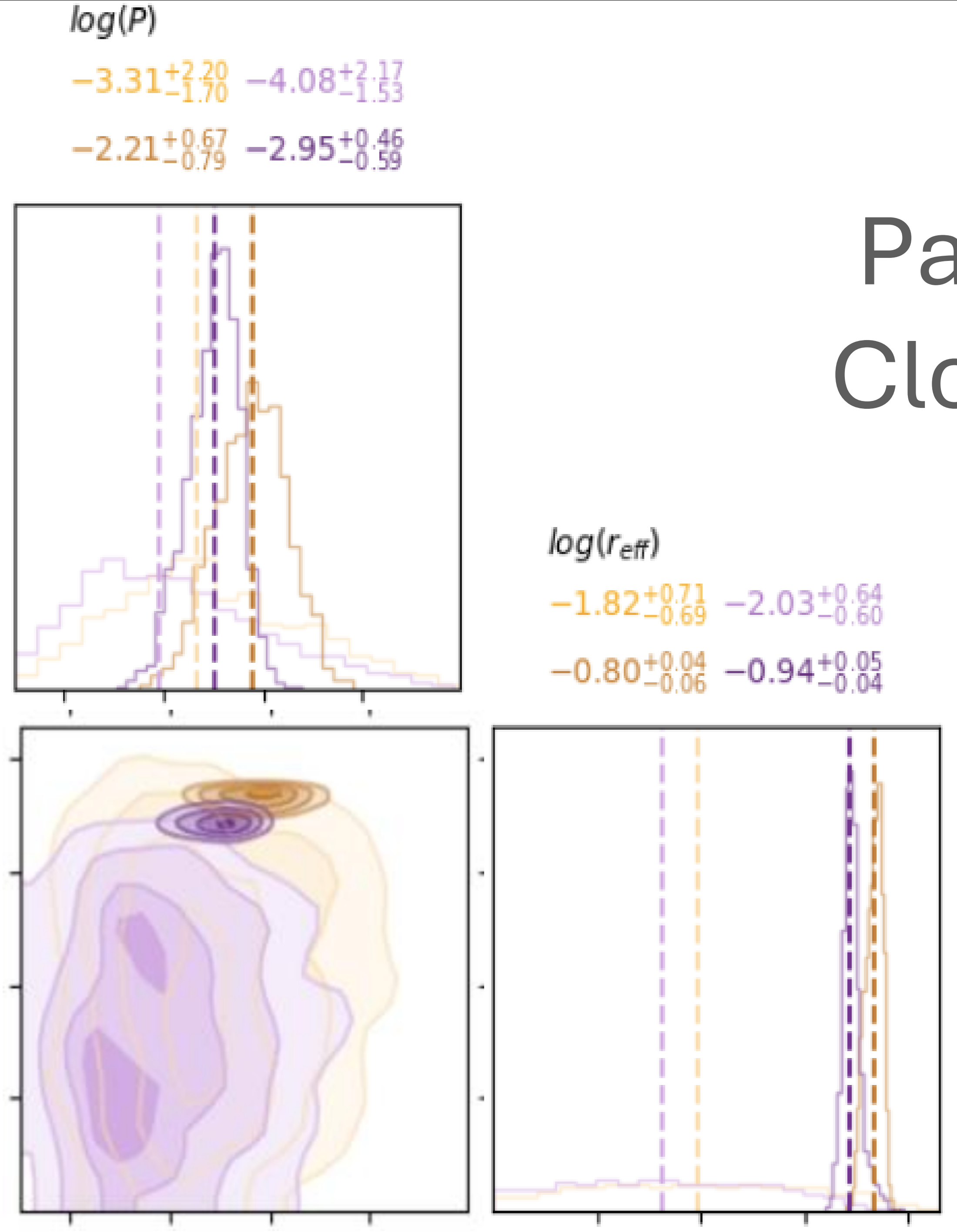




Together Hubble & JWST Unlock Clouds

JWST Identifies the Species, Hubble Constrains the Conditions

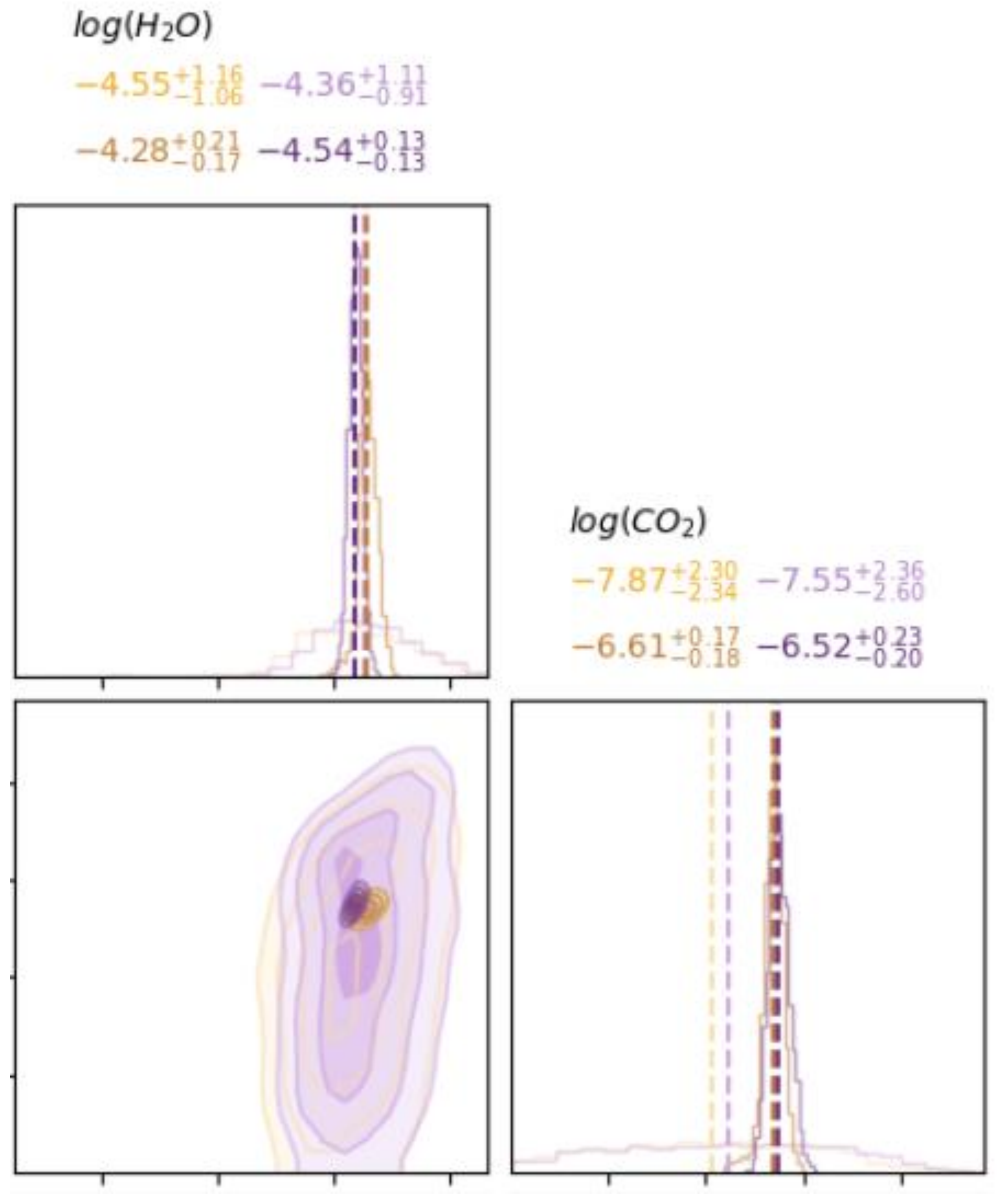




Particle size ~0.1 μm
Cloud pressure ~1–10 mbar

Chubb+ (2026, AJ)

Better molecular constraints: H_2O, CO_2



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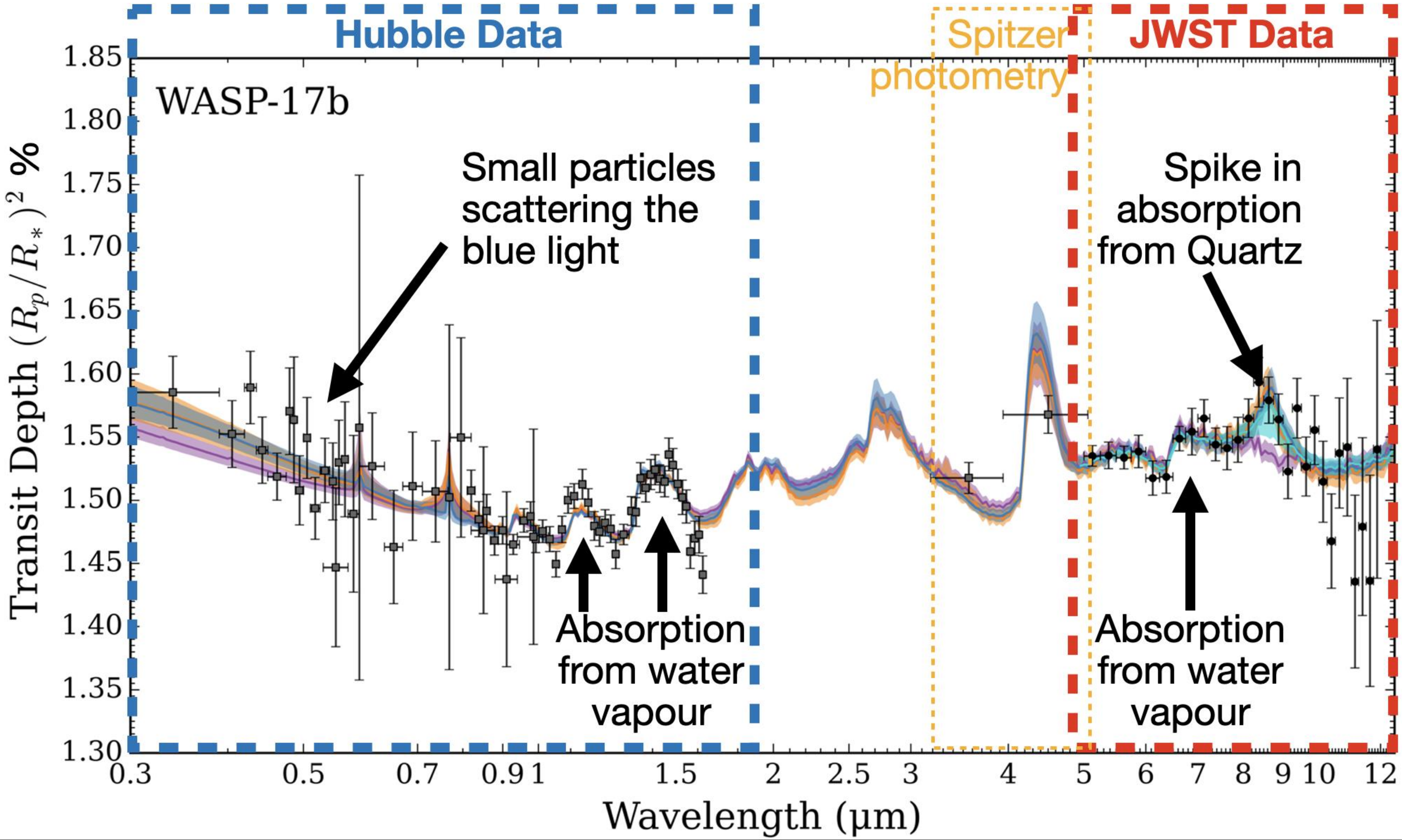

Retrievals and forward models show clouds made of 10 nm quartz crystals at ~0.1mbar pressures

Grant+ (2023, ApJL)

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JWST-Telescope Science Team: DREAMS

Deep Reconnaissance of Exoplanet Atmosphere through Multi-instrument Spectroscopy

- Transit and Eclipse Spectroscopy of a Hot Jupiter (74.28 hours)
  - Transmission 0.6 - 12 μm – 3 transits
  - Emission 0.6 - 12 μm – 3 eclipses

1 Program, 6 observations,11+ papers, & 2 spin off Programs

Transit Transmission

MIRI LRS transmission – **Grant+ (2023, ApJL)**
NIRISS SOSS transmission – **Louie+ (2024, AJ)**
Full transmission (inc. NIRSpec G395H) – Lewis+ (in prep)
Transmission strings mapping (all λ) – Alderson + (in review)

Eclipse Emission

NIRISS SOSS emission – **Gressier+ (2024, AJ)**
MIRI LRS emission – **Valentine+ (2024, AJ)**
Full emission (inc. NIRSpec G395H) – Wakeford+ (in prep)
Eclipse mapping (all λ) – Valentine+ (in prep)

Nightside emission with PIE – **Lustig-Yaeger+ (2025, ApJL)**
The Refined System Parameters for WASP-17b & HAT-P-26b – Valenti+ (in prep)
ExoTiC-CLEAN: Spectral contaminant removal with U-Net – Stewart+ (in prep)
High Resolution CO detections in transmission and emission – Glidden+ (in prep)

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Elijah Mullens
Sukrit Ranjan
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Spin off Programs

JWST: It's Polymorphin' Time: Solving the Quartz Quandary of WASP-17b – Moran & Mullens GO-8309

HST: HUSTLE WFC3/UVIS G280 Spectrum of WASP-17b – Wakeford GO-17183

Challenges with Slitless Spectroscopy

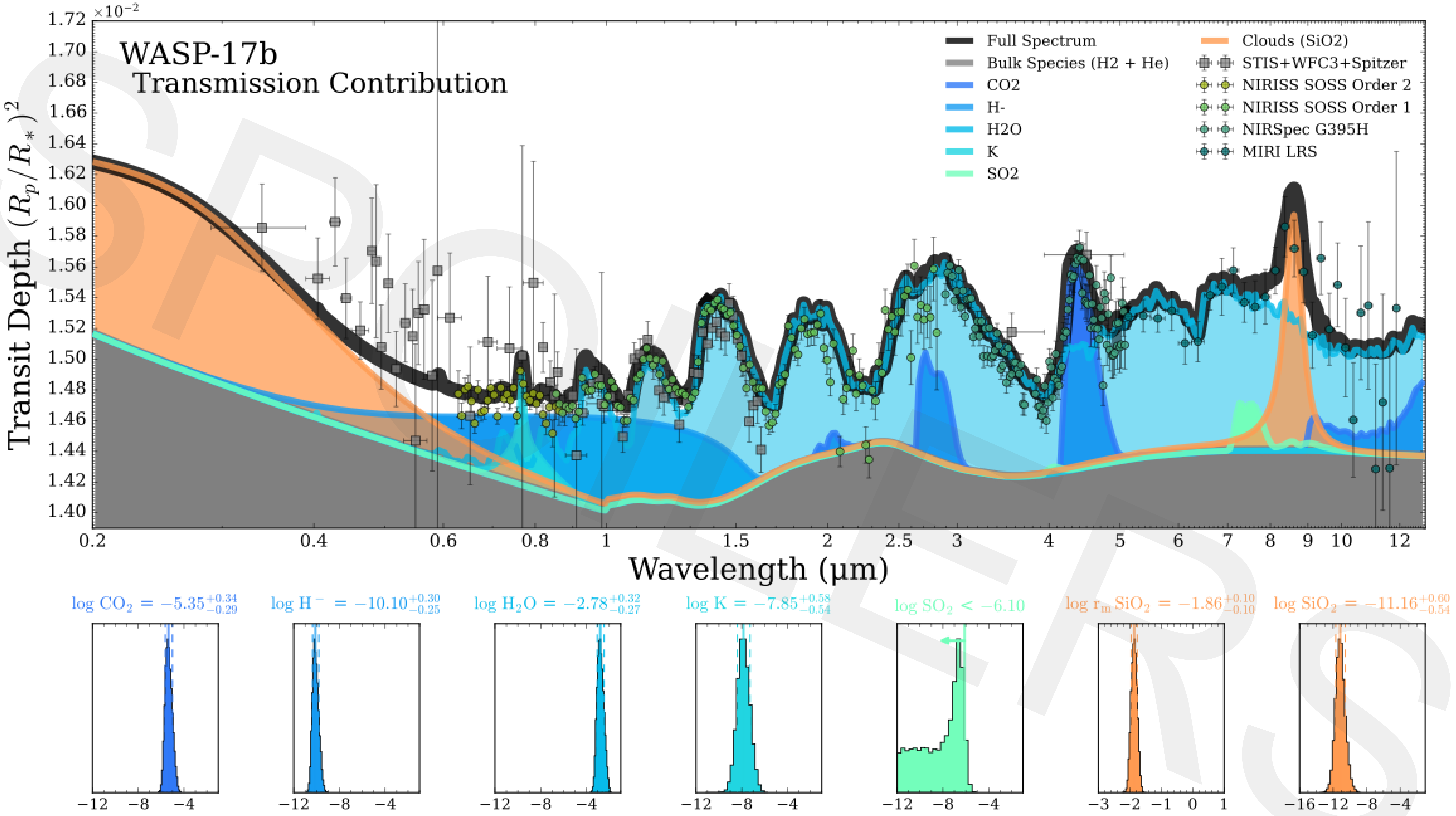
JWST SOSS is most affected by nearby stars contaminating spectral traces

Using an image segmentation network we have trained a model to clean the contaminating stars – ExoTiC-CLEAN – labelling, extracting and analysing the images to accurately remove the flux from contamination sources.

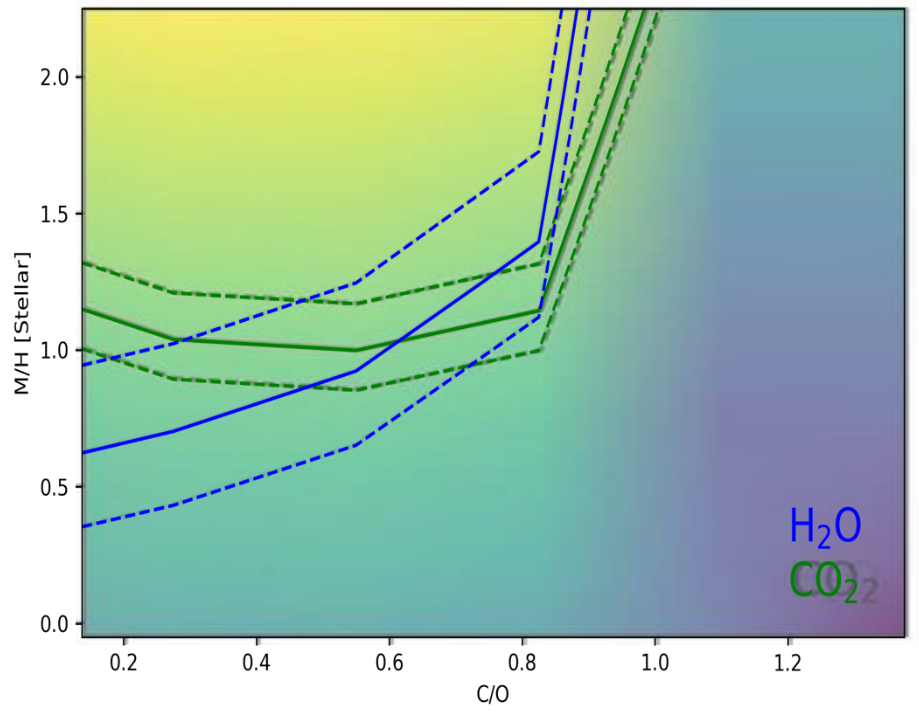
Stewart, Wakeford+ (in prep)

WASP-17b: The Full Transmission Spectrum

Strong H_2O, CO_2, super-solar [M/H] [Lewis & Mullens+ 2025, in prep]

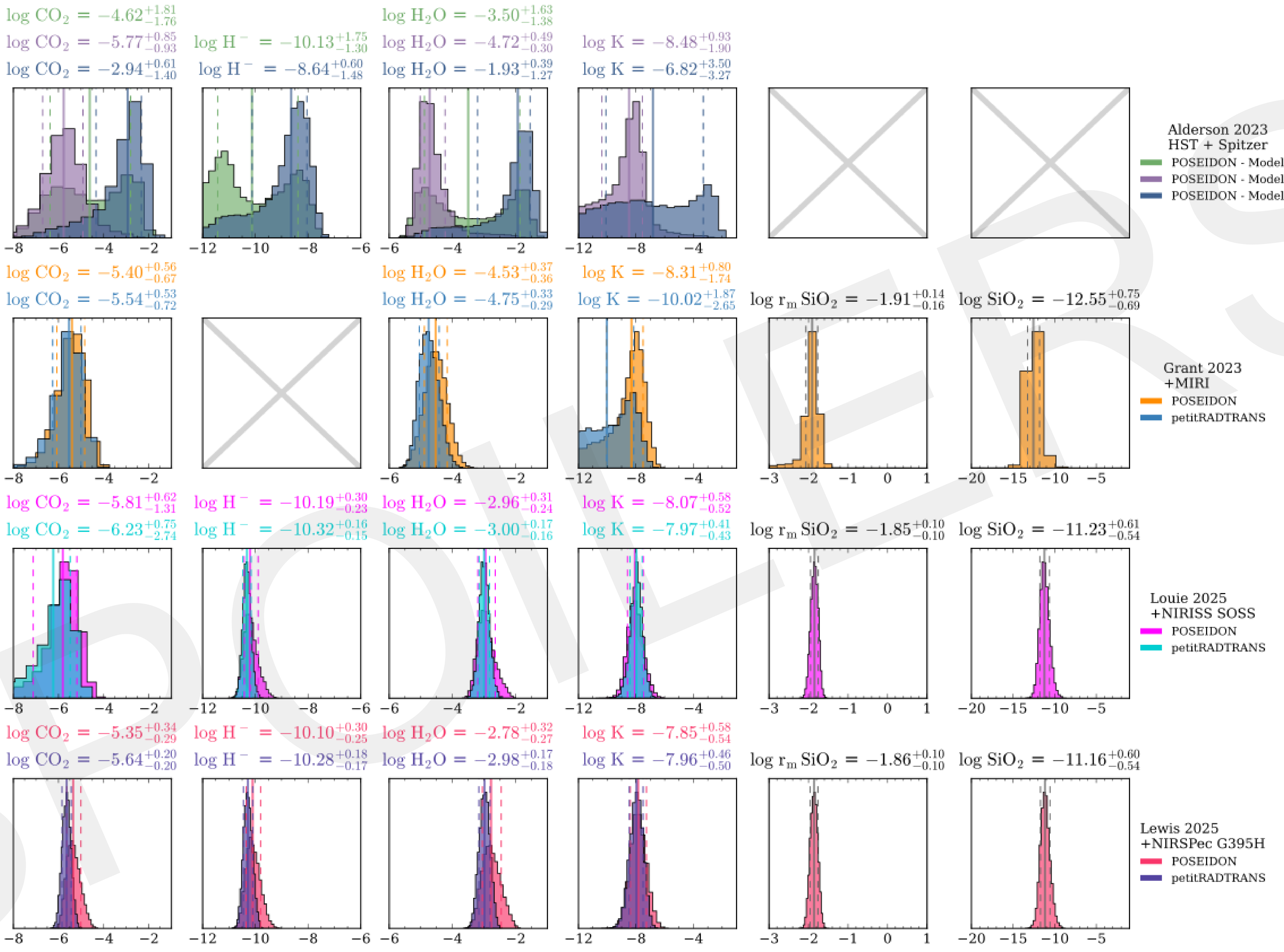


Strong detection of scattering+$SiO_{2[s]}$, H_2O, CO_2, and H-. Super-solar [M/H]



WASP-17b: The Full Transmission Spectrum

Strong H_2O, CO_2, super-solar [M/H] [Lewis & Mullens+ 2025, in prep]

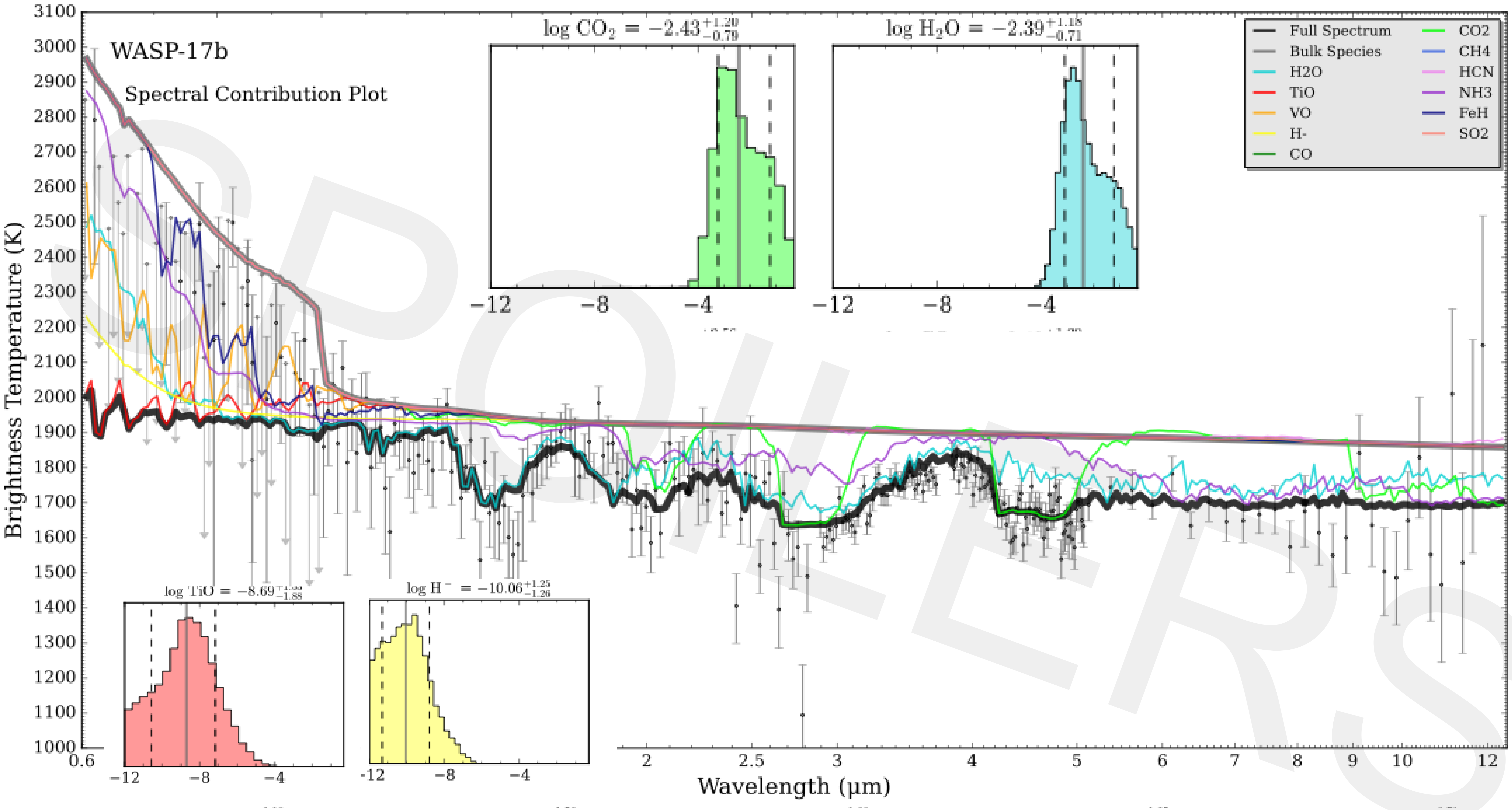


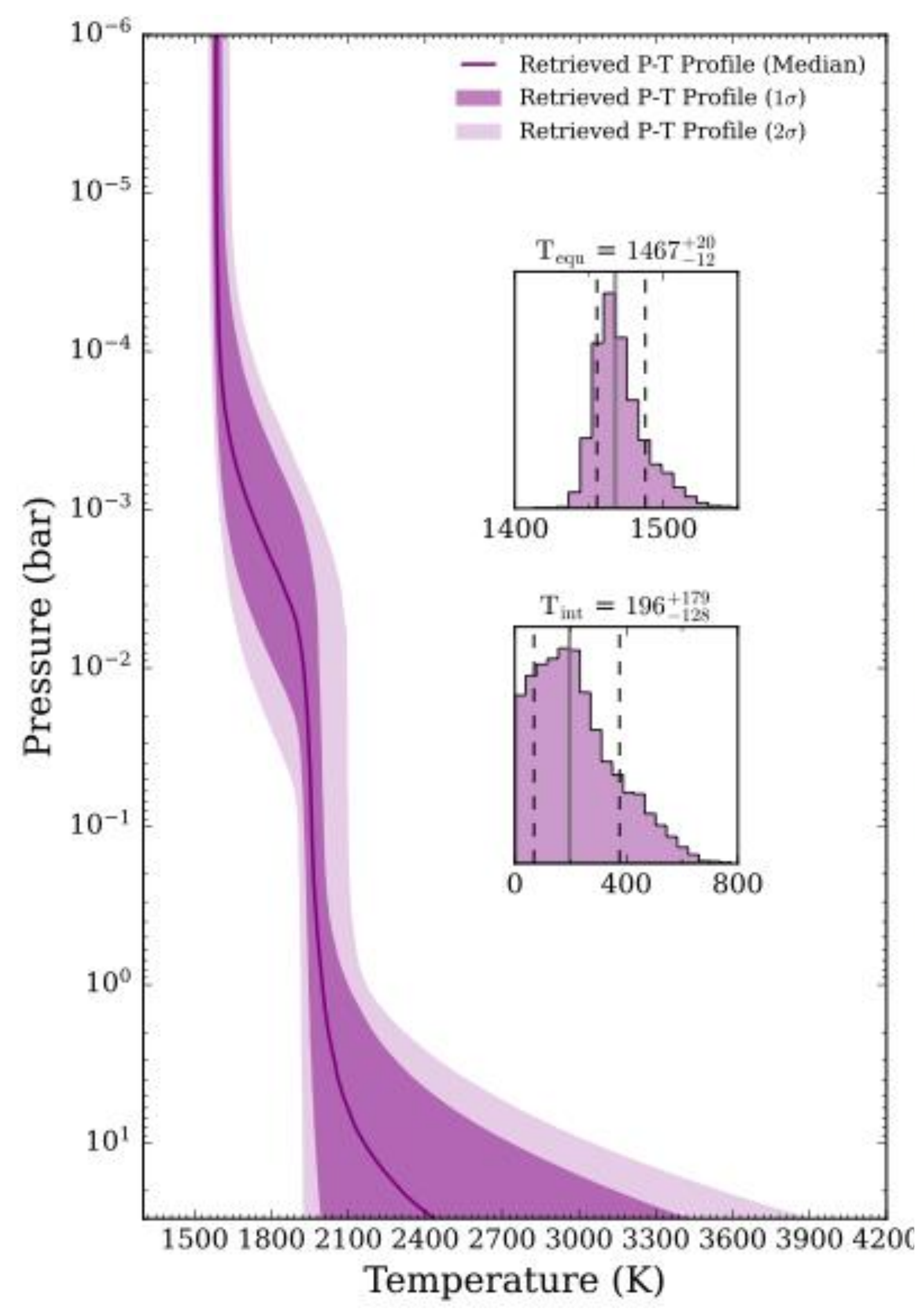
The evolution of information on WASP-17b from its atmospheric transmission

This demonstrates the need for short and long wavelengths to constrain clouds but near-IR to constrain the chemical abundances

WASP-17b: The Full Emission Spectrum

Super-Solar [M/H], H_2O, CO_2 [Wakeford & Challener,+ 2025, in prep]





No evidence of clouds on the dayside but abundance H2O and CO2

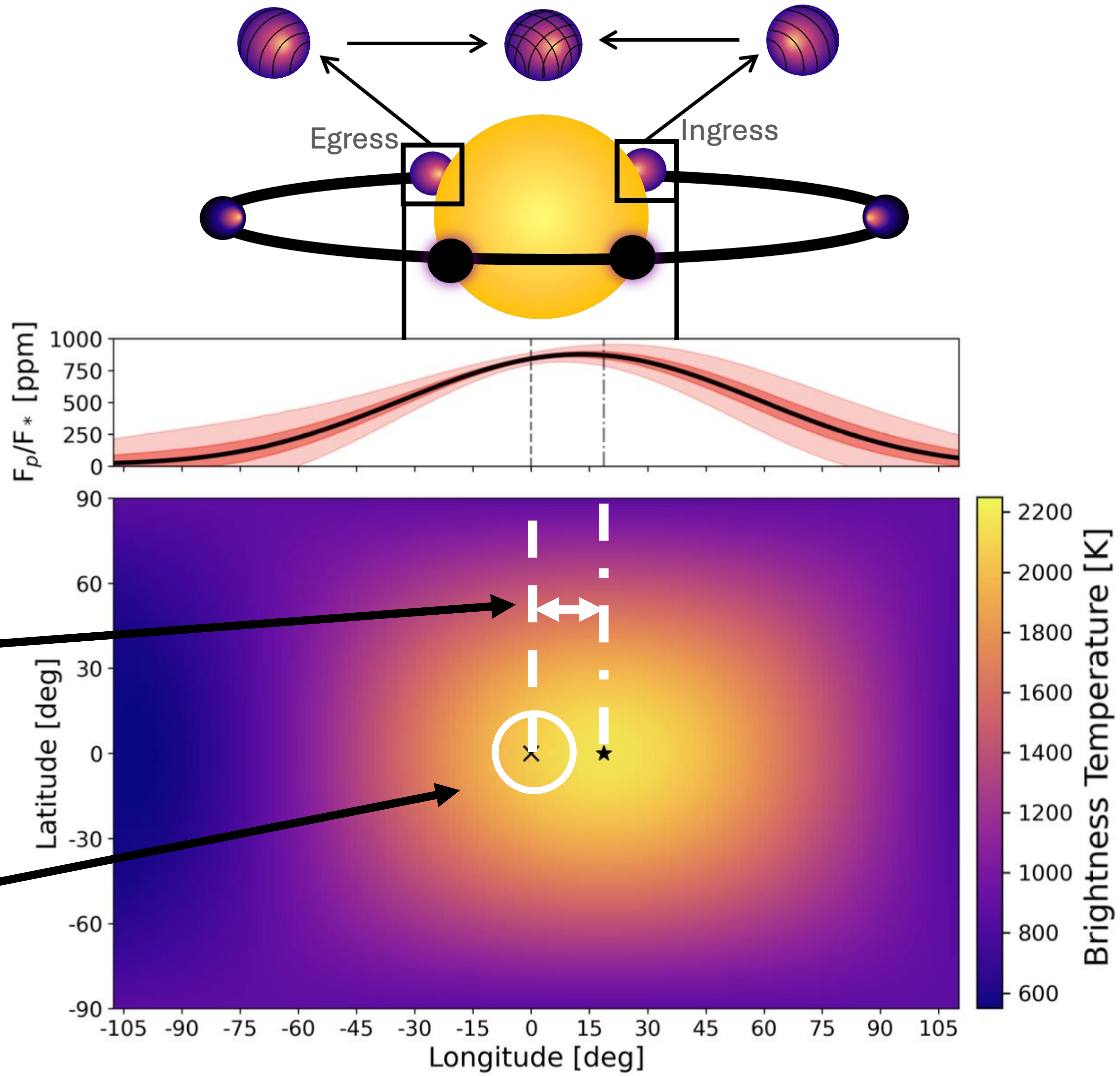
WASP-17b: MIRI Eclipse Mapping

Strong Day-Night Contrast and a shifted hotspot [Valentine+ 2024, AJ]

Using Eclipse Mapping we measure the hotspot shift to 18.7° and a day-to-night temperature contrast of 1000K

Shift in the hottest point in the atmosphere

Substellar point



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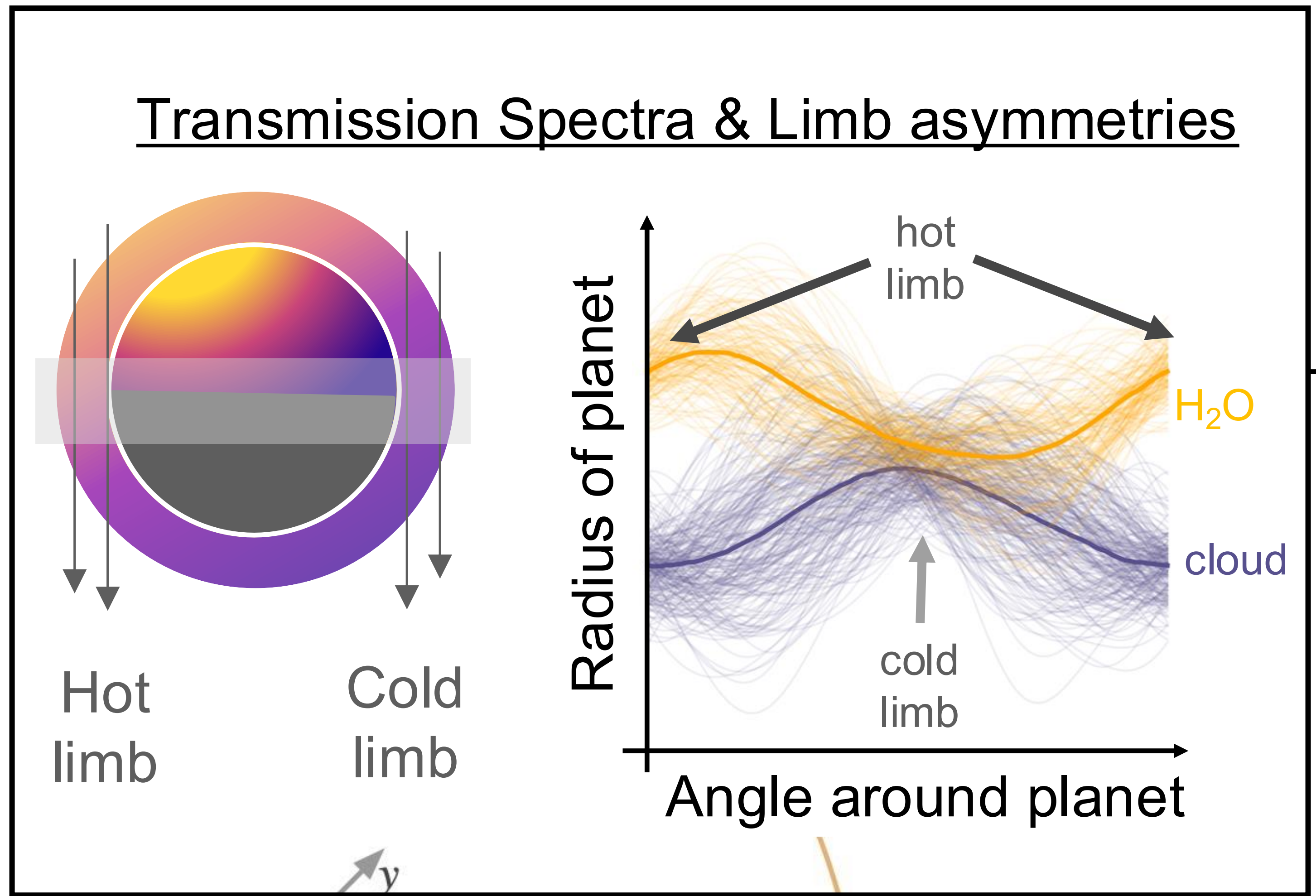
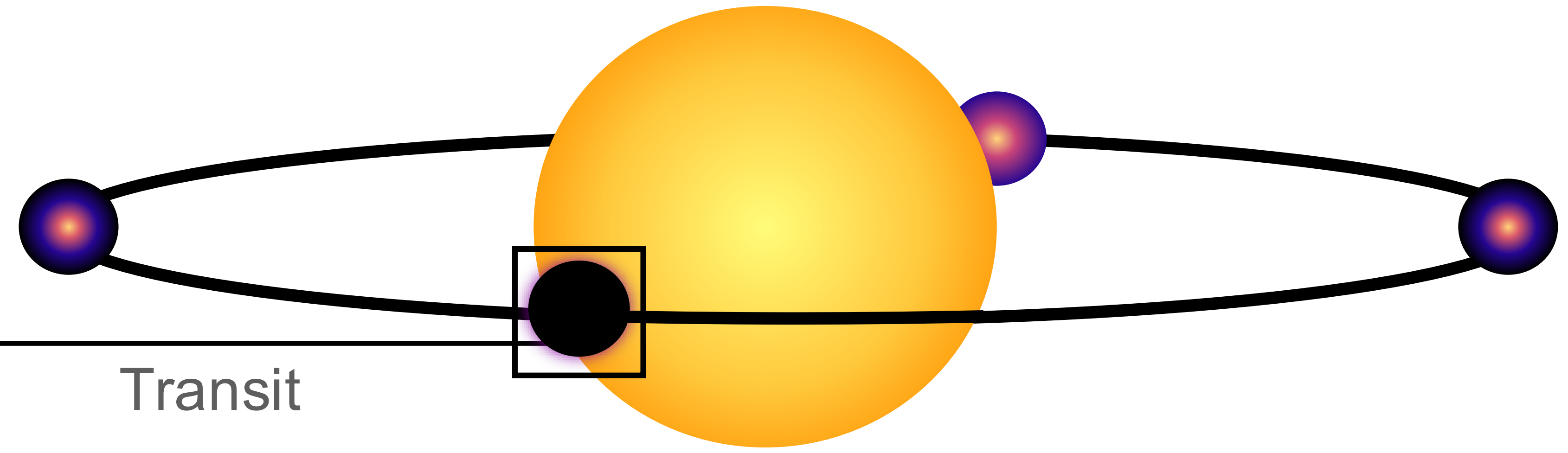
WASP-17b: Multi-Wavelength Eclipse Mapping

JWST-TST DREAMS 3D Eclipse Map [Valentine+ in prep]

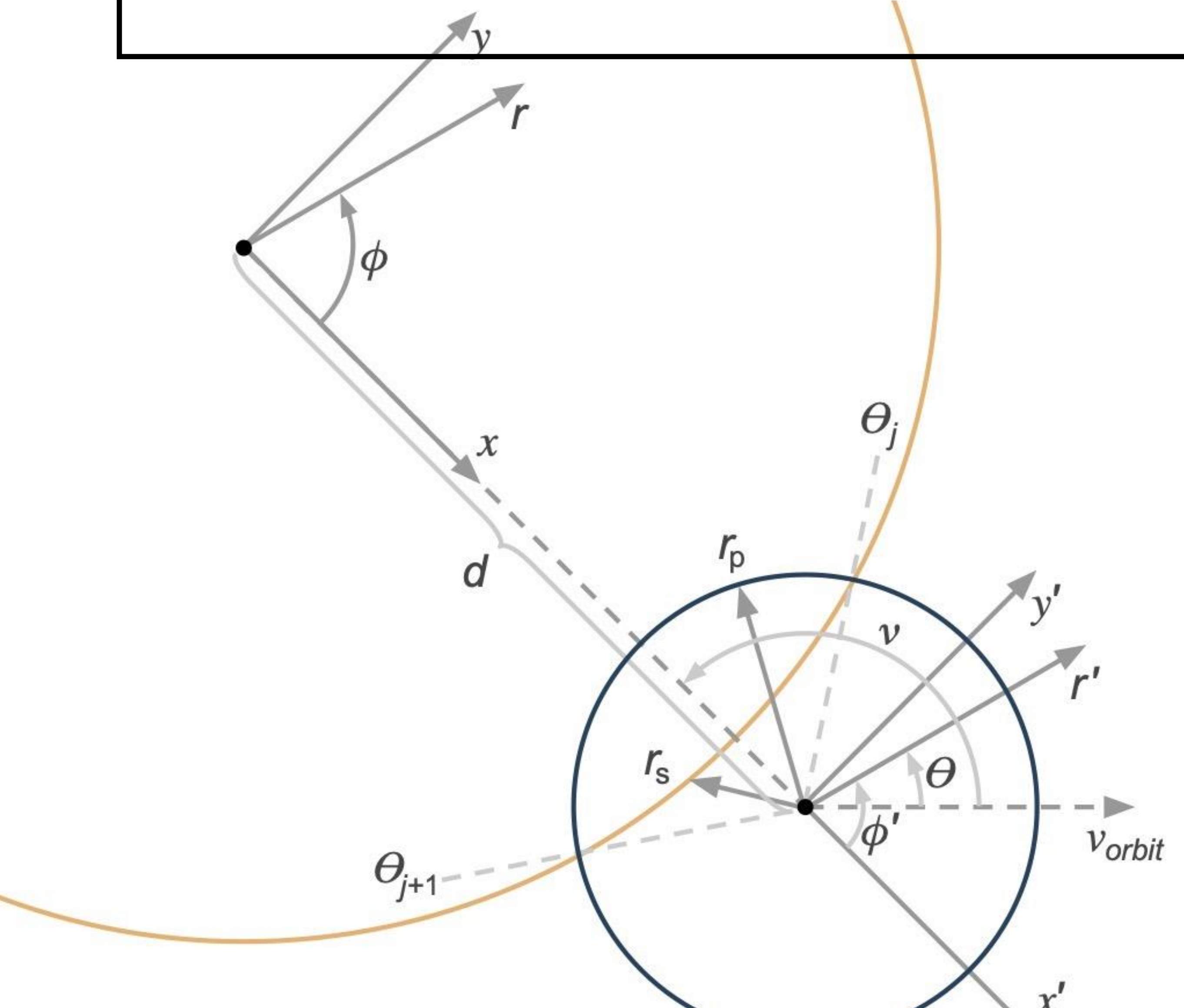
Transiting Exoplanet Atmospheres – in 2D/3D

Measuring the changing shape of the transmitting limb with Harmonica

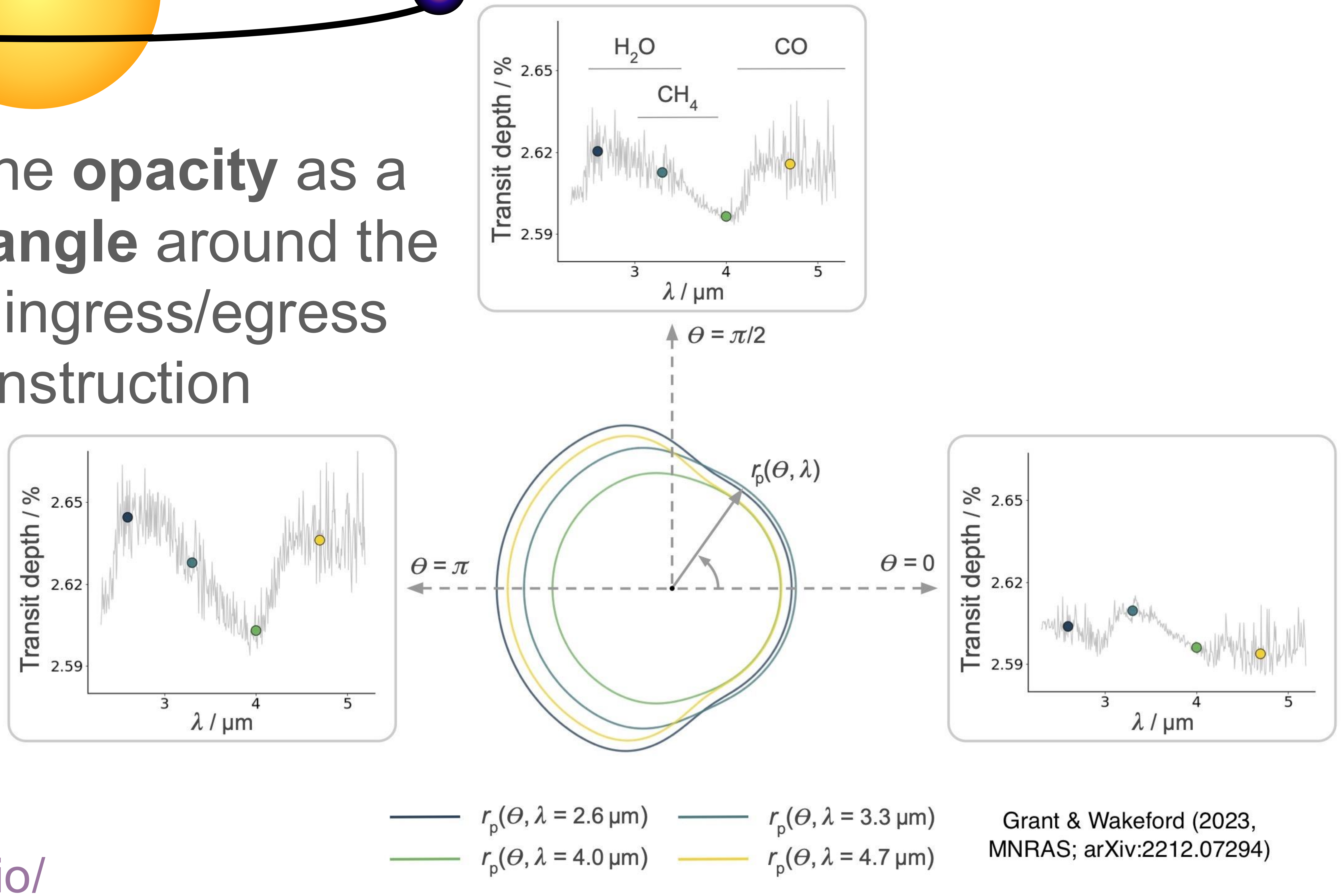




Measure the **opacity** as a function of **angle** around the limb from ingress/egress reconstruction



Grant & Wakeford (2023, MNRAS)
harmonica.readthedocs.io/



Grant & Wakeford (2023, MNRAS; arXiv:2212.07294)

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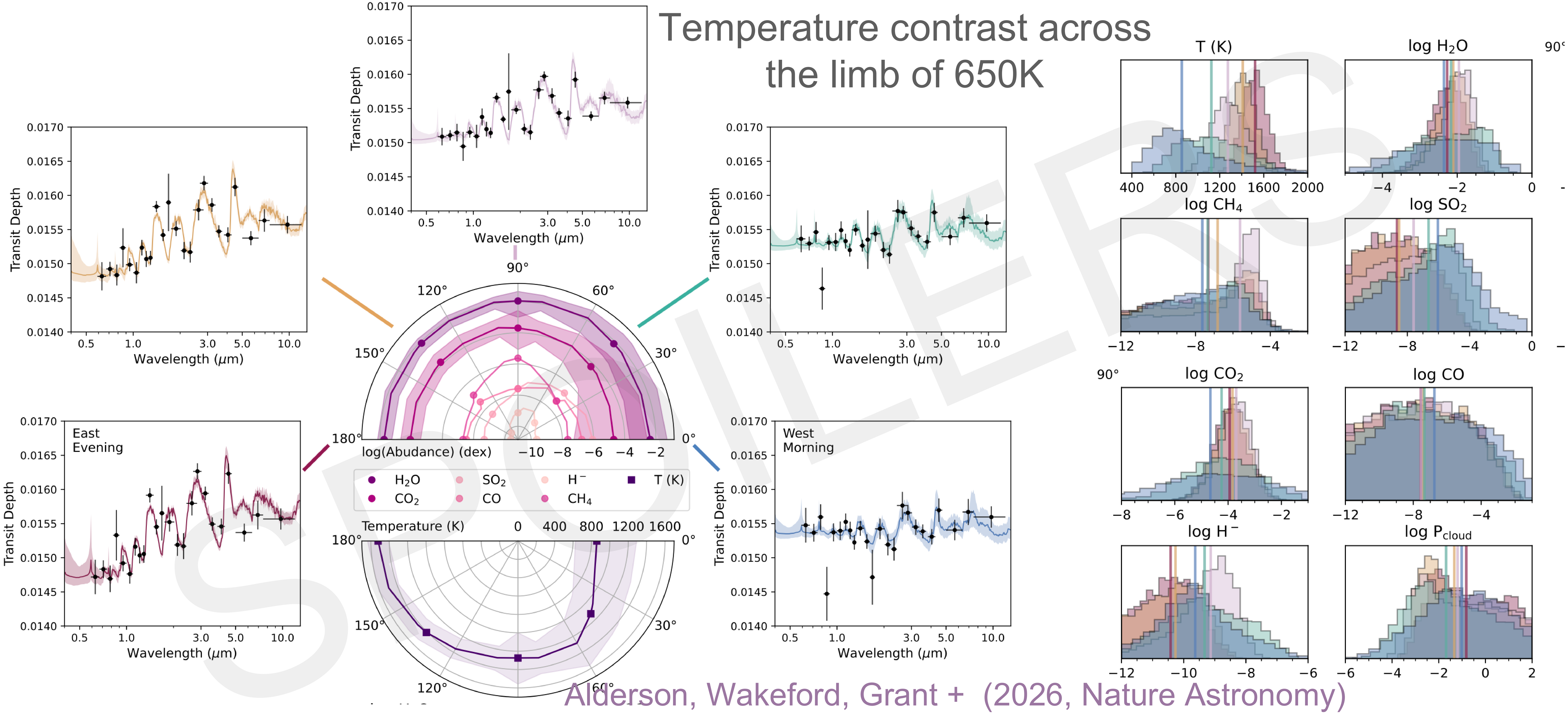
WASP-17b: Transmission String Mapping

Mapping directly shows the changing scale height [Alderson+ 2026, Nature Astronomy]

Temperature contrast across the limb of 650K



Alderson, Wakeford, Grant + (2026, Nature Astronomy)

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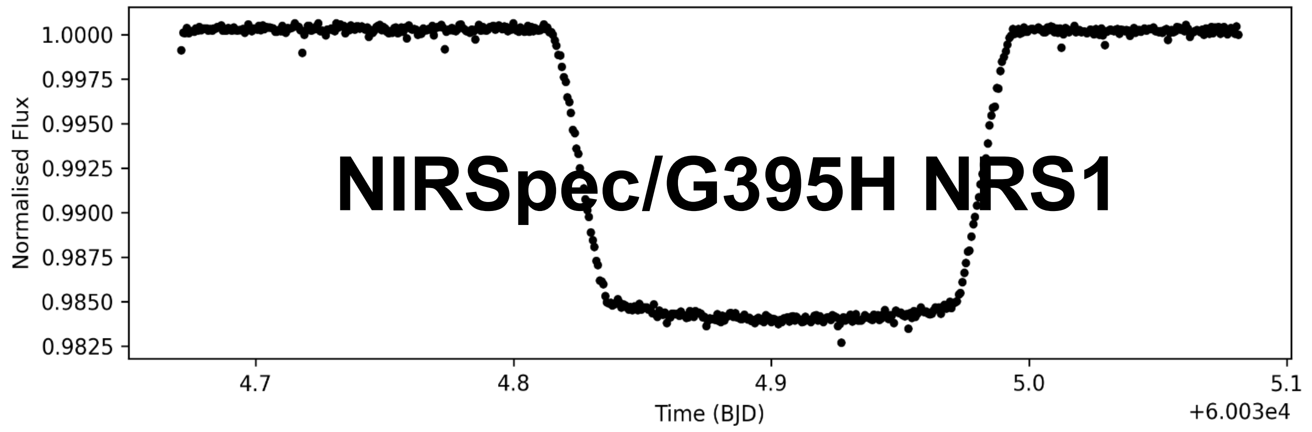
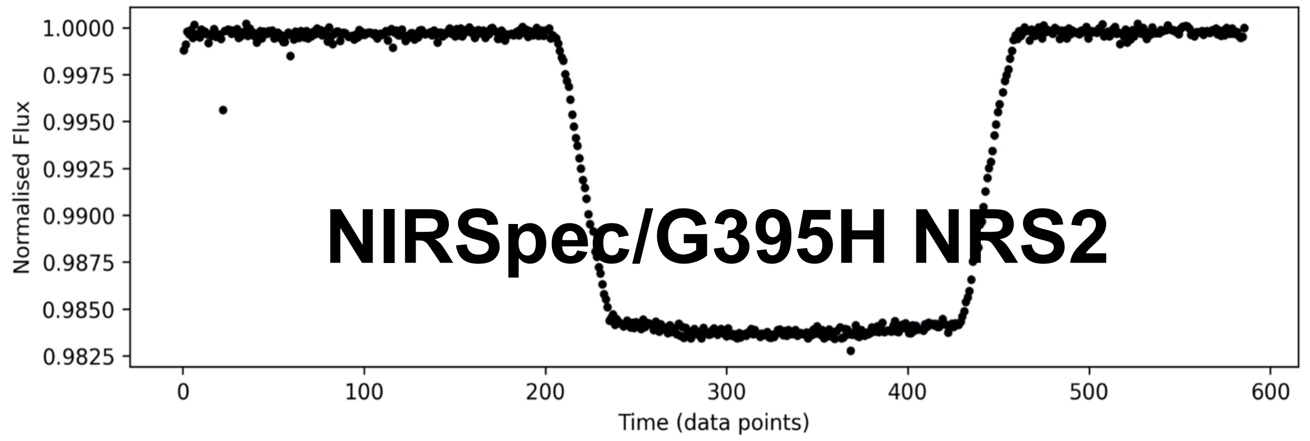
WASP-17b: Nightside Emission

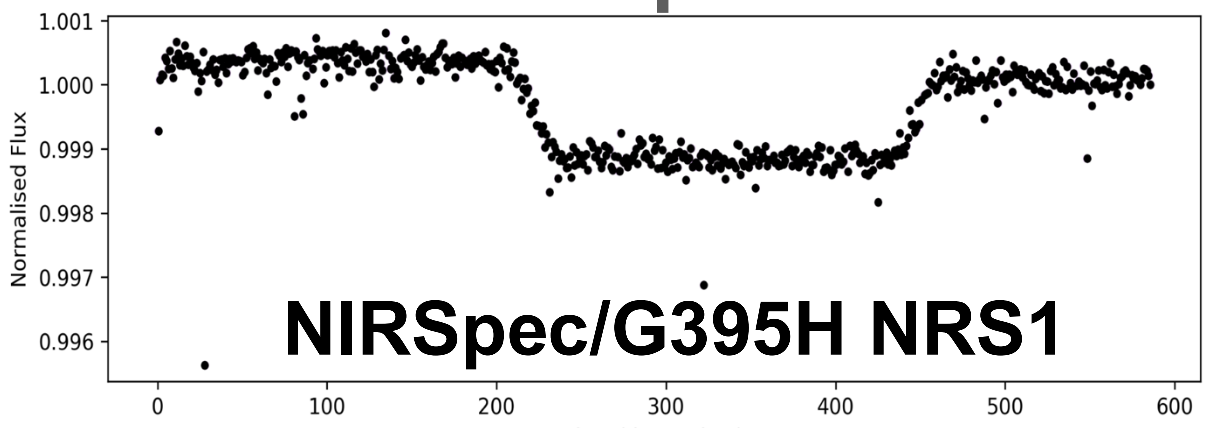
JWST-TST DREAMS Planetary Infrared Excess [Lustig-Yaeger & Sotzen+ 2025, ApJL]

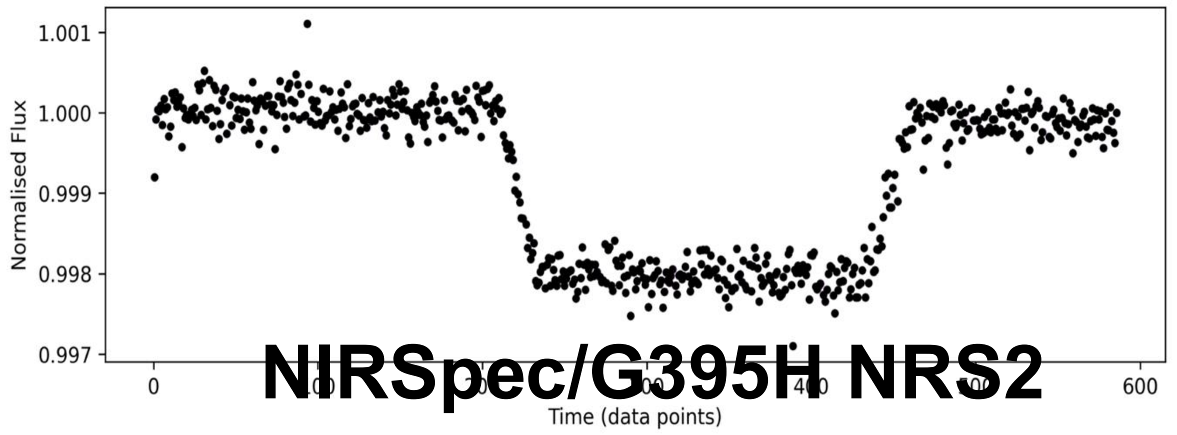
Transit



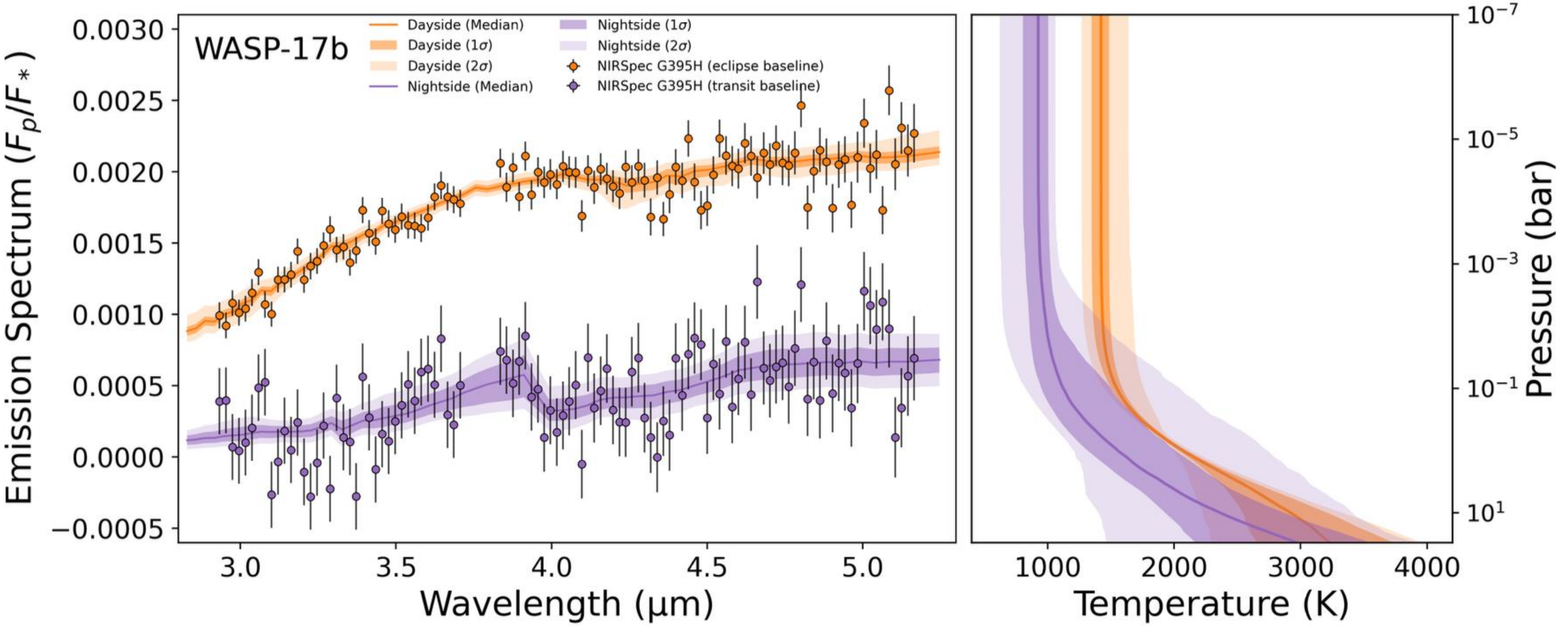


Eclipse





We can measure the nightside flux using Planet IR Excess

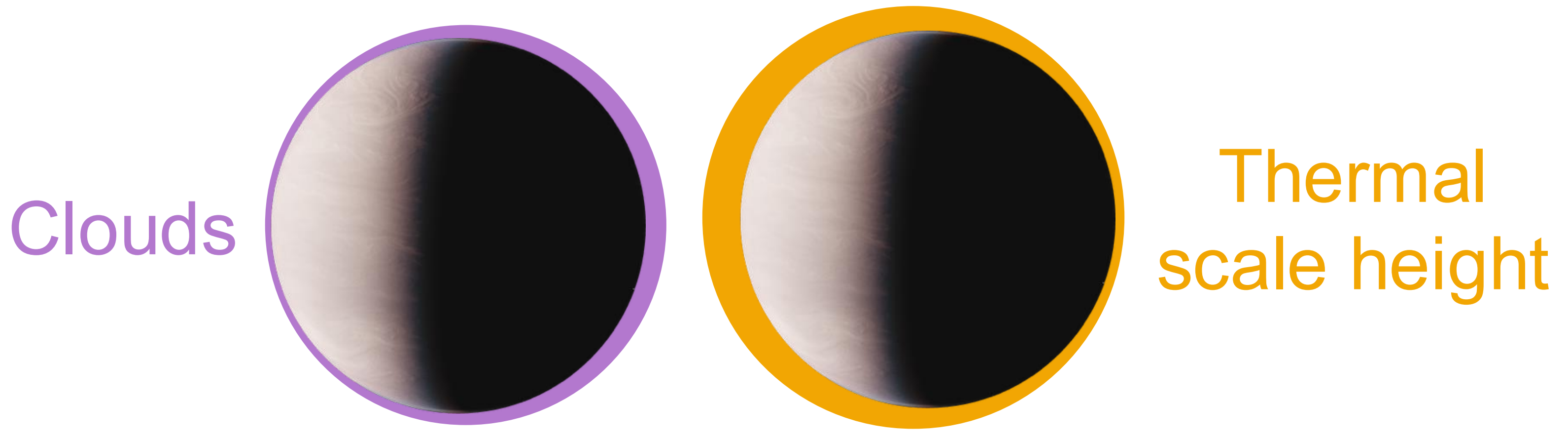


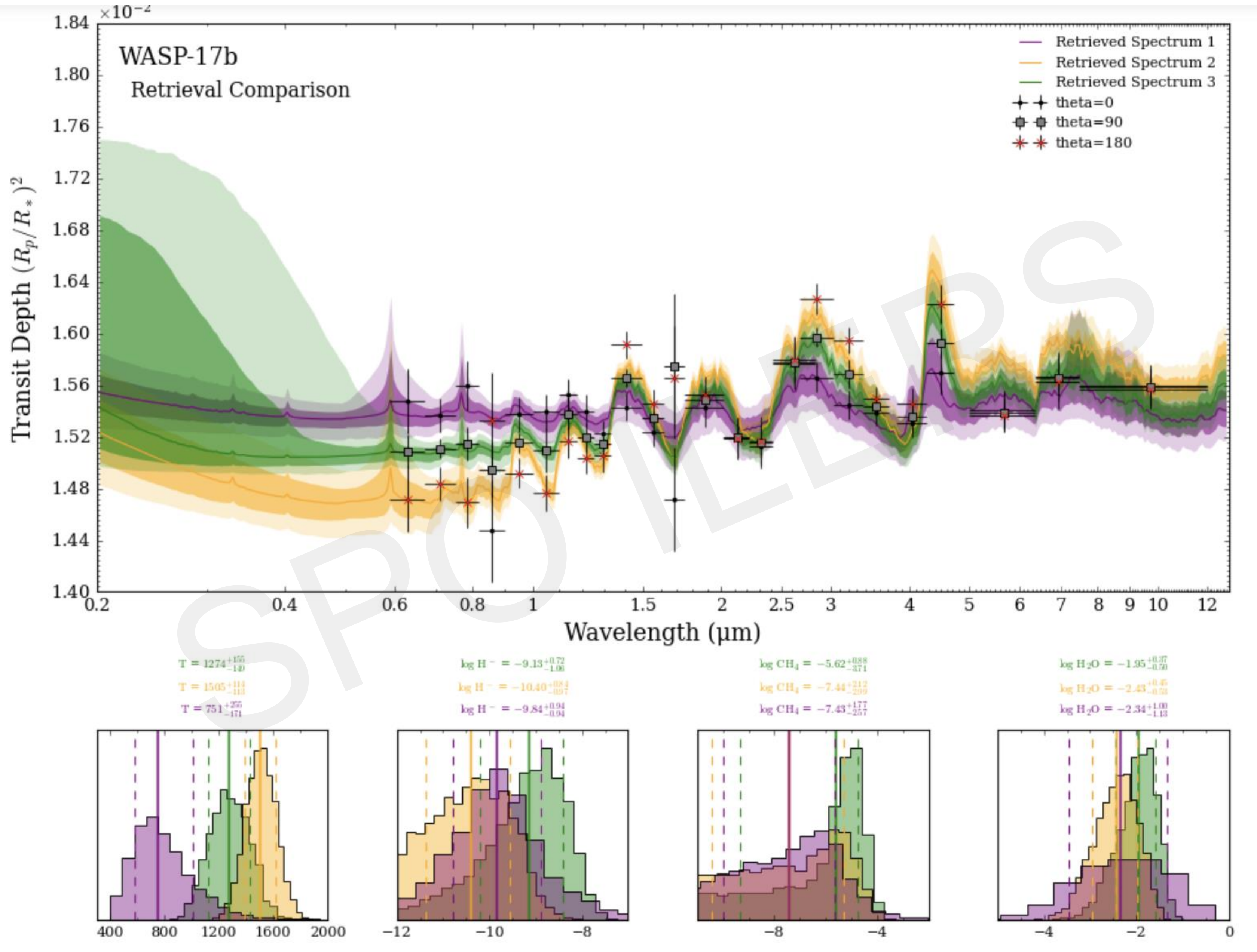
From the WASP-17b nightside spectrum, we measure an equilibrium temperature of 1005±256 K and find tentative evidence for nightside SO2 absorption.

Mapping the 3D Structure from Transit to Eclipse

Transmission Strings Map, Dayside Eclipse Map, & Nightside Flux!

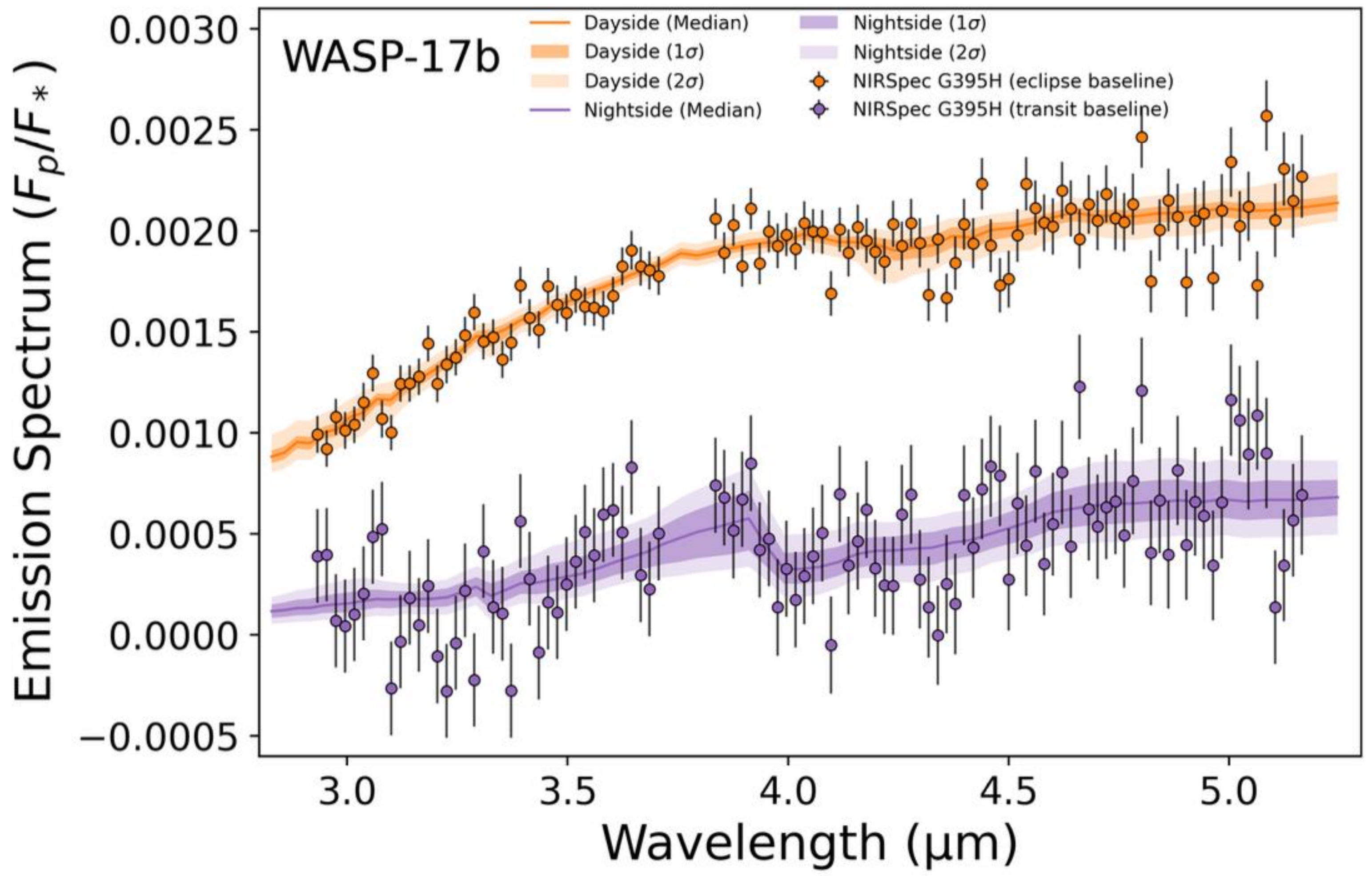
2D maps of the terminator reveal the thermal transport from day to nightside of the planet and cloud distribution

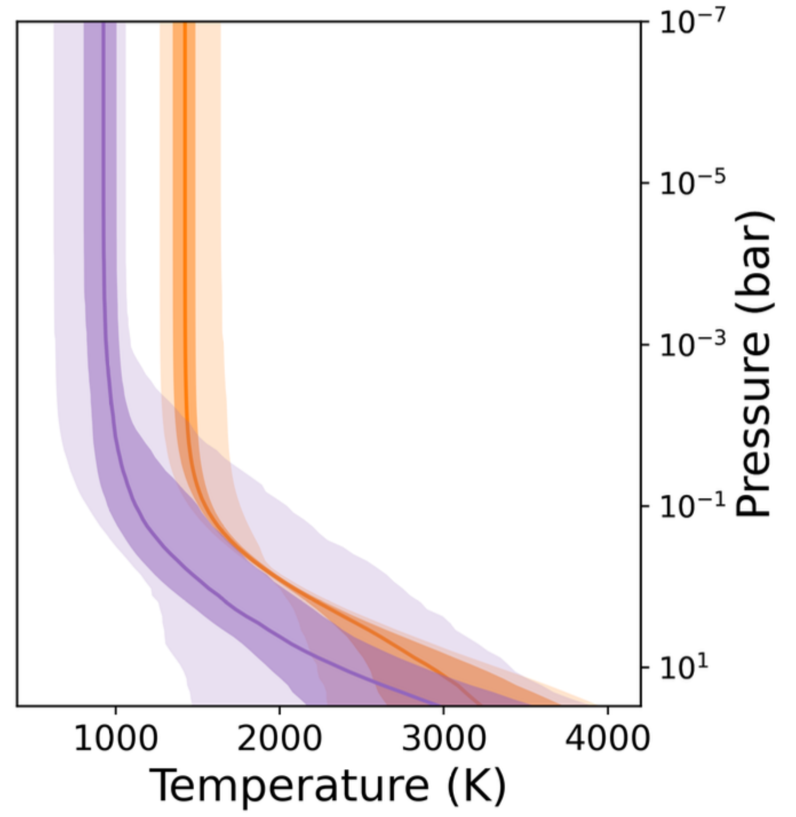




Alderson & Grant+ (in prep)

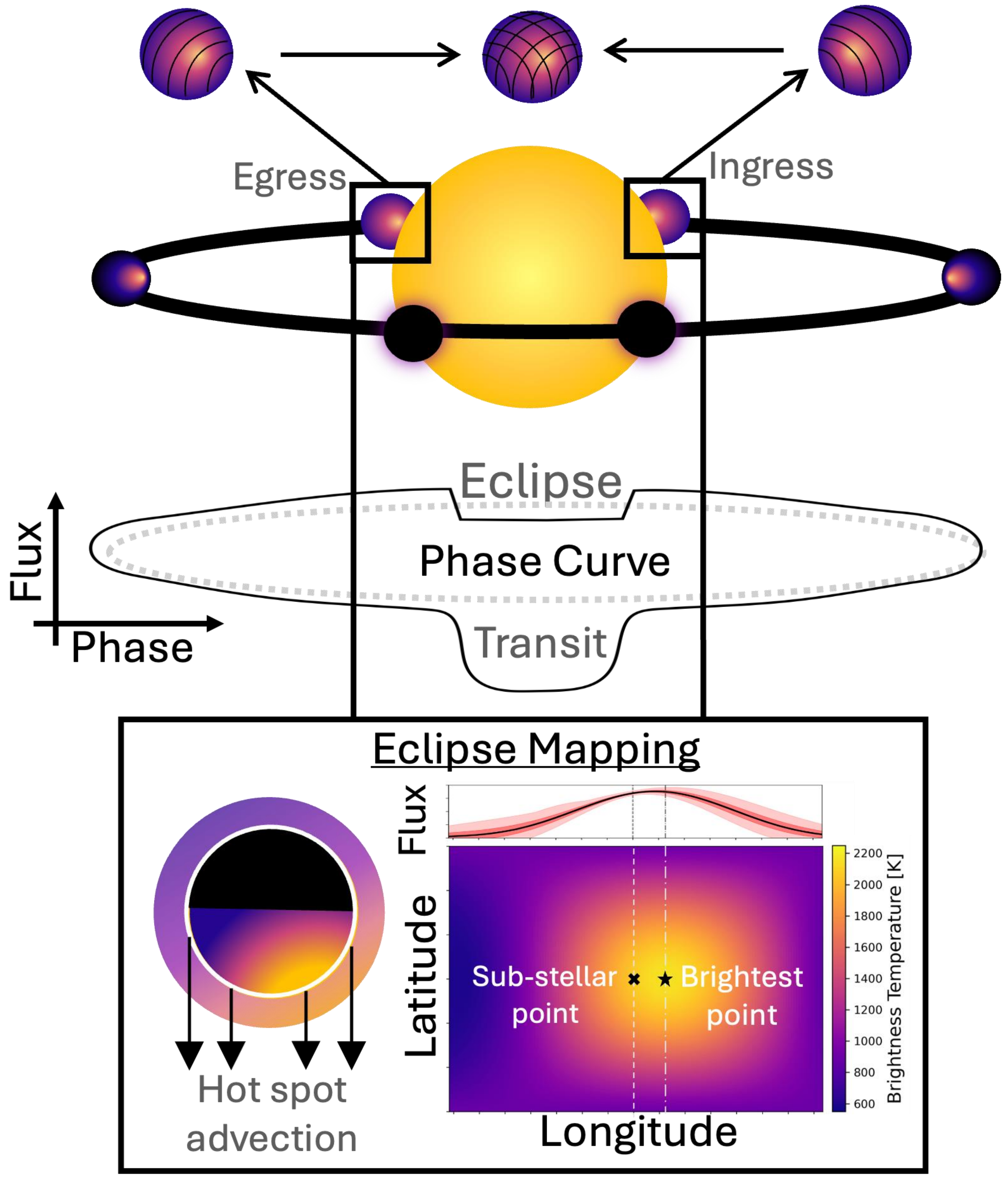
We can measure the nightside flux using Planet IR Excess





Lustig-Yaeger & Sotzen+ (2025, ApJL)

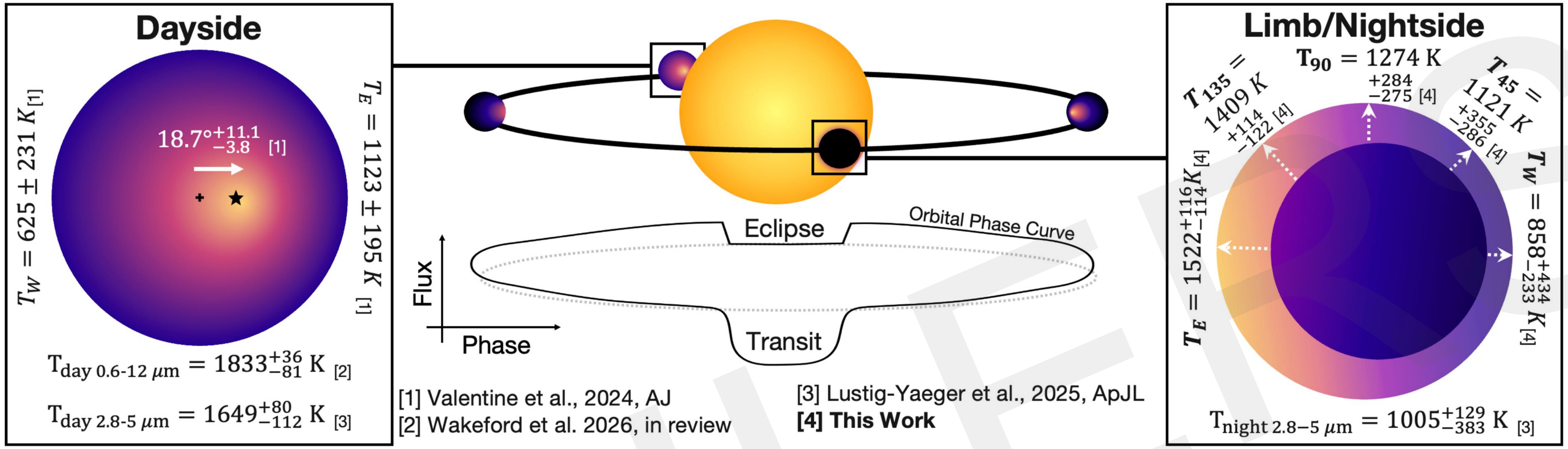
Using the eclipses we can map the dayside thermal structure across all λ



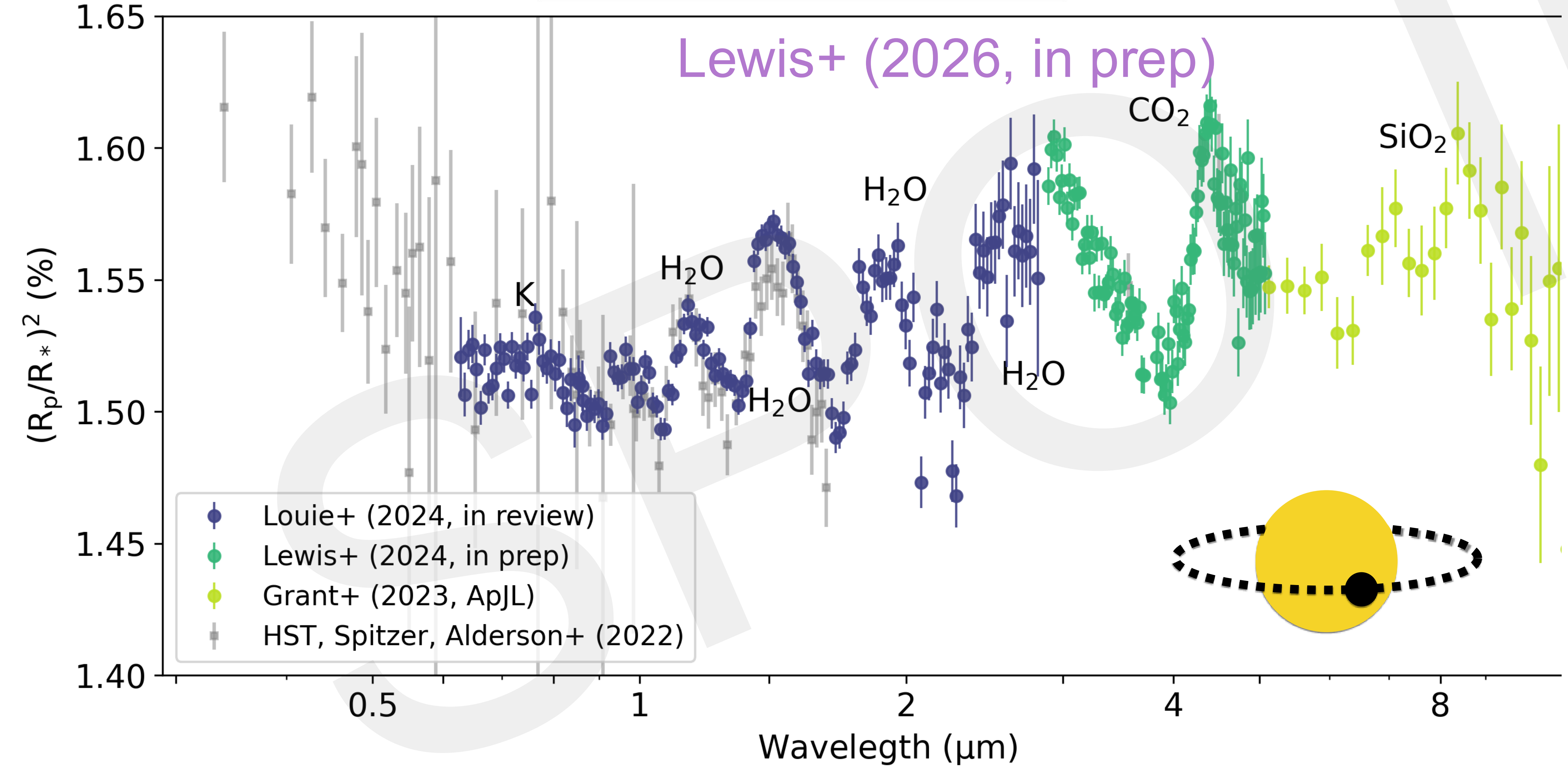
Valentine+ (2024, AJ)
Valentine + (2026, in prep)

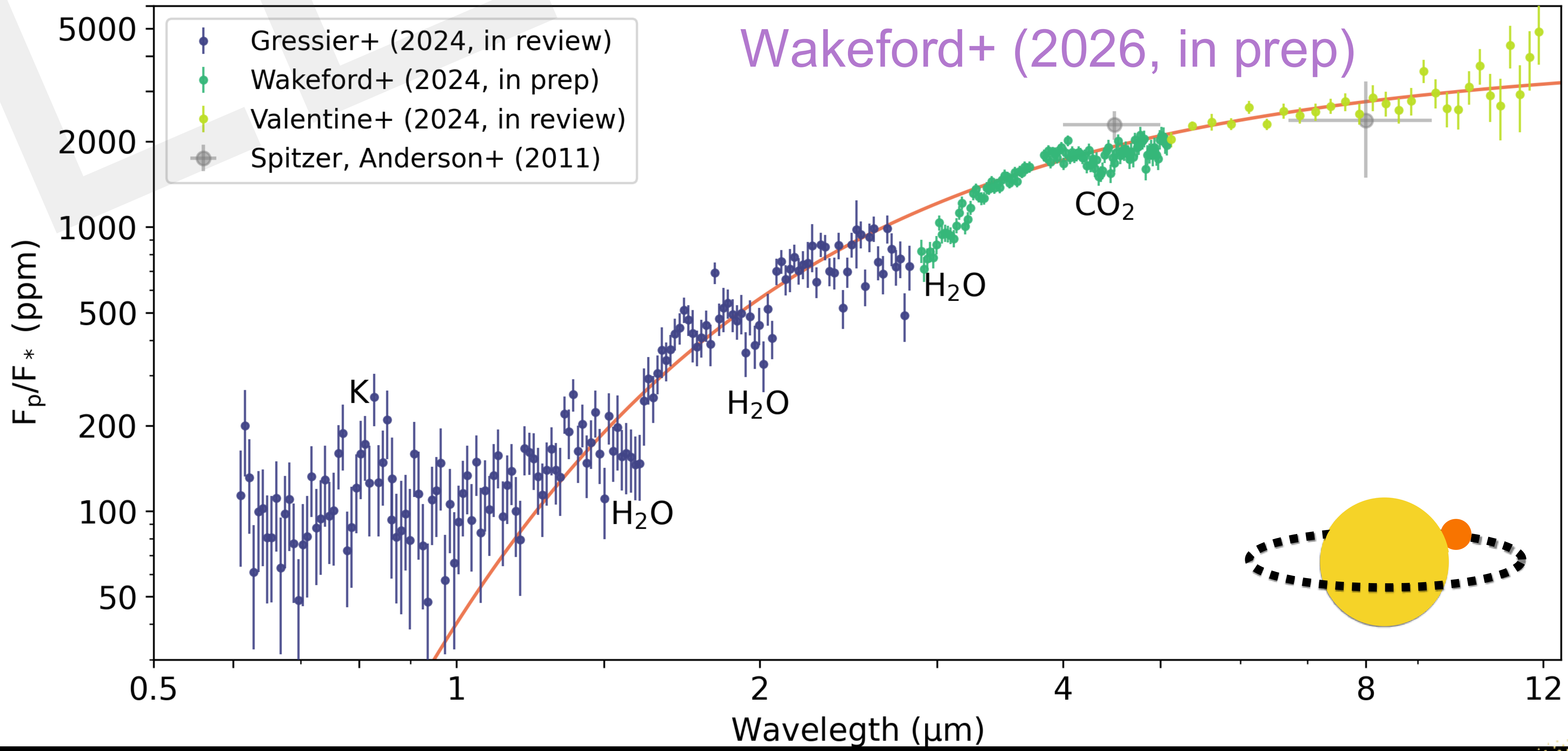
WASP-17b: The Complete Picture of an Exoplanet

1 Program, 6 observations,11+ papers, & 2 spin off Programs



Alderson+ (2026, Nature Astronomy)





WASP-17b: The Complete Picture of an Exoplanet

1 Program, 6 observations, 11+ papers, & 2 spin off Programs

But WASP-17b is relatively unique in that we can use **ALL** of these techniques to look at its atmosphere – **BUT** – it is not the best planet to look at for any one method.

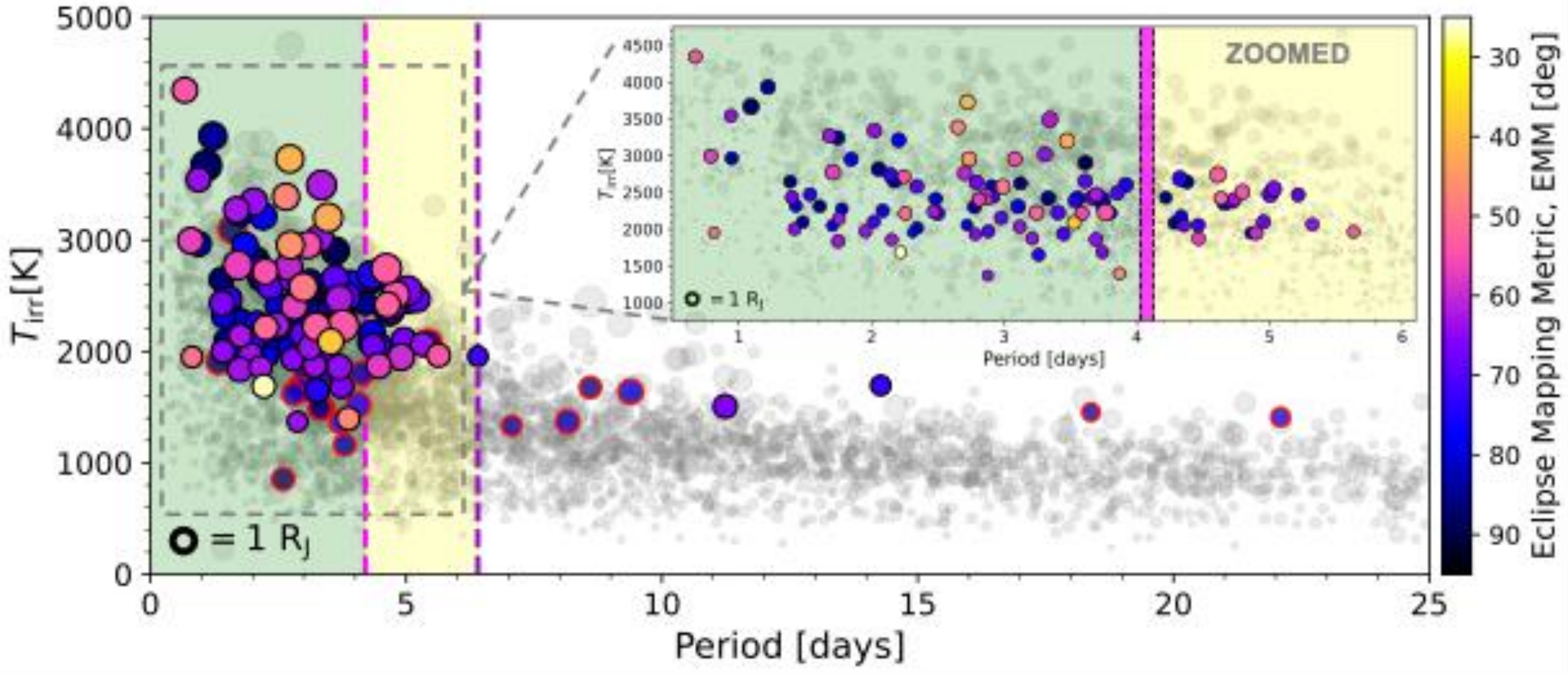
For most planets we will only get transmission or emission over limited wavelengths or phase coverage!

- Multi-dimensional mapping requires precise system parameters from RV & Transits
- Transit mapping requires large scale heights.
- Eclipse mapping requires high temperatures/flux.
- PIE requires coordinated observations and a quiet star.
- Etc.

The only way forward is through populations which takes time and trends emerging!

ESA Ariel could obtain 100s of exoplanet phase curves

Providing low resolution R~7 – R100 over 0.5 – 7.1 microns



For just 25% of the mission lifetime we can get complete spectral information for a population of worlds.

Valentine+ (2025, MNRAS)

BUT, while Ariel can give us a population the data will not be able to obtain detections of CO, condensate cloud signatures, or the impact of particle size in the optical nor that of the star. We still need Hubble & JWST and more to derive chemistry and dynamics of exoplanets

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1000’s of hours of Exoplanet Studies to Come

199 individual exoplanets, 400+ observation set-ups, 119 giants

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1000's of hours of Exoplanet Studies to Come

199 individual exoplanets, 400+ observation set-ups, **ONLY 6 with complete spectra!**

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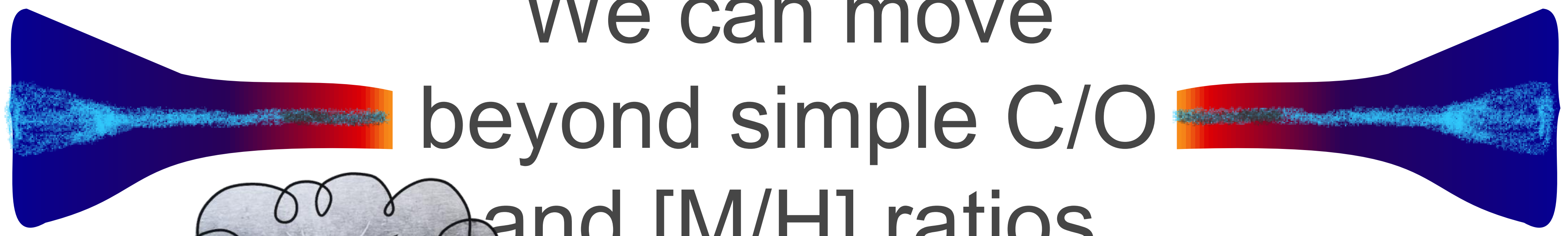
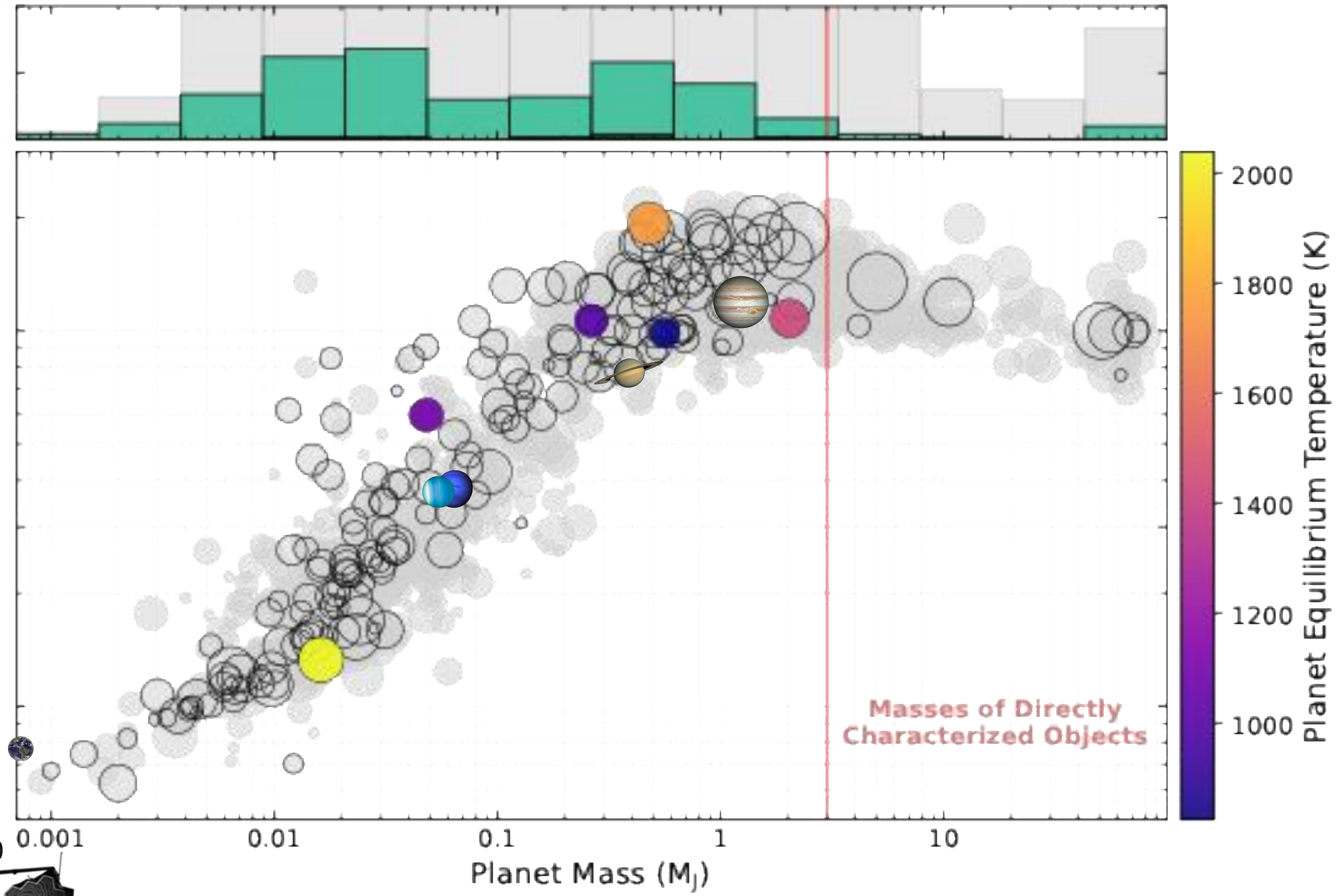
What do we know about exoplanet dynamics & chemistry and what's next?



We can move beyond simple C/O and [M/H] ratios

The exoplanet cloud sequence is more complex than first glance and we NEED combined HST + JWST data

We need HST (and more) to better understand the star



It is possible to access the multi-dimensional structure of exoplanet atmospheres and reveal their dynamical structures which inform the chemistry

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