Strict limits for secondary atmospheres on the small temperate TRAPPIST-1 d

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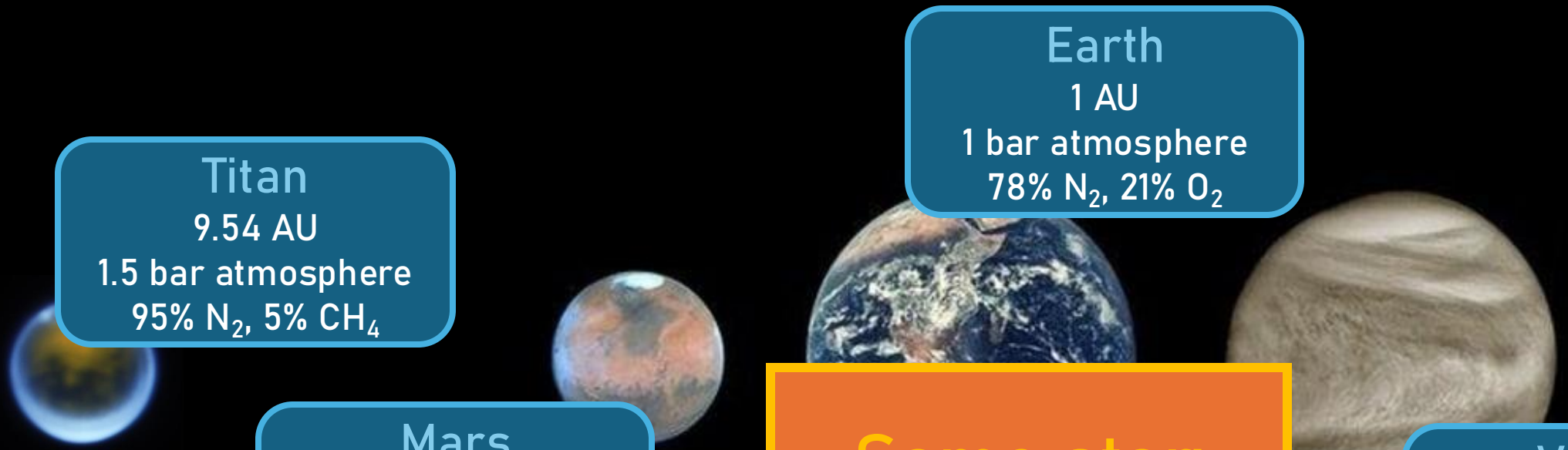
E. Margaret Burbridge Fellow at UChicago

On behalf of the NEAT GTO team. Key collaborators: Björn Benneke, Martin Turbet, Keavin Moore

Know Thy Star 2, February 2025

THE UNIVERSITY OF CHICAGO

A small sample of rocky planet atmospheres



Titan
9.54 AU
1.5 bar atmosphere
95% N_2, 5% CH_4

Earth
1 AU
1 bar atmosphere
78% N_2, 21% O_2

Mars
1.52 AU
0.006 bar atm.
96% CO_2, 2% N2, Ar

Same star: the Sun (G2)

Venus
0.72 AU
92 bar atmosphere
96% CO_2, 3% N_2

Credits:NASA/STScI/Keck

The challenge of predicting atmosphere presence for rocky exoplanets

To *predict* whether or not a planet has an atmosphere, theory depends on factors that observations can't provide:

Host star
XUV history
Stellar wind
Flares
...

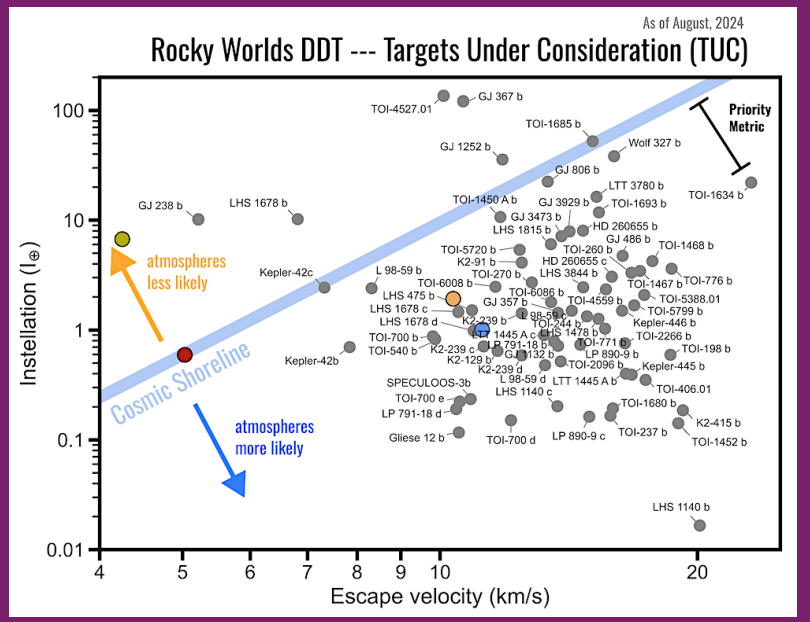
Planet
Volatile reservoirs
Internal composition
Energy budget
...

Atmospheric reconnaissance of small planets can inform where, when and for how long small planets can hold on to or revive atmospheres.

The challenge of predicting atmosphere presence for rocky exoplanets

ROCKY WORLDS

500-hr JWST DDT program



TRAPPIST-1

~400 hr on TRAPPIST-1 planets in GTO/GO programs

TRAPPIST-1 : the gift of intra-system uniformity

7 small rocky planets around the same small star, TRAPPIST-1

Host star
~~XUV history~~
~~Stellar wind~~
~~Flares~~
...

Planet
~~Volatile reservoirs~~
~~Internal composition~~
Energy budget
...

Main differences are initial volatile inventory, irradiation

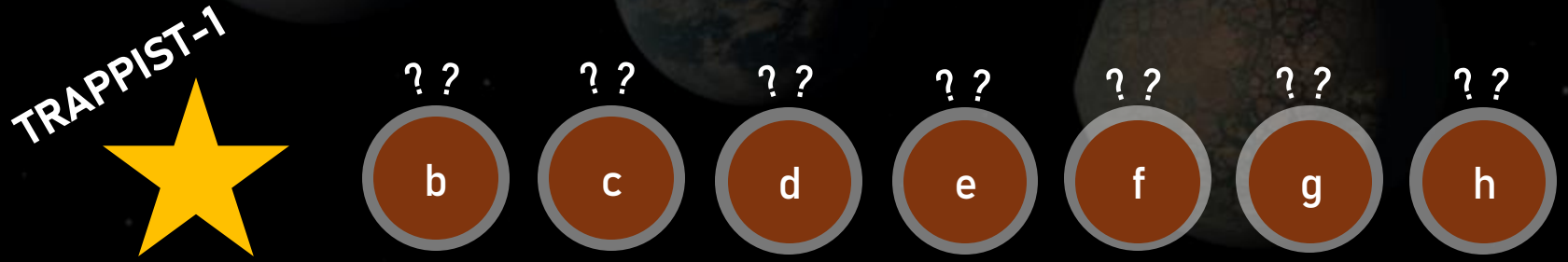
Piaulet Ghorayeb et al., in prep.

Multiple ~~*birds*~~ planets with one stone

Search for an atmosphere on a rocky planet:

NO atmosphere
Lower limit on XUV irradiation
Upper limit on initial volatile reservoirs
...

Atmosphere detection
Upper limit on XUV irradiation
Lower limit on initial volatile reservoirs
...



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Multiple ~~*birds*~~ planets with one stone

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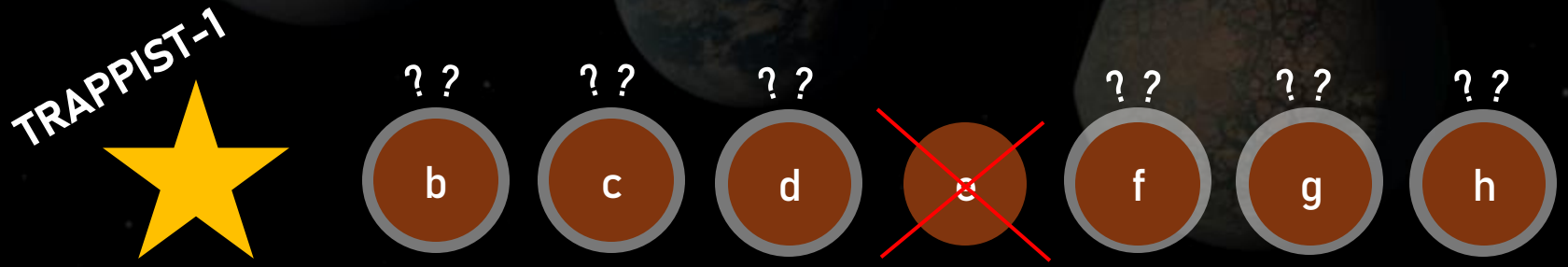
For the TRAPPIST-1 planets, any result on *one* planet



Piaulet Ghorayeb et al., in prep.

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Search for an atmosphere on a rocky planet:

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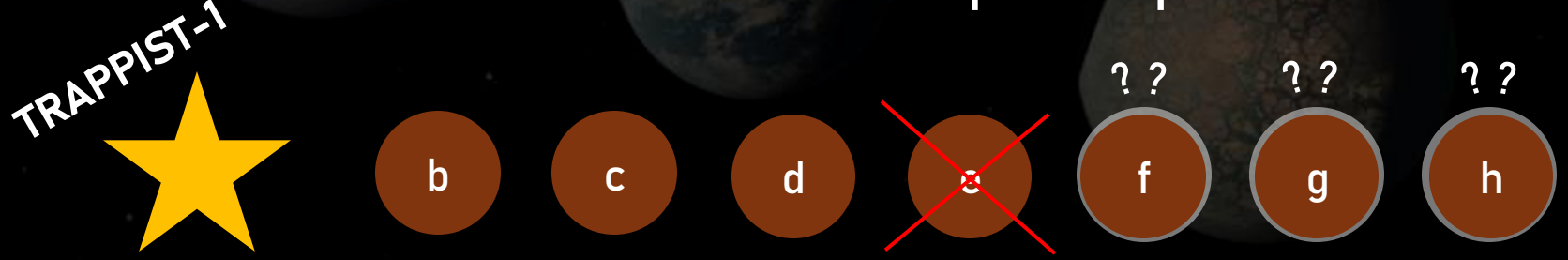
For the TRAPPIST-1 planets, any result on *one* planet informs the likelihood of atmospheric presence on *all* of them



Piaulet Ghorayeb et al., in prep.

Multiple ~~*birds*~~ planets with one stone

Search for an atmosphere on a rocky planet:

NO atmosphere
Lower limit on XUV irradiation
Upper limit on initial volatile reservoirs
...

Atmosphere detection
Upper limit on XUV irradiation
Lower limit on initial volatile reservoirs
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For the TRAPPIST-1 planets, any result on *one* planet
informs the likelihood of atmospheric presence on *all* of them

** BUT not all TRAPPIST-1 planets are equal for constraining atmosphere retention

TRAPPIST-1 b (Greene+2023; Lim+2023) & TRAPPIST-1 c (Zieba+ 2024; Radica, Piaulet-G.+2025)
were *~expected* to have lost their atmospheres (e.g. Krissansen-Totton 2023)

Piaulet Ghorayeb et al., in prep.

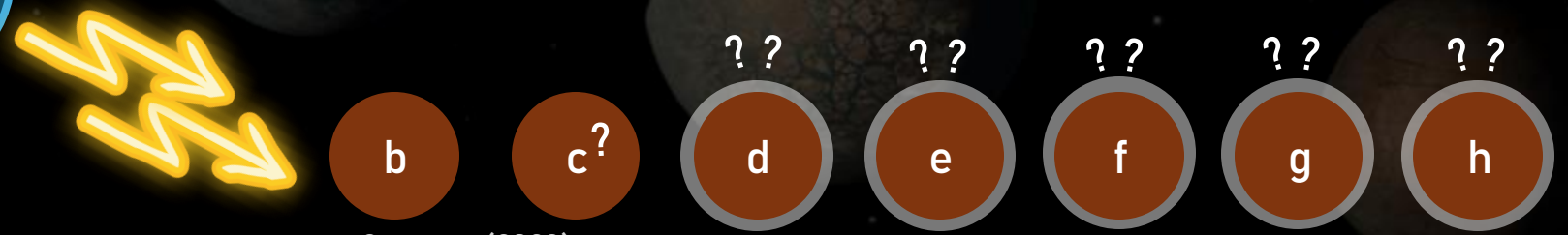
TRAPPIST-1 d: Entering the realm of high-reward atmospheric reconnaissance

TRAPPIST-1 d
Fact Sheet

M_p : 0.39±0.01 $M_\oplus$
R_p : 0.79±0.01 $R_\oplus$
S_p : 1.12±0.04 $S_\oplus$
$T_{eq,A=0}$: 286 K
Period : 4 days

values from Agol+ 2021

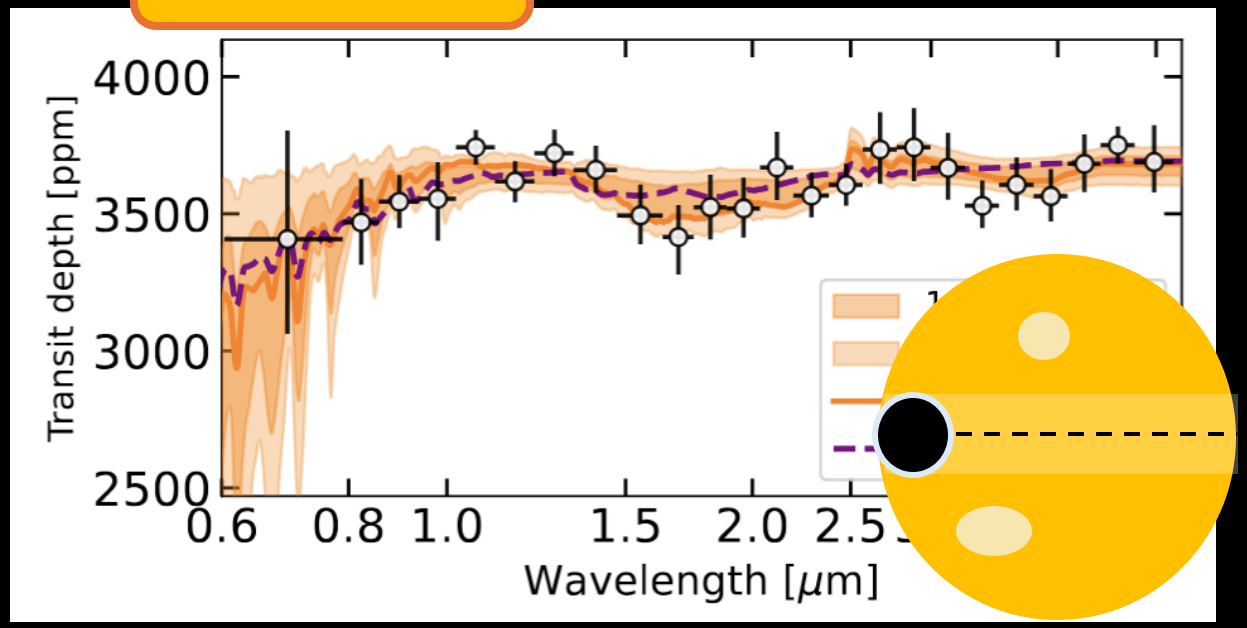
- Planet at the cusp of the HZ !
- ~50/50% odds of atmosphere loss (Krissanson-Totton 2023)
- 2 NIRSpec/PRISM transits (NEAT GTO)



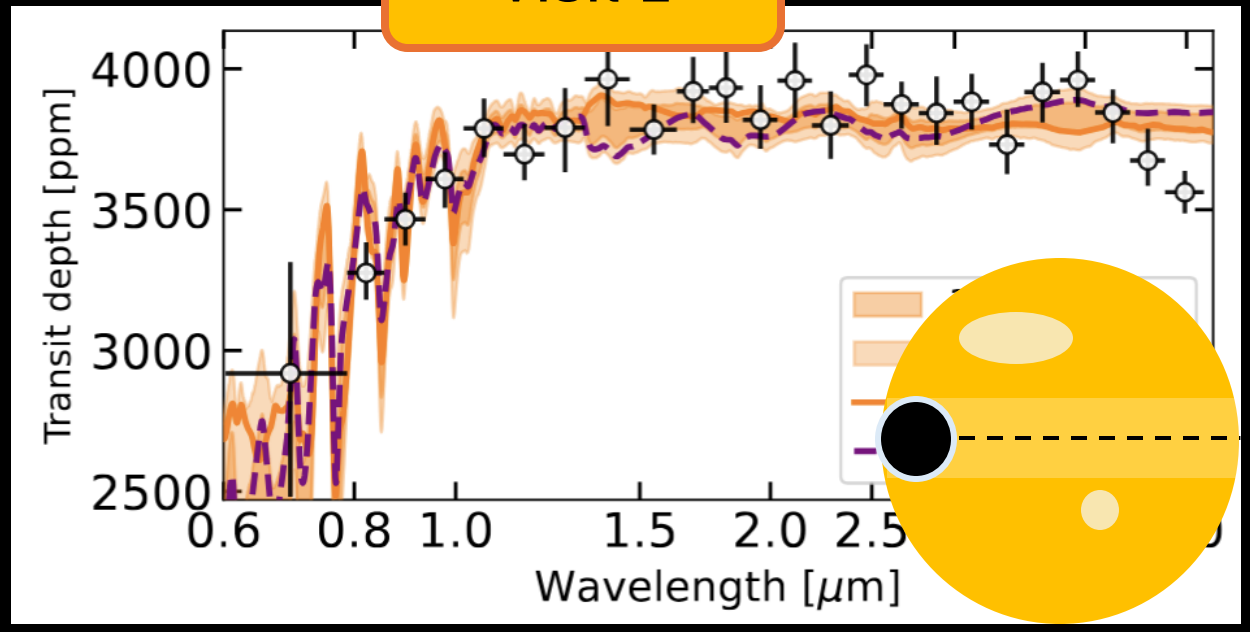
Greene+ (2023)
Lim, ..., Piaulet+ (2023)
Zieba+ (2023)
Radica, Piaulet-G.+ (2024)

Visit-to-visit variations in the TLS signature

Visit 1



Visit 2

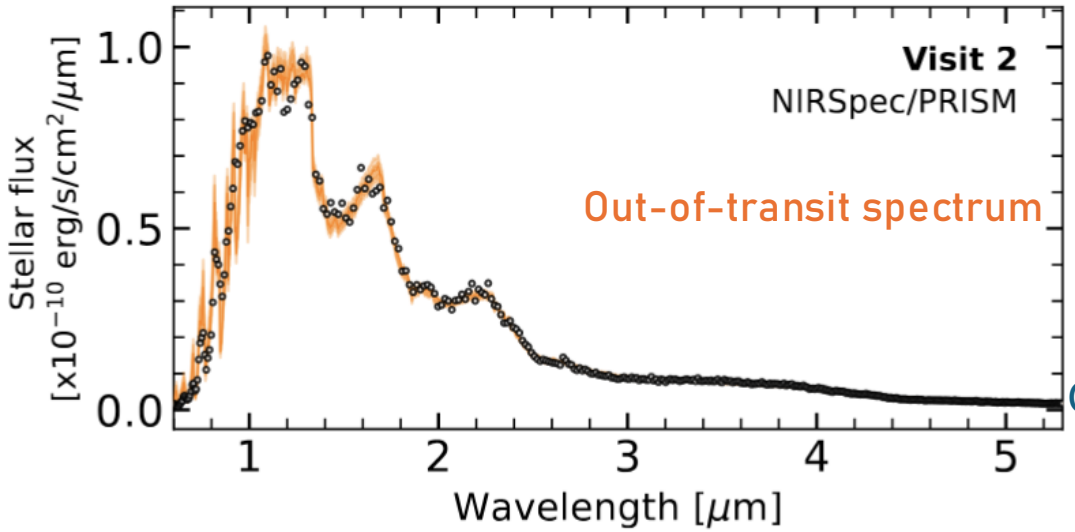


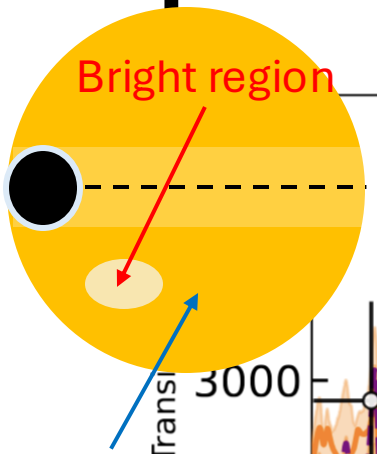
STCTM

cpiaulet / stctm

Piaulet Ghorayeb et al., in prep.

Taming the TLS beast: out-of-transit stellar spectrum retrievals





$$F_{\rm oot} = (1 - f_{\rm bright}) \times F_{\rm phot}(T_{\rm phot}) + f_{\rm bright} \times F_{\rm bright}(T_{\rm bright})$$

$$D(\lambda, TLS) = \frac{D}{1 - f_{\rm bright}\left(1 - \frac{F_{\rm bright}(T_{\rm bright})}{F_{\rm phot}(T_{\rm phot})}\right)}$$

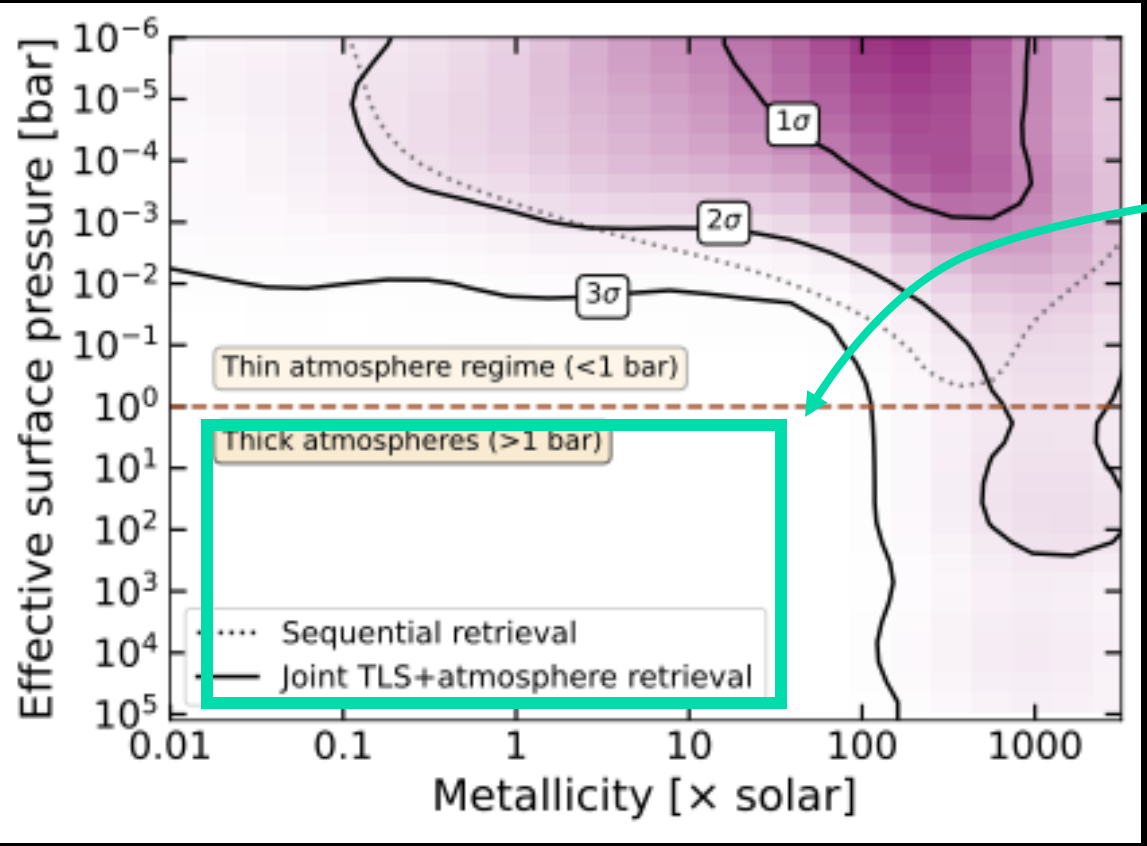
The out-of-transit spectrum is sensitive to temperatures & provides independent constraints on T_{phot}

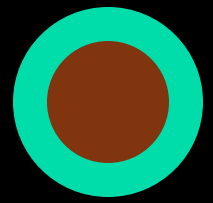
The TLS effect is sensitive to even small fractions of heterogeneities but does not probe T_{phot}

cpiaulet / stctm

Piaulet Ghorayeb et al., in prep..

NIRSpec/PRISM reaches sensitivity to <1 bar secondary atmospheres on TRAPPIST-1 d



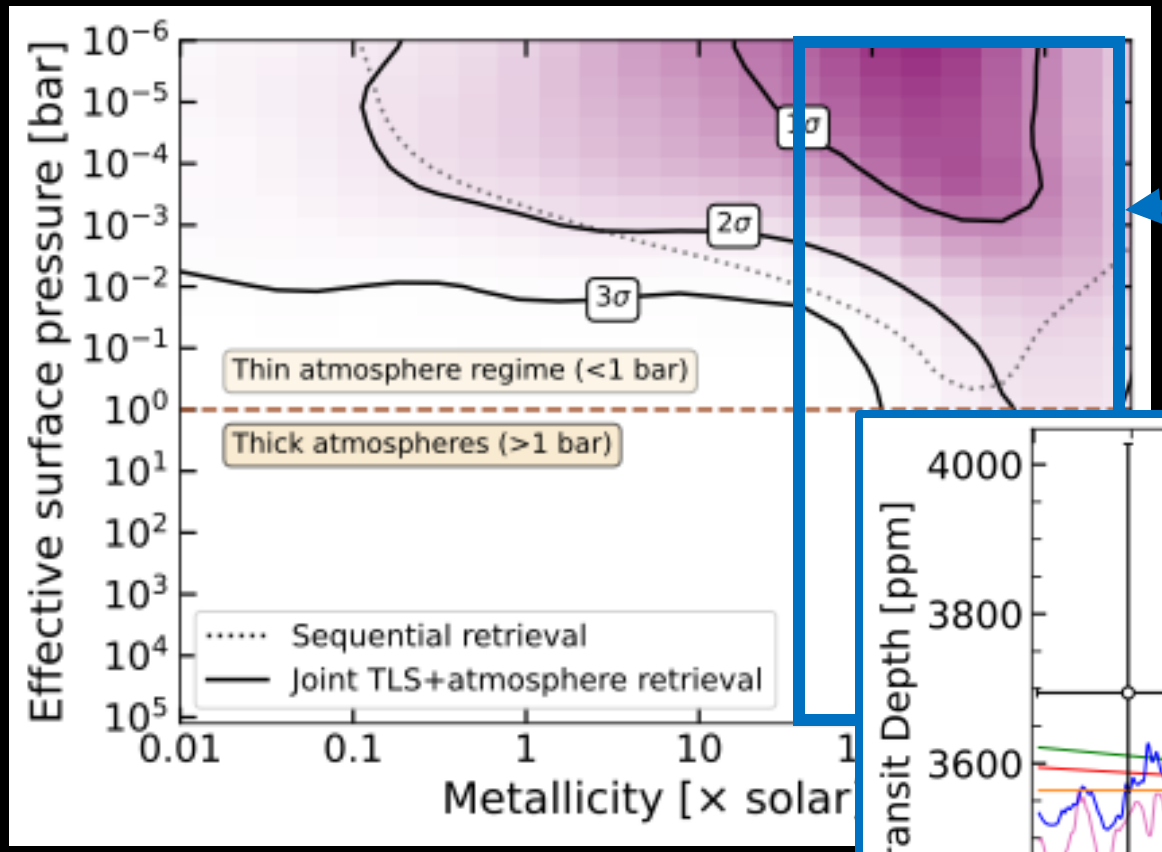


Thick H/He-rich atmosphere

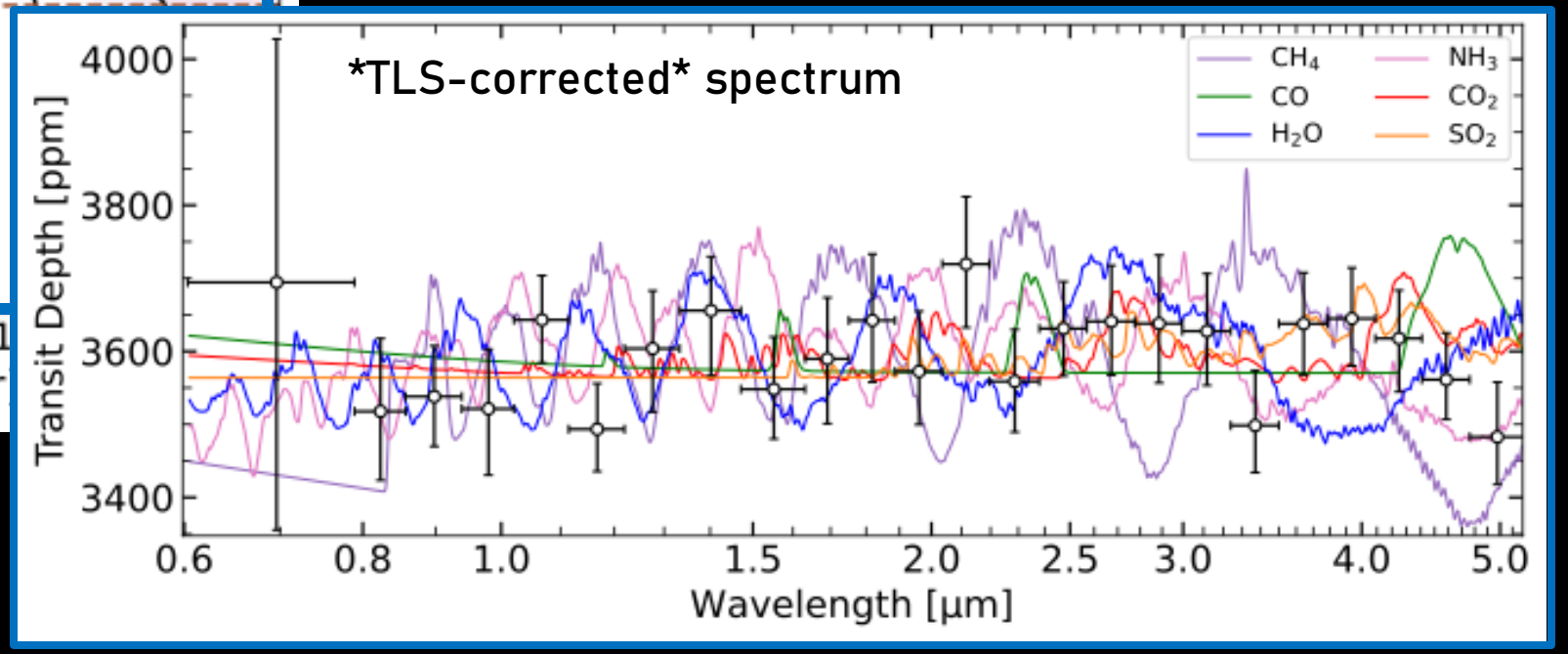
- Visit-dependent stellar contamination
- Shared planetary atmosphere properties

Piaulet Ghorayeb et al., in prep.

NIRSpec/PRISM reaches sensitivity to <1 bar secondary atmospheres on TRAPPIST-1 d



High-metallicity atmosphere

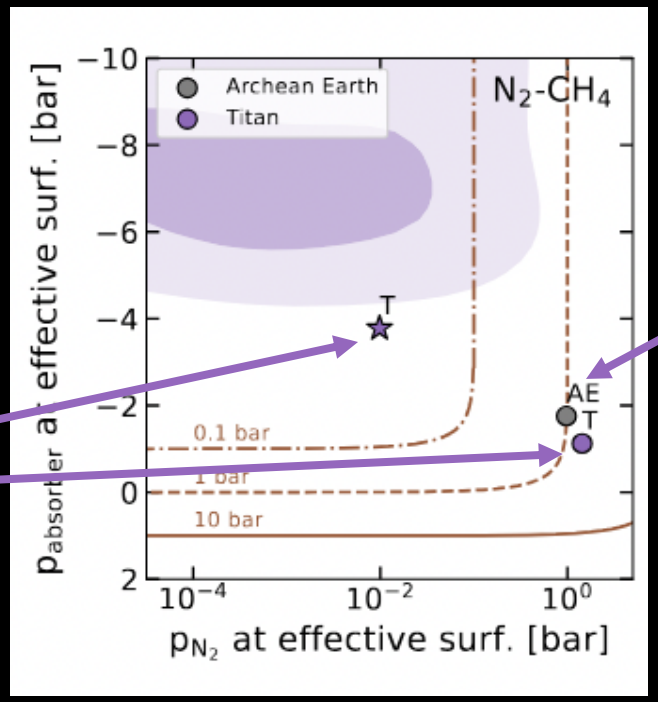


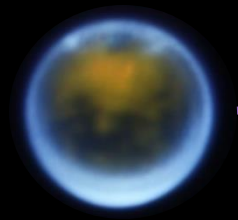
Piaulet Ghorayeb et al., in prep.

Strict limits on thin high mean molecular weight atmospheres for a 0.8 $R_\oplus$ rocky planet

Nitrogen + methane

MORE CH_4

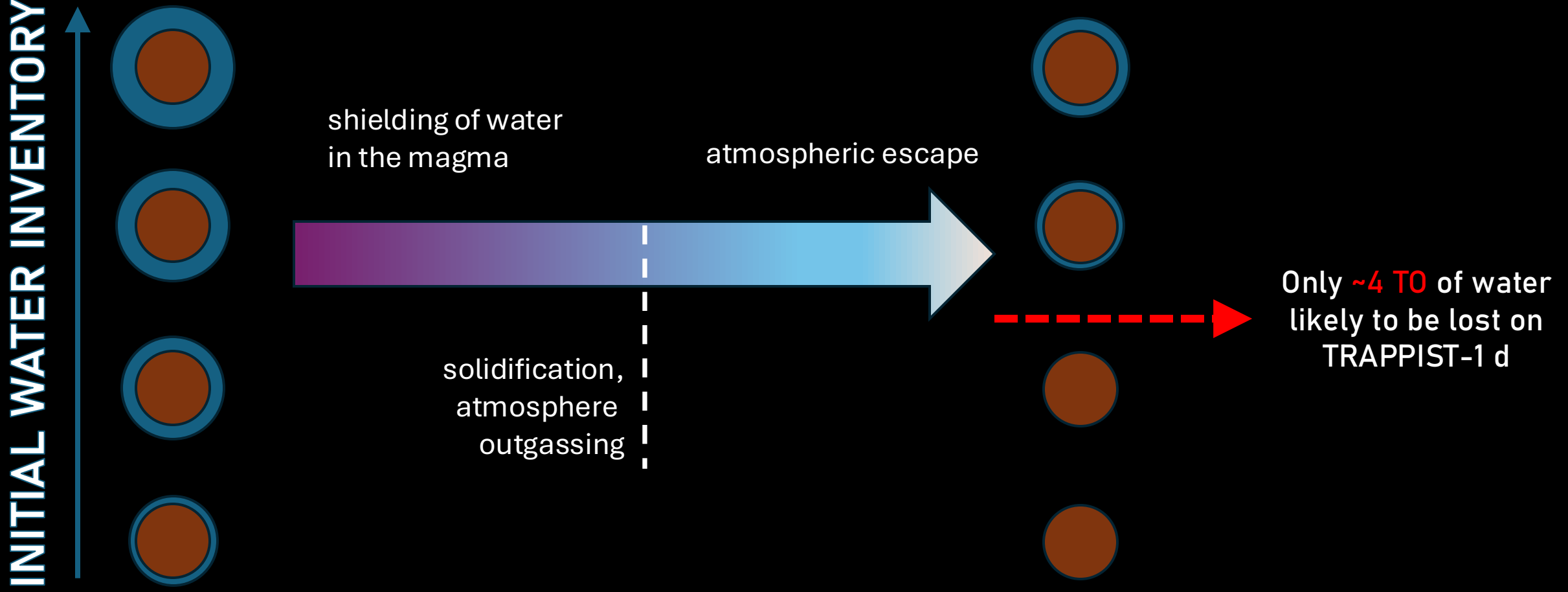




MORE N_2

Piaulet Ghorayeb et al., in prep.

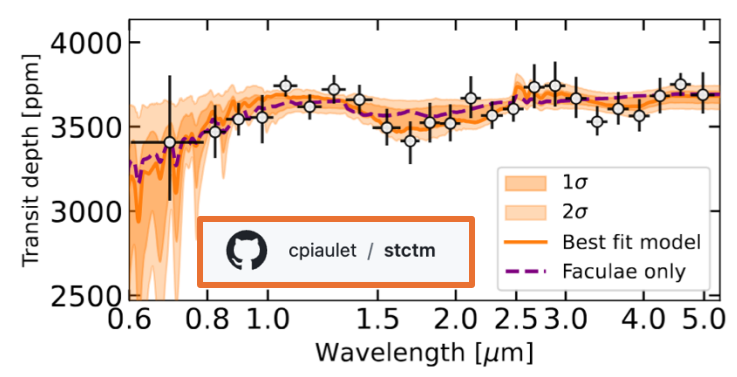
If TRAPPIST-1 d is desiccated, b & c formed dry



Modeling following methods of Moore, Cowan & Boukaré (2023)

Piaulet Ghorayeb et al., in prep.

Take-home messages

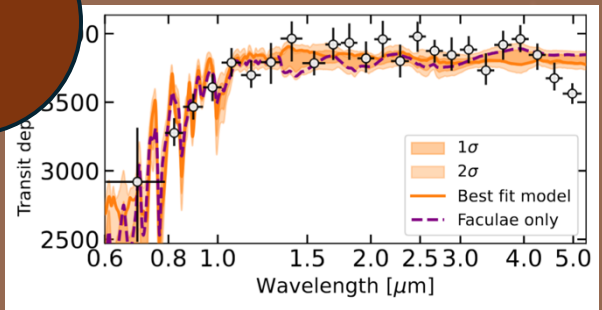


JWST + rigorous accounting for stellar heterogeneities
= precision to probe secondary atmospheres

Compositions compatible with the NIRSpec/PRISM spectrum:

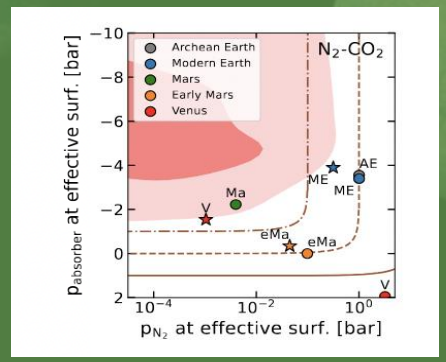
1

Bare rock ?
→ The inner TRAPPIST-1 planets likely formed dry



2

Solar system terrestrial-like ?
→ Either thin Mars-like atm. or cloudy Venus-like atm.



3

Other (e.g. H_2O-rich) composition ?
→ Water clouds at terminator could mask water in transmission

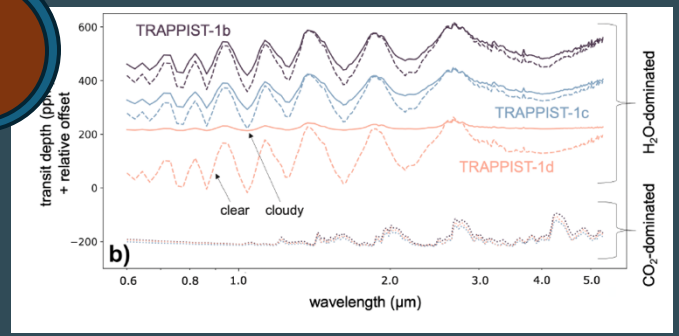
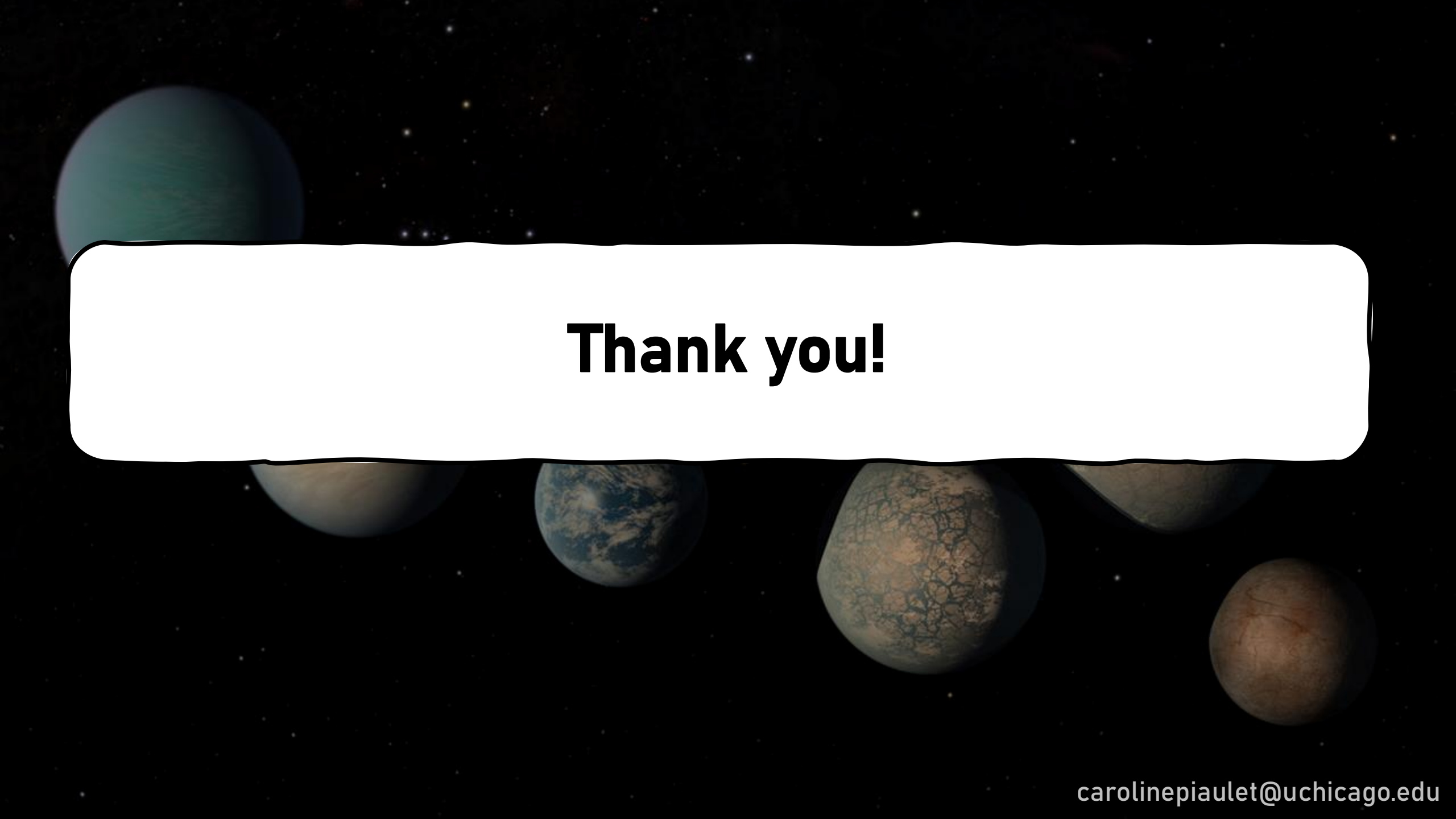


Fig. from Turbet et al. (2023)



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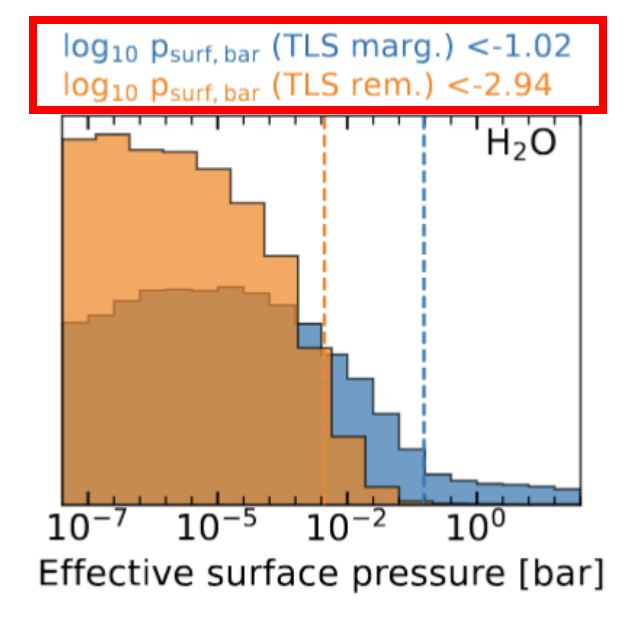
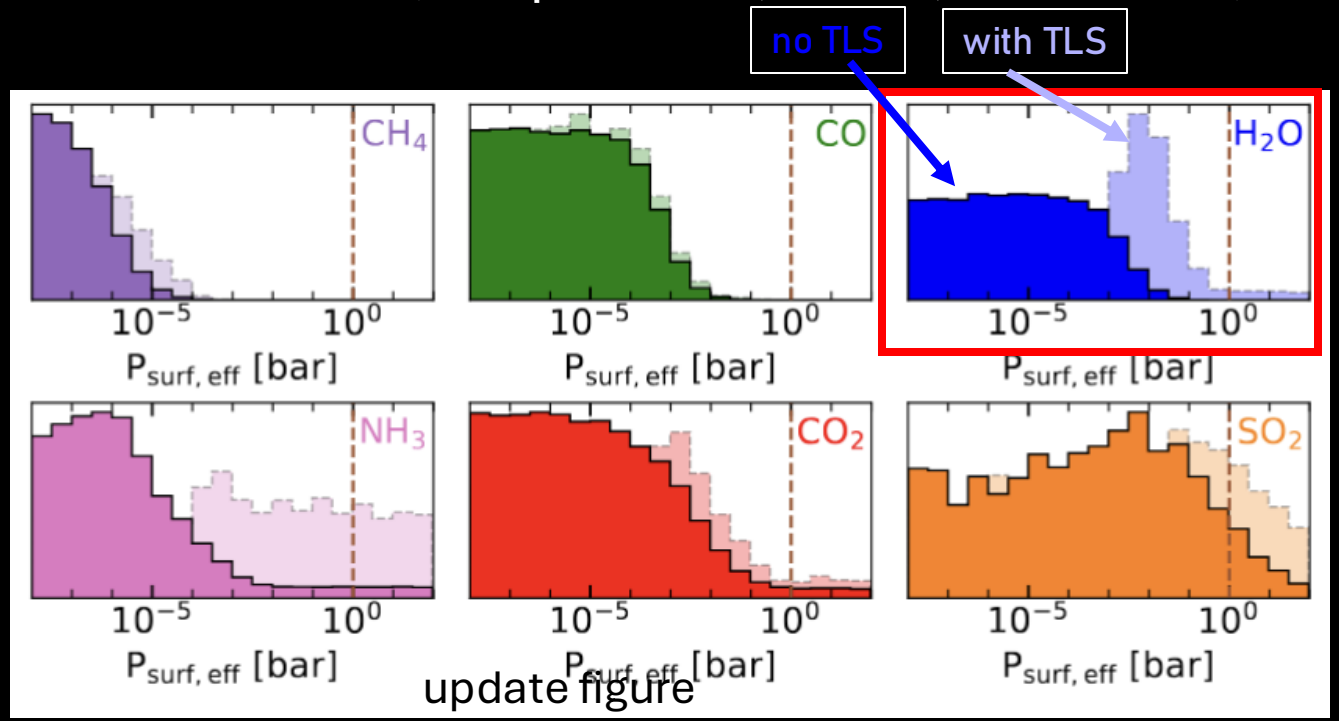
Stellar contamination as a limiting factor on molecular feature detections

TRAPPIST-1 c (NIRISS SOSS, 2 visits, *shared* TLS)
Radica, Piaulet-G. et al. (2025)



TRAPPIST-1 d (NIRSpec PRISM, 2 visits, *different* TLS)

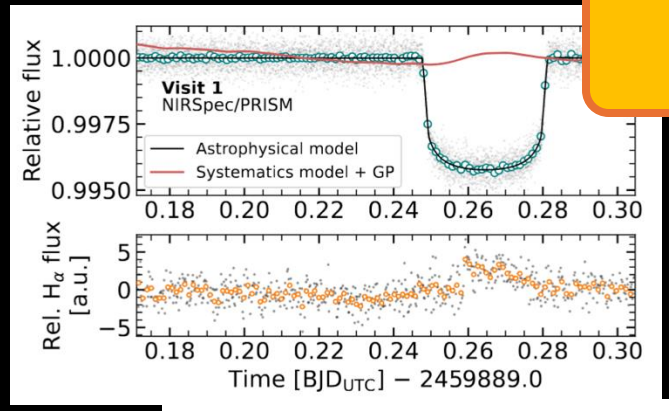


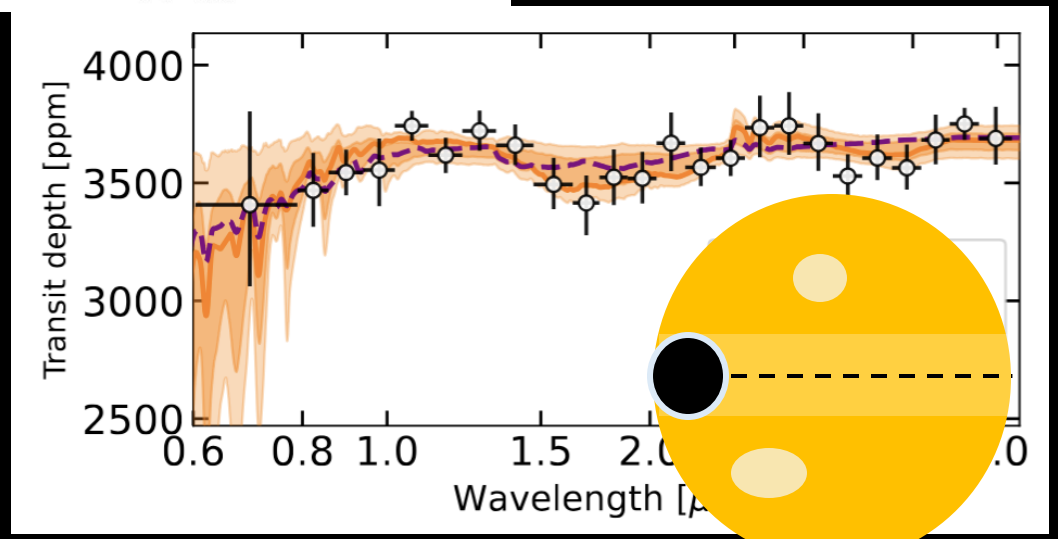
update figure

Piaulet Ghorayeb et al., in prep.

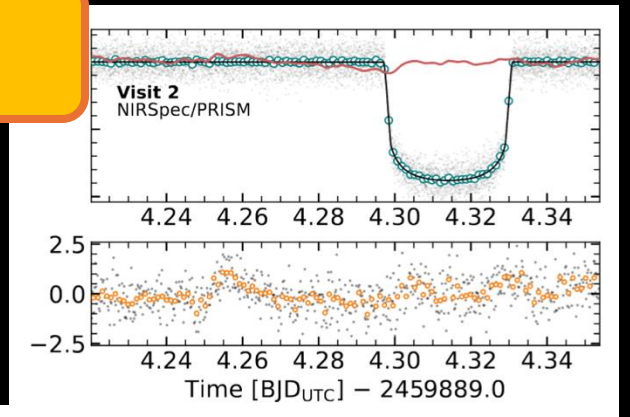
Visit-to-visit variations in the TLS signature

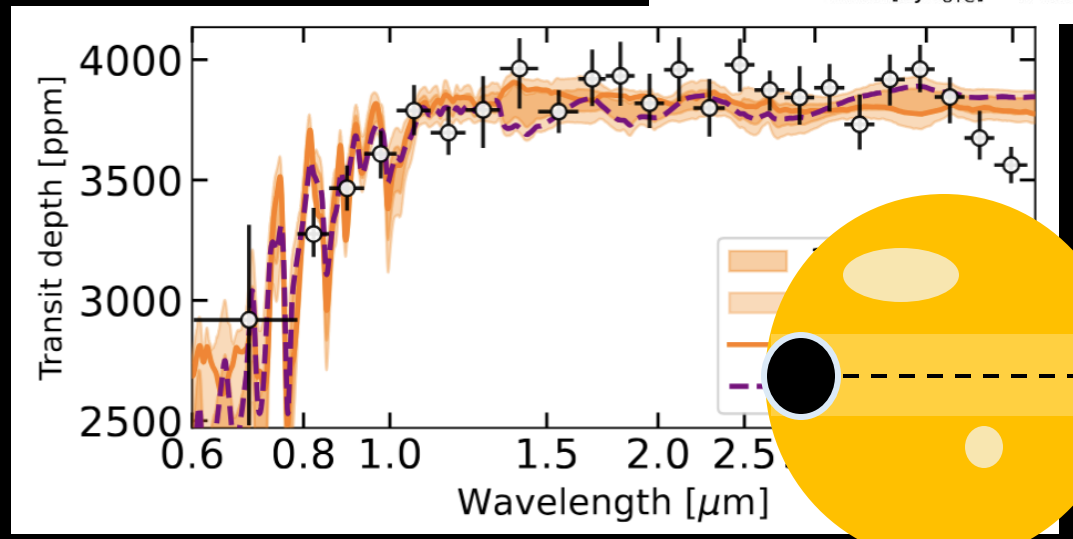
Visit 1





Visit 2



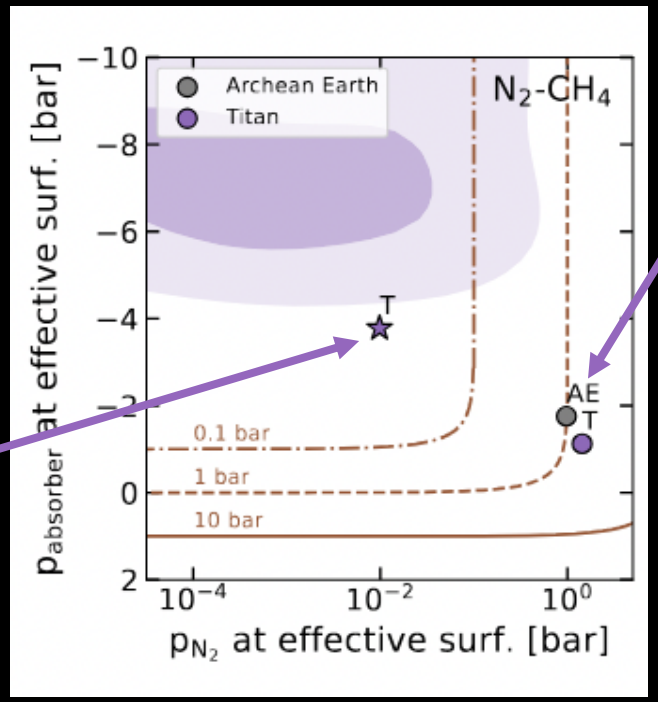


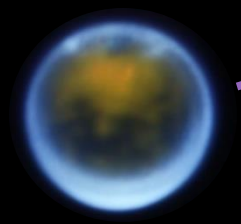
cpiaulet / stctm

Piaulet Ghorayeb et al., in prep.

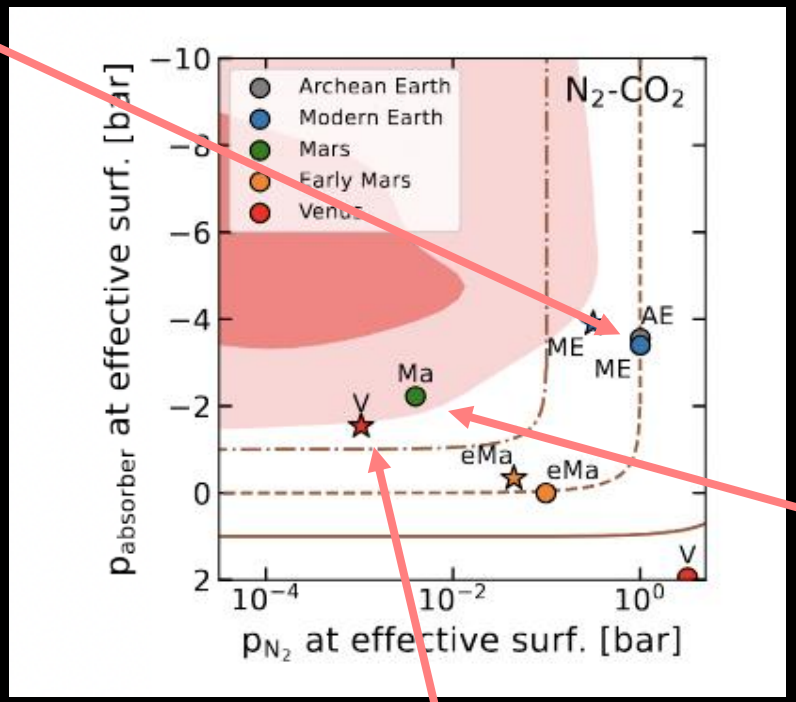
Strict limits on thin high mean molecular weight atmospheres for a 0.8 $R_\oplus$ rocky planet

Nitrogen + methane





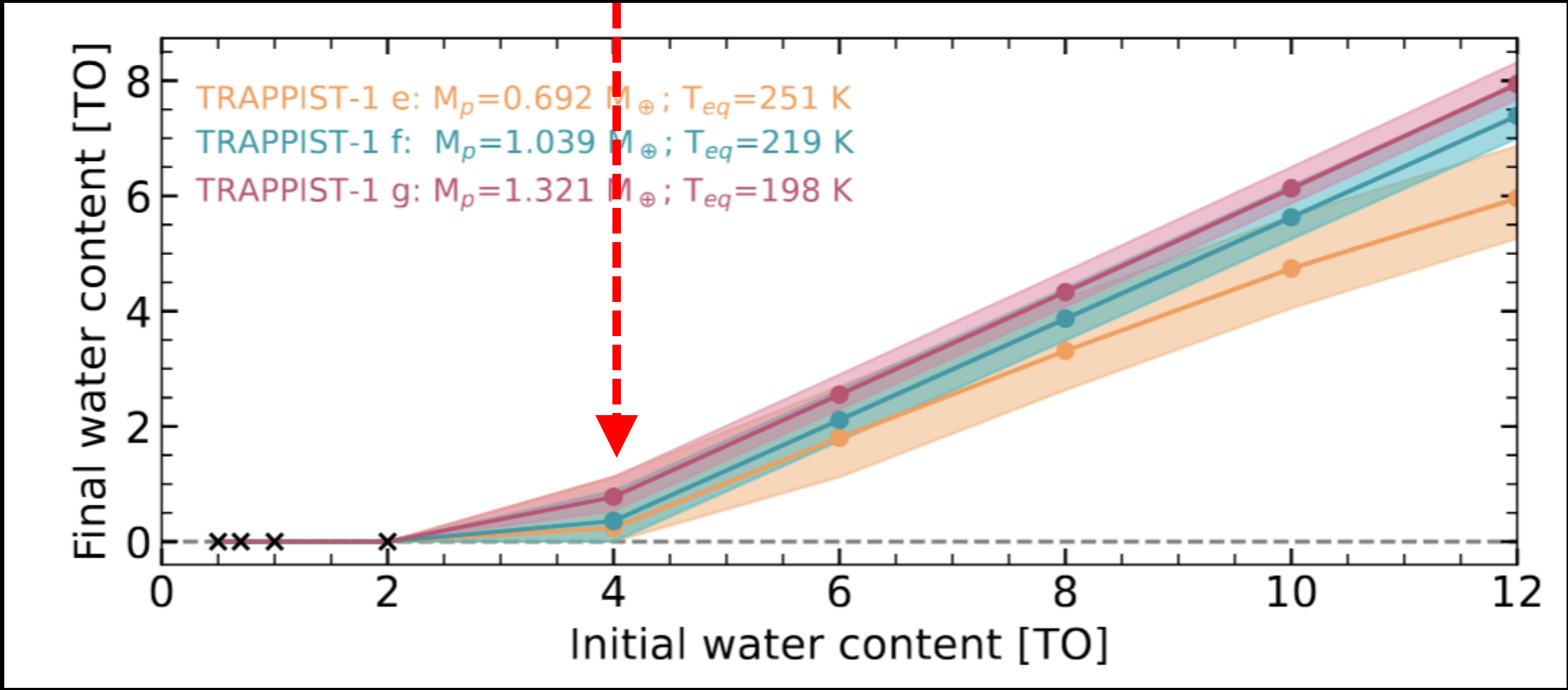
Nitrogen + carbon dioxide



Small amounts of CO_2, CH_4 similar to terrestrial planets not detected

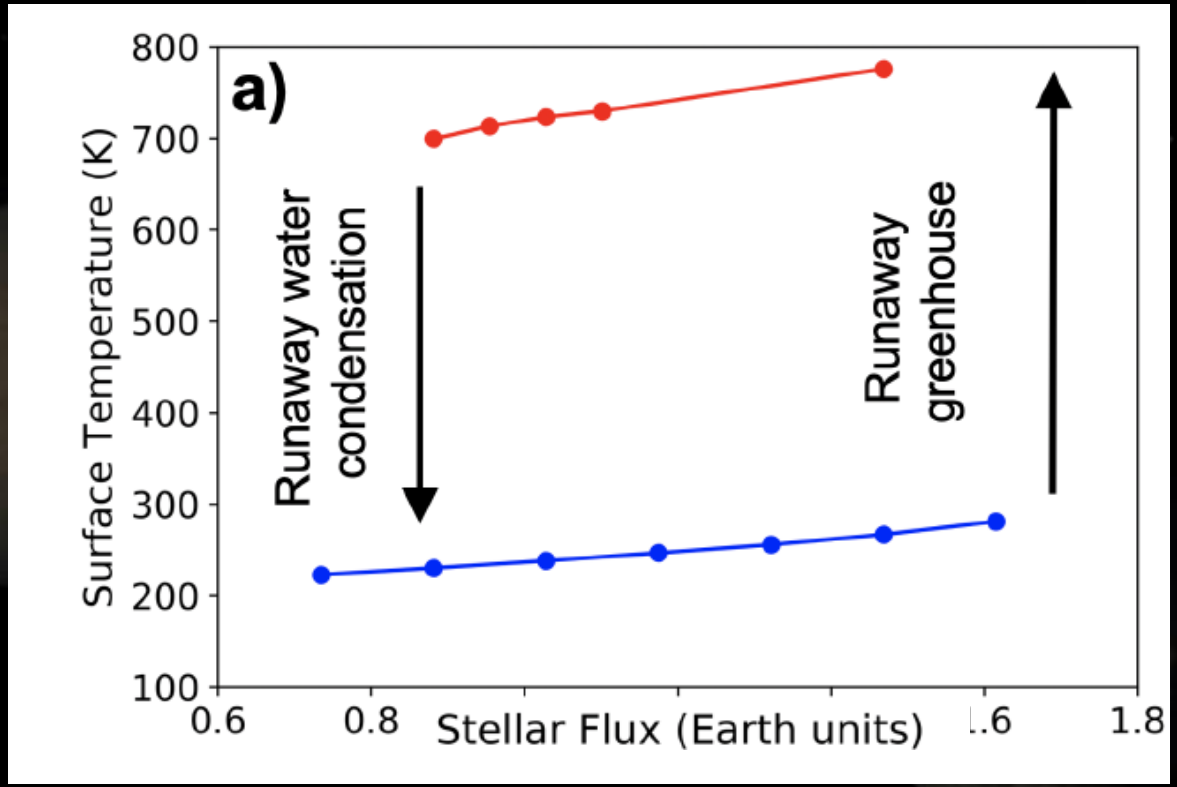
Piaulet Ghorayeb et al., in prep.

Absence of atmosphere on TRAPPIST-1 d does not preclude atmospheres on HZ planets



The case of water: TRAPPIST-1 d lies inside the water condensation zone

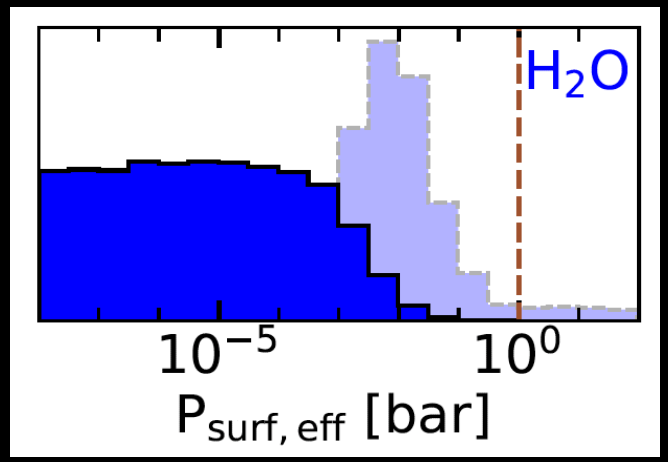
In "hot start" sceharios, water should be in the vapor form, in the atmosphere



Turbet et al. (2023)

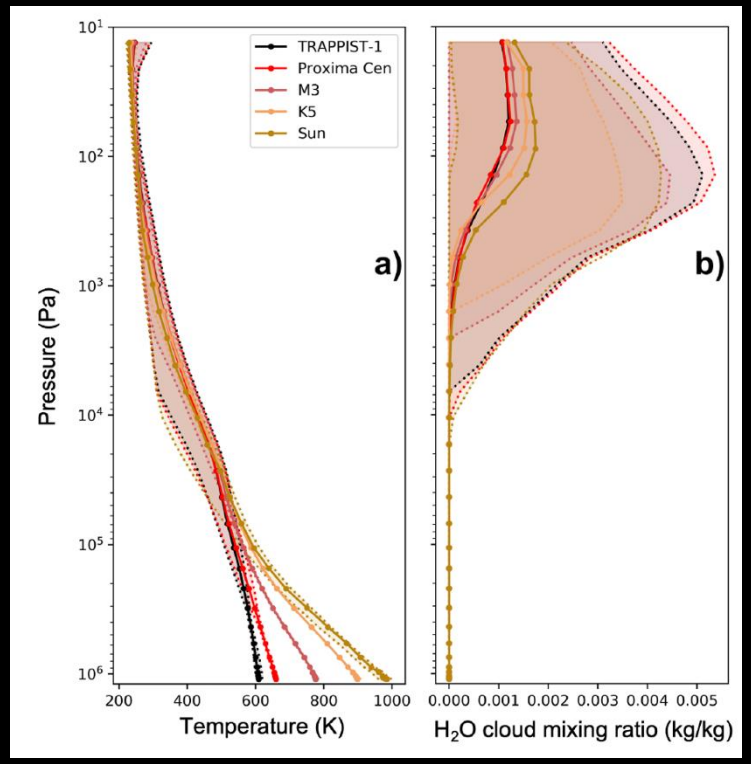
Non-detection of water in the spectrum is in line with 3D modeling predictions

Non-detection of H_2O



Piaulet-G. et al., in prep

Prediction of nightside stratospheric H_2O clouds...



Turbet et al. (2023)

... that reach the terminator as the planet approaches the HZ