Exoplanets atmospheres and habitability, JWST and beyond

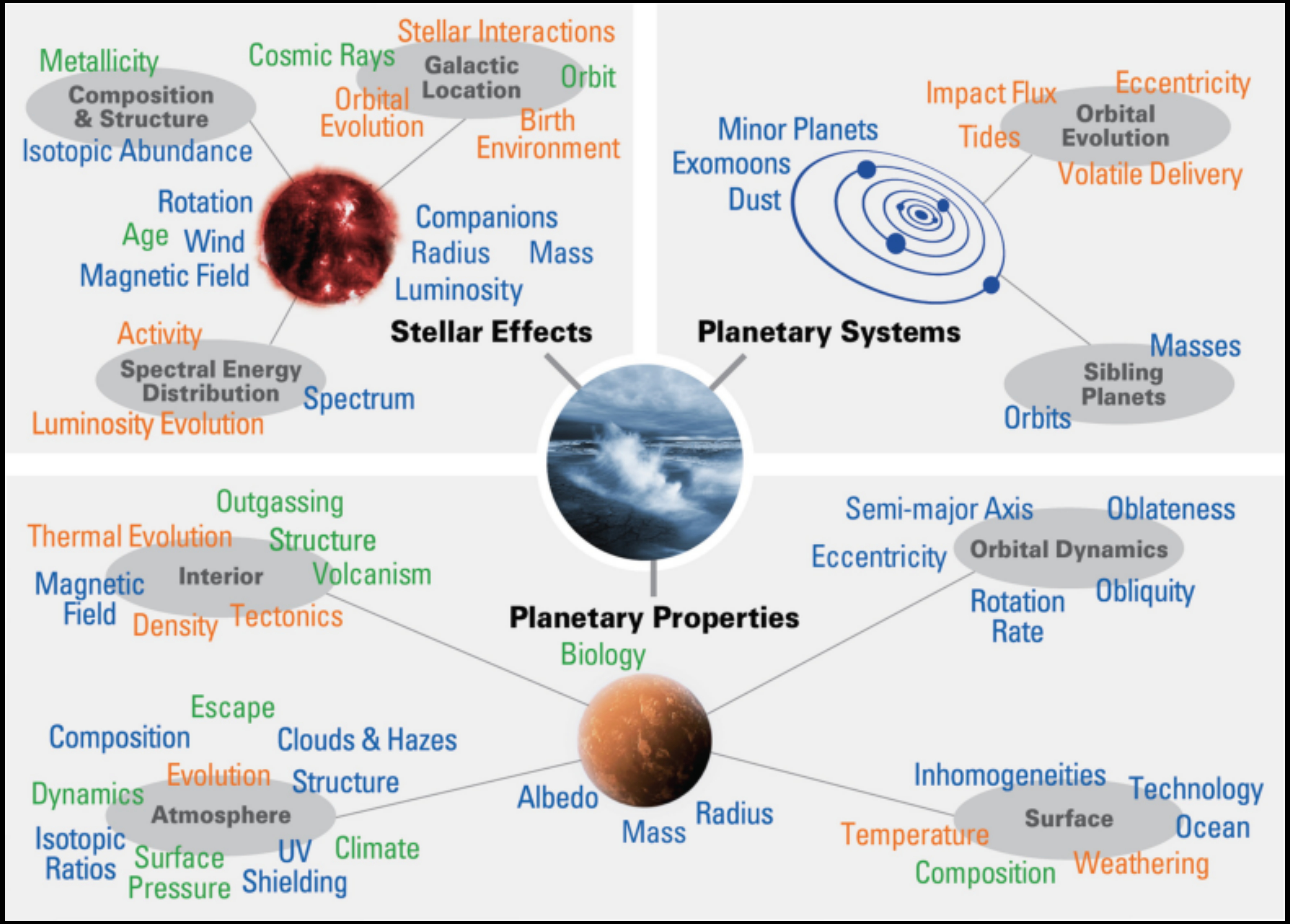
Elsa Ducrot, Franck Selsis

Credit: illustration NASA

First part: what can we learn about temperate exoplanet atmospheres in the JWST era?

Credit: Lionel Garcia

Habitability factors

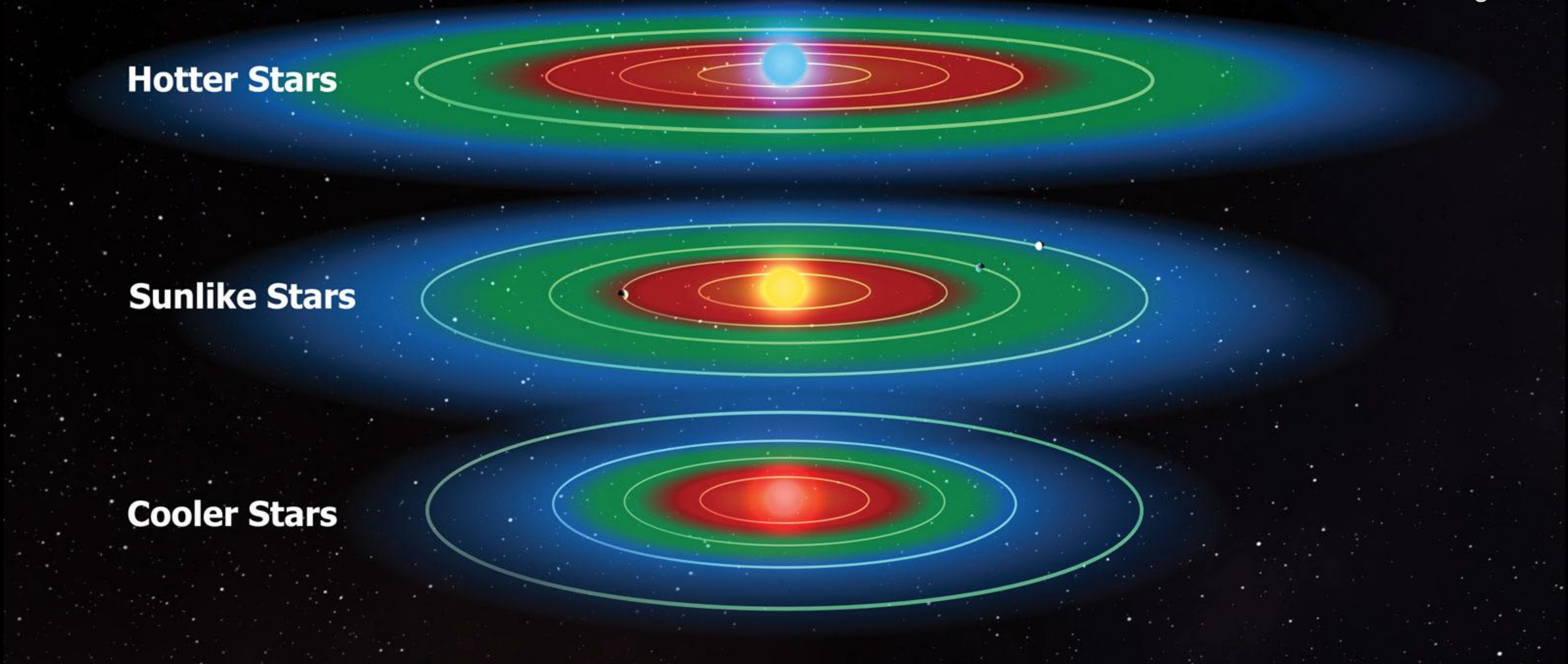


Meadows +2018

Habitable zone

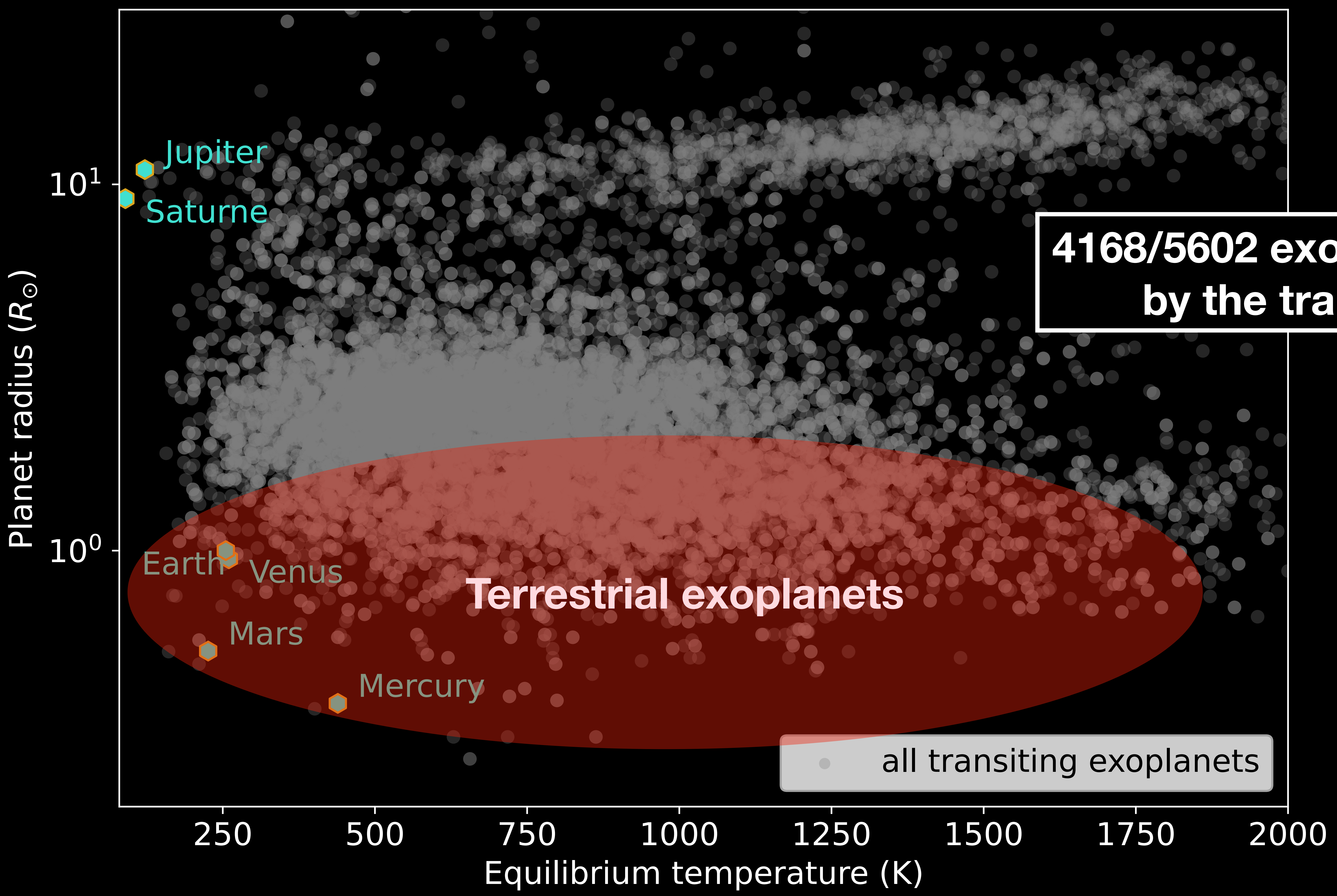
« That region around a star in which an Earth-like planet can maintain liquid water on its surface »

Kasting +1993



Credit: illustration NASA

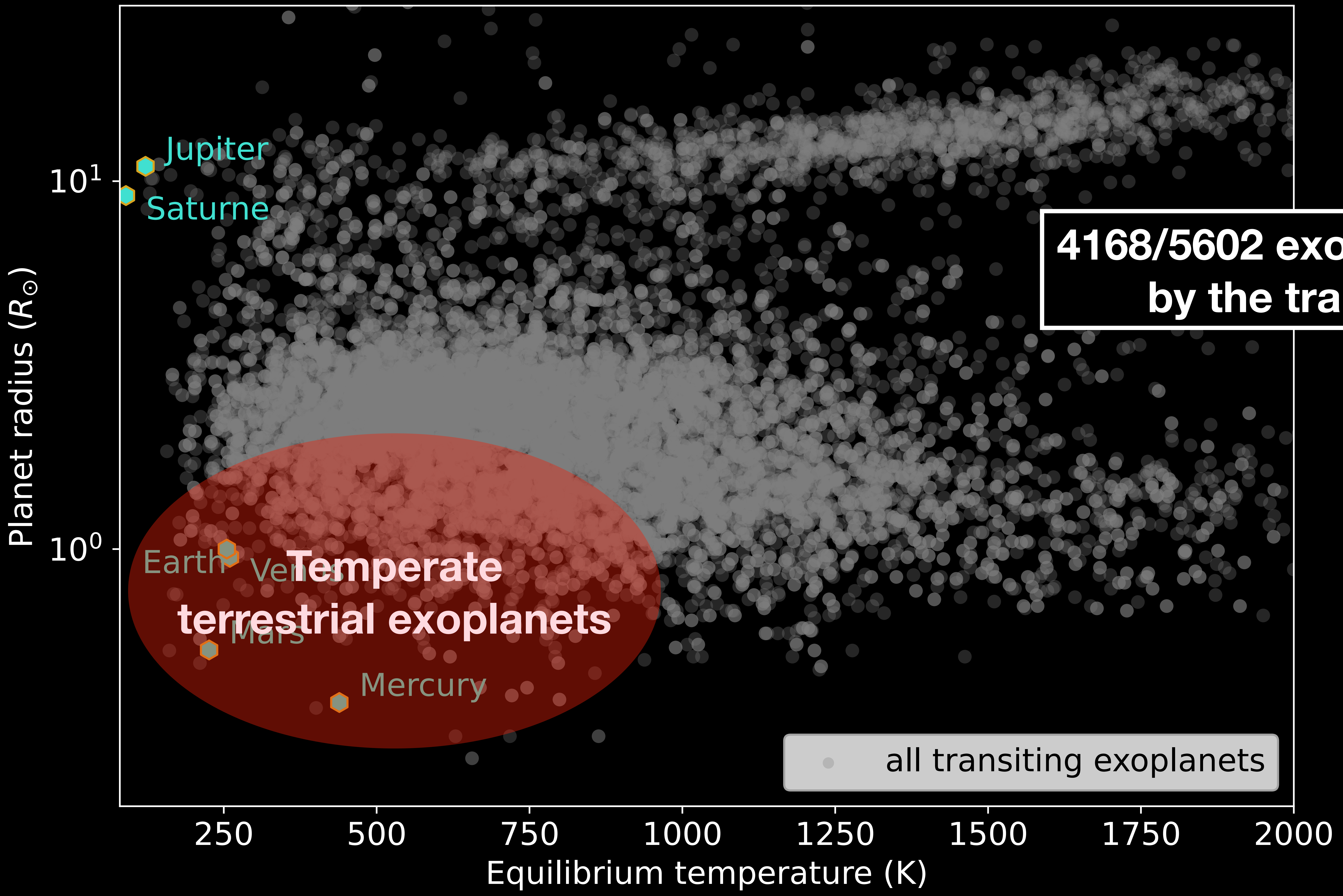
Transiting exoplanets detected



4168/5602 exoplanets detected by the transit method*

**source : NASA Exoplanet Archive (July 2024)*

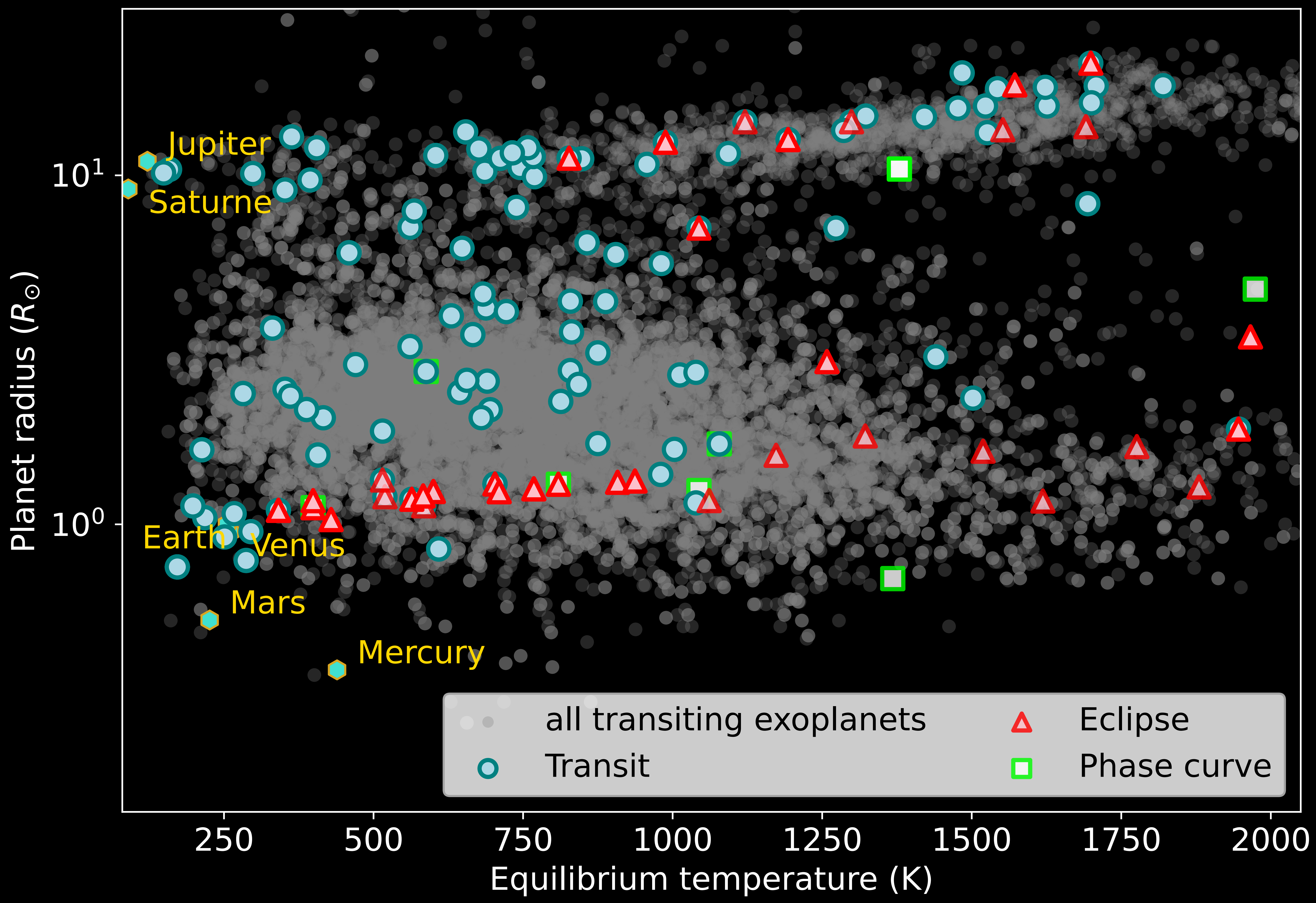
Transiting exoplanets detected



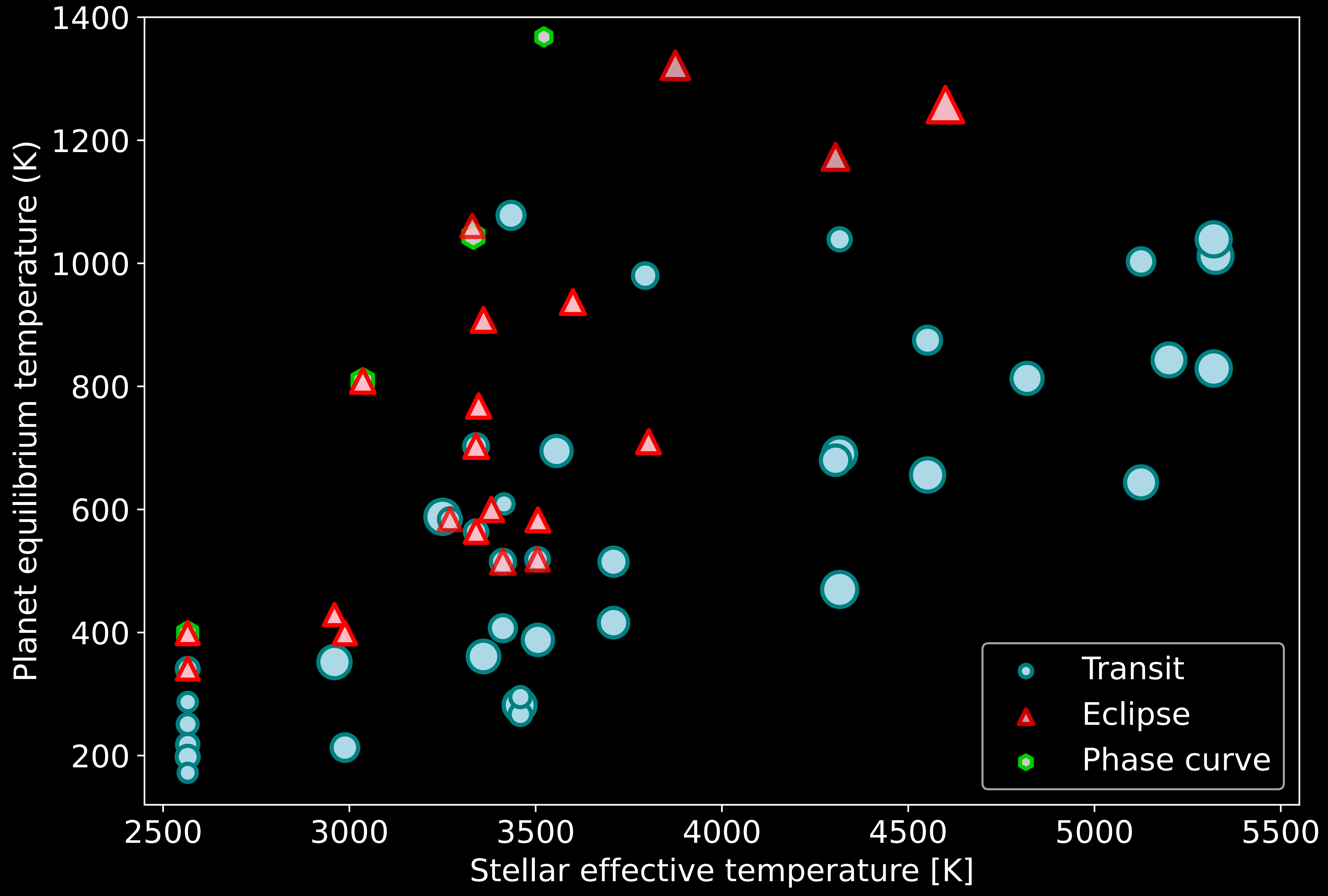
4168/5602 exoplanets detected by the transit method*

**source : NASA Exoplanet Archive (July 2024)*

Exoplanets observed with the JWST

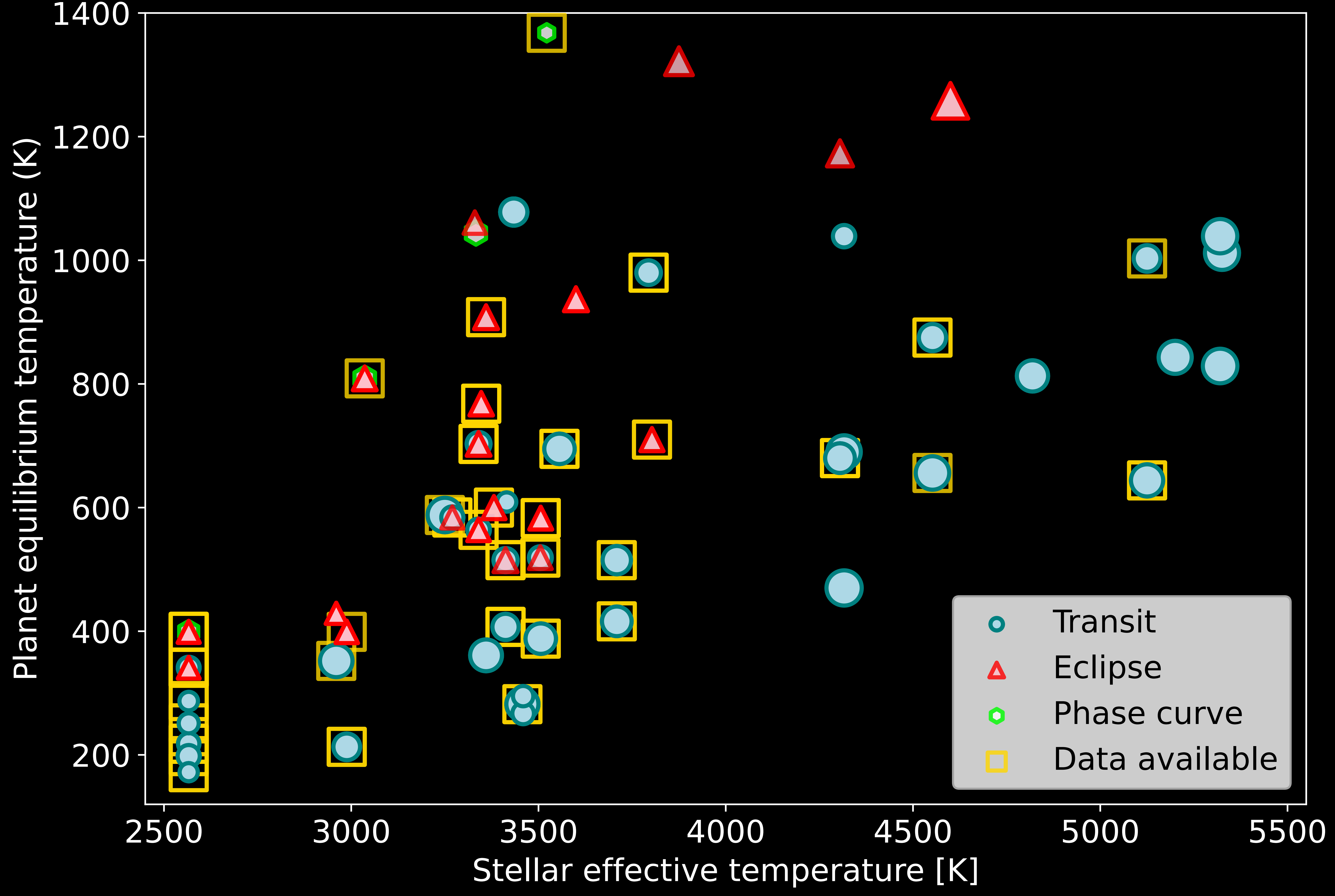


All planets with $R_p < 3\ R_\oplus$ observed with the JWST



- 50 exoplanets with $R_p < 3\ R_\oplus$ are observed with JWST
- Several in transit and eclipse for the hot rocky ones
- To study terrestrial exoplanets we have to focus on the ones around the smallest/coolest stars (late M are the best)

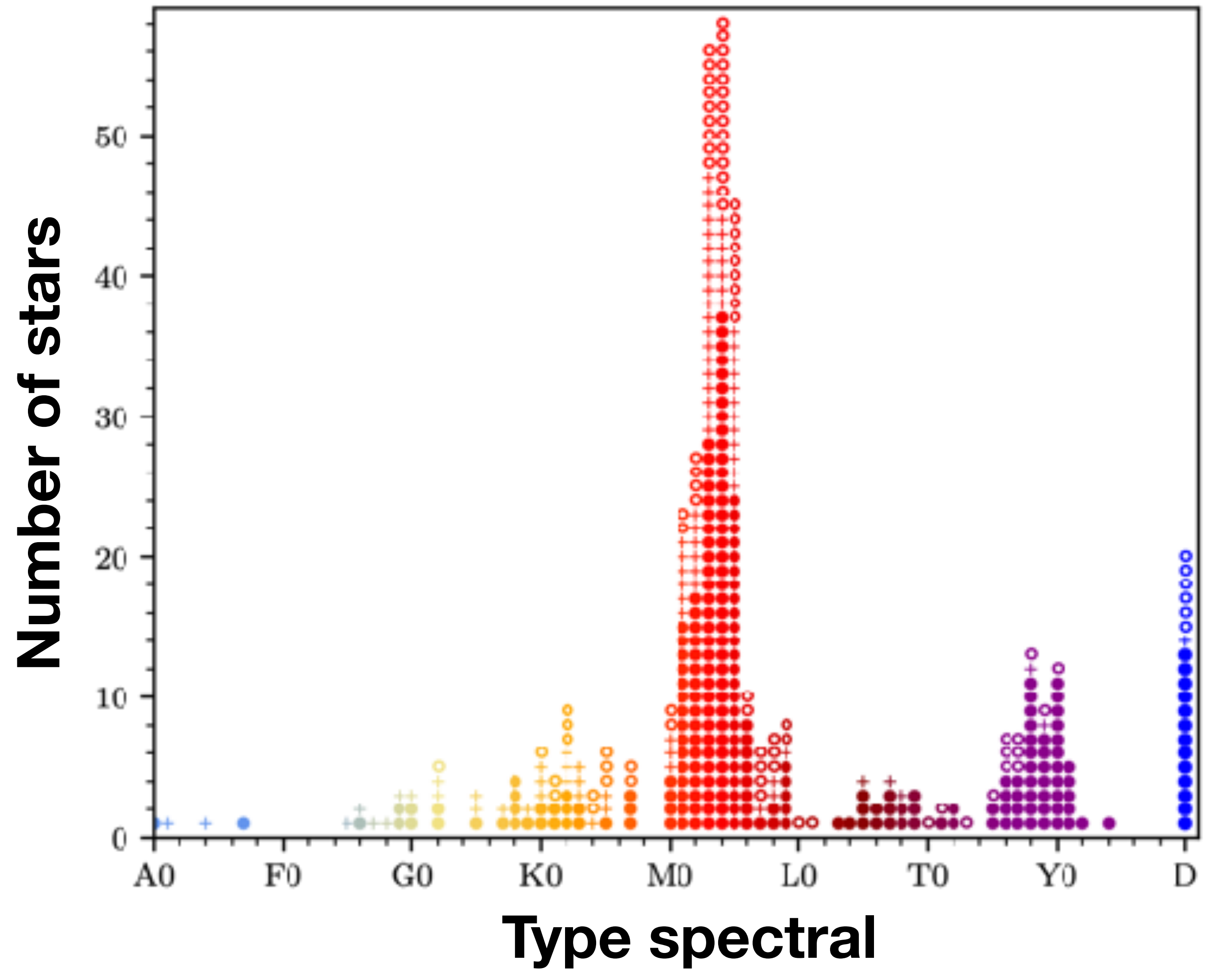
All planets with $R_p < 3\ R_\oplus$ observed, with data available



- 50 exoplanets with $R_p < 3\ R_\oplus$ are observed with JWST
- Several in transit and eclipse for the hot rocky ones
- To study rocky planets we have to focus on the ones around the smallest/coolest stars (late M are the best)
- 113 observations available on 79 distinct rocky/Super-Earth/Sub-Neptune planets

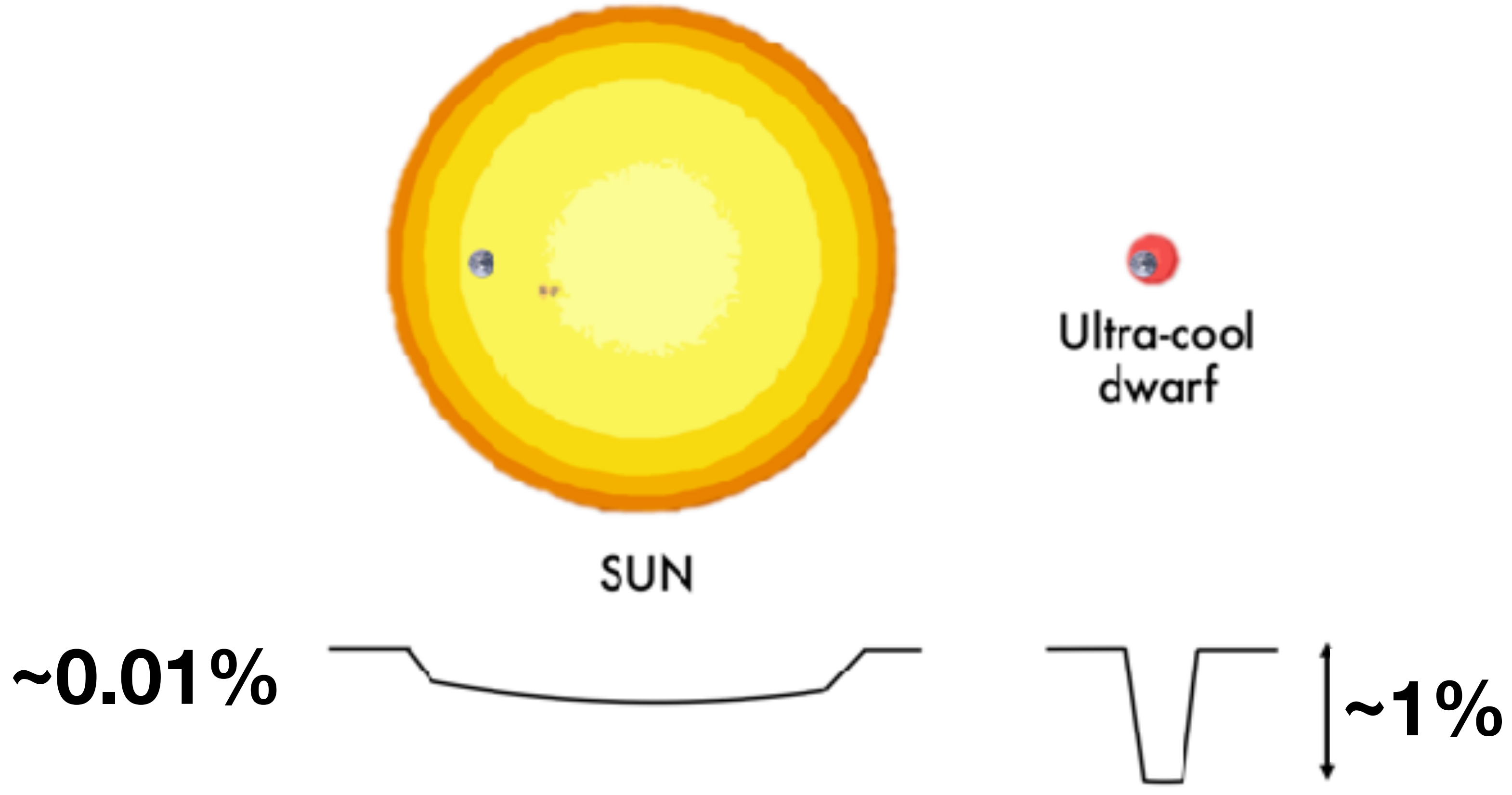
Why M-dwarfs stars?

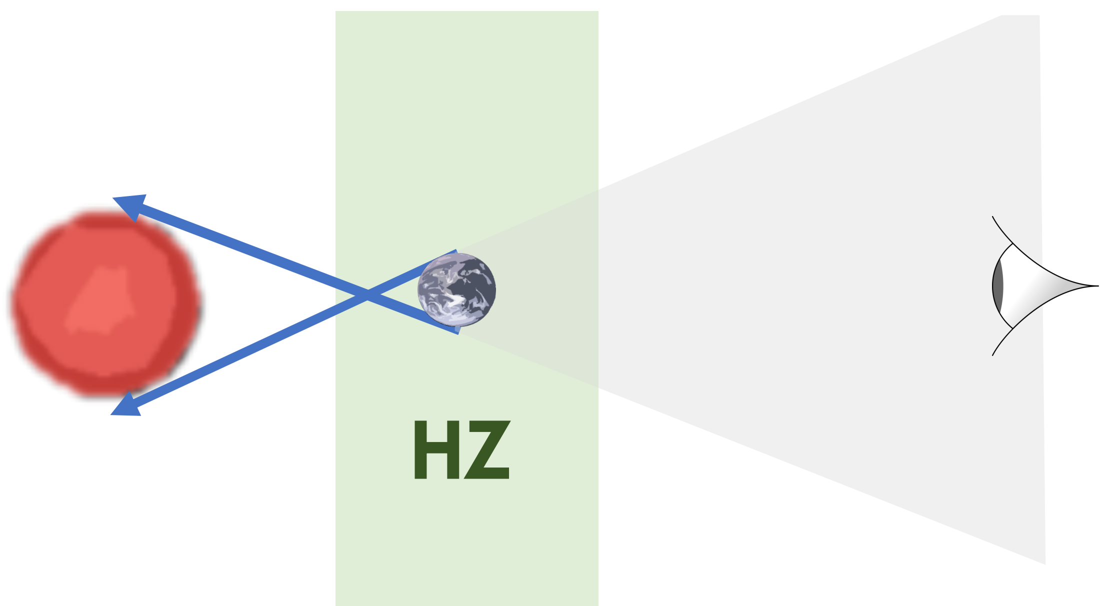
More common



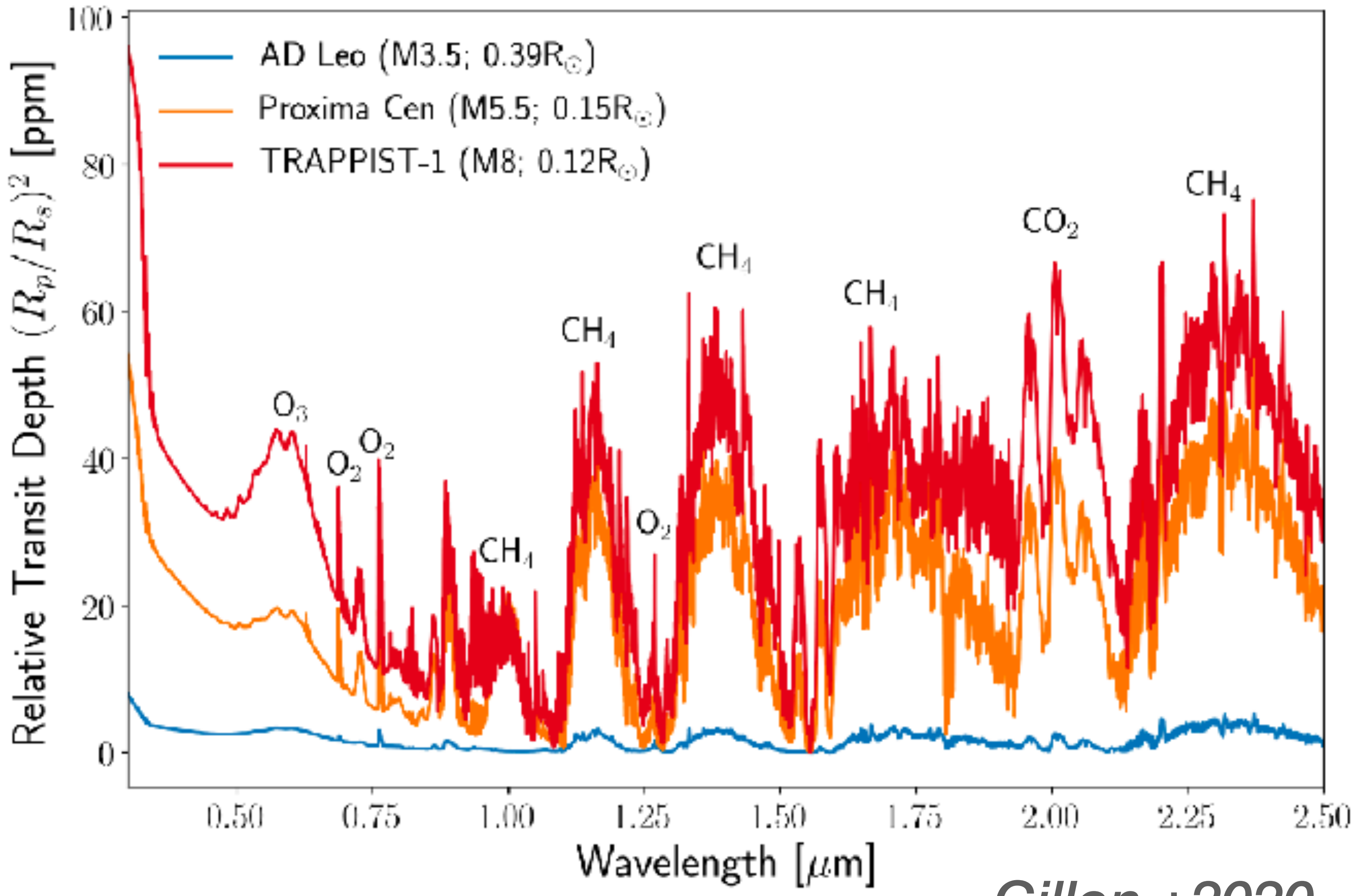
+ Rocky planets more frequent*

Easier to detect rocky planets





Easier to characterize the planet **

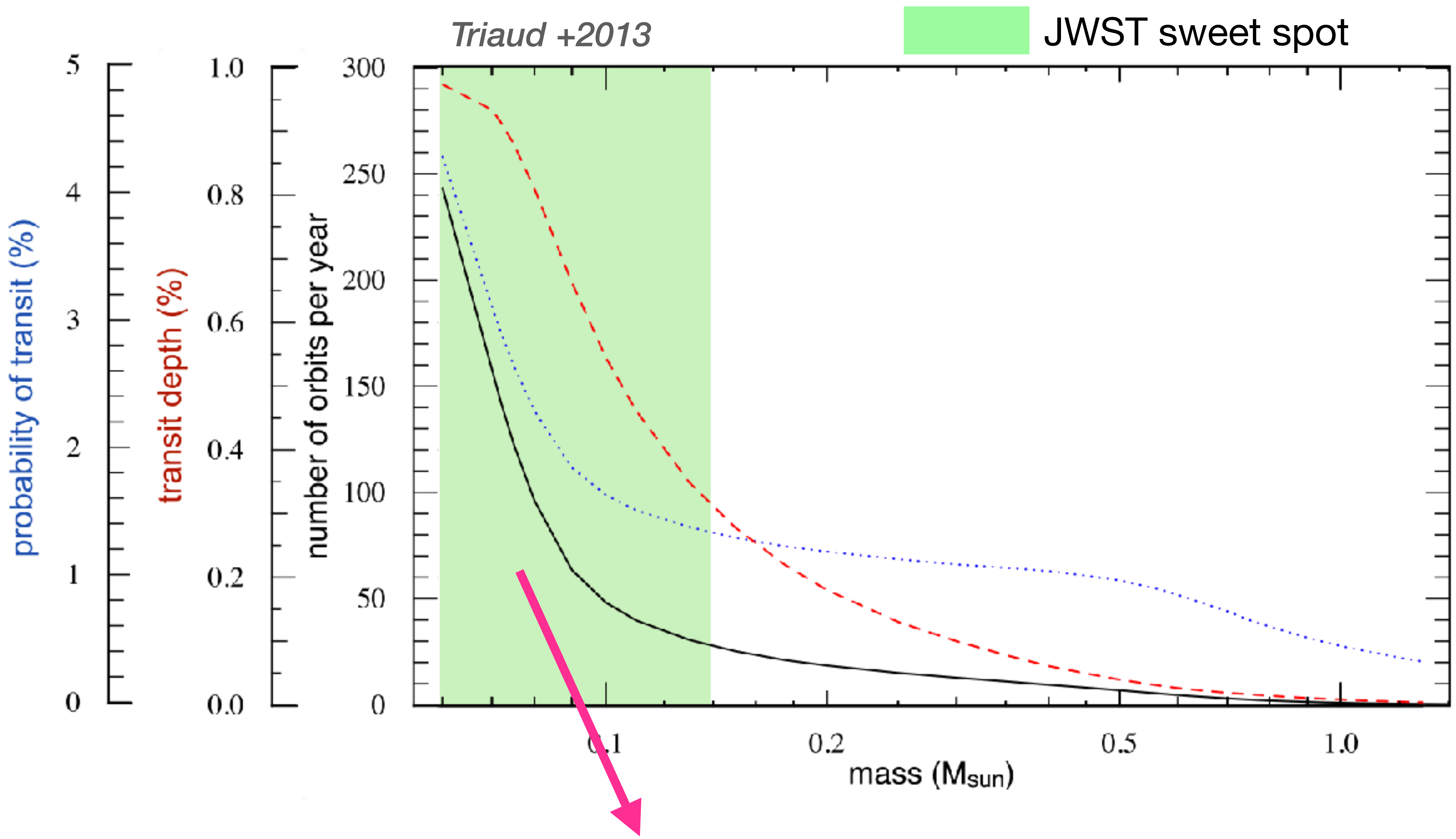


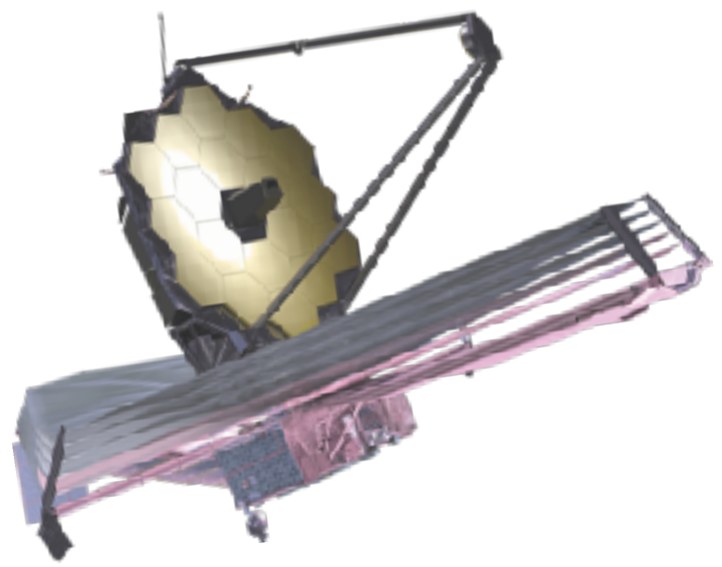
Gillon +2020

* *Pinamonti et al. 2022*

* *Wunderlitch et al. 2018*

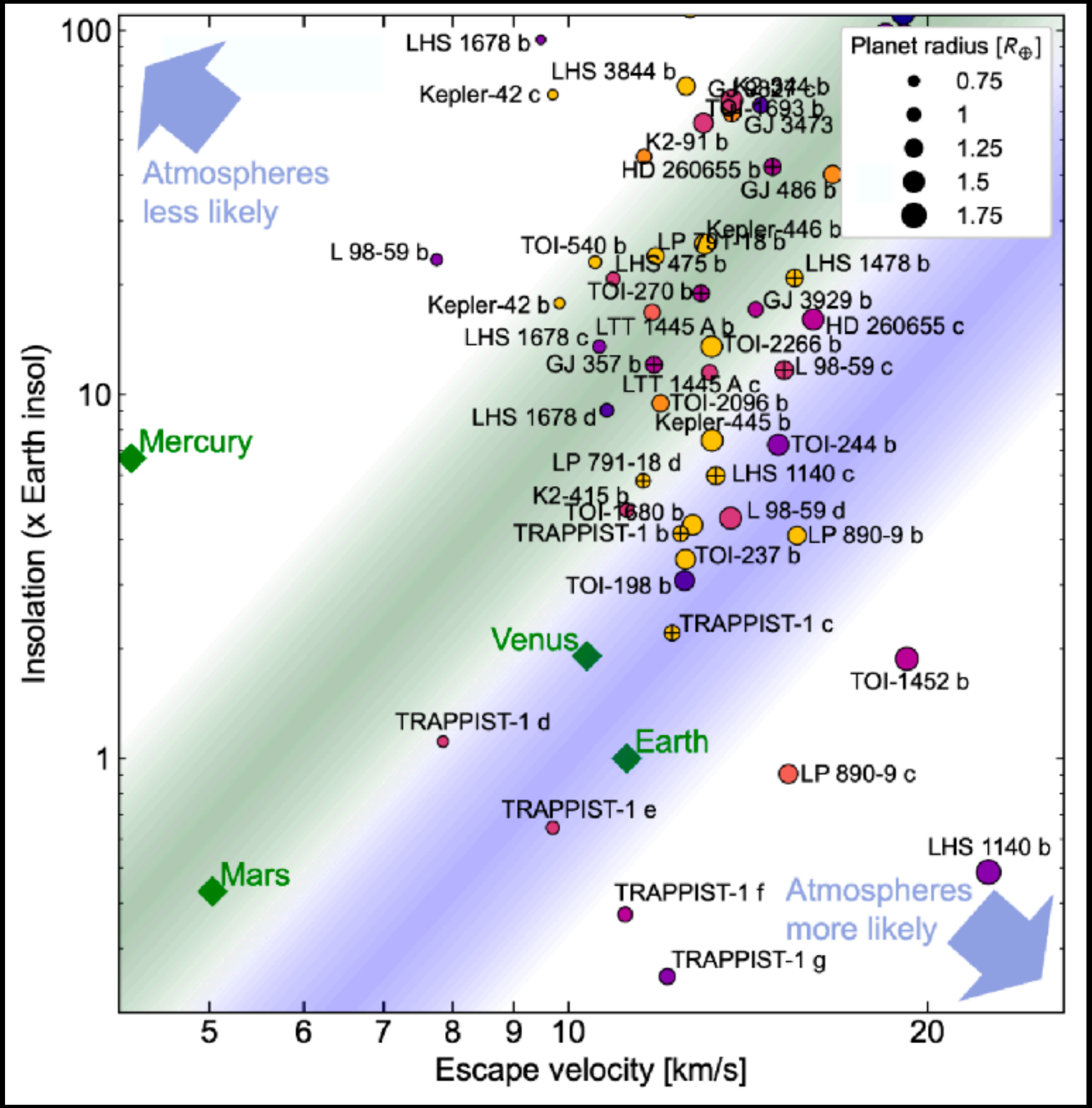
The JWST opportunity





- Any planet found in the HZ one of these cool stars becomes a prime target for characterization with the James Webb space telescope (JWST)

The big questions



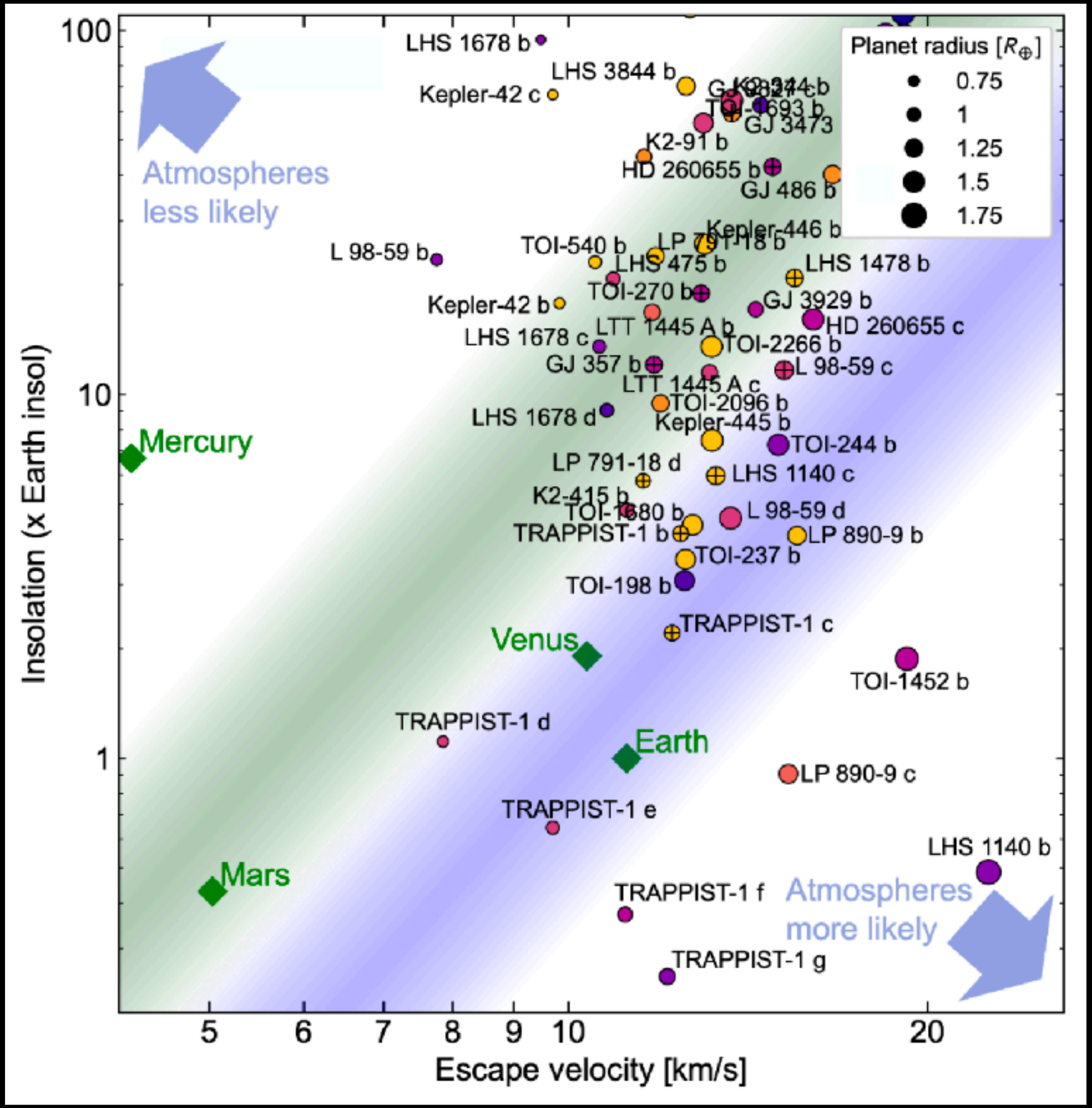
Redfield et al. 2024

<u>The cosmic shoreline:</u> empirical boundary that distinguishes planets likely to retain an atmosphere from those that are not based on their atmospheric escape velocities (~gravity) and insolation

Concept presented in Zahle & Catling 2017

* does not account for the fact that planet orbiting M-dwarf stars have different inherent properties

The big questions



Redfield et al. 2024

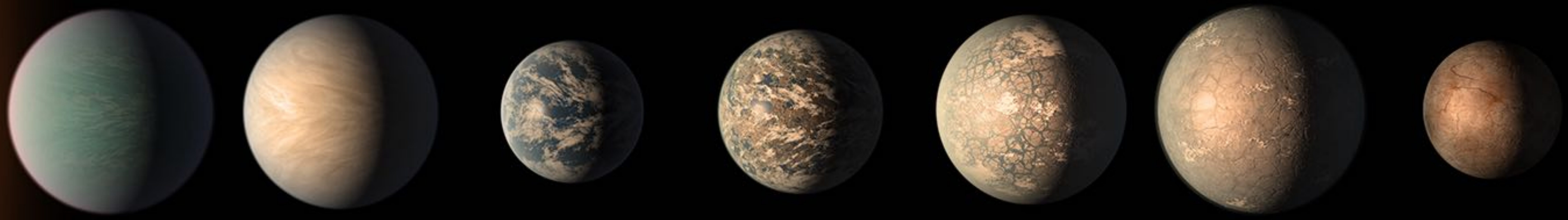
1. Is the concept of the cosmic shoreline real?
2. The environments of M-dwarf stars are very different… Can rocky planets around them keep an atmosphere?
3. If they kept an atmosphere ? What is it made of ?
4. If they did not, what can we learn about their surface composition ?
5. What are temperate super-Earths and Sub-Neptunes made of ? How could this explain the Fulton gap ?

Thanks to **JWST** it is now possible to address these questions observationally **for the first time** !


Results on Earth-sized rocky planets
Credit: NASA

TRAPPIST-1

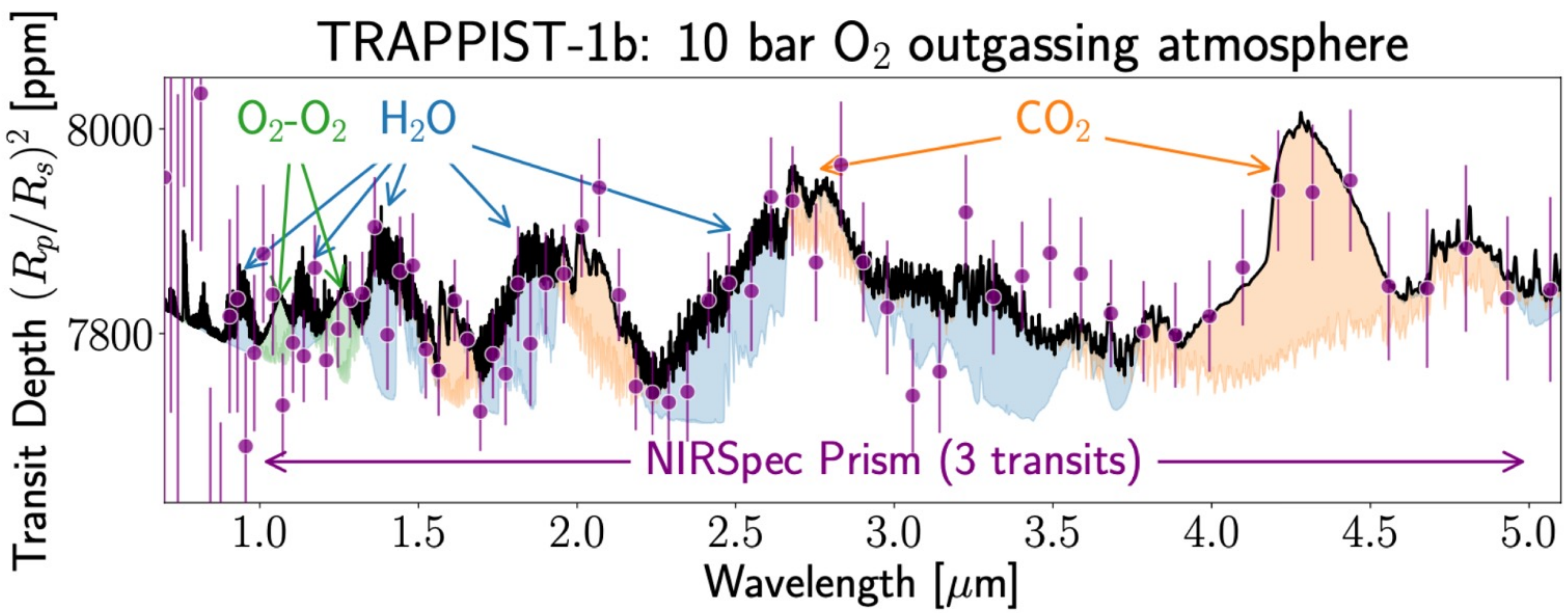
- 7 planets with masses, radii, insolation similar to the terrestrial planets in the solar system
- Coolest host star known to date -> the best temperate rocky targets for JWST



- >240 peer reviewed papers in only 7 years
- 11 JWST programs in transmission, emission and phase curve
- ~300 hr of JWST time on the TRAPPIST-1 planets acquired or planned

Credit: NASA
Gillon +2017

Example 1, TRAPPIST-1 b:

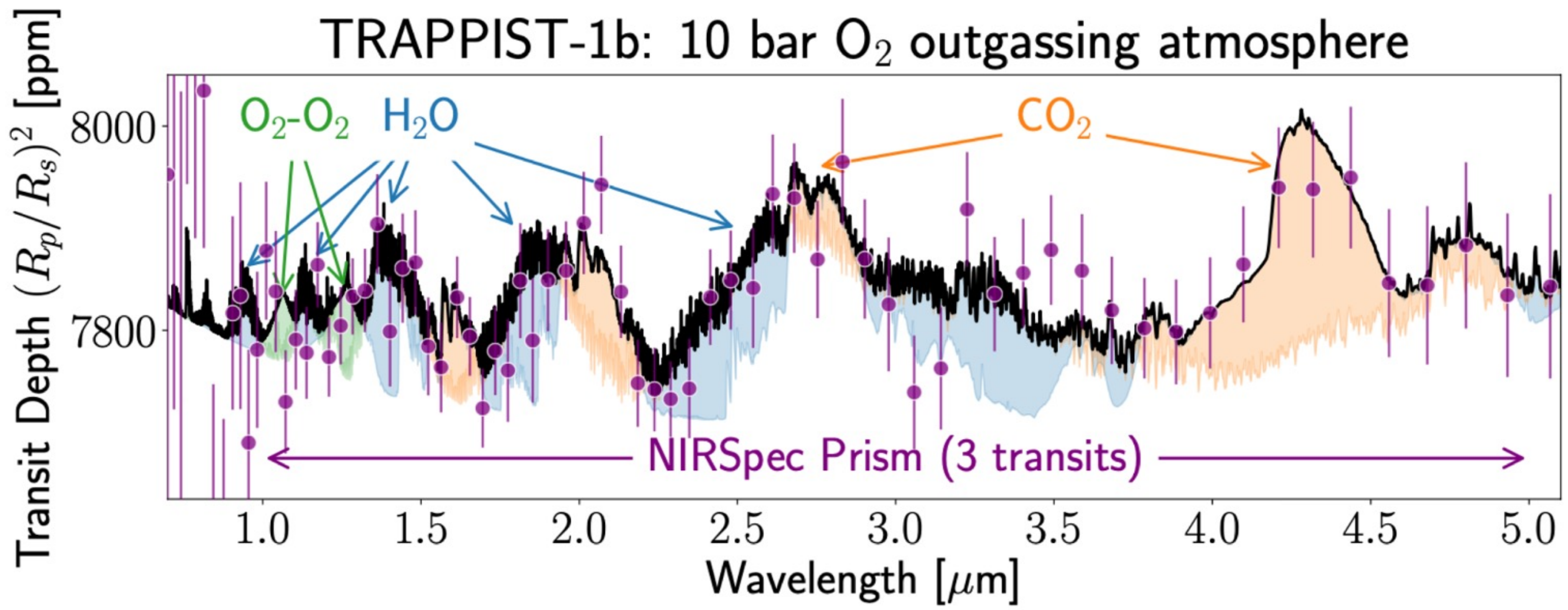


Lustig-Yaeger et al. 2019

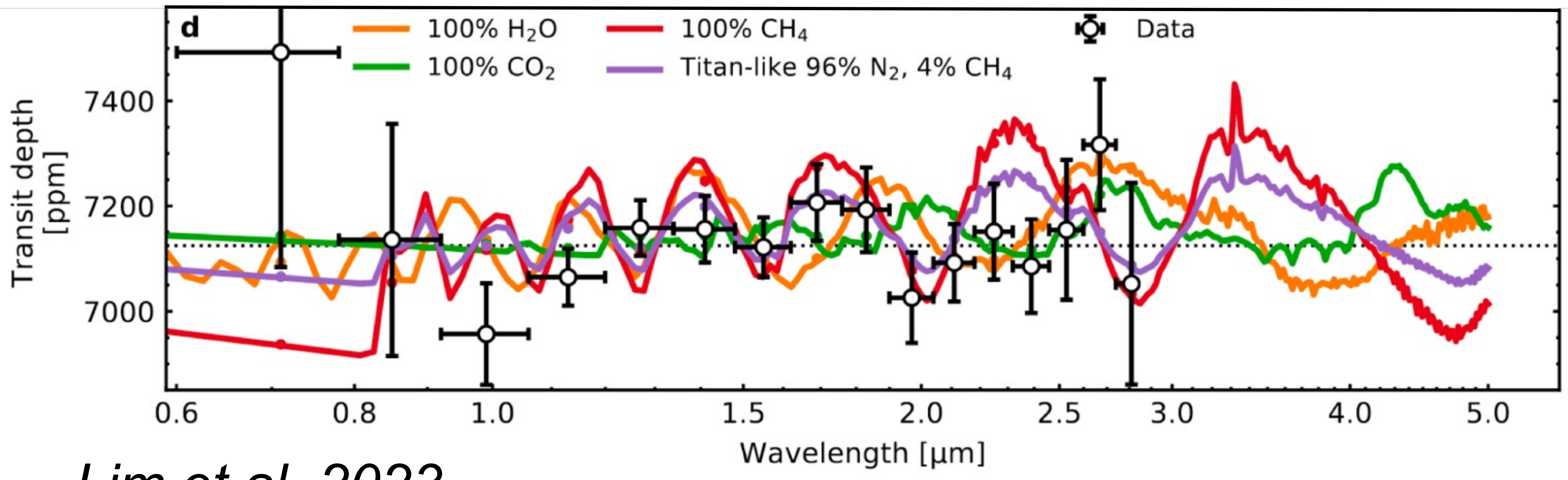
Predictions:

- Pre-launch predictions suggested we should be able to detect CO2 feature on TRAPPIST-1 b in transmission with only a couple of transits
- **But this is without accounting for the impact of stellar contamination**

Example 1, TRAPPIST-1 b:



Lustig-Yaeger et al. 2019



Lim et al. 2023

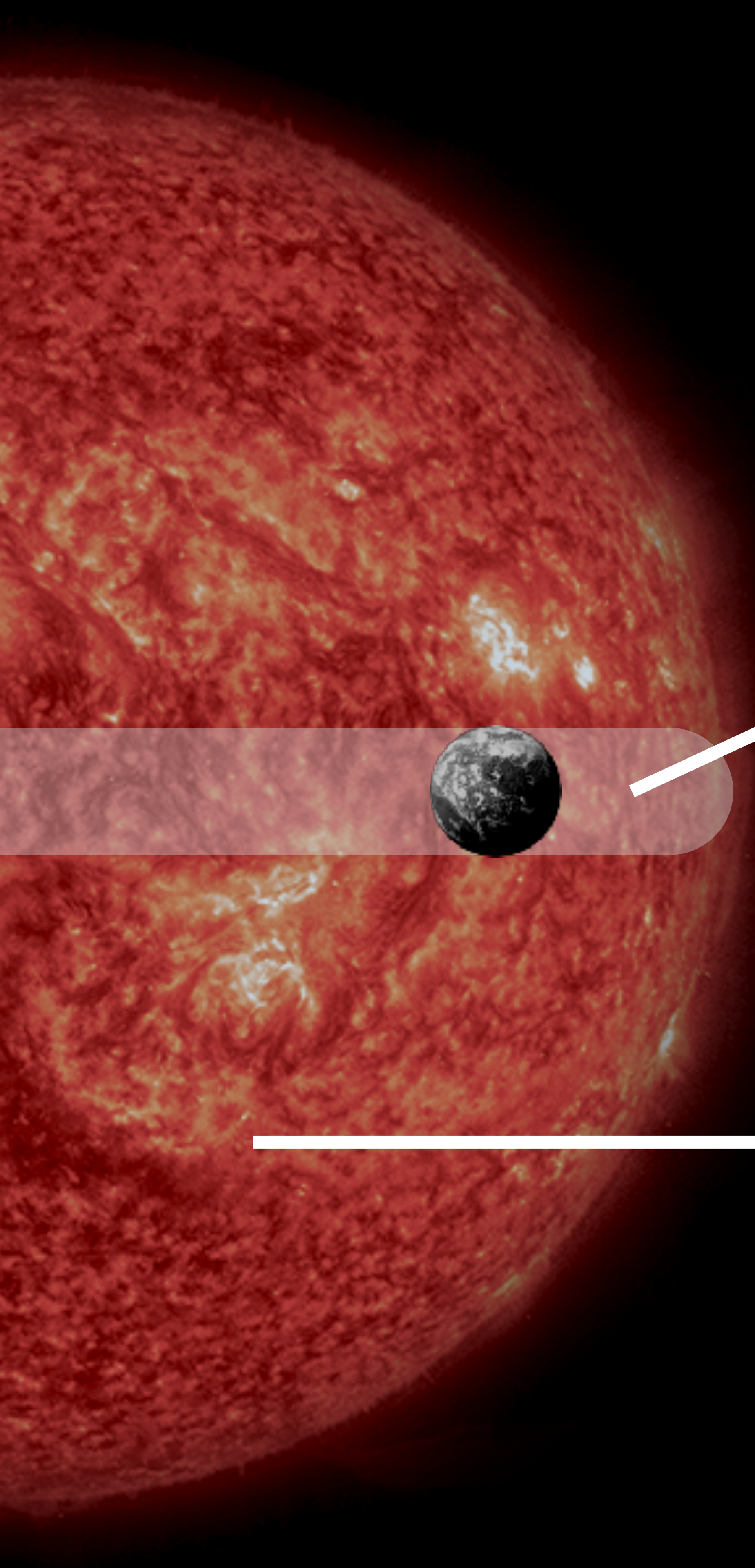
Predictions:

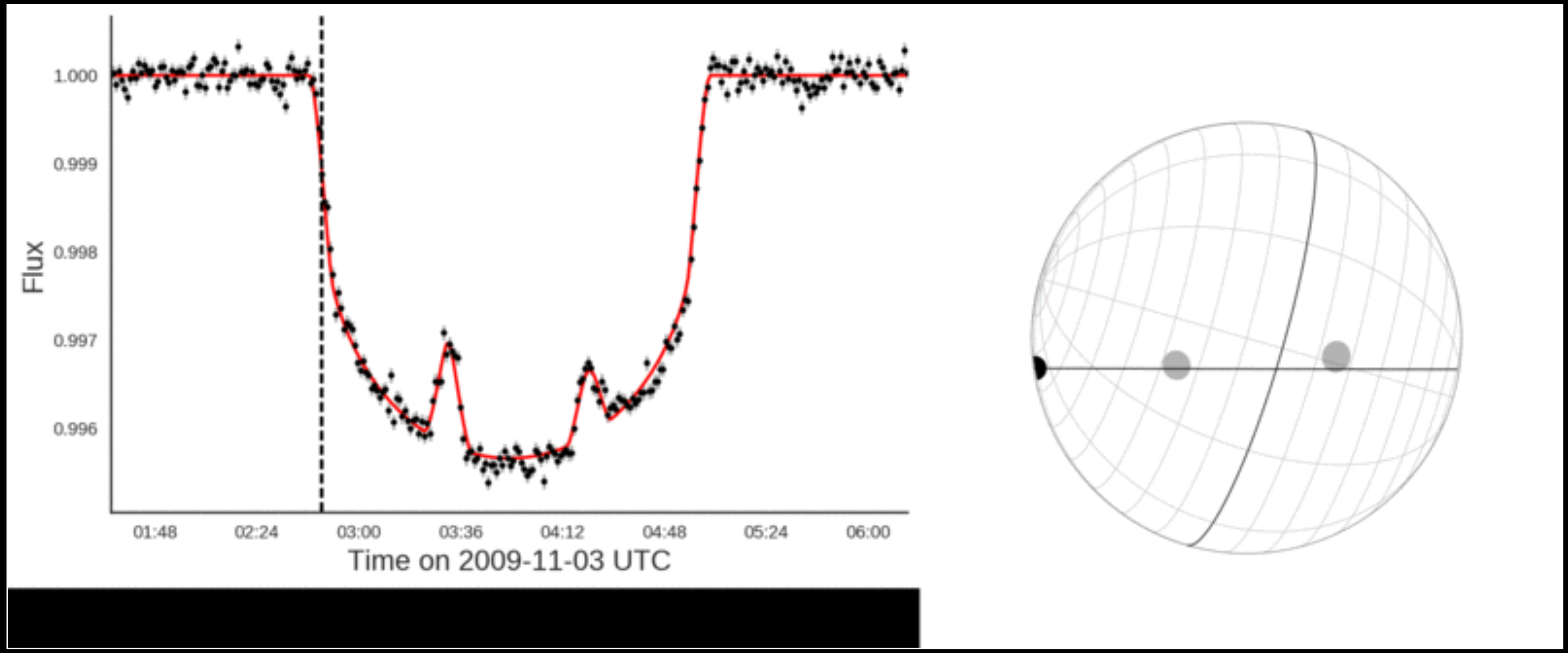
- Pre-launch predictions suggested we should be able to detect CO2 feature on TRAPPIST-1 b in transmission with only a couple of transits
- **But this is without accounting for the impact of stellar contamination**

Reality:

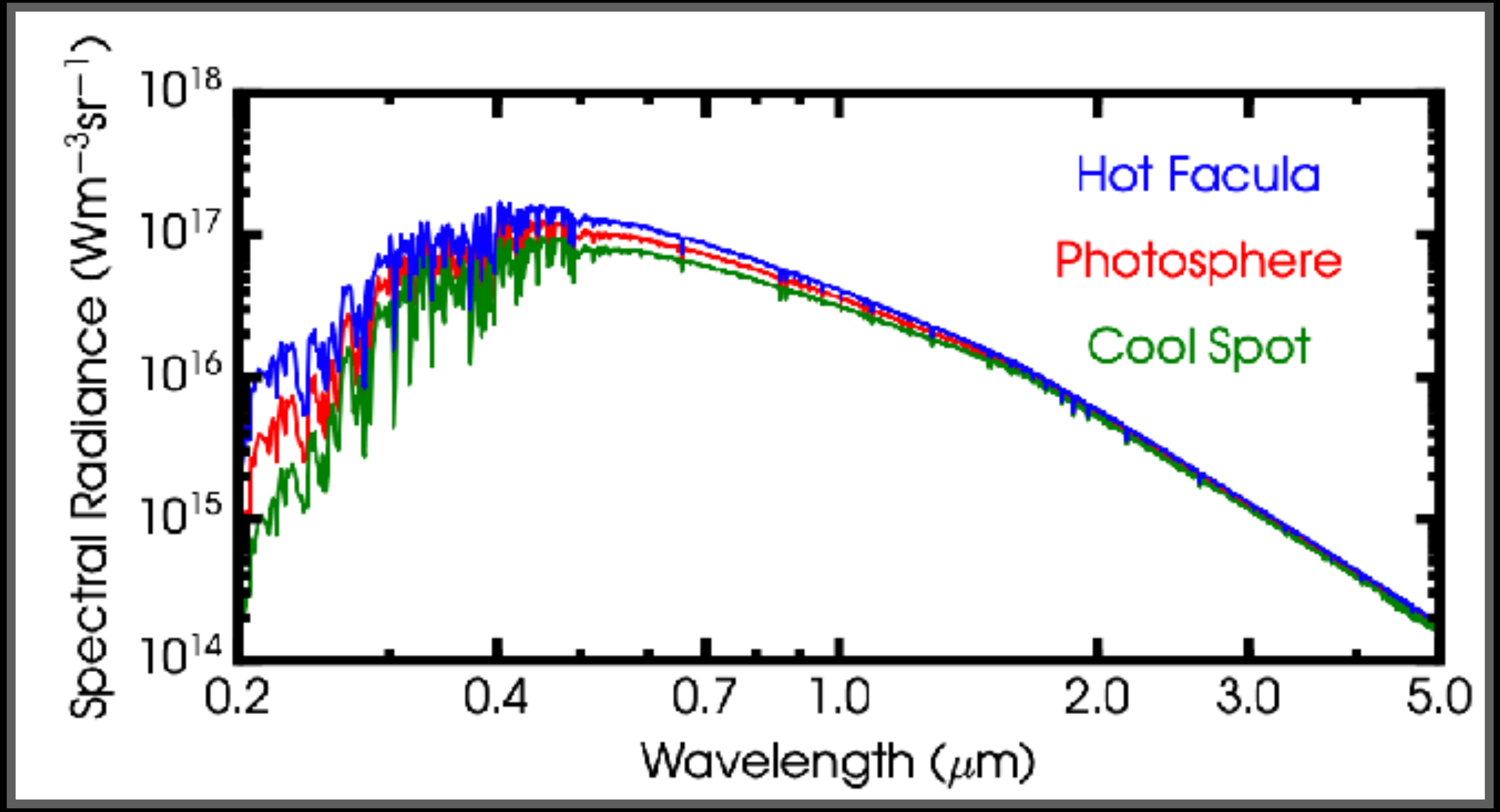
- Cool stars have heterogeneous photospheres leading the stellar contamination in the transmission spectra of the planets
- This creates spectral features that can mimic the presence of an atmosphere
- The size, coverage, and spectra of these heterogeneities are unknown and therefore very hard to model

Stellar contamination in transmission



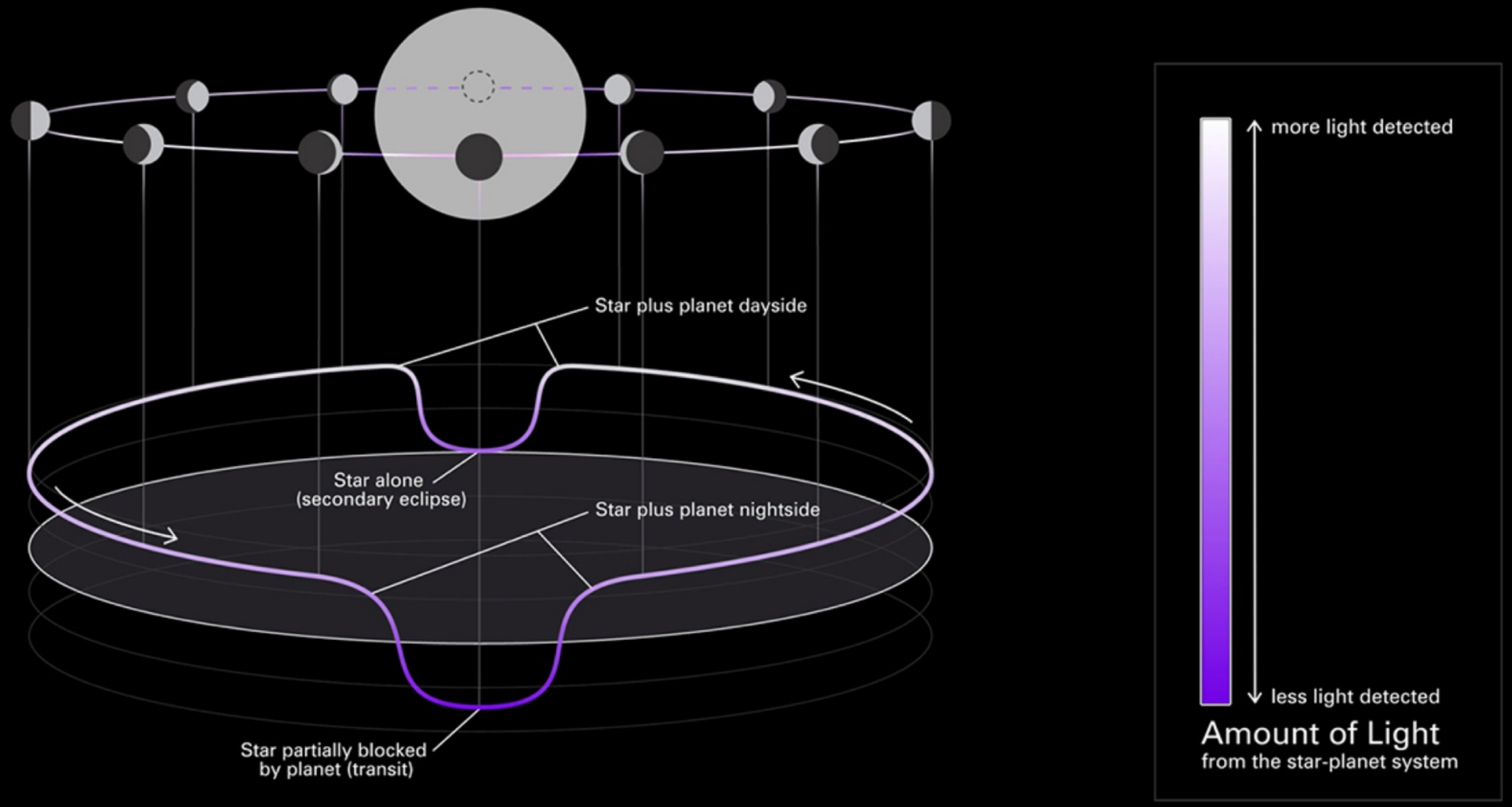


Courtesy of Brett Morris



Pinhas et al. 2018

Emission to the rescue:



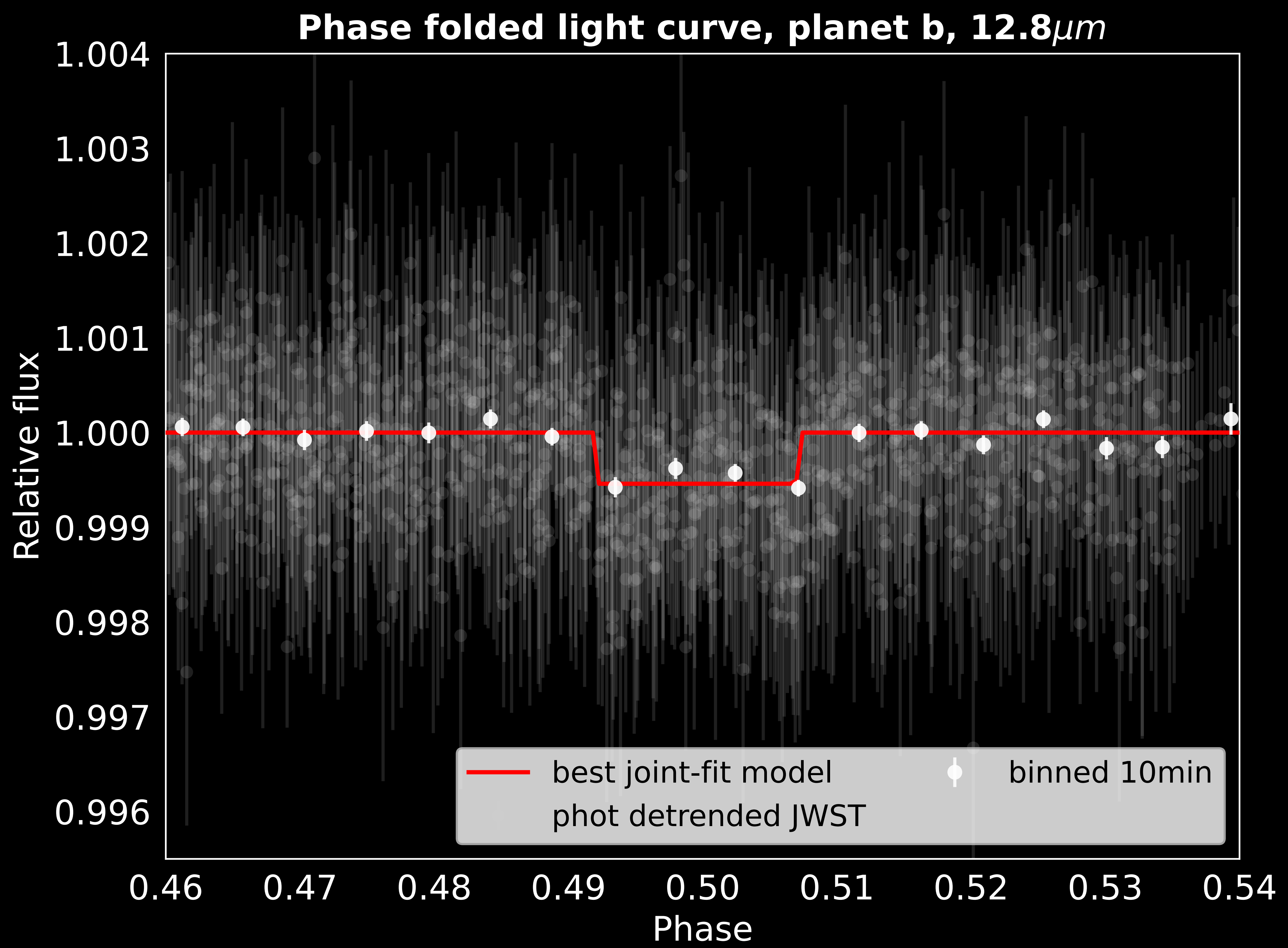
Aims:

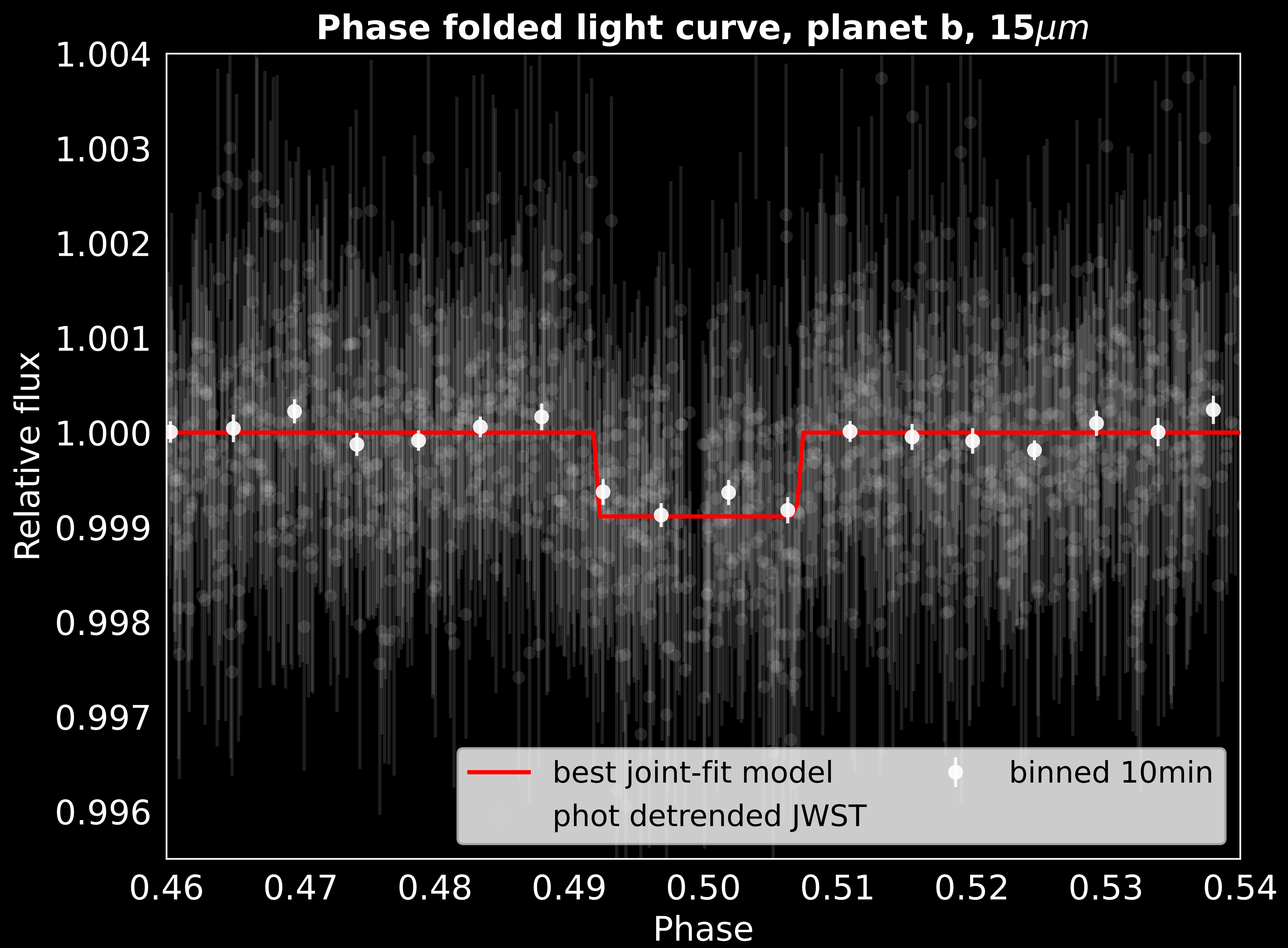
- Measure secondary eclipse (occultation) depth to infer the planetary flux
- Feasible on rocky temperate planets only with JWST Mid-IR capabilities
- Measure the flux in various broadband filters to infer if an atmosphere is present or not

On TRAPPIST-1 planets:

- Only b and c so far because warm enough
- 5 visits at 12.8 microns
- 5 visits at 15 microns
- A double phase curve of b+c

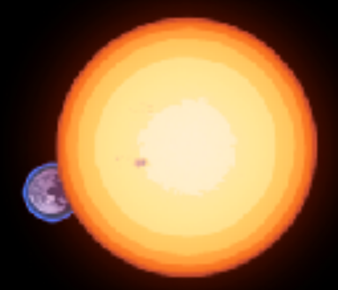
TRAPPIST-1 b, observations with the JWST

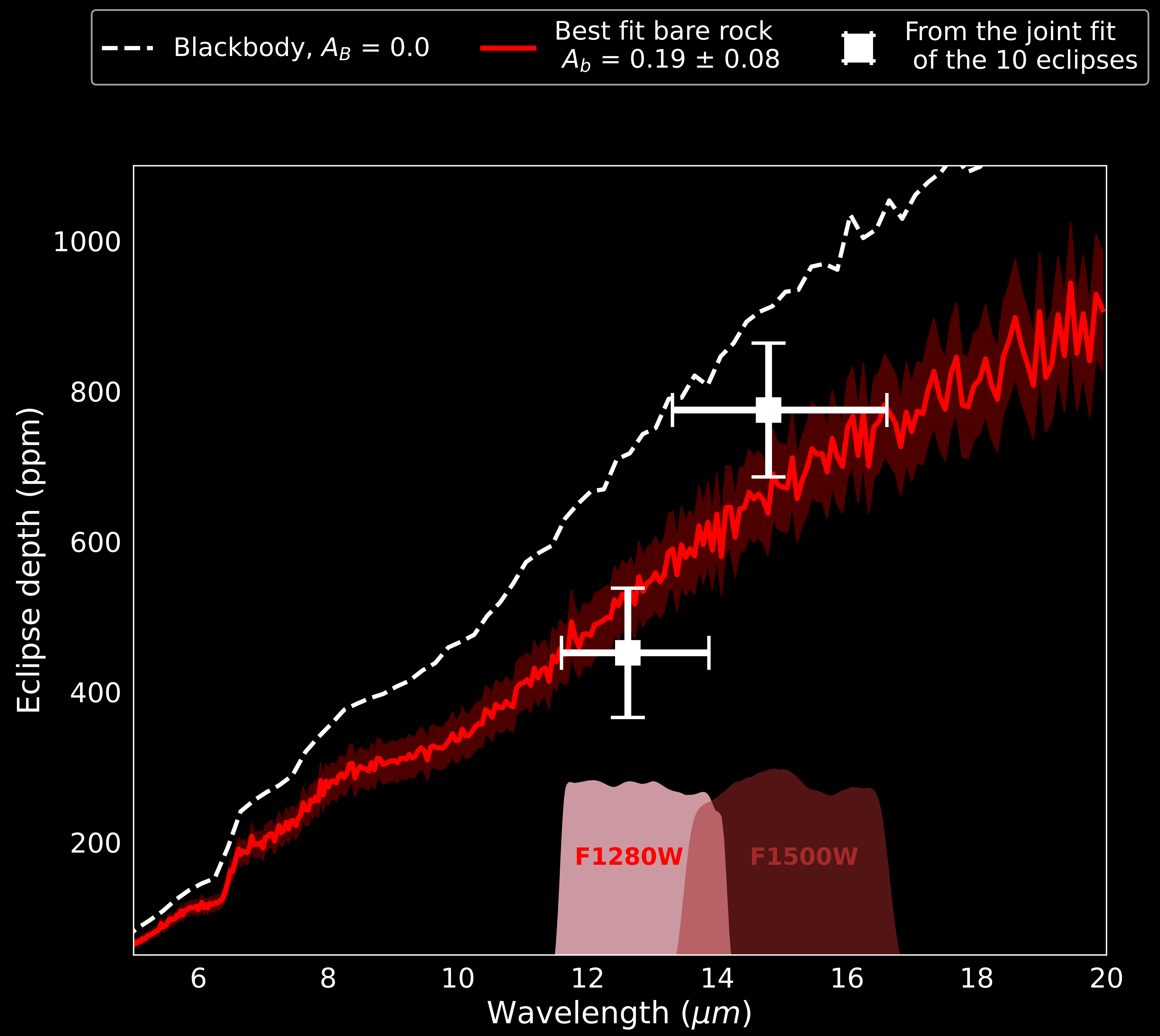




- Proceeded to a joint fit of the 10 eclipses to better constrain the orbital parameters of the planet
- The occultation at 12.8 microns and 15 microns are detected as planned but we see the opposite of a CO2 absorption: larger depth at 15 microns than at 12.8 microns.

Thermal emission of TRAPPIST-1 b

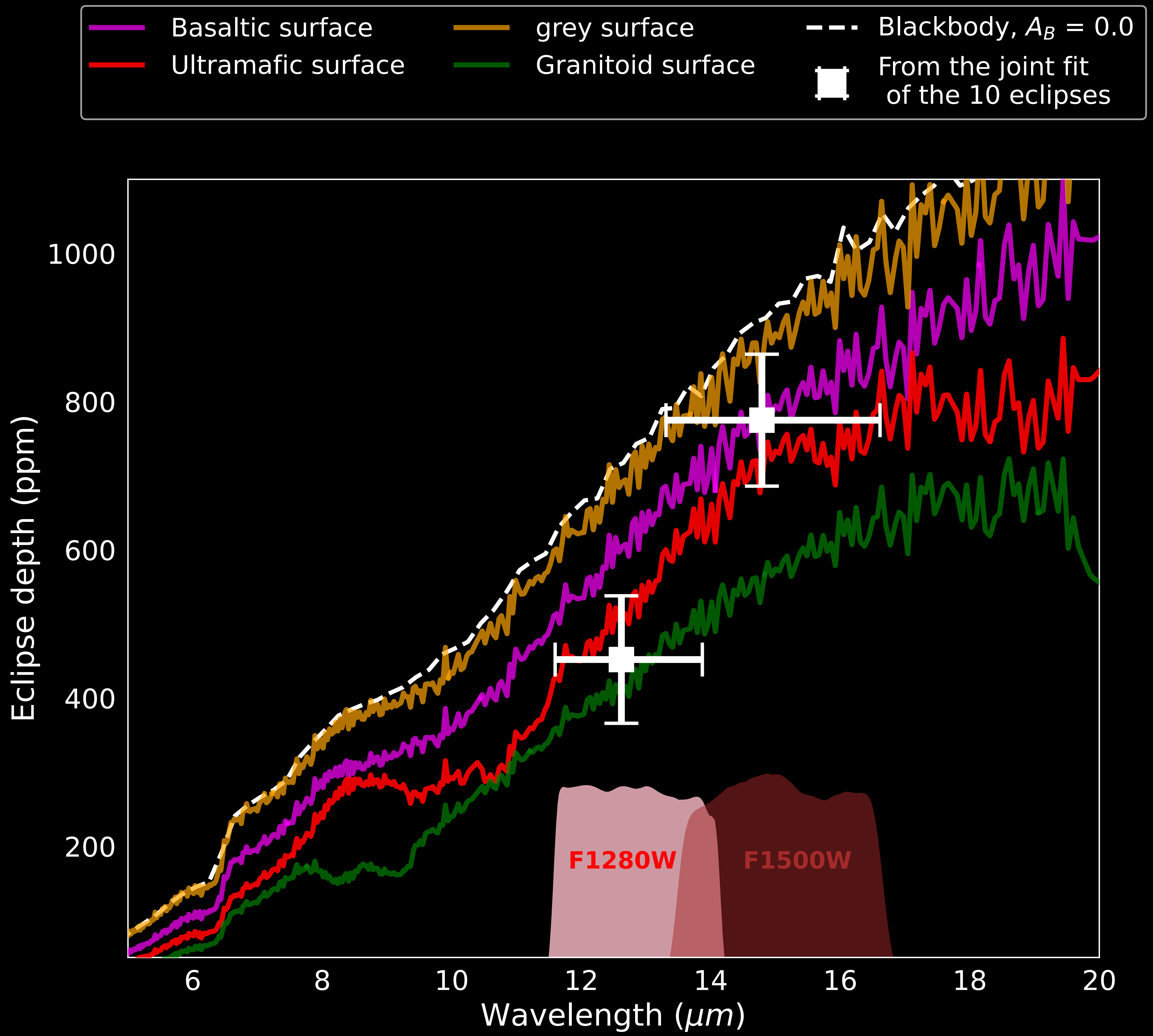


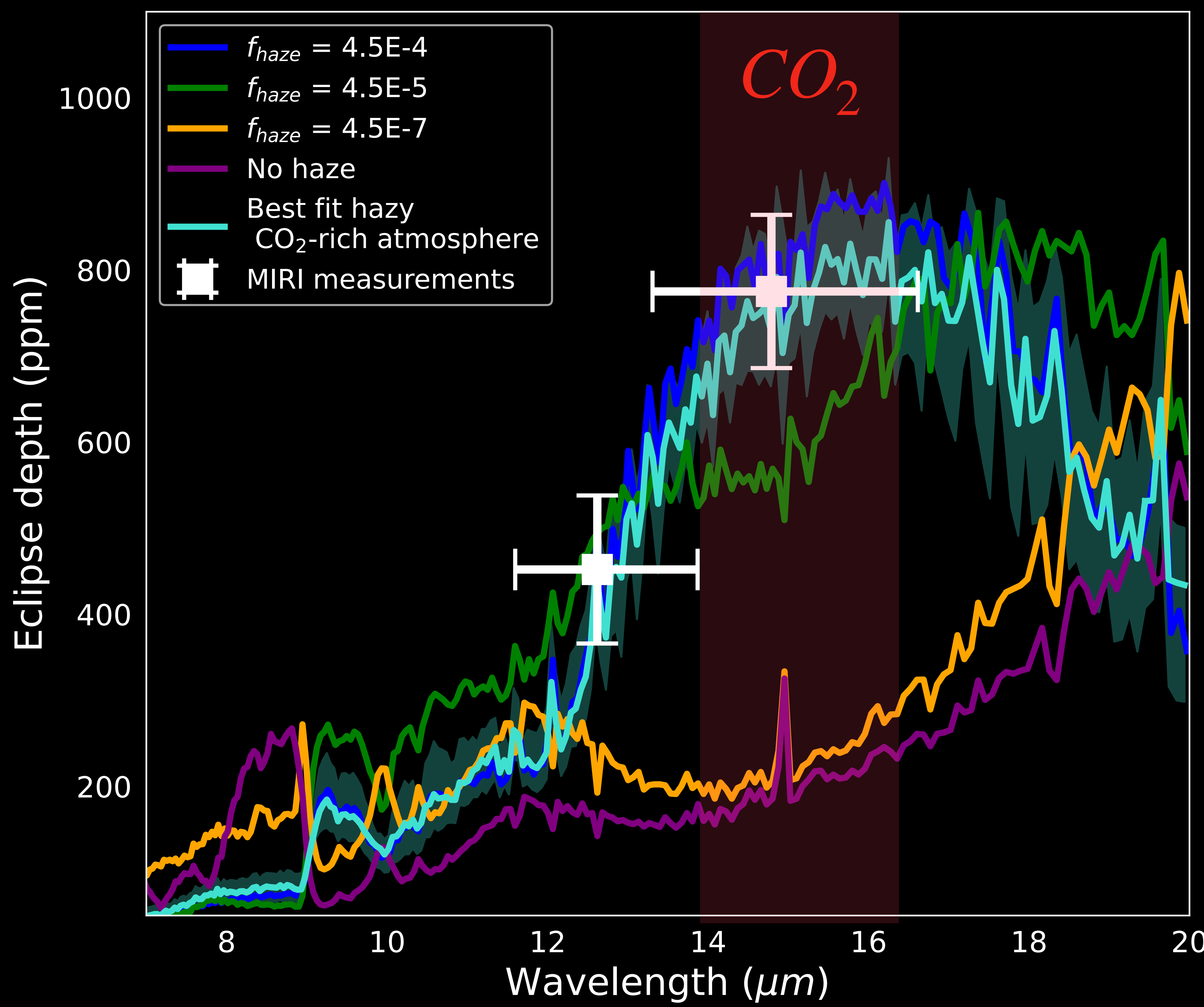


- How does this compare to bare surface models and atmospheric models ?

Thermal emission of TRAPPIST-1 b

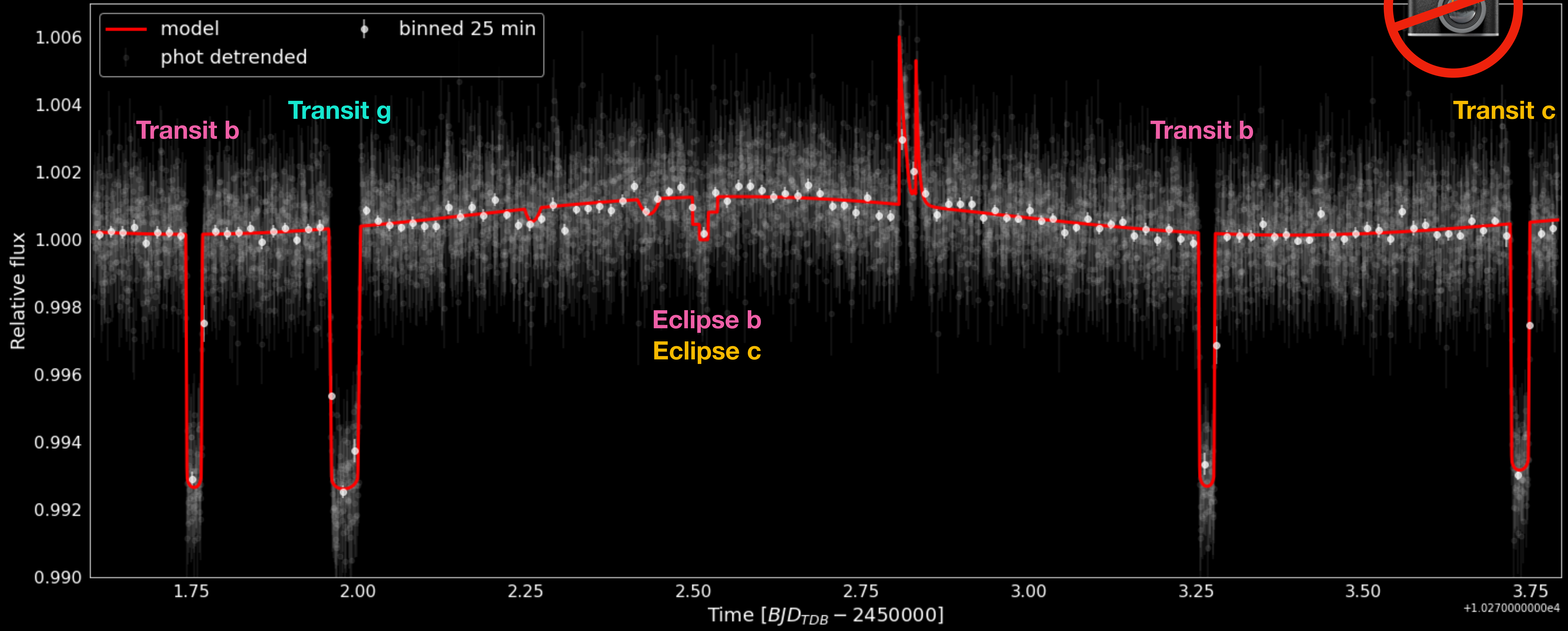
Ducrot, Lagage et al. in review
Models from Ih et al. 2023
Models atom by Michiel Min





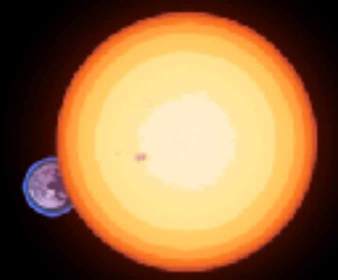
A phase curve is needed to disentangle between these two scenarios

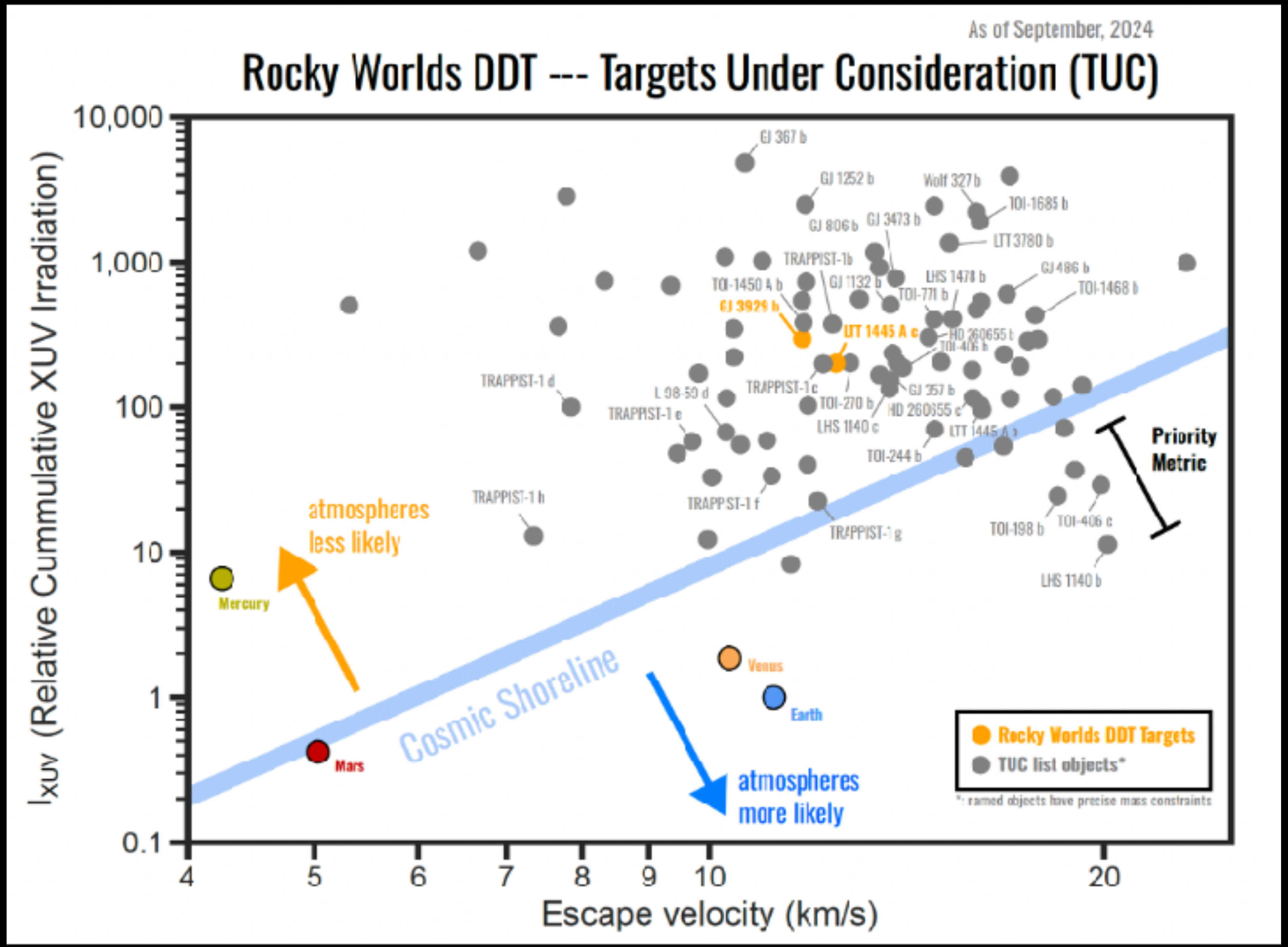
Double phase curve of TRAPPIST-1 b and c

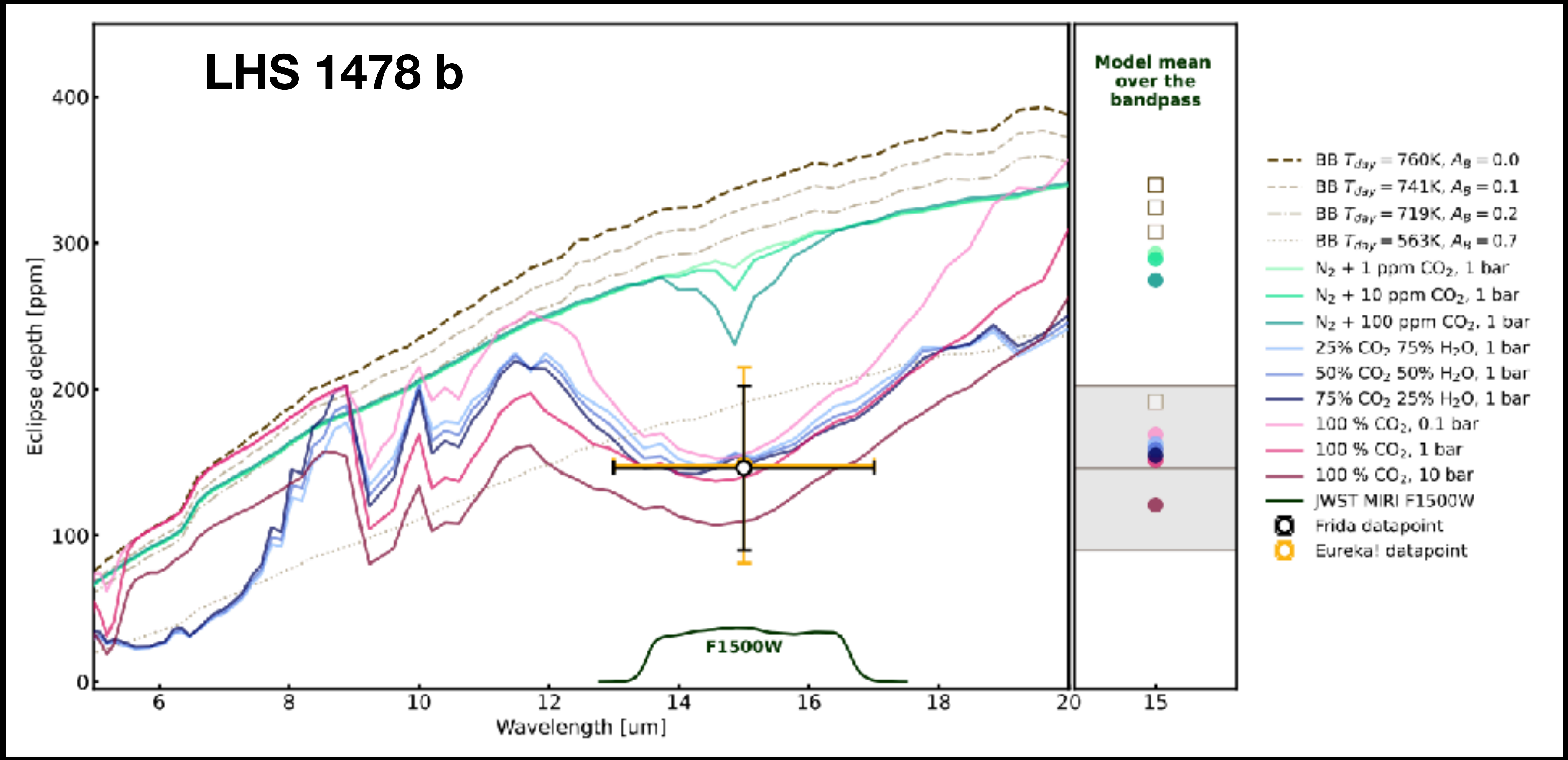


Gillon, Ducrot, et al. in review

Hot rock survey and the rocky worlds DDT







Concept:

- Target 15-20 rocky planets, between 200K and 600K that span the cosmic shoreline
- Detect planetary flux in emission at 15 μm
- Distinguish between full versus zero heat redistribution at 5σ confidence

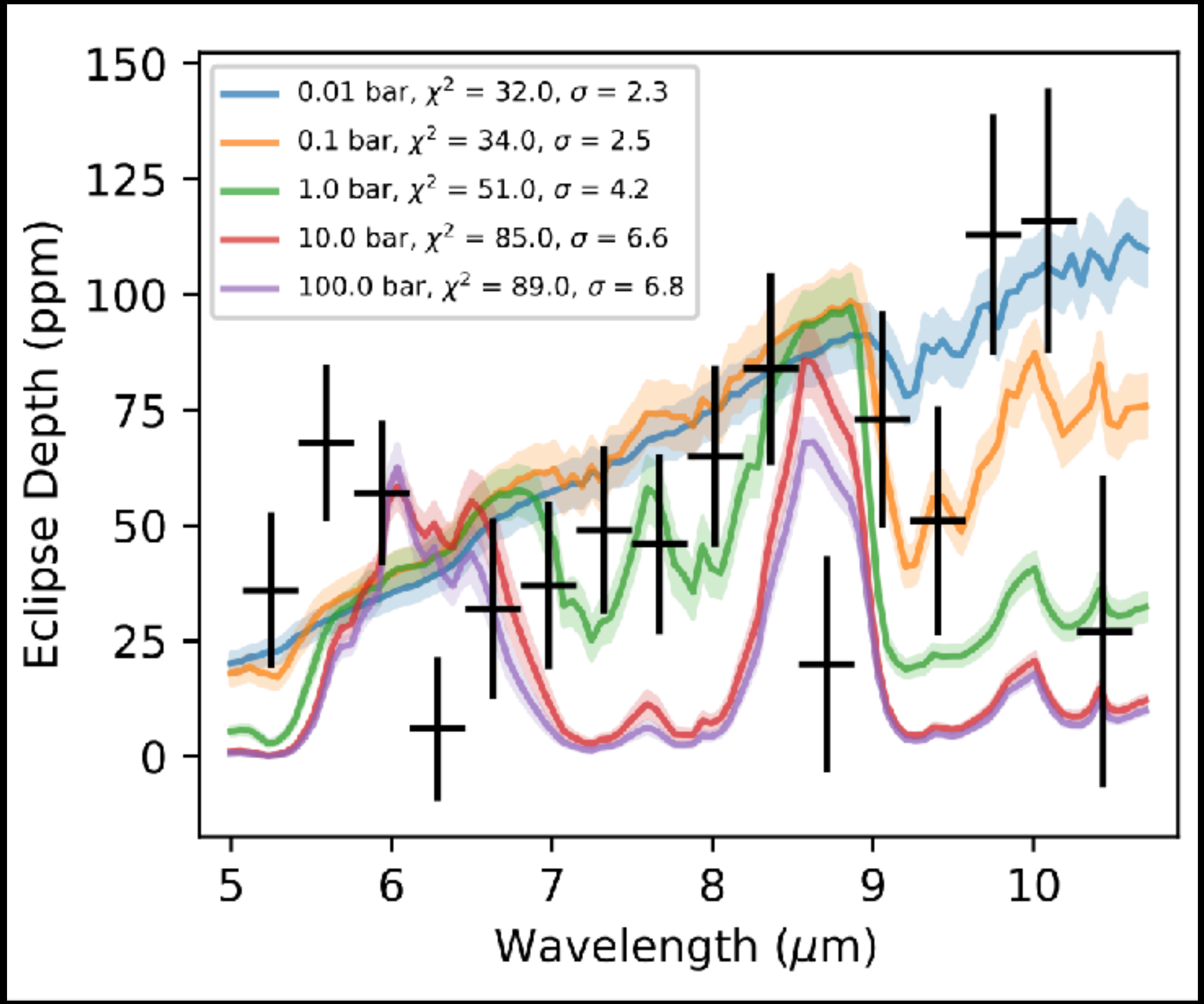
Limitations:

- One point on the emission spectrum is not enough (see TRAPPIST-1 b's results)
- We need precise stellar spectrum in the mid-IR as input to any surface and atmospheric models

August et al. 2024

What about emission spectroscopy ?

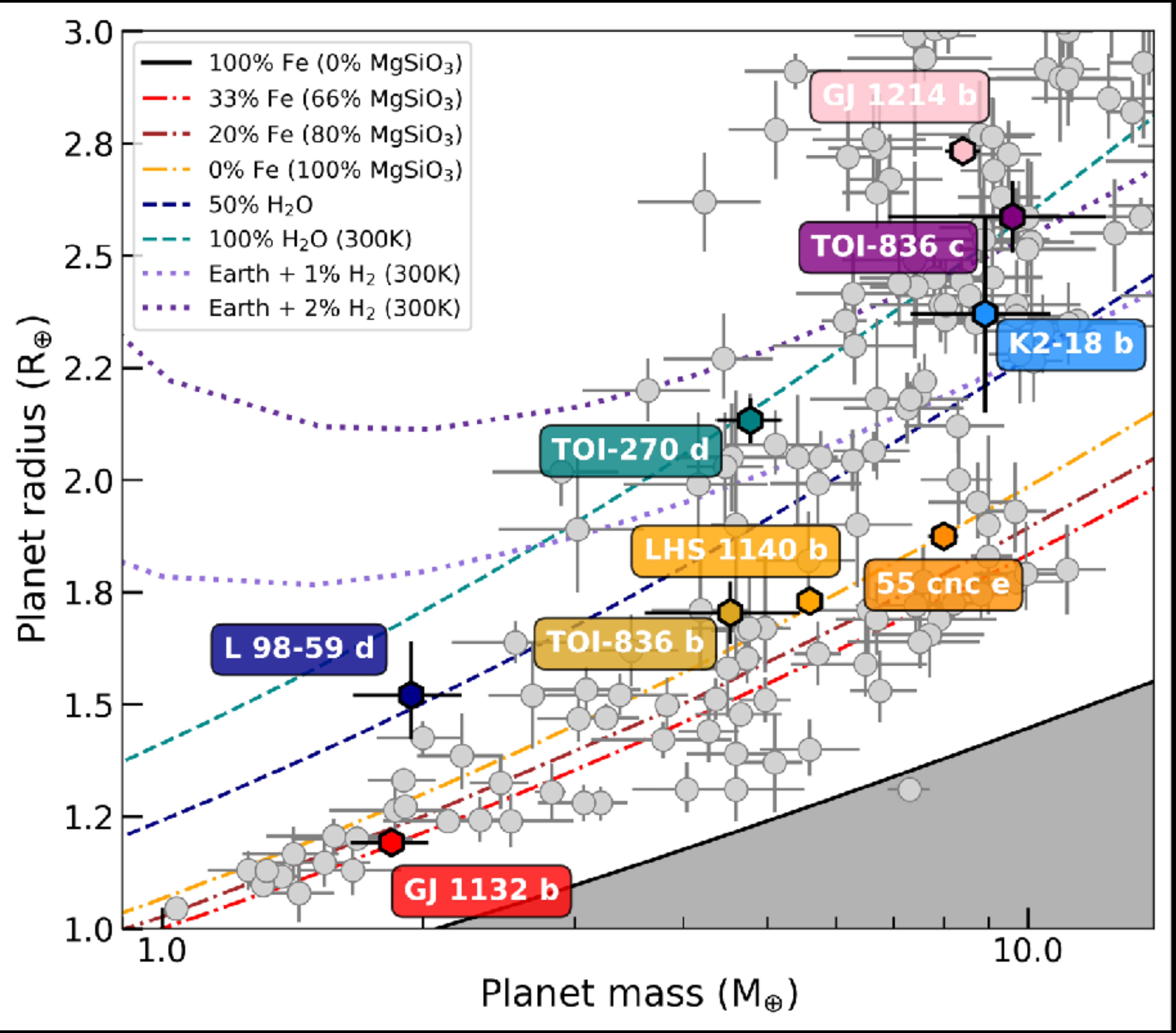
- MIRI LRS can be used in emission
- For very hot terrestrial planets like LHS-3844 b it works but it's very complicated for temperate planets (example with LTT 1478 b with Teq = 431 K below)
- Maybe next cycle thanks to the GO program 6219 (PI: Achrène Dyrek and Pierre-Olivier Lagage)



Wachirapan et al. 2024


Results on temperate Super-Earths and Sub-Neptune

JWST allows to look at a large diversity of super-Earths and sub-Neptunes

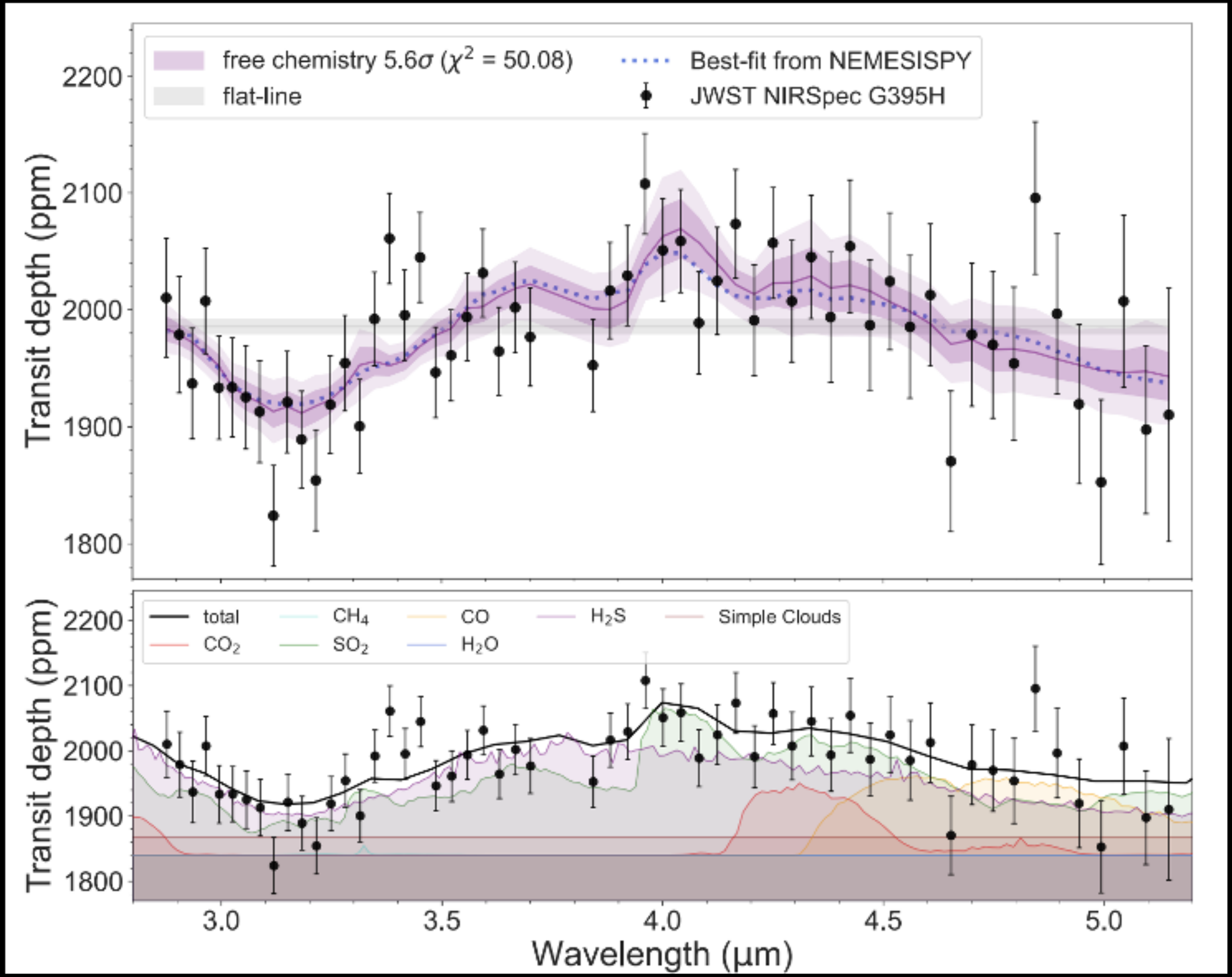


Aims:

- Measure the relative abundances of the major molecular species expected
- Provide key insights into the formation and evolution pathways of exoplanets
- Size their potential for habitability

+targets fully within reach of JWST

L 98-59 b



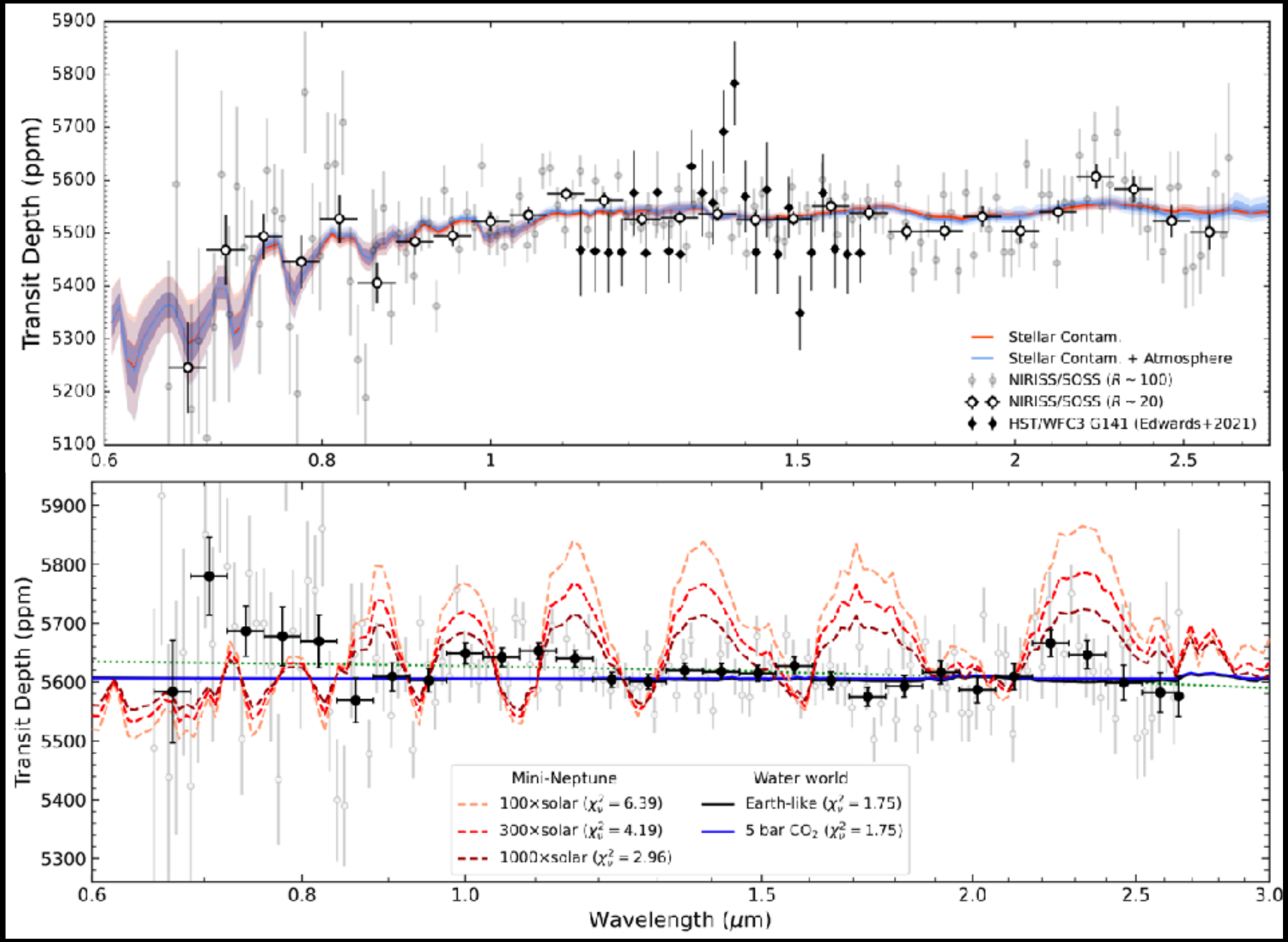
Planet portrait:

- A super-Earth around a late M star
- Located at the limit between rocky / gas-rich

Results:

- Hint a sulfur-rich atmosphere with hydrogen and helium as background gases
- Stellar contamination origin rejected
- Multiple origin possible for sulfur: photochemistry, out-gassing, volcanism, interaction between the atmosphere and the rocky surface etc
- Planet maybe had a different formation pathway

LHS 1140 b



Planet portrait:

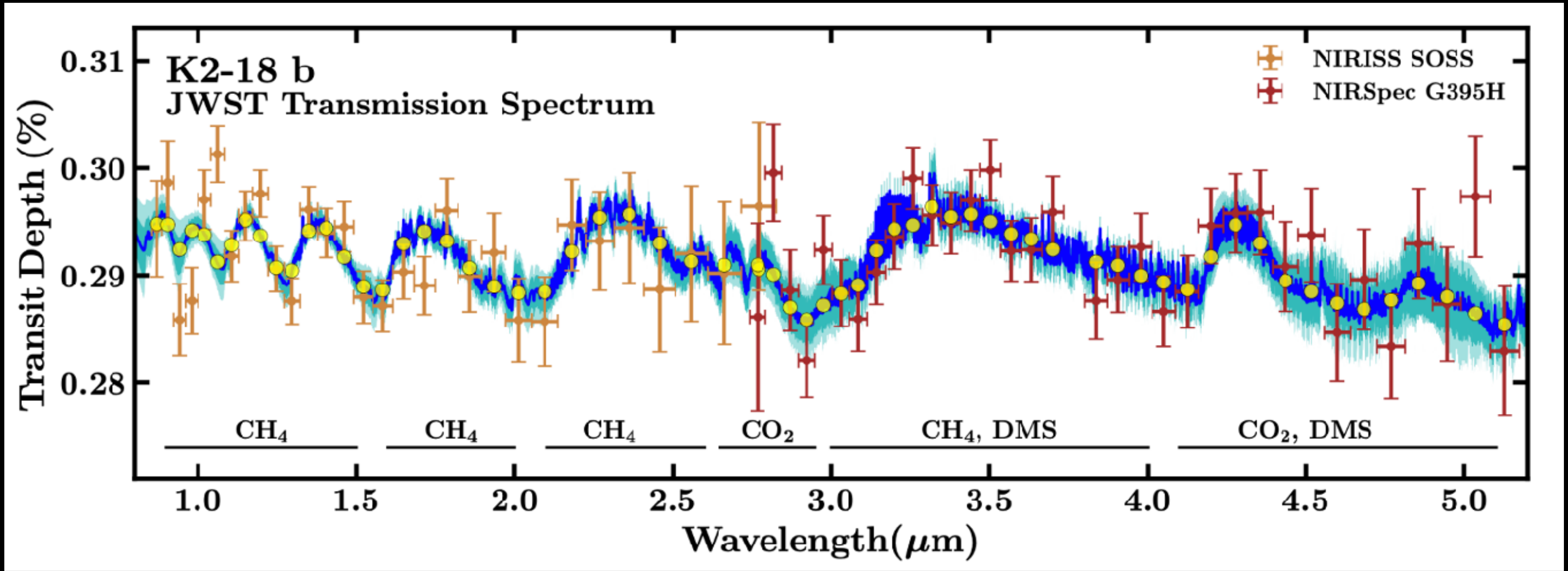
- A temperate super-Earth around a late M
- Falls within the radius valley

Results:

- Stellar contamination appears to be present (as expected for such a cool star)
- Flat spectrum is observed
- Scenario 1: water world, with water clouds form below the transit photosphere, limiting their impact on transmission data
- Scenario 2: airless
- Scenario 1 favours by the very low density of the planet

Cadieux et al. 2024

K2-18 b



Madhusudhan et al. 2023

Planet portrait:

- A habitable-zone sub-Neptune around a mid M-dwarfs star

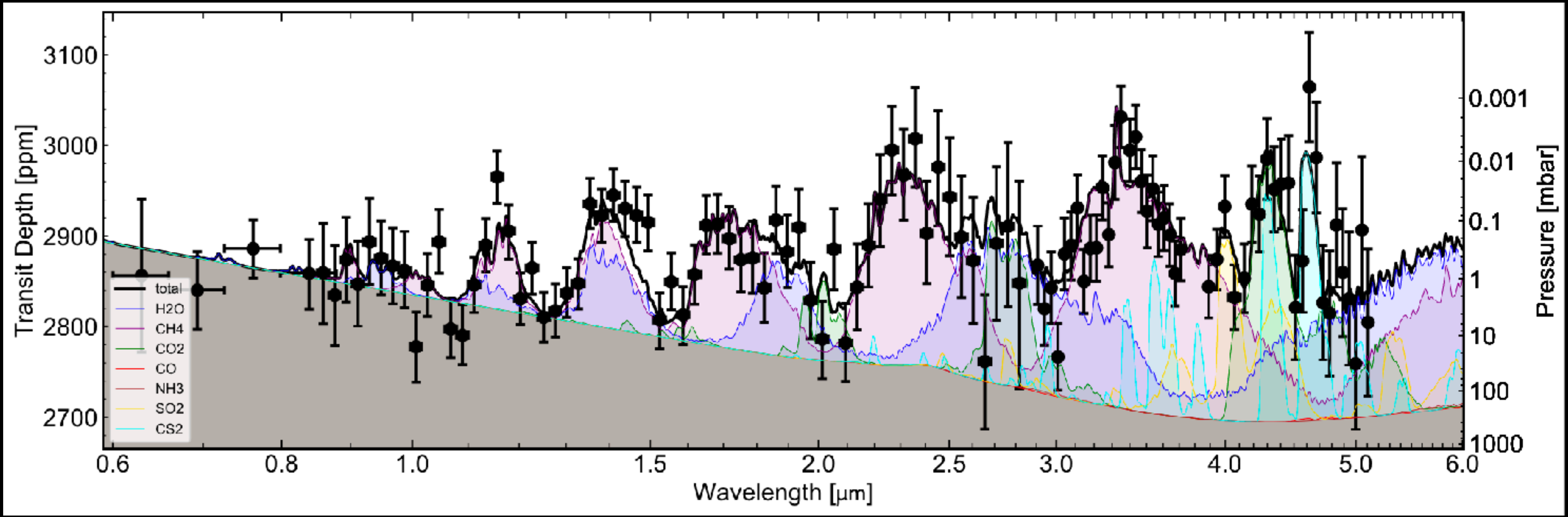
Results:

- Strong detections of methane (CH4) and carbon dioxide (CO2) , no NH3 (authors explained by an Hycean world scenario).
- Authors proposed Hycean world but experts in interiors advocate for a magma ocean + H/He atmosphere (credible with current observations + appears to be more feasible), see *Shorttle et al. 2024*

Holmberg & Madhusudhan 2023

Benneke et al. 2023

TOI-270 d



<u>Planet portrait:</u>

- A temperate sub-Neptune around a mid M-dwarf star

<u>Results:</u>

- Reveals strong detections of CH4, CO2 and H2O, high mean molecular weight, suggested signs of CS2
- Propose a new classification: miscible-envelope sub-Neptune, a mix of H2/He with the high-molecular-weight volatiles in a miscible supercritical metal-rich envelope

Conclusions

- **JWST** can probe the atmosphere of terrestrial worlds and habitable-zone worlds for the first time BUT only around cool stars. And it’s not easy ..
- Limitations:
  - Stellar contamination: Transmission spectra of planets around cool stars are polluted by stellar activity.
  - Emission observations: Observations in emission are challenging and limited in wavelength coverage.
  - M-stars environnement are very different from sun-like stars
- Yet, JWST delivers groundbreaking results on another population, exquisite observations of temperate Sup-Neptunes and some Super-Earth with clear detection of key molecules.
- We are in an « **observationally driven** » phase: observations will help us educate and refine our models (formation, evolution, atmosphere, surface, etc)
- Biosignatures detections are most likely out of reach of JWST, we must wait for ELT, HWO, LIFE

Second part: open questions on exoplanets atmospheres

Credit: Lionel Garcia

Prix Guzman 1900

COMPTES RENDUS

DES SÉANCES

DE L'ACADÉMIE DES SCIENCES.

SÉANCE PUBLIQUE ANNUELLE DU LUNDI 17 DÉCEMBRE 1900.

PRÉSIDÉE PAR M. MAURICE LEVY.

M. MAURICE LEVY prononce l'allocution suivante :

« MESSIEURS,

» Voici notre dernière séance solennelle d'un siècle où la Science aura tenu la plus grande place.

» C'est la première fois que le fait se produit. Mais aussi, nous sommes les premiers hommes que la Science, par une sorte de miracle, aura fait assister à deux existences terrestres : celle d'il y a soixante ans et celle d'aujourd'hui, infiniment plus dissemblables, à bien des égards, que si, en d'autres temps, elles avaient été séparées par des centaines, des milliers d'années, si bien que nous aurons vraiment vécu comme si nous étions nés deux fois à de longs siècles d'intervalle.

» Pourquoi cette rénovation de la vie s'est-elle produite juste à notre époque et pas avant? Est-ce un accident ou un commencement? Vivons-nous en un siècle fortuit ou est-il bien le premier d'une ère nouvelle et durable qui serait l'ère du Messianisme de la Science sur cette terre?

Ce prix, de la valeur de *deux mille francs*, sera décerné par l'Académie des Sciences, pour la première fois, dans sa séance publique de 1901.

PRIX PIERRE GUZMAN.

Mme *Clara Goguet*, veuve *Guzman*, a légué à l'Académie des Sciences une somme de *cent mille francs* pour la fondation d'un prix qui portera le nom de *prix Pierre Guzman*, en souvenir de son fils, et sera décerné à celui qui aura trouvé le moyen de communiquer avec un astre autre que la planète Mars.

Prévoyant que le prix de *cent mille francs* ne serait pas décerné tout de suite, la fondatrice a voulu, jusqu'à ce que ce prix soit gagné, que les intérêts du capital, cumulés pendant cinq années, formassent un prix, toujours sous le nom de *Pierre Guzman*, qui serait décerné à un savant français ou étranger, qui aurait fait faire un progrès important à l'Astronomie.

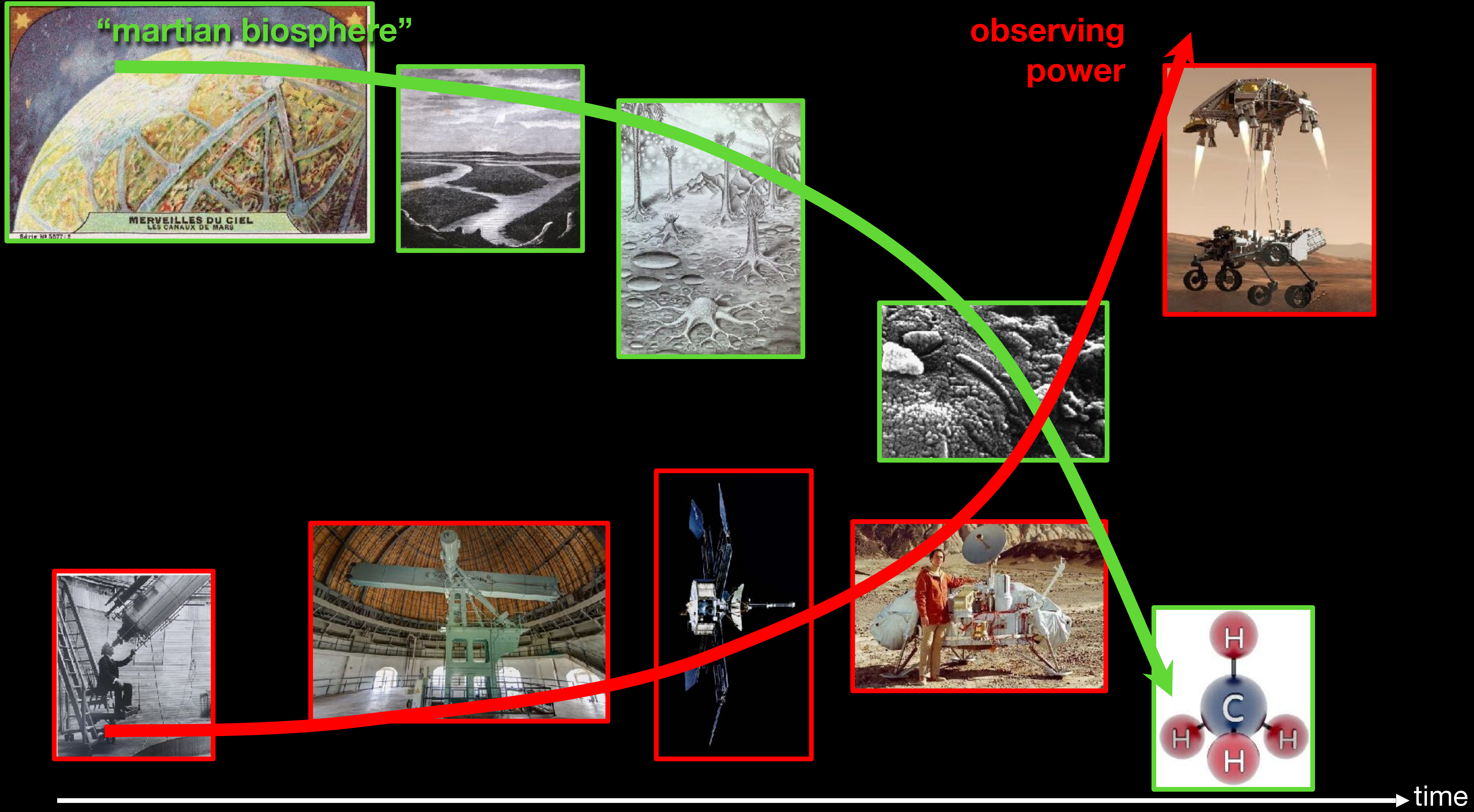
Le *prix quinquennal*, représenté par les intérêts du capital, sera décerné, s'il y a lieu, pour la première fois en 1905.

PRIX FONDÉ PAR Mme LA MARQUISE DE LAPLACE.

Ce prix, qui consiste dans la collection complète des Ouvrages de Laplace, est décerné, *chaque année*, au premier élève sortant de l'École Polytechnique.

PRIX FONDÉ PAR M. FÉLIX RIVOT.

Ce *prix*, qui est *annuel* et dont la valeur est de *deux mille cinq cents francs*, sera partagé entre les quatre élèves sortant chaque année de l'École Polytechnique avec les nos 1 et 2 dans les corps des Mines et des Ponts et Chaussées.



“martian biosphere”
MERVEILLES DU CIEL
LES CANAUX DE MARS
observing
power
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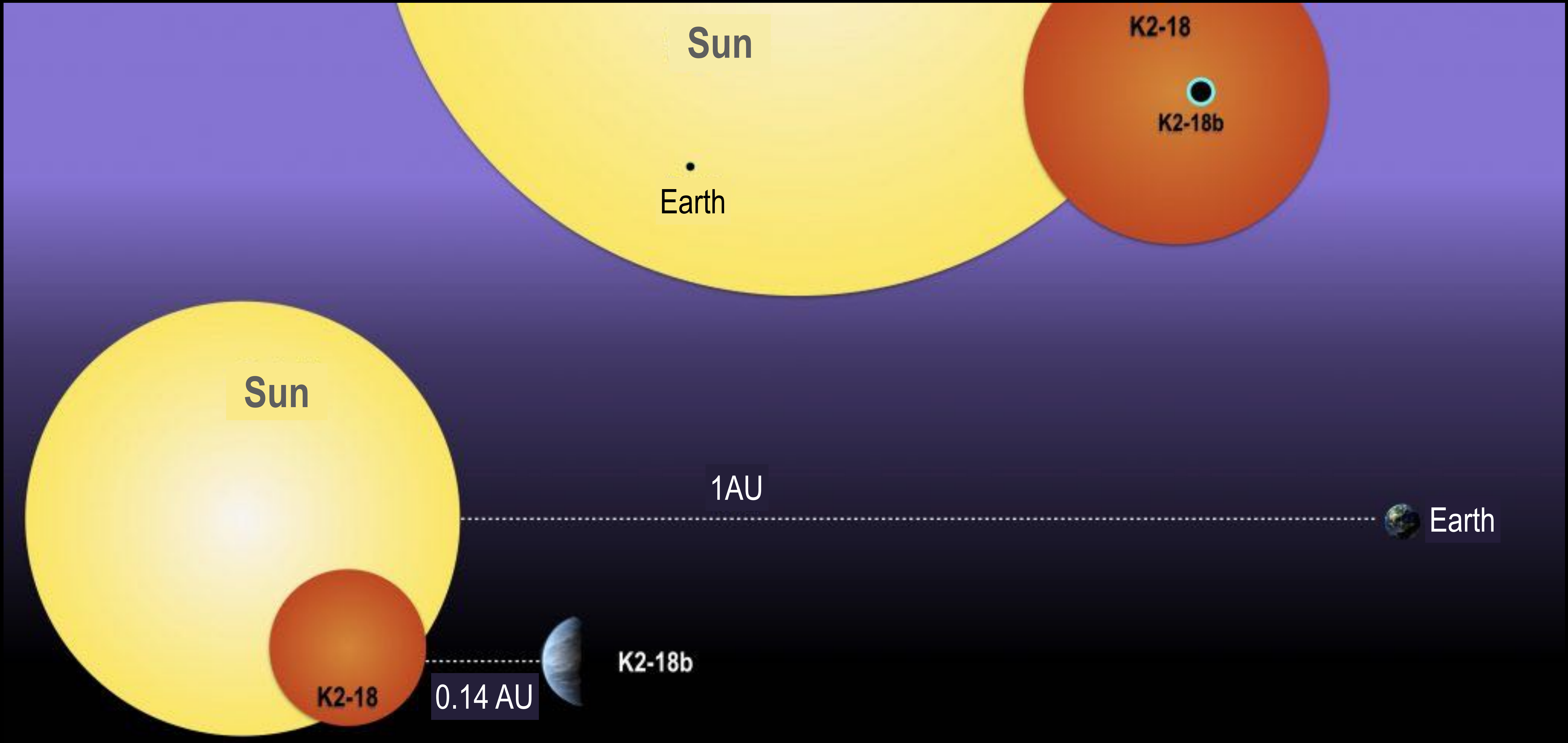
Sun
K2-18
K2-18b
Earth
Sun
1AU
Earth
K2-18b
K2-18
0.14 AU

The Astrophysical Journal Letters, 956:L13 (16pp), 2023 October 10 https://doi.org/10.3847/2041-8213/acf577

Carbon-bearing Molecules in a Possible Hycean Atmosphere

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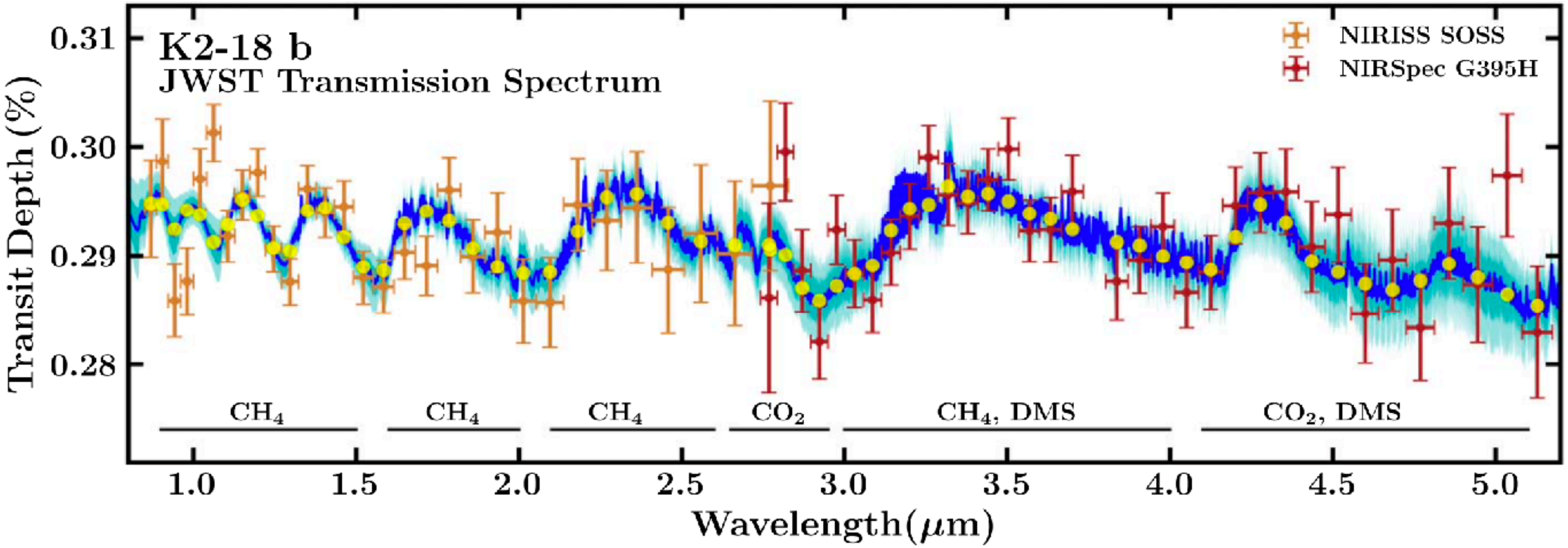
Abstract

The search for habitable environments and biomarkers in exoplanetary atmospheres is the holy grail of exoplanet science. The detection of atmospheric signatures of habitable Earth-like exoplanets is challenging owing to their small planet–star size contrast and thin atmospheres with high mean molecular weight. Recently, a new class of habitable exoplanets, called Hycean worlds, has been proposed, defined as temperate ocean-covered worlds with H_2-rich atmospheres. Their large sizes and extended atmospheres, compared to rocky planets of the same mass, make Hycean worlds significantly more accessible to atmospheric spectroscopy with JWST. Here we report a transmission spectrum of the candidate Hycean world K2-18 b, observed with the JWST NIRISS and NIRSpec instruments in the 0.9–5.2 μm range. The spectrum reveals strong detections of methane (CH_4) and carbon dioxide (CO_2) at 5σ and 3σ confidence, respectively, with high volume mixing ratios of $\sim$1% each in a H_2-rich atmosphere. The abundant CH_4 and CO_2, along with the nondetection of ammonia (NH_3), are consistent with chemical predictions for an ocean under a temperate H_2-rich atmosphere on K2-18 b. The spectrum also suggests potential signs of dimethyl sulfide (DMS), which has been predicted to be an observable biomarker in Hycean worlds, motivating considerations of possible biological activity on the planet. The detection of CH_4 resolves the long-standing missing methane problem for temperate exoplanets and the degeneracy in the atmospheric composition of K2-18 b from previous observations. We discuss possible implications of the findings, open questions, and future observations to explore this new regime in the search for life elsewhere.

The Astrophysical Journal Letters, 956:L13 (16pp), 2023 October 10 Madhusudhan et al.



The Astrophysical Journal, 918:1 (25pp), 2021 September 1 https://doi.org/10.3847/1538-4357/abfd9c

CrossMark

Habitability and Biosignatures of Hycean Worlds

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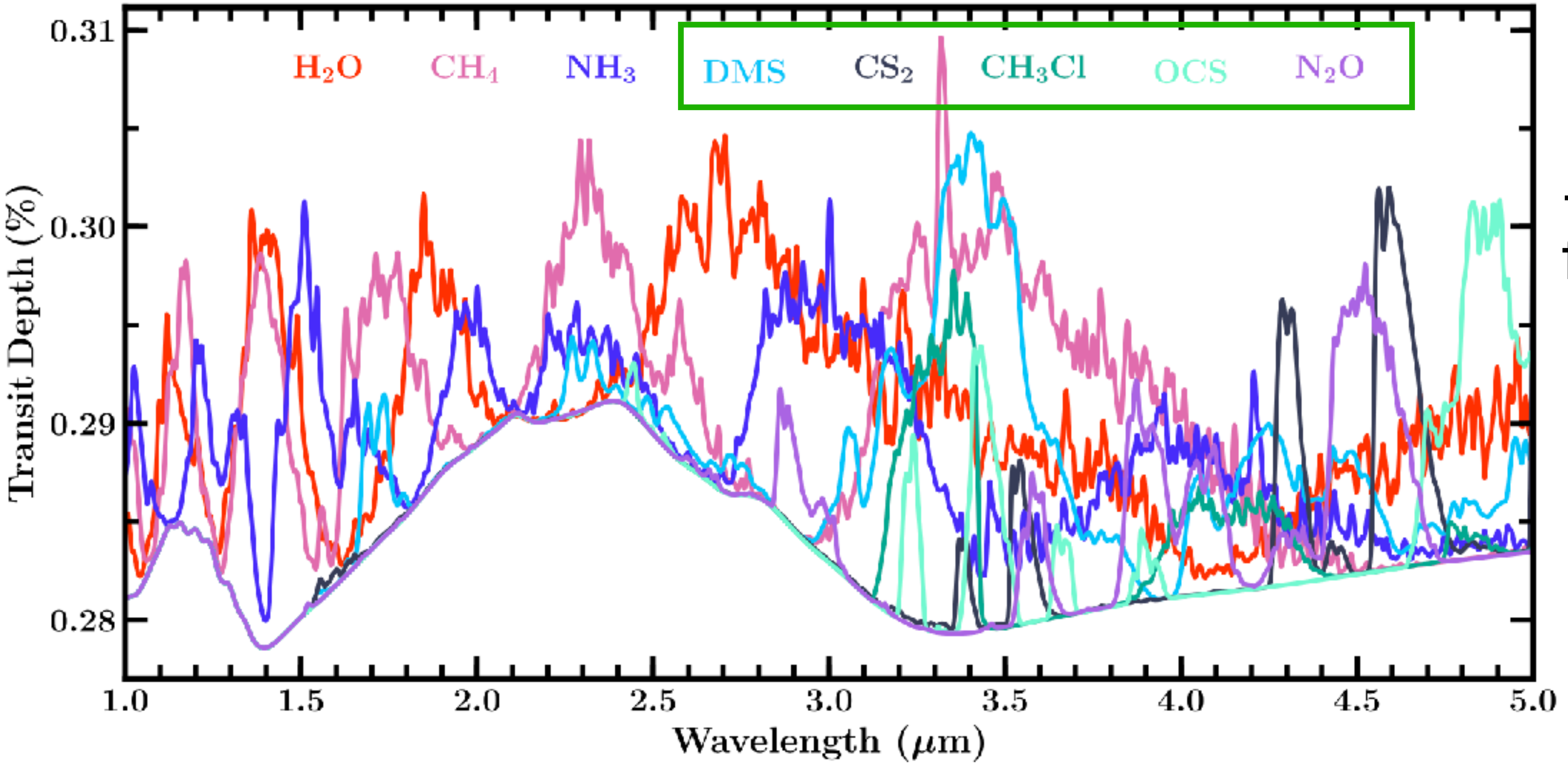
Abstract

We investigate a new class of habitable planets composed of water-rich interiors with massive oceans underlying H_2-rich atmospheres, referred to here as Hycean worlds. With densities between those of rocky super-Earths and more extended mini-Neptunes, Hycean planets can be optimal candidates in the search for exoplanetary habitability and may be abundant in the exoplanet population. We investigate the bulk properties (masses, radii, and temperatures), potential for habitability, and observable biosignatures of Hycean planets. We show that Hycean planets can be significantly larger compared to previous considerations for habitable planets, with radii as large as 2.6 $R_\oplus$ (2.3 $R_\oplus$) for a mass of 10 $M_\oplus$ (5 $M_\oplus$). We construct the Hycean habitable zone (HZ), considering stellar hosts from late M to Sun-like stars, and find it to be significantly wider than the terrestrial-like HZ. While the inner boundary of the Hycean HZ corresponds to equilibrium temperatures as high as ~500 K for late M dwarfs, the outer boundary is unrestricted to arbitrarily large orbital separations. Our investigations include tidally locked "Dark Hycean" worlds that permit habitable conditions only on their permanent nightsides and "Cold Hycean" worlds that see negligible irradiation. Finally, we investigate the observability of possible biosignatures in Hycean atmospheres. We find that a number of trace terrestrial biomarkers that may be expected to be present in Hycean atmospheres would be readily detectable using modest observing time with the James Webb Space Telescope (JWST). We identify a sizable sample of nearby potential Hycean planets that can be ideal targets for such observations in search of exoplanetary biosignatures.

Unified Astronomy Thesaurus concepts: Exoplanets (498); Habitable planets (695); Exoplanet atmospheres (487); Radiative transfer (1335); Planetary interior (1248); Biosignatures (2018); Transmission spectroscopy (2133)

Madhusudhan et al., ***2021***



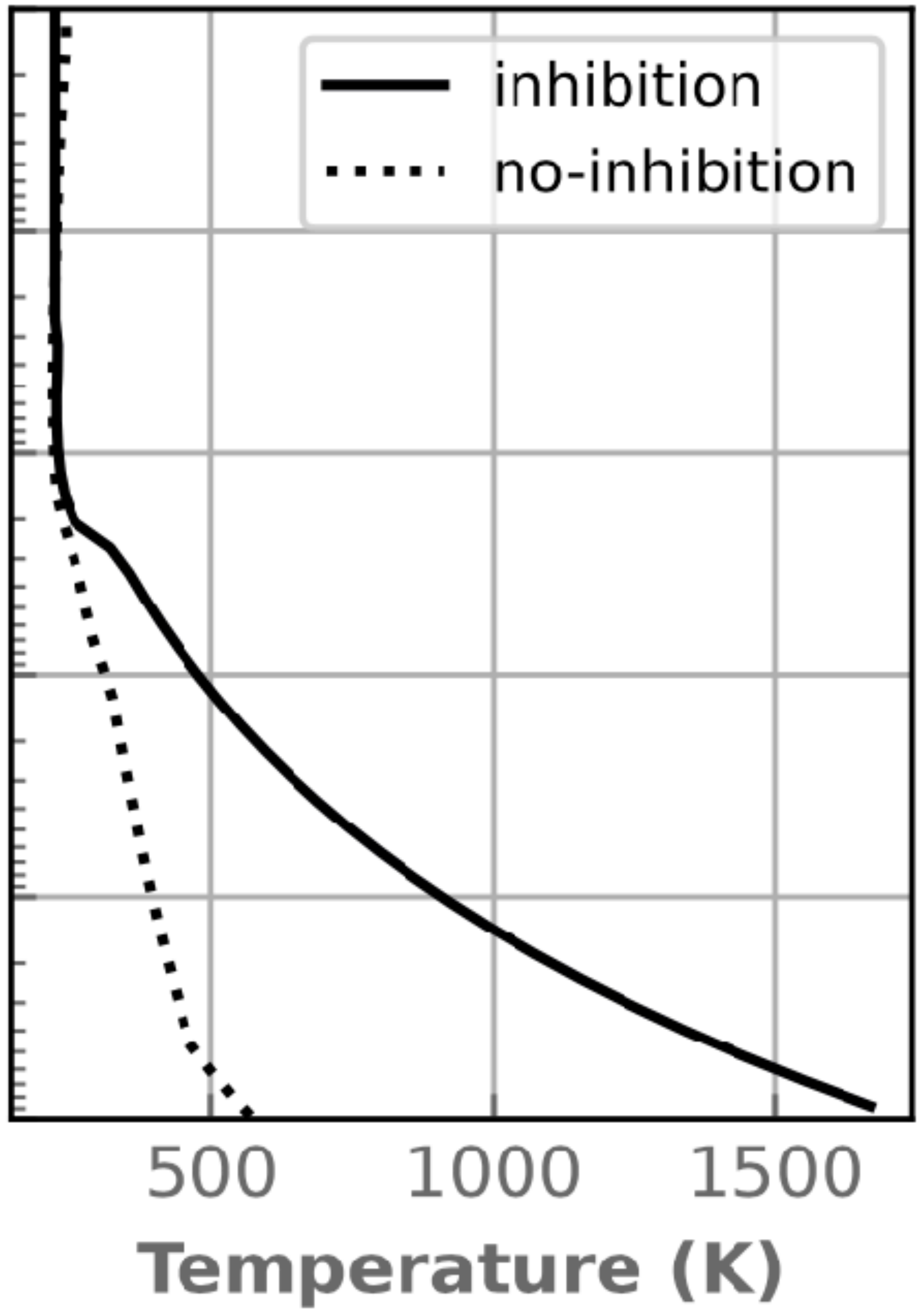
- among *biomarkers* to look for : DMS, diméthyl sufite

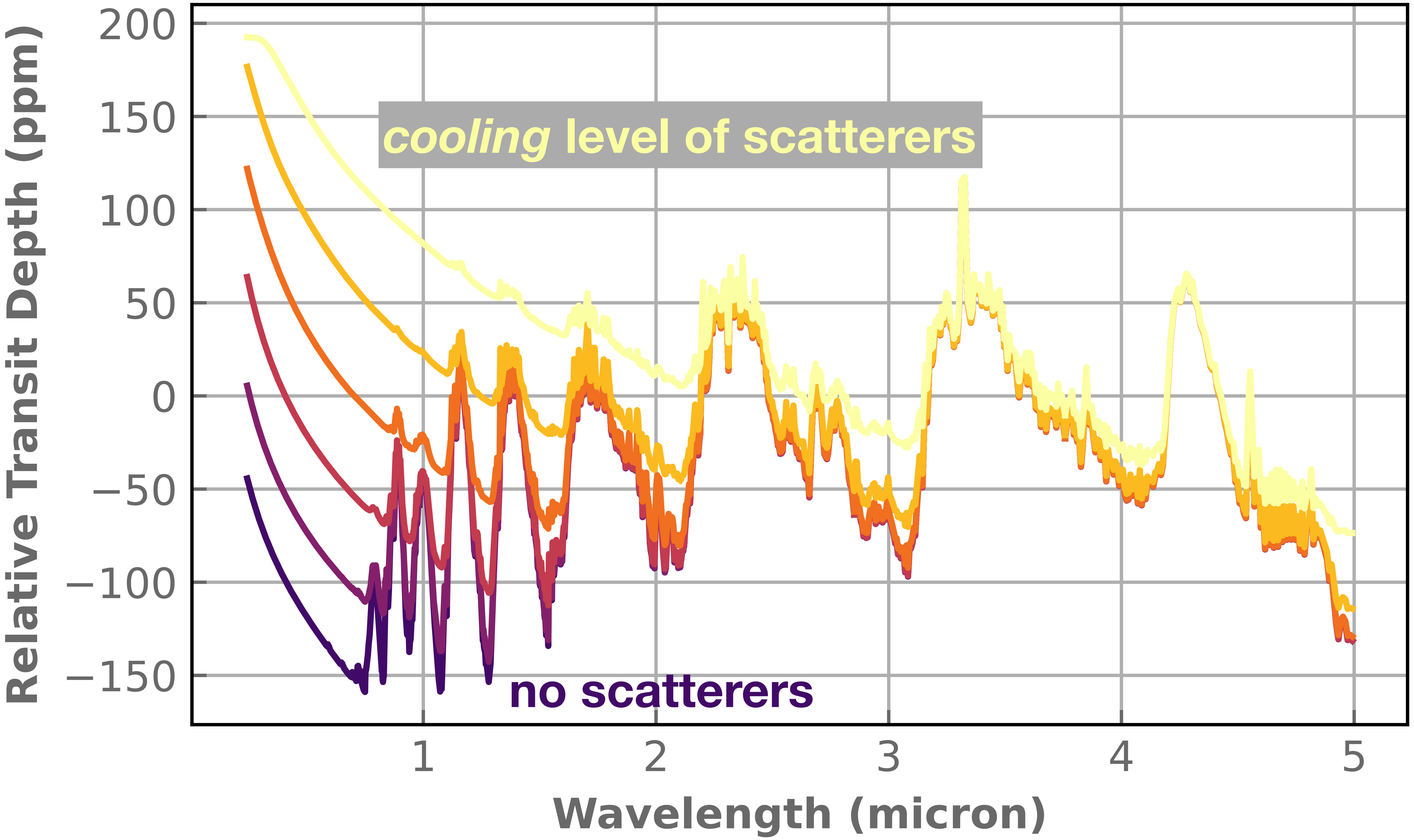
Figure 7. Molecular contributions to a model transmission spectrum of K2–18 b from the biomarkers, as well as H_2O, CH_4, and NH_3. Each molecule's contribution curve is the transmission spectrum generated by only including absorption from the molecule in question, as well as H_2–H_2 and H_2–He CIA. For each spectrum, we use the atmospheric properties and abundances for the canonical model described in Section 4.4. Contributions from several biomarkers are especially prominent in the ~3–5 μm range.

Madhusudhan et al., ***2021***

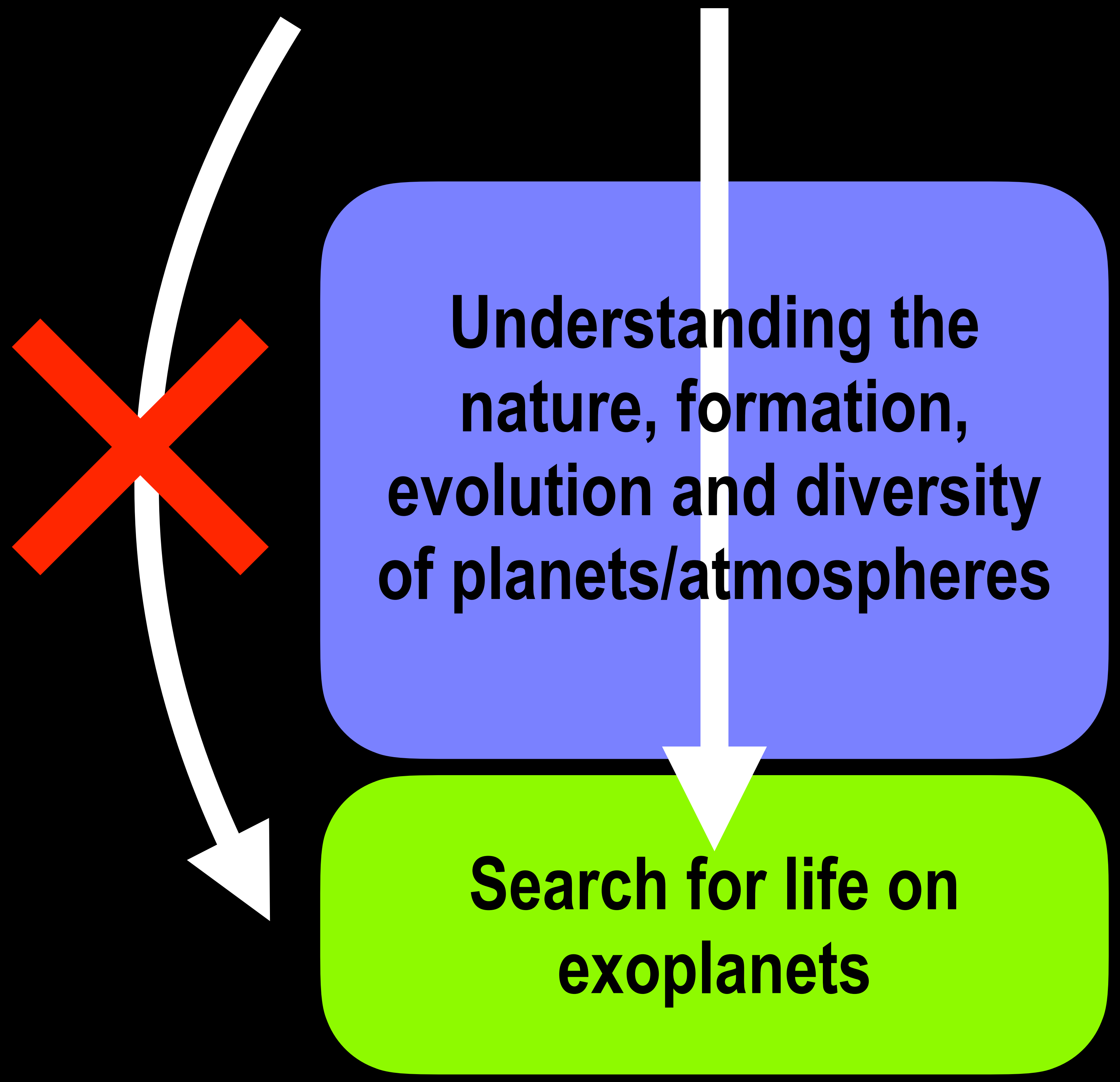
In order to keep a model of K2-18b cool enough to allow surface liquid water, one must considerably enhance the reflexion and stratospheric absobtion of stellar light.

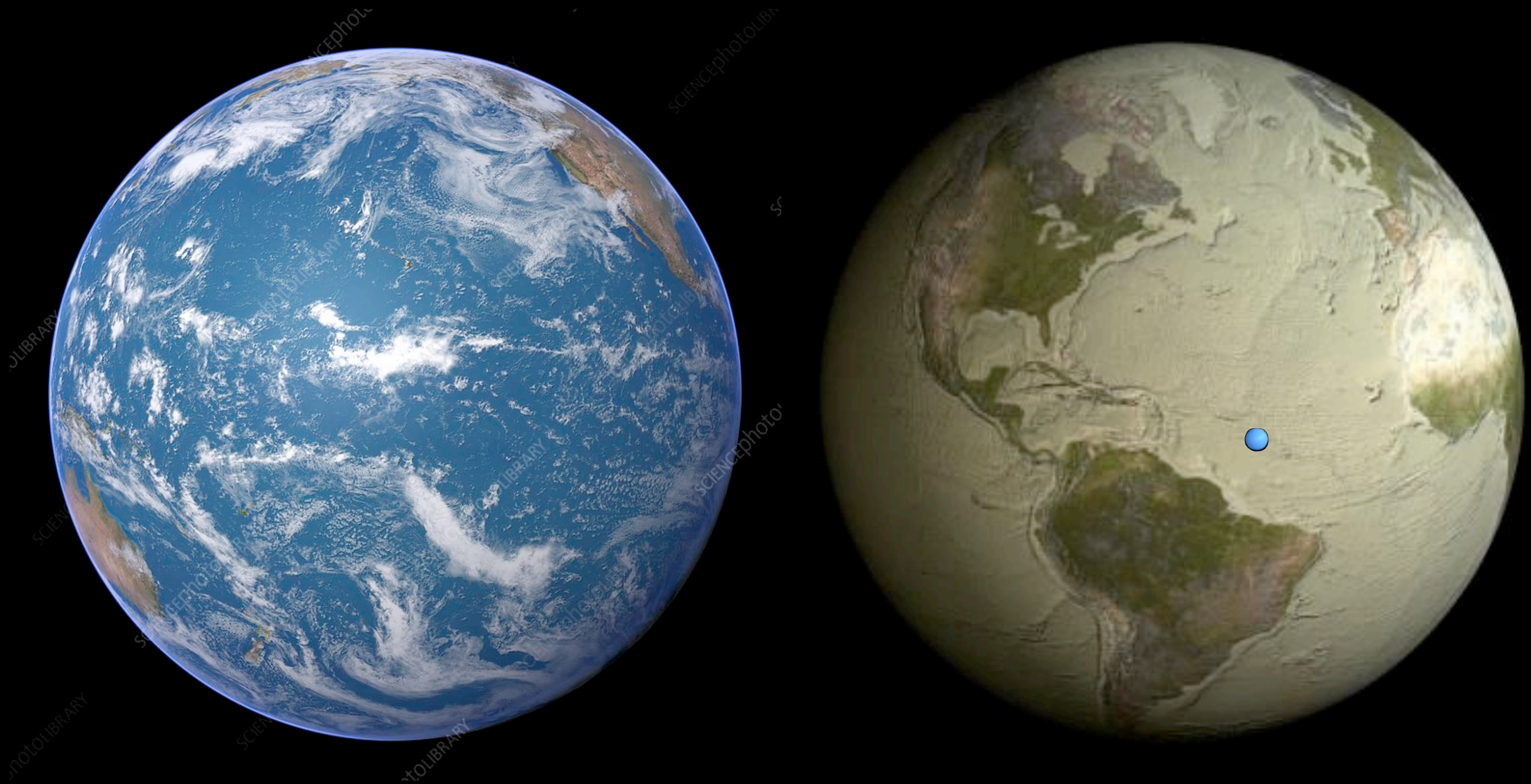
In Madhusudhan et al (2021, 2023), this is done by adding large amounts (Rayleigh) scattering particles. But these ad-hoc scatterers are no longer included in the spectral retrievel, as they would erase the observed features.



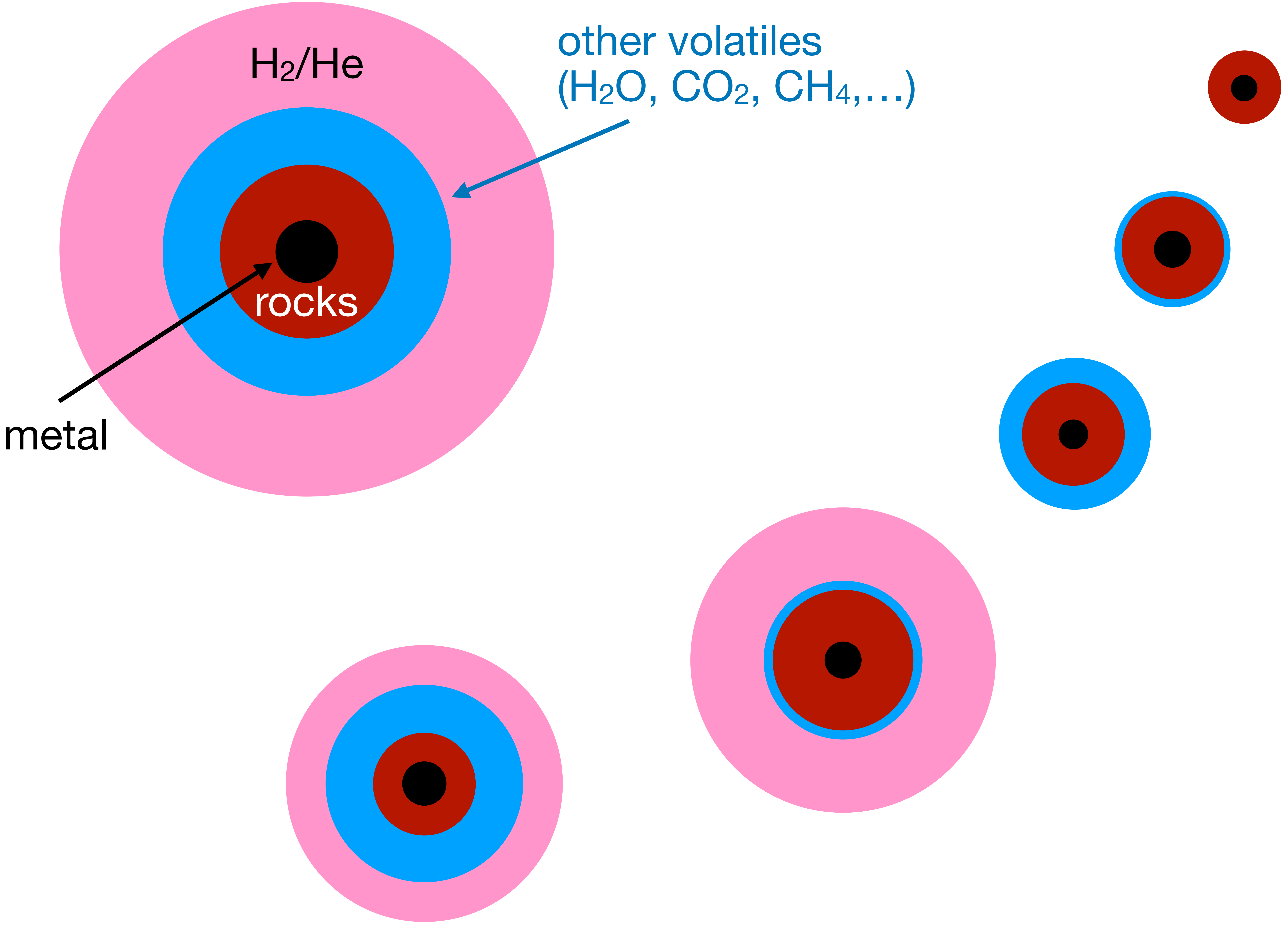


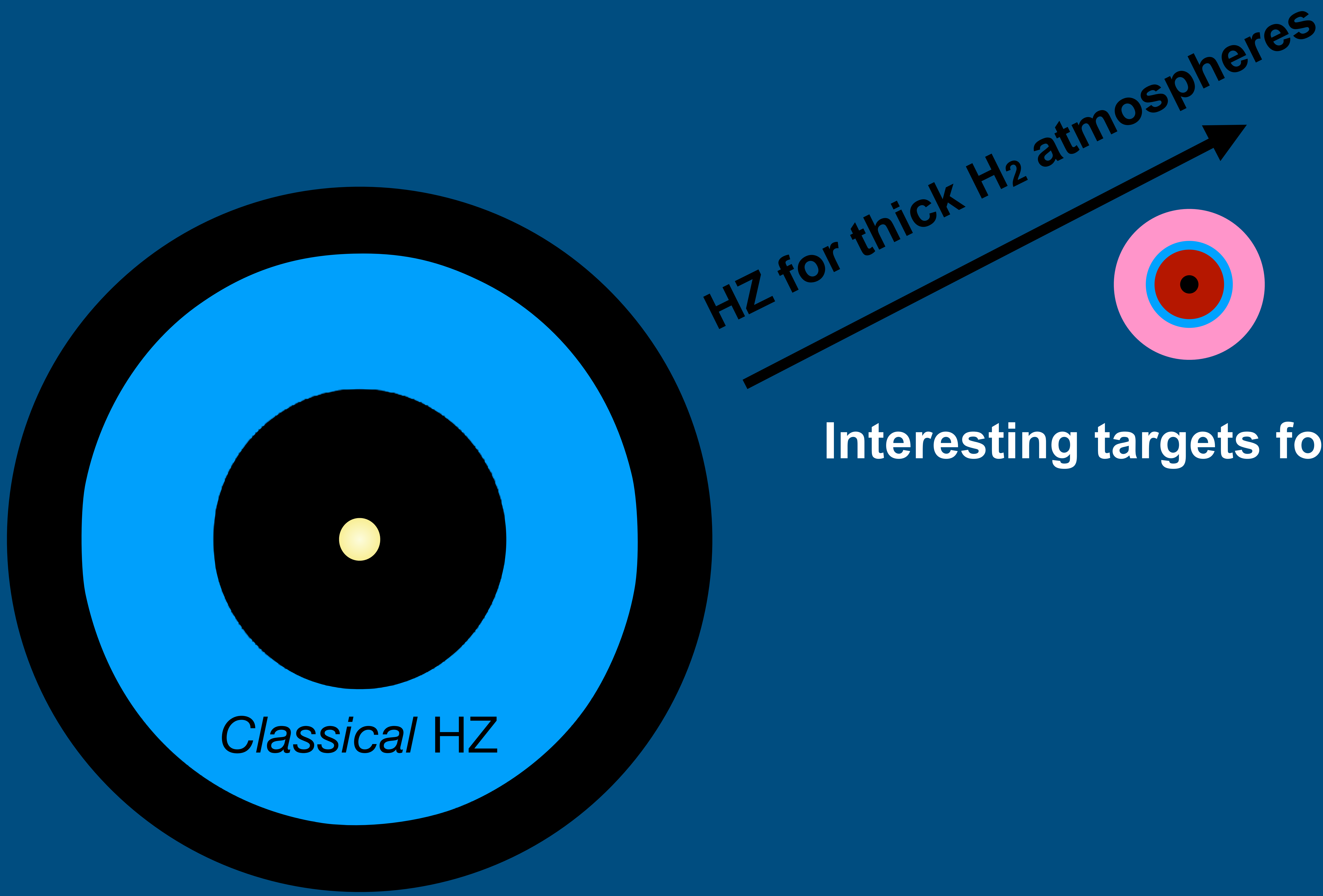
Leconte et al. (2024)


Understanding the nature, formation, evolution and diversity of planets/atmospheres
Search for life on exoplanets



Volatile delivery by pebbles, planetesimals, embryos, gas from the disc?

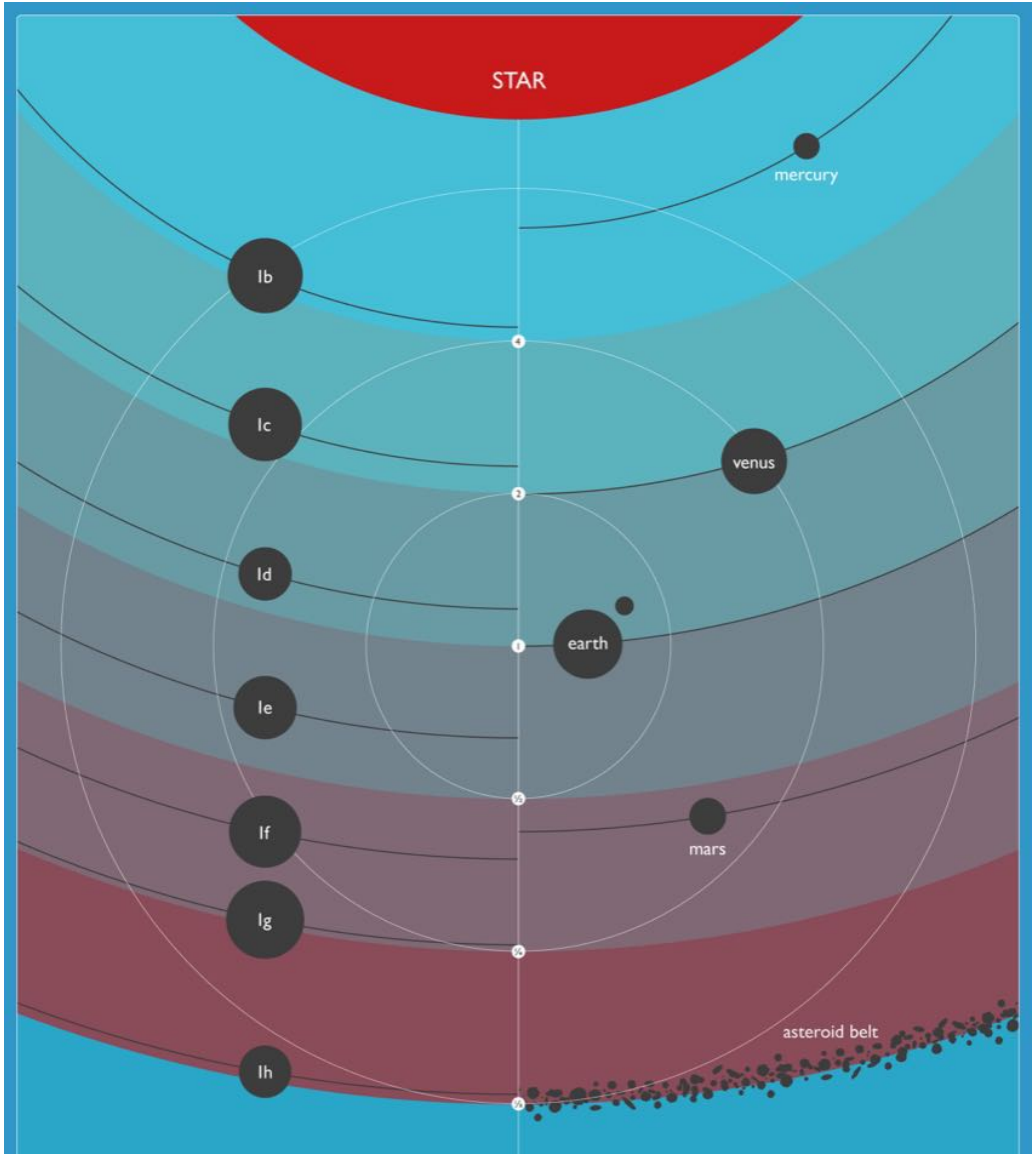

H2/He
other volatiles
(H2O, CO2, CH4,...)
rocks
metal



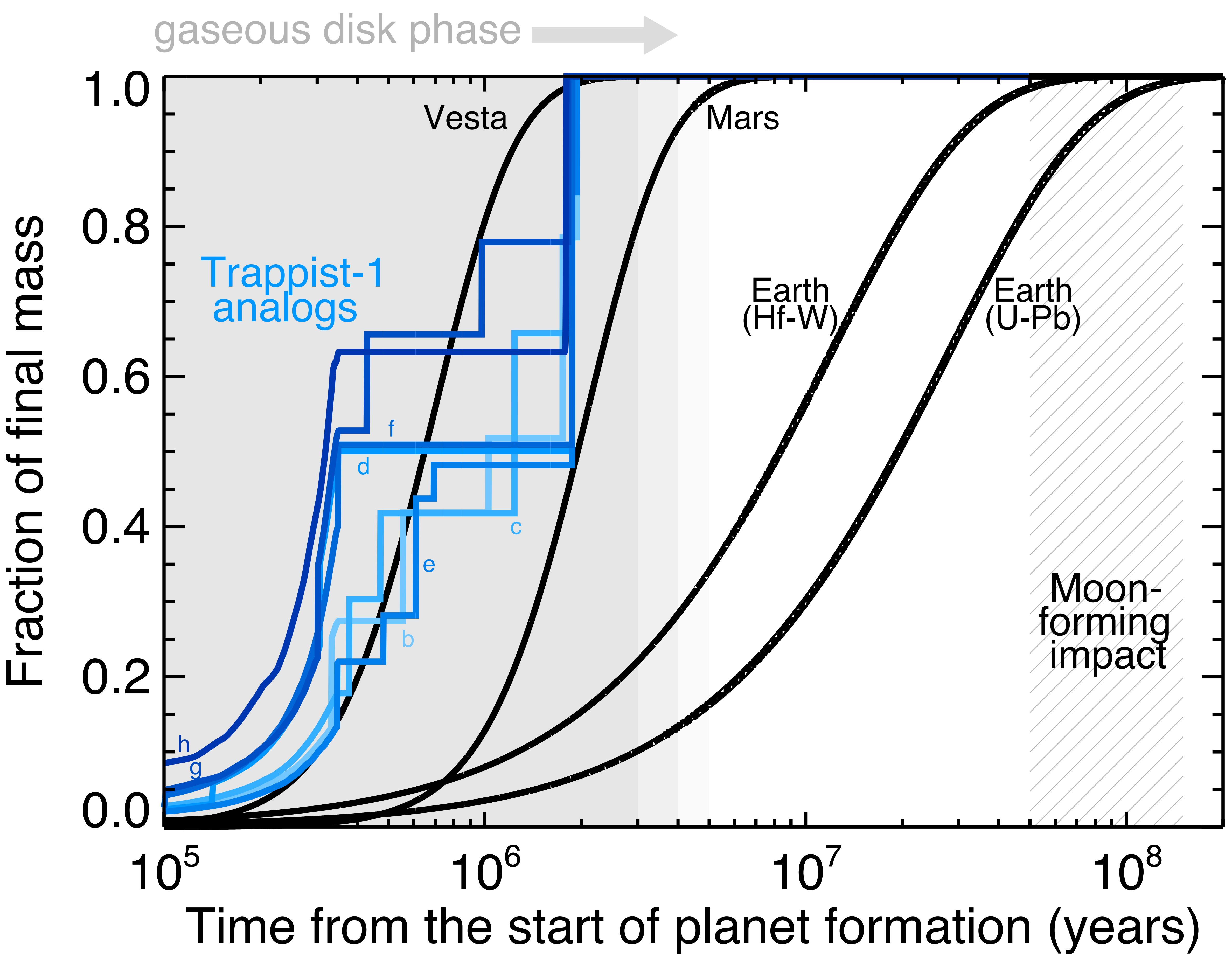
Interesting targets for HWO/LIFE?

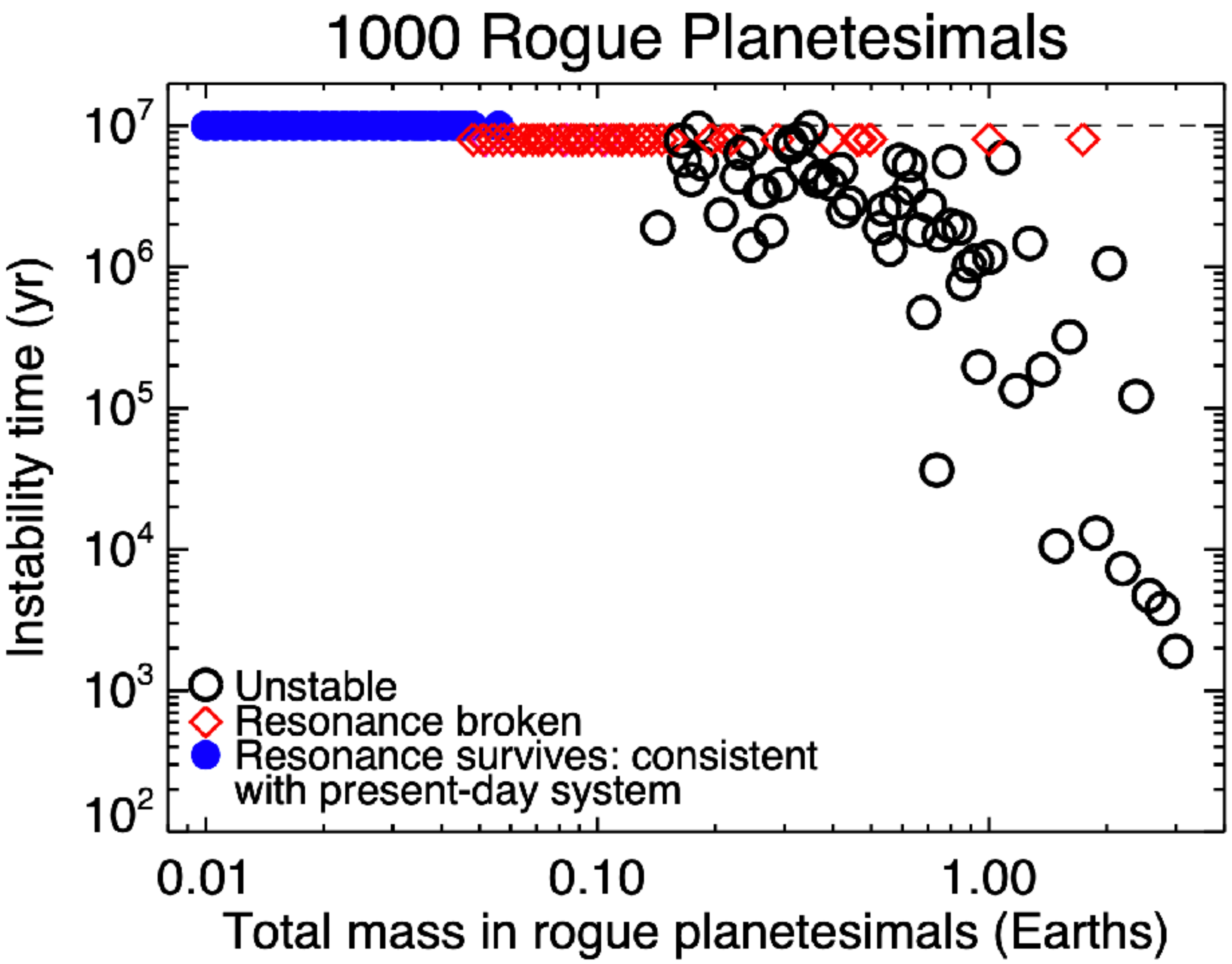
Trappist-1

inner solar system

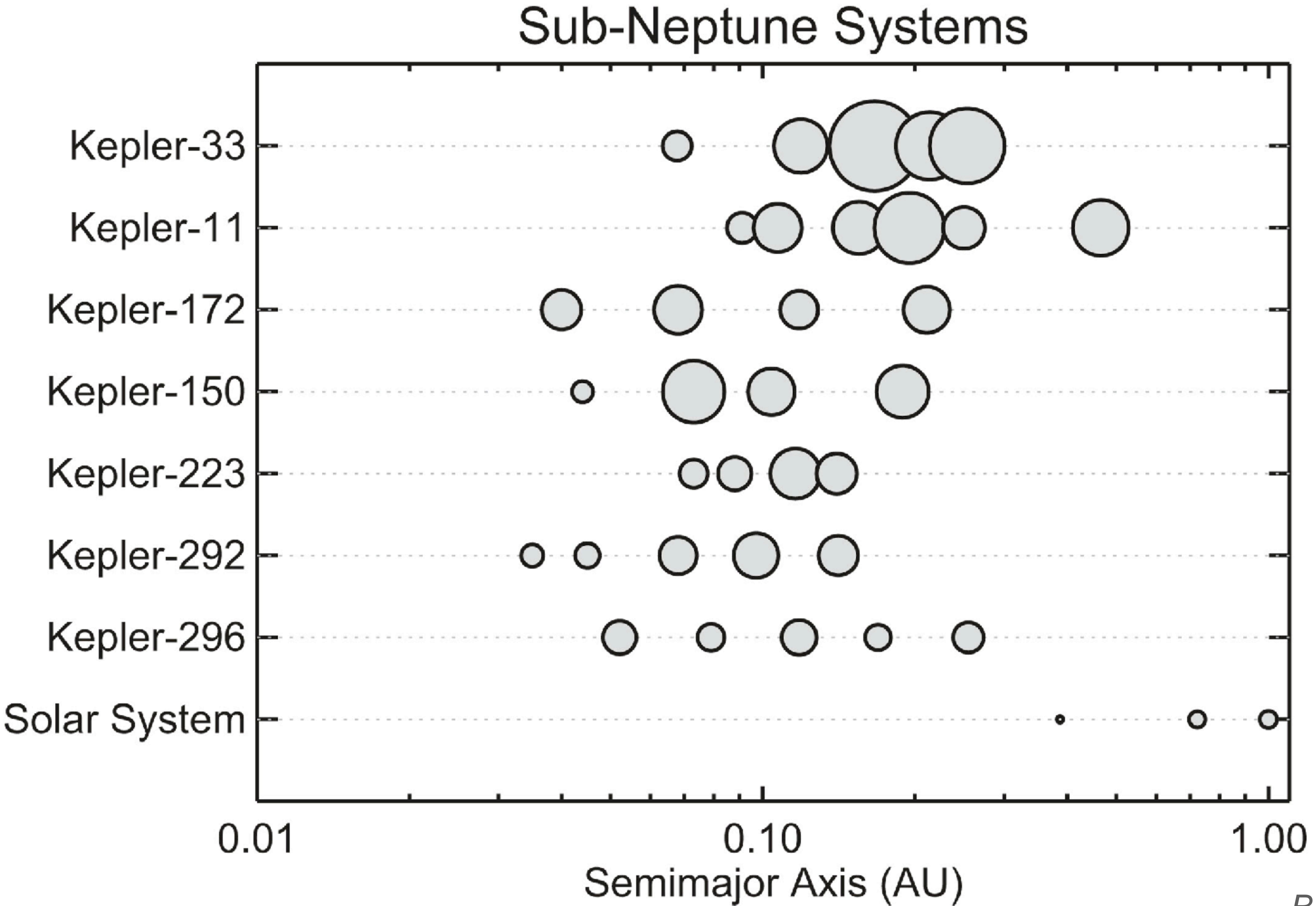


Trappist-1 system fast formation within a disk

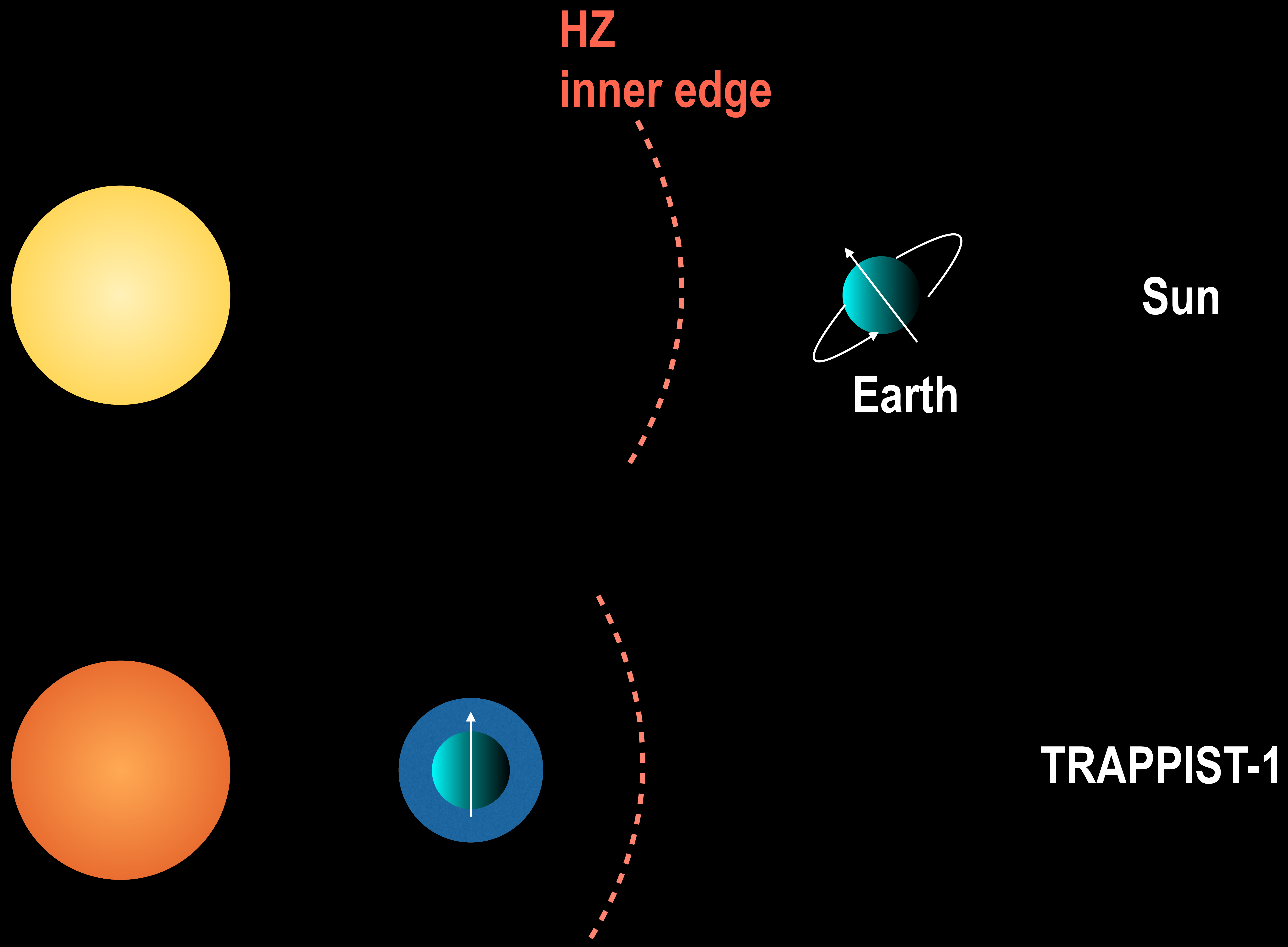




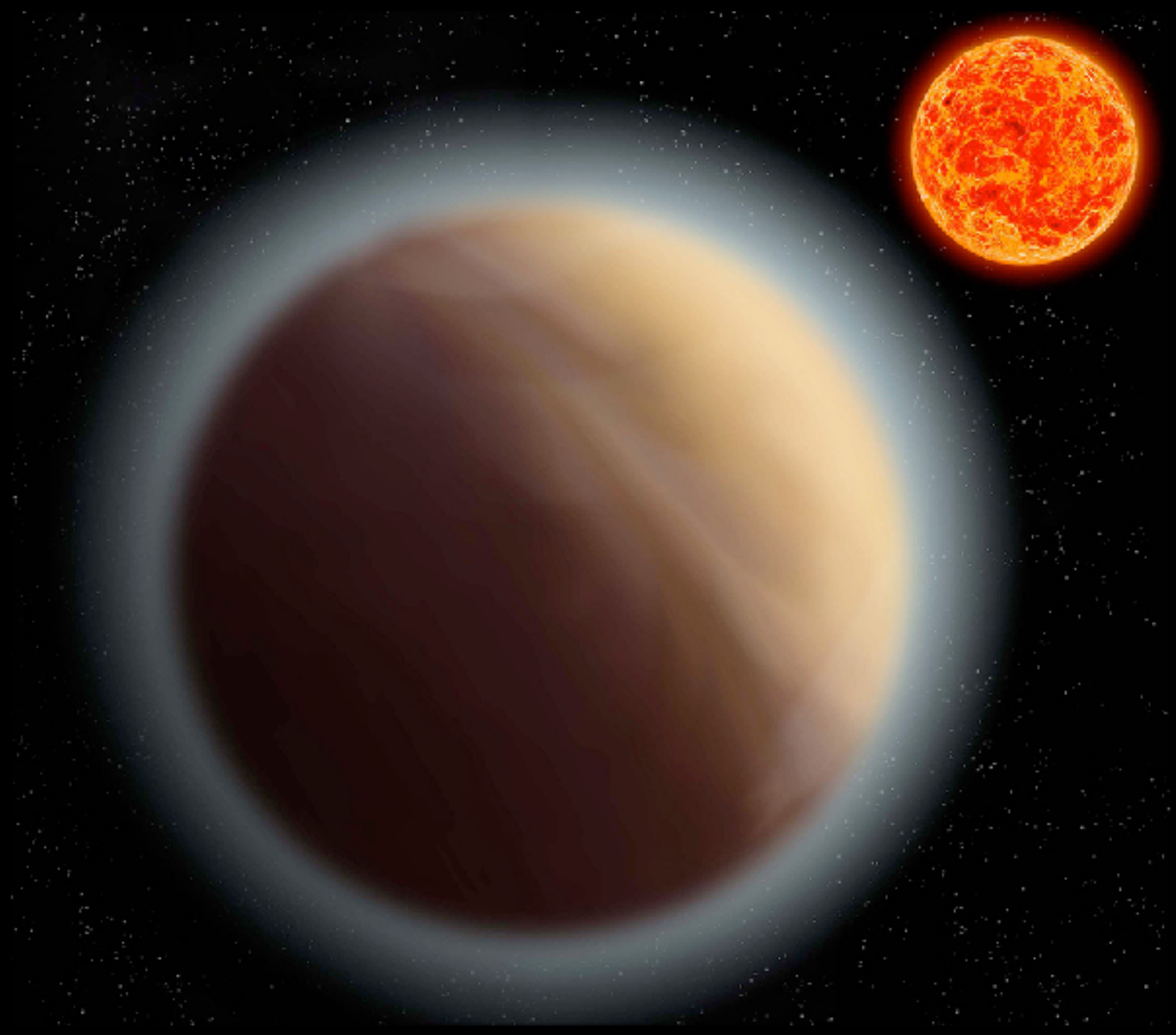
Raymond et al., 2022



Bean et al., 2022


HZ
inner edge
Earth
Sun
TRAPPIST-1

How does atmospheric escape shape planetary atmospheres ?

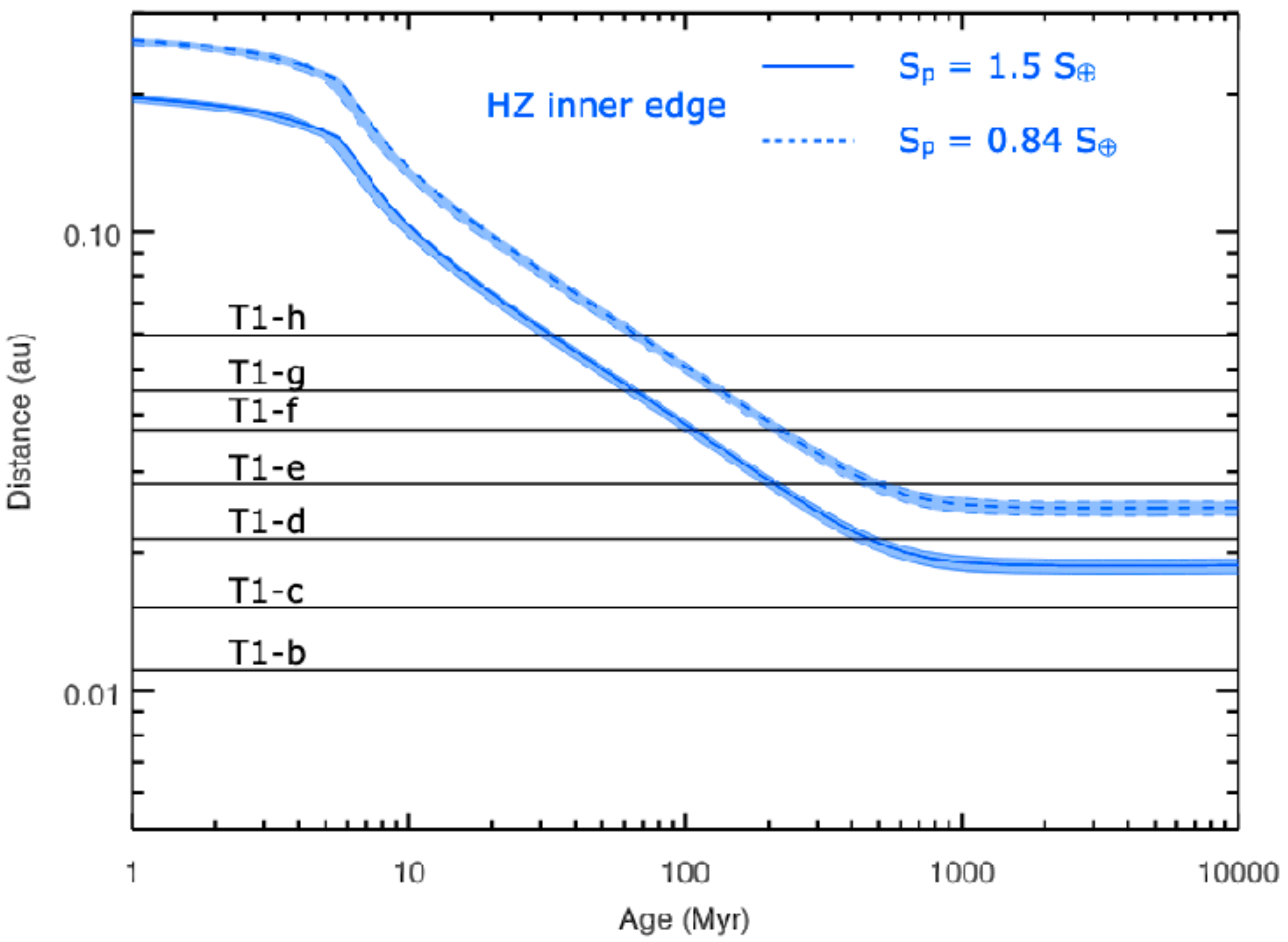


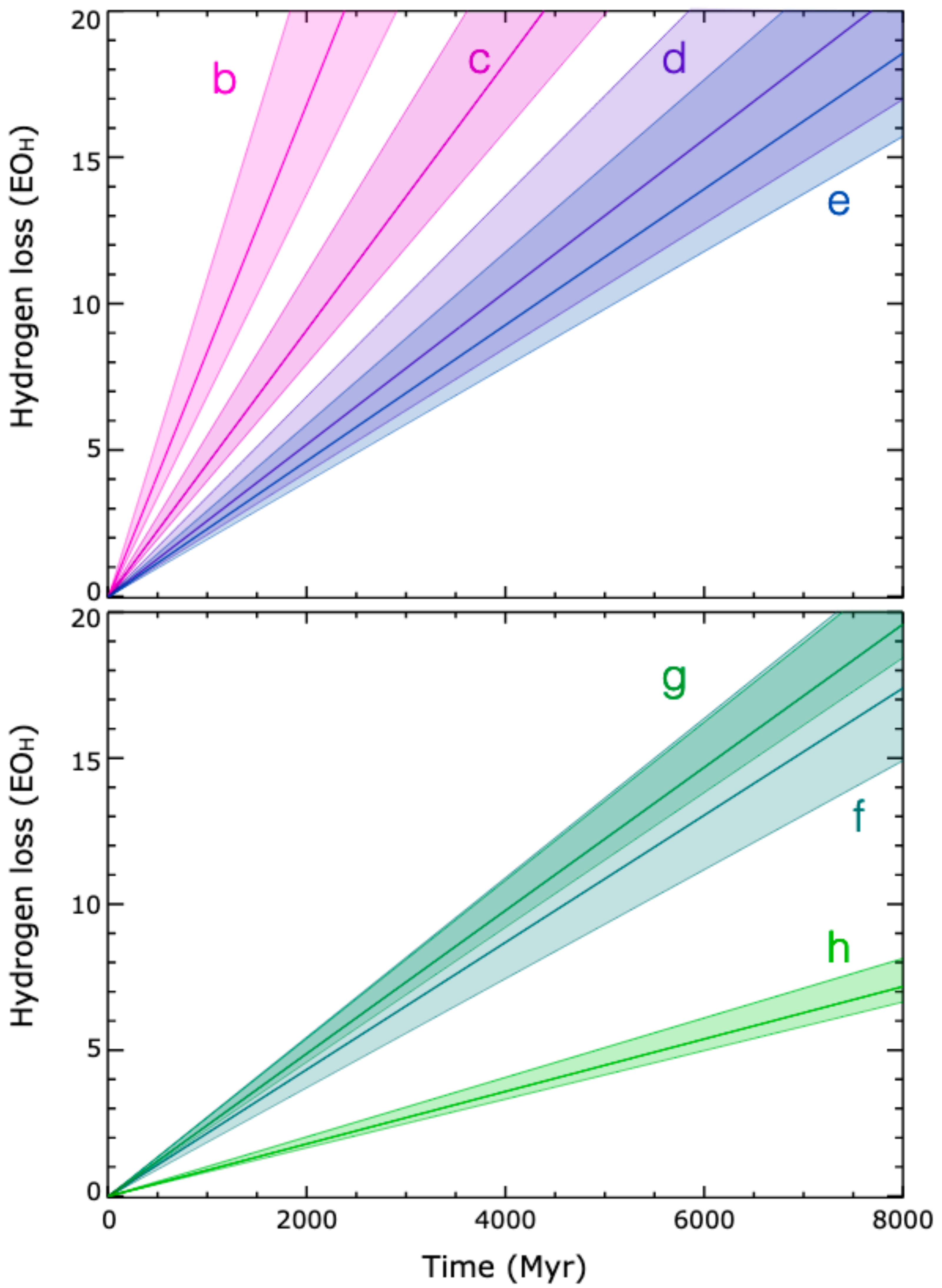
!! Robust models still TBD !!
Current models provide upper limit.

- hydrodynamics vs out-of-equilibrium kinetics
- 3D process (1D forces escape)
- wavelength-dependency of the stellar input
- photochemistry (e.g. H_2O recombination)
- distribution of volatiles within the interior, between the interior and the surface, outgassing history

- non-thermal escape (interaction with stellar wind) : no consistent models yet (ionosphere-induced magnetosphere)

Loss of water (H>>O) during the runaway phase



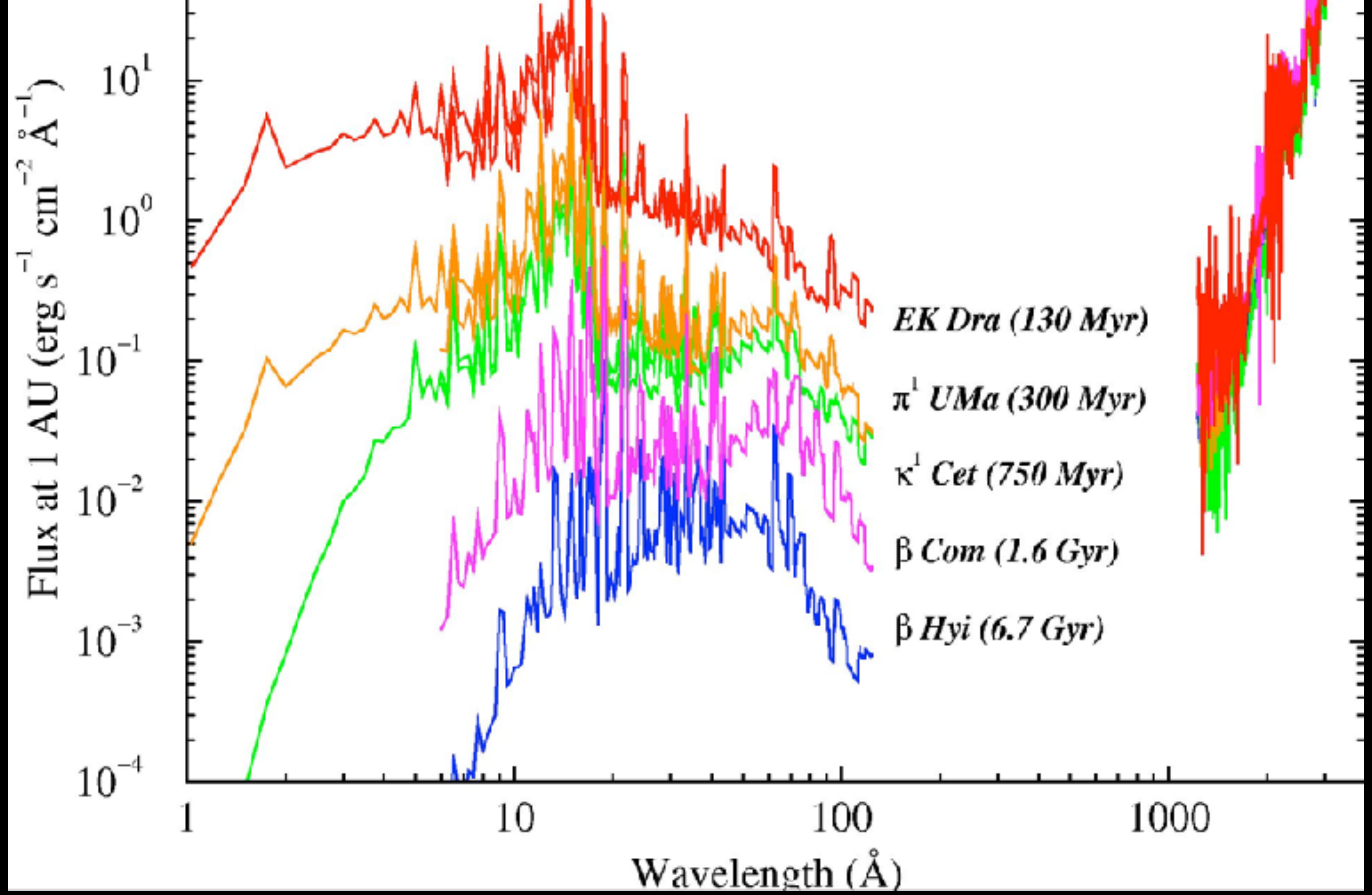


(a) Constant XUV luminosity

10-100s bar of residual O_2 can build up in HZ planets !

Bolmont et al., 2016 - Bourrier et al., 2017

How does atmospheric escape shape planetary atmospheres ?

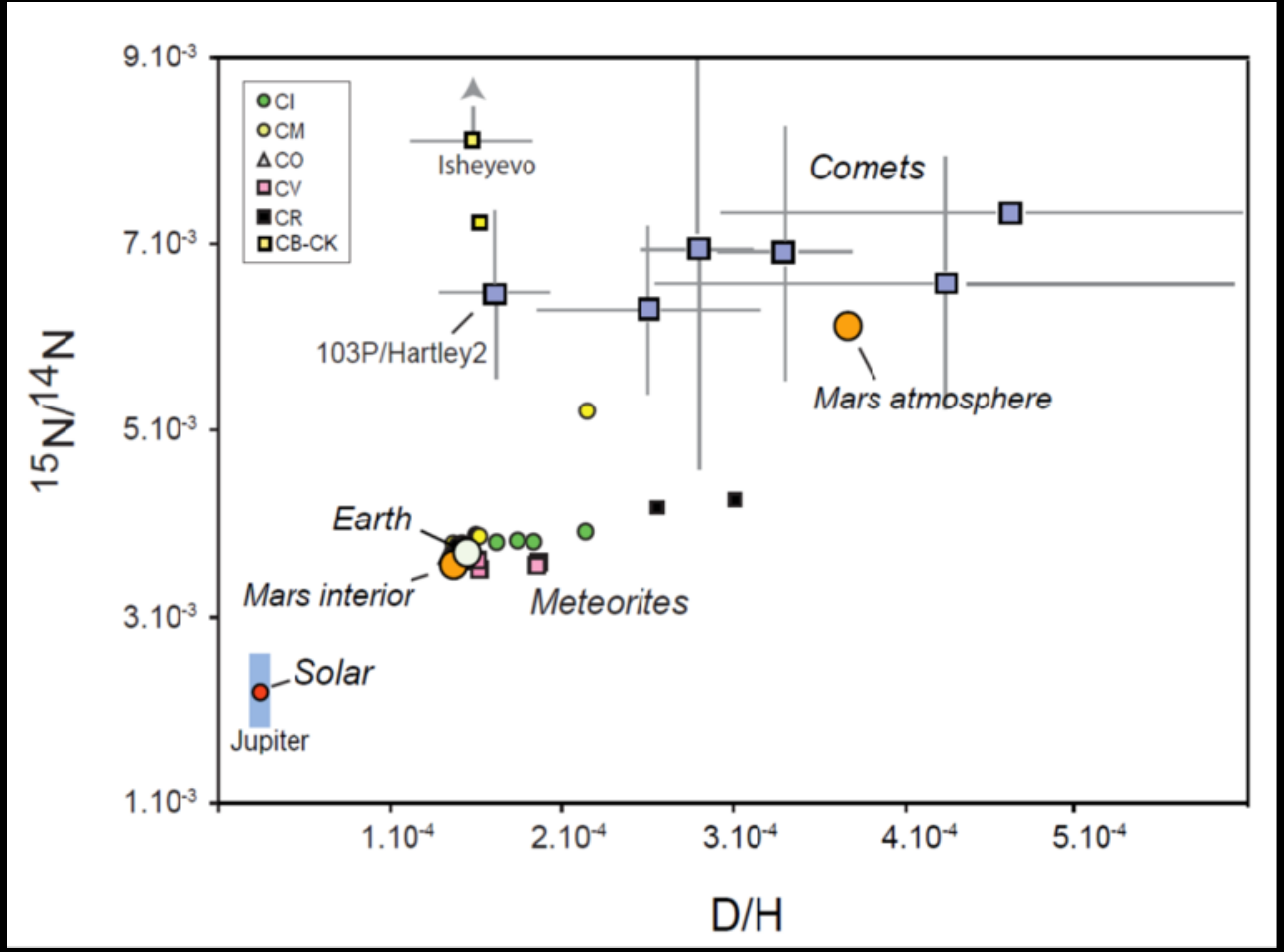


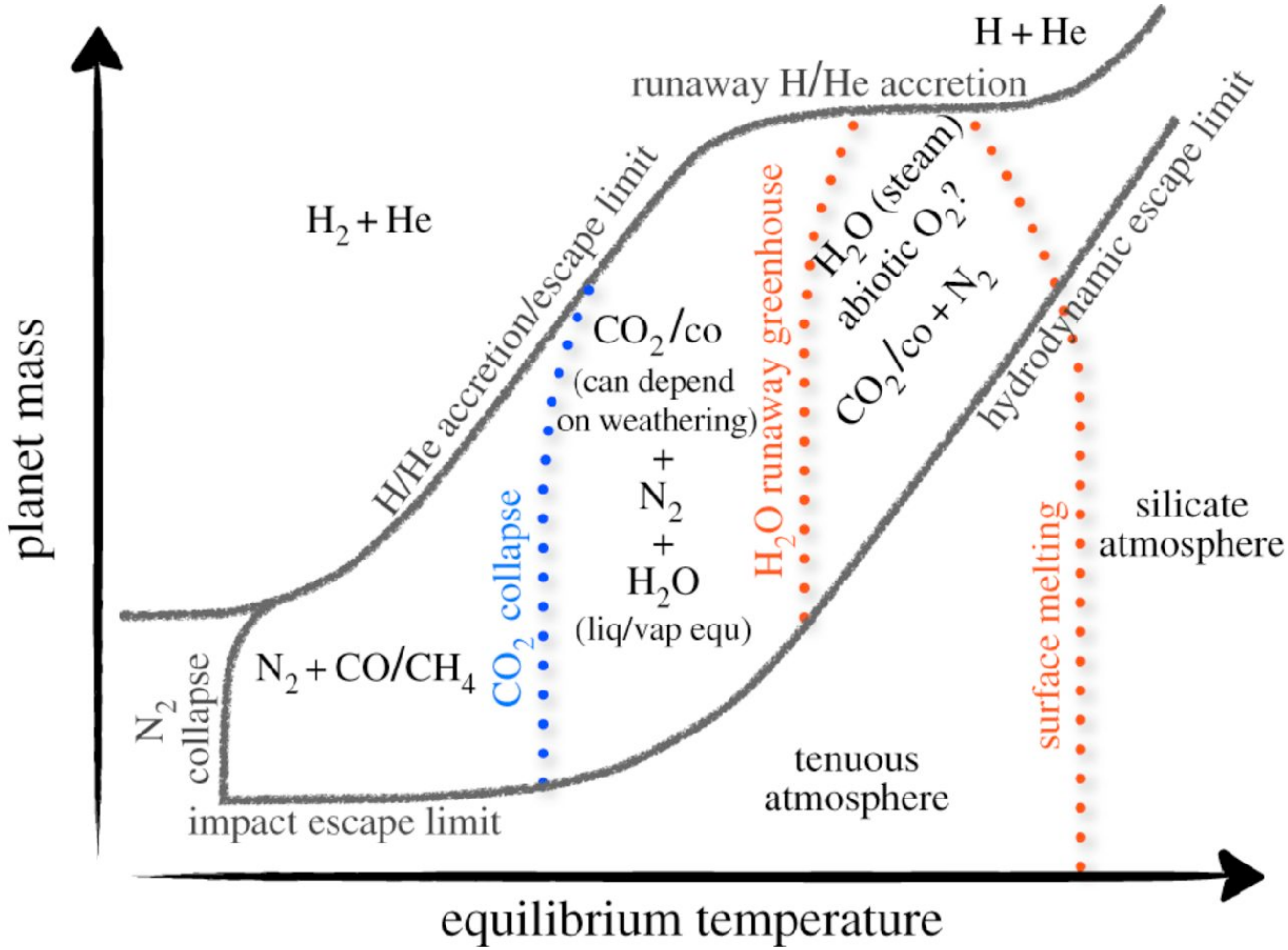
Earth's first 100 Myrs

~ 10-100 giant impacts with magma ocean and steam atmosphere
Marcq et al. (2017)

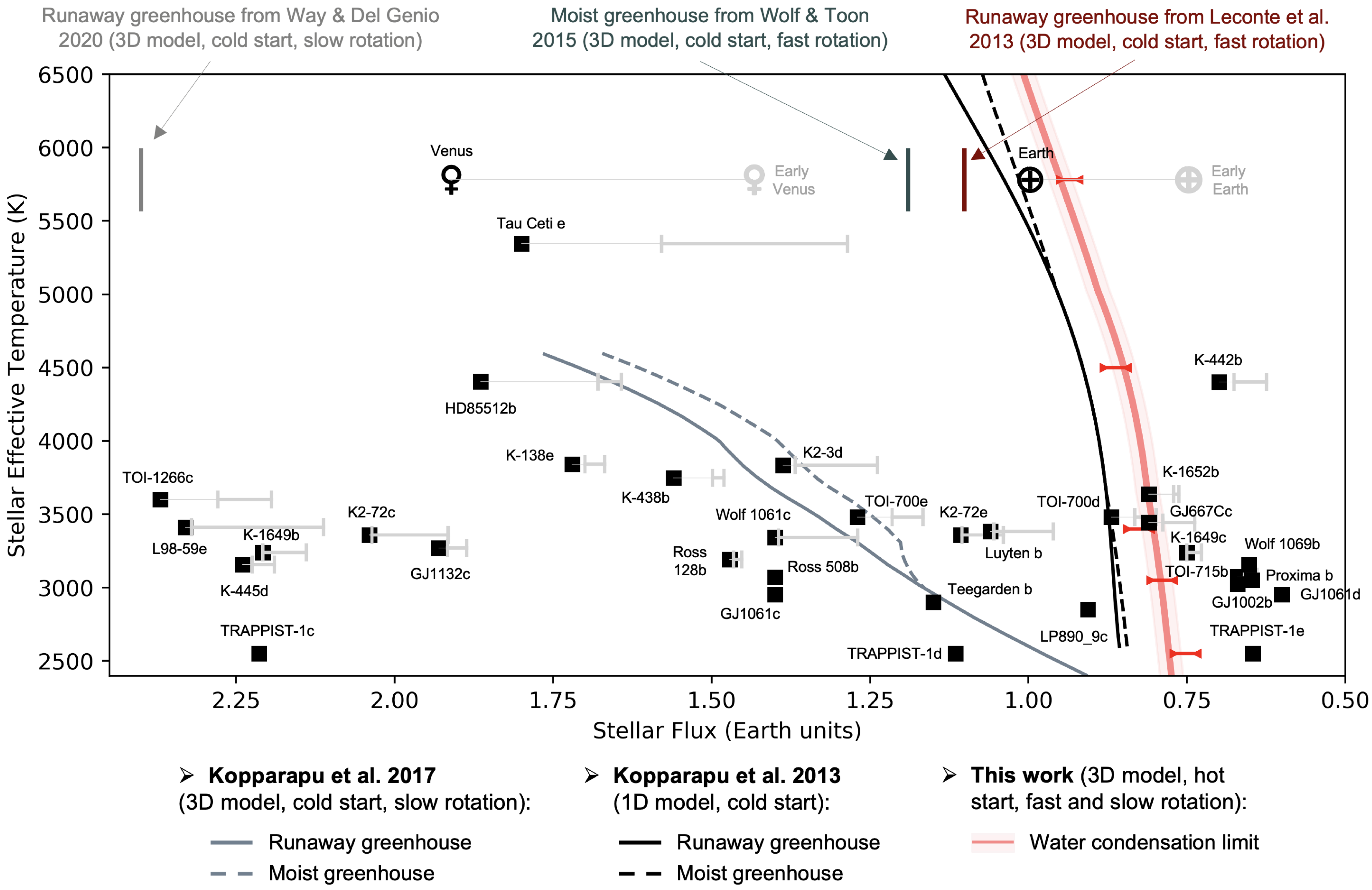
~ **Maximum** stellar activity
Ribas et al. (2005)

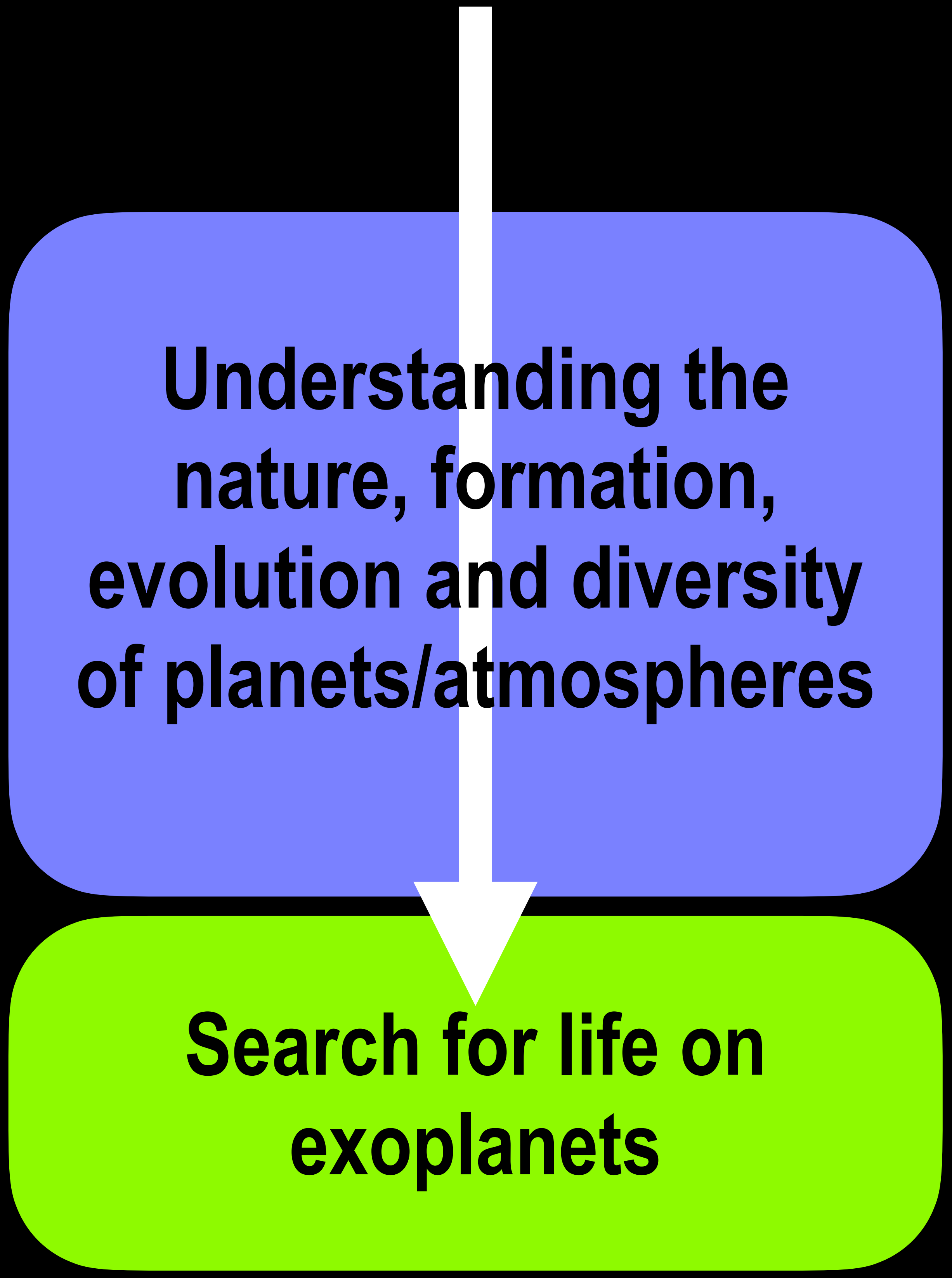
~ no isotopic signature of selective escape D/H, N14/N15, noble gases, except maybe Xe ! Marty et al. (2017)



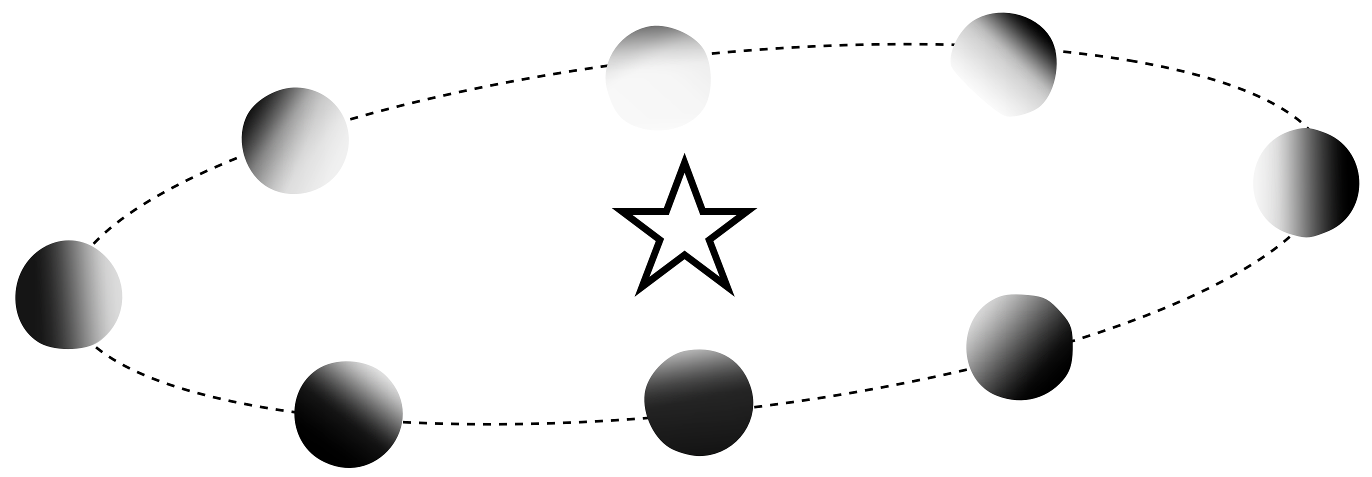


Forget & Leconte 2015


Runaway greenhouse from Way & Del Genio 2020 (3D model, cold start, slow rotation)
Moist greenhouse from Wolf & Toon 2015 (3D model, cold start, fast rotation)
Runaway greenhouse from Leconte et al. 2013 (3D model, cold start, fast rotation)
Stellar Effective Temperature (K)
Stellar Flux (Earth units)
Venus
Early Venus
Earth
Early Earth
Tau Ceti e
HD85512b
K-442b
K-138e
K2-3d
K-438b
TOI-1266c
L98-59e
K-1649b
K-445d
K2-72c
GJ1132c
TRAPPIST-1c
Wolf 1061c
Ross 128b
Ross 508b
GJ1061c
TOI-700e
K2-72e
Luyten b
Teegarden b
TRAPPIST-1d
TOI-700d
LP890_9c
K-1652b
GJ667Cc
K-1649c
Wolf 1069b
TOI-715b
Proxima b
GJ1002b
GJ1061d
TRAPPIST-1e
Kopparapu et al. 2017 (3D model, cold start, slow rotation):
Runaway greenhouse
Moist greenhouse
Kopparapu et al. 2013 (1D model, cold start):
Runaway greenhouse
Moist greenhouse
This work (3D model, hot start, fast and slow rotation):
Water condensation limit

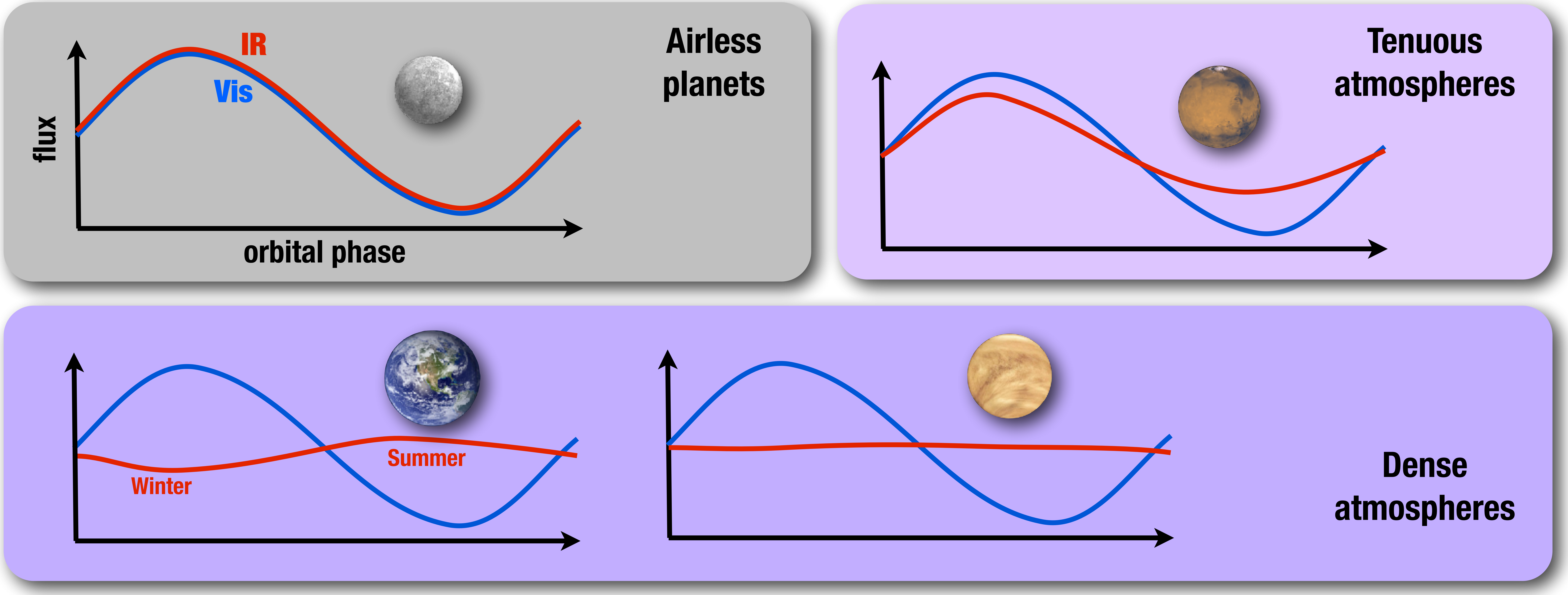


HWO/LIFE could be major contributors



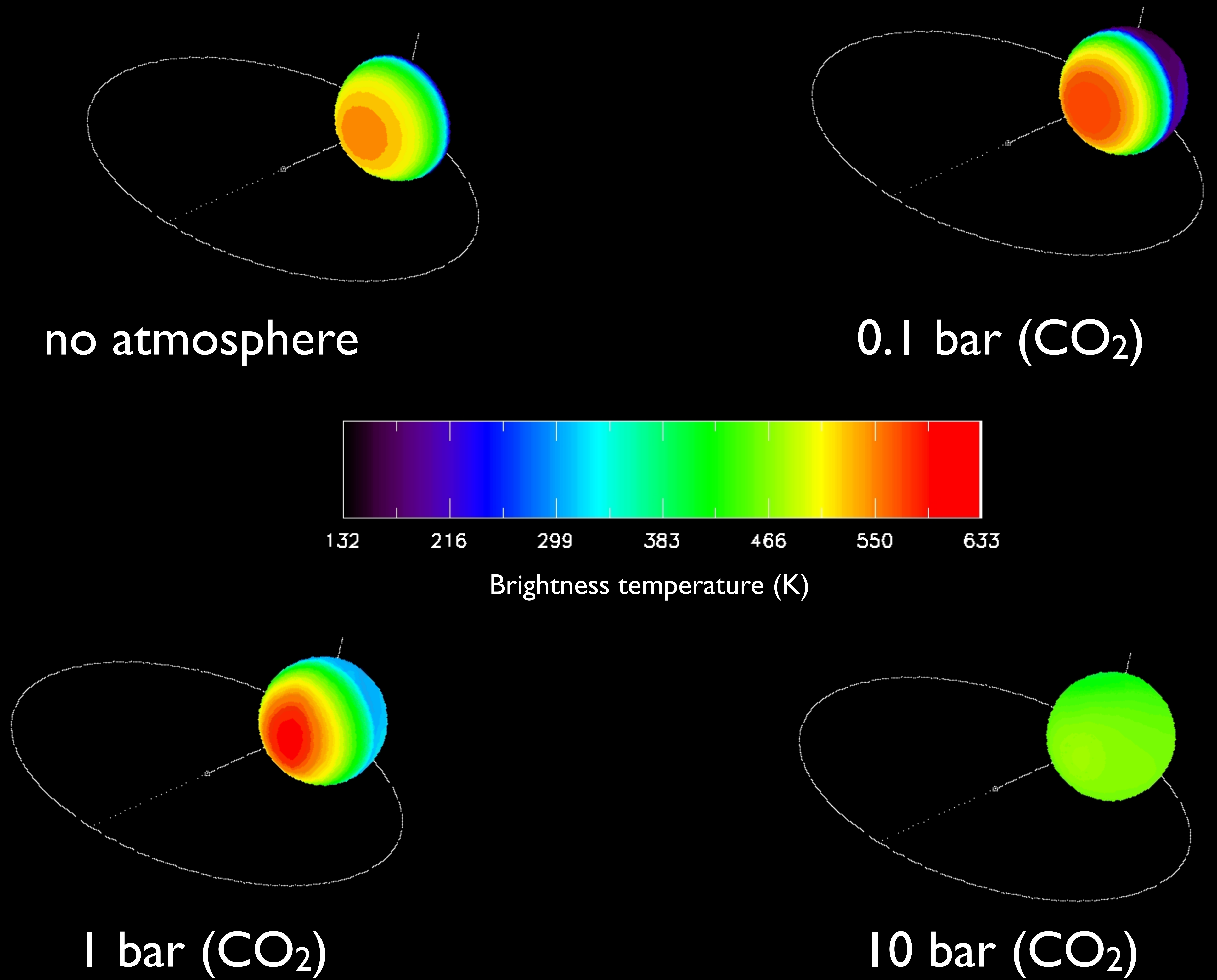
Imaging requires several observations:
- planet vs background object
- orbital parameters
- coronographic/nulling dead central zone

partial phase curve for free



Selsis, 2003, Darwin proposal

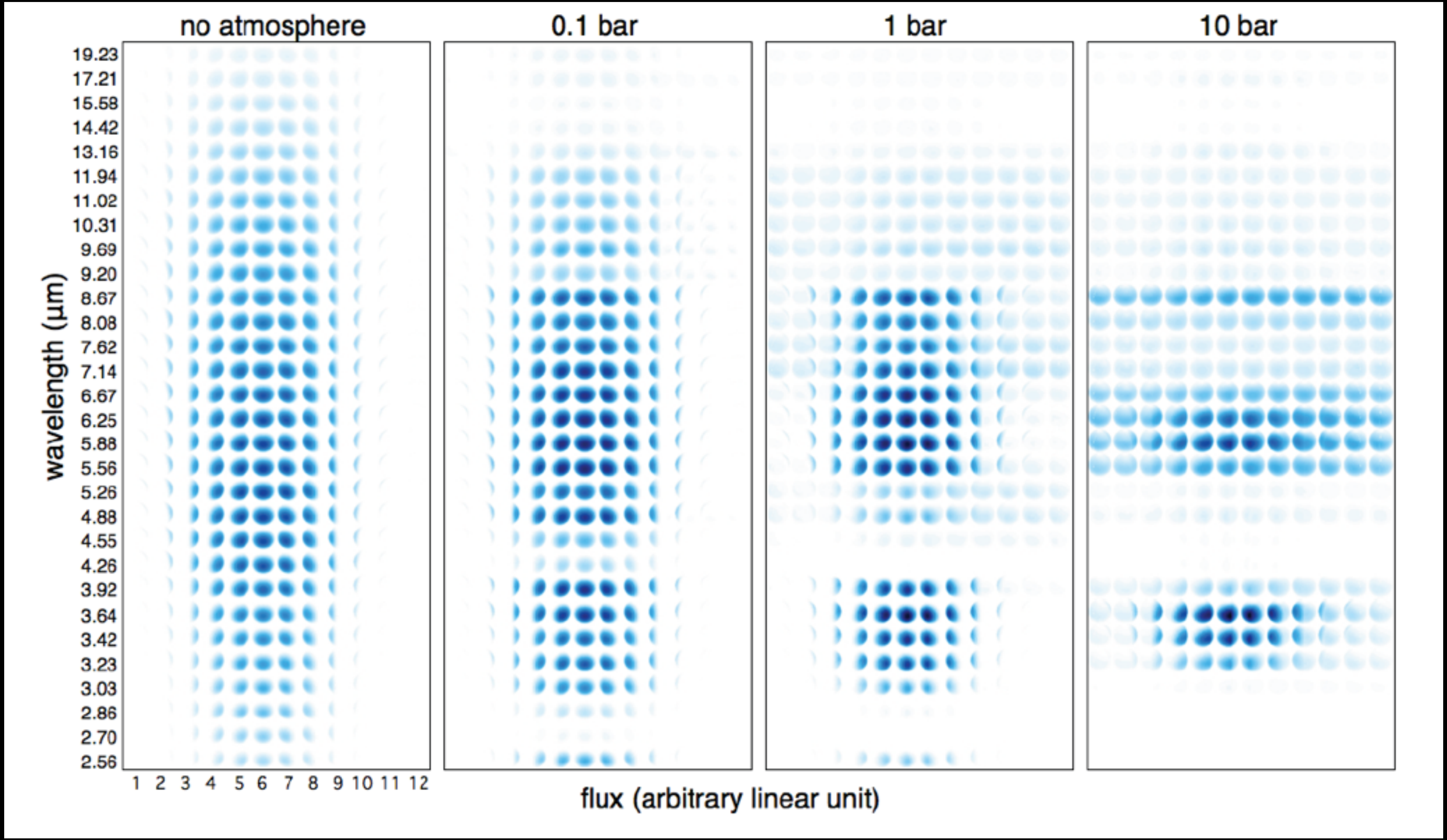
8.7 mm



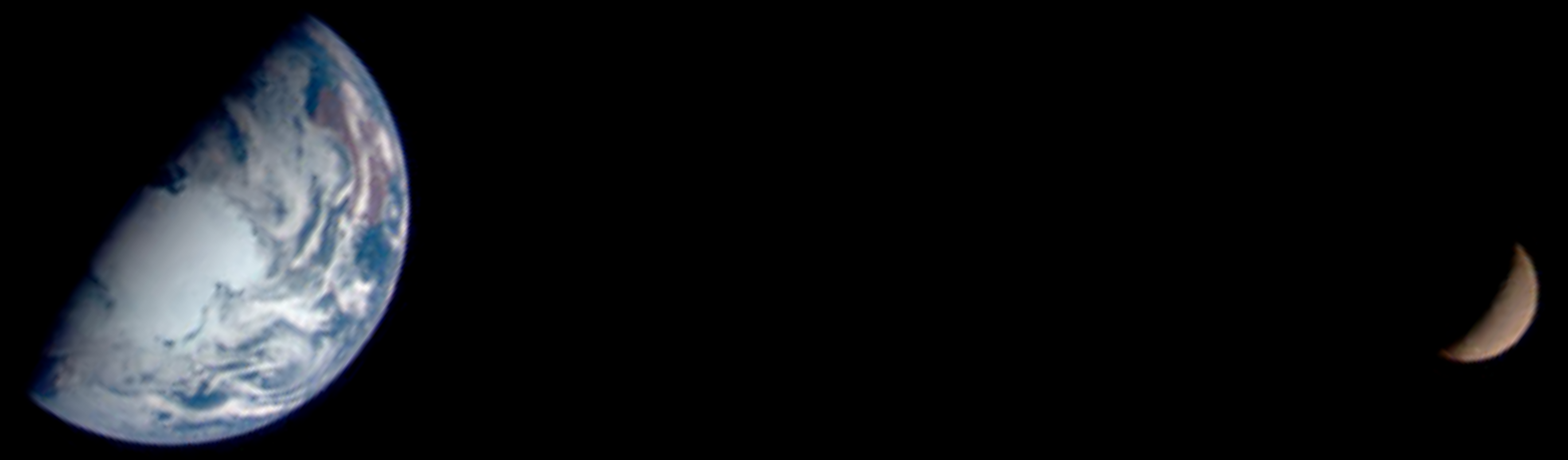
no atmosphere
0.1 bar (CO_2)
132
216
299
383
466
550
633
Brightness temperature (K)
1 bar (CO_2)
10 bar (CO_2)

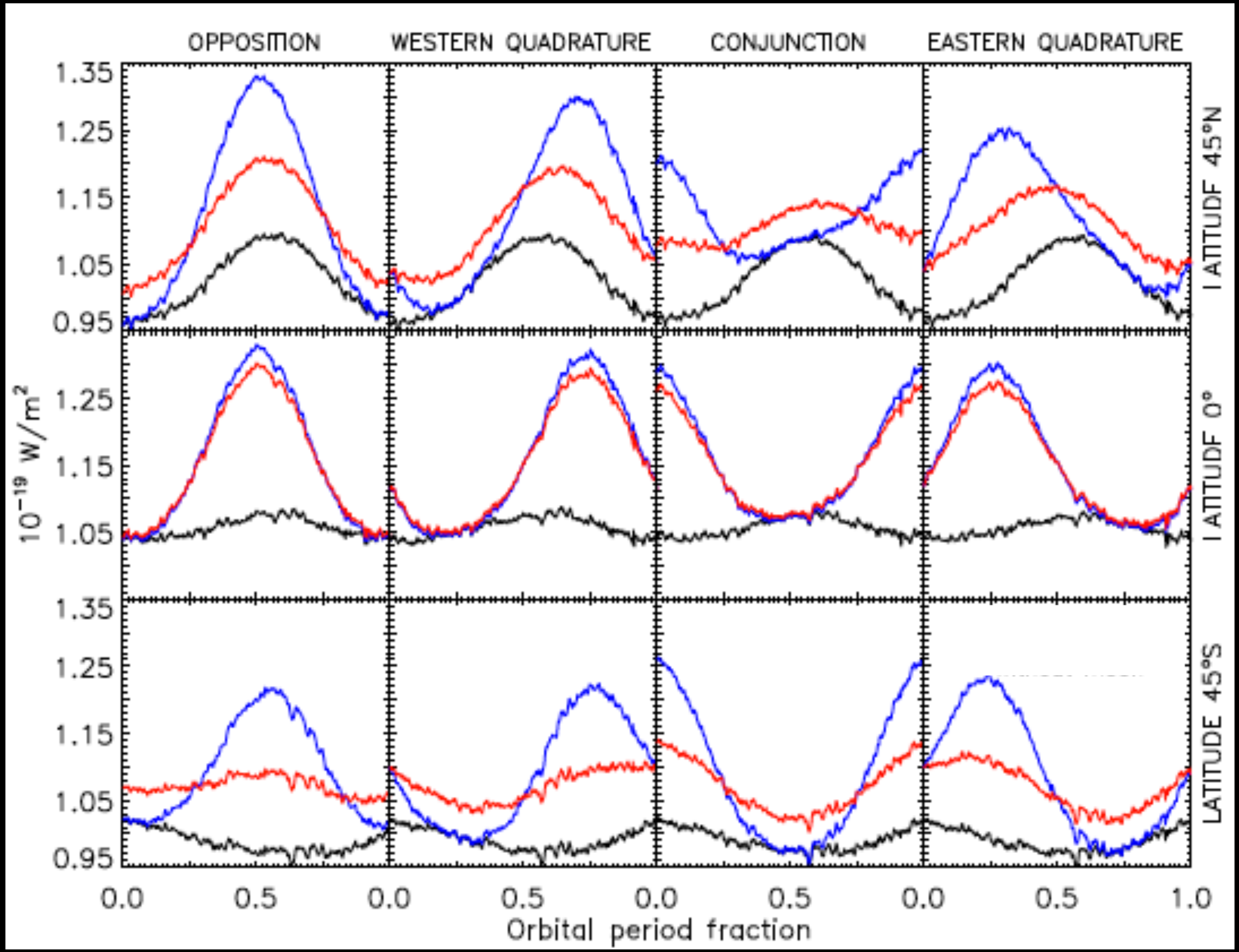
Phase curve T1b

Planet: 1.8 R_{Earth} ,10 M_{Earth} - Star: 0.3 M_{Sun} - 0.05 AU (P=8 days)
Circular orbit - tidally locked.
Only one atmospheric constituant: CO_2



Selsis, Wordsworth, Forget., 2011





Gomez-Leal et al., ApJ, 2012

Excellent complementarity of the HWO and LIFE spectral domains

UV-Vis-NIR (HWO) & Thermal IR (LIFE)

spectroscopy on a broad domain
(more molecules, more features of a same molecule)

comprehensive radiative budget

climate /thermal IR phase curves
vs
reflectivity of clouds, ice, liquid water (glint) / UV/vis/NIR

But can they target the same planets?

What modelers can do to help prepare LIFE/HWO

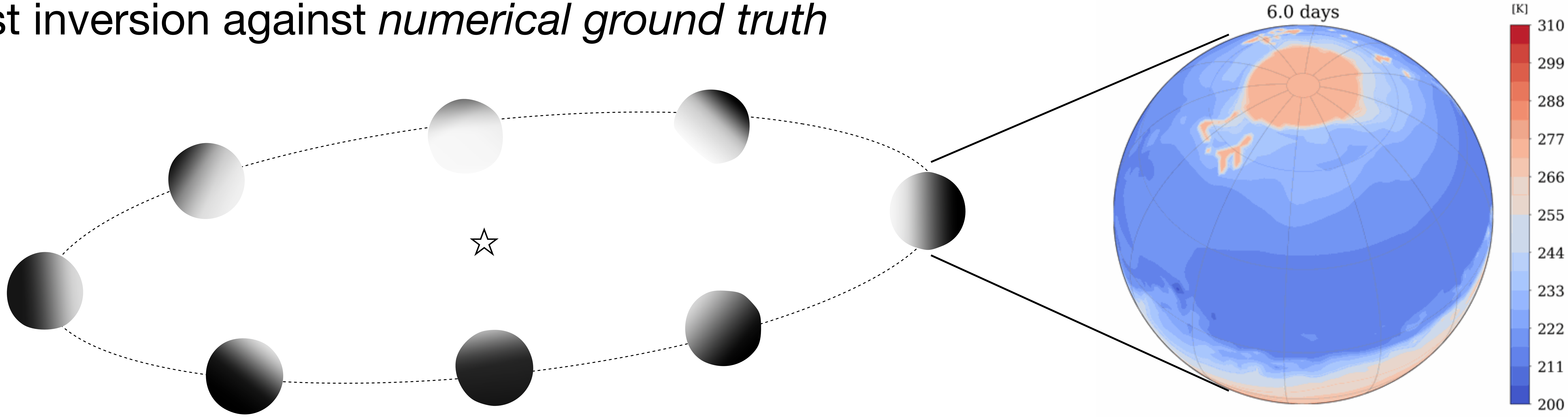
- Model a variety of planetary atmospheres/surfaces (atm pressure and composition, host star, orbit)

Talk by Benjamin Charnay

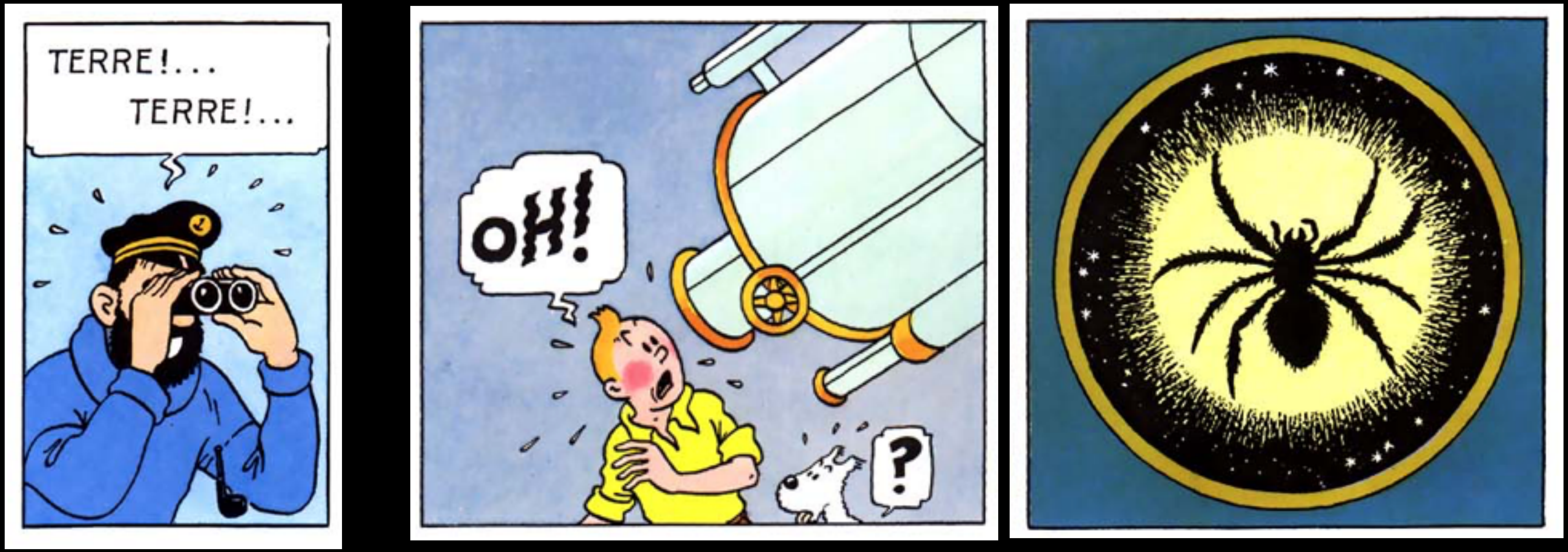
- Produce synthetic spectra/phase curves

- Pass them through instrument models

- Test inversion against *numerical ground truth*




planet LV307
planet LV021
planet LV232
planet LV021
planet LV088
planet LV420
time
observations
planet LV426
time
observations
ANOMALY
consensus



L'étoile mystérieuse (*The sooting star*) Hergé 1946

Are we alone in the Universe? We don't care.

The real question is:
Is the Universe so crowded with life(*) that we can find it on a nearby exoplanet?
For instance : 1000 inhabited planets /galaxy is not enough (but that is REALLY not being alone).

(*) life that changed its planet in an observable way