# Geochemical evolution of terrestrial planets and biosignatures

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NASA/JPL-
Caltech

# Comparative evolution of terrestrial planets

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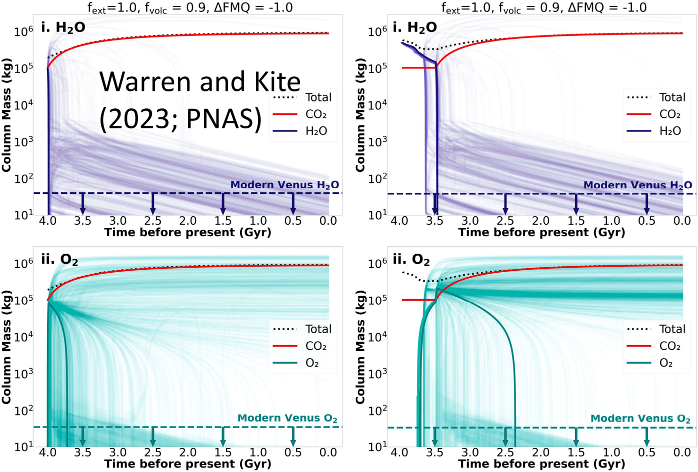
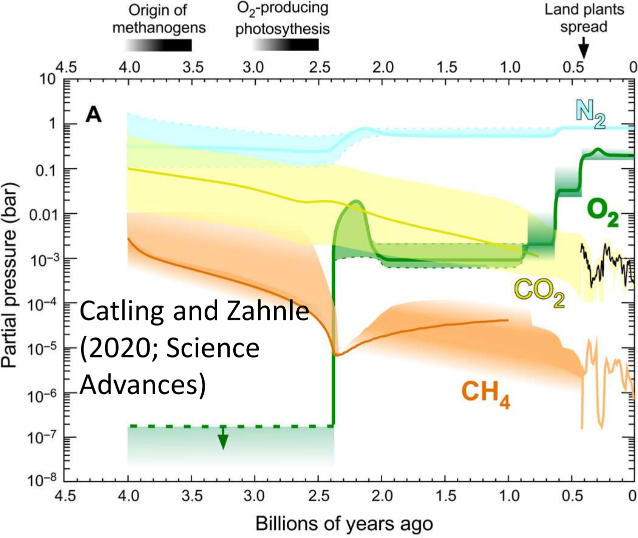
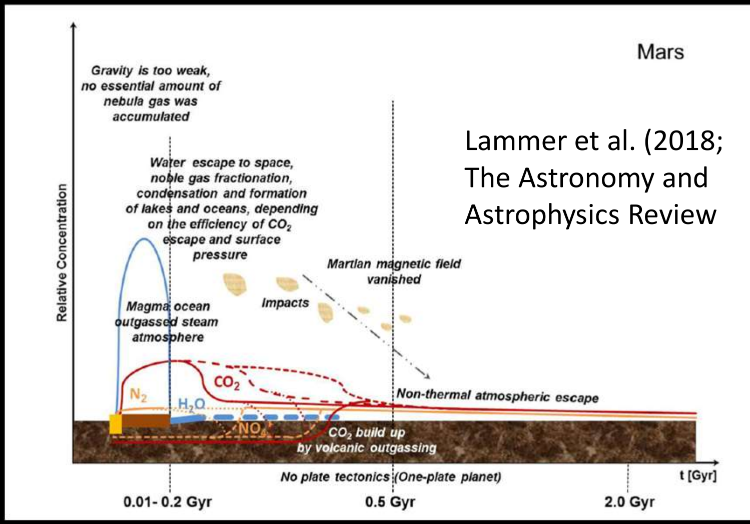


Warren and Kite (2023; PNAS)

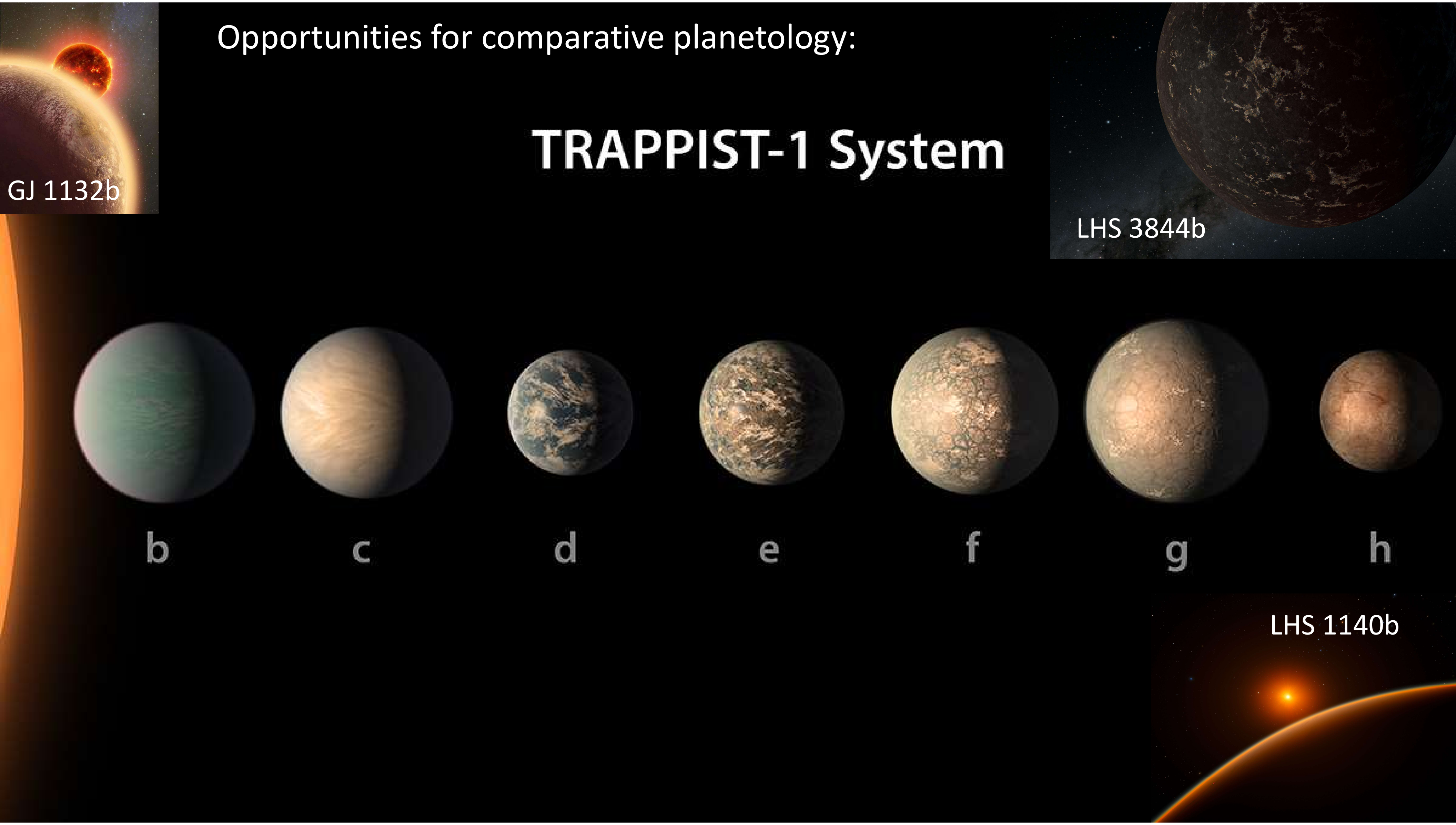


Catling and Zahnle (2020; Science Advances)

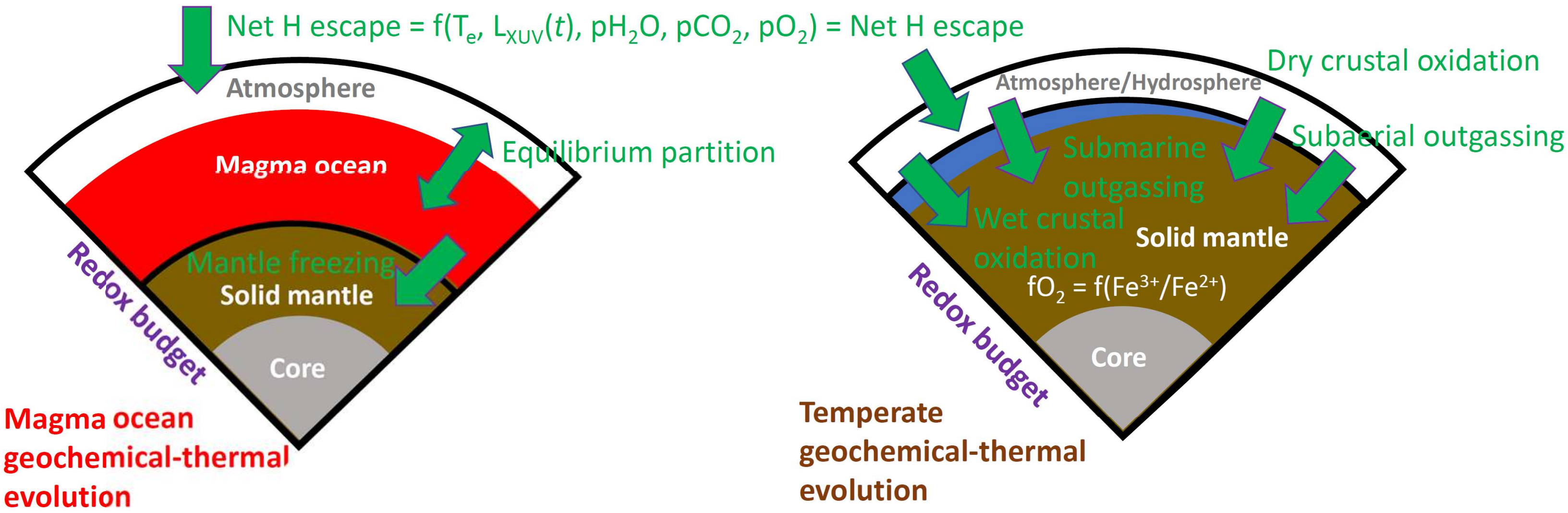


Lammer et al. (2018; The Astronomy and Astrophysics Review

## Opportunities for comparative planetology:



# Explicitly model terrestrial planet atmosphere-interior geochemical evolution



Net H escape = f($T_e$, $L_{XUV}(t)$, $pH_2O$, $pCO_2$, $pO_2$) = Net H escape

Atmosphere

Magma ocean

Equilibrium partition

Mantle freezing

Solid mantle

Core

Redox budget

**Magma ocean geochemical-thermal evolution**

Atmosphere/Hydrosphere

Dry crustal oxidation

Subaerial outgassing

Submarine outgassing

Wet crustal oxidation

Solid mantle

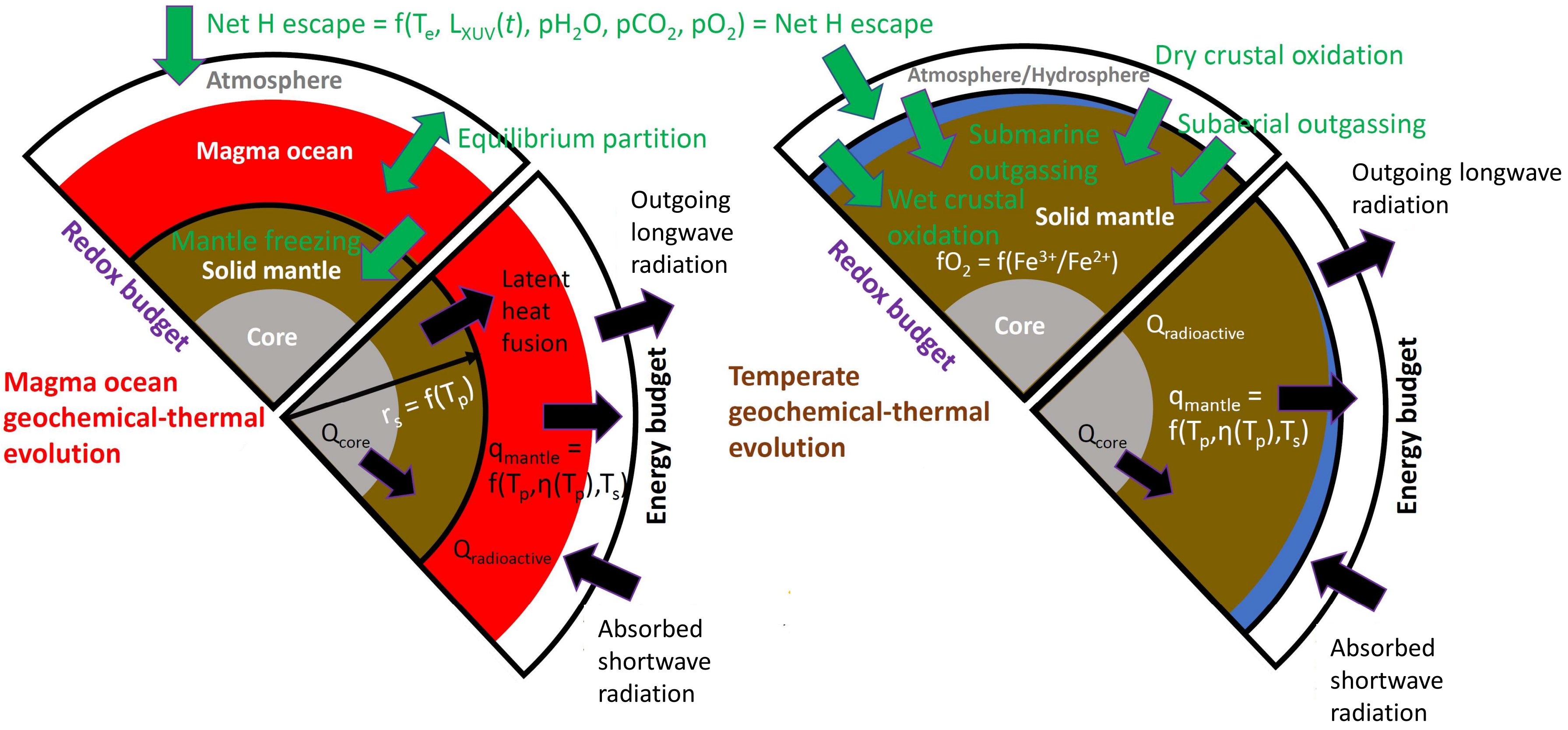
$fO_2 = f(Fe^{3+}/Fe^{2+})$

Core

Redox budget

**Temperate geochemical-thermal evolution**

# Explicitly model terrestrial planet atmosphere-interior geochemical evolution



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Atmosphere

Magma ocean

Equilibrium partition

Mantle freezing

Solid mantle

Core

Redox budget

Latent heat fusion

$r_s = f(T_p)$

$Q_{core}$

$q_{mantle} = f(T_p, \eta(T_p), T_s)$

$Q_{radioactive}$

Outgoing longwave radiation

Energy budget

Absorbed shortwave radiation

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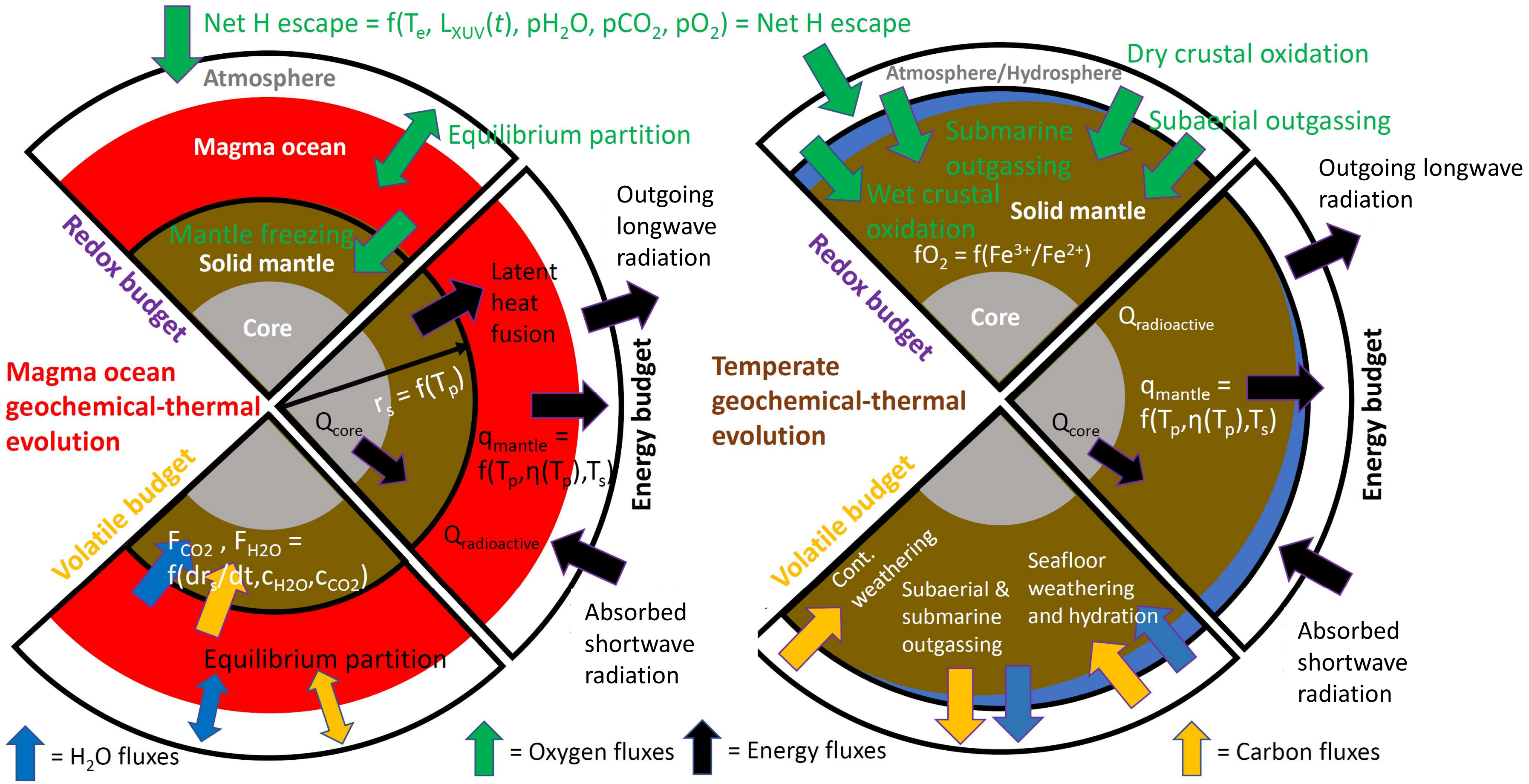
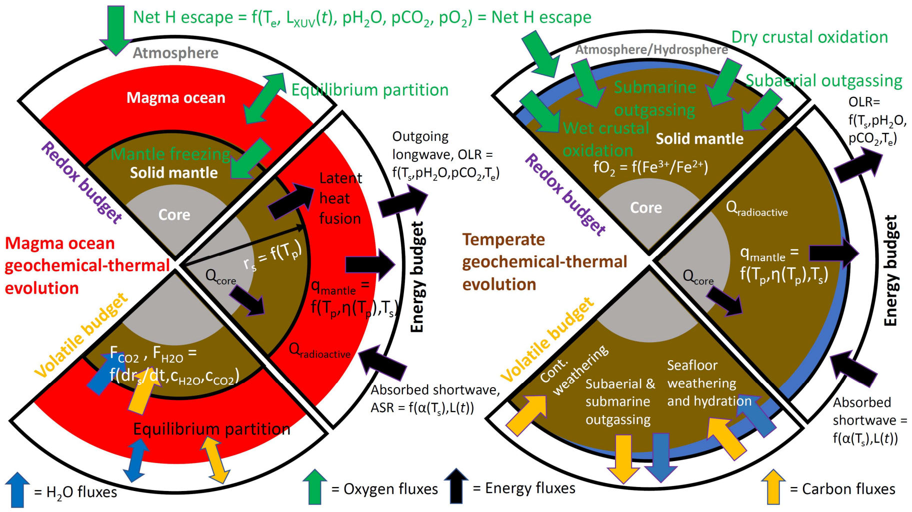
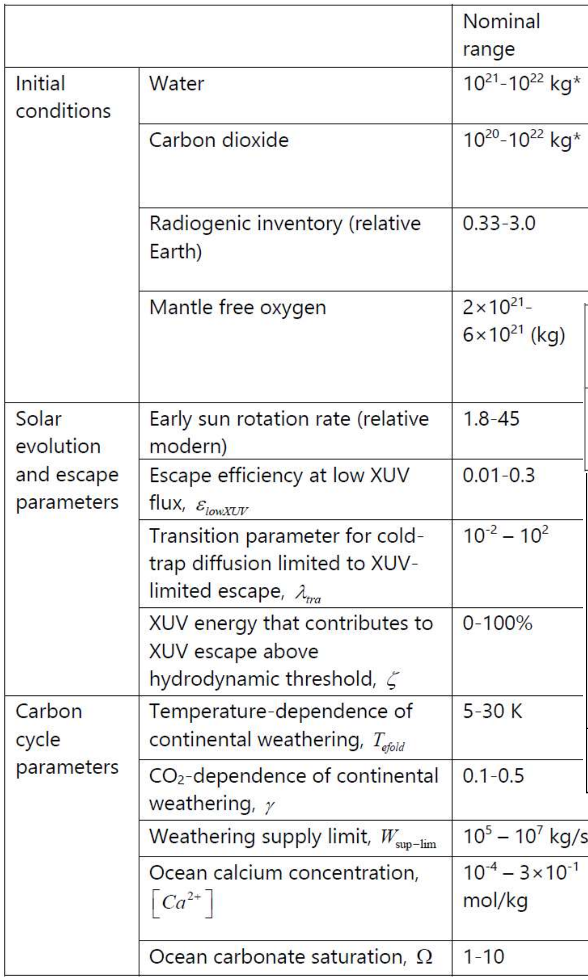
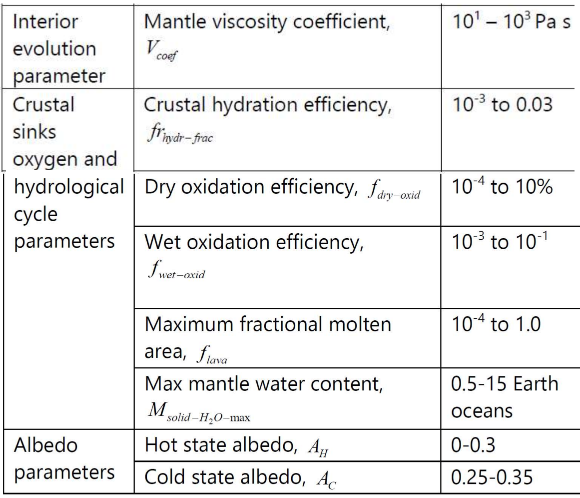


# Monte Carlo approach for uncertain parameters and initial conditions:



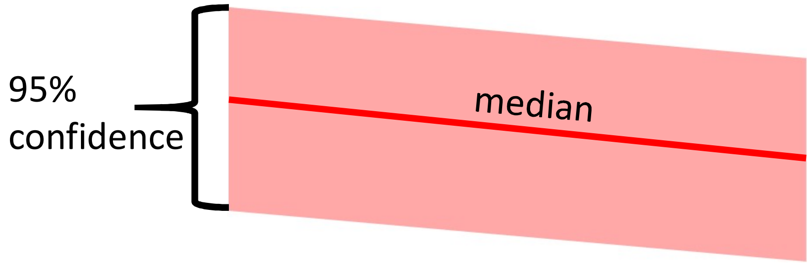


| | | Nominal range |
|---|---|---|
| Initial conditions | Water | $10^{21}$-$10^{22}$ kg* |
| | Carbon dioxide | $10^{20}$-$10^{22}$ kg* |
| | Radiogenic inventory (relative Earth) | 0.33-3.0 |
| | Mantle free oxygen | $2\times10^{21}$-$6\times10^{21}$ (kg) |
| Solar evolution and escape parameters | Early sun rotation rate (relative modern) | 1.8-45 |
| | Escape efficiency at low XUV flux, $\varepsilon_{lowXUV}$ | 0.01-0.3 |
| | Transition parameter for cold-trap diffusion limited to XUV-limited escape, $\lambda_{tra}$ | $10^{-2}$ – $10^{2}$ |
| | XUV energy that contributes to XUV escape above hydrodynamic threshold, $\zeta$ | 0-100% |
| Carbon cycle parameters | Temperature-dependence of continental weathering, $T_{efold}$ | 5-30 K |
| | $CO_2$-dependence of continental weathering, $\gamma$ | 0.1-0.5 |
| | Weathering supply limit, $W_{sup-lim}$ | $10^5$ – $10^7$ kg/s |
| | Ocean calcium concentration, $\left[Ca^{2+}\right]$ | $10^{-4}$ – $3\times10^{-1}$ mol/kg |
| | Ocean carbonate saturation, $\Omega$ | 1-10 |

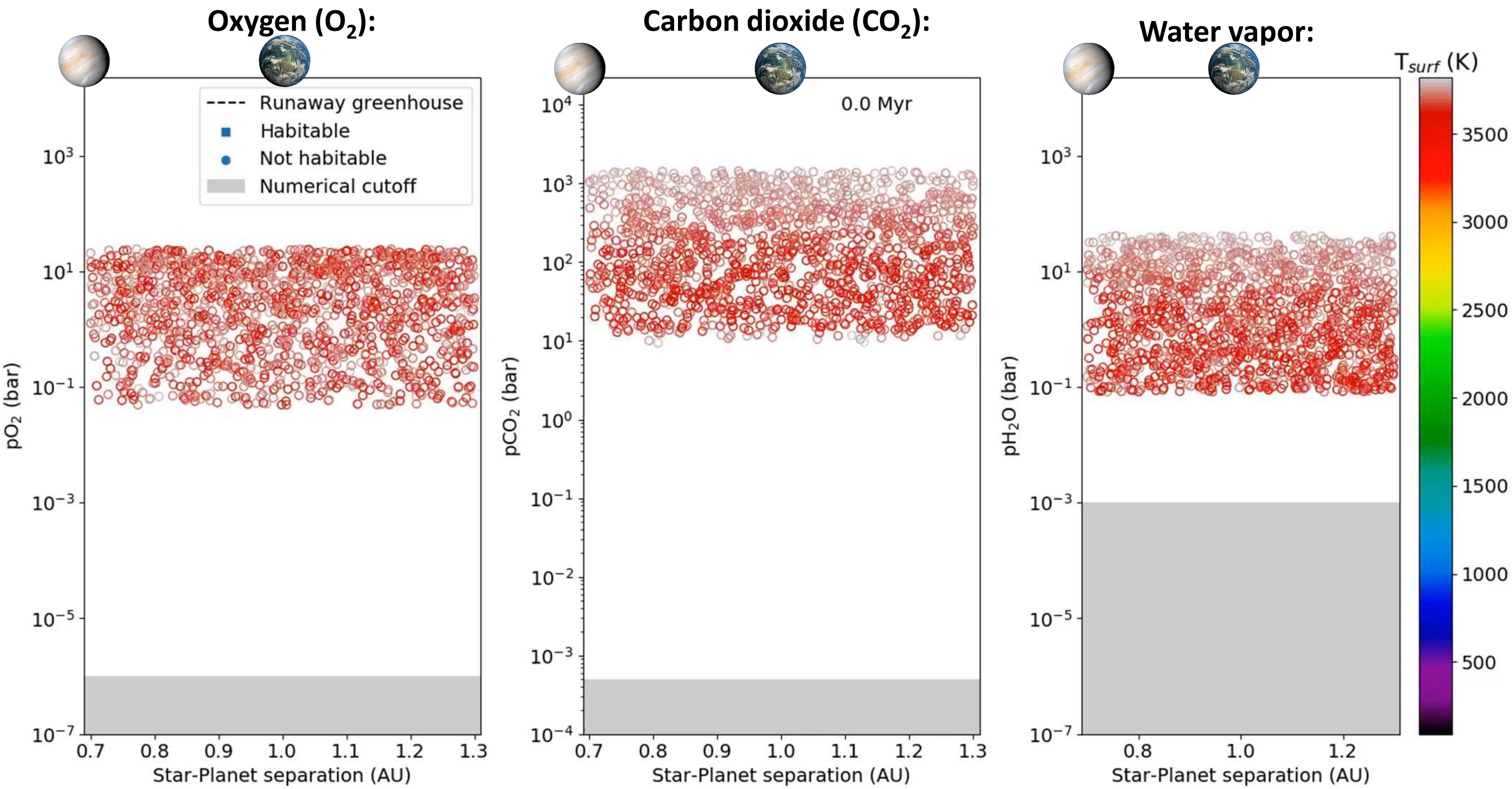


| | | |
|---|---|---|
| Interior evolution parameter | Mantle viscosity coefficient, $V_{coef}$ | $10^1$ – $10^3$ Pa s |
| Crustal sinks oxygen and hydrological cycle parameters | Crustal hydration efficiency, $fr_{hydr-frac}$ | $10^{-3}$ to 0.03 |
| | Dry oxidation efficiency, $f_{dry-oxid}$ | $10^{-4}$ to 10% |
| | Wet oxidation efficiency, $f_{wet-oxid}$ | $10^{-3}$ to $10^{-1}$ |
| | Maximum fractional molten area, $f_{lava}$ | $10^{-4}$ to 1.0 |
| | Max mantle water content, $M_{solid-H_2O-max}$ | 0.5-15 Earth oceans |
| Albedo parameters | Hot state albedo, $A_H$ | 0-0.3 |
| | Cold state albedo, $A_C$ | 0.25-0.35 |

Randomly sampling 21 model parameters over 1000s of model runs

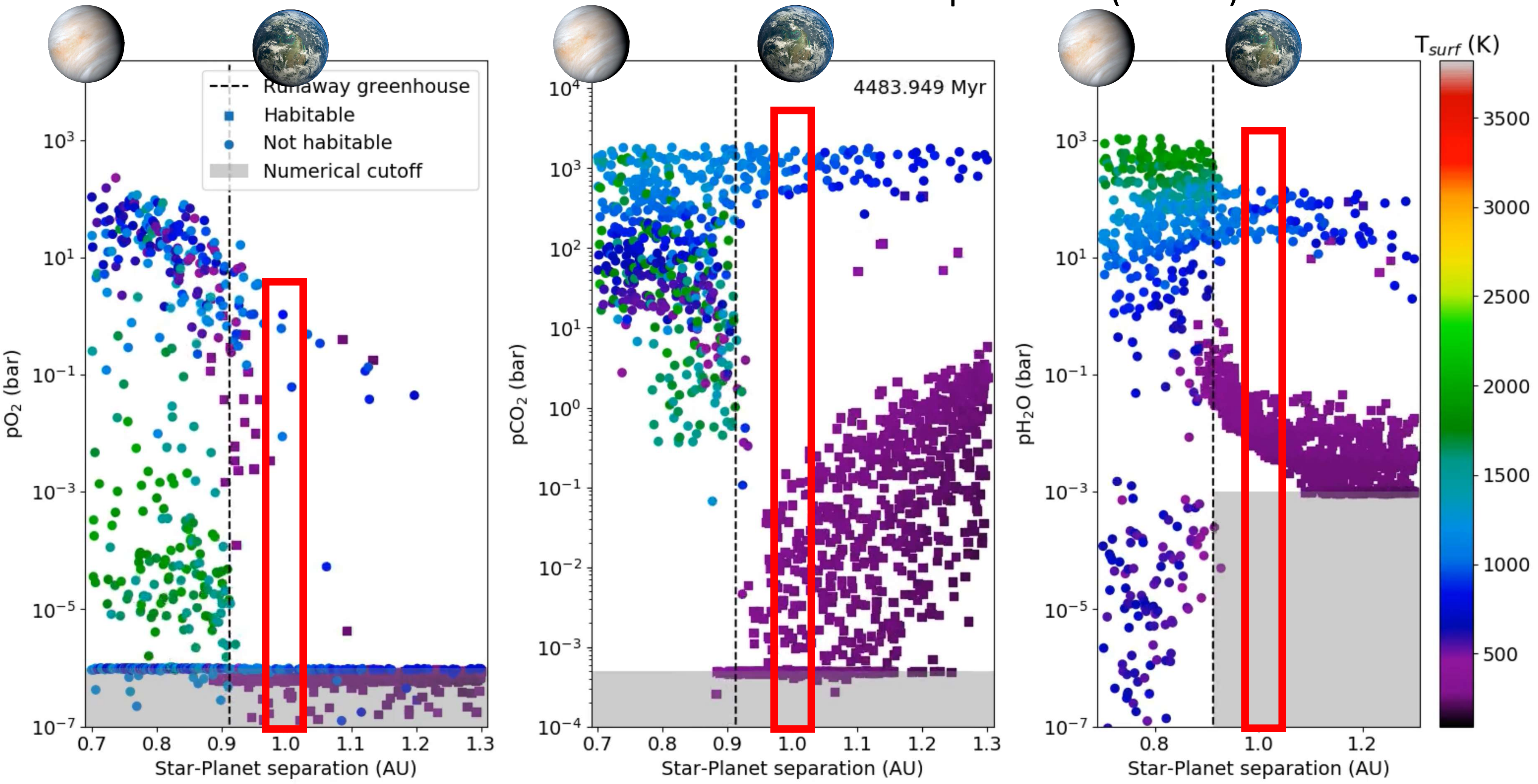


# An example of a Monte Carlo approach to planetary geochemical evolution

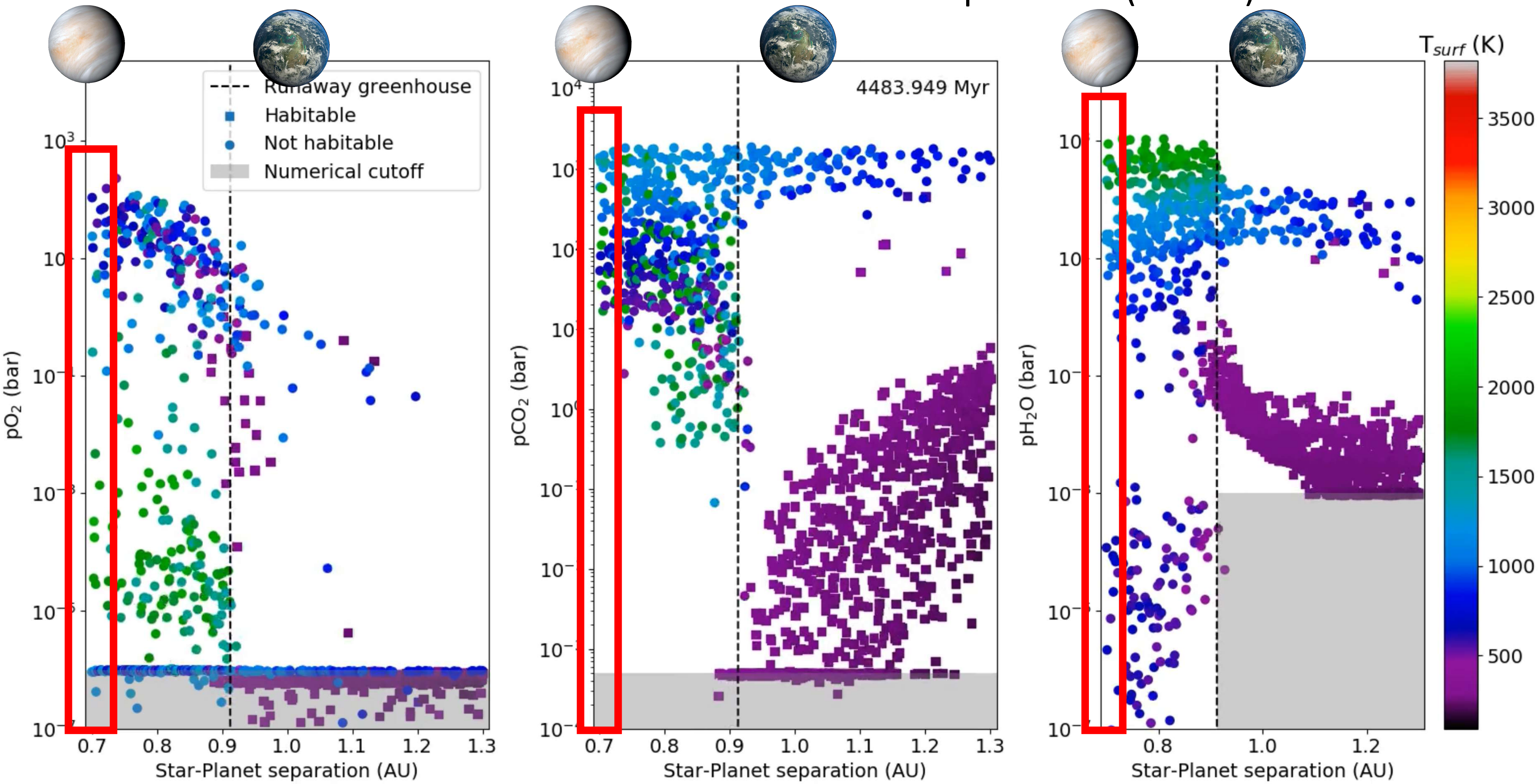


Krissansen-Totton, et al. (2022) *Nature Astronomy*

# Earth can be recovered at Earth-Sun separations (1.0 AU)



# Venus can be recovered at Venus-Sun separations (0.7 AU)



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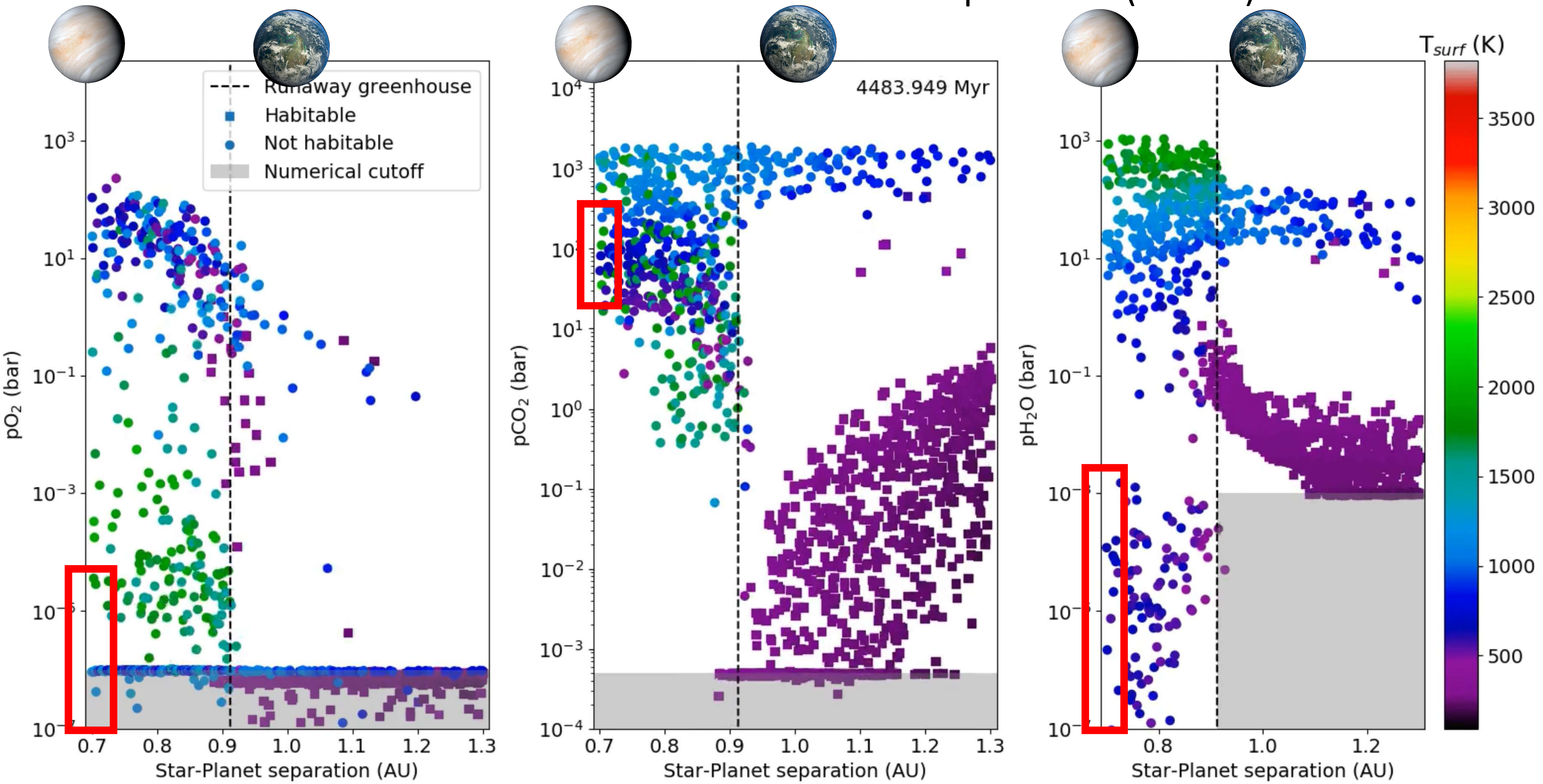
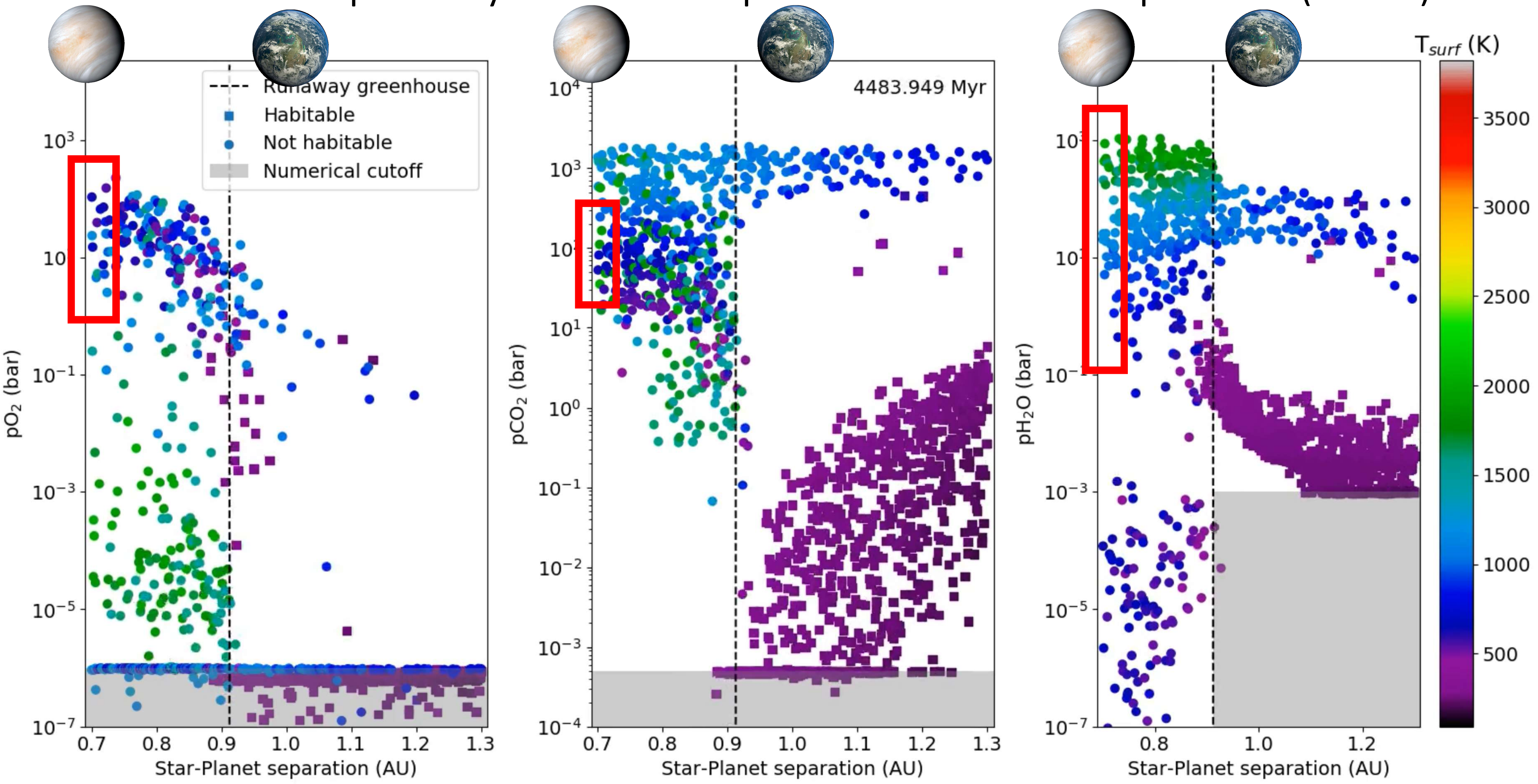
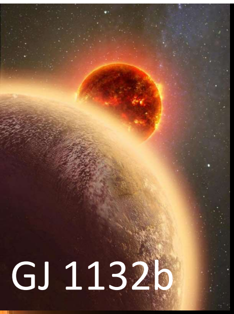
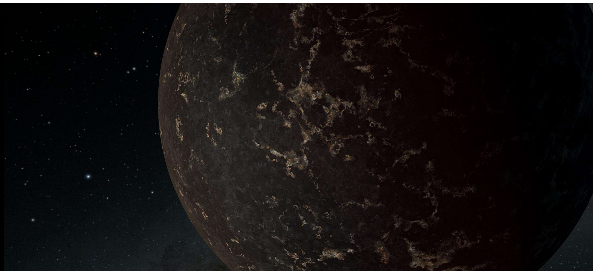


# But a diverse planetary outcomes are possible at Venus-Sun separations (0.7 AU)

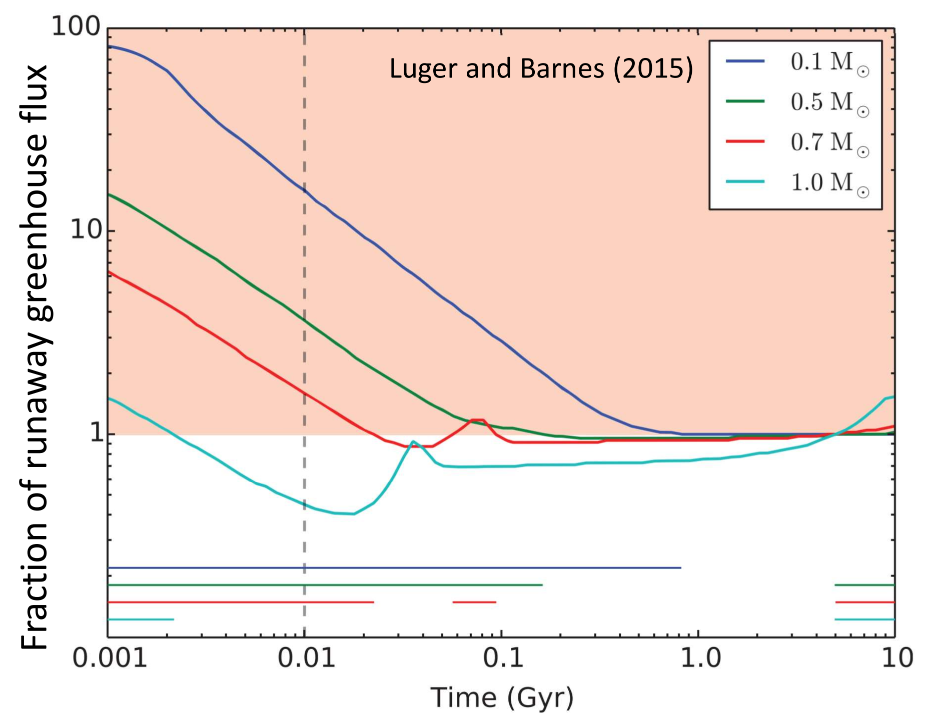




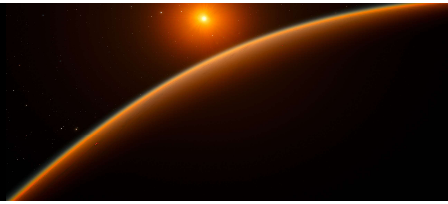
## Opportunities for comparative planetology:

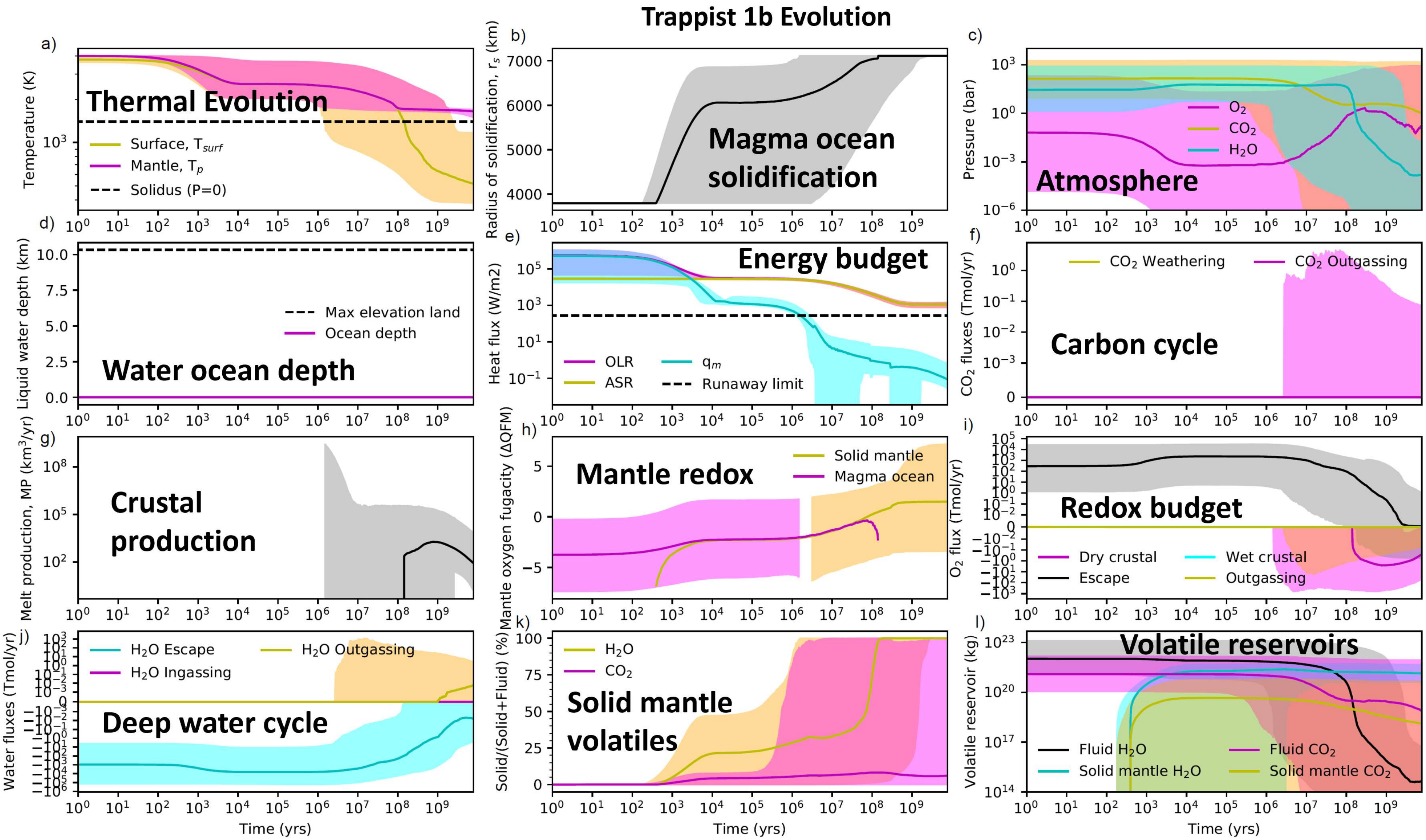


# TRAPPIST-1 System

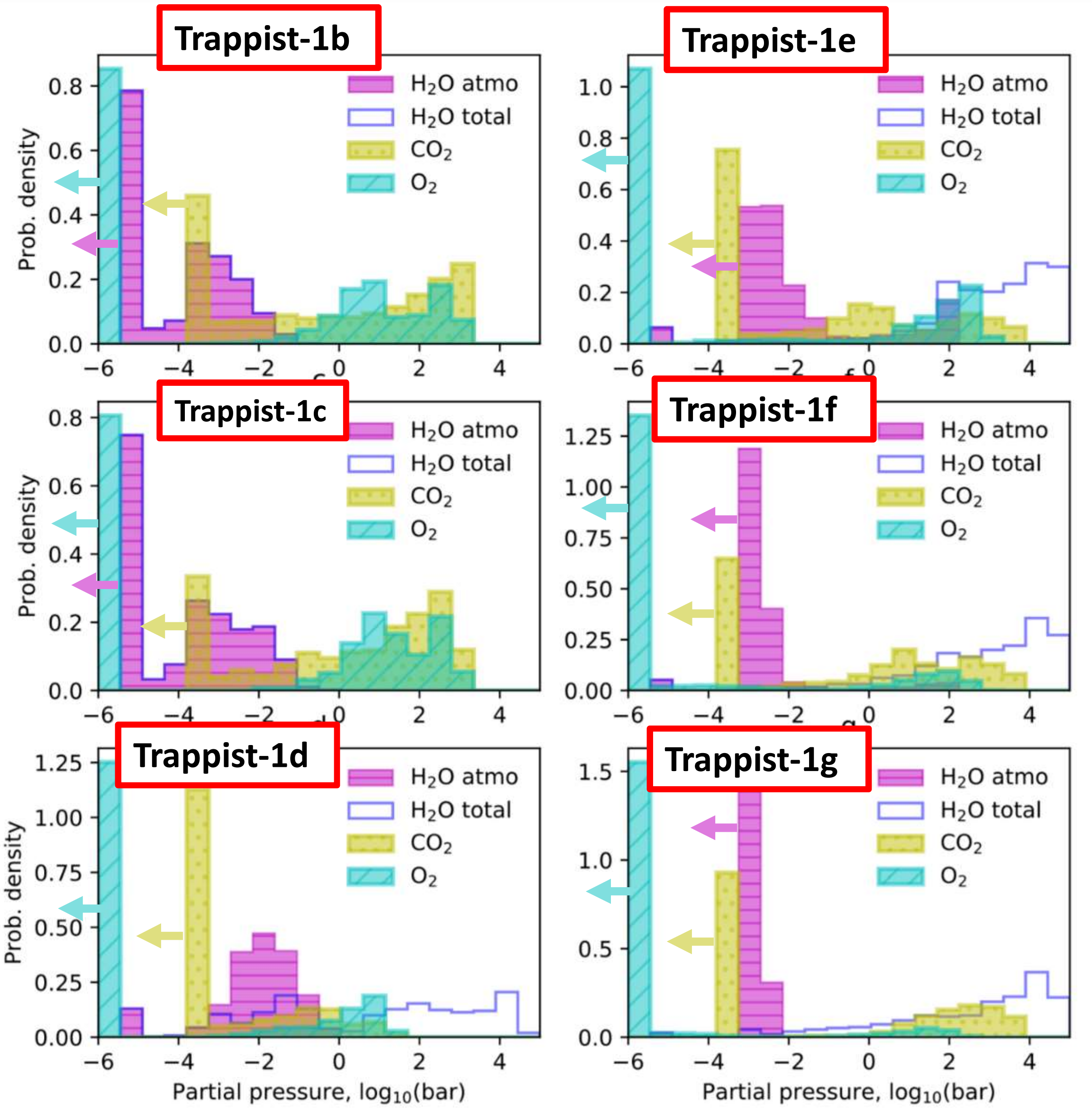


- Do these planets have atmospheres?
- Do they possess $O_2$-rich atmospheres from H loss?

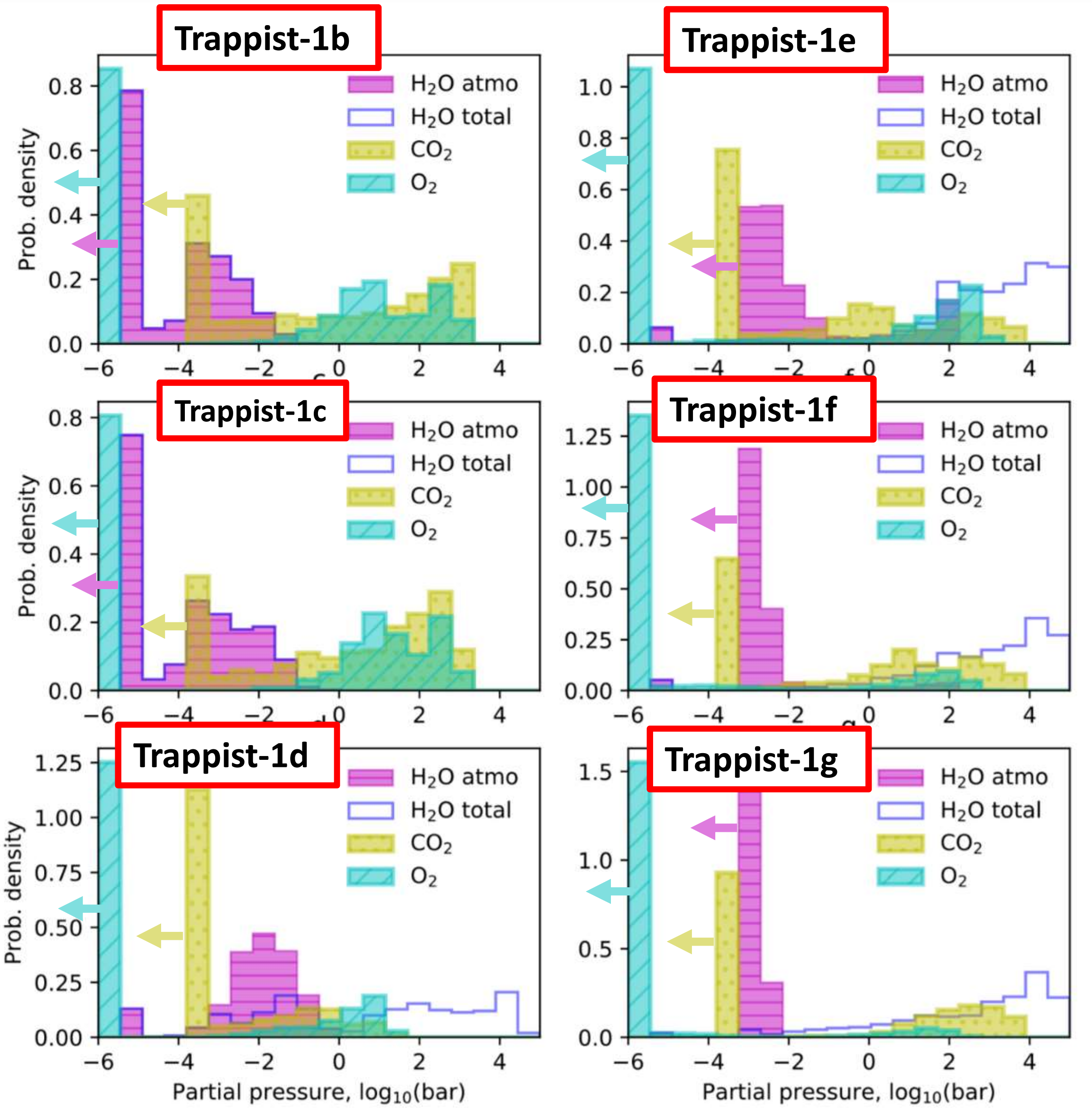



Trappist 1b Evolution
a)
Thermal Evolution
Temperature (K)
$10^3$
Surface, $T_{surf}$
Mantle, $T_p$
Solidus (P=0)
b)
Magma ocean solidification
Radius of solidification, $r_s$ (km)
7000
6000
5000
4000
c)
Atmosphere
Pressure (bar)
$10^3$
$10^0$
$10^{-3}$
$10^{-6}$
$O_2$
$CO_2$
$H_2O$
d)
Water ocean depth
Liquid water depth (km)
10.0
7.5
5.0
2.5
0.0
Max elevation land
Ocean depth
e)
Energy budget
Heat flux (W/m2)
$10^5$
$10^3$
$10^1$
$10^{-1}$
OLR
ASR
$q_m$
Runaway limit
f)
Carbon cycle
$CO_2$ fluxes (Tmol/yr)
$10^0$
$10^{-1}$
$10^{-2}$
$10^{-3}$
0
$CO_2$ Weathering
$CO_2$ Outgassing
g)
Crustal production
Melt production, MP ($km^3/yr$)
$10^8$
$10^5$
$10^2$
h)
Mantle redox
Mantle oxygen fugacity (ΔQFM)
5
0
−5
Solid mantle
Magma ocean
i)
Redox budget
$O_2$ flux (Tmol/yr)
$10^5$
$10^4$
$10^3$
$10^2$
$10^1$
$10^0$
$10^{-1}$
$10^{-2}$
0
$-10^{-2}$
$-10^{-1}$
$-10^0$
$-10^1$
$-10^2$
$-10^3$
Dry crustal
Wet crustal
Escape
Outgassing
j)
Deep water cycle
Water fluxes (Tmol/yr)
$10^3$
$10^2$
$10^1$
$10^0$
$10^{-1}$
$10^{-2}$
$10^{-3}$
0
$-10^{-3}$
$-10^{-2}$
$-10^{-1}$
$-10^0$
$-10^1$
$-10^2$
$-10^3$
$-10^4$
$-10^5$
$-10^6$
$H_2O$ Escape
$H_2O$ Outgassing
$H_2O$ Ingassing
k)
Solid mantle volatiles
Solid/(Solid+Fluid) (%)
100
75
50
25
0
$H_2O$
$CO_2$
l)
Volatile reservoirs
Volatile reservoir (kg)
$10^{23}$
$10^{20}$
$10^{17}$
$10^{14}$
Fluid $H_2O$
Fluid $CO_2$
Solid mantle $H_2O$
Solid mantle $CO_2$
$10^0$
$10^1$
$10^2$
$10^3$
$10^4$
$10^5$
$10^6$
$10^7$
$10^8$
$10^9$
Time (yrs)

**“Probability distributions” for current Trappist-1 planetary atmospheres**

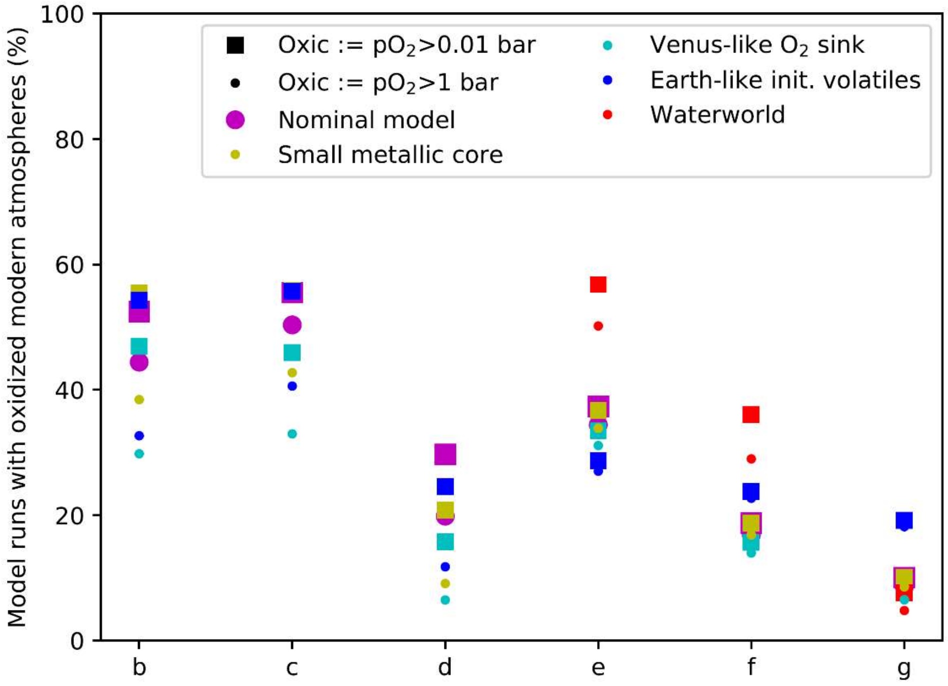


Krissansen-Totton and Fortney (2022, ApJ)



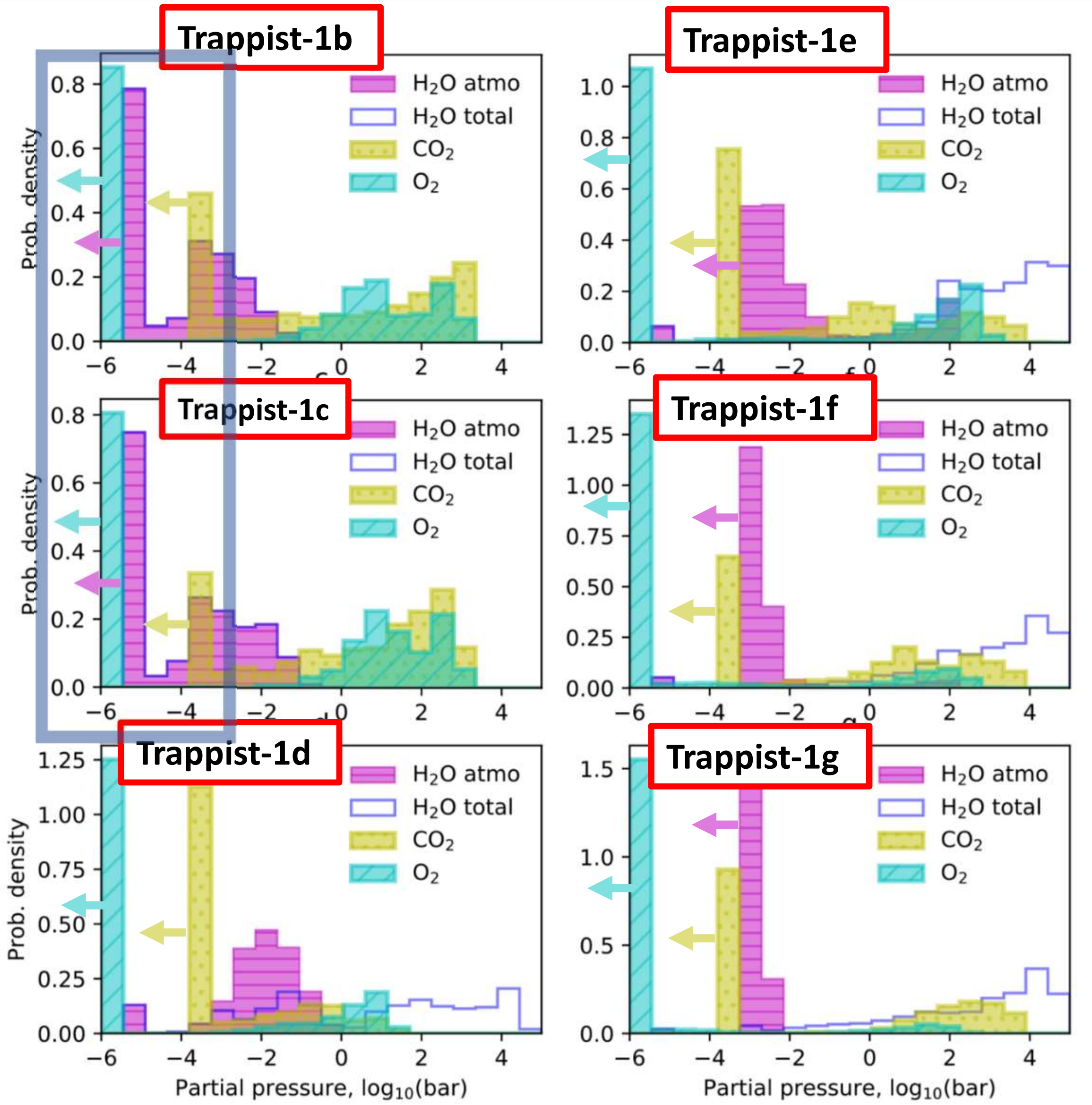
# “Probability distributions” for current Trappist-1 planetary atmospheres

More likely $O_2$–rich atmospheres



More likely $O_2$–free atmospheres

Krissansen-Totton and Fortney (2022, ApJ)



## “Probability distributions” for current Trappist-1 planetary atmospheres

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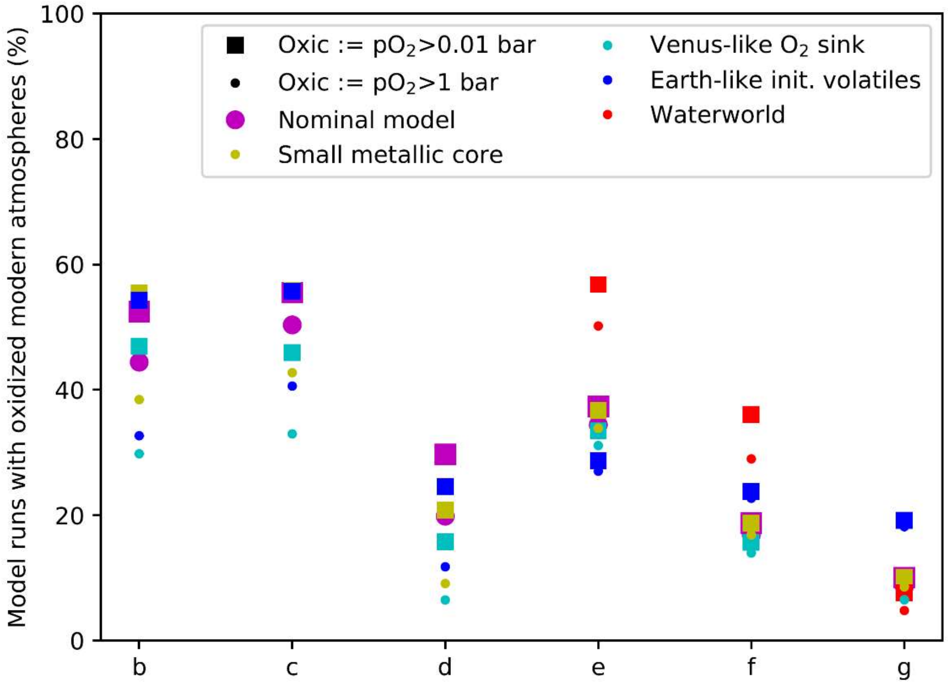
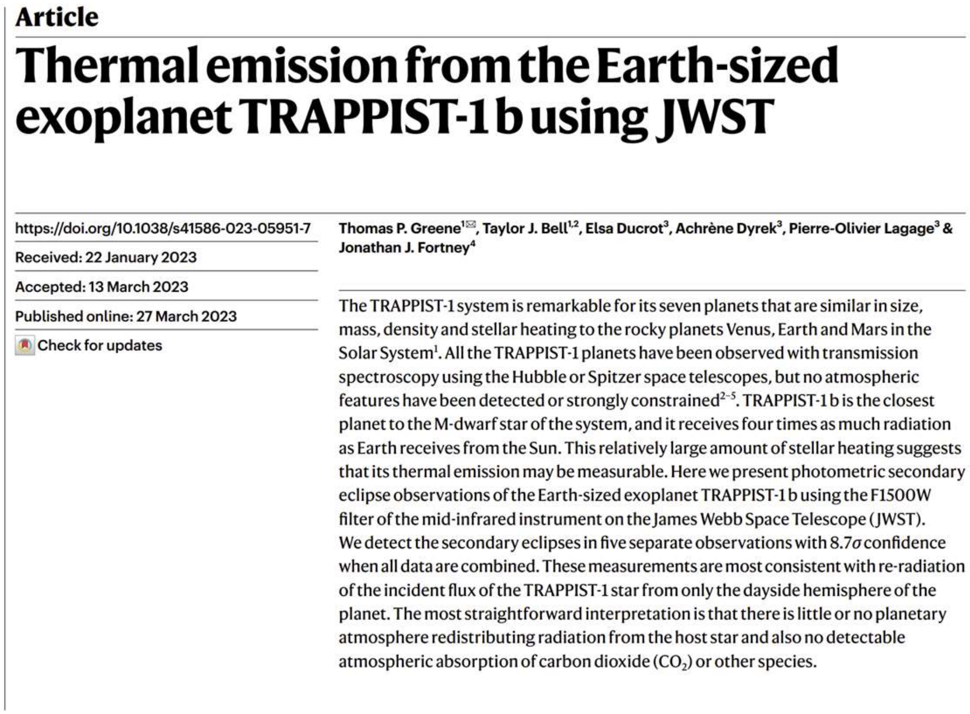


More likely $O_2$–free atmospheres

Krissansen-Totton and Fortney (2022, ApJ)

# How do recent JWST observations inform theoretical models of Trappist-1 evolution?



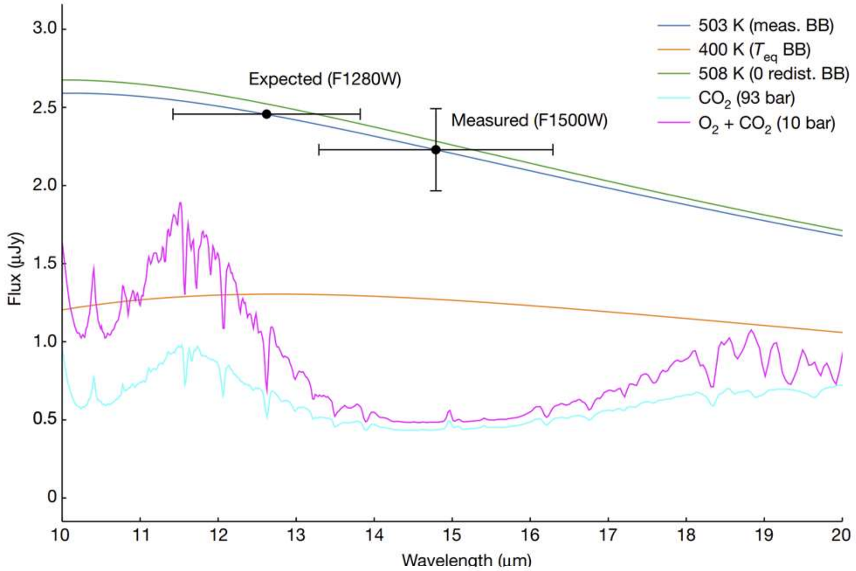
**Article**

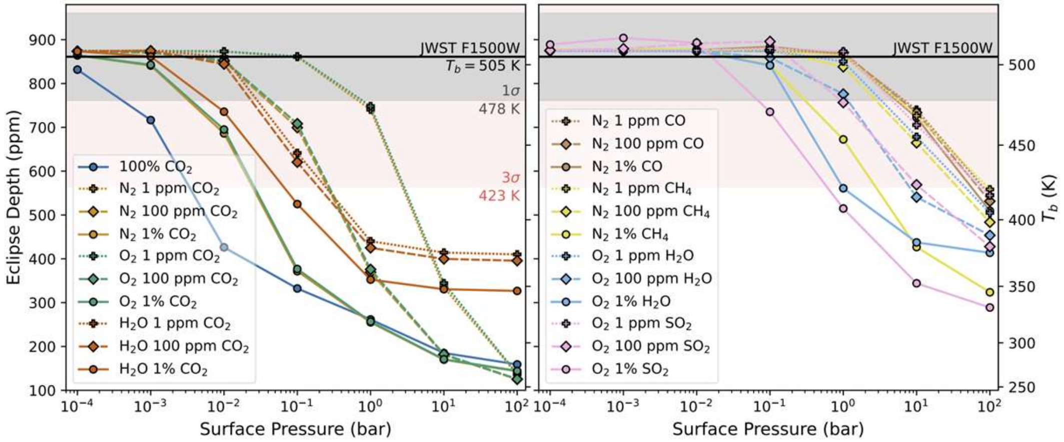
## Thermal emission from the Earth-sized exoplanet TRAPPIST-1 b using JWST

https://doi.org/10.1038/s41586-023-05951-7
Received: 22 January 2023
Accepted: 13 March 2023

Thomas P. Greene[1✉], Taylor J. Bell[1,2], Elsa Ducrot[3], Achrène Dyrek[3], Pierre-Olivier Lagage[3] & Jonathan J. Fortney[4]

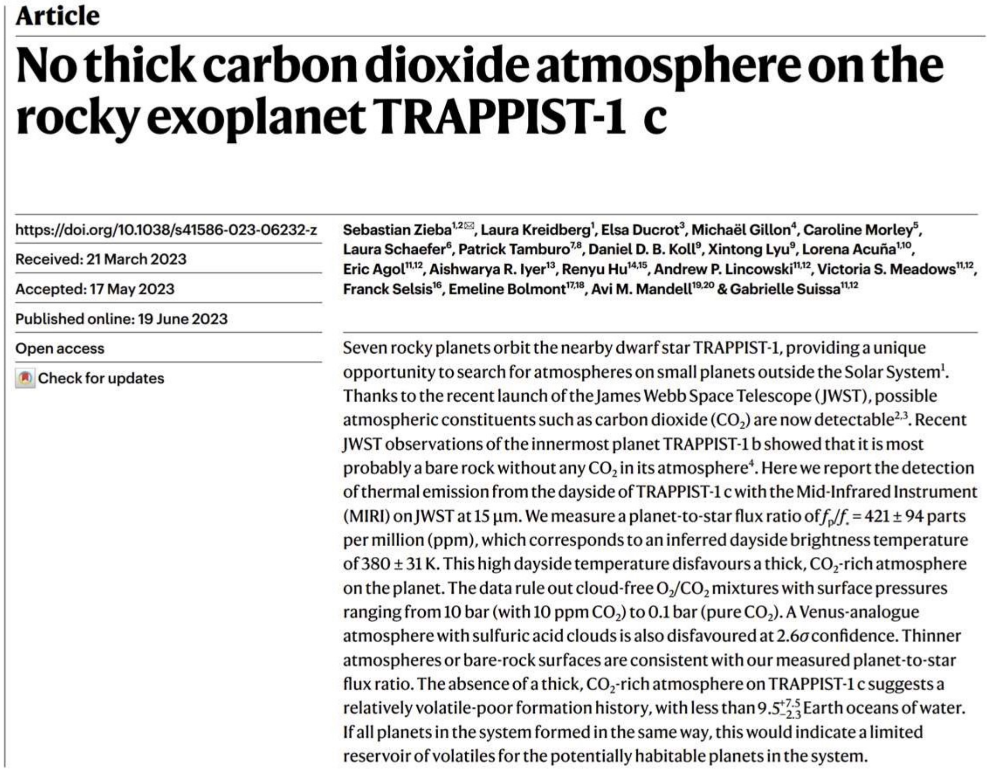
The TRAPPIST-1 system is remarkable for its seven planets that are similar in size, mass, density and stellar heating to the rocky planets Venus, Earth and Mars in the Solar System[1]. All the TRAPPIST-1 planets have been observed with transmission spectroscopy using the Hubble or Spitzer space telescopes, but no atmospheric features have been detected or strongly constrained[2–5]. TRAPPIST-1 b is the closest planet to the M-dwarf star of the system, and it receives four times as much radiation as Earth receives from the Sun. This relatively large amount of stellar heating suggests that its thermal emission may be measurable. Here we present photometric secondary eclipse observations of the Earth-sized exoplanet TRAPPIST-1 b using the F1500W filter of the mid-infrared instrument on the James Webb Space Telescope (JWST). We detect the secondary eclipses in five separate observations with 8.7σ confidence when all data are combined. These measurements are most consistent with re-radiation of the incident flux of the TRAPPIST-1 star from only the dayside hemisphere of the planet. The most straightforward interpretation is that there is little or no planetary atmosphere redistributing radiation from the host star and also no detectable atmospheric absorption of carbon dioxide ($CO_2$) or other species.





Ih, J., Kempton, E. M. R., Whittaker, E. A., & Lessard, M. (2023). Constraining the Thickness of TRAPPIST-1 b's Atmosphere from Its JWST Secondary Eclipse Observation at 15 μm. *The Astrophysical Journal Letters*, *952*(1), L4.

# How do recent JWST observations inform theoretical models of Trappist-1 evolution?



**Article**

**No thick carbon dioxide atmosphere on the rocky exoplanet TRAPPIST-1 c**

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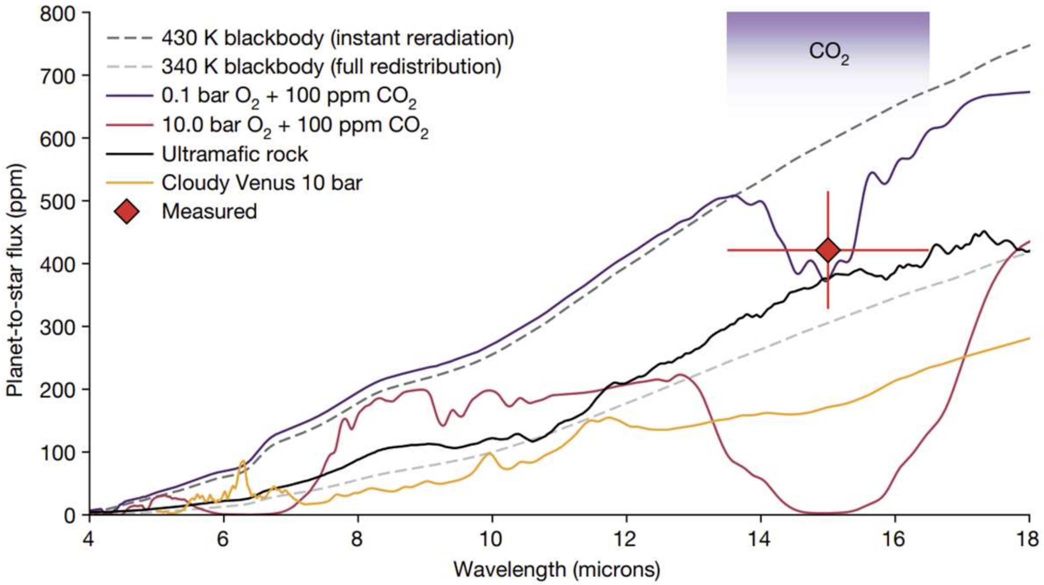
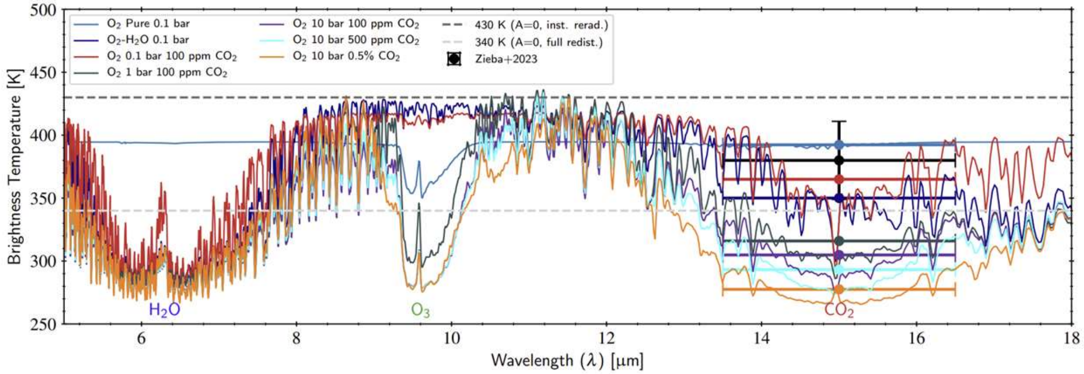
Check for updates

**Sebastian Zieba[1,2], Laura Kreidberg[1], Elsa Ducrot[3], Michaël Gillon[4], Caroline Morley[5], Laura Schaefer[6], Patrick Tamburo[7,8], Daniel D. B. Koll[9], Xintong Lyu[9], Lorena Acuña[1,10], Eric Agol[11,12], Aishwarya R. Iyer[13], Renyu Hu[14,15], Andrew P. Lincowski[11,12], Victoria S. Meadows[11,12], Franck Selsis[16], Emeline Bolmont[17,18], Avi M. Mandell[19,20] & Gabrielle Suissa[11,12]**

Seven rocky planets orbit the nearby dwarf star TRAPPIST-1, providing a unique opportunity to search for atmospheres on small planets outside the Solar System[1]. Thanks to the recent launch of the James Webb Space Telescope (JWST), possible atmospheric constituents such as carbon dioxide ($CO_2$) are now detectable[2,3]. Recent JWST observations of the innermost planet TRAPPIST-1 b showed that it is most probably a bare rock without any $CO_2$ in its atmosphere[4]. Here we report the detection of thermal emission from the dayside of TRAPPIST-1 c with the Mid-Infrared Instrument (MIRI) on JWST at 15 µm. We measure a planet-to-star flux ratio of $f_p/f_* = 421 \pm 94$ parts per million (ppm), which corresponds to an inferred dayside brightness temperature of $380 \pm 31$ K. This high dayside temperature disfavours a thick, $CO_2$-rich atmosphere on the planet. The data rule out cloud-free $O_2/CO_2$ mixtures with surface pressures ranging from 10 bar (with 10 ppm $CO_2$) to 0.1 bar (pure $CO_2$). A Venus-analogue atmosphere with sulfuric acid clouds is also disfavoured at $2.6\sigma$ confidence. Thinner atmospheres or bare-rock surfaces are consistent with our measured planet-to-star flux ratio. The absence of a thick, $CO_2$-rich atmosphere on TRAPPIST-1 c suggests a relatively volatile-poor formation history, with less than $9.5^{+7.5}_{-2.3}$ Earth oceans of water. If all planets in the system formed in the same way, this would indicate a limited reservoir of volatiles for the potentially habitable planets in the system.

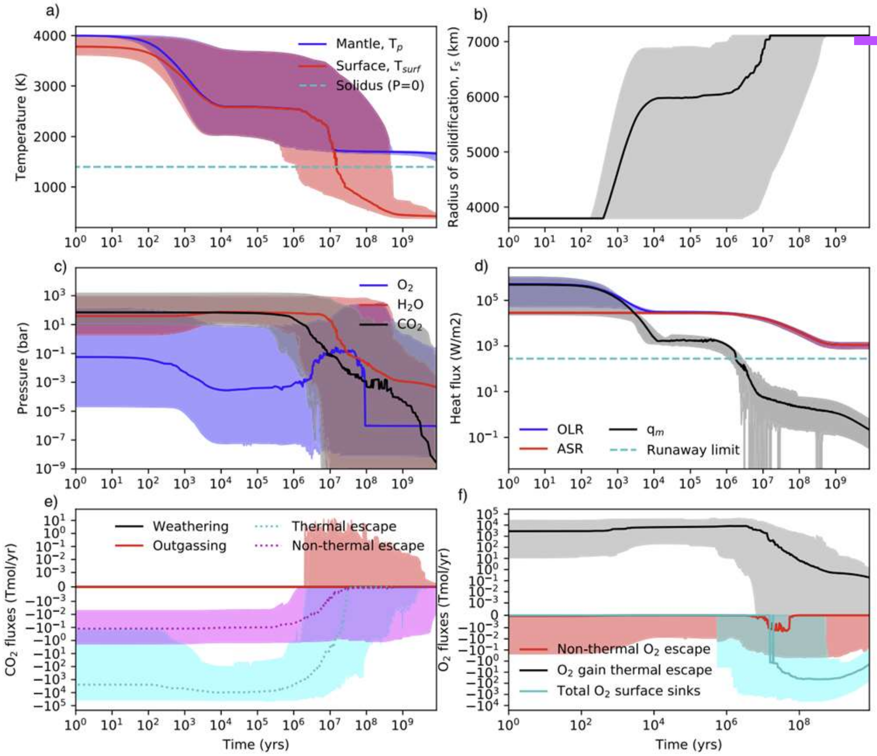




Lincowski, A. P., Meadows, V. S., Zieba, S., Kreidberg, L., Morley, C., Gillon, M., ... & Tamburo, P. (2023). Potential Atmospheric Compositions of TRAPPIST-1 c constrained by JWST/MIRI Observations at 15$\mu $ m. *arXiv preprint arXiv:2308.05899*.

# How do recent JWST observations inform theoretical models of Trappist-1 evolution?

**Take all model runs that result in b (and c) being airless:**



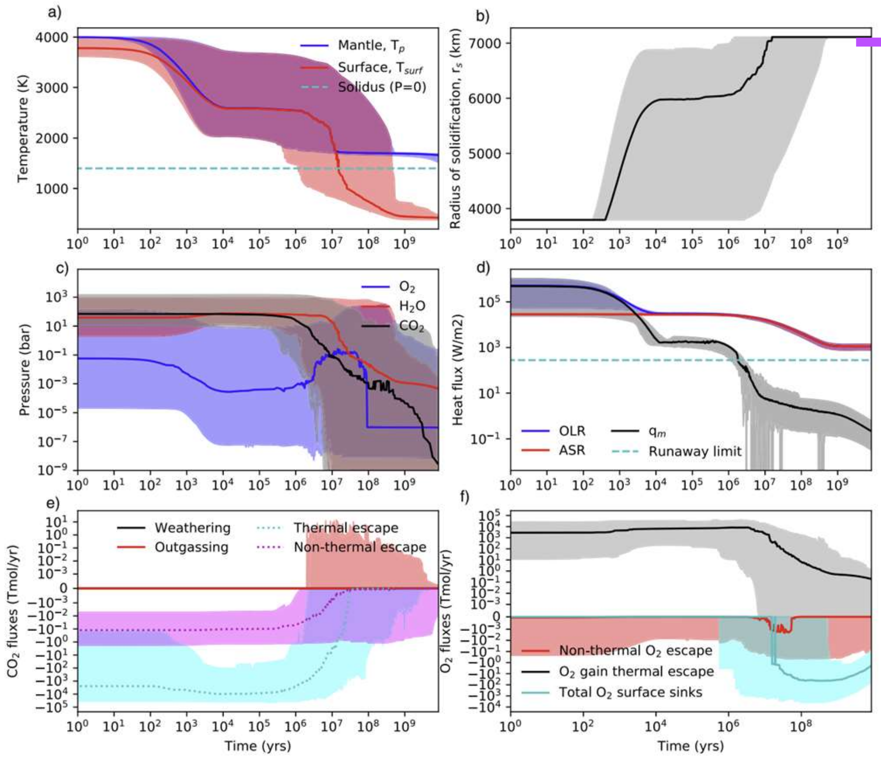
Assume same stellar and planetary properties then repeat evolutionary calculations for e and f

Krissansen-Totton (2023, ApJL)

# How do recent JWST observations inform theoretical models of Trappist-1 evolution?

**Take all model runs that result in b (and c) being airless:**

**Odds that e and f are airless are virtually unchanged**



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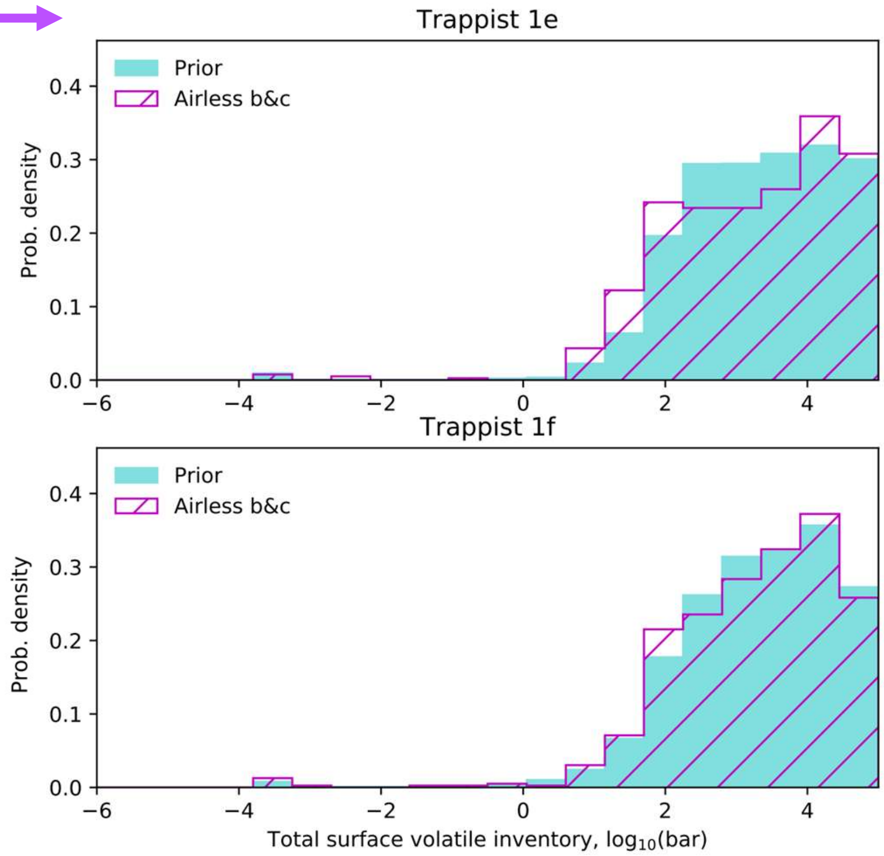

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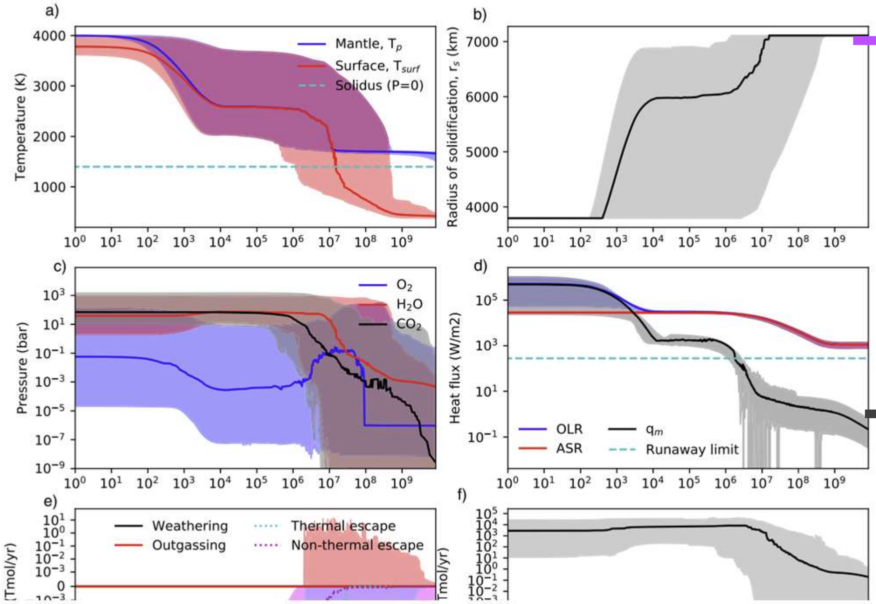
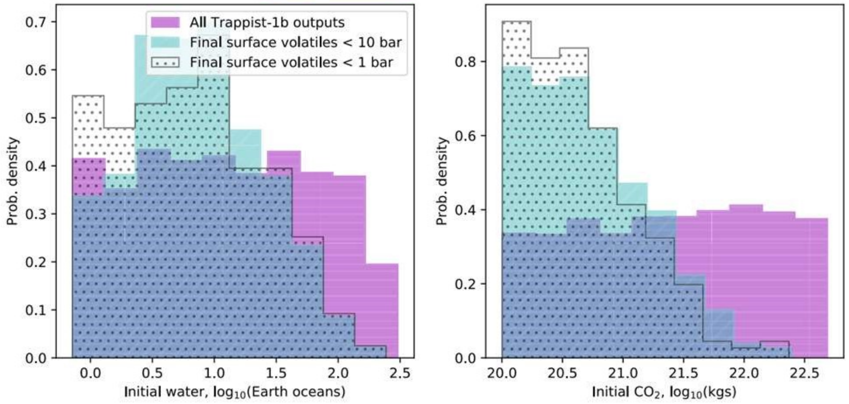
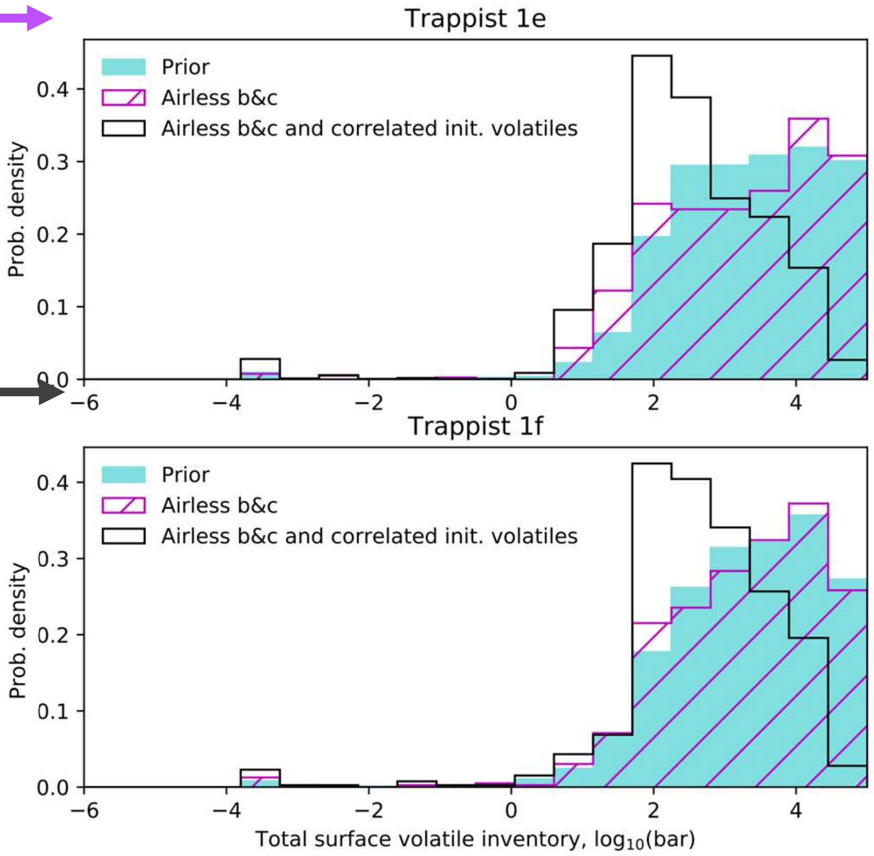




**Odds that e and f are airless are virtually unchanged**

Assume same stellar and planetary properties then repeat evolutionary calculations for e and f

Assume same stellar and planetary properties AND initial volatiles then repeat evolutionary calculations for e and f



**This remains true even if same initial volatile inventory is sampled**

Krissansen-Totton (2023, ApJL)

# How do recent JWST observations inform theoretical models of Trappist-1 evolution?

**Odds that e and f are airless are virtually unchanged**

**Why?**

# How do recent JWST observations inform theoretical models of Trappist-1 evolution?

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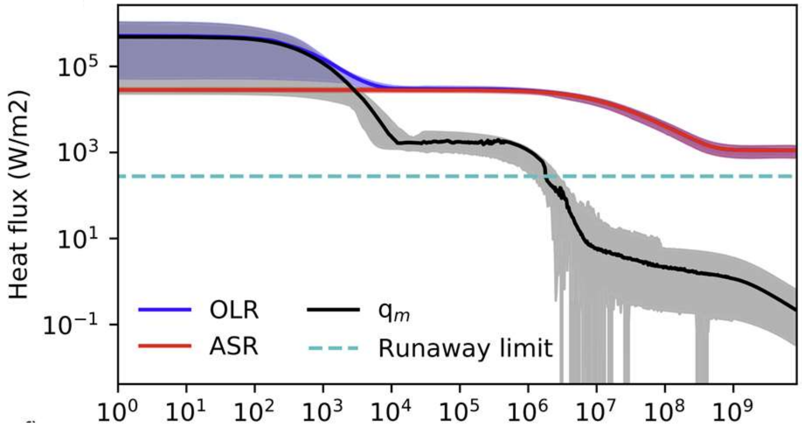
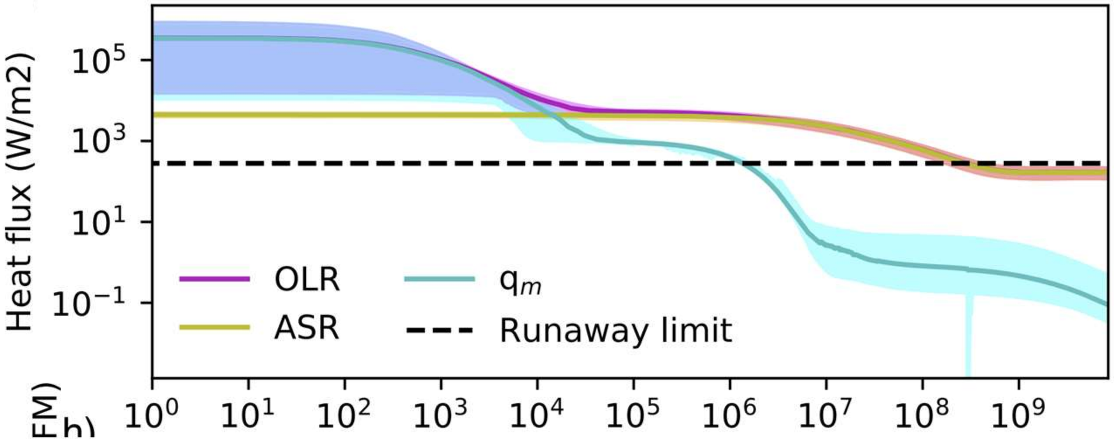
**Trappist-1b is always in runaway greenhouse**



**Trappist-1e is unambiguously not in a runaway greenhouse**



# How do recent JWST observations inform theoretical models of Trappist-1 evolution?

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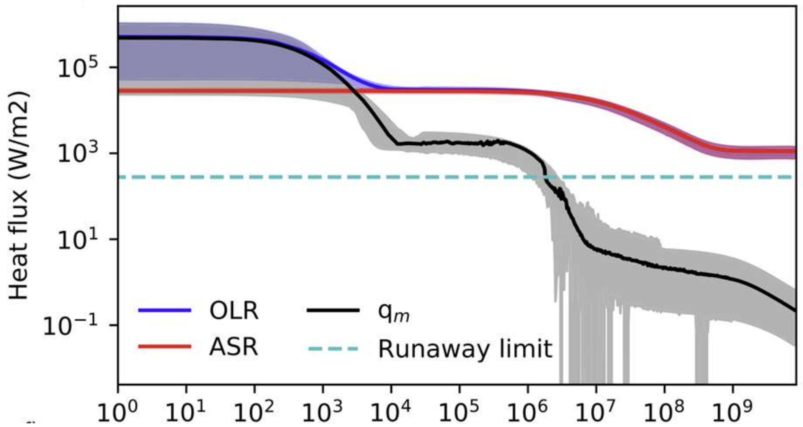
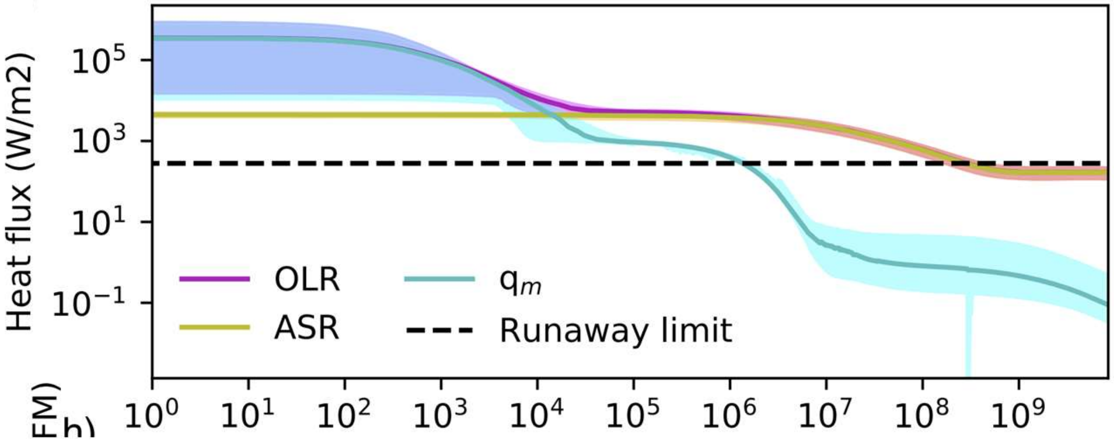


**Trappist-1e is unambiguously not in a runaway greenhouse**



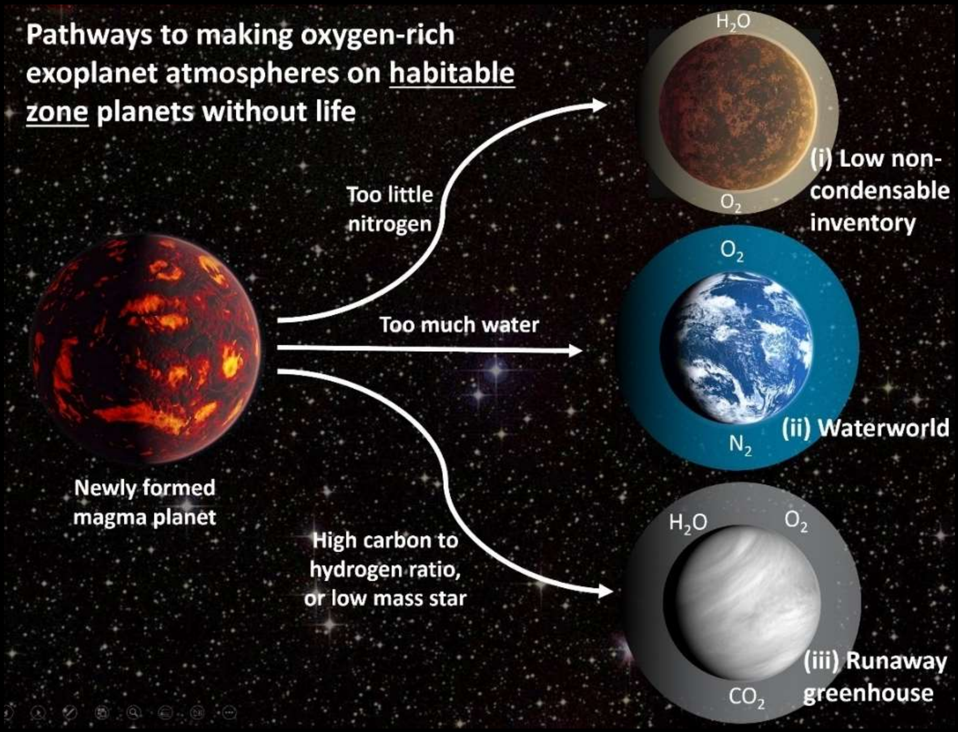
**- All water present as steam on planets interior to runaway greenhouse limit, easily lost to XUV-driven escape (and heavier species dragged along)**

**- Condensation of surface water -> temperate carbon cycle -> $CO_2$ sequestered in interior where it is shielded from escape**

**- Remains possible that all planets formed volatile poor and are all airless, but the airlessness of b and c does not require this to be true.**

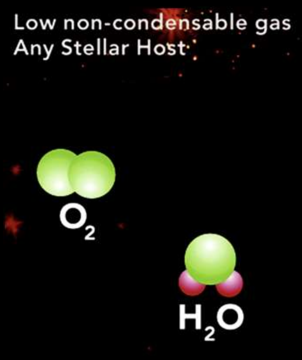
# Leveraging geochemical evolution models to inform next generation terrestrial planet observations

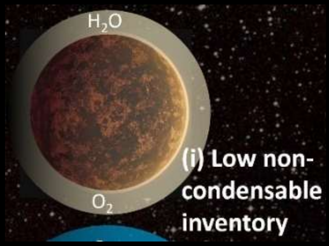
HABITABLE WORLDS OBSERVATORY



# Leveraging geochemical evolution models to inform next generation terrestrial planet observations

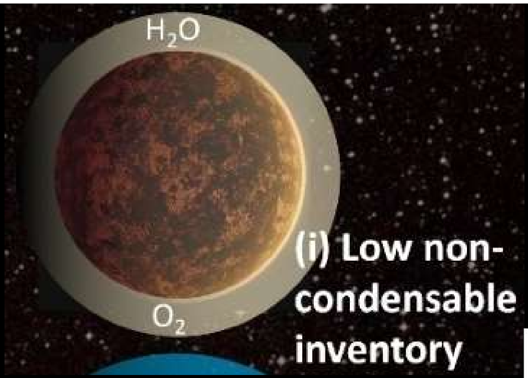
HABITABLE WORLDS OBSERVATORY



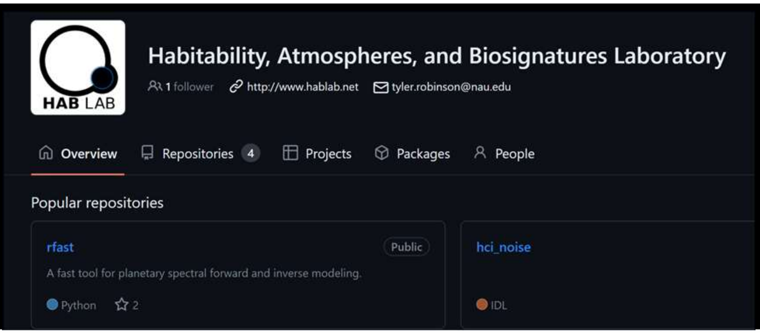


Meadows (2017)

Low non-condensable oxygen false positives could occur around sun-like stars (c.f. Wordsworth and Pierrehumbert 2014)



# Low non-condensable oxygen false positives (c.f. Wordsworth and Pierrehumbert 2014) may be identified in reflected light



Habitability, Atmospheres, and Biosignatures Laboratory

1 follower · http://www.hablab.net · tyler.robinson@nau.edu

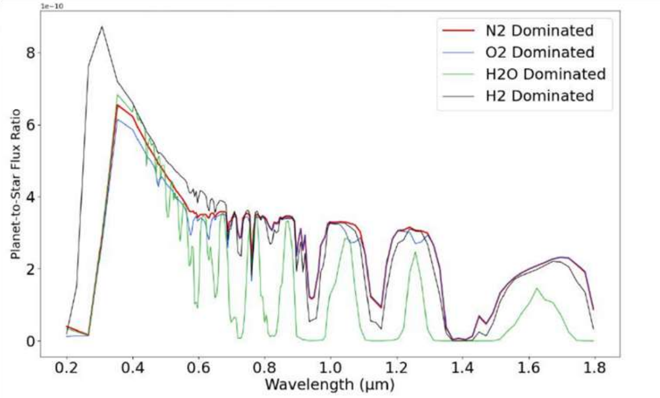
Popular repositories

rfast

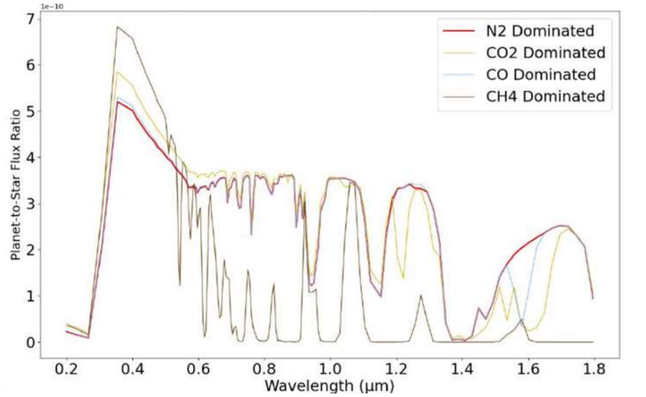
A fast tool for planetary spectral forward and inverse modeling.

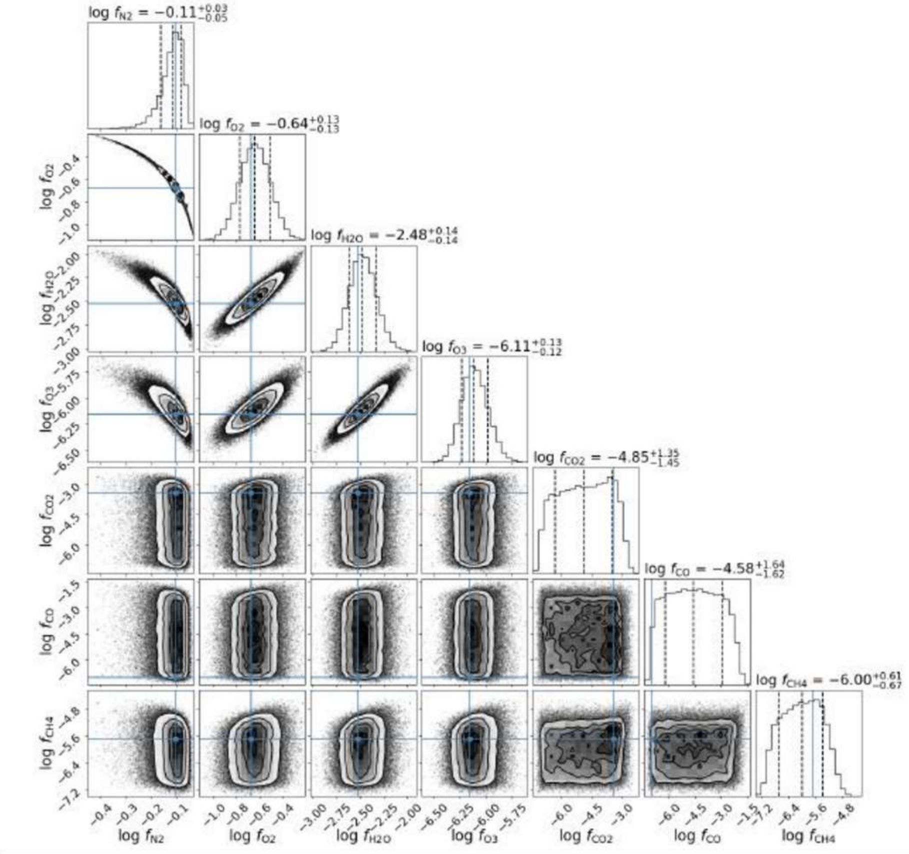
hci_noise

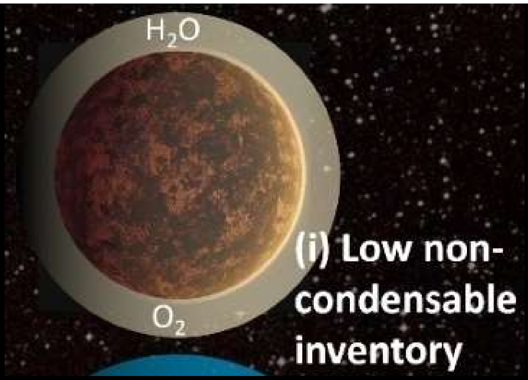
Hall, Sawyer et al. (in revision) “Constraining Background N2 Inventories on Directly Imaged Terrestrial Exoplanets to Rule Out O2 False Positives”



a) Nominal $N_2$-Dominated Spectrum vs. Non-Carbon Based Atmospheric Gas Dominated Spectra







# Low non-condensable oxygen false positives (c.f. Wordsworth and Pierrehumbert 2014) may be identified in reflected light

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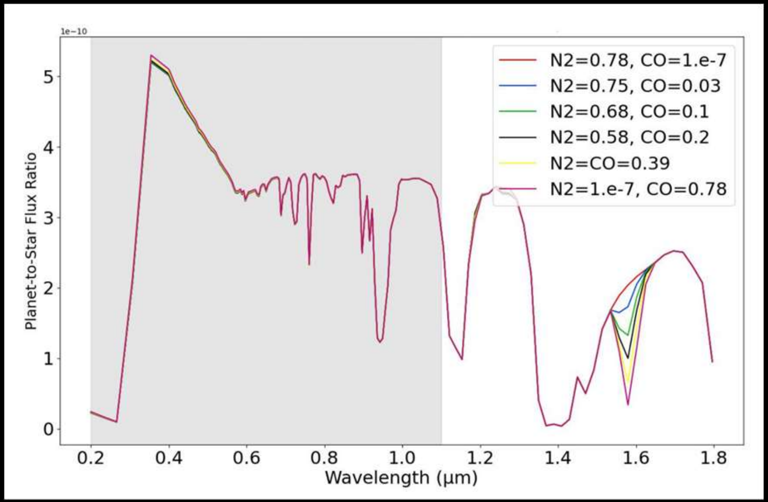
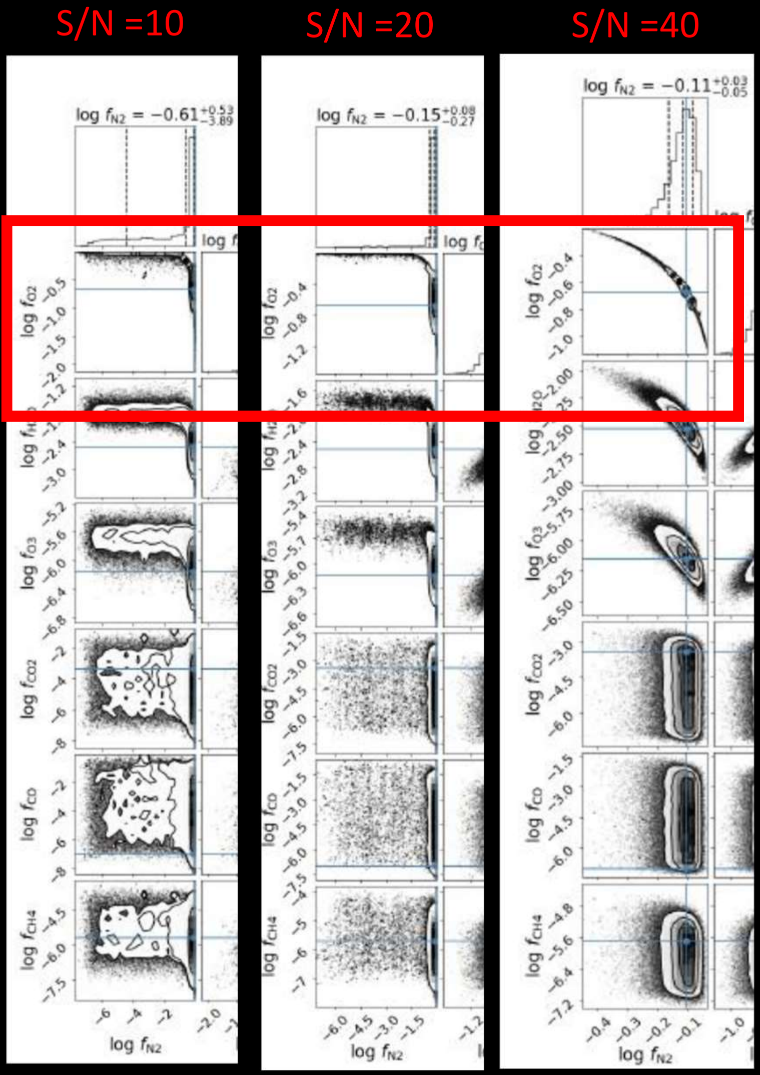
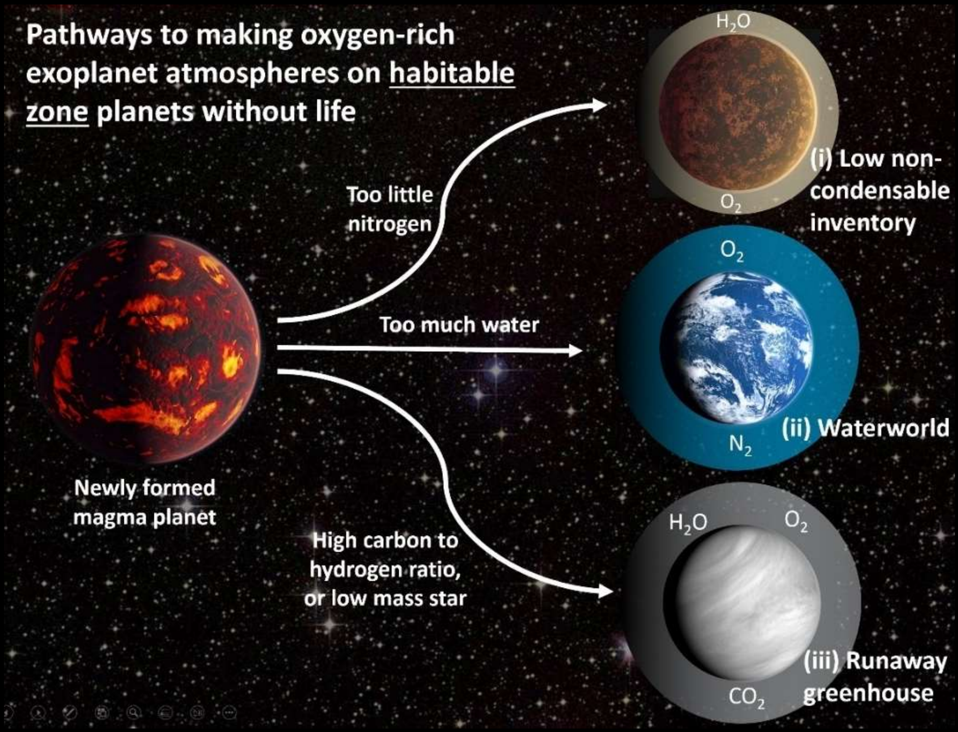




**NIR coverage (to 1.7 um) and large aperture (~8 m) needed to unambiguously identify $N_2$ background.**

# Leveraging geochemical evolution models to inform next generation terrestrial planet observations

HABITABLE
WORLDS
OBSERVATORY


Pathways to making oxygen-rich exoplanet atmospheres on habitable zone planets without life

## Conclusions

Atmosphere-Interior planetary evolution models will be crucial tools for interpreting potential biosignatures and habitability indicators:

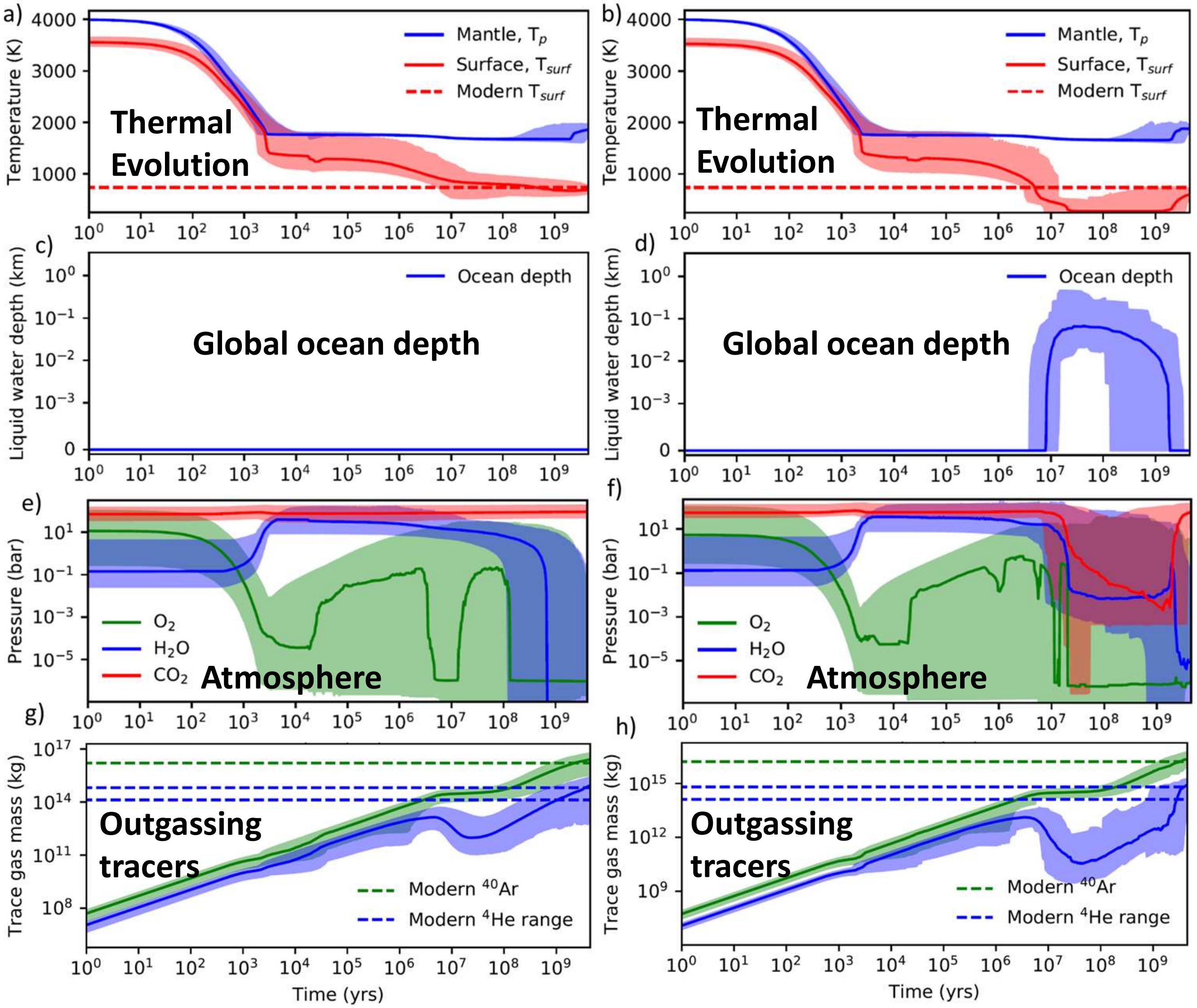
- Understanding the atmospheric evolution of Venus is a prerequisite to anticipating exoplanet habitability and interpreting oxygen biosignatures.
- The lack of substantial atmospheres on Trappist 1b and c would not say much about the likelihood of the outer planets retaining secondary atmospheres.
- Oxygen false positives may be positive on planets around sun-like stars, and next generation telescopes must be built with the capability to disentangle this from biogenic oxygen.

**More info:**

- Venus evolution and potential for past habitability: Krissansen-Totton et al. (2021, PSJ)
- Trappist-1 application: Krissansen-Totton and Fortney (2022, ApJ), Krissansen-Totton (2023, ApJL)
- Constraining N2 in reflected light: Hall et al. (2023, in revision)

# Extra Slides

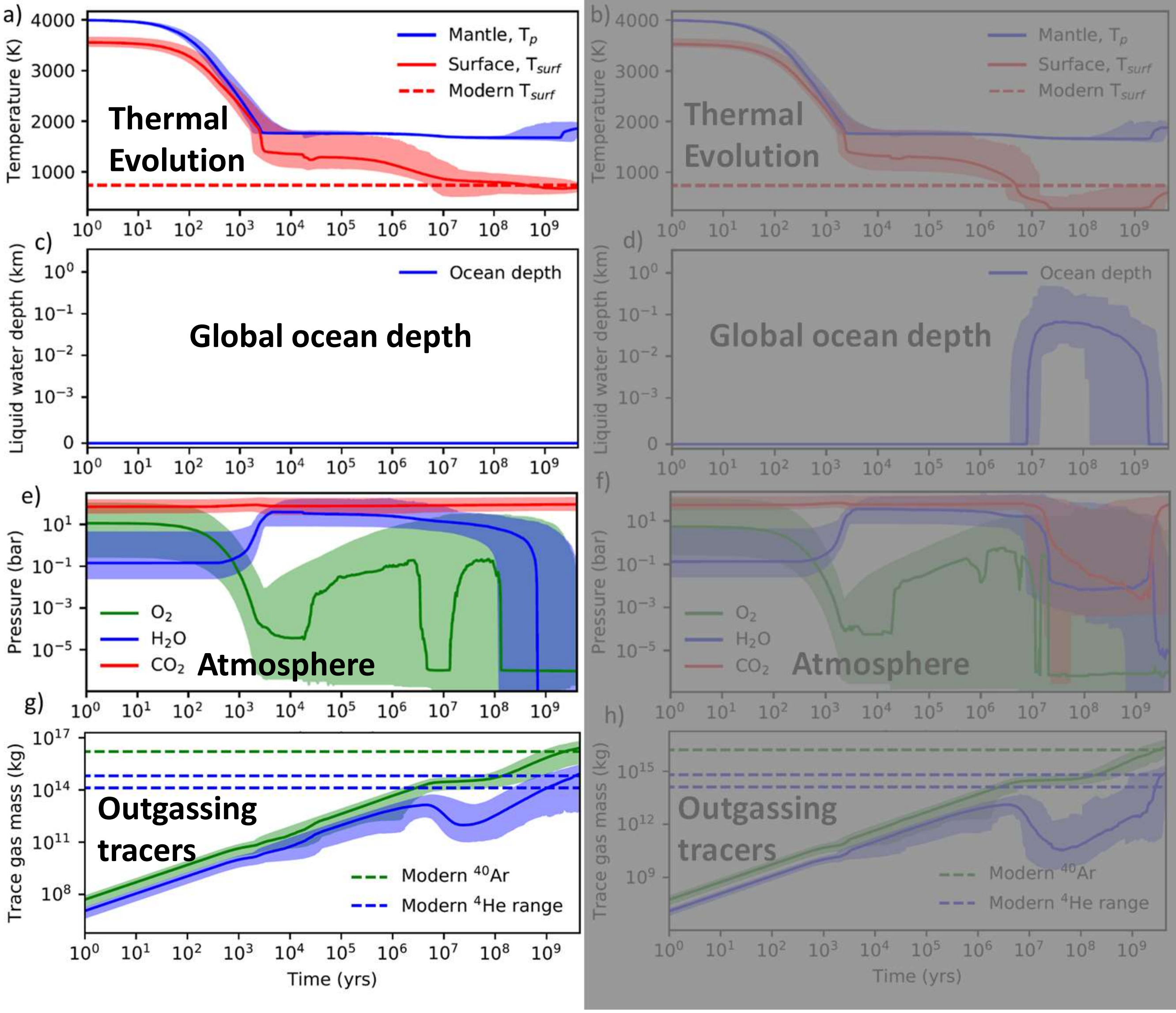
Venus was never habitable



Venus experienced several Gyr of habitability

Krissansen-Totton et al. (2021), The Planetary Science Journal.

Venus was never habitable



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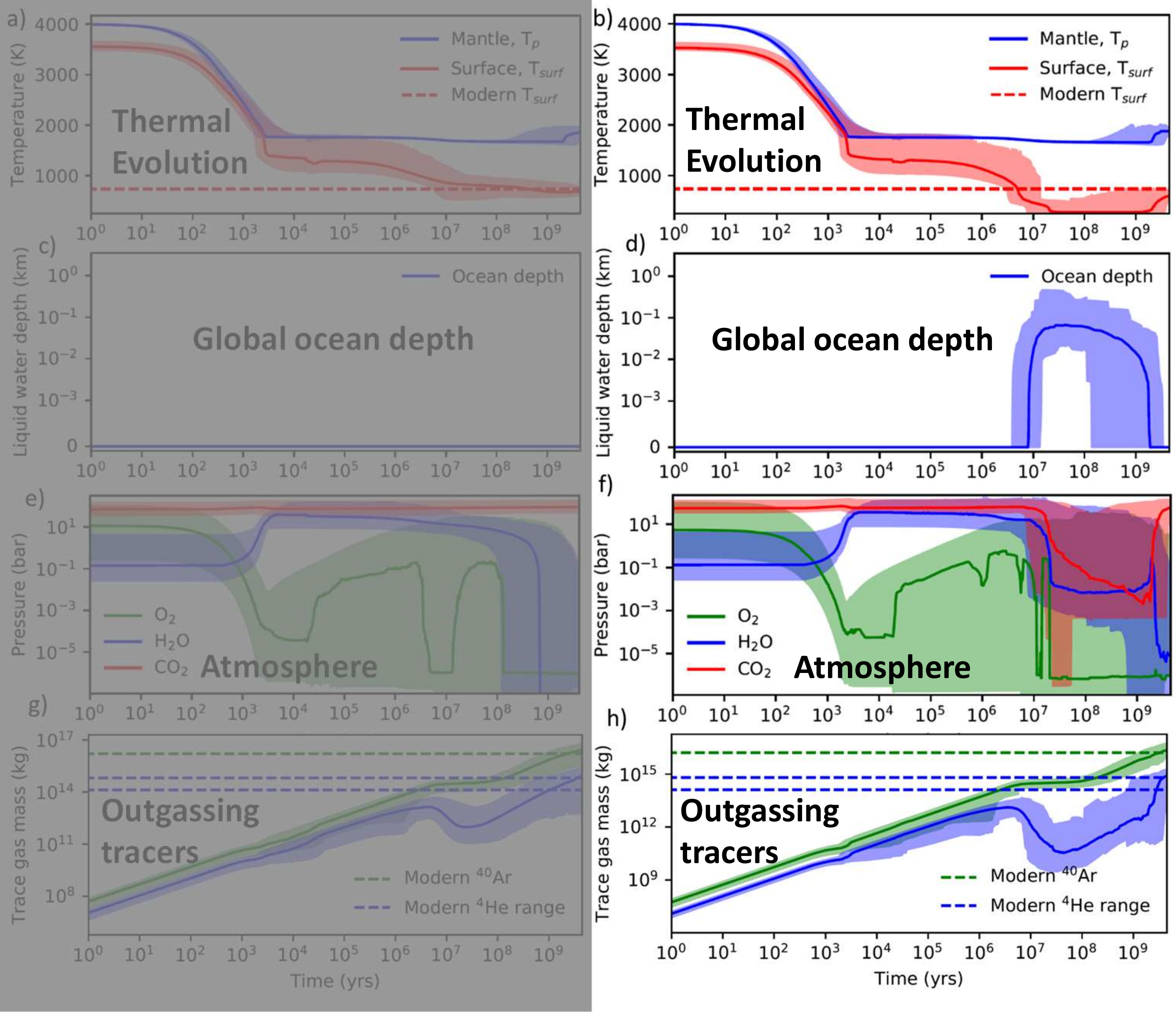
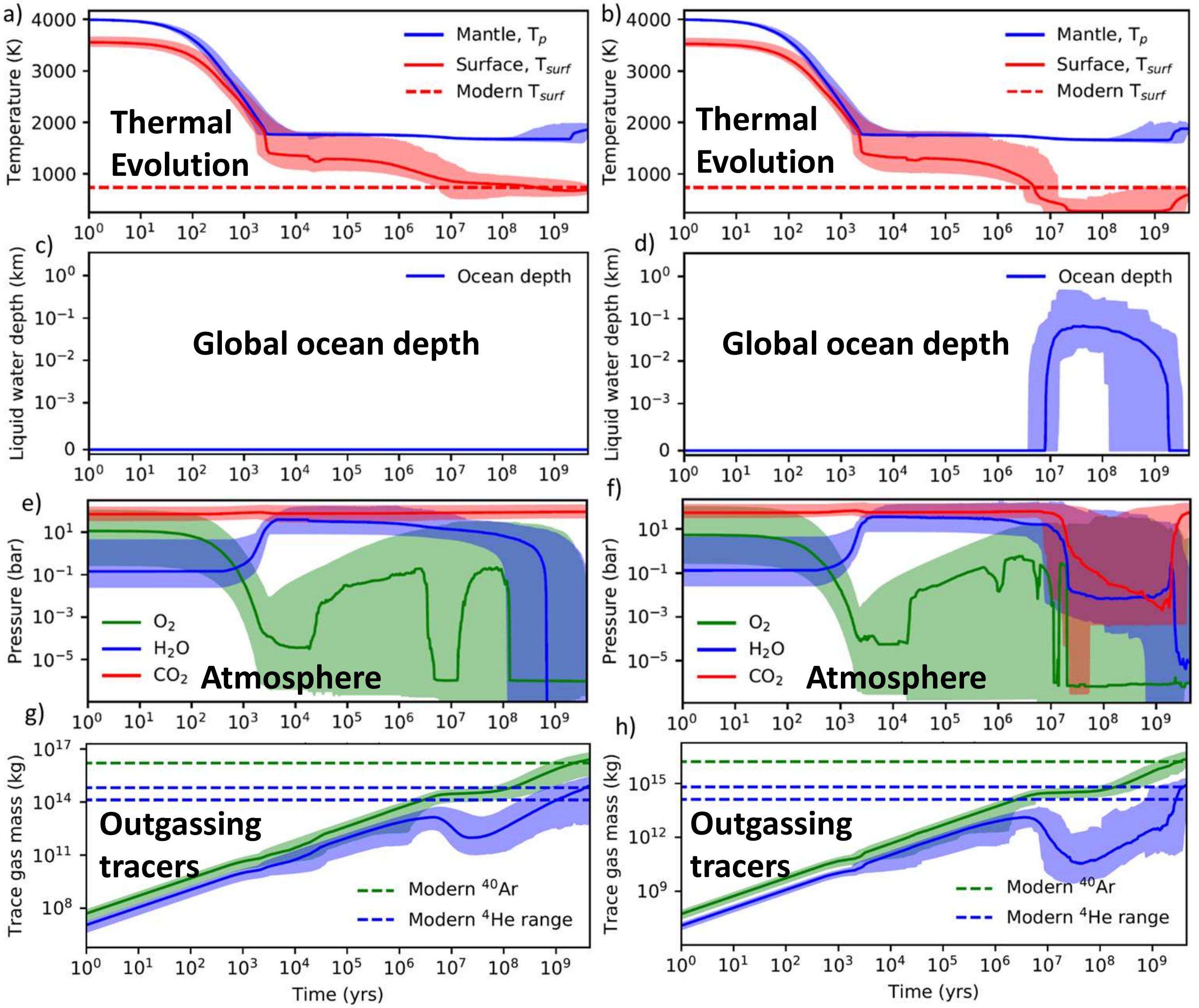


Venus experienced several Gyr of habitability

Krissansen-Totton et al. (2021), The Planetary Science Journal.

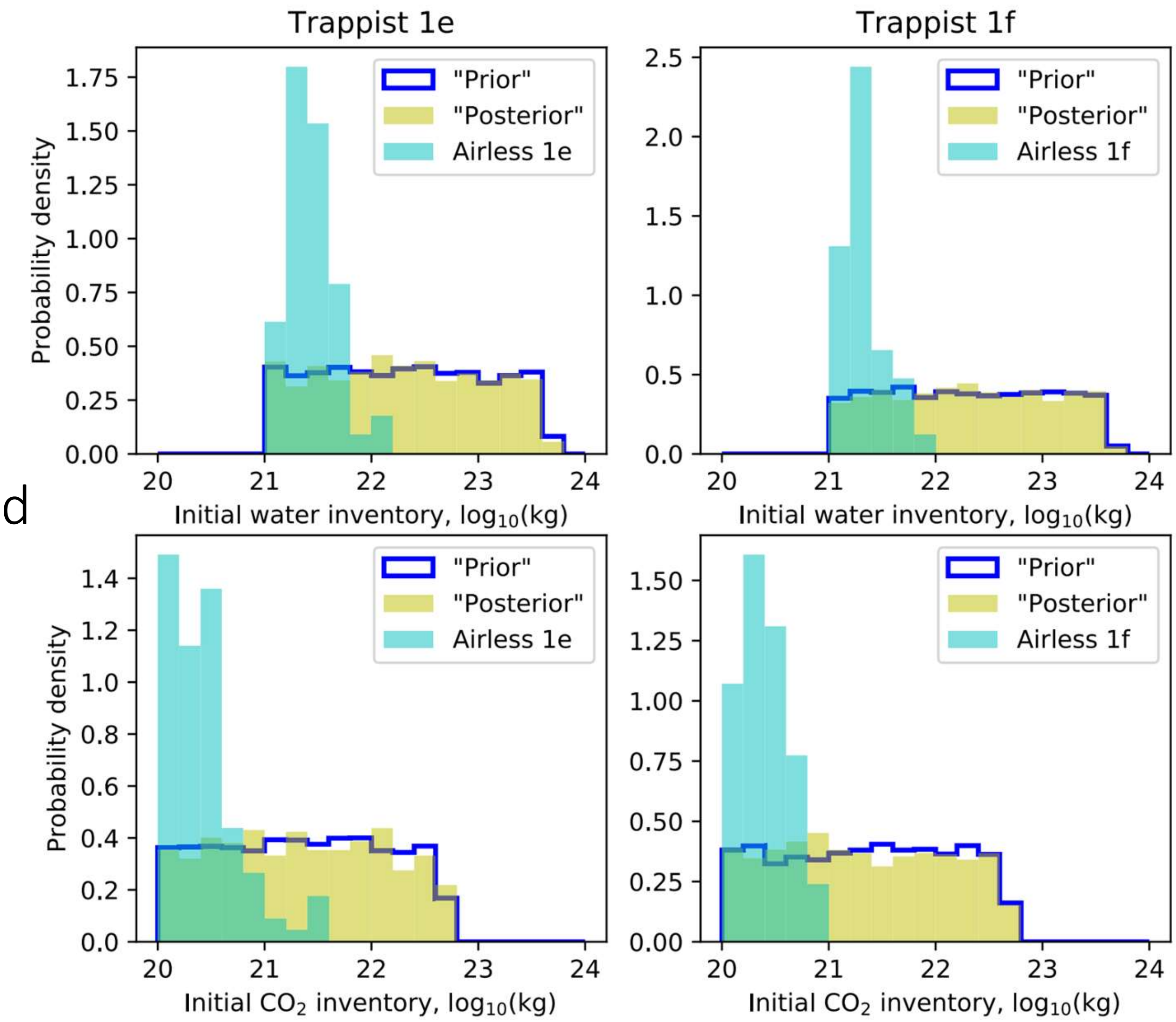
Venus was never habitable **Requires efficient dry crustal oxidation**



Venus experienced several Gyr of habitability, **Requires high bond albedo, efficient dry crustal oxidation**

Krissansen-Totton et al. (2021), The Planetary Science Journal.

If the outer planets are airless, then that would strongly suggest they formed relatively volatile poor.



## Table 1
Uncertain Parameter Ranges Sampled in Nominal Trappist-1 Monte Carlo Calculations

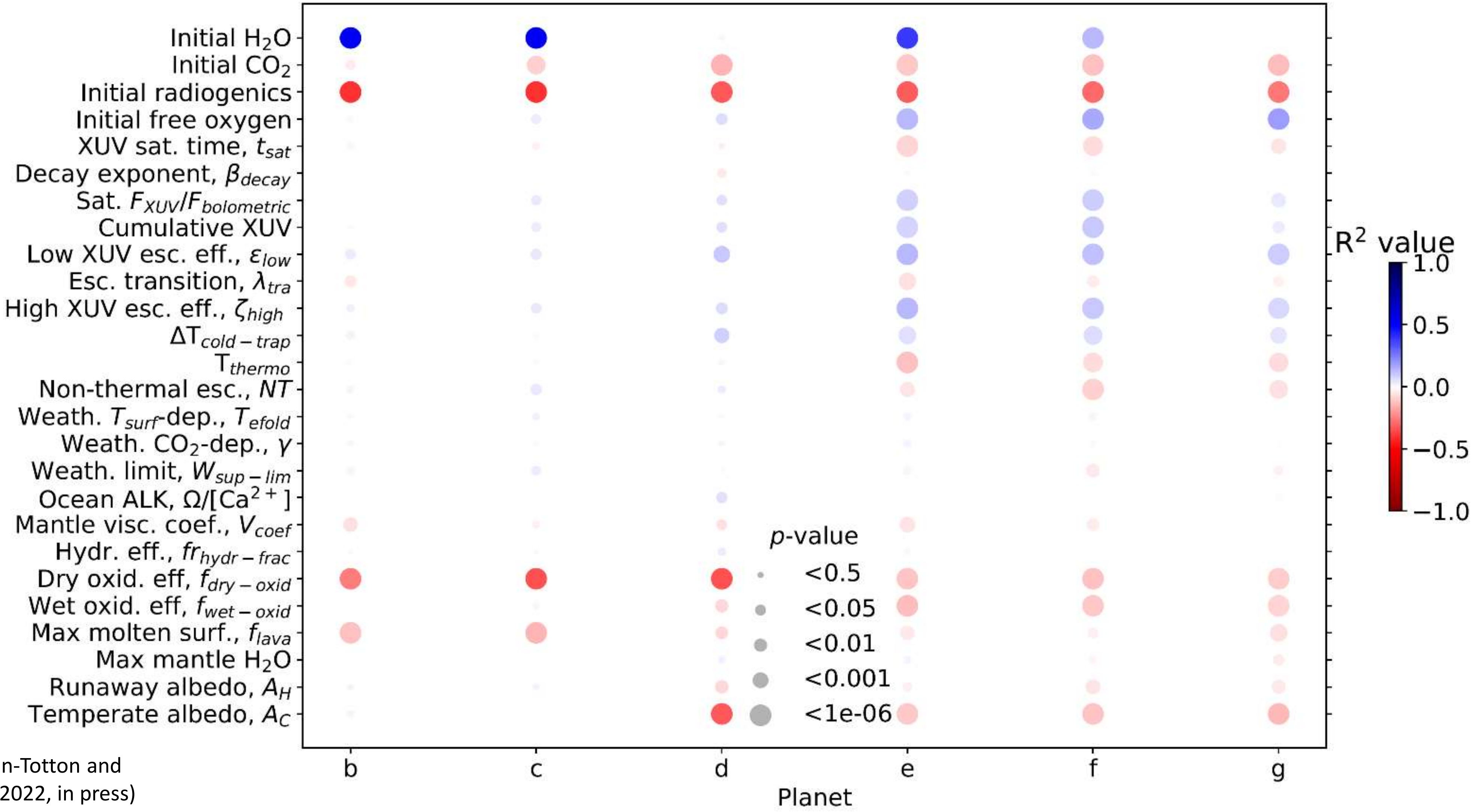
| | | Nominal Range | References/Notes |
|---|---|---|---|
| Initial conditions | Water[a] | $10^{21}$–$10^{23.63}$ kg[b] | 0.7–300 Earth oceans, or 0.02–7 wt% water for an Earth-mass planet |
| | Carbon dioxide[a] | $10^{20}$–$10^{22.69}$ kg[b] | Approximately 20 bar–10 kbar, pending other atmospheric constituents and gravity. |
| | Radionuclide U, Th, and K inventory (relative to Earth) | 0.33–30.0[b] | Scalar multiplication of Earth's radionuclide inventories in Lebrun et al. (2013). Allows for modest tidal heating. |
| | Mantle free oxygen[a] | $10^{20.6}$–$10^{22}$ kg[b] | This ensures postsolidification mantle redox within 3–4 log units of the quartz–fayalite–magnetite buffer. |
| Stellar evolution and escape parameters | **Trappist-1 XUV saturation time, $t_{sat}$** | **$3.14^{+2.22}_{-1.46}$ Gyr** | **XUV evolution parameters drawn randomly from joint distribution (Birky et al. 2021).** |
| | **Post saturation phase XUV decay exponent, $\beta_{decay}$** | **$-1.17^{+0.27}_{-0.28}$** | **XUV evolution parameters drawn randomly from joint distribution (Birky et al. 2021).** |
| | **Saturated $\log_{10}(F_{XUV}/F_{BOLOMETRIC})$ flux ratio** | **$-3.03^{+0.25}_{-0.23}$** | **XUV evolution parameters drawn randomly from joint distribution (Birky et al. 2021).** |
| | **Escape efficiency at low XUV flux, $\varepsilon_{low}$** | **0.01–0.3** | **See escape section in Krissansen-Totton et al. (2021b).** |
| | **Transition parameter for diffusion limited to XUV-limited escape, $\lambda_{tra}$** | **$10^{-2}$–$10^{2}$[b]** | **See escape section in Krissansen-Totton et al. (2021b).** |
| | **XUV energy that contributes to XUV escape above hydrodynamic threshold, $\zeta_{high}$** | **0%–100%** | **See escape section in Krissansen-Totton et al. (2021b).** |
| | Cold trap temperature variation, $\Delta T_{cold\text{-}trap}$ | −30 to +30 K | Cold trap temperature, $T_{cold\text{-}trap}$, equals planetary skin temperature plus a fixed, uniformly sampled variation, $T_{cold\text{-}trap} = T_{eq}(1/2)^{0.25} + \Delta T_{cold\text{-}trap}$. Here, $T_{eq}$ is the planetary equilibrium temperature given assumed albedo. |
| | **Thermosphere temperature, $T_{thermo}$** | **200–5000 K[b]** | (Lichtenegger et al. 2016; Johnstone et al. 2018, 2021) |
| | Nonthermal escape (total loss over Trappist-1 evolution), $NT$ | 1–100 bar[b] | (Garcia-Sage et al. 2017; Dong et al. 2018) |
| Carbon cycle parameters | Temperature-dependence of continental weathering, $T_{efold}$ | 5–30 K | Plausible Earth-like range (Krissansen-Totton et al. 2018a) |
| | $CO_2$-dependence of continental weathering, $\gamma$ | 0.1–0.5 | Plausible Earth-like range (Krissansen-Totton et al. 2018a) |
| | Weathering supply limit, $W_{sup-lim}$ | $10^{5}$–$10^{7}$ kg $s^{-1}$[b] | Broad terrestrial planet range (Foley 2015) |
| | Ocean calcium concentration, $[Ca^{2+}]$ | $10^{-4}$–$3 \times 10^{-1}$[b] mol $kg^{-1}$ | Plausible range for diverse terrestrial planet compositions (Kite & Ford 2018; Krissansen-Totton et al. 2018a) |
| | Ocean carbonate saturation, $\Omega$ | 1–10 | (Zeebe & Westbroek 2003) |
| Interior evolution parameter | Solid mantle viscosity coefficient, $V_{coef}$ | $10^{1}$–$10^{3}$ Pa s[b] | Solid mantle kinematic viscosity, $\nu_{rock}$, ($m^2\ s^{-1}$) is given by the following equation: $\nu_{rock} = V_{coef}\, 3.8 \times 10^{7} \exp\left(\frac{350000}{8.314 T_p}\right) \Big/ \rho_m$ Here $T_p$ is mantle potential temperature (K) and $\rho_m$ is mantle density (kg $m^{-3}$). See Krissansen-Totton et al. (2021b). |
| Crustal sinks oxygen and hydrological cycle parameters | Crustal hydration efficiency, $fr_{hydr\text{-}frac}$ | $10^{-3}$ to 0.03[b] | Upper limit wt % $H_2O$ in oceanic crust. Lower limit hydration limited by cracking. |
| | **Dry oxidation efficiency, $f_{dry\text{-}oxid}$** | **$10^{-4}$ to 10%[b]** | **Plausible range of processes for Venus (Gillmann et al. 2009)** |
| | Wet oxidation efficiency, $f_{wet\text{-}oxid}$ | $10^{-3}$–$10^{-1}$[b] | Based on oxidation of Earth's oceanic crust (Lécuyer & Ricard 1999). |
| | **Maximum fractional molten area, $f_{lava}$** | **$10^{-4}$–1.0[b]** | **See explanation in Krissansen-Totton et al. (2021b).** |
| | Max mantle water content, $M_{solid-H_2O-max}$ | 0.5–15 Earth oceans | Best estimates maximum hydration of silicate mantle (Cowan & Abbot 2014) |
| | | 0.0–0.2 | (Pluriel et al. 2019) |
| Albedo parameters | Hot state albedo (during runaway greenhouse/magma ocean), $A_H$ | | |
| | Cold state albedo (during temperate state), $A_C$ | 0.0–0.5 | (Shields et al. 2013; Kopparapu et al. 2017; Rushby et al. 2020; Macdonald et al. 2022) |

**Notes.** Bold parameters are assumed to be common to all planets in the Trappist-1 system, whereas other parameters are sampled independently for each planet in the system.

[a] Denotes variables sampled independently for all planets in nominal calculations, but drawn from the distribution that ensures an airless Trappist-1b subsequently.

[b] Denotes this variable was sampled uniformly in log space. All others (except stellar XUV parameters) sampled uniformly in linear space.

# What variables control atmospheric evolution:



Krissansen-Totton and Fortney (2022, in press)

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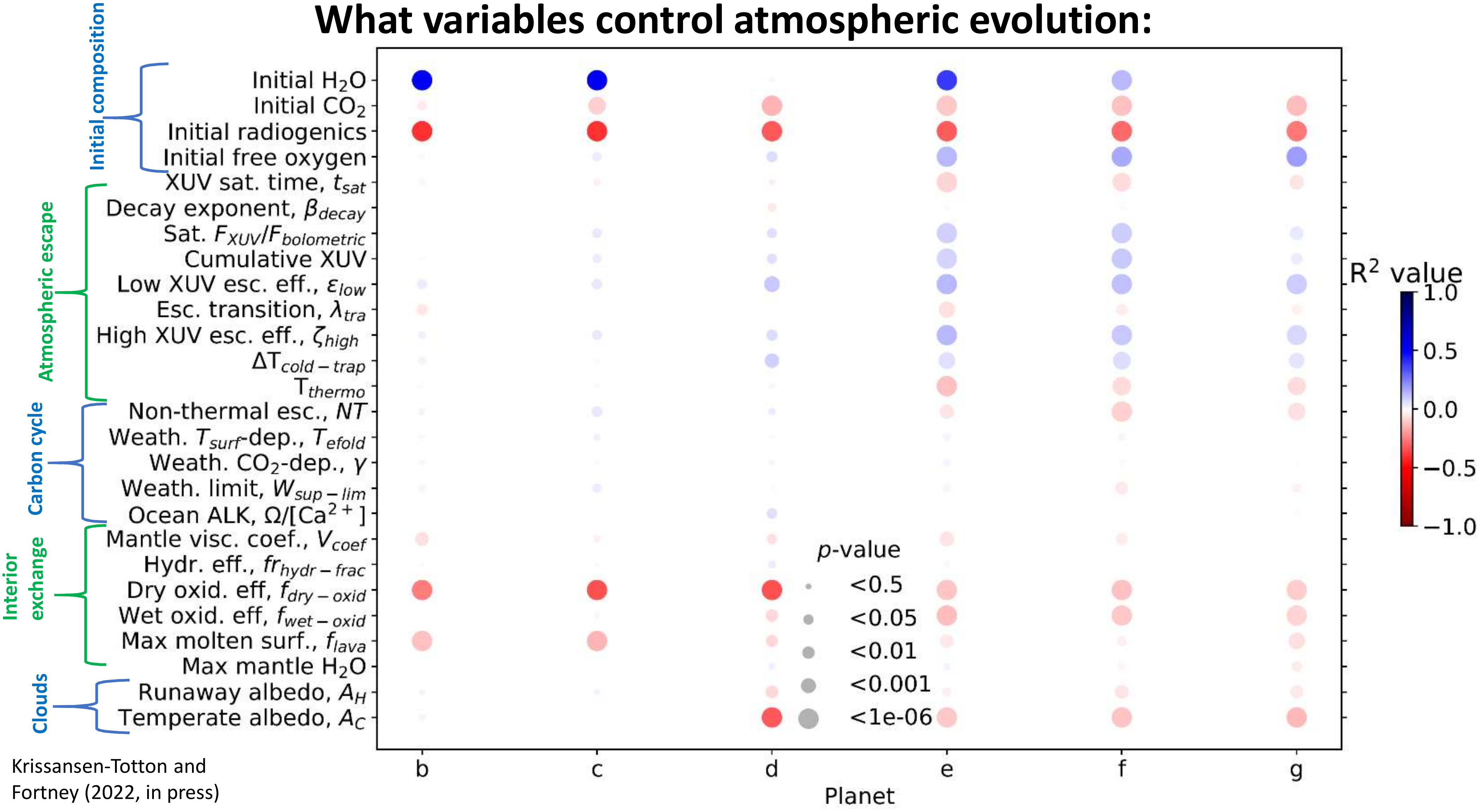

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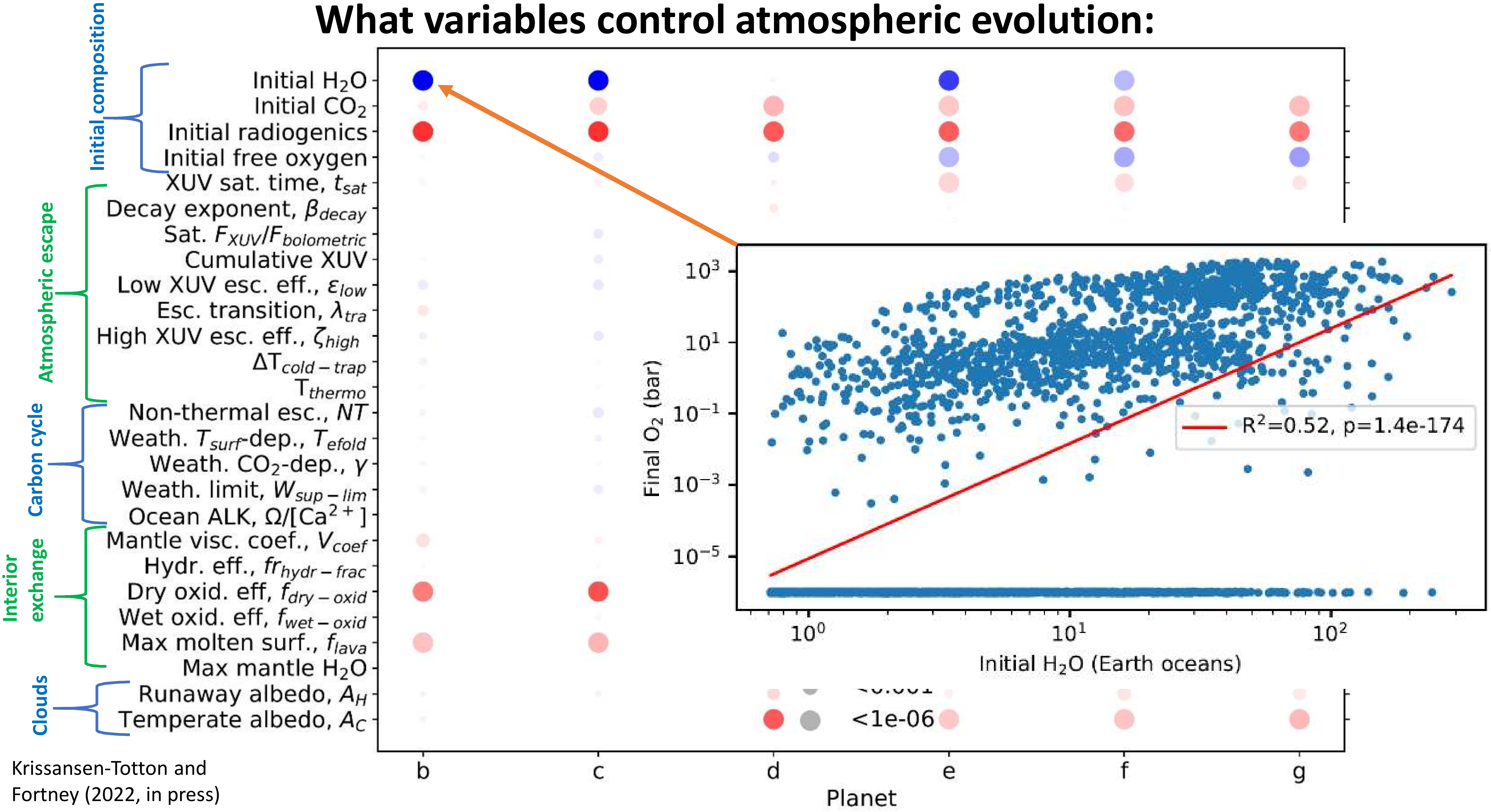

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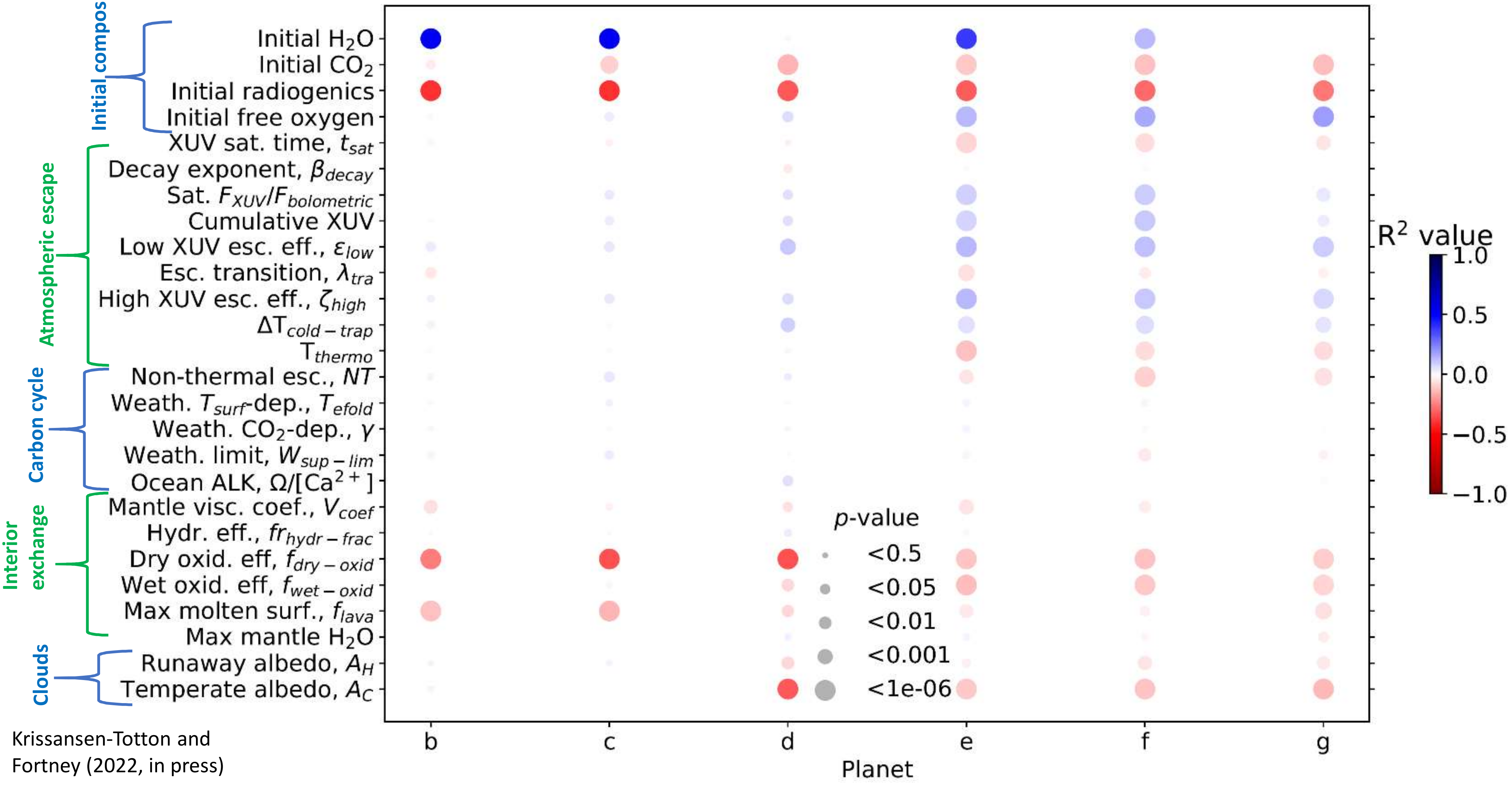
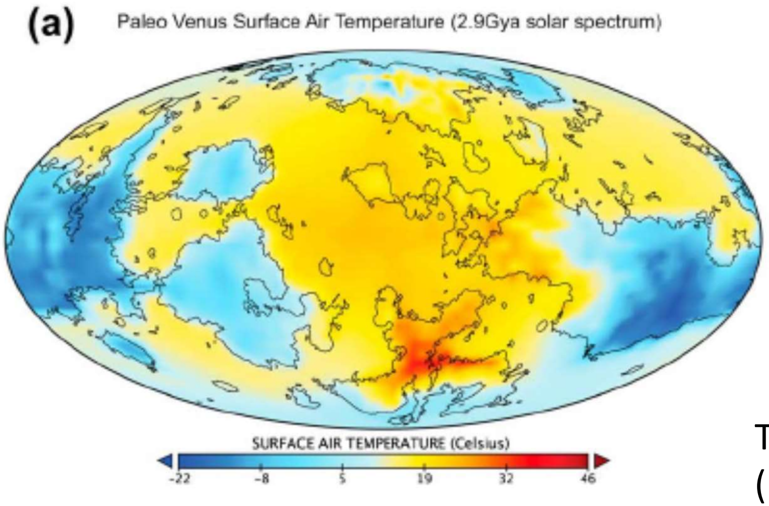
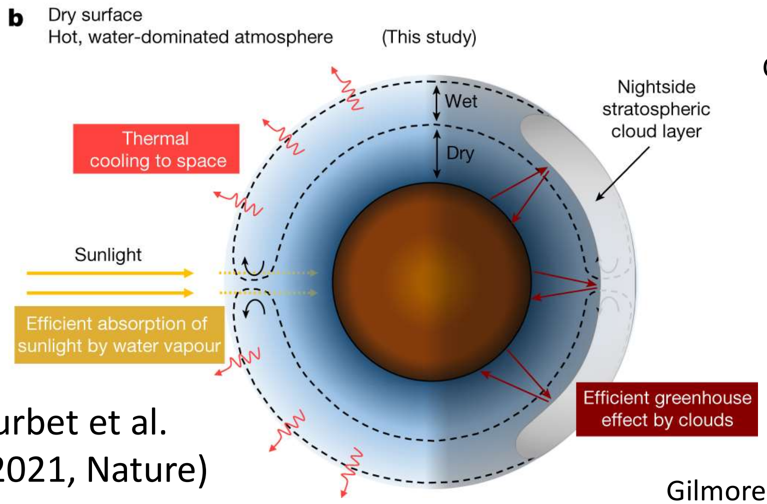


Krissansen-Totton and
Fortney (2022, in press)

# The climate evolution of Venus is uncertain

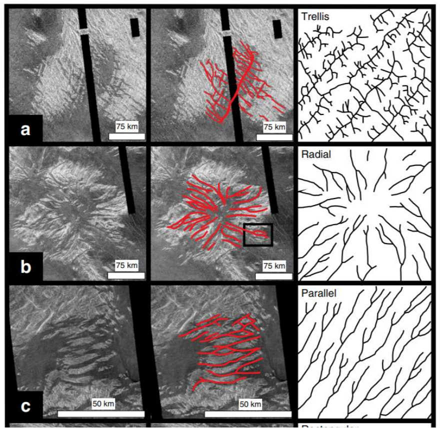


Way et al. (2016; GRL),
Way and Del Genio (2020)



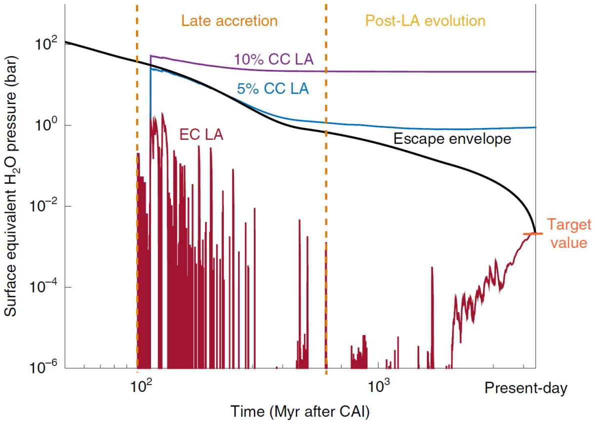
Turbet et al.
(2021, Nature)

Khawja et al. (2020; Nature Communications) Tesserae on Venus may preserve evidence of fluvial erosion.

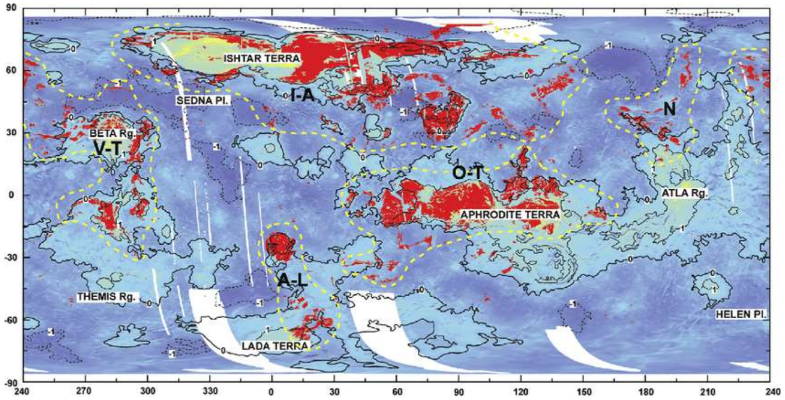


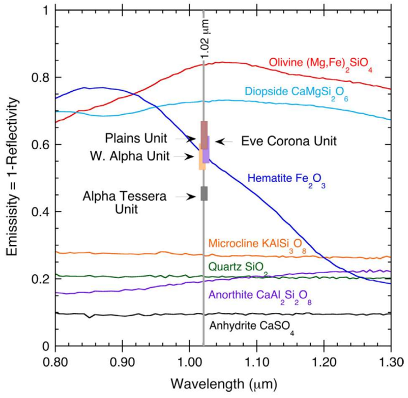
Gilmore et al.
(2015) Icarus,
254, 350-361.

Recent H loss harder to reconcile with the lack of $O_2$ (Lammer et al. 2018; Gillmann et al. 2009; Gillmann et al. 2020; Warren and Kite 2023)

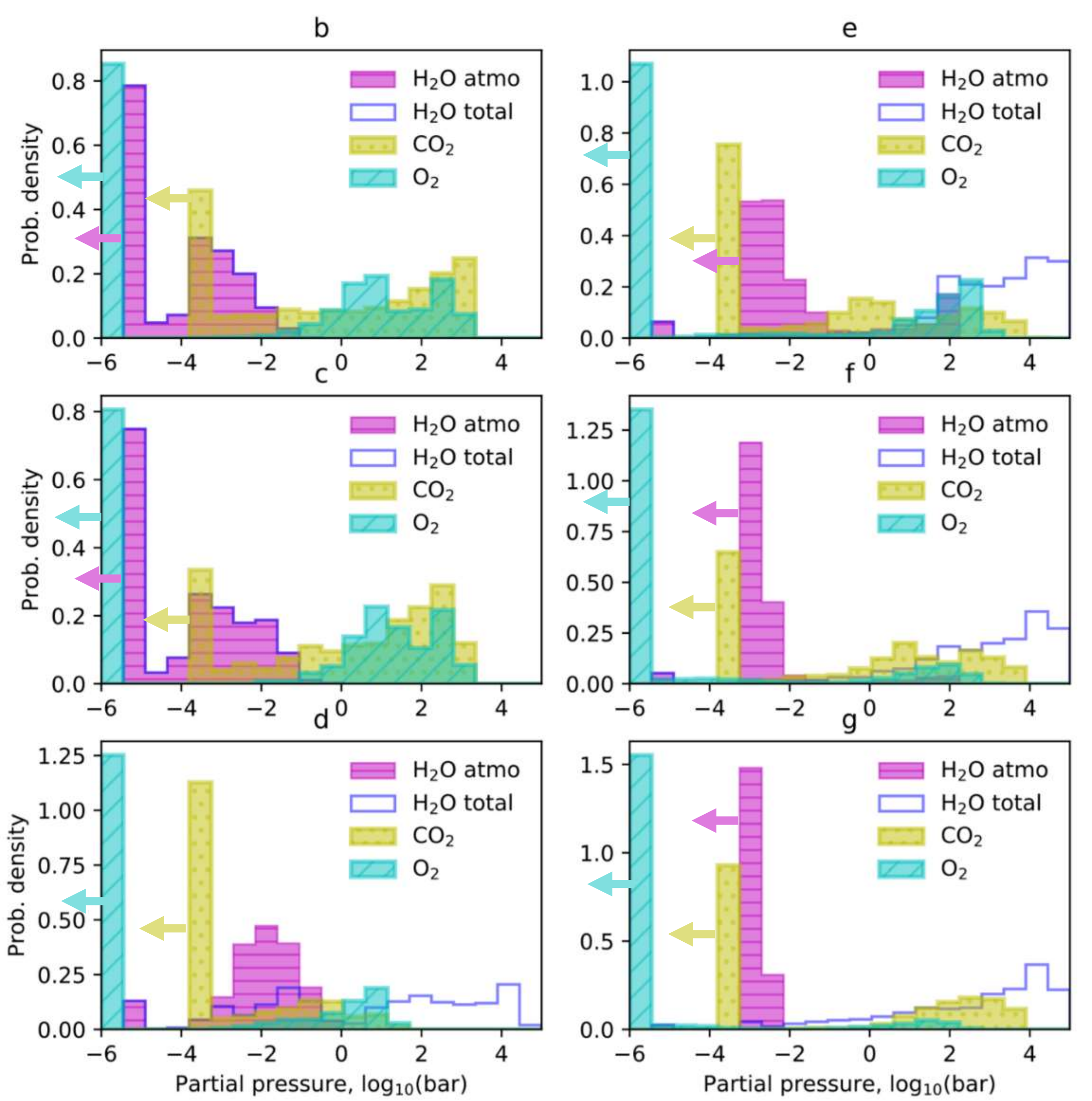


Ivanov and Head (2013 "Evolution of Tectonics on Venus")

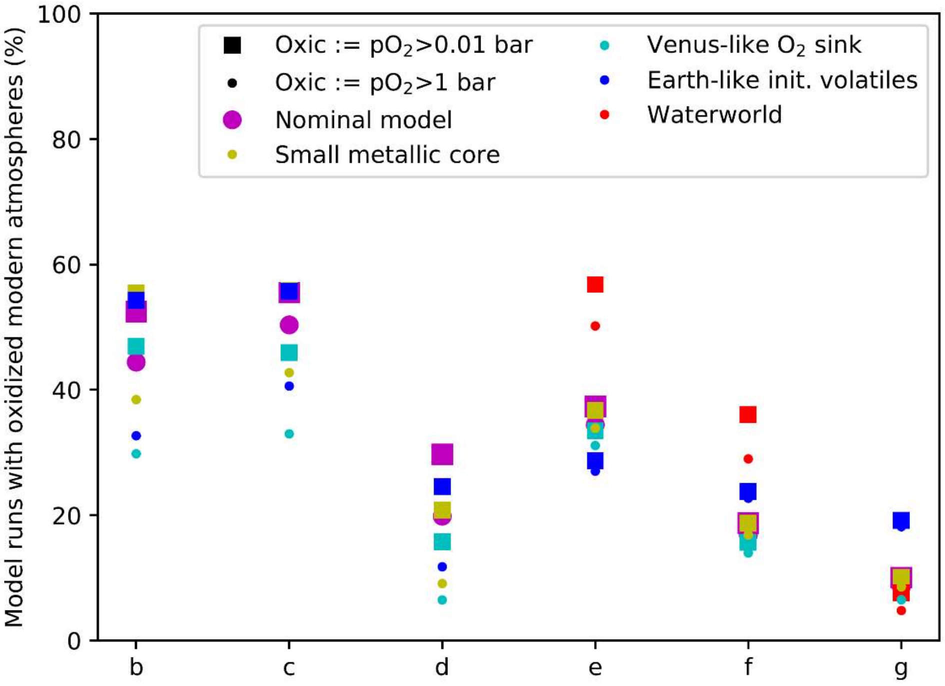




# "Probability distributions" for current Trappist-1 planetary atmospheres



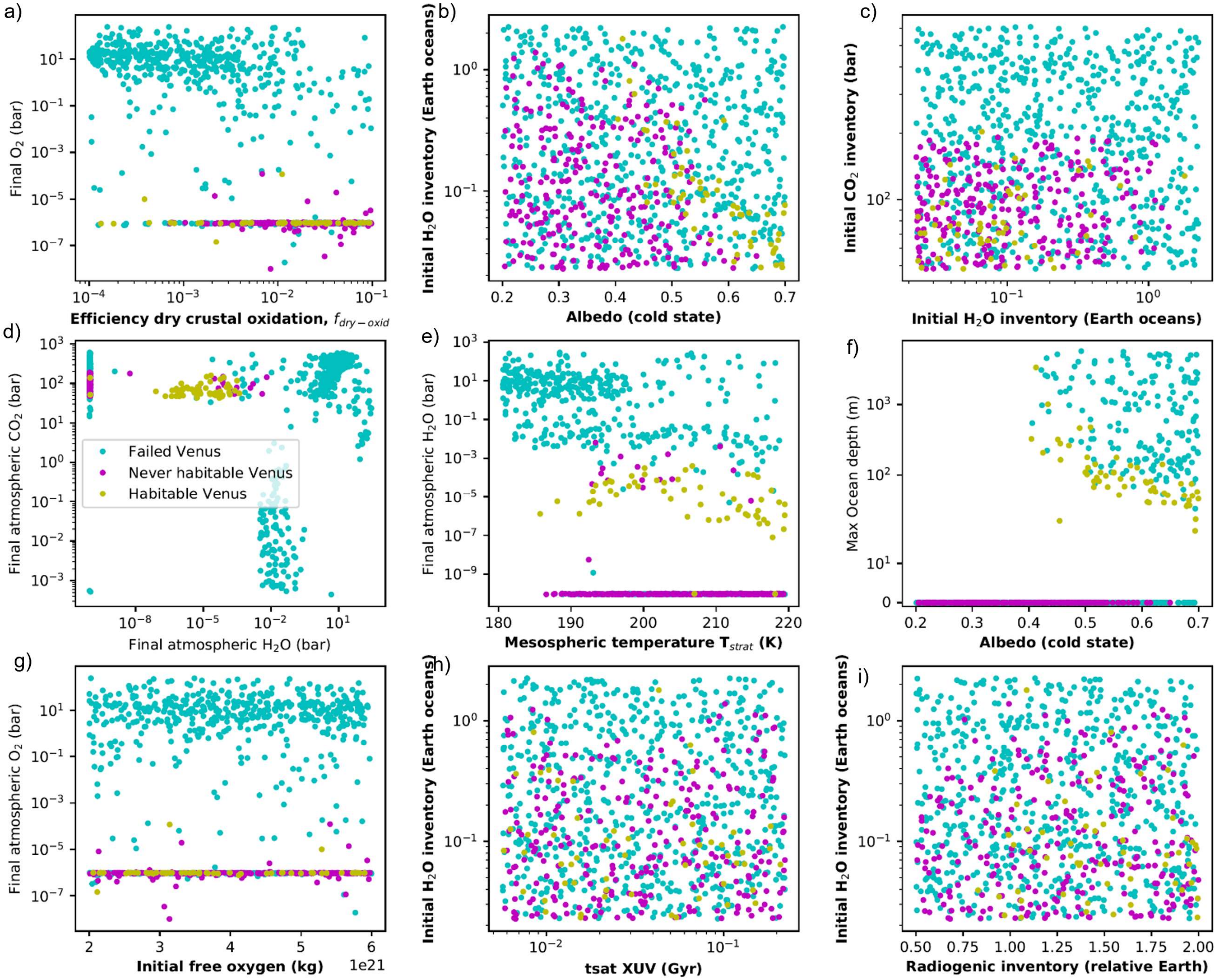
More likely $O_2$–rich atmospheres



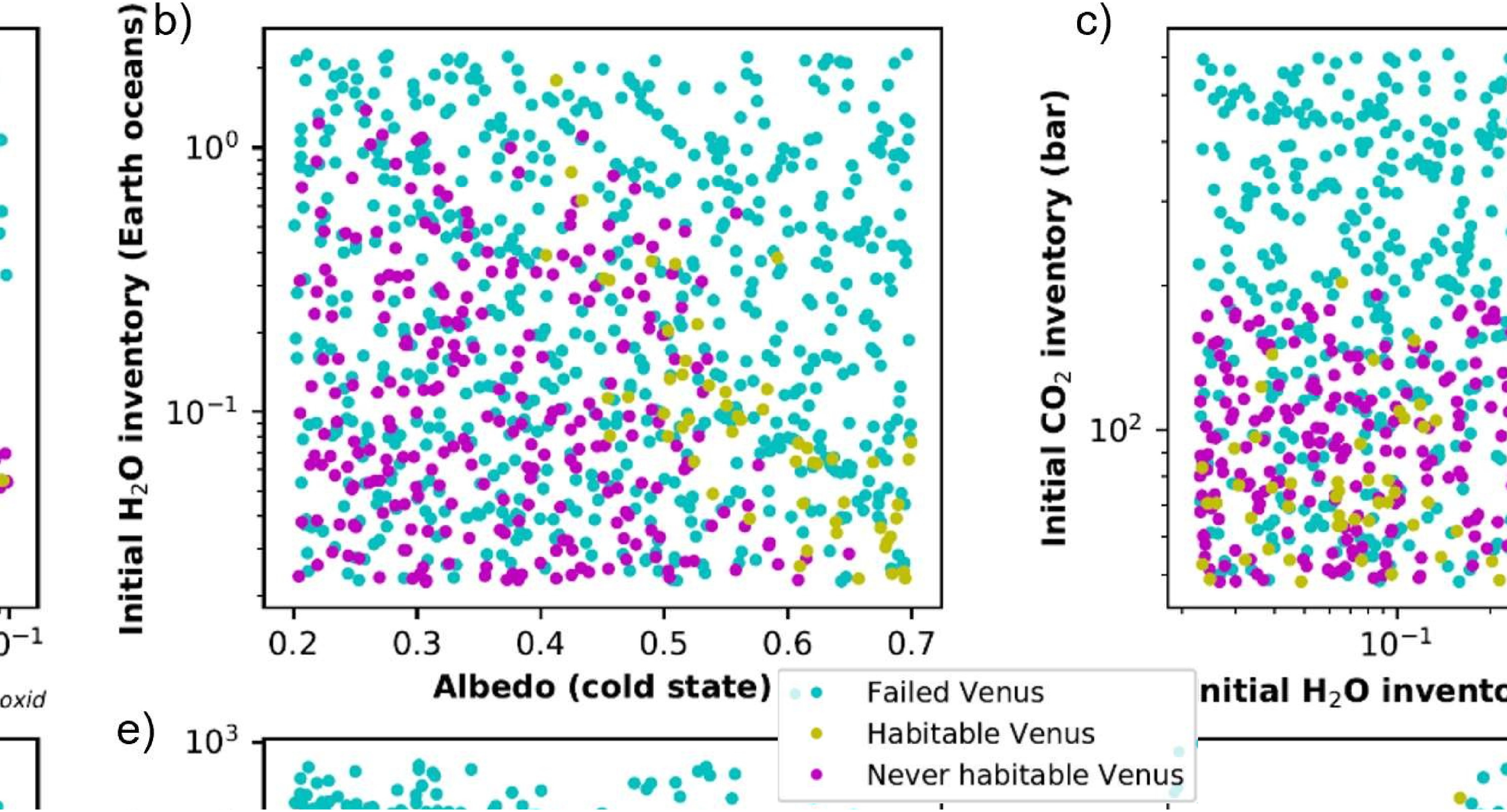
More likely $O_2$–free atmospheres

Krissansen-Totton and Fortney (2022, ApJ)

# Conditions required to recover modern Venus



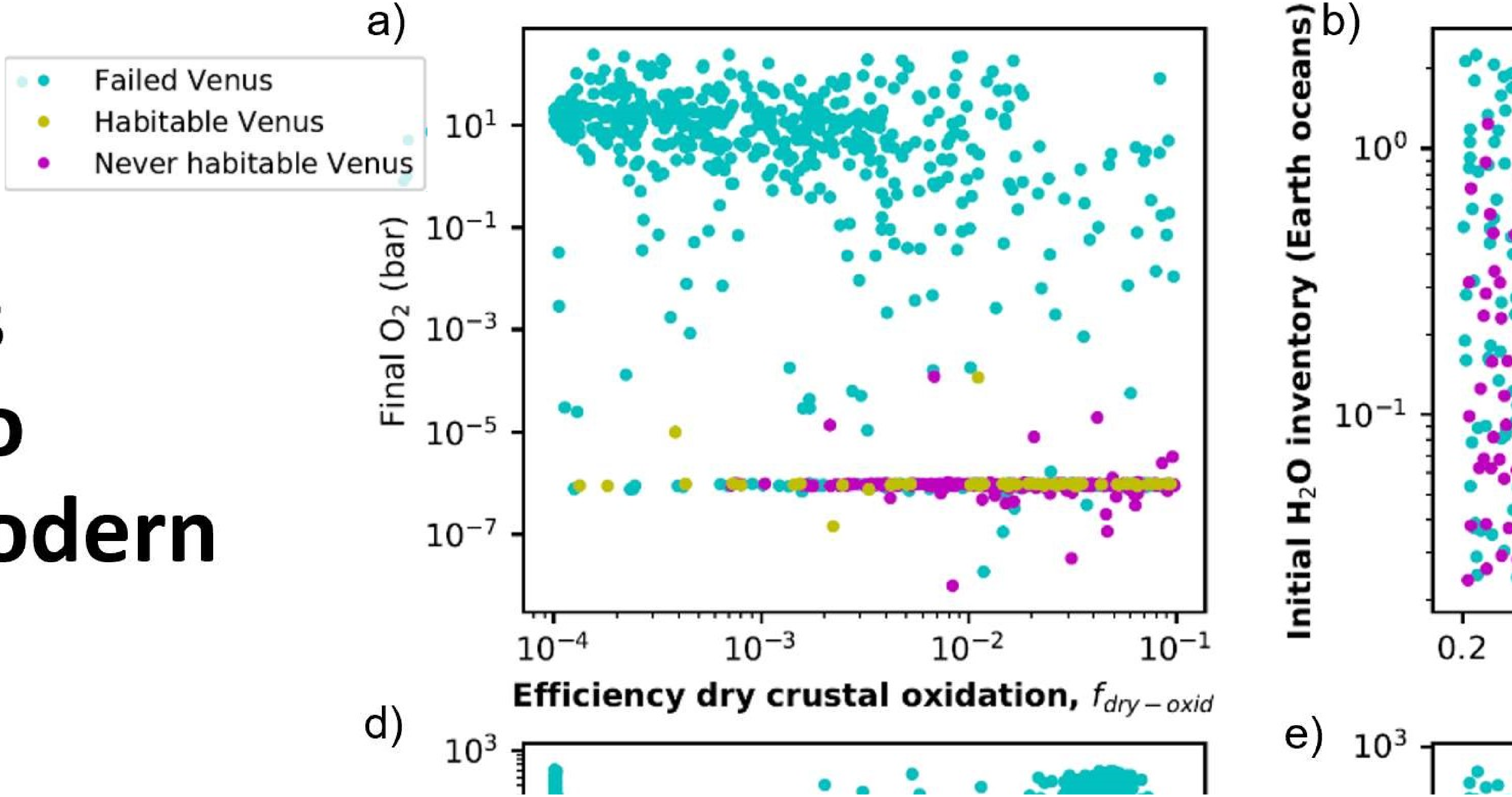
- ● Failed Venus
- ● Habitable Venus
- ● Never habitable Venus


b)
Initial H$_2$O inventory (Earth oceans)
10$^0$
10$^{-1}$
0.2
0.3
0.4
0.5
0.6
0.7
Albedo (cold state)
c)
Initial CO$_2$ inventory (bar)
10$^2$
10$^{-1}$
Initial H$_2$O invento
Failed Venus
Habitable Venus
Never habitable Venus
e)
10$^3$
0$^{-1}$
oxid

s

O

odern


a)
Failed Venus
Habitable Venus
Never habitable Venus
Final $O_2$ (bar)
$10^1$
$10^{-1}$
$10^{-3}$
$10^{-5}$
$10^{-7}$
$10^{-4}$
$10^{-3}$
$10^{-2}$
$10^{-1}$
Efficiency dry crustal oxidation, $f_{dry-oxid}$
b)
Initial $H_2O$ inventory (Earth oceans)
$10^0$
$10^{-1}$
0.2
d)
$10^3$
e)
$10^3$

# Sensitivity test:
# What if $CO_2$ throttles H escape due to strong radiative cooling?

- High $CO_2$ mixing ratio in the upper atmosphere -> strong radiative cooling (Wordsworth & Pierrehumbert 2013; Johnstone et al. 2018; 2019; Kulikov et al. 2007).

- Crudely represent this in our model:

$$T_{meso} = 214 - 44 \times f_{CO_2-meso}$$

- Earth-like temperatures for $N_2$-$O_2$ atmospheres, 170 K for $CO_2$-dominated atmosphere (actual Venus atmosphere is 150-180 between cloud deck and homopause).