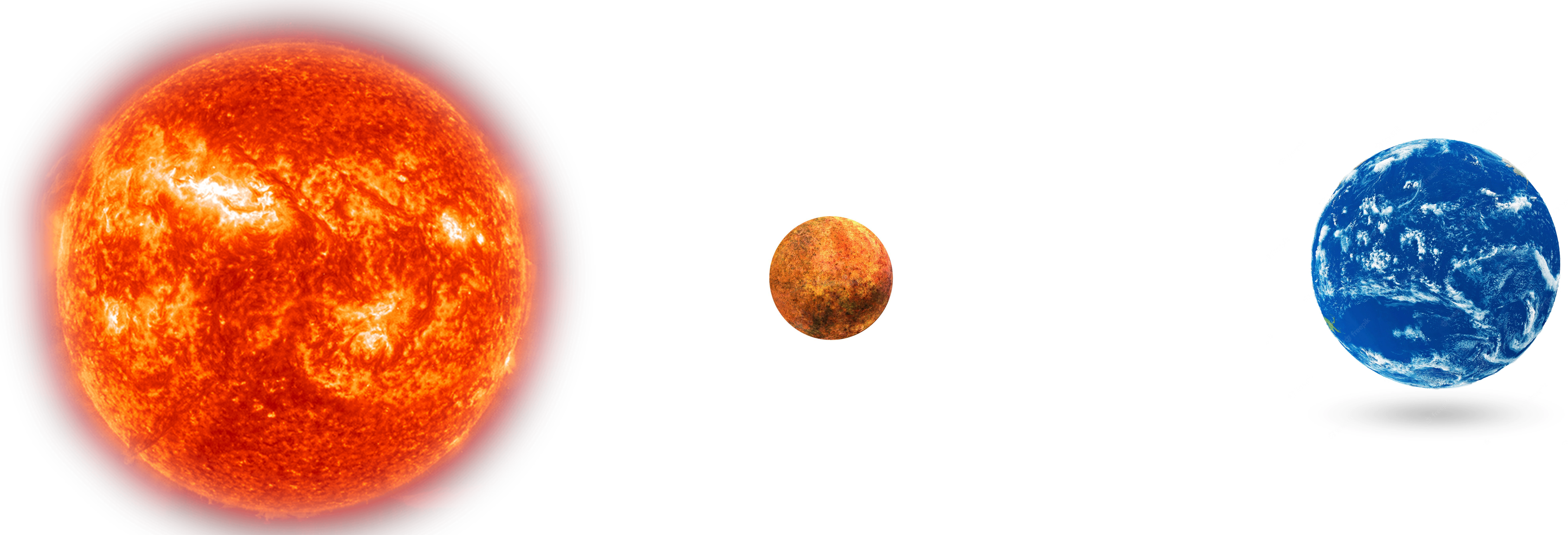
Water content trends in low-mass multiplanetary systems



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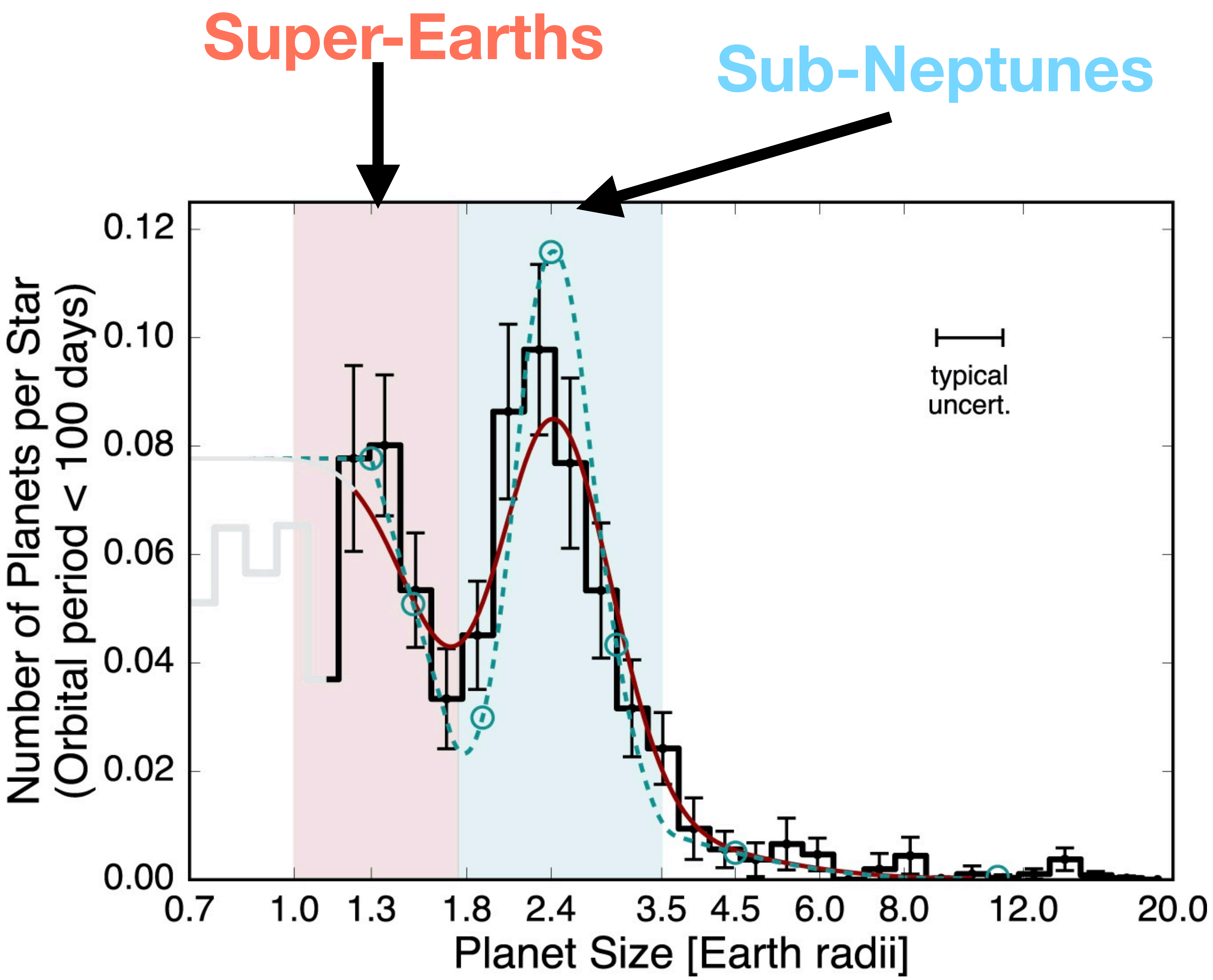
The composition of low-mass exoplanets

- Low-mass planets present **two subpopulations** based on radius and composition
  - **Super-Earths**: dominated by silicates and iron (Fe)
  - **Sub-Neptunes**: volatile-rich
- Open questions:
  - Super-Earths: **bare rock or rocky + thin atmosphere?**
  - Volatiles in sub-Neptunes: **H/He, water, or both?**

→ **Use interior models**



Super-Earths

Sub-Neptunes

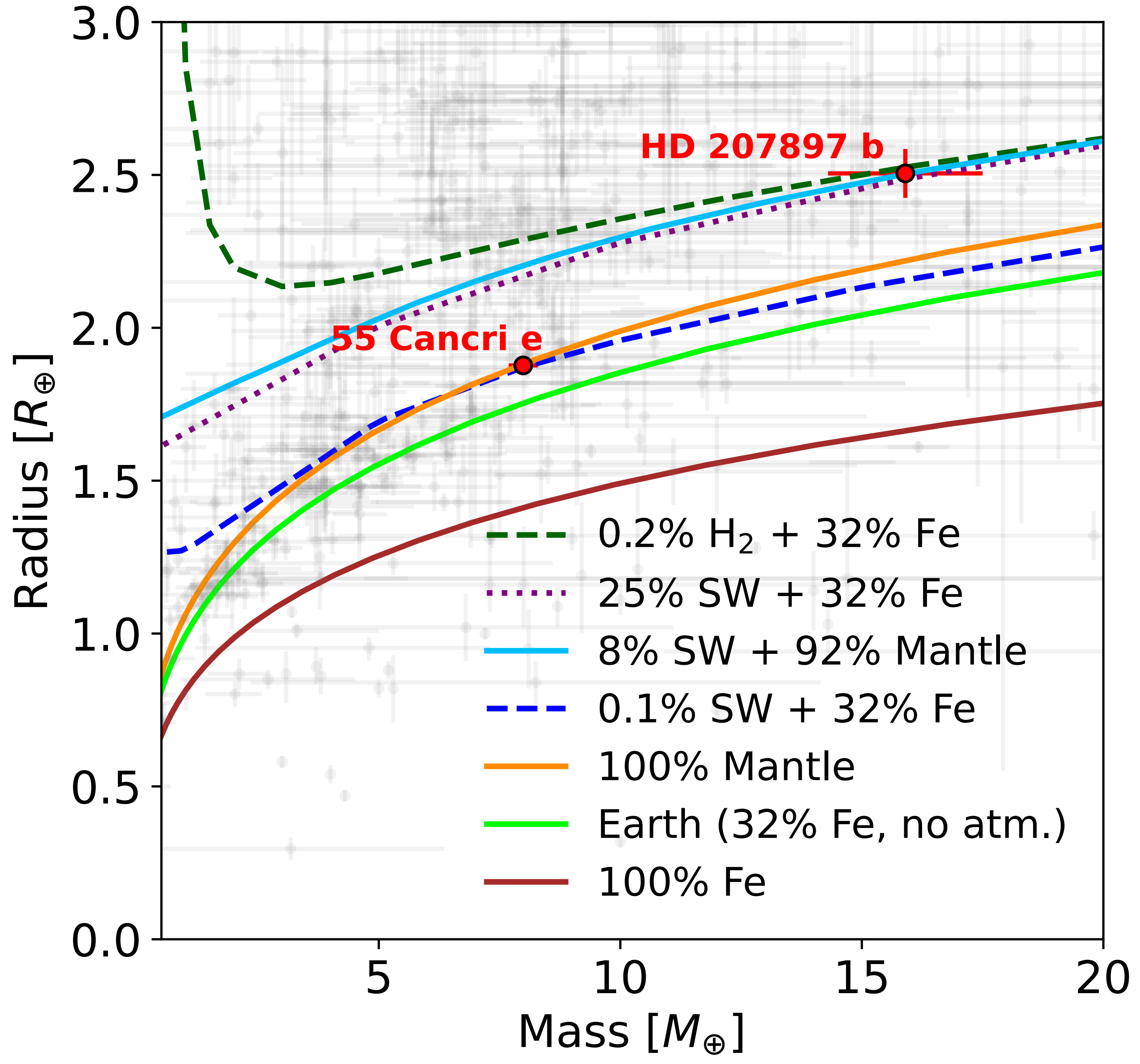
Fulton et al. 2017, 2018

Why planetary interior models?

- Mostly used to calculate **mass-radius diagrams to interpret data**

- **Support to atmospheric modelling.** Ex:
  - **clouds** (GJ1214 b: Gao et al. 2023)
  - **stellar contamination** (TRAPPIST-1: Zhang et al. 2018, Ducrot et al. 2018)
  - **degeneracies in chemical species** (K2-18 b: Bézard et al. 2022, Tsiaras et el. 2016)

- **Degeneracies in interior models**: different compositions can explain the mass and radius of one planet



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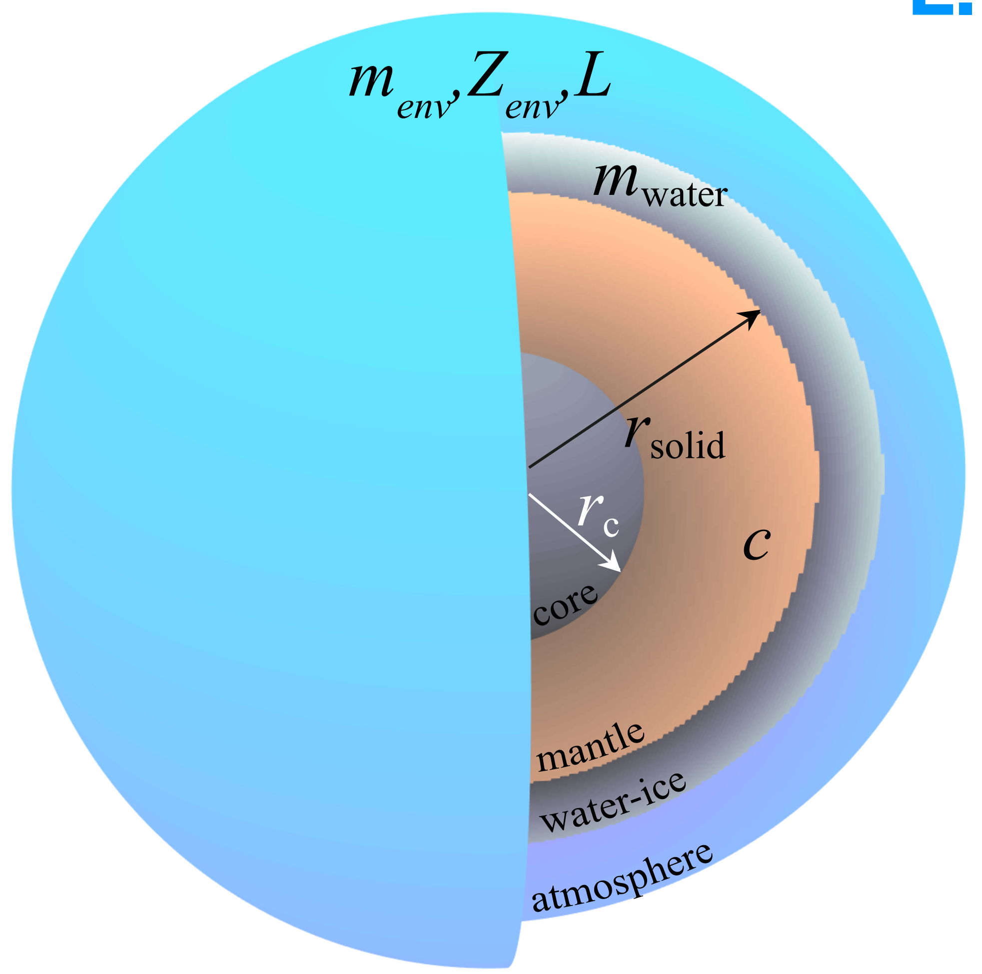
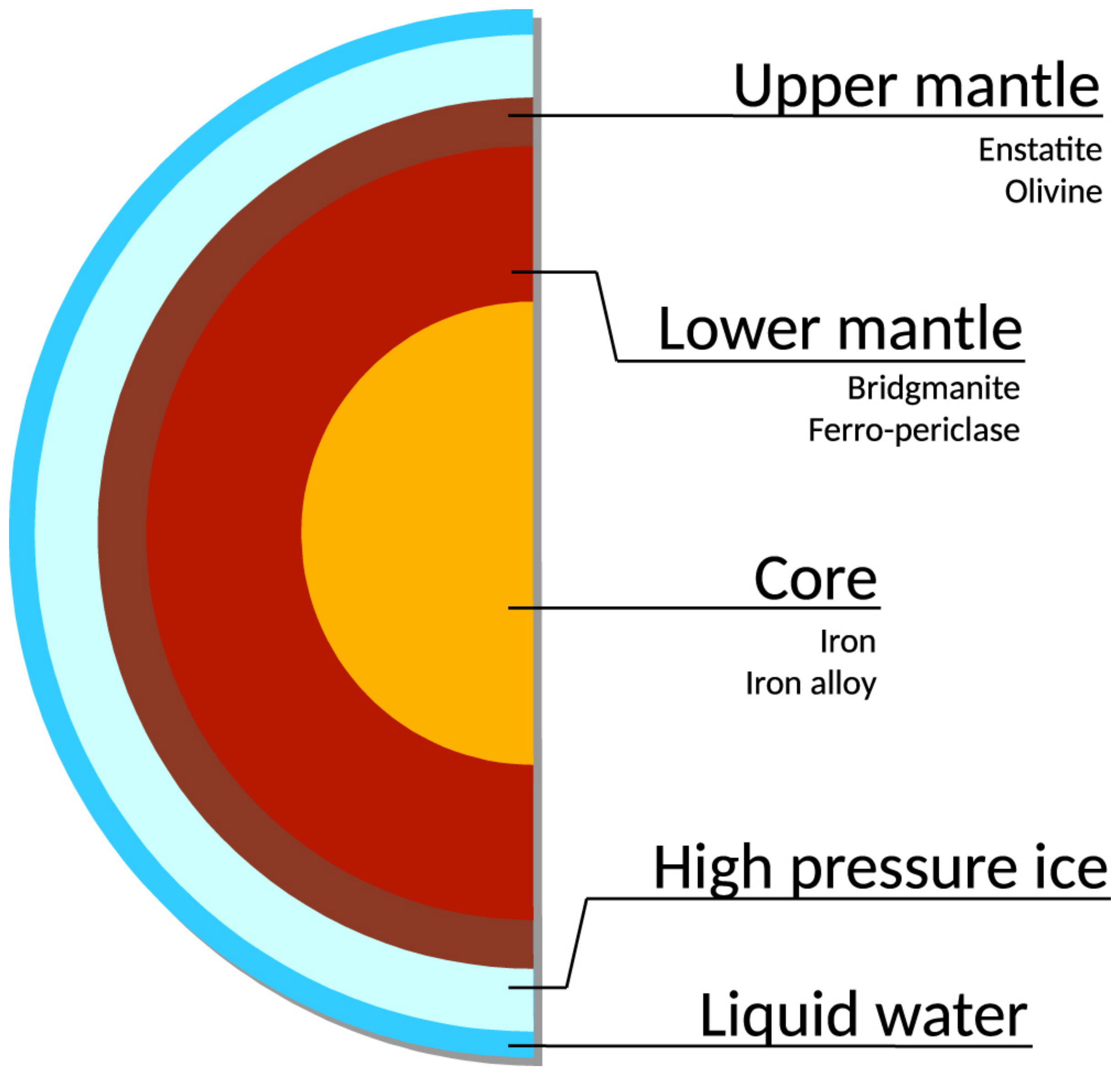


Dorn et al. 2015

Marseille's Super-Earth Interior Model (MSEI)

Input:

- Mass
- Composition: core mass fraction (CMF), and water mass fraction (WMF)
- Surface pressure and temperature



Output:

- Radius
- Fe/Si mole ratio

Brugger et al. 2016, 2017

Differential equations

$$\frac{dP}{dr} = -\rho g$$ → Pressure

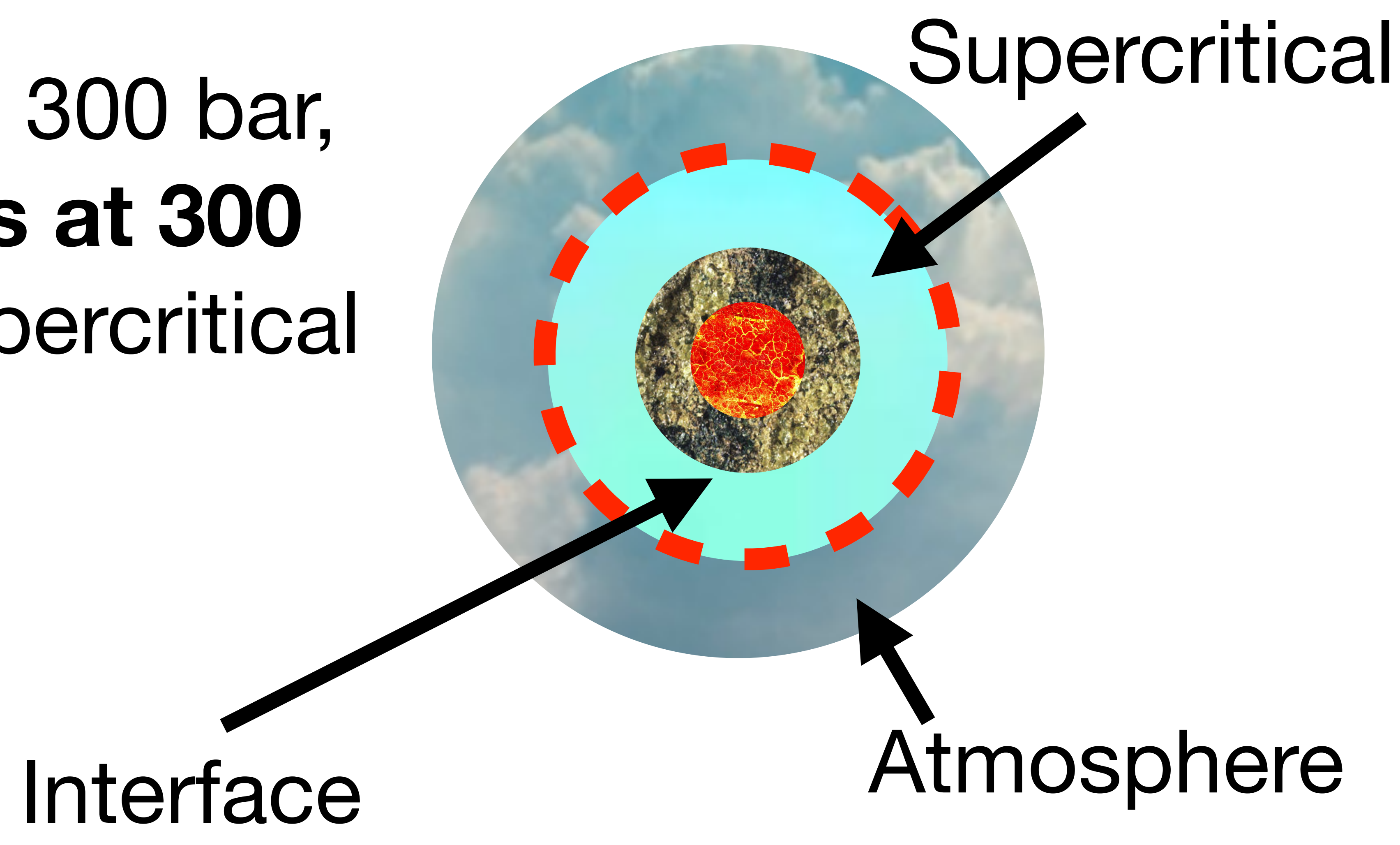
$$\frac{dg}{dr} = 4\pi G\rho - \frac{2Gm}{r^3}$$ → Gravity

$$\frac{dT}{dr} = -g\frac{\gamma T}{\phi}$$ → Temperature

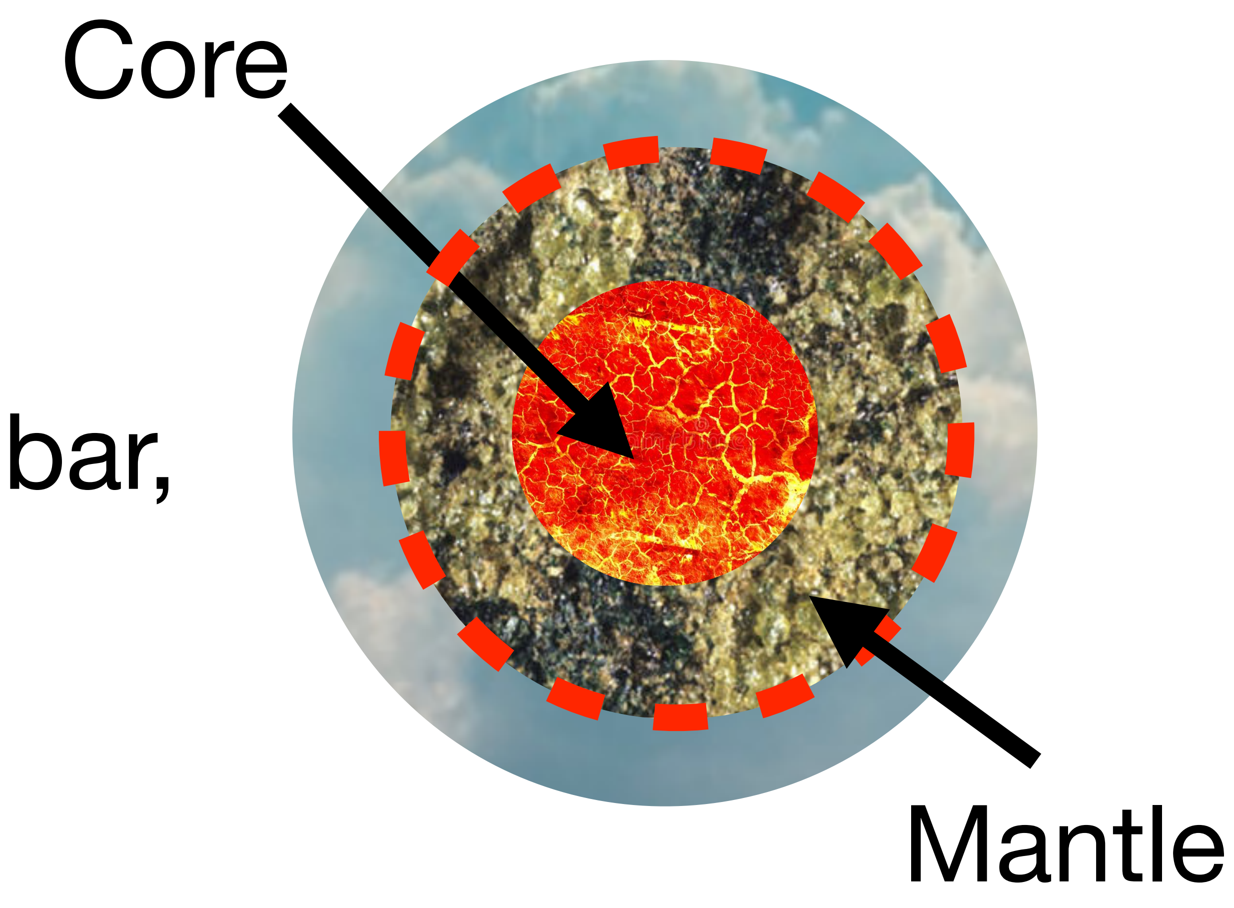
$$\frac{dm}{dr} = 4\pi r^2\rho$$ → Enclosed mass

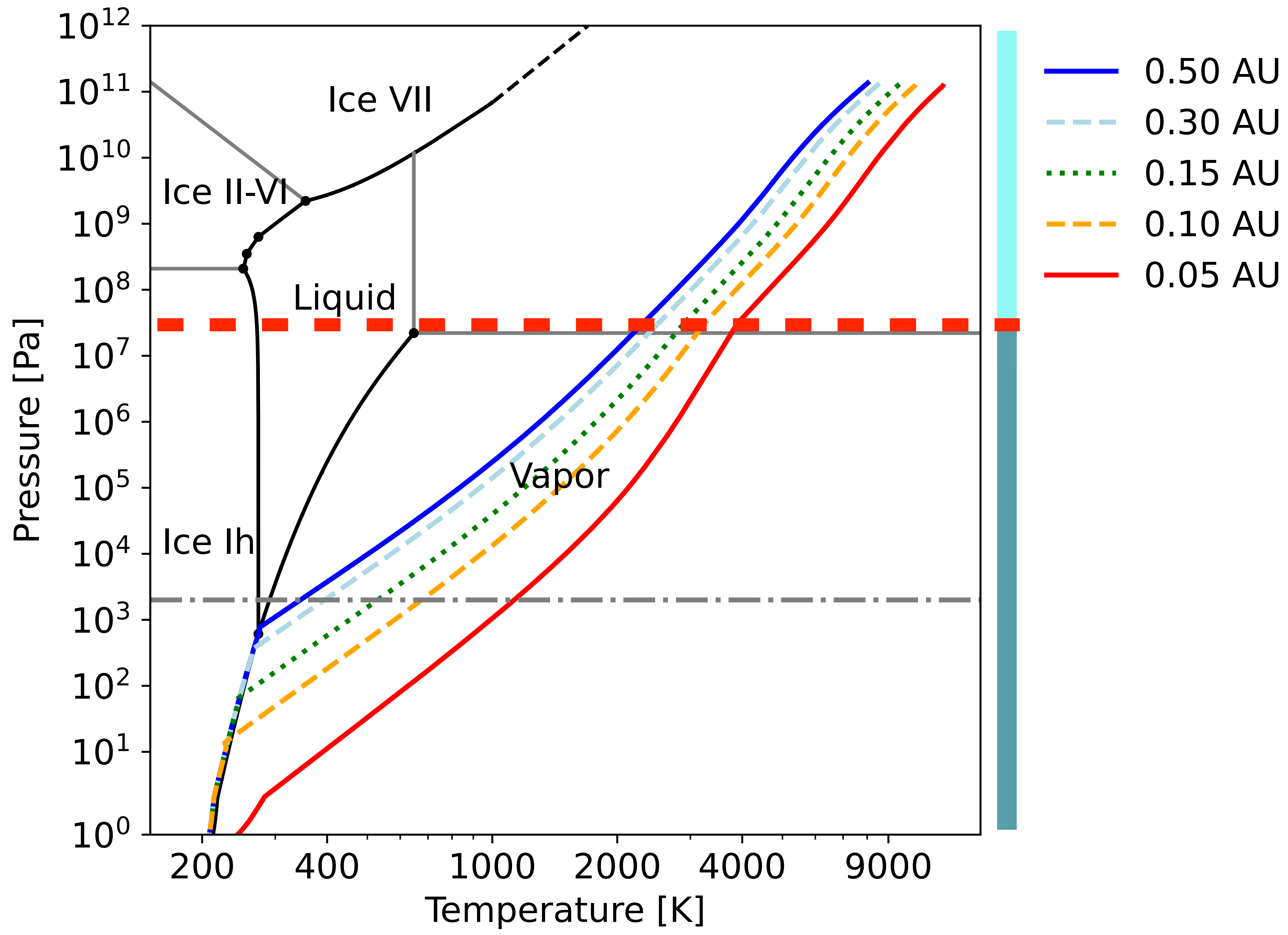
Interior-atmosphere interface

- If surface pressure > 300 bar, **Atmosphere base is at 300 bar.** Atmosphere-supercritical interface



- If surface pressure < 300 bar, **Atmosphere base is the surface.**





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PT profiles assuming a Sun-like star

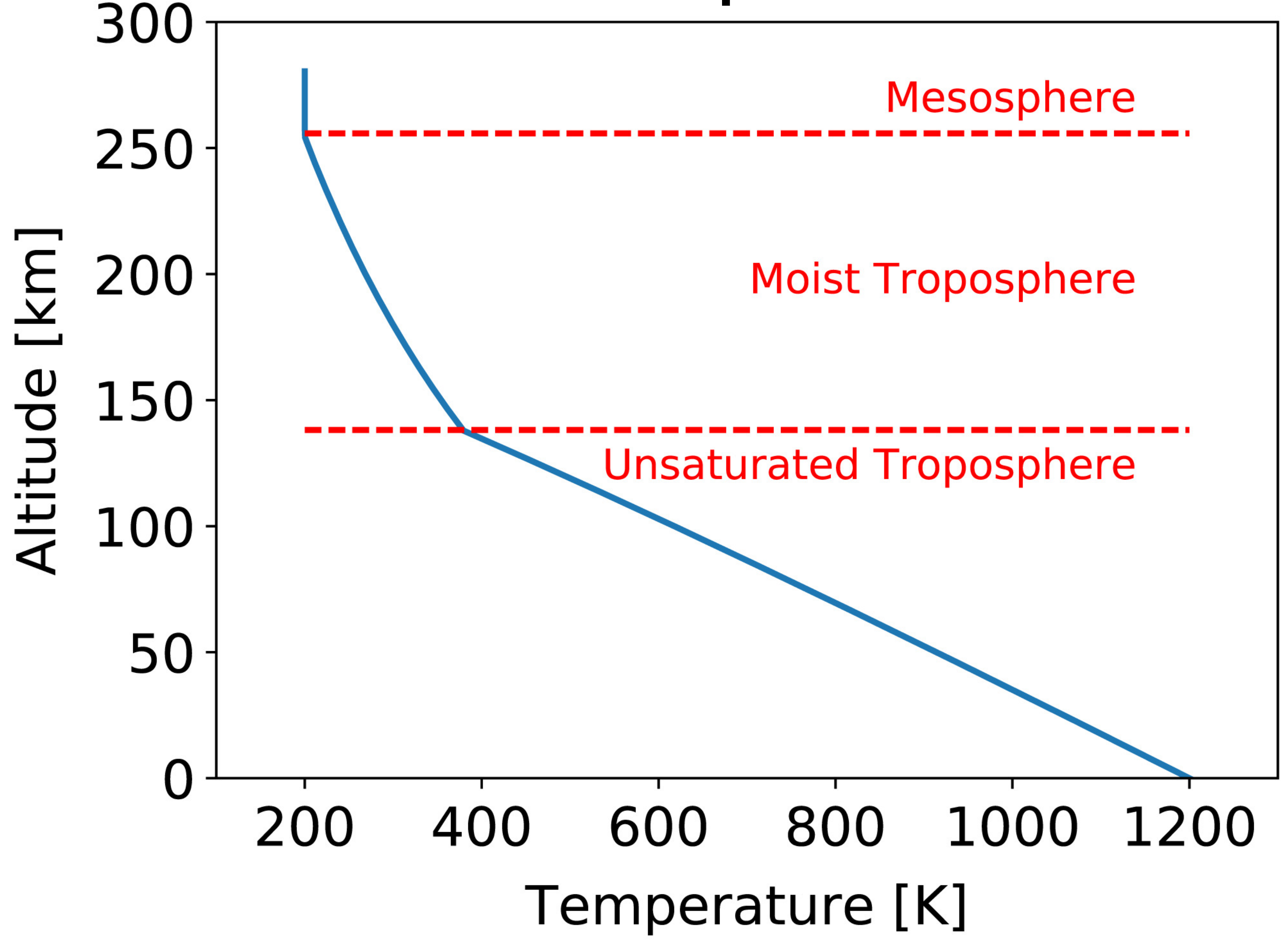
Interior-atmosphere coupling: atmospheric model

- RADCONV1D: Atmospheric model by **Marcq et al. 2017, Pluriel et al. 2019**

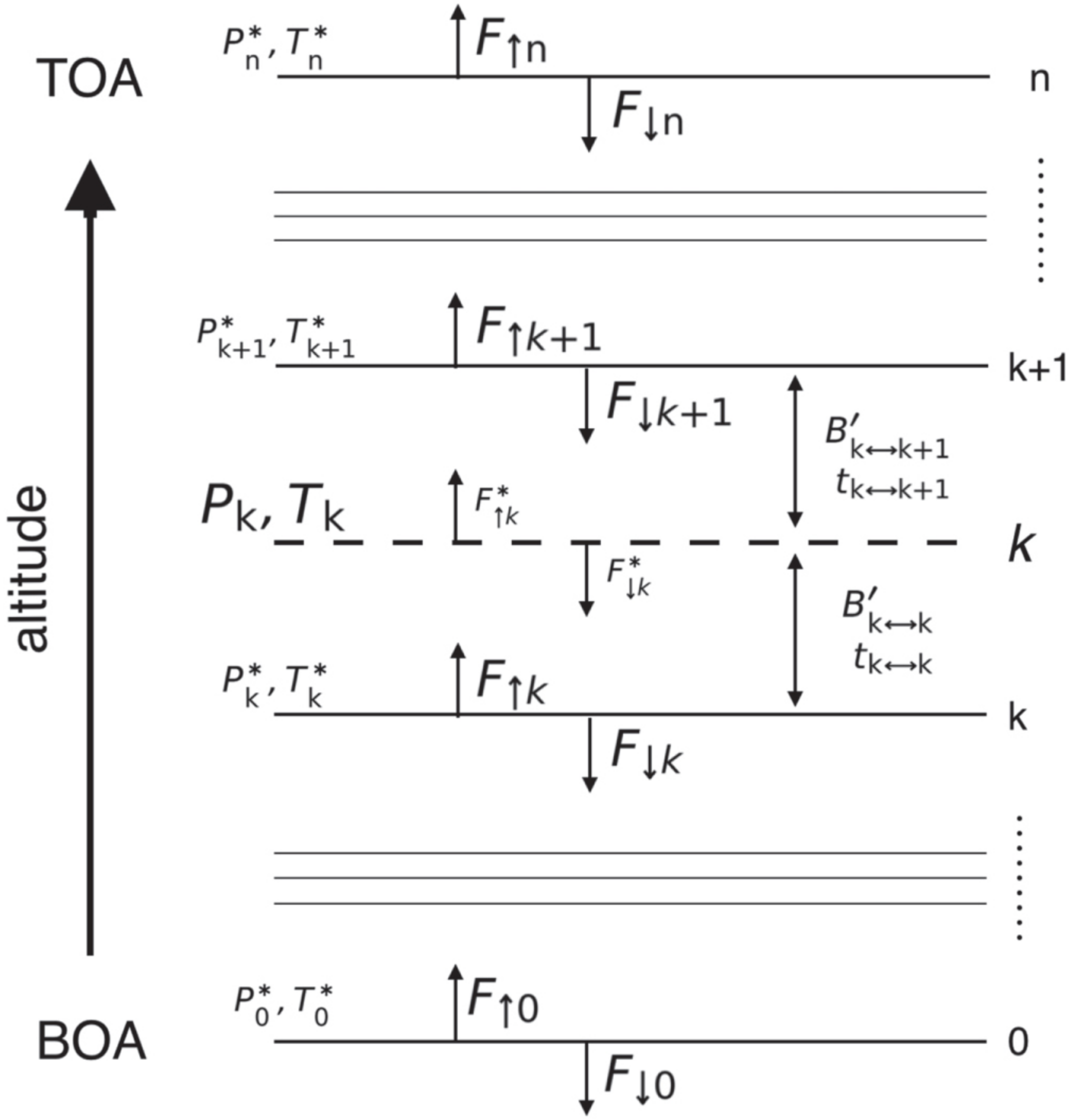
Input:

- Surface pressure and temperature
- Atm. Composition (water-dominated)
- Mass and radius of planet from centre up to bottom of atmosphere

Pressure, temperature and altitude profiles



Solve radiative transfer equation



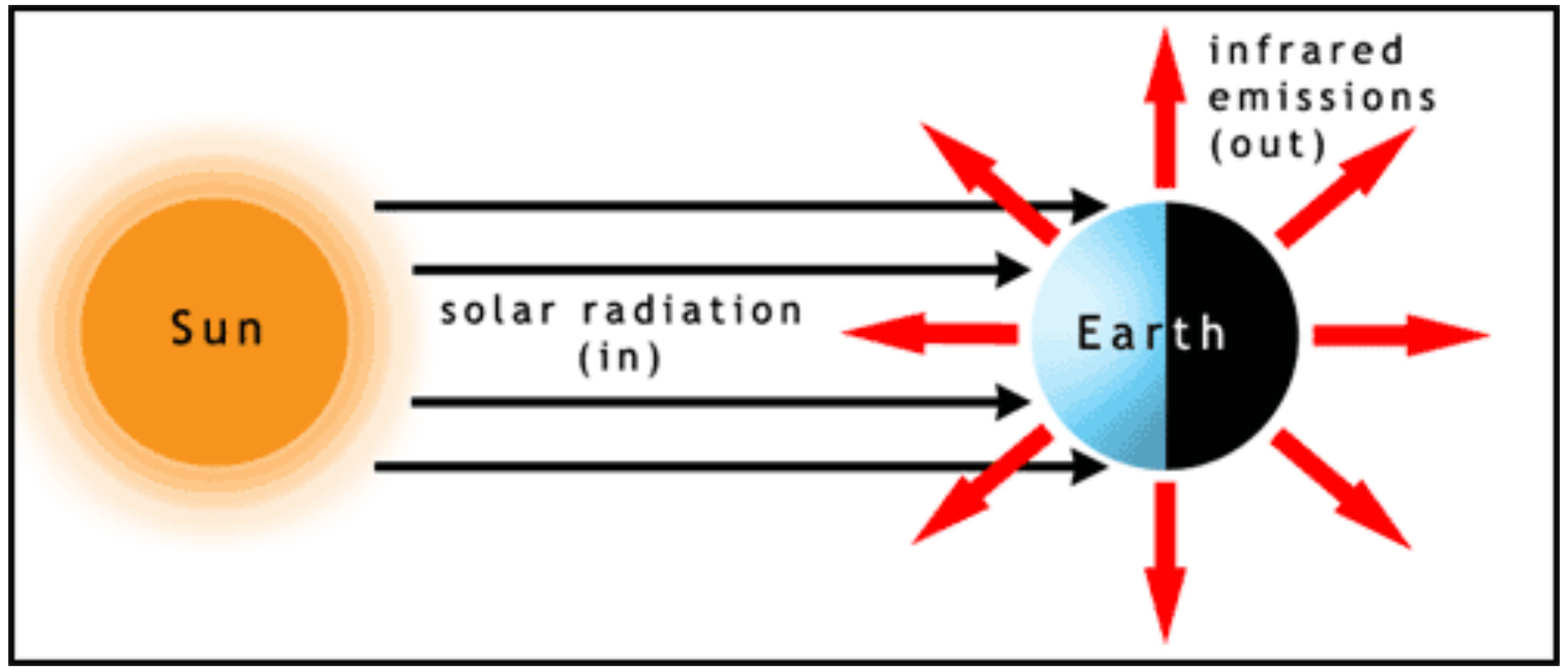
Output:

- Outgoing Longwave Radiation (OLR)
- Bond albedo (A_B)
- Atmospheric thickness and mass

Radiative-convective equilibrium (RCE)

Output:

- Outgoing Longwave Radiation (OLR)
- Bond albedo (A_B)



RCE condition:

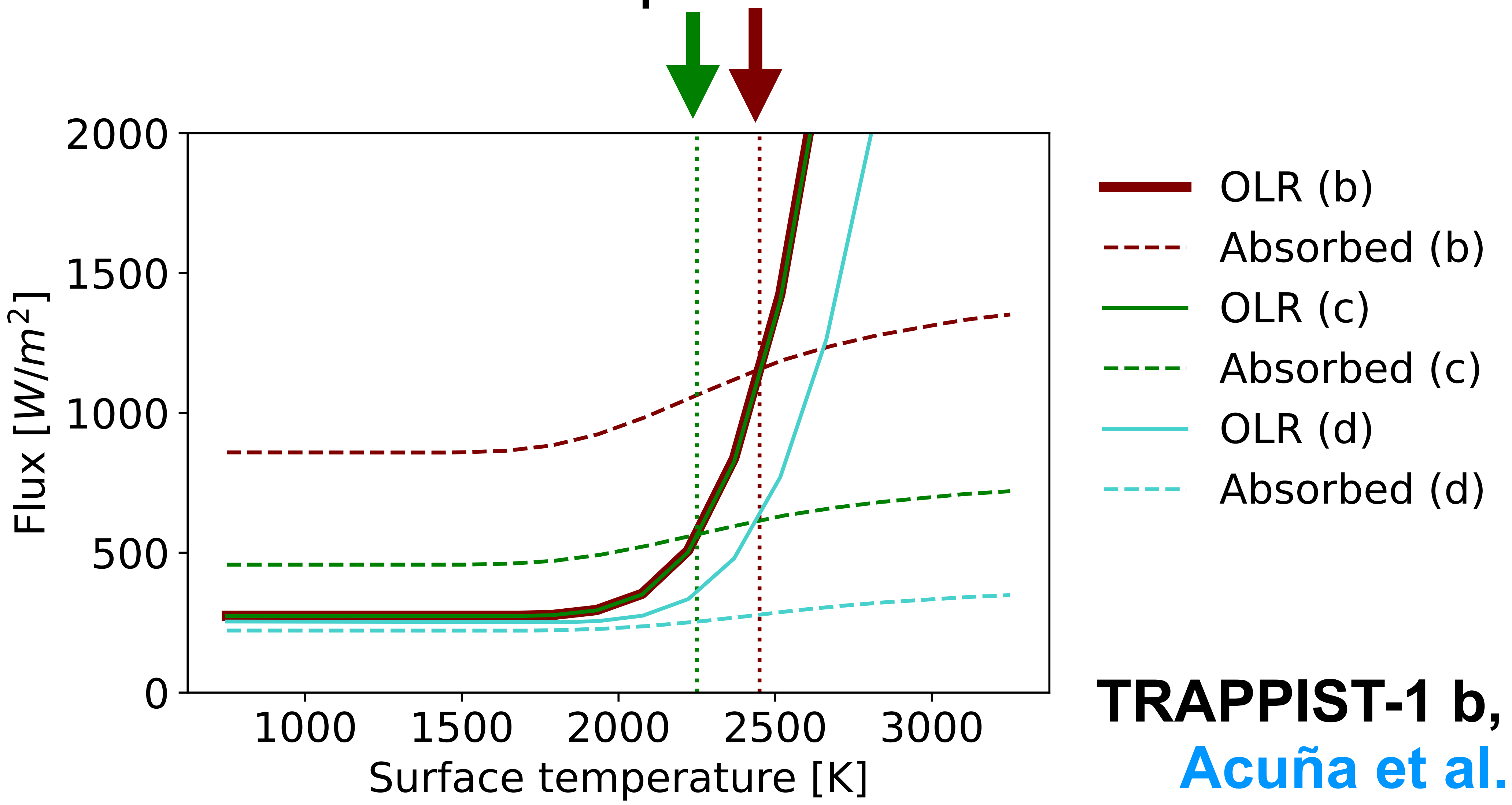
Emitted radiation equals absorbed radiation:

OLR - F_{abs} = 0

$$F_{abs} = \sigma T_{eq}^4$$

$$T_{eq} = (1 - A_B)^{0.25} \left(\frac{R_\star}{2a_d}\right)^{0.5} T_\star$$

Surface temperatures at RCE



TRAPPIST-1 b, c and d

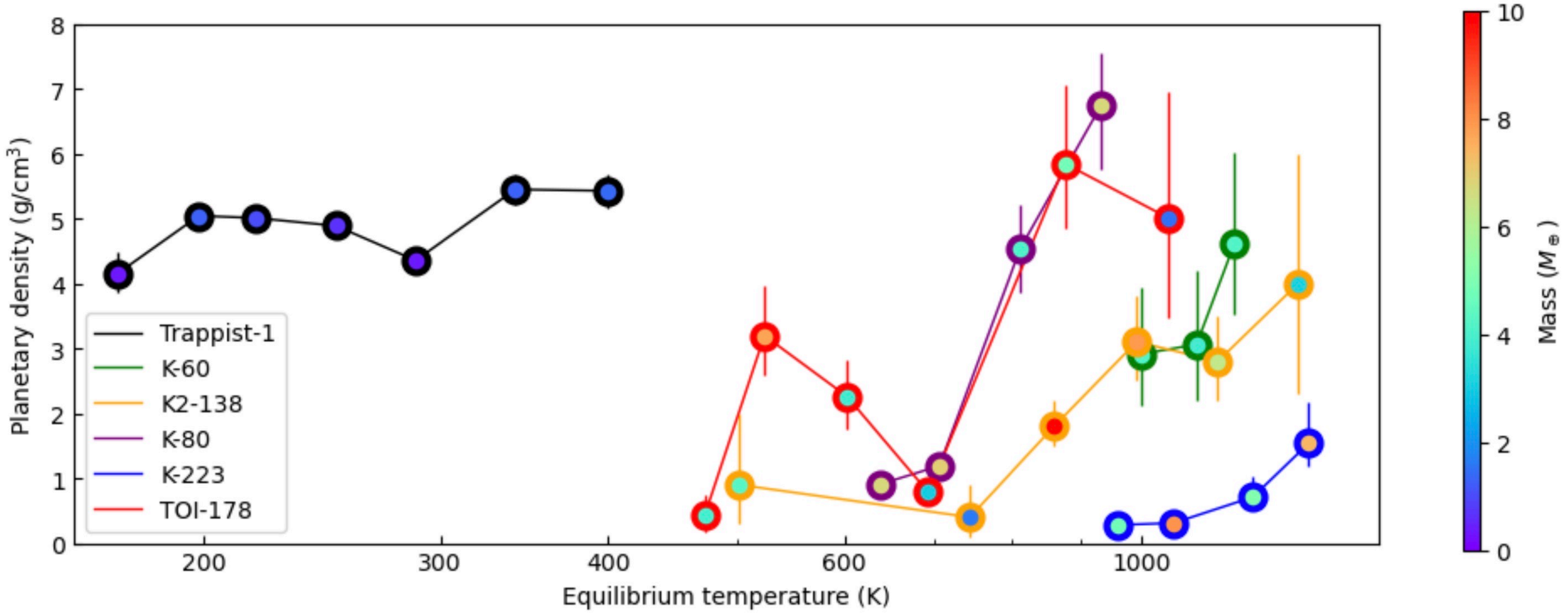
Acuña et al. 2021

Multiplanetary systems

- **Multiplanetary systems are environments suitable to explore the compositional diversity** of low-mass planets, their formation and evolution.

- Aim: Explore the compositional diversity of low-mass planets, in a **homogeneous analysis** to constrain their **formation** and evolution

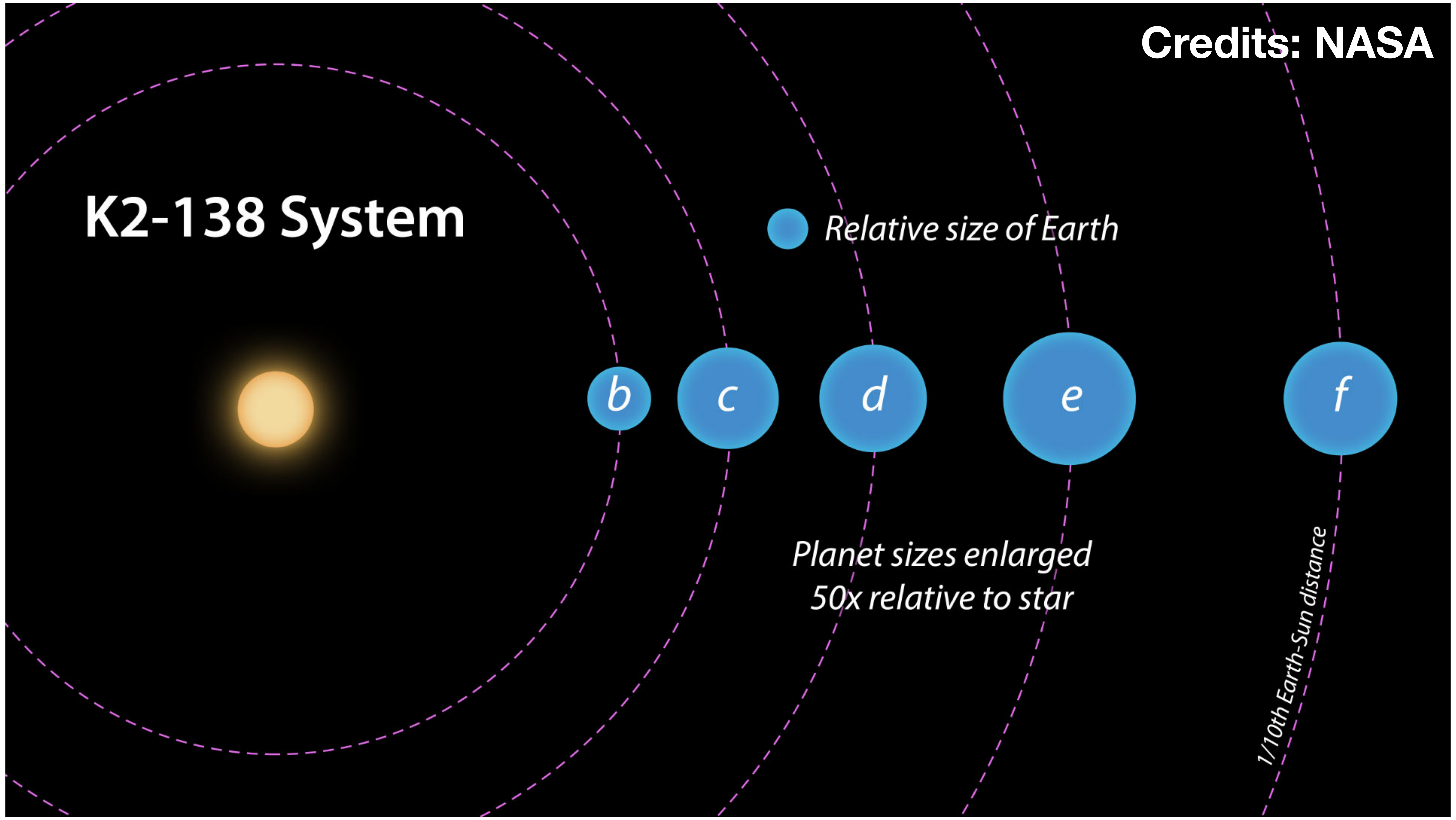
- Perform **MCMC retrievals on mass and radius data** to obtain **posteriors** for CMF and **WMF**



Leleu et al. 2021

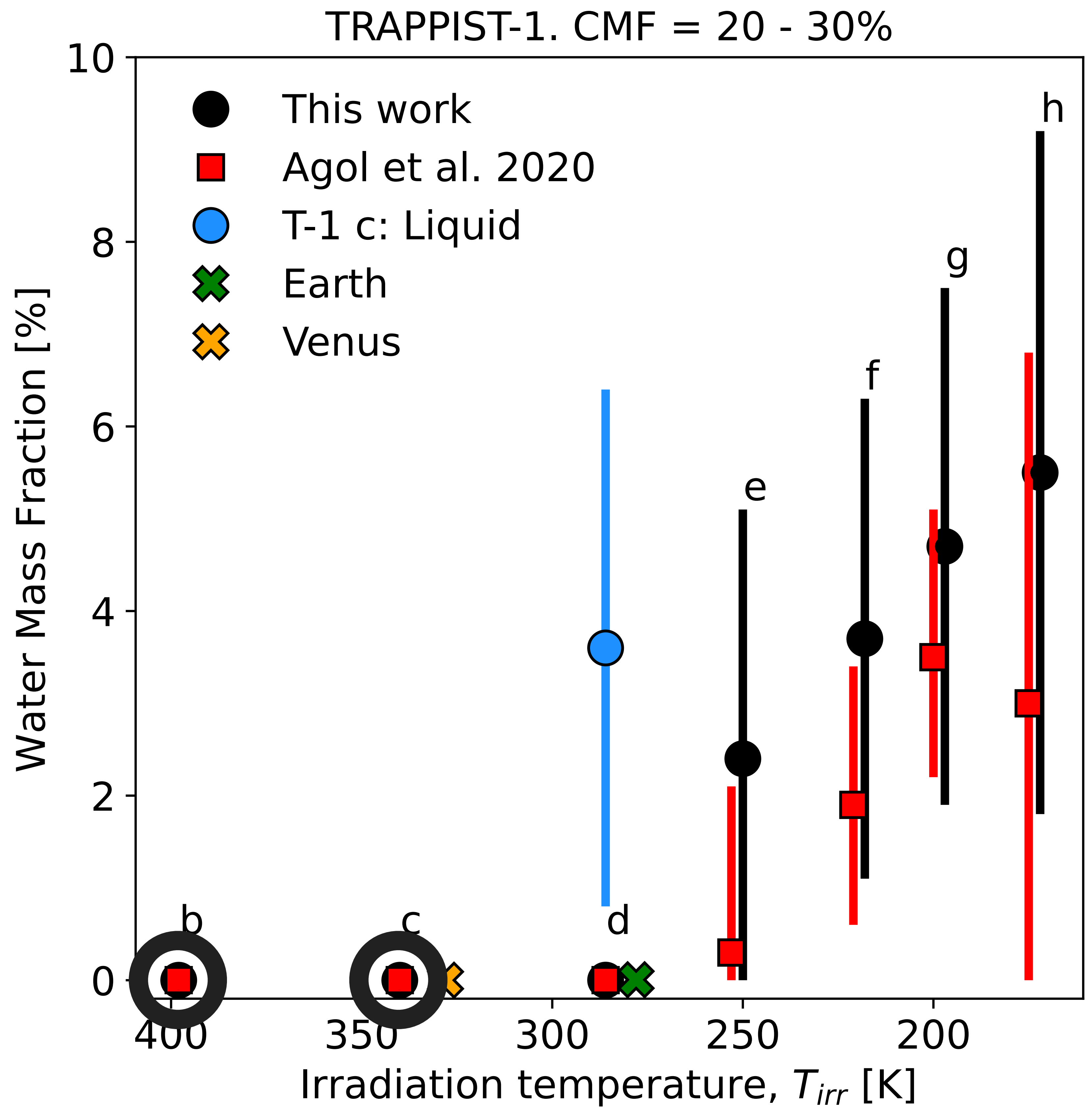
Multiplanetary systems

- Selection:
  - Low-mass planets ($M < 20\ M_\oplus$)
  - Systems with 5 or more planets
- Final sample:
  TRAPPIST-1 (**Acuña et al. 2021**)
  K2-138 (new RV masses by T. Lopez)
  TOI-178
  Kepler-11
  Kepler-102
  Kepler-80



TRAPPIST-1: Water mass fractions

- Planets b and c:
  - **Most likely no atmosphere** (see also talk by Elsa Ducrot, Greene et al. 2023, Ih et al. 2023)
  - Max. Surface pressure (T-1 c) = 80 bar (**Acuña et al. 2023**)



Acuña et al. 2021

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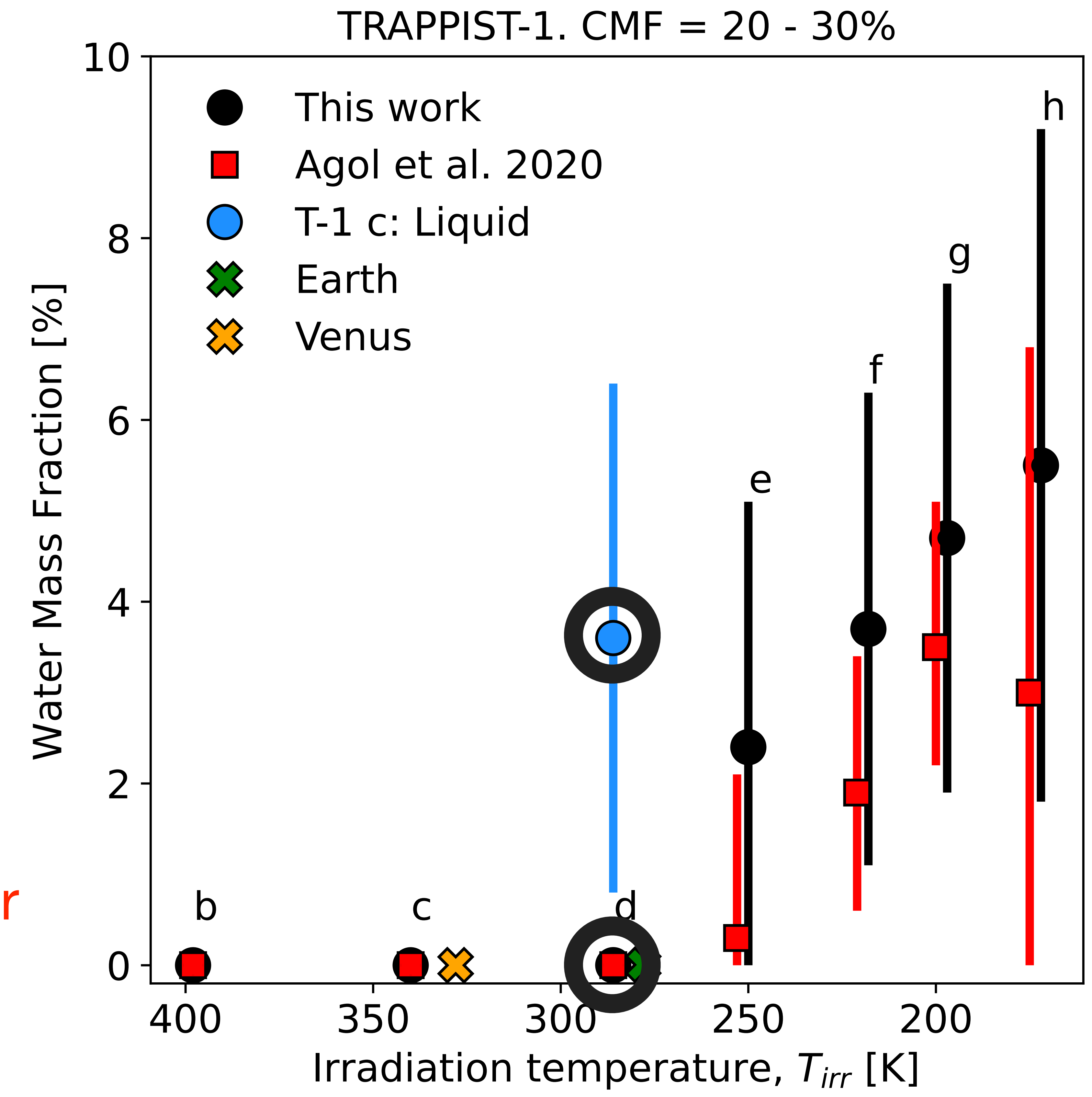
- Planet d:
    - Observed mass and radius also compatible with **with water vapor in a CO_2-dominated envelope (up to 300 bar)**



T-1 d: liquid water phase (unlikely)

T-1 d: water vapour with N_2 and CO_2 background

Acuña et al. 2021

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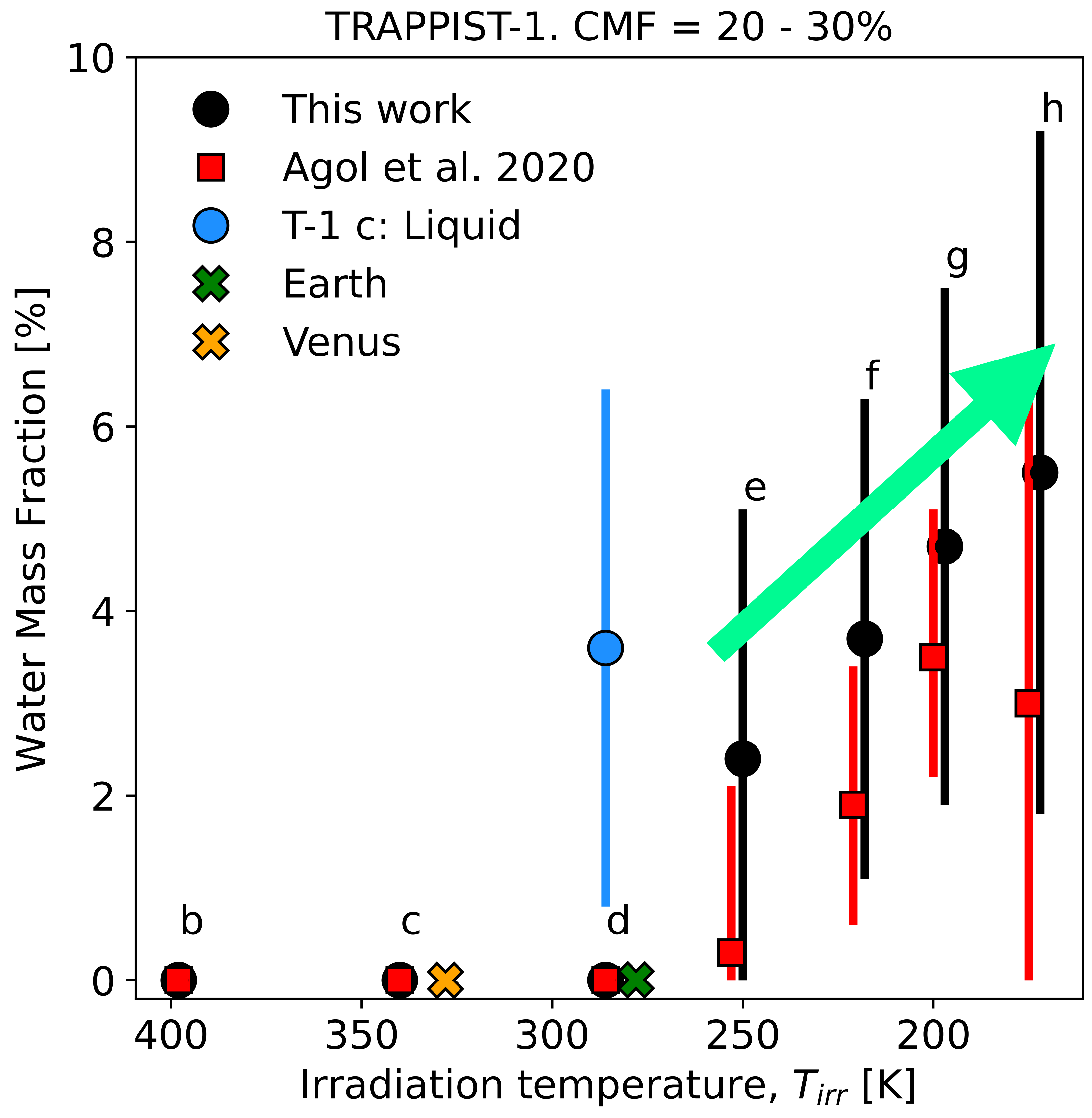
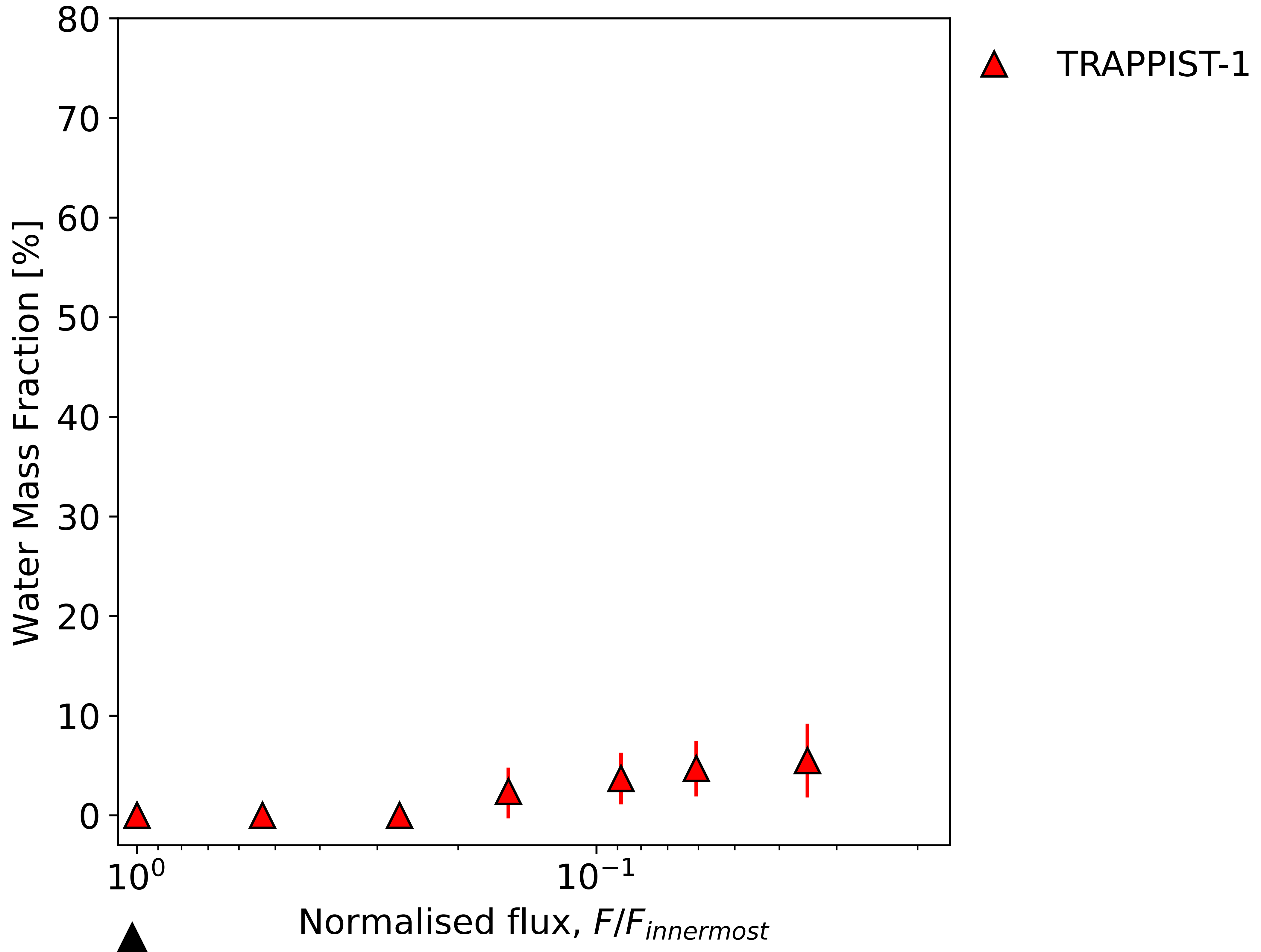
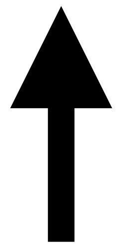
- Planet d:
  - Observed mass and radius also compatible with **with water vapor in a CO_2-dominated envelope (up to 300 bar)**
- **WMF increases with distance from star**



Acuña et al. 2021

Water mass fraction in multiplanetary systems



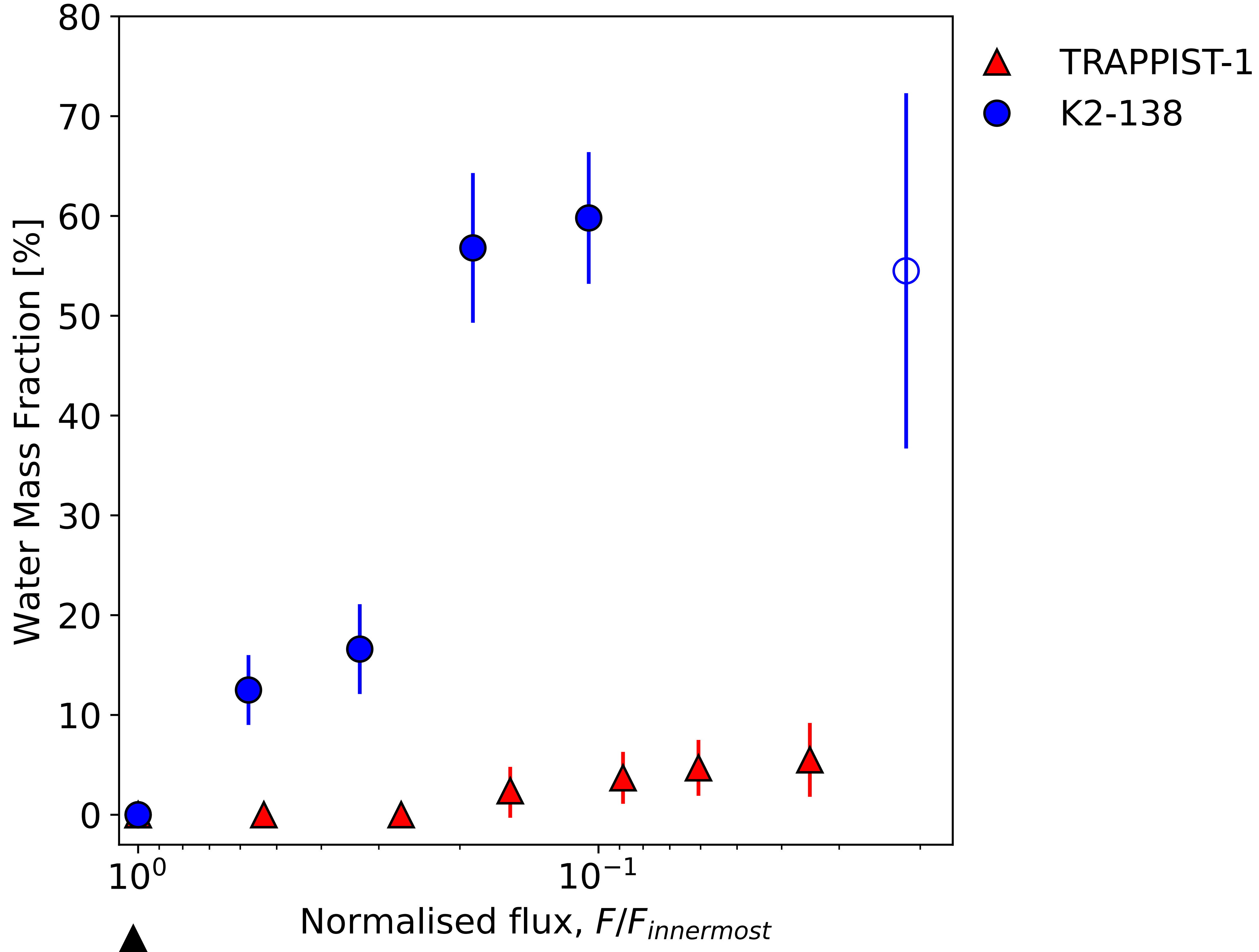


Innermost planet in each system

Acuña et al. 2022

Water mass fraction in multiplanetary systems

- **TRAPPIST-1 and K2-138**: clear increasing WMF trend

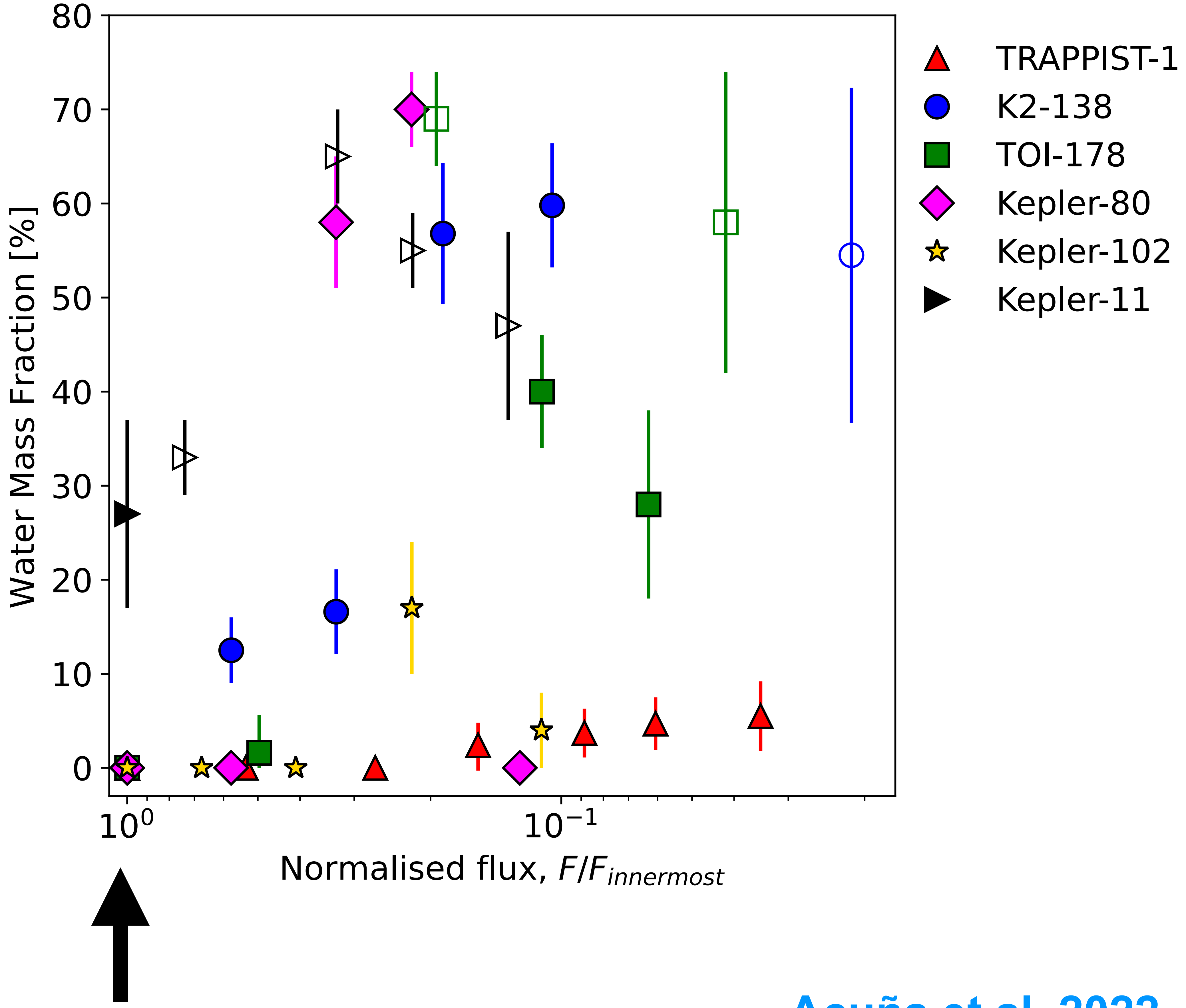


Innermost planet in each system

Acuña et al. 2022

Water mass fraction in multiplanetary systems

- **TRAPPIST-1 and K2-138**: clear increasing WMF trend
- **<u>Diversity in WMF trends</u>**
- All systems have in common:
  - **Inner planets** tend to be dry
  - **Volatile-rich** (water or H/He planets) are in outer part

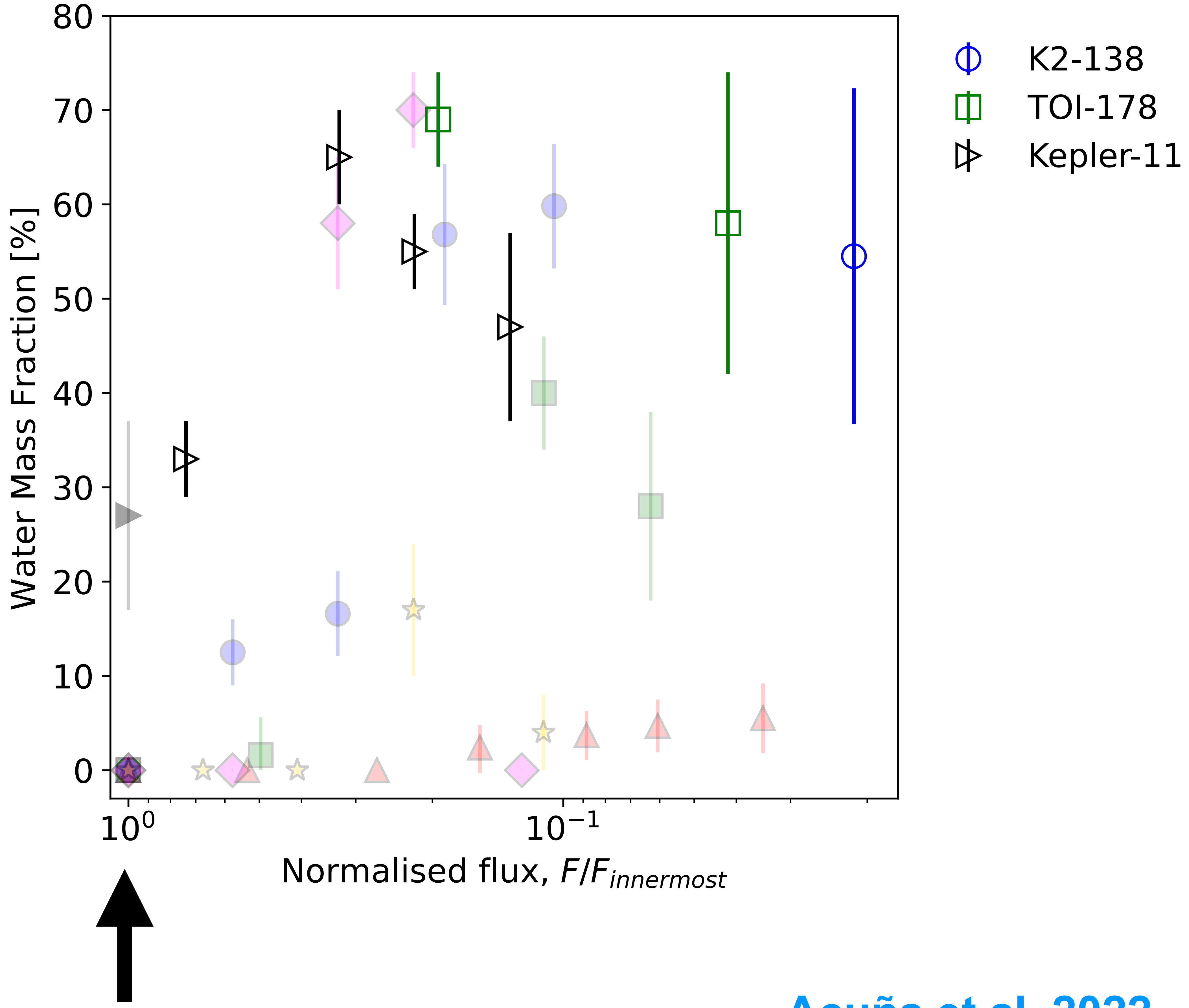


Innermost planet in each system

Acuña et al. 2022

H/He envelopes

- Some planets are not compatible with water envelopes in hydrostatic equilibrium
- **We quantify the likelihood of water envelopes:**
  - $R_{water} < R_{observed}$: empty markers
- H/He envelope, atmospheric escape, or both?
  - We **estimate Jeans and XUV atmospheric escape** in the energy-limited approximation (**Aguichine et al. 2021**)



Innermost planet in each system

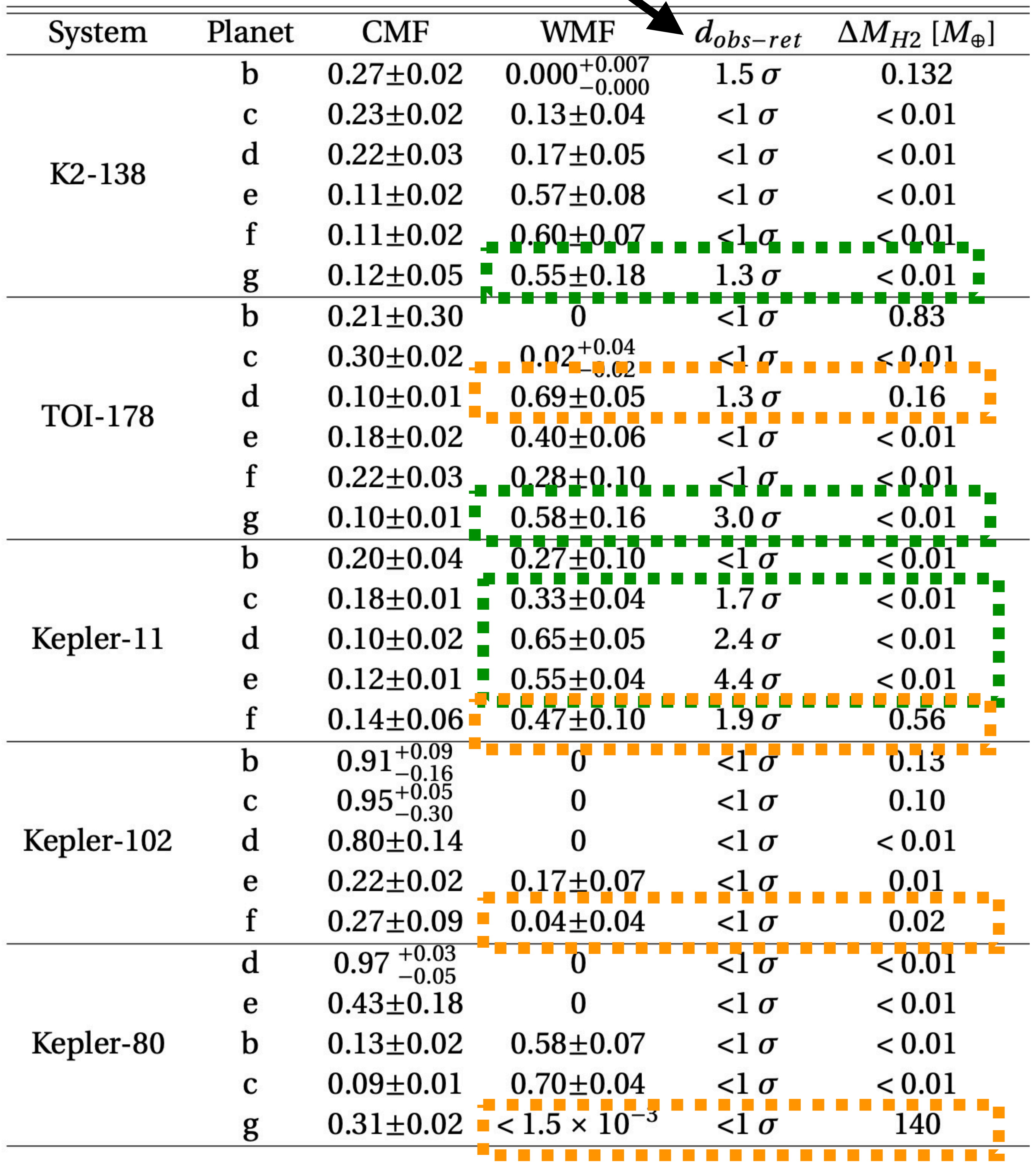
Acuña et al. 2022

Planet formation in multiplanetary systems

- Planets with $R_{water} < R_{observed}$:
  - Planets with **H/He envelopes** are in outer part of system.
  - Some planets undergo **Jeans escape**
- Planet formation mechanisms:
  - Volatile-rich, outer planets: formation in the **vicinity of water ice line**
  - Rocky, inner planets: formation close to **refractory (Fe,Si) lines**. Jeans and XUV atmospheric escape.

Difference between R_{water} and $R_{observed}$

Mass lost due to Jeans escape



System	Planet	CMF	WMF	$d_{obs-ret}$	ΔM_{H2} [$M_\oplus$]
K2-138	b	0.27±0.02	$0.000^{+0.007}_{-0.000}$	1.5 σ	0.132
	c	0.23±0.02	0.13±0.04	<1 σ	< 0.01
	d	0.22±0.03	0.17±0.05	<1 σ	< 0.01
	e	0.11±0.02	0.57±0.08	<1 σ	< 0.01
	f	0.11±0.02	0.60±0.07	<1 σ	< 0.01
	g	0.12±0.05	0.55±0.18	1.3 σ	< 0.01
TOI-178	b	0.21±0.30	0	<1 σ	0.83
	c	0.30±0.02	$0.02^{+0.04}_{-0.02}$	<1 σ	< 0.01
	d	0.10±0.01	0.69±0.05	1.3 σ	0.16
	e	0.18±0.02	0.40±0.06	<1 σ	< 0.01
	f	0.22±0.03	0.28±0.10	<1 σ	< 0.01
	g	0.10±0.01	0.58±0.16	3.0 σ	< 0.01
Kepler-11	b	0.20±0.04	0.27±0.10	<1 σ	< 0.01
	c	0.18±0.01	0.33±0.04	1.7 σ	< 0.01
	d	0.10±0.02	0.65±0.05	2.4 σ	< 0.01
	e	0.12±0.01	0.55±0.04	4.4 σ	< 0.01
	f	0.14±0.06	0.47±0.10	1.9 σ	0.56
Kepler-102	b	$0.91^{+0.09}_{-0.16}$	0	<1 σ	0.13
	c	$0.95^{+0.05}_{-0.30}$	0	<1 σ	0.10
	d	0.80±0.14	0	<1 σ	< 0.01
	e	0.22±0.02	0.17±0.07	<1 σ	0.01
	f	0.27±0.09	0.04±0.04	<1 σ	0.02
Kepler-80	d	$0.97^{+0.03}_{-0.05}$	0	<1 σ	< 0.01
	e	0.43±0.18	0	<1 σ	< 0.01
	b	0.13±0.02	0.58±0.07	<1 σ	< 0.01
	c	0.09±0.01	0.70±0.04	<1 σ	< 0.01
	g	0.31±0.02	$< 1.5 \times 10^{-3}$	<1 σ	140

Acuña et al. 2022

Conclusions

- Our **homogeneous analysis** on the composition of planets in **multiplanetary systems:**
  - show a clear **separation** between the **inner, dry** planets, and the **outer, volatile-rich** planets.
  - our CMF and WMF estimates can be used to constrain **formation site** with respect to **ice and refractory lines**, and formation mechanisms, such as **Jeans escape**.
  - Inner planets typical **WMF < 5%**. Moderately volatile-rich sub-Neptunes have **WMF = 10 - 25%**. Sub-Neptunes with **WMF > 30% are good candidates for H/He envelopes.**